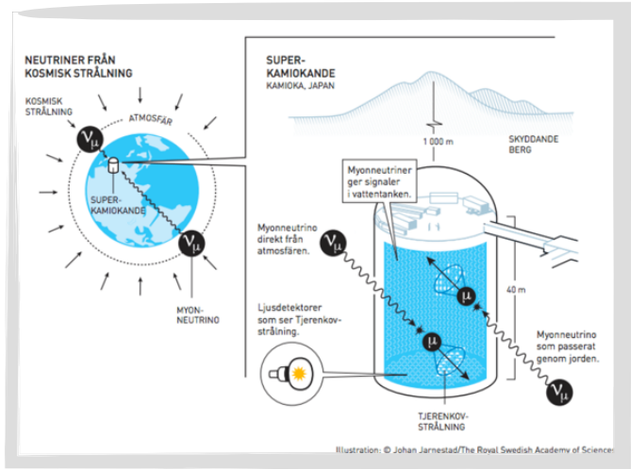
Test of Neutrino Mass Models at CMS

Sitian Qian (PKU), *on behalf of CMS Collaboration*

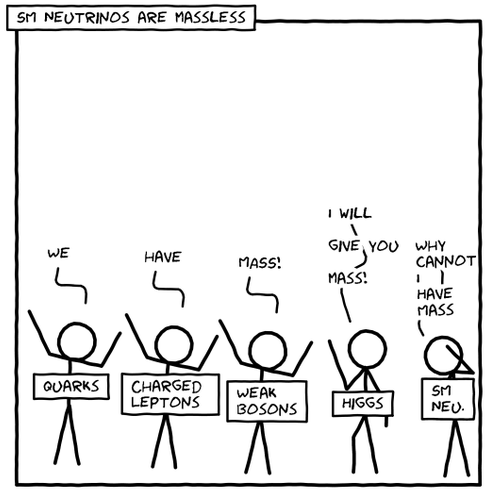
NUFACT 2022, Salt Lake City

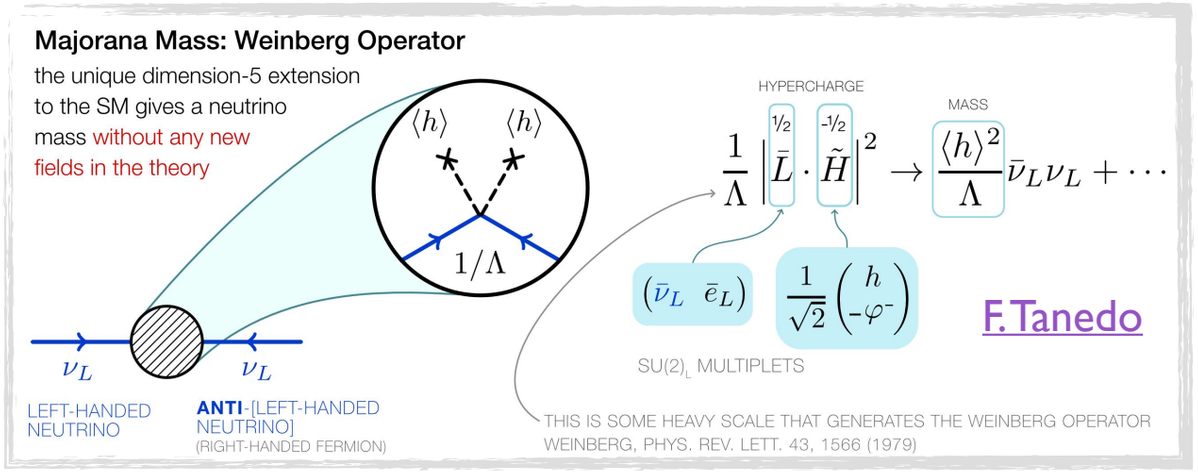
July 31st - August 6th, 2022

Introduction



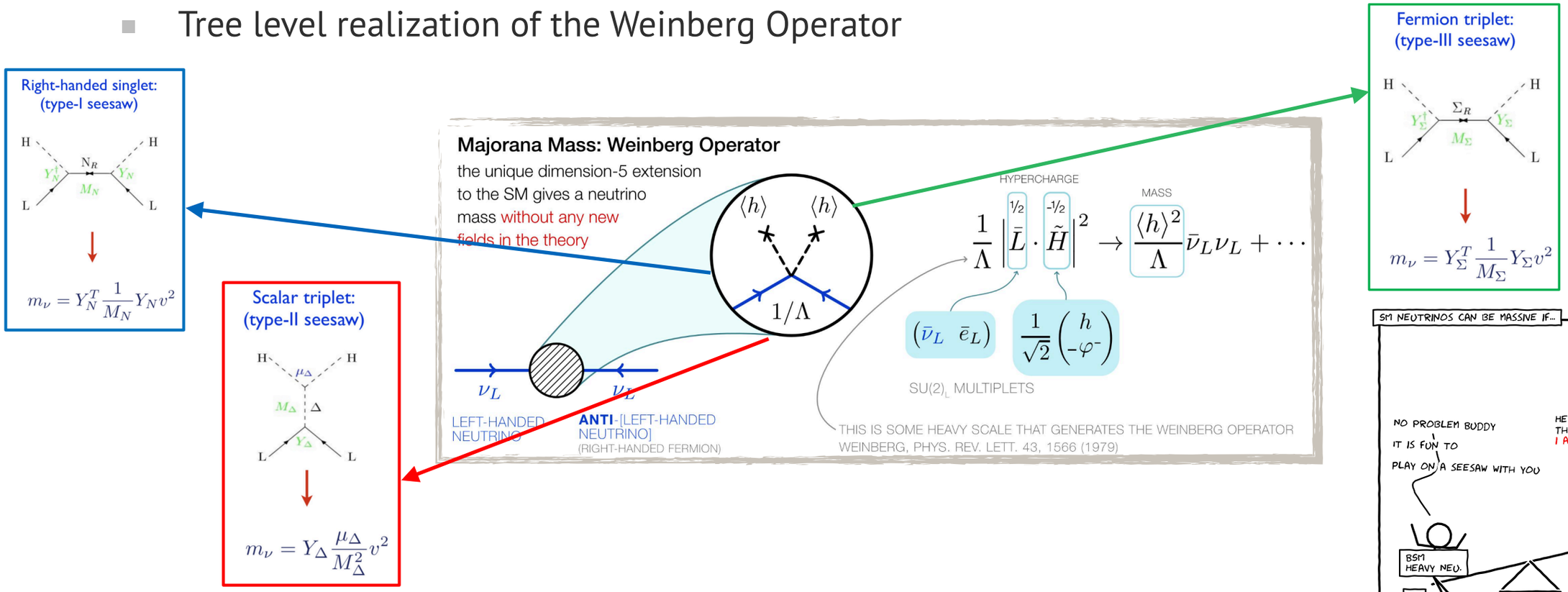
- Neutrino mass:
  - Confirmed by Neutrino Oscillation experiments
  - Beyond the Standard Model (SM) description
- In the context of SM, neutrinos have to be massless because:
  - $SU(2)_L \times U(1)_Y$ symmetry group for EW theory & Dimension-4 operators only
  - Economical particle content:
    - Only left handed neutrinos: Dirac mass term is forbidden
    - Only one neutral Higgs doublet: Majorana mass is forbidden
- Neutrino mass can be explained with:
  - Model independent operators from effective field theory:
    - Example: Majorana mass term introduced by the dimension-5 Weinberg Operator





Introduction

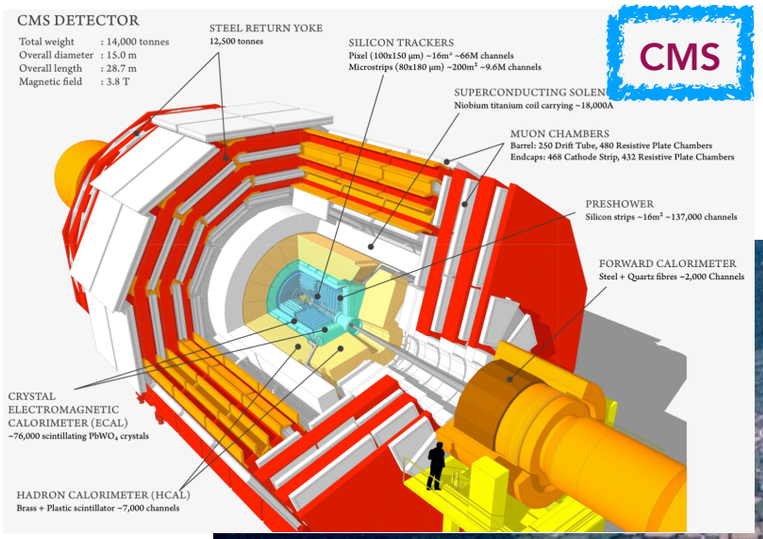
- Neutrino mass can be explained with:
  - Specific Beyond the Standard Model (BSM) theory with UV completeness
    - Example: Seesaw models
      - Tree level realization of the Weinberg Operator

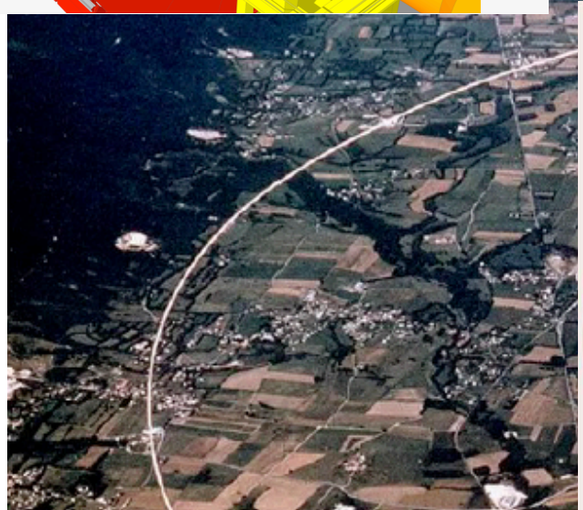


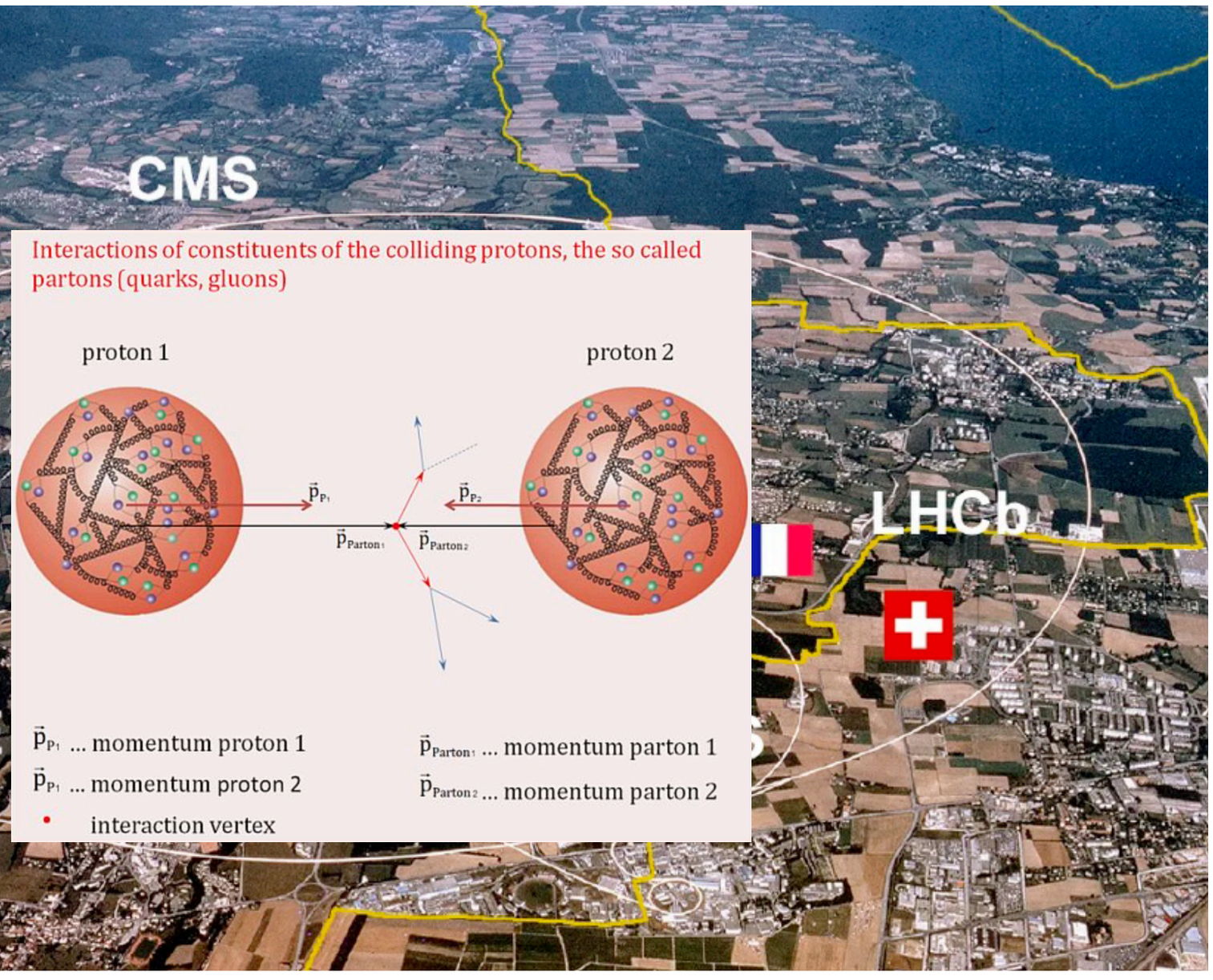
        - Why named with "Seesaw"?: **Heavier** BSM particles leads to **lighter** SM neutrinos
    - Seesaw models and their variations become the neutrino mass generation mechanism of many complicated BSM models
      - Example: Left Right Symmetric Model (LRSM) introduces heavy right handed neutrino (type-I seesaw) but generate neutrino masses with extra scalar fields (type-II seesaw like).

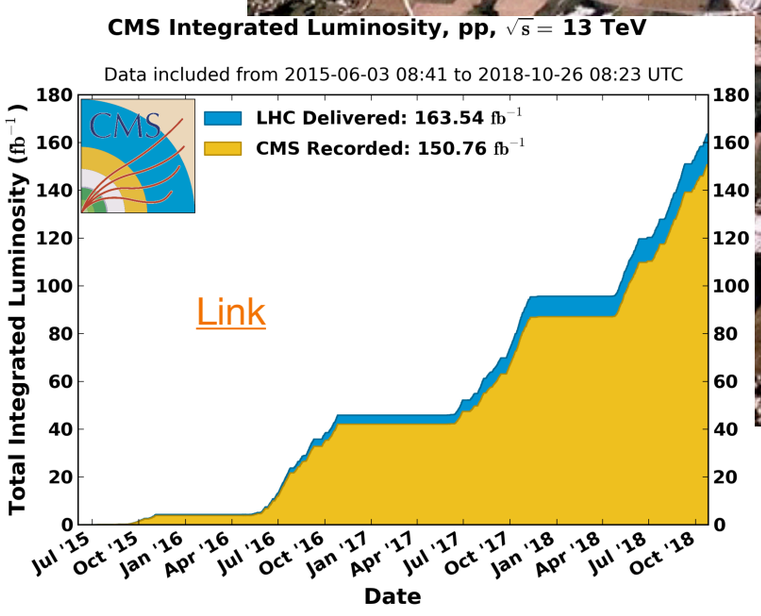
Compact Muon Solenoid @ Run-II

Compact Muon Solenoid (CMS): A multi-purpose detector at the Large Hadron Collider (LHC)









~ 140 /fb proton-proton collision data collected during LHC Run-2

Today's focus

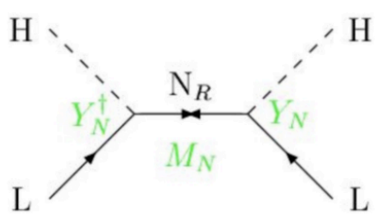
- Latest results from CMS on neutrino mass models!
  - Type-I seesaw model:
    - Probing heavy Majorana neutrinos & Weinberg Operator via Vector Boson Fusion (VBF)
      - EXO-21-003, arXiv: 2206.08956
    - Long-lived heavy neutral leptons with displaced vertices
      - EXO-20-009, JHEP07(2022)081
  - Type-III seesaw model:
    - Inclusive nonresonant multilepton probe for new physics
      - EXO-21-002, PhysRevD.105.112007
  - Heavy Composite Majorana Neutrino
    - Two same-flavor lepton and two jets final state
      - EXO-20-011
  - Left-Right Symmetric Model
    - W_R decay to heavy right handed neutrino
      - EXO-20-002, JHEP04(2022)047
    - Z' boson decaying to pairs of heavy Majorana neutrinos
      - EXO-20-006
  - Prospects of High Luminosity LHC (HL-LHC)
    - Inclusive nonresonant multilepton probes of type-I and type-II seesaw models.
      - FTR-22-003

PROBING **HEAVY MAJORANA NEUTRINOS** & WEINBERG OP. VIA VBF

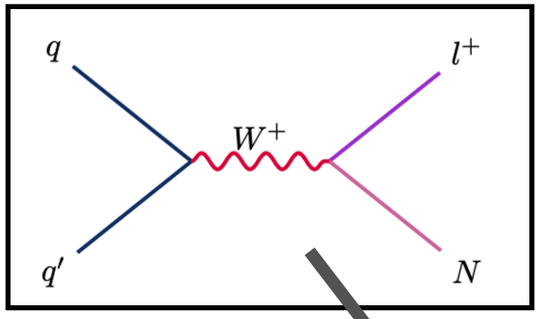
EXO-21-003
arXiv: 2206.08956

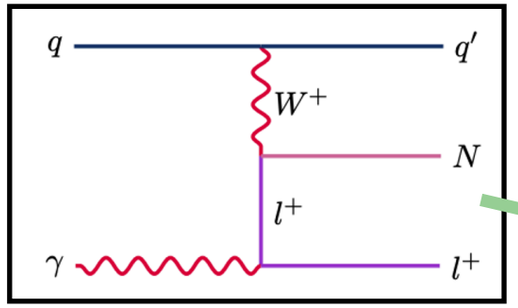
Type-I Seesaw Heavy Majorana neutrino (**HMN**) **only interacts with the SM neutrinos:**
$\nu_{\rm SM} \Leftrightarrow N$ **mixing** with probability $|V_{\ell N}|^2$

Right-handed singlet:
(type-I seesaw)



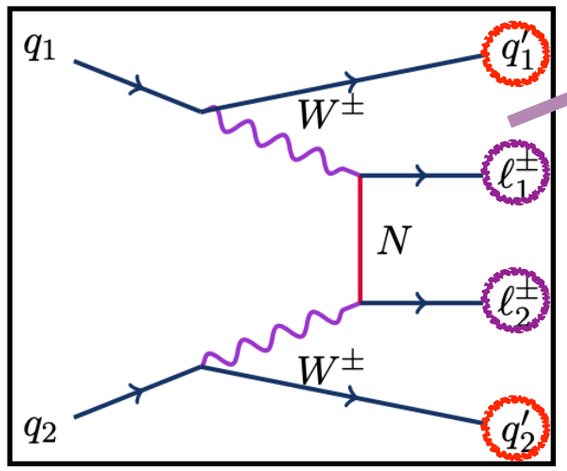
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

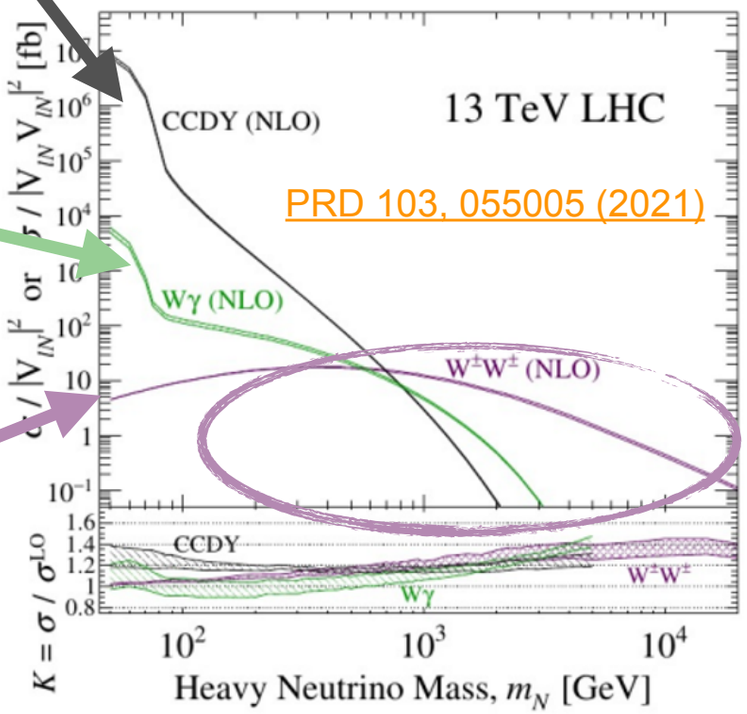




VBF production of Type-I Seesaw HMN

$$\sigma^{\ell\ell'}(s) \equiv \left|V_{\ell N} V^*_{\ell' N}\right|^2 \times \sigma_0^{\ell\ell'}(s)$$





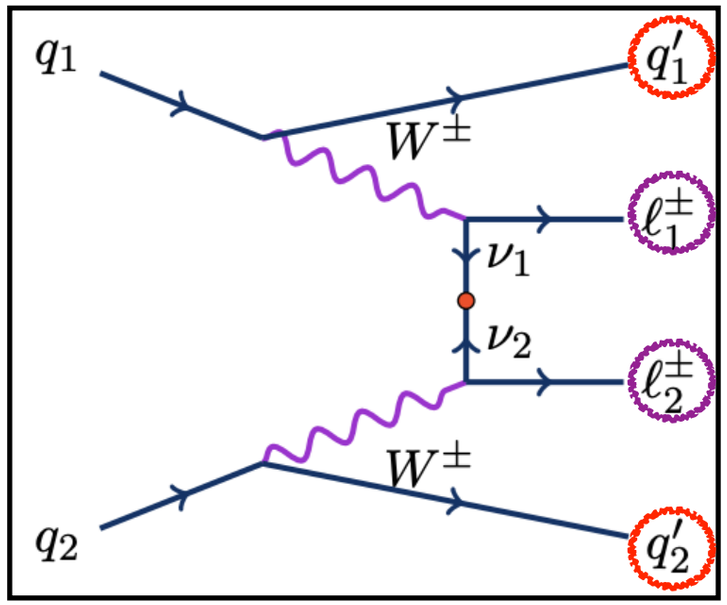
PRD 103, 055005 (2021)

More sensitivity for TeV mass hypothesis

- LHC version of inverted "neutrino less double beta decay"
- Signal topology: **two same-sign muons** + **a pair of back-to-back jets**

Probing Heavy Majorana neutrinos & **Weinberg op.** via VBF

EXO-21-003
arXiv: 2206.08956



Wilson Coefficients

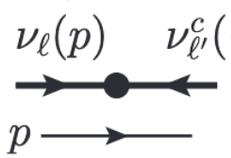
$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L}_\ell^c\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$

EFT Scale

$$v = \sqrt{2}\langle\Phi\rangle \approx 246\ \text{GeV}$$

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

Effective Majorana Mass



$$= \frac{i\not{p}}{p^2}\,\frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\,\frac{i\not{p}}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

$$\sigma \sim \left|m_{\ell\ell'}\right|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

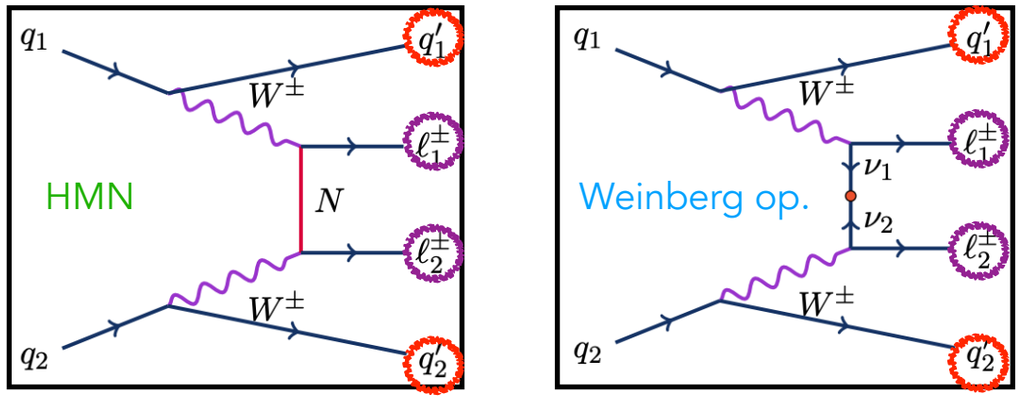
Phys. Rev. D 103, 115014

First ever direct examination of Weinberg Operator at colliders!

- LHC version of inverted "neutrino less double beta decay"
- Signal topology: **two same-sign muons** + **a pair of back-to-back jets**

Probing Heavy Majorana neutrinos & Weinberg op. via VBF

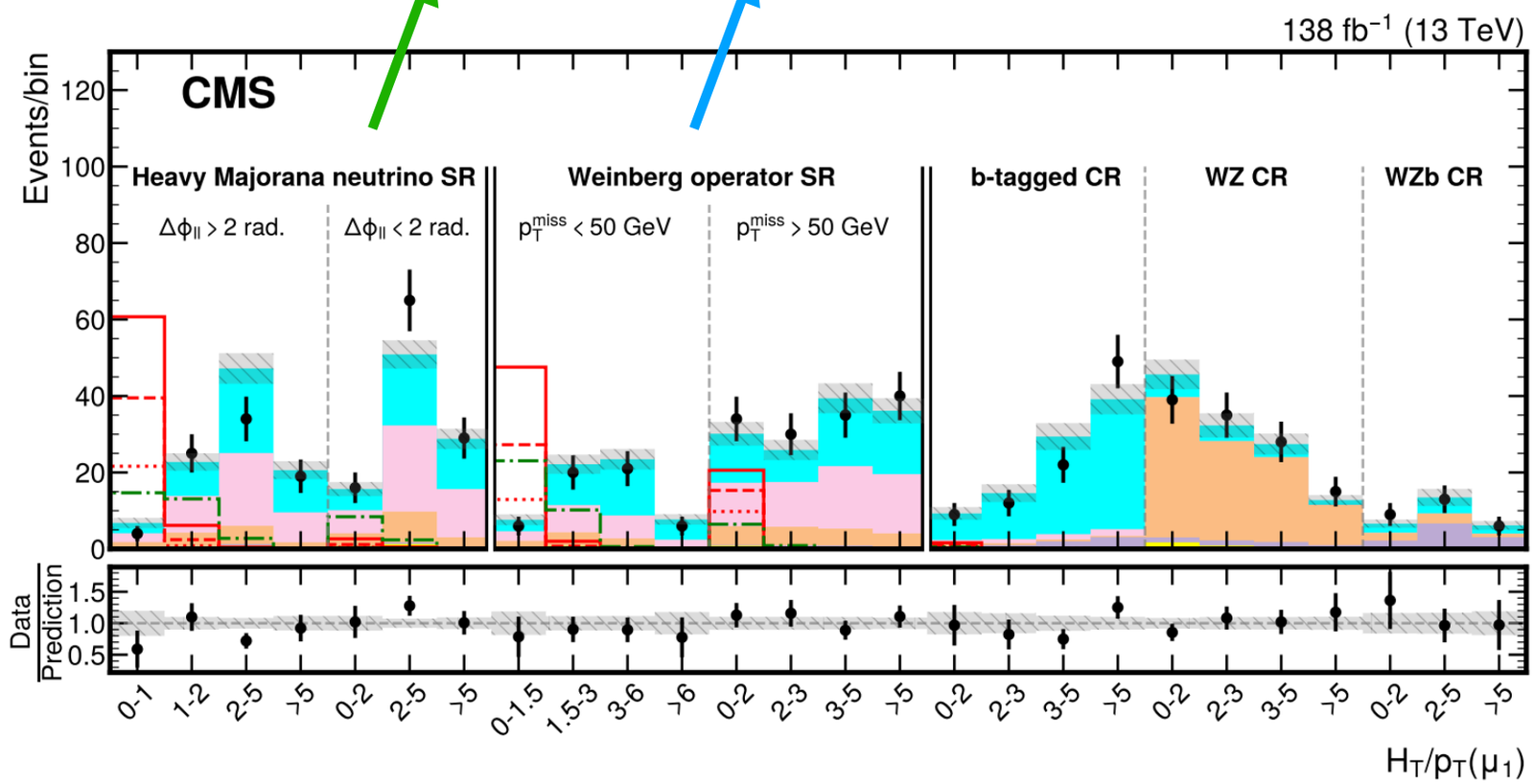
EXO-21-003
arXiv: 2206.08956



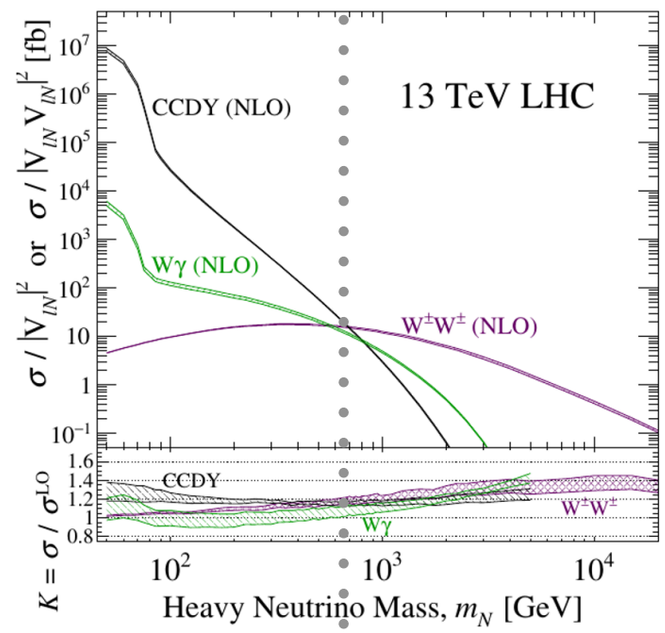
*Jets: clustered by **Anti-K_T** with radius R=0.4 (**AK4**)*

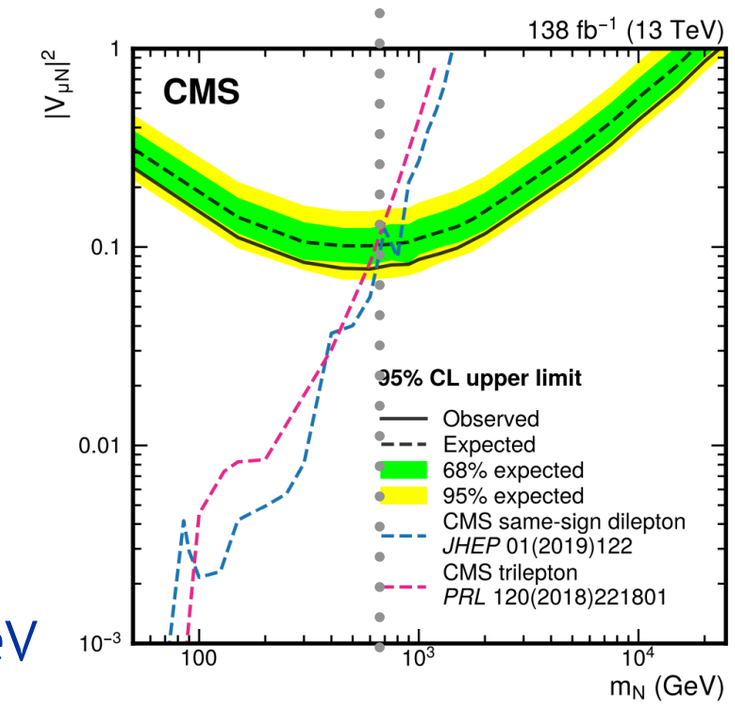
For HMN signals

For Weinberg op. signal



$qq \to W \to \ell N$ ⟷ VBF t-channel



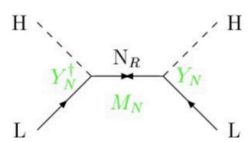


- **HMN**: m_N excluded up to ~ **23 TeV** & best limits since ~ **650 GeV**!
- **WO**: **obs.** (exp.) upper limit on effective mass $|m_{\mu\mu}|$: **10.8** (12.8) GeV

LONG-LIVED HEAVY NEUTRAL LEPTON WITH DISPLACED VERTICES

EXO-20-009
JHEP07(2022)081

Right-handed singlet:
(type-I seesaw)

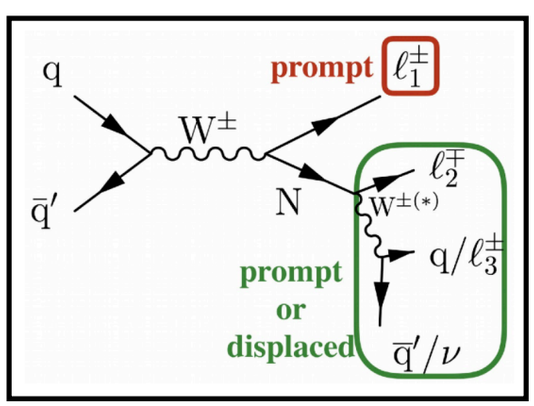


$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

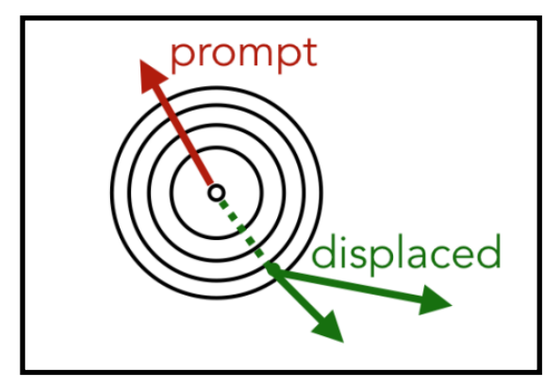
BSM Heavy Neutral Lepton (HNL) of interest: Heavy neutrino from Type-I seesaw

Type-I Seesaw HNL only interacts with the SM neutrinos in terms of the **mixing** $\nu_{\rm SM} \Leftrightarrow N$ with probability $|V_{\ell N}|^2$

HNL Lifetime (τ) :
$\tau \propto |V_{\ell N}|^{-2} m_N^{-5}$
Smaller HNL mass and smaller mixing leads to longer HNL life!



Changed from very small displacement (**prompt decays**) to macroscopic distances away from production vertex (**displaced decays**) with **very low mass and couplings.**

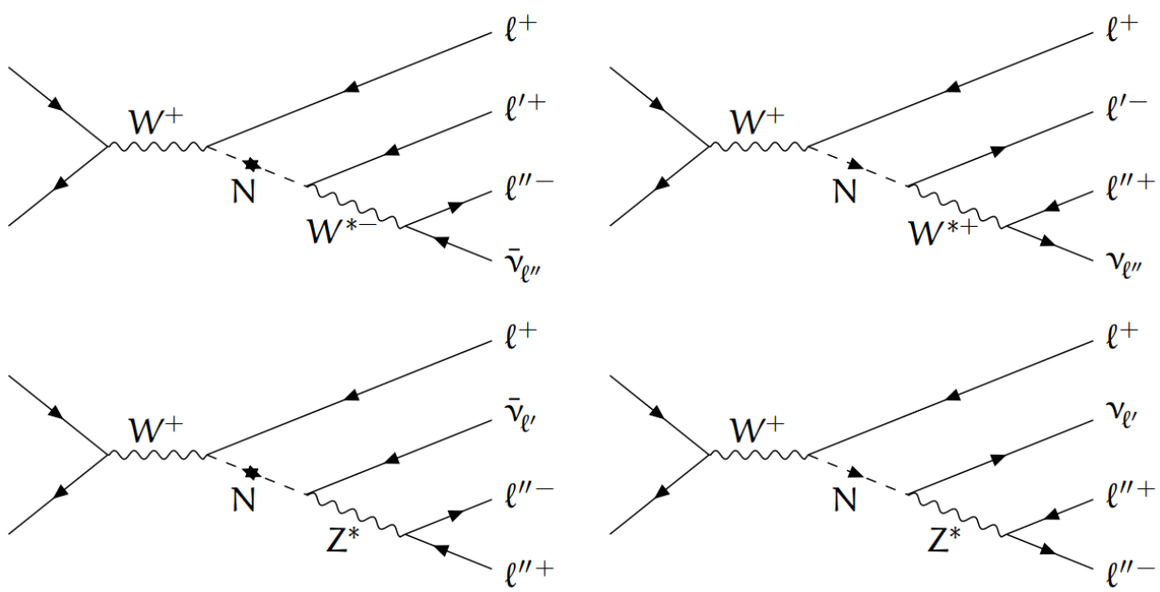


Pioneering signatures:
displaced objects

LONG-LIVED HEAVY NEUTRAL LEPTON WITH DISPLACED VERTICES

EXO-20-009
JHEP07(2022)081

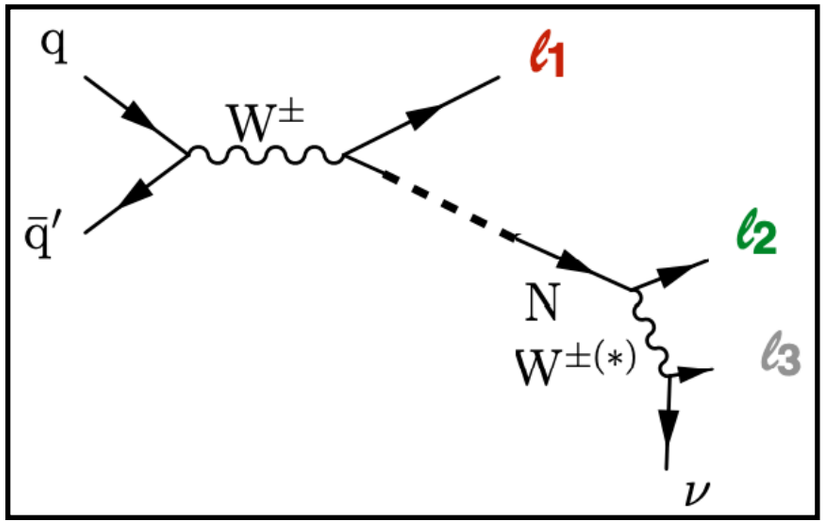
Today's focus:
trilepton final state



Majorana **Dirac**

Dirac and Majorana limits

- **Dirac limit**: lepton number conserved (**LNC**)
- **Majorana limit**: lepton number conserved (**LNC**) or violated (**LNV**)



3 leptons in the final state

$q\bar{q}' \to W \to \ell N \to \ell\ell' W^* \to \ell\ell'\ell'' \nu_{\ell''}$

$q\bar{q}' \to W \to \ell N \to \ell \nu_{\ell'} Z^* \to \ell \nu_{\ell'} \ell''\ell''$

3 leptons final state:

- **1 prompt lepton (ℓ_1)**
- **2 displaced leptons (ℓ_2 — ℓ_3)**

Features and requirements of the HNL-displaced signature:

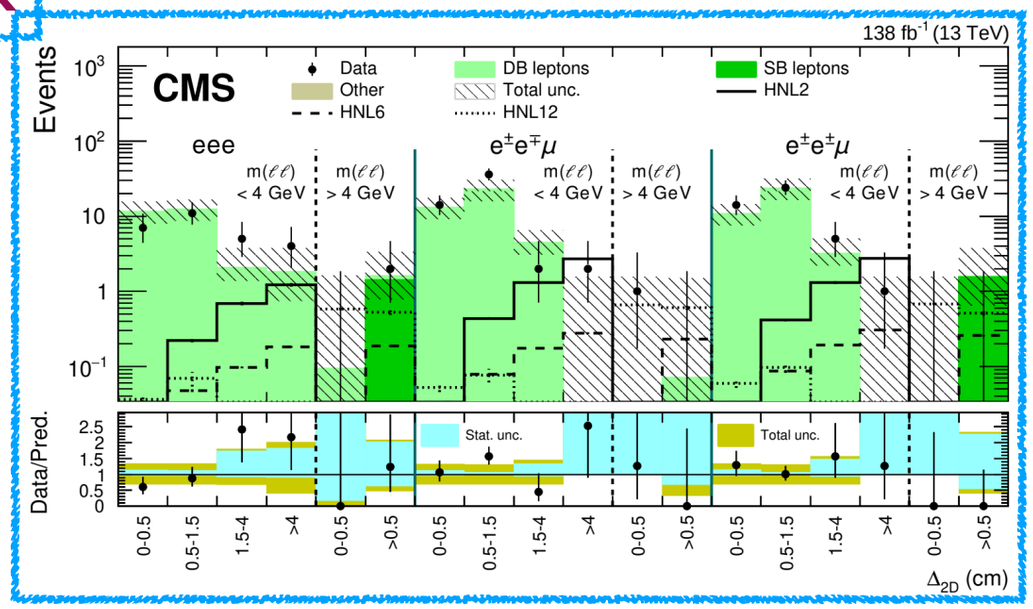
- **Low dilepton mass** $M_{\ell_2\ell_3}$
- **Soft** leptons, ℓ_2 — ℓ_3 → trigger on ℓ_1
- **Collimated** leptons, ℓ_2 — ℓ_3
- **Displaced** leptons, ℓ_2 — ℓ_3 → loose impact parameters

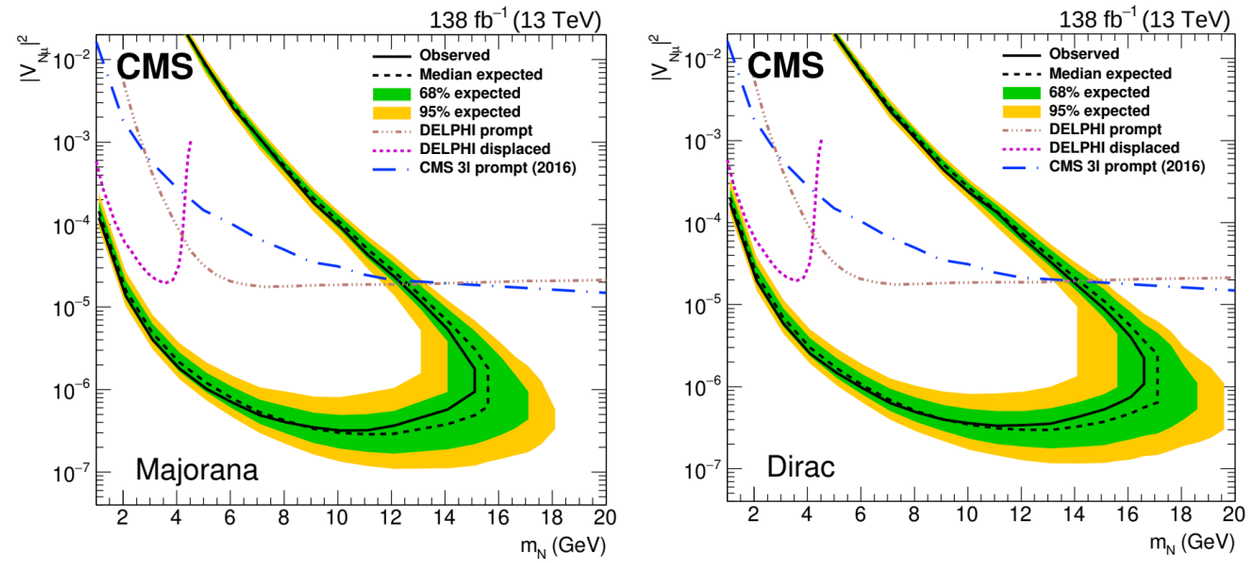
LONG-LIVED HEAVY NEUTRAL LEPTON WITH DISPLACED VERTICES

EXO-20-009
JHEP07(2022)081

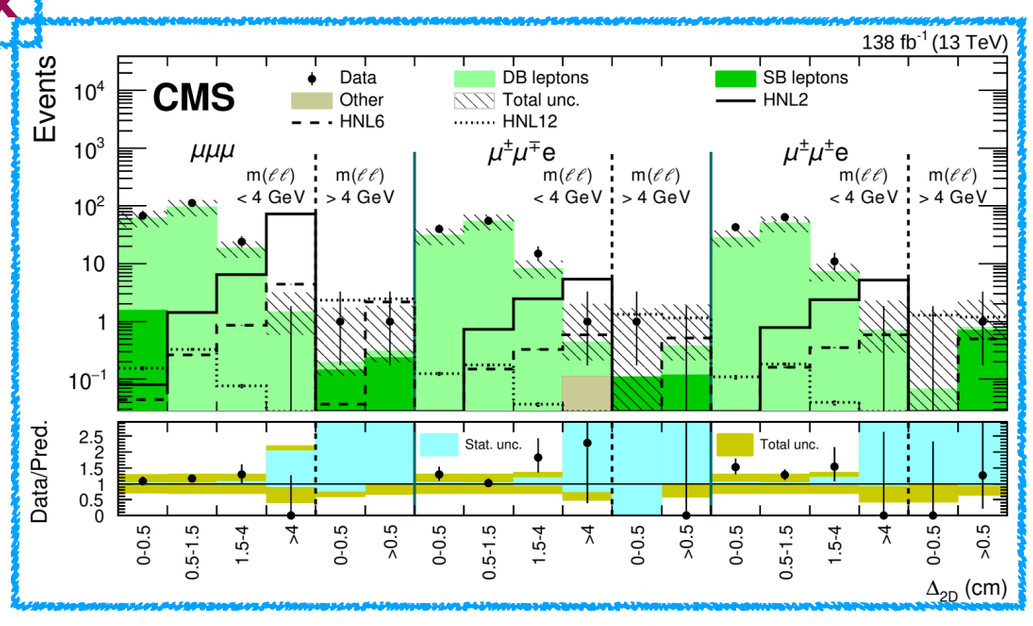
- CMS analysis only considers the HNL mixes with a single neutrino flavor (**1SFH**)

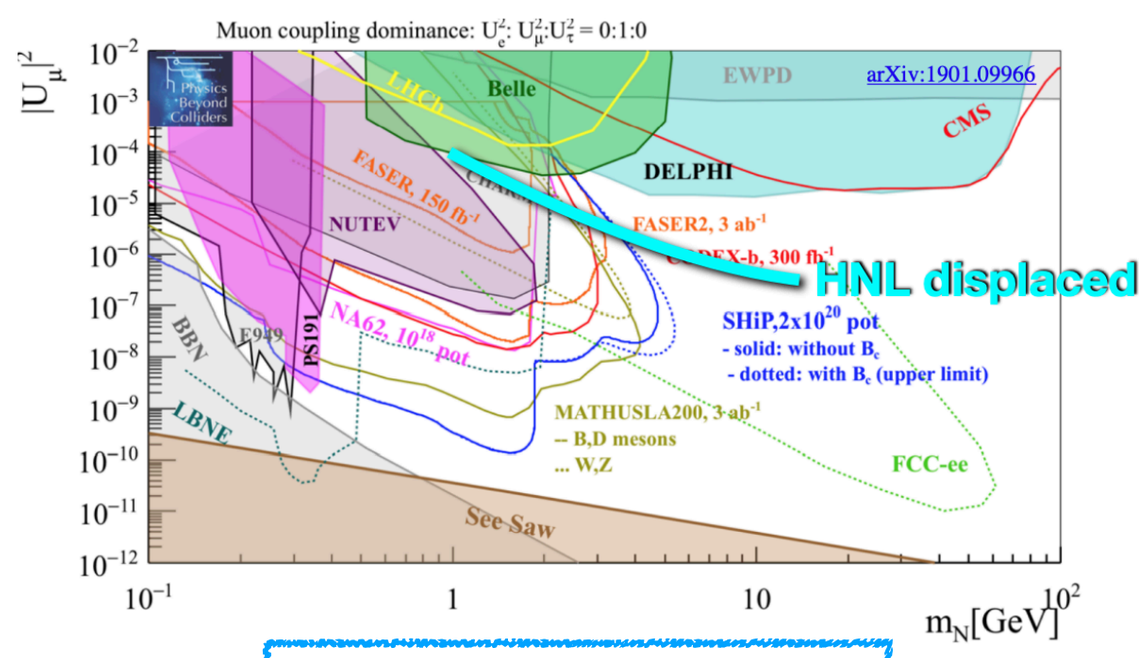
eeX





μμX





Distances between the PV and the SV in the transverse plane (Δ_{2D})

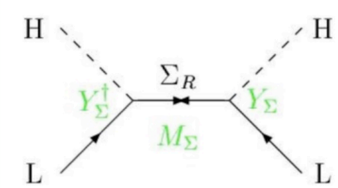
Clear improvement w.r.t. DELPHI results in the displaced regime!

Inclusive Multilepton Probe for New Physics

EXO-21-002
PhysRevD.105.112007

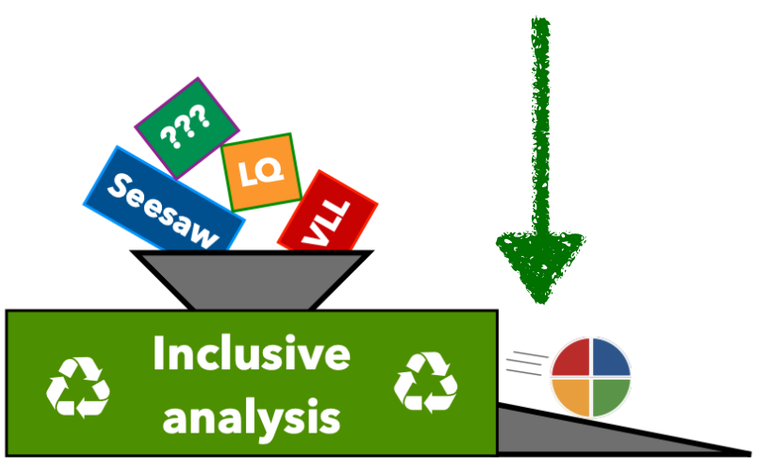
- A multi-bin, inclusive, model-independent multilepton analysis with full Run2
- Covering light leptons and **hadronic decaying taus**
- Results will be interpreted in the context of three signal models
  - **Type-III Seesaw model (Today's focus)**
  - Vector-like leptons (singlet and doublet)
  - Leptoquarks (coupling to top quark and a changed lepton)

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Complete set of **HEPData** will be provided to allow reinterpretation of the results for many other models with multilepton signatures in the final state.



Trilepton channels	Quadlepton channels*
• **3L**: 3 light leptons, 0 had. taus • **2L1T**: 2 light leptons, 1 had. tau • **1L2T**: 1 light lepton, 2 had. taus	• **4L**: 4 light leptons, 0 had. tau • **3L1T**: 3 light leptons, 1 had. tau • **2L2T**: 2 light lepton, 2 had. taus • **1L3T**: 2 light lepton, 2 had. taus

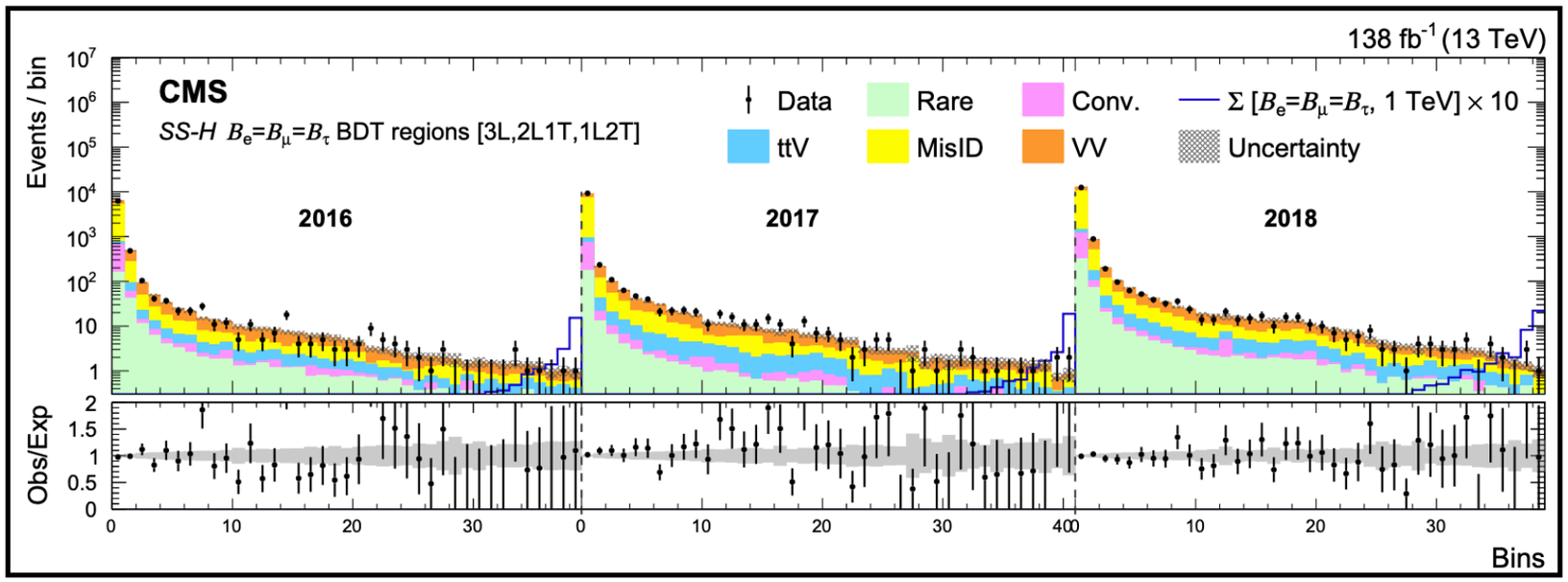
** No veto on additional leptons*
→ only lead. four objects are considered

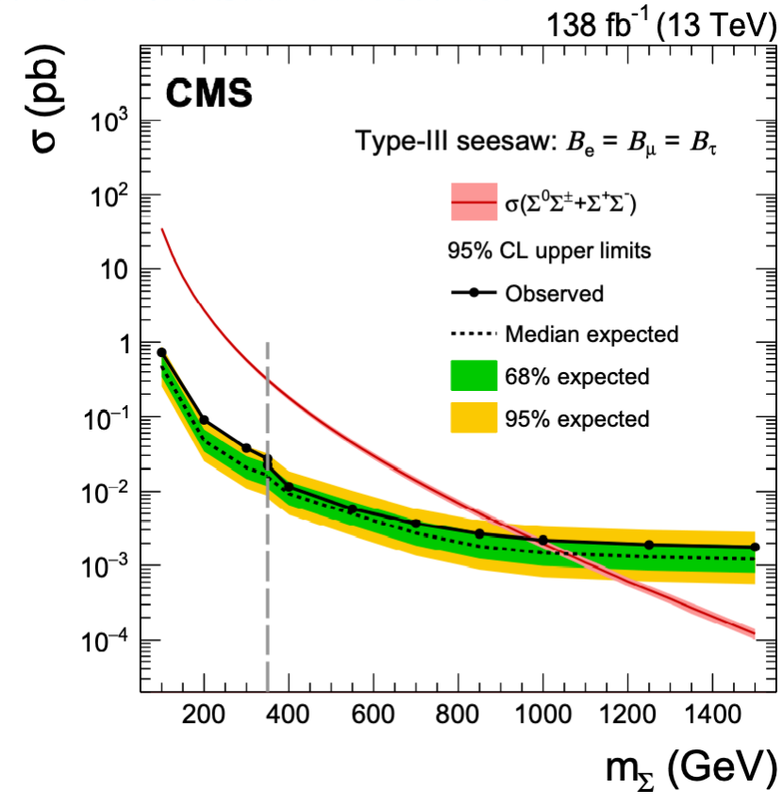
Inclusive Multilepton Probe for New Physics

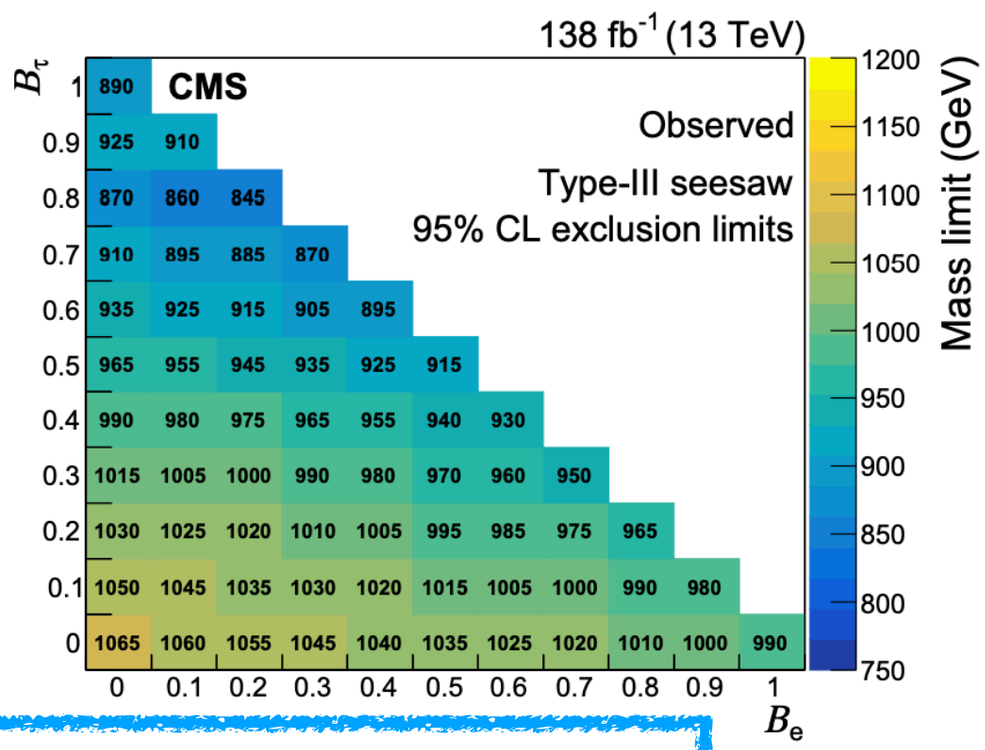
EXO-21-002
PhysRevD.105.112007

Dedicated Boosted Decision Tree (BDT) for each specific signal model

1D limits: $B_e = B_\mu = B_\tau$







2D limits: $B_e + B_\mu + B_\tau = 1$

Upper observed mass limits

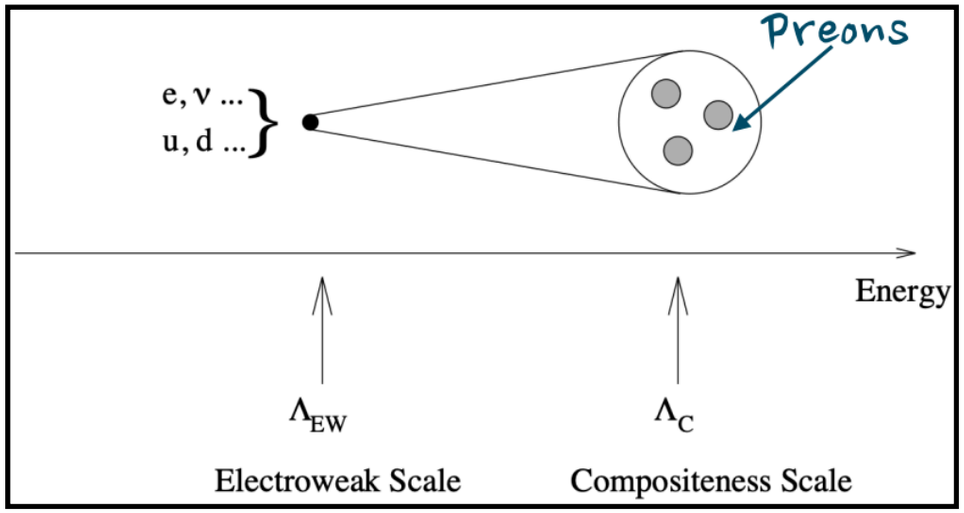
- **980** GeV assuming the flavor-democratic scenario
- **990** GeV assuming the $B_e = 1$ scenario
- **1065** GeV assuming the $B_\mu = 1$ scenario
- **890** GeV assuming the $B_\tau = 1$ scenario

Test of Neutrino Mass Models at CMS, Sitian Qian (PKU) on behalf of CMS Collaboration, NUFACT 2022, July 31st - August 6th, 2022

Heavy Composite Majorana Neutrino

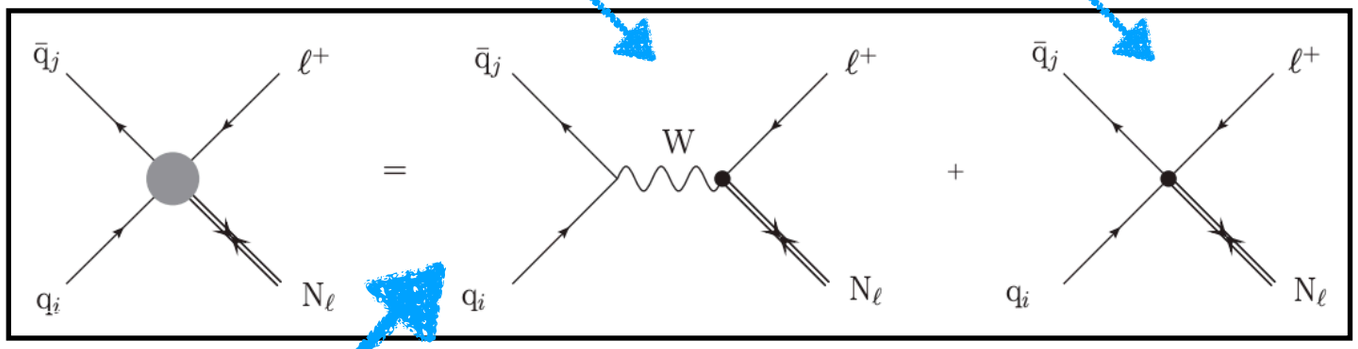
EXO-20-011

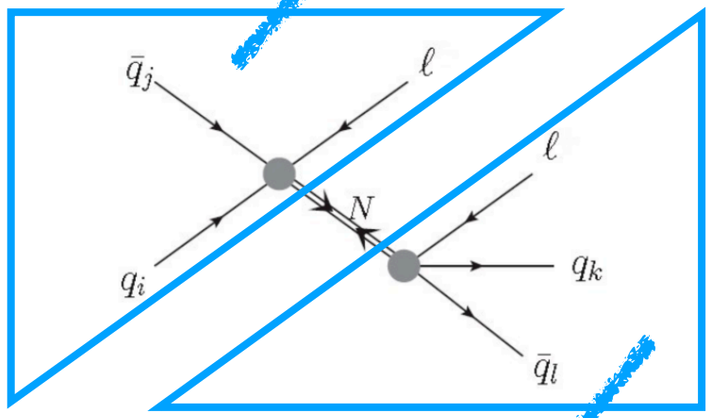
Heavy Composite Majorana Neutrino (HCMN):
Heavy Majorana Neutrino considered as a composite state of other elementary particles



Gauge interaction

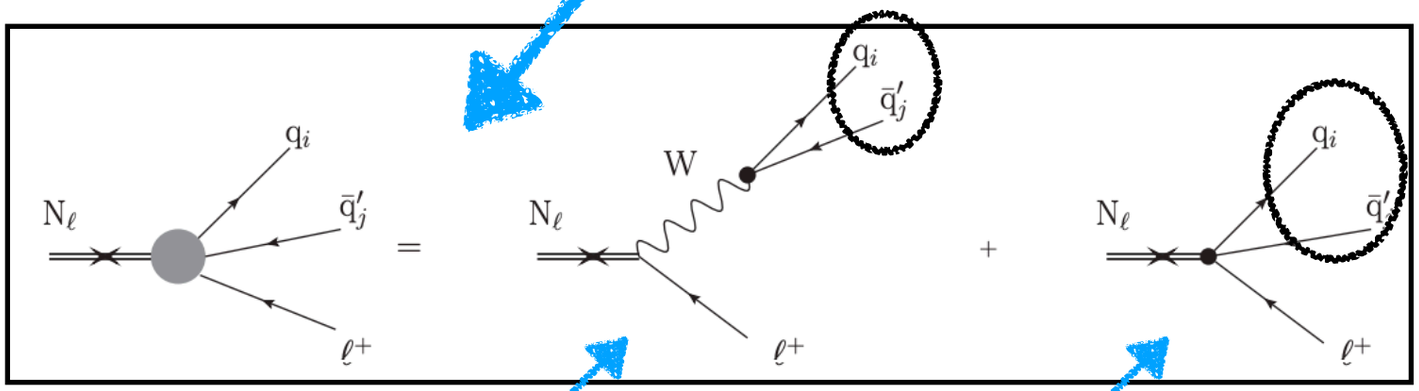
Contact interaction





Signal topology
- Di-electron or di-muon
- One **Fatjet** (Originate from multiple collinear partons, clustered with large radius (**A**nti-**K**$_T$**,** R=0.**8**, **AK8**))

Features of HCMN:
1. **Lepton Number Violation (LNV) can arise from Majorana nature.**
2. **Based on an EFT description: settings of model parameters should be self-consistent!**



Gauge interaction

Contact interaction

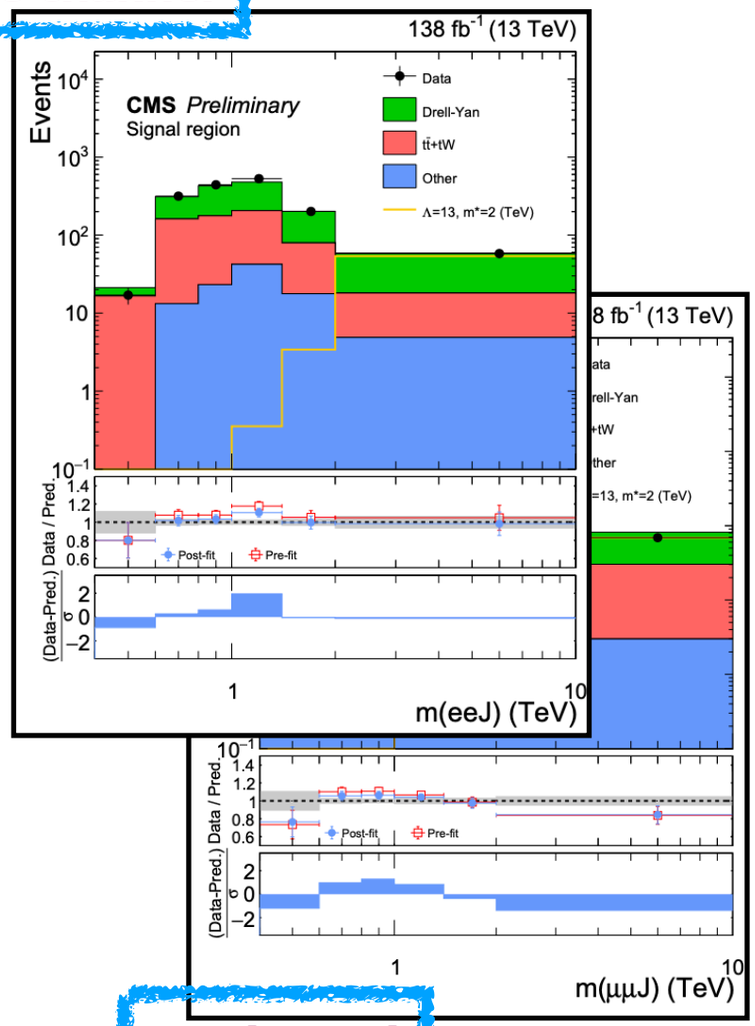
Heavy Composite Majorana Neutrino

EXO-20-011

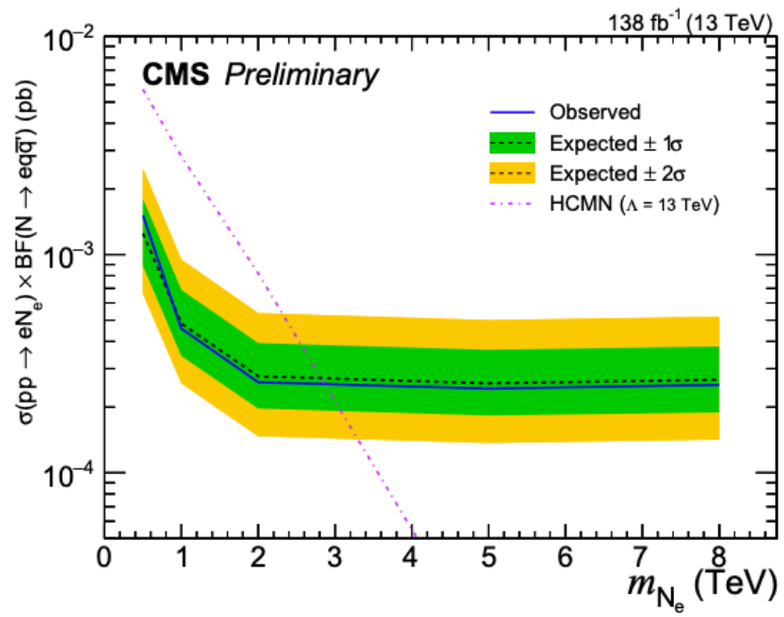
Unitarity constraints (link): Focus on a valid EFT expansion region

- For $\Lambda = 6$ TeV, N_e (N_μ) is excluded for masses up to 5.2 (5.4) TeV

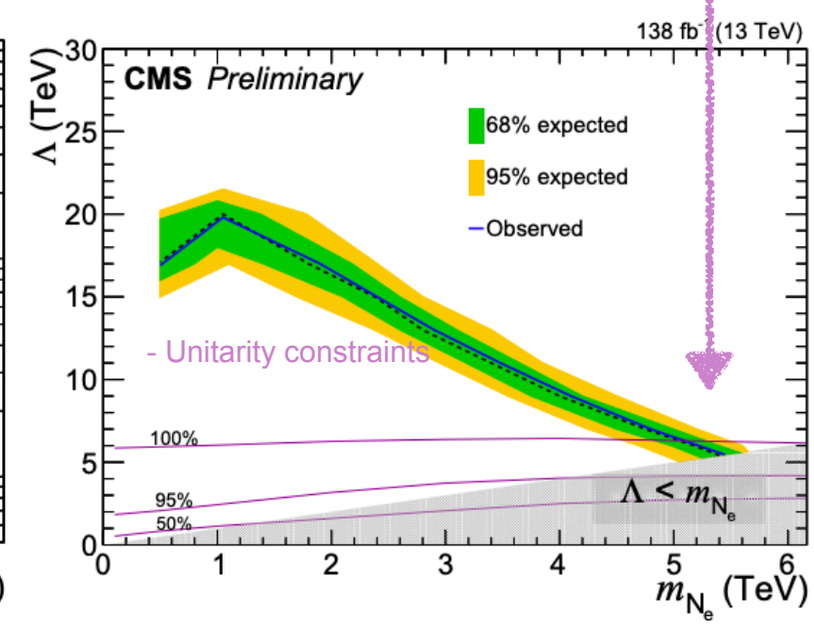
ee channel



μμ channel



ee channel



ee channel

1D limits:

For $\Lambda = 13$ TeV

- N_e (N_μ) is excluded for masses up to ~3.0 (3.4) TeV

$\Lambda - m_{N_\ell}$ 2D plane:

For $\Lambda = m_{N_\ell}$

- N_e (N_μ) is excluded for masses up to 5.5 (5.7) TeV

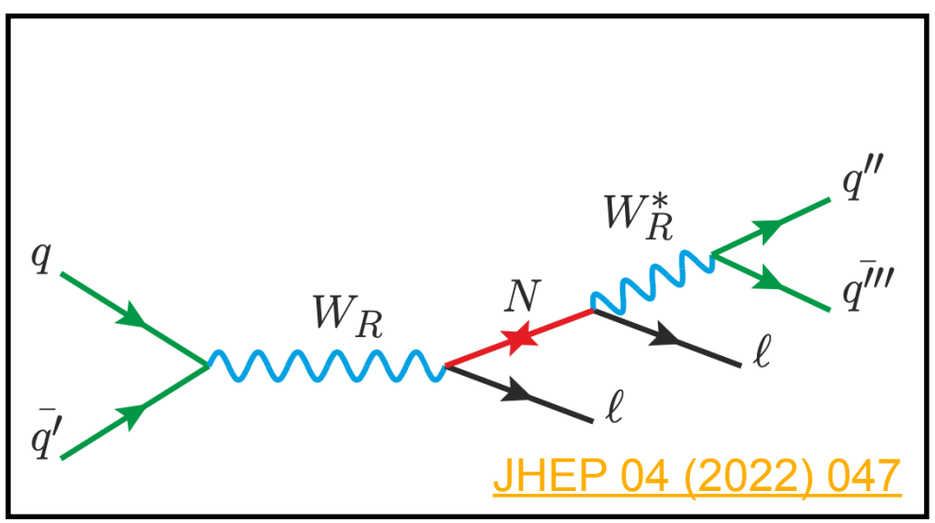
Test of Neutrino Mass Models at CMS, Sitian Qian (PKU) on behalf of CMS Collaboration, NUFACT 2022, July 31st - August 6th, 2022

Left Right Symmetric Model

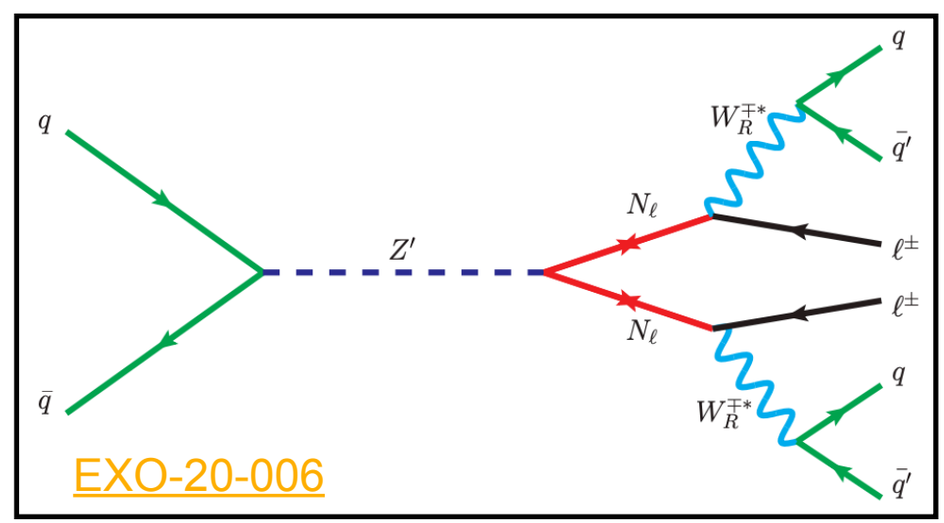
EXO-20-002
JHEP04(2022)047
&
EXO-20-006

- Left Right Symmetric Model (LRSM) completes the handedness of SM:
  - The SM only includes left handed W boson and neutrinos $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_{B-L}$
  - LRSM introduce right handed W_R boson and thus right handed neutrinos $N_\ell, \ell = e, \mu, \tau$ $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$
    - A new neutral boson (Z') is introduced simultaneously for completing the gauge group.
- LRSM offers the Seesaw scale and **heavy neutrino**
  - Three new gauge bosons $W_R^\pm$ and Z', three new right-handed neutrinos N_ℓ
  - Search for LRSM: search for extra gauge bosons + heavy Neutrinos

Charged Current



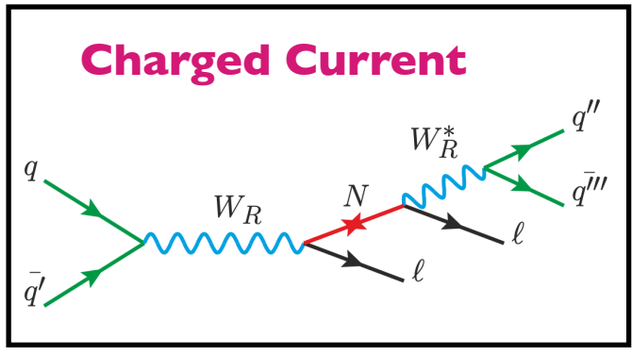
Neutral Current



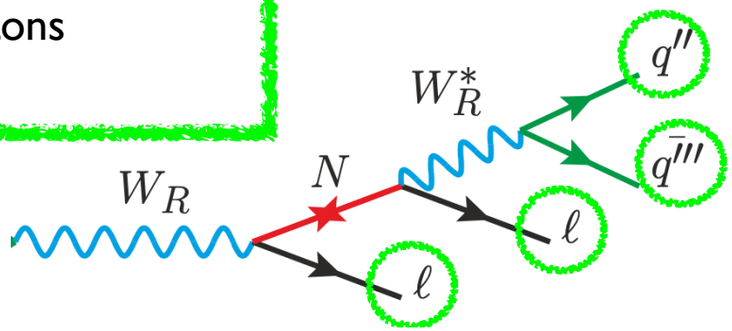
LRSM Charged Current Search

EXO-20-002
JHEP04(2022)047

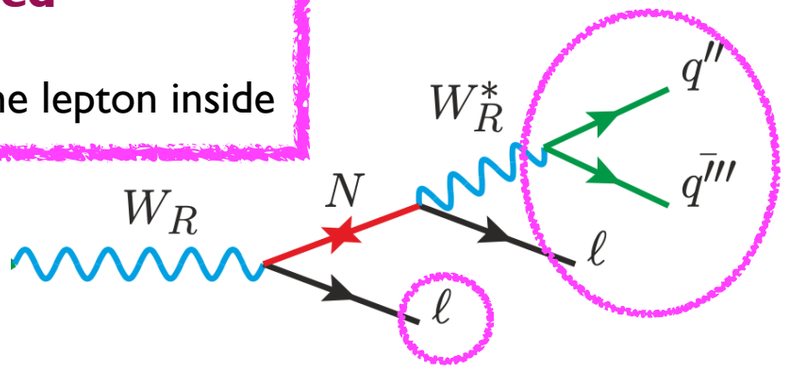
- Charged current search: W_R and N_ℓ
  - Final state leptons are of the same flavor:
    - Search channels: both **dielectron** and **dimuon** considered
    - Signal topology: **Resolved** and **Boosted**



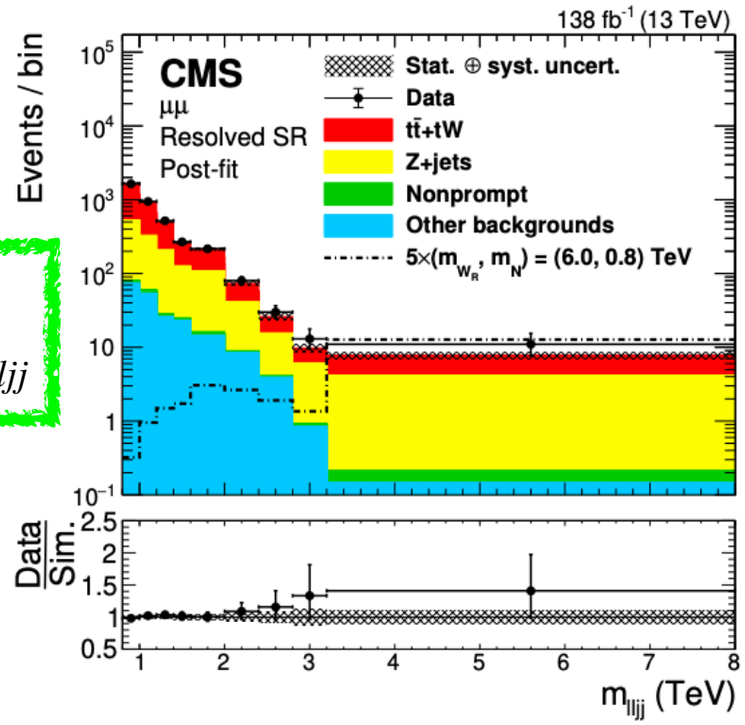
Resolved
- Two leptons
- Two jets



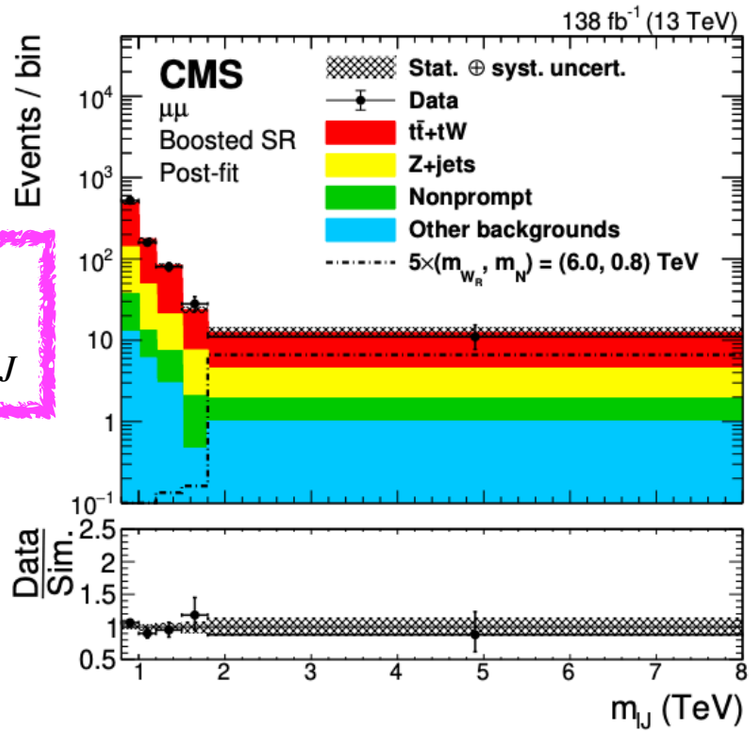
Boosted
- One lepton
- One fatjet with one lepton inside



Resolved:
Invariant mass m_{lljj}



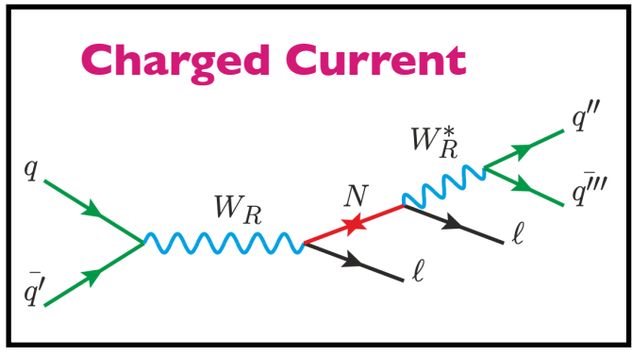
Boosted:
Invariant mass m_{lJ}



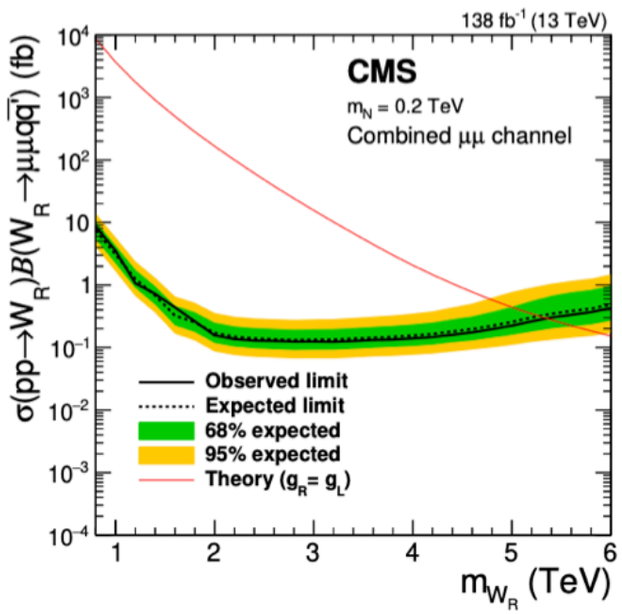
LRSM Charged Current Search

EXO-20-002
JHEP04(2022)047

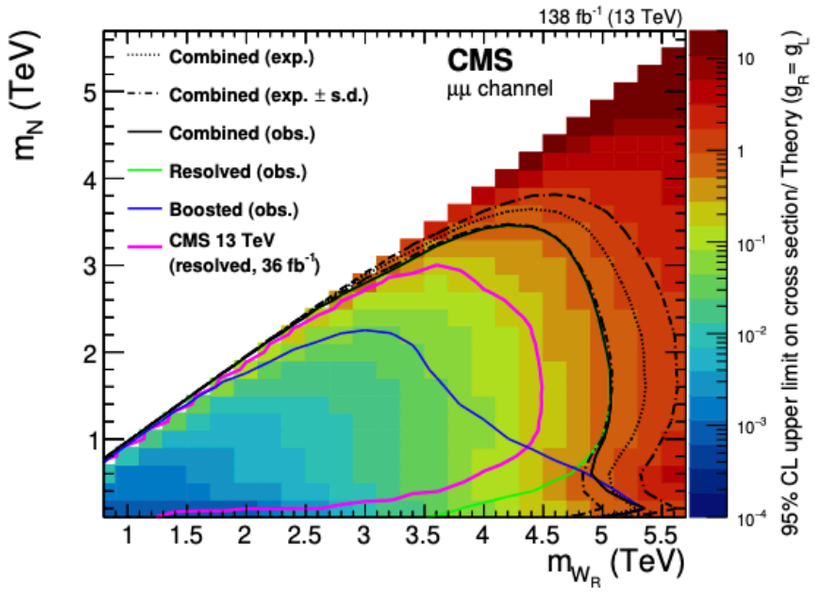
- Charged current search: W_R and N_ℓ
  - Final state leptons are of the same flavor:
    - Search channels: both **dielectron** and **dimuon** considered
    - Signal topology: **Resolved** and **Boosted**
    - Interpretation: **1D** (only m_{W_R} varying) and **2D** (both m_{W_R} and m_N varying)



1D limits:
- Muon channel example
- m_N = 0.2 TeV



2D limits:
- Muon channel example

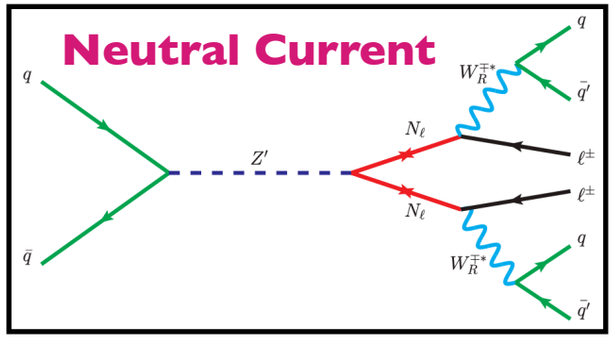


Exclude the phase space up to
- m_{W_R} = 4.8 (5.0) TeV for the electron channel
- m_{W_R} = 5.4 (5.3) TeV for the muon channel

Significant improvement in boosted channel
- For $m_N = 200GeV, ee(\mu\mu) : m_{W_R}$ 4600 (5400) GeV excluded

LRSM Neutral Current Search

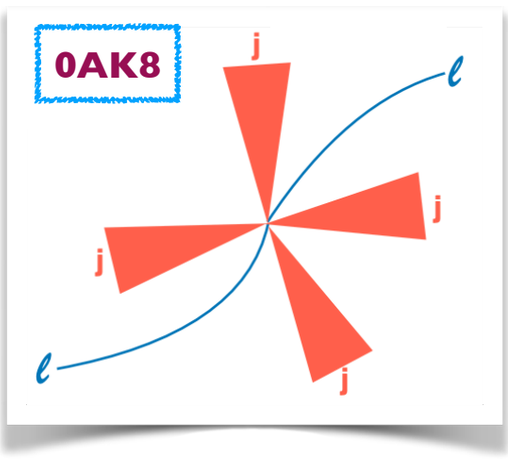
EXO-20-006

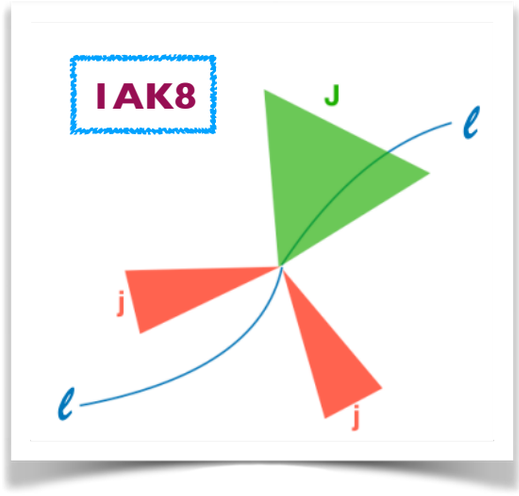


- Neutral current search: Z' and N_ℓ
  - Final state leptons are of the same flavor:
    - Search channels: both **dielectron** and **dimuon** considered
    - Signal topology: based on multiplicities of jets (AK4) & fatjets (AK8)

SR	N(AK8 jet)	N(tight leptons)	N(AK4 jet)
SR1 (0AK8)	=0	=2	≥4
SR2 (1AK8)	=1	≥1	≥2
SR3 (2AK8)	≥2	—	—

AK4 jet AK8 jet





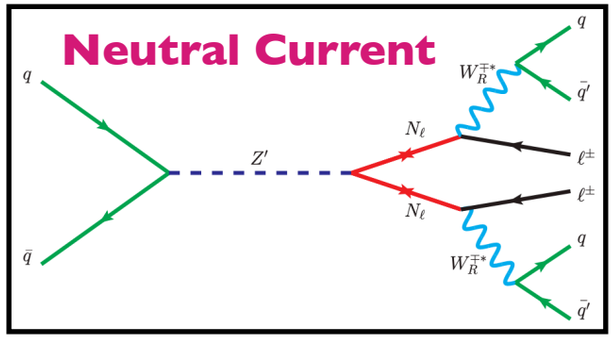
- Two N (= one ℓ + two j)
- $Z' = N_1 + N_2$

- N (two j and the tight lepton)
- The other N (J)
- $Z' = N_1 + N_2$

- N (tight lepton and the closest J)
- The other N (remaining J)
- $Z' = N_1 + N_2$

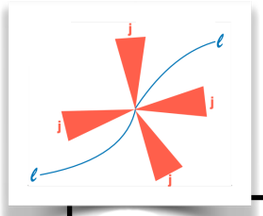
LRSM Neutral Current Search

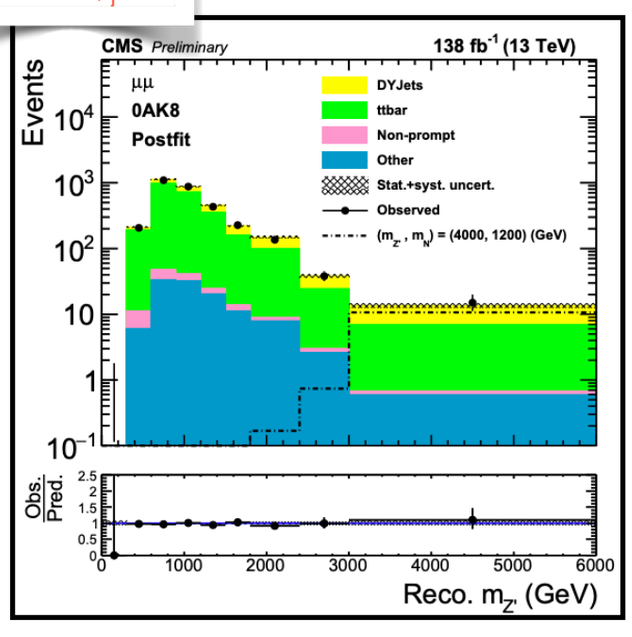
EXO-20-006

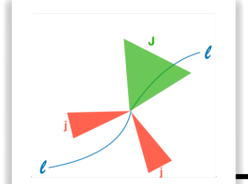


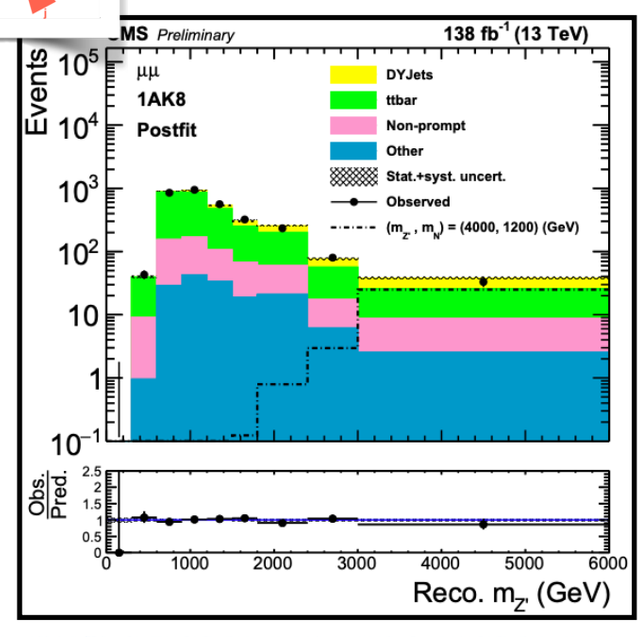
- Neutral current search: Z' and N_ℓ
  - Final state leptons are of the same flavor:
    - Search channels: both **dielectron** and **dimuon** considered
    - Signal topology: based on multiplicities of jets (AK4) & fatjets (AK8)

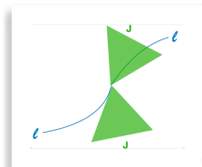
SR	N(AK8 jet)	N(tight leptons)	N(AK4 jet)
SR1 (0AK8)	=0	=2	≥4
SR2 (1AK8)	=1	≥1	≥2
SR3 (2AK8)	≥2	—	—

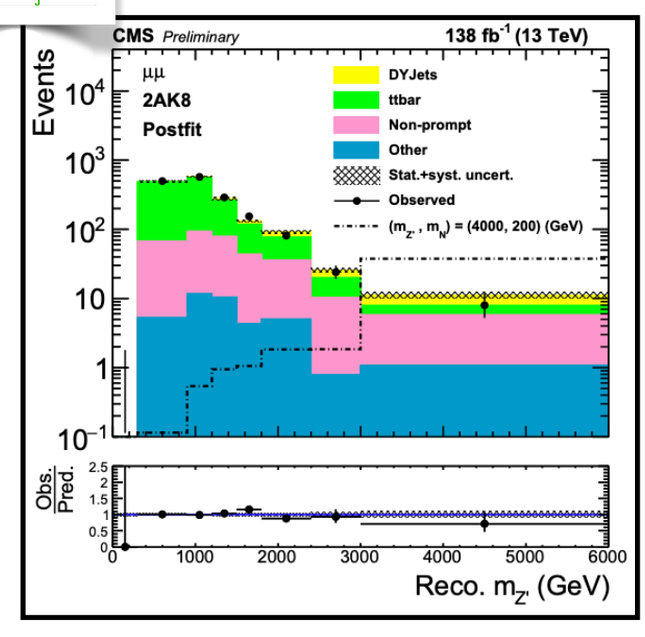










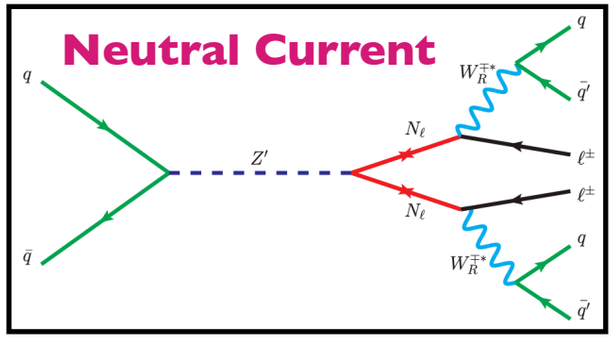


Reconstruct $m_{Z'}$

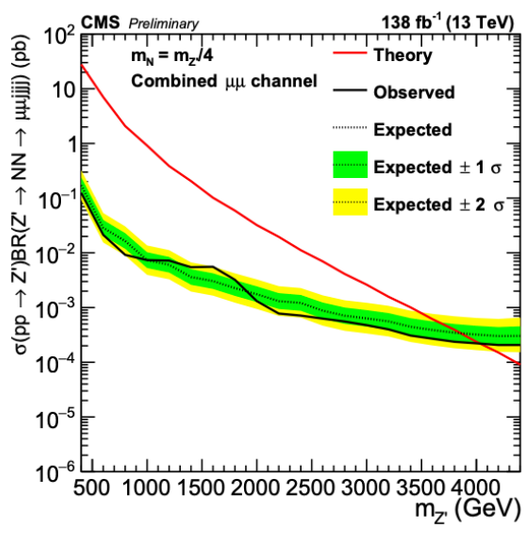
LRSM Neutral Current Search

EXO-20-006

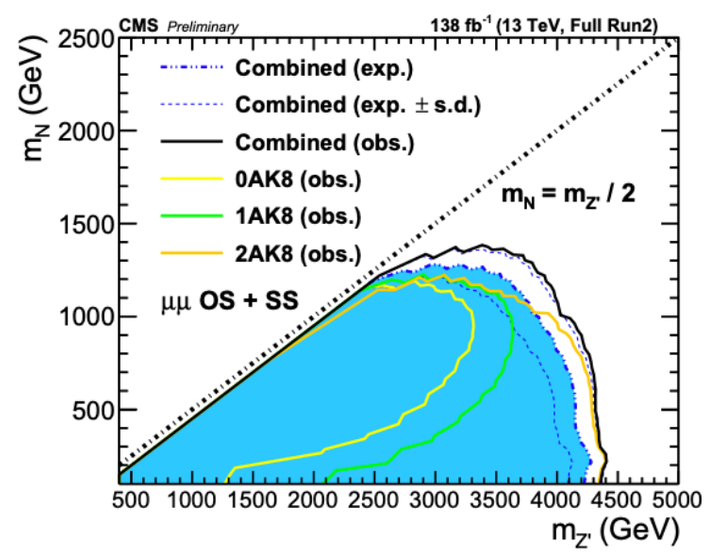
- Neutral current search: Z' and N_ℓ
  - Final state leptons are of the same flavor:
    - Search channels: both **dielectron** and **dimuon** considered
    - Signal topology: based on multiplicities of jets (AK4) & fatjets (AK8)
    - Interpretation: **1D** ($m_N = m_{Z'}/4$) and **2D** ($m_{Z'}$ and m_N varying under $m_{Z'} > 2 \times m_N$)



1D limits:
- Muon channel example
- Set $m_N = m_{Z'}/4$



2D limits:
- Muon channel example



Exclude the phase space up to
- $m_{Z'}$ = 3.60(3.87) TeV for the electron channel
- $m_{Z'}$ = 4.04(3.87) TeV for the muon channel

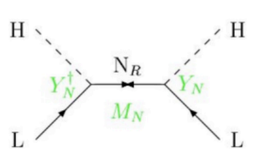
Significant improvement
- 0AK8 SR: $m_{Z'}$ = 1 to 2 TeV and m_N = 0.5 to 1 TeV
- 1AK8 SR: higher $m_{Z'}$ with resolved Ns
- 2AK8 SR: dominant where Ns are boosted

Prospects for High-Luminosity LHC

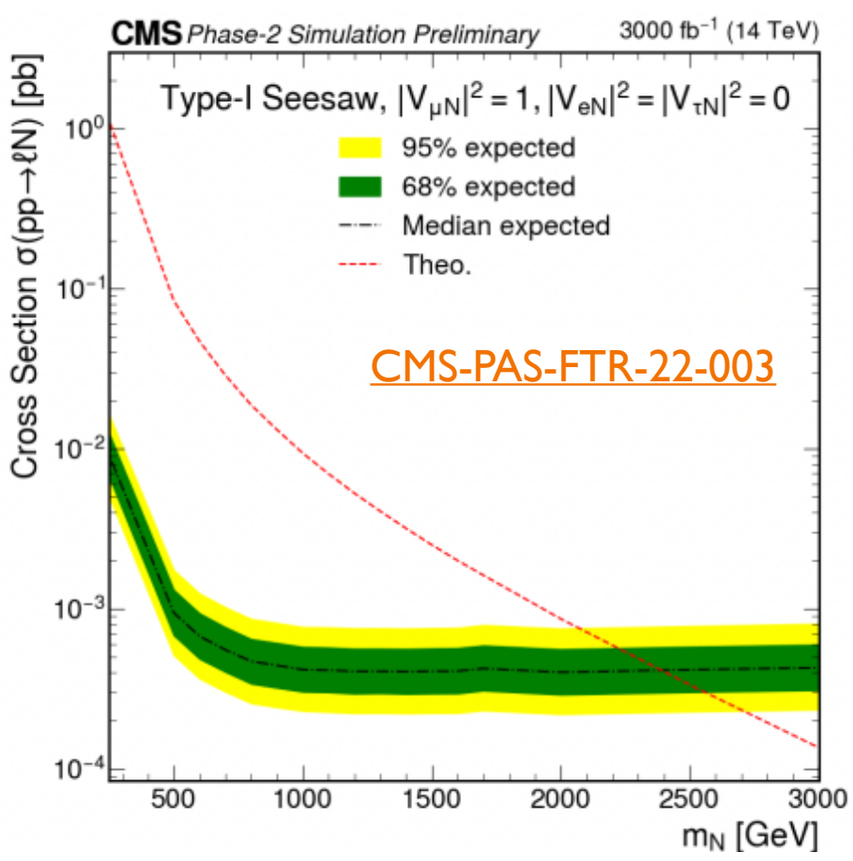
FTR-22-003

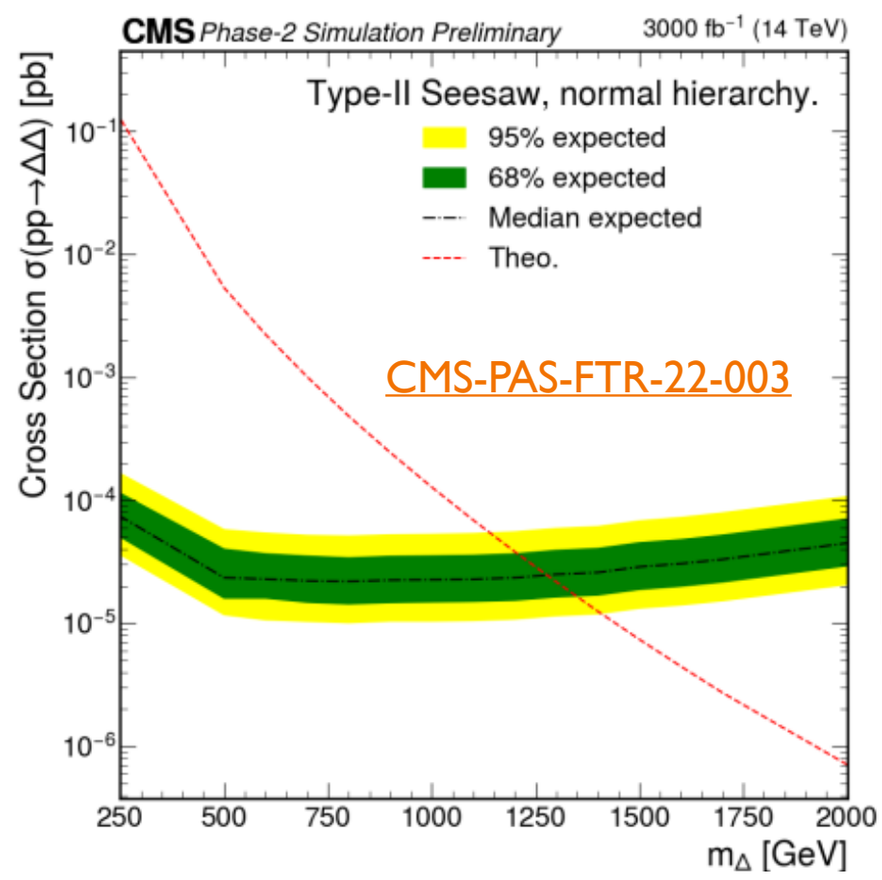
- Run-3 has started. After Run-3, LHC will be upgraded to phase-2: the High Luminosity LHC (HL-LHC)
  - More data will be recorded (~ 300 /fb for LHC Run-3, ~ 3000 /fb for HL-LHC)
  - More powerful detectors will be installed
- The physics potential of incoming HL-LHC on Seesaw models has been studied:
  - A generic search with multilepton final state, targeting on both Type-I and Type-II Seesaw models
  - Limits are put on BSM fermion singlet mass or scalar triplet mass.

Right-handed singlet:
(type-I seesaw)

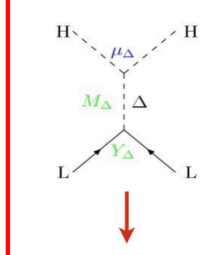


$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$





Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

SUMMARY

- Nonzero and small neutrino masses motivates the study of neutrino mass generation mechanisms.
  - Various theoretical solutions are provided, calling for tests from multipurpose detectors at the energy frontier of elementary particle physics.
- At CMS, enormous efforts have been put on tests of neutrino mass models with different analysis strategies
  - Type-I & III Seesaw models, Weinberg Operator, Heavy Composite Majorana Neutrino, Left-Right Symmetric model…
  - Prompt production, long-lived search, VBF topology
- New stories just begin:
  - Run-3 and HL-LHC bring us more opportunities for revealing the neutrino mass mystery!
  - Novel analysis techniques boost performance for collider tests on neutrino mass models.

THANK YOU!