Tests of Neutrino Mass Models at CMS

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On behalf of CMS collaboration

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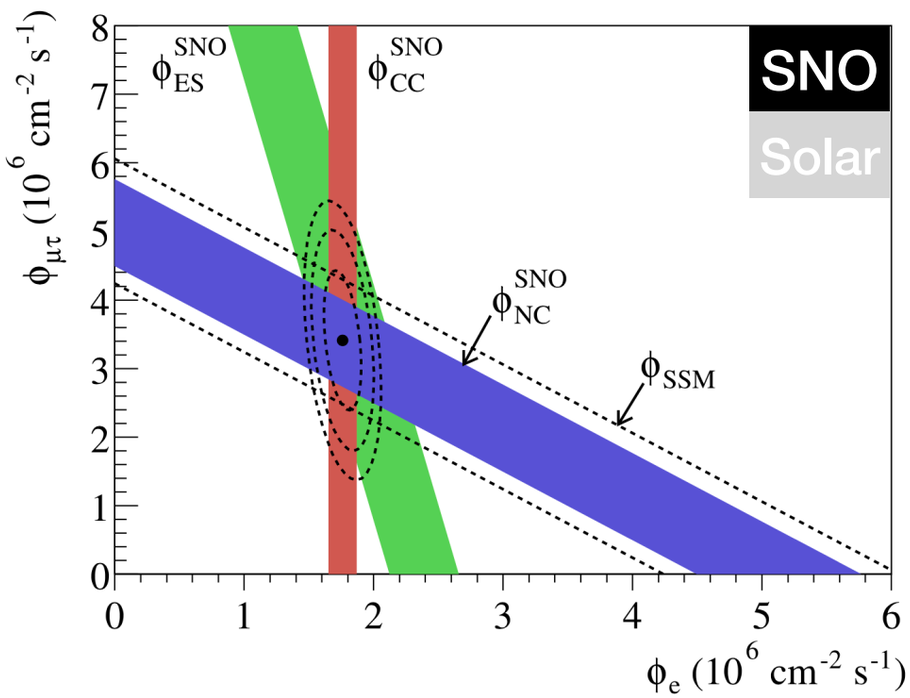
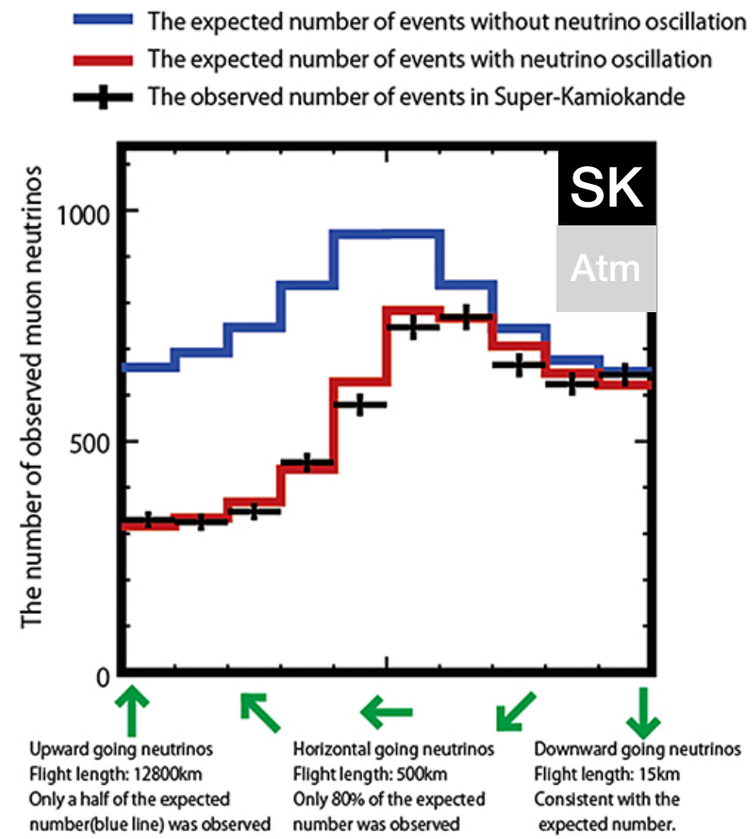
Introduction

- Discovery of neutrino oscillations





  - At least two neutrinos are **massive**
  - Direct measurement of m_{ν_e} at KATRIN experiment : < 1.1 eV

- What is the mechanism of neutrino mass generation?
  - Yukawa? Then, where are **right-handed** fields?
  - Why neutrinos have such **small masses**?

- Seesaw mechanism - Majorana and Yukawa mass terms

$$\begin{pmatrix} \overline{\nu_L} & \overline{N_R^{\,C}} \end{pmatrix} \boxed{\begin{pmatrix} 0 & M_D \\ M_D^{\,T} & M_M \end{pmatrix}} \begin{pmatrix} \nu_L^{\,C} \\ N_R \end{pmatrix}$$

Diagonalize mass matrix
$M_D << M_M$

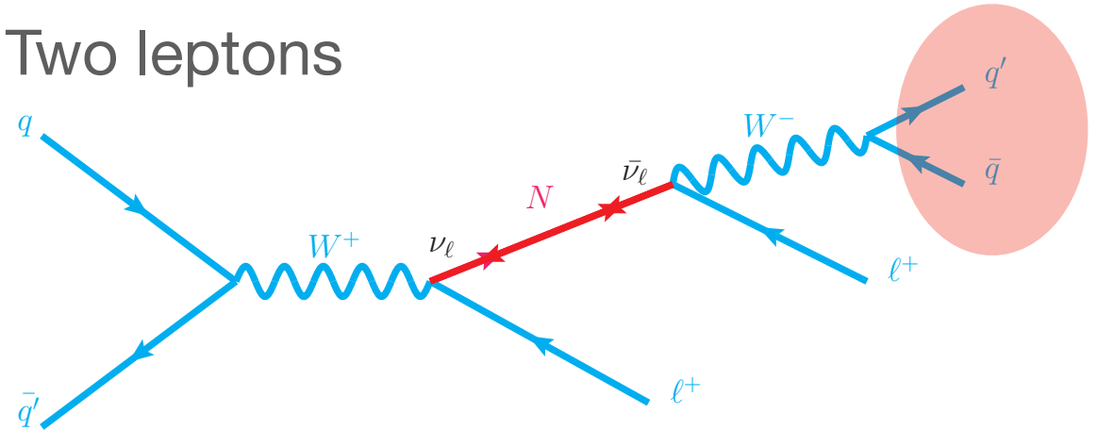
$$\begin{cases} M_1 = M_M & \text{Heavy Majorana neutrino} \\ M_2 = -\dfrac{M_D^{\,2}}{M_M} & \text{Small neutrino masses} \end{cases}$$

  - **Origin** and **smallness** of neutrino masses are explained

- The left-right symmetry model
  - Maximum parity violation of the Standard Model (SM) - Why?
  - Spontaneous symmetry breaking of the left-right symmetric group
  - $SU(2)_L$ X $SU(2)_R$ X $U(1)_{B-L}$
    - Extra gauge bosons (Z', $W_R^{\pm}$) and right-handed neutrinos (ν_R)
    - B-L : baryon number - lepton number
      - Matter/anti-matter asymmetry of the universe
  - Natural seesaw mechanism via VEVs of scalar fields

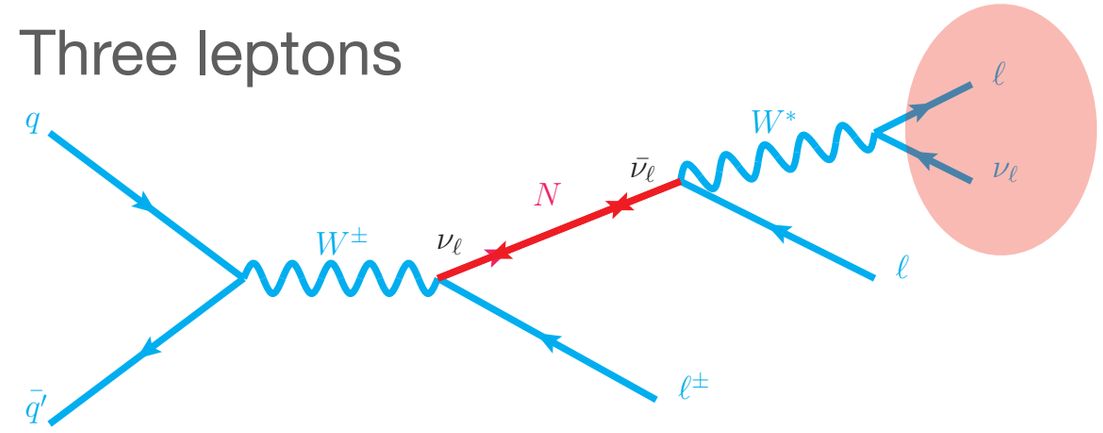
- Signal processes at proton-proton collisions
  - Type-I seesaw model (TISM)

Two leptons



mTISM : *JHEP01(2019)122*
Composite model : *Phys.Lett.B775(2017)315*

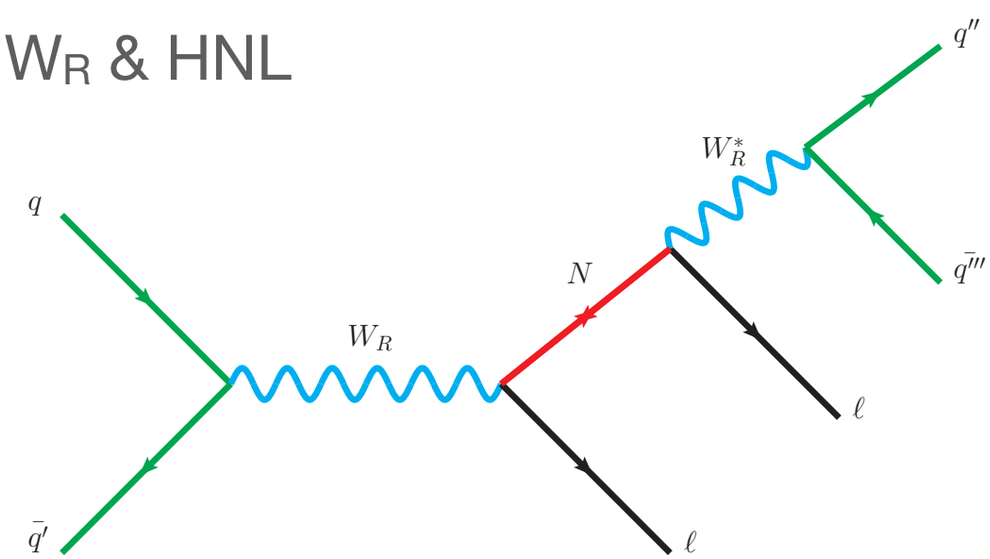
Three leptons



Prompt : *Phys.Rev.Lett.120,221801(2018)*
Long-lived : *CMS-EXO-20-009* NEW!!

  - Left-right symmetric model (LRSM)

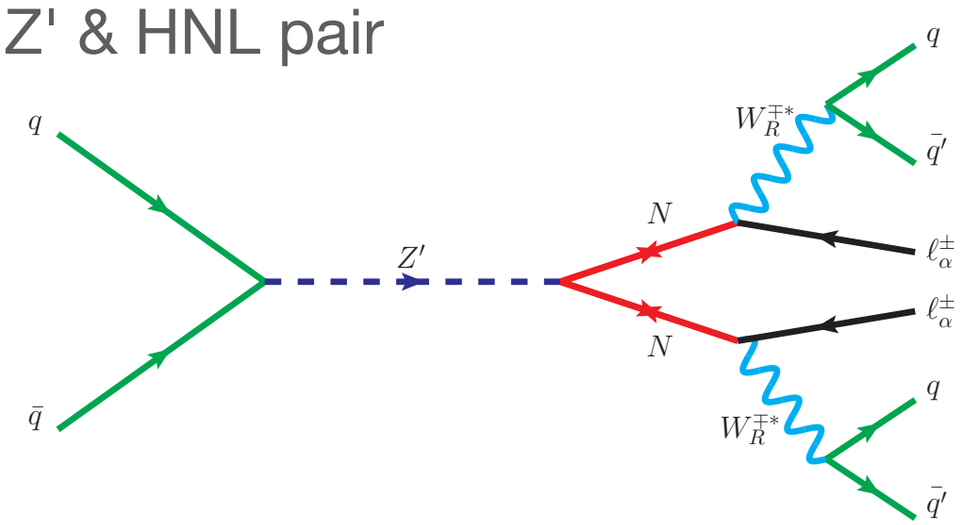
W_R & HNL



ττ : *JHEP07(2017)121*
JHEP03(2017)077

NEW!! ee, μμ : *CMS-EXO-20-002*

Z' & HNL pair

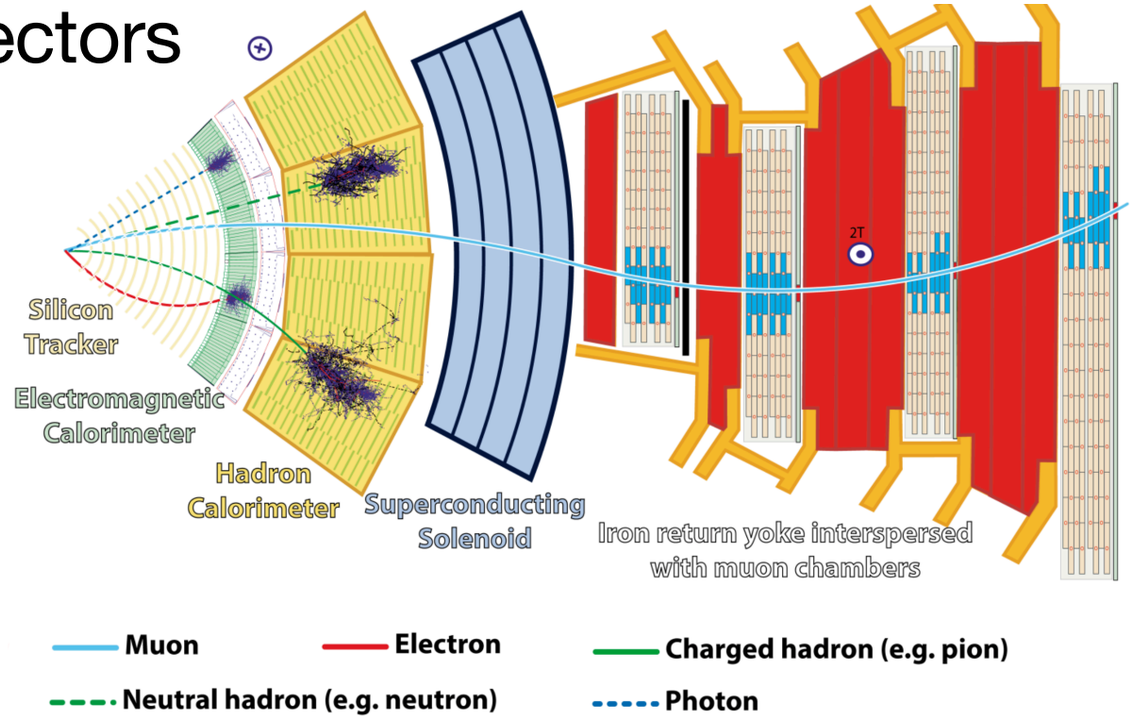


Soon!! ee, μμ : *CMS-EXO-20-006*

The Compact Muon Solenoid

- Multi-purpose detector
  - Silicon tracker (pixel & strip)
  - $PbWO_4$ ECAL
  - Brass - Scintillator tile HCAL
  - Superconducting magnet - 3.8 T
  - Gaseous muon system

- Reconstruct particles using all sub-detectors
  - The particle-flow algorithm
  - Energy/momentum resolutions
    - e/γ : 1 (0.6) % @ 20 (100) GeV
    - muon : 1 (2) % @ 20 (100) GeV
    - Jets : 10 (5) % @ 100 (1000) GeV

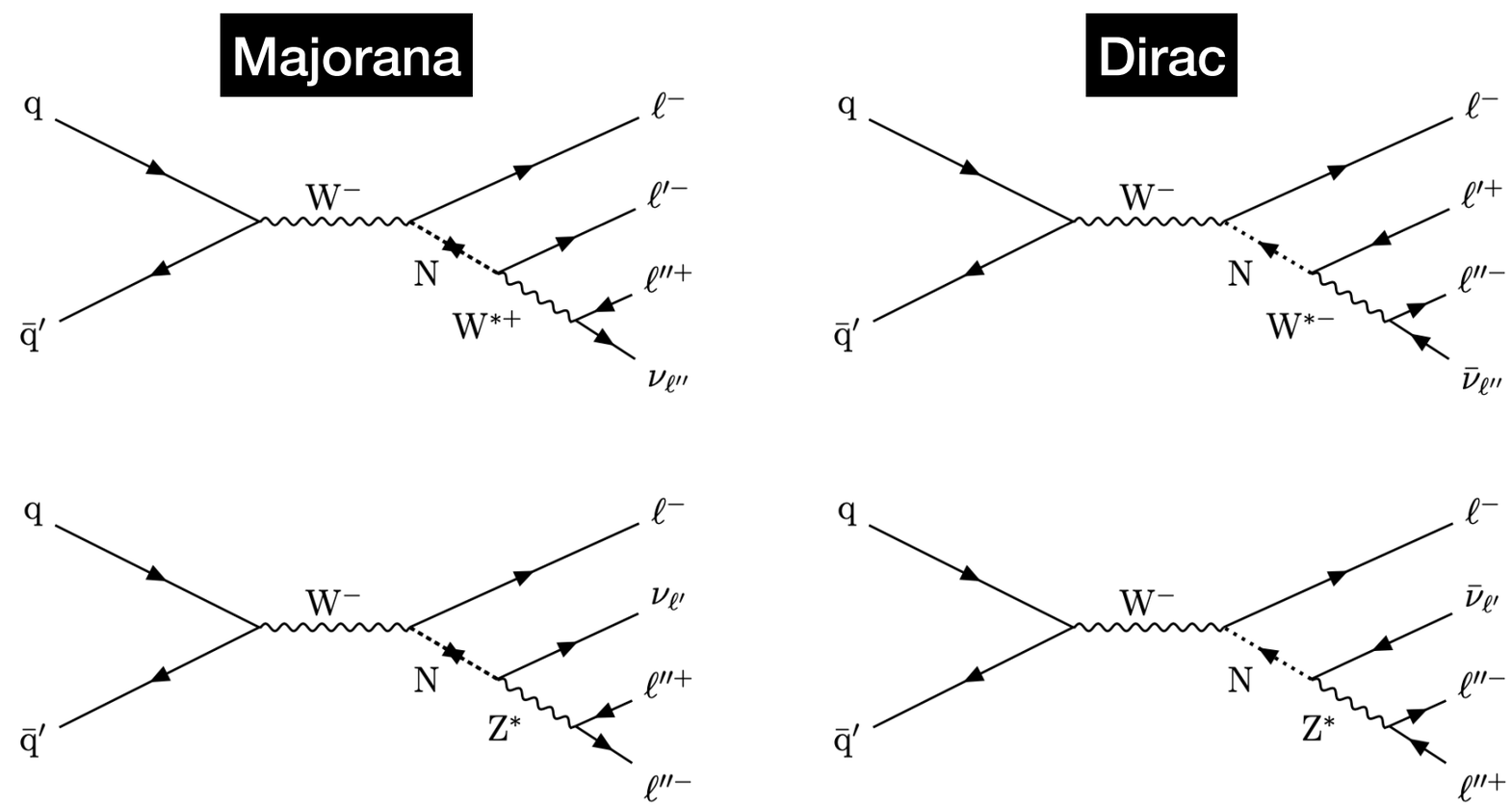


Type-I seesaw Model (TISM)
3-leptons with long-lived heavy neutrino

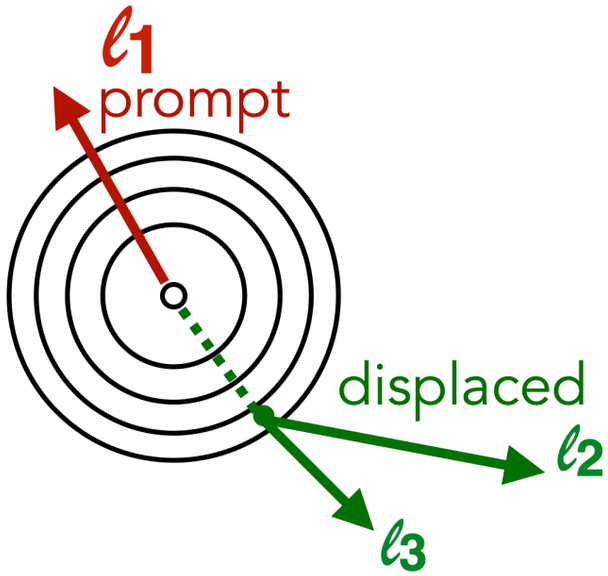
TISM 3-leptons : Long-lived

- The life-time of heavy neutral lepton (HNL)
  - $\tau_N \propto 1/ m_N^5 V_{LN}^2$
    where V_{LN} is mixing between HNL and ν_L (L = e, μ, and τ)
  - Significant where $m_N < 20$ GeV : several cm ~ few m

- Majorana HNL
  - $N \rightarrow W^* \ell$
    - No opposite-sign same flavor (OSSF) dilepton
    - Background reduction



- Only one among V_{eN}, $V_{\mu N}$, and $V_{\tau N}$ is nonzero
- Event selection
  - Using electrons and muons
  - One prompt lepton (ℓ_1) + two displaced leptons (ℓ_2, ℓ_3)
  - 1 GeV < m_N < 20 GeV
    - Small opening angle between ℓ_2 and ℓ_3
    - Large angular separations between ℓ_1 and ℓ_2, ℓ_3
  - OSSF diletpon mass veto : ω, ϕ, J/ψ(1S, 2S), Υ(1S, 2S, 3S), and Z
  - Secondary vertex of ℓ_2, ℓ_3
    - Δ_{2D} : transverse position of ℓ_2, ℓ_3 vertex
    - $\Delta_{2D}/\sigma(\Delta_{2D}) > 20$
  - No bottom quark tagged jet : B meson semi-leptonic decay background
- For $V_{\mu N}$, μμμ, $\mu^\pm\mu^\mp e^\pm$ (Dirac), and $\mu^\pm\mu^\pm e^\mp$ (Majorana)
- For V_{eN}, eee, $e^\pm e^\mp \mu^\pm$ (Dirac), and $e^\pm e^\pm \mu^\mp$ (Majorana)

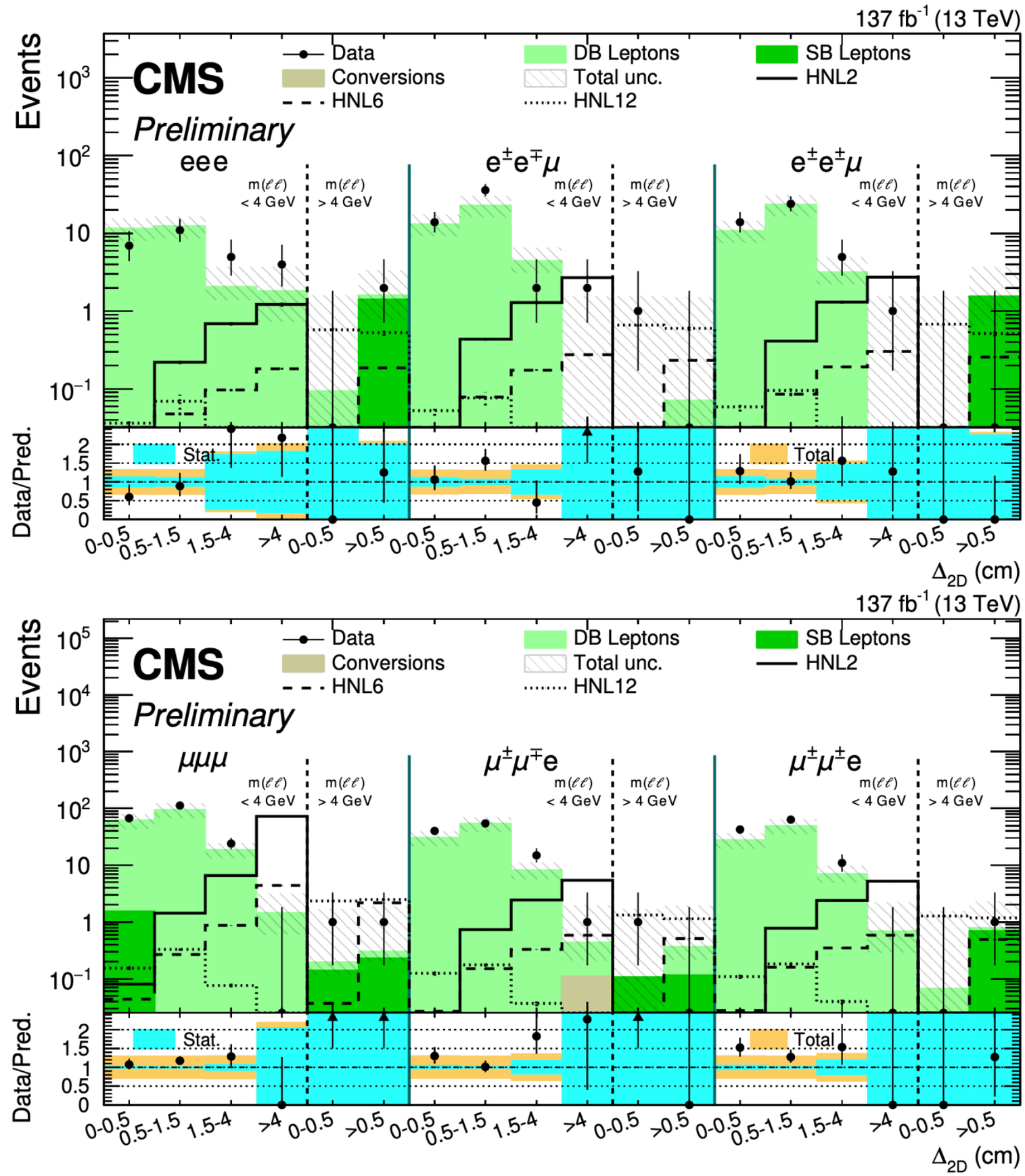


- Further categories

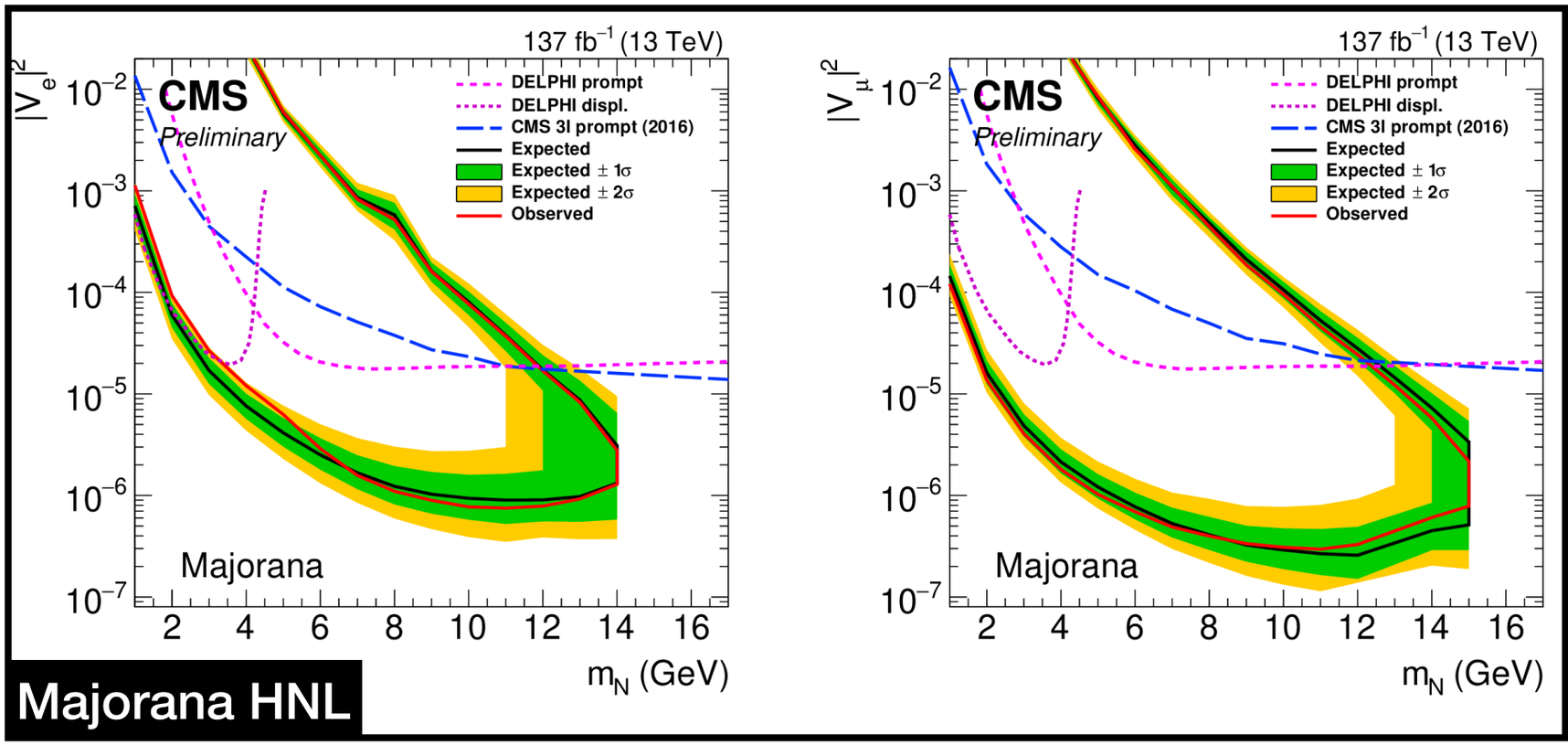
$m(\ell_2\ell_3)$ (GeV)	Δ_{2D} (cm)
<4	<0.5
	0.5–1.5
	1.5–4
	>4
>4	<0.5
	>0.5

- No excess beyond the expected background

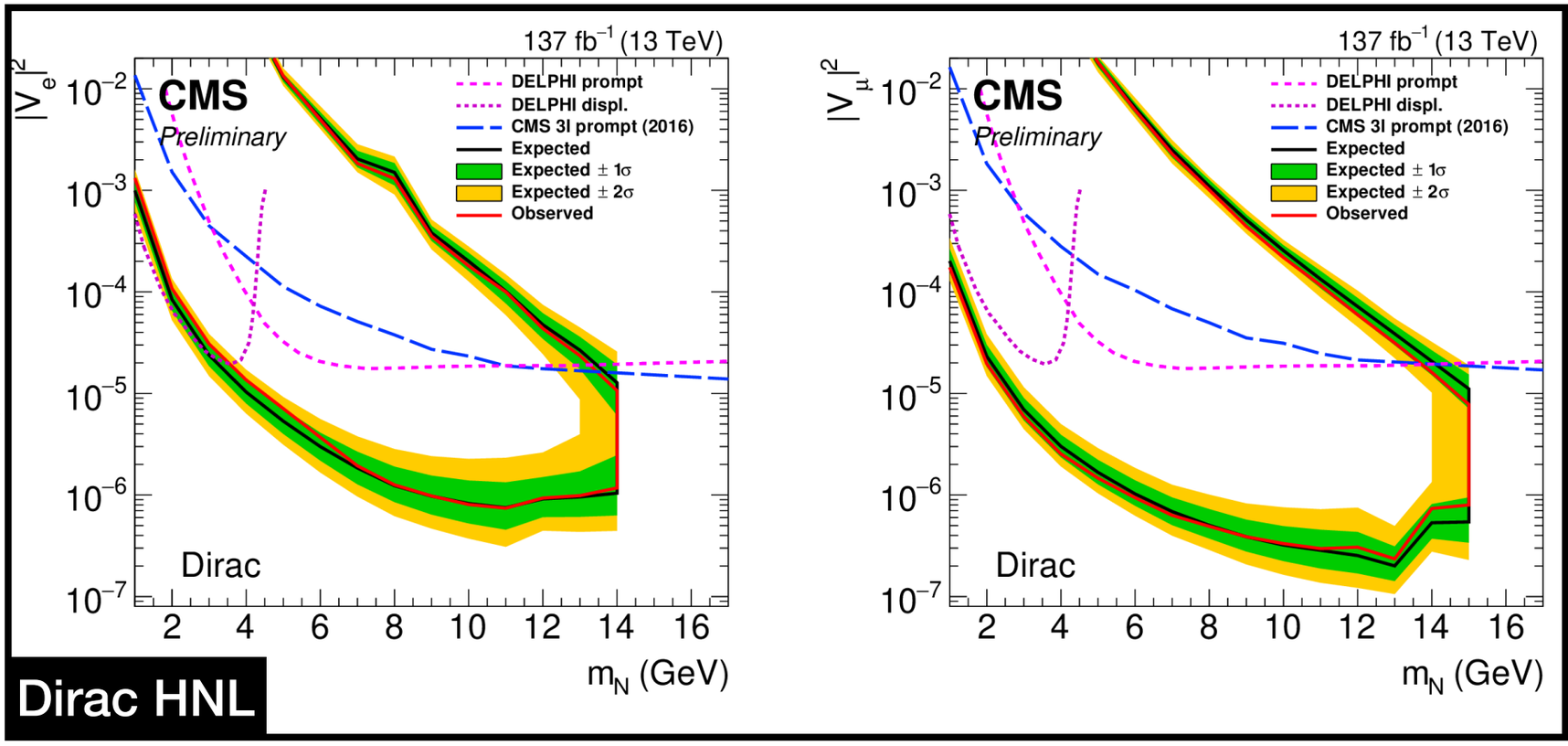
- Binned likelihood fit is performed to exclude $|V_{LN}|^2$ as functions of HNL masses



- Limits on V_{LN} vs m_N planes
  - Regions inside curves are excluded
  - Short-lived at top-right corner
    - Not sensitive



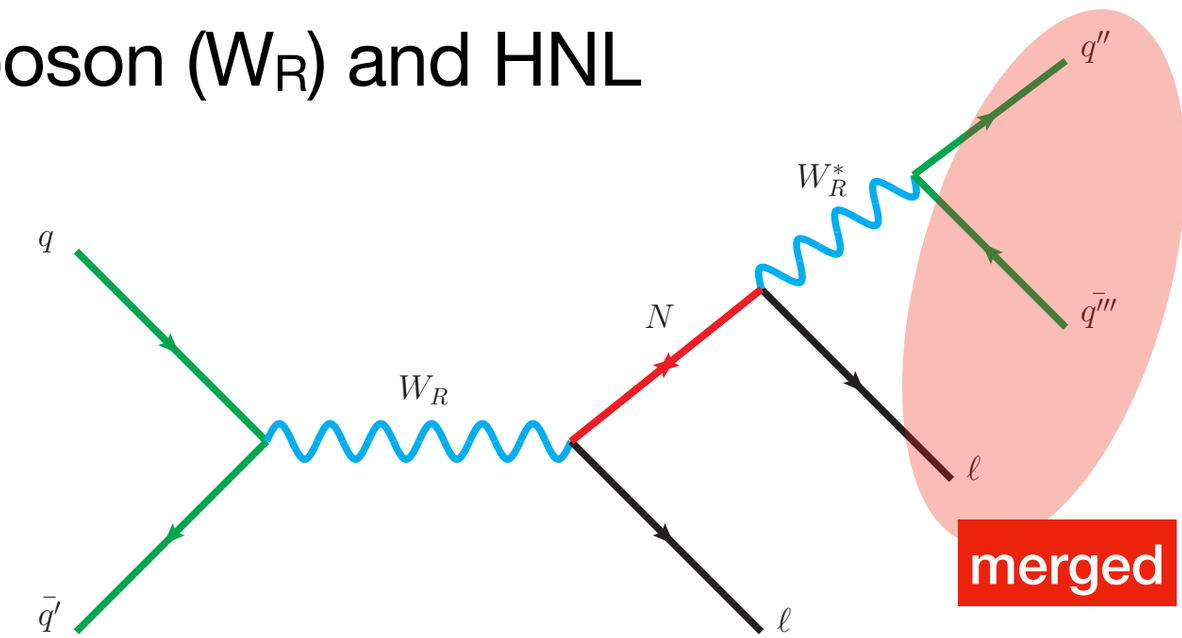
- Clear improvement w.r.t. DELPHI results in the displaced regime
- World best sensitivity where m_N is 1~14 GeV



Left-right Symmetric Model
W_R + heavy Majorana neutrino

LRSM : W_R + HNL

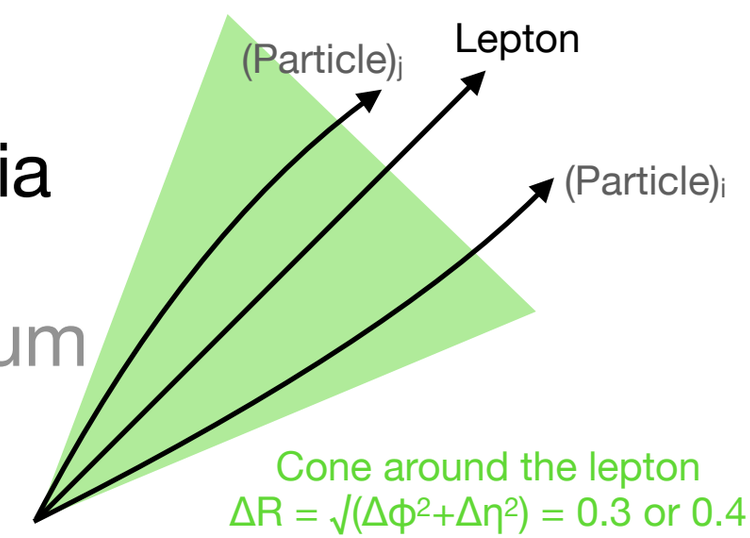
- Simultaneous search for extra gauge boson (W_R) and HNL
  - Challenging kinematic signature
    - Boosted HNL
    - $mW_R >> mN$
    - A lepton and two jets are merged



- Multiple object definitions
  - Loose and tight leptons : different isolation criteria

    $\Sigma_i\, p_T(\text{Particle})_i \,/\, p_T(\text{Lepton}) < \text{Cut}$

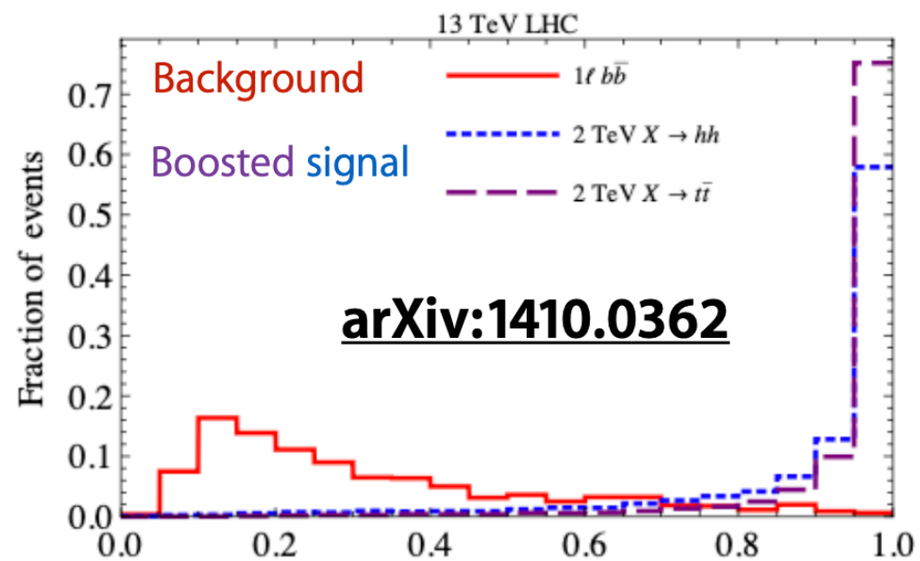
    , where p_T is transverse momentum



  - Jets
    - Merged debris of parton shower and hadronization : anti-k_T algorithm
    - AK4 and AK8 jets : different merging cone sizes (ΔR = 0.4 and 0.8)

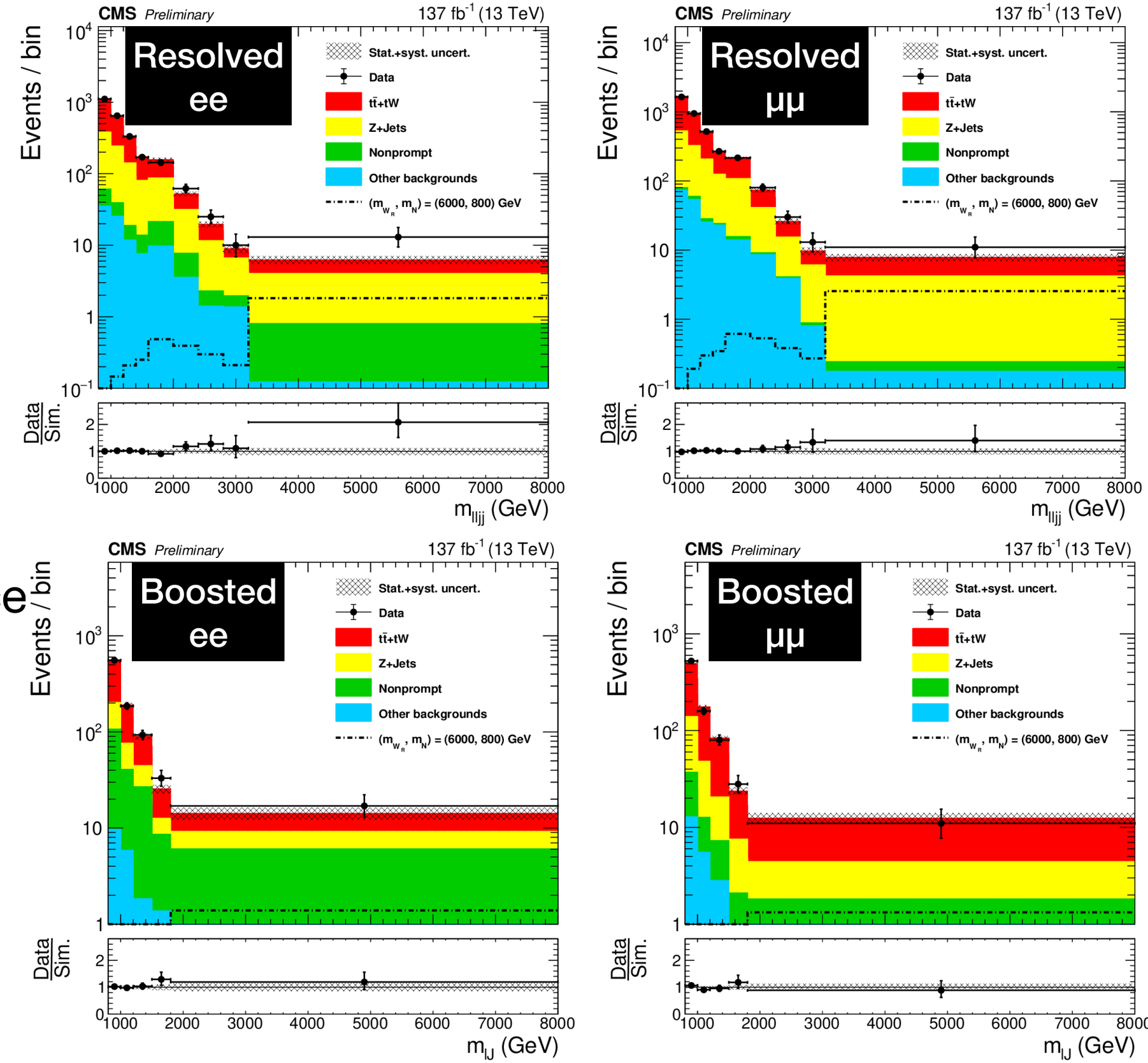
- The Lepton Subjet Fraction (LSF)
  - For boosted HNL
  - Recluster the jet into 3-subjets with exclusive kt algorithm : Rewinding the parton shower back to the hardest splitting
  - Signal lepton is from hard process → left alone until the last steps
    - Good discriminating power between background and signal

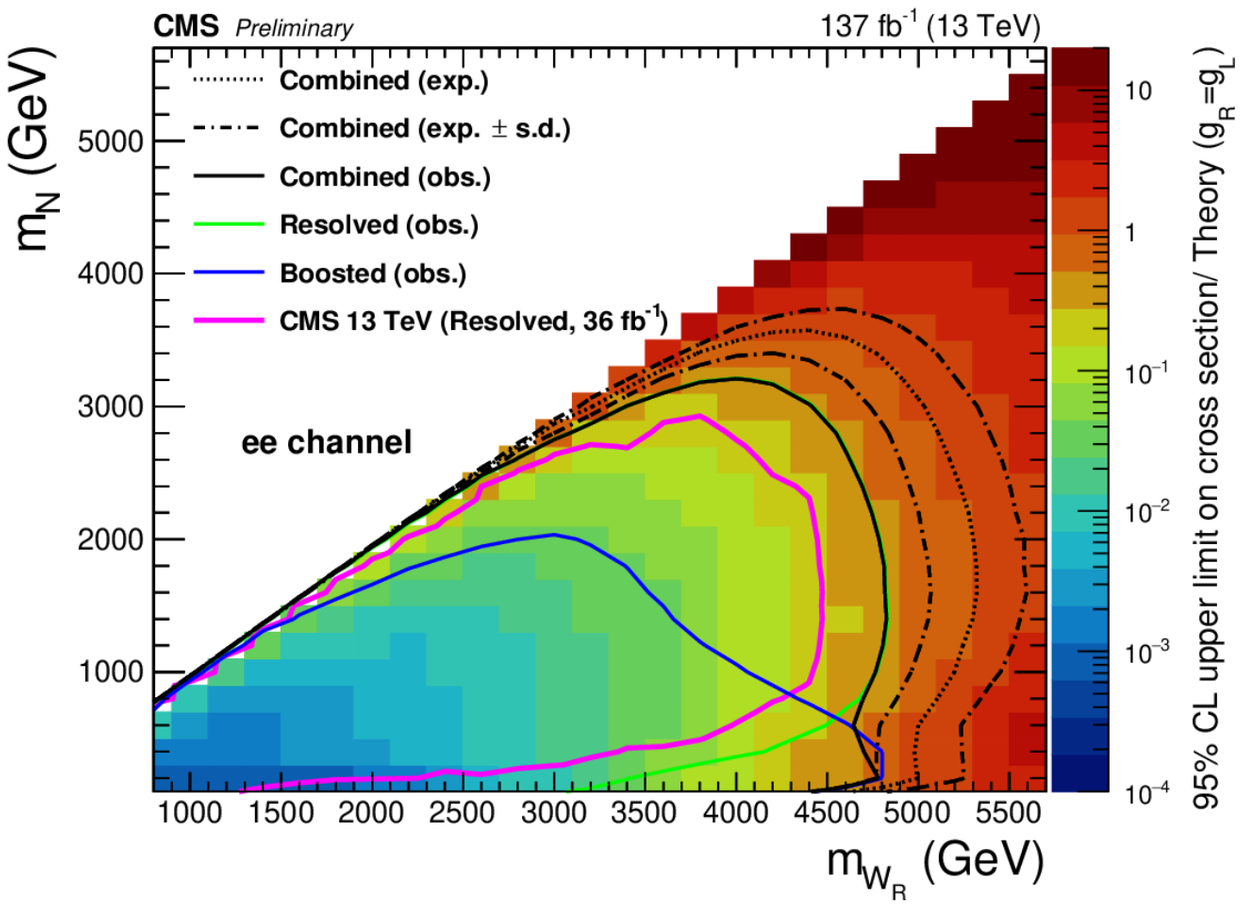
$$\mathrm{LSF} = \frac{p_T(\text{lepton})}{p_T(\text{subjet})}$$

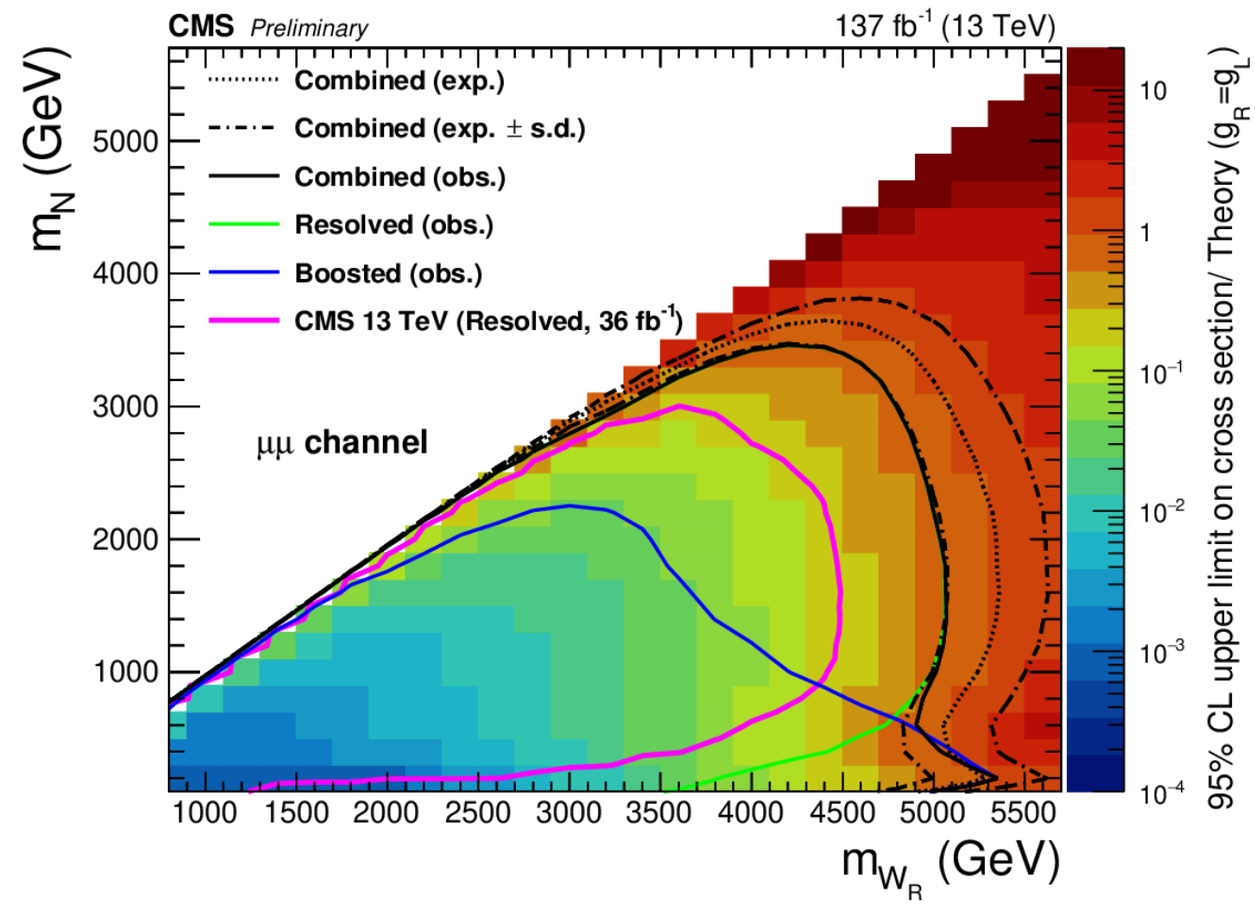


- Event selection
  - Resolved : two tight leptons + at least two AK4 jets
  - Boosted : one tight lepton + at least one AK8 jet with LSF > 0.75
  - Additional cuts on W_R and HNL candidate masses

- Reconstructed W_R mass plots
- No significant excess beyond the expected background
- Set exclusion curve in (mW_R , mN) space using binned likelihood







- Expected limit is improved in both resolved and boosted regions
  - Expected (observed) lower limit at 95% CL
    - mN=200 GeV : 5.0 (4.6) TeV in ee and 5.3 (5.4) TeV in μμ
    - mN=mW_R/2 : 5.2 (4.7) TeV in ee and 5.2 (5.0) TeV in μμ
- Significant improvements in the boosted (mN ≪ mW_R) regions
  - The world best limit in the boosted region

Summary

- Nonzero and smallness of neutrino masses arise questions for mass generation mechanism of neutrinos

- It could be related with more fundamental questions such as matter/anti-matter asymmetry of the universe

- Various models for neutrino masses have been tested at CMS
  - Two new interesting searches
  - TISM 3-lepton targeting long-lived HNL and LRSM W_R + HNL

- New techniques improved sensitivity much
  - The improvement is ongoing
  - LHC Run 3 will start next year
  - Interesting results are waiting for us - Stay tuned!