

**UNIVERSITY OF CUKUROVA
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

Ph.D. THESIS

Ali Eren ŞİMŞEK

**DIJET RESONANCE SEARCH WITH THE CALO-SCOUTING
TECHNIQUE USING 122 fb^{-1} OF RUN 2 DATA FROM CMS at $\sqrt{s} =$
13 TEV**

DEPARTMENT OF PHYSICS

ADANA, 2022

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DEPARTMENT OF PHYSICS

We certify that the thesis titled above was reviewed and approved for the award of degree of the Doctor of Physics by the board of jury on 01/09/2022.

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Sevgili Doruk'uma...

ÖZ

DOKTORA TEZİ

**CMS'DE $\sqrt{s} = 13$ TEV'DE ALINAN 122 fb^{-1} VERİ KULLANILARAK
CALO-SCOUTING TEKNİĞİ İLE DİJET REZONANS ARAŞTIRMASI**

Ali Eren ŞİMŞEK

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Bu çalışmada çift-jetler halinde bozunan rezonans aramaları, 122 fb^{-1} toplam parlaklığa karşılık gelen ve $\sqrt{s} = 13$ TeV'de toplanan proton-proton çarpışma verileri kullanılarak yapılmıştır. Kalorimetre bilgilerinden tetikleyici seviyesinde yeniden yapılandırılan çift-jetler ile, olaylara dayalı olarak 0.6 ve 1.6 TeV arasındaki kütleli rezonanslar için düşük kütleli bir arama gerçekleştirilmiştir. Dijet kütle tayfı, uygun bir parametreleştirme ile iyi tanımlanmıştır ve yeni parçacıkların üretimi için hiçbir kanıt gözlenmemiştir. %95 güven seviyesindeki (CL) üst sınırlar, dar kuark-kuark, kuark-gluon ve gluon-gluon rezonanslarının üretim tesir kesitinde sunulmuştur.

Anahtar Kelimeler: Çift Jet, Quark, Gluon, Rezonans, CMS

ABSTRACT

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Resonance searches that decay into jet pairs are performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of up to 122 fb^{-1} . A low mass search is performed for resonances between 0.6 and 1.6 TeV based on events with dijets that reconstructed at the trigger level from the calorimeter information. The dijet mass spectrum is well defined with proper parameterization and no evidence was observed for the production of new particles. 95% CL upper limits are presented on the cross-section of narrow quark-quark, quark-gluon, and gluon-gluon resonances.

Key Words: DiJet, Quark, Gluon, Resonance, CMS

GENİŞLETİLMİŞ ÖZET

Standart modelin genişletilmiş fizik modelleri, sıklıkla çift-jetlere bozunan, gluonlara ve kuarklara bağlanan yeni parçacıklar gerektirir. Çift-jet kütle spektrumundaki (m_{jj}) rezonansların doğal genişliği, çiftlenme ile artar. Bu durum, deneysel çözünürlüğe kıyasla dar rezonanstan geniş rezonansa kadar değişebilir. Örneğin, karanlık madde (DM) parçacıklarının bir DM aracı tarafından kuarklara bağlandığı bir modelde, bu aracı bir çift DM parçacığına veya jetlere bozunabilir ve bu nedenle, bir çift-jet rezonansı olarak gözlenebilir. Bu, çiftlenme gücüne bağlı olarak geniş veya dar bir rezonans olabilir. Gözlenen şekil, rezonans geniş olduğunda önemli ölçüde rezonans spin değerine bağlıdır. Deneysel çözünürlükle karşılaştırıldığında, her iki yaklaşım da küçük iç genişliğe sahip rezonanslara duyarlıdır. Ancak geniş rezonans aramaları, daha büyük iç genişliğe sahip rezonanslara da duyarlıdır.

BHÇ Run-I'deki veri keşif başarısı, Run-II için stratejiler geliştirmesinin yolunu açtı. Bu stratejilerde, 2012 yılında olduğu gibi kalorimetre jetleri kullanılarak çok düşük H_T değerlerinde keşif kabiliyetinin devam ettirilmesi amaçlanmıştır. 2015 ve 2016 yıllarında alınan veriler HLT'de iki akıma ayrılmaktadır: Birincisi Kalo-İzcilik, ikincisi ise Parçacık Akışı'dır. 2016'daki kalo-izcilik yöntemi ile toplanan veriler, 0.6 TeV ile 1.6 TeV arasındaki çift-jet rezonans kütlelerini aramak için kullanılmış ve bu çalışmalar 27 fb^{-1} pp çarpışma verileriyle gerçekleştirilmiştir. CMS deneyindeki dedektör güncelleme ve yükseltmeleri (foto çoğaltıcıların, radyasyondan zarar görmüş malzemelerin değiştirilmesi ve parçacıkların saçıldığı alanlarda daha verimli malzemelerin kullanılması gibi), düşük kütleli çift-jet rezonanslarında yeni parçacıkların keşfi için önemlidir. Bu araştırmada; 2011-2012 yılları arasında yürütülen düşük kütleli çift-jet rezonans çalışmaları, 2016, 2017 ve 2018 yıllarına ait henüz araştırılmamış veriler ile tekrarlanmıştır.

Deneysel yaklaşımımız, CMS deneyinden elde edilen verilerde çift-jet kütle spektrumu ölçüm yöntemini kullanarak çift-jet rezonanslarını araştırmaktır. Çift-jet olay seçimi, değişmez kütle spektrumunu ölçmek için birbirinin karşısına yerleştirilmiş iki Yüksek P_T 'li jeti gerektirir. Bir çift-jet rezonansı varsa rezonans, çift-jet kütle spektrumunda bir tümsek olarak görünmelidir.

Analizde, Run-II sürecinde CMS dedektöründe alınan veriler kullanılmıştır. İlk olarak, veri keşif ve verimlilik çalışması için uygun bir tetikleme belirlenmiştir. Olayların yeniden yapılandırılması, CMS dedektöründe keşif analizine göre gerçekleştirilmiştir. Parçacıklar, Calo-İzcilik yeniden yapılandırma teknikleri kullanılarak ayrı ayrı tanımlanmıştır. Olayların yeniden yapılandırılması işlemlerinin amacı, olaydaki kararlı parçacıkları tanımlamak ve yönlerini, enerjilerini ve tiplerini belirlemektir. Bu işlemin sonucunda seçilen parçacıklar, daha sonra anti-kT algoritması kullanılarak jetler halinde kümelendirilmiştir. Ayrıca bu aşamada, jetler için PF Jet Enerjisi Düzeltmesi (JEC) uygulanmıştır. PYTHIA'dan gelen QCD öngörüsü (Monte Carlo (MC) - simülasyon verileri), dedektörde ölçülen çift-jet kütle spektrumu ile kıyaslanmıştır. Elde edilen sonuçlara göre; MC ve dedektör verilerinin yüksek oranda uyduğu belirlenmesi, kullanılan JEC'lerin istatistiksel olarak yüksek oranda doğru olduğunu göstermiştir.

CMS deneyinde alınan veriler ile teorik şartlarda hazırlanan simülasyon verilerinin iyi bir uyum içinde olması durumunda, veri analizinde seçilen fizik objelerinin yüksek oranda doğru yapılandırıldığı ve dedektörden gelen gürültü katkısının dışarılandığı sonucuna varılmıştır. Doğruluğundan emin olunan çift-jet kütle dağılımındaki tümsek oluşumlarına bakmak için dağılıma bir fonksiyon eğrisi uydurmak (fit) gerekmektedir. Bunun için 4, 5 ve 6 parametrelili standart çift-jet fit fonksiyonlarını kullanarak veriye en uyumlu olan eğri belirlenmeye çalışılmıştır.

Fit olasılık değerleri 2016 yılı verileri için en iyi, 2017 ve 2018 verileri için

kötü ve maalesef tüm Run-II için kabul edilemez oranda sonuçlar vermiştir. Tüm Run-II verilerinin fit ve olasılık sonuçlarını iyileştirmek için 2017 ve 2018 verileri kalibre edilmelidir. Kalibrasyon işlemi için 2017 ve 2018 verileri, düzgün kalibrasyon faktörleri ile çarpılmıştır. Bu kalibrasyon faktörleri; 2017 ve 2018 yılı tesir kesiti fit sonuçlarının, 2016 yılı tesir kesiti fit sonuçlarına bölünmesi ile elde edilmiştir. 2017 ve 2018 yılı kalibrasyonları; bireysel veri kümelerinin istatistiksel dalgalanmalarını değiştirmezken, üç yılın veri kümelerinin toplanması ile oluşturulan Run-II veri kümesindeki istatistiksel dalgalanmaları çok az değiştirmiştir. Kalibrasyondan sonra, χ^2 değeri biraz daha iyi hale gelmiştir.

Limit sonuçları düzgün ve kararlı görünse de, negatif maksimum olasılık (Delta-NLL) grafikleri kararsızlık göstermiştir ve noktalar tek bir eğri oluşturmamıştır. Sonuçların kararlılığını artırmak için veri setlerini daha düşük parlaklığa karşılık gelen parçalara bölme kararı verilmiştir. Bu yaklaşım, daha kararlı limitlere ve Delta-NLL sonuçlarına sahip olmamızı sağlamıştır. Sonuç olarak, veri setlerinin tüm parçaları için çok kararlı limitler elde edilmiştir. Bu sonuçlar, yüksek miktarda veri ile üretilen Delta-NLL eğrileri ve limitlerinde kararsızlıkların oluştuğunu kanıtlamaktadır. Bu durumda daha küçük parlaklığa karşılık gelen parçaları ile limitler belirlemek ve bunları istatistiksel olarak birleştirmek sonuçların kararlılığını arttırmıştır.

Çift-jet rezonans aramaları, $\sqrt{s}=13$ TeV’de, 122.2 fb^{-1} toplam parlaklığa karşılık gelen proton-proton çarpışmaları kullanılarak gerçekleştirilmiştir. Düşük kütleli aramalar, HLT tarafından yeniden oluşturulan ve sıkı bir biçimde kaydedilen kalorimetre jetleri üzerinde gerçekleştirilmiştir. Çift-jet kütle spektrumunun düzgün azalan dağılımlar oluşturduğu gözlenmiştir. Ne yazık ki, analiz edilen veri örneklerinde parçacık rezonans üretimine dair bir kanıt bulunamamıştır. Dar rezonanslar (gg, qg, qq) için üretim tesir kesitinde 95% güven düzeyinde sunulan

genel üst limitler, daha önce yayınlanmış 2016 yılı limit sonuçlarından yaklaşık iki kat daha iyi limit ile belirlenmiştir. Ayrıca, DM aracı ile kuark çiftlenim limitlerinin genişletilmesinde önemli ilerlemeler kaydedilmiştir. Elde edilen limit sonuçları, çift-jet izciliği araştırmalarında daha önce bildirilen limitleri önemli ölçüde genişletmiştir.



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ABBREVIATIONS

CERN	: Conseil Européen pour la Recherche Nucléaire
LHC	: Large Hadronic Collider
CMS	: Compact Muon Solenoid
ATLAS	: A Toroidal LHC ApparatuS
ALICE	: A Large Ion Collider Experiment
LHCb	: Large Hadron Collider beauty
ECAL	: Electromagnetic Calorimeter
HCAL	: Hadronic Calorimeter
HGCAL	: High-Granularity Calorimeter
σ	: Cross Section or Standard Deviation
DM	: Dark Matter
pp	: Proton-Proton
$\sqrt{s}$	: Center-Of-Mass
m_{jj}	: Di-Jet Mass
H_T	: Scalar Sum of Jet Transverse Momentum
L1	: Level-1 Trigger
HLT	: High-Level Trigger
PF	: Particle Flow
CALO	: Calorimeter
P_T	: Transverse Momentum
QCD	: Quantum Chromodynamics
MET	: Missing Transverse Energy
Jet-ID	: Jet identification

q^*	: Excited Quarks
qq	: Quark-Quark
qg	: Quark-Gluon
gg	: Gluon-Gluon
<i>MIP</i>	: Minimum Ionizing Particle
kA	: Kilo Ampere
GJ	: Giga Joule
CNGS	: The CERN Neutrinos To Gran Sasso Project
CL	: Confidence Level
BW	: Breit-Wigner
SiPM	: Silicon Photo-Multiplier
PCB	: Printed Circuit Board
CE-E	: HGCAL Electromagnetic Part
CE-H	: HGCAL Hadronic Part
Cu	: Copper
Pb	: Lead
CO ₂	: Carbon Dioxide
CuW	: Carbon Tungsten
MIP	: Minimum Ionizing Particle
n_{eq}	: Number of Neutrons Equivalent to 1 MeV / cm ²
pF	: picoFarad
S/B	: Signal / Background
HGCROC	: Readout ASIC Designed for HGCAL
ASIC	: Application-Specific Integrated Circuit
HE	: Hadronic Endcap
HB	: Hadronic Barrel

HO	: Hadronic Outer
HF	: Hadronic Forward
EB	: Electromagnetic Barrel
EE	: Electromagnetic Endcap
CALICE	: Calorimeter for Linear Collider Experiment
AHCAL	: Analog Hadronic Calorimeter
r	: Radius
FNAL	: Fermi National Accelerator Laboratory
DWC	: Delay Wire Chamber
SCIROC-2	: 64-channel front-end ASIC
PMT	: Photo-Multiplier Tube
ZedBoard	: A Complete Development Kit
DDC	: Dual-Daughterboard Carrier
FH	: Front Hadronic Calorimeter
BH	: Backing Hadronic Calorimeter
DESY	: Deutsches Elektronen-Synchrotron
Mylar	: Polyester Film
DAQ	: Data Acquisition
JEC	: Jet Energy Correction
JES	: Jet Energy Scale
JER	: Jet Energy Resolution
FPGA	: Field Programmable Gate Array
DT	: Drift Tube
SR	: Synchrotron Radiation
G4BL	: G4Beamline



1. INTRODUCTION

Standard Model (SM) has successfully passed all the tests performed so far. It can predict many parameters very precisely. In spite of all these achievements, it is inevitable that SM is an incomplete theory because it cannot answer the ongoing problems such as dark matter, dark energy, neutrino masses, matter, and anti-matter asymmetry. SM also does not include general relativity. Many theories such as Super-symmetry and String theory have been developed to answer such questions that SM cannot explain.

Many experiments were carried out around the world to test SM and these theories, especially in the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), the world's most advanced particle laboratory. One of the most significant experiments in LHC is the Compact Muon Solenoid (CMS) Experiment, which looks for the existence of very short-lived new particles called resonance, which is predicted by the theories that SM cannot explain. The aim of this research is to investigate these resonance particles in the dijet final state using proton-proton (pp) collisions with $\sqrt{s} = 13$ TeV energy. The discovery of these particles will be a big contribution to our understanding of the physics theories beyond SM and hence the structure of the universe.

Physics models that allow the extension of SM over a wider area frequently require new particles that decay into dijets and are attached to gluons and quarks. The natural width of the resonances in the dijet mass spectrum (m_{jj}) increases with coupling. This can range from narrow resonance to broad resonance compared to experimental resolution. For example, in a model in which dark matter (DM) particles are bound to quarks by a DM Mediator, this mediator can decay into a pair of DM particles or jets and therefore can be observed as a dijet resonance. This can be a broad

or narrow resonance depending on the strength of the coupling. The observed shape depends significantly on the resonance spin when the resonance is broad. Compared to experimental resolution, both approaches are sensitive to resonances with small internal widths, but a broad resonance search is also sensitive to resonances with larger internal widths [A. M. Sirunyan et al., 2018].



2. THEORETICAL OVERVIEW

The LHC provides a $\sqrt{s} = 13$ TeV pp beam intersecting with a 40-MHz maximum rate. The CMS detector produces an unprecedented amount of raw collision data. While many of them are potentially suitable for physical analysis, complete reconstruction of all collision events is impossible with the existing computing resources. For this reason, the CMS uses a two-level trigger system; Level-1 Trigger (L1) and High-Level Trigger (HLT).

The CMS L1-Trigger is hardware-based and makes a pre-selection for the physics events. It reduces the approximately 40-MHz input event rate to roughly 100-kHz. HLT is a software-based system with over 500 triggering methods running on custom processor farms. In this stage, HLT selects approximately 100-Hz events and sends them to the recording system.

HLT reconstructs physics objects to determine an appropriate trigger for each event and then applies a selection based on the reconstructed object's properties. Trigger methods also include filter modules that reject events that do not meet specific criteria. Most of the trigger methods include filtering and multiple reconfiguration stages. Physics objects whose performance is close to their offline counterparts are given to the restructuring stages, and events that can reach the end of any trigger method are accepted [D. J. Anderson, 2016].

2.1. History of Scouting in CMS Detector

The first scouting trigger was used on the CMS-HLT during the 2011 LHC run. 0.13 fb^{-1} data was collected on the trigger and associated stream. Events with the scalar sum of the jet transverse momentum (H_T) 350 GeV were selected and recorded in reduced format containing only the reconstructed jet set from the Particle Flow (PF) candidates by the HLT algorithm. The data were used to search for heavy resonances

that decay into dijets. The research demonstrated the resonance sensitivities between 600 and 900 GeV. In this region, the standard CMS dijet resonance search was not available.

After 2011, the studies showed the discovery technique feasibility and repeated the technique for the entire 2012 CMS dataset. The scouting trigger selection cut was reduced to $H_T > 250$ GeV to achieve a greater event rate. Due to the Central Processing Unit (CPU) concerns, the calorimeter jets were reconstructed and saved instead of PF jets. 18.8 fb^{-1} data was used to perform a dijet resonance search similar to that performed in 2011. The search results were interpreted as limits on the mass and coupling of a hypothetical leptophobic Z' resonance that decayed to quarks [D. J. Anderson, 2016].

The data scouting success in the LHC Run-I led to the strategy development for Run-II. The aim is to continue the discovery ability at very low H_T values using calorimeter jets, as was done in 2012. The data received in 2015 and 2016 are divided into two streams in HLT: the first is the calo-scouting, and the second is the PF. Data collected in the calo-scouting in 2016 were used to search for dijet resonance masses between 0.6 TeV and 1.6 TeV. These studies were carried out with the 27 fb^{-1} pp collision data [Mukherjee, 2017].

Detector update and upgrade progresses in the CMS experiment (such as replacing photo-multipliers, radiation-damaged materials, and using more efficient materials in the areas where particles are scattered) are important for the discovery of new particles in low-mass dijet resonance and other physics research. In this research; Low-mass dijet resonance studies conducted between 2011-2012 is being repeated with integrated data from 2016, 2017 and 2018 that have not yet been investigated.

2.2. Methodology

The experimental technique begins with the measurement of the inclusive process $pp \rightarrow jet + jet + anything$. The inclusive means that measuring processes contains at least two jets in the final state, but events are allowed to contain additional jets or anything else. The dijet system is represented by the two highest P_T jets, which are defined as the leading jets. In the SM, our dataset is expected to predominantly dominated by the $2 \rightarrow 2$ hard parton scattering process with additional radiation from the initial and final state partons that naturally provide additional jets. No cuts were used for these events, which contain similar amounts of radiation and unnecessarily limit the signals to a narrower topology.

Events may also include additional particles, such as leptons or photons, but this rarely occurs in the SM. In order to suppress some backgrounds produced by the presence of a false reconstructed high P_T muon, jets with a large energy contribution are removed from a reconstructed muon ($> 80\%$). The dijet selection is open to the signals of many new physics, including high P_T jets, leptons (except muons) and photons. However, the selection is optimized for the signals in $2 \rightarrow 2$ parton scattering and, thus, it dominates the dijets' signal background from Quantum Chromodynamics (QCD) in the SM.

2.3. Low Mass Calo-Scouting

The analysis is carried out on data collected in the CMS calo-scouting stream in Run-II. This stream contains events triggered by a special set of scouting triggering methods. Events in this stream are not quickly restructured. Instead, the relevant physics objects are restructured at the HLT level and saved directly. For each event, a list of the calo-jet 4-momenta and some additional information (for example; the missing transverse energy (MET) in the event) are recorded.

Calo-Scouting data samples in this analysis contains events selected by a trigger that requires $H_T > 250$ GeV at the HLT level. Table 2.1. shows the datasets used in this analysis.

Table 2.1. Datasets used for the low-mass Calo-Scouting analysis

<u>2016 ScoutingCaloHT Datasets</u>	<u>2017 ScoutingCaloHT Datasets</u>
/ScoutingCaloHT/Run2016B-v2/RAW	
/ScoutingCaloHT/Run2016C-v2/RAW	/ScoutingCaloHT/Run2017C-v1/RAW
/ScoutingCaloHT/Run2016D-v2/RAW	/ScoutingCaloHT/Run2017D-v1/RAW
/ScoutingCaloHT/Run2016E-v2/RAW	/ScoutingCaloHT/Run2017E-v1/RAW
/ScoutingCaloHT/Run2016F-v1/RAW	/ScoutingCaloHT/Run2017F-v1/RAW
/ScoutingCaloHT/Run2016G-v1/RAW	
<u>2018 ScoutingCaloHT Datasets</u>	
/ScoutingCaloHT/Run2018A-v1/RAW	
/ScoutingCaloHT/Run2018B-v1/RAW	
/ScoutingCaloHT/Run2018C-v1/RAW	
/ScoutingCaloHT/Run2018D-v1/RAW	

2.4. Event Pre-Selection

At least one reconstructed vertex is required with $|z| < 24$ cm. The primary vertex has the highest sum of P_T^2 of the associated tracks. The jet energies and momenta are corrected with test-beam results, simulation calibration constants, and pp collision data at $\sqrt{s} = 13$ TeV. All jets are required to have $P_T > 30$ GeV and $|\eta| < 2.5$. The two largest P_T jets are described as the leading jets. Jet identification (jet-ID) criteria are applied to eliminate fake jets related to the calorimeter noise. The Jet-ID for Calo-jets are required that the fraction of jet energy deposited within the electromagnetic calorimeter be between 5% and 95% of the total jet energy. An event is rejected if either of the two leading jets does not satisfy the jet-ID criteria [Albert M Sirunyan et al., 2017].

2.5. Wide-Jet Reconstruction and Event Selection

Geometrically close jets are combined into “wide-jets” and used to determine the dijet mass. The wide-jet algorithm, designed for dijet resonance event reconstruction, reduces the analysis sensitivity to gluon radiation from the final state partons. The two leading-jets are used as seeds and the 4-vectors of all other jets, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$ are added to the nearest leading jet to obtain two wide-jets, which then form the dijet system. The background is suppressed by requiring the pseudo rapidity separation of the two wide-jets to satisfy $|\Delta\eta| < 1.3$. These requirements maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD dijet background [A. M. Sirunyan et al., 2018].

2.6. Background Prediction Method (Fit Method)

In order to test the smoothness of the dijet mass spectrum, it should be fitted with a background-only function, and the various parameterizations (CMS, ATLAS, Mod-Exp, Poly-Ext, etc.) should be checked to find the most compatible function. These continuous functions have been used extensively in previous searches to fit the falling dijet spectrum.

2.6.1. Standard CMS Dijet Fit Functions

The standard 4, 5, and 6 parameters CMS dijet fit functions for the dijet scouting analysis, respectively defined as:

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)}} \quad (2.1)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)+p_4\log^2(x)}} \quad (2.2)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)+p_4\log^2(x)+p_5\log^3(x)}} \quad (2.3)$$

2.6.2. ATLAS Dijet Fit Functions

The 4, 5, and 6 parameters ATLAS dijet fit functions for the dijet scouting analysis, respectively defined as:

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0 e^{-p_2 x - p_3 x^2}}{x^{p_1}} \quad (2.4)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0 e^{-p_2 x - p_3 x^2 - p_4 x^3}}{x^{p_1}} \quad (2.5)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0 e^{-p_2 x - p_3 x^2 - p_4 x^3 - p_5 x^4}}{x^{p_1}} \quad (2.6)$$

2.6.3. Poly-Ext Dijet Fit Functions

The 5, 6, and 7 parameters Poly-Ext dijet fit functions for the dijet scouting analysis, respectively defined as:

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}(1+p_4x)}{x^{p_2+p_3*\log(x)}} \quad (2.7)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}(1+p_4x+p_5x^2)}{x^{p_2+p_3*\log(x)}} \quad (2.8)$$

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}(1+p_4x+p_5x^2+p_6x^3)}{x^{p_2+p_3*\log(x)}} \quad (2.9)$$

2.6.4. Mod-Exp Dijet Fit Functions

The 4 and 5 parameters Mod-Exp dijet fit functions for the dijet scouting analysis, respectively defined as:

$$\frac{d\sigma}{dm_{jj}} = p_0 * e^{(p_1 * x^{p_2} + p_1 * (1-x)^{p_3})} \quad (2.10)$$

$$\frac{d\sigma}{dm_{jj}} = p_0 * e^{(p_1 * x^{p_2} + p_3 * (1-x)^{p_4})} \quad (2.11)$$

2.7. Quantum Chromodynamics

QCD, the gauge field theory, describes the strong interactions of colored quarks and gluons. The Lagrangian of QCD is given by:

$$\mathcal{L}_{QCD} = \sum_i \bar{q}_{i,a} (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C G_\mu^C - m_i \delta_{ab}) q_{i,b} - \frac{1}{4} F_{\mu\nu}^A F^{\mu\nu,A} \quad (2.12)$$

where repeated indices are summed over. The γ^μ are the Dirac γ -matrices. The $q_{i,a}$ are *quark – fieldspinors* for a quark of flavor i and mass m_i , with a color-index that runs from $a = 1$ to 3 (quarks come in 3 colors). The G_μ^C correspond to the gluon fields associated with the generator t_{ab}^C , with C running from 1 to 8 (there are eight kinds of gluon). Finally, the field tensor $F_{\mu\nu}^A$ is given by:

$$F_{\mu\nu}^A = \partial_\mu G_\nu^A - \partial_\nu G_\mu^A - g_s f_{ABC} G_\mu^B G_\nu^C \quad (2.13)$$

where the f_{ABC} are the structure constant given by:

$$[t^A, t^B] = i f_{ABC} t^C \quad (2.14)$$

Neither quarks nor gluons are observed as free particles. Hadrons are color-singlet (color-neutral) combinations of quarks, anti-quarks, and gluons. The QCD samples used in this analysis given in Table 2.2.

Table 2.2. MC datasets for QCD background in RunIIFall17 with cross-sections

Dataset [AODSIM] RunIIFall17DRPremix-PU2017_94X_mc2017_realistic_v11	Cross-Section [pb]
/QCD_Pt_50to80_TuneCP5_13TeV_pythia8/	15710000.0
/QCD_Pt_80to120_TuneCP5_13TeV_pythia8/	2336000.0
/QCD_Pt_120to170_TuneCP5_13TeV_pythia8/	407300.0
/QCD_Pt_170to300_TuneCP5_13TeV_pythia8/	103500.0
/QCD_Pt_300to470_TuneCP5_13TeV_pythia8/	6830.0
/QCD_Pt_470to600_TuneCP5_13TeV_pythia8/	552.1
/QCD_Pt_600to800_TuneCP5_13TeV_pythia8/	156.5
/QCD_Pt_800to1000_TuneCP5_13TeV_pythia8/	26.28
/QCD_Pt_1000to1400_TuneCP5_13TeV_pythia8/	7.47
/QCD_Pt_1400to1800_TuneCP5_13TeV_pythia8/	0.6484
/QCD_Pt_1800to2400_TuneCP5_13TeV_pythia8/	0.08743
/QCD_Pt_2400to3200_TuneCP5_13TeV_pythia8/	0.005236
/QCD_Pt_3200toInf_TuneCP5_13TeV_pythia8/	0.0001357

2.8. Partonic Resonance Models

Parton – Parton resonance models contain a limited number of free parameters. Experimental searches traditionally consider benchmark models with certain parameter assumptions and these are then used to set limits on the masses of the corresponding resonances [Soffi, 2016]. Below is a summary of the benchmark patterns:

- Excited Quarks (q^*): SM couplings are assumed ($f_s = f = f' = 1$) and compositeness scale is equal to excited quark mass ($\Lambda = M^*$).

- Randall-Sundrum Graviton: The ratio $k/\bar{M}_{\text{Pl}}$ is set to $k/\bar{M}_{\text{Pl}} = 1$
- Axigluons: The number of quark flavors that axigluon can decay is set to $N = 6$ corresponding to known quarks.
- Colorons: The number of quark flavors that the coloron can decay is set to $N = 6$ and the gauge boson mixing angle is set to $\cot\theta = 1$.
- Z', W' : SM couplings are assumed.
- Color octet scalars: The gauge coupling is equal to the QCD coupling ($\kappa = 1$) and characteristic scale of the interaction is equal to resonance mass ($\Lambda = M^*$).

Table 2.3. shows the properties of the resonances. The decay widths are approximate values for benchmark models as they also depend on α_s [HARRIS et al., 2011].

Table 2.3. Properties of the resonances

Resonance	Symbol	J^P	Color Multiplet	$\Gamma/(2m_R)$	Decay Channels
Excited Quark	q^*	$1/2^+$	triplet	0.02	qg
RS Graviton	G	2^-	singlet	0.01	$q\bar{q}, gg$
Axigluon	A	1^+	octet	0.05	$q\bar{q}$
Coloron	C	1^-	octet	0.05	$q\bar{q}$
Heavy Z	Z'	1^-	singlet	0.01	$q\bar{q}$
Heavy W	W'	1^-	singlet	0.01	$q_1\bar{q}_2$
Color octet scalar	S_8	0^+	octet	0.04	gg

2.8.1. Excited Quarks

The increase in colliding energy at the LHC and improvement in detector technology increased the potential of the search for extensions of the SM. Many such extensions of the SM predict quark substructure or composite quarks. A compelling signature for substructure of quarks would be the discovery of an excited state of a

quark (q^*). Excited quarks may couple to the ground state quark via gauge transitions described by the Lagrangian:

$$\mathcal{L}_{int} = \frac{1}{2\Lambda} \bar{q}_R^* \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{\Upsilon}{2} B_{\mu\nu} \right] q_L + h.c. \quad (2.15)$$

where $G_{\mu\nu}^a$, $W_{\mu\nu}$, and $B_{\mu\nu}$ are the field-strength tensors; λ_a , τ , Υ are the corresponding gauge structure constants and g_s , g , g' are the gauge coupling constants; Λ denotes the typical scale of these interactions, and f_s , f , f' are unknown dimensionless constants determined by the compositeness dynamics, representing the coupling strength and naively assumed to be of order unity. In pp collisions excited quarks would be produced predominantly by quark-gluon annihilation (qg), and would then decay into a quark and a gauge boson (g , W , Z , γ) [HARRIS et al., 2011].

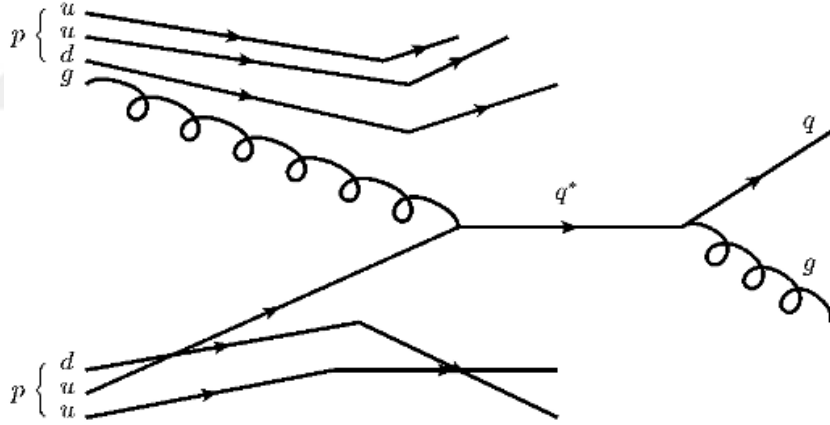


Figure 2.1. Feynman diagram representing q^* production from qg scattering in pp collisions

2.8.2. Randall-Sundrum Graviton Model

Randall-Sundrum (RS) model, proposed by Lisa Randall and Raman Sundrum in 1999 has evolved out of the “Large-Extra-Dimension” model. It is an alternative approach, based on the idea of extra dimensions, to address the hierarchy problem. According to this model, there is only one extra dimension in addition to $(3 + 1)$ dimensional space-time.

There are two 4-dimensional (4-D) sub-space (brane) sitting in a 5-dimensional (5-D) bulk with a “warped” geometry. One of them is the “visible brane” which contains all the SM fields and the other is the “invisible brane” where gravity is strong and only gravitons can propagate in the extra dimension. The extra dimension forms a circle which is folded about a diameter and the two branes are placed at $\phi = 0$ (invisible brane) and $\phi = \pi$ (visible brane). The solution to the 5-D Einstein equation is:

$$ds^2 = e^{-2kR_c\phi} g_{\mu\nu} dx^\mu dx^\nu + R_c^2 d\phi^2 \quad (2.16)$$

where ds is a line element in the 5-D bulk, $g_{\mu\nu}$ is the $(3 + 1)$ dimensional metric, R_c is the radius of curvature and $e^{-2kR_c\phi}$ is the “warp” factor. The relation between the 4-D Planck scale M_{Pl} and fundamental Planck scale M_5 obtained from this 5-D model is:

$$M_{Pl}^2 = \frac{M_5^3}{k} \left[1 - e^{-2kR_c\pi} \right] \quad (2.17)$$

In the RS model, the scale “ k ” is of the order of the Planck scale ($\sim 10^{16}$ TeV) and equation 2.9 tells us that the fundamental 5-D Planck scale is of the order of the Planck scale ($M_{Pl} \sim M_5$). The effective interaction Lagrangian on the visible brane is given by:

$$\mathcal{L} = -\frac{1}{M_{\text{Pl}}} T^{\alpha\beta}(x) h_{\alpha\beta}^0(x) - \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h_{\alpha\beta}^n(x) \quad (2.18)$$

The Lagrangian consists of two parts. The first part corresponds to the “zero-mode” which describes the gravitational interaction that we experience [HARRIS et al., 2011]. The second part is the sum over the “*Kaluza – Klein*(*KK*)” excitation modes and corresponds to the interaction of the *KK* excited modes of the graviton with SM fields:

$$\Lambda_\pi \sim e^{-2kR_c\pi} M_{\text{Pl}} \quad (2.19)$$

2.8.3. Axiguons

Axiguons are colored heavy neutral gauge bosons couple to quarks by an axial vector current and the same strong coupling as gluons. The most important model-independent manifestation of axiguons is the formation of back-and-forth asymmetry in $t\bar{t}$ quark production in $p\bar{p}$ collisions resulting from charge asymmetry [Krnjaic, 2012].

Axiguons can decay into $q\bar{q}$ pairs, leading to a dijet experimental signature. Note that due to the preservation of parity, axiguons cannot be decay into a gluon-gluon pair (all gluon-axiguon vertices should have an even number of axiguons). The decay of axiguon into fermions is described by Lagrangian as follows:

$$\mathcal{L}_A = -ig_s \left(\sum_{ij} \bar{q}_i \gamma_5 t_a q_j \right) A^{q\mu} \quad (2.20)$$

where $g_s = \sqrt{4\pi\alpha_s}$, A is the axiguon field, and t_a are the usual color group generators.

The width of axiguon decay can be shown as:

$$\Gamma_A = \frac{N\alpha_s M_A}{6} \quad (2.21)$$

where N indicates the open decay channels, and M_A is the axigluon mass. The chiral color symmetry is a free parameter of theory determined by the breaking scale and the details of the pattern [Soffi, 2016; HARRIS et al., 2011].

2.8.4. Colorons

The mass of colorons is expressed as a function of the fundamental parameters:

$$M_C = \left(\frac{g_s}{\sin\theta\cos\theta} \right) f \quad (2.22)$$

where θ is the gauge boson mixing angle with $\cot\theta = \frac{\xi_1}{\xi_2}$ ($\xi_{1,2}$ are the gauge couplings), and f is the vacuum expectation value of the scalar field. The Lagrangian of the interaction between the coloron field and quarks is similar to QCD:

$$\mathcal{L} = -g_s \cot\theta \left(\sum_{ij} \bar{q}_i \gamma_\mu t_a q_j \right) C^{\mu a} \quad (2.23)$$

The previous interaction predicted the decay of colorons into quarks with kinematically allowable masses. It can be shown that the decay width is as follows:

$$\Gamma_C \approx \frac{N}{6} \alpha_s \cot^2\theta M_C \quad (2.24)$$

where N is the number of quark flavors with mass less than $M_C/2$ [ibid.].

2.8.5. W' and Z'

In the models where the symmetry $SU(2)_L \otimes U(1)_Y$ of the electro-weak SM sector is enlarged, new gauge bosons arise. General features in these models are the

new gauge coupling constants that are in the same order as the $SU(2)_L$ coupling of the SM and the presence of new gauge bosons called Z' and W' . Under the assumption that the new gauge bosons couple to ordinary quarks and leptons, similar to their SM counterparts, the cross-sections of these particles are calculated by scaling the corresponding SM cross-section. In particular, the Fermi constant G_F becomes:

$$G'_F = G_F \left(\frac{M}{M'} \right)^2 \quad (2.25)$$

where M and M' are the masses of Z or W , and Z' or W' , respectively [Soffi, 2016].

2.8.6. Color Octet Scalars

Bosonic states can be caused by gluon-gluon fusion in various theoretical models. The color octal scalar model (S_8) is an example of exotic color resonances. The union of the S_8 field with gluons is expressed in Lagrangian:

$$\mathcal{L} = g_s \frac{\kappa}{\Lambda} d^{abc} S_8^a G_{\mu\nu}^b G^{c,\mu\nu} \quad (2.26)$$

where g_s is the strong coupling constant, κ scalar coupling, Λ is the characteristic scale of interaction, d^{abc} is the structure constants of the $SU(3)$ group defined by the $\{t^a, t^b\} = \frac{1}{3}\delta^{ab} + d^{ab}t^c$ relation, and S_8 is the color octet scalar field and, $G_{\mu\nu}$ is the gluon field tensor [HARRIS et al., 2011]. The width of color octet scalar resonance is given by:

$$\Gamma = \frac{5}{6} \alpha_s \kappa^2 \frac{M^3}{\Lambda^2} \quad (2.27)$$

3. EXPERIMENTAL APPARATUS

3.1. CERN and LHC

Theoretical research on high energy physics is tested in laboratories around the world with experiments. One of the largest laboratories designed to solve the mystery of the universe is the CERN, established on the border between Switzerland and France.

In total, 23 countries are full members of CERN (Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, and the United Kingdom) and three more countries (Cyprus, Estonia, Slovenia) will participate in them. In addition to these, seven countries (Croatia, India, Latvia, Lithuania, Pakistan, Türkiye, and Ukraine) are associate members, and there are six observers (European Union, Japan, JINR, Russia, UNESCO, United States). In addition to these, 35 countries can participate in research without being a member.

CERN has the world's largest particle accelerator, 27 km long and located about 100 meters below the ground, called LHC. The machine, which started operating in 2008, sends two high-energy particle bunches in opposite directions, causing them to collide. Figure 3.1. shows the schematic view of the LHC complex and the experiment locations.

pp collisions are basically carried out in the LHC. Each proton bunch is ~ 7.5 meters apart and contains 2808 proton clusters, with 10^{11} protons in each cluster. These particles must be well guided in order to collide them. In this context, superconducting electromagnets are used. The magnetic field used is 8.33 T, which is more than 100 thousand times the magnetic field of the Earth. For this purpose,

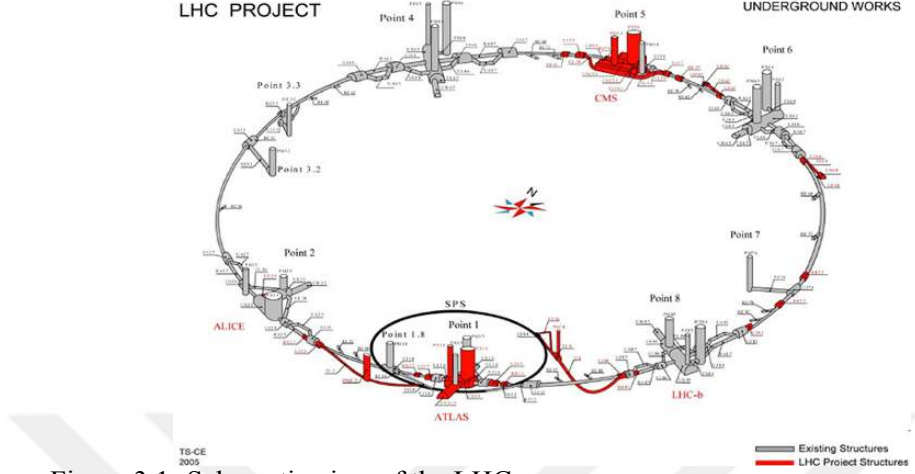


Figure 3.1. Schematic view of the LHC

cryogenic systems are used in LHC. The niobium-titanium (NbTi) wires of the coils that create a strong magnetic field are enclosed by a closed liquid-helium circuit. Cooling takes weeks to occur, and this process takes place in three stages. In the first stage, the Helium is cooled to -193°C and then to -268°C . In the second stage, the cooled helium is directed into the masses of the magnets and in the last stage, it is cooled to a temperature of -271°C .

The LHC is designed according to the center of mass energy of 14 TeV. The center of mass energy represented by $\sqrt{s}$ is equal to the square of the sum of the momentum of each particle beam. The pp collision is the sum of the four vectors of each proton.

$$s = (p_1 + p_2)^2 \quad (3.1)$$

where the momentum values of each particle are expressed as follows:

$$p_1 = (E_p, \vec{p}) \quad (3.2)$$

$$p_2 = (E_p, -\vec{p}) \quad (3.3)$$

If we put them in place in Equation 3.1:

$$s = p_1^2 + p_2^2 + 2p_1 \cdot p_2 \quad (3.4)$$

$$s = (E_p^2 - |\vec{p}|^2) + (E_p^2 - |\vec{p}|^2) + 2(E_p^2 + |\vec{p}|^2) \quad (3.5)$$

$$s = 4E_p^2 \quad (3.6)$$

In the LHC, 7 TeV protons were colliding. If we write this in the equation, it will give us:

$$\sqrt{s} = \sqrt{4 \times 7^2} \text{TeV} = 14 \text{ TeV} \quad (3.7)$$

The total number of events generated per second calculated by:

$$N_{\text{Event}} = L \sigma_{\text{Event}} \quad (3.8)$$

σ_{Event} is the cross-section for the event, L is the luminosity of the machine. The expected cross-section represents an area and expressed in *barn* units. The instantaneous unit of luminosity is denoted by $\text{cm}^{-2} \text{s}^{-1}$. Machine luminosity (*lumi*) depends only on beam parameters and a Gaussian beam distribution can be written as:

$$L = \frac{N_b^2 n_b f_{\text{rot}} \Upsilon_T}{4\pi \epsilon_b^*} F \quad (3.9)$$

where; N_b is the number of particles per beam, n_b is the number of the bunch per beam, f_{rot} is the rotation frequency, Υ_T is the relative gamma factor, ϵ_b is the transverse beam emitting power, β^* is the beta function at the collision point and F is factor of the geometric luminance reduction due to the cross-section at the point of interaction [Wu, 2017].

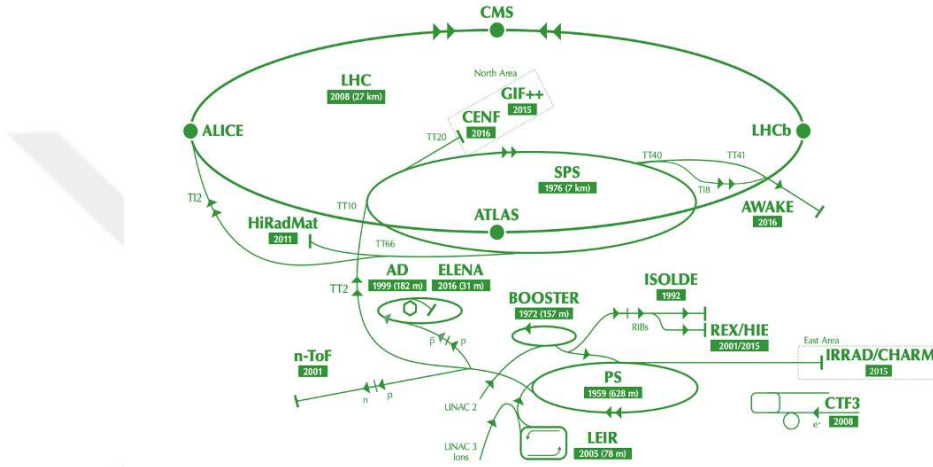


Figure 3.2. A simple demonstration of the LHC accelerator system

The particles follow an accelerator sequence (Figure 3.2.) to achieve high collision energy in the LHC. Hydrogen gas is used as the proton source for the collision. Electrons are removed from the hydrogen atom by applying an electric field. The remaining protons then enter the Linac-2 linear accelerator, where they are accelerated to an energy of 50 MeV. Subsequently, the energy of the proton beam entering the Proton Synchrotron Booster (PSB) increases to 1.4 GeV, and then it transfers to Proton Synchrotron (PS) and reaches 26 GeV energy. The next step to increase the energy is that the protons entering the Super Proton Synchrotron (SPS) are accelerated here to 450 GeV and finally pass into the LHC, where they increase their energy up to 7 TeV. Each proton beam has an energy of 7 TeV and when a

head-to-head collision is achieved, 14 TeV energy is obtained. These head-to-head collisions occur at 4 points on the LHC, where there are different detectors (ALICE, ATLAS, CMS, and LHCb).

This gigantic system (LHC), which is installed approximately 100 meters below the ground, is not exactly circular but consists of 8 parts. There are approximately 300 magnets in each part and technical systems (such as cooling or electrical) are also separate from each other. The detector system, divided into several parts, is straightforward when it is lowered under the ground and combined. In addition, this design is very useful for maintenance and repair works. In particle-anti-particle colliders, although there are beams rotating in the same direction in a common space within a single ring, in a particle-particle collision, there are two different rings and the beams inside are rotated in opposite directions.

3.2. Super Proton Synchrotron

The Super Proton Synchrotron (SPS) is used not only as an LHC injector but also to accelerate & extract protons & ions for fixed-target experiments and produce neutrinos for the CERN Gran Sasso (CNGS) neutrino project. The fast extraction risk of LHC and CNGS beams must be considered in case of failure during this procedure which might lead to severe equipment damage [Tahir et al., 2009].

The SPS is a 6.9 km long cycling machine and accelerates 14 or 26 GeV/c protons to 450 GeV/c. It cycles the particles around 10 seconds. The transverse beam size is greatest at the injection point, and during acceleration, the square root of beam energy decreases. For the operation of SPS, the beam size is commonly in the order of 1 mm.

When SPS operates as the LHC injector, up to 288 bunches are accelerated and each bunch has approximately 1.1×10^{11} protons. Two adjacent bunches are separated

by 25 ns and their length is 0.5 ns. Therefore, the whole beam's duration is $\sim 7 \mu\text{s}$ [Tahir et al., 2007].

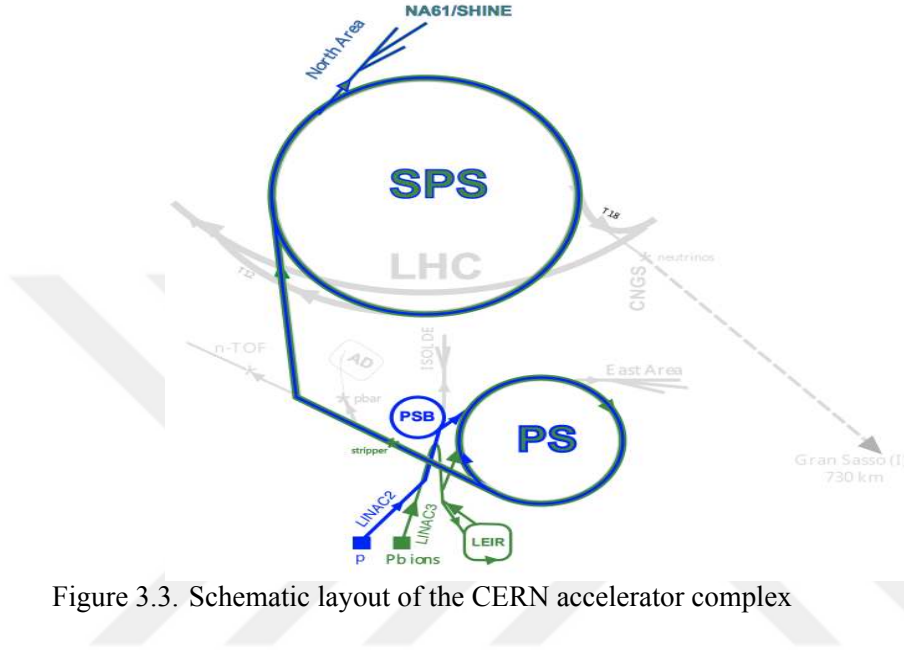


Figure 3.3. Schematic layout of the CERN accelerator complex

3.3. The CMS Experiment

The CMS is a 21 m long, 15 m wide, 15 m high particle detector with a cylindrical onion-like structure, and weighing 14000-tons which is about twice the weight of the ATLAS detector. In the center of the CMS, there is a ~ 4 T superconducting solenoid magnet with a length of 13 m and an inner diameter of 11.8 m. There is a tracker in the innermost part to detect traces of charged particles formed in a collision. Just behind the tracker, there is an Electromagnetic Calorimeter (ECAL), which measures the energies of electrons and photons, and then a hadronic calorimeter to measure strongly interacting particles. Finally, there are muon chambers on the outermost to measure the charge and momentum of muons.

The schematic view of the CMS detector is shown in Figure 3.4.

The physics topics that the CMS experiment investigates are as follows:

- Quantum Color Dynamics Physics
- B-Physics
- Dark matter
- Exotic Particles
- Heavy Ion Physics
- Higgs Physics
- Standard Model Physics (Vector Bosons and Jets)
- Super-symmetry
- Top Quark Physics

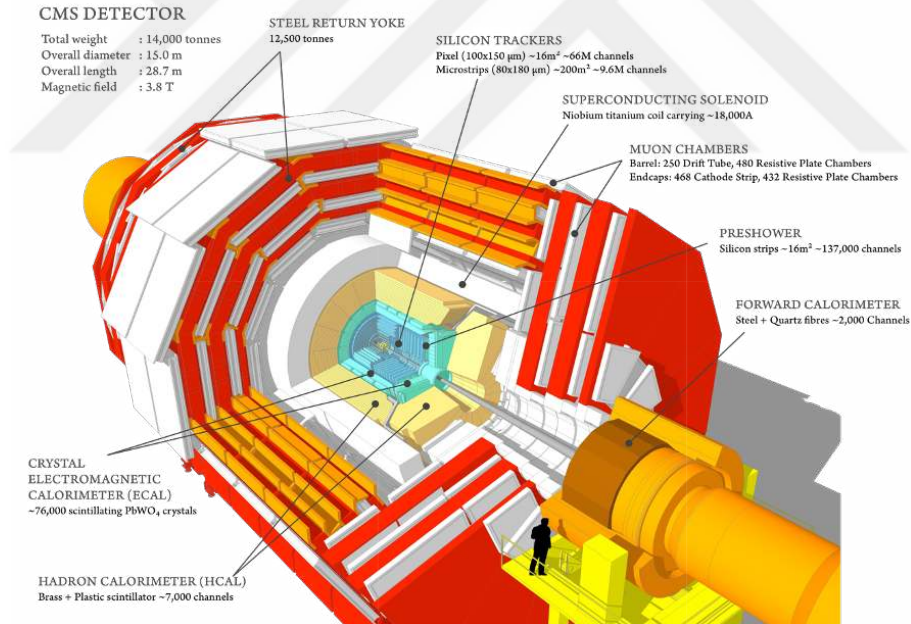


Figure 3.4. The schematic view of the CMS detector with all sub-detectors

3.3.1. Coordinate System

The CMS coordinate system in Figure 3.5. has an origin that is the center of the nominal collision point in the experiment. x–axis; radially towards the center of the LHC ring, y–axis; up from the origin, the z–axis is in the beam direction. The planar angle (ϕ) is measured from the x–axis in the x–y plane and the polar angle θ measured from the z–axis. CMS uses pseudorapidity (η) instead of pole angle and η is given by equation 3.10 [Bayatian et al., 2006: Gupta et al., 1999].

$$\eta = -\ln\left(\frac{\theta}{2}\right) \quad (3.10)$$

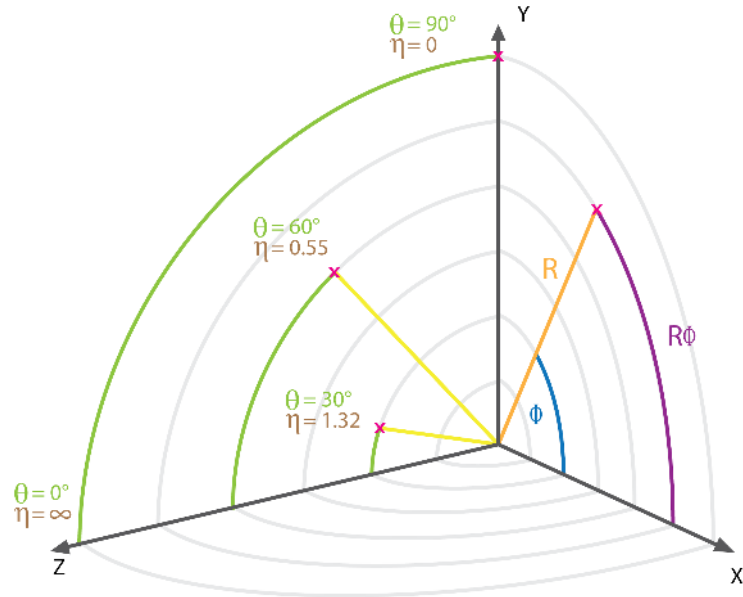


Figure 3.5. The coordinate system of the CMS Detector

3.3.2. Superconducting Solenoid Magnet

One of the important points in the design of the CMS detector is the high sensitivity in measuring the muon momentum. To achieve this, a high magnetic field is required. Therefore, a superconducting solenoid magnet is used in CMS (Figure 3.6.). Thanks to this magnet, 4 T magnetic field parallel to the beam axis (on the z -axis) is obtained.

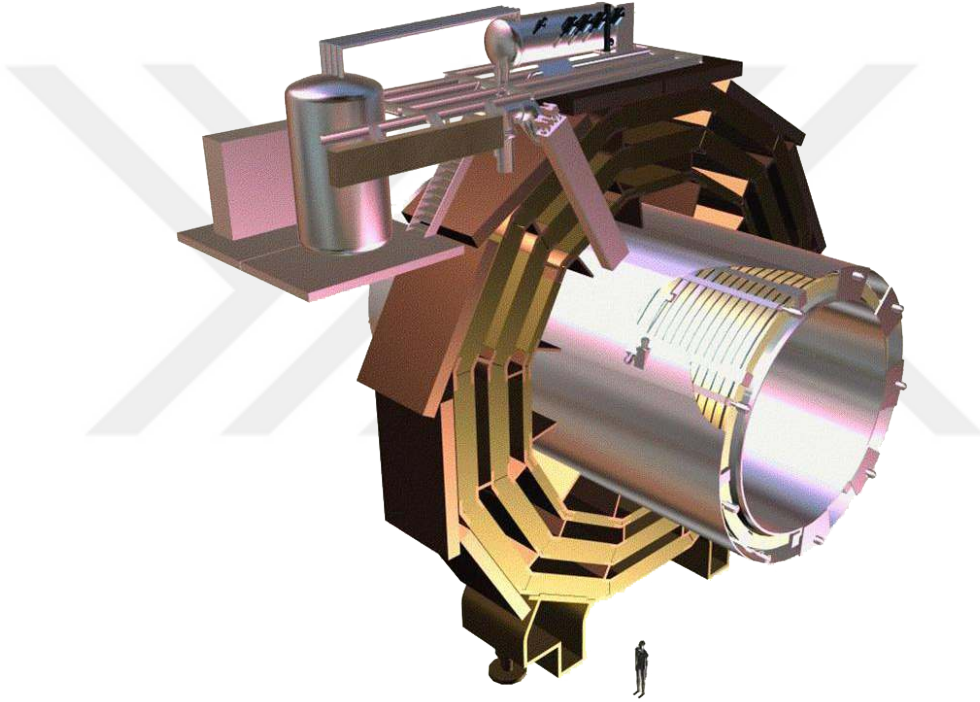


Figure 3.6. Superconducting Magnet of the CMS detector

The parameters of the solenoid are given in Table 3.1. Due to the size of the solenoid, a large bending force can be obtained and the bending starts at the first incident corner due to the high superconducting area. A proper length/radius ratio is required to ensure good momentum resolution in the forward region.

Table 3.1. Parameters of the CMS superconducting solenoid

Magnetic Field	4 Tesla
Length	12.9m
Inner Diameter	5.9m
Number Of Turns	2168
Current	19.5 kA
Stored Energy	2.7 GJ
Ring Pressure	64 ATM

3.3.3. Tracking System

The CMS detector has a powerful monitoring system. This system is placed in the region where any particle that will emerge in the pp collision first comes to the detector. The charges, momentums, and orbits of charged particles are determined in the tracker.

The tracking system consists of two different detectors, pixel and silicon strip track detectors. Position measurements are made to determine the tracks (trajectories) of charged particles in the tracking system. The tracker detector is a cylindrical structure with a diameter of 2.6 m and a length of 6 m. In this detector, 13 points will be measured for each track. Since the track density decreases rapidly as the radius increases, the silicon pixel detector is placed in the area closest to the interaction point. This detector is followed by a 5-layer silicon micro-strip detector. High radiation near pipes passing through them will damage the detectors. Therefore, the detector must be resistant to high radiation. The charged particles follow a spiral path as they pass through the magnetic field in the CMS. Particle momenta will be measured by

examining the curvature of these tracks. The schematic view of the CMS detector tracker system given in Figure 3.7. [Focardi, 2012].

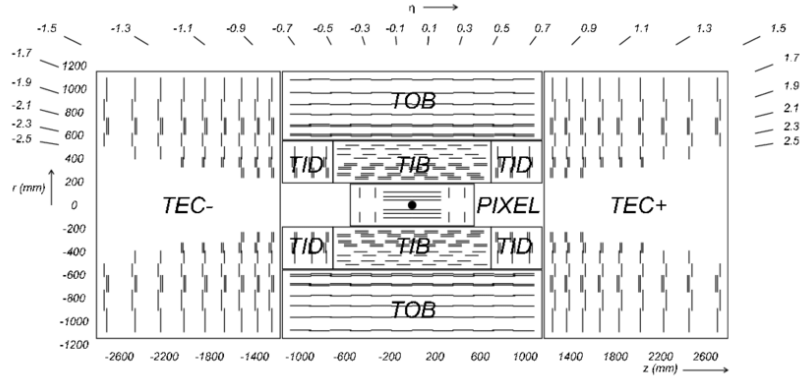


Figure 3.7. Schematic representation of the CMS Tracker System. Each line represents one detector module. Double lines show two-sided modules

3.3.4. Electromagnetic Calorimeter

The CMS intends to have a high-performance ECAL. The designed scintillator crystal calorimeter provides excellent performance for the energy resolution for all electrons and photons, accumulated in the crystal. To achieve the tight calorimetry system expected from CMS, lead tungsten (PbWO_4) crystals with high density, small Moliere radius and short radiation length were used. High-resolution electromagnetic crystal calorimetry played an important role in the discovery of the Higgs boson through its decay in the $H \rightarrow \gamma\gamma$ channel in the initial low-luminosity studies at the LHC [CMS, 2000].

The $H \rightarrow \gamma\gamma$ decay channel is an important motivation for the design of the ECAL of the CMS. This is an excellent evaluation channel for detecting photons with high purity and efficiency and is used to optimize the energy resolution and calibration

of the ECAL [TDR, 2007].

ECAL is made of ~ 76000 PbWO_4 scintillator crystal. It consists of an Electromagnetic Barrel (EB) consisting of 36 super-modules, each containing 1700 crystals, and an Electromagnetic Endcap (EE) containing 7324 crystals each. The EB section covers the pseudorapidity range of $|\eta| < 1.48$, and the EE section covers the pseudorapidity range of $1.48 < |\eta| < 3.0$. One quadrant of the CMS ECAL system layout is shown in Figure 3.8. [CMS, 2002].

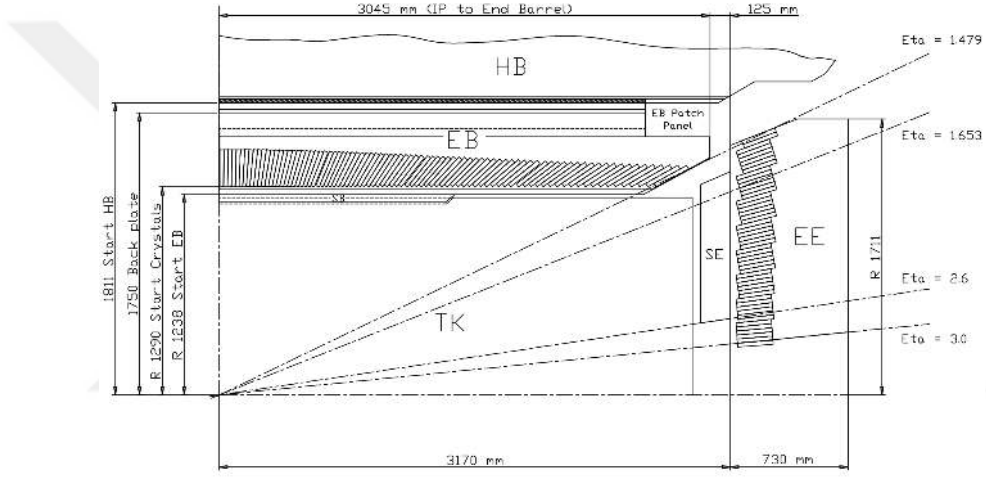


Figure 3.8. Schematic representation of the CMS ECAL System (One quadrant)

3.3.5. Hadronic Calorimeter

The calorimeter system of the CMS detector is designed to measure the direction of quarks, gluons, and neutrinos, as well as their energies, using the jet direction and the MET flow. Determination of the missing energy can be used to search for super-symmetric partners of quarks and gluons and create an important signature for new particles and phenomena. Hadronic Calorimeter (HCAL) is an

important detector for the measurement of hadronic jets and neutrinos or any exotic particles [CMS, 1997].

Figure 3.9. shows the longitudinal schematic view of the CMS detector. Hadronic Barrel (HB) and Hadronic Endcap (HE) sit behind the tracker and ECAL. The hadron calorimeter is radially bounded between the outer extension ($R = 1.77$ m) of the EB calorimeter and the inner width of the magnet coil ($R = 2.95$ m). This constrain the total amount that can be used to absorb the hadronic shower. Because of this limitation, HB is insufficient to stop hadronic showers that start late. For this reason, the Hadronic Outer (HO) calorimeter is placed outside the solenoid as a complementary for the HB. The Hadronic Forward (HF) calorimeter is placed beyond the $|\eta| = 3.0$ and at a distance of 11.2 m from the interaction point and ensured to be radiation resistant by using a Cherenkov-based radiation resistant technology. This extended the pseudo-rapidity range to $|\eta| = 5.0$ [CMS, 2008].

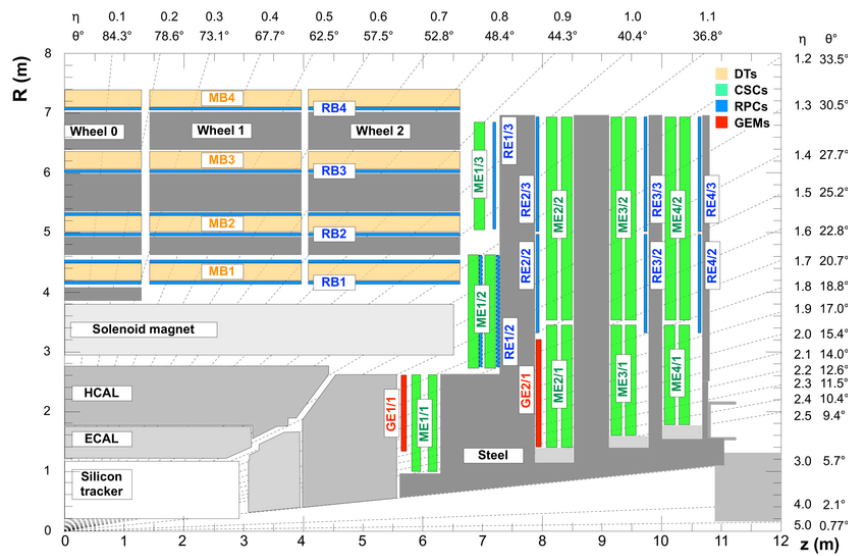


Figure 3.9. One quadrant of the CMS Detector's schematic representation. The dashed lines indicate the η value

3.3.5.1. Hadronic Barrel Calorimeter

The HB Calorimeter is a sampling calorimeter covering the $|\eta| < 1.3$ pseudorapidity range. The HB consists of two half-barrels (HB+ and HB-), and each of them consists 36 identical wedges with a planar angle of 20° ($\Delta\phi = 20^\circ$). Each wedge consists of four planar ($\Delta\phi = 5^\circ$) sectors. The HB plates are made from stainless steel to provide structural support. The scintillator was separated into 16 η sectors, and as a result, HB was formed by $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$ compartments. Absorber materials (steel & brass plate) were used as passive materials, and plastic scintillators were used as active materials in the detector. Figure 3.10. shows the isometric HB wage [Abdullin et al., 2008].

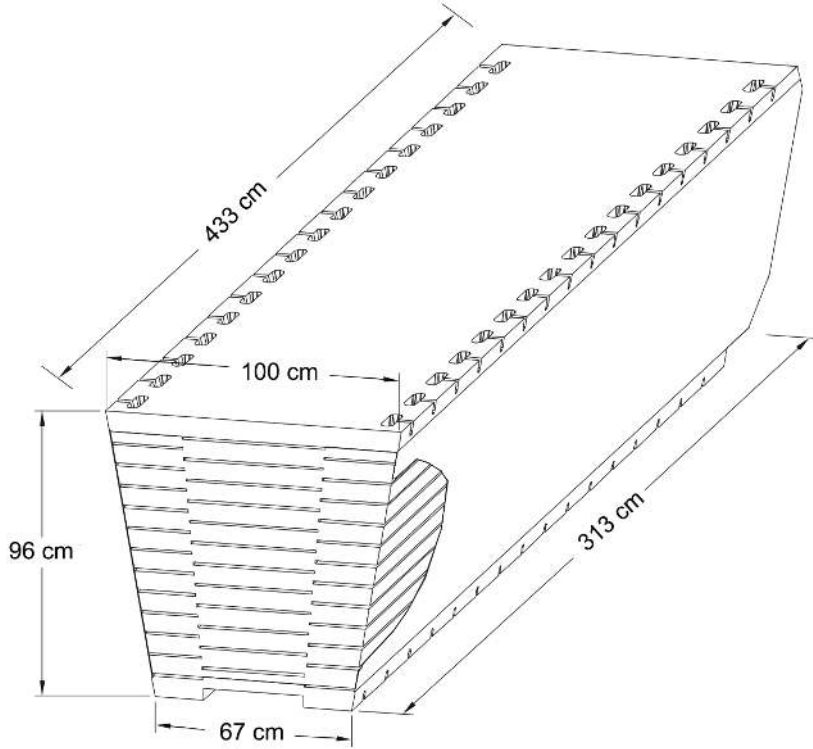


Figure 3.10. CMS HB wage's isometric view

3.3.5.2. Hadronic Endcap Calorimeter

The HE Calorimeter covers the pseudorapidity range of $1.3 < |\eta| < 3.0$ in the CMS detector, and 34% of the produced particles pass through this part. Due to the High-Luminosity LHC (HL-LHC), the HE must have a high count rate and radiation tolerance. HE's absorber part is made of a material that is not affected by the magnetic field because HE is located at the end of the 4 T solenoid magnet [CMS, 2008]. Figure 3.11. shows HE Calorimeter, placed on iron yoke.

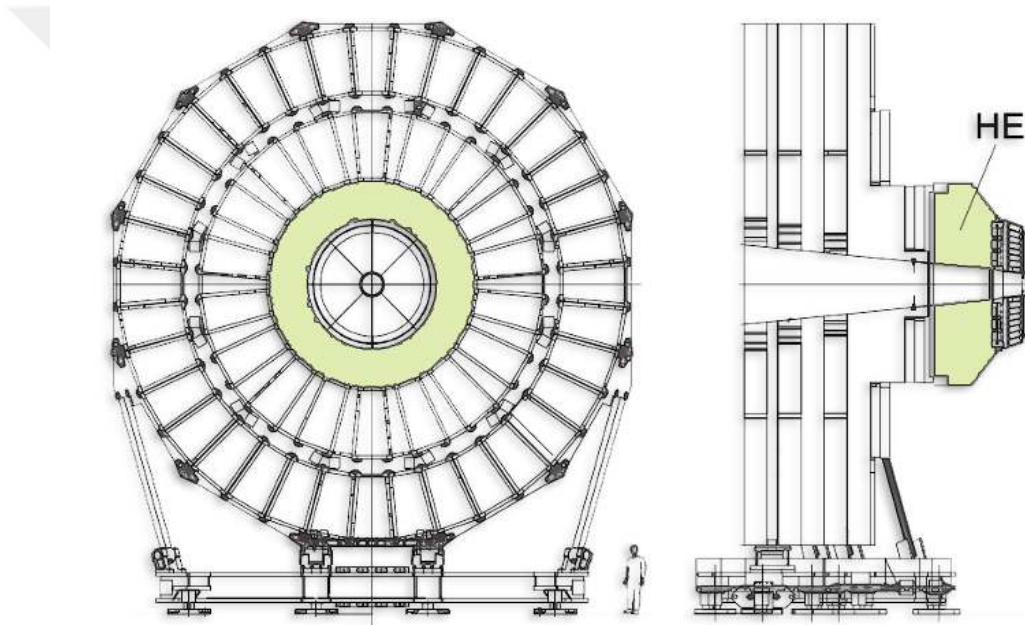


Figure 3.11. HE Calorimeter, placed on iron yoke

3.3.5.3. Hadronic Outer Calorimeter

HO Calorimeter is placed outside the solenoid magnet to provide an adequate sampling for the HCAL. It covers the pseudorapidity range of $|\eta| < 1.26$. HO

calorimeter measures the shower energy beyond the geometry of the HB. The area outside the magnetic solenoid is designed as five 2.536 m wide rings along the z-axis. Rings are identified by the numbers $-2, -1, 0, +1, +2$. The increment in the numbers of these five rings depends on the z-axis starting from the interaction point, and their positions are -5.342 m, -2.686 m, 0 , $+2.686$ m, and $+5.342$ m, respectively. At $\eta = 0$, HB provides low-level interaction with hadrons produced in the pp collision. Therefore, the central ring has HO scintillators at radial distances of 3820 mm and 4070 mm. All other HO layers have a radial distance of 4070 mm, except for the HB-HE boundary region.

HO is constrained by the geometry and structure of the muon system. Figure 3.12. shows the layer of HO position in the muon rings. Each ring is subdivided into 12 identical Φ -sectors, separated from each other by 75 mm thick stainless steel shafts. In addition, the HO is constrained in the chimneys area in sector 3 of ring HO-1 and sector 4 of ring HO+1. These chimneys are used for the magnet system's coolant (cryogenic) lines and power cables. The mechanical structures required to position the scintillator trays further constrain the HO along the Φ [B. S. Acharya et al., 2006].

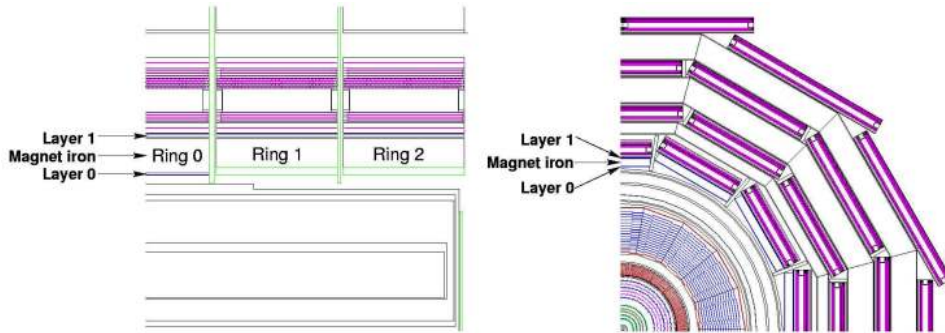


Figure 3.12. The position of HO layers in CMS detector

3.3.5.4. Hadronic Forward Calorimeter

The HF Calorimeter is in the $3.0 < |\eta| < 5.0$ pseudorapidity range and is 11.2 m away from the interaction point. It plays an essential role in the jet and MET determination. HF has two parts (HF $\pm$), and each part consists of 18-wedges corresponding to an angle of 20° . However, as seen in Figure 3.13., each HF wedge has two sectors divided by an equal 10° angle. The HF calorimeter consists of steel absorbers and radiation-resistant quartz fibers inside these absorbers. HF uses two kinds of quartz fibers; 1.65 m electromagnetic and 1.43 m hadronic, placed at 5 mm intervals. These fibers are formed into bundles and combined at the back of the detector. The signal is transmitted to the photo-tubes via the fibers, and reading information is obtained separately. [HCAL, 2006: CMS, 2006].

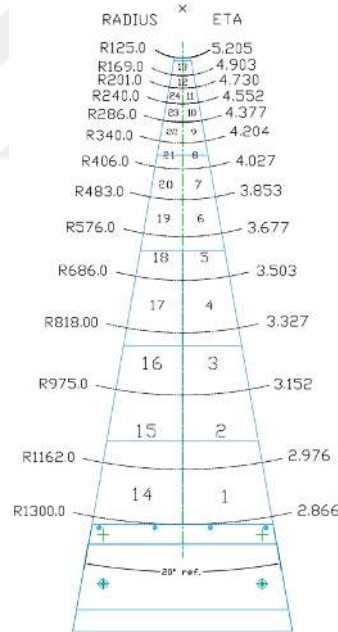


Figure 3.13. Expanded view of the HF wage

3.3.6. The Muon System

The muon system is located at the outermost part of the detector with the purpose of detecting muons. This system consists of two parts, the Muon Endcap (ME), and the Muon Barrel (MB) regions. The MB is in the pseudorapidity range of $|\eta| \leq 1.2$ and the ME is in the $|\eta| \leq 2.4$. MB and ME sections are divided into four discs containing 250 muon chambers. Each disk is divided into 12 sectors (MB1, MB2, MB3, ...) corresponding to a planar angle of $\phi = 30^\circ$. The innermost (MB1, MB2, MB3) Drift Tubes (DT) consists of 12 drift chamber layers in four groups in triplicate, and these layers are called Super-Layer (SL). But, standard drift tubes are not good for detecting muons in the endcap regions, due to the higher particle ratios in this regions and the uniformity of the magnetic field. Thus, muon endcaps consist of Cathode Strip Chambers (CSC). They have a fast response and can be finely divided and operated in the presence of a non-uniform magnetic field. In addition, when the LHC operates at high luminosity, it requires a complementary and dedicated trigger system with excellent time resolution to accurately identify beam transition. Therefore, the MB and ME regions are equipped with the Resistive Plate Chambers (RPC) that provide an independent trigger with lower thresholds of P_T down to $|\eta| = 1.6$ [CMS, 2006: TDR, 2007].

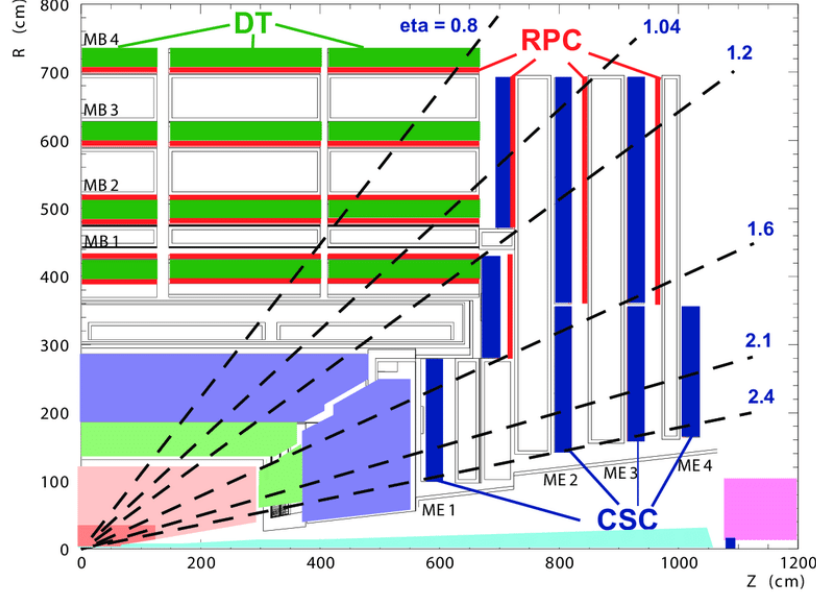


Figure 3.14. One quadrant of the HF Calorimeter's schematic representation. The dashed lines indicate the η value

3.3.7. The Trigger System

In LHC collisions, the proton beams interact every 25 ns, corresponding to a frequency of 40-MHz. The raw data produced at each interaction is approximately 1 MB. This corresponds to 40 TB of data per second. It isn't easy to store and process such a large amount of data. As a result, the obtained data was reduced by applying some processes by the CMS trigger system. This system is a sequential but independent software and hardware-based automatic system and was designed together with the Data Acquisition (DAQ) System. The first stage is a hardware-based system called L1 trigger, and the second stage is the software-based HLT [Adolphi et al., 2008].

3.3.7.1. Level-1 Trigger System

They only consider unsegmented data from low-resolution ECAL, HCAL, and muon systems, using Field Programmable Gate Arrays (FPGA) and Application Specific Integrated Circuits (ASIC). It takes sensor data at 40-MHz and reduces them to 100-kHz. Figure 3.15. shows the L1 trigger processing steps for different systems and detectors [Rác et al., 2002].

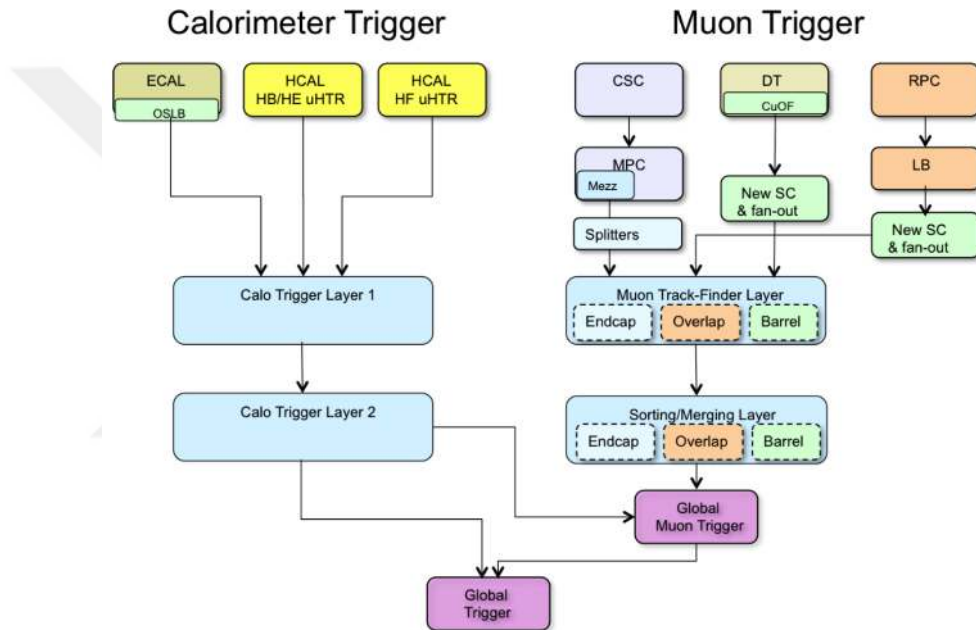


Figure 3.15. The L1 trigger contains two main section that separately process the information from the muon system and the calorimeters

3.3.7.2. High Level Trigger System

The HLT is a software-based detector that contains 16000 processors and runs on a large computer network, reducing the 100-kHz data it receives from the L1 Trigger to 100-Hz. Algorithms can access data from all CMS sub-detectors with full

granularity and resolution, including the tracker. The HLT is largely designed to allow logically independent trigger paths that can be run in parallel. They are known as a set of algorithms that reconstruct physics candidates and apply various selections to the reconstructed objects [Agostino et al., 2009]. Figure 3.16. shows the processing steps of the CMS Trigger systems.

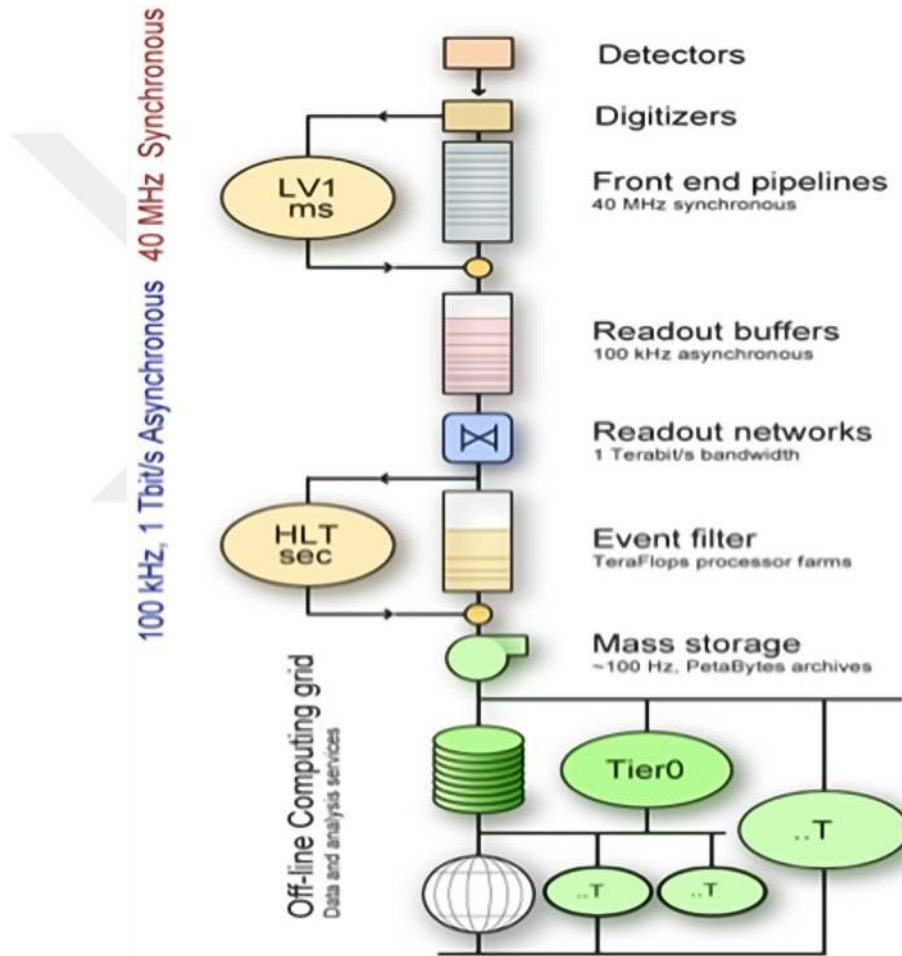


Figure 3.16. Processing steps of the CMS trigger system, effectively reduces the data amount from 40-MHz to 100-Hz

3.4. CMS Phase-2 Upgrade: High-Granularity Calorimeter

One of the ultimate goals of the upgrades made in the CMS both regularly and as needed is to make the CMS detector capable of operating at higher luminosity values. The instantaneous luminosity value of the LHC will increase to $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ after approximately 2026 with the HL-LHC phase. By the middle of 2030, the total luminance value is expected to reach 3000fb^{-1} . This high value leads to higher PF, radiation levels, and pile-ups.

The existing PbWO_4 based ECAL and plastic scintillator based hadronic calorimeter are designed for an internal luminosity of 500fb^{-1} . Increasing the luminosity level that the calorimeter can detect causes performance degradation and an unacceptable loss of physics performance. In addition, some parts are subject to physical damage due to the radiation they are exposed to. To solve the situation, the CMS collaboration decided to replace their existing endcap calorimeters with a new High-Granularity endcap Calorimeter known as HGCAL. This new piece will contain both electromagnetic and hadronic sections and will have unprecedented resolution. The longitudinal section of the upper half of HGCAL, which has 52 longitudinal layers, thin silicon sensors and scintillators in total, is shown in Figure 3.17. [CMS, 2017b].

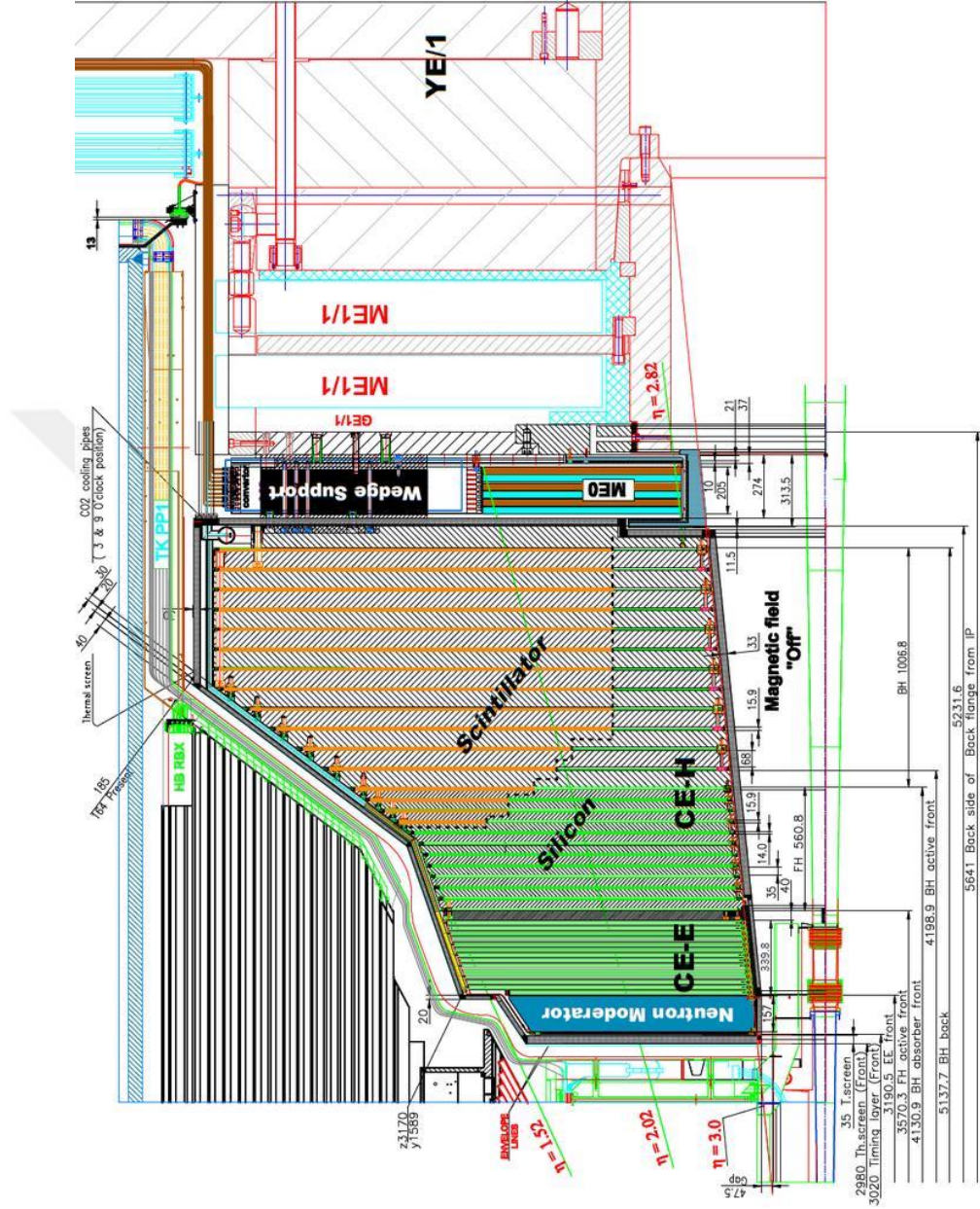


Figure 3.17. Longitudinal cross section of the upper half of one end cap calorimeter. It consists of an electromagnetic compartment (CE-E) followed by a hadronic compartment (CE-H). The green area to the lower left is instrumented with silicon detectors and the blue region to the upper right with scintillator tiles

Other reasons for HGCALE upgrade can be listed as follows:

- It contains high luminosity as well as high radiation. The sensor must fully maintain its energy resolution after 3000 fb^{-1} , and the channels of the sensor with these high requirements must be individually adjusted with the Minimum Ionized Particles (MIP).
- For the use of PF methods in the compressed environment of the HL-LHC, the identification of samples should be facilitated, and for this, they should be dense enough to limit the lateral extension of the showers.
- It should be fine lateral granular to allow a high enough Signal/Background (S/B) ratio to allow MIP calibration. In addition, the resistance of the silicon section and therefore, the cell sizes must be small to limit electronic and residual current noise.
- It should be of fine longitudinal granular structure to sampling the longitudinal shower development. This allows the energy saved to be estimated or determined and the direction of the showers to be measured.
- Each cell with a significant amount of accumulated energy can give precise timing information, and sensitivity increases with increasing energy accumulation. Precise timing helps to reduce the pile-up effect and determine the vertex of the chosen interaction.
- The selection of interesting physics phenomena in the HL-LHC is very challenging, especially due to the large number of pile-up interactions in the end cap regions. HGCALE will also contribute to the L1 trigger that makes this selection process.

3.4.1. HGCAL Design

The HGCAL is a sampling calorimeter with active parts made of silicon and plastic. It is divided into two parts: electromagnetic (CE-E) and hadronic (CE-H). While copper (Cu), copper-tungsten (Cu: 25%, W: 75%), lead (Pb) are used as the main absorber in the electromagnetic part, silicon sensors are used as active material. These silicon sensors will also be used in areas of the hadronic section exposed to very high radiation. Plastic scintillator tiles with silicon photo-multiplier (SiPM) will be used for the outer part of the hadronic section. In the hadronic calorimeter, 35 mm and 68 mm thick stainless steel will be used as absorber. The entire calorimeter will be cooled with a two-stage CO₂ system and placed in a single cold volume of -30°C to keep electronic noise and leakage currents low enough and to operate effectively. This calorimeter design provides the high transverse and longitudinal granularity required for PF reconstruction algorithms.

The radiation length of CE-E is approximately $26 X_0$ and the interaction length is 1.7λ deep and consists of 28 sampling layers with a total thickness of 34 cm. The active detector element is 163 mm wide hexagonal silicon sensors. These sensors are sandwiched between an 8-inch plate, a 1.4 mm thick CuW base plate, and a printed circuit board (PCB) carrying front-end electronics to form a silicon module. Sensors will have different depletion thicknesses depending on the radiated area. Accordingly, it is 300 μm in the lowest radiation zone in the silicon part, 200 μm in the middle and 120 μm in the highest zone. The modules are placed on either side of a 6 mm Cu cooling plate forming an absorber layer with two CuW base-plates. The alternative absorber layer consists of two 2.1 mm thick lead planes covered with 0.3 mm thick stainless steel sheets placed on both sides of the module cooling plates. Each plane of this structure is divided into 60° units called cassettes [CMS, 2017b].

The absorber in CE-H consists of 12 stainless steel plates of 35 mm thickness followed by another 12 stainless steel plates of 68 mm thickness. In total, 24 sampling hadronic sections have an interaction length of 9λ . These absorber plates include silicon modules and scintillator tile sheets mounted on 6 mm thick copper cooling plates to create 30° wide cassettes. Although these cassettes resemble those in the electromagnetic section, they contain sensors on only one side of the cooling plate and do not contain absorbers formed as a separate mechanical structure. This leads to a total thickness of 10.7λ , including CE-E and the neutron moderator layer in front of the calorimeter. The polyethylene (C_2H_4) neutron moderator, which aims to reduce the neutron flux in the tracker, has a thickness of 120 μm . All layers are read to be used in energy measurement, but alternative layers in CE-E and CE-H are used for L1-trigger. Scintillator tiles with SiPM are used on the tiles in the low radiation areas of CE-H.

As can be seen in Figure 3.17., the radius in CE-H varies according to the level of radiation. While the neutron flux does not exceed $8 \times 10^{13} n_{\text{eq}}/\text{cm}^2$, it is ensured that the light loss caused by the radiation dose in the scintillators does not exceed 50%. In this way, due to the increased leakage current and light loss of the SiPM, the energy equivalent of electronic noise is kept low enough to ensure a good measurement of the MIP response [CMS, 2017b].

Table 3.2. HGCAL parameters

	CE-E	CE-H	
	Si	Si	Scintillator
Area (m²)	368	215	487
Channels (k)	3916	1939	389
Si Modules (Tileboards)	16008	8868	(3960)
Partial Modules	1008	1452	-
Weight (t)	23	205	
Si-Only Planes	28	8	
Mixed (Si + Scintillator) Planes	-	16	

The parameter values of the HGCAL design are summarized in Table 3.2. The values for area, channel count, modules, and partial modules are the totals for both end caps. The weight and the number of planes refer to a single end cap [CMS, 2017b].

3.4.2. Silicon Sensors of HGCAL

During R&D studies for existing silicon trackers in LHC experiments, it was determined that the sensors should be operated much higher than the full depletion voltage. Even at such high voltages, the charge collected from the radiant traps in bulk silicon is significantly reduced. In addition, the leakage current in the sensors is directly proportional to the flux. This causes an increase in noise and, in the case of very high biases, a significant loss of power inside the sensors. As a result of such observations, studies have started to investigate the sensors thinner than 300 μm to cope with the difficulties of higher flux levels expected in the HL-LHC.

The main difference between Tracker and HGCAL is that while the tracker uses thinly divided strips with $\sim 90 \mu\text{m}$ spacing, HGCAL uses $\sim 1 \text{ cm}^2$ large area pads. While the charged hadrons in the tracker affect the flux, neutrons for the HGCAL affect the flux.

3.4.2.1. Sensor Properties and Layout

Silicon sensors of CE-E and interior parts of CE-H will consist of planar DC-coupled hexagonal silicon sensors produced on 8-inch plates. The shape of the sensors is hexagonal because the hexagonal structure is more useful in circular layers than square or rectangular structures. In addition, the corners of the hexagonal sensors allow space for the mounting / fixation system, which further increases the use of the wafer surface. Another advantage is that the designs of both hexagonal and square sensors were examined before and when the effects of different geometries on the system were considered and compared, a serious cost reduction was achieved by the use of silicon wafers and the placement of hexagonal sensors.

Sensors will have an active thickness of 300 μm , 200 μm , and 120 μm in order to keep the charge collection and working conditions at the best level throughout the working period of the HGCal. 300 μm and 200 μm thick sensors are the basic substrate material physically thinned p-type flat-zone silicon wafers and 120 μm thick sensors are p-type epitaxial layer on the handle-wafer. P-type sensors are preferred because they are more resistant to non-Gaussian noise due to surface charge effects due to radiation. Nevertheless, the possible use of n-type 300 μm sensors in downstream regions in terms of cost savings is still being investigated [CMS, 2017b].

Different sensor cell geometry and tiling options were examined and as a result, the “three-fold diamond” configuration shown in Figure 3.18. was preferred. This is because neighboring cells in the 2x2 and/or 3x3 structure create trigger primitives, just like the different color clusters in the figure and the subdivision of the module into symmetric domains for the readout chips, simplifying the layout of the module readout PCB. The layouts of the silicon wafers using the three-piece diamond configuration are shown in Figure 3.19.

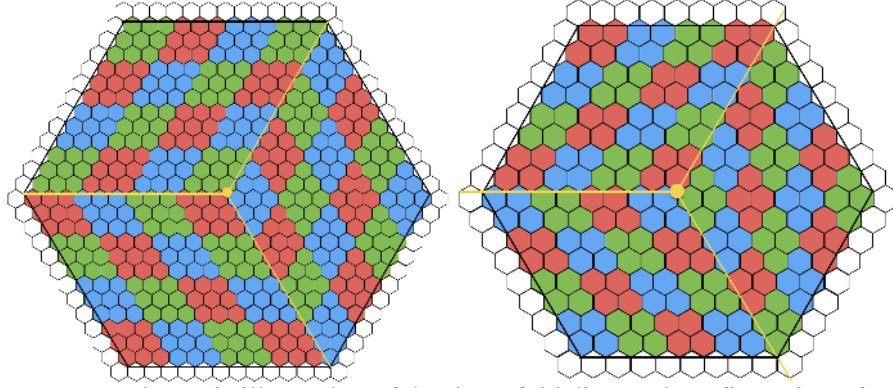


Figure 3.18. Schematic illustration of the three-fold diamond configuration of sensor cells on hexagonal 8-inch silicon wafers. The small cells 0.52 cm^2 shown on the left and the large sensor cells 1.18 cm^2 shown on the right

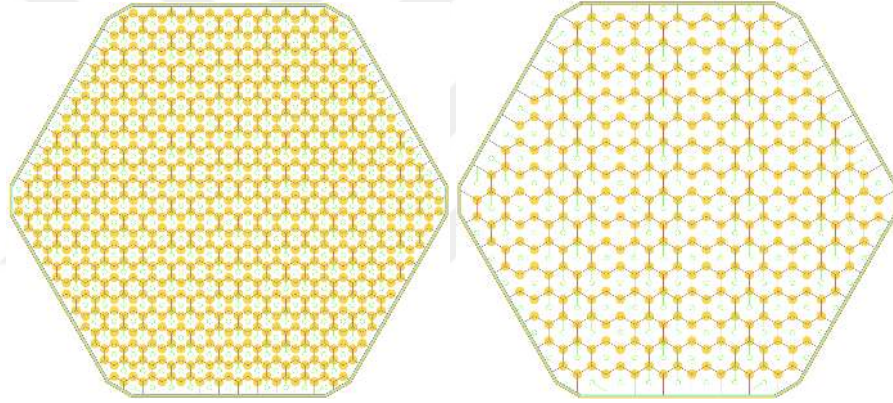


Figure 3.19. Drawing of hexagonal 8-inch silicon wafers, with the layout of small cells 0.52 cm^2 shown on the left and large sensor cells 1.18 cm^2 shown on the right

Cell size works with the limitations of both physics performances of electromagnetic showers such as lateral spread, and the need to keep the cell capacity within a manageable range. In practice, this leads to cell sizes of $\sim 1 \text{ cm}^2$ for $300 \mu\text{m}$ and $200 \mu\text{m}$ active thickness sensors and $\sim 0.5 \text{ cm}^2$ for $120 \mu\text{m}$ active thickness sensors, which corresponds to a maximum cell capacity of 65 pF. Each sensor consists of 192 or 432 individual diodes that act as sensor cells.

The sensor cells are DC-coupled to the reading electronics on the module, which keeps them on the virtual ground and can supply up to 20 mA per cell. The reading chips will be connected to each sensor cell by wire ties passing through holes in the readout PCB. Prototype wafers were tested using single probes, 7-probe arrays, and full wafer pogo-pin-based probe cards.

Table 3.3. provides a detailed overview of the three sensor types and their properties. Table 3.4. and Table 3.5. shows cell size and S/B information for a MIP before and after an integrated luminosity of 3000 fb^{-1} . The field information in this table is the sum of the two end caps [CMS, 2017b].

Table 3.3. Properties of different sensor types

Active Thickness (μm)	300	200	120
Area (m^2)	245	181	72
Largest Life-Time Dose (Mrad)	3	20	100
Largest Life-Time Fluence ($n_{\text{eq}}/\text{cm}^2$)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest Outer Radius (cm)	~ 180	~ 100	~ 70
Smallest Inner Radius (cm)	~ 100	~ 70	~ 35
Cell Size (cm^2)	1.18	1.18	0.52
Initial S/B for MIP	11	6	4.5
Smallest S/B (MIP) after 3000 fb^{-1}	4.7	2.3	2.2

Table 3.4. Different sensor types, properties, and the expected radiation fluences

Active Thickness (mm)	300	200	120	
Cell Size (cm ²)	1.18	1.18	0.52	
Cell Capacitance (pF)	45	64	50	
Expected Range of Fluence ($\times 10^{15} n_{eq}/\text{cm}^2$)	0.1-0.5	0.5-2.5	2-7	
Number Of Wafers	13164	8712	3000	Total: 24876
Number of Partial Wafers	1284	144	324	Total: 1752

Table 3.5. Cell size and S/B information for a MIP

Sensor Thickness	Scintillator 3 mm	Si 300 μm	Si 200 μm
Area (m ²)	480	71	15
Largest Life-Time Dose (Mrad)	< 0.3	30	100
Largest Life-Time Fluence (n_{eq}/cm^2)	8×10^{13}	5×10^{14}	2.5×10^{15}
Smallest/Largest Outer Radius (cm)	$\sim 90/235$	$\sim 80/160$	$\sim 45/100$
Cell Size (cm ²)	$2 \times 2/5.5 \times 5.5$	1.18	0.52
Initial S/B for a MIP	$\gg 5$	11	6
Smallest S/B (MIP) after 3000 fb^{-1}	5	5.7	2.3

3.4.2.2. Silicon Modules

It requires $\sim 27,000$ silicon detector modules to be assembled and installed in one section of the CE-H and the CE-E section of the HGCal. One module is actually a hexagonal component stack, as seen in Figure 3.20. These components are respectively from bottom to top: Base Plate, Kapton Gold Sheet (Polyimide Foil), Silicon Sensor, and PCB, with an Araldite Epoxy Layer between them. All of these components have roughly the same area as the sensor. Also, 6-inch modules were used instead of 8-inch modules for preliminary sample construction and testbeam

measurements.

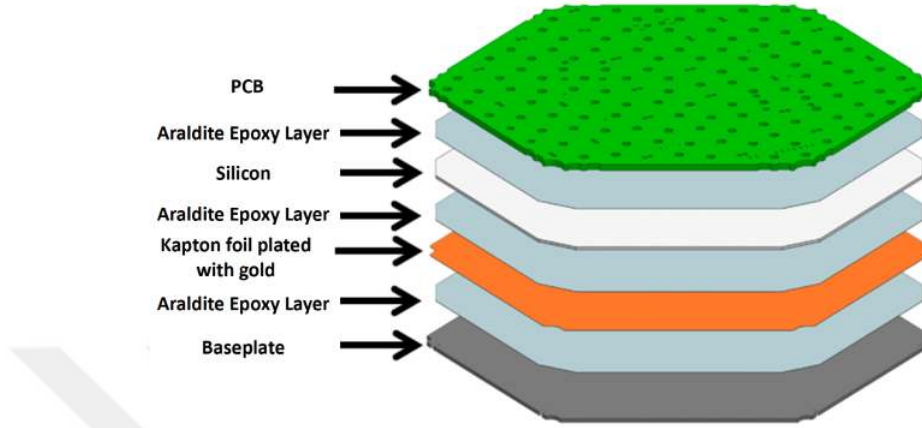


Figure 3.20. CE-E silicon module with stacked layers

The base plate has precise reference holes for placement on cassettes and precision assembly. CE-E base plate material is a sintered CuW metal structured composite. While the copper used in the material provides a good thermal conductivity, tungsten decreases the thermal expansion coefficient. The combination of these two creates a material with a short radiation length, which is an important component of the CE-E absorber. Also, the base plate material for CE-H units is carbon fiber with high thermal conductivity [CMS, 2017b].

The 105 mm thick Kapton foil base plate coated with a thin layer of gold is covered to the base plate as an epoxy, and almost completely envelops the surface. The thin gold layer on the Kapton's open side is used to provide the high voltage bias connection to the back plane of the sensor via a conductive epoxy bond. Kapton also provides that the sensor back plane is electrically isolated from the base plate.

Silicon sensors and hexagonal plates are hexagonal structures with tiny cut-outs at the six corners. Tiny cutouts provide access to positioning and mounting holes in

the base plate. The tiny cutouts also allow access to part of Kapton-Au for cable connections to the hexagonal plates. In this way, the bias voltage is applied to the backplane of the sensor. The hexagonal plate will contain HGCal Read-Out Chip (HGCROC) front-end reading ASICs. Signals from the sensor pads are routed to the HGCROC for internal signal digitization. Holes in hexaboards reveal the zone around the intersections of groups of four pads. A zoomed-in view of the hexagonal plate module layout and rotating rings for the 432 channel sensor is shown in Figure 3.21.

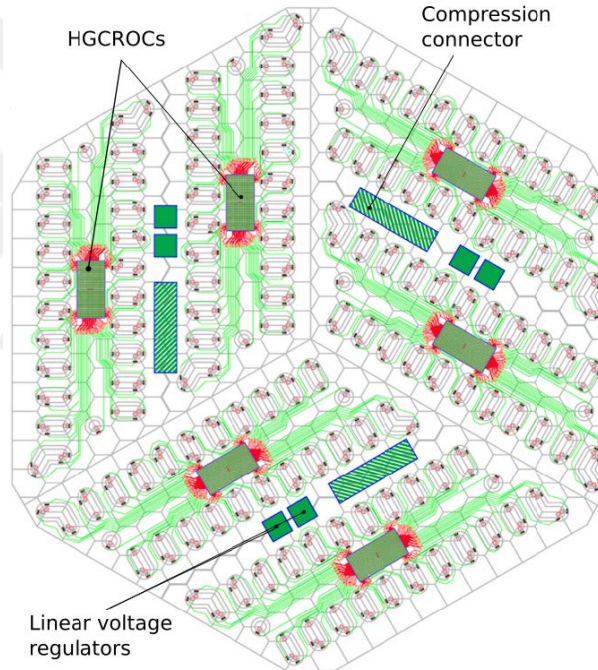


Figure 3.21. PCB module layout for 432-channel sensor shows the placement of HGCROCs, linear voltage regulators, and compression connector

3.4.3. Plastic Scintillator Materials

The effect of ionizing radiation on existing HE has been studied in detail using ultraviolet laser, radioactive sources and beam data. The measurements showed that there was a linear relationship between the damage to the detector and the dose rate. Dose rate dependence appears to be an effect of detector chemistry and oxygen diffusion with increased damage from a lower dose rate. In addition to these, the working temperature of the detector should be close to -30°C .

3.4.4. SiPM Photodetectors

Light from the scintillation plates is read by SiPM Photodetectors. Used in many systems, including Phase-1 HCAL upgrade, these photo detectors provide a very high gain ($> 10^5$) and excellent light detection efficiency ($> 30\%$).

The equipment such as cooling and cable of scintillators should be tight and should not take up too much space on the outer edge of the calorimeter. A few designs have been considered in this regard, and the tile-based SiPM technology used in the Analog Hadronic Calorimeter (AHCAL) was selected. The main reason for this choice is that it offers sufficient performance for particle tracking and identification at the most affordable cost.

The tile-based SiPM technology uses a direct reading of light from the scintillator tile. This reading is performed with the SiPM, which collects the light through the hole on the surface of the tile. This hole provides a mechanical space for the attachment of a SiPM and improves the regularity of the response across the tile by reducing the response of particles passing very close to the SiPM, compared to those at greater distances [CMS, 2017b].

A MIP, Passing through a solid 3 cm x 3 cm x 3 mm tile, has been

shown to generate more than 20 photo-electrons by the Calorimeter for Linear Collider Experiment (CALICE) Collaboration. Test-Beam studies have supported this performance and also showed several important geometric relationships:

- The magnitude of the MIP signal is directly proportional to the inverse square root of the tile surface area ($\frac{1}{\sqrt{A_{\text{tile}}}}$). In this case, the smaller the tile, the greater the photo-electron efficiency from a MIP.
- The photo-electron efficiency has been shown to increase linearly with the SiPM area.

This geometric effect is utilized in the arrangement of scintillator tiles. They are arranged within the r – ϕ grid of radial dimension where each tile is the same as the pole width in the middle. As a result, smaller sized tiles with smaller diameters give larger signals where the radiation damage to scintillators and SiPM noise would be greatest. At larger r with less damage and noise, the cells are larger to reduce the number of channels and total calorimeter cost.

The $\Delta\phi$ angular size of the cells is chosen to match the 5° cells of the HB calorimeter. Also, the size of the scintillator cell should be close to the physical size of the silicon trigger cells at the boundary between the scintillator and the silicon. This match minimizes the effect of inevitable separation between the two regions for reconstruction algorithms.

The boundary between the silicon and scintillator parts of the calorimeter is determined provided the detector measures the S/B ratio of MIP at least 5, over its lifetime. The boundary has been extended somewhat along the radius according to the minimum area possible to provide silicon coverage for $|\eta| > 2.4$. The limit is also set in such a way that only hexagonal or half-hexagonal sensors are needed at the boundary [CMS, 2017b].

3.4.5. Test-Beam Studies

Several test-beam studies have been conducted since 2016 to measure the performance of the HGICAL design. The test-beams also play an important role in the development of models used in Monte Carlo simulations. In the modules of the first test-beams, two 64-channel SKIROC-2 ASIC Chips were mounted on each reading PCB. The hanging file structure was used for flexibility in placing these modules. The purpose of using this structure is to be suitable for researching different installation configurations. In this way, layers or modules can be changed more easily. The first system established in Fermi National Accelerator Laboratory (FNAL), consisted of 16 sampling layers and tungsten absorbers with a depth of $\sim 1\text{-}15 X_0$ were used. The particle type used in the system was the electron (only the CE-E part has been tested) and the energy range was 4 GeV - 32 GeV (see. Figure 3.22.). 6-inch sized p-insulator-n (p-in-n) silicon plates produced by Hamamatsu Photonics K.K. The 320 μm thick plate has 128 cells. The area of the hexagons was $\sim 1.1 \text{ cm}^2$ and the energies of the protons used for adjustment were 120 GeV [Akchurin et al., 2018].

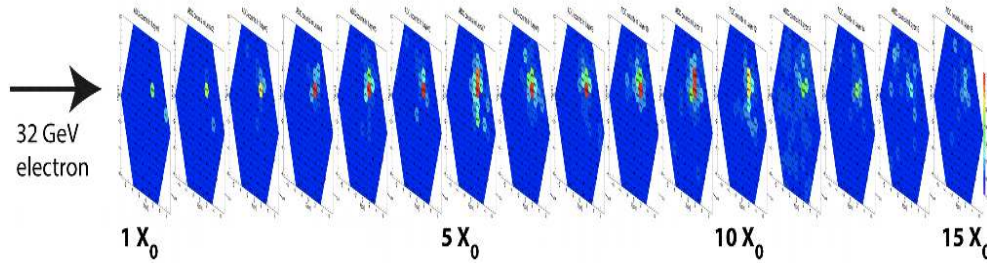


Figure 3.22. Demonstration of 2016 16-layers test-beam setup with 32 GeV electrons at FNAL passing through HGICAL modules

Two different configurations were also investigated at CERN. Both configurations consisted of 8-layers (see. Figure 3.23.). In the first configuration layout, the modules were placed in the depth of 6-15 X_0 , and in the second

configuration layout modules were placed in the depth of $5\text{--}27 X_0$, and tungsten absorbers were used. Calibrations were made with 125 GeV energy muons and pions. Besides, data were taken with the electron beam at 250 GeV energy. Both installations were simulated by a Geant4 simulation. As a result of these studies, the simulation and experimental studies were compared and it was observed that the results were good. The reliability in the use of SKIROC-2 front sensors has been tested and has been successful. A special fast digitizer was used to measure the pulse pattern caused by signals in silicon.

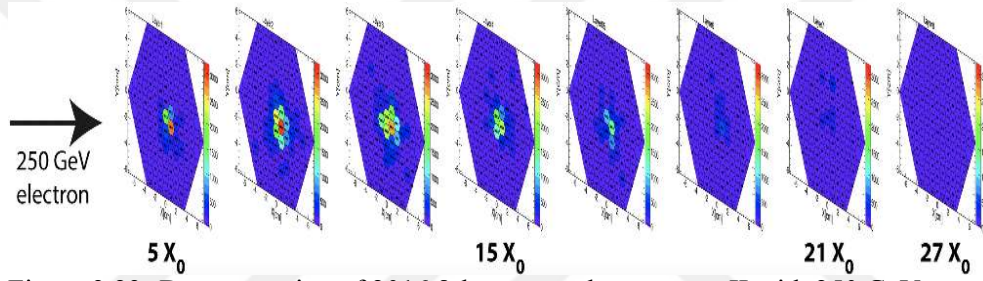


Figure 3.23. Demonstration of 2016 8-layers test-beam setup-II with 250 GeV electrons at CERN passing through HGCAL modules

The main trigger source at both laboratories (FNAL and CERN) were plastic scintillators. While only one $2 \times 2 \text{ cm}^2$ scintillator, that read with two SiPMs, used in the FNAL, two $4 \times 4 \text{ cm}^2$ sequential scintillators, that read with photo-multiplier tube, used at the CERN. Besides, there are delay wire chambers (DWC) placed approximately 1.5 m and 2.7 m above the installation. Thanks to the DWCs, the trajectory of the beam particles could be measured with an accuracy of approximately 1 mm.

The CuW plates used during the test-beams at CERN in 2016 had three functions; providing mechanical support, providing a thermal path from the ASICs on the PCB to the copper heat sink, and became the absorber part of the calorimeter.

The thickness of the base plates used in test-beams were 0.8 mm ($\sim 0.15 X_0$), 1.2 mm ($\sim 0.25 X_0$) and 1.6 mm ($\sim 0.5 X_0$).

The base plate, polyimide board, silicone, and the first PCB are bonded together using Araldite 2011 epoxy. This assembly was done using a semi-automatic gantry system to hold the parts and dispense the optimized adhesive molds. The glue cured within 24-hours at room temperature, resulting in a total assembly time of approximately three days for the three bonding steps. The merge stages are summarized in Figure 3.24. After these operations, the silicone pads were connected to the signal lines on the PCB using aluminum wire bonds, which required a deep reach wire bonding machine for the holes. The wire ties also bonded the PCB to the gold top surface of the polyimide layer, which was bonded to the back of the silicon using conductive epoxy. Finally, the reading PCB was connected to the first place in Figure 3.25. and the modules were tested [Akchurin et al., 2018].

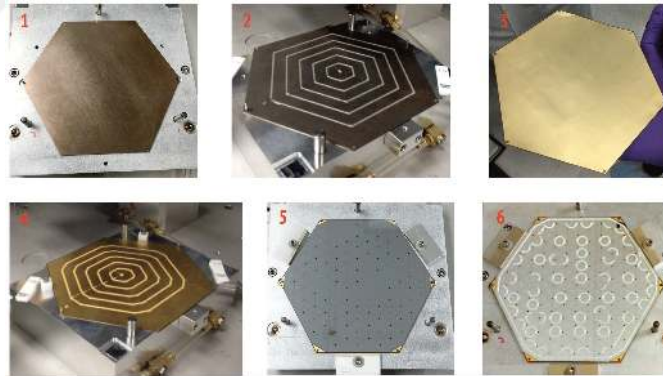


Figure 3.24. The assembly stages of the units used in the 2016 test-beams at CERN. 1: CuW base plate in bonding apparatus; 2: Addition of Araldite 2011 epoxy; 3: polyimide gold plated foil; 4: with polyimide foil adhered to the base plate and its own adhesive layer; 5: gluing the silicon sensor to the polyimide foil, and 6: adding a special glue that spreads over the whole silicon surface (except the PCB addition)

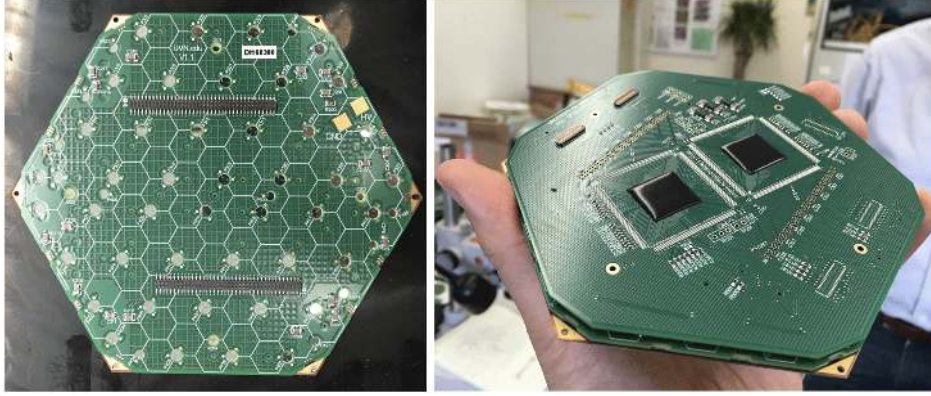


Figure 3.25. Photo of the module showing the holes of the PCB (left), readout PCB with two-chip connected to SKIROC-2 ASICs (Right)

The silicon sensor shown in Figure 3.26. was used in this experiment and had a depletion thickness of $200\ \mu\text{m}$ and a physical thickness of $320\ \mu\text{m}$. The majority of the sensors were $\sim 1.1\ \text{cm}^2$ in size. Here are two hexagonal cells divided into two parts. These are an inner calibration pad with about $1/9$ of the area of the full-hexagonal cell and the surrounding outer calibration cell. The first of these makes it easy to adjust the S/B ratio of a standard cell using MIPs after irradiating. This calibration means that single MIPs are detected efficiently if the S/B ratio is too small. Smaller area results in a smaller capacity, which reduces the internal noise of the cell while the MIP signal size remains the same. There are semi-hexagonal cells at the corners of the sensor and these are called mouse-bite-cells. Each sensor has 134 separate cells. Since this exceeded the number of electronic channels found on the front-end CuW pairs, some cell pairs around the sensor were electrically connected to the PCB to form merged-mouse-bites and merged-cells resulting in a total of 127 reading channels. The number of readout channels and cell types are summarized in Table 3.6. [Akchurin et al., 2018].

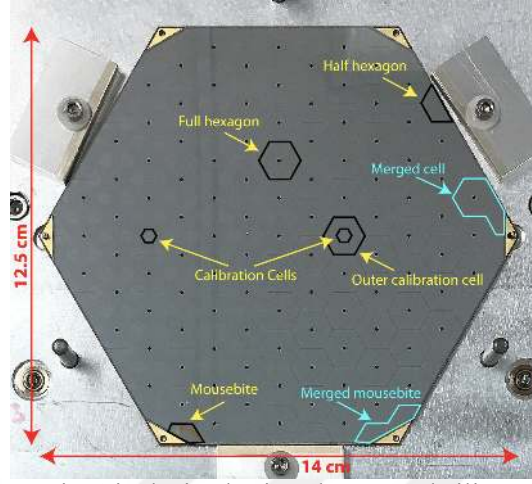


Figure 3.26. Cell types in 6-inch sized p-in-n hexagonal silicon sensor used in 2016 test-beams

Table 3.6. The number of readout channels and cell types

	Sensor Cells	Readout Channels
Hexagons Full/Half	106/12	103/12
Mouse-Bite-Cells	12	0
Calibration Cells (Inner/Outer)	2/2	2/2
Merged-Mouse-Bites	0	4
Merged-Cells	0	4
Total:	134	127

It was necessary to keep the gap between consecutive absorbers/cassettes to a minimum in order to ensure the tight construction of the CE. Due to this requirement, flexible polyimide cables and connectors that can be mounted on their surface were used. This usage provides low profile connectivity. Digital data from SKIROC-2's are transferred to the passive right-angle PCB via two flexible cables and from there to the Dual-Daughterboard Carrier (DDC) Card via another pair of cables. The data is then transferred to Zedboard via a standard HDMI cable. Data from 14 DDCs were

collected with another passive private board known as ZED-IO. In the last step, all information coming from Zedboard was directed to the computer via Ethernet.

Modules were attached to 6 mm ($0.4 X_0$) thick copper plates as shown in Figure 3.27. Although these plates were not used in 2016, they had embedded channels to allow the coolant flow. One module can be placed on either side of the copper plate. This was similar to the final HGCal design in which groups of approximately 25 to 100 modules would be mounted on wedge-shaped cooling plates to form cassettes.

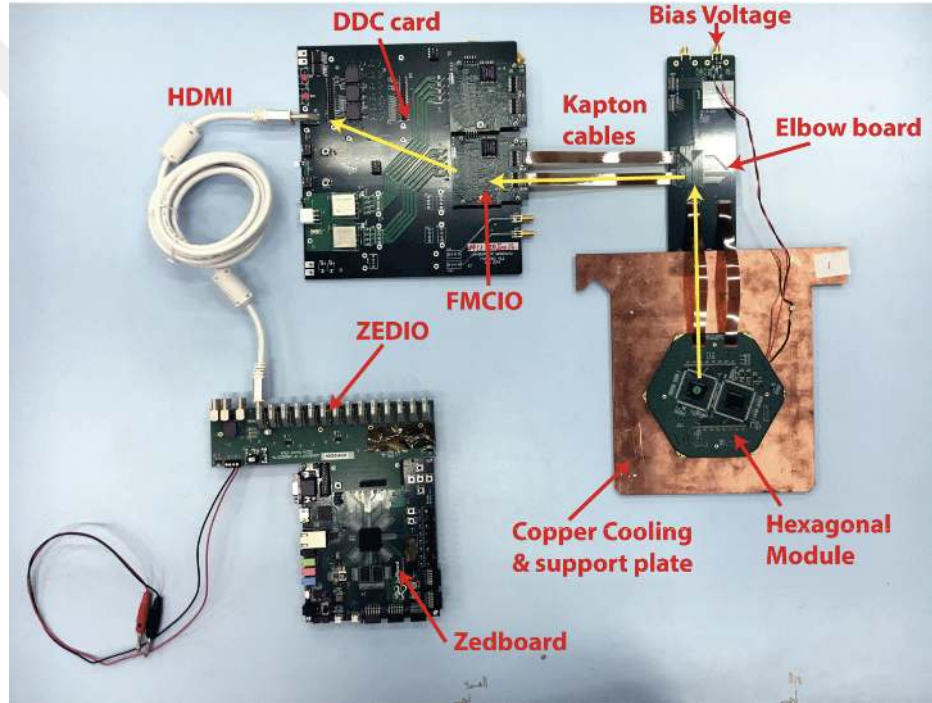


Figure 3.27. Data collection system from module to Zedboard

A flexible mechanical support system was built using the hanging-file design (see. Figure 3.28.) for easy mounting of the absorber plates, allowing the exploration of units and different setups attached to the cooling plates. Aluminum frames supporting tungsten plates of three different thicknesses were used in the system as

absorbers (2 mm: $\sim 0.57 X_0$; 2.8 mm: $\sim 0.87 X_0$; 4 mm: $\sim 1.14 X_0$).

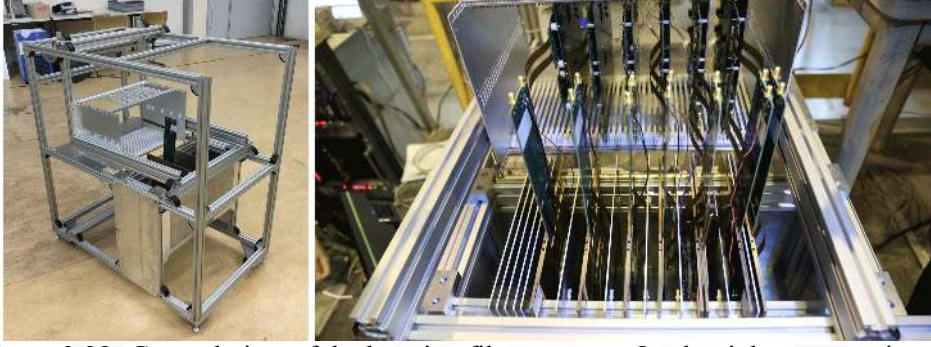


Figure 3.28. General view of the hanging file structure. On the right, some units and absorbers are added

In the 2017 test-beams, SKIROC-2 CMS ASICs designed with 4-chips per module were used. Each CALICE SKIROC-2 based part consisted of 64-channels. Their intended use was to shape, amplify and digitize signals from silicon sensors.

The copper cooler plate is shown in Figure 3.27. was added to the configuration in 2017. Also added hadronic section with 12 layers of steel absorbers and each layer containing 7 modules. After this process, the overall layout of the sensor took the form of EE + FH + BH, named CALICE AHCAL Prototype. EE test-beams were performed with a silicon module in May, EE + FH test-beams with 10 silicon modules in June, and EE + FH + BH test-beams were performed first with 17 and then with 20 silicon units in July [Akchurin et al., 2018].

Three test-beams were performed in 2018. The first of these happened at DESY in March and studied the response of single silicon modules to low-energy electrons. Using precise tracking with the beam telescope, the accuracy of up to $10 \mu\text{m}$ was achieved in the impact/collision position. In June, a major installation took place on the H2 Beamline of SPS at CERN, including 28 single module layers of the ECAL

section. The arrangement of the modules is made similar to the envisaged sensor design. In this context, double-sided cassettes with active cooling are used. Data were taken with muon and electron beams in the energy range of 10-150 GeV.

In October 2018, the CE-H section containing 12-layers (66-modules) was added after the CE-E, which contains 28-layers consisting of a single module. The total number of modules of CE-E and CE-H was 94. (A few of them failed towards the end of the test-beam). The prototype design of the CALICE AHCAL sensor was used for the scintillator part of the hadronic section. While 200 μm sensors were used in the first and second test-beams, 90 sensors of 300 μm and the remaining four 200 μm sensors were used in the last test-beam. Most cells in the sensors are $\sim 1.1 \text{ cm}^2$ in size.

The ECAL prototype consists of 14 mini-cassettes. Each cassette consists of a 4 mm thick lead plate and a 6 mm thick copper plate held by 2-modules. Mini-cassettes were covered with an aluminum frame and a mylar plate. A copper cooling pipe was placed through a hole in the copper plate. During the test-beams, water was used at 28°C to cool the prototype silicon modules and keep them at a constant temperature. The total depth of the ECAL was approximately 50 cm and the radiation length was $24 X_0$.

The CE-H prototype consists of 12-layers positioned just behind the CE-E prototype. The layers are made of a 6 mm thick copper plate to which up to 7-modules are connected on one side and a copper cooling pipe on the other. Makrolon Polycarbonate Plate was placed on top of the copper plate. This plate holds the panels needed to connect modules to a DAQ system. The layers are placed in one of two mechanical structures that also hold 4 cm thick steel absorption plates. The total depth of the silicon hadronic calorimeter prototype is approximately 4λ . The peripherals of the silicon CE-H prototype are grounded to the copper cooling plates via short wires.

The same scheme has been tried for central modules but did not perform well due to the use of longer cables. Grounding for the central modules is made by connecting a ground pad to the ground pad of one of the peripherals.

Two types of units were built with different grounding methods. Both are based on placing a grounding layer between the gold layer on the Kapton foil and the copper heat sink. The first method consists of bonding a second Kapton foil with a layer of gold on the base plate. The top foil is used to connect the high voltage and is cut at the corners of the module to gain access to the bottom foil. Then the gold layer of the bottom foil is attached to the bottom of the hexagonal plate. Seven units were built using this method and placed in the same silicon CE-H layer. The second method is to use a PCB as the base plate with three gold layers. The top layer is used to apply high voltage on silicon.

The PCB designs of the SKIROC-2 CMS ASICs used in 2017 were changed and used here. Also, the basic shapes of some modules were different; PCBs were used for some, and double Kapton for others. However, no changes were made to the base plates (Cu and CuW were used).

Three different configurations were used during the October test-beams, and these configurations shown on Figure 3.29., 3.30., and 3.31..

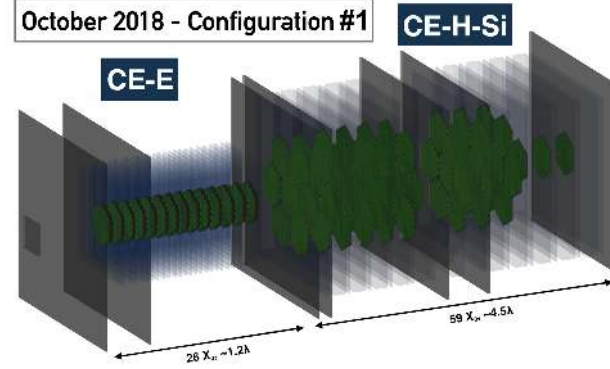


Figure 3.29. Electromagnetic part with 14x2 layers + Hadronic part with 7x9 + 3x1 layers, and FH absorbers are between all layers

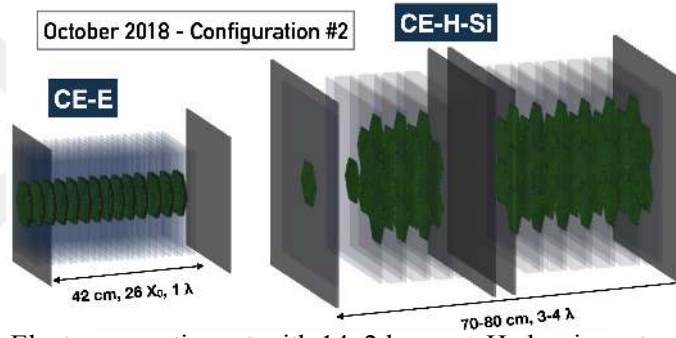


Figure 3.30. Electromagnetic part with 14x2 layers + Hadronic part with 2x1 + 7x9 layers, and no FH absorbers between the 2x1 layers

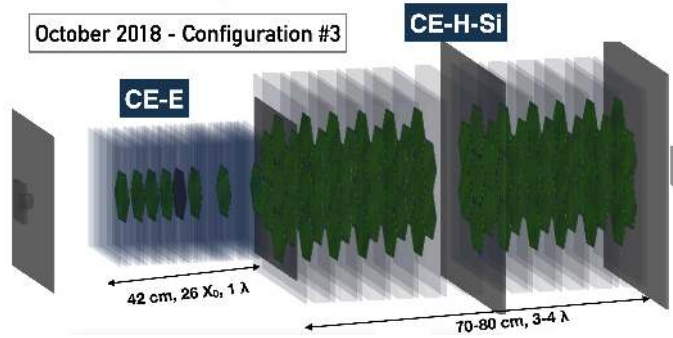


Figure 3.31. Electromagnetic part with 5x2 layers + Hadronic part with 7x12 layers, and FH absorbers are between all layers

3.4.6. Detector MIP Calibration

MIP constant is defined as the most probable energy deposition in Analogue to Digital Counts (ADC) of a channel for an incident MIP particle. Muons are generally used in calibration analysis. Besides the other calibration constant, the MIP constant is a crucial constant to convert the ADC value to the energy scale of MIP, showing the energy deposition in the calorimeter in MIP equivalents. This work's ultimate goal was to calibrate each channel of the HGCal detector with the MIP.

Initially, noise contributions to ADC spectra are reduced when requiring a hit to be part of a MIP-like track and using DWC and tracking scintillator information. As shown on Figure 3.32., it was defined the calibrated electric response to MIPs with the maximum of the fitted model (Convolved Gaussian Landau) to these spectra for each module/chip/channel. Furthermore, Figure 3.33. proves that MIP Calibration can be done very efficiently with also hadronic particles (π) instead of Muons (μ) up to 10 layers of the HGCal Detector.

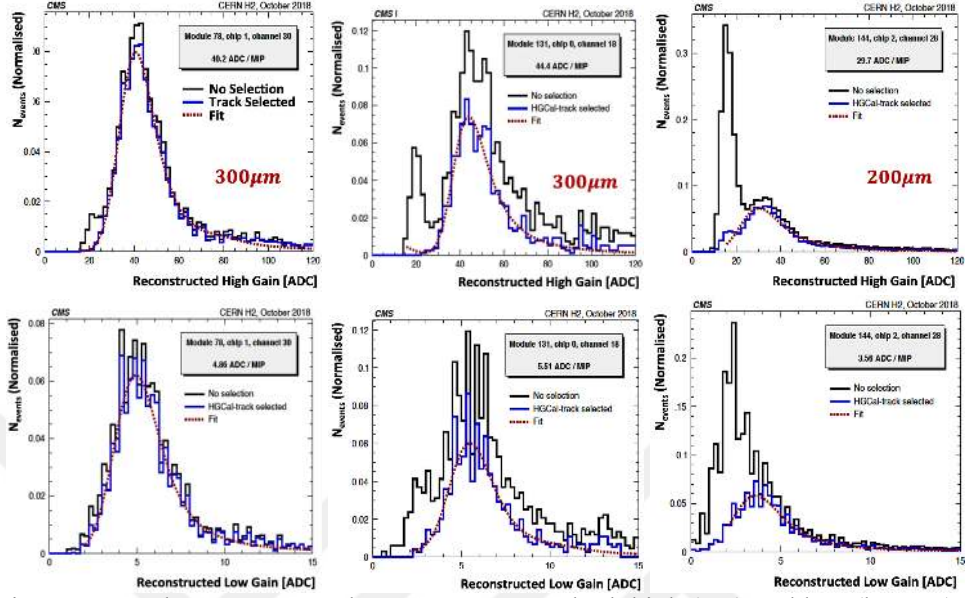


Figure 3.32. The reconstructed ADC spectrum at both high (top) and low (bottom) gain for the three sample read channels due to 200 GeV/c Muon events. Module 144 is equipped with a sensor that has a depletion thickness of 200 μm instead of 300 μm , resulting in a lower response

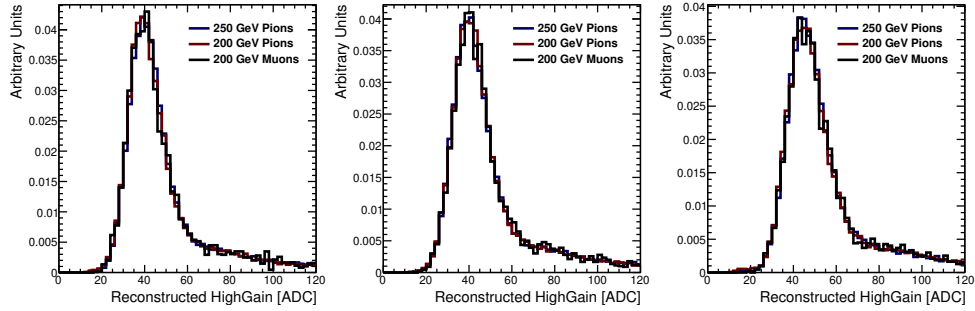


Figure 3.33. Comparison of reconstructed high-gain distributions of Pion beams with 200 GeV/c & 250 GeV/c initial energies with the 200 GeV Muon beams

3.4.7. Energy Loss and Material Impact at HGICAL Test-Beam

Energy loss was observed in the data obtained during the testbeam studies in October 2018 HGICAL Test-Beam, especially for electron beams. Figure 3.34. shows the loss rates according to the initial energies used during the testbeam. Although the energy loss is mainly caused by known phenomena called Synchrotron Radiation (SR), it's evident that the beamline materials used to control the beam in the air zones have radiation length (X_0) and cause energy loss. (such as; scintillators, wire chambers, etc.) The reason for this energy drop investigated by performing on-site measurements and making realistic simulations of the SPS H2 Beamline with the Geant4-based G4Beamline.

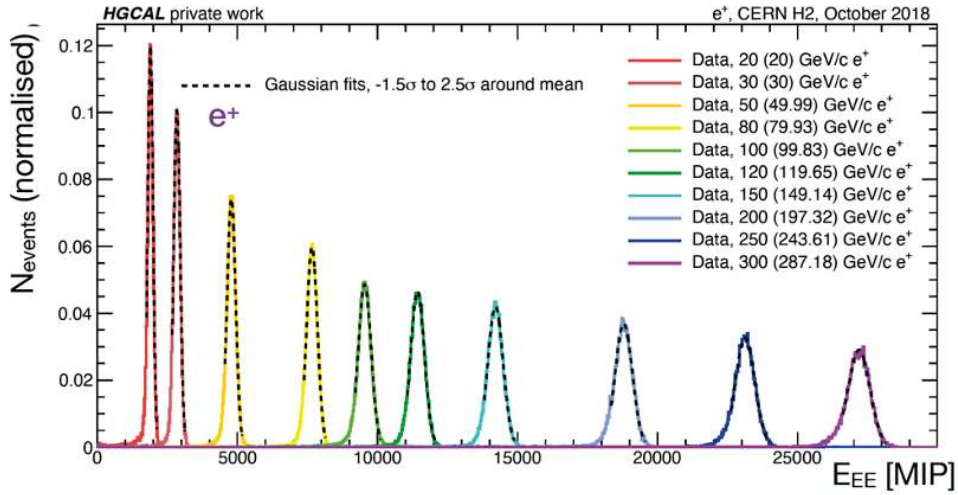


Figure 3.34. Initial beam energies and the amount of energy losses

3.4.7.1. H2 & H4 Beamlines

SPS H2 & H4 Beamlines are precise, robust, flexible magnetic spectrometers. It means, these beamlines select the momentum with better than 2% resolution. The

process starts with a proton beam with a momentum of 400 GeV/c which is extracted on an underground target. In the target, all particles are produced, and the beamlines, like H2 and H4, select only the desired particles. These particles bent by the magnets at the right angle go through the beamline and reach the detector at the ground level. This process is also demonstrated in Figure 3.35. The choice of target and converter, as well as the unique magnets around the target, allow for significant flexibility in the beam conditions and particle types (such as; hadrons, electrons, purity, intensity, etc.) that are transported to the experimental areas.

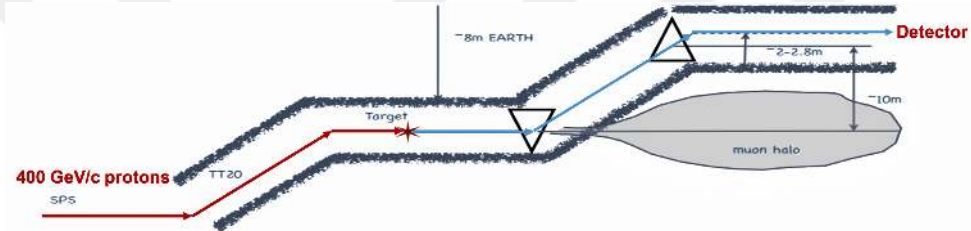


Figure 3.35. Demonstration of the working principle of the H2 Beamline

3.4.7.2. Particle Production Principle

The electron beams are exceptional, and they are usually produced via the neutral channels ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^-e^+$). More specifically, 400 GeV/c protons accelerated by the SPS hit to 500 mm Beryllium target. After the target, the magnet sweeps the particles and only allows the neutral particles (such as; π^0). In this time, neutral particles decays in flight to $\gamma\gamma$. Then, these gamma particles hit to 4 mm Lead Converter and produced electrons & positrons. These particles go through the beamline and reach the detector. This process is also demonstrated in Figure 3.36. For this process, the maximum momentum for the electron is around 300 GeV/c and the rate of the electrons are decreasing with the increasing momentum.

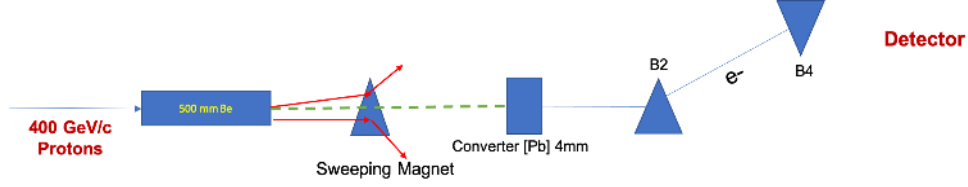


Figure 3.36. Demonstration of the particle production principle of the H2 Beamline

The electron momentum is selected via the beamline collimators. But, in higher momenta, we cannot avoid hadronic contamination. It means that even the positron beams contain a trace amount of hadronic particles. Fortunately, SR helps to get a pure beam, but this comes at the expense of the momentum definition because the electrons lose their energy with the SR, which creates a spread in the momentum. At the same time, electrons are also very sensitive to the materials present at the beam line. And these materials can cause phenomena called Bremsstrahlung and Multiple Scattering.

3.4.7.3. H2 Beam Line Simulation With Geant-4 Beamline

Geant-4 based G4Beamline is used to simulate the H2 beamline from the target to the HGCal. Magnetic elements (such as; quadrupoles, bending magnets, collimators) and other materials (like; scintillators, beam windows, etc.) added precisely to the model. Corrector magnets and Halo/Veto counters also added upstream and inside the PPE-172 (HGCal) zone. Materials of fixed experiment NA61/SHINE on the beamline also simulated, as well as HGCal's materials during the October 2018 testbeam. Figure 3.37. shows the full H2 Beamline model and Figure 3.38. is a closer look to the PPE-172 Zone, created with G4Beamline. The model size is approximately 607 m, and the magnets have a length of ~ 5 m.

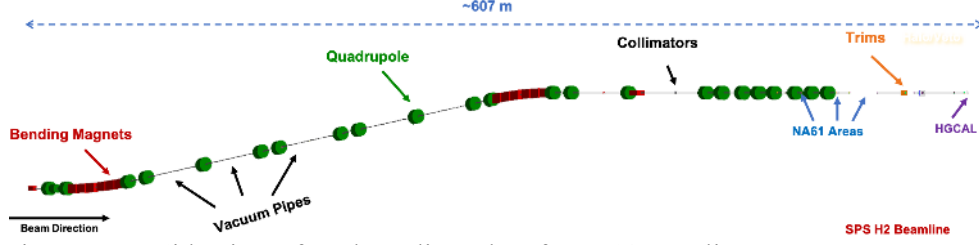


Figure 3.37. Side view of H2 beamline taken from G4Beamline



Figure 3.38. Side view of PPE-172 zone taken from G4Beamline

3.4.7.4. Energy Loss; Synchrotron Radiation and Materials

The main source of energy loss especially for the electron beams is the SR. Initially, a check was performed to see whether the SR effect was calculated correctly or not. Assuming an un-physical monochromatic, 250 GeV/c positron pencil beam passes through all the beamline magnets and reaches the HGCal, Figure 3.39. shows that the SR effects are accurately reproduced by G4Beamline. The equilibrium of centrifugal and magnetic Lorentz Force can be used to calculate the diffraction angle thus magnetic field of bending magnets [Wiedemann, 1994].

$$\Theta = \frac{299.79 \cdot B \cdot L_{\text{eff}}}{P} \quad (3.11)$$

where L_{eff} is the length of magnet and expressed in meter and P in GeV/c. The Larmor formula can be used to calculate the energy loss due to the SR

$$\Delta P = -\frac{2}{3} \cdot \frac{r_0}{(m_0 \cdot c^2)^3} \cdot \frac{p^4 \cdot \Theta^2}{L_{\text{eff}}} \quad (3.12)$$

where P is expressed in GeV/c and Θ in Rad. And the momentum spread can be calculated with

$$\sigma = n_{\text{eff}}^{-1/2} \cdot \Delta P \quad (3.13)$$

where $n_{\text{eff}} = 0.144B \cdot L_{\text{eff}}$, B is in kG and L_{eff} is in meter.

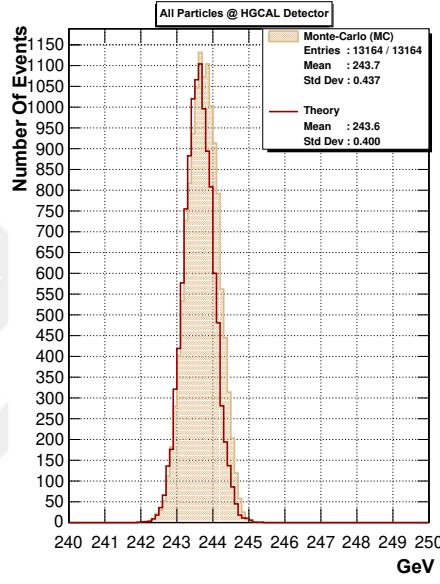


Figure 3.39. MC Momentum distribution of a pencil beam at the HGICAL detector

The mean momentum in HGICAL is not 250 GeV/c, but 243.7 GeV/c, and an extra momentum spread is introduced of the order of 0.1%. This effect needs to be convoluted for a realistic calculation with the initial emittance, the collimator settings, and the material present at the line.

After completing the modeling of the full H2 beamline, (pipes, materials, magnetic elements, etc.), results are implemented to the detector's own Geant4 simulation by the simulation group of the HGICAL. Agreement between the HGICAL data and MC with full beamline simulation is pretty good, especially for higher beam energies. Energy response as a function of beam energy shows linearity within 0.5%. Theoretical and MC momentum spreads are given in Table 3.7. and these results are shown at the 8th BTTB Conference in Georgia [TOK et al., 2020], and Figure 3.40. shows the MC agreement with the HGICAL testbeam data, shown by the HGICAL group at the same conference [Ceard, 2020].

Table 3.7. Beam momentum spread at HGICAL. Theoretical and MC results are shown separately for each initial beam energy

Initial e ⁺ Beam	Estimated		Monte Carlo	
	Final Energy [GeV]	dp/p (%)	Final Energy [GeV]	dp/p (%)
20	20	0.1009	19.91	0.561
30	30	0.1009	29.87	0.568
50	49.99	0.1009	49.79	0.573
80	79.93	0.1009	79.62	0.582
100	99.83	0.1009	99.45	0.589
120	119.65	0.1610	119.20	0.598
150	149.16	0.2018	148.50	0.623
200	197.32	0.2018	196.30	0.642
250	243.61	0.6050	242.50	0.651
300	287.18	0.6050	286.02	0.671

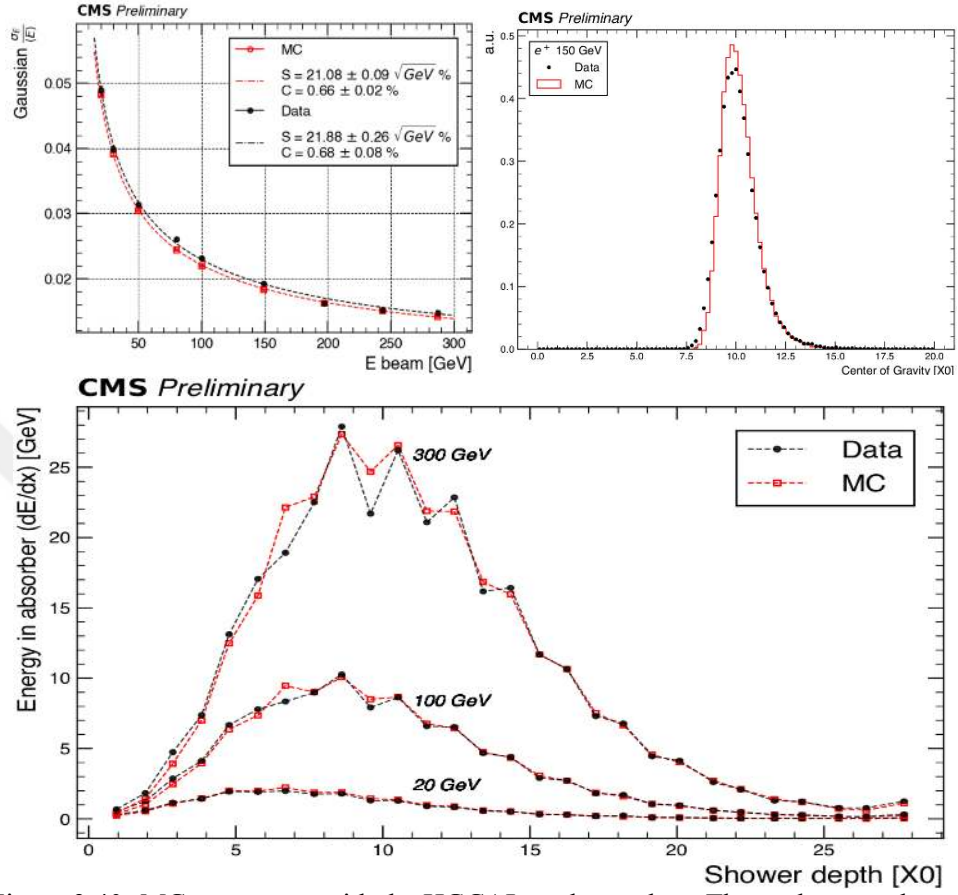


Figure 3.40. MC agreement with the HGCAL testbeam data. These plots are shown at the 8th BTTB Conference by HGCAL Testbeam Group

4. LOW-MASS DIJET RESONANCE SEARCH

Our experimental approach is to investigate dijet resonances using the dijet mass spectrum measurement method in the data from the CMS experiment. Dijet event selection requires two High- P_T jets located opposite each other to measure the invariant mass spectrum. If there is a dijet resonance, the resonance should appear in the dijet mass spectrum as a bump, as shown in Figure 4.1.

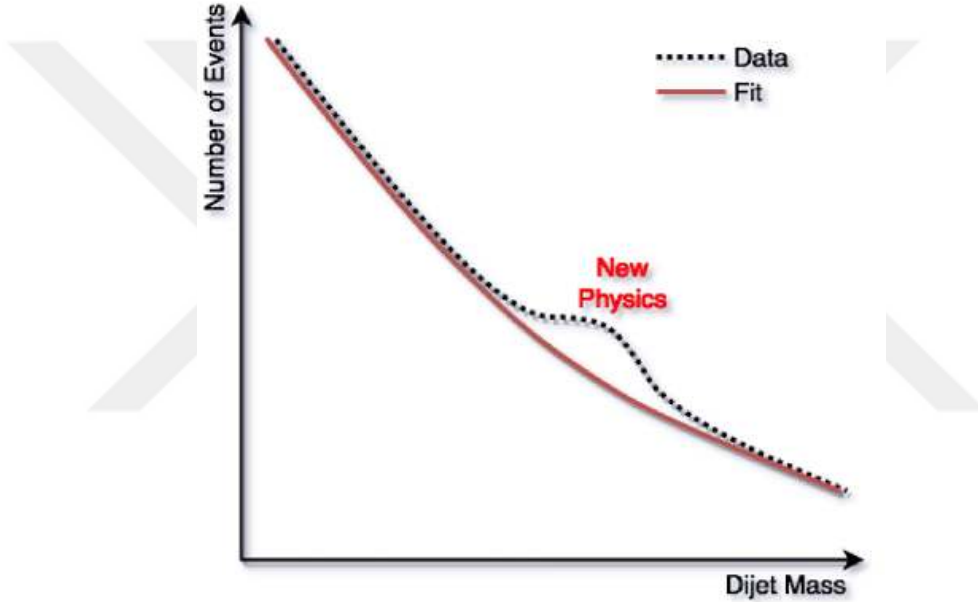


Figure 4.1. If an excess (bump) is observed in the dijet mass distribution, it can be interpreted as a signal caused by a new resonance

4.1. Data Quality

The heart of the search for dijet resonances is the measurement of the dijet mass distribution and also the estimation of the background. Unlike several alternative searches in high energy physics, the search for dijet resonances is totally dominated by

only one background which is: $2 \rightarrow 2$ scattering of partons predicted by perturbative QCD [HARRIS et al., 2011].

The QCD event distributions obtained from the simulation were not used to extract the physics results in the analysis but were used for checking the data quality of jet-related quantities and the comparison with the MC.

Data collected in the calo-scouting stream in 2016, 2017, and 2018 were used to perform the search for dijet resonances with masses between 0.5 TeV and 2.3 TeV. The search was carried out on 122.2 fb^{-1} of data produced from 139 fb^{-1} CMS data. The comparisons between data and simulated events were analyzed for each year separately and also for all Run II data. The trigger is not fully efficient for each dataset until 489 GeV dijet mass.

After the event selection procedures that mentioned at the section 2.4. and 2.5., the agreement between data and simulated events for jet kinematic quantities $\Delta\eta$ and $\Delta\phi$ was examined, as shown in Figure 4.2. and Figure 4.3.

It can be inferred from $\Delta\eta$ and $\Delta\phi$ comparison, that the data, and MC matches almost perfectly and dijet production is dominated by $t - channel$ parton exchange with a production rate increases with increasing $\Delta\eta$ and $\Delta\phi$. Figure 4.4. shows the spectra of the data and QCD, which fall steeply and smoothly as a function of dijet mass.

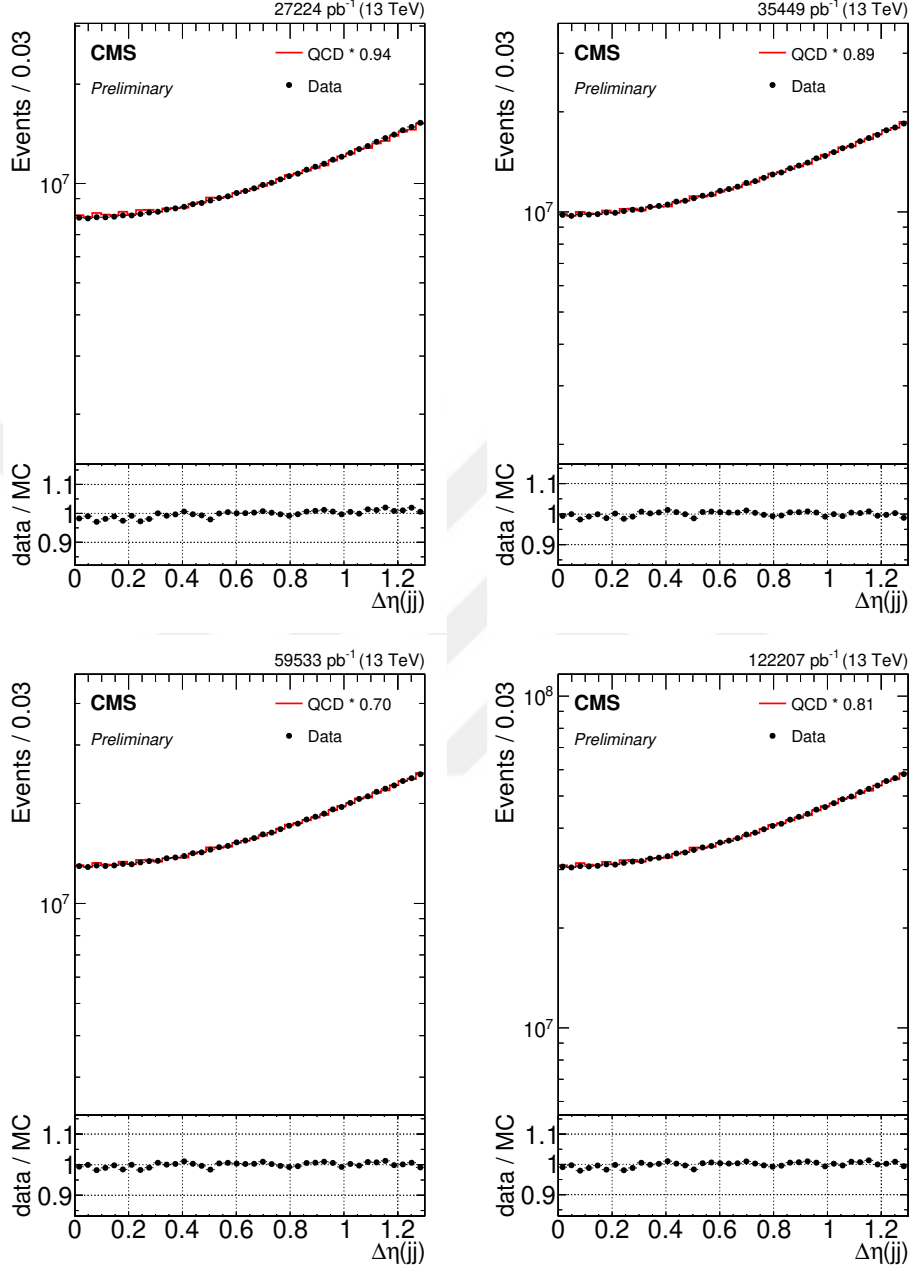


Figure 4.2. $\Delta\eta$ agreement between data and QCD MC, (top-left) for 2016 data (top-right) for 2017 data (bottom-left) for 2018 data (bottom-right) for all Run II data

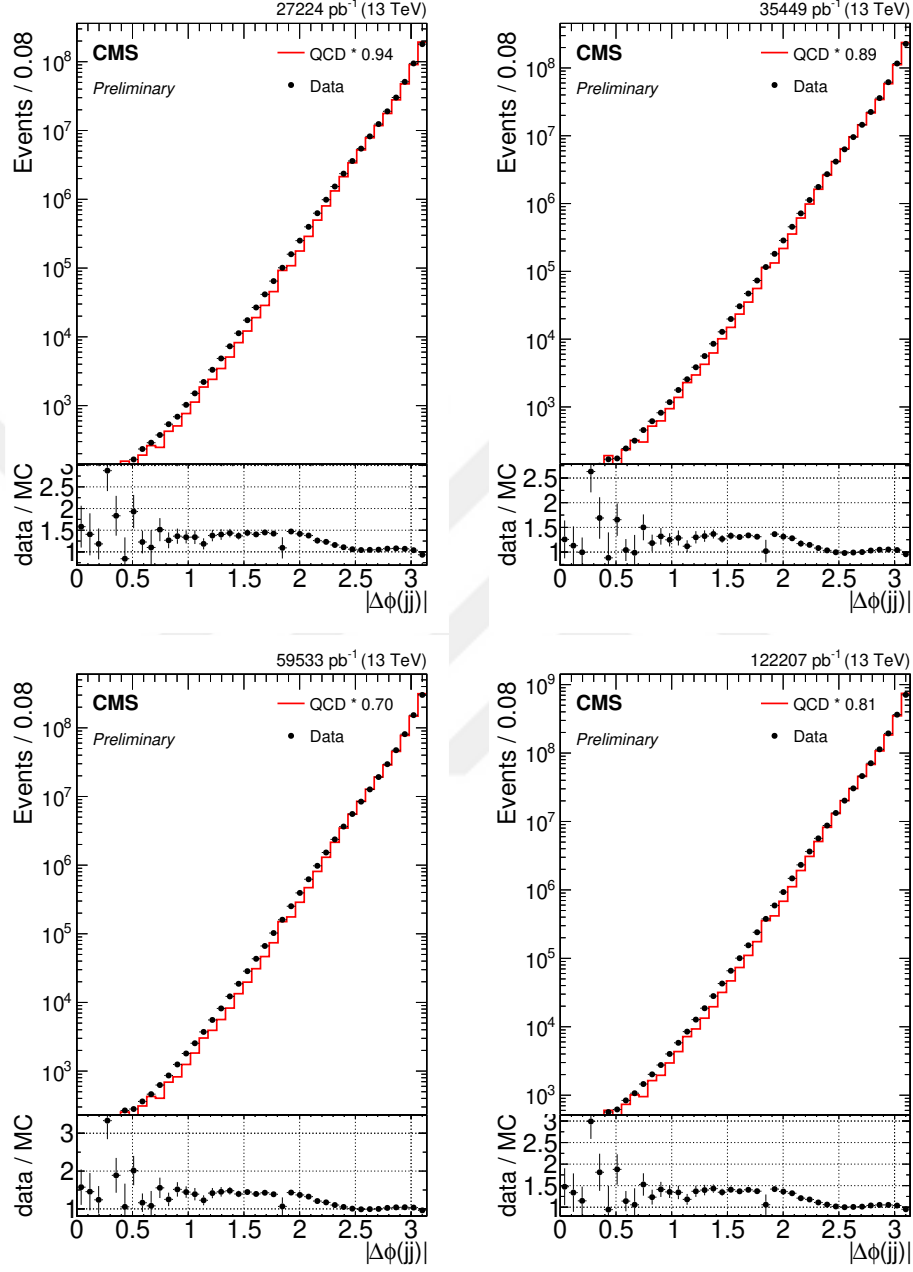


Figure 4.3. $\Delta\phi$ agreement between data and QCD MC, (top-left) for 2016 data (top-right) for 2017 data (bottom-left) for 2018 data (bottom-right) for all Run II data

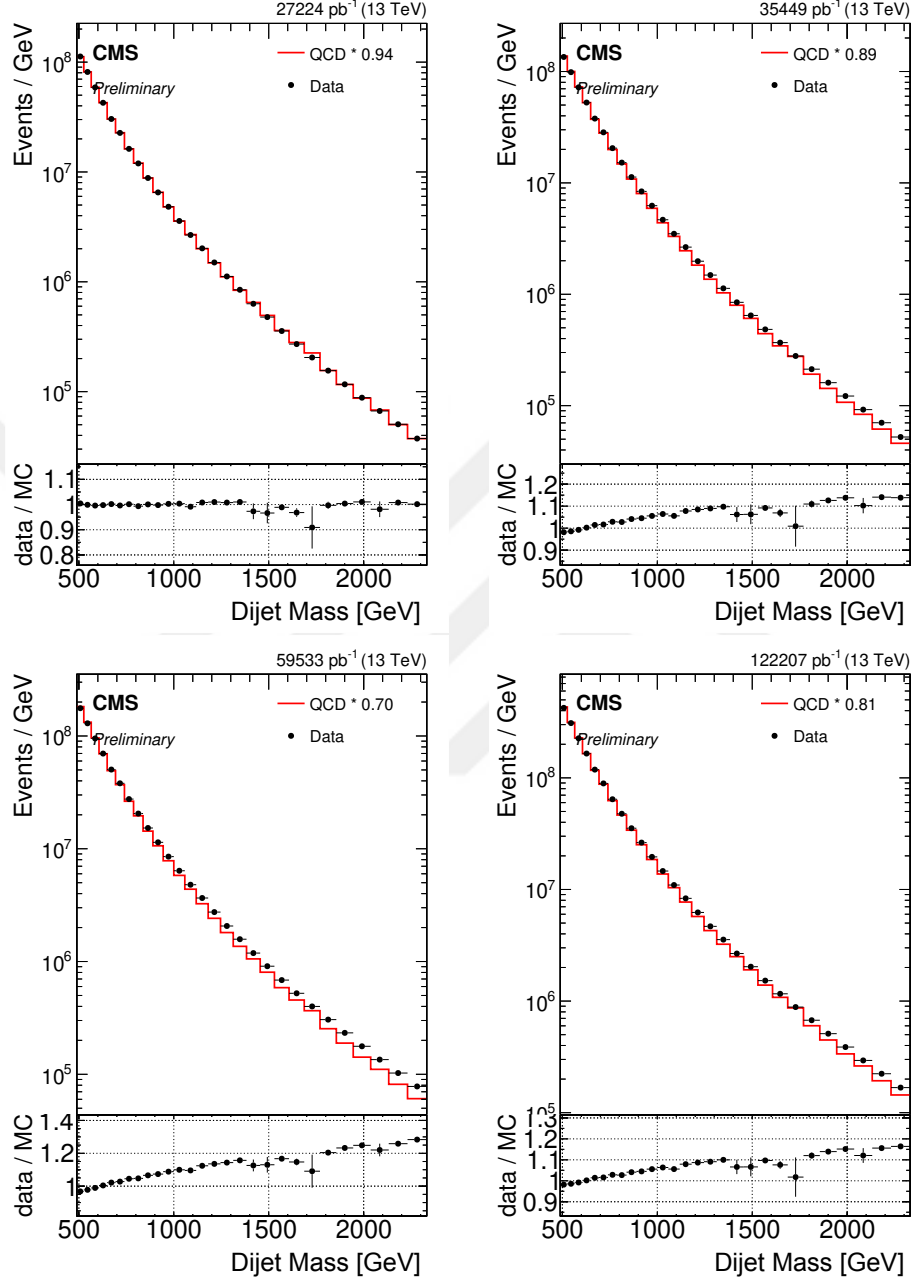


Figure 4.4. Agreement between data and QCD MC as a function of dijet mass [GeV], (top-left) for 2016 data (top-right) for 2017 data (bottom-left) for 2018 data (bottom-right) for all Run II data

4.2. Dijet Mass Spectrum And Background Prediction

As indicated in Section 2.6., the dijet mass spectrum should be fitted with a background-only function to test the smoothness. The background-only, 5-parameter cross-section fit results, using only MC-Truth JEC truth to the data, for the low-mass analysis are shown in Figure 4.5. The agreement between data and QCD MC in Figure 4.4. gets progressively worse with the integrated luminosity, best for 2016 and more jagged for 2018. This is due to a shift in MC-Truth-based JEC, which might be better with the L2L3-Residual corrections.

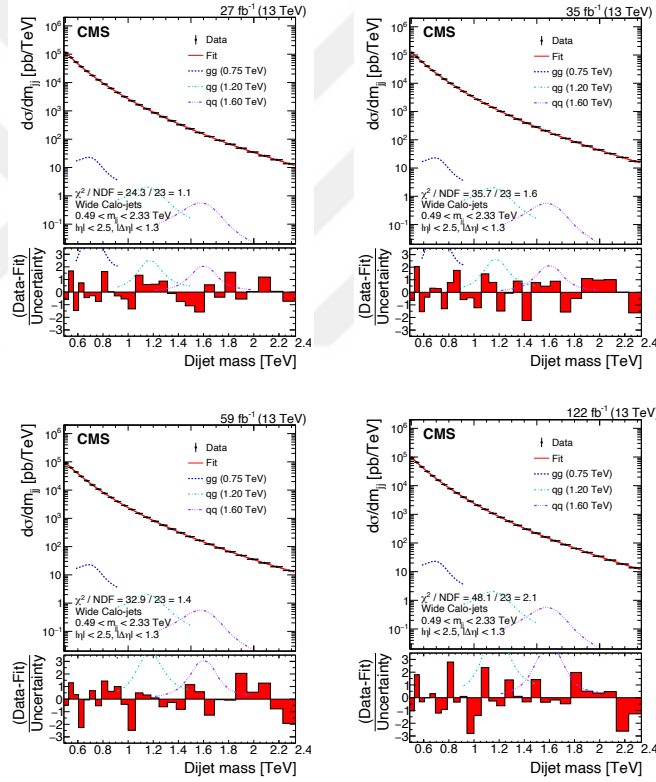


Figure 4.5. Cross-Section fit results using ONLY MC-Truth JEC, (top-left) for 2016 data (top-right) for 2017 data (bottom-left) for 2018 data (bottom-right) for all Run II data

The cross-section of data samples differed slightly between individual years; The 2017 cross-section is fairly close to the 2016 data (8% lower at 0.5 TeV and 8% higher at 2.3 TeV), and the 2018 cross-section looks quite different from the 2016 data (28% lower at 0.5 TeV and also 5% lower at 2.3 TeV). Although 2016, 2017, and 2018 data samples can be fitted individually, the probability of overall Run-II fit is weak ($< 1\%$) due to cross-section differences.

As mentioned in section 4.2., the background-only cross-section fit results might be better with the L2L3-Residual correction. For this purpose, all individual datasets were reproduced again using both MC-Truth JEC & L2L3-Residual corrections. The cross-section comparison of the 2016 data with only MC-Truth JEC and with MC-Truth JEC & L2L3-Residual correction is shown in Figure 4.6.

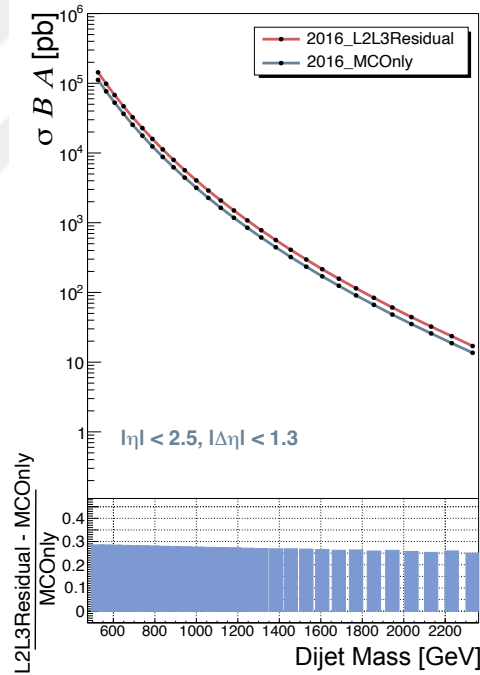


Figure 4.6. Cross-section comparison of 2016 data with only MC-Truth JEC and "MC-Truth JEC + PF L2L3-Residual" correction

The L2L3-Residual correction significantly changed the cross-section of the 2016 data compared to Only MC-Truth JEC. The cross-section of 2016 dataset is: $\sim 27\%$ higher at 0.5 TeV decreasing to $\sim 25\%$ higher at 2.3 TeV when using MC-Truth JEC & PF L2L3-Residual correction. The shift is pretty constant, and what would be expected for a flat difference in JEC of around 5%. Figure 4.7. shows that the L2L3-Residual correction in 2017 and 2018 does not increase the cross-section as significantly as in the 2016 data.

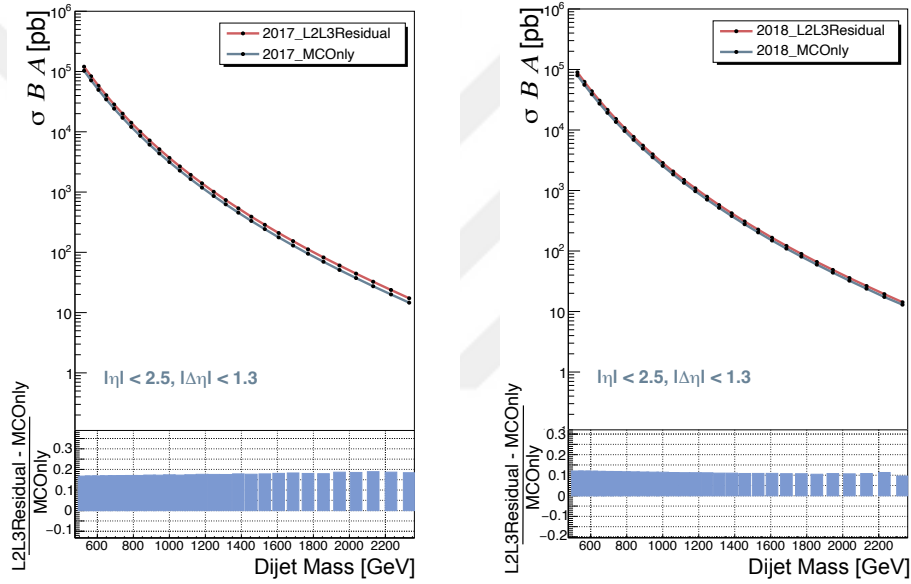


Figure 4.7. Cross-section comparison with only MC-Truth JEC and MC-Truth JEC & PF L2L3-Residual correction (left) for 2017 data and (right) for 2018 data

The cross-section of 2017 dataset is: $\sim 16\%$ higher at 0.5 TeV rising to $\sim 18\%$ higher at 2.3 TeV compared to MC-Truth JEC. The cross-section of 2018 dataset is: $\sim 12\%$ higher at 0.5 TeV decreasing to $\sim 9\%$ higher at 2.3 TeV compared to MC-Truth JEC.

A PF L2L3 residual JEC is used to correct our 2016 CaloHLT data because there are no CaloJet or CaloHLT L2L3 residual JEC. The comparison between the published HEPData results and our CaloHLT results should show the effect of the L2L3 Residuals. PF L2L3 residual JEC significantly improved the agreement between HEPData and CaloHLT in 2016. This agreement is shown in Figure 4.8.. Data with L2L3 residuals is 2 – 4% above HEPData, which is an acceptable difference. Data with only MC truth JEC was 19% lower than HEPData, which is a rather big difference. The PF L2L3 residuals are adequate to correct the 2016 data, resulting in the same spectrum as the 2016 published analysis, which derived and applied its own CaloHLT-to-PF calibration. Cross-section fit results for 2016, 2017, and 2018 data after using PF L2L3-Residual correction are shown in Figure 4.9.

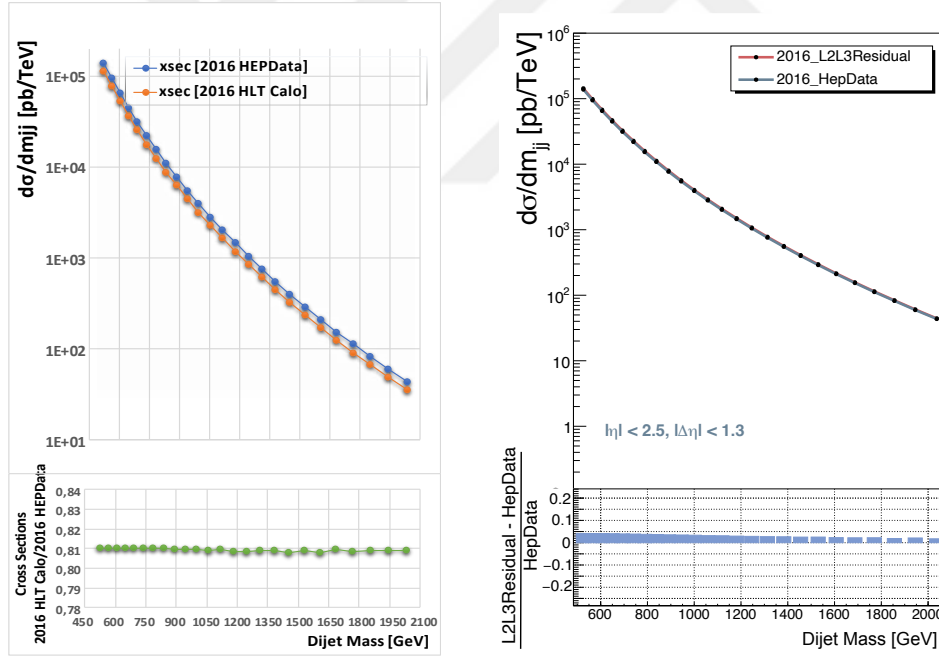


Figure 4.8. Agreement between 2016 HEPData and CaloHLT results; (left) before PF L2L3 Residual, (right) after PF L2L3 Residual

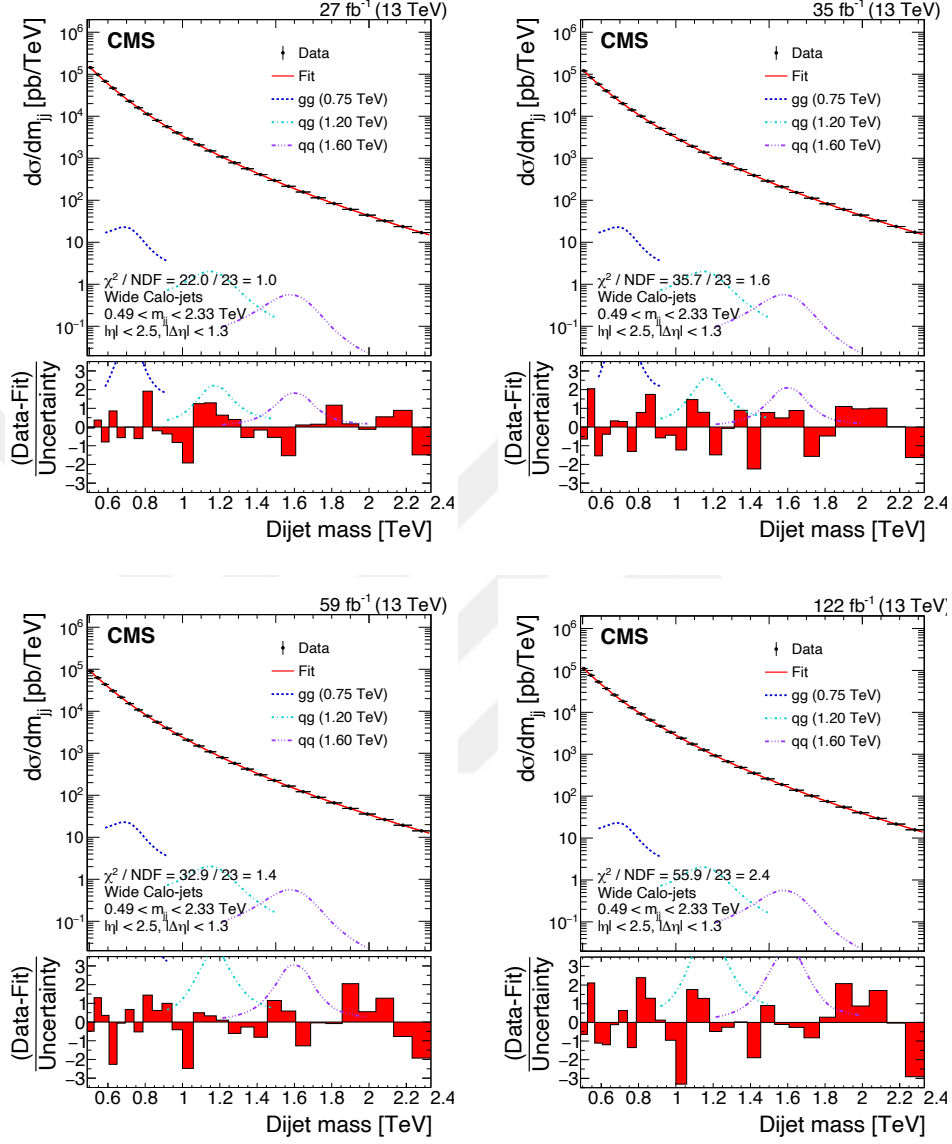


Figure 4.9. Cross-section fit results after using PF L2L3-Residual correction; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, (bottom-right) for all Run II data

Cross-section fit results of the 2017 and 2018 data are just fair with both MC-Truth JEC & L2L3-Residual correction (p-value: 5% and 8%), similar to cross-section fit results with only MC-Truth JEC (p-value: 9% and 9%). But, the cross-section fit results of the 2016 data are good with both MC-Truth JEC & PF L2L3-Residual correction (p-value: 52%) or with only MC-Truth JEC (p-value: 39%). The cross-section fit results of the summed Run II dataset are very poor; the p-value is 0.02% using both MC-Truth JEC & PF L2L3-Residual correction and 0.2% for only MC-Truth JEC.

Further calibration of the 2017 and 2018 data is needed to improve the fit of the full Run II dataset. For that, the 2017 and 2018 datasets are multiplied by a smooth ratio as the calibration factors; (2017 fit / 2016 fit) and (2018 fit / 2016 fit), respectively. This calibration factor varies smoothly between from 1.19 to 0.98 in 2017, and from 1.60 to 1.20 in 2018. The calibration results of 2017 and 2018 cross-sections are shown in the Figure 4.10. and fit results are shown in Figure 4.11.

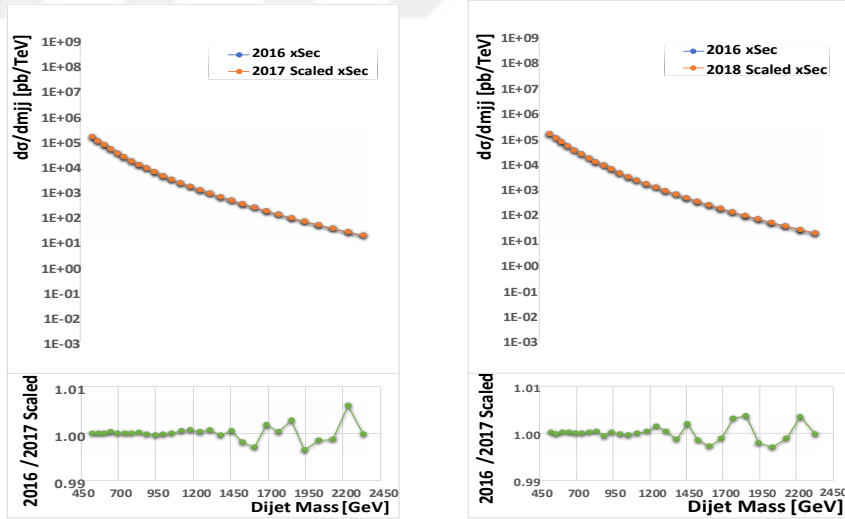


Figure 4.10. Agreement between 2016 HEPData and CaloHLT results; (left) before PF L2L3 Residual, (right) after PF L2L3 Residual

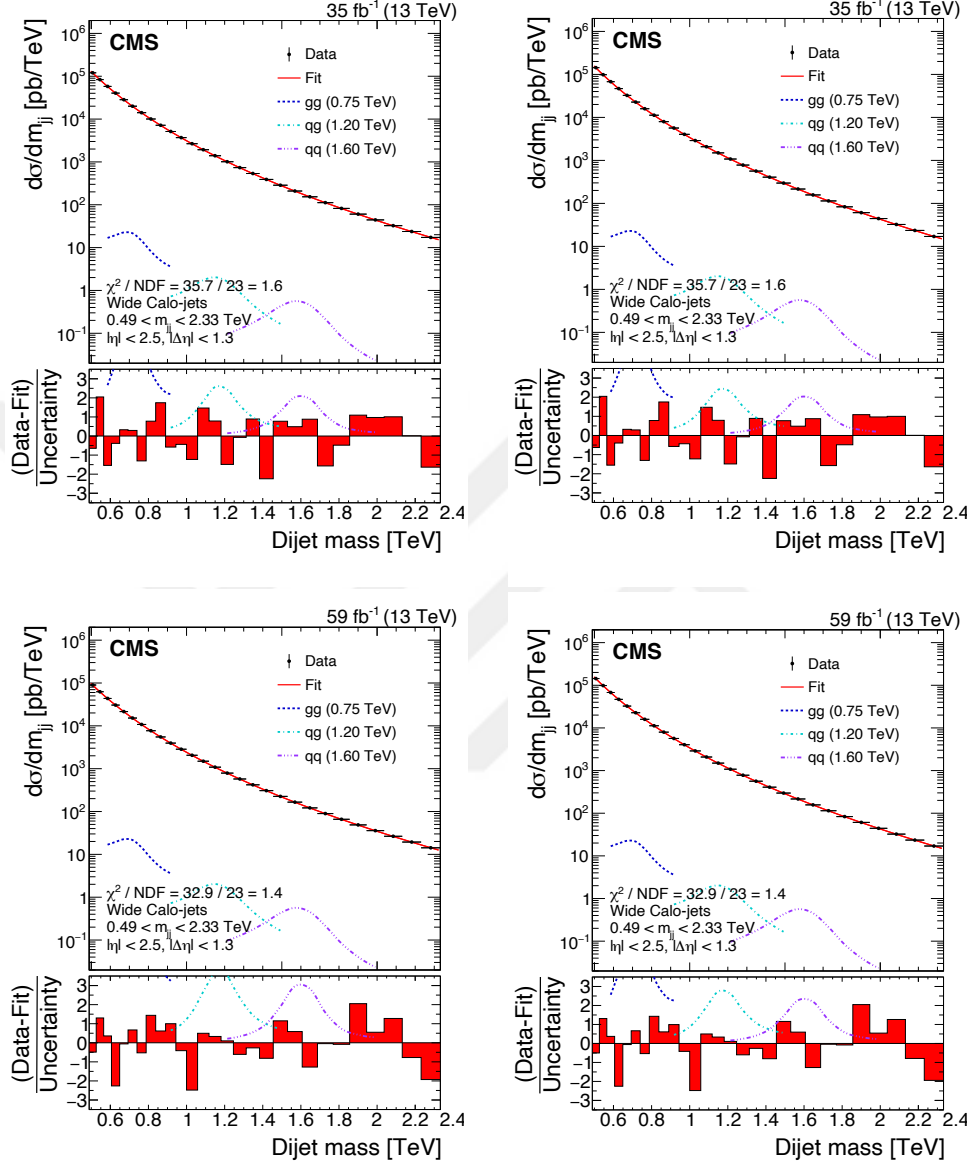


Figure 4.11. The cross-section results before and after the calibration; (top-left) before calibration for 2017, (top-right) after calibration for 2017, (bottom-left) before calibration for 2018, (bottom-right) after calibration for 2018

The calibration increases the cross-section and leaves the goodness of the fit and pulls unchanged. The calibration also increases the full Run-II cross-section as shown in Figure 4.12.

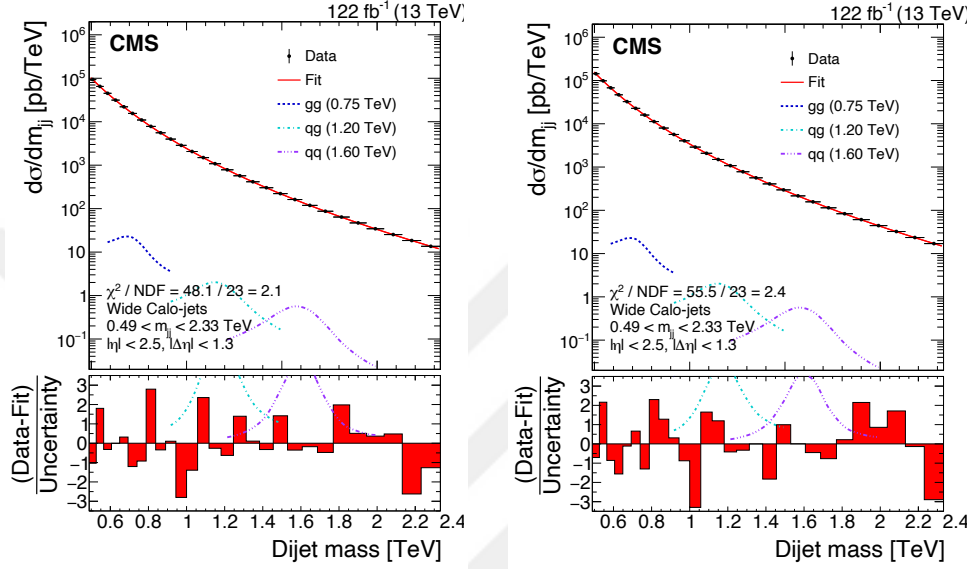


Figure 4.12. The cross-section results of combined Run-II data; (left) before calibration and (right) after calibration

The pulls after calibration are almost identical to the pulls before calibration. However, there are a few pulls that are slightly different. For example, two pulls near 0.6 TeV used to be around -1.0 , and now they are -0.8 and -1.5 . The calibrations of 2017 and 2018 slightly change the bin-to-bin statistical fluctuations in the summed dataset. The χ^2 after calibration is slightly better.

4.3. Partonic Resonance Shapes

Narrow resonances are those in which the experimental resolution dominates the observed width. The natural width of these resonances is smaller than the observed widths. These searches are common in high-energy physics because it requires only one shape to be used for the signal where experimental resolution prevails.

Analytical techniques used in older dijet resonance searches started with a natural resonance shape which was then smeared with the functions of experimental resolution. This natural shape was either a delta function for narrow resonance or a Breit-Wigner (BW) for broad resonances where natural width couldn't be ignored. The principle of this technique is the idea that resolution can be understood separately from the natural line shape, and then both can be combined. In practice, searches have been performed this way in older searches due to the limitations in MC modeling or detector simulation.

The 2010 CMS search introduced generic types of final state narrow resonance shapes for gluon-gluon, quark-gluon, and quark-quark. Although all narrow resonance shapes presented in the literature are well described by a Gaussian nucleus and a radiation tail, the different resonance shapes in a single experiment also show that the narrow resonance concept is mostly approximate. Quark-Quark, Quark-Gluon and Gluon-Gluon final state resonance shapes from CMS simulations are shown in Figure 4.13. [HARRIS et al., 2011].

The calo-scouting quark-quark final state parton signal resonance shapes in 2016, 2017, and 2018 MC agrees with each other to within 1 – 2%. The 2016 shapes were used to set limits and evaluate signal significance for all years.

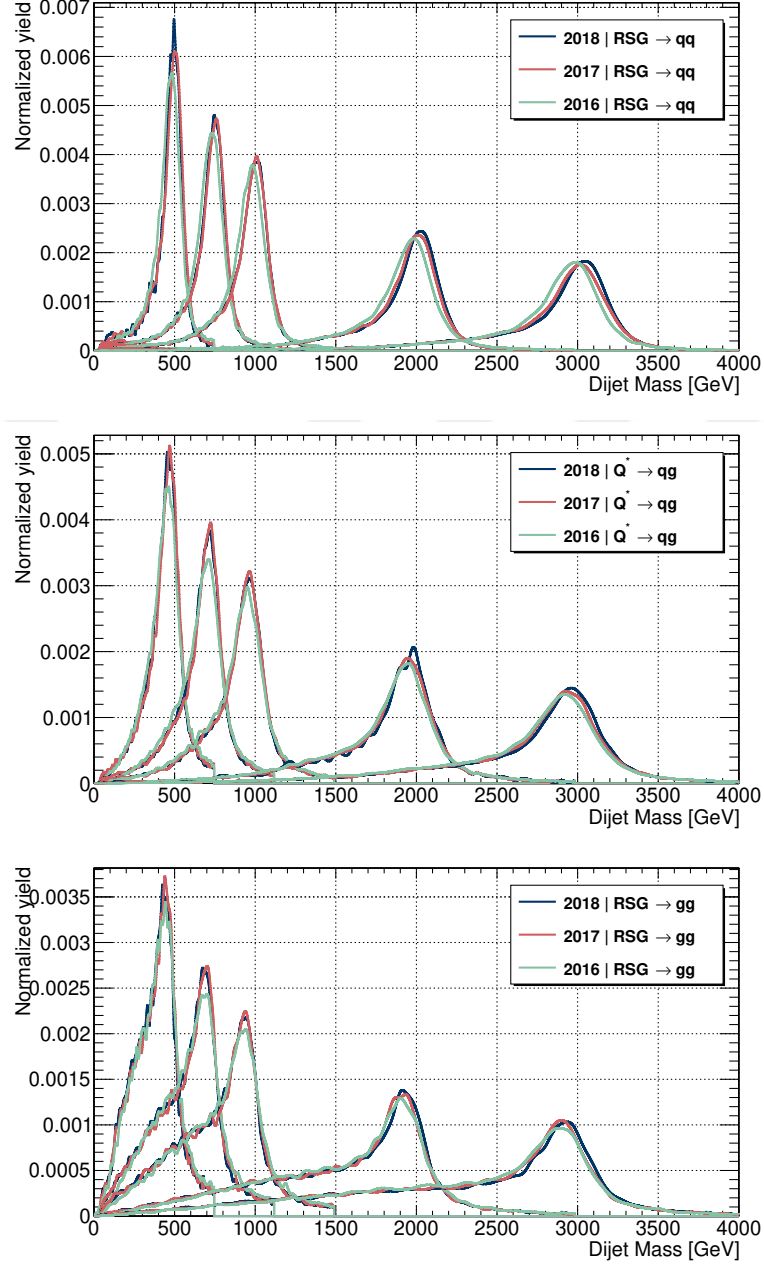


Figure 4.13. 0.5 TeV, 0.75 TeV, 1 TeV, 2 TeV and 3 TeV resonance shapes from CMS PYTHIA simulations are shown for the quark-quark, quark-gluon and gluon-gluon final states, respectively

4.4. Setting The Limits on Dijet Resonances

The limits on dijet resonances are usually performed in three stages. The first stage is setting the limits on the dijet cross-section that can be experimental measurements defined using a statistical technique or can be entirely model-independent. The second stage evaluates the model's theoretical cross-section as a function of the resonance mass. This is an entirely model-dependent procedure. And the third and last stage is to compare the experimental cross-section upper limits with the model's theoretical cross-section and identify the excluded resonance masses if there are any [HARRIS et al., 2011].

The green band surrounding the expected limits is the ± 1 standard (std) deviation error on the expected limit. The 1σ error on the expected limit. When searching for a resonance, if there was none, the limit we find will fall within the green band 68% of the time (± 1 std deviation is 68% probability). This means that if the experiment is conducted 100-times, searching for a given resonance mass, on average, 68 of the limits obtained at that resonance mass will fall within the green band (32% of the limits will fall above it). Similarly, the yellow band is the ± 2 std deviation error on the expected limit. When searching for resonance, the limit will fall within the yellow band 95% of the time (± 2 std deviation is 95% probability). The 2σ error on the expected limit. If the experiment is conducted 100-times, on average, 95 of the limits obtained at that resonance mass will fall within the yellow band.

The cross-section limit results were produced for qq, qg, and gg resonance shapes using the standard COMBINE tool. The qq cross-section limit results are shown in Figure 4.14., qg cross-section limit results are shown in Figure 4.15. and gg cross-section limit results are shown in Figure 4.16. for 2016, 2017, 2018 and Run-II data.

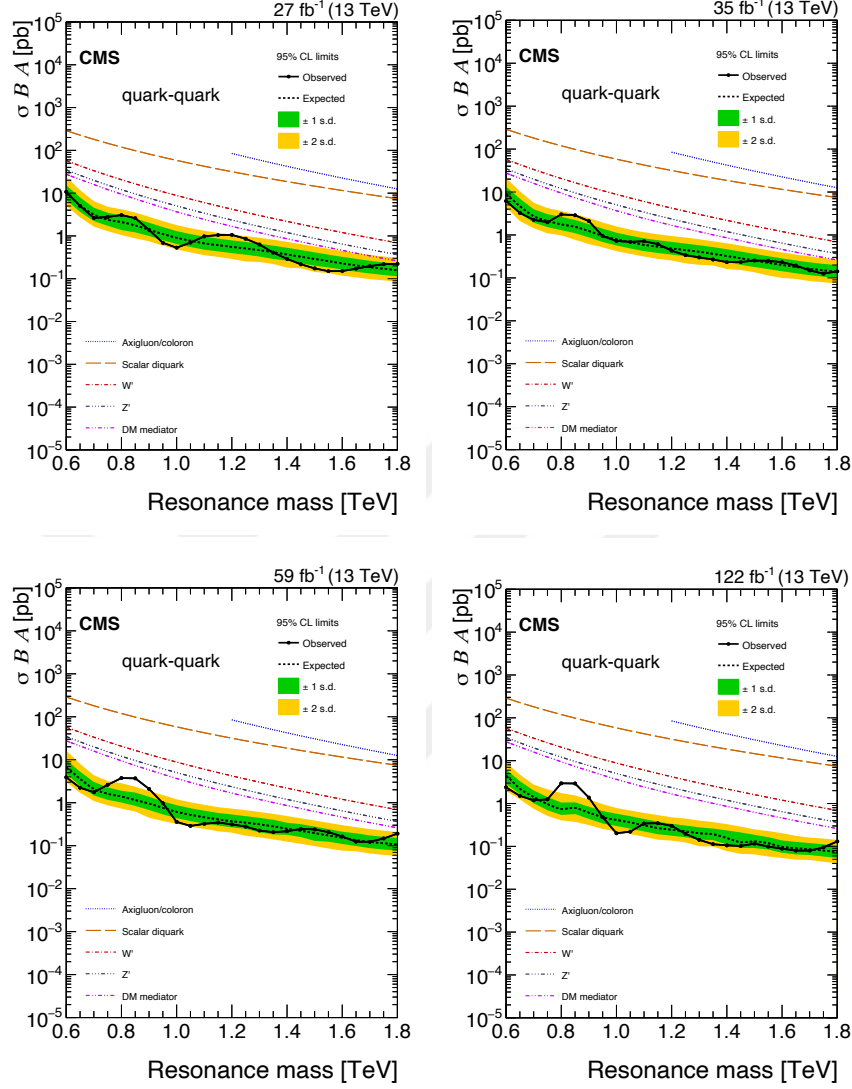


Figure 4.14. The quark-quark cross-section limit results compared with the theoretical predictions; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

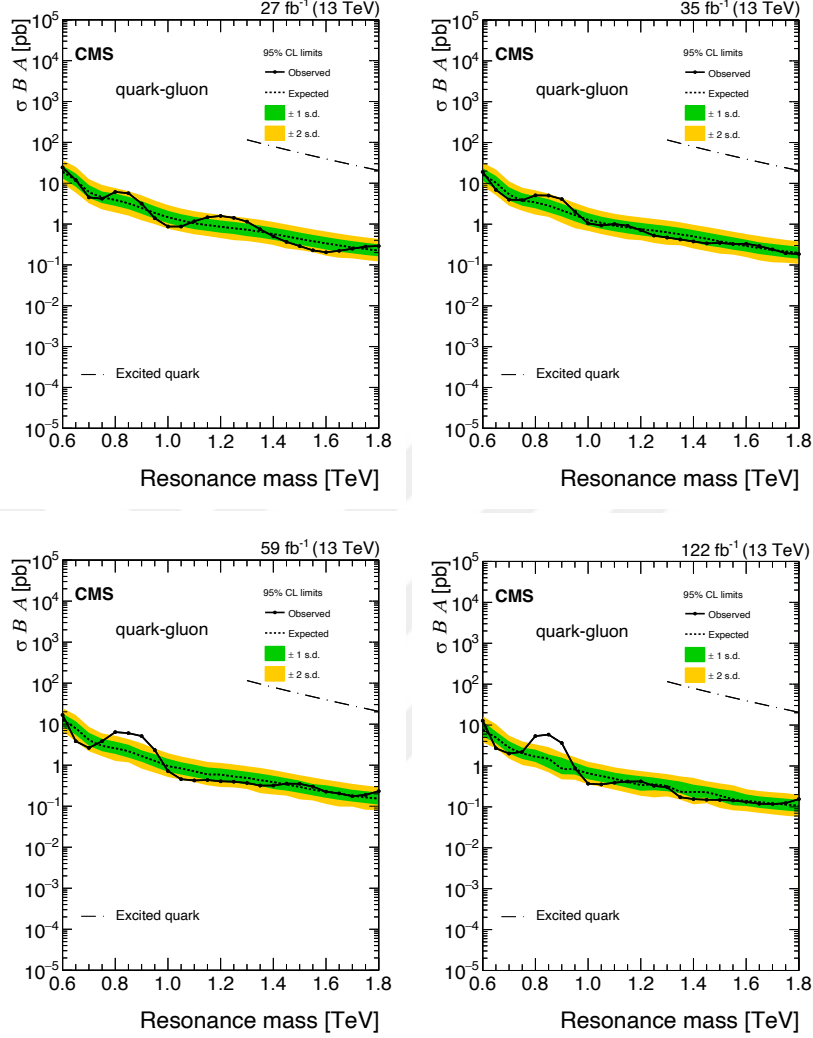


Figure 4.15. The quark-gluon cross-section limit results compared with the excited quark theoretical prediction; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

Similarly, the bump at 0.85 TeV has been present for three years, and this bump increases significantly as the integrated luminosity increases.

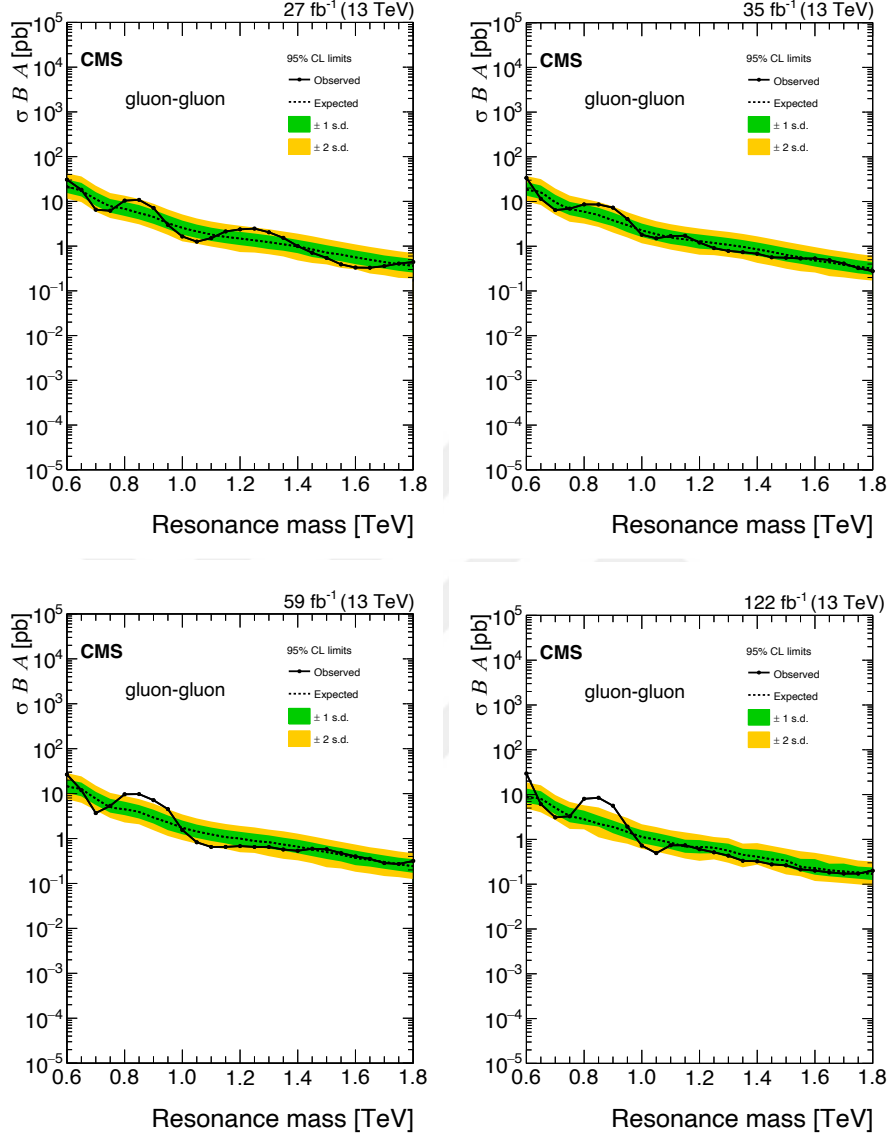


Figure 4.16. The gluon-gluon cross-section limit results; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

4.4.1. Calculation of The Significance

Dijet mass spectrum from wide jets, background parameterization, and dijet resonance shapes are used to set the limits of the production cross-section of new particles decaying into qq (or $q\bar{q}$), qg and gg parton pairs. Due to the dijet resonance shape dependence on the two final-state partons types, separate limits are produced for each final state partons.

The 95% confidence level (CL) upper limits are presented on dijet resonance cross-section times branching ratio times acceptance, including only statistical uncertainties. Limits for quark-quark, quark-gluon, and gluon-gluon resonances are shown separately. The 95% CL upper limit σ_{95} is calculated from the posterior probability density P_{POST} as in Equation 4.1;

$$\frac{\int_0^{\sigma_{95}} P_{\text{POST}}(\sigma) d\sigma}{\int_0^{\infty} P_{\text{POST}}(\sigma) d\sigma} = 0.95 \quad (4.1)$$

Signal pseudo-significance indicates sensitivity to the background signal as a function of dijet mass and is used as an alternative method to evaluate the sensitivity of low-mass tail search [Albert M Sirunyan et al., 2017]. The quark-quark significance result is shown in 4.17., quark-gluon significance result is shown in 4.18. and gluon-gluon significance result is shown in Figure 4.19. using 2016, 2017, 2018 and Run-II data.

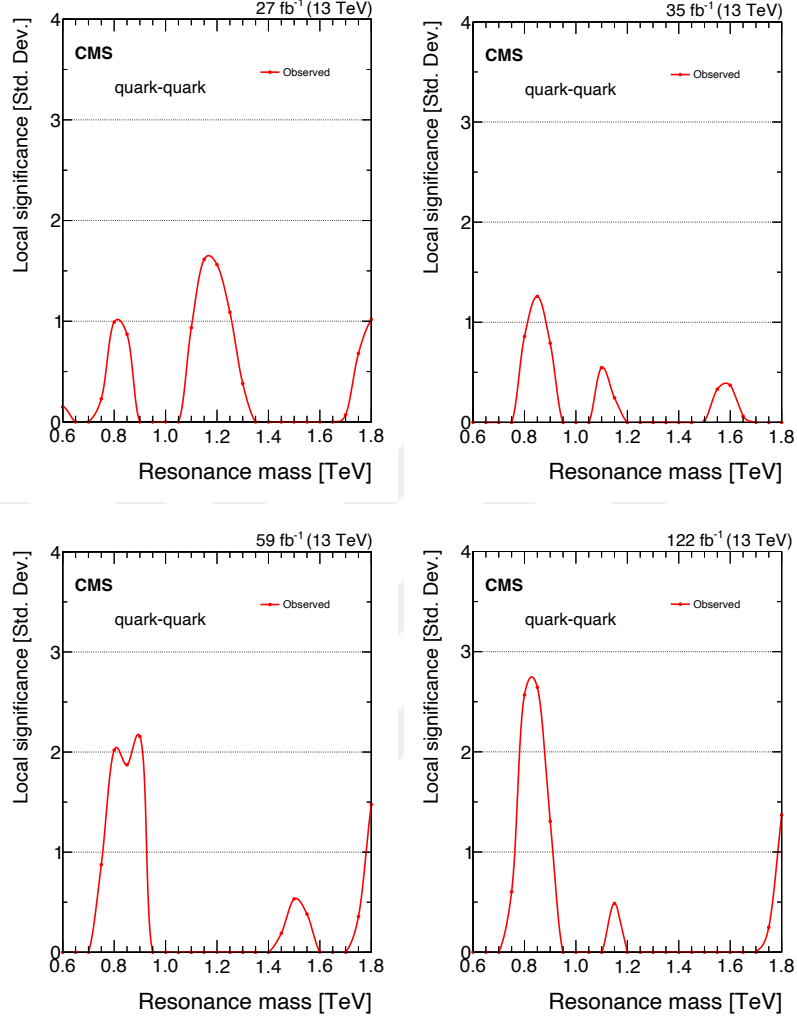


Figure 4.17. The quark-quark significance results; (top-left) 1.6σ for 2016 data, (top-right) 1.3σ for 2017 data, (bottom-left) 2.2σ for 2018 data, and (bottom-right) 2.6σ for Run-II data

The signal significance at 0.85 TeV grows with integrated luminosity and reaches 2.6σ for all Run-II. However, the significance does not perfectly scale as the square root of the integrated luminosity.

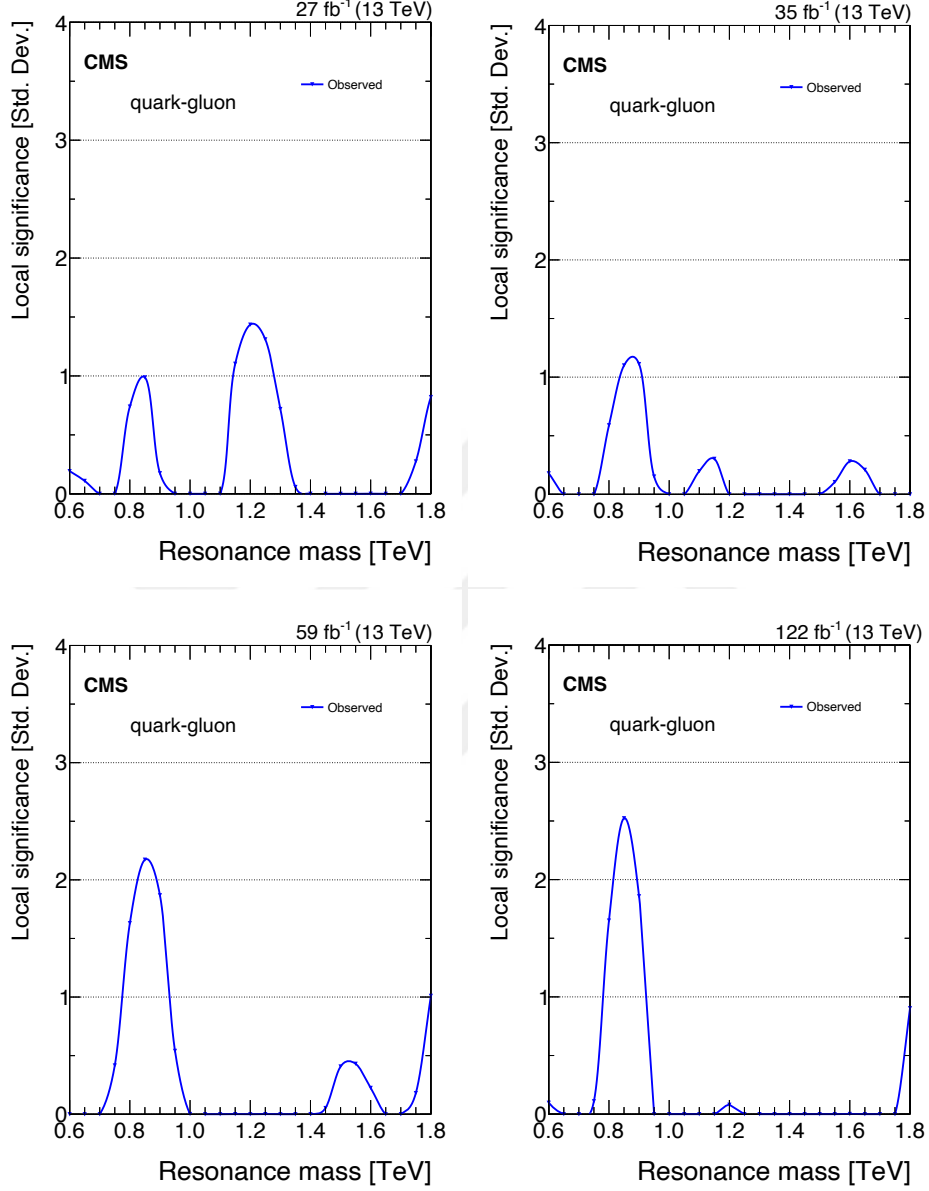


Figure 4.18. The quark-gluon significance results; (top-left) 1.5σ for 2016 data, (top-right) 1.2σ for 2017 data, (bottom-left) 2.2σ for 2018 data, and (bottom-right) 2.5σ for Run-II data

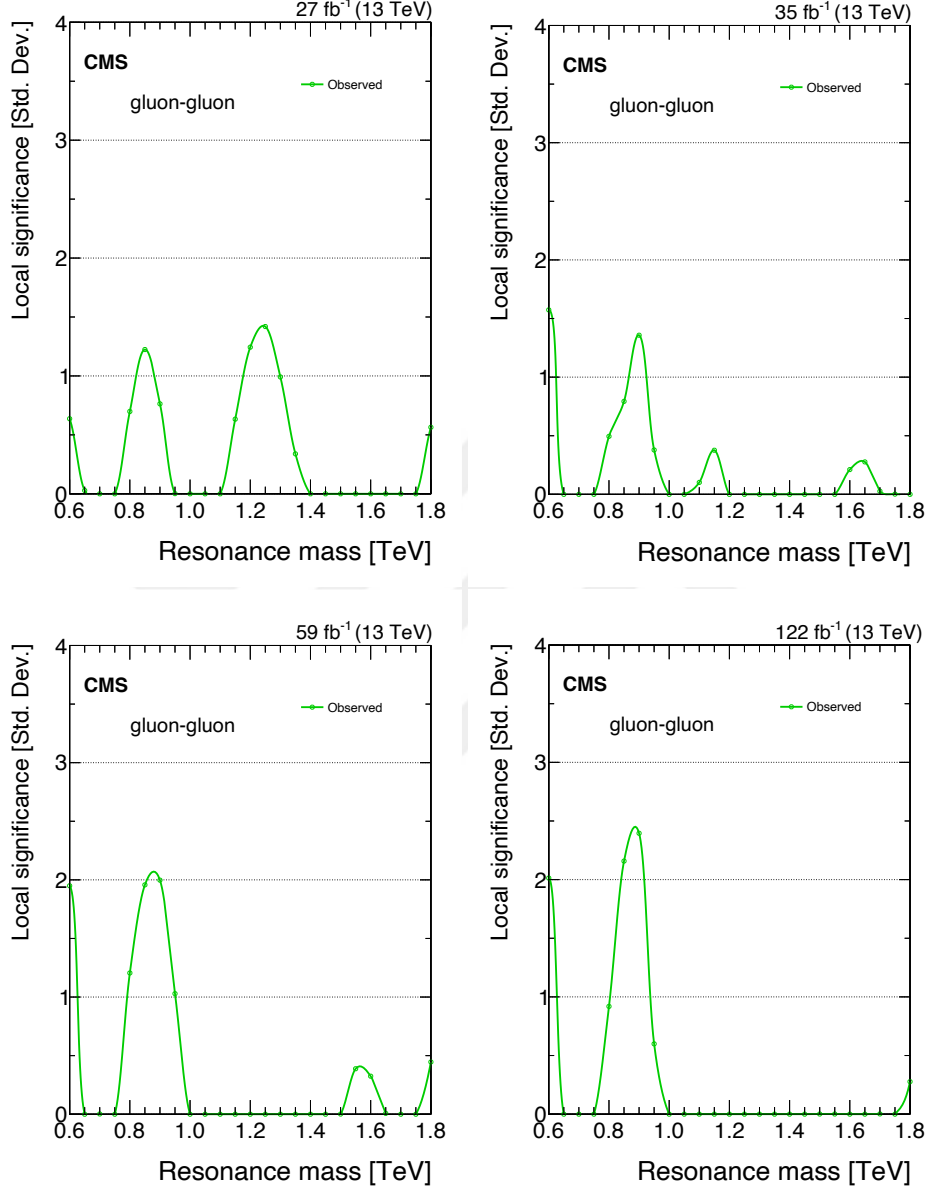


Figure 4.19. The gluon-gluon significance results; (top-left) 1.2σ for 2016 data, (top-right) 1.4σ for 2017 data, (bottom-left) 2.0σ for 2018 data, and (bottom-right) 2.4σ for Run-II data

4.4.2. DeltaNLL Surface and Limit Stability

Although the limit results look smooth and stable, the nuisance parameters negative-maximum likelihood (Delta-NLL) plots demonstrated instability, and points were not forming a single curve. Also, the minimum point of the curve has to be greater than zero. The first idea was that it might come from instability in background fit results as a function of signal strength (μ), or the COMBINE tool might fail because of the high number of fit parameters. Therefore, the limits and Delta-NLL surface results were also produced using the 4-Parameter CMS Dijet fit function given in Section 2.6.1. Lowering the fit parameter size affected the Delta-NLL surface results, and curves showed slightly better behavior, but it was still ghosting. The Delta-NLL curves created with the 4 & 5 parameters CMS Dijet fit function for the 0.85 TeV dijet mass and the quark-quark final state resonance are shown in Figure 4.20.

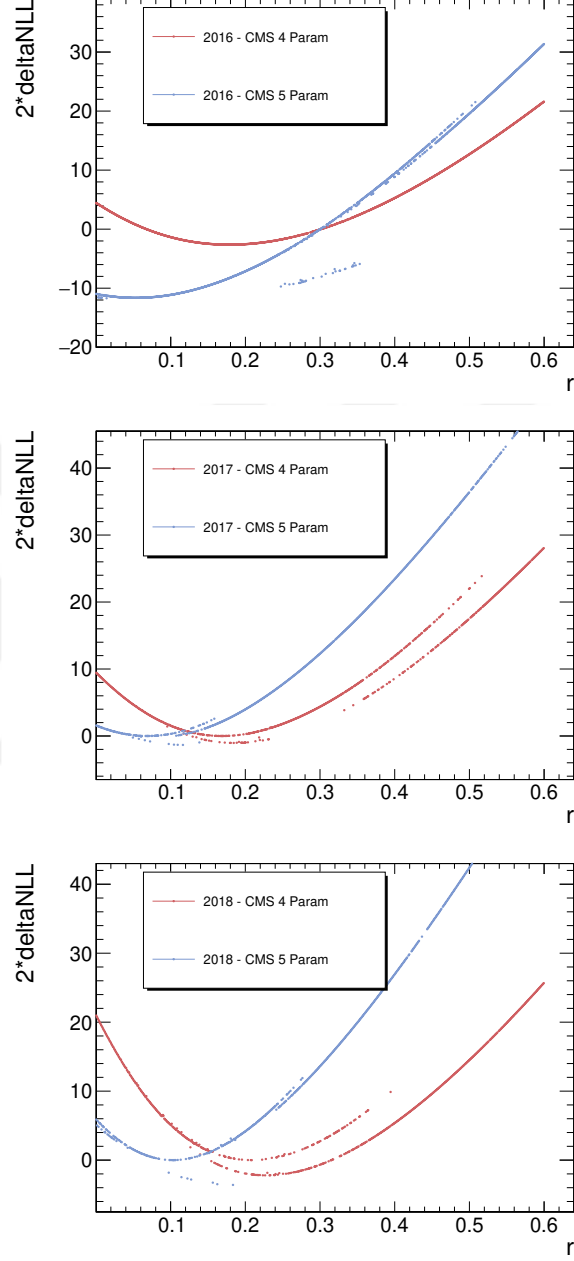


Figure 4.20. The Delta-NLL Curves created for (top) 2016, (middle) 2017 and (bottom) 2018. All curves are ghosting with both 4 & 5 parameter fit functions

In order to increase the stability of the results, we decided to slice the datasets into lower lumi fractions, thinking that this approach would allow us to have more stable limits and Delta-NLL surface results. The results were very stable for all fractions of the datasets. Figure 4.21. shows the stability of Delta-NLL curves produced with smaller (sliced) dataset fractions. These results prove that instabilities occur in the Delta-NLL curves and limits produced with a high amount of data. In this case, setting limits with smaller lumi fractions and statistically combining them will increase the stability of the results. Figure 4.22. shows the Delta-NLL curves produced from statistically combined datasets. Statistically combined results using the 4-Parameter fit function show the best stable curve giving zero maximum likelihood cross section in 2017 and 2018.

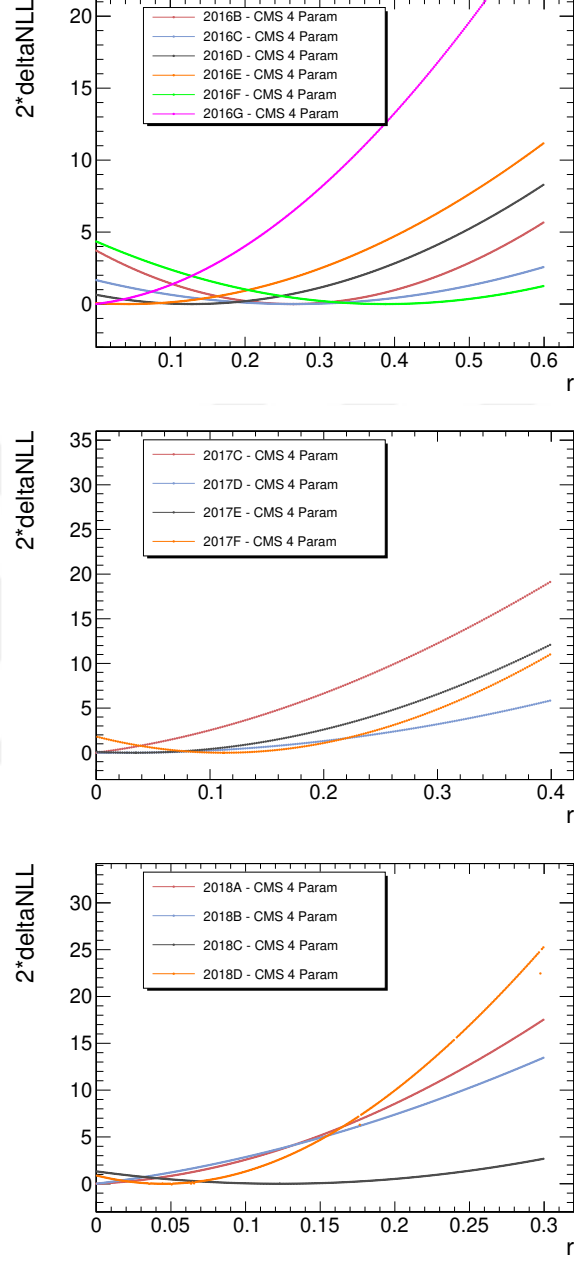


Figure 4.21. The Delta-NLL Curves created with sliced datasets; (top) 2016, (middle) 2017 and (bottom) 2018. All curves are very stable with the 4-parameter fit function

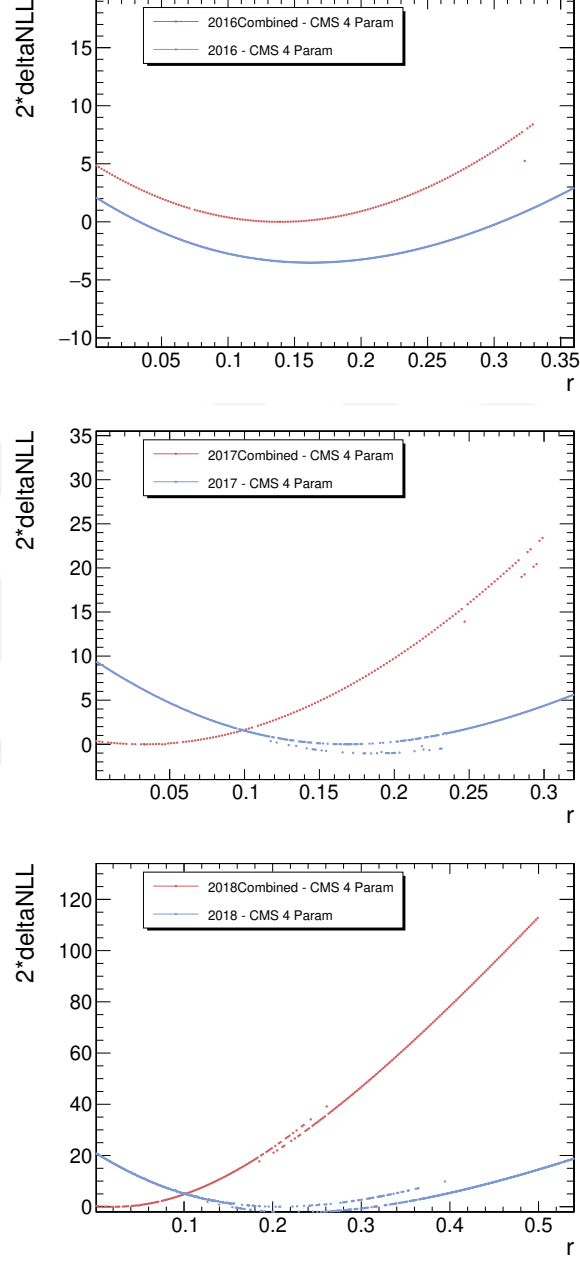


Figure 4.22. The Delta-NLL Curves produced from statistically combined datasets; (top) 2016, (middle) 2017 and (bottom) 2018. All combined curves are more stable than the curves from full dataset

4.4.3. Statistically Combined Limits

All sliced (small) limits are combined using the COMBINE tool, as the sliced dataset theory gives better and stable Delta-NLL results with the CMS 4-Param Function. Figure 4.23. shows the combined sliced limits for quark-quark final state resonance. The new 2016 combined limits are similar to previous limits, but the new 2017 and 2018 ones have smaller bumps than the previous ones. Notably, the 0.85 TeV mass bump is significantly smaller than the previous one for 2018. The combined limits for Quark-Gluon final state resonances shown in Figure 4.24. and for Gluon-Gluon final state resonances are shown in Figure 4.25.

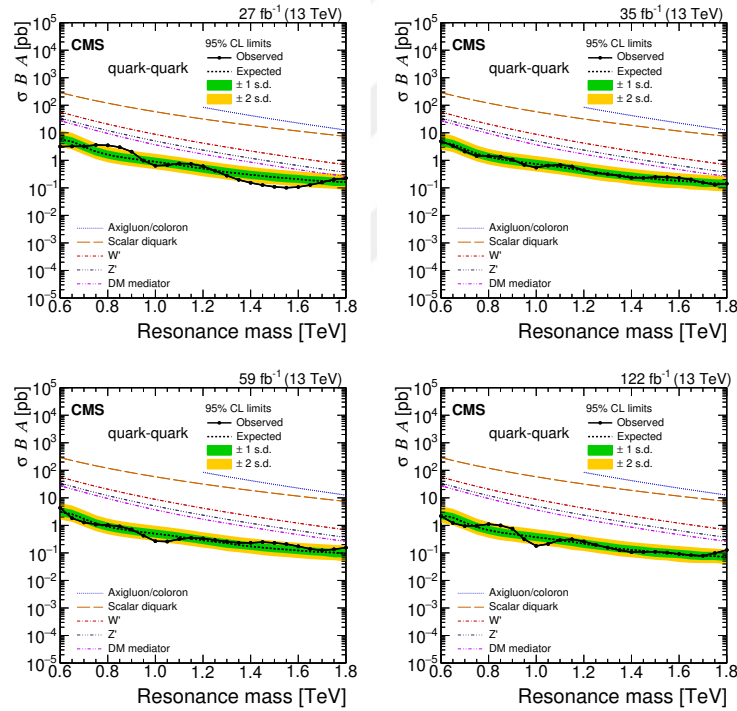


Figure 4.23. The quark-quark cross-section limit results compared with the theoretical predictions; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

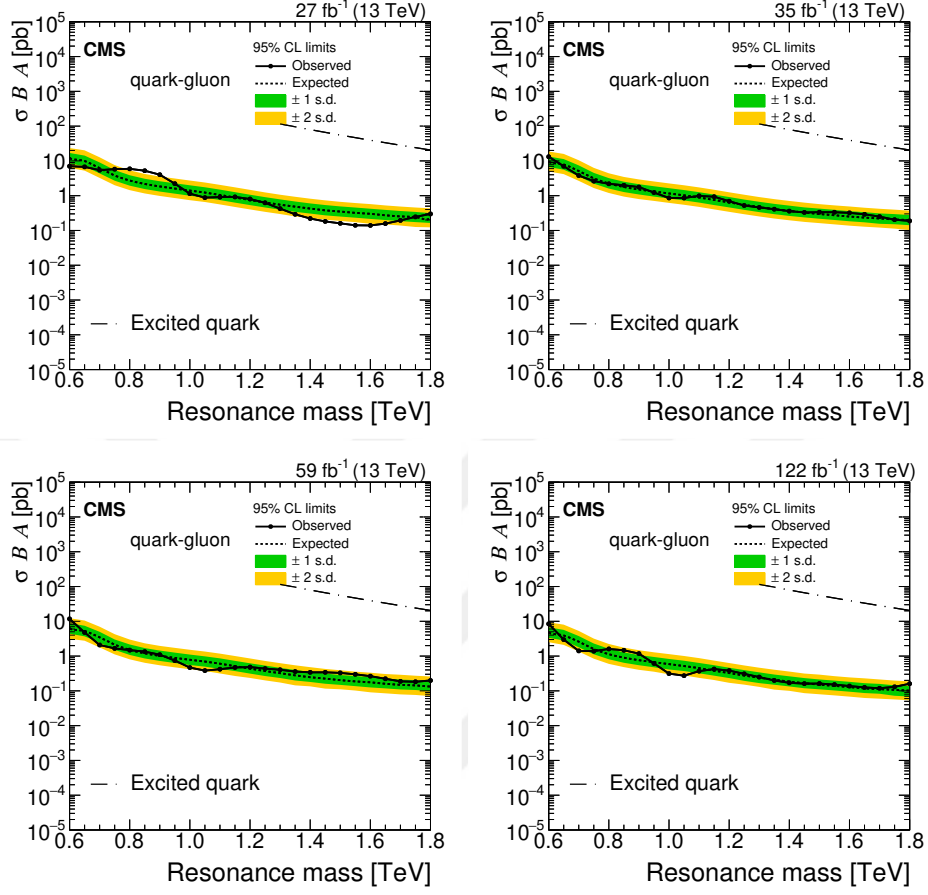


Figure 4.24. The quark-gluon cross-section limit results; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

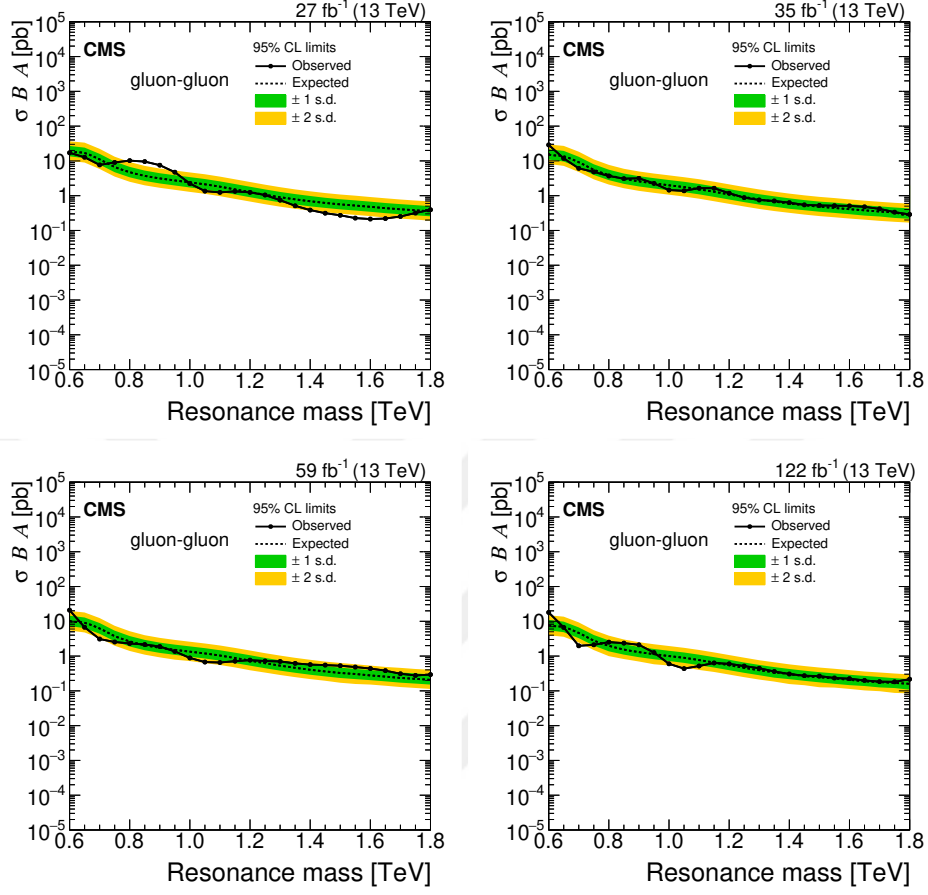


Figure 4.25. The gluon-gluon cross-section limit results; (top-left) for 2016 data, (top-right) for 2017 data, (bottom-left) for 2018 data, and (bottom-right) for Run-II data

Table 4.1. Limits from the low-mass calo scouting search. The observed and expected upper limits at 95% CL on σ_{BA} for a gg, qg, and qq resonances are given as a function of the resonance mass

Mass [TeV]	95% CL upper limit [pb]					
	gg		qg		qq	
	Observed	Expected	Observed	Expected	Observed	Expected
0.60	15.486875	7.628515	6.105712	4.619531	1.945287	2.281250
0.65	5.674324	6.706640	2.756823	3.870702	1.187318	1.856250
0.70	2.017893	4.505664	1.449962	2.478515	0.923062	1.248828
0.75	2.167863	2.731054	1.413510	1.545117	0.930159	0.859375
0.80	2.476350	1.953222	1.565795	1.123242	1.076878	0.659374
0.85	2.457003	1.526855	1.521007	0.893847	0.985243	0.546875
0.90	2.123365	1.296386	1.091721	0.756738	0.593173	0.471875
0.95	1.137715	1.132177	0.560816	0.661816	0.271403	0.415625
1.00	0.557183	0.999658	0.300450	0.577441	0.175307	0.365624
1.05	0.427792	0.884423	0.266023	0.514160	0.192433	0.321874
1.10	0.468897	0.763427	0.326035	0.445605	0.280653	0.284375
1.15	0.593681	0.648193	0.397853	0.377050	0.311290	0.246875
1.20	0.565465	0.544482	0.363529	0.319042	0.250223	0.209375
1.25	0.483277	0.458056	0.287273	0.271582	0.186173	0.184374
1.30	0.416349	0.388916	0.239410	0.234667	0.149553	0.159375
1.35	0.343171	0.337060	0.190253	0.208300	0.119987	0.140625
1.40	0.293895	0.296728	0.167939	0.181933	0.105472	0.128125
1.45	0.265978	0.267919	0.156593	0.166113	0.106154	0.115625
1.50	0.247818	0.239111	0.156384	0.150292	0.110664	0.103125
1.55	0.229556	0.221826	0.146065	0.139746	0.101253	0.096875
1.60	0.213949	0.204541	0.131332	0.129199	0.090071	0.090625
1.65	0.189828	0.187255	0.122437	0.118652	0.079248	0.084375
1.70	0.176241	0.175732	0.114750	0.108105	0.076291	0.078125
1.75	0.166252	0.164208	0.115198	0.102832	0.085713	0.071875
1.80	0.185354	0.152685	0.133567	0.097558	0.103753	0.071875

4.5. Systematic Uncertainties

Jet Energy Scale (JES), Jet Energy Resolution (JER), integrated luminosity, and the values of the functional parameters that model the background in the dijet mass distribution are the dominant sources of systematic uncertainty. The JES uncertainty in low mass search is 2% and is determined from $\sqrt{s} = 13 \text{ TeV}$ data using the methods given in Ref. [Khachatryan et al., 2017]. This uncertainty is propagated to the limits by shifting the dijet mass shape by 2% for the signal. The JER uncertainty translates into 10% uncertainty in the dijet mass resolution [ibid.]. It propagates to the limits by observing the effect of reducing and increasing the reconstructed dijet mass shape width by 10%. The integrated luminosity uncertainty is 2.5% [CMS, 2017a] and propagated to the signal normalization. Changes in the values of parameters define the background that introduces a change in signal yield, which is considered a systematic uncertainty.

The systematic uncertainties are implemented as likelihood model nuisance parameters with log-normal constraints for the integrated luminosity and gaussian constraints for the JES and JER. The background systematic uncertainty is automatically evaluated through profiling, effectively re-fitting for the optimal background parameters for each resonance cross-section value [CMS, 2018]. This way, the background parameters can freely float to their most probable values for all signal cross-sections within the likelihood function. The most probable background value decreases as the signal cross section within the likelihood function increases since the observed data effectively limits the sum of the background and signal. Therefore, this statistical method provides a smaller background for larger signals in the likelihood function than the methods that keep the background parameters in the likelihood constant. This leads to greater possibilities for larger signals and, therefore, higher upper limits on the signal cross section. The extent to which the background

uncertainty affects the limit is highly dependent on the signal shape and resonance mass. The greatest effect is in gg resonances because they are wider, and the smallest effect occurs in quark-quark resonances. The effect increases as the resonance mass decreases and is strongest at the lowest resonance masses in each search, where the sideband is smaller, which is used to constrain the background present in the lower dijet mass [Belforte et al., 2017]. The effect of the systematic uncertainties on the limit for quark-quark final state resonances is shown in Figure 4.26. For almost all resonance masses, the systematic background uncertainty produces most of the effect on the limit.

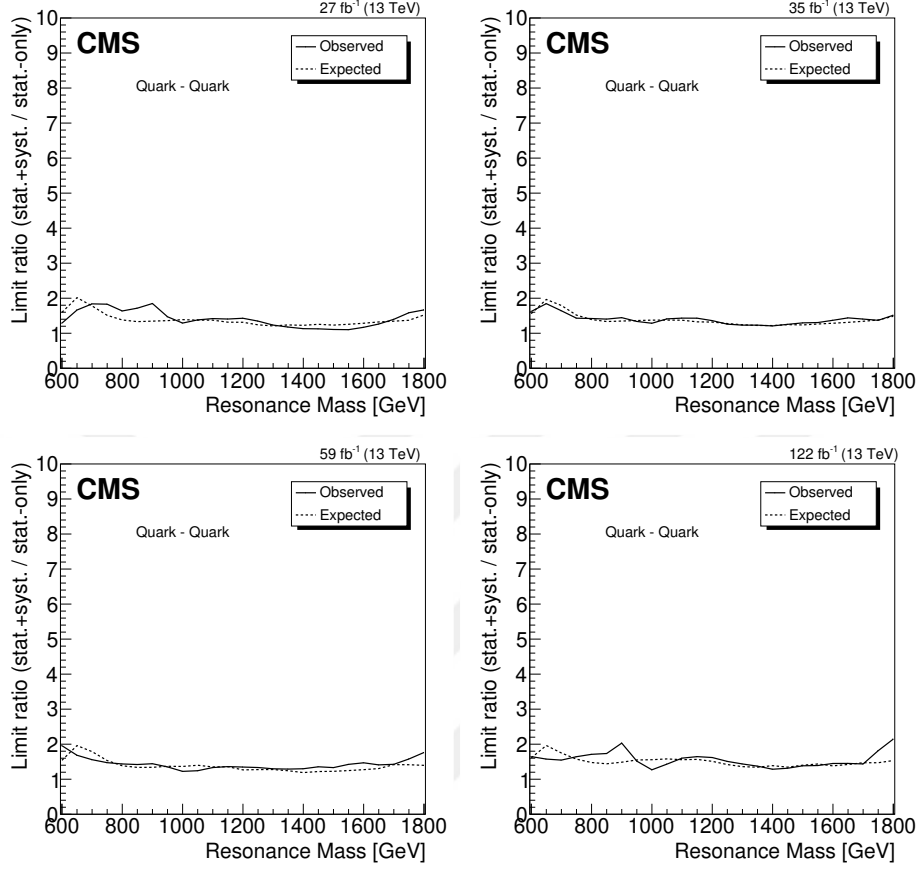


Figure 4.26. Observed and expected ratios between the cross-section limits include systematic uncertainties, and the cross-section limits include only statistical uncertainties. These limits are produced for dijet resonances decaying to quark-quark final state partons. 2016 (top-left), 2017 (top-right), 2018 (bottom-left), and Full Run-II (bottom-right)

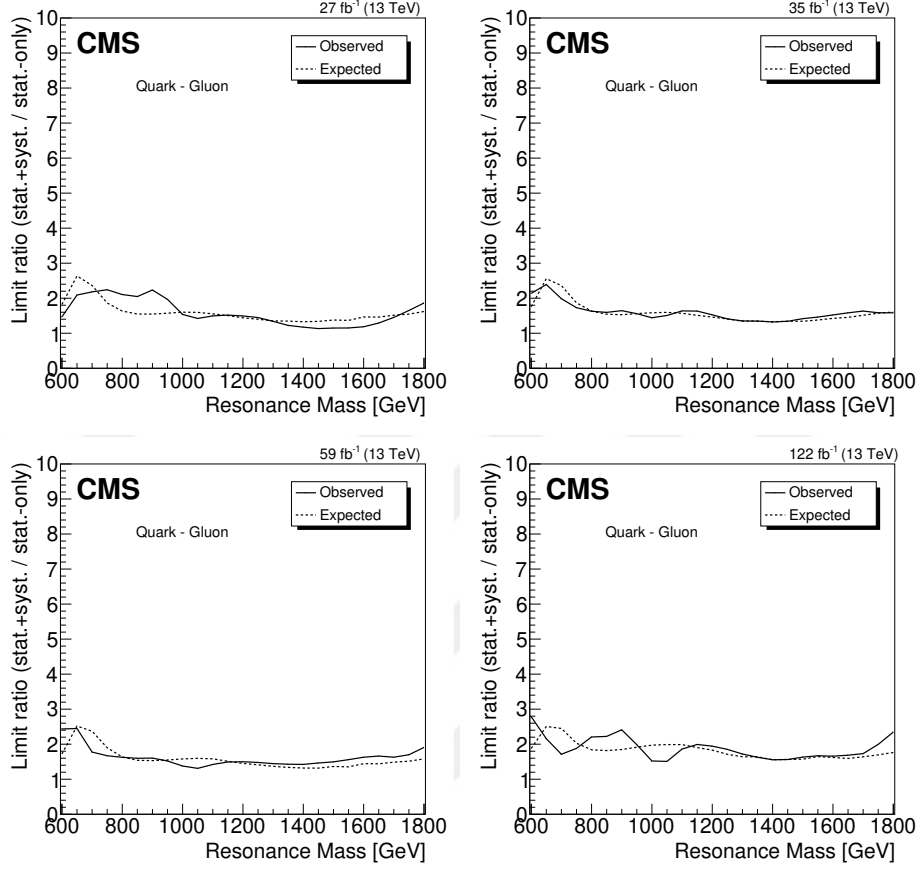


Figure 4.27. Observed and expected ratios between the cross-section limits include systematic uncertainties, and the cross-section limits include only statistical uncertainties. These limits are produced for dijet resonances decaying to quark-gluon final state partons. 2016 (top-left), 2017 (top-right), 2018 (bottom-left), and Full Run-II (bottom-right)

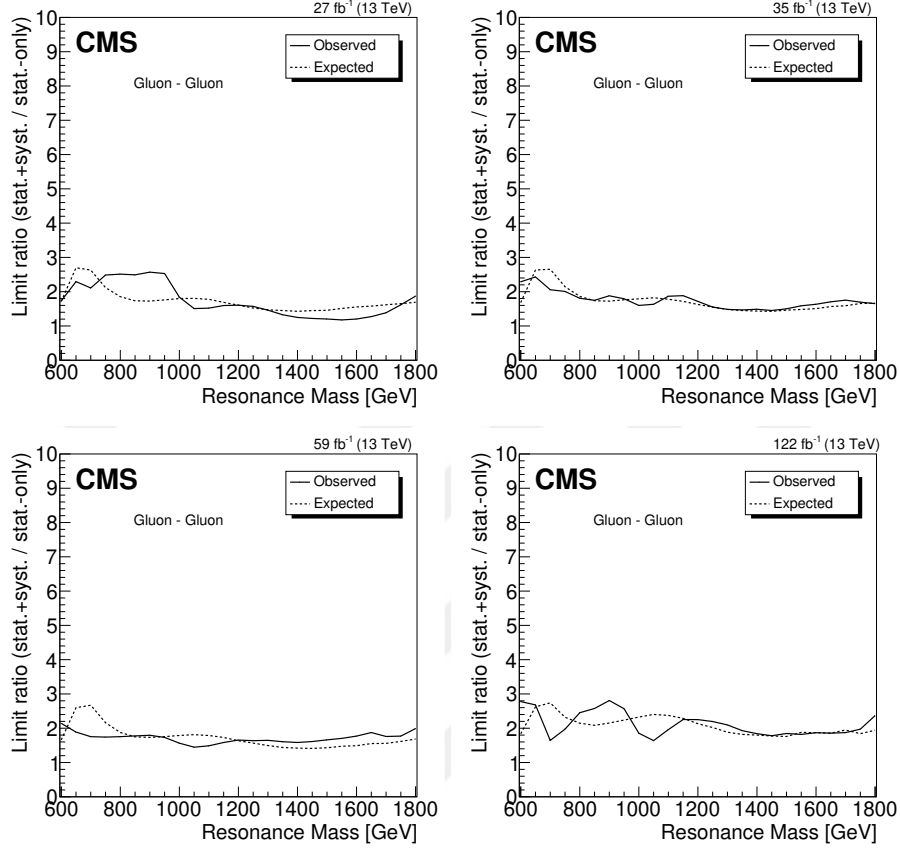


Figure 4.28. Observed and expected ratios between the cross-section limits include systematic uncertainties, and the cross-section limits include only statistical uncertainties. These limits are produced for dijet resonances decaying to gluon-gluon final state partons. 2016 (top-left), 2017 (top-right), 2018 (bottom-left), and Full Run-II (bottom-right)

The effect of background systematics to the limits with the current approach is smaller, especially at lower masses, due to the smaller number of parameters utilized in the function used to describe the QCD background and extended fitting range, including bins at lower masses. Also, the effects of background systematics on the limits are the same regardless of the number of slices of the overall dataset.

4.6. Limits on a Dark Matter Mediator

Mass limits on new particles are very sensitive to the assumptions about their coupling. Furthermore, as the search sensitivity increases at a fixed resonance mass, we can exclude models with smaller couplings. Figure 4.29. shows upper limits on the coupling as a function of mass for a leptophobic Z' resonance which has a natural width;

$$\Gamma = \frac{3(g'_q)^2 M}{2\pi} \quad (4.2)$$

where; M is the resonance mass limit for $g'_q < 0.45$. This corresponds to $< 10\%$ width of the resonance mass that our narrow resonance limits are approximately valid. Up to this width value, the quark-quark Breit-Wigner natural line shape does not significantly change the observed line shape for resonance masses less than 4 TeV. Therefore, the dijet resonance can be defined as narrow [A. M. Sirunyan et al., 2018].

DM mediators are the mediators of interaction between quarks and dark matter [Abdallah et al., 2015]. We considered the suggestions of Ref. [Boveia et al., 2020] on the coupling values and model choice. We used a simplified version [Abdallah et al., 2015] of a spin-1 mediator that decays only to DM particle pairs and qq , with an unknown mass m_{DM} , and with a DM coupling $g_{DM} = 1.0$ and a universal quark coupling $g_q = 0.25$ [Penning, 2018].

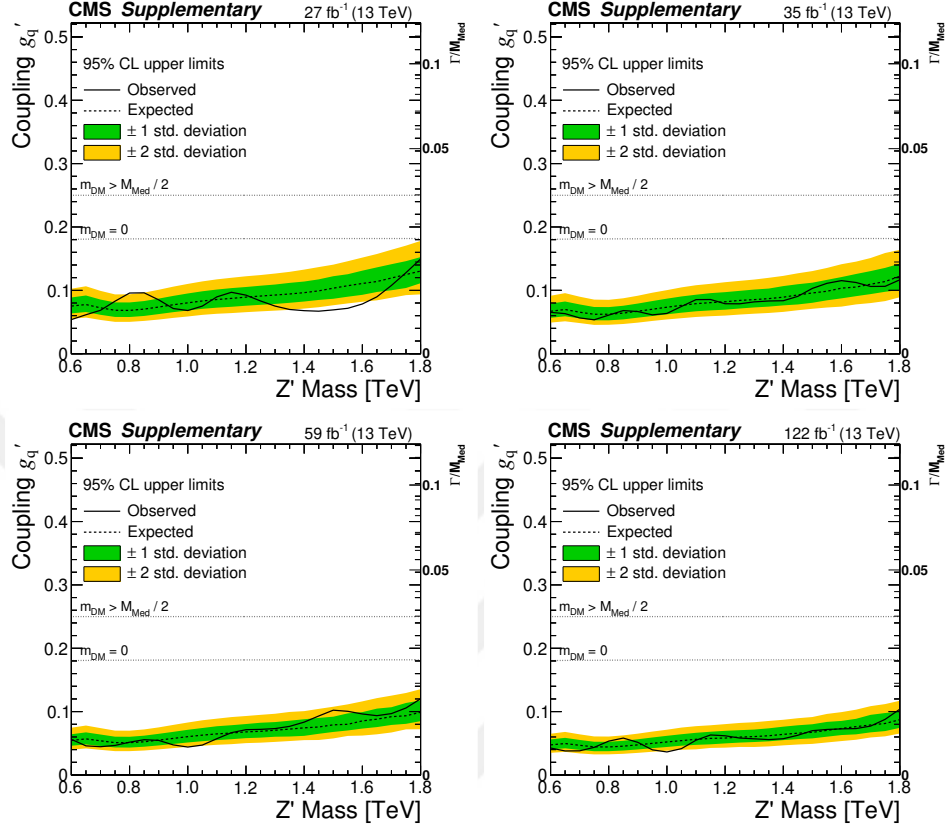


Figure 4.29. The g_q upper limits as a function of resonance mass for interactions between dark matter and quarks. The right vertical axis demonstrates the mediator's natural width divided by its mass. (top-left) for 2016, (top-right) for 2017, (bottom-left) for 2018, and (bottom-right) for Run-II

Table 4.2. The 95% CL upper limits on the quark coupling g_q

Mass [TeV]	95% CL upper limit [pb]	
	Observed	Expected
0.60	0.04749796	0.04256970
0.65	0.04961728	0.03790938
0.70	0.04681657	0.03809374
0.75	0.04439710	0.04357557
0.80	0.04419631	0.05342480
0.85	0.04548961	0.05822456
0.90	0.04750779	0.05147381
0.95	0.04988357	0.03966931
1.00	0.05210582	0.03632383
1.05	0.05421389	0.04158004
1.10	0.05628303	0.05486301
1.15	0.05770698	0.06312834
1.20	0.05828135	0.06183728
1.25	0.05979160	0.05827591
1.30	0.06060244	0.05706511
1.35	0.06190060	0.05584464
1.40	0.06410327	0.05720353
1.45	0.06593680	0.06269928
1.50	0.06731077	0.06994187
1.55	0.07041707	0.07182635
1.60	0.07341433	0.07273122
1.65	0.07625955	0.07324361
1.70	0.07890224	0.07715368
1.75	0.08128251	0.08779915
1.80	0.08720637	0.10370841

As shown in Figure 4.30., we made significant progress in extending the limits in the DM mediator quark coupling.

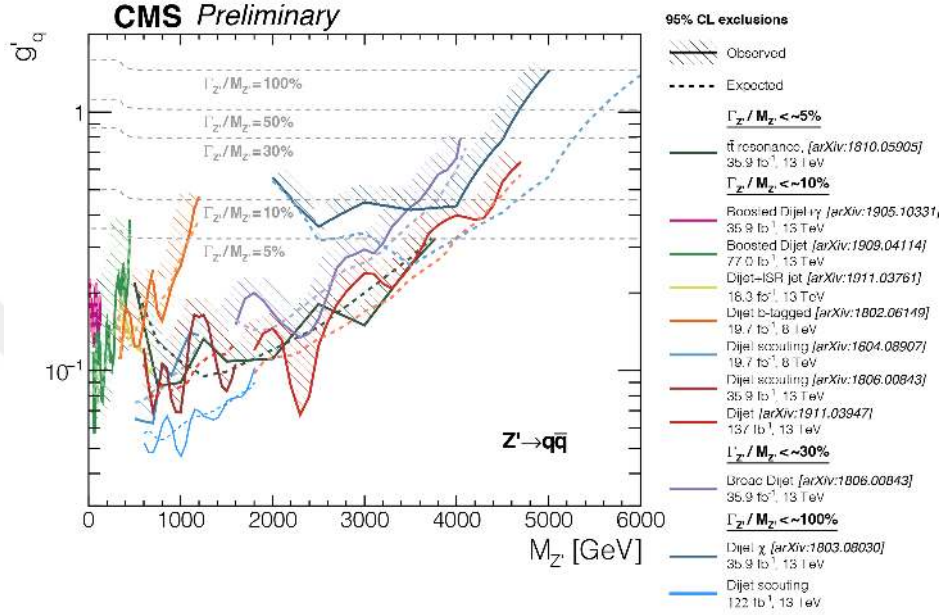


Figure 4.30. Dark Matter Mediator (g'_q) summary sensitivity plot; Light-blue straight & dashed lines at bottom is the new dijet scouting results at $\sqrt{s}=13$ TeV with 122.2 fb^{-1} of data



5. CONCLUSION

In this thesis, searches for dijet resonances have been carried out using pp collisions at $\sqrt{s}=13$ TeV, corresponding to a 122.2 fb^{-1} integrated luminosity. The low-mass search was conducted on calorimeter jets reconstructed by the HLT and saved in a compact form.

Dijet mass spectrum was observed to form smooth falling distributions and is fitted with an appropriate function to identify the bump formations. But unfortunately, the fit probabilities of 2017 and 2018 were unacceptable; thus, they were calibrated with 2016 cross-sections to increase the fit probability. With the calibration, limits for all individual datasets are produced and combined using the COMBINE tool to have full Run-II limits.

The results were smooth and stable for all datasets, and the significance plots showed a mass bump at the 0.85 TeV mass region that increased with the integrated luminosity. While the limit plots were stable and smooth, the Delta-NLL results were not forming a single & stable curve which means the COMBINE tool could not determine the best calculation for all points. The investigation of this problem leads to the use of a smaller fraction of datasets and lower fit parameters since the COMBINE tool is not efficient with high statistics and a high number of fit parameters. Concerning this idea, the datasets were sliced, and the limits were produced for each slice. This approach was very successful, and Delta-NLL curves were forming smooth & stable structures. Therefore, the limits from sliced datasets were combined using the COMBINE tool to achieve limit results of individual years and full Run-II.

As a result, unfortunately, there was no evidence of particle resonance production in the analyzed data samples. Generic upper limits presented at 95%

confidence level on the production cross-section for narrow resonances (gg , qg , qq), with approximately a factor of two better limits than the published 2016 only limit results. We also made significant progress in extending the DM mediator quark coupling limits. These limit results extend previously reported limits in the dijet scouting.



REFERENCES

- Abdallah, Jalal et al. (Sept. 2015). “Simplified models for dark matter searches at the LHC”. In: *Physics of the Dark Universe* 9-10, pp. 8–23. DOI: 10.1016/j.dark.2015.08.001. URL: <https://doi.org/10.1016/j.dark.2015.08.001>.
- Abdullin, S, V Abramov, B Acharya, M Adams, N Akchurin, U Akgun, EW Anderson, G Antchev, S Ayan, S Aydin, et al. (2008). “Design, performance, and calibration of CMS hadron-barrel calorimeter wedges”. In: *The European Physical Journal C* 55.1, pp. 159–171.
- Acharya, Bannaje Sripathi, B Satyanarayana, Piyush Verma, et al. (2006). *The CMS outer hadron calorimeter*. Tech. rep. CERN-CMS-NOTE-2006-127.
- Adolphi, Roman et al. (2008). “The CMS experiment at the CERN LHC”. In: *Jinst* 803, S08004.
- Agostino, Lorenzo, Gerry Bauer, Barbara Beccati, Ulf Behrens, Jeffrey Berryhil, Kurt Biery, Tulika Bose, Angela Brett, James Branson, Eric Cano, et al. (2009). “Commissioning of the CMS High Level Trigger”. In: *Journal of Instrumentation* 4.10, P10005.
- Akchurin, N, A Apreysan, S Banerjee, D Barney, B Bilki, A Bornheim, J Bueghly, S Callier, V Candelise, Y-H Chang, et al. (2018). “First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter”. In: *Journal of Instrumentation* 13.10, P10023.
- Anderson, Dustin James (2016). *Data Scouting in CMS*. Tech. rep. URL: <https://pos.sissa.it/282/190/pdf>.
- Antuñano, Oscar, Johann H. Kühn, and Germán Rodrigo (Jan. 2008). “Top quarks, axigluons, and charge asymmetries at hadron colliders”. In: *Physical Review*

- D* 77.1. ISSN: 1550-2368. DOI: 10 . 1103 /physrevd . 77 . 014003. URL: <http://dx.doi.org/10.1103/PhysRevD.77.014003>.
- Bauce, Matteo (2017). “Search for new physics in dijet final states in ATLAS and CMS”. arXiv: 1709.04754 [hep-ex].
- Bayatian, GL, A Korablev, A Soha, O Sharif, M Chertok, W Mitaroff, F Pauss, V Genchev, M Wensveen, V Lemaitre, et al. (2006). *CMS Physics: Technical Design Report Volume 1: Detector Performance and Software*. Tech. rep. CMS-TDR-008-1. URL: <https://cds.cern.ch/record/922757>.
- Belforte, S, V Candelise, M Casarsa, G Della Ricca, A Zanetti, et al. (2017). “Search for dark matter produced with an energetic jet or a hadronically decaying W or Z boson at $\sqrt{s}=13$ TeV”. In:
- Boveia, Antonio, Oliver Buchmueller, Giorgio Busoni, Francesco D’Eramo, Albert De Roeck, Andrea De Simone, Caterina Doglioni, Matthew J Dolan, Marie-Helene Genest, Kristian Hahn, et al. (2020). “Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter”. In: *Physics of the Dark Universe* 27, p. 100365. DOI: 10 . 48550 /ARXIV . 1603 . 04156. URL: <https://arxiv.org/abs/1603.04156>.
- Brüning, Oliver, Paul Collier, Paul Lebrun, Stephen Myers, Ranko Ostojic, John Poole, and Paul Proudlock (2004). “LHC design report(Volume I, The@ LHC main ring)”. In: *Reports- CERN*.
- Ceard, Ludivine (2020). “Beam-tests of CMS High Granularity Calorimeter prototypes at CERN”. URL: <https://indico.cern.ch/event/813822/contributions/3648335/>.
- Chatrchyan, S. et al. (June 2013). “Search for narrow resonances using the dijet mass spectrum in pp collisions $\sqrt{s}=8$ TeV”. In: *Physical Review D* 87.11. ISSN:

- 1550-2368. DOI: 10.1103/physrevd.87.114015. URL: <http://dx.doi.org/10.1103/PhysRevD.87.114015>.
- Chatterjee, Rajdeep Mohan (2016). *First results from a beam test of a high-granularity silicon-based calorimeter for CMS at HL-LHC*. Tech. rep.
- CMS, Collaboration (1997). “The CMS hadron calorimeter project: Technical Design Report. Technical Design Report CERN-LHCC-97-031. CERN (1997)”.
- (2000). “CMS Detector Posters”.
- (2002). “The Electromagnetic Calorimeter Project, Technical Design Report, CERN/LHCC 97-33 (1997)”. In: *CMS Addendum CERN/LHCC 27*, p. 2002.
- (2006). “CMS Physics-Technical Design Report Volume I: Detector Performance and Software; CERN/LHCC 2006-001”. In: *CMS TDR 8*.
- (2008). “The CMS experiment at the CERN LHC. JINST, 3 (S08004), 2008”.
- (2017a). *CMS luminosity measurements for the 2016 data taking period*. Tech. rep. CMS-PAS-LUM-17-001.
- (2017b). *The phase-2 upgrade of the CMS endcap calorimeter*. Tech. rep.
- (2018). “Search for heavy resonances decaying into a vector boson and a Higgs boson in final states with charged leptons, neutrinos and b quarks at $\sqrt{s} = 13$ TeV”. In: *arXiv preprint arXiv:1807.02826*.
- Duarte, Javier Mauricio Gonzalez (2017). “Naturalness confronts nature: searches for supersymmetry with the CMS detector in pp collisions at $\sqrt{s} = 8$ and 13 TeV”. PhD thesis. California Institute of Technology.
- Focardi, Ettore (2012). “Status of the CMS Detector”. In: *Physics Procedia* 37, pp. 119–127. URL: <https://www.sciencedirect.com/science/article/pii/S1875389212016732>.

- Gupta, Ambreesh K, Naba K Mondal, and Sreerup Raychaudhuri (1999). “Constraining large extra dimensions using dilepton data from the Tevatron collider”. In: *arXiv preprint hep-ph/9904234*.
- HARRIS, ROBERT M. and KONSTANTINOS KOUSOURIS (Dec. 2011). “SEARCHES FOR DIJET RESONANCES AT HADRON COLLIDERS”. In: *International Journal of Modern Physics A* 26.30n31, pp. 5005–5055. ISSN: 1793-656X. DOI: 10.1142/S0217751X11054905. URL: <https://www.worldscientific.com/doi/abs/10.1142/S0217751X11054905>.
- HCAL, Collaboration (2006). “Design, Performance, and Calibration of CMS Forward Calorimeter Wedges”. In: *CMS Note, CMS NOTE* 44.
- Khachatryan, V. et al. (Feb. 2016). “Search for Narrow Resonances Decaying to Dijets in Proton-Proton Collisions at $\sqrt{s}=13$ TeV”. In: *Physical Review Letters* 116.7. ISSN: 1079-7114. DOI: 10.1103/physrevlett.116.071801. URL: <http://dx.doi.org/10.1103/PhysRevLett.116.071801>.
- Khachatryan, V. et al. (Feb. 2017). “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”. In: *Journal of Instrumentation* 12.02, P02014–P02014. DOI: 10.1088/1748-0221/12/02/p02014. URL: <https://doi.org/10.1088/1748-0221/12/02/p02014>.
- Krätschmer, I, H Kirschenmann, G Steinbrück, O Gutsche, AM Sirunyan, A Tumasyan, W Adam, F Ambrogio, E Asilar, T Bergauer, et al. (2018). “Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s}=13$ TeV and constraints on dark matter mediators and other new particles”. In: 130. DOI: 10.1007/JHEP08(2018)130. URL: https://www.zora.uzh.ch/id/eprint/160137/1/Sirunyan2018_Article_SearchForNarrowAndBroadDijetRe.pdf.

- Krnjaic, Gordan Z (Jan. 2012). “Very light axigluons and the top asymmetry”. In: *Physical Review D* 85.1, p. 014030. ISSN: 1550-2368.
- Mukherjee, Swagata (2017). “Data Scouting : A New Trigger Paradigm”. arXiv: 1708.06925 [hep-ex].
- Penning, Björn (2018). “The pursuit of dark matter at colliders—an overview”. In: *Journal of Physics G: Nuclear and Particle Physics* 45.6, p. 063001.
- Rácz, Attila and Paris Sphicas (2002). *CMS The TriDAS Project: Technical Design Report, Volume 2: Data Acquisition and High-Level Trigger*. Tech. rep. CMS-TDR-006.
- Sayre, Joshua, Duane A. Dicus, Chung Kao, and S. Nandi (July 2011). “Searching for colorons at the Large Hadron Collider”. In: *Physical Review D* 84.1. ISSN: 1550-2368. DOI: 10.1103/physrevd.84.015011. URL: <http://dx.doi.org/10.1103/PhysRevD.84.015011>.
- Simsek, A. E. et al. (2020a). “Construction and commissioning of CMS CE prototype silicon modules”. arXiv: 2012.06336 [physics.ins-det].
- (2020b). “The DAQ system of the 12,000 Channel CMS High Granularity Calorimeter Prototype”. arXiv: 2012.03876 [physics.ins-det].
- Sirunyan, A. M., A. Tumasyan, W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, and et al. (Aug. 2018). “Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter mediators and other new particles”. In: *Journal of High Energy Physics* 2018.8. ISSN: 1029-8479. DOI: 10.1007/jhep08(2018)130. URL: https://www.zora.uzh.ch/id/eprint/160137/1/Sirunyan2018_Article_SearchForNarrowAndBroadDijetRe.pdf.

- Sirunyan, A. M., A. Tumasyan, W. Adam, F. Ambroggi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, and et al. (May 2020). “Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s}=13$ TeV”. In: *Journal of High Energy Physics* 2020.5. ISSN: 1029-8479. DOI: 10.1007/jhep05(2020)033. URL: [http://dx.doi.org/10.1007/JHEP05\(2020\)033](http://dx.doi.org/10.1007/JHEP05(2020)033).
- Sirunyan, A.M. et al. (June 2017). “Search for dijet resonances in proton–proton collisions at $s=13$ TeV and constraints on dark matter and other models”. In: *Physics Letters B* 769, pp. 520–542. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2017.02.012. URL: <http://dx.doi.org/10.1016/j.physletb.2017.02.012>.
- Sirunyan, Albert M, Armen Tumasyan, Wolfgang Adam, Federico Ambroggi, Ece Asilar, Thomas Bergauer, Johannes Brandstetter, Erica Brondolin, Marko Dragicevic, Janos Erö, et al. (2018). “Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter mediators and other new particles”. In: *Journal of High Energy Physics* 2018.8, pp. 1–57.
- Sirunyan, Albert M, Armen Tumasyan, Wolfgang Adam, E Asilar, Thomas Bergauer, Johannes Brandstetter, Erica Brondolin, Marko Dragicevic, Janos Erö, Martin Flechl, et al. (2017). “Search for dijet resonances in proton–proton collisions at $s=13$ TeV and constraints on dark matter and other models”. In: *Physics Letters B* 769, pp. 520–542.
- Soffi, Livia (2016). “Search for new exotic particles decaying to photons at the LHC.” PhD thesis. Rome U. URL: <https://www.roma1.infn.it/cms/tesiPHD/soffi.pdf>.

- Tahir, NA, R Schmidt, M Brugger, R Assmann, A Shutov, IV Lomonosov, VE Fortov, AR Piriz, C Deutsch, and DHH Hoffmann (2009). “Interaction of Super Proton Synchrotron beam with solid copper target: Simulations of future experiments at HiRadMat facility at CERN”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 606.1-2, pp. 186–192.
- Tahir, NA, R Schmidt, M Brugger, R Assmann, AV Shutov, IV Lomonosov, AR Piriz, DHH Hoffmann, C Deutsch, and VE Fortov (2008). “The CERN Super Proton Synchrotron as a tool to study high energy density physics”. In: *New Journal of Physics* 10.7, p. 073028.
- Tahir, NA, R Schmidt, M Brugger, IV Lomonosov, A Shutov, AR Piriz, S Udrea, DHH Hoffmann, and C Deutsch (2007). “Prospects of high energy density physics research using the CERN super proton synchrotron (SPS)”. In: *Laser and Particle Beams* 25.4, pp. 639–647.
- TDR, CMS (2007). “8.2, “CMS Physics Technical Design Report, Volume II: Physics Performance”, CERN/LHCC 2006-021”. In: *J. Phys. G: Nucl. Part. Phys* 34, pp. 995–1579.
- TOK, Ufuk Güney, Ali Eren SIMSEK, and Nikolaos Charitonidis (2020). “SPS H2 Beam Line Simulation: Energy Loss and Material Impact at HGCal Test Beam”. URL: <https://indico.cern.ch/event/813822/contributions/3648319/>.
- Wiedemann, Helmut (1994). “Particle accelerator physics”. In: *Physics Today* 47.7, p. 61.
- Wu, Sean Daniel (2017). “Applying Vector Boson Fusion Topologies to Search for Supersymmetric and Higgs Portal Dark Matter at the LHC”. PhD thesis. URL: <https://oaktrust.library.tamu.edu/handle/1969.1/165978>.



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