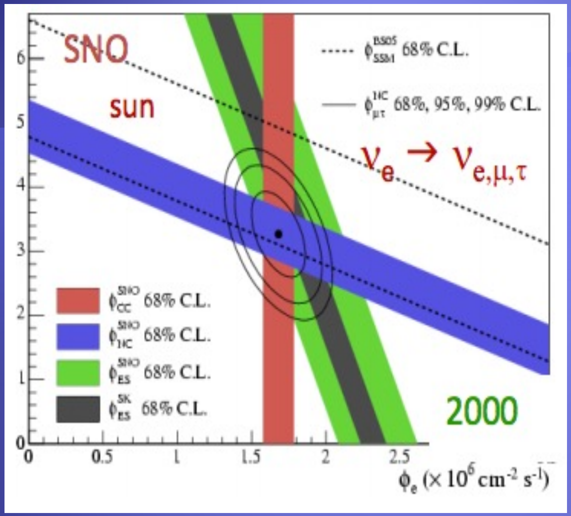
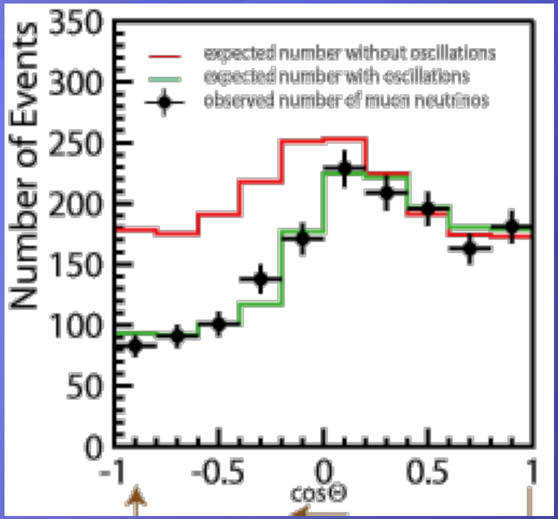
Searches for Heavy Neutrinos at the LHC

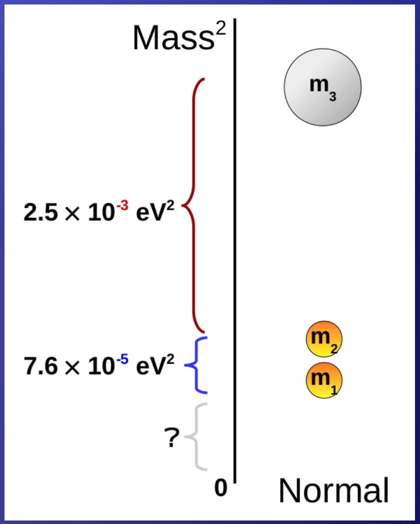
Un-ki Yang
Seoul National University

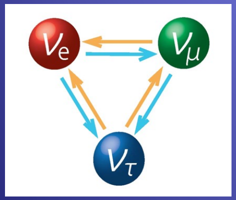
CPNR Workshop 2025: Neutrinos and Physics BSM
October, 24-27, 2025, Chonnam National University

Neutrino Oscillations



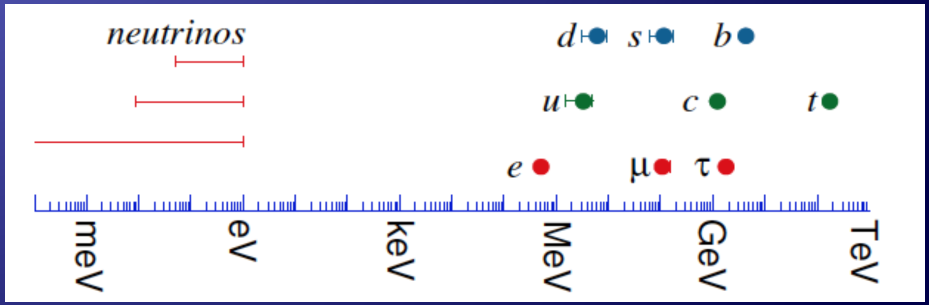






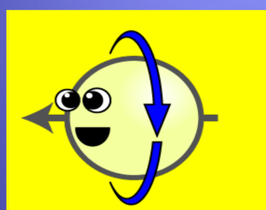
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

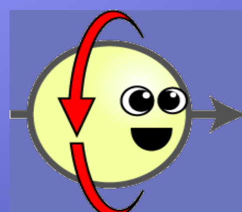
- All neutrinos oscillate
- Require small masses
- Why small and why no right-handed neutrinos?

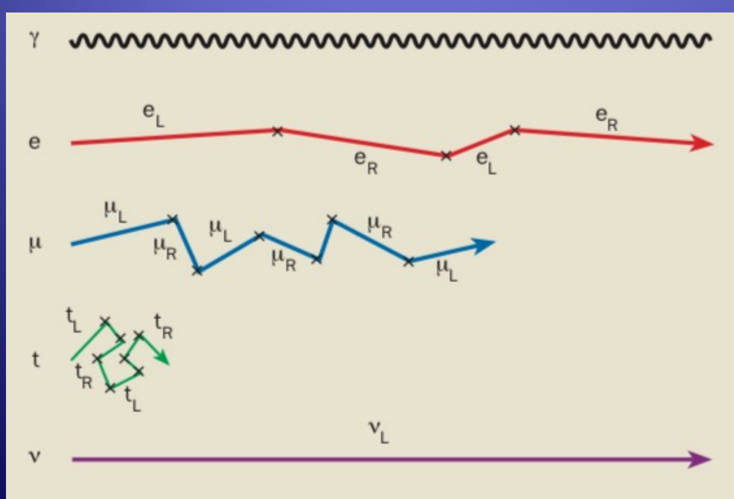


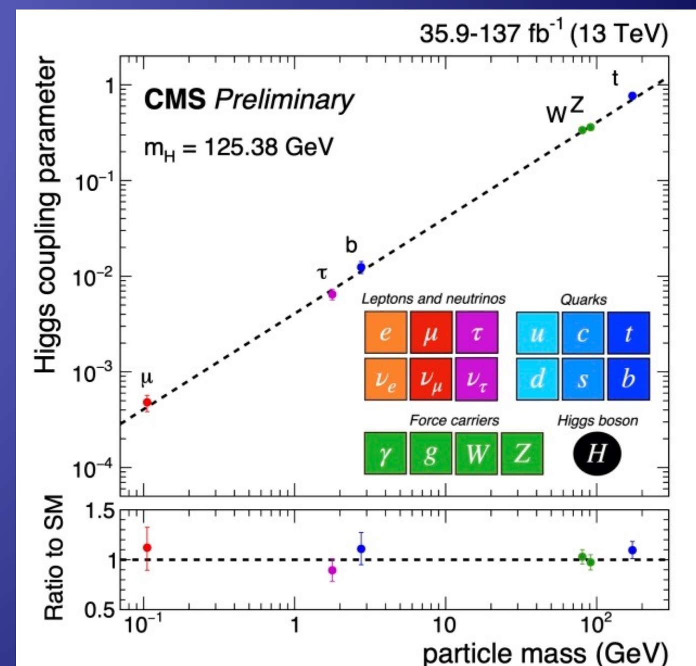
Neutrino Mass

- How do neutrinos get masses?
- Electron get its mass with Yukawa interaction
  (left-handed electron becomes right-handed electron after interaction)
- Where is right-handed neutrino?





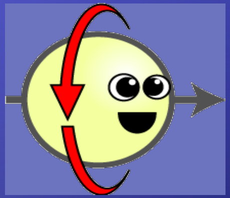


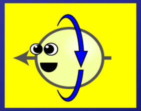


$$\mathcal{L}_{\text{fermion-mass}} = -\lambda_f[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L]$$

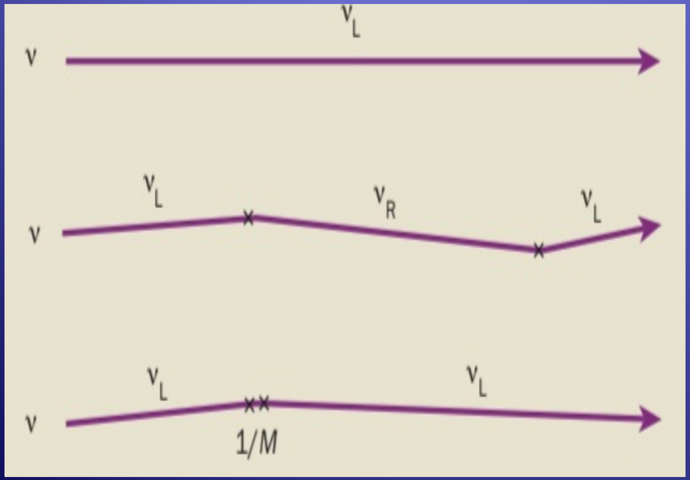
Heavy Neutrinos

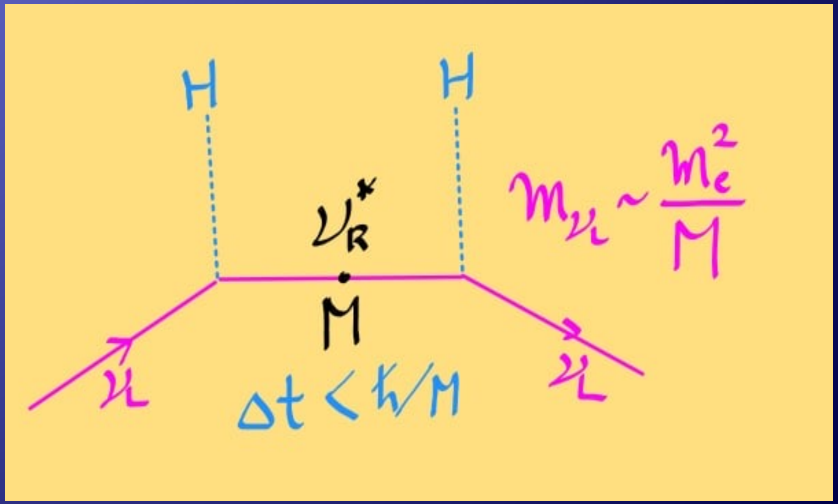
- Why can't we see ν_R ?
  - Dirac-type neutrino, ν_R
    - Higgs Yukawa coupling is very small (10^{-12})





  - Heavy Majorana-type neutrino, ν_R
    (as a virtual particle at low energy)
    (SeeSaw Mechanism)



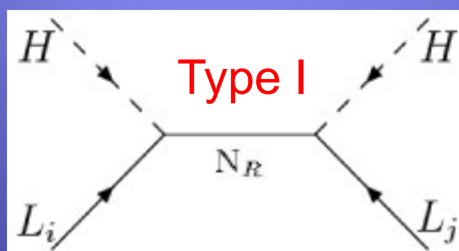


Neutrino: Physics Beyond SM

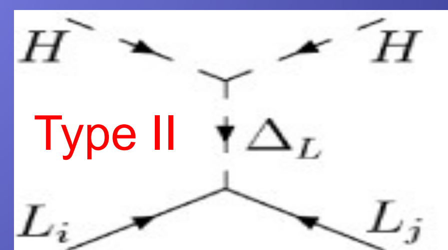
- A natural way to generate LNV and neutrino mass
  - Introduce an effective operators to the SM

$$\sim \frac{Y_L}{\Lambda_L} LLH^2$$

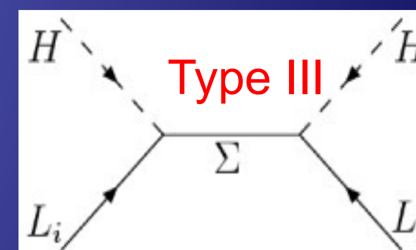
  - Seesaw Mechanism (type I, II, III)



Singlet Fermion (N_R)



Scalar triplet
(Δ^{++}, Δ^{+} ,Δ)



Triplet Fermion
(Σ^0, $\Sigma^{+/-}$)

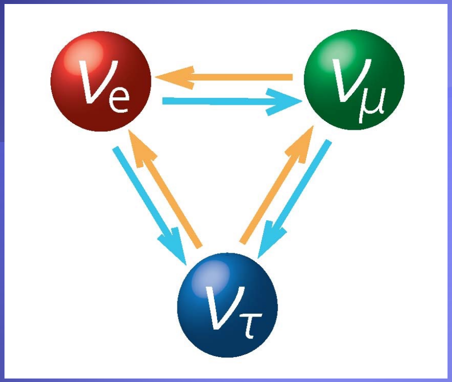
$$m(\nu_R) \sim M \ \text{(heavy)}$$
$$m(\nu_L) \sim m_D^2 / M \ \text{(very small)}$$

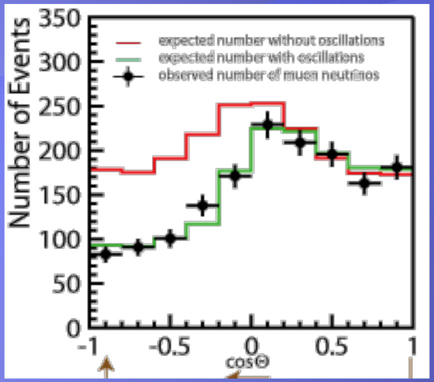
Neutrino: Physics Beyond SM

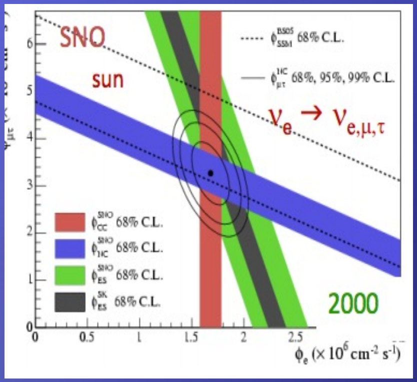
- Physics behind the Seesaw?
- Left-Right Symmetry model (LRSM)
  offers the Seesaw scale and heavy dark neutrinos (HN)
  - Spontaneous symmetry breaking of the L-R symmetry group
  - Parity violation in weak interaction occurs
  - Extra gauge bosons (W_R, Z’) and heavy ν_R

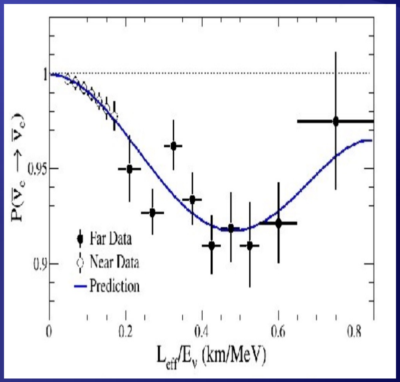
$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \qquad M_{W_R} \gg M_{W_L}$$

Right-handed Neutrino?

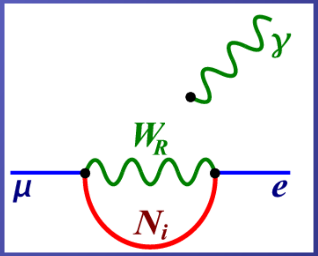


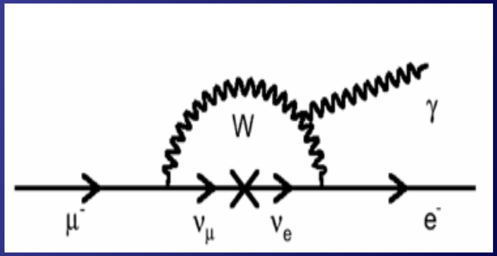






- Neutrino Oscillation!
  - Small neutrino mass
  - Right-handed neutrino?
  - Origin of neutrino mass?
  - Heavy Neutrinos (LNV, if Majorana)
  - Charged Lepton Flavor Violation
  - Searches for Heavy Neutrinos

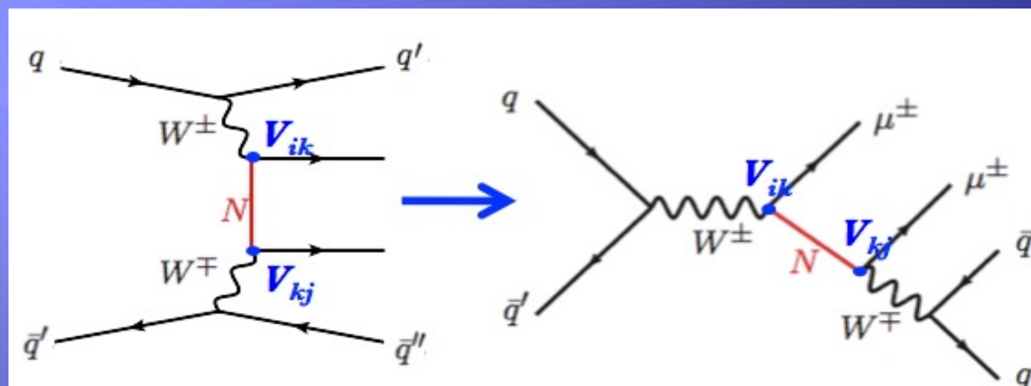


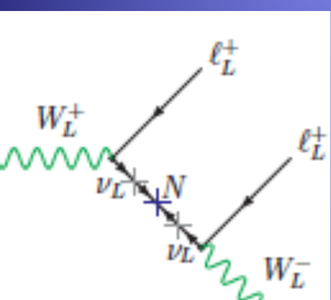


$$\mathcal{L}_{\text{fermion-mass}} = -\lambda_f[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L]$$

Search at the Energy Frontier?

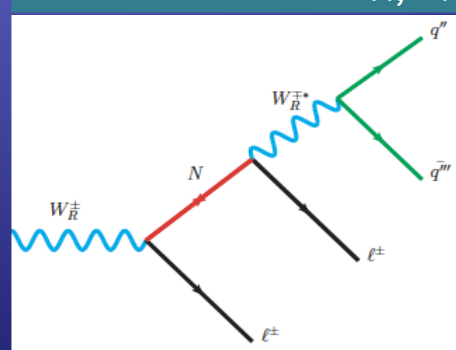
- **Direct production of heavy neutrinos (*N*)**
  - **Complementary program to the $0\nu\beta\beta$**

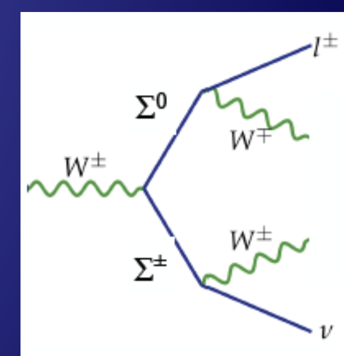




1. Type-I seesaw
- Right-handed N_R
- Only mix with SM ν

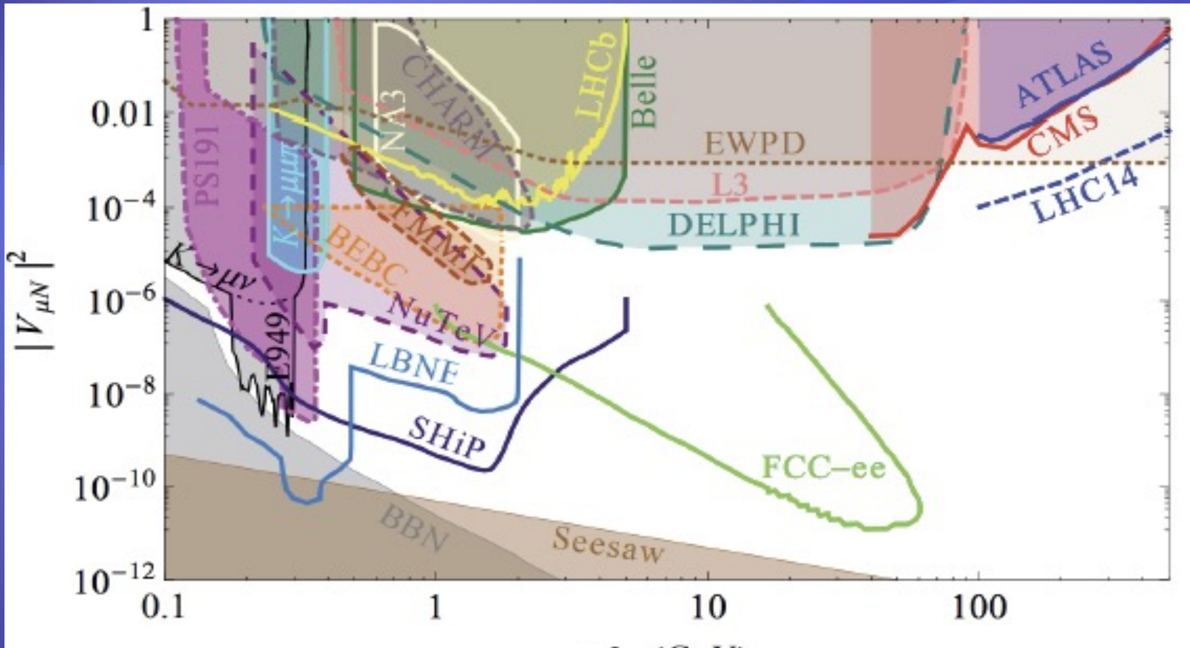
2. LRSM
- Right-handed N_R
- N_R couple to RH bosons, W_R, Z_R



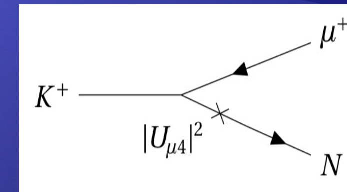


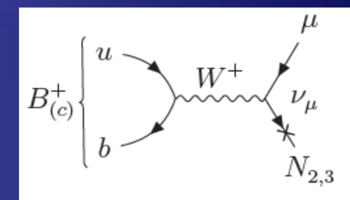
3. Type-III seesaw
- at least two $SU(2)_L$ triplets (Σ^0, $\Sigma^{+/-}$) couple to SM gauge bosons

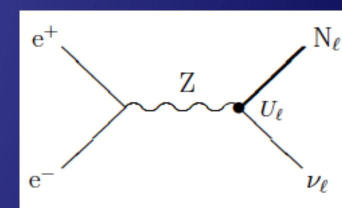
N_R searches for 40 years

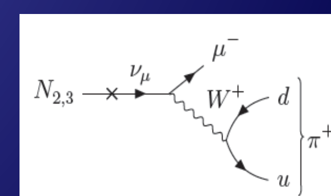


[Deppisch, BD, Pilaftsis (NJP '15)]



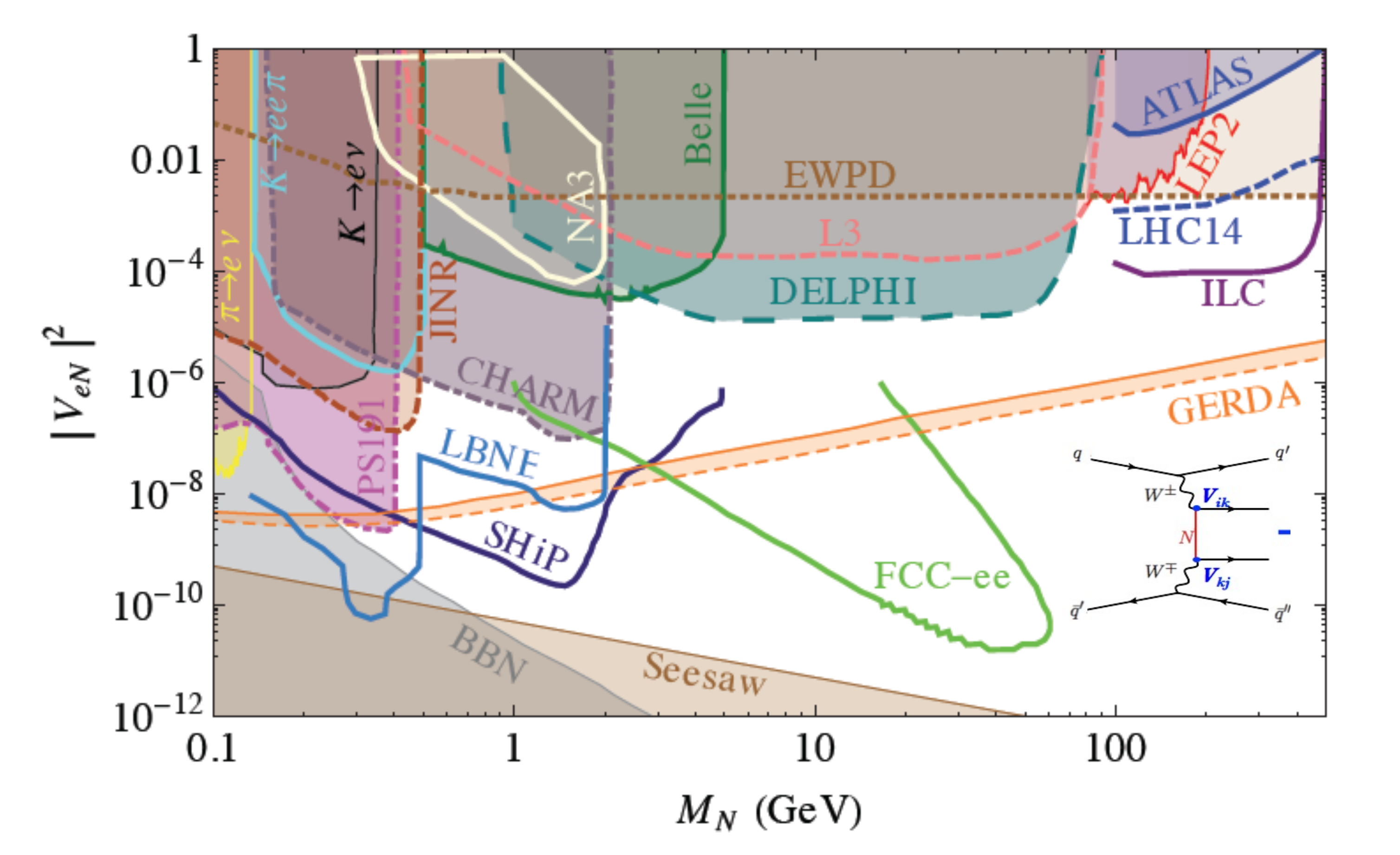






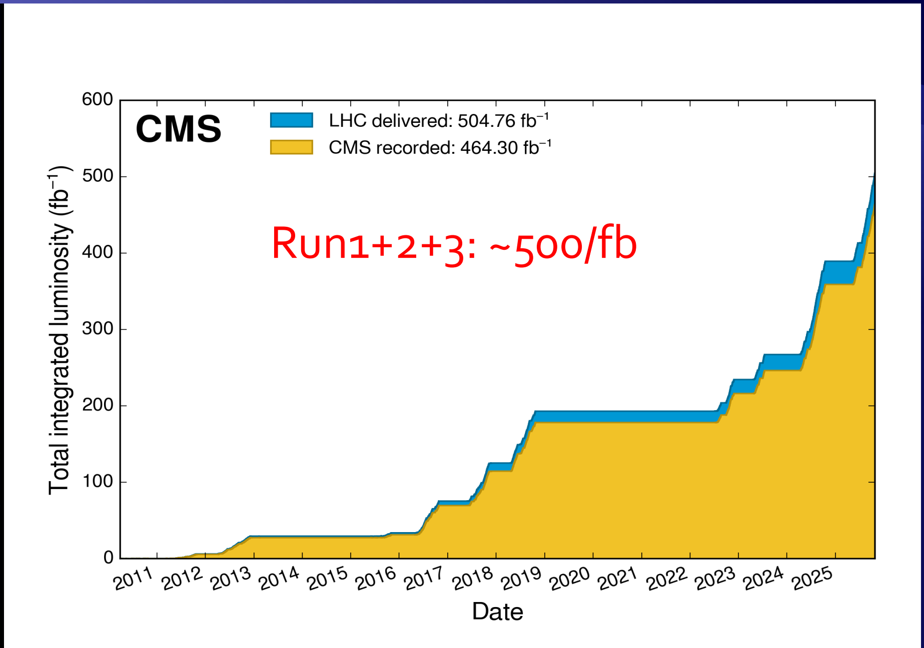
- $m_N <$ 500 MeV: $K \to \mu N$
- $m_N <$ 2 GeV: $N \to \mu\pi, \mu K$ (NuTeV, NA62)
- $m_N <$ 5 GeV: $D,B \to \mu\mu\pi$ (Belle, LHCb, SHiP)
- $m_N <$ 90 GeV: $Z \to \mu N$ (LEP), and LHC
- $m_N >$ 90 GeV: LHC (ALTAS, CMS)

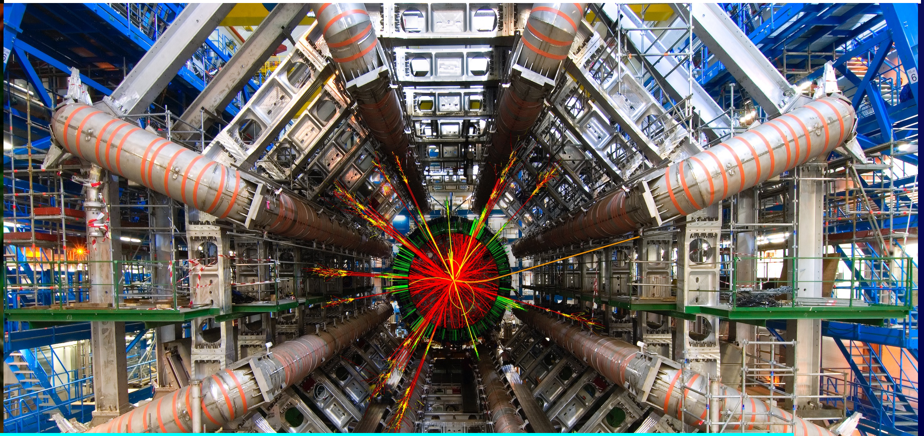
N_R searches (electron channel)



[Deppisch, BD, Pilaftsis (NJP '15)]

Use the Large Hadron Collider!

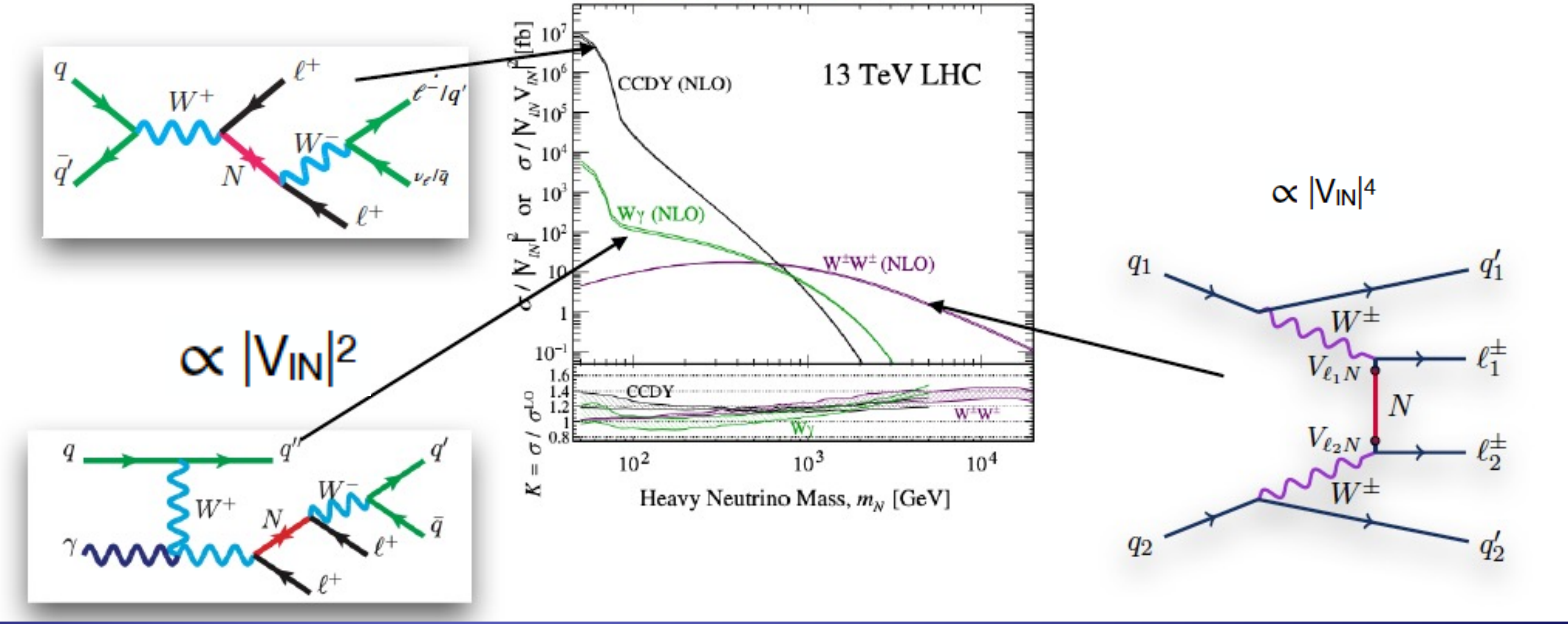




- **Multi-purpose detectors at LHC: ATLAS & CMS**
- **Great LHC performance and impressive data taking**

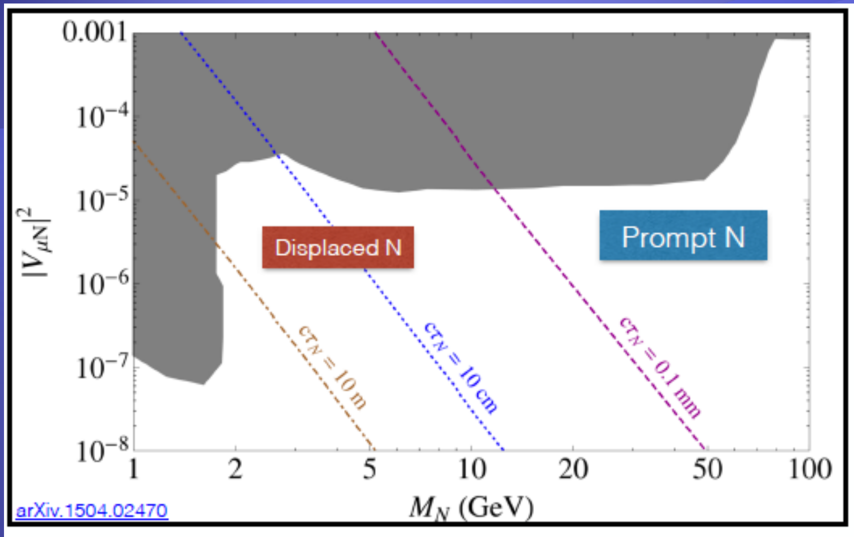
Type-I N_R search at LHC

Phys. Rev. D 103, 055005



- Three major production channels
- Netrino-less double beta decay, mN> 1 TeV

Search Strategy

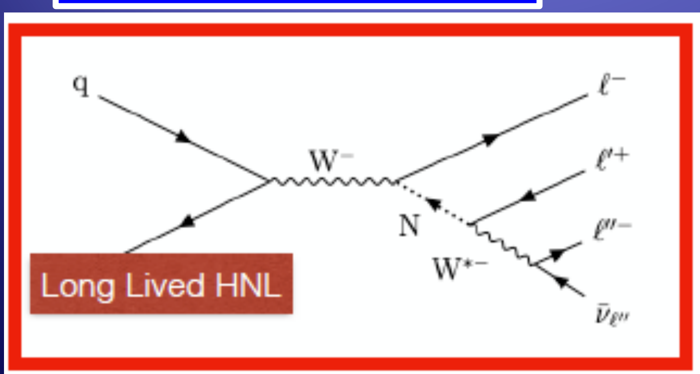


HNL Lifetime (τ) :

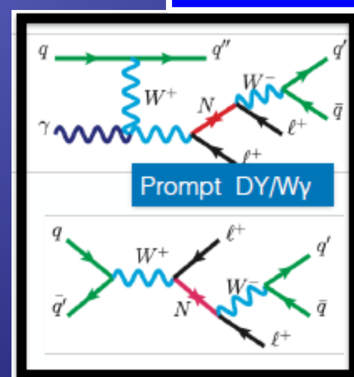
$\tau \propto |V_{\ell N}|^{-2} m_N^{-5}$

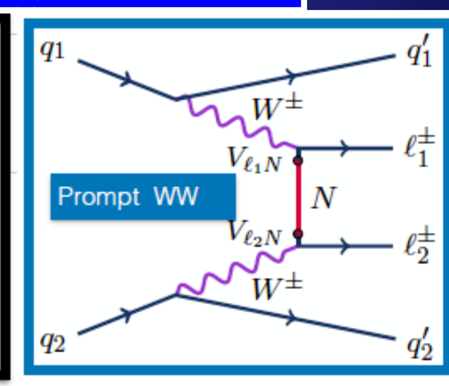
Smaller HNL mass and smaller mixing leads to longer HNL life!

1 < m_N < 20 GeV



20 < m_N < 25 TeV



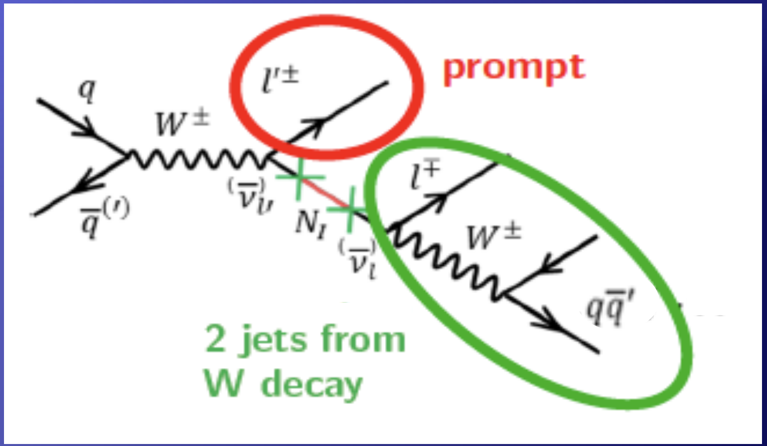


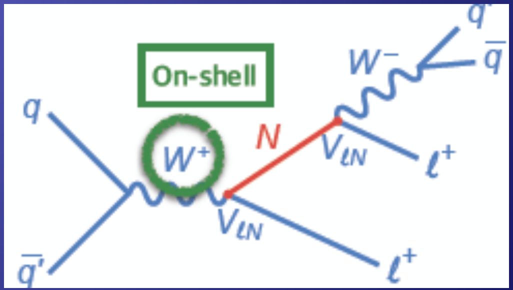
Type-I N_R search in dilepton

- *N_R from* 20 GeV to TeV
  - 2 same-sign hi-pt leptons (LNV only)
  - 2 jets or 1 boosted jet (collinear)
  - Flavor combinations

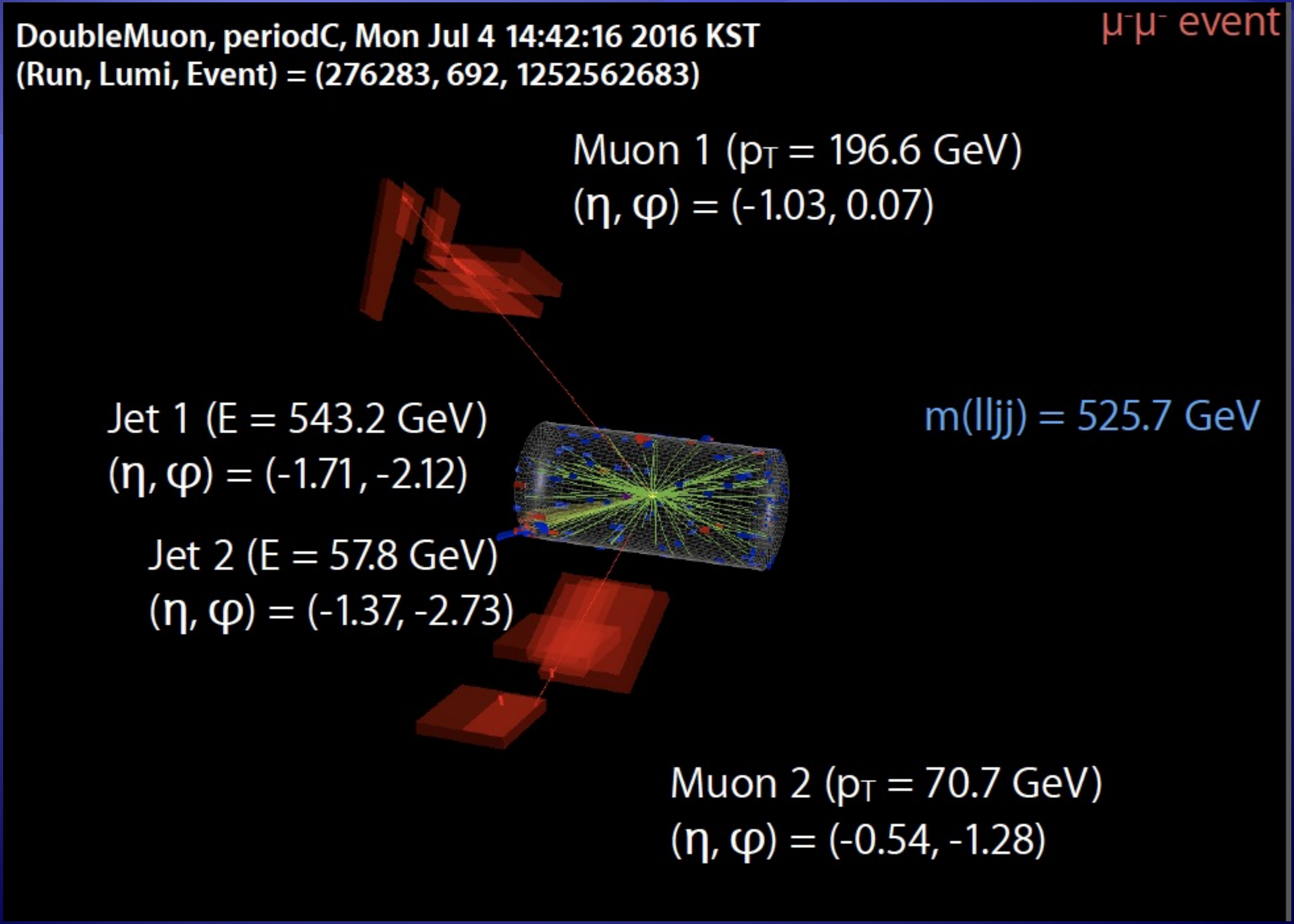
$$e^\pm e^\pm, \quad \mu^\pm\mu^\pm, \quad e^\pm\mu^\pm$$
$$\downarrow \qquad \downarrow \qquad \downarrow$$
$$\left|V_{eN}\right|^2, \quad \left|V_{\mu N}\right|^2, \quad \frac{\left|V_{eN}V_{\mu N}^*\right|^2}{\left|V_{eN}\right|^2+\left|V_{\mu N}\right|^2}$$

  - Different search strategy for low mass ($m_N < m_W$) and high mass ($m_N > m_W$)





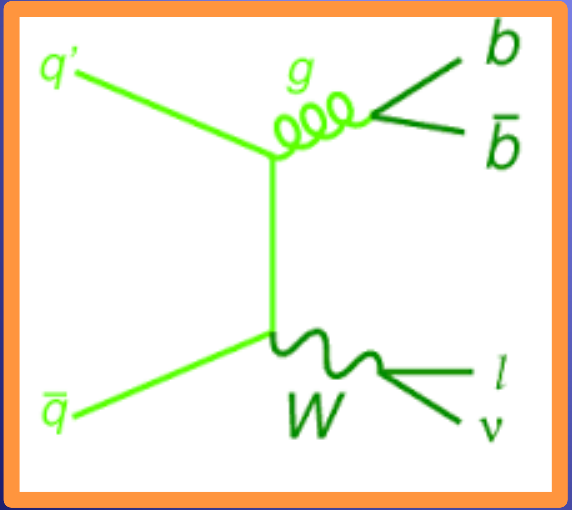
SS Dimuon + 2 jets event observed in the CMS detector

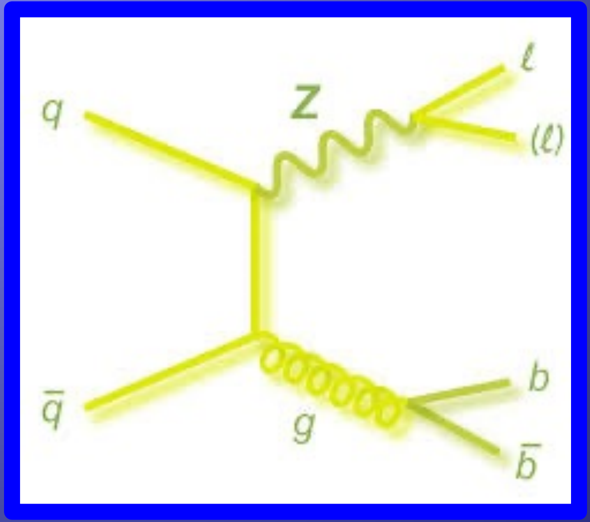


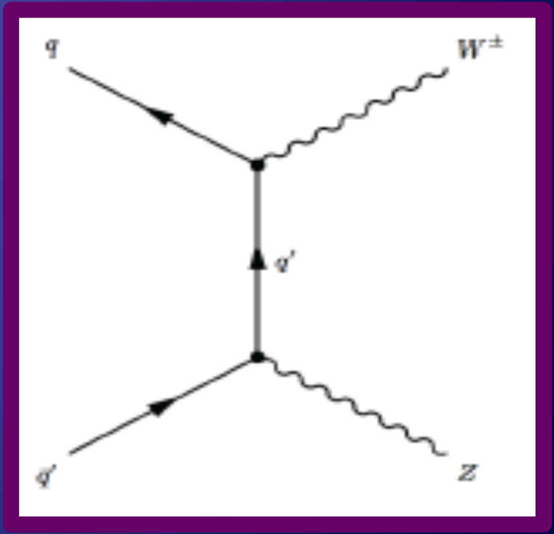
Backgrounds: ee/$\mu\mu$/eμ+2 jets

Fake leptons: "data"
W(e,μ)+jets:
dominant bkgd

SM prompt lepton;
MC
dibosons(VV), tt+V





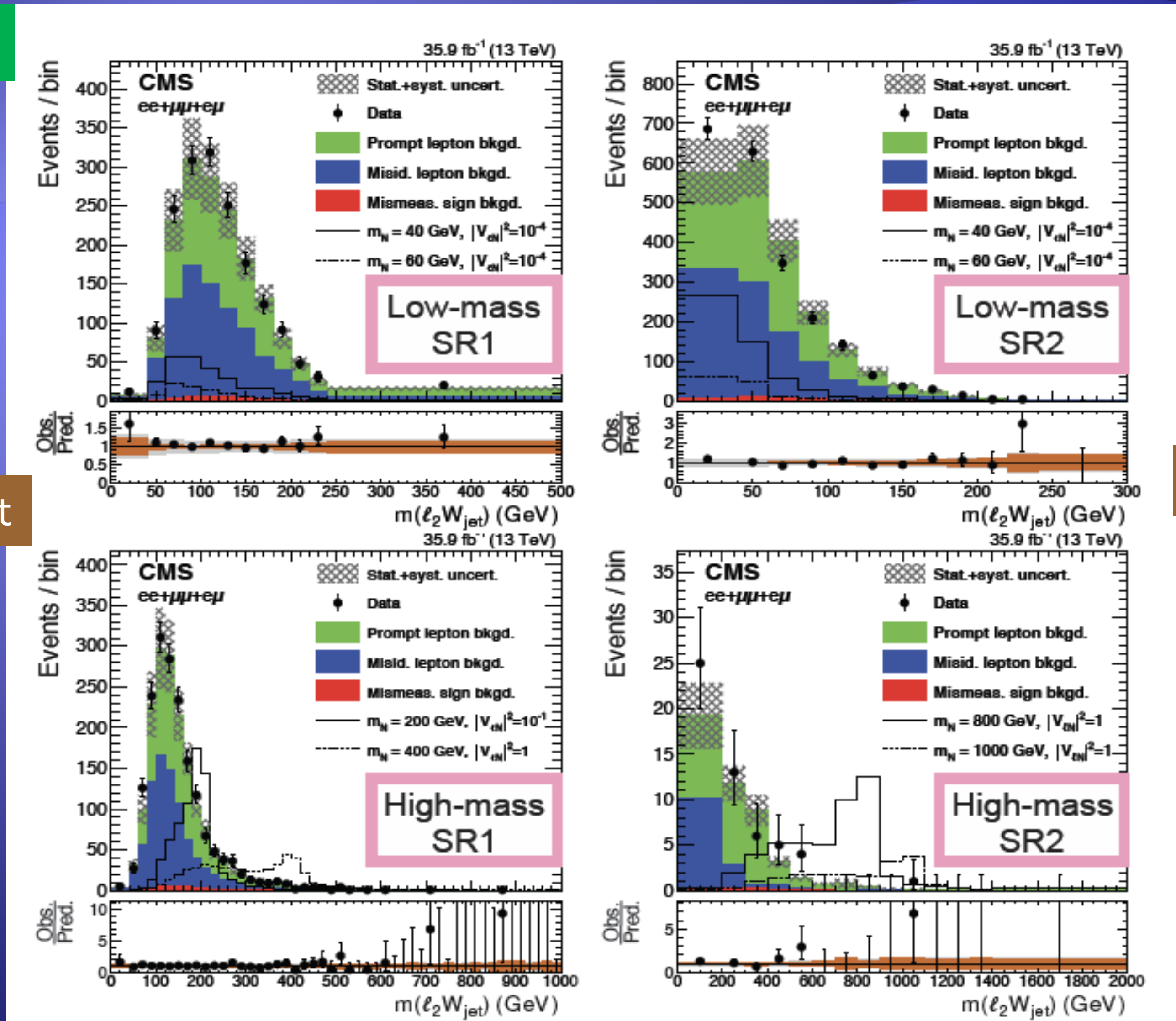


Charge-flip: "data+MC"
Z(ll)+2jets

CMS Results at 13 TeV

Mass (N_R)

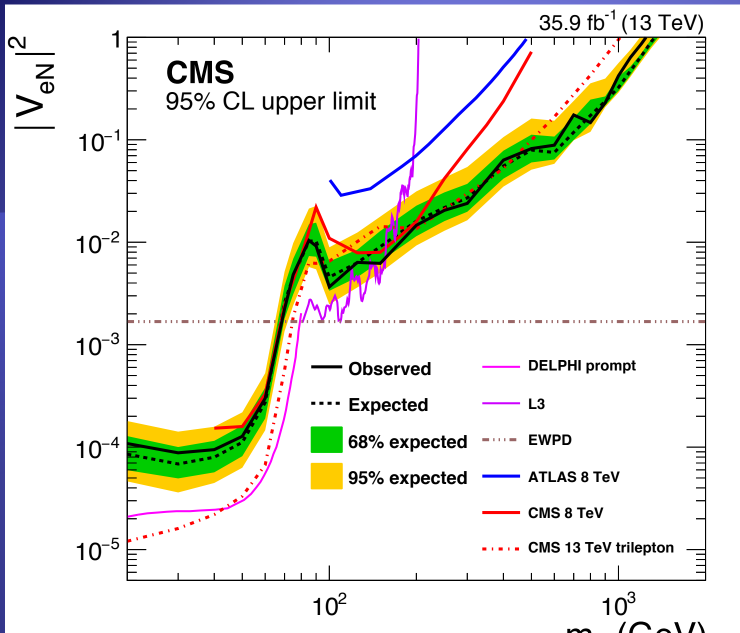
SR1: W: 2 jet

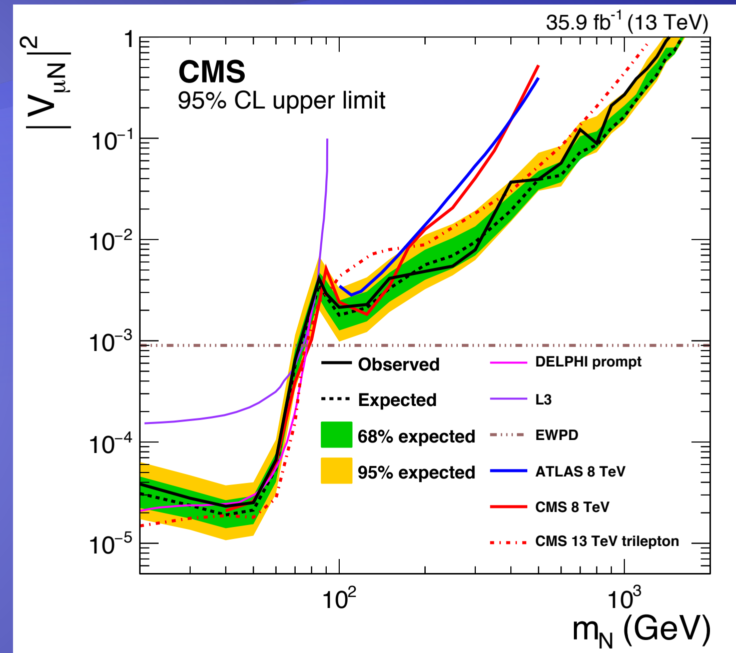


SR2: W: 1 jet

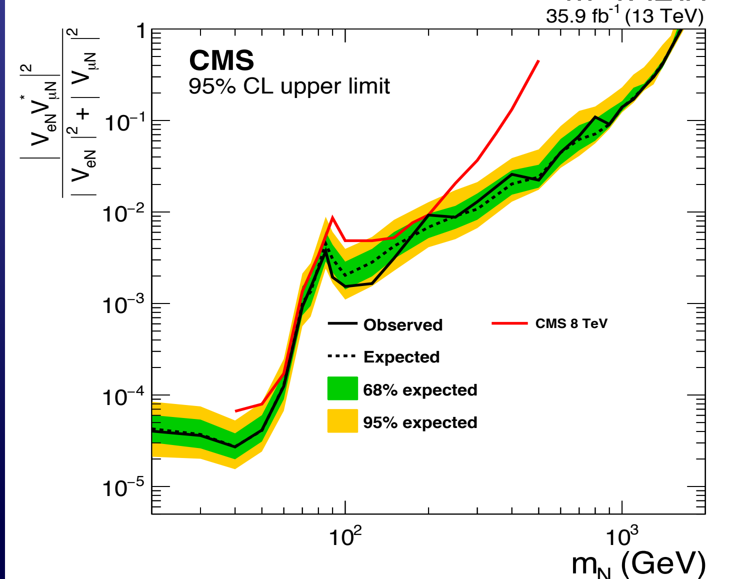
No significant deviation from the SM

Results on the Search





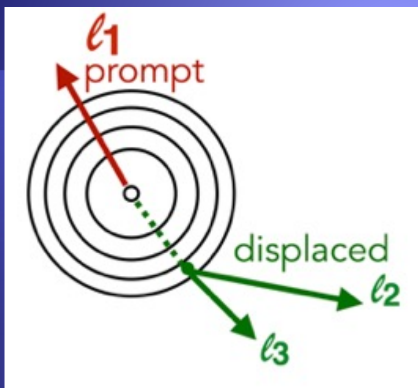
JHEP01 (2019) 122



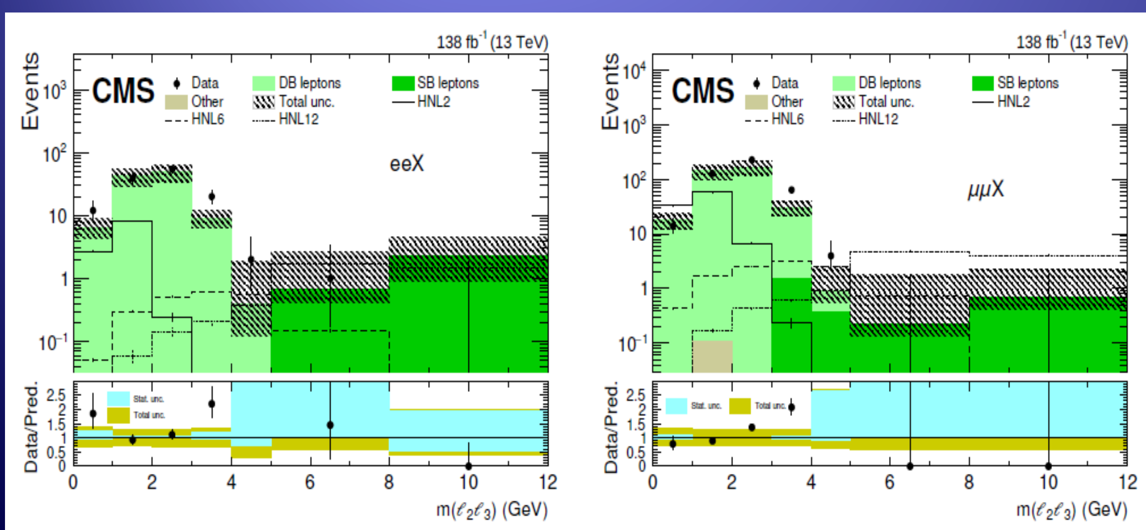
- LHC provides the best direct limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$, & $|V_{eN}^*V_{\mu N}|$ for high m_N
  - CMS limits down to 20 GeV, and up to 1.2 TeV
  - Lepton flavor mixing case by CMS

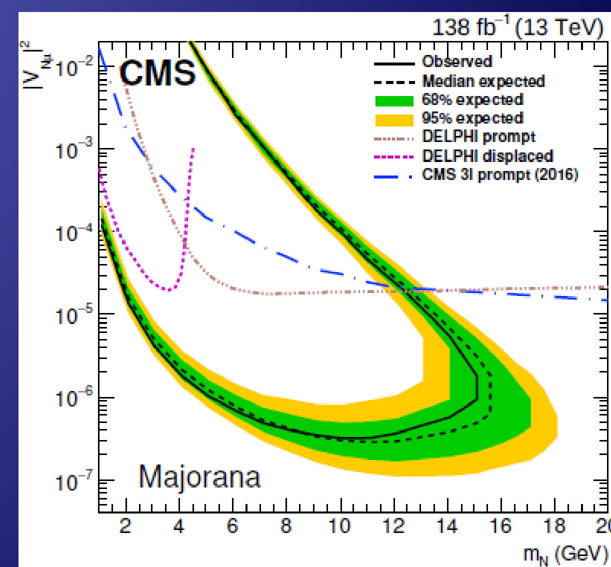
2016 data only

Trilepton (long-lived) at CMS



- One prompt lepton (ℓ_1) + two displaced leptons (ℓ_2, ℓ_3)
- Search region: 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
- Use Δ_{2D} : transverse position of ℓ_2, ℓ_3 vertex

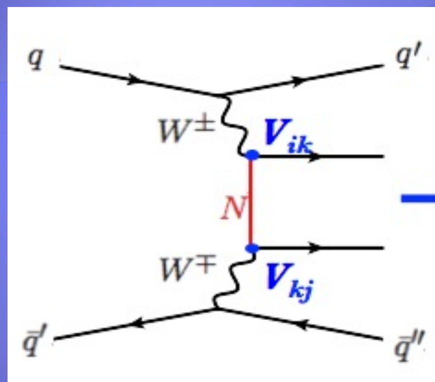




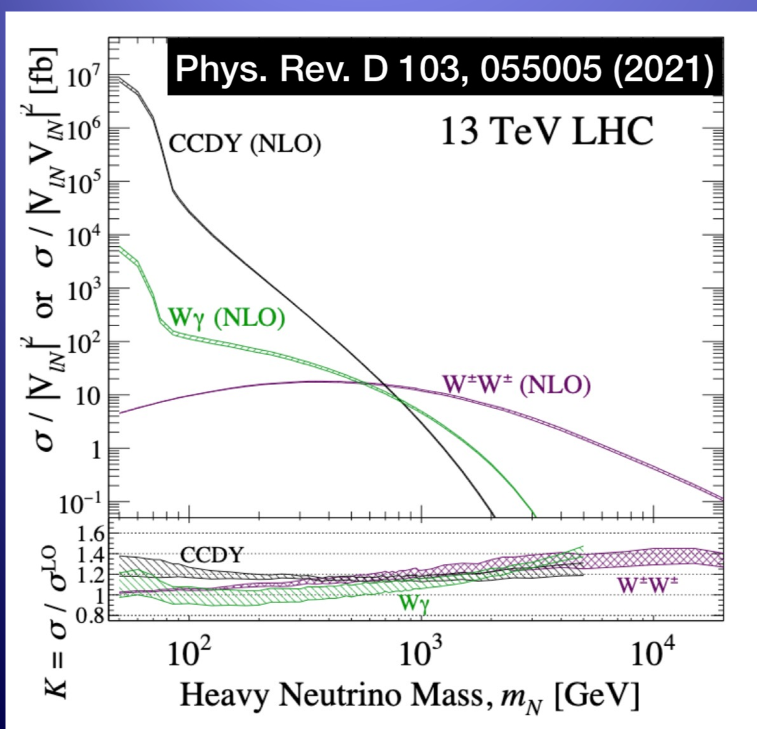
JHEP07 (2022) 081

Very heavy mass, N

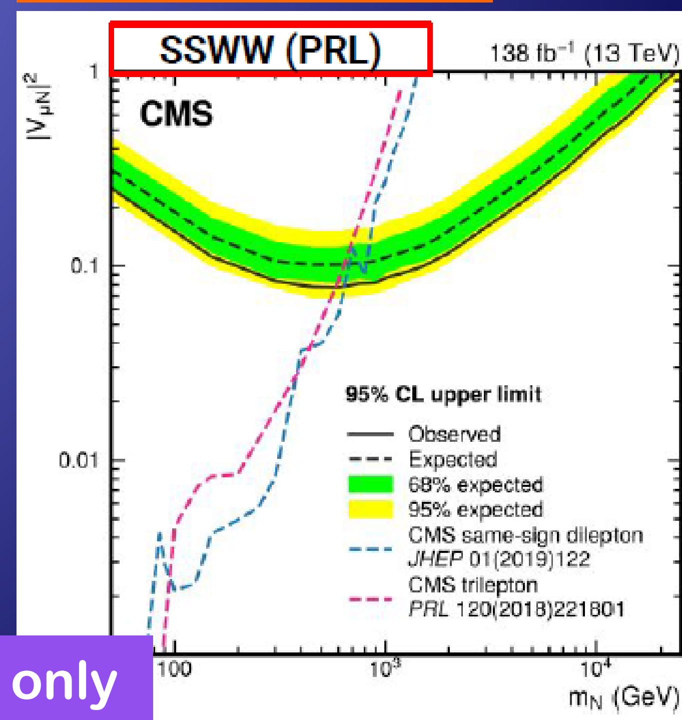
- Neutrino-less double beta decay channel (WW)



Very effective at high mass m_N> 1 TeV



PRL 131 (2023) 011803



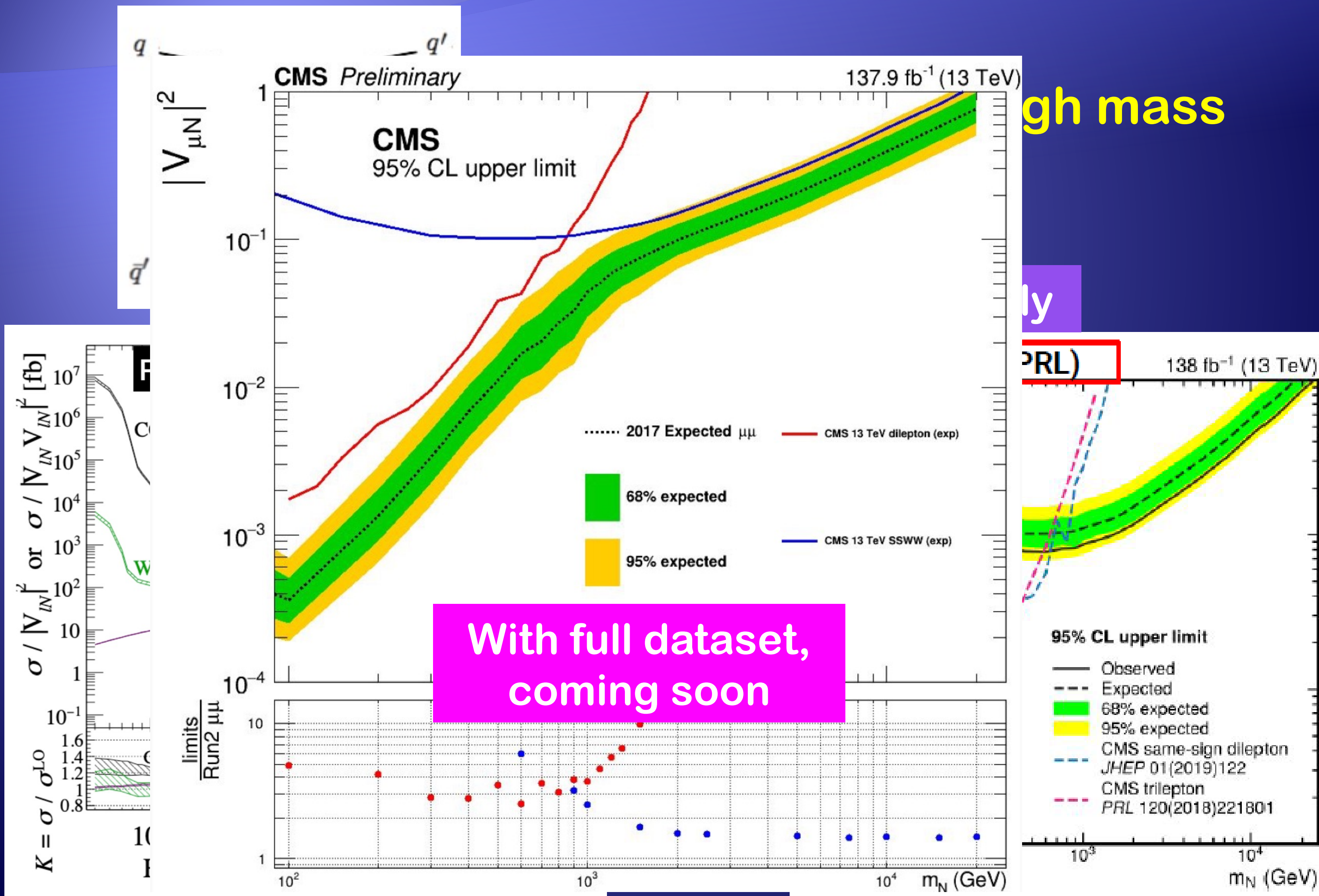
dimuon only

Very heavy mass, N

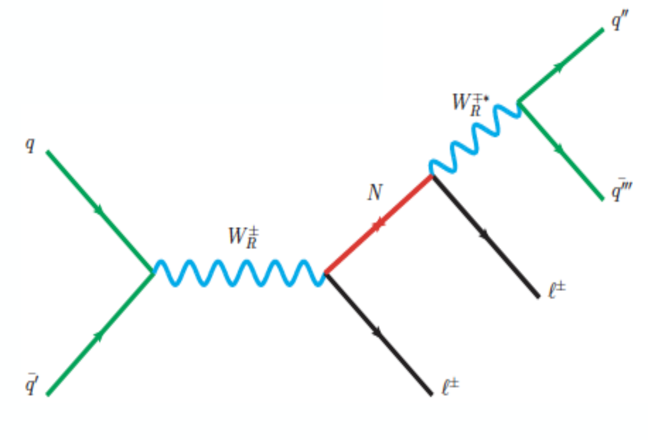
- Neutrino-less double beta decay channel (WW)

gh mass

ly



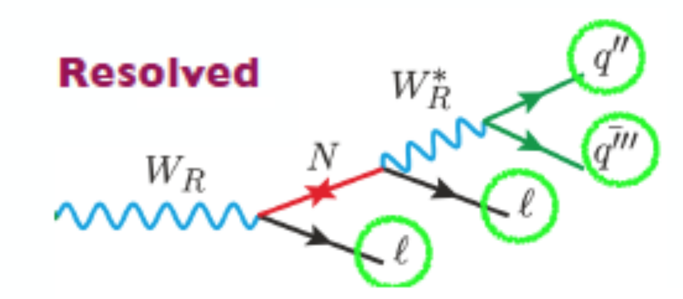
Searches in LRSM

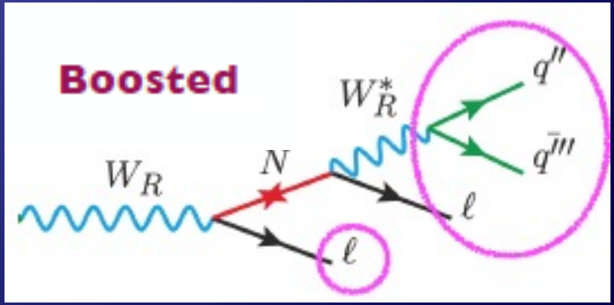


Same Final state as type-I
But different kinematics

Resonant Production
$M(lljj) = M_{W_R}$
$M(l_2jj) = m_N$

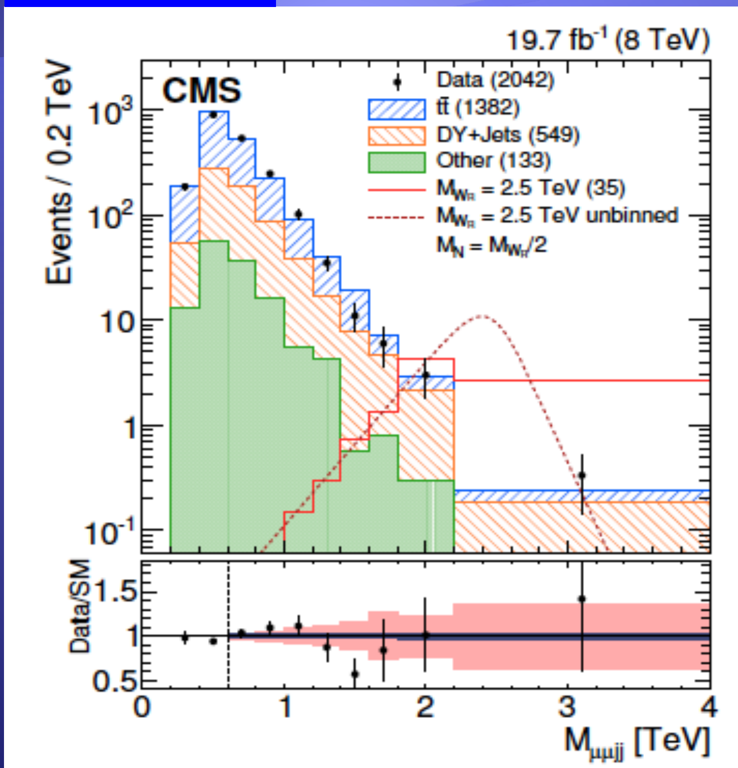
- For $m_N << m_{WR}$, jets and lepton from N decays overlap
  → requirement of lepton isolation will kill signal
  → use boosted jet to resolve lepton and jet
- Signal topology: resolved and boosted



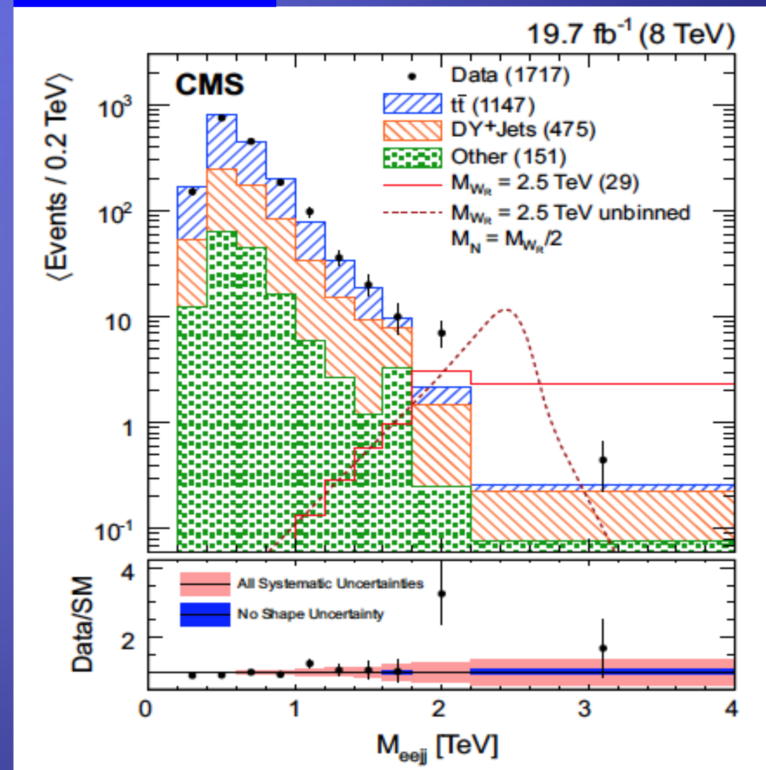


Interesting Run 1 results from CMS

μμ channel



ee channel

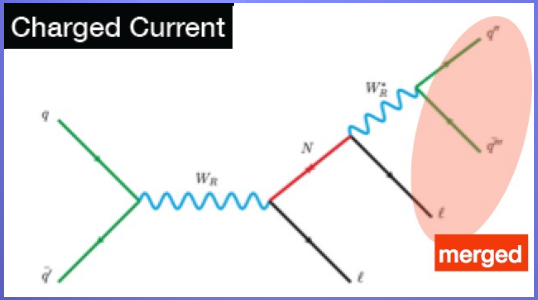


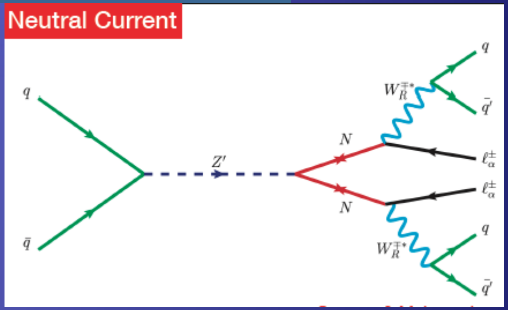
EPJ C74 (2014) 3149

- A local significance, 2.8σ effect
- Consistency with the LRSM?

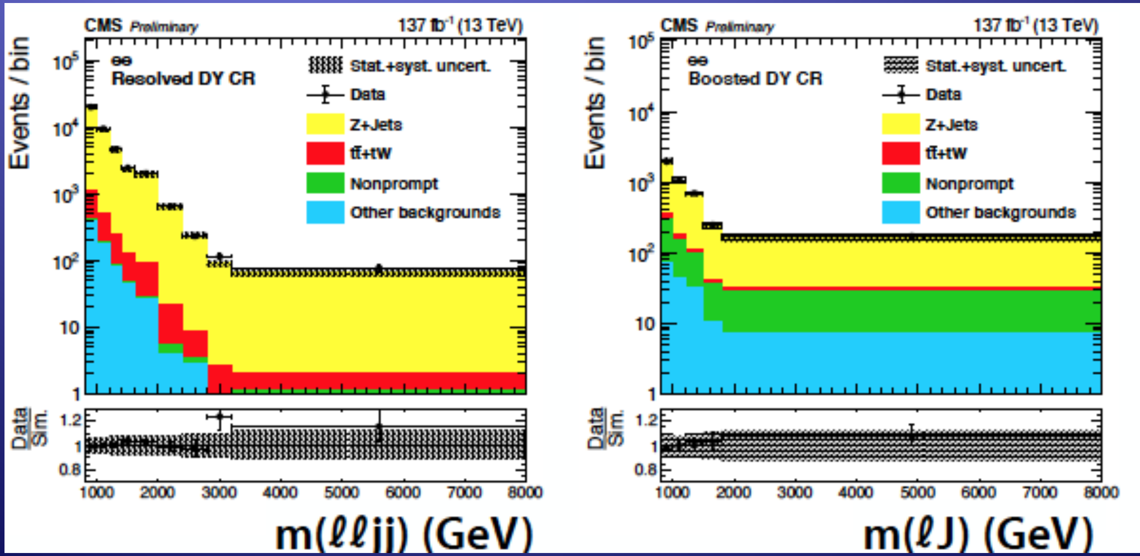
N_R searches in LRSM

- Searches are done in CC and NC
- Resolved and boosted cases
- Use AK4 (anti-kt with R=0.4) jets and AK8

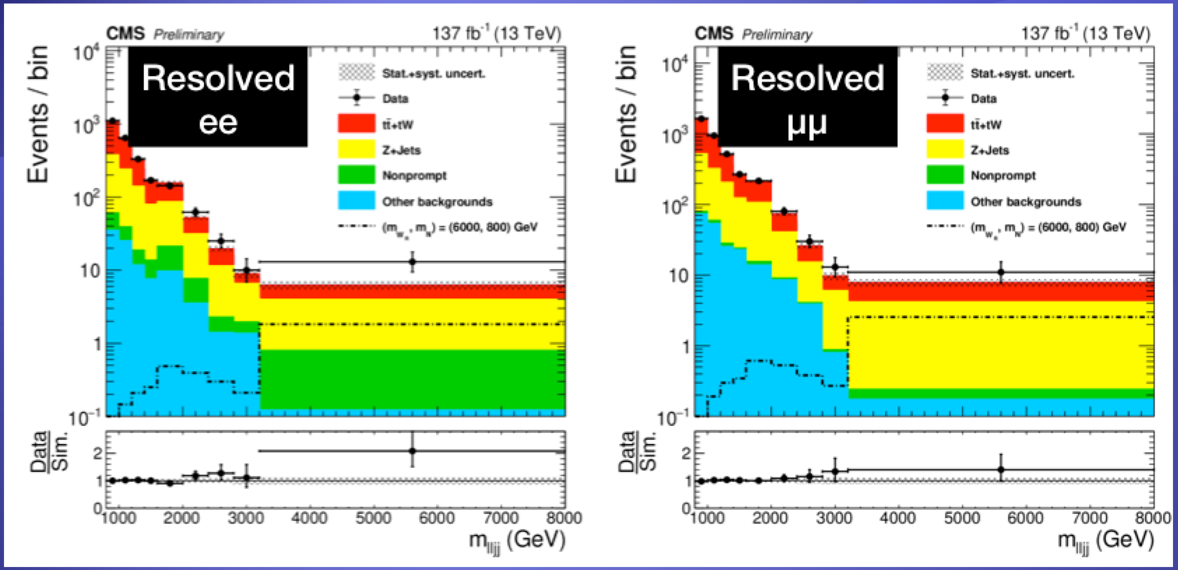




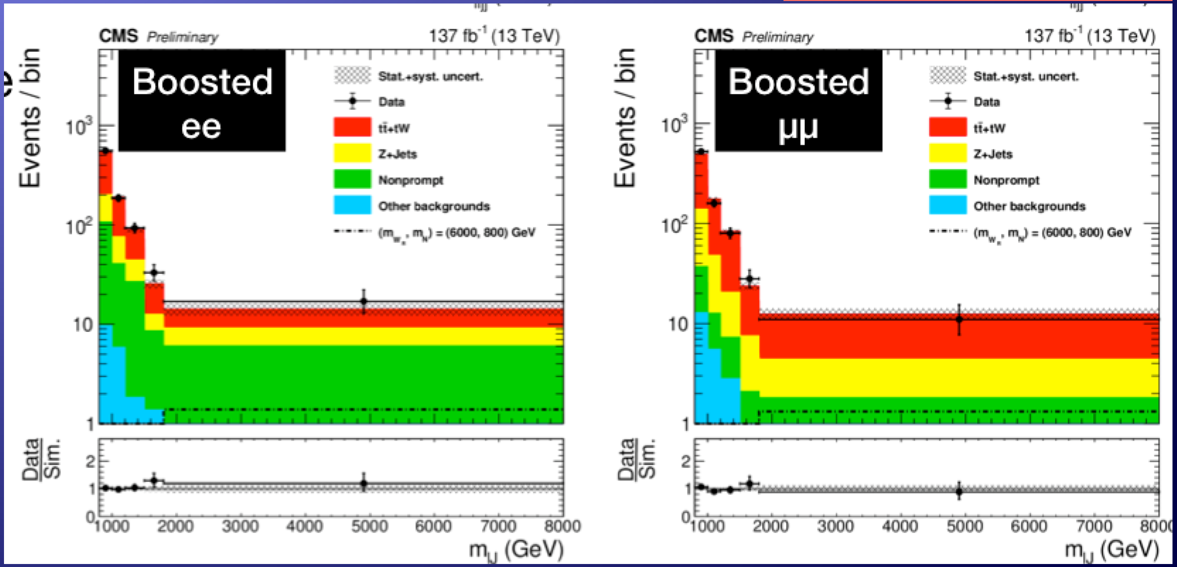
- CC: Control region (Drell-Yan)



Search results for N_R

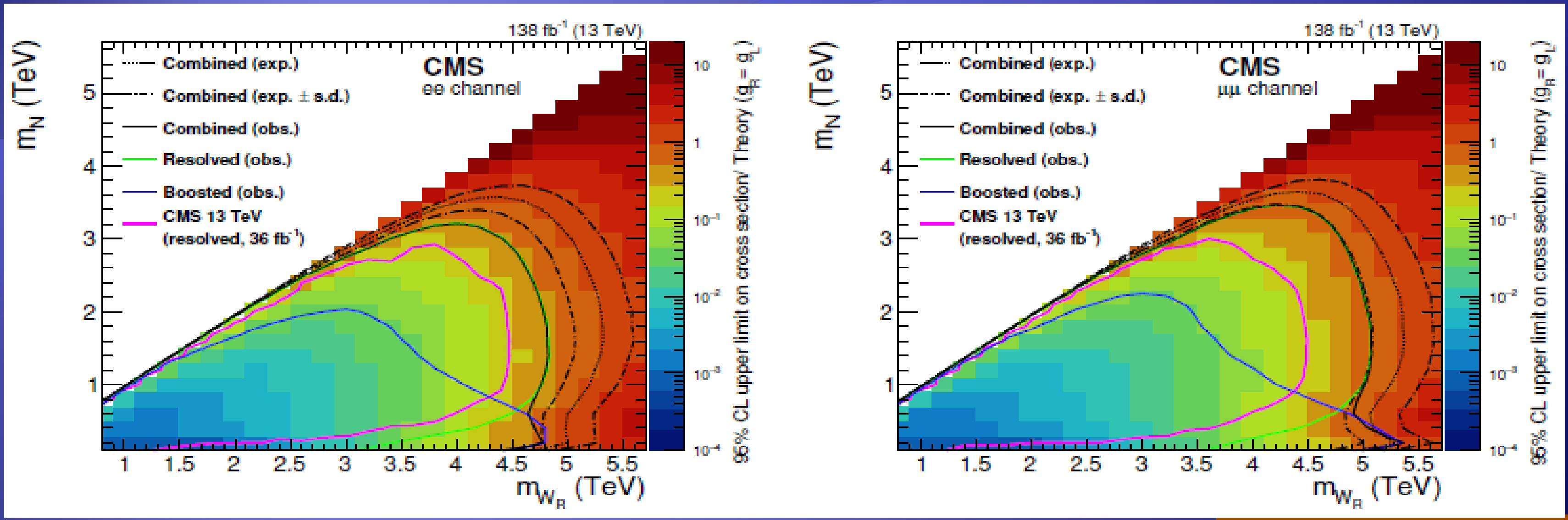


JHEP04(2022)047



No significant Excess shown

LRSM results for N_R



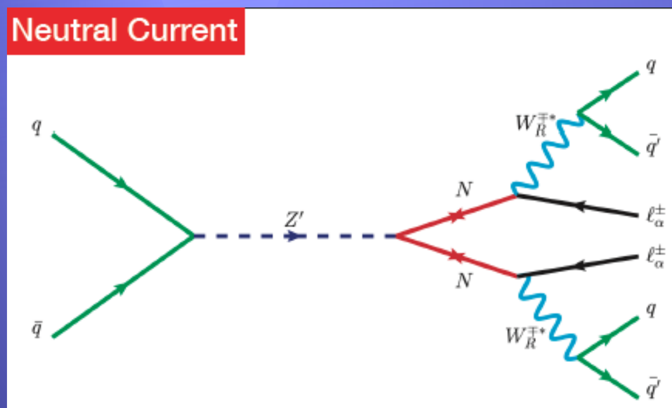
JHEP04(2022)047

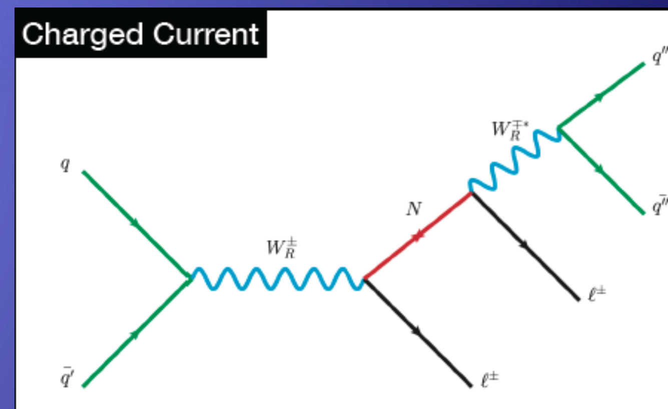
Exclusion limits are improved

- 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=mWR/2 : 5.2 (4.7) TeV in ee and 5.2 (5.0) TeV in μμ

Search for $Z' \rightarrow N_R N_R$

- Search for heavy N in pair productions of HN
- Signature: dilepton + 4 jets

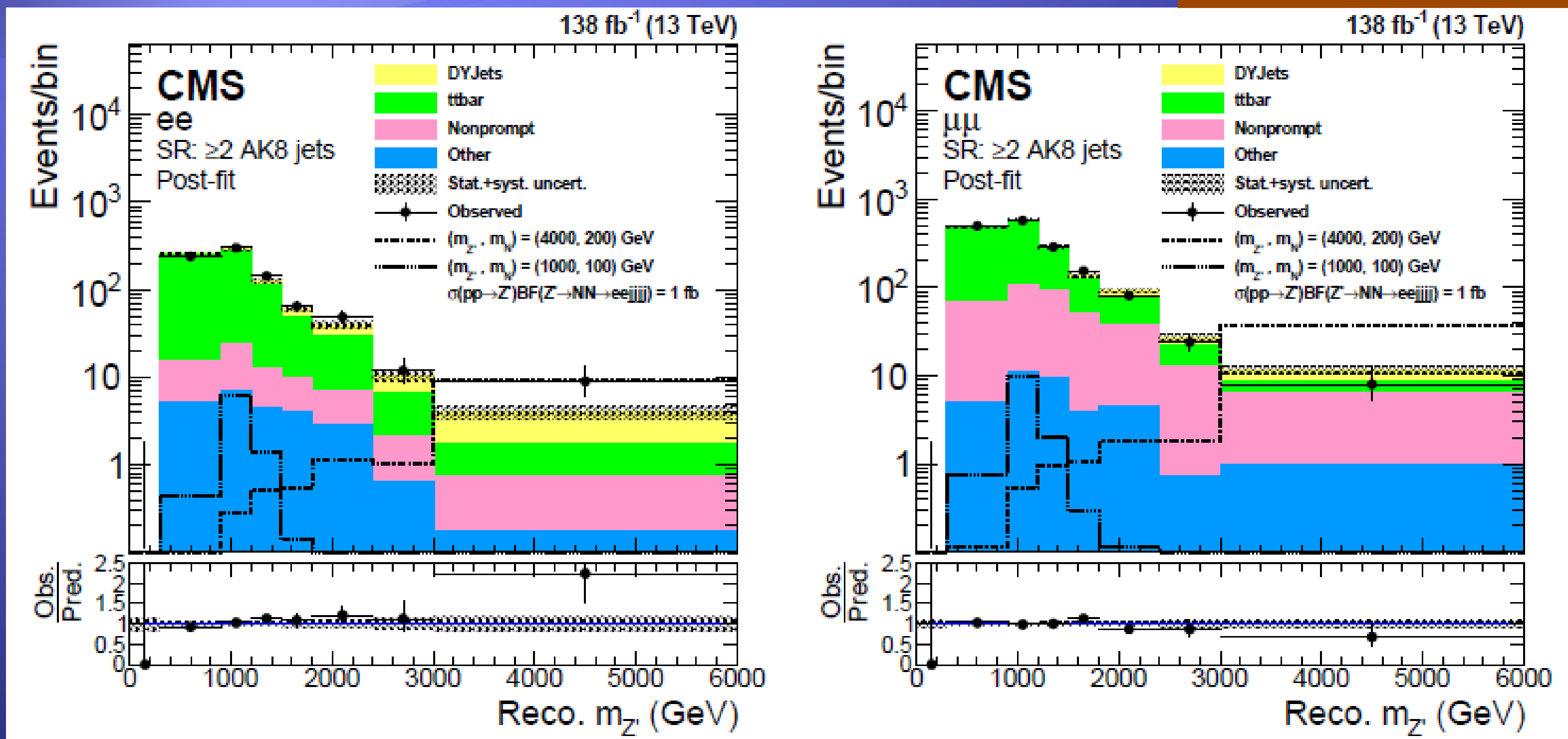




- Search signatures depending on m(Z') and m(N)
  - A lepton + two jets can be merged.

Looking for Signals

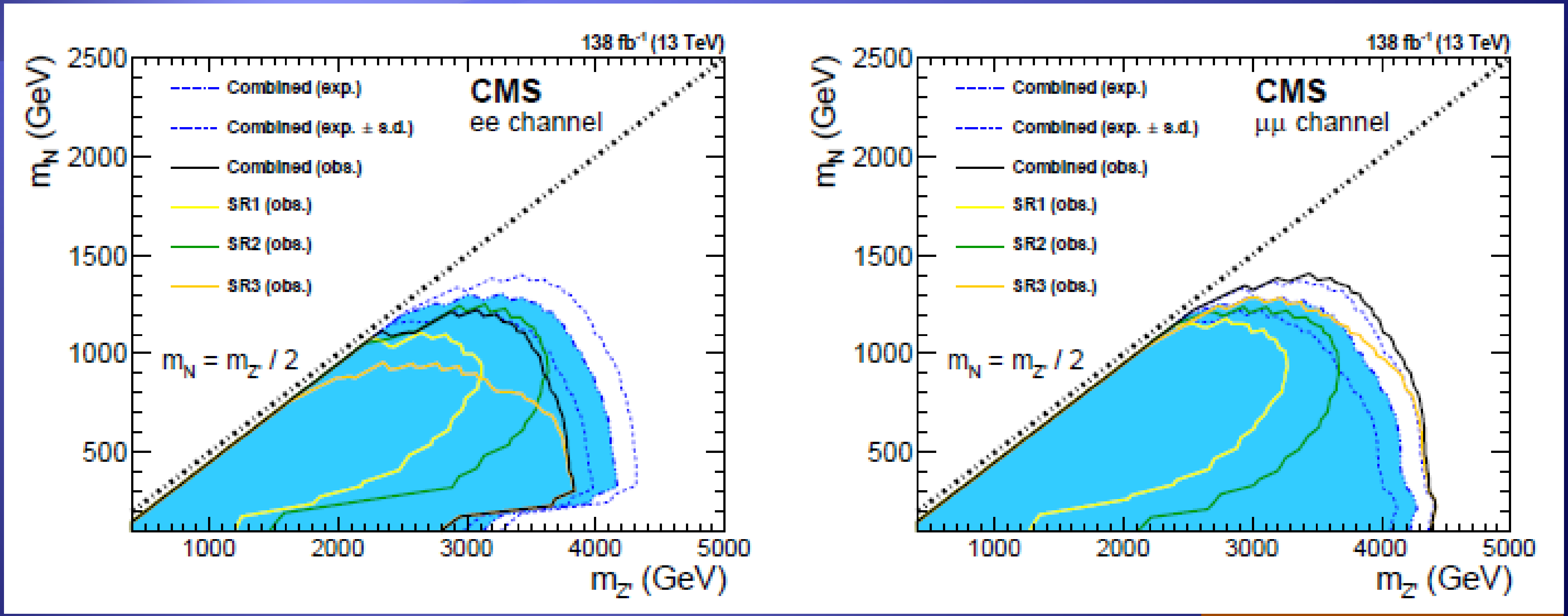
JHEP 11 (2023) 181



3.3 local significance in ee-channel (Z' = 4.6 TeV)

No excess in $\mu\mu$–channel

Searches results in LRSM (NC)



JHEP 11 (2023) 181

Z'_R are excluded up to ~ 4 TeV

Summary

- Neutrino oscillations attracts many interesting searches at the LHC: the origin of neutrino mass
  - Searches for heavy neutrinos provide a direct guide for the origin of neutrino mass (various Seesaw models, and LRSM etc)
- CMS has searched for heavy neutrinos but with no excess seen in data
  - Upper limits are set on $|V_{lN}|^2$
  - Exclusion on W_R mass up to 5.4 TeV
- Now we have accumulated ~500 fb^{-1}.
- Searches will continue… and a great potential for discovery with HL-LHC data (3000 fb^{-1})