Distinguishing Dirac/Majorana Sterile Neutrinos at the LHC

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DESY theory workshop, September 28, 2016
Based on [Phys. Rev. D 94 (2016) 013005]
Outline

★ **Introduction of sterile neutrinos**
  - Simplified Model
  - Productions @ LHC
  - Current limits

★ **Distinguishing Dirac/Majorana**
  - Basic idea
  - Collider simulation & background
  - Results

★ **Summary**
Theory Model

Discovery of neutrino oscillations => neutrinos have mass
→ In SM, neutrinos are massless
→ A window to BSM physics

Type-I see-saw: Singlet (Sterile) Fermions

\[ -\mathcal{L} = h_{\ell\alpha} \bar{\ell}_\ell \Phi N_\alpha + \frac{1}{2} M_{N_{\alpha\beta}} \bar{N}_\alpha N_\beta + \text{H.c.} \]

\[ \mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \]

Interactions: [0901.3589]

Simplified model with assumption:
Only 1 generation of sterile neutrinos is light & within experimental reach;
\[ U_{N_T} = 0; \]
3 free parameters: \( m_N, U_{Ne}, U_{N\mu} \), Dirac/Majorana.
Interesting Mass Scales of $m_N$

- Original Seesaw
- Fits well with GUTs
- Elegantly explains $m_\nu$
- Leptogenesis

Hard to test experimentally!

- Models with small $m_N$
  - Inverse seesaw
  - Loop-induced neutrino models

Testable at the LHC!

- $\nu$MSM (Neutrino Minimal Standard Model)
  - Explains all known BSM evidences
  - Fine-tuned model but testable

- DM candidate (warm or cold)
  - X-ray bound (3.5 KeV line)

- Neutrino oscillation anomaly (LSND)
  - Reactor / gallium anomaly
  - Dark radiation

$M_{ISS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & 0 \\ 0 & M & \mu \end{pmatrix}$

$\mu \ll m_D, M$

$m_\nu \approx m_D^T \frac{1}{M} \mu \frac{1}{M^T} m_D$
Productions @ LHC

\[ q\bar{q} \rightarrow Z^{(*)} \rightarrow \nu N \]
\[ gg \rightarrow H^{(*)} \rightarrow \nu N \]

almost unobserved
(final states $l^+l^-$, $l^\pm$ suffer from huge background)

Suppressed!
(no resonance enhancement)

Mostly studied
(important for $m_N < 1$ TeV)

More important for $m_N > 1$ TeV
Main Search Channels:

\[ 2l + 2j \]

need well isolated energetic 2 jets;
need SS di-lepton to suppress BG;
\[ \rightarrow \] better for Majorana N with \( m_N > m_W \).

Majorana:

\[ pp \rightarrow W^\pm \rightarrow l^\pm N \rightarrow l^\pm l^\pm jj \quad (l = e, \mu) \]

Dirac:

\[ pp \rightarrow W^\pm \rightarrow l^\pm N \rightarrow l^\pm l^\pm jj \quad (l_{1,2} = e, \mu) \]

\[ 3l + \text{MET} \]

\[ \rightarrow \] better for Majorana or Dirac N with \( m_N < m_W \)

Majorana:

\[ W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu \]

Dirac:

\[ W^+ \rightarrow e^+ e^+ \mu^- \nu_e \]
Global Constraints

from [Deppisch, Dev and Pilaftsis, New J. Phys. 17 (2015) 085019]

\[ m_N: 0.1 \sim 500 \text{ GeV} \]

Figure 3. Limits on the mixing between the electron neutrino and a single heavy neutrino in the mass range 100 MeV - 500 GeV. For details, see text.
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  ✷ Productions @ LHC
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★ Distinguishing Dirac/Majorana
  ✷ Basic idea
  ✷ Collider simulation & background
  ✷ Results

★ Summary
Basic Idea

tri-lepton + MET with no OSSF lepton pairs

\[
\text{Br} \left( W^+ \rightarrow e^+ e^+ \mu^- \nu_e \right) \propto \frac{|U_{Ne} U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}
\]

Scale factors for different tri-lepton states

|                      | Dirac (LNC) | Majorana (LNC+LNV) |
|----------------------|-------------|---------------------|
| \(e^+ e^+ \mu^- \nu\) | \(s\)       | \(s (1 + r)\)       |
| \(\mu^+ \mu^+ e^- \nu\) | \(s\)       | \(s (1 + \frac{1}{r})\) |

normalization factor  \(s \equiv 2 \times 10^6 \times \frac{|U_{Ne} U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}\)

disparity factor  \(r \equiv \frac{|U_{Ne}|^2}{|U_{N\mu}|^2}\)

For benchmark point  \(|U_{Ne}|^2 = |U_{N\mu}|^2 = 10^{-6}\) \(\rightarrow r = s = 1\)

Basic idea: Distinguish Dirac/Majorana sterile neutrinos by counting and comparing events in different channels!
Collider Simulation

Simulation
MadGraph (jet matching up to 2 extra partons) + PYTHIA + Delphes

Signal:
tri-lepton + MET with no OSSF lepton pairs
e^+ e^+ \mu^- / \mu^+ \mu^- e^- / e^- e^- \mu^+ / \mu^- \mu^- e^+ + MET.

SM background:

→ Leptonic τ decay:
WZ -> (l \bar{\nu}) (\tau \tau) -> 3 l + MET

→ Fake leptons from jets containing heavy-flavor mesons:
γ*/Z+jets: γ*/Z (\tau \tau) + a 3^{rd} faked lepton
t tBar+jets: prompt decay of t tBar + a 3^{rd} fake lepton
Cuts

Apply various cuts to reduce BG
→ Basic cuts:
  | leptons, $p_T>10$ GeV & $|\eta|<2.5$;
  | jets, $p_T>20$ GeV & $|\eta|<5.0$.
→ $M_T(3\ell,\text{MET})<90$ GeV
→ MET < 40 GeV
→ b-jet veto & $H_T<50$ GeV
→ For $m_N=20$ GeV,
  $M(l_N,l'_N)<20$ GeV
### Cut Flow Tables

#### Signal

|       | 14 TeV, 3000 fb⁻¹ |
|-------|-------------------|
|       | \(e^+e^+\mu^-\) | \(\mu^+\mu^+e^-\) | \(e^-e^-\mu^+\) | \(\mu^-\mu^-e^+\) |
| Cuts  | LNC | LNV | LNC | LNV | LNC | LNV | LNC | LNV |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| Basic cuts | 27.7 | 30.7 | 30.7 | 33.3 | 23.7 | 26.6 | 26.3 | 29.8 |
| \(M^\ell_0(\text{leps, MET}) < 90\text{ GeV}\) | 26.4 | 29.0 | 29.2 | 31.7 | 22.5 | 25.1 | 25.0 | 28.1 |
| MET < 40 GeV | 26.1 | 28.7 | 28.9 | 31.4 | 22.3 | 25.1 | 24.8 | 28.1 |
| \(N(\text{b-jets}) = 0, H_t < 50\text{ GeV}\) | 23.7 | 26.0 | 26.2 | 28.4 | 20.1 | 22.8 | 22.4 | 25.5 |

#### SM background

\(l = e\) or \(\mu\)

|       | \(WZ\) | \(\gamma^* / Z + \text{jets}\) | \(t\bar{t}\) |
|-------|--------|-------------------------------|--------------|
| Cuts  | \(\ell^+\ell^+\ell^-\) | \(\ell^-\ell^-\ell^+\) | \(\ell^\pm\ell^\pm\ell^\mp\) | \(\ell^\pm\ell^\pm\ell^\mp\) |
|-------|--------|-------------------------------|--------------|
| Basic cuts | 779 | 550 | 1055 | 17147 |
| \(M_T(\text{leps, }E_T) < 90\text{ GeV}\) | 52 | 34 | 374 | 160 |
| \(E_T < 40\text{ GeV}\) | 46 | 28 | 356 | 113 |
| \(N(\text{b-jets}) = 0, H_T < 50\text{ GeV}\) | 39 | 23 | 323 | 15 |
| \(M(\ell^N, \ell') < 20\text{ GeV}\) | 7.4 | 4.4 | 62 | 2.7 |

**dominant!**
Sensitivity of Excluding Dirac

(assuming Majorana)

\[
|U_{Ne}|^2 = \frac{1}{2 \times 10^6} \times (1 + r) \times s
\]

\[
|U_{N\mu}|^2 = \frac{1}{2 \times 10^6} \times \left(1 + \frac{1}{r}\right) \times s
\]

$\rightarrow$ 3σ level exclusion

Provided $s > 5$, $r = |U_{Ne}|^2 / |U_{N\mu}|^2 < 0.7$ (or > 1/0.7=1.4),

$\rightarrow$ $|U_{Ne}| / |U_{N\mu}| < 0.84$ or > 1.20
Summary

★ Sterile neutrinos may exist over a wide range of masses

★ A simple method to discriminate Dirac / Majorana
  → @ LHC, $m_N < m_W$ & $r \neq 1$
  → trilepton channel
  → excluding the Dirac by counting and comparing the numbers of events in the $e e \mu$ and $\mu \mu e$ channels

★ Sensitivities @ 14 TeV LHC, 3000 fb$^{-1}$
  → $m_N = 20, 50$ GeV
  → $3\sigma$ exclusion on Dirac for $|U_{Ne}|^2 < 0.7 |U_{N\mu}|^2$ or $|U_{Ne}|^2 > 1.4 |U_{N\mu}|^2$
  → provided $|U_{Ne}|^2 > 2 \times 10^{-6}$

★ Further directions
  → $r \sim 1$, challenging, kinematical distributions of final state leptons to enhance discriminating power
Thank you for your attention!

Any Questions?
FIG. 6. Validation results for fake lepton simulation. Black dots indicate experimental results in Ref. [31]. Our simulated results for $\gamma^*/Z + \text{jets}$, $t\bar{t}$, and $WZ + \text{jets}$ are given by upper light gray bars, middle brown bars, and bottom pink bars, respectively. Eight bin categories are (1) 0-bjet, 1-OSSF, $M_{\ell^+,\ell^-} < 75$ GeV, (2) 0-bjet, 1-OSSF, $|M_{\ell^+,\ell^-} - M_Z| < 15$ GeV, (3) 0-bjet, 1-OSSF, $M_{\ell^+,\ell^-} > 105$ GeV, (4) 0-bjet, 0-OSSF, (5–8) are the same as the first four bins, but with at least one b-jet.

A pheno. FL simulation method

→ data-driven methods to estimate the fake lepton contributions

→ modeling parameters, pinned down by validating simulated results against actual experimental ones.

1. Mistag rate
   (probability of converting a jet to a lepton)

\[
e_{j\rightarrow\ell}(p_{Tj}) = e_{200} \left[ 1 - \left(1 - r_{10}\right) \frac{200 - p_{Tj}/\text{GeV}}{200 - 10} \right]
\]

2. Transfer function
   (how much $p_T$ is transferred into the lepton)

\[
p_{T\ell} \equiv (1 - \alpha)p_{Tj} \quad \tau_{j\rightarrow\ell}(\alpha) = \frac{1}{N} \exp \left[ -\frac{(\alpha - \mu)^2}{2\sigma^2} \right]
\]
A test statistic \( T = \chi^2_{\text{Dirac}} - \chi^2_{\text{Maj}} \)

\[ 
\chi^2_H = -2 \min_{s, r \subset H} \left\{ \ln \left( \prod_i \text{Poiss}[N_i^{\text{exp}}(s, r; H), N_i^{\text{obs}}] \right) \right\} 
\]

- Statistical fluctuation → spread of 2 distributions
- Level of overlap → CL of discriminating 2 hypotheses
- Median discrimination → \( T = 0 \), median possible value for Dirac

\( \text{CL} = 1 - \alpha \)

- \( \alpha \), area under the Maj. curve for \( T < 0 \).

→ To quantify how well the data sets are described within a given hypothesis.