1. Motivation

The Mass of Neutrino ($\nu$)
- In the Standard Model (SM), neutrinos are massless
- Neutrinos have mass! (BUT, $\Sigma m < 0.2$ eV, WHY SO SMALL?)
- Clear evidence of physics beyond the SM (BSM)

Seesaw Mechanism (Phys. Rev. Lett. 44 912)
- Introduce a right-handed neutrino (N) which mixes with SM $\nu$'s
- Neutrino mass term:

$$\left( \begin{array}{c} \nu_e \\ N \end{array} \right) \left( \begin{array}{c} 0 \\ M_N \end{array} \right) \left( \begin{array}{c} \nu_e \\ N \end{array} \right)$$

- Diagonalization gives $M_{1,2} = \frac{M_N^2 + 4M^2_N}{2}$

For $M_{1,2} \ll M_N$:
- $M_1 \approx M_N$: Heavy $N$ (GeV)
- $M_2 \approx - \frac{M_N^2}{M_N}$: small $\nu$ mass!

Search for Majorana Neutrinos at the LHC
- $m_N < 0.1$ eV predicts $m_N$ 100-1000 GeV
- Two main production mechanisms are s- and t-channel:

2. Event Selections

High-Level Trigger
- Unprescaled dilepton (e or $\mu$) triggers

Offline Selection
- Preselection
- Two same-sign (SS) leptons ($l$)
- At least one jet (j, AK4) or wide jet (J, AK8)
- Two mass categories with two signal regions
  - Low-mass ($m_N < m_W$)
    - No b-tagged jet, $m(tW) < 300$ GeV, $p_T^{miss} < 80$ GeV
    - SR1: $N(j) \geq 2, W_{jet} =$ dijet with $m(j(j))$ closest to $m_N$,
      $W_{jet} =$ the jet
    - SR2: $N(j) = 1, W_{jet} =$ the jet
  - High-mass ($m_N > m_W$)
    - No b-tagged jet, $m(W_{jet}) < 150$ GeV, $p_T^{miss} S_T < 15$ GeV,
      where $S_T$ is scalar $p_T$ sum of lepton, jet and $p_T^{miss}$
    - SR1: $N(j) = 0$ and $N(j) \geq 2, W_{jet} =$ dijet with $m(j(j))$ closest to $m_N$,
      $W_{jet} =$ the jet
    - SR2: $N(j) \geq 1, W_{jet} =$ the jet
- Additional optimized selections for each $m_N$ hypothesis

3. Backgrounds

Prompt Same-sign Lepton Backgrounds
- Multiboson, t\(t\)boson, W+W-, double-parton scattering
- Systematics on the cross sections and detector effects $\sim 13-45$
- Use Monte-Carlo simulation (WZ, ZZ and Z$\nu$ are normalized in data)

Misidentified-lepton Backgrounds
- Fake electron : $n_e - W_l$ near track, photon conversion
- Fake muon : $mK$ decay into muons, punch through to muon system
- Measure T/L, where T is lepton passing tight selection, and L is lepton passing loose selection
- Apply T/L weights to data, which has "loose but NOT tight" leptons
  - Data-driven estimation
- Systematic $\sim 30\%$ from simulation closure test

Mismeasured-sign Backgrounds
- Opposite-sign (OS) backgrounds mismasured as SS events
  - Negligible small probability for muon
  - Electron chargeflip (CF) rate measured from simulation
  - Obtained scale factor in $Z$ + ee data events
  - Multiplied to OS data events
  - Data-driven estimation
- Systematic $\sim 29-88$
- Yield of this background is small compared to others

4. Search Results

5. Result Interpretations

5.9% CL Upper Limits on the mixing matrix element, $|V_{eN}|^2$

6. Conclusion

- Heavy Majorana neutrino search in SS dilepton final states at 13 TeV has been performed
- $m_N$ between 20 and 1600 GeV was searched, but no significant deviation from SM prediction observed
- Upper limits of the mixing matrix elements are set for electron, muon, and electron-muon.
- Most stringent direct limits for N masses above 400 GeV
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