Dark Matter Search with a Mono-Z’ Pencil Jet with the Compact Muon Solenoid Detector at the Large Hadron Collider

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Preliminary Examination
Overview

• Theoretical and Experimental Motivation
• Large Hadron Collider
• Compact Muon Solenoid
• Event Reconstruction
• Background Sources
• Analysis Strategy and Cut Flow
• Results
• Conclusion and Future Plans
The Standard Model

1st generation
- up (2/3)
- charm (2/3)
- top (2/3)
- 1/2
- charge
- color charge (r, g or b)
- mass (eV)
- spin

2nd generation
- down (-1/3)
- strange (-1/3)
- bottom (-1/3)
- 1/2
- charge
- color charge (r, g or b)
- mass (eV)
- spin

3rd generation
- electron (-1)
- muon (-1)
- tau (-1)
- 1/2
- charge
- color charge (r, g or b)
- mass (eV)
- spin

Higgs
- H

12 fermions (+12 anti-matter)

5 bosons (+1 opposite charged W)

Standard Model Interactions

- Fermions interact through gauge bosons
  - **Photons**: Mediate Electromagnetic Force
  - **W⁺/W⁻, Z**: Mediate the Weak Force
  - **Gluons**: Mediate the Strong Force
- Higgs field provides mass for:
  - Weak bosons
  - Massive fermions
Composition of Matter:

- Majority of matter content in the universe is of unknown nature.
- We know it is out there but we do not know what it is.
Evidence for Dark Matter

- **Galactic rotation curves** characteristically exhibit flat behavior at large distances i.e. far beyond the edge of visible disks
  - Behavior proves the existence of a dark matter “halo”
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  - Separation of dark and normal matter seen in the data
  - Gravitational potential (via **lensing**) consistent with DM distribution (**blue**) centered in galaxies
  - X-ray emitting (**red**) is visible matter
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- **Cosmic microwave background**
  - Planck 2015 cosmic microwave background (CMB) temperature anisotropy power spectrum encodes information about cosmological parameters
    - First acoustic peak: Universe is spatially flat overall
    - Second peak: $\Omega_b \sim 0.05$.
    - Third peak: Overall nonrelativistic matter density $\Omega_M \sim 0.3$
      - Therefore, $\Omega_{DM} = \Omega_M - \Omega_b = 0.25$

01/25/2018  $\Omega_{DM} = 5 \times \Omega_b$  Usama Hussain
• **Indirect detection (ID)** involves looking for Standard Model particles produced by astrophysical sources of Dark Matter.
Dark Matter Detection techniques

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- **Indirect detection (ID)** involves looking for Standard Model particles produced by astrophysical sources of Dark Matter.

- **Direct Detection (DD)** involves detecting recoil due to scattering of DM particles off target nuclei.

- **Collider Searches** are an effort to produce DM via collisions of SM particles.
  - Dark Matter interaction with SM particles has low cross-section so difficult to observe.
• **Effective Field Theory (EFT)** with a contact interaction between DM and SM particles.

• EFT depends on two parameters:
  
  • DM mass: \( m_\chi \)
  
  • Interaction scale: \( \Lambda \)

• EFT are reliable only if \( M^2 >> <Q^2> \) which is not always true at LHC energies.
Dark Matter Simplified Models

- Search for visible (SM) particles (Gluon/photon/boson) recoiling against MET
- Photons/gluons/bosons emitted as ISR, DM escapes undetected as MET

**Mono-Z' Simplified Model:**
- DM particle is a Dirac fermion
- DM particles are pair-produced
- A new massive particle mediates the DM-SM interaction
- There is an additional Z' emitted as FSR in this model
- Mediator has minimal decay width

**Minimal set of parameters**
- $M_{\text{MED}}, M_{\text{DM}}, g_{\text{SM}} (0.25), g_{\text{DM}} (1)$
- Reduce to EFT in **high-$M_{\text{med}}$** limit:
  \[ \Lambda = M_{\text{med}}/\sqrt{g q g_{\text{DM}}} \]
• Final State radiation of dark matter can generate the signature of a mono-
  Z' jet plus missing transverse energy.

• We study dominant decay of Z' into quarks.

• For GeV-scale Z', there are 2 important effects:
  • The boosted Z' appears as a jet with a very narrow cone of radiation and a small multiplicity of charged particles.
  • The rate for dark matter FSR of Z' jets can be larger than the rate for ISR jets.

• For a GeV-scale Z' (produced in association with large $E_T^{\text{miss}}$) decaying to hadrons, the boosted Z' gives a new collider signature.

• Mono-Z' model depends on the following parameters (initial values provided):
  • $M_{Z'} = 1 \text{ GeV}$
  • DM Mass, $m_\chi = 5 \text{ GeV}$
  • $g_{\text{SM}} = 0.25$, $g_{\text{DM}} = 1.0$
  • $M_{\text{MED}} = 1000 \text{ GeV}$

$E_T^{\text{miss}} > 300 \text{ GeV}$
The Large Hadron Collider

- 27 km circumference

- Depth 100m; tilt 1.4°

- 1600 superconducting magnets at 1.9° K (-271.3° C or -459.7° F)

- Accelerates beams of protons to 99.99999991% the speed of light
• LHC is capable of colliding protons and heavy ions
• Serves four primary experiments
  ▸ CMS and ATLAS: general purpose
  ▸ LHCb: forward hadronic physics
  ▸ ALICE: heavy ion collisions
• Designed for 14TeV center of mass energy
  • Achieved 8TeV in 2012
  • Achieved 13 TeV in 2015-2016

<table>
<thead>
<tr>
<th>Year</th>
<th>LHC center of mass energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2011</td>
<td>7 TeV</td>
</tr>
<tr>
<td>2012</td>
<td>8 TeV</td>
</tr>
<tr>
<td>2015-2017</td>
<td>13 TeV</td>
</tr>
<tr>
<td>Design</td>
<td>14 TeV</td>
</tr>
</tbody>
</table>
Proton Beam and Luminosity

- Number of events for a given process:
  \[ N = \sigma \int L \, dt \]
  - \( \sigma \) = cross section of process
  - \( L \) = Instantaneous luminosity of collider

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>2012</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (TeV)</td>
<td>7</td>
<td>4</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>2808</td>
<td>1368</td>
<td>2232</td>
<td>2208</td>
<td>2448</td>
</tr>
<tr>
<td>Bunch Spacing (ns)</td>
<td>25</td>
<td>50</td>
<td>50/25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Integrated Luminosity (fb(^{-1}))</td>
<td>23.3</td>
<td>4.2</td>
<td>40.8</td>
<td>51.0</td>
<td></td>
</tr>
</tbody>
</table>

- Present analysis uses part of 2016 data: 1.89 fb\(^{-1}\)
- 2018: Reach \(~150\) fb\(^{-1}\)

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The Compact Muon Solenoid

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16 m² ~66M channels
- Microstrips (80x180 μm): ~200 m³ ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
CMS Magnet

- **Purpose:** Strong magnetic field to bend path of charged particles
  - Allows momentum calculation
- 12.5 m length x 6.3 m diameter, cooled to 4.7 K by liquid Helium
- Superconducting high field (3.8T) solenoid coil inside central barrel
- Iron return yoke provides ~2T field outside solenoid
- Largest magnet in the world by measure of stored energy

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Silicon Tracker

- **Purpose:** High resolution tracks for $p_T$ and vertex measurement & matching
- Over 200m$^2$ Silicon cooled to below -10°C
- **Pixel detector** on the inside $r<15$ cm
  - 66 million channels
  - 3 layers, now upgraded to a new 4-layer detector
- **Silicon strip detector** outside to radius 1.1 m
  - 9.6 million channels

**$p_T$ Resolution (barrel):**

$$\frac{\delta p_T}{p_T} = \left( 15 \frac{p_T}{TeV} \oplus 0.5 \right) \%$$

The track $p_T$ resolution is roughly 0.5–2% for most of the relevant kinematic range, with less good track $p_T$ resolution (up to 5%) for low $p_T$ tracks (less than 1 GeV) at high pseudorapidities.
Electromagnetic Calorimeter

- **Purpose:** High resolution position and energy measurements for electrons and photons
- Over 75k Lead Tungstate crystals with Photodetectors
  - 61200 in Barrel region \((EB, |\eta| < 1.48)\)
  - 14648 in Endcap \((EE, 1.48 < |\eta| < 3.0)\)

**Barrel:** Avalanche PhotoDiodes (APD)
**Endcap:** Vacuum PhotoTriodes (VPT)

- **Resolution in Barrel:**
  \[
  \frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%
  \]
  e.g. a 50 GeV photon has energy resolution of 0.55% in the barrel.

**Lead Tungstate \((PbWO_4)\)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8.28 g/cm³</td>
</tr>
<tr>
<td>Radiation Length</td>
<td>0.89 cm</td>
</tr>
<tr>
<td>Molière radius</td>
<td>2.19 cm</td>
</tr>
</tbody>
</table>

The ECAL energy resolution for electrons and photons is roughly 0.5–3%, depending on both pseudorapidity and energy, for electron/photon energies greater than 10 GeV.
• **Purpose:** Long lived hadrons (Jets) and missing energy (MET) measured and triggered by compact (inside solenoid), hermetic ($|\eta| < 5$) sampling hadronic calorimeter (HCal)

• The CMS HCal:
  - **HCAL Barrel (HB)**
    - $5.8-10.6 \lambda (+1.1 \lambda$ from ECAL)
  - **HCAL Endcap (HE)**
    - $\sim 10 \lambda$ (including ECAL)
    - Over 1000 tons of brass plates interleaved with scintillator tiles
  - **Resolution (HB/HE):**
    \[
    \frac{\sigma}{E} = \frac{115\%}{\sqrt{E}} \oplus 5.5\%
    \]
  - **HCAL Forward (HF)**
    - Steel plates embedded with quartz fibers
    - Cherenkov-based detector
    - Measures EM rich jets outside of ECal acceptance.
    - **Resolution:**
    \[
    \frac{\sigma}{E} = \frac{280\%}{\sqrt{E}} \oplus 11\%
    \]
• **Purpose**: triggering, identification, and assisting inner tracker in measuring high-$p_T$ muons

• ~14,000 tonnes of iron absorber and solenoid flux return

• Three types of gas detectors
  - Cover very large ~40K m$^2$ area at low cost

Momentum measurement below about 200 GeV is tracker dominated, but above that the full system has better resolution
Trigger System

- 40 MHz of beam crossings, with an average of ~25 interactions/crossing means that there are nearly 1 billion interactions/second
- Beam crossings generate ~1 MB of data per event or 40 Terabytes/s
- CMS can record ~1kHz at a MB per event
- Need to reject 99.9998% of events in quasi real time

Rate reduction in two steps:
- **Level-1 Trigger**
  - Custom hardware
  - Subset of detector information
  - Reduces rate to ~100kHz
- **High-Level Trigger**
  - Software, CPU-limited
  - Full detector information
  - Reduces rate to ~1kHz
• Using only calorimeters and muon systems, Level 1 (L1) Hardware trigger finds
  • EG Candidates (electrons/photons)
  • Jet Candidates
  • Missing Energy estimate
  • Muon Candidates

• Constraints from the detectors readout
  • pipeline: ~ 4 μs long
  • 100 kHz maximum output rate
High Level Trigger

- Full detector readout, full granularity
  - 100 kHz input rate
- Implementation
  - Subset of reconstruction algorithms used for simulation and offline analyses
  - running on a cluster of commercial PCs (filter farm)
  - Over 450 trigger paths in HLT menu
- Constraints
  - ~220 ms *average* processing time to take a decision
  - 1 kHz *average* output rate (limited by offline resources)

Schematic representation of a HLT menu in CMS and of the HLT paths in it. The final trigger decision is the logical OR of the decisions of the single paths.
Particle Flow Reconstruction combines information from sub-detectors in the best possible way to reconstruct all stable particles in an event

- Muon system tracks are matched to tracks in inner tracker - **Muons**
- Remaining tracks are then associated with energy deposits in ECAL (**electrons**) and HCAL (**charged hadrons**)
- Remaining energy deposits are clustered to form **photon candidates** (ECAL) and **neutral hadron candidates** (HCAL)

Higher level physics objects such as hadronic taus, jets, missing transverse energy can be built from these objects
Jet Reconstruction

Most physics channels of interest at the LHC require good understanding of jet reconstruction.

- Collimated bunches of stable hadrons, originating from partons (quarks and gluons) after fragmentation and hadronization
- Jets are the observable objects to relate experimental observations to theory predictions.

- Jet reconstruction algorithms
  - Iteratively cluster nearby particles into jet objects

In this analysis,

- Use **AK4PFCHS** jets (charged particles from non-primary vertices (pileup) are removed before clustering).
- Anti-$$k_T$$ jet algorithm distance metric with $$R = 0.4$$:
  $$d_{ij} = \min\left(\frac{1}{E_{T_i}}, \frac{1}{E_{T_j}}\right) \frac{\Delta_{ij}^2}{R^2}$$
  $$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$
- distance $$d_{ij}$$ between two particles $$i$$ and $$j$$
• Compute energy weighted $\eta$ width and $\phi$ width by looping over all Particle Flow Constituents of the jet

• $\eta$ Width = $\sqrt{\frac{\sum (\eta_i^2 E_i)}{\sum E_i} - \left(\frac{\sum \eta_i E_i}{\sum E_i}\right)^2}$

• $\phi$ Width = $\sqrt{\frac{\sum (\phi_i^2 E_i)}{\sum E_i} - \left(\frac{\sum \phi_i E_i}{\sum E_i}\right)^2}$

• $Z' \rightarrow$ two quarks $\rightarrow$ hadronize

• Boosted $Z'$ is highly collimated and energy deposits from its constituents are concentrated in $\eta$ and $\phi$

• See event display
Missing Transverse Energy (MET)

- Negative vector sum of transverse momentum from all reconstructed particles (PF objects).

\[ \vec{E}_T = - \sum_{i \in \text{vis.}} \vec{p}_T i \]

- Neutrinos and potentially beyond the standard model particles will not deposit energy in the CMS detector resulting in MET.

In this analysis,

- Use pfMET (all particle flow candidates are summed)
- pfMET measurement sensitive to:
  - detector effects: noise, dead/hot cells
  - beam halo, cosmics, pile-up
- MET Filters are applied to account for some of these effects
- Jet energy corrections are applied to particles associated with a jet

\[ \vec{E}_T^{\text{corr}} = \vec{E}_T - \sum_{\text{jets}} (\vec{p}^{\text{corr}}_{T,\text{jet}} - \vec{p}_T \text{,jet}) \]
Event Simulation

Full data taking process is simulated, from hard scatter process through event reconstruction: “Monte Carlo” (MC)

Common programs for hard scatter simulation at CMS:
- MadGraph5_aMC@NLO
- POWHEG
- PYTHIA

Pythia simulates:
- Parton Shower
- Hadronization
- Decay

Modeled in GEANT4:
- Particle Interactions with matter
- Simulate detector response

Event Reconstruction

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• Use the topology of the signal where the Z' appears as a narrow “Pencil” Jet to improve the limits obtained by Mono-Jet Analysis.

• Find a set of selection criteria that would optimally identify this unique signature.

• The more sophisticated selection criteria can then be better optimized to reduce background that is more likely to be faking signal.
Backgrounds

- Jet+MET final state can be mimicked by a variety of non-signal processes
- All significant background MC processes used in this analysis are summarized:

<table>
<thead>
<tr>
<th>Data</th>
<th>ZprimeSignal</th>
<th>Signal Simulation, produced with Madgraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z→νν</td>
<td></td>
<td>Main irreducible background in this analysis</td>
</tr>
<tr>
<td>W→lν</td>
<td></td>
<td>Second largest background in this analysis</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td></td>
<td>One weak boson decays leptonically (W→lν, Z→νν) while the other decays hadronically producing jets and $E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>Top Quark</td>
<td></td>
<td>W produced from top decay, W decays leptonically producing genuine $E_T^{\text{miss}}$ in the event</td>
</tr>
<tr>
<td>γ+jets</td>
<td></td>
<td>Fake MET due to events in which the photon goes undetected</td>
</tr>
<tr>
<td>DYJets→LL</td>
<td></td>
<td>Fake MET</td>
</tr>
<tr>
<td>QCD</td>
<td></td>
<td>Mismeasured or undetected jet events can serve as background events</td>
</tr>
</tbody>
</table>
Preselection reduces ~6.4 million events from the MET primary dataset to ~2.2 million events.

**Preselection:**
- Require MET filters to reduce fake MET from detector effects, beam halo, cosmics etc.
- Require HLT path with
  - PFMET > 170 GeV

**Selection Cuts:**
- Cuts motivated in following slides
<table>
<thead>
<tr>
<th>HLT path</th>
<th>L1 seed</th>
<th>Primary dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_PFMET170_*</td>
<td>L1_ETM70</td>
<td>MET</td>
</tr>
<tr>
<td>HLT_PFMETNoMu[X]_PFMHTNoMu[X]_IDTight</td>
<td>L1_ETM70</td>
<td>MET</td>
</tr>
<tr>
<td></td>
<td>L1_ETM60_NotJet52WdPhi2</td>
<td></td>
</tr>
</tbody>
</table>
**MET Cleaning and Trigger**

- Data Events pass the $E_T^{\text{miss}}$ triggers described in previous slide.
- Reject fake MET caused by detector noise, cosmic rays and beam-halo particles which improves the agreement of the MET spectrum with Monte Carlo, in which causes of false MET are not explicitly simulated.

---

**CMS : Preliminary**

$s = 13$ TeV, 1.89 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>6.4E+06</td>
<td>2.3E+06</td>
</tr>
<tr>
<td><strong>QCD</strong></td>
<td>3.65E+10</td>
<td>3.6E+10</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>88.3</td>
<td>87.7</td>
</tr>
<tr>
<td><strong>$S/\sqrt{B}$</strong></td>
<td>0.000462</td>
<td>0.000458</td>
</tr>
</tbody>
</table>

QCD is the dominant background at this stage given the large cross-section with which these events are produced.
• A good jet candidate passes:
  • Loose Particle Flow JetID
  • Reject fake, badly reconstructed and noise jets
• Kinematic cuts
  • jet momentum is greater than 200 GeV
  • Neutral Hadron Fraction of the Jet < 0.8
  • Charged Hadron Fraction of the Jet > 0.1
  • |jetEta| < 2.4
• MET filters remove a lot of fake MET events from detector noise and beam halo
• Additional Cleaning of Jets required to suppress backgrounds due to detector noise and beam backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>2.3E+06</td>
<td>563938</td>
</tr>
<tr>
<td>W+Jets</td>
<td>1.1E+08</td>
<td>193971</td>
</tr>
<tr>
<td>Z+Jets</td>
<td>868754</td>
<td>45562</td>
</tr>
<tr>
<td>QCD</td>
<td>3.6E+10</td>
<td>1.0E+08</td>
</tr>
<tr>
<td>Signal</td>
<td>87.7</td>
<td>63.7</td>
</tr>
<tr>
<td>S/√B</td>
<td>0.000458</td>
<td>0.00637</td>
</tr>
</tbody>
</table>
• Expect significant amount of missing energy (MET) in our signal

• Cut MET > 250 GeV
**CaloMET**: MET of all energy deposits in calorimeter towers in EB, EE, HB, HE, and HF

- Badly measured tracks/muons reconstructed as high momentum Particle Flow candidates
- Particle Flow MET is mismeasured
- CaloMET is not affected
- \((\text{caloMET-pfMET})/\text{pfMET}\) variable typically has a large value for events in which PF MET is mismeasured.

**CMS**: Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, \, 1.89 \text{ fb}^{-1} \]

Cut Flow - CaloMET based Cut

Cut applied here at 0.5 to suppress bad/mismeasured muons faking MET
No significant change in the main backgrounds as expected and a large reduction in QCD events.
## Cut Flow - Lepton Veto

- **Electron Veto**
  - Electron with transverse momentum greater than 10 GeV
  - Electron does not overlap with jet (deltaR > 0.5)

- **Muon Veto**
  - Muon with transverse momentum greater than 10 GeV
  - Muon does not overlap with jet (deltaR > 0.5)

- Lepton veto reduces the W+Jets reducible background
- Z+Jets is the irreducible background in this analysis

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>41452</td>
<td>31318</td>
</tr>
<tr>
<td><strong>Z+Jets</strong></td>
<td>16162</td>
<td>11506</td>
</tr>
<tr>
<td><strong>W+Jets</strong></td>
<td>11613</td>
<td>8965</td>
</tr>
<tr>
<td><strong>QCD</strong></td>
<td>5919</td>
<td>5769</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>61.7</td>
<td>61.1</td>
</tr>
<tr>
<td><strong>S/√B</strong></td>
<td>0.318</td>
<td>0.363</td>
</tr>
</tbody>
</table>
B-Jet Cleaning

- Top quarks predominantly decay to a W boson + b quark.
- Veto of b-tagged jets lowers top background
- Kinematics of the $Z'$ jet and MET considered together
- Most events ‘back-to-back’ except QCD events
- Azimuthal separation between closest jet and MET $\Delta \Phi (\text{Jet, MET}) > 0.5$

Cut applied here at 0.5 to suppress QCD
As expected, this cut gets rid of essentially all of the QCD background and it also reduces the W+ Jets background significantly making Z+Jets as the dominant irreducible background in this analysis.
• First, identified our signal using the “Jet $\eta$ width” variable as shown in the next few slides
Pencil Jet $\eta$ width Cut

- Compute energy weighted $\eta$ width by looping over all Particle Flow Constituents of the jet

$$\eta \text{ Width} = \sqrt{\frac{\sum (\eta_i^2 E_i)}{\sum E_i} - \left(\frac{\sum (\eta_i E_i)}{\sum E_i}\right)^2}$$

- Leading Jet $\eta$ Width < 0.04

 Expected Counts

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>50.9</td>
<td>40</td>
</tr>
<tr>
<td>$Z+$Jets</td>
<td>8758</td>
<td>1080</td>
</tr>
<tr>
<td>$W+$Jets</td>
<td>5093</td>
<td>639</td>
</tr>
</tbody>
</table>

Cut applied here at 0.04 to reduce main backgrounds

CMS: Preliminary

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$
## Expected Counts

<table>
<thead>
<tr>
<th></th>
<th>Baseline Selection Cuts</th>
<th>Baseline + Leading Jet $\eta$ Width Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data (1.89 fb^{-1})</strong></td>
<td>14,874</td>
<td>1842</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>50.9</td>
<td>40</td>
</tr>
<tr>
<td><strong>$Z \rightarrow \nu\nu$</strong></td>
<td>8758</td>
<td>1080</td>
</tr>
<tr>
<td><strong>$W \rightarrow l\nu$</strong></td>
<td>5093</td>
<td>639</td>
</tr>
<tr>
<td><strong>Top Quark</strong></td>
<td>95.7</td>
<td>9</td>
</tr>
<tr>
<td><strong>QCD</strong></td>
<td>17.6</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>$\gamma$+Jets</strong></td>
<td>58.5</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>WZ/WW/ZZ</strong></td>
<td>161.8</td>
<td>20</td>
</tr>
<tr>
<td><strong>DYJets$\rightarrow$ LL</strong></td>
<td>49</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td><strong>14,234</strong></td>
<td><strong>1766</strong></td>
</tr>
<tr>
<td><strong>Data/MC</strong></td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td><strong>$S/\sqrt{B}$</strong></td>
<td><strong>0.43</strong></td>
<td><strong>0.95</strong></td>
</tr>
</tbody>
</table>
Before Leading Jet $\eta$ Width Cut

CMS: Preliminary

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

Data/MC

ZprimeSignal, mchi5GeV, $\nu\nu \rightarrow Z\nu \rightarrow W\nu W$ $W$ $W$, $W$ $Z$, Z $Z$
Top Quark
$\gamma$+jets
DYJets→$LL$
QCD

After Leading Jet $\eta$ Width Cut

CMS: Preliminary

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

Data/MC

ZprimeSignal, mchi5GeV, $\nu\nu \rightarrow Z\nu \rightarrow W\nu W$ $W$ $W$, $W$ $Z$, Z $Z$
Top Quark
$\gamma$+jets
DYJets→$LL$
QCD

Results: Leading Jet $P_T$
• First, identified our signal using the “Jet $\eta$ width” variable as shown in the last few slides

• Now, I will show some more techniques for signal extraction
  
  • Basically, we split up our signal region into **Three Categories** and present results in each category separately.
    
    • **Category 1**: $\pi^+ \pi^-$
    
    • **Category 2**: $\pi^+ \pi^- + 1$ boosted $\pi^0$ (Photon)
    
    • **Category 3**: Remaining Events $<$ 2 Charged Hadrons
Category 1: $\pi^+ \pi^-$

(24.1 % of the Signal)
We sum the $P_T$ of the two leading oppositely charged hadron constituents of the Leading Jet and calculate the fraction with respect to the overall jet transverse momentum.

$P_{T12} \text{ Fraction} = \frac{(P_{T1} + P_{T2})}{j1PT}$

$P_{T12} \text{ Fraction} > 0.7$

### Expected Counts

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>13.6</td>
<td>12.8</td>
</tr>
<tr>
<td>Z+Jets</td>
<td>1595</td>
<td>98</td>
</tr>
<tr>
<td>W + Jets</td>
<td>934</td>
<td>57.7</td>
</tr>
</tbody>
</table>

Cut applied here at 0.7 to reduce main backgrounds
<table>
<thead>
<tr>
<th></th>
<th>Baseline Selection Cuts</th>
<th>Baseline + P_{T}\text{PF}^{12} \text{ Frac} &gt; 0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data (1.89 fb^{-1})</td>
<td>2802</td>
<td>189</td>
</tr>
<tr>
<td>Signal</td>
<td>13.6</td>
<td>12.8</td>
</tr>
<tr>
<td>Z\rightarrow\nu\nu</td>
<td>1595</td>
<td>98</td>
</tr>
<tr>
<td>W\rightarrow\ell\nu</td>
<td>934</td>
<td>57.7</td>
</tr>
<tr>
<td>Top Quark</td>
<td>16.5</td>
<td>0.68</td>
</tr>
<tr>
<td>QCD</td>
<td>3.0</td>
<td>0.07</td>
</tr>
<tr>
<td>γ+Jets</td>
<td>12.3</td>
<td>1.8</td>
</tr>
<tr>
<td>WZ/WW/ZZ</td>
<td>28.3</td>
<td>2.1</td>
</tr>
<tr>
<td>DYJets\rightarrow LL</td>
<td>9</td>
<td>0.6</td>
</tr>
<tr>
<td>Total Background</td>
<td>2598</td>
<td>161</td>
</tr>
<tr>
<td>Data/MC</td>
<td>1.08</td>
<td>1.17</td>
</tr>
<tr>
<td>S/\sqrt{B}</td>
<td>0.27</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Results: Leading Jet $P_T$

**Before $P_T^{12}$ Fraction Cut**

CMS: *Preliminary*

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

**After $P_T^{12}$ Fraction Cut**

CMS: *Preliminary*

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$
Category 2: \( \pi^+ \pi^- + 1 \) boosted \( \pi^0 \) (Photon)

(30.4% of the Signal)
We sum the $P_T$ of the two leading oppositely charged hadron constituents and the high $P_T$ photon in the Leading Jet and calculate the fraction with respect to the overall jet transverse momentum.

$$P_{T123} \text{ Fraction} = (P_{T1} + P_{T2} + P_{T3})/j1PT$$

$$P_{T123} \text{ Fraction} > 0.7$$

**Expected Counts**

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>16.5</td>
<td>16.0</td>
</tr>
<tr>
<td><strong>Z+Jets</strong></td>
<td>2879</td>
<td>652</td>
</tr>
<tr>
<td><strong>W + Jets</strong></td>
<td>1678</td>
<td>381.5</td>
</tr>
</tbody>
</table>

Cut applied here at 0.7 to reduce main backgrounds

CMS: Preliminary

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

Rejected
### Expected Counts

<table>
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<tr>
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<th>Baseline Selection Cuts</th>
<th>Baseline + $P_{T\text{PF}}^{123}$ Frac &gt; 0.7</th>
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</thead>
<tbody>
<tr>
<td><strong>Data (1.89 fb$^{-1}$)</strong></td>
<td>4590</td>
<td>1145</td>
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<tr>
<td><strong>Signal</strong></td>
<td>16.5</td>
<td>16.0</td>
</tr>
<tr>
<td>$Z\rightarrow vv$</td>
<td>2879</td>
<td>652</td>
</tr>
<tr>
<td>$W\rightarrow lv$</td>
<td>1678</td>
<td>381.5</td>
</tr>
<tr>
<td><strong>Top Quark</strong></td>
<td>7</td>
<td>4.6</td>
</tr>
<tr>
<td><strong>QCD</strong></td>
<td>8.8</td>
<td>0.5</td>
</tr>
<tr>
<td>$\gamma+$Jets</td>
<td>18.1</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>WZ/WW/ZZ</strong></td>
<td>52.7</td>
<td>12.0</td>
</tr>
<tr>
<td><strong>DYJets $\rightarrow LL$</strong></td>
<td>16.1</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>4660</td>
<td>1058</td>
</tr>
<tr>
<td><strong>Data/MC</strong></td>
<td>0.98</td>
<td>1.08</td>
</tr>
<tr>
<td><strong>S/$\sqrt{B}$</strong></td>
<td>0.24</td>
<td>0.49</td>
</tr>
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</table>
Results: Leading Jet $p_T$

Before $p_T^{123}$ Fraction Cut

<table>
<thead>
<tr>
<th>CMS: Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$</td>
</tr>
</tbody>
</table>

**Data/MC**

<table>
<thead>
<tr>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z' \rightarrow \nu\nu$</td>
</tr>
<tr>
<td>$W \rightarrow l\nu$</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
</tr>
<tr>
<td>Top Quark</td>
</tr>
<tr>
<td>$\gamma$ +jets</td>
</tr>
<tr>
<td>DYJets→LL</td>
</tr>
<tr>
<td>QCD</td>
</tr>
</tbody>
</table>

**Leading Jet $p_T$ (GeV)**

0 - 2500

After $p_T^{123}$ Fraction Cut

<table>
<thead>
<tr>
<th>CMS: Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$</td>
</tr>
</tbody>
</table>

**Data/MC**

<table>
<thead>
<tr>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z' \rightarrow \nu\nu$</td>
</tr>
<tr>
<td>$W \rightarrow l\nu$</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
</tr>
<tr>
<td>Top Quark</td>
</tr>
<tr>
<td>$\gamma$ +jets</td>
</tr>
<tr>
<td>DYJets→LL</td>
</tr>
<tr>
<td>QCD</td>
</tr>
</tbody>
</table>

**Leading Jet $p_T$ (GeV)**

0 - 2500

01/25/2018

Usama Hussain
Category 3: Remaining Events < 2 Charged Hadrons

(45.5% of the Signal)
- Compute energy weighted $\eta$ width by looping over all Particle Flow Constituents of the jet

$$\eta \text{ Width} = \sqrt{\frac{\sum (\eta_i^2 E_i)}{\sum E_i} - \left( \frac{\sum (\eta_i E_i)}{\sum E_i} \right)^2}$$

- Leading Jet $\eta$ Width < 0.04

**Expected Counts**

<table>
<thead>
<tr>
<th></th>
<th>Before Cut</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>20.8</td>
<td>16.0</td>
</tr>
<tr>
<td><strong>Z+Jets</strong></td>
<td>4283</td>
<td>490.8</td>
</tr>
<tr>
<td><strong>W + Jets</strong></td>
<td>2481</td>
<td>298.5</td>
</tr>
</tbody>
</table>

**CMS: Preliminary**

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

Data/MC

Cut applied here at 0.04 to reduce main backgrounds
## Expected Counts

<table>
<thead>
<tr>
<th></th>
<th>Baseline Selection Cuts</th>
<th>Baseline + Leading Jet $\eta$ Width Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data (1.89 fb$^{-1}$)</td>
<td>7482</td>
<td>866</td>
</tr>
<tr>
<td>Signal</td>
<td>20.8</td>
<td>16.0</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>4283</td>
<td>490.8</td>
</tr>
<tr>
<td>$W \rightarrow l\nu$</td>
<td>2481</td>
<td>298.5</td>
</tr>
<tr>
<td>Top Quark</td>
<td>51.2</td>
<td>4.1</td>
</tr>
<tr>
<td>QCD</td>
<td>5.8</td>
<td>1.2</td>
</tr>
<tr>
<td>$\gamma$+Jets</td>
<td>28.2</td>
<td>3.1</td>
</tr>
<tr>
<td>$WZ/WW/ZZ$</td>
<td>80.7</td>
<td>9.5</td>
</tr>
<tr>
<td>DYJets $\rightarrow LL$</td>
<td>23.8</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td><strong>6954</strong></td>
<td><strong>810</strong></td>
</tr>
<tr>
<td>Data/MC</td>
<td>1.08</td>
<td>1.07</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td><strong>0.25</strong></td>
<td><strong>0.56</strong></td>
</tr>
</tbody>
</table>
Before Leading Jet $\eta$ Width Cut

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$

After Leading Jet $\eta$ Width Cut

$\sqrt{s} = 13$ TeV, 1.89 fb$^{-1}$
Limit Descriptions

- Limits are computed using Cut and Count Approach
- Following Systematics are considered
  - Luminosity: 6%
  - EWK Uncertainty for Z+Jets and W+Jets
    - Following Monojet procedure (Full correction applied for nominal estimate)
  - MET energy scale: 5%
  - B-jet veto: 2%
  - Trigger: 1%
NoCategories vs 3 Categories Expected Limits

CMS

Internal

\( \sqrt{s} = 13 \text{ TeV}, 1.89 \text{ fb}^{-1} \)

\( g_{\text{SM}} = 0.25 \)

\( g_{\text{DM}} = 1.0 \)

\( M_{Z'} = 1 \text{ GeV} \)

\( 95\% \text{ CL limit on } \sigma/\sigma_{\text{theor}} \)
Summary & Outlook

• Summary:
  • Studied the Mono-Z' model with 1.89 fb\(^{-1}\) of p-p collisions data using the PencilJet analysis.
  • No significant excess above the SM prediction is observed

• Ongoing:
  • Extension of analysis to full 2016 + 2017 dataset (36 + 41 fb\(^{-1}\))
  • Make an effective comparison with results from Direct Detection Searches.

• Outlook:
  • Transition from “cut-and-count” to shape-based approach.
  • Data-driven approach to Z + Jets and W + Jets background estimates
  • Thesis work with ~ 150 fb\(^{-1}\) data
Backup Slides
Signal Efficiency

\[ \text{Signal Efficiency} = \frac{\text{events passing selection}}{\text{Total no. of events}} \]

<table>
<thead>
<tr>
<th>( m_x ) [GeV]</th>
<th>( \sigma ) [pb]</th>
<th>Signal Efficiency After Leading Jet ( \eta ) Width Cut</th>
<th>Signal Efficiency Baseline Selection Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.056</td>
<td>0.547</td>
<td>0.434</td>
</tr>
<tr>
<td>5</td>
<td>0.047</td>
<td>0.566</td>
<td>0.452</td>
</tr>
<tr>
<td>10</td>
<td>0.040</td>
<td>0.564</td>
<td>0.455</td>
</tr>
<tr>
<td>20</td>
<td>0.034</td>
<td>0.575</td>
<td>0.459</td>
</tr>
<tr>
<td>50</td>
<td>0.025</td>
<td>0.572</td>
<td>0.463</td>
</tr>
<tr>
<td>100</td>
<td>0.019</td>
<td>0.579</td>
<td>0.469</td>
</tr>
</tbody>
</table>
• Upper limit on signal production cross section as a function of dark matter mass
• Excluded $\Lambda$ up to 1.3 TeV for dark matter masses $\sim$1 GeV

$\Lambda_{\text{theor}} = 2$ TeV

$\Lambda = \Lambda_{\text{theor}} \times \left(\frac{\sigma_{\text{theor}}}{\sigma}\right)^{1/4}$ TeV

- No previous experimental results with Mono-Z' FSR model
- Both ATLAS and CMS have results from ISR searches for dark matter
- Results are dependent on coupling values and choice of models.
Figure 7: Left panel: projected constraints on dark matter-proton spin-independent scattering cross sections from the standard mono-jet analysis at the 14 TeV LHC with 100 fb\(^{-1}\) and the mono-\(Z'\) jet-substructure based analysis. The model parameters are \(M_{Z'} = 1\) GeV and \(g_x = 1.0\), and we take the limits on \(\Lambda\) assuming 10\% systematic error. Also shown are the current constraints from direct detection experiments: LUX [69], SuperCDMS [70] and CDMSLite [71]. Right panel: similar to the left panel but for dark matter-proton spin-dependent scattering cross sections. The current experimental bounds are from: PICASSO [72], SIMPLE [73], PICO-2L [74] and IceCube [75].

source: arXiv:1504.01395v2
Table 4.1: LHC design beam conditions and conditions in operation between 2010 and 2016.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
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<td>Center of Mass Energy (TeV)</td>
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<td>7</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Energy per Beam (TeV)</td>
<td>3.5</td>
<td>3.5</td>
<td>4</td>
<td>6.5</td>
<td>6.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Proton bunch spacing (ns)</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>50/25</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>$N_b \times 10^{11}$</td>
<td>1.2</td>
<td>1.5</td>
<td>1.7</td>
<td>1.15</td>
<td>1.25</td>
<td>1.25</td>
<td>1.15</td>
</tr>
<tr>
<td>$n_b$</td>
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<td>1331</td>
<td>1368</td>
<td>2232</td>
<td>2208</td>
<td>2808</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.8</td>
<td>0.4</td>
<td>0.33</td>
<td>0.55</td>
</tr>
<tr>
<td>$\epsilon_n$</td>
<td>2.2</td>
<td>2.3</td>
<td>2.5</td>
<td>3.5</td>
<td>3.0</td>
<td>2.3</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak Instantaneous $\mathcal{L} \times 10^{34}$</td>
<td>0.02</td>
<td>0.35</td>
<td>0.77</td>
<td>0.52</td>
<td>1.53 (above design)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total Integrated $\mathcal{L} \ (fb^{-1})$</td>
<td>0.04</td>
<td>6.1</td>
<td>23.3</td>
<td>4.2</td>
<td>41.1</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

Courtesy: L.Dodd

$L \sim f \cdot N_2/ (4 \cdot \epsilon \cdot \beta^*)$
To understand the basic principles of the particle-flow event reconstruction, an event display of a very simple hadronic jet with four particles (π⁺, π−, π⁰, K⁰L) and a pT of 65 GeV/c

The K⁰L, the π− and the two photons from the π⁰ decay are detected as four well separated ECAL clusters (b). The π⁺ leaves no energy in the ECAL. The two charged pions are reconstructed as charged-particle tracks, appearing as vertical solid lines in the (η, φ) views and circular arcs in the (x, y) view. These tracks point towards two HCAL clusters (c). In all three views, the cluster positions are represented by dots, the simulated particles by dashed lines, and the position of their impact on the calorimeter surfaces by various open markers.
Categories of reconstructed muons:

- **Tracker muons** - inner tracks matched with at least one segment in the muon system
  - High efficiency for low $p_T$ muons
- **Standalone muons** - tracks from segments and hits in muon systems
- **Global muons** - match standalone muon tracks with silicon tracks

In the Mono-Z' analysis:

- Z' specifically decays to hadrons so lepton channel not being considered
- Muon Veto ensures muons ($p_T > 10$ GeV) do not overlap with Jet
Electron Reconstruction

- Electron candidates identified by a combination of detectors
  - ECAL superclusters
  - Gaussian Sum Filter (GSF) track reconstruction

Electron candidates are found when a supercluster can be associated to a track reconstructed in the silicon tracker detector, and in particular its innermost layers.
  - Track must be close to primary interaction vertex
  - ECal supercluster includes elongated area in \( \phi \) to contain bremsstrahlung photons radiated from electron

In the Mono-Z' analysis:
  - \( Z' \) specifically decays to hadrons so lepton channel not being considered
  - Electron Veto ensures electrons (\( p_T > 10 \) GeV) do not overlap with Jet
Dark Matter: Previous Results

Summary of ISR searches

- 95% CL exclusion regions in $M_{\text{med}}$ – $m_{\text{DM}}$ plane for di-jet searches and different $E_{T}^{\text{miss}}$ based DM searches from CMS in the lepto-phobic Axial Vector model.
  
  - **Limits:** $M_{\text{med}} \sim 2$ TeV, $m_{\text{DM}} \sim 600$ GeV
    Mono-jet most stringent - all channels contribute to interpretation

  Source: CMS DP -2016/057

- A summary of ATLAS limits on the lepto-phobic axial vector mediators coupling to DM, with variable mediator and DM masses, from both the leading $E_{T}^{\text{miss}}+X$ analyses and dark mediator searches.
  
  - **Limits:** $M_{\text{med}} \sim 1$ TeV, $m_{\text{DM}} \sim 250$ GeV

  Source: ATL-PHYS-PROC-2016-206

Source: ATL-PHYS-PROC-2016-206
CMS searches for dark matter have been performed with various mono-X final states:

- 90% CL exclusion limits with 12.9 fb\(^{-1}\) of 2016 data from mono-jet/photon/Z.

Results were recast in terms of nucleon-DM scattering cross section for comparison to direct detection (DD) searches.

No sign of excess yet:

- LHC especially competitive for SD (Pseudoscalar & Axial) and clearly better at low mass.
- CMS results shown are dependent on coupling values and choice of models.
• **Effective Field Theory (EFT)** with a contact interaction between DM and SM particles.

• EFT depends on two parameters:
  
  • DM mass: $m_\chi$
  
  • Interaction scale: $\Lambda$

  • Cross section: $\propto \Lambda^{-4}$

  • $\Lambda \approx \frac{M}{\sqrt{g_\chi g_q}}$

  • $\mu = \frac{m_\chi m_p}{m_\chi + m_p}$

  • Cross section: $\propto \mu^2$ for both Spin-Independent (SI) and Spin-dependent (SD) cross-sections.

• **Couplings:**
  
  • $g_q$ : Mediator coupling to quarks
  
  • $g_\chi$ : Mediator coupling to dark matter
Direct and Indirect Detection Experiments

**Direct detection:** A number of experiments look for elastic scattering of ambient DM off target nuclei

- SuperCDMS: 10 kg Ge crystal
- CRESST-II: 5 kg CaWO$_4$ crystal
- LUX: 250 kg dual-phase Xe
- PandaX-II: 580 kg dual-phase Xe – PICO-2L: 2.9 kg liquid C$_3$F$_8$
- PICO-60: 36.8 kg liquid CF$_3$I

**Indirect detection:**

IceCube and Super-Kamiokande look for neutrinos produced by dark matter annihilating into $\tau^+\tau^-$, $bb$, or $W^+W^-$ in the sun
Pair production of $\chi$ can be characterized by a contact interaction with most prominent couplings.

Two important couplings used by CMS are:

Vector coupling ($V$)

$$O_V = \frac{(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2}$$

Spin-independent (SI)

Axial-Vector coupling ($AV$)

$$O_{AV} = \frac{(\bar{\chi}\gamma_{\mu}\gamma_5\chi)(\bar{q}\gamma^{\mu}\gamma_5q)}{\Lambda^2}$$

Spin-dependent (SD)

$$\sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4}$$

$$\sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4}$$

Source: DarkMatter_Seminar_SLAC.pdf (B.Gomber)
**Type of PF Constituents of Leading Jet**

- **Signal Sample**
  - $m_{\chi} = 5$ GeV

- **Sample of events**
  - Total of 1205 events
  - Signal Efficiency = $1205/2133 = 0.565$

---

### PF Constituents of Leading Jet

<table>
<thead>
<tr>
<th>TYPE OF CONSTITUENTS</th>
<th>TOTAL (1205 EVENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Pions</td>
<td>6,983</td>
</tr>
<tr>
<td>Photons</td>
<td>6,128</td>
</tr>
<tr>
<td>K$^0_L$ mesons</td>
<td>2,885</td>
</tr>
<tr>
<td>Other particles</td>
<td>139</td>
</tr>
</tbody>
</table>

---

**Column Chart**

- Charged Pions: 6,983
- Photons: 6,128
- K$^0_L$ mesons: 2,885
- Other particles: 139
The CMS magnet is a central feature of the detector

- Huge – used for Silicon tracking, but placed outside of calorimeters to
  - not interfere with precision $e$ and $\gamma$ measurement,
  - give long “lever arm” for precision muon measurement at very high momentum

- 2.6GJ stored energy

During Installation,

- Huge amount of superconducting wire
- Large and complex cryogenic infrastructure for liquid He

The magnet bends charged particles, allowing the tracker to measure transverse momentum ($p_T$)
Evidence for DM

The main objective of Planck is to measure the spatial temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation.

- The CMB is a blackbody radiation with $T=2.7$ K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was $\sim 400,000$ years old.

Its tiny ($\sim 10^{-5}$) temperature and polarization anisotropies encode a wealth of cosmological information.

TT refers to temperature angular power spectrum, to distinguish it from the temperature-polarization cross-power spectrum TE, as well as other possibilities such as EE, TB, EB, BB.
Corrections

Jet Energy Corrections:

The detector response to particles is not linear and therefore it is not straightforward to translate the measured jet energy to the true particle or parton energy. The jet corrections are a set of tools that allows the proper mapping of the measured jet energy deposition to the particle-level jet energy.

**L1 Pile Up:** remove energy coming from pile-up events

**L2L3 MC-truth:** The simulated jet response corrections are determined on a QCD dijet sample, by comparing the reconstructed pT to the particle-level one (i.e. particle-level jets do not include energy from neutrino contributions).

**L2L3Residuals:** The L2 and L3 residuals are meant to correct for remaining small differences (of the order of %) within jet response in data and MC.

Monte Carlo : L1 + L2L3 MC-truth

Data : L1 + L2L3 MC-truth + L2L3Residuals
### Backgrounds Cross-Sections

<table>
<thead>
<tr>
<th>Dataset Name</th>
<th>Cross-section (pb)</th>
<th>Cross-section Order in QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>/ZJetsToNuNu_HT-100To200.13TeV-madgraph</td>
<td>280.5</td>
<td>LO</td>
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<tr>
<td>/ZJetsToNuNu_HT-200To400.13TeV-madgraph</td>
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<tr>
<td>/ZJetsToNuNu_HT-400To600.13TeV-madgraph</td>
<td>10.71</td>
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<tr>
<td>/ZJetsToNuNu_HT-600ToInf.13TeV-madgraph</td>
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<td>LO</td>
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<tr>
<td>/WJetsToLNu.TuneCUETP8M1.13TeV-amcatnloFXFX-pythia8</td>
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<td>NNLO</td>
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<tr>
<td>/WJetsToLNu_HT-100To200.TuneCUETP8M1.13TeV-madgraph</td>
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<tr>
<td>/WJetsToLNu_HT-200To400.TuneCUETP8M1.13TeV-madgraph</td>
<td>359.6</td>
<td>LO</td>
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<tr>
<td>/WJetsToLNu_HT-400To600.13TeV-madgraph</td>
<td>48.85</td>
<td>LO</td>
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<tr>
<td>/WJetsToLNu_HT-600To800.13TeV-madgraph</td>
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<tr>
<td>/WJetsToLNu_HT-800To1200.13TeV-madgraph</td>
<td>5.501</td>
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<tr>
<td>/WJetsToLNu_HT-1200To2500.13TeV-madgraph</td>
<td>1.329</td>
<td>LO</td>
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<td>/WJetsToLNu_HT-2500ToInf.13TeV-madgraph</td>
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<td>/DYJetsToLL_M-50.13TeV-madgraph.LM-50_HT-100to200.TuneCUETP8M1.13TeV-madgraph</td>
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<td>/DYJetsToLL_M-50.13TeV-madgraph.LM-50_HT-400to600.TuneCUETP8M1.13TeV-madgraph</td>
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<td>LO</td>
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<td>LO</td>
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<td>LO</td>
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<td>/DYJetsToLL_M-50.13TeV-madgraph.LM-50_HT-600toInf.TuneCUETP8M1.13TeV-madgraph</td>
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<td>NNLO</td>
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<tr>
<td>/DYJetsToLL_M-50.13TeV-madgraph.LM-50_HT-400to600.TuneCUETP8M1.13TeV-madgraph</td>
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<td>NNLO</td>
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<td>/QCD_HT100to200.13TeV-madgraph.LM-50_HT-100to200.TuneCUETP8M1.13TeV-madgraph</td>
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<tr>
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<td>1.735 \times 10^6</td>
<td>LO</td>
</tr>
<tr>
<td>/QCD_HT300to500.13TeV-madgraph.LM-50_HT-300to500.TuneCUETP8M1.13TeV-madgraph</td>
<td>3.67 \times 10^5</td>
<td>LO</td>
</tr>
<tr>
<td>/QCD_HT500to700.13TeV-madgraph.LM-50_HT-500to700.TuneCUETP8M1.13TeV-madgraph</td>
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<td>/QCD_HT1500to2000.13TeV-madgraph.LM-50_HT-1500to2000.TuneCUETP8M1.13TeV-madgraph</td>
<td>121.5</td>
<td>LO</td>
</tr>
</tbody>
</table>

Table 3: Background Monte Carlo datasets produced in the Spring16 campaign.
Jet phi Width is not a good variable for this analysis which is confirmed by this plots and some other studies that we have done.

\[ \text{phiWidth} = \sqrt{\frac{\sum (\phi_i E_i)}{\sum E_i}} - \left( \frac{\sum (\phi_i E_i)}{\sum E_i} \right)^2 \]
Some more Jet substructure variables (N-1 Plots)

- Unfortunately, these jet variables do not show good data/mc agreement and so we have not used them in the analysis so far. In most cases we think things can be improved when we shift to data-driven backgrounds, add systematic uncertainties etc. However, it might also be interesting to study how MC samples from different generators will behave in the context of this analysis.
95\% CL limit on $\sigma/\sigma_y^b$ for CMS Internal.

$\sqrt{s} = 13$ TeV, 12.8 fb$^{-1}$

$\Lambda_{theor} = 5$ TeV
95\% CL limit on $\Lambda$ (TeV)

CMS $\sqrt{s} = 13$ TeV, 12.8 fb$^{-1}$

- Black dots: Observed
- Red line: Expected

$\Lambda_{\text{theor}} = 5$ TeV