SEARCH FOR HEAVY MAJORANA NEUTRINOS IN SAME-SIGN DILEPTON + JETS EVENTS IN PP COLLISIONS AT $\sqrt{s} = 8$ TeV

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For the CMS Collaboration

DPF MEETING
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OUTLINE

• Motivation
• Majorana Neutrino Search at LHC
• Selection Overview
• Backgrounds
• Systematics
• Results
• Summary
The Standard Model of particle physics has many successes.

However, there are a number of unanswered questions:
  • It predicts neutrinos are massless due to absence of right-handed fields and etc.

Neutrino experiments have shown that SM neutrinos have mass.

Several BSM theories try to answer those questions.

These models can be tested by searching new predicted particles.
Majorana Neutrino (MN)

- Number of theory that explains this, including Seesaw mechanism:
  - Majorana mass terms can be added to the SM Lagrangian.
  - $m_\nu \sim m_D^2/M_N$, $m_\nu$ is observed neutrino mass, $m_D$ is Dirac mass and $M_N$ is the Majorana term.
  - For the SM $m_\nu, M_N >> \text{TeV}$ (not interesting at the LHC)

- Some frameworks possible with smaller heavy neutrino such as: Inverse Seesaw Mechanism:
  - The simplest way to add N to SM. It produces a light neutrino and a corresponding very heavy neutrino for each flavor.

\[ m_{\nu}^{\text{light}} \sim \frac{m_e^2}{m_N} \sim 0.1 \text{ eV} \]
The LHC and CMS

- Fantastic LHC performance
- Vast amount of data in 2011 and 2012

- It allows us to probe new physics with low cross sections.
- The analysis presented here will be from 2012 data with $\sqrt{s}=8$ TeV, $L=19.7$ fb$^{-1}$. 
MN Search at LHC

- We search for resonant s-channel production of MN
- Majorana Nature of N can lead to LNV processes, resulting in same sign di-lepton events: $\mu^+\mu^-, e^\pm e^\pm, e^\pm\mu^\pm$
- Signature characterized by:
  - two same-sign isolated leptons
  - two jets
  - no significant missing energy (MET)
- Daughter particles can be very soft (for low $m_N$)
- T. Han, B. Zhang# and F. del Aguila et al.*: provided estimates for heavy neutrino production.
- The total cross section depends on the MN mass and the mixing angle

[Graph and table showing cross-sections vs. Majorana mass]

For $|V_{lN}|^2 = 1$

# arXiv:hep-ph/0604064 & * 0703261
• The direct limits were set on coupling squared previously by LEP, CMS*, ATLAS...
• No excess observed

CMS 7 TeV – 4.98 fb⁻¹ Limits

- √s = 8 TeV, L = 19.7 fb⁻¹ – our analysis is an extension

MN Selection Overview

- Lepton $p_T$ min 20, 15 GeV
- Veto on extra leptons (reduce diboson)
- Jets chosen as $m(jj) = m(W)$
- We used tight cuts on ID (isolation and impact parameter) to remove QCD which is our largest background

**Electron ID**
- $|dxy| < 0.1$ cm
- RelIso < 0.09 in Barrel and < 0.05 in Endcap

**Muon ID**
- $|dxy| < 0.05$ cm
- RelIso < 0.05
- Isolation cone 0.3

✓ ID is optimized using modified Punzi FoM

\[
\epsilon(s) = \frac{1}{1 + \sqrt{(B_{tot} + (0.28B_{fake})^2)}}
\]

0.4 for dielectron

Final States: 2 leptons + 2 jets + No MET
MN Selection Overview

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Final States: 2 leptons + 2 jets + No MET

Challenges:
- Small signal cross sections but large backgrounds from mis-identified leptons from multijet QCD events
- Understanding charge misidentification rate for electron: important from Z+jets background
**MN Selection Overview**

**Low Mass – M(N) < 90 GeV**
- Below 90 GeV the first W is real and the second W is virtual
- All particles produced soft and we put strong upper bounds
- MET < 30 GeV
- M(lljj) < 200 GeV
- M(jj) < 120 GeV
- Remove events with a b-jet

**High Mass M(N) >=90 GeV**
- Above 90 GeV the first W is virtual and the second W is real
- As m_N increases the particles produced are no longer soft
- MET < 35 GeV
- M(ll) < 15 GeV
- 50 < M(jj) < 110 GeV
- Remove events with b-jet.

*We optimize cuts on p_T and m(lljj) for each mass point using Punzi FoM*
The same-sign requirement reduces the possible backgrounds and they can be divided into three categories:

- **Data-driven estimate**

**Charge-flip** (dielectron): the charge of one of the electrons from Z decay is mis-measured. It’s negligible in dimuon channel.

**Misidentification**: Called “fakes” – it consists of events where one or both electrons do not come from a W or Z decay. Jets are misidentified.

**Prompt**: It consists in SM processes (such as WZ, ZZ, ttbarW) that can give a same-sign pair of electrons in the final state.

<table>
<thead>
<tr>
<th></th>
<th>Charge-Flip</th>
<th>Misidentification</th>
<th>Prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm e^\pm + jj$</td>
<td>30%</td>
<td>55%</td>
<td>15%</td>
</tr>
<tr>
<td>$e^\pm e^\pm + jj (</td>
<td>m(ee)-90</td>
<td>)&gt;10$</td>
<td>8%</td>
</tr>
</tbody>
</table>
The dominant systematical uncertainty in our analysis coming from signal model, efficiencies and background prediction.

**Signal Prediction**
- PDF (Alpgen MC)
- $Q^2$ Scale
- Trigger and Selection
- Jet Energy Scale and Resolution
- Unclustered Energy
- b-Tag efficiency and miss-tag
- Pile-up model

**Background Estimate**
- Fake Background
  - 40% for dielectron
  - 28% for dimuon
- Charge flip
  - 19% for dielectron
  - Negligible for dimuon
Low Mass Signal Region

<table>
<thead>
<tr>
<th>Events</th>
<th>Dimuon</th>
<th>Dielectron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>51.4 ± 1.9</td>
<td>32.47 ± 3.2</td>
</tr>
<tr>
<td>Observed</td>
<td>45</td>
<td>33</td>
</tr>
</tbody>
</table>

### Events

<table>
<thead>
<tr>
<th></th>
<th>Dimuon</th>
<th>Dielectron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>87.6 ± 2.5</td>
<td>55.26 ± 3.6</td>
</tr>
<tr>
<td>Observed</td>
<td>81</td>
<td>54</td>
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</table>

• No excess seen above background estimation
• We get limits using CLs method.
• By counting number of events passing final selection cuts.
• 95% exclusion limit was set
• 7 TeV 50-200 GeV, we extended 40-500 GeV
• First upper limits for $m_N > 200$ GeV
Limits on Neutrino Mixing

- By assuming the theoretical prediction for the branching fraction for $N \rightarrow W^\pm \mu^\mp$

\[ |V_{\mu N}|^2 < 0.00470 \text{ for } m_N = 90 \text{ GeV} \]
\[ |V_{\mu N}|^2 < 0.0123 \text{ for } m_N = 200 \text{ GeV} \]
\[ |V_{\mu N}|^2 < 0.583 \text{ for } m_N = 500 \text{ GeV} \]

- These results extend considerably the regions excluded by previous direct searches.

Expanded view of the region:
$40 \text{ GeV} < m_N < 250 \text{ GeV}$
We have performed a search for new physics signal in the same-sign dilepton channels due to an heavy MN.

We extended the previous limit up to 500 GeV at high mass and as low as 40 GeV.

No excess events observed above background estimation.

The limits are better than previous results across all mass scans – the best limits especially above 100 GeV.

We have set an 95% exclusion limit.

Analysis at 13 TeV is ongoing – including additional channels emu, and also t channel.
BACK UP SLIDES
Low Mass Signal Region

Dimuon

Not low mass region - general

Unpublished

CMS

19.7 fb⁻¹ (8 TeV)

Events/10 GeV

<table>
<thead>
<tr>
<th>jj invariant mass (GeV)</th>
<th>Events/10 GeV</th>
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<td>300</td>
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<tr>
<td>350</td>
<td>0</td>
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<tr>
<td>400</td>
<td>0</td>
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CMS

19.7 fb⁻¹ (8 TeV)

Events/10 GeV

<table>
<thead>
<tr>
<th>Trailing muon p_T (GeV)</th>
<th>Events/10 GeV</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
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<td>6</td>
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<td>80</td>
<td>8</td>
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<tr>
<td>100</td>
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<td>120</td>
<td>12</td>
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CMS Muon Reconstruction

- Muon are reconstructed combining information from the central tracker and the muon system.
- Achieving a momentum resolution of ~3% for muon $p_T < 300$ GeV.
- Charge mis-ID for this range is ~ $10^{-5}$
- The acceptance region is:
  
  $p_T > 3.3$ GeV for $|\eta| < 1.3$
  
  $p > 2.9$ GeV for $1.3 < |\eta| < 2.2$
  
  $p_T > 0.8$ GeV for $2.2 < |\eta| < 2.4$

Legend reads

$VV = WZ, ZZ, W^+W^+$

$VVV = WWW, WWZ, WZZ, ZZZ$

$tt+V = ttW, ttZ, ttWW$

Higgs = WH, ZH, ttH ($H \to WW$)
• Tracker records the paths taken by charged particles to locate them...
• To calculate pT of a particle: track its path through a magnetic field; the more curved the path, the less momentum the particle has...
• ECAL measure the high accuracy of the electron and photon energies
• Lead tungstate heavy, optically clear material – to stop high energy particles...
Two complementary algorithms are used: tracker driven and ECAL driven

- **Tracker Driven:** tracks the path of charged particles by finding their positions at key points (CTF).
- **ECAL Driven:** starts with reconstruction of “superclusters” of transverse energy $E_T > 4$ GeV, that are one or more associated clusters of energy deposits in ECAL constructed in terms of their characteristic width in $\eta$ coordinate and characteristic spread) in $\phi$ coordinate.
- **Filtering:** superclusters are matched to track seeds (pairs or triplets of hits) in the tracker layer.
- **Finally,** trajectories are reconstructed by using energy loss modeling and fitted with a GSF.

- Tracker: hits (GSF, CTF) → track, vertex
- ECAL: superclusters → energy, position
- Electron objects: `gsfElectron`, `particleFlowElectron`

**GSF:** Gaussian-Sum Filter
**CTF:** Combinatorial Track Finder
Electron Reconstruction at CMS

- 75,848 PbWO$_4$ scintillating crystals
- Barrel ($0 < |\eta| < 1.479$): 61,200 crystals
- Endcaps ($1.48 < |\eta| < 2.7$): 2 x 7,324 crystals

Pseudorapidity:

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