Heavy neutrino searches at ATLAS and CMS

CKM 2023

12th INTERNATIONAL WORKSHOP ON THE CKM UNITARITY TRIANGLE

ETH zürich

Riccardo Manzoni
on behalf of the ATLAS and CMS Collaborations

Heavy Neutral Leptons

in a scallop shell

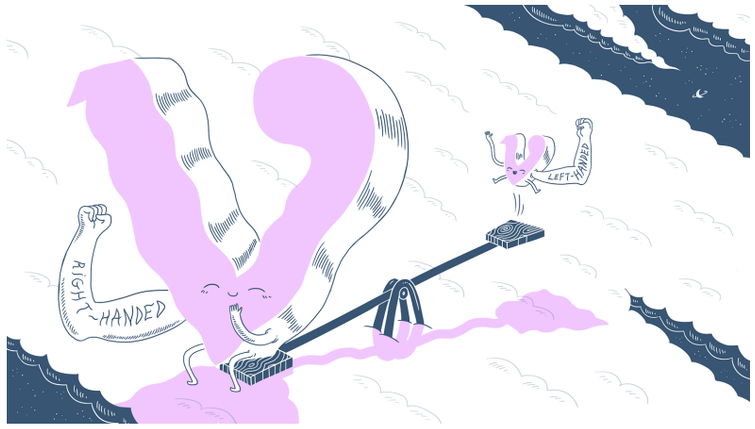
- **neutrino oscillations → (at least two) neutrinos are massive**
  requires right-handed ν_R (Yukawa)

- **mass via seesaw mechanism**

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}(\bar{\nu}_L\ \bar{\nu}_R)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

with $m \ll M$

SM neutrino mass m/M, HNL mass M

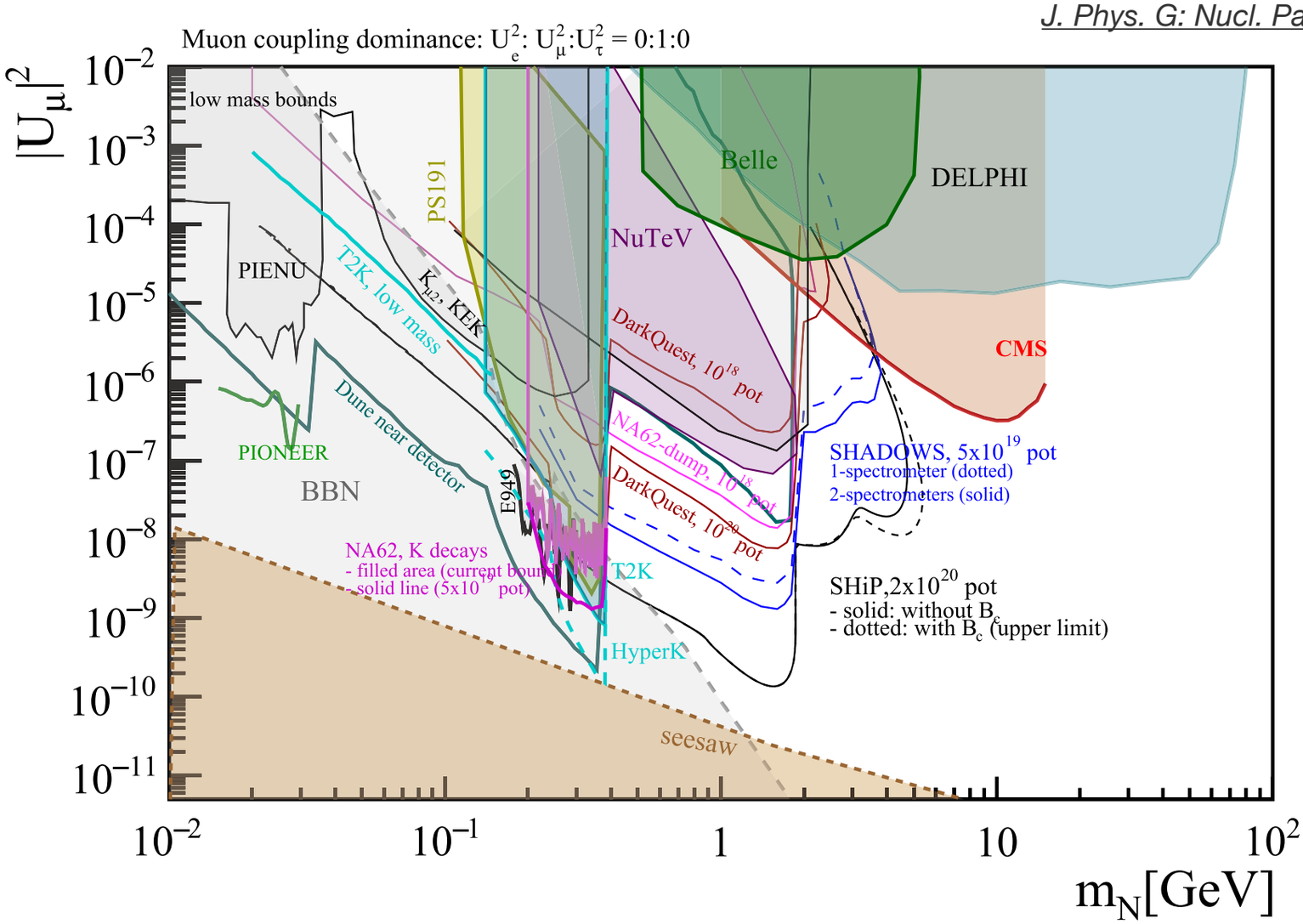


- **extend SM to accomodate HNL** e.g. νMSM Phys.Lett.B 631 (2005) 151-156
  sterile under EWK, mix with SM neutrinos
  possibly long-lived (displaced signatures)
  can mix flavours and introduce Lepton Number Violation
  Majorana $\nu = \bar{\nu}$ or (quasi-)Dirac $\nu \neq \bar{\nu}$

- **could explain baryogenesis, DM candidate, g-2 anomaly…**

Experimental scenario

J. Phys. G: Nucl. Part. Phys. 50 020501

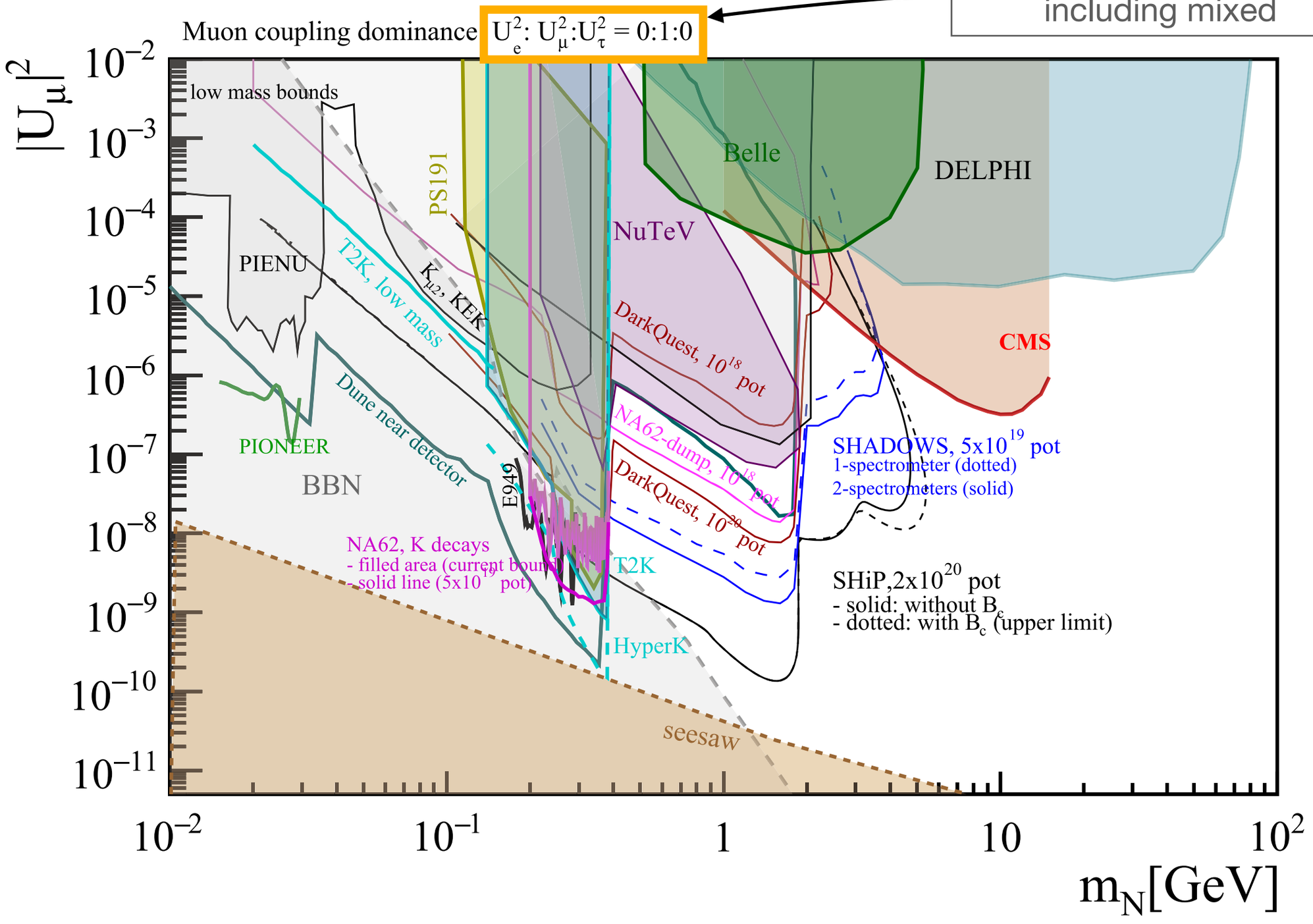


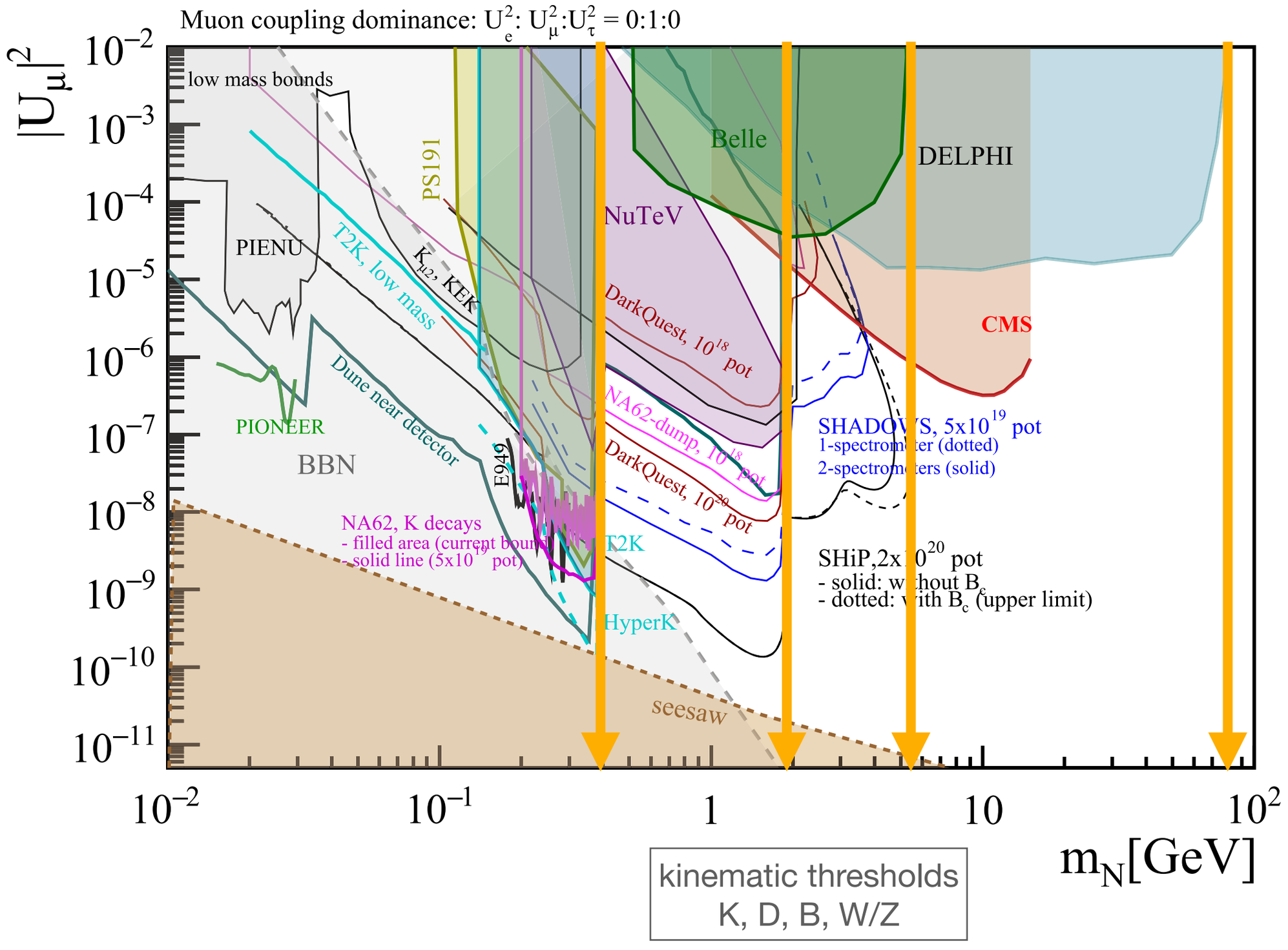
- **bounds in the mass vs. coupling plane** $\tau_N \propto U^{-2} m_N^{-5}$
- **rich set of results set by complementary experiments over the last few decades** (plus future experiments planned)

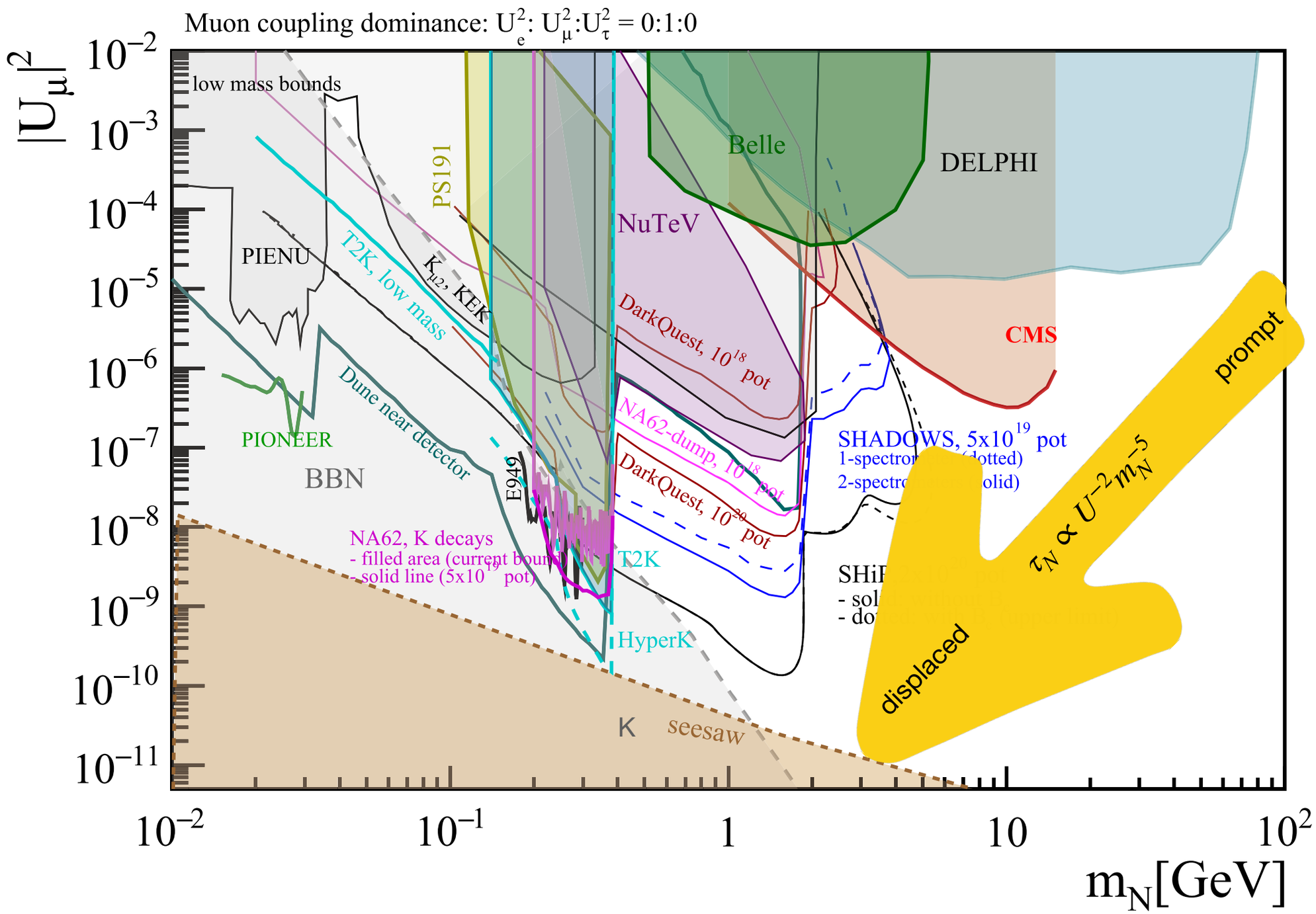
  colliders, fixed-target, β nuclear decays, atmospheric neutrinos

  energy frontier, intensity frontier…

different flavour couplings, including mixed




Muon coupling dominance: U_e^2: U_μ^2:U_τ^2 = 0:1:0
$|U_\mu|^2$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
low mass bounds
PIENU
PS191
$K_{\mu 2}$, KEK
T2K, low mass
Dune near detector
PIONEER
BBN
E949
NA62, K decays
- filled area (current bound)
- solid line (5x10^{19} pot)
T2K
HyperK
seesaw
Belle
NuTeV
DELPHI
DarkQuest, 10^{18} pot
CMS
NA62-dump, 10^{18} pot
DarkQuest, 10^{20} pot
SHADOWS, 5x10^{19} pot
1-spectrometer (dotted)
2-spectrometers (solid)
SHiP,2x10^{20} pot
- solid: without B_c
- dotted: with B_c (upper limit)
10^{-2}
10^{-1}
1
10
10^2
m_N[GeV]
kinematic thresholds
K, D, B, W/Z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SHADOWS, 5x10^{19} pot
1-spectrom (dotted)
2-spectro olid)
SHiP
- sol
- do
prompt
displaced
$\tau_N \propto U^{-2} m_N^{-5}$
10^{-2}
10^{-1}
1
10
10^2
m_N[GeV]

Selection of recent results

prompt displaced

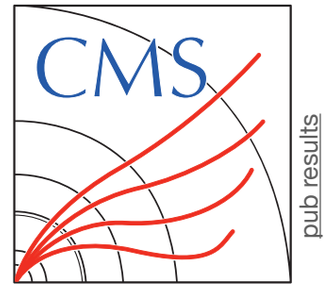
Majorana neutrinos in same-sign WW scattering
Eur. Phys. J. C 83 (2023) 824

HNLs and W_R in final states with leptons and jets
arXiv:2304.09553, acc. by EPJC

Type-III seesaw HNLs in leptonic final states
EPJC 82 (2022) 988

HNLs in W decays with a di-lepton displaced vertex
PRL 131 (2023) 061803

all these results on full Run2 datasets
$\mathscr{L} \approx 137 - 140\,\mathrm{fb}^{-1}$



Heavy Majorana Neutrinos and the Weinberg Operator through VBF
PRL 131 (2023) 011803

Search for Z' boson decays into HNL pairs
arXiv:2307.06959, sub to JHEP

Search for a heavy composite Majorana neutrino
Phys. Lett. B 843 (2023) 137803

Long-lived HNLs in the three-lepton final state
10.1007/JHEP07(2022)081

Long-lived HNLs with a displaced jet tagger and two leptons
CMS-PAS-EXO-21-013

Long-lived HNLs in the muon system
CMS-PAS-EXO-22-017

Majorana neutrinos in same-sign WW scattering

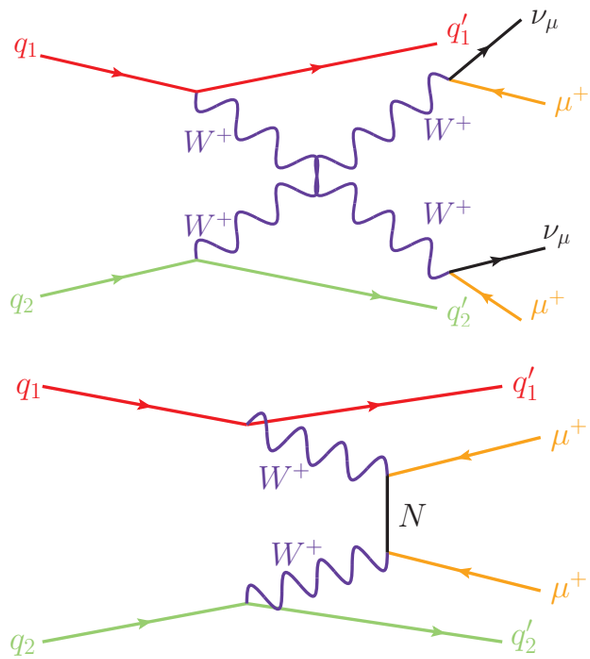
Eur. Phys. J. C 83 (2023) 824

- **like-sign μμ plus forward, η separated jets**
- EFT approach: **Weinberg operator** Phys.Rev.Lett. 43 (1979) 1566-1570

  dimension-5 operator $\mathscr{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \bar{L}_\ell^c][\bar{L}_{\ell'} \cdot \Phi]$, Φ Higgs doublet $L_\ell = (\nu_\ell, \ell)$

  generates effective Majorana neutrino mass $m = C_5^{\ell\ell'} v^2/\Lambda$

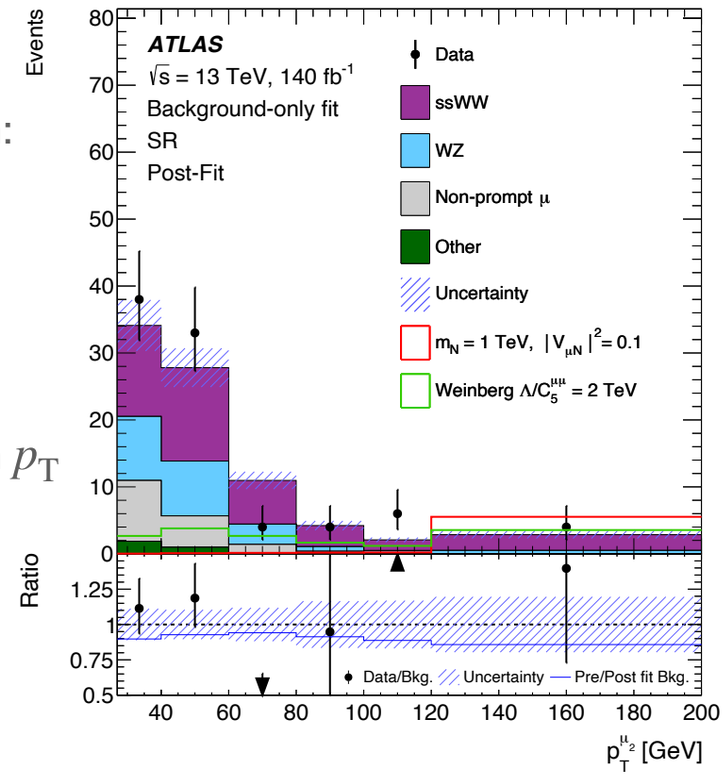
  w/o adding any extra field to SM

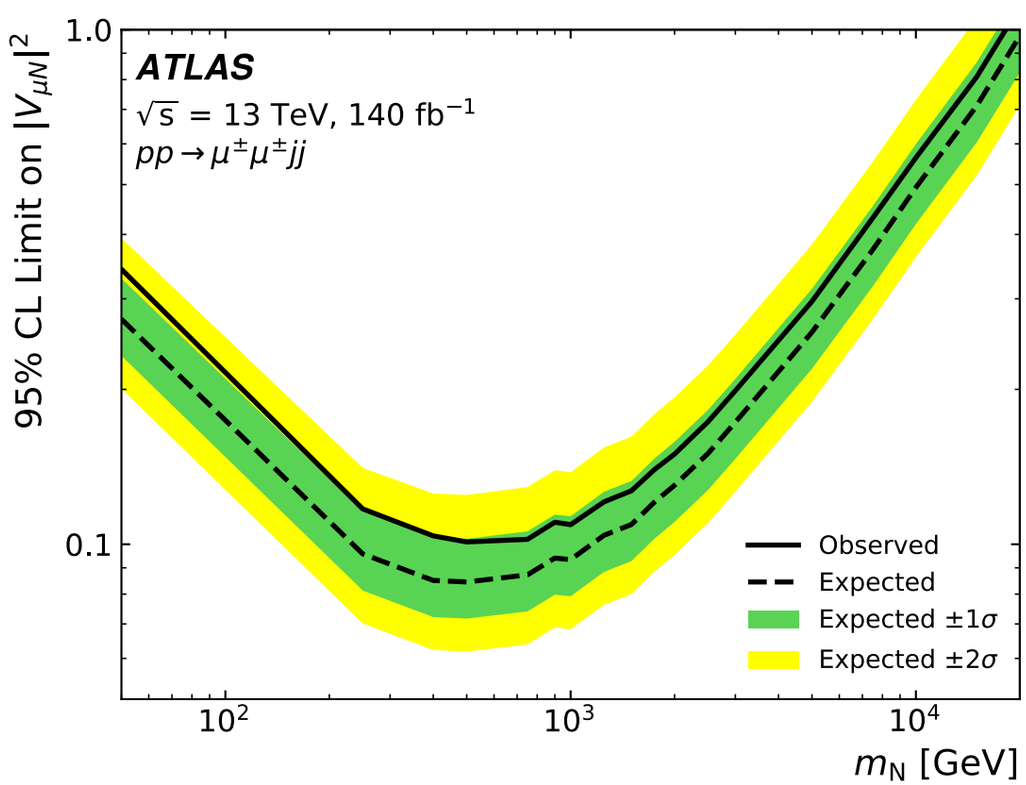


- **test Majorana neutrinos up to m_N = 20 TeV via t-channel**
  assuming $(f_e : f_\mu : f_\tau) = (0 : 1 : 0)$
- **limits on Weinberg operator, $m_{\mu\mu} < 16.7\,(13.1)$ GeV obs (exp)**

signal region:
low $E_{\mathrm{T}}^{\mathrm{miss}}$ significance,
third ℓ veto

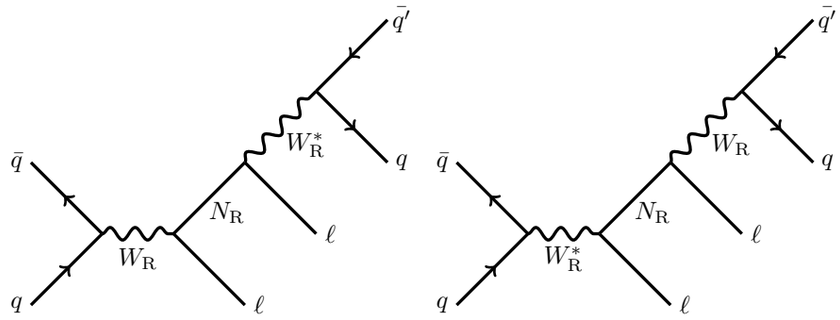
trailing muon p_{T}





HNLs and W_R in final states with leptons and jets

arXiv:2304.09553



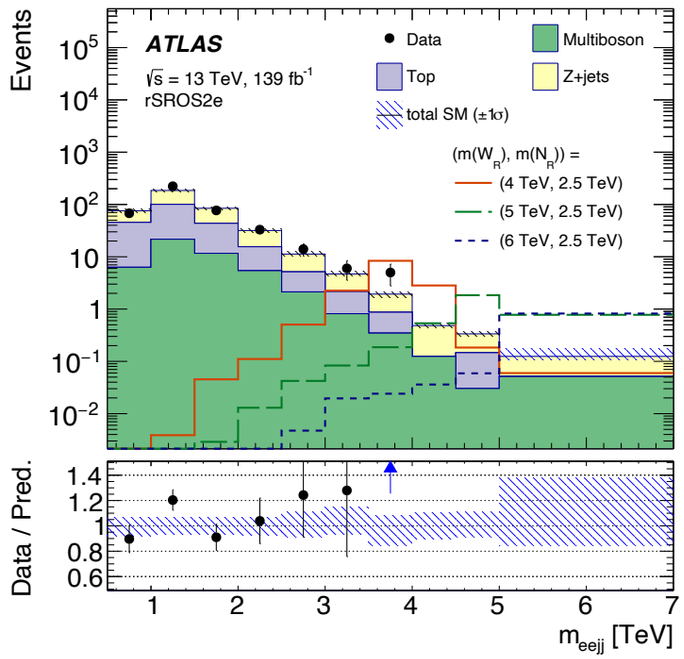
- **L**eft **R**ight **S**ymmetric **M**odel additional heavy right-handed bosons W_R, Z_R and heavy neutrinos N_R

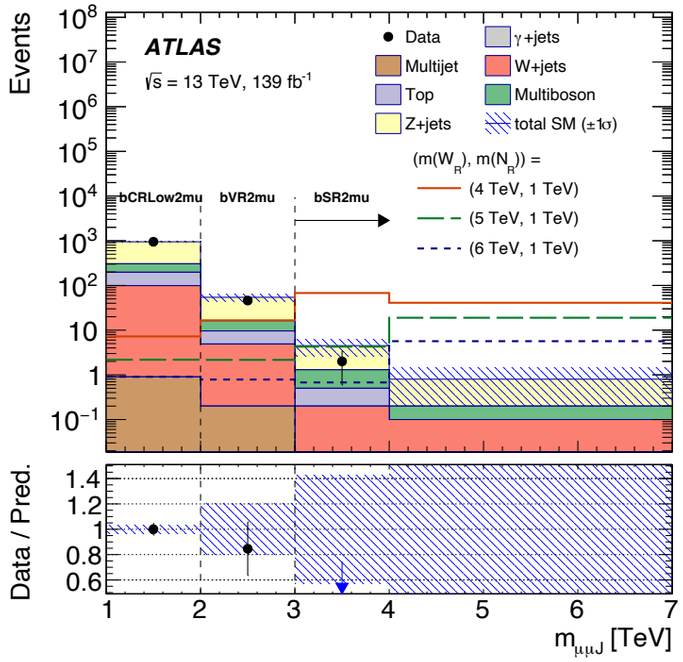
- **various final states depending on** $\Delta m(W_R, N_R)$**:** $\ell\ell jj$, $\ell\ell J$, eJ
  j resolved, J boosted, $\ell = e, \mu$

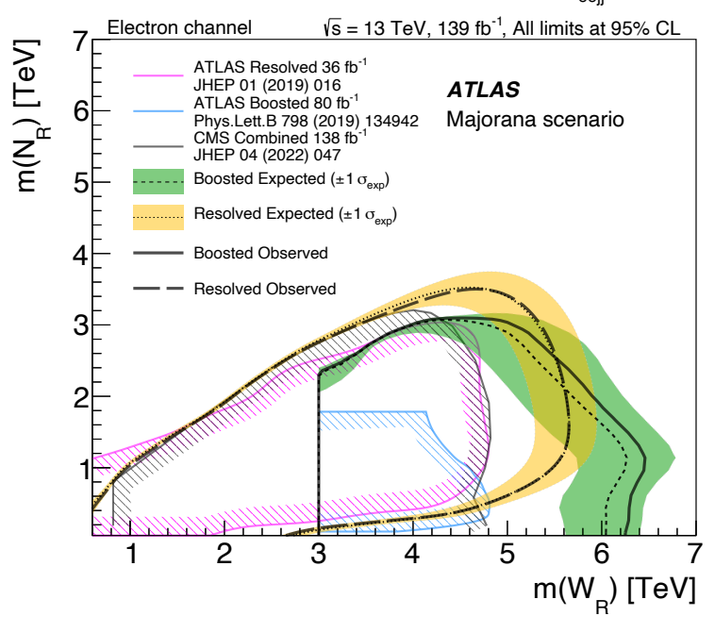
- deep categorisation, including data control regions for multi boson process

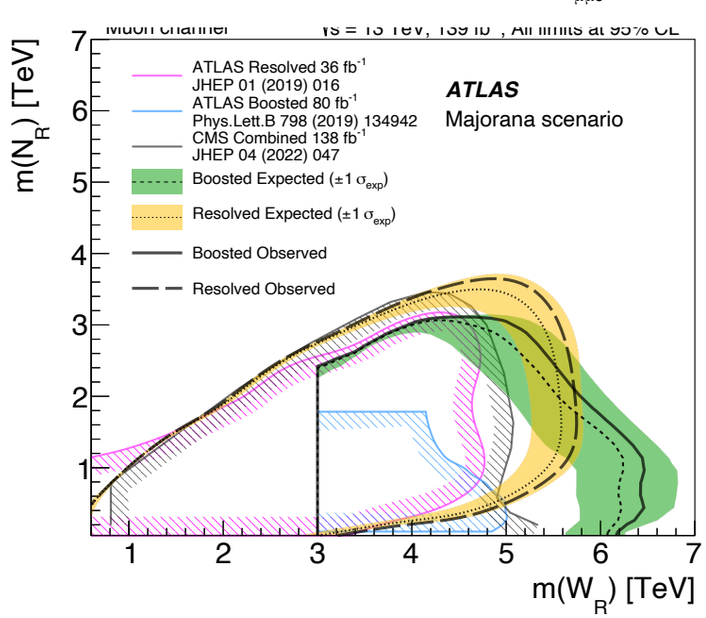
- probe Majorana & Dirac

- **stringent exclusions up to**
  $m_{W_R} > 6.4$ TeV **for** $m_N \sim 1$ TeV **and**
  $m_N > 3.6$ TeV **for** $m_{W_R} \sim 5$ TeV



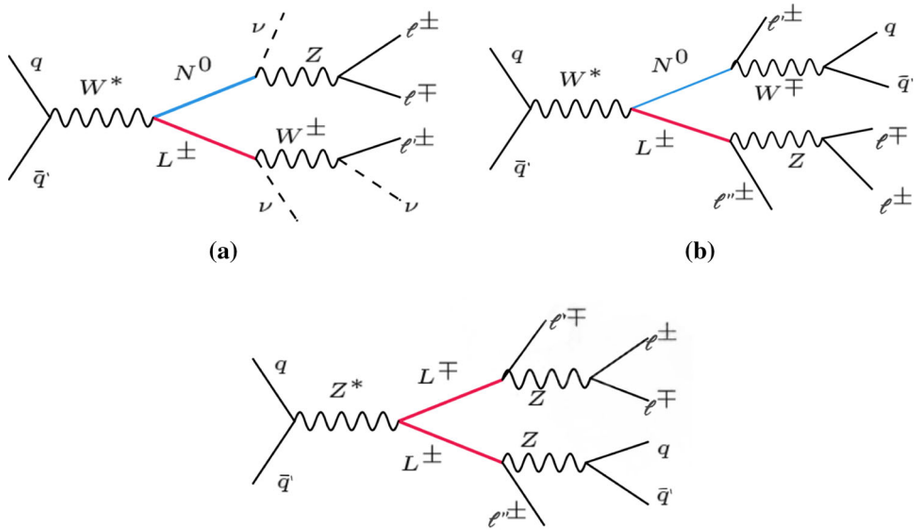


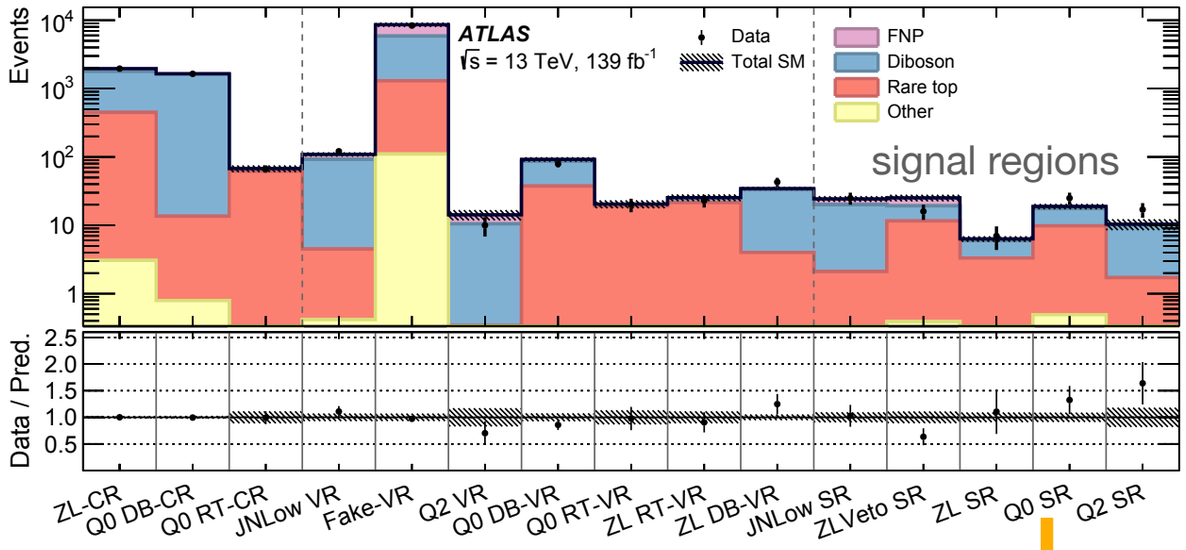


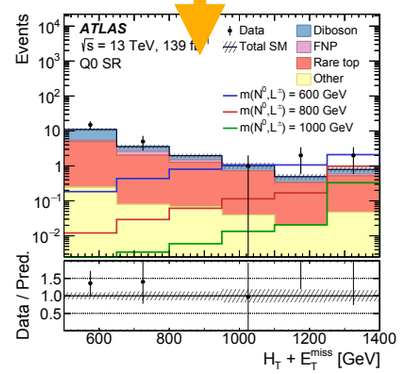


Type-III seesaw HNLs in leptonic final states

EPJC 82 (2022) 988







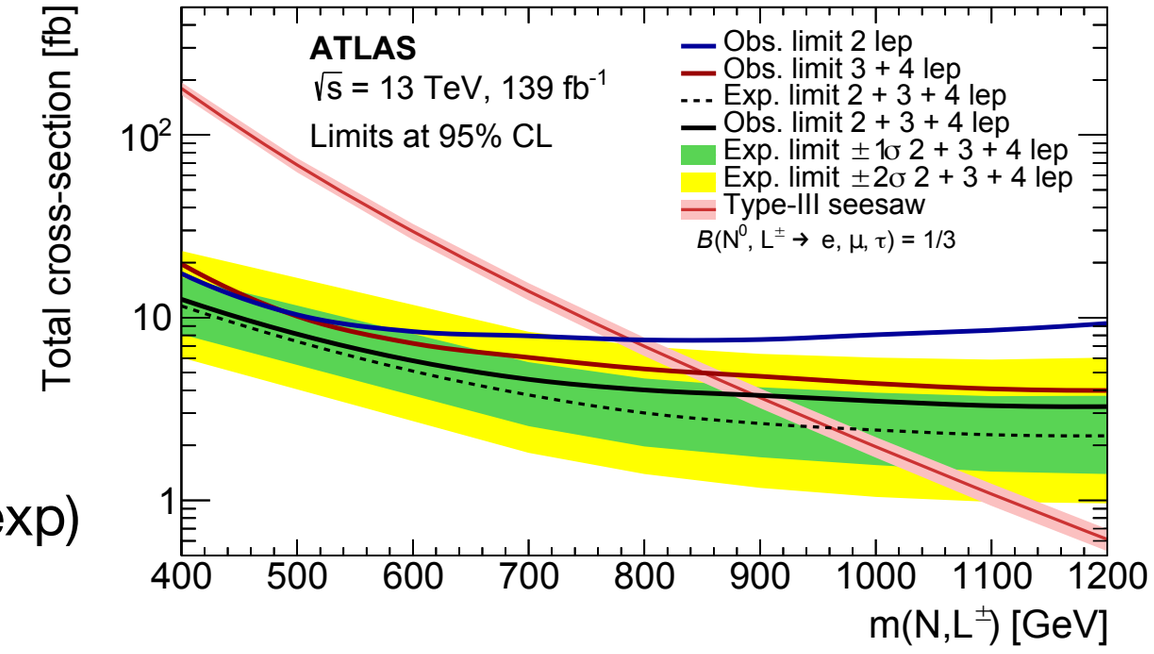
- **type-III seesaw:** one extra fermionic $SU(2)_L$ triplet coupled to W, Z, $m_{N^0} \sim m_{L^\pm}$
- **categorisation leverages rich experimental signature with 3, 4 light leptons (including $\tau \to \ell\nu$), jets and $p_{\mathrm{T}}^{\mathrm{miss}}$**
- democratic scenario

$$L^\pm \to H\ell^\pm, Z\ell^\pm, W^\pm\nu_\ell \quad \ell = e, \mu, \tau$$
$$N^0 \to H\nu_\ell, Z\nu_\ell, W^\pm\ell^\mp$$
$$\mathscr{B}_e = \mathscr{B}_\mu = \mathscr{B}_\tau = 1/3,$$
$$2\mathscr{B}_Z = 2\mathscr{B}_H = \mathscr{B}_W = 1/2$$

- **combined with previous 2 lepton analysis**

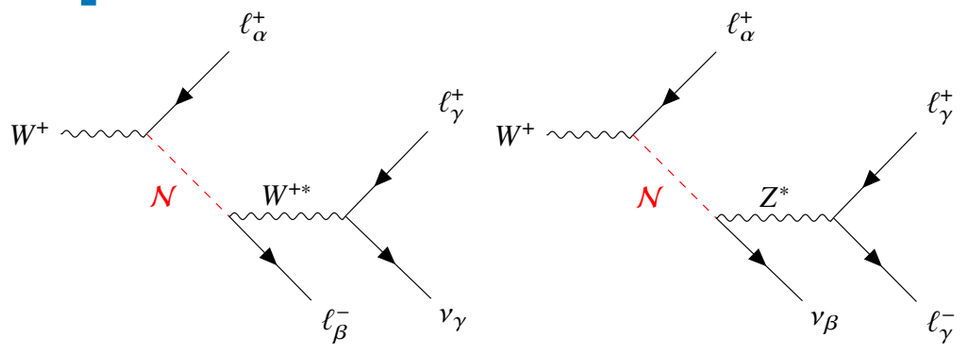
Eur. Phys. J. C **81**, 218 (2021)

- **95% exclusion at $m_{(N,L^\pm)} > 910\,(960)$ GeV obs (exp)**



HNLs in W decays with a di-lepton displaced vertex

PRL 131 (2023) 061803

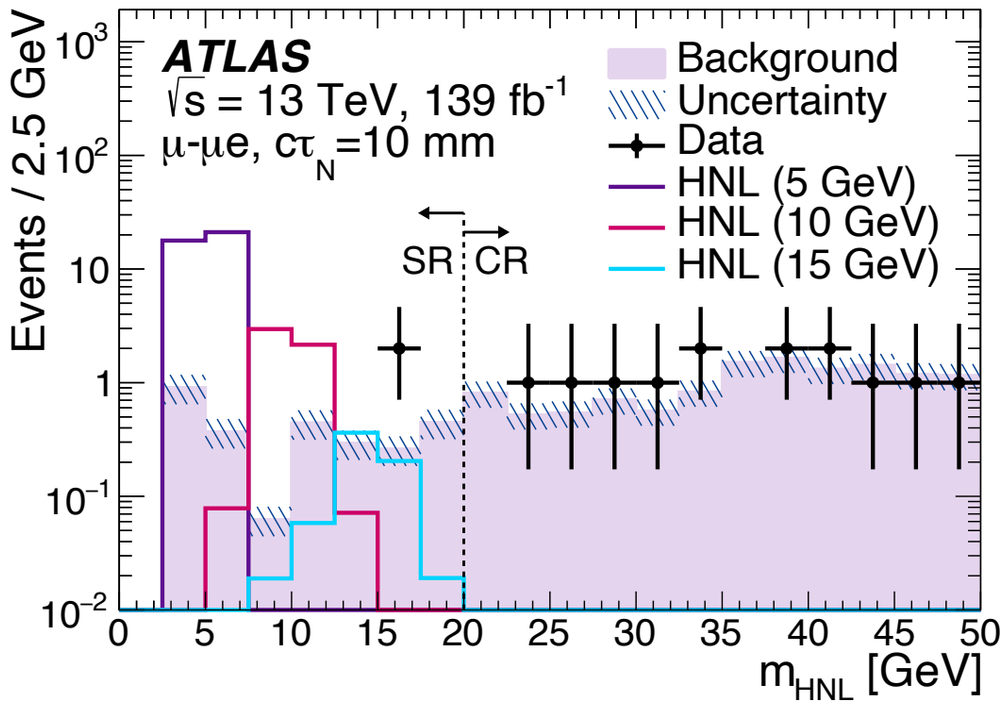


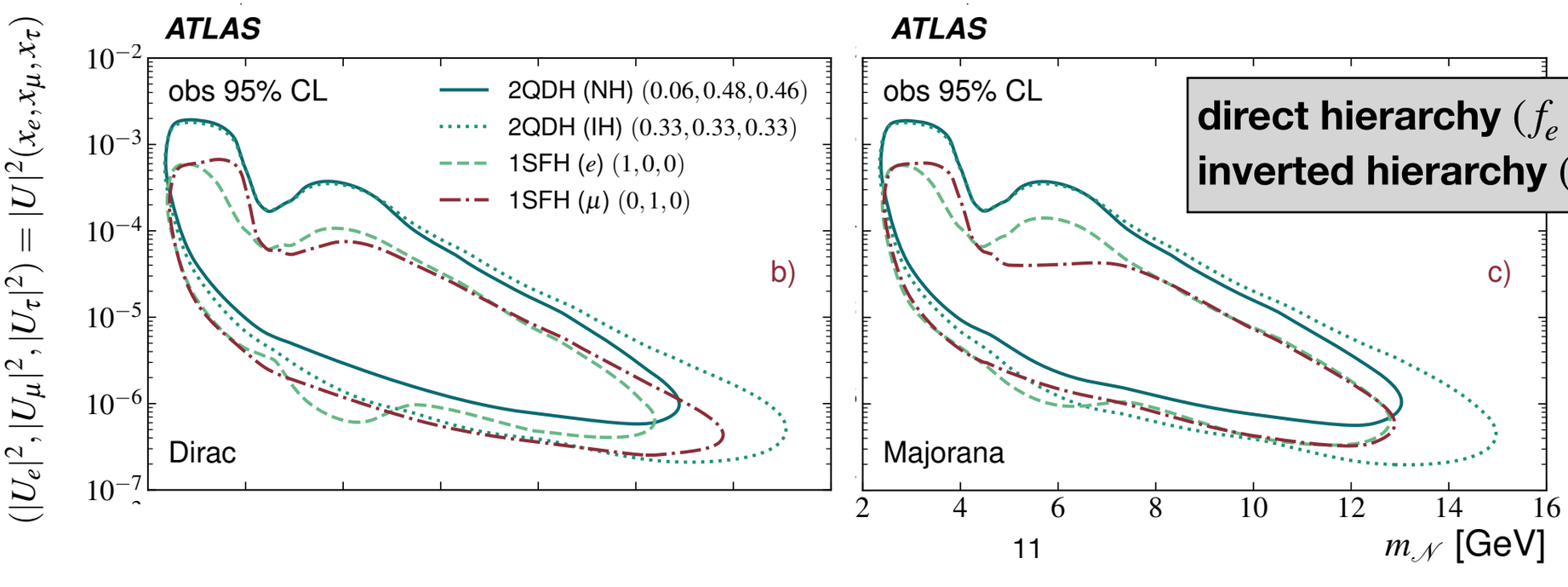
- $\mathbf{W \to \ell N,\ N \to \ell \ell \nu}$ $\quad \ell = e, \mu$
  long-lived N, 1 prompt ℓ, 2 displaced ℓ forming a displaced vertex DV with $4\,\text{mm} < r_{DV} < 300\,\text{mm}$

- Dirac & Majorana interpretations

- ***first* interpretation in *2 quasi-degenerate HNLs model***
  motivated by evidence of oscillations

m_{HNL} inferred from solving kinematics and PV-DV flight direction





direct hierarchy $(f_e : f_\mu : f_\tau) = (0.06 : 0.48 : 0.46)$
inverted hierarchy $(f_e : f_\mu : f_\tau) = (1/3 : 1/3 : 1/3)$

HNL & Weinberg operator in VBS

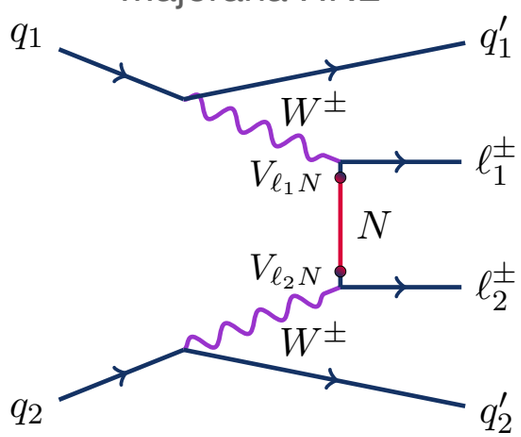
PRL 131 (2023) 011803

- **like-sign leptons, VBS jets**
  Majorana N: large $\Delta\phi_{\ell\ell}$
  Weinberg operator: small $p_{\mathrm{T}}^{\mathrm{miss}}$

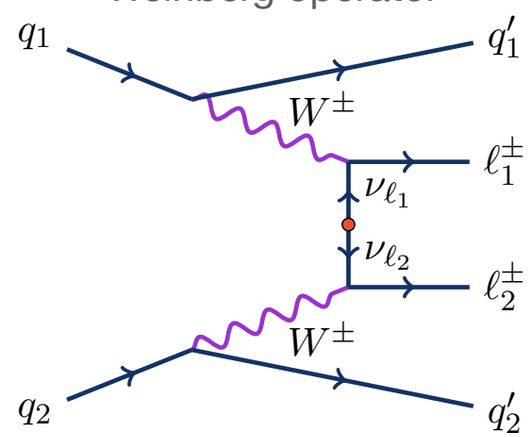
- **test majorana neutrinos up to m_N = 25 TeV via t-channel:** strongest limits for m_N>650 TeV

- **Weinberg operator probed for the first time at LHC**
  limits on $m_{\mu\mu} < 10.8\,(12.8)$ GeV obs (exp)

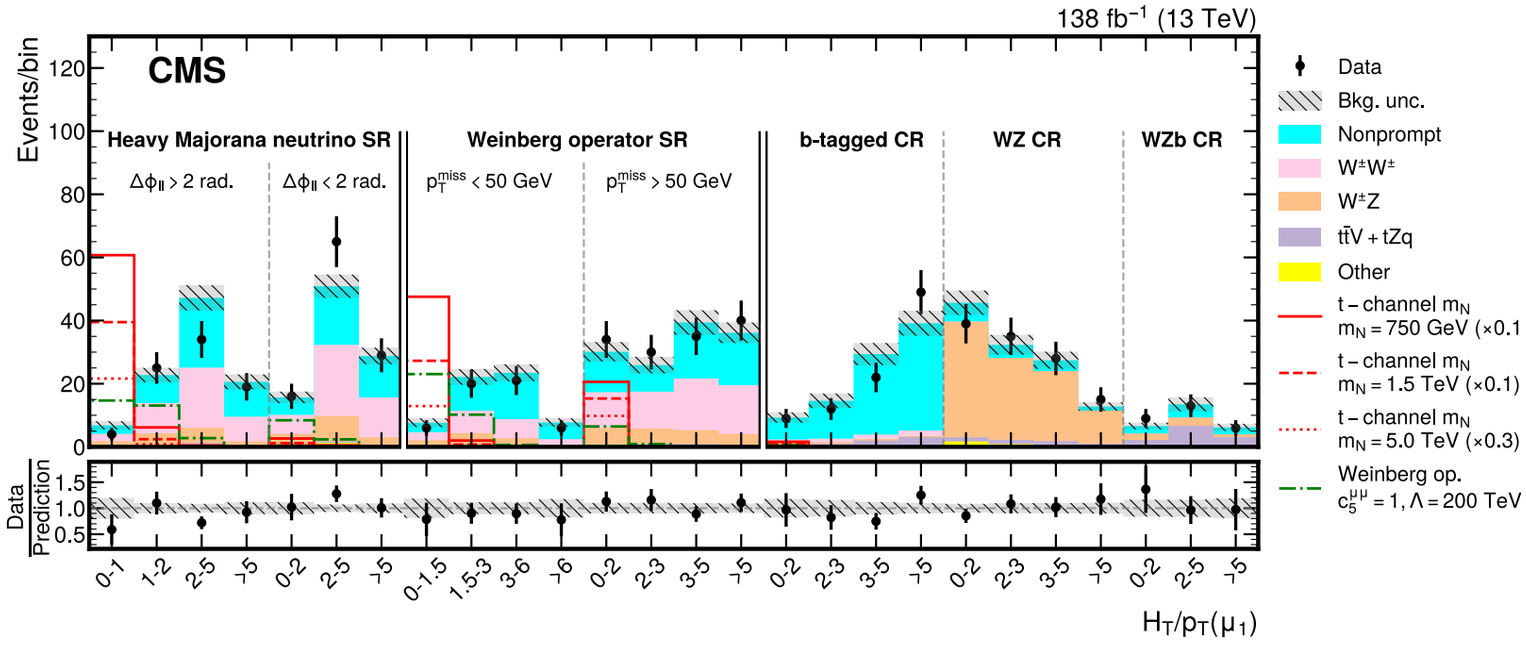
Majorana HNL

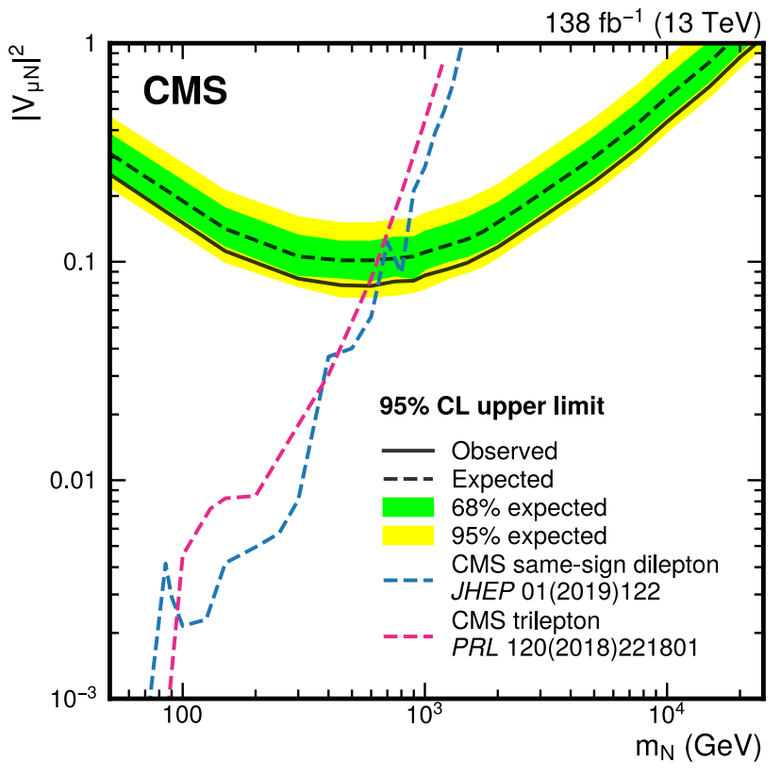


Weinberg operator



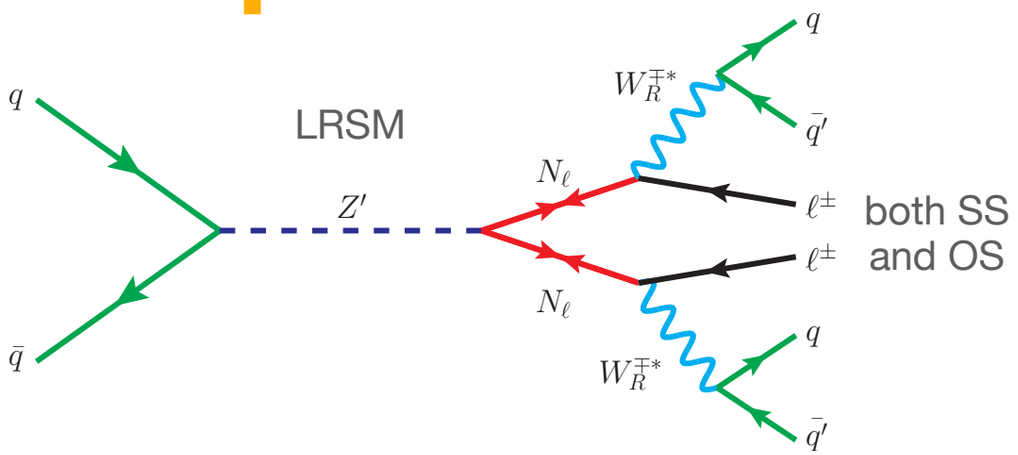
like sign ℓ, lepton number violation



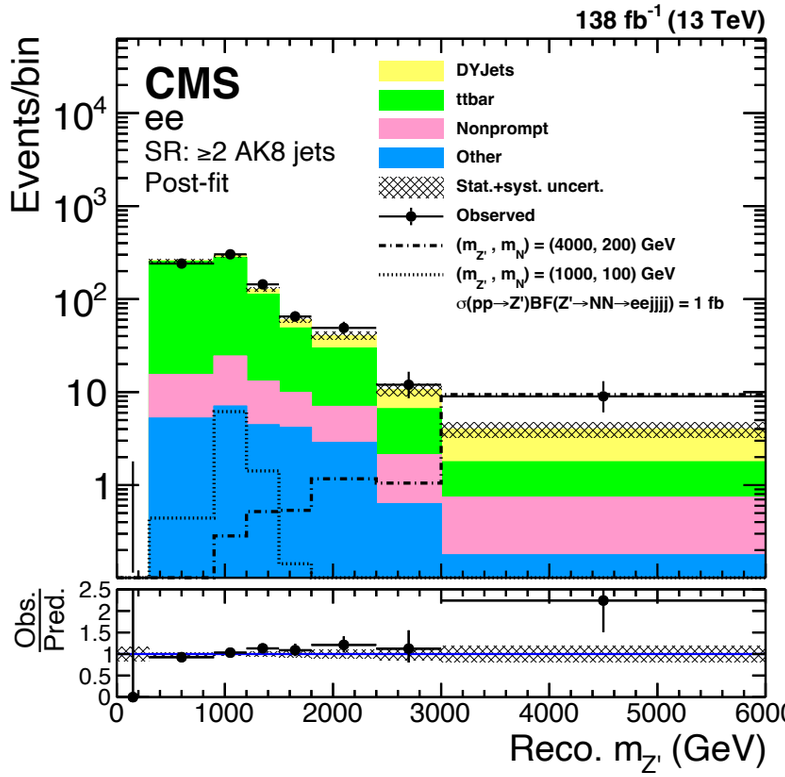


Search for Z' boson decays into HNL pairs

arXiv:2307.06959



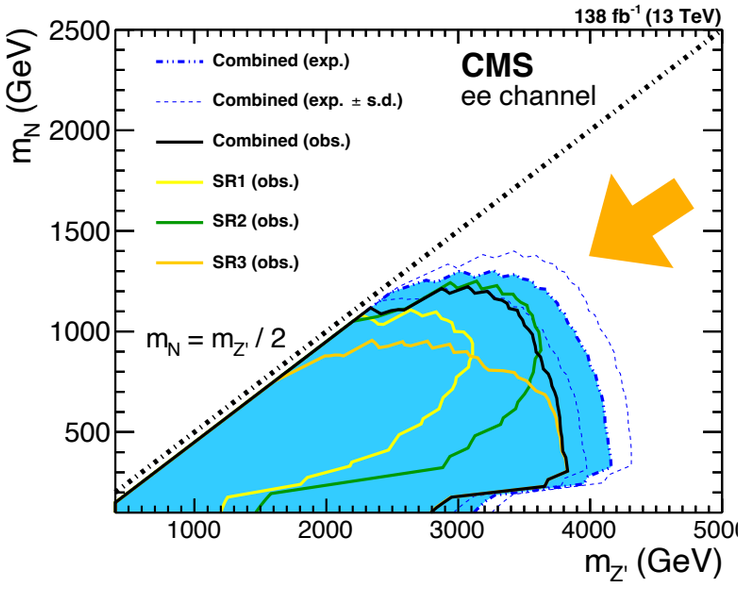
- **search for excess in $Z' = \ell\ell + n\,\text{jets}$ invariant mass, with $\ell = e, \mu$**

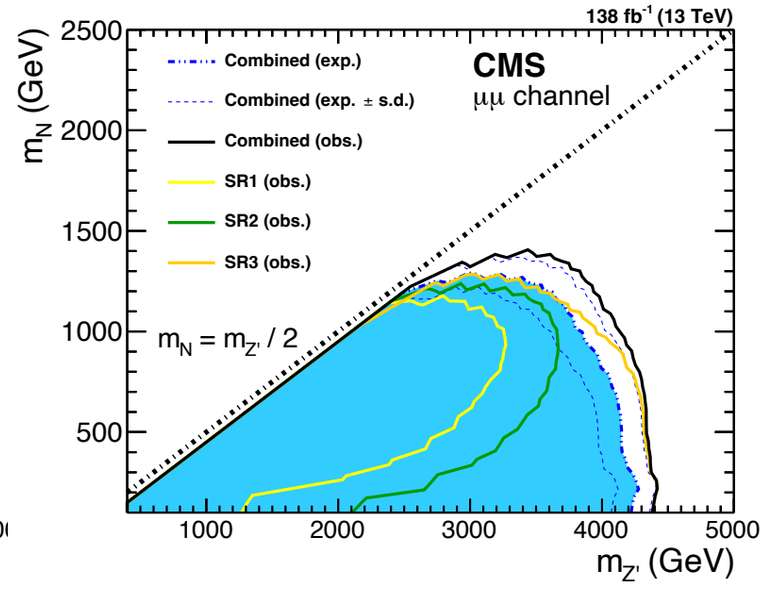


- categorisation based on resolved, merged jets (up to 4). Depends on $m_N/m_{Z'}$

- **reconstruct Z' and HNL mass** sensitive to $m_N \ll m_{Z'}$

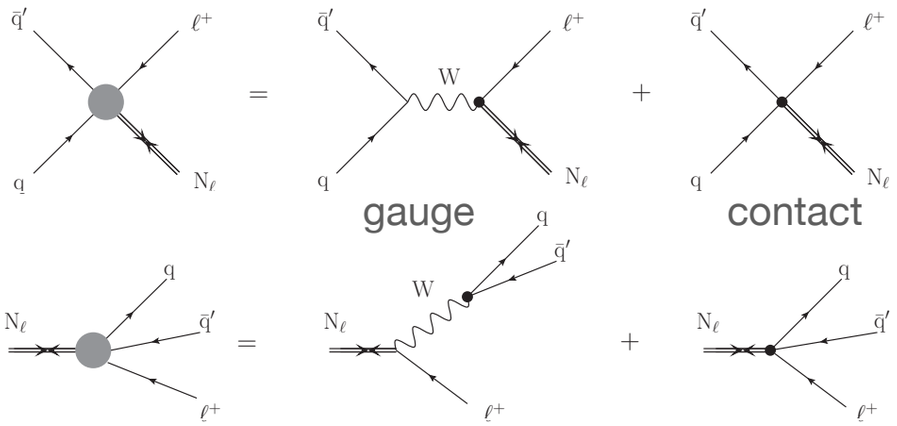
- **excess in the ee channel, max significance** $\sigma = 3.32\,(2.28)$ global (local) **at** $(m_{Z'}, m_N) = (4.6, 0.1)$ TeV



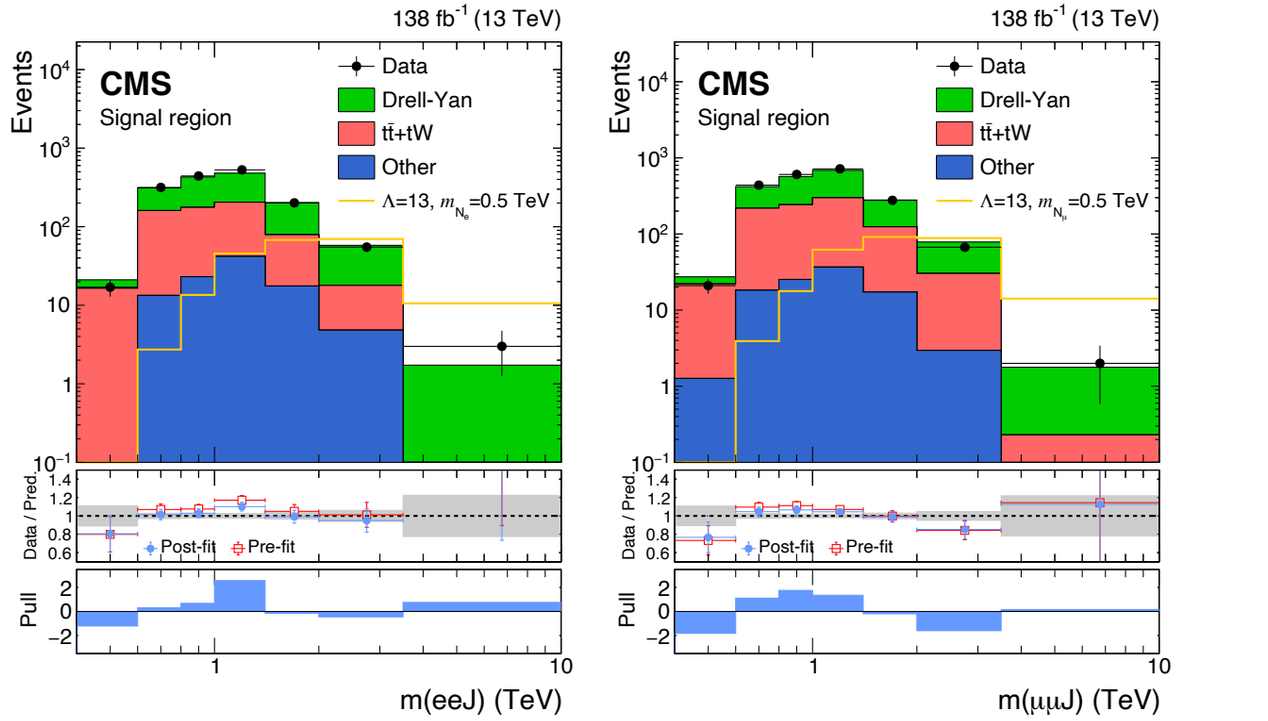


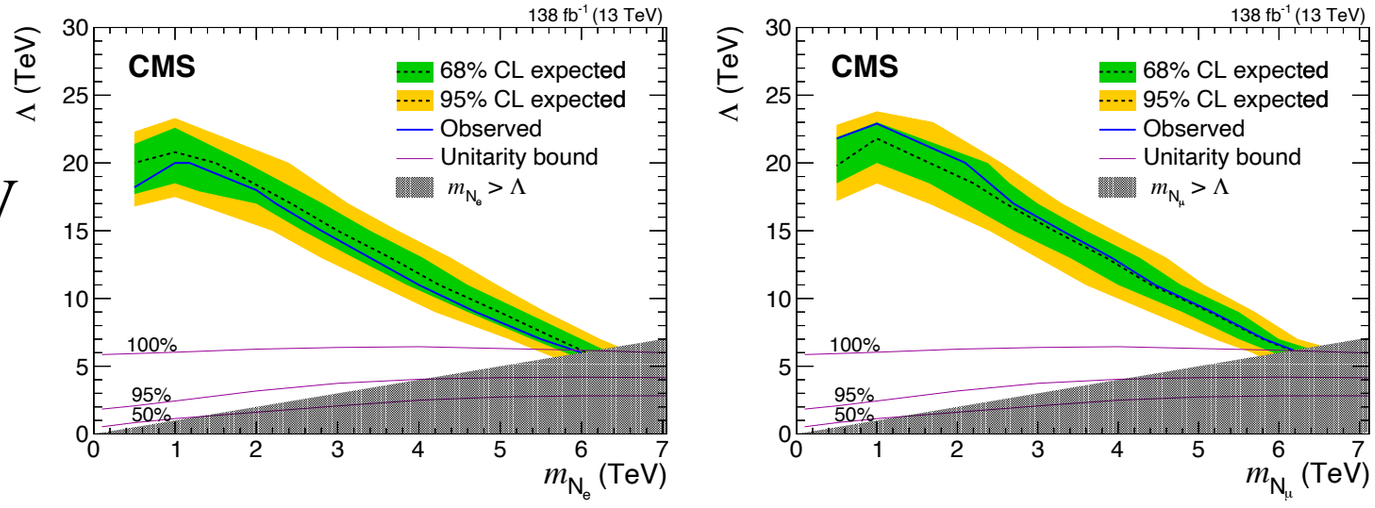
Search for a heavy, composite Majorana neutrino

Phys. Lett. B 843 (2023) 137803



- **postulate ℓ, q (and HN) to have substructure at scale Λ** for $E \ll \Lambda$ akin to contact interactions (EFT)
- $\ell^\pm\ell^\pm(q\bar{q}), \ell = e, \mu$ final states
- large radius $(q\bar{q})$ *J*et, $p_T > 190\,\mathrm{GeV}$
- **exclusions on $m_N = \Lambda$ up to $6\,\mathrm{GeV}$**





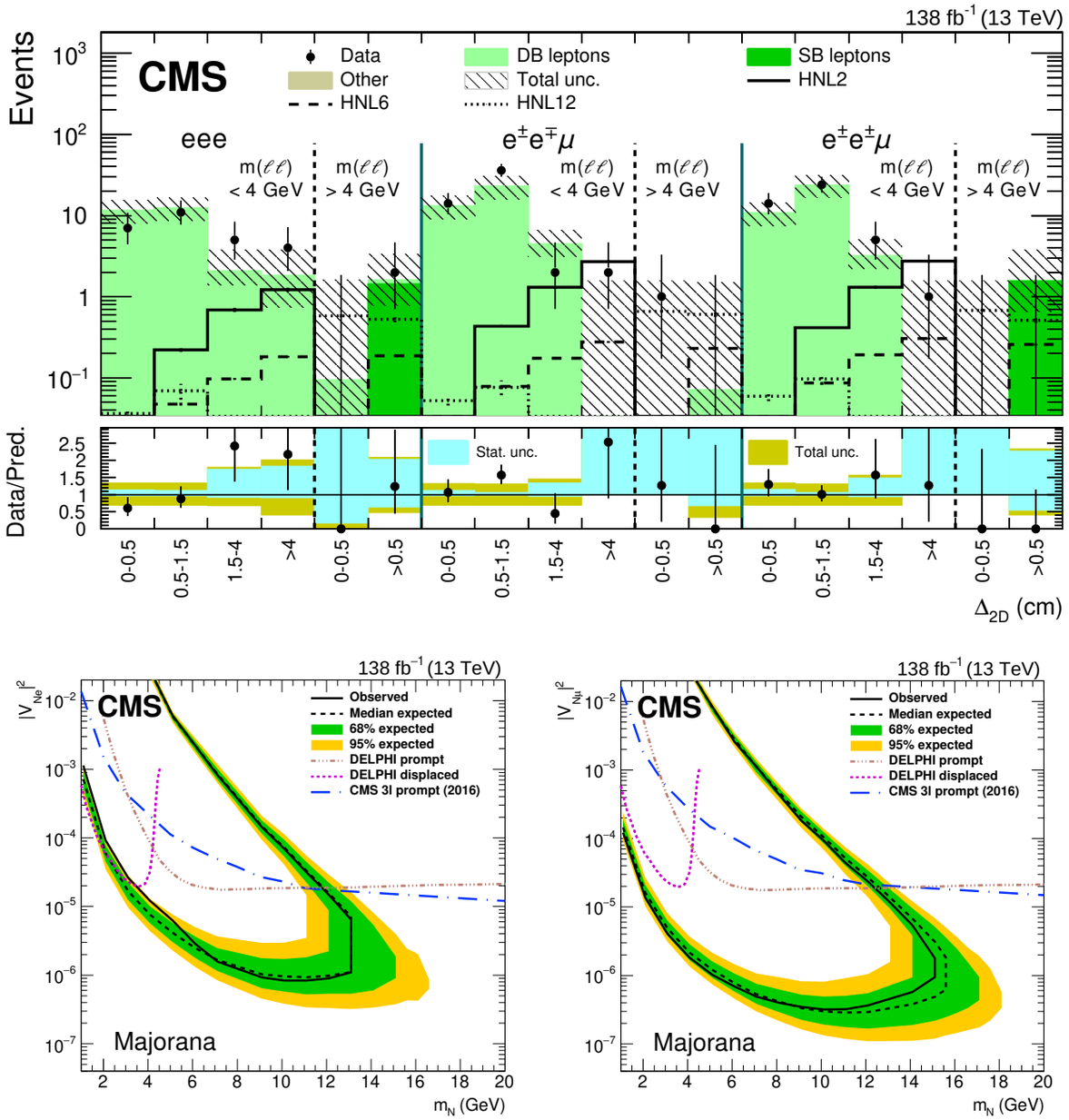
Long-lived HNL in 3ℓ final state

10.1007/JHEP07(2022)081

- $\mathbf{W} \to \ell \mathbf{N}$, $\mathbf{N} \to \ell\ell\nu$, $\ell = e, \mu$
  1 prompt lepton
  2 displaced leptons forming a displaced vertex
  Majorana / Dirac models

- **categorisation**
  6 final states
  $\mu(\mu\mu)$, $\mu^{\pm}(\mu^{\mp}e^{\pm})$, $\mu^{\pm}(\mu^{\pm}e^{\mp})$
  $e(ee)$, $e^{\pm}(e^{\mp}\mu^{\pm})$, $e^{\pm}(e^{\pm}\mu^{\mp})$
  displacement $\Delta(\mathrm{PV} - \mathrm{SV})_{2D}$
  di-lepton mass

- **data-driven fake lepton bkg**
  mostly non-prompt from HF



Long-lived HNLs with a displaced jet and 2 leptons - 1

CMS-PAS-EXO-21-013

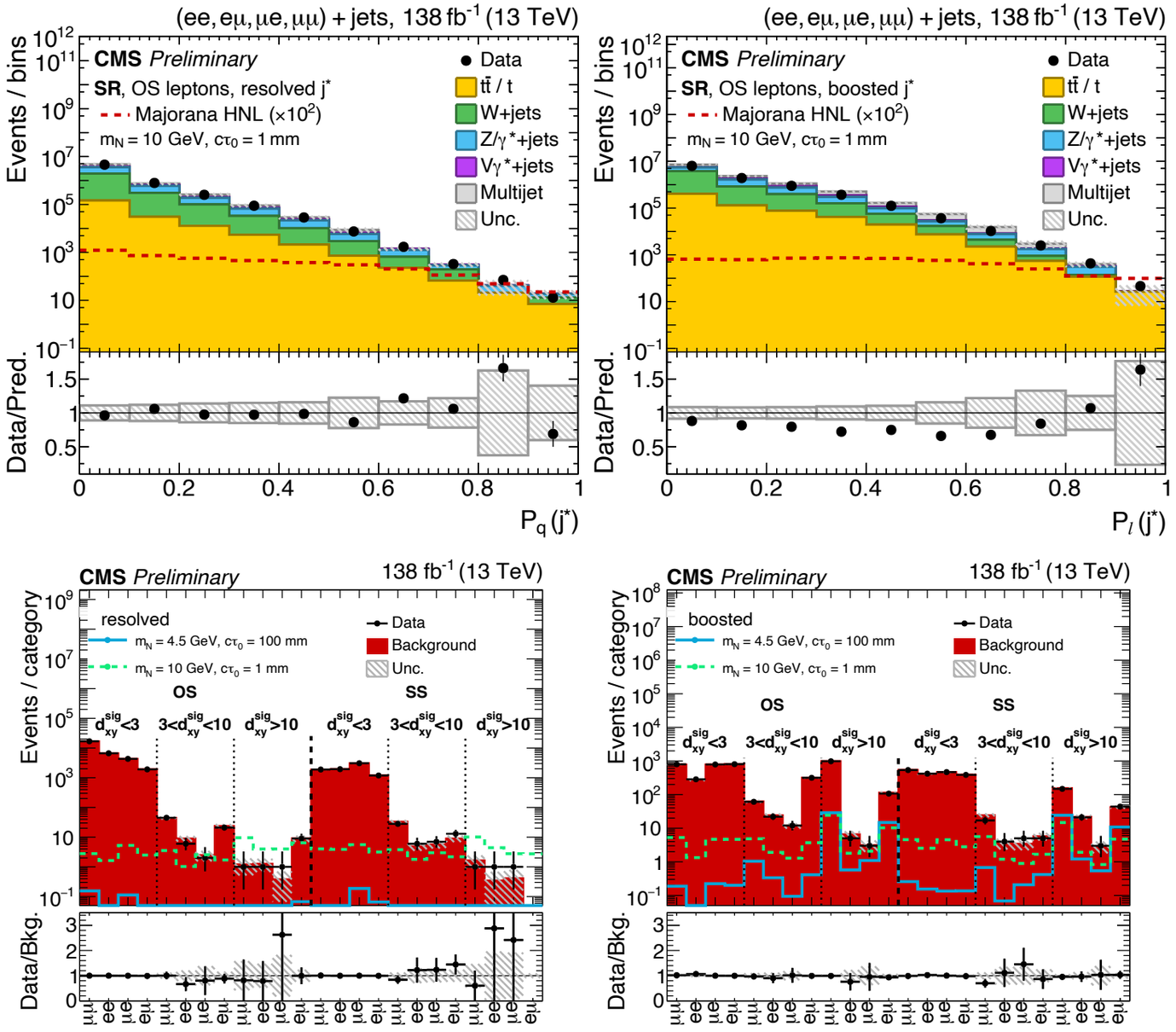
- $\mathbf{W \to \ell_1 N,\ N \to \ell_2 q\bar{q}}$
  trigger on prompt ℓ_1

- **NN-based displaced jet tagger trained on jet constituent features**
  uses data from control region
  → good modeling of NN score

- **categorisation**
  $\ell_1\ell_2$ charge × flavour × d_{xy}^{sig}
  both Majorana/Dirac considered

- **backgrounds**
  ABCD $m_{\ell\ell j}$, tagger score

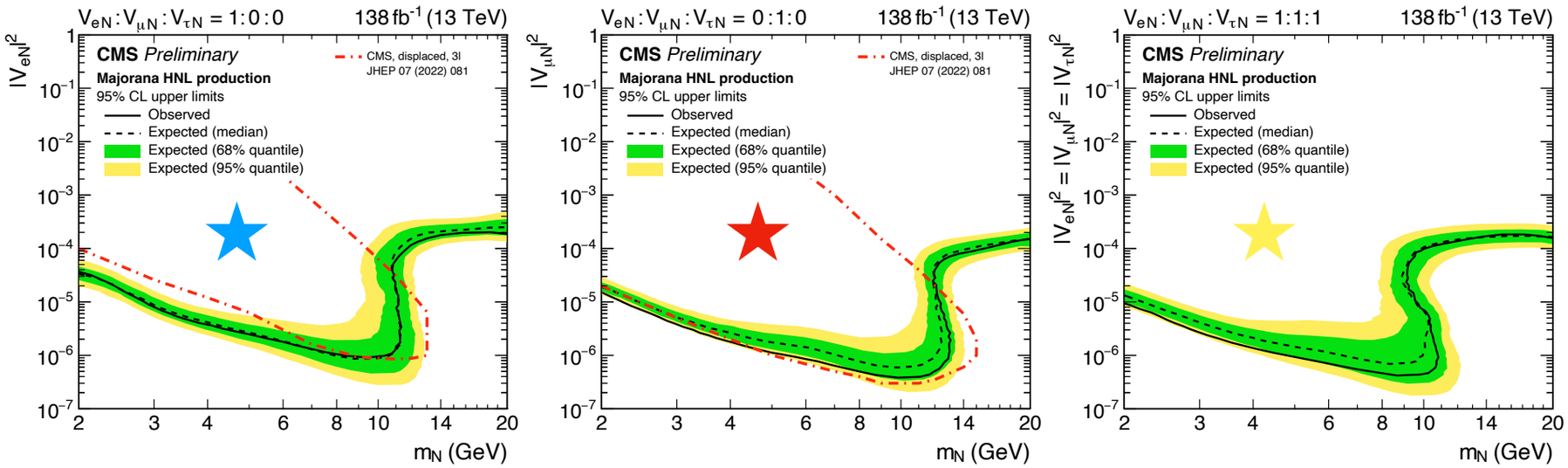
NN score



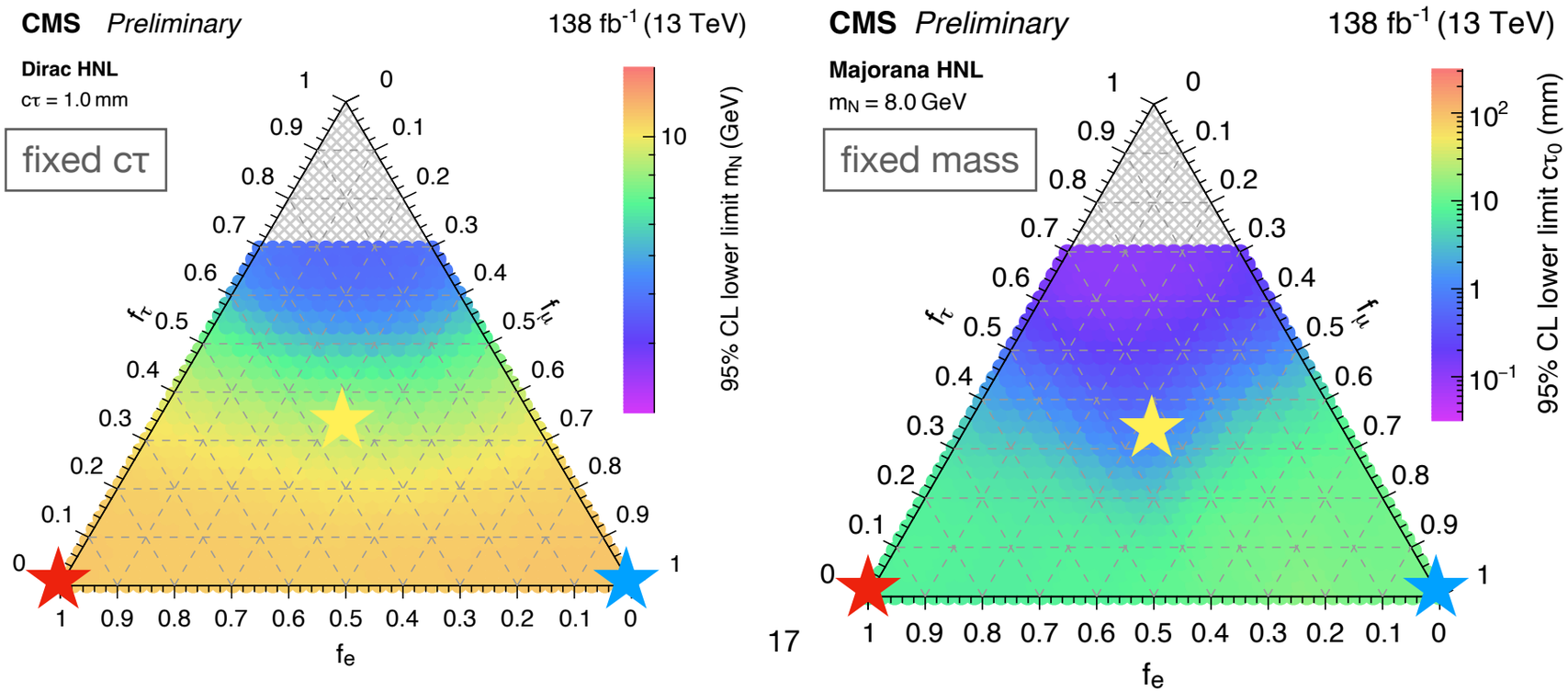
distributions for final fit

Long-lived HNLs with a displaced jet and 2 leptons - 2

CMS-PAS-EXO-21-013



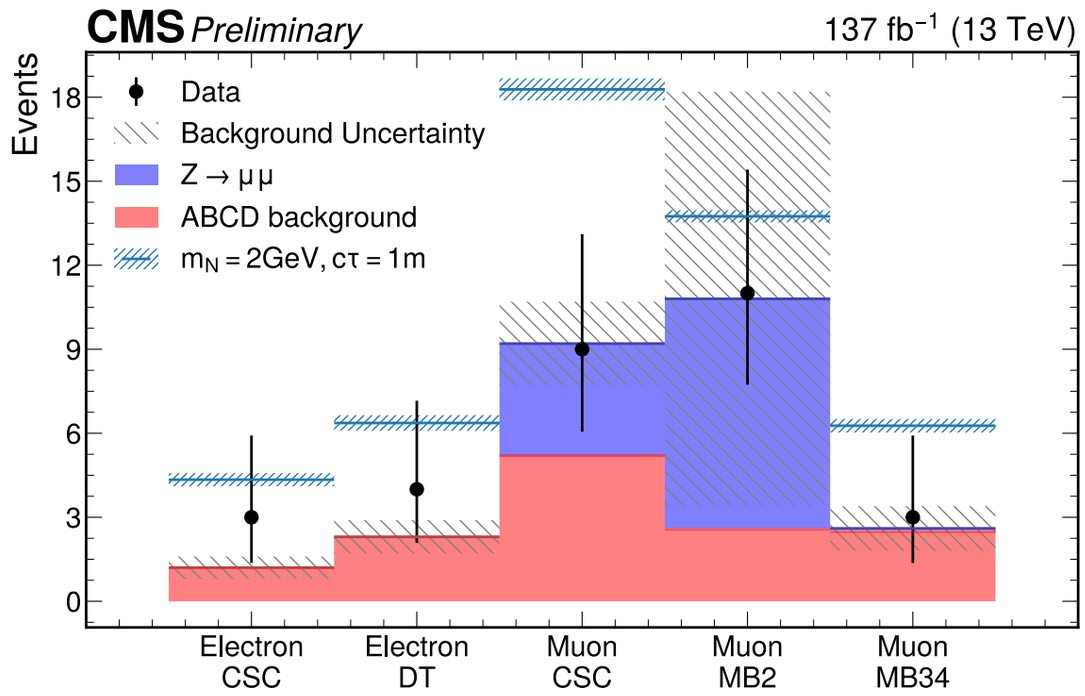
95% CL exclusion limits provided in various $(f_e : f_\mu : f_\tau)$ mixing scenarios



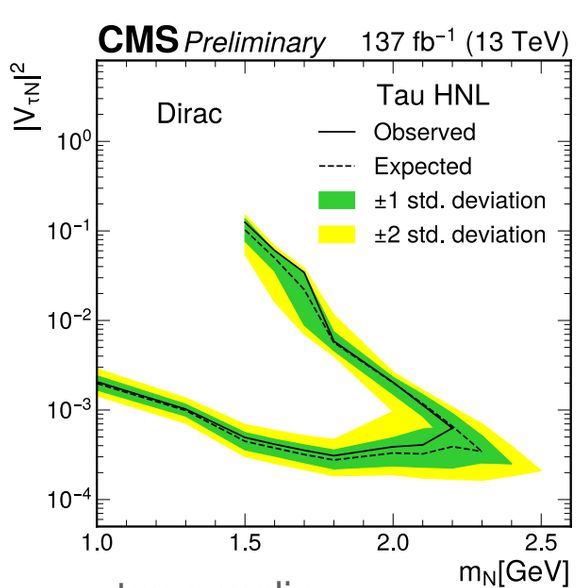
Long-lived HNL in the muon system

CMS-PAS-EXO-22-017

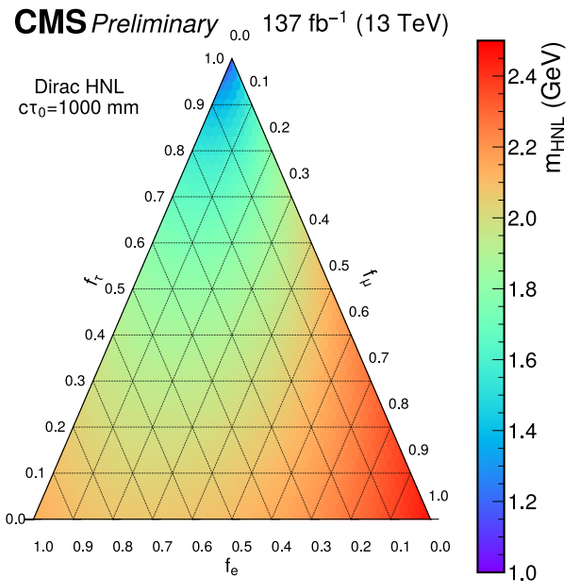
- **decays in CMS muon system**
  $3 < r < 7\ m$
- **HNL signature**
  localized hits cluster in muon system
- background from OOT PU, jet punch throughs
- $\mathbf{W \to \ell N,\ N \to X}$
  trigger on prompt ℓ
  inclusive HNL decays, maximise acceptance
- nonprompt background from data ABCD
  $\Delta\phi(\ell, \text{cluster})$ & N_{hits}
- **best limits**
  $|V_{eN}|^2 > 8.6 \cdot 10^{-6}\ @ m_N = 2.6\ \text{GeV}$
  $|V_{\mu N}|^2 > 4.6 \cdot 10^{-6}\ @ m_N = 2.8\ \text{GeV}$
- **limits for arbitrary flavour mixing scenarios**
  $(f_e : f_\mu : f_\tau)$



categorise by muon subsystem / station

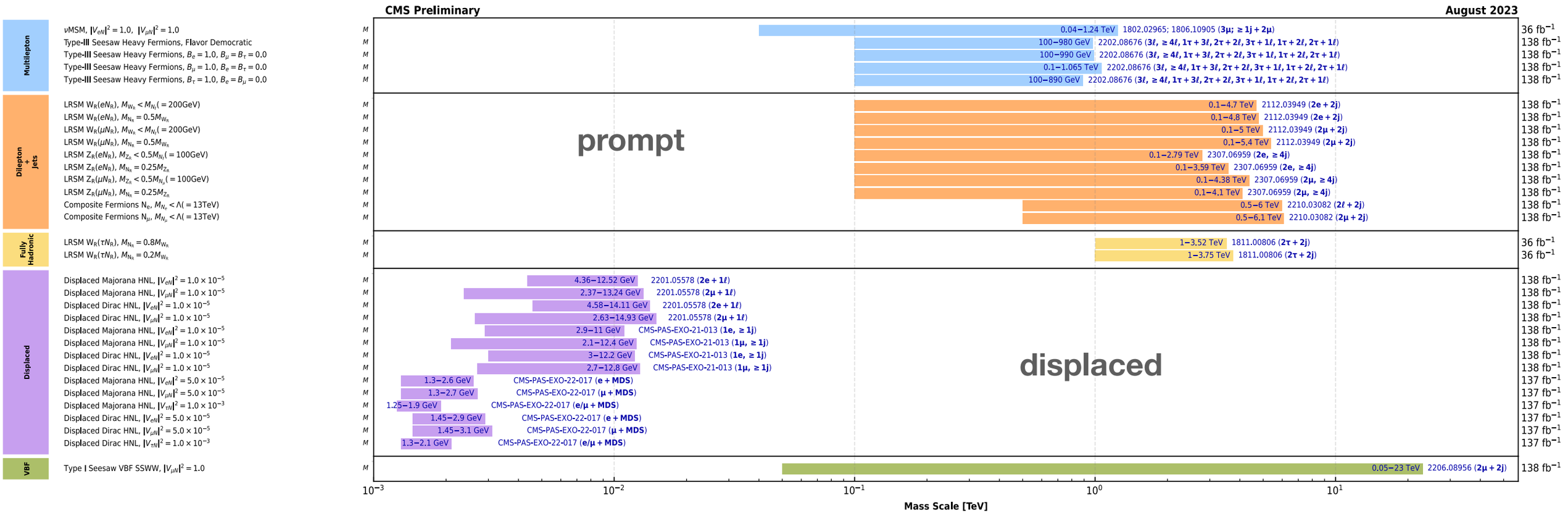


tau coupling



CMS results on HNL at a glance

link



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Where we are

vast program of HNL searches by ATLAS and CMS

heavy neutrino appears in a multitude of models

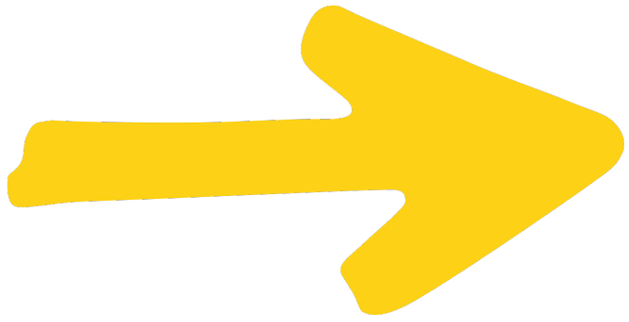
full Run2 dataset analysed

leveraged broad array of experimental signatures

VBF, displaced vertices, displaced jet taggers, resolved/boosted jets…

complementarity with other experiments

$m_N > m_B$ is exclusive LHC domain



where we’re going

better explore third generation couplings
tau more challenging, constraints are weaker

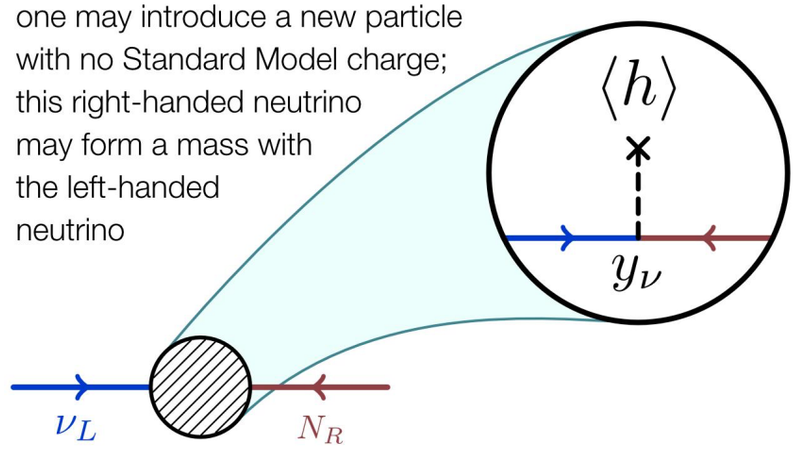
investigate flavour mixing scenarios
neutrino oscillation experiments indicate mixed couplings

add Run3 data, include more signatures and improve performance at large displacement
large parts of parameter space still untouched

backup

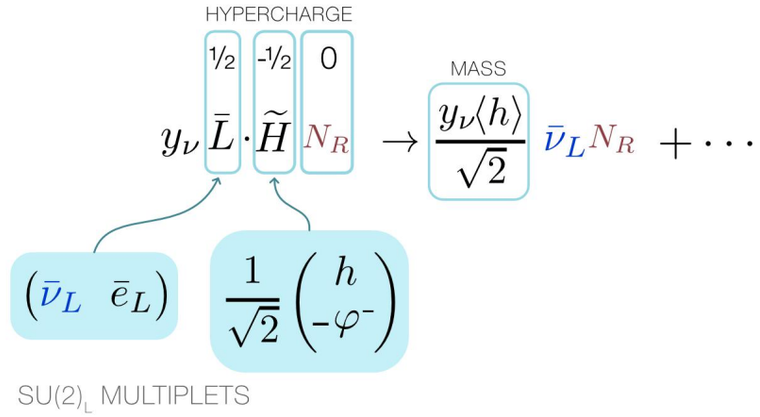
Dirac Mass: neutrino Yukawa

one may introduce a new particle with no Standard Model charge; this right-handed neutrino may form a mass with the left-handed neutrino



LEFT-HANDED NEUTRINO

RIGHT-HANDED NEUTRINO **(NEW PARTICLE)**

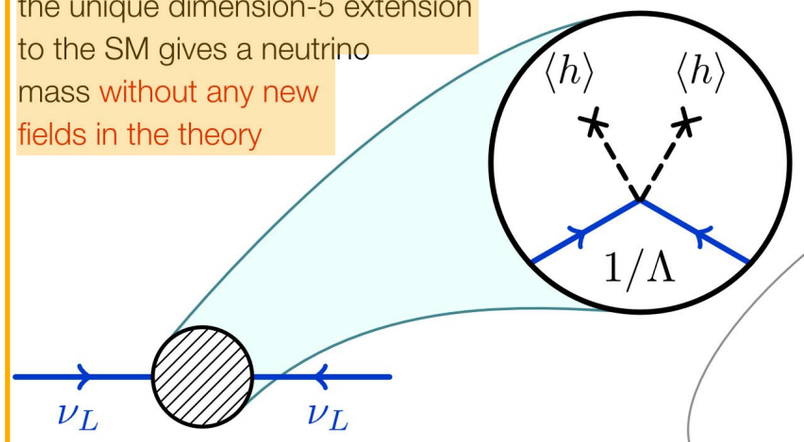


$\tilde{H} = \varepsilon H^*$ THIS REFLECTS THE GROUP THEORETICAL EQUIVALENCE OF THE FUNDAMENTAL AND ANTI-FUNDAMENTAL REPS; SU(2) IS PSEUDOREAL

Filip Tanedo

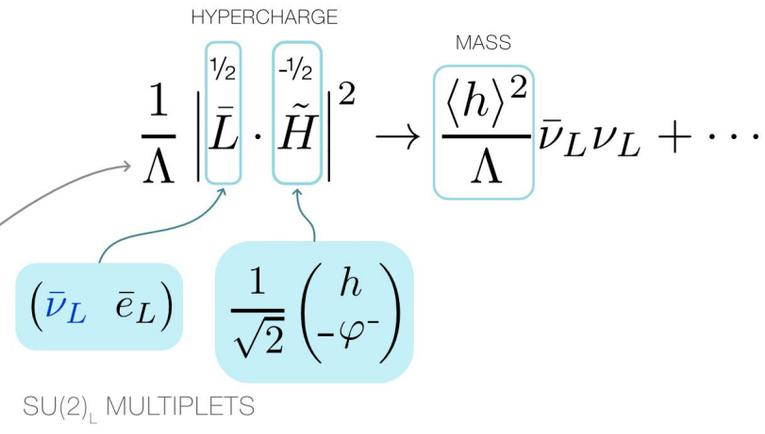
Majorana Mass: Weinberg Operator

the unique dimension-5 extension to the SM gives a neutrino mass without any new fields in the theory



LEFT-HANDED NEUTRINO

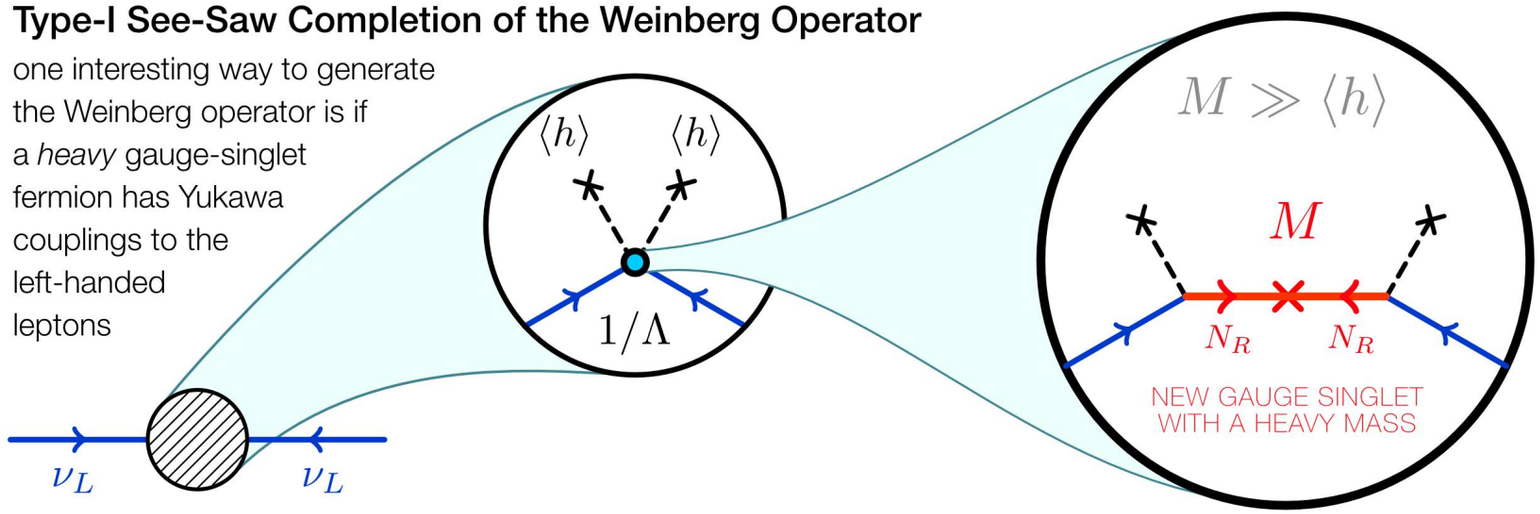
ANTI-[LEFT-HANDED NEUTRINO] (RIGHT-HANDED FERMION)



THIS IS SOME HEAVY SCALE THAT GENERATES THE WEINBERG OPERATOR
WEINBERG, PHYS. REV. LETT. 43, 1566 (1979)

Type-I See-Saw Completion of the Weinberg Operator

one interesting way to generate the Weinberg operator is if a *heavy* gauge-singlet fermion has Yukawa couplings to the left-handed leptons



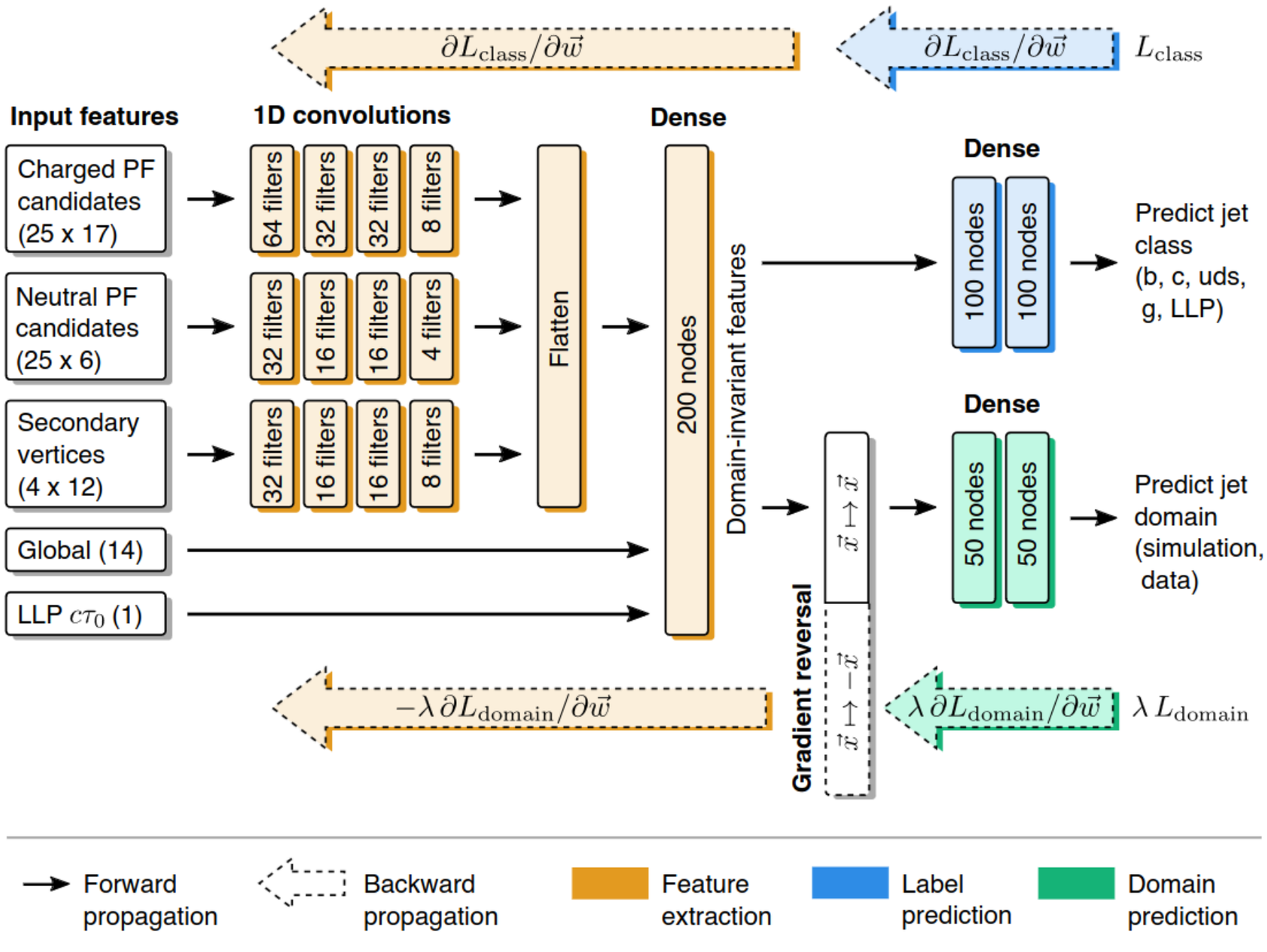
LEFT-HANDED NEUTRINO

ANTI-[LEFT-HANDED NEUTRINO] (RIGHT-HANDED FERMION)

UNLIKE THE DIRAC CASE, THE NR HAS A LARGE MAJORANA MASS. THE OBSERVED NEUTRINOS ARE "SEE SAW" ADMIXTURES OF THE WEAK-CHARGED LEFT-HANDED NEUTRINOS WITH THE HEAVY GAUGE SINGLET NEUTRINOS.

Displaced jet tagger

MLST 1 (2020) 035012



Long-lived HNL in CMS muon system