A measurement of $Wb\bar{b}$ production and a search for monophoton signals of dark matter using the CMS detector at the CERN LHC

Thomas Mastrianni Perry
Thesis Endorsement Presentation
3 August 2016

Committee:
Wesley Smith (Advisor), Bjorn Wiik Professor, Physics
Sridhara Dasu, Professor, Physics
Matt Herndon, Professor, Physics
Yang Bai, Professor, Physics
David C. Schwartz, Professor, Chemistry
Overview

The Standard Model is a Local Quantum Field Theory

• Local Fields = Position dependent, obey Lorentz symmetry
• Quantum = Probabilities, number of particles not conserved
  • some particles don’t interact via all forces

Dark matter is out there

• Overwhelming evidence for General Relativity to be correct
• 5/6 of all mass is not visible - particle dark matter (DM)

Wbb and monophoton measurements test the Standard Model

Monophoton is a search for dark matter

F. Zwicky - 1933
Die Rotverschiebung von extragalaktischen Nebeln
The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

Wbb cross section measurement

Monophoton analysis

Conclusions and future prospects
Standard Model Particles

**Fundamental Fermions (spin $\frac{1}{2}$)**
- 3 generations of SU(2) doublets
  - Quarks \([u, d], [s, c], [b, t]\)
  - Leptons \([e, \nu_e], [\mu, \nu_\mu], [\tau, \nu_\tau]\)

**Fundamental Bosons**

**Spin 1:** Force Carriers
- Gluon: Strong Force
  - massless
  - color / anti-color
- Photon: Electroweak (EM)
  - massless
  - uncharged
- \(W^\pm, Z\): Electroweak (Weak)
  - 80.4 GeV, 91.2 GeV
  - electric charge

**Spin 0:** Higgs
- 125 GeV
- EWK Symmetry Breaking
- Mass to \(W^\pm, Z, \) quarks, leptons
Standard Model Couplings

All interactions in the SM are built from these vertices

- $f$ is any fermion
- $Q$ is electrically charged
- $q$ is any quark
- $g$ is any gluon
- $m$ is any massive particle
- $X$ is $Z$ or $\gamma$
- $X$ and $Y$ are EW bosons such that charge is conserved
- $u$ is an up-type quark and $d$ is a down-type quark
- $\ell$ is a lepton and $\nu$ is the corresponding neutrino
Renormalization

Feynman diagrams containing the minimum number of vertices with desired initial and final state particles are Leading Order (LO)

Renormalization accounts for corrections to LO from virtual particles in closed loops

Diagrams with one line more than LO are next-to-LO (NLO) Two more lines than LO are next-to-NLO (NNLO)
Primary and Secondary Vertices

Primary vertex (PV)
initial collision and decays within CMS resolution

Secondary vertex (SV)
vertex from a decay spatially resolved from PV

Primary Vertices

Secondary Vertex

2.5 mm at 30 GeV in lab frame
Neutrinos and $E_T$

Neutrinos interact only via weak force
Pass through CMS undetected
Signature is “missing" transverse momentum

$W \rightarrow \ell \nu$

$Z \rightarrow \nu \nu$
Hadronization and Jets

Quarks / Gluons at high energy can separate

At $\sim 10^{-15}$ m,
$E(\text{strong force}) > mc^2(q\bar{q})$

Quarks / Gluons radiate / split, dividing energy until strong force confinement stops process

result is "jets" - collimated collection of color singlets propagating in $\sim$same direction
Protons
Protons are hadrons - a composite of quarks and gluons
• u u d quarks + gluons and sea of q̅q̅ pairs
• at high energy, more gluons

Parton Distribution Functions (PDF) provide the fraction of momentum carried by each parton (quarks and gluons)
• four-flavor (4F) includes u d c s in proton PDF
• five-flavor (5F) includes u d c s b in proton PDF

Hard Interaction
The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

Wb̅b̅ cross section measurement

Monophoton analysis

Conclusions and future prospects
LHC General Information

At CERN: Located Near Geneva, Switzerland

Proton – Proton Collider
4.3 km radius
8 TeV CM Energy (2012)
100 m underground

Four Detectors
CMS, ATLAS
General Purpose
ALICE
Heavy Ions
LHC-B
B Quark Physics
LHC Acceleration

Proton Source
90 keV energy, pulsed every 1.2 s

Radio Frequency Quadrupole
750 keV, pulsed every 1.2 s

Linac 2
50 MeV, pulsed every 1.2s

PS Booster
1.4 GeV, 1.2s cycle time

Proton Synchrotron
25 GeV, 3.6 s cycle time

Super Proton Synchrotron
450 GeV, 200 MHz

Large Hadron Collider
8 (13) TeV, 89 μs orbit time
Collisions Every 50 (25) ns
Luminosity and Pileup

Number of events \( \frac{dN}{d\Omega} \) \( \propto \) Cross section \( \frac{d\sigma}{d\Omega} \)

Solid angle \( \propto \) Luminosity

Luminosity is effectively the number of particles per unit area per unit time

Many (~\(10^{11}\)) protons per bunch

Pileup is the number of collisions per bunch crossing
LHC Operating Conditions

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2015</th>
<th>2016+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (TeV)</td>
<td>4</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Bunches / Beam</td>
<td>1380</td>
<td>~2200</td>
<td>2000+</td>
</tr>
<tr>
<td>Protons / Bunch (10^{11})</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Peak Luminosity (10^{32} cm^{-2} s^{-1})</td>
<td>77</td>
<td>51</td>
<td>120+</td>
</tr>
<tr>
<td>Integrated Luminosity (/fb)</td>
<td>21.8</td>
<td>3.8</td>
<td>~30-40</td>
</tr>
<tr>
<td>Nr. Wb̅b Interactions</td>
<td>15000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nr. Monophoton Interactions</td>
<td>630</td>
<td>77</td>
<td>1000-1400</td>
</tr>
</tbody>
</table>
CMS Overview

- Tracker
  Silicon Pixels and Microstrips

- Electronic Calorimeter (ECAL)

- Hadronic Calorimeter (HCAL)

- Solenoid Magnet 3.8 Tesla

- Muon Barrel and Endcap
  Drift Tube (DT) (B)
  Resistive Plate Chamber (RPC) (B,E)
  Cathode Strip Chamber (CSC) (E)

- Iron Yoke

Proton Beam
  Mass: 12 500 T
  Radius: 7.5 m
  Length: 21.5 m
**CMS Geometry**

- **$\rho_T$, Transverse Momentum**: Momentum in radial direction.
- **$\phi$, Polar Angle**
- **$p_T$, Transverse Momentum**
- **$M_{T}$, Transverse Momentum**
- **$\eta$, Pseudorapidity**: Lorentz Invariant* angle down to beam line (* for massless particles)\n  \[ \eta=-\log[\tan(\theta/2)] \]

\[ (\Delta R)^2 = (\Delta \phi)^2 + (\Delta \eta)^2 \]

- $\eta = 0$ ($\theta = \pi/2$)
- $\eta = 0.88$ ($\theta = \pi/4$)
- $\eta = \infty$ ($\theta = 0$)
**CMS Tracker**

All Silicon

$|\eta| < 2.5$

**Outer Barrel (TOB)**

**Pixel**

**Endcap**

**Inner Barrel (TIB)**

Used for detecting

- High $p_T$ Muons
- Hadrons with high momentum resolution
- Isolated Electrons
- Secondary Vertices

$\delta p_T/p_T \approx (15 \times p_T[\text{TeV}] + 0.5)\%$

Radius: 1.2 m Length: 5.4 m

- Two Double-Sided Outer Barrel Layers
- Four Inner Barrel Layers
- Three Pixel Layers

Closest detector component to PV $\sim 4\text{cm}$
**CMS: Electromagnetic Calorimeter**

80,000 Lead-Tungstate Crystals attached to avalanche photodiodes (barrel) phototriodes (endcap)

**Crystals**
- Radiation Length = 0.89 cm
- Length: 26 RL = 23 cm
- Molière Radius = 22 mm
- Cross Section: 22 mm x 22 mm
- $\Delta \eta \times \Delta \phi = 0.0175 \times 0.0175$

$\sigma/E[GeV] \approx (2.83/\sqrt{E}) + (0.124/E) + 0.3 \%$

**Used for detecting**
- EM Interacting Particles
- Electrons, Photons
**CMS: Hadronic Calorimeter**

**Barrel (HB):** $|\eta| < 1.4$

**Endcap (HE):** $1.3 < |\eta| < 3.0$
- 50 mm brass plates
- 4 mm scintillator sheets
- Tiles: $\Delta\eta \times \Delta\phi = 0.87 \times 0.87$

**Forward (HF):** $3.0 < |\eta| < 5.0$
- Steel + Quartz Fibers

HB + HE ($|\eta| < 3$): $\sigma/E[GeV] \approx (115/\sqrt{E}) + 5.5\%$

HF ($3 < |\eta| < 5$): $\sigma/E[GeV] \approx (280/\sqrt{E}) + 11\%$

**Used for detecting**
- Neutral hadrons
- Jets
- Total particle energy, $E_T$
**CMS: Muon Spectrometer**

**Barrel**
- DT, RPC: $|\eta| < 1.3$

**Endcap**
- CSC: $0.9 < |\eta| < 2.4$
- RPC: $|\eta| < 1.6$

All Components are used in triggering

**Cathode Strip Chambers**
- Crossed Wires ($r$)
- Cathode Strips ($\phi$)

**Drift Tubes**
- $40 \text{ mm } \times 11 \text{ mm}$
- Ar/CO$_2$ Mixture

**Resistive Plate Chambers**
- Gasious Parallel Plate
- Plastic Anode + Cathode

**Momentum Resolution**

\[ \Delta p/p \text{ (GeV)} \]

B = 2 Tesla, External to Magnet
Data Acquisition

Bunch crossing rate 20/40 MHz
- more data produced than can be stored
Reduce rate, keeping “interesting” events

Stores data from detector electronics after Level 1 Trigger accepts event

Provides interconnections between readout and filter systems

Runs High Level Trigger (HLT) algorithms to select events for final offline processing

Four Stages:

Detector Readout - store event data after Level 1 Trigger accepts event
Event Building - data from subdetectors is merged into a single event
Selection - HLT algorithms select events to be saved and analyzed
Storage/Analysis - Selected events are forwarded for storage and analysis

Makes initial decision to further analyze event
Level-One Trigger

Custom hardware, reduce rate from 40 (20) MHz to 100 kHz

2012 Trigger

2015 Upgrade

Optical

Upgrade Calorimeter Trigger

Data Acquisition (DAQ)

Global Trigger

Global Muon Trigger

Pattern Comparator

Track Finder

Segment Finder

CSC Hits

DT Hits

RPC Hits

Regional Calorimeter Trigger

Global Calorimeter Trigger

Upgrade Calorimeter Trigger

\[ |\eta| < 5 \]

\[ |\eta| < 3 \]

\[ |\eta| < 2.1 \]

\[ 0.9 < |\eta| < 2.4 \]

\[ |\eta| < 2.1 \]

\[ |\eta| < 1.2 \]

\[ |\eta| < 1.2 \]
High Level Trigger

100 kHz Level One Output Rate to 1 kHz for Permanent Storage
Custom Software on Commercial Processor Farm
Algorithms Similar to Offline Reconstructions
Uses Full Event Data

**HLT Triggers used:**
- Single Isolated Muon
  \[ p_T > 24 \text{ GeV} \]
- Single Isolated Electron
  \[ p_T > 27 \text{ GeV} \]
- Single Isolated Photon
  \[ p_T > 165 \text{ GeV} \]
  \[ E_{ECAL}/E_{HCAL} > 90\% \]
The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

$\text{Wb\bar{b}}$ cross section measurement

Monophoton analysis

Conclusions and future prospects
Event Simulation

Ultimately data are compared to simulation
Simulation of collision events use Monte Carlo techniques
  • Calculate scattering amplitude (Matrix Element)
  • Decay, hadronization, radiation, higher order corrections
  • Other collision products (underlying event)

GEANT4: Simulation of energy deposits in CMS detector
  • detailed model of CMS (detector, inert material, electronics)
  • passage of particles through matter, background noise

CMSSW: CMS particle reconstruction / analysis software
  • Number of generated MC events scaled to match data luminosity
  • Pileup distribution reweighted in MC to match data
  • Real and simulated data are processed in the same way
Monte Carlo Generators

Matrix Element Generators
MADGRAPH / MADEVENT Version 5.1
Matrix element at fixed order (LO + fixed number of jets)
A Monte Carlo for FeMtobarn (MCFM) Version 7.0
Matrix element at NLO, parton level (hadronization needed)
Fully Exclusive W,Z Production (FEWZ) Version 3.1
Matrix element at NNLO

Secondary Effects (Hadronization, NLO effects, Underlying Event)
PYTHIA Version 6.4 (Fortran) / 8.2 (C++)
Radiation/Hadronization, Lund string model, underlying event
Positive Weight Hardest Emission Generator (POWHEG) Version 2.0
Replace leading jet from other generator with NLO prediction
aMC@NLO Version 2.2
like POWHEG, but designed to be interfaced with Madgraph in 2015
Particle Flow combines information from subdetectors to reconstruct particles with better resolution.

Three Basic Elements:
- Charged Particle Tracks
- Calorimeter Clusters
- Muon Tracks

Reconstruction Steps:
- Iterative Track Finding
  - ID Tracks in Tracker, Direction of Particle at PV
- Calorimeter Clustering
  - Energy/Direction of Hadrons, Separate Neutral/Charged Deposits
  - ID Electrons/Bremsstrahlung Photons
- Linking
  - Match Elements to form ‘blocks’ and avoid double counting

Reconstructed Particles:
- Photons, Charged/Neutral Hadrons, Muons, Electrons, $E_T = - \sum (p_T \text{ PF cands})$
- Serves as an input for higher level reconstruction algorithms
Electron/Photon Reconstruction

Electron: match superclusters to track seeds
Photon: superclusters unmatched to track seeds

Supercluster:
Group of clusters of ECAL energy deposits
Uses Strip in \( \phi \) to Account for Bremsstrahlung Radiation
Loose cut on HCAL / ECAL energy deposit ratio

Track Seed:
Iteratively ID hits in tracker
Expect helical path if no Bremsstrahlung radiation
Kinks indicate emission of Bremsstrahlung Photons
Search a straight line tangent to track for ECAL hit
Muon Reconstruction

Global-Muon Reconstruction
(outside-in: high $p_T$ muons)
For each standalone-muon track
find matching tracker track + reconstruct

Tracker-Muon Reconstruction
(inside-out: low $p_T$ muons)
For tracker track ($p_T > 0.5$ GeV, $p > 2.5$ GeV)
find standalone-muon track + reconstruct

Tracker Muon Track
Reconstructed from inner tracker

Standalone Muon Track
Using muon stations
Isolation

Muons, electrons from W decay and ISR photons leave collimated energy deposits in the detector

Require only minimal energy deposits nearby (isolated) reduces incorrect identification

Leptons: $I < 0.12 \ (0.10)$ for muon (electron) in $\Delta R < 0.4 \ (0.3)$

$$I = \frac{\sum p_T^{\text{charged}}}{p_T^\ell} + \max(0, \sum p_T^\gamma + \sum E_T^{\text{neutral}} - 0.5 \cdot p_T^{\text{PU}})$$

Photon: sums within $\Delta R < 0.3$

$\sum (p_T \text{ photons}) < 0.28 + 0.0053 \ p_T$
$\sum (p_T \text{ neutral hadrons}) < 1.06 + 0.014 \ p_T + 0.000019 \ p_T^2$
$\sum (p_T \text{ charged hadrons}) < 1.37$
Jets Clustering and SV Identification

Energetic colored particles hadronize to into "jets"

Anti-\(k_T\) Algorithm for Jet Clustering

\[
d_{ij} = \min\left( \frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2} \right) \frac{\Delta R_{ij}^2}{R^2}
\]

Highest \(p_T\) track, \(i\), called a jet

For Subsequent Tracks, \(j\):

1. If \(d_{ij} < d_{iB}\): combine with \(i\)
2. Else \(j\) is a jet

Soft particles cluster around hard ones

Hard shape is circular, clips from soft particles

Collinear and Infrared Safe

Combined Secondary Vertex (CSV) Algorithm

\(b\) hadrons have long life (travel mm)

CSV is a multivariate analysis / neural network

displaced tracks, secondary vertices, soft leptons
combine information into single variable to "b-tag" jets
The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

W(bb) cross section measurement

Monophoton analysis

Conclusions and future prospects
**Wb\bar{b} Phenomenology**

Gluon from initial state radiation (ISR)

\( q \)

\( g \)

\( \bar{b} \)

\( b \)

\( q' \)

\( \ell \)

quarks from proton PDF

\( W \)

\( \nu \)

\( m_{T}^2 = 2 \ p_{T\text{lep}} \ \mathbb{E}_{T} \ (1 - \cos \phi) \)

\( \phi = \text{angle btw lepton and } \mathbb{E}_{T} \)

**b\bar{b} signature is two hadron showers (jets), each from a SV**

Neutrinos leave \( \mathbb{E}_{T} \) in the detector

Leptons (electron or muon) leave isolated energy deposits
**Wb̅b Major Backgrounds**

- **tt** multi-lepton multi-jet
- **W+light jets**
- **Single top**

Misidentified as b jets

Missed during object reconstruction
Previous $Wb(\bar{b})$ measurements

**Fermilab (Tevatron) at 1.96 TeV**

$p\bar{p} \rightarrow Wbj \rightarrow \ell vbj$ (j is a jet, b is a b jet)

CDF Collaboration measured cross section twice as high as best NLO prediction at the time

DØ Collaboration measured cross section 20%-40% higher than various NLO predictions

**CERN (LHC) at 7 TeV**

Atlas Collaboration: $pp \rightarrow Wbj \rightarrow \ell vbj$

1 jet: 70% high, 2 jets: 30% high

CMS Collaboration: $pp \rightarrow Wb\bar{b} \rightarrow \ell vbb$

Agreement within 4% (I also worked on this)
Wb̅b in the Standard Model

Atlas, CDF, DØ Collaborations see tension between simulation and observation for W+b(b̅)

Important for Searches
H(bb̅) has highest branching ratio
E_T^{miss} + lepton + heavy quark
predicted in non-SM models

This is the only cross section measurement in this phase space and energy

125 GeV
**Wb̅b : Selections**

**Exactly two jets**
- $p_T > 25 \text{ GeV}, \ |\eta| < 2.4$
- $\Delta R(\text{jet, lepton}) > 0.5$
- both b-tagged with CSV

**Jet veto**
- reject events with 3rd jet
- $p_T > 25 \text{ GeV}, \ |\eta| < 4.7$

**Exactly one isolated lepton**
- muon or electron
- passed HLT path (slide 25)
- $p_T > 30 \text{ GeV}, \ |\eta| < 2.1$

**Lepton veto**
- reject events with 2nd lepton
- $p_T > 10 \text{ GeV}, \ |\eta| < 2.1$

Require two b jets not merged

Light / Charm background rejection

TTbar background rejection

W identification

Background rejection for TTbar and Drell-Yan (Z+qq)
**Wb\bar{b} : Pre-Fitting Procedure**

Use two ttbar control regions very similar to signal region
isolate b-tagging efficiency and jet energy scale (JES) uncertainties

**TTbar-multijet region:**
Drop veto on events with 3rd jet, require at least three jets
No jet veto = not sensitive to JES
rescale simulation by 14% (b-tagging efficiency)

**TTbar-multilepton region:**
Drop veto on events with 2nd lepton
require two leptons, opposite flavor
Sensitive to JES and b-tag efficiency
Rescale by \(~3.4\%\) (process-dependent)
**Wb̅b : TTbar Fits**

**TTbar Multijet Control Region Fit Result**

![Graphs showing data and fit results for Wb̅b in multijet control region](image)

**TTbar Multilepton Control Region Fit Result**

![Graphs showing data and fit results for Wb̅b in multilepton control region](image)
## Wb̅b : Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Effect on Measured Cross Section</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTbar cross section</td>
<td>3.8 %</td>
<td>Theoretical uncertainty on cross section of specific process (published measured uncertainty for TTbar)</td>
</tr>
<tr>
<td>Single top cross section</td>
<td>2.5 %</td>
<td></td>
</tr>
<tr>
<td>QCD rate</td>
<td>2-3 %</td>
<td></td>
</tr>
<tr>
<td>Other SM cross sections</td>
<td>&lt; 2 %</td>
<td></td>
</tr>
<tr>
<td>b-tag efficiency rescaling</td>
<td>9.2 %</td>
<td>Uncertainties from fitting procedures</td>
</tr>
<tr>
<td>Jet Energy Scale rescaling</td>
<td>3.8 %</td>
<td></td>
</tr>
<tr>
<td>Lepton Energy Scales</td>
<td>&lt; 2 %</td>
<td>Uncertainty on reconstruction of particles</td>
</tr>
<tr>
<td>Lepton ID / Isolation / Trigger efficiencies</td>
<td>&lt;2 %</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6 %</td>
<td>Measured centrally by CMS</td>
</tr>
<tr>
<td>Theoretical on Simulation</td>
<td>10 %</td>
<td>Theoretical uncertainty on simulation</td>
</tr>
</tbody>
</table>
After fitting, good agreement between data and simulation

Left: $m_T$ distributions used in fit

Right: separation between b jets and lepton $p_T$
**Wb̅b : Cross Section**

Yields in data and simulation before and after fitting in the signal region.

Signal strength from fit factors systematic effects from cross section.

<table>
<thead>
<tr>
<th></th>
<th>Muon Initial</th>
<th>Muon Fitted</th>
<th>Electron Initial</th>
<th>Electron Fitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>7432</td>
<td>7357</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wb̅b</td>
<td>1323</td>
<td>1712</td>
<td>1121</td>
<td>1456</td>
</tr>
<tr>
<td>Wc̅c</td>
<td>60</td>
<td>61</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>Wusdcg</td>
<td>182</td>
<td>179</td>
<td>220</td>
<td>217</td>
</tr>
<tr>
<td>tt̅</td>
<td>3049</td>
<td>3296</td>
<td>2640</td>
<td>2864</td>
</tr>
<tr>
<td>Single top</td>
<td>958</td>
<td>1008</td>
<td>820</td>
<td>865</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>261</td>
<td>265</td>
<td>220</td>
<td>224</td>
</tr>
<tr>
<td>Diboson</td>
<td>175</td>
<td>181</td>
<td>139</td>
<td>144</td>
</tr>
<tr>
<td>γ+jets</td>
<td>-</td>
<td>-</td>
<td>98</td>
<td>105</td>
</tr>
<tr>
<td>QCD</td>
<td>1109</td>
<td>803</td>
<td>1654</td>
<td>1373</td>
</tr>
<tr>
<td>Total MC</td>
<td>7116</td>
<td>7505</td>
<td>6948</td>
<td>7284</td>
</tr>
</tbody>
</table>

**Signal strength**

$$
\sigma(pp \rightarrow Wb̅b \rightarrow \ellνb̅b) = \frac{N^{\text{Data signal}}}{A \cdot \epsilon \cdot \mathcal{L}} = \frac{N^{\text{Data signal}}}{(N^{\text{MC generated}}/N^{\text{MC generated}}) \cdot \mathcal{L}} = \alpha \sigma_{\text{gen}}
$$
**Wb̅b : Cross Section Comparisons**

Measured cross section is within one standard deviation of predictions - systematically high

**MCFM (NLO)**

Parton level calculation (81% correction factor for parton→hadron)

**MCFM / 4F MADGRAPH samples**

Don’t include effects of multiple partons scattering - additive correction calculated at $0.06 \pm 0.06$ fb

Double Parton Interaction = DPI

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma(pp \rightarrow Wb̅b \rightarrow ℓνb̅b)$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>$0.64 \pm 0.03$ (stat) $\pm 0.10$ (syst) $\pm 0.06$ (theo) $\pm 0.02$ (lumi)</td>
</tr>
<tr>
<td>Muon</td>
<td>$0.62 \pm 0.04$ (stat) $\pm 0.11$ (syst) $\pm 0.06$ (theo) $\pm 0.02$ (lumi)</td>
</tr>
<tr>
<td>Electron</td>
<td>$0.70 \pm 0.05$ (stat) $\pm 0.15$ (syst) $\pm 0.07$ (theo) $\pm 0.02$ (lumi)</td>
</tr>
</tbody>
</table>
The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

$W\bar{b}b$ cross section measurement

Monophoton analysis

Conclusions and future prospects
SM Monophoton Phenomenology

An ISR photon recoils against a Z boson
Z decays to neutrinos
The photon and missing energy are back-to-back

\[ q \rightarrow \gamma \]

the monophoton

\[ q \rightarrow Z \rightarrow \nu \]

the entire Z boson goes to \( E_T \)
**DM Monophoton Phenomenology**

An ISR photon is emitted by $q\bar{q}$ pair

The photon recoils off a mediator $M$, that decays to dark matter, $\chi$

Mediator can have vector or axial-vector couplings

The photon directly couples with DM in an effective field theory (EFT)

This coupling takes a scale $\Lambda$
**Monophoton Major Backgrounds**

- Lepton misidentified as photon
- Missed during object reconstruction

Also important are noncollision backgrounds:
- Beam halo - particles (muons) collinear with beam
- Spikes - random fluctuations in ECAL
Particles (muons) collinear with beam are called beam halo. Can interact with detector and leave energy in ECAL. Monophoton has no tracks so halo can fake signal. ID halo by performing linear fit on ECAL hits: add all energy deposits along line. Identified as halo if $E > 4.9$ GeV. This technique can only work in the barrel.
Monophoton Measurements

Standard Model

Measure Cross Section

DM with Mediator

Limits on mediator mass

DM with EFT

Limit on coupling scale, $\Lambda$

Dark Matter with Mediator

Dark Matter with EFT

$\gamma$
$q$
$Z$
$\nu$
$q$
$\gamma$
$q$
$\delta$
$q$
$\delta$
$q$
$\gamma$
$q$
$\delta$
$q$
$\delta$
$q$
$\gamma$
$q$
$\delta$
$q$
$\delta$
Monophoton Selections

Photon passes HLT path
\[ p_T > 165 \text{ GeV}, \frac{E_{\text{ECAL}}}{E_{\text{HCAL}}} > 90\% \]

Photon ID, Isolation (calculated wrt. all vertices)
\[ p_T > 175 \text{ GeV}, |\eta| < 1.44 \]
beam halo rejection, spike cleaning

Lepton Veto (mu, ele)
\[ p_T^{\text{lep}} > 10 \text{ GeV} \]

Well-reconstructed (mono)photon at high energy

Beam halo is difficult to model in endcaps, so restrict to barrel

Monophoton has no extra leptons

\[ \text{PF } E_T > 170 \text{ GeV} \]
\[ \Delta\phi(\text{photon}, E_T) > 2 \]  
Photon and \( E_T \) should be equal and opposite

\[ \min \Delta\phi(\text{jet}, E_T) > 0.5 \]  
Avoid jet mismeasurement as source of \( E_T \)
SM Monophoton Processes

The main SM processes with apparent monophoton signatures are $Z(\nu\bar{\nu})\gamma$ (54%), $W(l\nu)\gamma$ (14%), $W(e\nu)$ (10%), QCD (4%).

$Z(\nu\bar{\nu})\gamma$ estimate using $E_T = E_T + \text{dilepton}$

QCD fake rate estimate

$$y = m x + b$$

- $m = -0.00011 \pm 0.00003$
- $b = 0.070 \pm 0.009$
# Monophoton Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Effect on Measured Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.3 %</td>
</tr>
<tr>
<td>Theoretical on Simulation</td>
<td>3.5 %</td>
</tr>
<tr>
<td>Electroweak corrections</td>
<td>7.2 %</td>
</tr>
<tr>
<td>JET, MET, Photon energy scale</td>
<td>3.9 %</td>
</tr>
<tr>
<td>Data/MC efficiency scale factors</td>
<td>5.2 %</td>
</tr>
</tbody>
</table>

**Uncertainty on Data driven estimates**

- Jet faking photon: 35%
- Electron faking photon: 8%

- Measured and published by CMS
- Theoretical uncertainty on choice of parameters used in simulation
- Zγ and Wγ use LO→NNLO scaling, theoretical uncertainty on factor
- Use Z boson mass to calibrate
- Charged hadron isolation, beam halo, and lepton veto have different efficiencies in data and MC
- Vary the parameters used in fake rate estimation, largest bound
- Compare Z→eē with Z→eγ yields
**Z(νν)γ Cross Section**

Final distributions with the monophoton signature

Good agreement is seen between data and MC

Measured cross section = 66.5 ± 13.6 (stat) ± 14.3 (syst) ± 2.2 (lumi) fb

NNLO Predicted cross section = 65.6 ± 3.3 fb

---

**Figure:**

- **Final distributions with the monophoton signature**
  - Good agreement is seen between data and MC
  - Measured cross section = 66.5 ± 13.6 (stat) ± 14.3 (syst) ± 2.2 (lumi) fb
  - NNLO Predicted cross section = 65.6 ± 3.3 fb
**Previous Dark Matter Limits**

Limits can be translated between cross sections and coupling scale $\mu = \text{reduced mass (proton / DM)}$

Spin Independent

$$\sigma_{SI} = \frac{9}{\pi} \left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin Dependent

$$\sigma_{SD} = \frac{0.33}{\pi} \left(\frac{\mu}{\Lambda^2}\right)^2$$

2012 Results
Monophoton DM Interpretation

New limits are set on parameters in DM models

Mediator model (vector or axial vector couplings)
limits set on mediator mass

Mediator Mass > 600 GeV for DM Mass < 10 GeV
(translates into cross section : $10^{-40}$, $10^{-41}$ cm$^2$ for vector / axial-vector)

EFT model, limits set on coupling scale, $\Lambda$

$\Lambda > 540$ GeV
Conclusions

Measurements were performed at the LHC using proton-proton collisions at 8 and 13 TeV

Wbb at 8 TeV (pp→Wb¯b→ℓνb¯b):
Three consecutive fits in closely related regions
Agreement with SM within one standard deviation
Only measurement of W boson with two identified b jets at 8 TeV

Monophoton at 13 TeV:
SM process pp→Zγ→ν¯νγ cross section agrees with prediction
Dark Matter searches set new limits on
  • Vector / Axial Vector mediator masses
  • EFT coupling strength
Outlook

Some 2016 data is already here and more comes in daily

Wbb
Higher energy - more gluons in PDF - even more TTbar background
Higher energy - more boosted - jets less separated

Monophoton
With 30-40 \( \text{fb} \) predicted, can put limits (or discover!) DM
with mediator mass up to \( \sim 1 \) TeV

The SM predicts no direct coupling \( ZZ\gamma \) - this can also be tested via
the monophoton signature \( (pp \rightarrow Z \rightarrow Z\gamma \rightarrow \nu\bar{\nu}\gamma) \)

The future is bright

Dark
Bonus Slides
**Wbb Control Regions**

Selections listed counter clockwise as difference w.r.t. signal region

**W+jj:**
Remove b-tag requirement on jets

**Single top:**
one central jet b-tagged, one forward jet no tag

**Drell-Yan+bb:**
Drop lepton veto, require same sign lepton

**Drell-Yan:**
Same as Drell-Yan+bb but no b-tag requirement
**Wbb QCD estimation**

All backgrounds in signal region are taken from simulation except QCD - use a data-driven method.

For $m_T$, invert lepton isolation, $I > 0.20$ (0.15) for mu (e)

For other variables, require $\not\!E_T < 30$ GeV

Subtract (Data - All MC) to get QCD shape

Fit for final normalization
## Monophoton Yields

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\gamma \rightarrow \nu\bar{\nu}\gamma$</td>
<td>$41.74 \pm 6.67$</td>
</tr>
<tr>
<td>$W\gamma \rightarrow \ell\nu\gamma$</td>
<td>$10.60 \pm 1.58$</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>$7.80 \pm 1.78$</td>
</tr>
<tr>
<td>Jet $\rightarrow \gamma$ misidentified</td>
<td>$1.75 \pm 0.61$</td>
</tr>
<tr>
<td>Beam halo</td>
<td>$5.90 \pm 4.70$</td>
</tr>
<tr>
<td>Spurious ECAL signals</td>
<td>$5.63 \pm 2.20$</td>
</tr>
<tr>
<td>Rare backgrounds</td>
<td>$3.03 \pm 0.69$</td>
</tr>
<tr>
<td><strong>Total Expectation</strong></td>
<td><strong>76.45 \pm 8.82</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>77</strong></td>
</tr>
</tbody>
</table>