Searches for Heavy Neutral Leptons at the LHC

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Why Heavy Neutral Lepton? (heavy neutrino)

- Neutrino Oscillation!
- Small neutrino mass
- Right-handed neutrino
- Origin of neutrino mass
- Heavy Neutral Leptons (LNV, if Majorana)
- Charged Lepton Flavor Violation
- Bayron asymmetry through Leptogenesis
Neutrino: Physics Beyond SM

- A natural way to generate LNV and neutrino mass
  - Introduce an effective operators to the SM

\[ \sim \frac{Y_L}{\Lambda_L} L L H^2 \]

- Seesaw Mechanism (type I, II, III)

- Physics behind the Seesaw? Left-Right Symmetry model (LRSM) offers the Seesaw scale and heavy neutral lepton (HNL)

\[ SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \]

\[ M_{W_R} \gg M_{W_L} \]
Search for HNL at the LHC

- Direct production of HNL ($N$)
  - Complementary program to the $0\nu\beta\beta$

1. Type-I seesaw
   - Right-handed $N_R$
   - Only mix with SM $\nu$

2. LRSM
   - Right-handed $N_R$
   - $N_R$ couple to RH bosons, $W_R, Z_R$

3. Type-III seesaw
   - at least two $SU(2)_L$ triplets ($\Sigma^0, \Sigma^{\pm/-}$) couple to SM gauge bosons
HNL Searches for 40 yrs

- $m_N < \sim 500$ MeV: $K \rightarrow \mu N$
- $m_N < \sim 2$ GeV: $N \rightarrow \mu \pi, \mu K$ (NuTeV, NA62)
- $m_N < \sim 5$ GeV: $D, B \rightarrow \mu \mu \pi$ (Belle, LHCb, SHiP)
- $m_N < \sim 90$ GeV: $Z \rightarrow \mu N$ (LEP), and LHC
- $m_N > \sim 90$ GeV: LHC (ALTAS, CMS)
- Results since Neutrino 2018
Multi-purpose detectors at LHC: ATLAS & CMS

Great LHC performance and impressive data taking
Type-I HNL Searches

- Resonant production via s-channel W or W*
  - $m_N$ and $\nu - N$ mixing angle, $|V_{lN}|^2$
  - Conserving or violating lepton number

- $N$ decays

  **Trilepton (3l + $\nu$)**
  - Low background
  - No $m_N$ peak

  **Dilepton (2l + 2q)**
  - Large background, but relatively small for (LNV) with same lepton charge
  - Measurable $m_N$ peak
### Search in Dilepton

- \( N \) with mass 20 GeV \( \sim \) TeV
  - 2 same-sign hi-pt leptons (LNV only)
  - 2 jets or 1 boosted jet (large con jet)
  - Flavor combinations

\[
|V_{eN}|^2, \quad |V_{\mu N}|^2, \quad \frac{|V_{eN}V_{\mu N}^*|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}
\]

- Separate searches for low mass (\( m_N < m_W \)) vs high mass (\( m_N > m_W \)) regions
No significant deviation from the SM
LHC provides the best direct limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$, and $|V_{eN}^* V_{\mu N}|$ for high mass region

Significant improvement to the previous searches

- CMS limits down to 20 GeV, and up to 1.2 TeV
- Lepton flavor mixing case by CMS
Searches in trilepton

- In dilepton+2 jets: difficulty to explore small $m_N$ region due to jet $p_T$ cut (hard to select jets below 20 GeV, but lepton is easier)
- In trilepton channel: smaller BR
- It is promising with high-statistics
- At small $m_N$, $N$ has a longer lifetime

$\tau \sim m_N^{-5} |V_\ell|^2$

- **ATLAS**
  - Focused on the region of high sensitivity (4.5 – 50 GeV)
  - Low mass with prompt muon + displaced vertex (4-300 mm)
  - Use same-sign dilepton with no b-jet

- **CMS**
  - A broad range: 1–1200 GeV
  - 33 categories by lepton $p_T$, 2l and 3l mass, missing $E_T$
Results from ATLAS

Tri-lepton channel for 4.5 – 50 GeV

$e^\pm e^\pm \mu^\mp$

$\mu^\pm \mu^\mp e^\mp$

$|V_{eN}|^2$

$|V_{\mu N}|^2$

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Contour limit: $c\tau = 1-30\text{mm}$
Results from CMS
Searches in the LRSM

Challenges:
- For $m_N \ll m_{WR}$, jets and lepton from N decays overlap
  - standard lepton isolation will kill signal
  - use boosted jet to resolve lepton and jet

ATLAS
- Separate OS and SS pairs from Majorana/Dirac
- Kinematic shape analysis $m(jjll)$, $m(jj)$

CMS
- No distinction for OS & SS
- For each $W_R$ mass hypothesis, a counting experiment in $m(jjll)$ window
Run 1 results from CMS

- **µµ channel**

- **ee channel**

- A local significance, 2.8σ effect
- Consistency with the LRSM?
Update result with 13 TeV

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- No excess in signal region

£ ¥ Mass (eejj)

£ ¥ Mass (µµjj)
The exclusion of $W_R$ up to 4.4 TeV
Update result with 13 TeV

Mass (eejj)  

Mass (µµjj)
Look for decay of new heavy fermions ($N^0$, $L^+$, $L^-$)

- ATLAS: OS or SS leptons + 2 jets (2018)
- CMS: 3 or 4 leptons with MET (2017)
- Both used MET + $H_T$ (scalar sum) as search variable
ATLAS Search for Type III

- Used MET + $H_T$ (scalar sum) as search variable

ATLAS-CONF-2018-020
Future SHiP

- SHiP experiment looks for NHL (N) from charmed or B mesons decays
- SHiP can reconstruct exclusive decays

![Diagram showing the processes of D_s^+ and B_{(c)}^+ decays leading to muon emissions through W^+ and neutrino muon emissions, followed by muon decays to W^+ and quark decays to pi^+ and u quark.]

![Graph showing the mass squared of HNL (U_{\mu}^2) as a function of HNL mass (GeV), with shaded regions indicating experimental bounds. The graph includes the SHiP result from JHEP 1904 (2019) 077.]
Summary

- Neutrino oscillations attracts many interesting searches at the LHC: the origin of neutrino mass
  - Searches for HNL provides tests for various Seesaw models and LRSM

- LHC has searched for heavy neutral leptons but with no excess seen in data
  - Upper limits are set on $|V_{\text{IN}}|^2$
  - Exclusion on $W_R$ mass up to 4.5 TeV

- Searches will be explored using the full 13 TeV data from many different channels
- SHiP will explore in low mass region near future
SS Dimuon + 2 jets event observed in the CMS detector

Muon 1 ($p_T = 196.6$ GeV)
($\eta, \varphi$) = (-1.03, 0.07)

Jet 1 ($E = 543.2$ GeV)
($\eta, \varphi$) = (-1.71, -2.12)

Jet 2 ($E = 57.8$ GeV)
($\eta, \varphi$) = (-1.37, -2.73)

Muon 2 ($p_T = 70.7$ GeV)
($\eta, \varphi$) = (-0.54, -1.28)

$m(lljj) = 525.7$ GeV

DoubleMuon, periodC, Mon Jul 4 14:42:16 2016 KST
(Run, Lumi, Event) = (276283, 692, 1252562683)