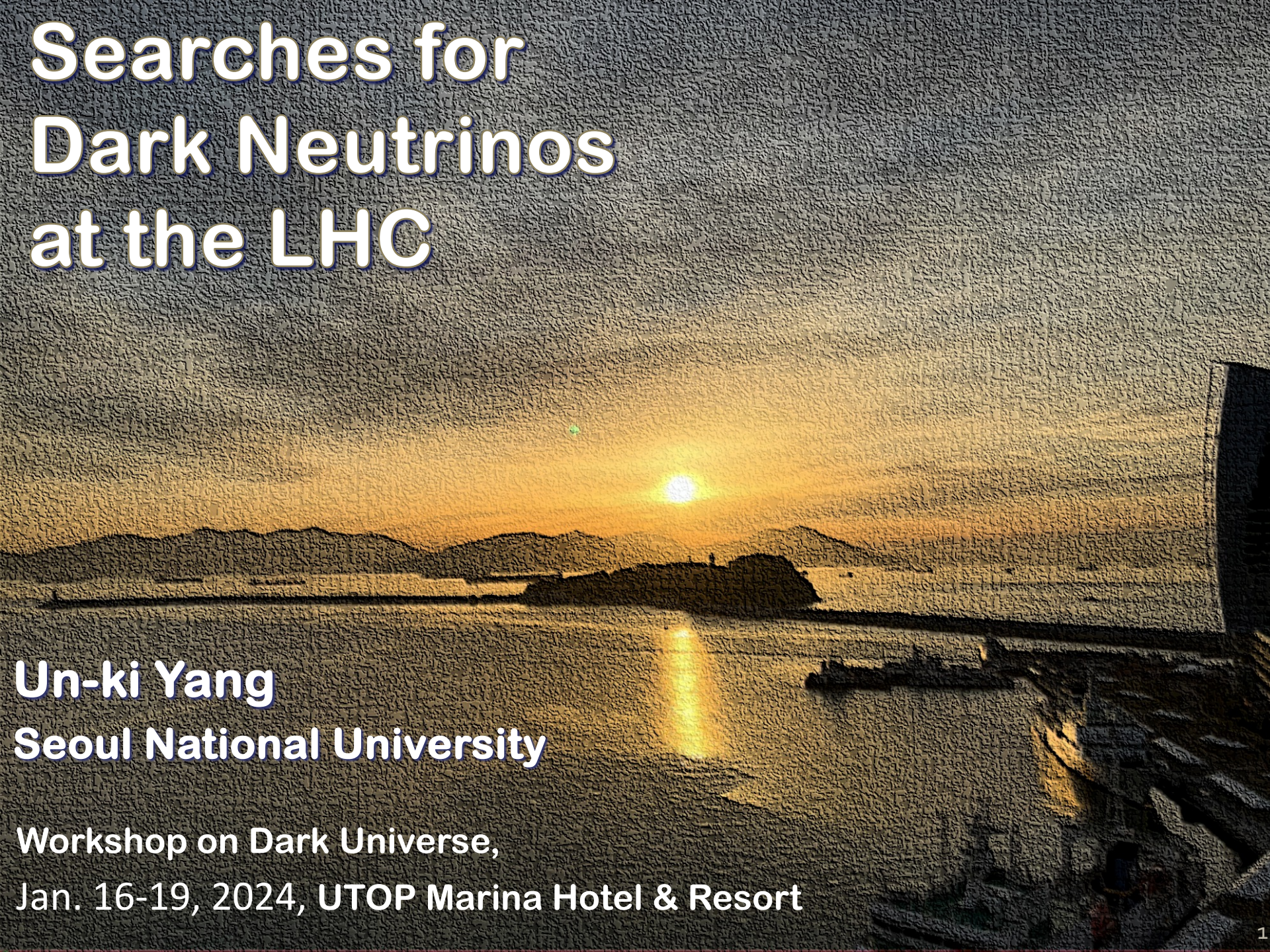
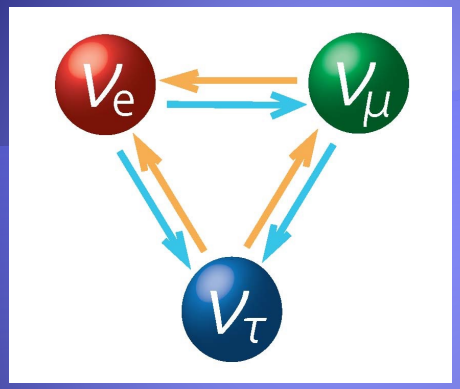
Searches for Dark Neutrinos at the LHC

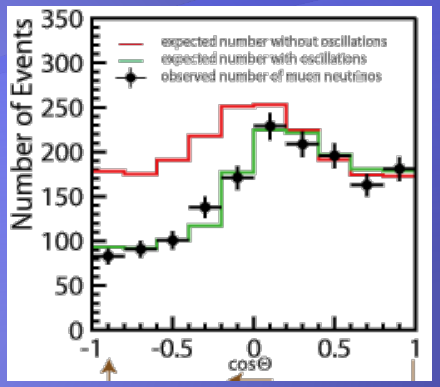


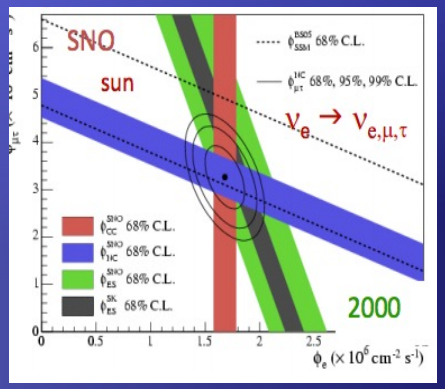
Un-ki Yang
Seoul National University

Workshop on Dark Universe,
Jan. 16-19, 2024, **UTOP Marina Hotel & Resort**

Right-handed Neutrino?

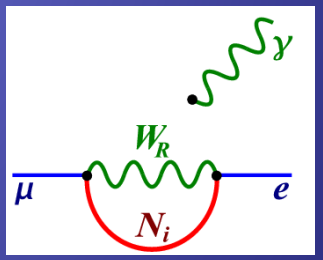


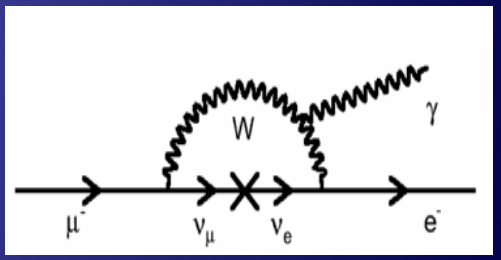




- Neutrino Oscillation!

- Small neutrino mass
- Right-handed neutrino





- Origin of neutrino mass
- CLN violation

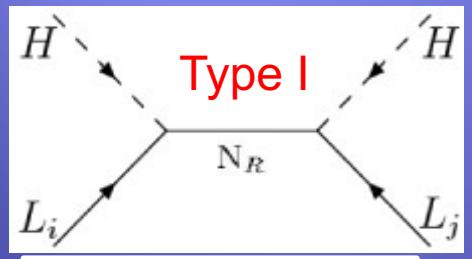
- Heavy Right-handed Neutrinos?
  not observed yet, dark neutrinos?

Neutrino: Physics Beyond SM

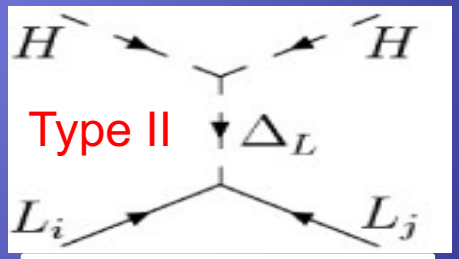
- A natural way to generate LNV and neutrino mass
  - Introduce an effective operators to the SM

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

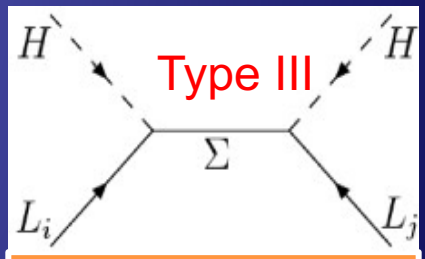
  - Seesaw Mechanism (type I, II, III)



Singlet Fermion (N_R)



Scalar triplet (Δ^{++}, Δ^{+} ,Δ)



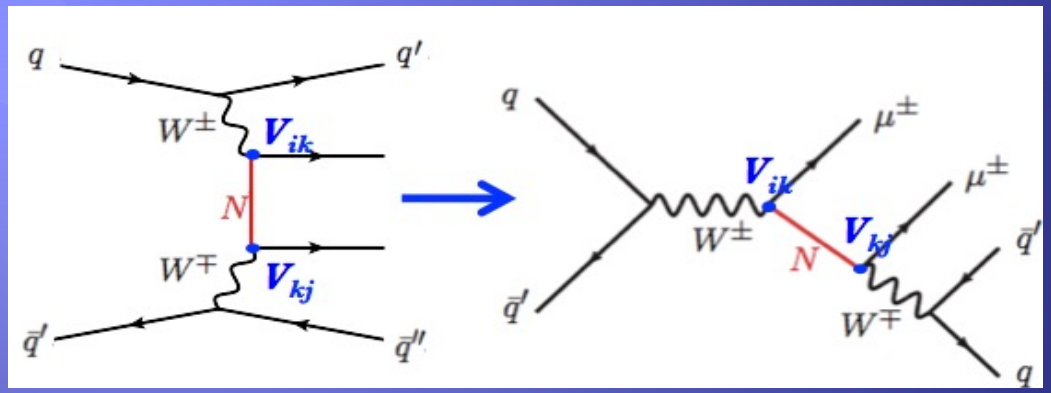
Triplet Fermion (Σ^0, $\Sigma^{+/-}$)

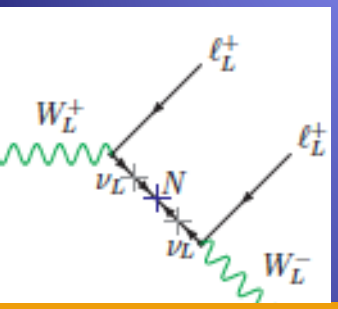
- Physics behind the Seesaw? Left-Right Symmetry model (LRSM) offers the Seesaw scale and heavy dark neutrinos (HN)

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

Search for HN at the LHC

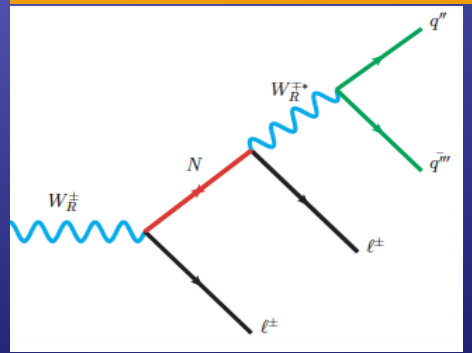
- Direct production of HN (N_R)
  - Complementary program to the $0\nu\beta\beta$

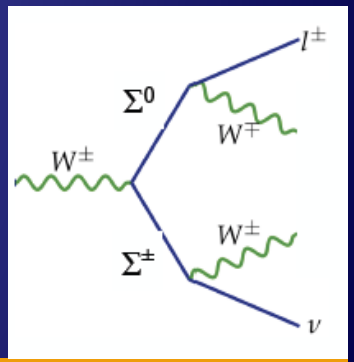




1. Type-I seesaw
- Right-handed N_R
- Only mix with SM ν

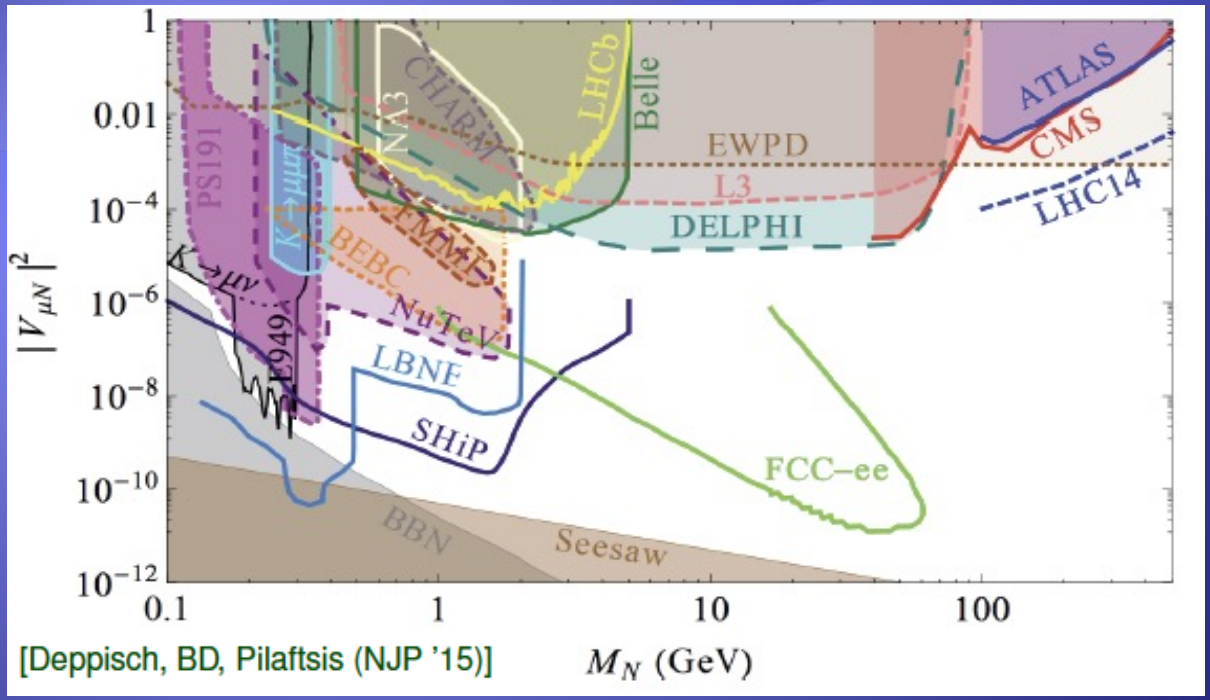
2. LRSM
- Right-handed N_R
- N_R couple to RH bosons, W_R,Z_R



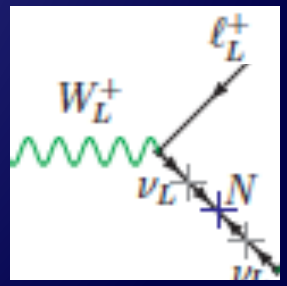


3. Type-III seesaw
- at least two $SU(2)_L$ triplets (Σ^0, $\Sigma^{+/-}$) couple to SM gauge bosons

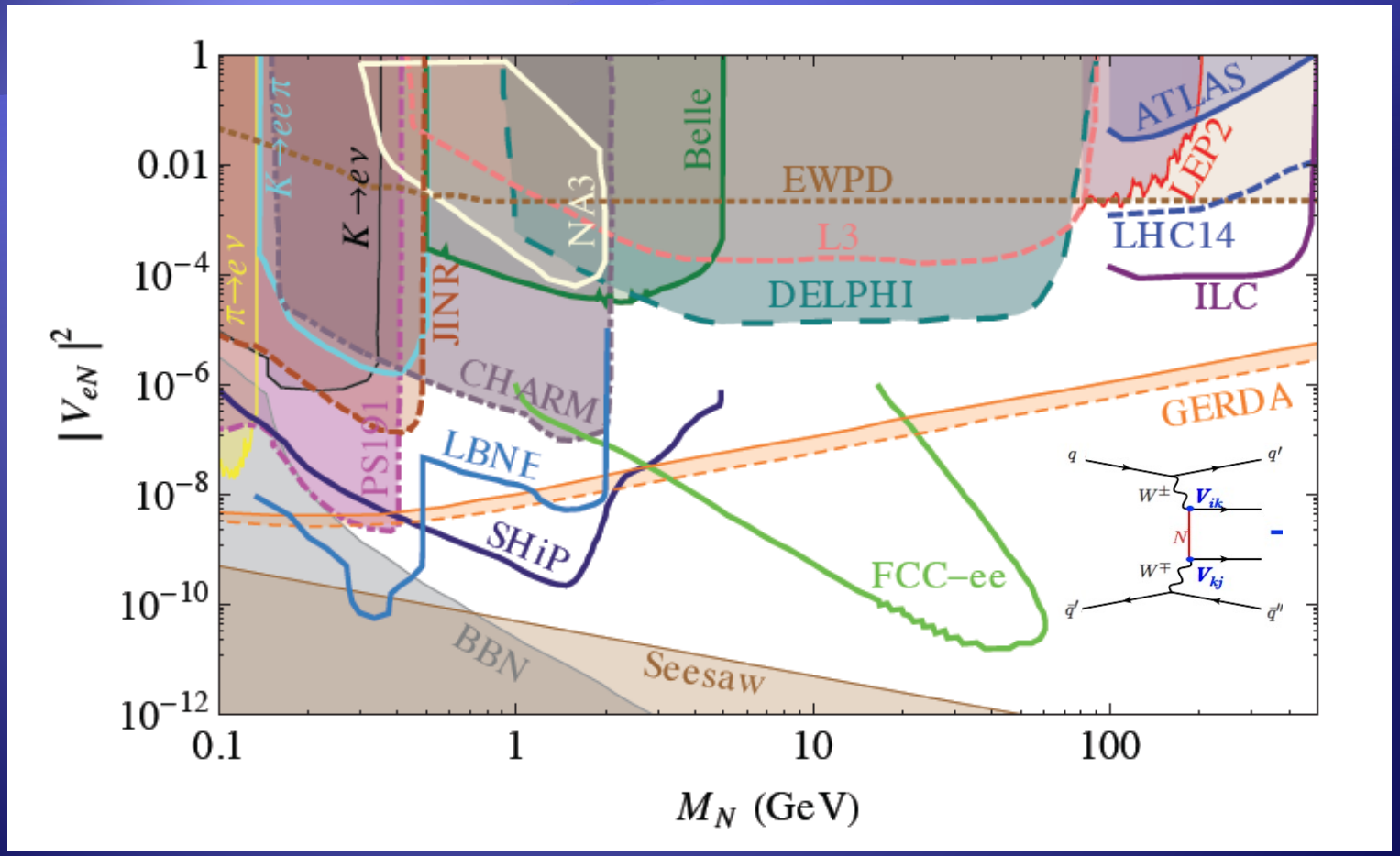
N_R searches for 40 years



- 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: $Z \to \nu N$ (LEP), and $W \to \mu N$ (LHC)
- m_N> ~90 GeV: $W \to \mu N$ (LHC)

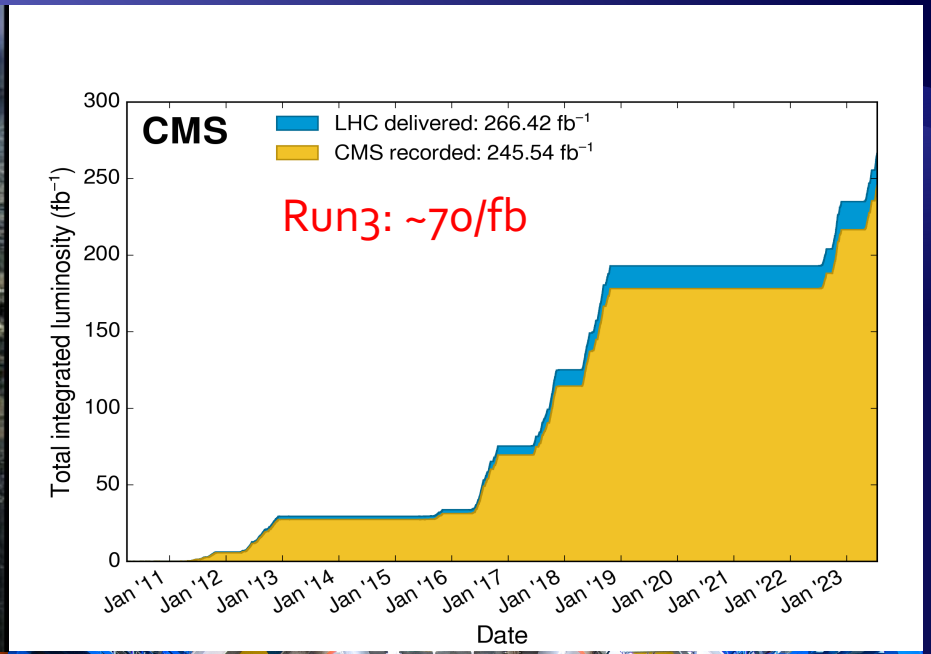


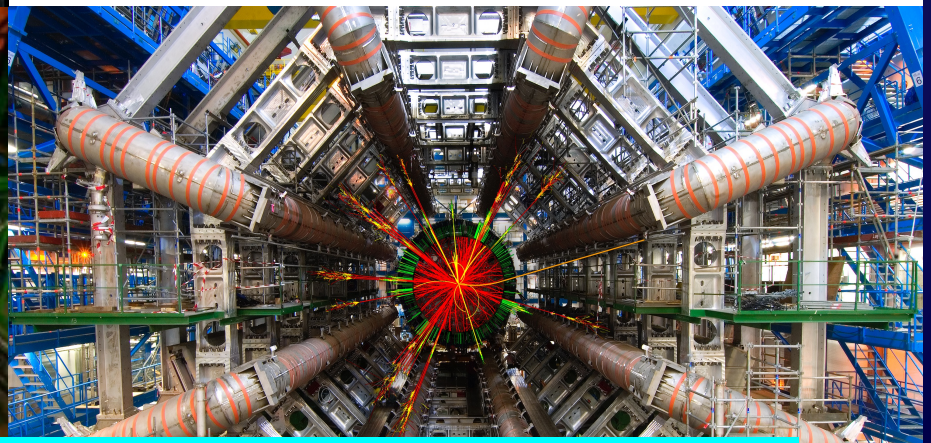
N_R searches (electron channel)



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

Use the Large Hadron Collider!





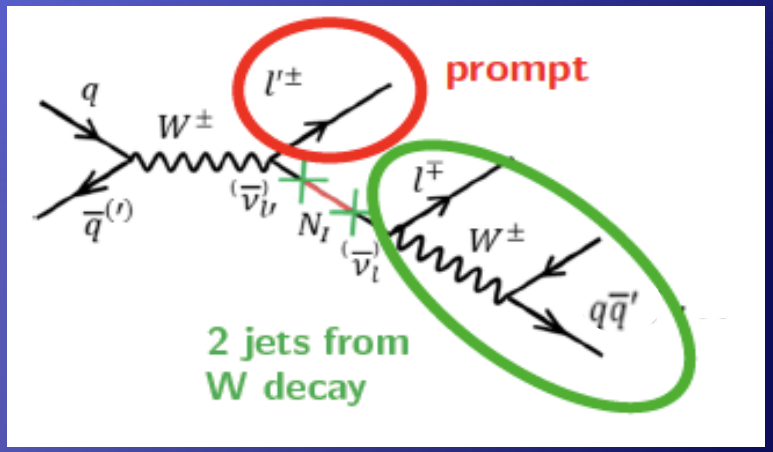
- **Multi-purpose detectors at LHC: ATLAS & CMS**
- **Great LHC performance and impressive data taking**

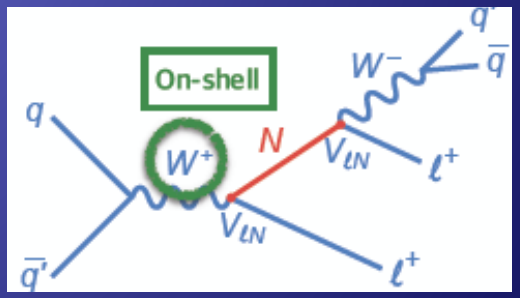
Type-I N_R search in dilepton

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

$e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$

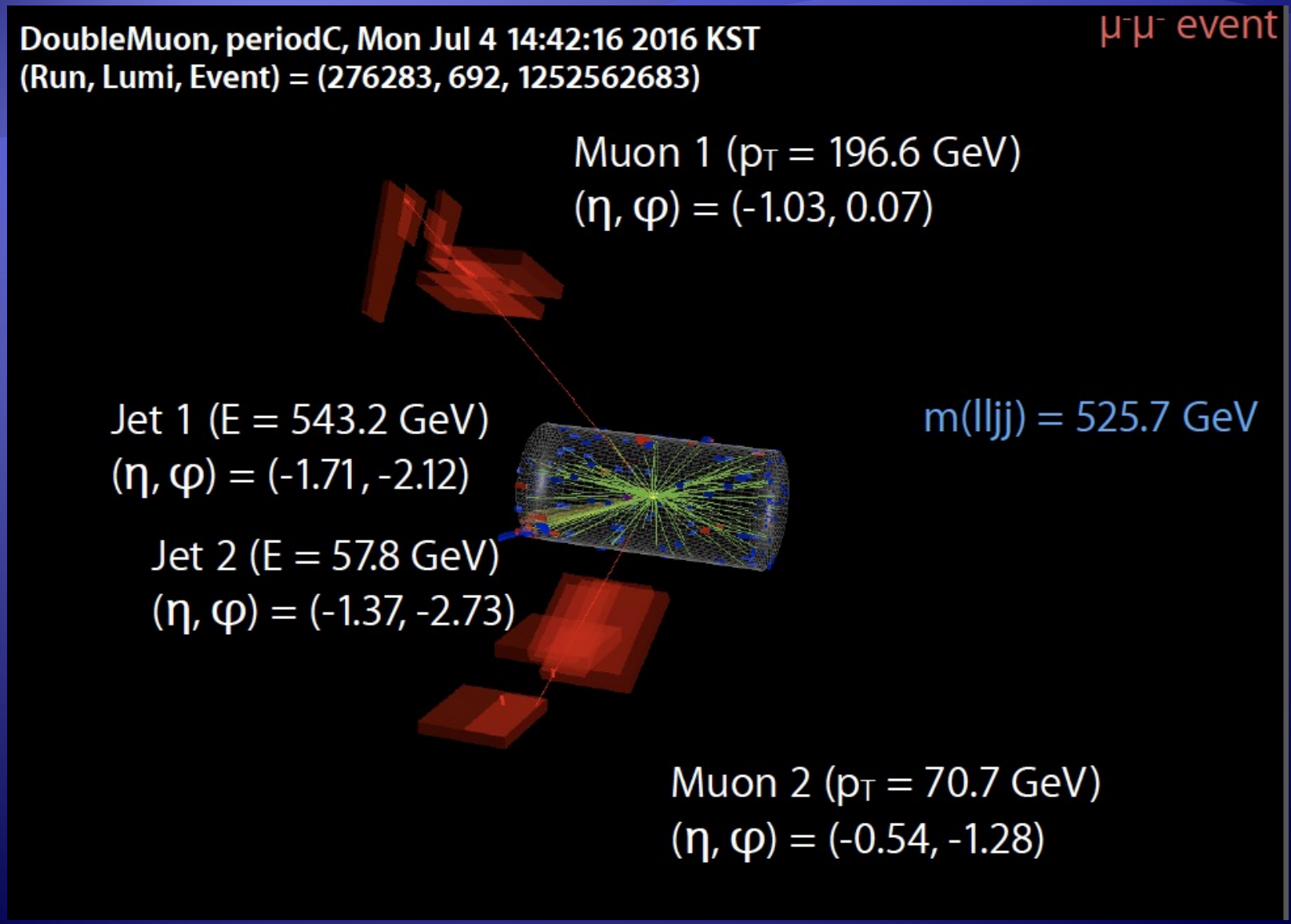
$|V_{eN}|^2$, $|V_{\mu N}|^2$, $\dfrac{|V_{eN}V_{\mu N}^*|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}$





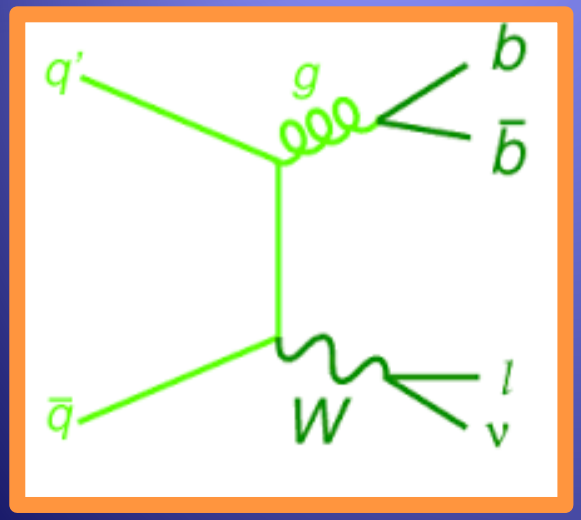
- Different search strategy for low mass ($m_N < m_W$) and high mass ($m_N > m_W$)

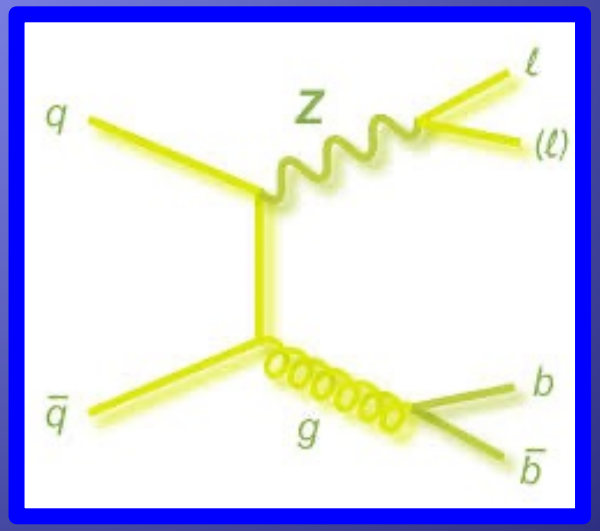
SS Dimuon + 2 jets event observed in the CMS detector



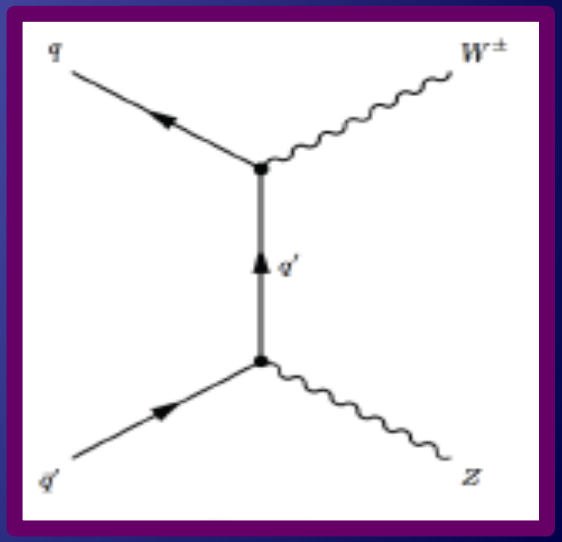
Backgrounds: ee/μμ/eμ+2 jets

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





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

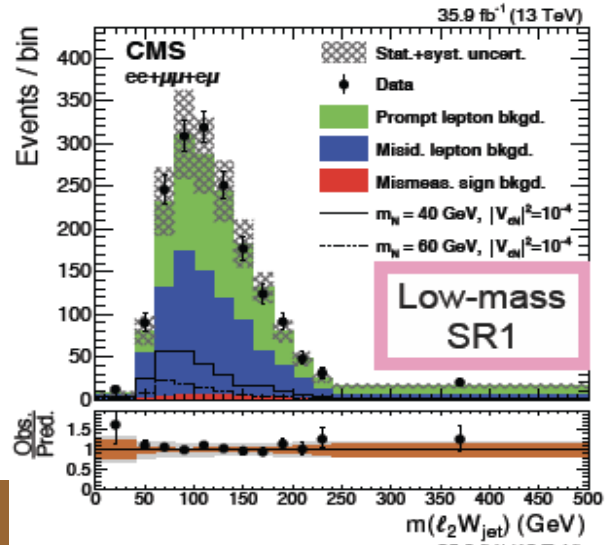


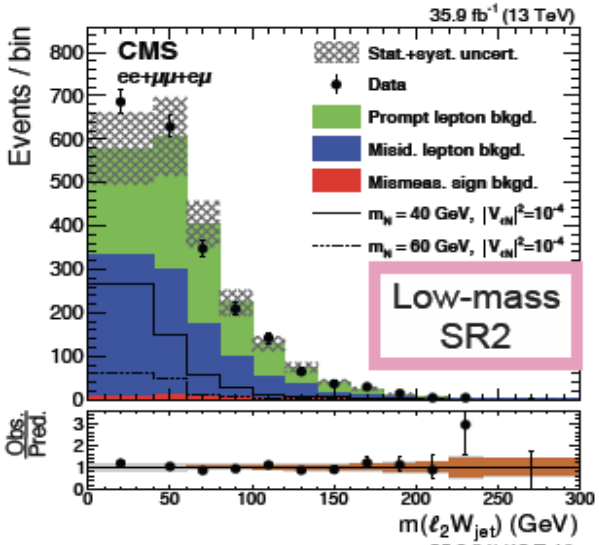
Charge-flip: "data+MC"
Z(ll)+2jets

CMS Results at 13 TeV

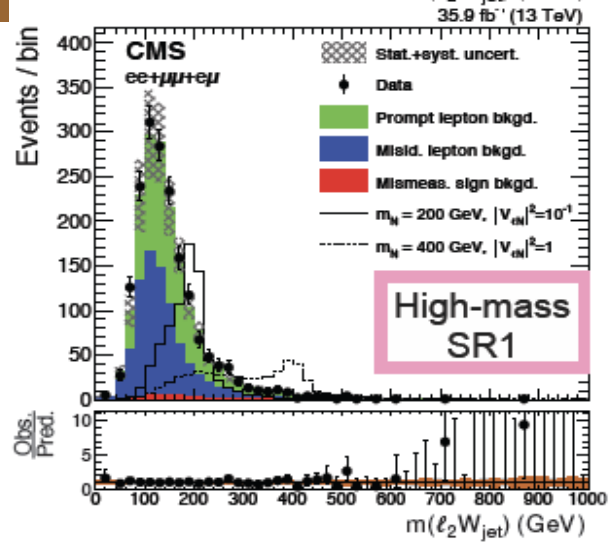
Mass (N_R)

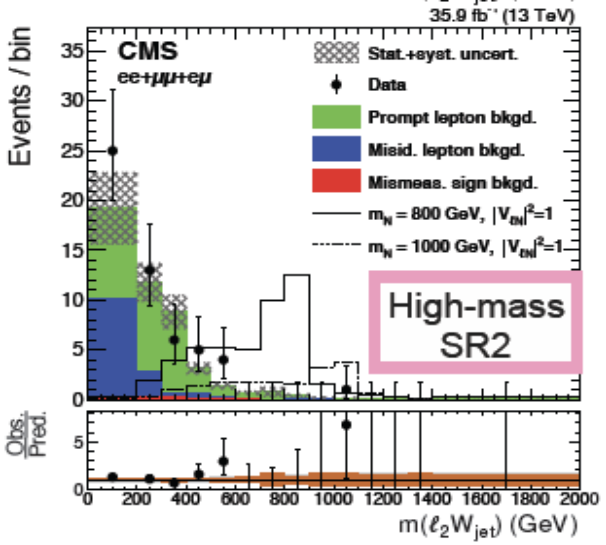
SR1: W: 2 jet





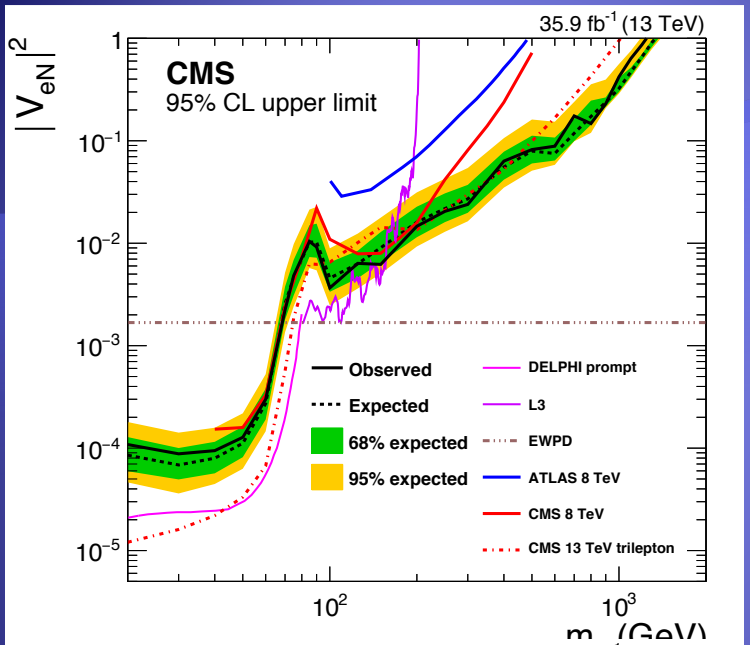
SR2: W: 1 jet

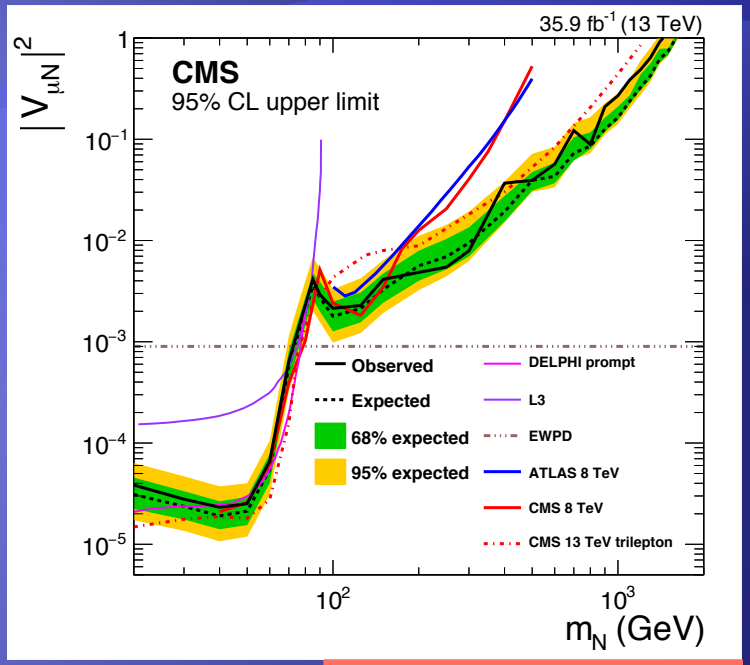




No significant deviation from the SM

Results on the Search





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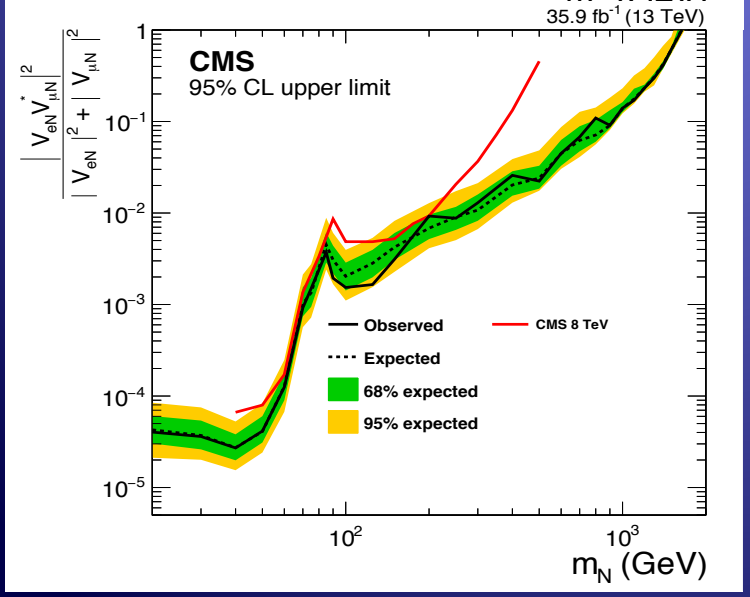
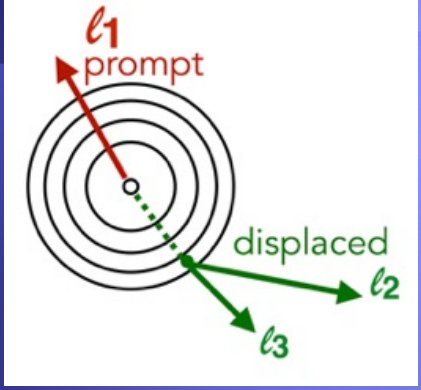


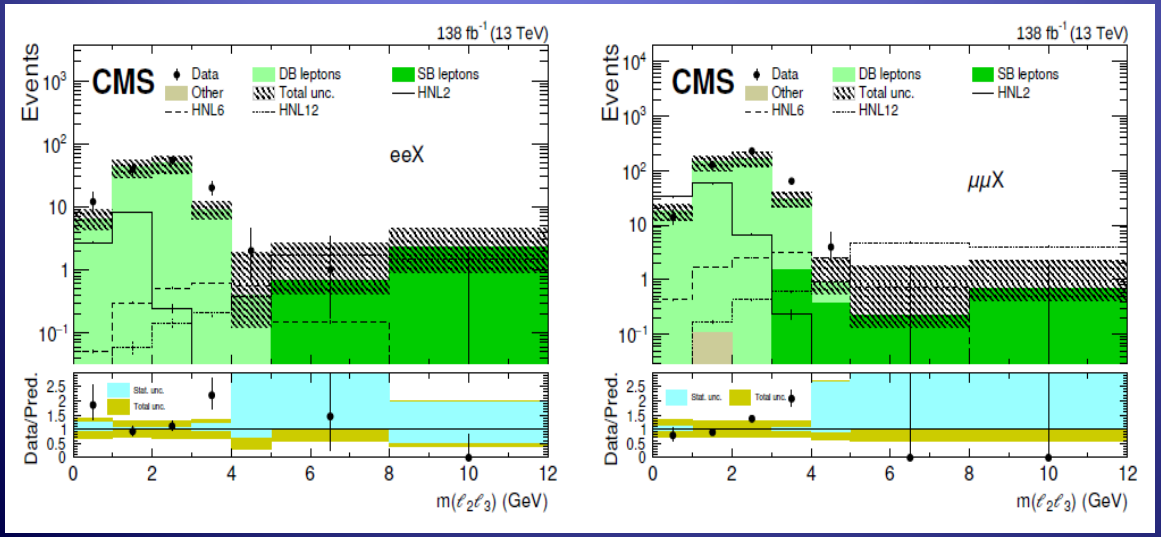
- LHC provides the best direct limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$, & $|V_{eN}{}^*V_{\mu N}|$ for high m_N
  - CMS limits down to 20 GeV, and up to 1.2 TeV
  - Lepton flavor mixing case by CMS

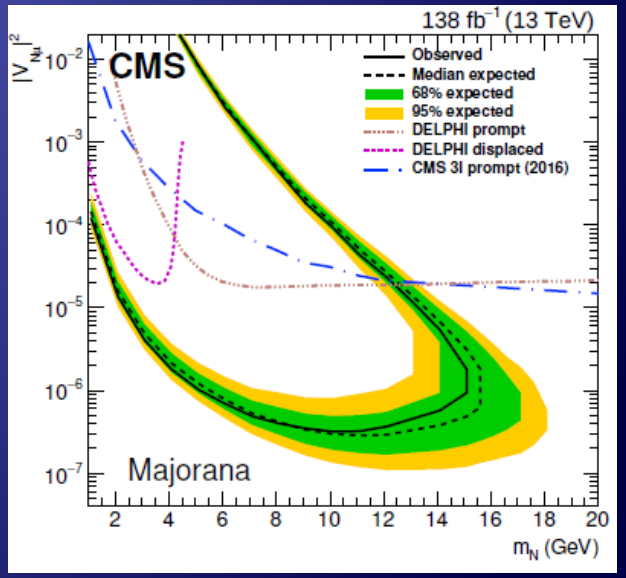
2016 data only

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

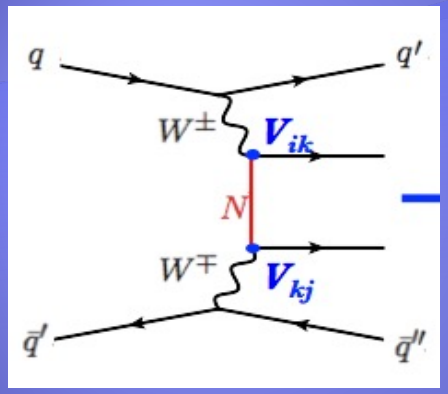




JHEP07 (2022) 081

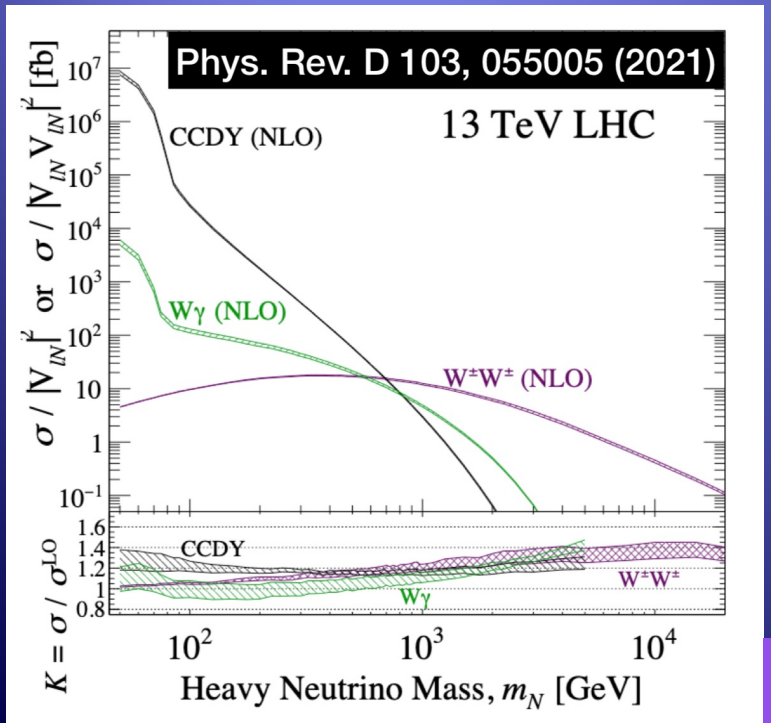
Very heavy mass, N

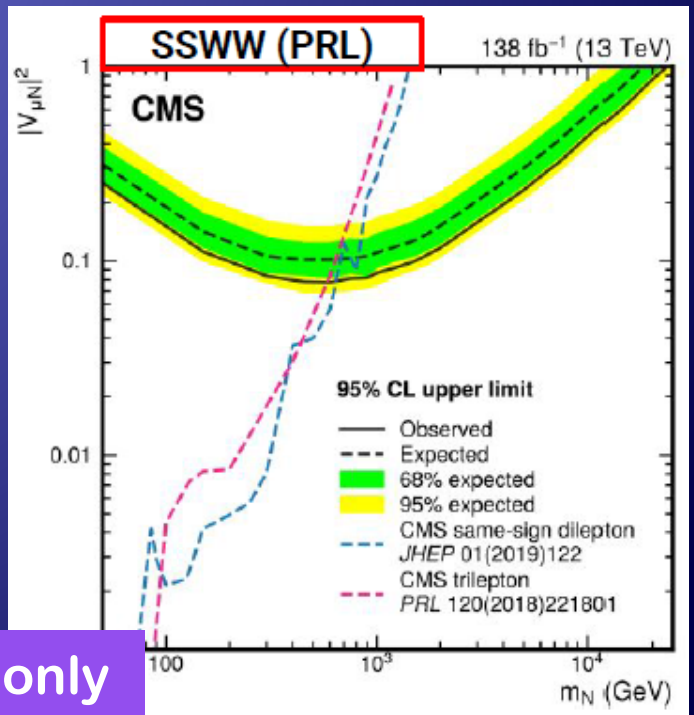
- Neutrino-less double beta decay channel (WW)



Very effective at high mass
m_N> 1 TeV

PRL 131 (2023) 011803





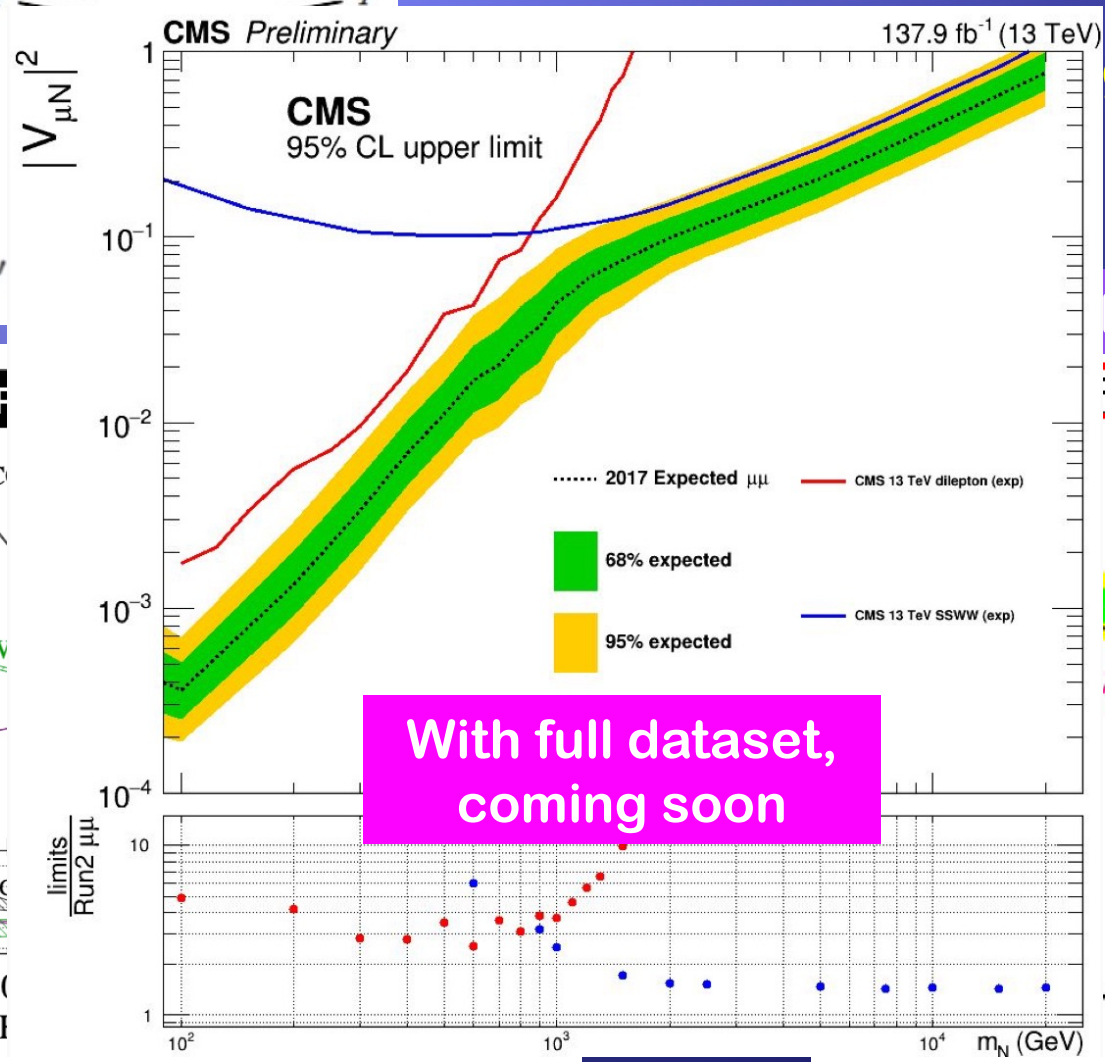
dimuon only

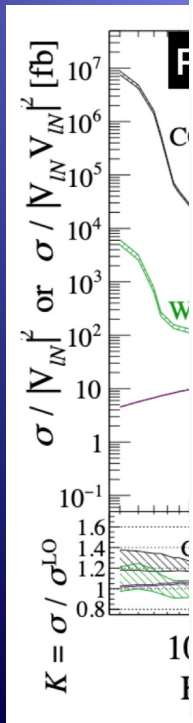
Very heavy mass, N

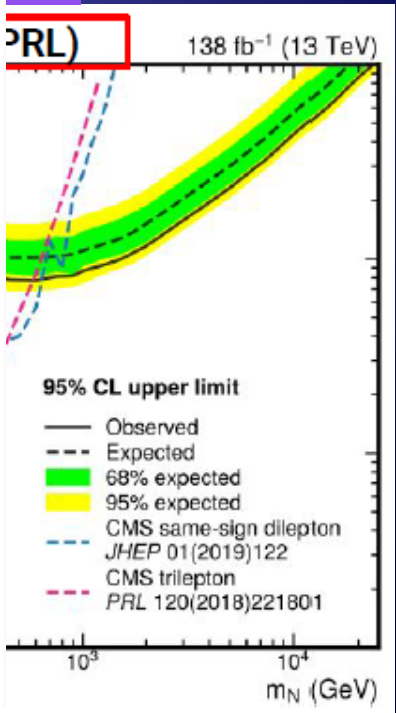
- Neutrino-less double beta decay channel (WW)

gh mass

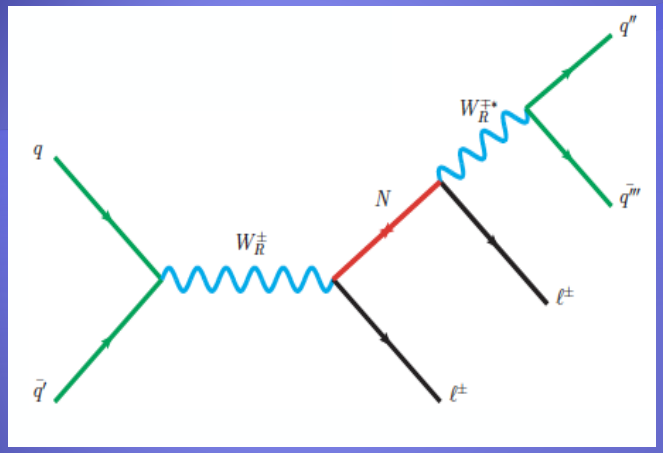
ly







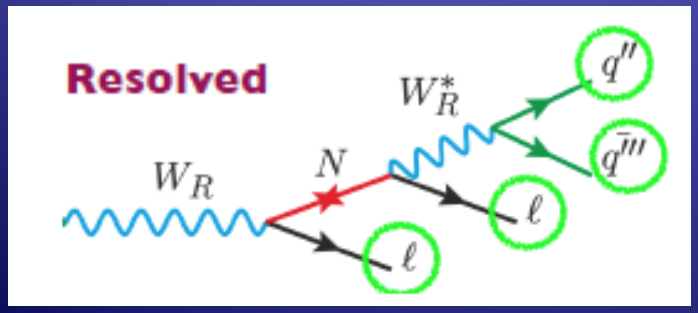
Searches in LRSM

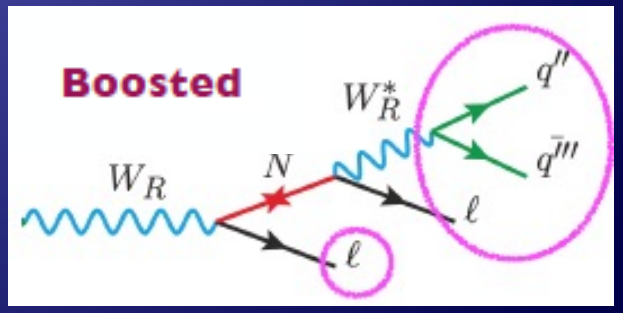


Same Final state as type-I
But different kinematics

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

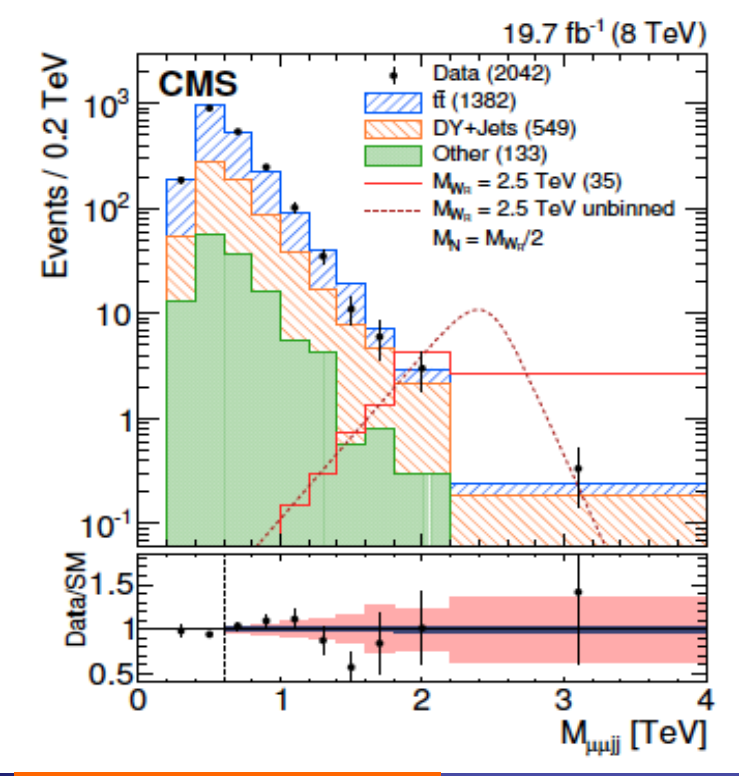
- For $m_N << m_{WR}$, jets and lepton from N decays overlap
  → requirement of lepton isolation will kill signal
  → use boosted jet to resolve lepton and jet
- Signal topology: resolved and boosted





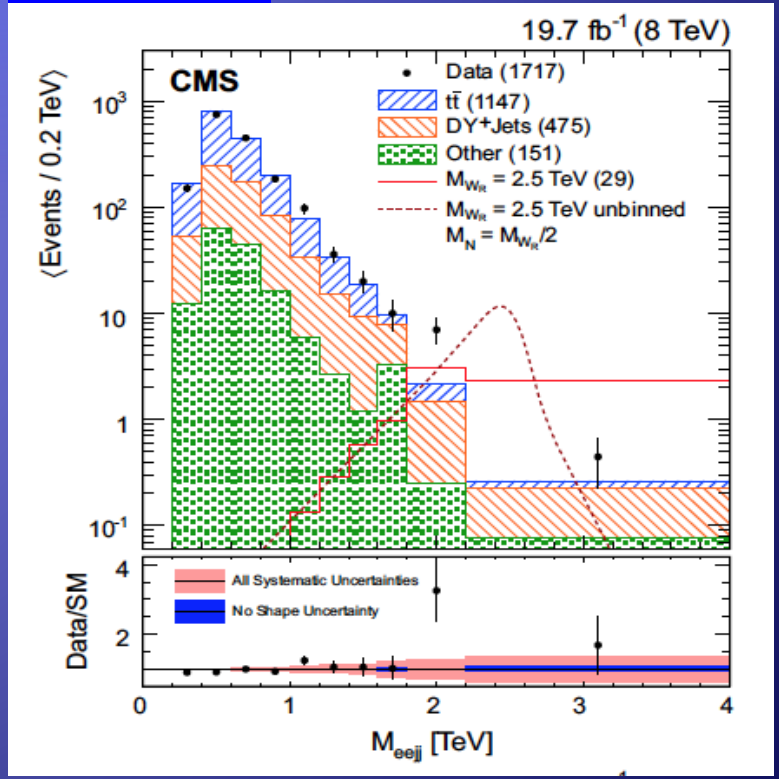
Interesting Run 1 results from CMS

μμ channel



EPJ C74 (2014) 3149

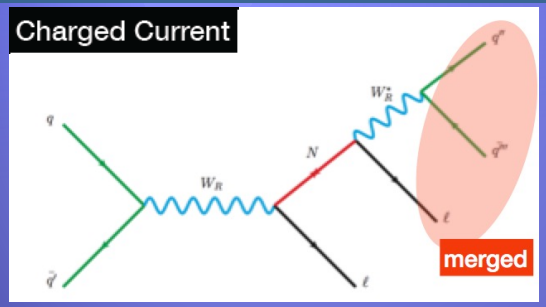
ee channel

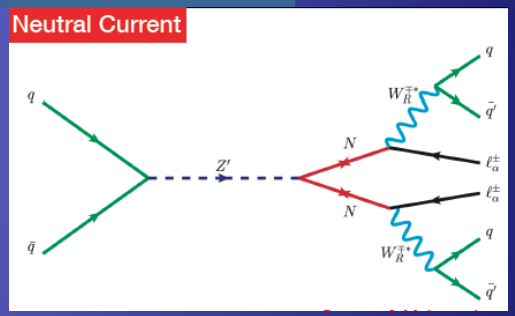


- **A local significance, 2.8σ effect**
- **Consistency with the LRSM?**

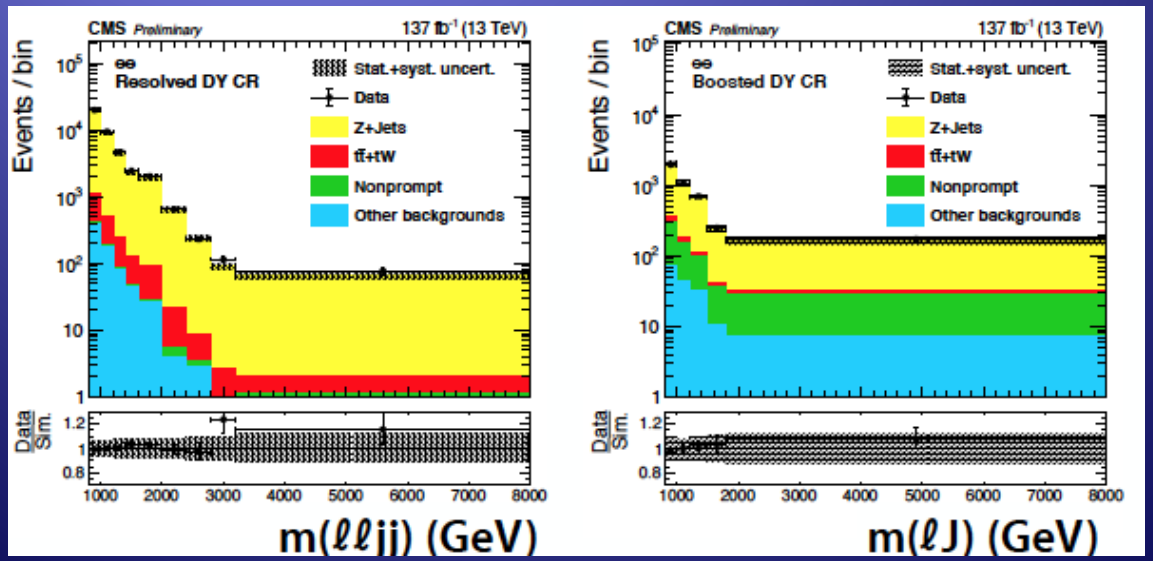
N_R searches in LRSM

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

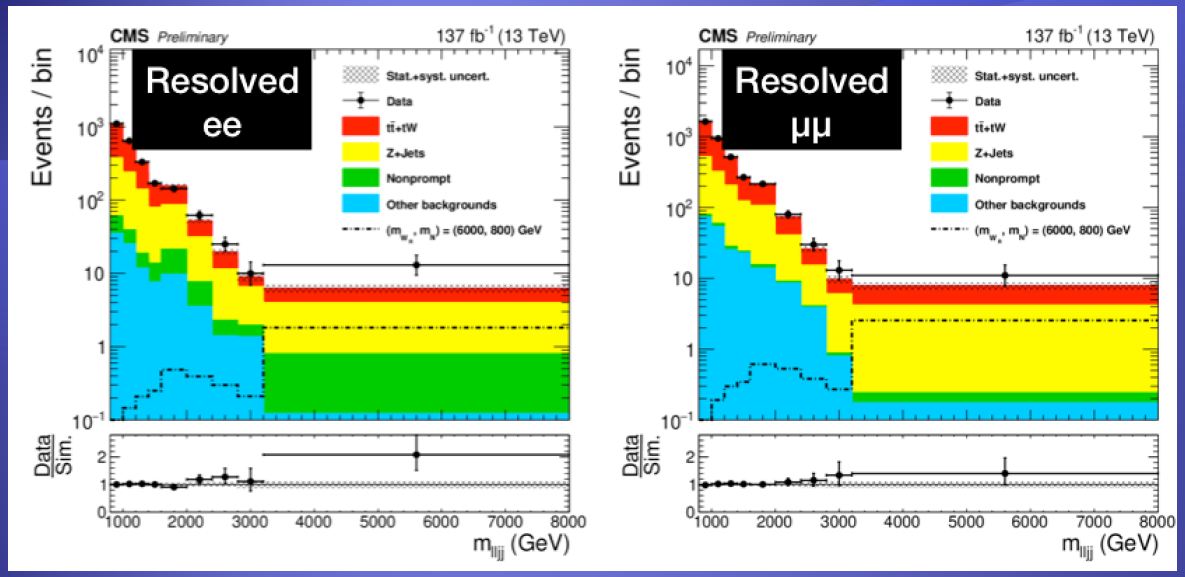




- CC: Control region (Drell-Yan)



Search results for N_R



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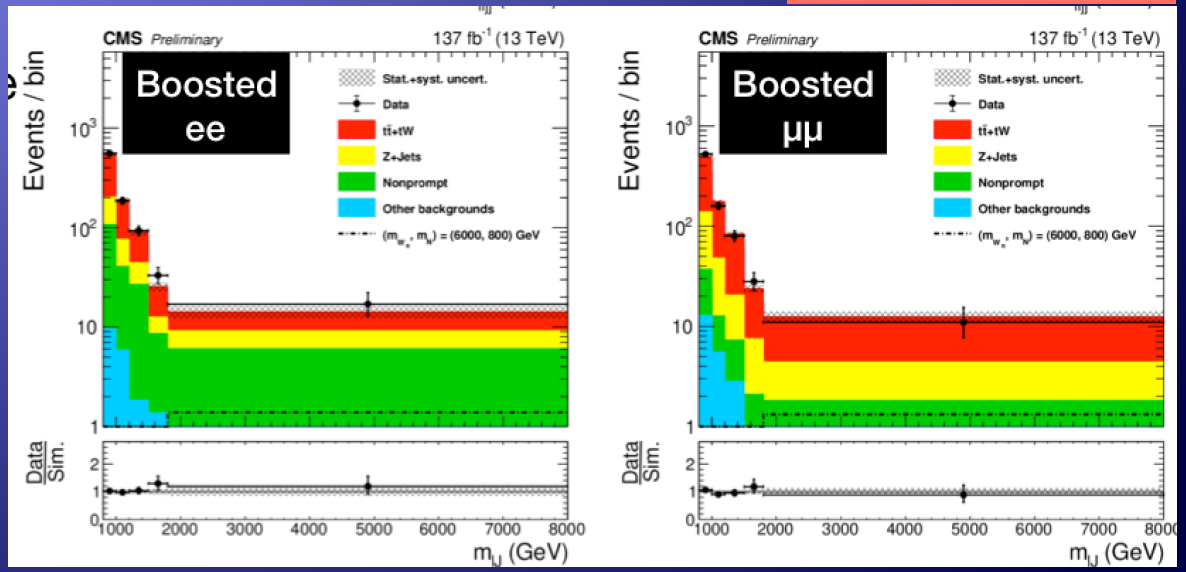
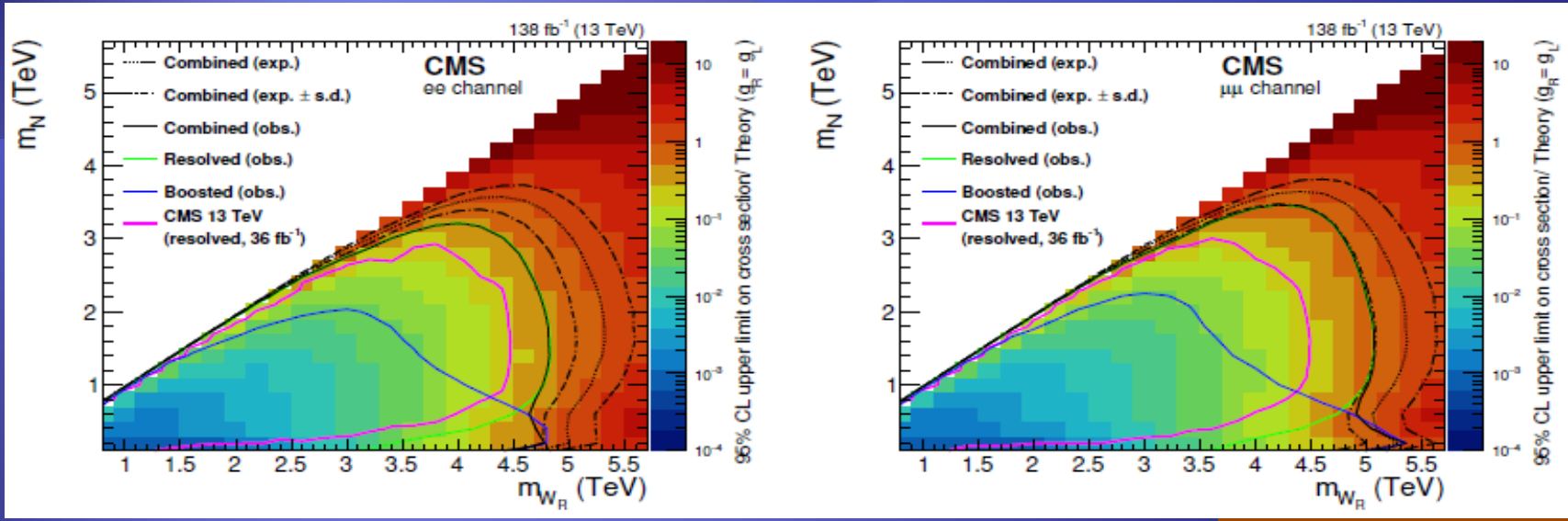


No significant Excess shown

LRSM results for N_R



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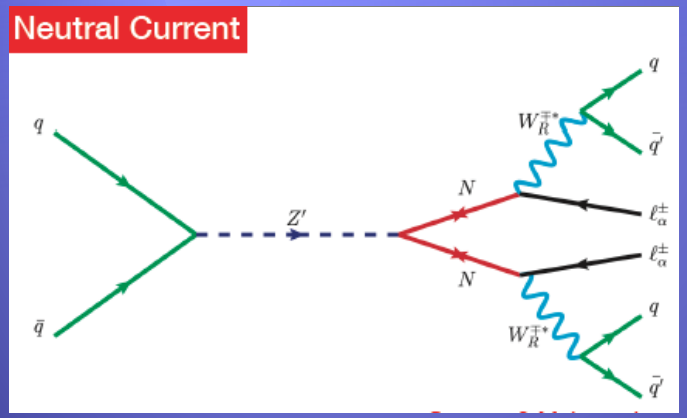
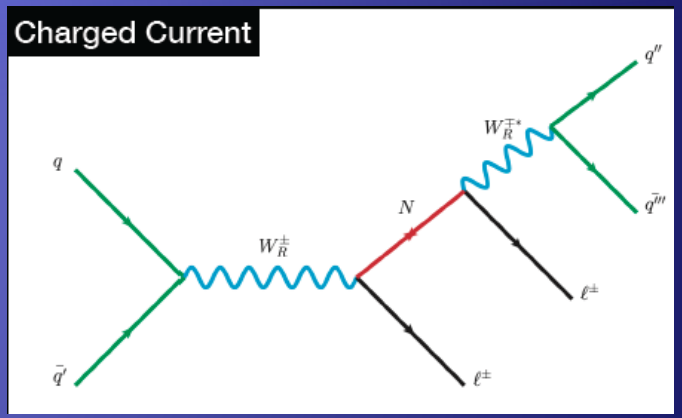
Exclusion limits are improved

- 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=m_{W_R}/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

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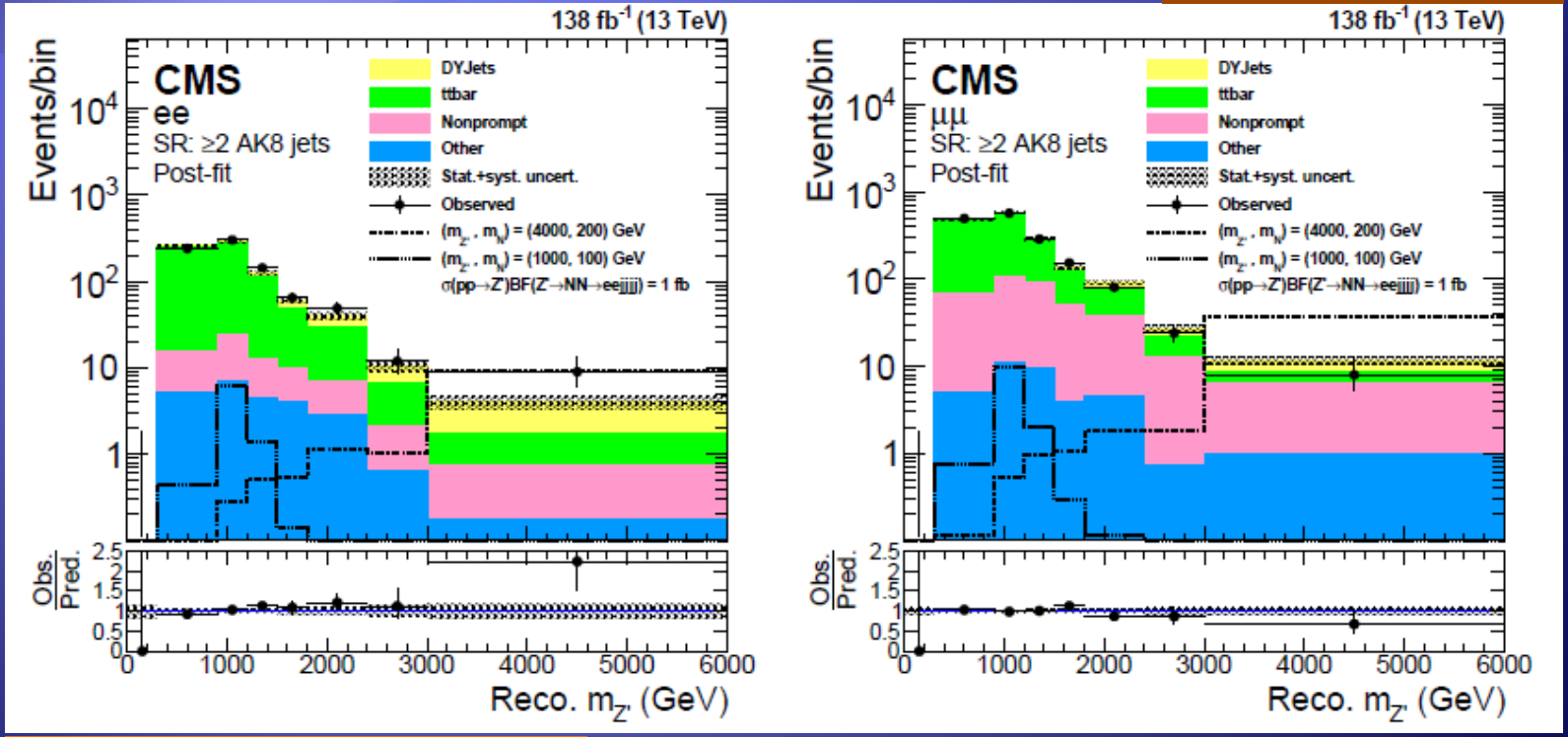
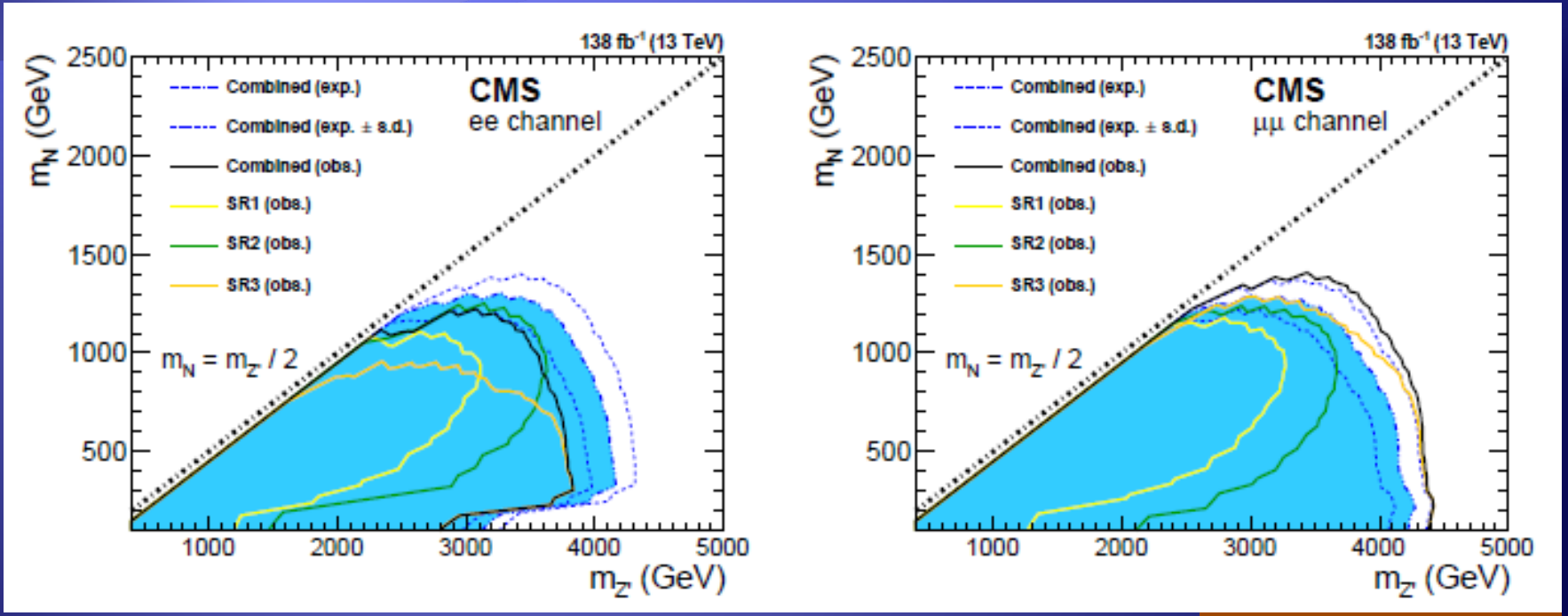


3.3 local significance in ee-channel (Z' = 4.6 TeV)

No excess in μμ–channel

Searches results in LRSM (NC)



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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 $|V_{IN}|^2$
  - Exclusion on W_R mass up to 5.4 TeV

- Run 3 started from last year, we expect to get 300 fb^{-1}. Searches will continue… and a great potential for discovery with HL-LHC data (3000 fb^{-1})