Discovering new νs (HNLs) at the LHC

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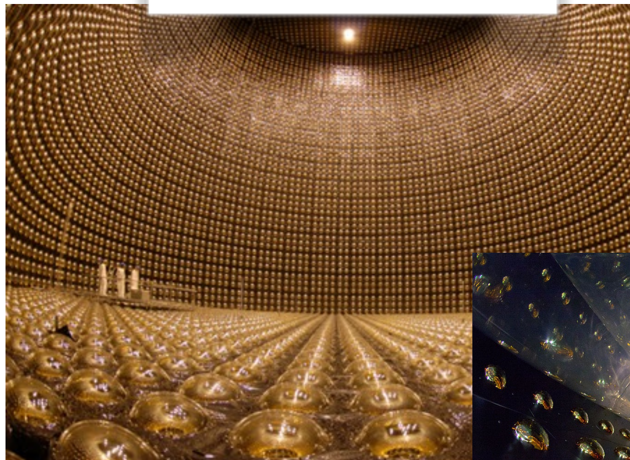
New-ν Physics: From Collider to Cosmology

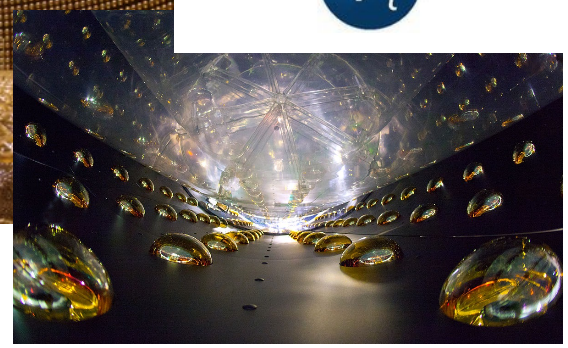
Experimental Observations

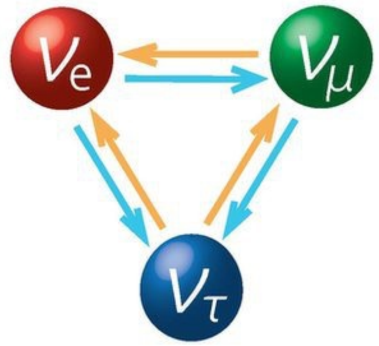
eV neutrino mass and mixing from oscillation and non-oscillation experiments

$$\nu_1, \nu_2, \nu_3 \longrightarrow m_1, m_2, m_3$$

Oscillation







Mass square differences and mixings

$$\Delta m^2_{21} = (6.92 - 8.05) \times 10^{-5}\,\text{eV}^2$$

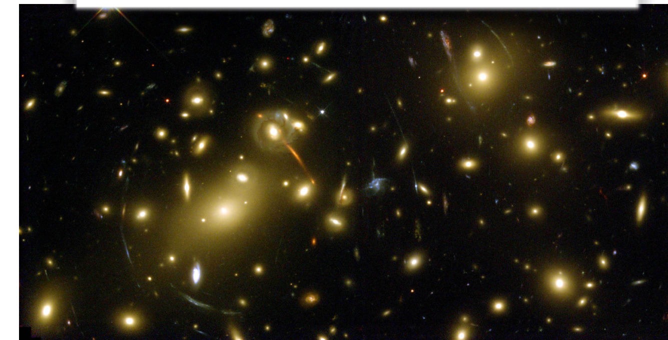
$$\Delta m^2_{31} = (2.46 - 2.60) \times 10^{-3}\,\text{eV}^2$$

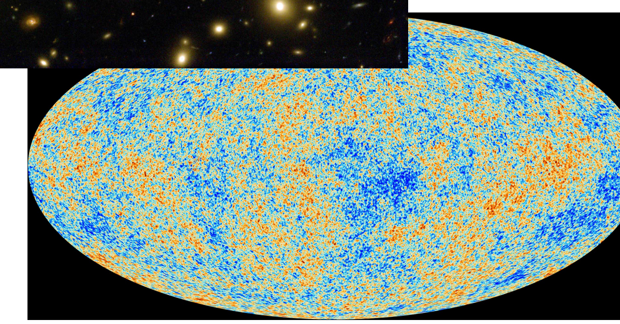
Large angle $\theta_{12} \sim 33.6^\circ, \theta_{23} \sim 48.5^\circ$

Non-zero $\theta_{13} \sim 8.5^\circ$ (DAYA BAY, RENO)

I. Esteban et al.,JHEP 12 (2024) 216, *JHEP* 09 (2020) 178

Non-Oscillation





Sum of neutrino masses

Bound from cosmology

$$\Sigma m_i < \mathcal{O}(0.12 - 0.72) \quad \text{eV}$$

(Planck Collaboration, arXiv 1807.06209)

Beta decay and Neutrinoless double beta decay

$$m_\beta < 0.45\,\text{eV}, \; |\text{m}_{\text{ee}}| < (28 - 122)\,\text{meV}$$

KATRIN Collaboration 2024 and KAMLND-Zen 2024

Can not be explained with SM without adding any additional particle

Origin of Neutrino Mass

Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979,

Yanagida 1979, Mohapatra, Senjanovic 1980

Majorana mass of the standard model neutrino is generated from higher dimensional operator

$\mathcal{L}_f(\phi,\chi)$ at higher scale $\xrightarrow{\chi \text{ integrated out}}$ $\mathcal{L}_{\text{eff}}(\phi)$ at lower scale

EFT Description → **UV Completion**

$$\hat{O}_5 = \frac{LLHH}{M}$$

- **Violates $B-L$ by 2 units**
- Gauge invariance (Weinberg, PRL 43, 1979)

$$\frac{y^2 LL\langle H\rangle\langle H\rangle}{M} \Rightarrow m_\nu = \nu^T C^{-1} \nu$$

$$m_\nu \propto \frac{y^2 v^2}{M} \rightarrow \textbf{eV neutrino due to heavy } M$$

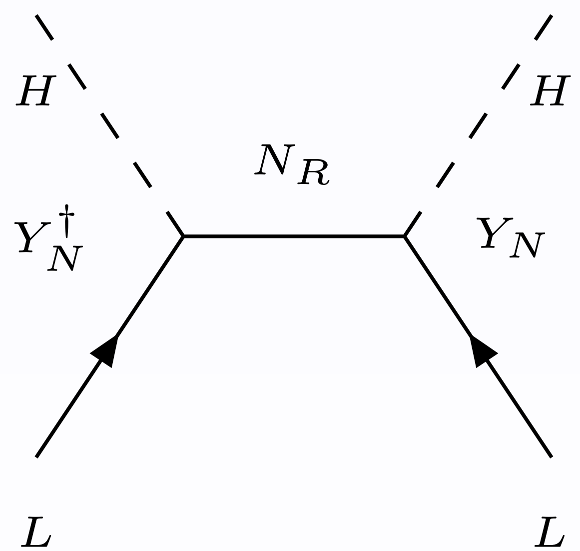
UV Completion

- **Type-I,II,III**
- **Inverse Seesaw**
- **Gauged B-L and Left Right Symmetric Model**
- **Scotogenic model**

Type-I (also Type-III) contains heavy neutral lepton

Type-I

SM gauge singlet



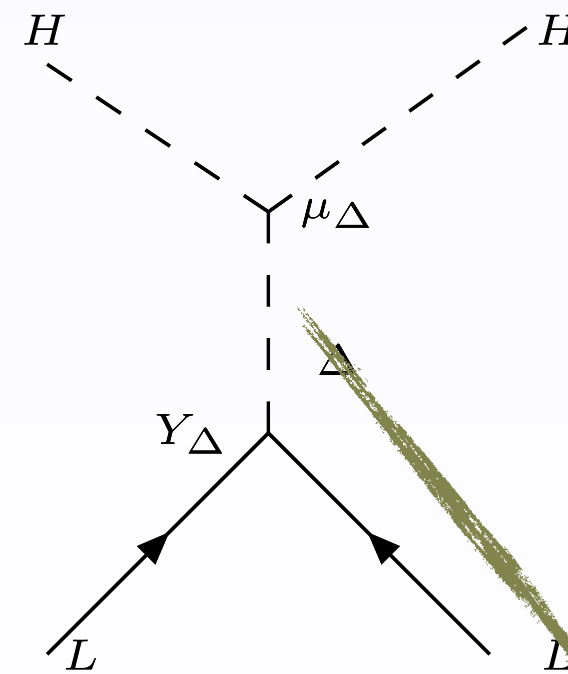
interaction of N with other SM particles is proportional to the active-sterile mixing

$$V_{lN} \rightarrow \frac{m_D}{M}$$

Suppressed

Type-II

$SU(2)$ Triplet, $Y = 2$

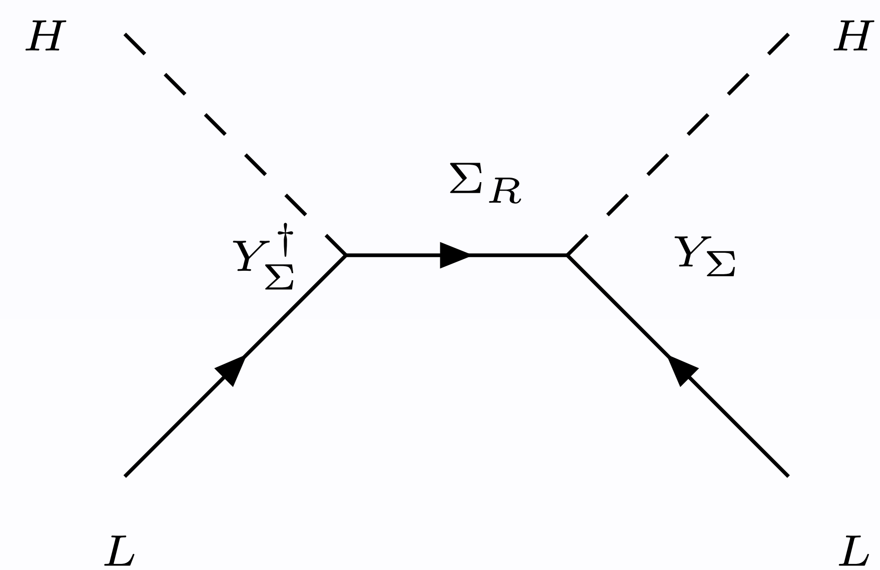


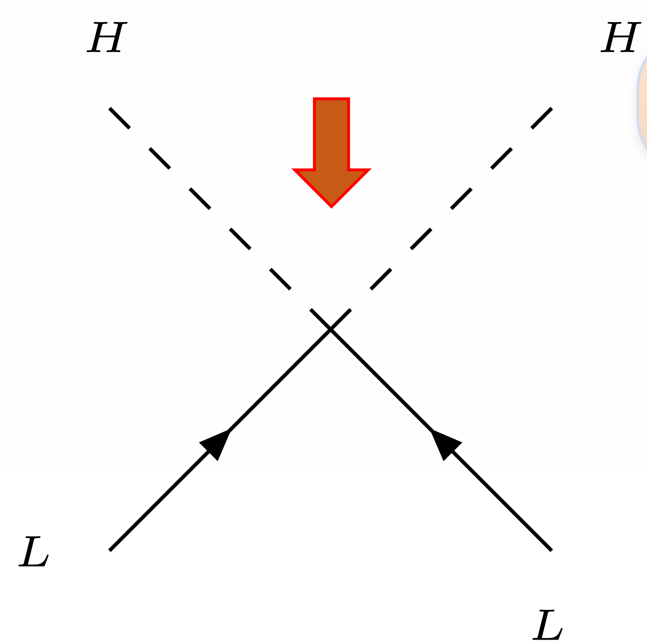
H^{++} Doubly charged Higgs

Type-III

$SU(2)$ Triplet, $Y = 0$

Σ_R → Gauge interaction





Heavy modes integrate out

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980; Magg, Wetterich, 1980; Foot et al., 1989

Quasi-degenerate neutrinos

$M_{N_{1,2}} = M \pm \mu$

Inverse Seesaw

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

Unsupressed mixing $\frac{m_D}{M} \to \sigma$ large

Mohapatra, Valle, 1986

- For $\mu \ll m_D < M \to$ $m_\nu \sim \mu \frac{m_D}{M}^2$

$\mu \sim 0$

enhances lepton number symmetry

- R-parity violating supersymmetry-(Masiero, 1982; Santamaria, Valle, 1987; Romao, Valle, 1992; Borzumati, 1996; B. Mukhopadhyaya, S Roy, F Vissani, PLB 1998, Anjan S Joshipura, Sudhir K Vempati, PRD 60, 1999...)

- Loop generated mass? Radiative inverse seesaw (A. Zee, 1980; A. Zee, K. S. Babu 1988; D, Choudhury et al., PRD 1994; Dev, Pilaftsis, 2012...)

- Others—dimension 7 $\frac{(LLHH)HH}{\Lambda^3}$ operators etc (K.S. Babu et al.,, 2009)

Higher Dimensional Probe of Seesaw

Babu-Nandi-Tavartkiladze (BNT) Model

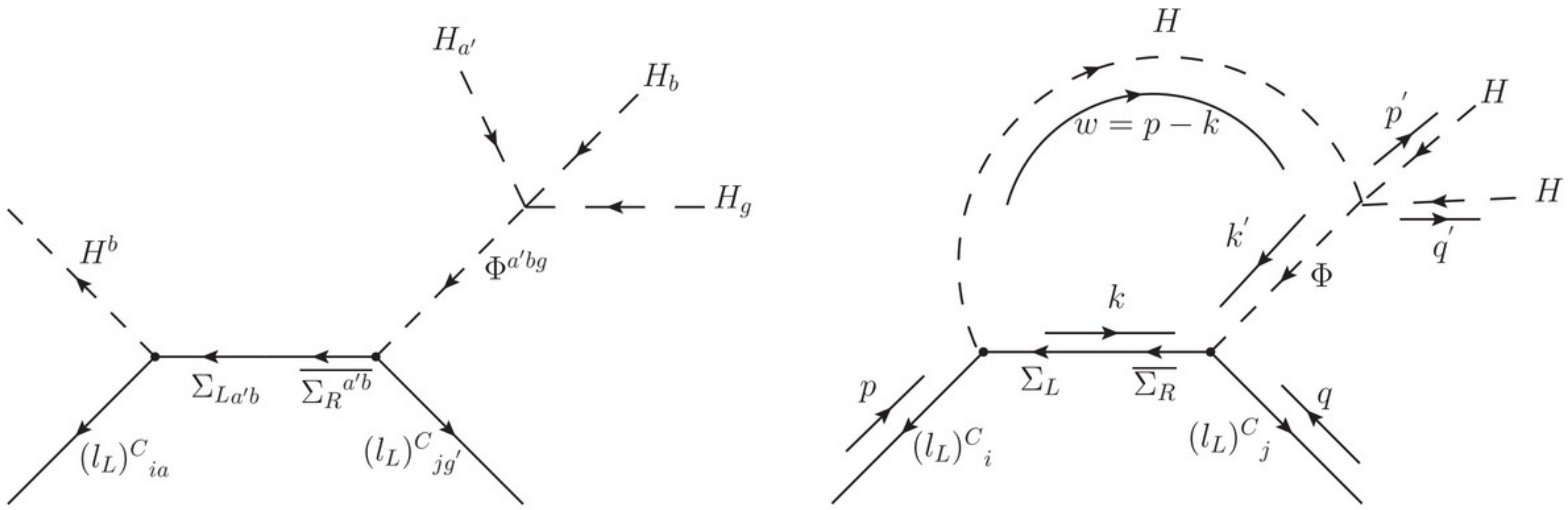
Scalar isospin 3/2 quadruplet (Φ)

$$\Phi = \left(\Phi^{+++} \quad \Phi^{++} \quad \Phi^{+} \quad \Phi^{0} \right)_{Y=3}$$

Vecor like triplet (Σ)

$$\Sigma_{R,L} = \left(\Sigma^{++}_{R,L} \quad \Sigma^{+}_{R,L} \quad \Sigma^{0}_{R,L} \right)_{Y=2}$$

Tree level (d=7) 1-loop level (d=5)



$$V = \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger\Phi)^2$$
$$+ \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi)$$
$$+ \{\lambda_5 H^3 \Phi^* + \text{H.c.}\},$$

$$(m_\nu)_{ij} = -\frac{\lambda_5 (Y_i Y'_j + Y'_i Y_j) v^4}{(M_\Sigma M^2_{\Phi^0})}$$

Rich Phenomenology with **"Multi-lepton"** final states

$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$
$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

3ℓ, 4ℓ, 5ℓ and 6ℓ events
Same-sign-tri-lepton events
Lepton flavour violating (LFV) 4 lepton events

Small v_Φ

K. S. Babu, S. Nandi, and Zurab Tavartkiladze, PRD (Rap Comm) 80, 071702(R) (2009)

Gauged B-L Model

Gauge extensions → $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

R. N. Mohapatra and R. E. Marshak, Phys. Rev. Lett. 44 (1980) 1316

Particle contents → **SM fields, three N, BSM Higgs S, BSM gauge boson Z'**

RHN mass, BSM gauge boson mass and SM-BSM Higgs mixing are proportional to the B-L breaking vev

Salient features →

- **Mass of RHN is proportional to B-L breaking vev** $M_R = Y_M v_{BL}$
- **SM-BSM Higgs mixing** $\tan 2\alpha = \frac{v v_{BL} \lambda_3}{v^2 \lambda_1 - v_{BL}^2 \lambda_2}.$
- **BSM gauge boson mass** $M_{Z'} = 2 g' v_{BL},$

$$\mathcal{L}_{B-L} = \left(D_\mu S\right)^\dagger \left(D^\mu S\right) - \frac{1}{4} F_{BL\mu\nu} F_{BL}^{\mu\nu} + i \bar{\nu}_{Ri} \gamma^\mu D_\mu \nu_{Ri} - V_{B-L}\left(\phi, S\right)$$
$$- \sum_{i=1}^{3} y^M S \bar{\nu}_{Ri}^c \nu_{Ri} - \sum_{i,j=1}^{3} y_{ij}^\nu \bar{L}_i \tilde{\phi} \nu_{Rj} + h.c. \ ,$$

with

$$V_{B-L}\left(\phi, S\right) = \mu_S^2 S^\dagger S + \mu_\phi^2 \phi^\dagger \phi + \lambda_1 \left(\phi^\dagger \phi\right)^2 + \lambda_2 \left(S^\dagger S\right)^2 + \lambda_3 \left(\phi^\dagger \phi\right)\left(S^\dagger S\right).$$

Left-Right symmetric theory

Type-I and Type-II

Pati; Salam; Mohapatra, Senjanović, 74, 75

Enlarged gauge sector $\rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Parity symmetric theory $\rightarrow$ parity violating SM

- Two Higgs triplet $\Delta_L = (3, 1, 2)$, $\Delta_R = (1, 3, 2)$.
  $\langle \Delta_R \rangle$ **breaks the** $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$
- Sterile neutrino N is part of the gauge multiplet $\begin{pmatrix} N \\ e \end{pmatrix}_R$
- Additional gauge bosons W_R and Z'. $M_{W_R} \propto \langle \Delta_R \rangle$

Natural way to embed the sterile neutrinos

N, W', Z', Δ^{++} $\longrightarrow$ Phenomenology

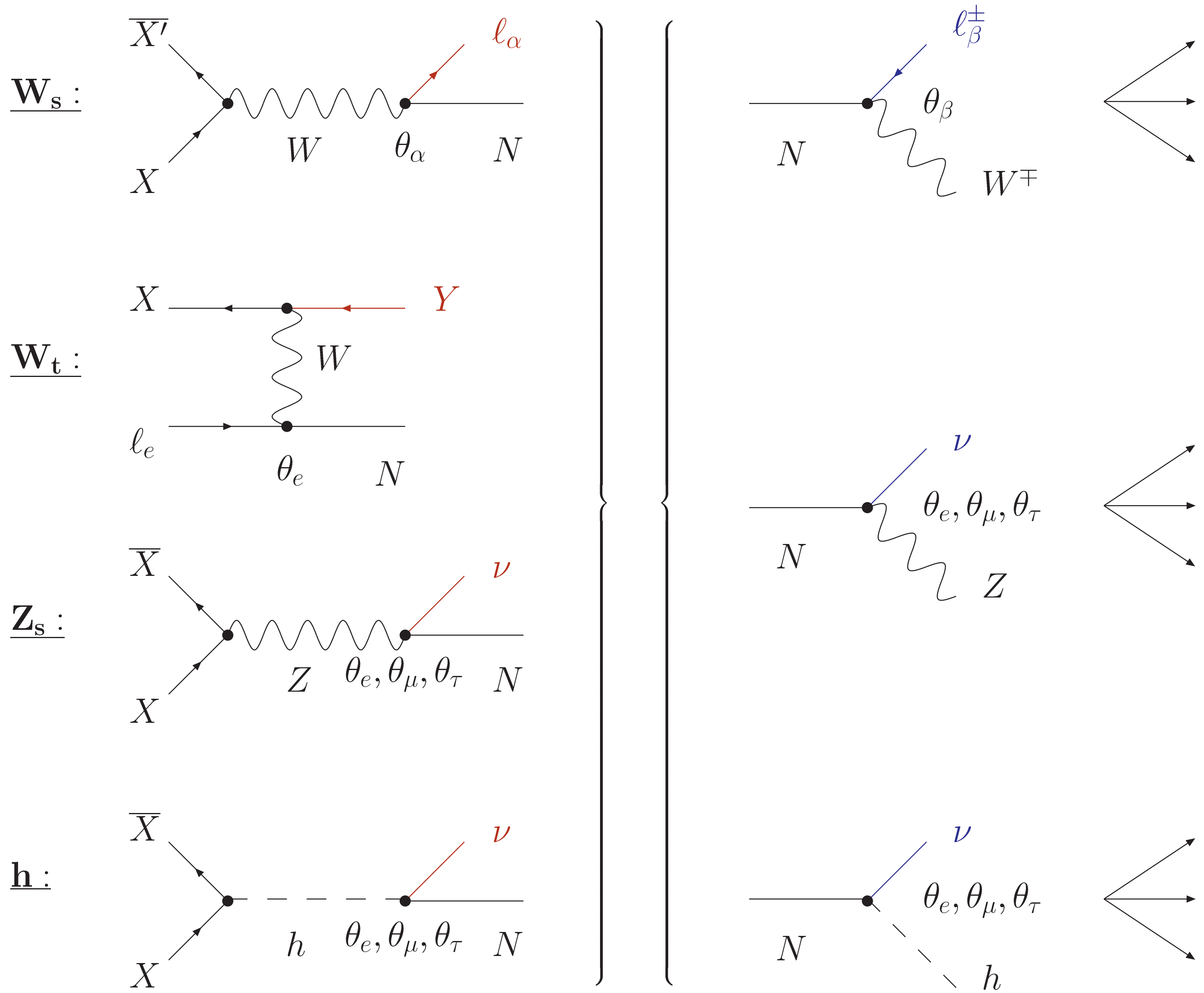
HNL at Colliders (single production along with a SM particle):

Charged current $-\frac{g}{\sqrt{2}}\bar{l}\gamma^\mu W_\mu \theta_\alpha N_R$; N.C $-\frac{g}{2c_w}\bar{\nu}\gamma^\mu Z_\mu \theta_\alpha N_R$; Higgs $\frac{gM}{2M_w}\bar{\nu}\theta_\alpha N_R H$

Without any additional gauge symmetry

Interaction depends on the mass M and mixing θ_α → $\frac{m_D}{M}$

Production | Decay | Final States



pp : $\ell_\alpha \ell^\pm_\beta jj$, $\ell_\alpha \ell^\pm_\beta \ell^\mp_\gamma \nu$

e⁻e⁺, e⁻p : $Y \ell^\pm_\beta jj$, $Y \ell^\pm_\beta \ell^\mp_\gamma \nu$

e⁻e⁺, pp : $\nu \ell^\pm_\beta jj$, $\nu \ell^\pm_\beta \ell^\mp_\gamma \nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu\nu\nu$

e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu\nu\nu$

e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu\nu\nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$

e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu VV$

e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu VV$

Multilepton, multijet final states

From arXiv: 1612.02728, S. Antusch et al.,

Heavy Neutral Lepton at colliders

pp collider - LHC (and FCC-hh)

1. *T. Han et al., JHEP 05 (2009) 030*
2. *R.Ruiz et al., JHEP 02 (2015) 072, Front.in Phys.* 6 (2018) 40
3. *S. Goswami et al., Phys.Rev.D 91 (2015) 075007*
4. *P. Konar et al., Phys.Rev.D 91 (2015) 9, 095007, JHEP 02 (2018) 083*
5. *P. Fileviez Perez et al., Phys.Rev.D 80 (2009) 073015*
6. *S. Antusch et al., Int.J.Mod.Phys.A 32 (2017) 14, 1750078, Phys.Lett.B 774 (2017) 114-118*
7. *B. Bajc et al., Phys.Rev.D 76 (2007) 055011*
8. *A. Maezza et al., Phys.Rev.D 82 (2010) 055022*
9. *V. Tello et al., Phys.Rev.Lett. 106 (2011) 151801*
10. *M. Nemevsek et al., Phys.Rev.D 83 (2011) 115014*
11. *G. Cottin et al., Phys.Rev.D 97 (2018) 5, 055025, Phys.Rev.D 98 (2018) 3, 035012, JHEP 09 (2021) 039*
12. *M. Mitra et al., Phys.Rev.D 94 (2016) 9, 095016, Phys.Rev.D 111 (2025) 1, 015005*
13. *P. S. Bhupal Dev et al., Phys.Rev.D 88 (2013) 033014, Phys.Rev.D 86 (2012) 093010.*
14. *A. Abada et al., Eur.Phys.J.C 82 (2022) 11, 1030*
15. *R. Padhan et al., Eur.Phys.J.C 82 (2022) 10, 858*
16. *M. Drewes et al., Phys.Rev.D 101 (2020) 5, 055002*
17. *R. Beltran et al., arXiv: 2501.09065*
18. *M. Chala et al., Phys.Rev.D 100 (2019) 11, 115019; Eur.Phys.J.C 80 (2020) 8, 743,*

And more…..

FCC-ee/CLIC/ILC/CEPC

1. P. Hernandez et al., *JHEP* 03 (2021) 117, *Eur.Phys.J.C* 79 (2019) 3, 220
2. S. Antusch et al., *JHEP* 05 (2015) 053,
3. S. Antusch et al., *JHEP* 04 (2016) 189, *JHEP* 12 (2016) 007,
4. M. Mitra et al., *Phys.Rev.D* 92 (2015) 075002
5. D. Marfatia et al., *JHEP* 04 (2023) 013
6. Q. H. Cao et al., *Phys.Rev.Lett.* 134 (2025) 2, 021801

And more…..

LHeC, FCC-he, Electron-Ion

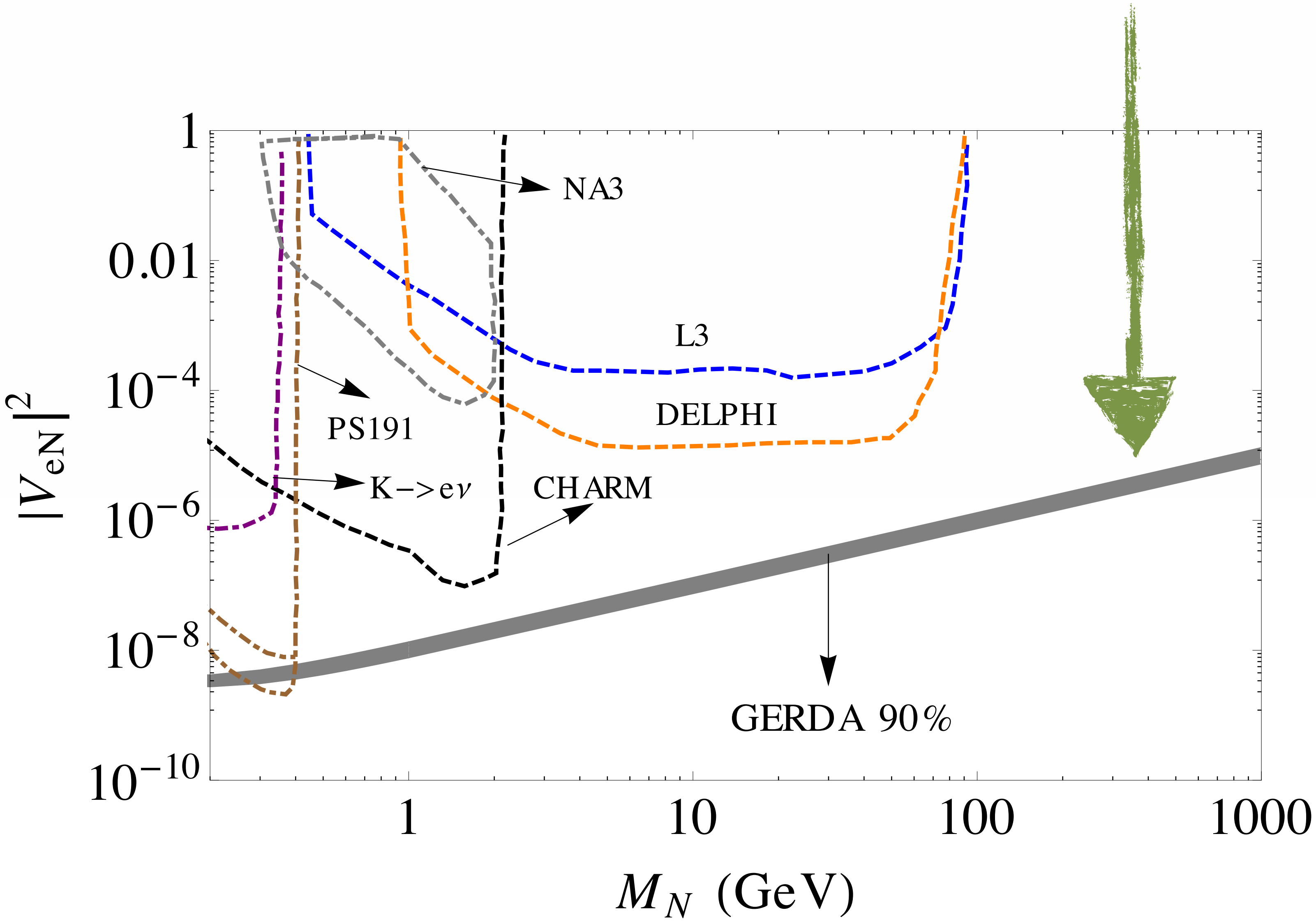
1. S. Antusch et al., *Int.J.Mod.Phys.A* 32 (2017) 14, 1750078
2. R. Padhan et al., *JHEP* 06 (2022) 168
3. T. Ghosh et al., *JHEP* 03 (2023) 020

And more…..

Bounds:

Limits on active-sterile neutrino mixing V from neutrino mass, $(\beta\beta)_{0\nu}$-decay, beam dump experiments and others...

- Light neutrino mass $V \sim 10^{-5}/\sqrt{M}$.
- For $M = 100$ GeV, $V \sim 10^{-6} \rightarrow$ extremely small
- Experimental constraints $\rightarrow$ $(\beta\beta)_{0\nu}$-decay, beam dump experiments. $(\beta\beta)_{0\nu}$-decay $\rightarrow$ stringent. **(Assumption is of a Majorana HNL)**

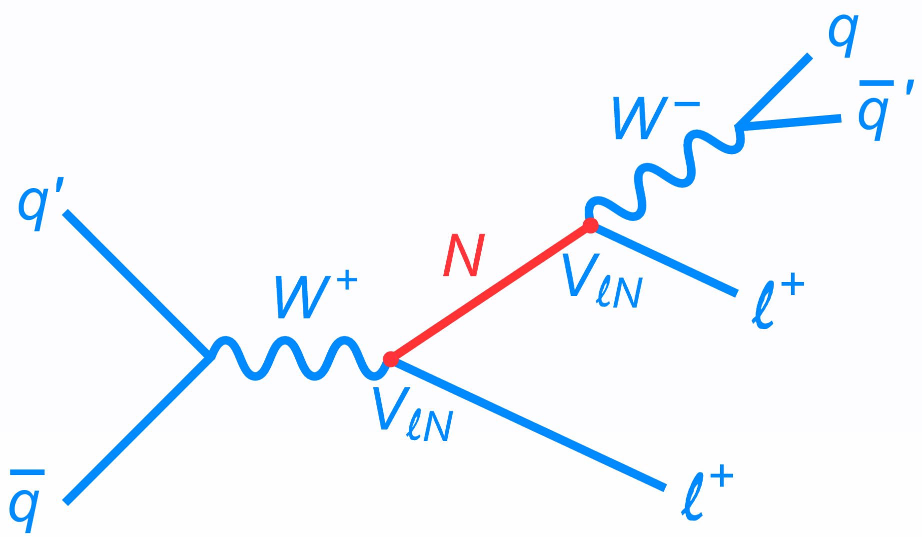


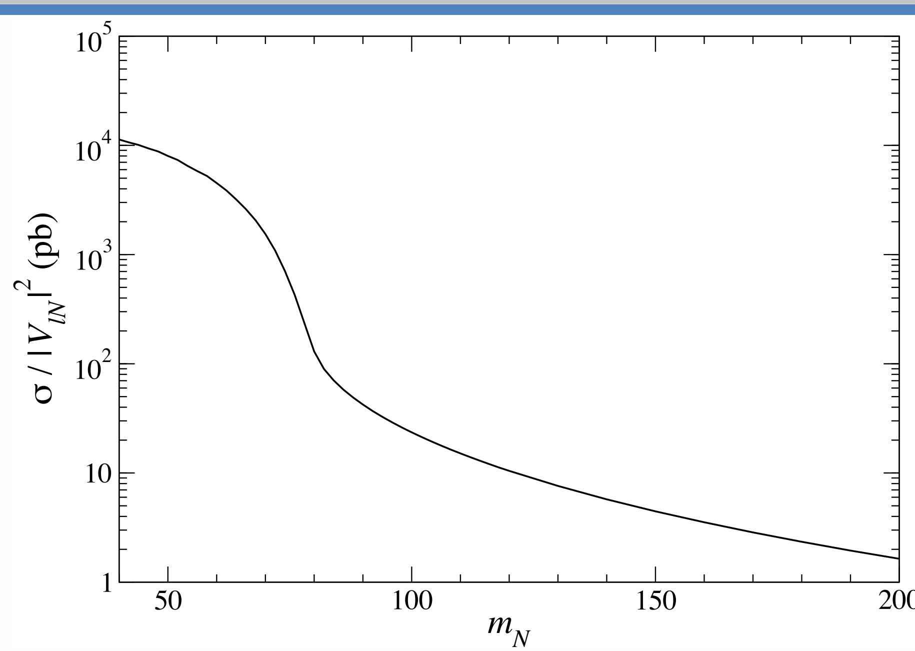
Mitra, Pascoli, Wong, 2013 ;

Atre et al., JHEP **0905**, 030 (2009);

Mitra at el, , NPB **856**, 26 (2012)

Collider Searches (LHC)





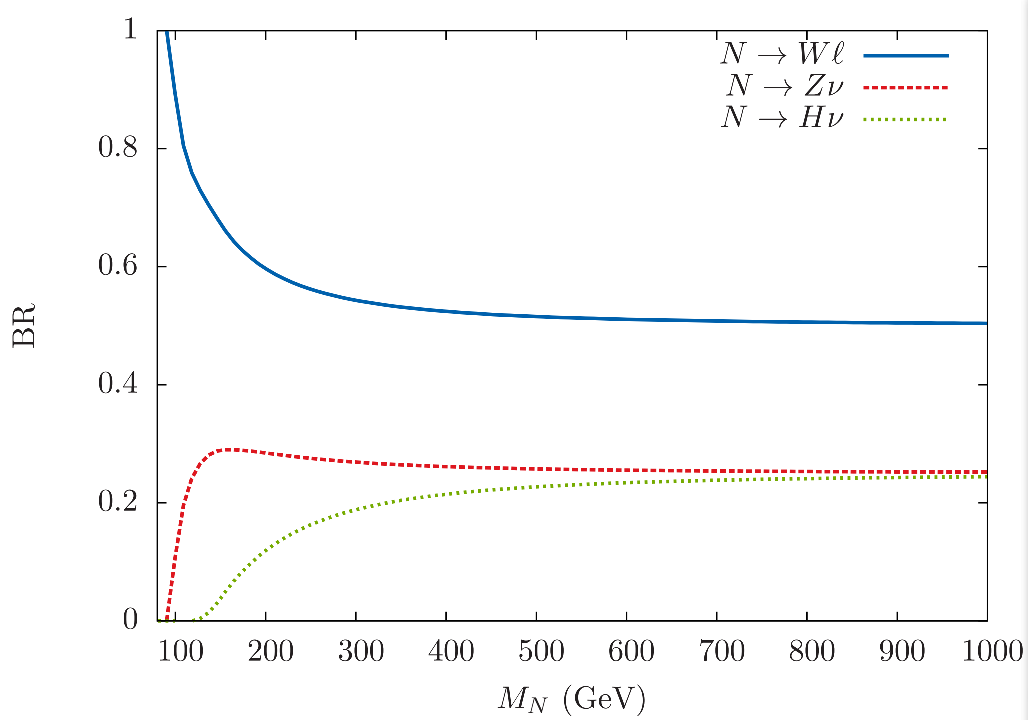
$$pp \to l^{\pm} N$$

S. Pascoli et al., JHEP 05 (2009) 030

$m_N \sim 100$ GeV $\to$ collider sensitive

Heavy Majorana Decay

- To gauge bosons $N \to lW$ and $N \to Z\nu$. To Higgs $N \to \nu H$



- ***For higher mass almost 60% branching in lW mode***
- ***Other decay modes has branching ~ 20%***
- ***For lighter N with $M_N < M_W$, HNL has three body decays via off-shell W, Z, and H***
- ***For $M_N \sim$ few GeV, decay of N into lepton and a meson dominant***

Collider signatures → lepton channels

- Like sign/ different flavor diliptons $l^{\pm}l^{\pm}/l^{\pm}l'^{\mp}+2j$
- Trilepton channels $l^{\pm}l^{\mp}l^{\pm}$ → For Dirac neutrinos N_R
- Lepton number violating $l^{\pm}l^{\pm}$ → Proof of heavy Majorana neutrinos N_R

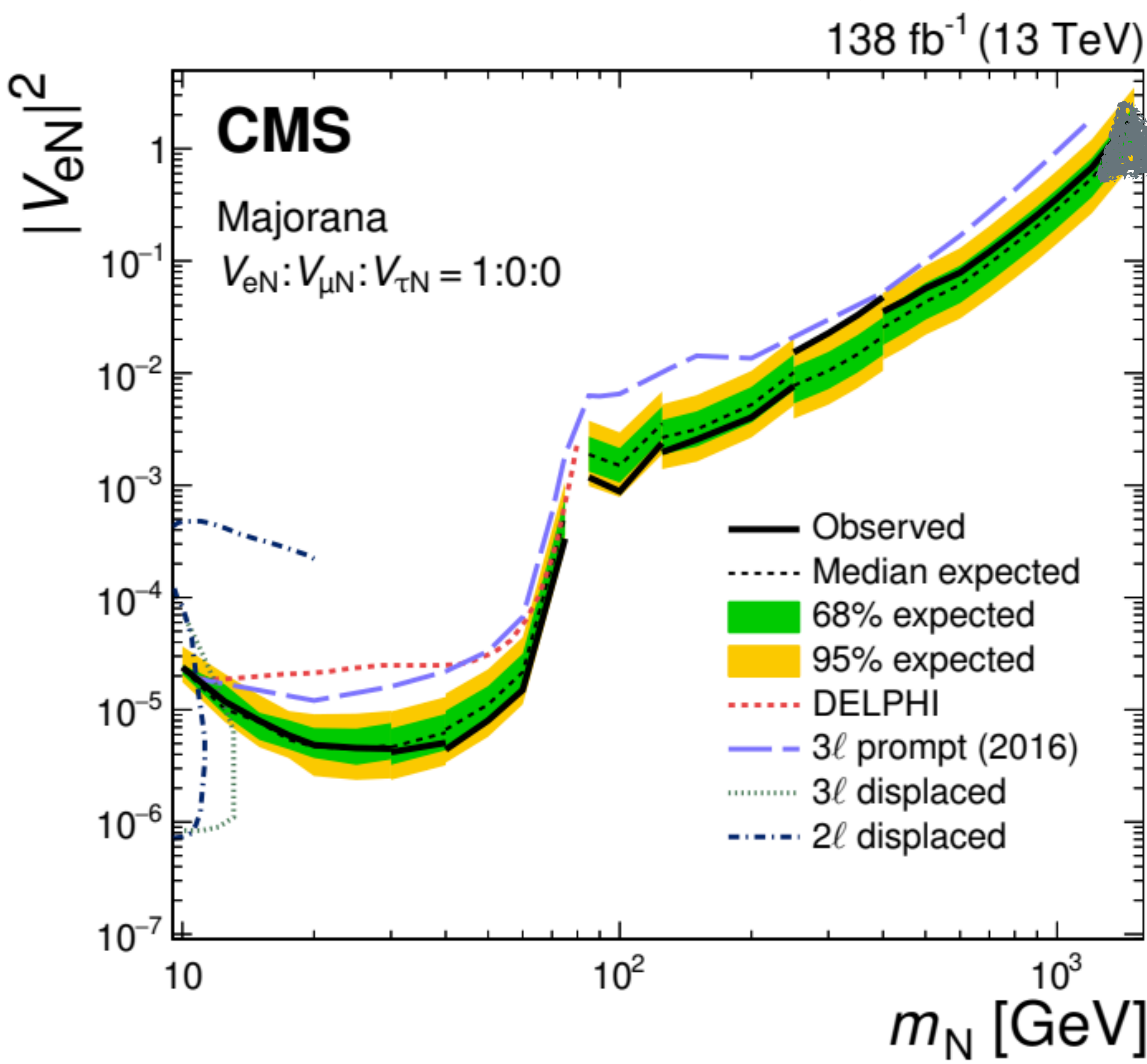
Atre et al., JHEP **0905**, 030 (2009); Aguila et al., NPB **813**, 2009; Aguila et al., 2007; Aguila et al., PLB **672**, 2009; Arhib et al., 2010, ...

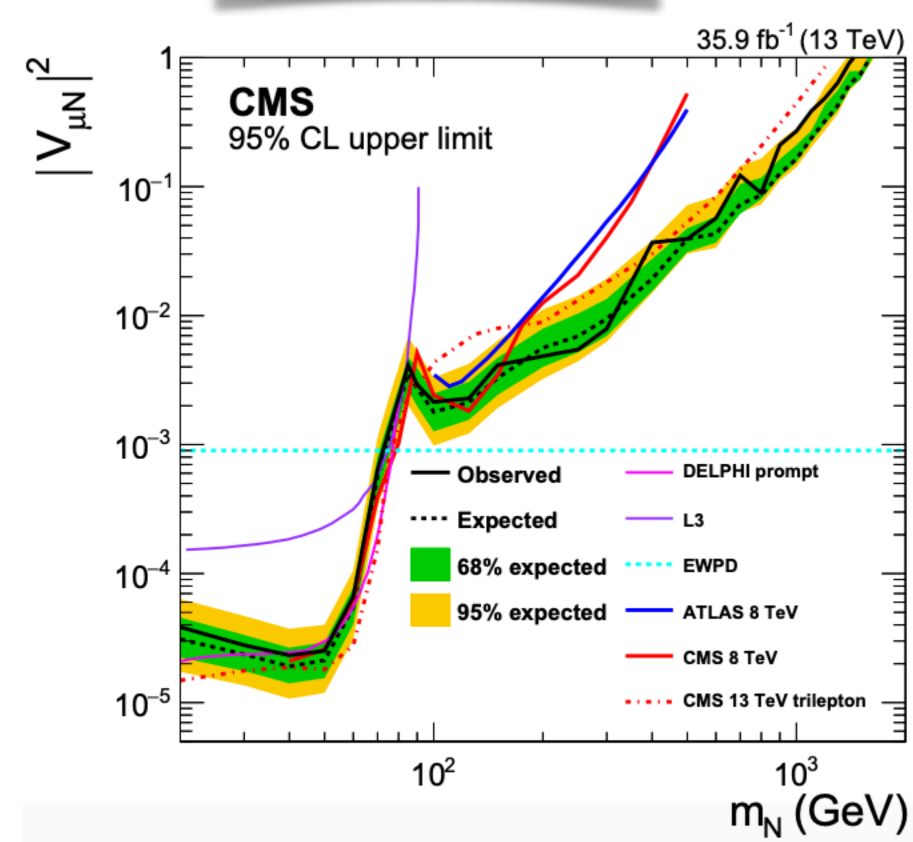
3l+X search

Low sensitivity in high mass regime

$l^{\pm}l^{\pm}+jj$

CMS collaboration, arXiv 1802.02965, JHEP06(2024)123



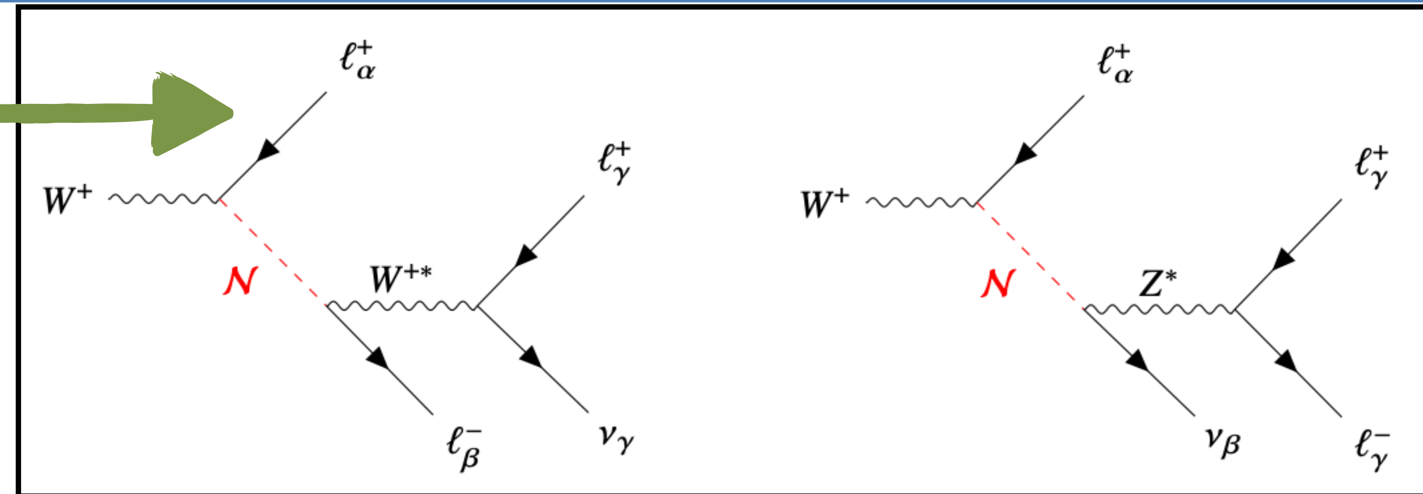


CMS collaboration, 1603.02248

CMS collaboration, *JHEP* 01 (2019) 122

Displaced HNL Search:

For $m_N < M_W$ three body decay $N \to lqq',\ \ 3l + MET,\ \ \nu\nu\nu$

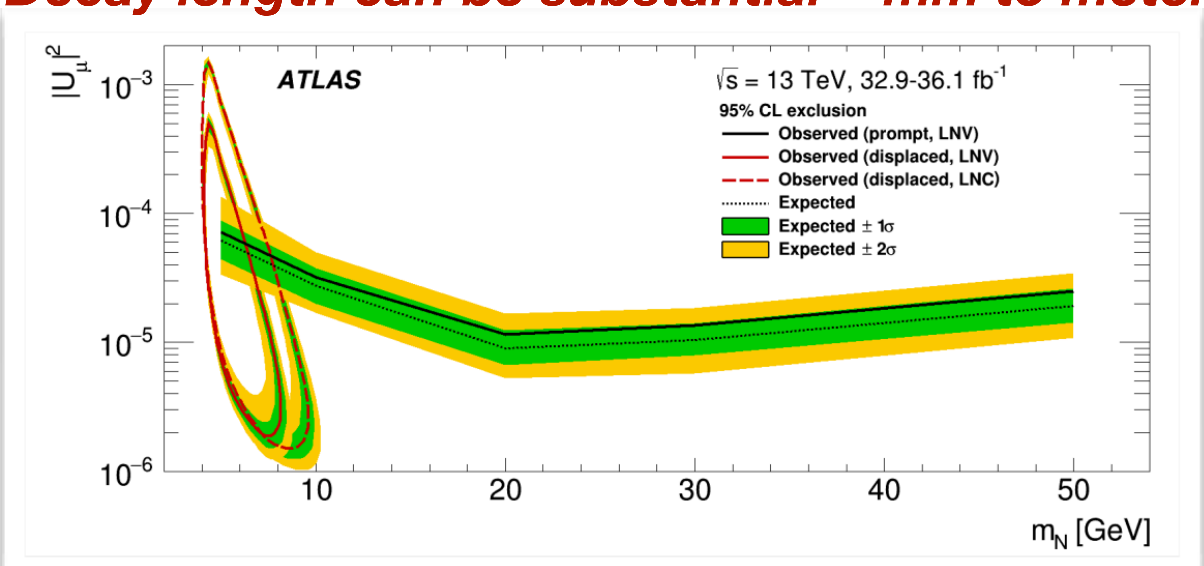


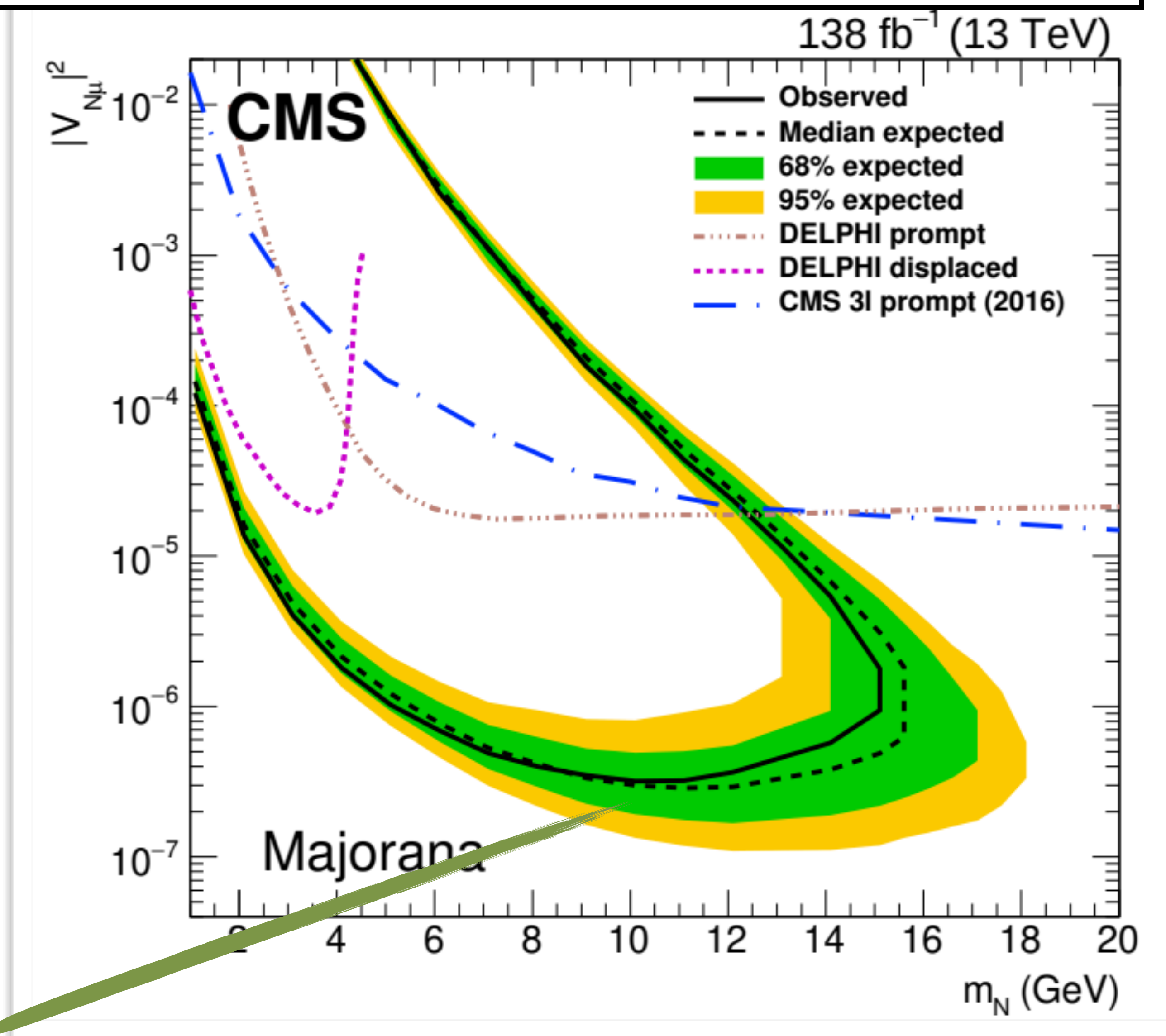
Active-sterile mixing is constrained from light neutrino mass measurement

$$V_{lN} \approx 10^{-6}\sqrt{\frac{m_\nu/(0.1\text{ eV})}{M_N/(50\text{ GeV})}}.$$

$$L_N \approx 0.025\text{ m}\cdot\left(\frac{10^{-6}}{V_{\mu N}}\right)^2\cdot\left(\frac{100\text{ GeV}}{M_N}\right)^5,$$

Decay length can be substantial ~ mm to meter





Higher than the active-sterile mixing preferred by neutrino mass measurement for a conventional Type-I seesaw

CMS collaboration: arXiv: 2201.05578
ATLAS collaboration: arXiv: 2204.11988, 1905.09787

Displaced decay of HNL in gauged B-L framework

RHN decay can give rise to displaced decay signatures

↓

Production vertex and decay vertex are separated

→ **One of the most important probe of BSM physics**

$$pp \to h \to NN, \quad N \to \mu jj$$

JHEP 08 (2018) 181
Deppisch, Liu, Mitra

Gauged B-L model

Scalar S

Right handed neutrino N

Low MN ~ 3 body decays *Final states are displaced muon and jets*

Production of N

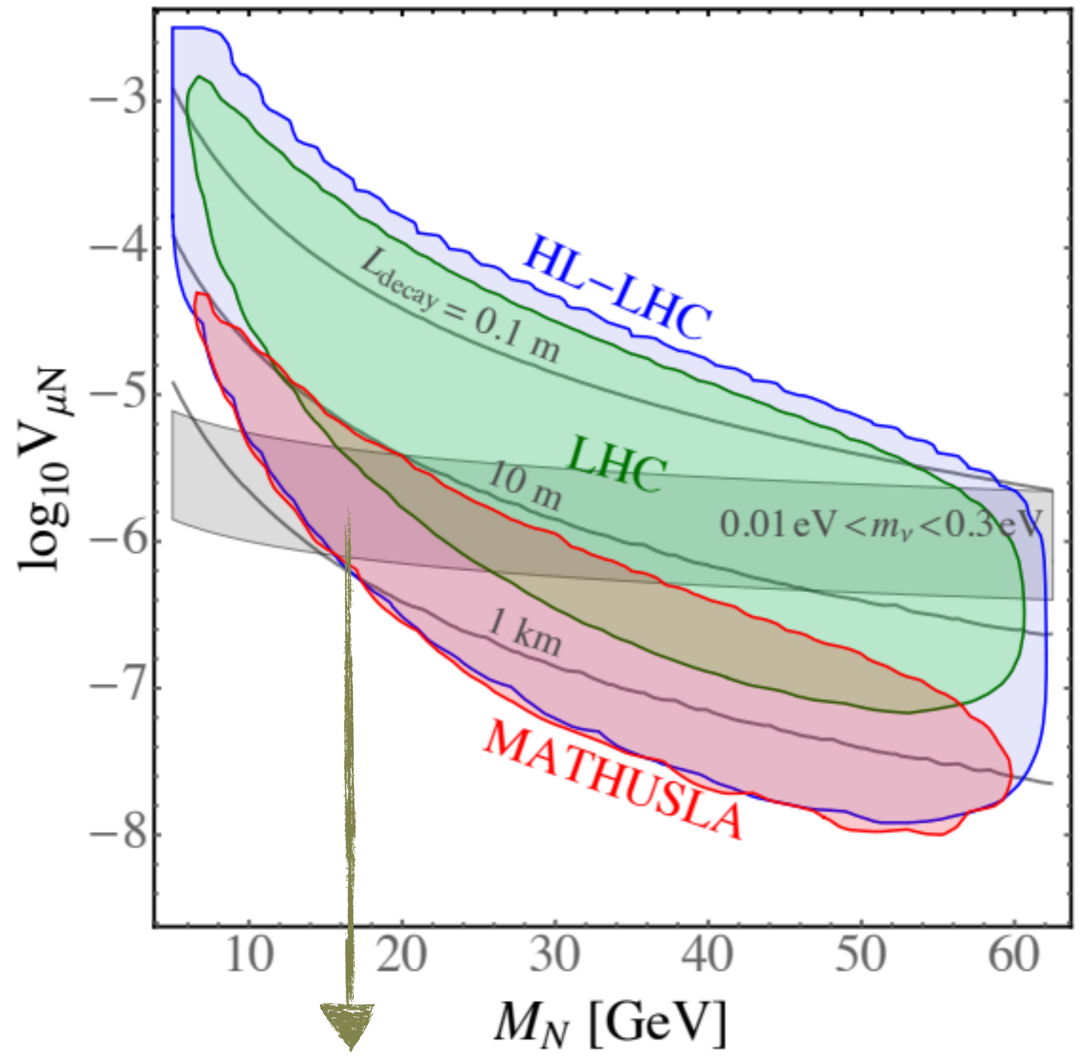
↓

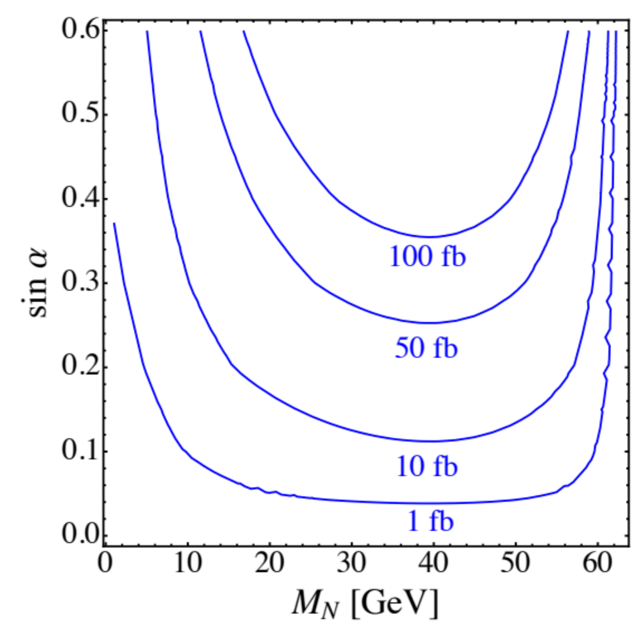
Depends on h-S mixing

Decay of N

↓

Depends on active-sterile mixing



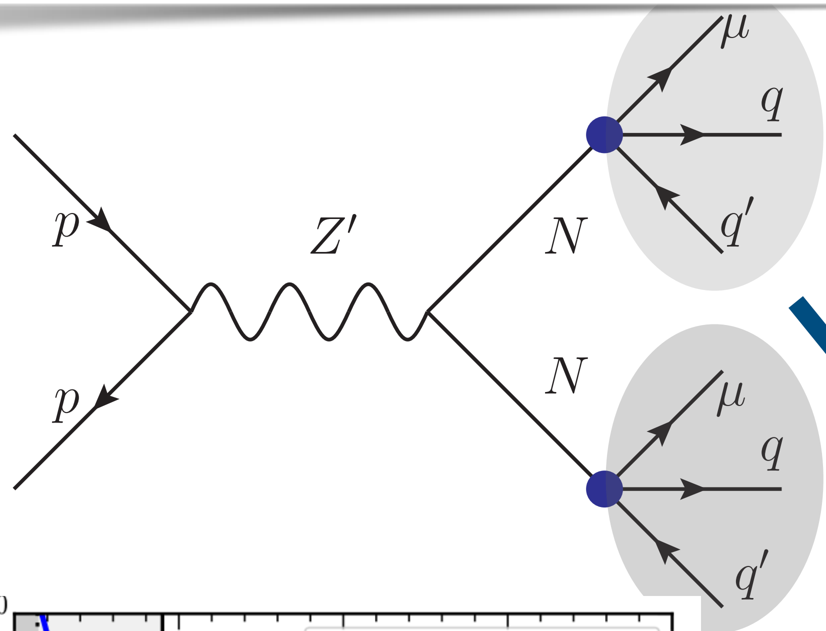


10 fb cross-section with mixing 0.1, and RHN mass ~ 40 GeV

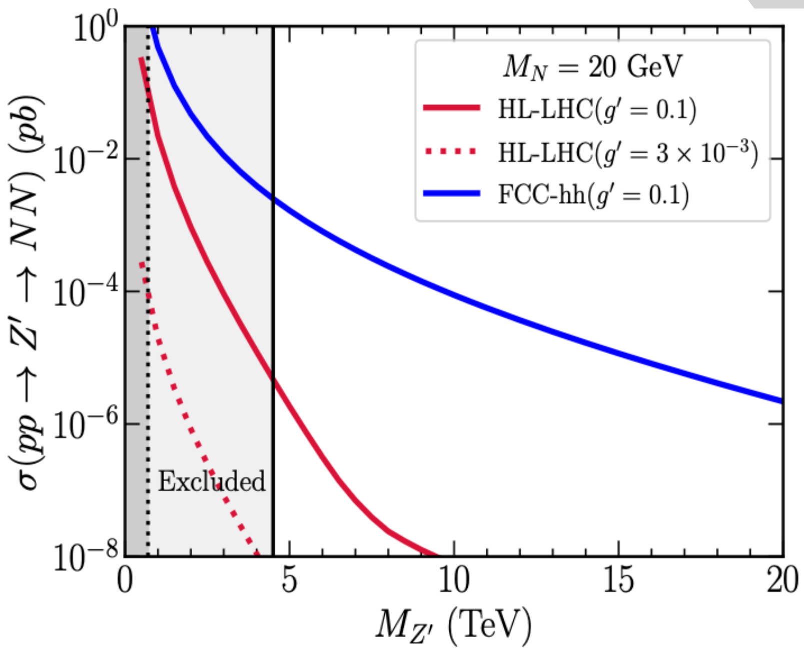
Seesaw favoured region can be accessed at the LHC/HL-LHC

Displaced decay of a boosted HNL

Another important probe of HNL is displaced fat-jet signature



- Occurs when N is boosted
- Decay products are collimated
- All the decay products can not be separately identified
- Appear as a fat-jet



- Displaced fat-jet (for decay within inner-detector ~ within 400 mm)

- $pp \to Z' \to NN \to \underbrace{\mu jj} \; \underbrace{\mu jj} \to J_{fat}^{dis} \; J_{fat}^{dis}$

- Displaced tracks (for decay in muon spectrometer ~ 6000-9000 mm)

- $pp \to Z' \to NN \to \underbrace{\mu q q'} \; \underbrace{\mu q q'} \to \mu^{dis} \mu^{dis} + X^{dis} \to \underbrace{track_1 + track_2 + ...track_n} + \underbrace{Y}$

$$\sigma(pp \to NN \to J_{fat}^{dis} J_{fat}^{dis})\big|_{after-cut} = \sigma_p \times \mathcal{P}(L_1, L_2, \sqrt{s}, M_N, M_{Z'}, \theta) \times \epsilon_k, \qquad (5.8)$$

and

$$\sigma(pp \to NN \to \underbrace{track_1 + ..track_n} + \underbrace{Y})\big|_{after-cut} = \sigma_p \times \mathcal{P}(L_1, L_2, \sqrt{s}, M_N, M_{Z'}, \theta) \times \epsilon_k,$$

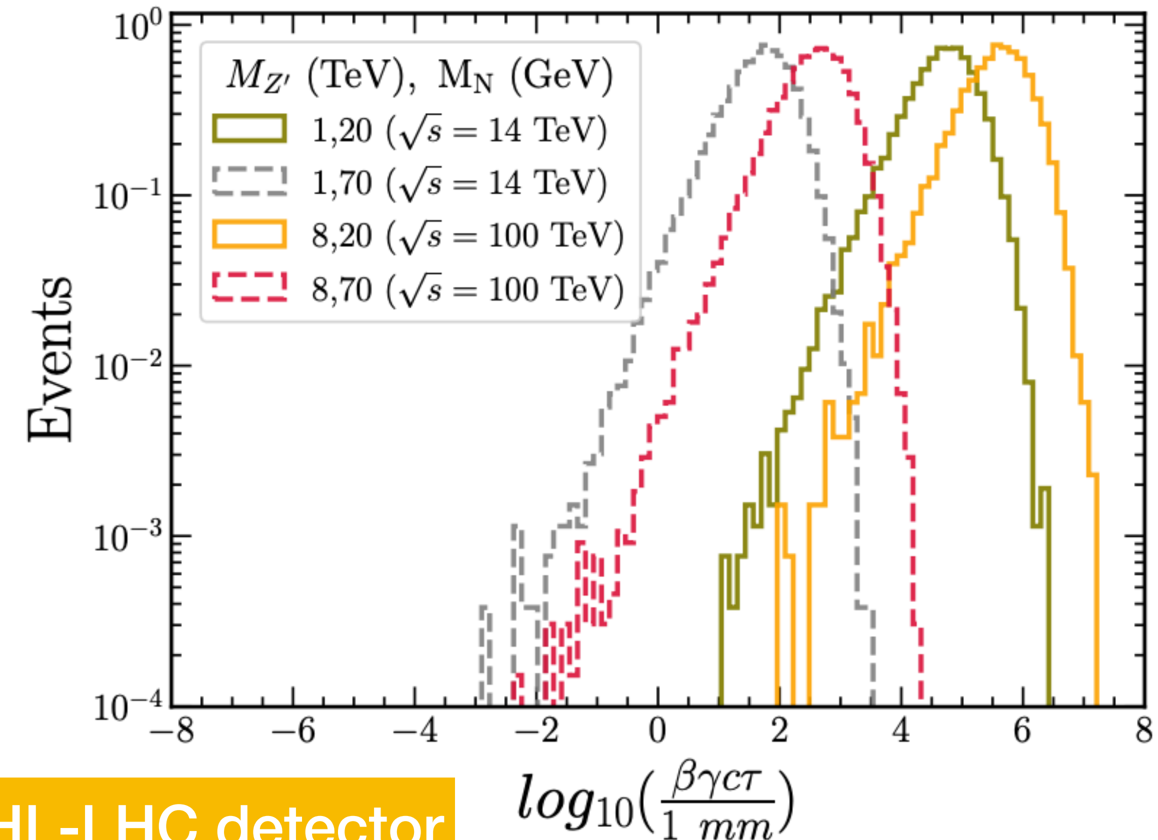
Deppisch, Padhan, Kulkarni and Mitra, Eur.Phys.J.C 82 (2022) 10, 858

Displaced and boosted decay of HNL

$$\Gamma(N \to l_\alpha^- u\bar{d}) = N_c |V_{ud}^{CKM}|^2 |V_\alpha|^2 \frac{G_F^2 M_N^5}{192\pi^3} \mathcal{I}(x_u, x_d, x_l)$$

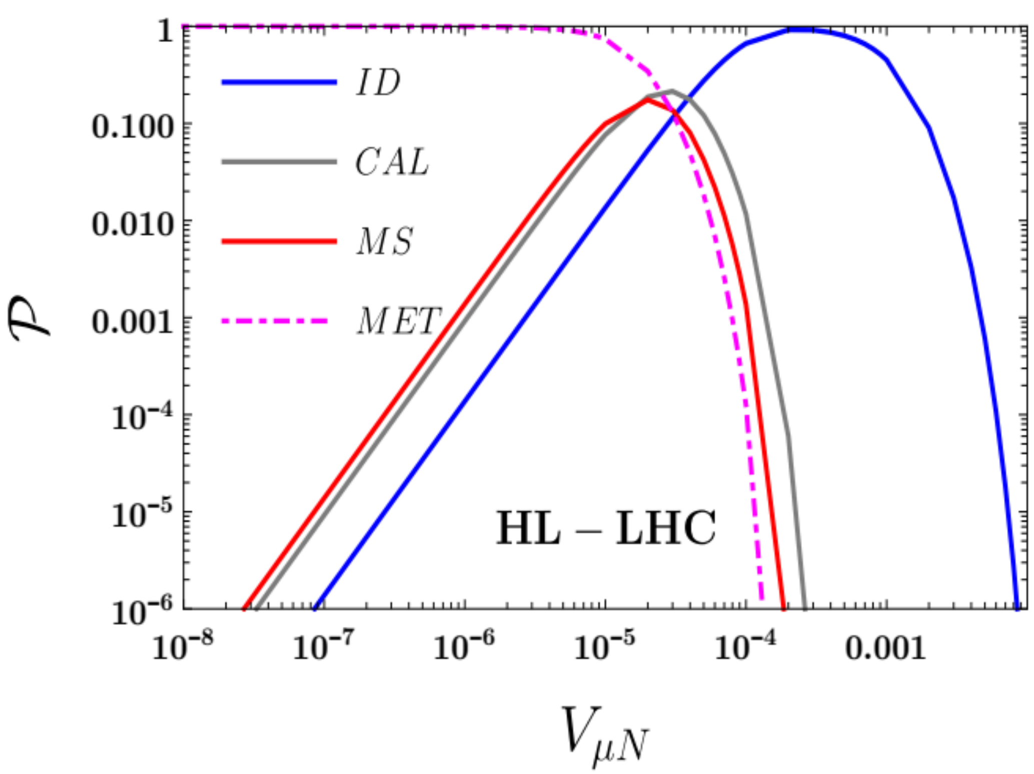
$$\Gamma(N \to l_\alpha^- \nu_\beta l_\beta^+) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{192\pi^3} \mathcal{I}(x_{l_\alpha}, x_{l_\beta}, x_{\nu_\beta})$$

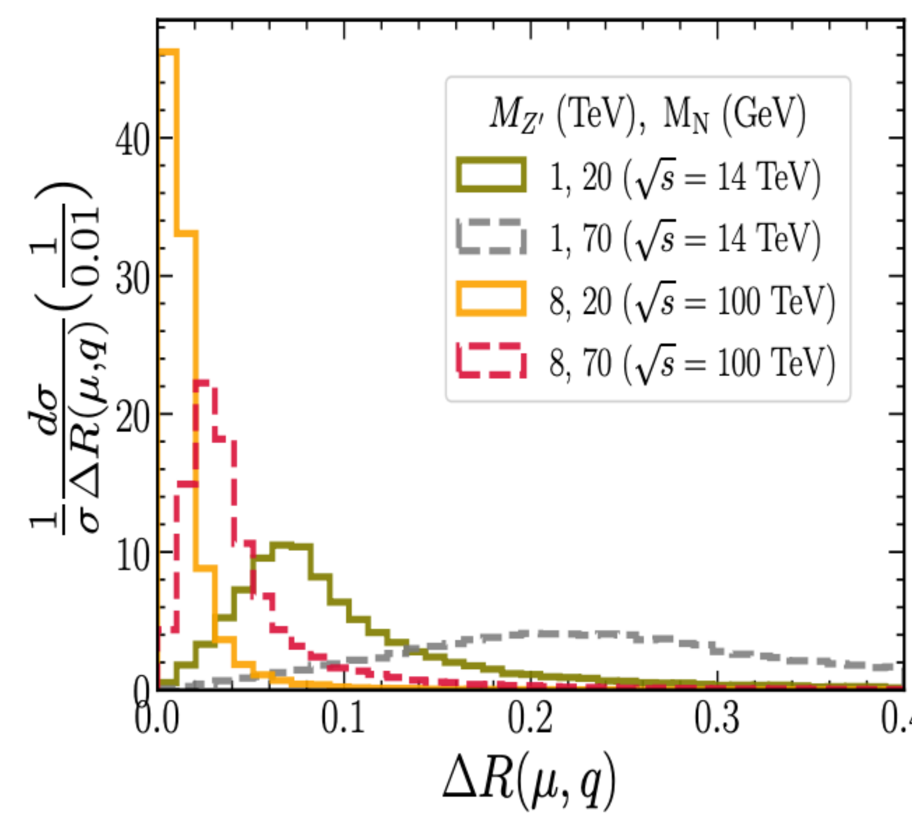
$$\Gamma(N \to \nu\nu\nu) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{96\pi^3}$$



Probability of RHN to decay at different parts of the HL-LHC detector

$$\mathcal{P}(L_1, L_2, \sqrt{s}, M_N, M_{Z'}, \theta) = \int db_1 db_2\ f(\sqrt{s}, M_N, M_{Z'}, b_1, b_2) \prod_{i=1}^{2} \left[e^{\frac{-L_1}{b_i c\tau(\theta)}} - e^{\frac{-L_2}{b_i c\tau(\theta)}} \right] ($$

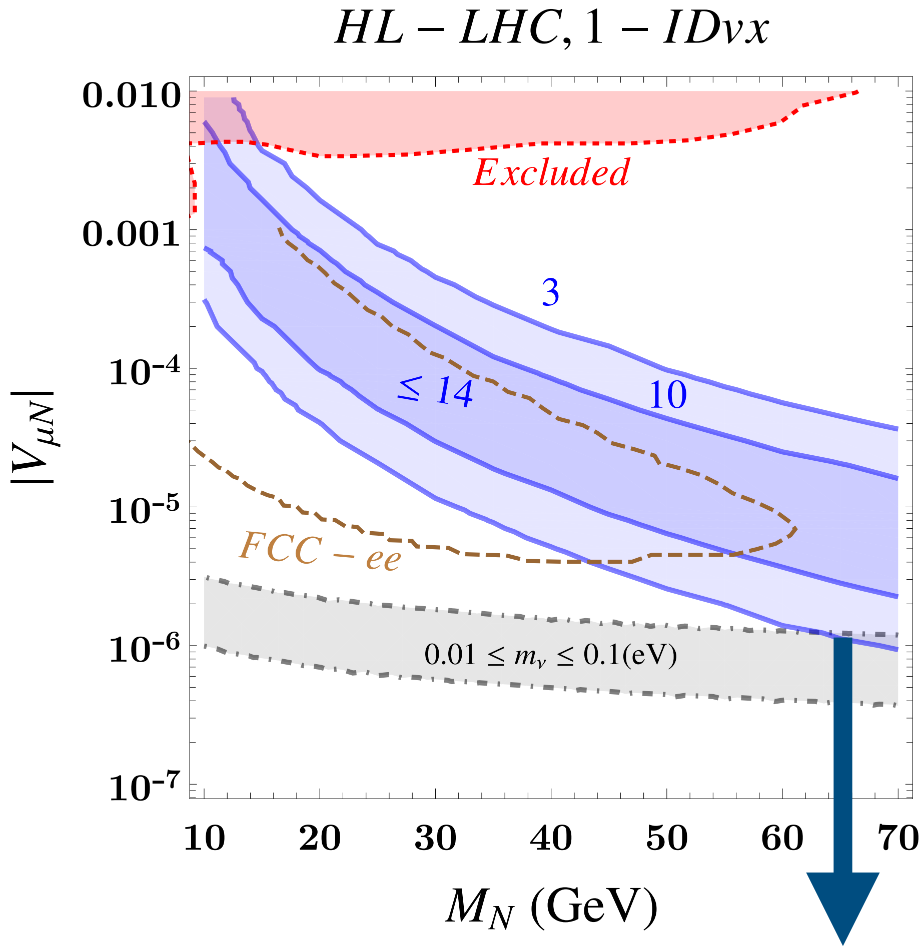


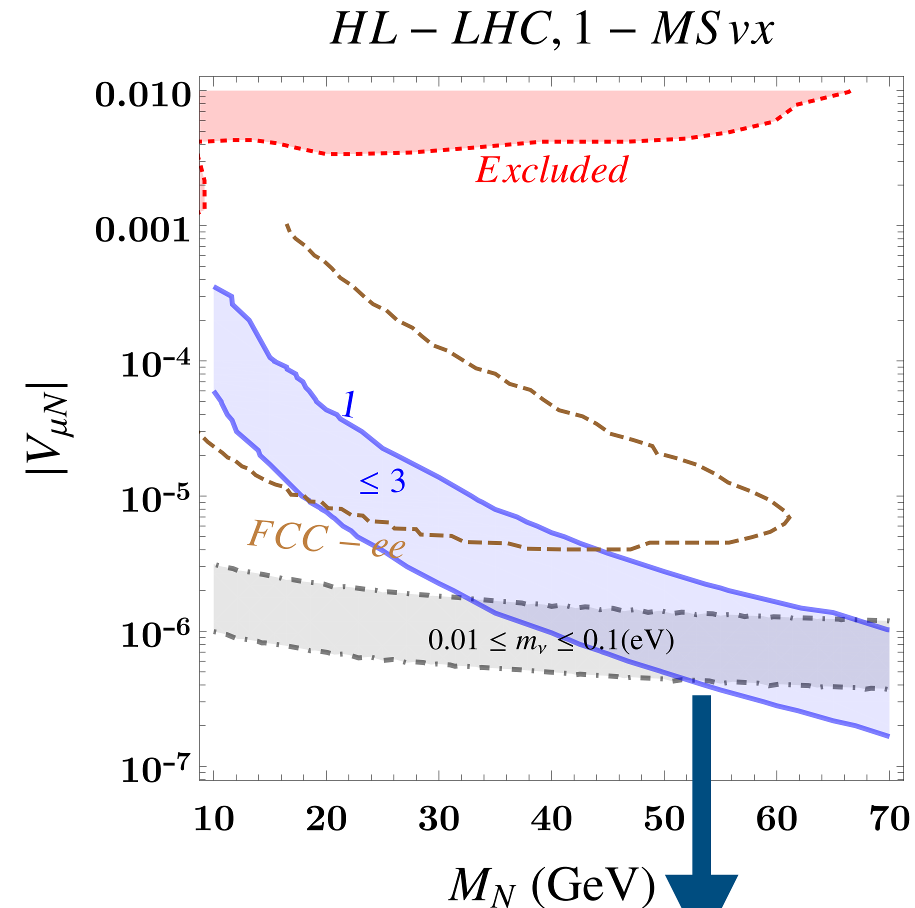


Displaced fat-jet signature

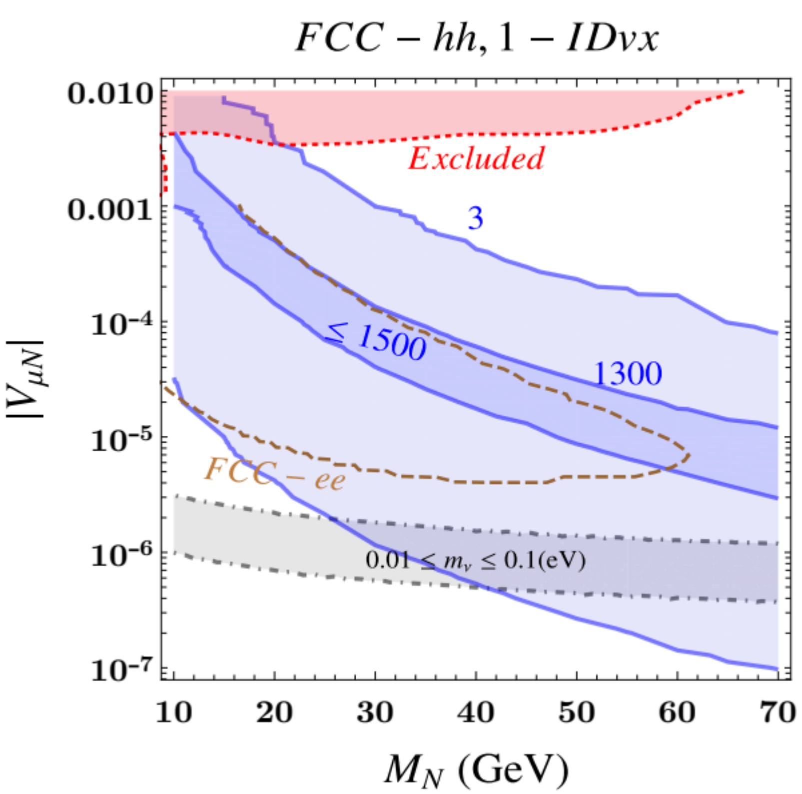
Deppisch, Padhan, Kulkarni and Mitra,
Eur.Phys.J.C 82 (2022) 10, 858

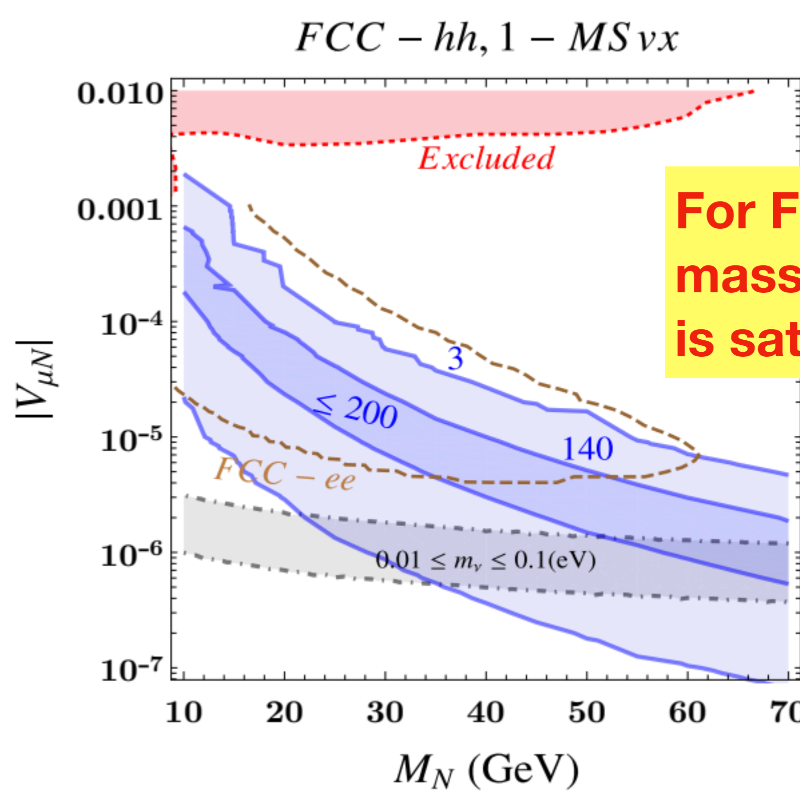
Hits/Tracks in MS





Seesaw favoured region can be accessed at the LHC/HL-LHC

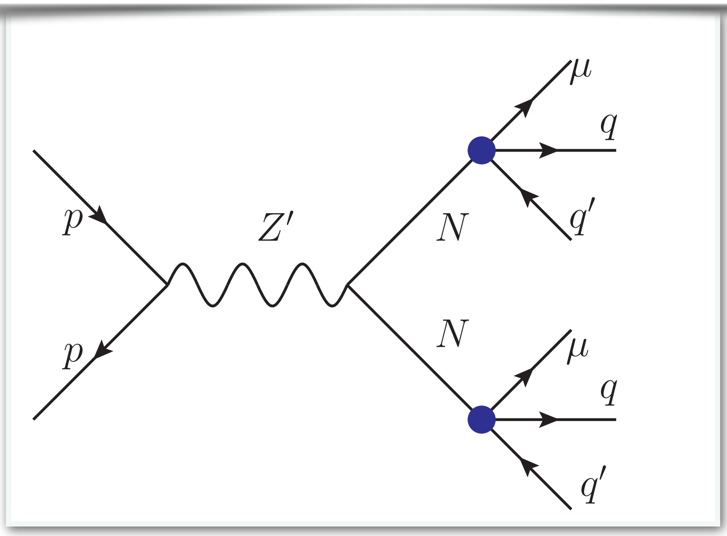




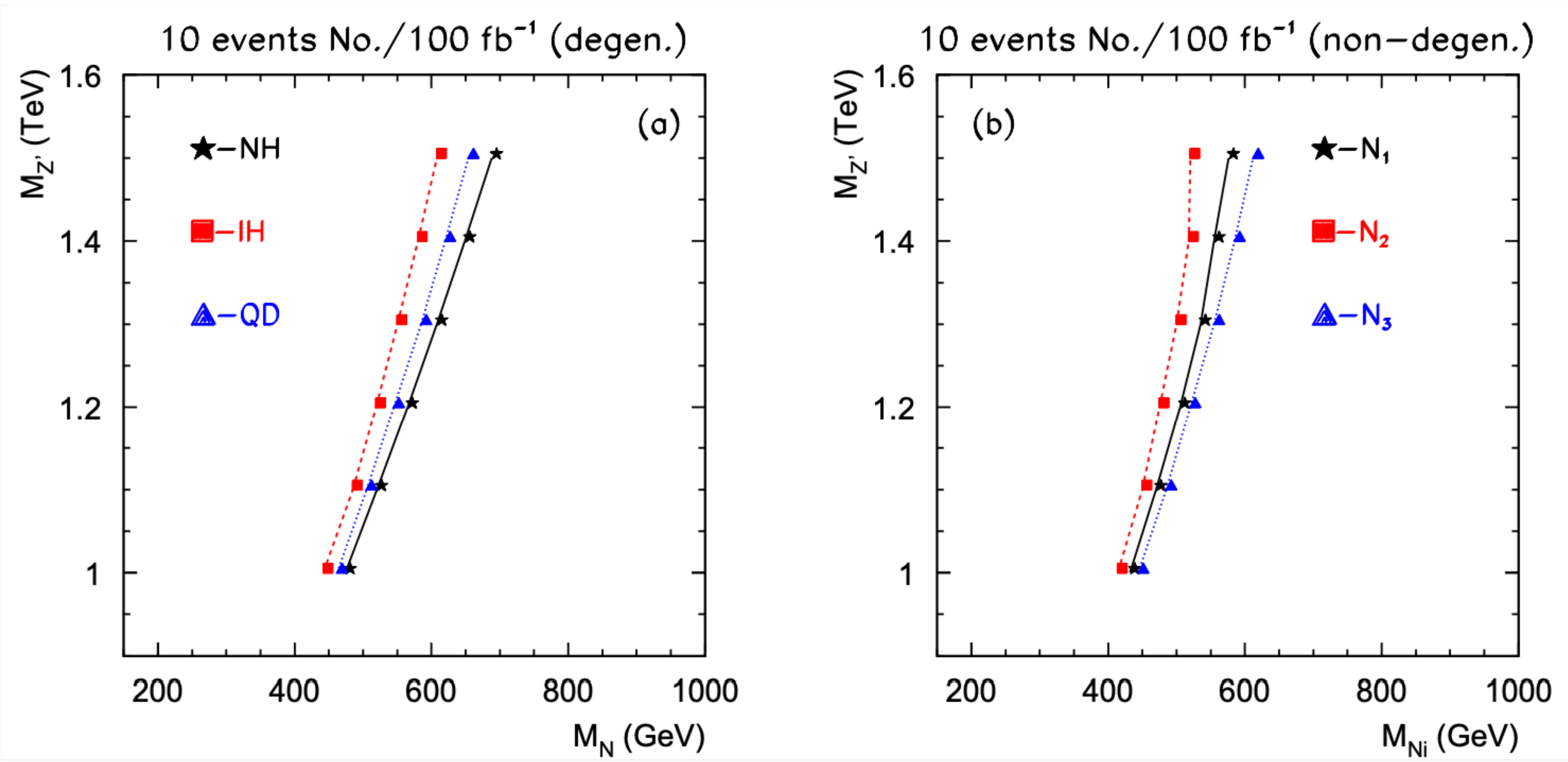
For FCC-hh, for a wide range of HNL mass, light neutrino mass constraint is satisfied

Degenerate vs non-degenerate HNL in gauged B-L Model

HNL is via prompt signal in $\Delta L = 2$ channel



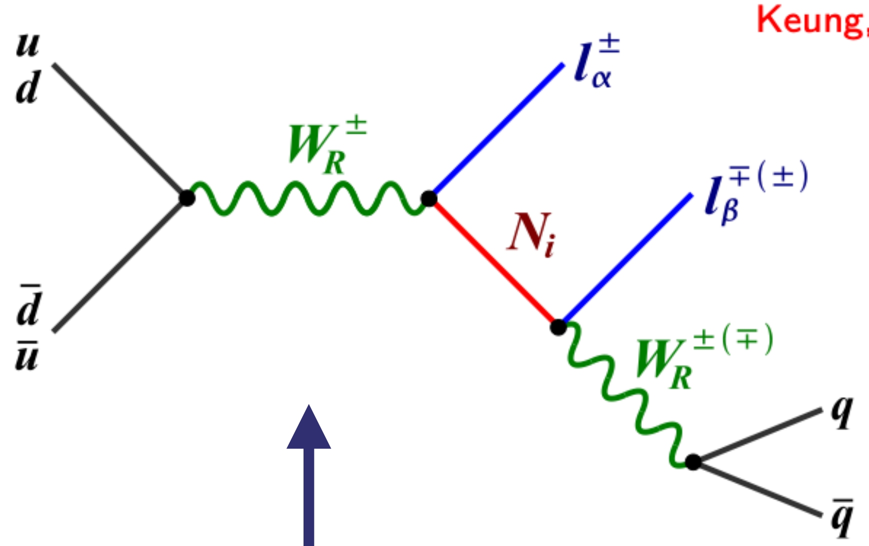
- Occurs when N is heavier than W and active-sterile mixing is large
- Resolved final state of $2l + \geq 4j$ with same-sign lepton
- Decay pattern $N_{1,2,3} \to e(\mu, \tau)W$ is sensitive to neutrino mixing parameter and Majorana phases



Pavel Fileviez Perez, Tao Han and Tong Li, Phys.Rev.D80:073015,2009

Left Right Symmetry- Alternate Signal Topology at LHC

Heavy Neutrino, BSM Gauge boson WR are present, enriched gauge sector



Keung, Senjanović, PRL, 83

LHC smoking gun signal is two same-sign leptons + two jets

Two electron/muon with two jets

Conventional Search

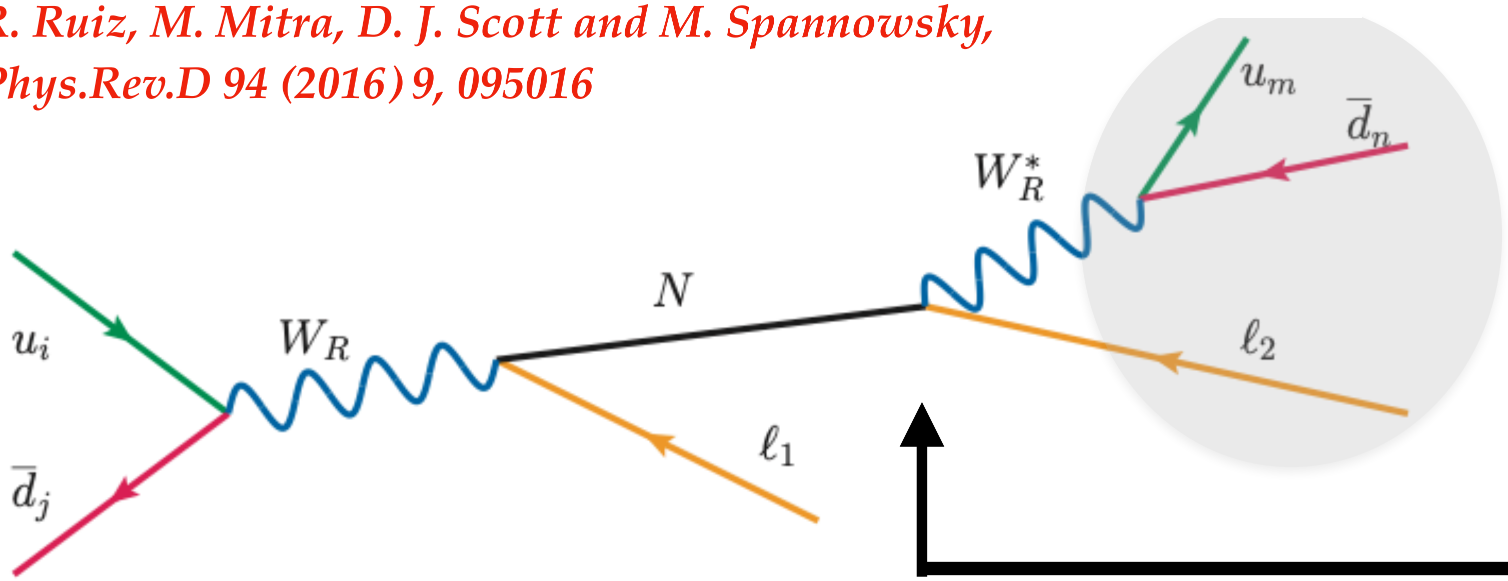
Proposed

Alternate signal topology → $l + j_{\text{fat}}$

R. Ruiz, M. Mitra, D. J. Scott and M. Spannowsky, Phys.Rev.D 94 (2016) 9, 095016

For N and WR having hierarchical masses

Collimated decay products of N



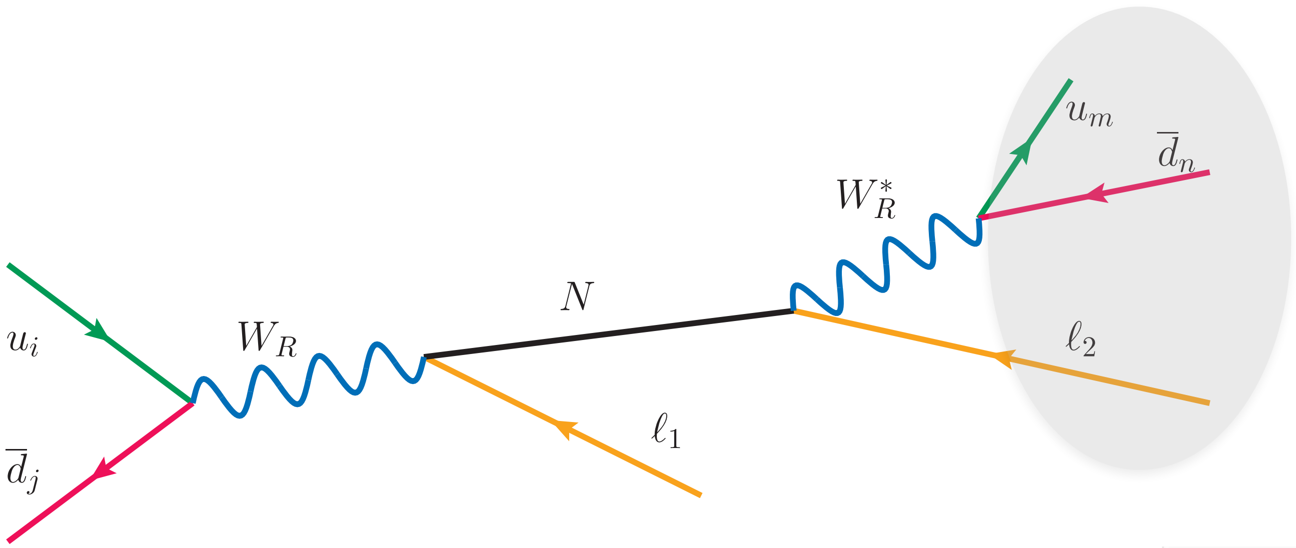
A single lepton with a fat jet

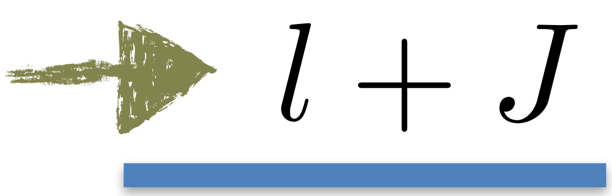
Electron with a large radius jet

M_N and M_{W_R} are hierarchical $\rightarrow l_2$ is collimated with the jets

Alternate signal topology ➡ $l + j_{\text{fat}}$

Manimala Mitra, Richard Ruiz, Darren J. Scott, and Michael Spannowsky - PRD 94, 095016, 2016





An electron with a high transverse momentum and a fat-jet

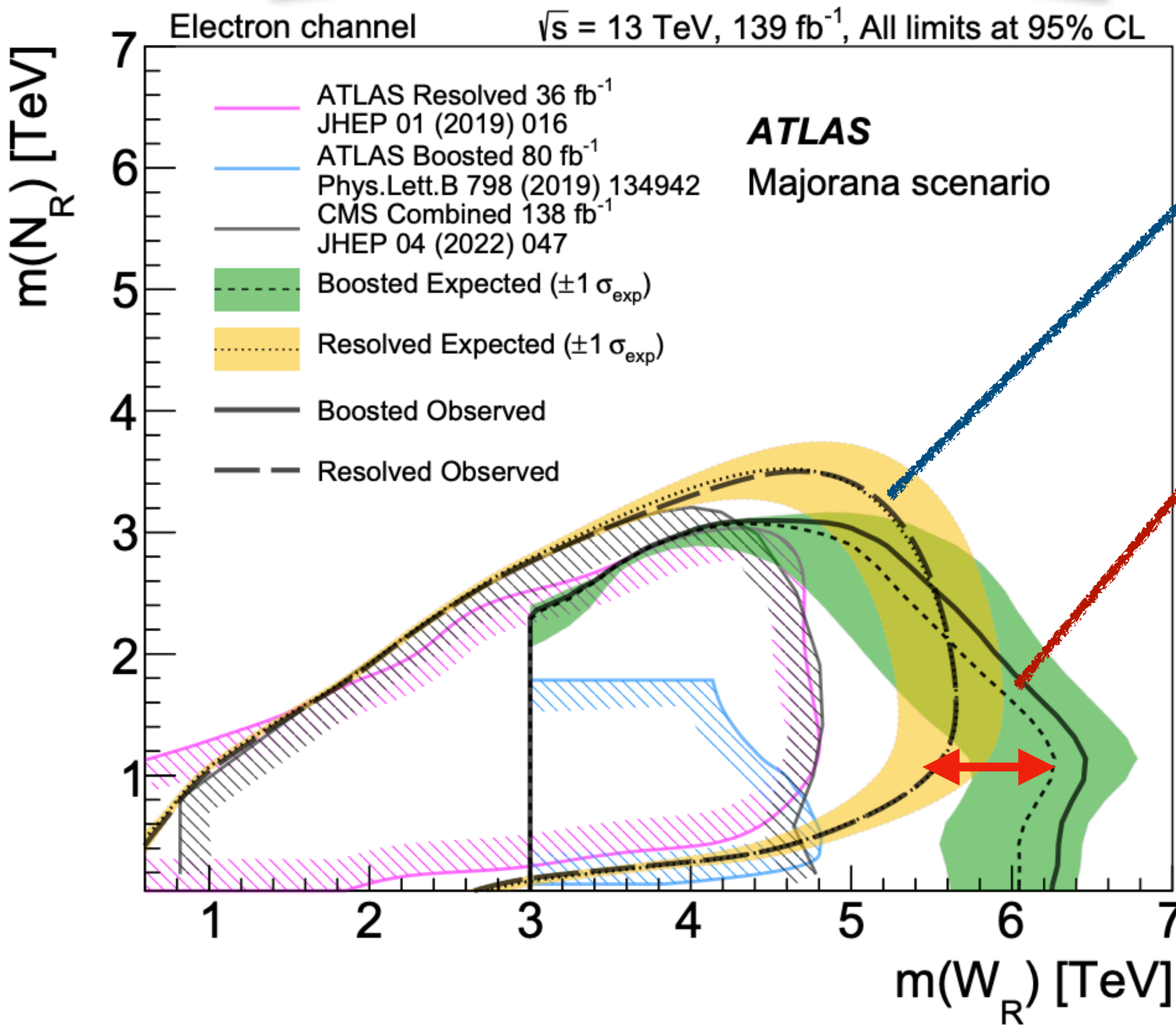
Simple 2 body topology

- **The transverse momentum** $p_T(l, j_{\text{fat}}) \sim M_{W_R}/2$
- **The separation between** l_2 **and** q, q' **will be small.**

Boosted HNL in LRSM:

The proposed search has been performed by the LHC-ATLAS collaboration

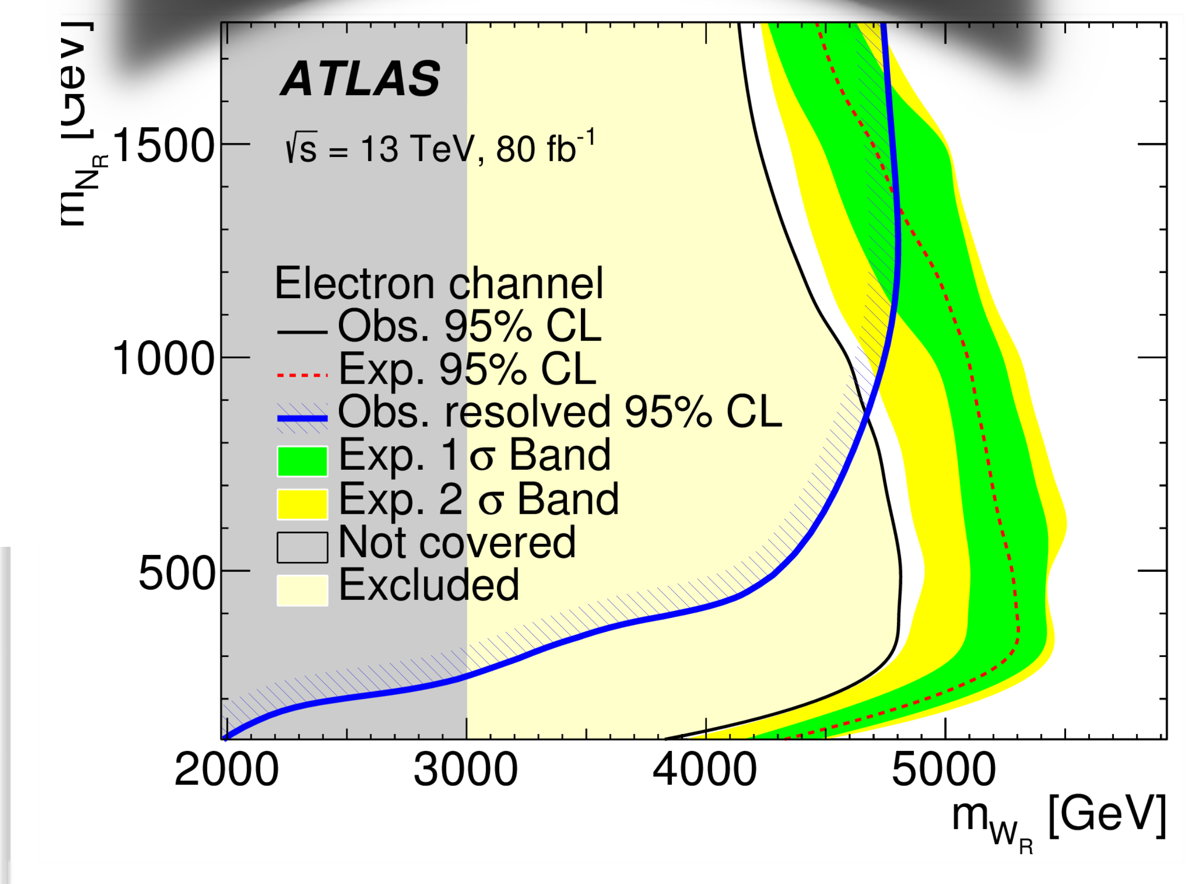
ATLAS Collaboration,
Phys. Lett. B 798 (2019) 134942,
Eur.Phys.J.C 83 (2023) 12, 1164,



- Conventional search
two electrons+di-jet

- Boosted HNL search
electrons+fat-jet

Improved Mass Limit of WR

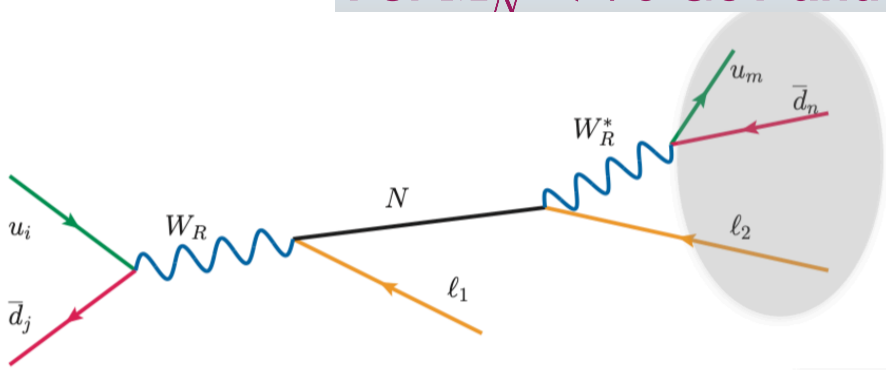


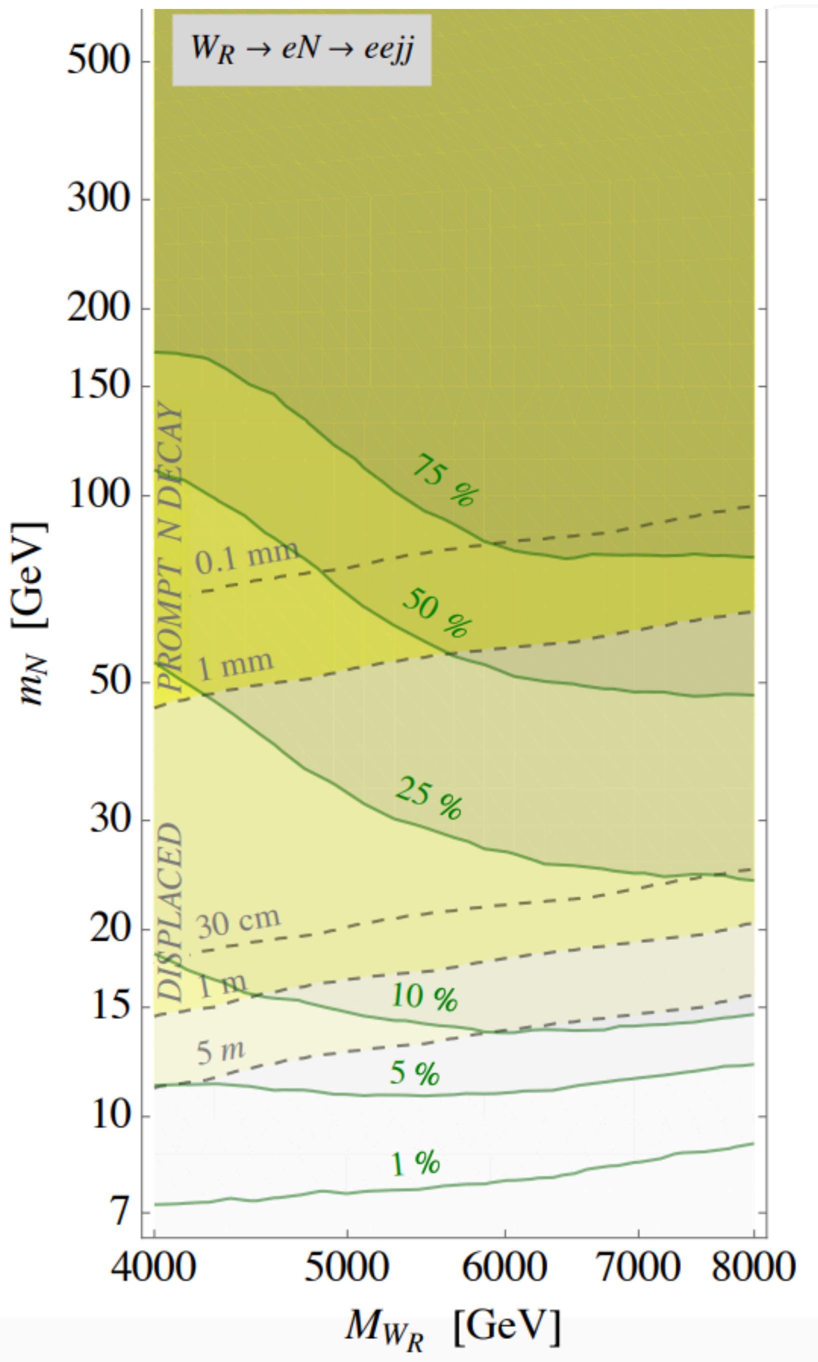
ATLAS Collaboration,
Eur.Phys.J.C 83 (2023) 12, 1164,
arXiv:2304.09553

$m_{W_R} \sim 6\text{TeV},\ 200\,\text{GeV} < m_N < 2\text{TeV}$ disallowed

Boosted and displaced HNL in LRSM:

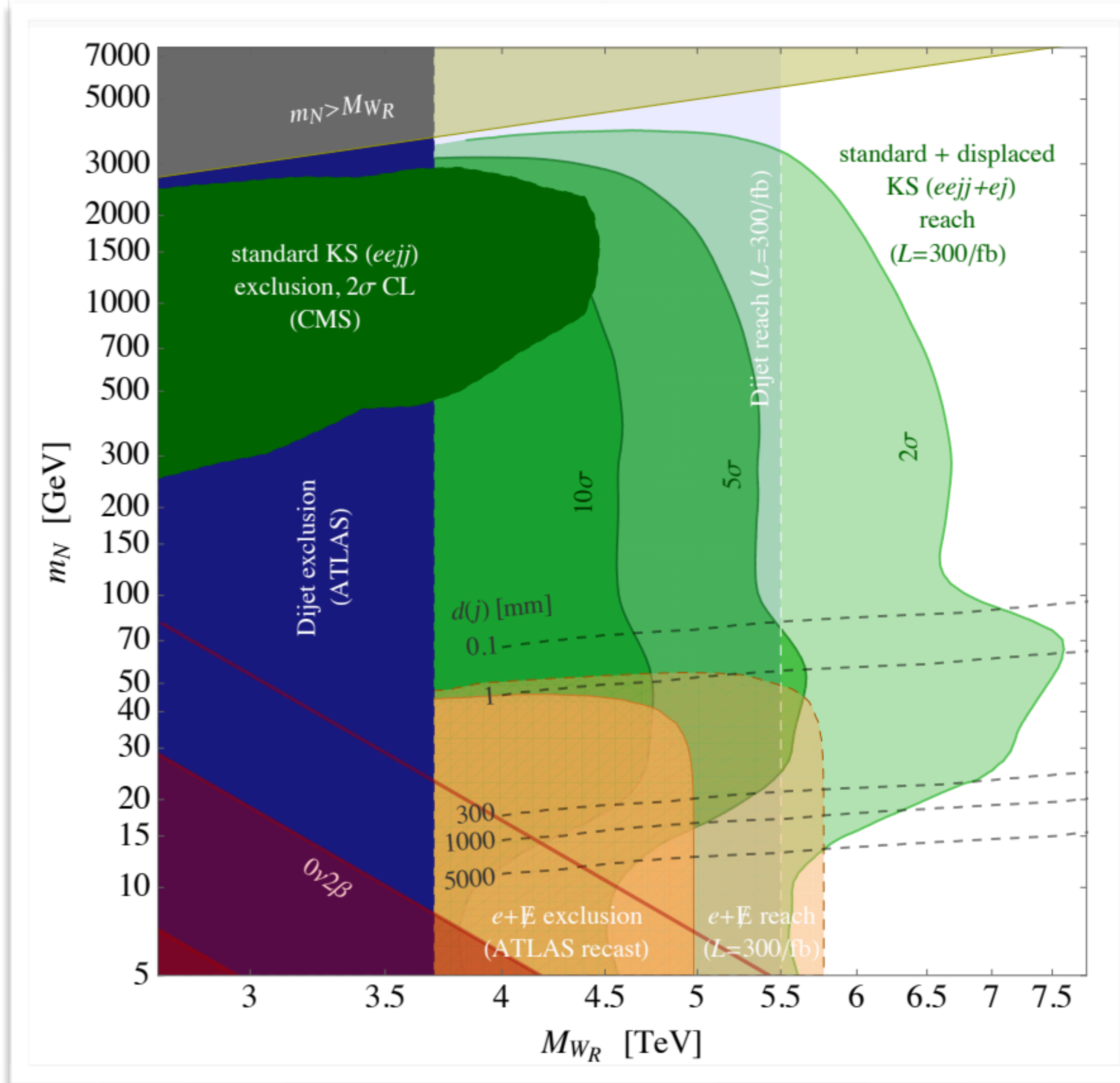
For $M_N < 70$ GeV and W_R of TeV mass range, HNL has large decay length





$$pp \to W_R \to lN = l + j_N^{displaced}$$

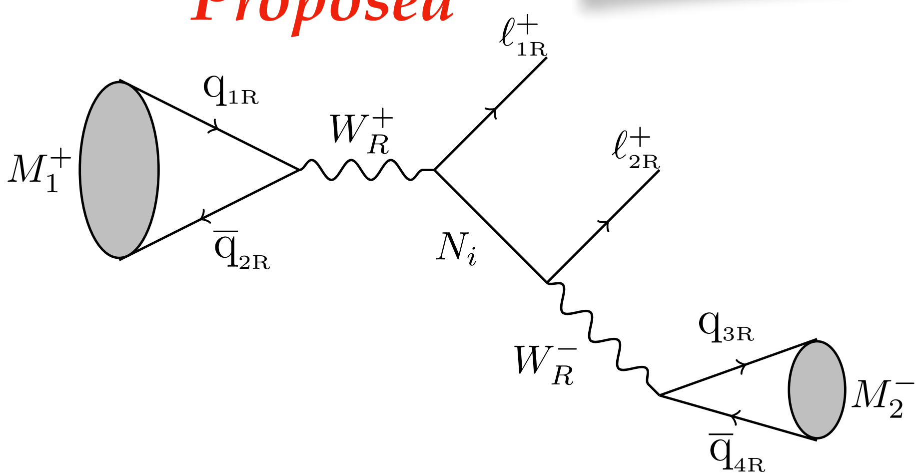
M. Nemevsek et al., Phys. Rev. D 97, 115018 (2018)



Dedicated analysis on HNL displaced decay(MS vs HCaL) is required

Lepton Number Violating Meson Decays

Proposed



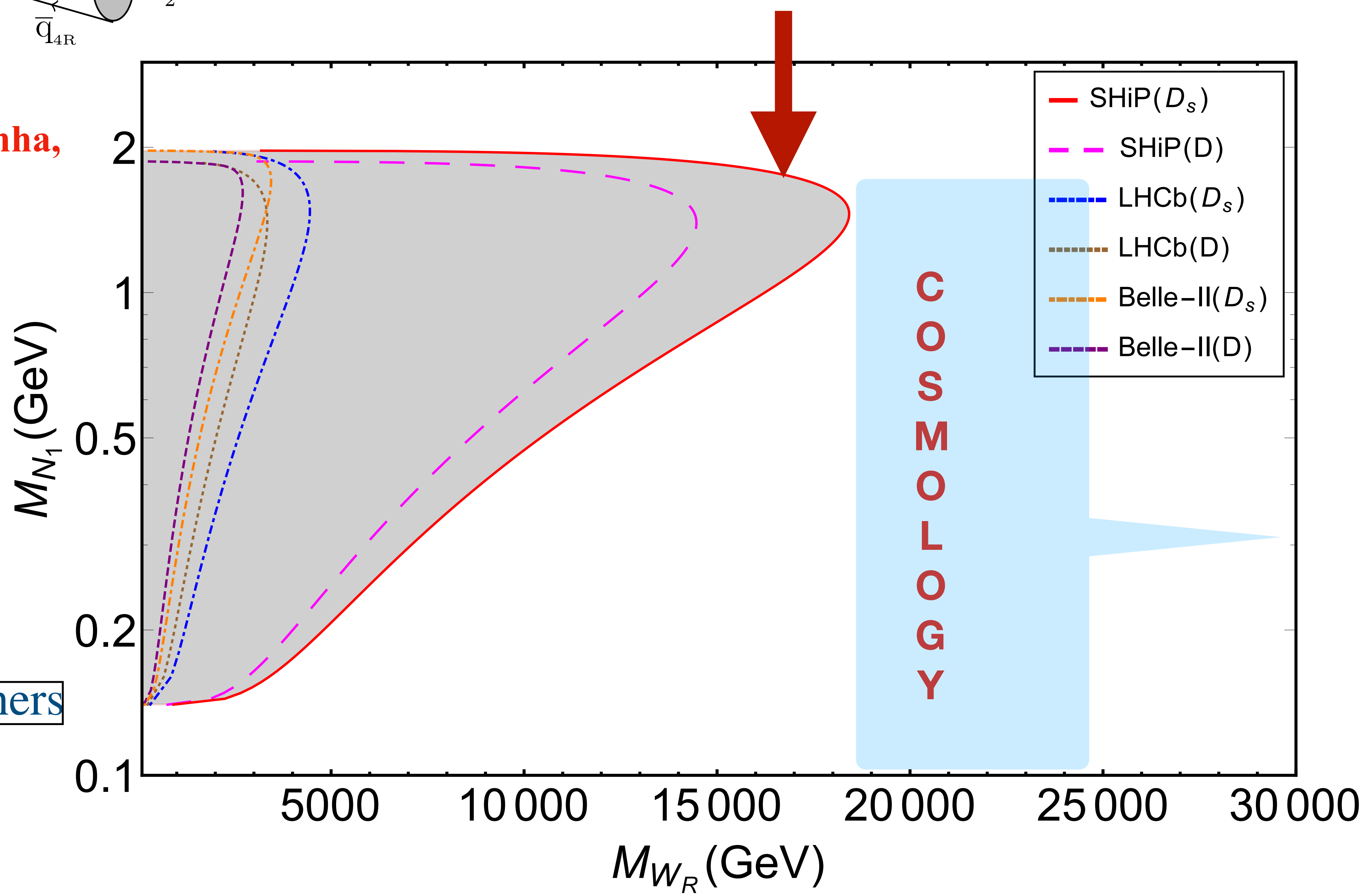
$$M^+ \to e^+ e^+ \pi^-$$

Sensitive to Sub-GeV Neutrino

Sensitive to a very high mass WR

S. Mandal, M. Mitra, N. Sinha, PRD 96 (2017) 3, 035023

- **M. Mitra et al., *Phys.Rev.D* 100 (2019) 9, 095022, *Phys.Rev.D* 104 (2021) 9, 095009**



LFV processes?

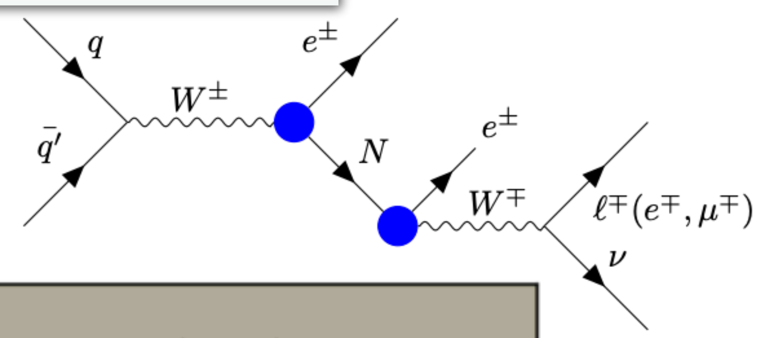
$\mu \to e\gamma, \mu \to 3e$ and others

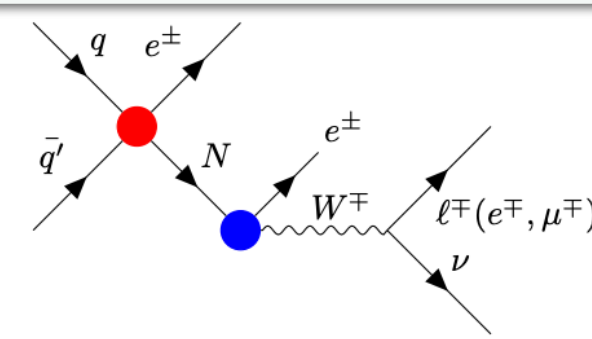
LHC search and LNV meson decays ($0\nu2\beta$ decay) are complimentary probes

HNL at LHC/HL-LHC for tri-lepton+MET in EFT framework

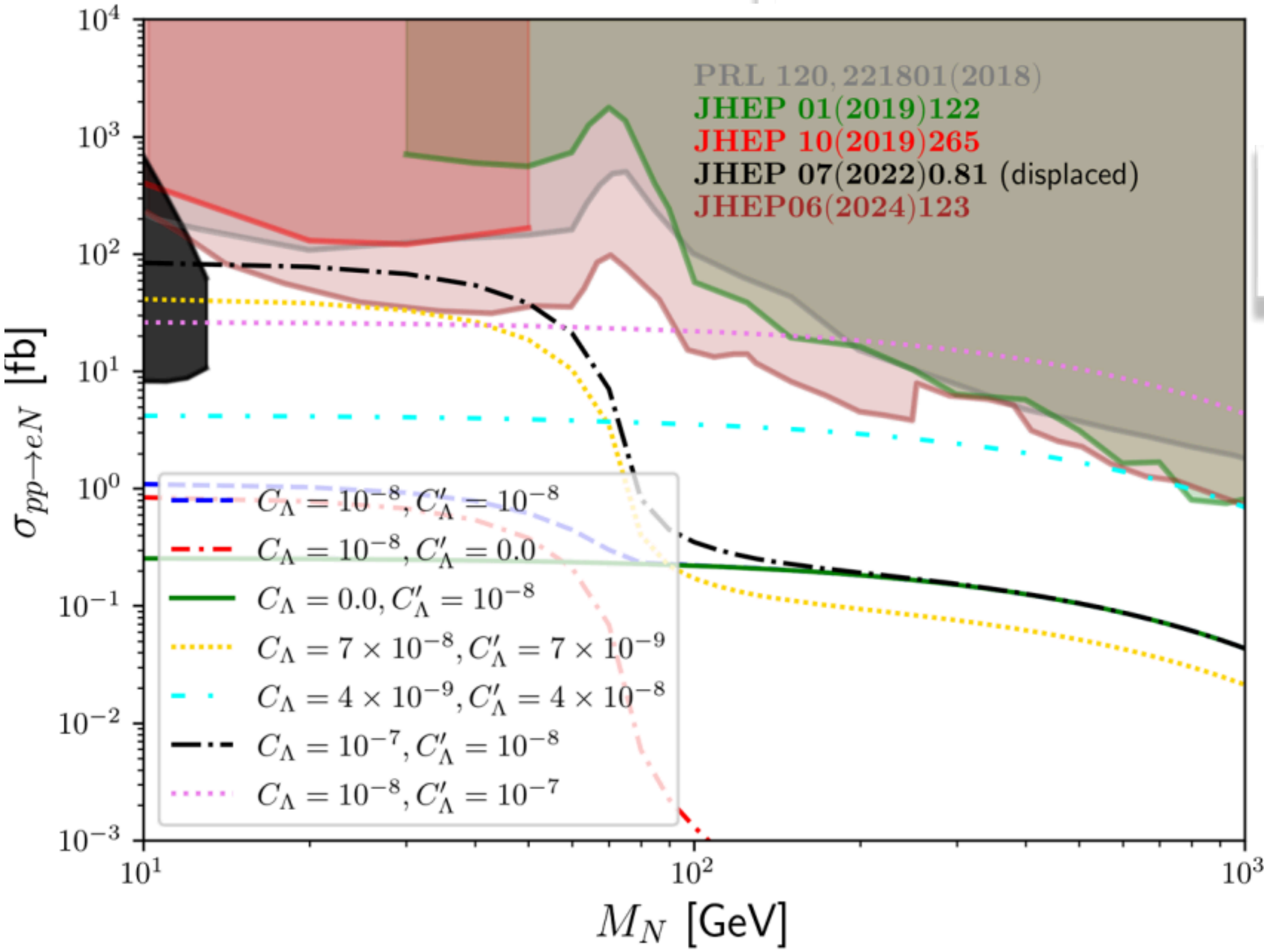
$$\mathcal{O}_{HNe} = \frac{c}{\Lambda^2}(\overline{N}_R\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$$

$$\mathcal{O}_{duNe} = \frac{c'}{\Lambda^2}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{N}_R\gamma_\mu e_R\right)$$





Mitra, Saha, Spannowsky and Takeuchi, Phys. Rev. D 111, 015005 (2025)



Difference with respect to a renormalisable Type-I seesaw model

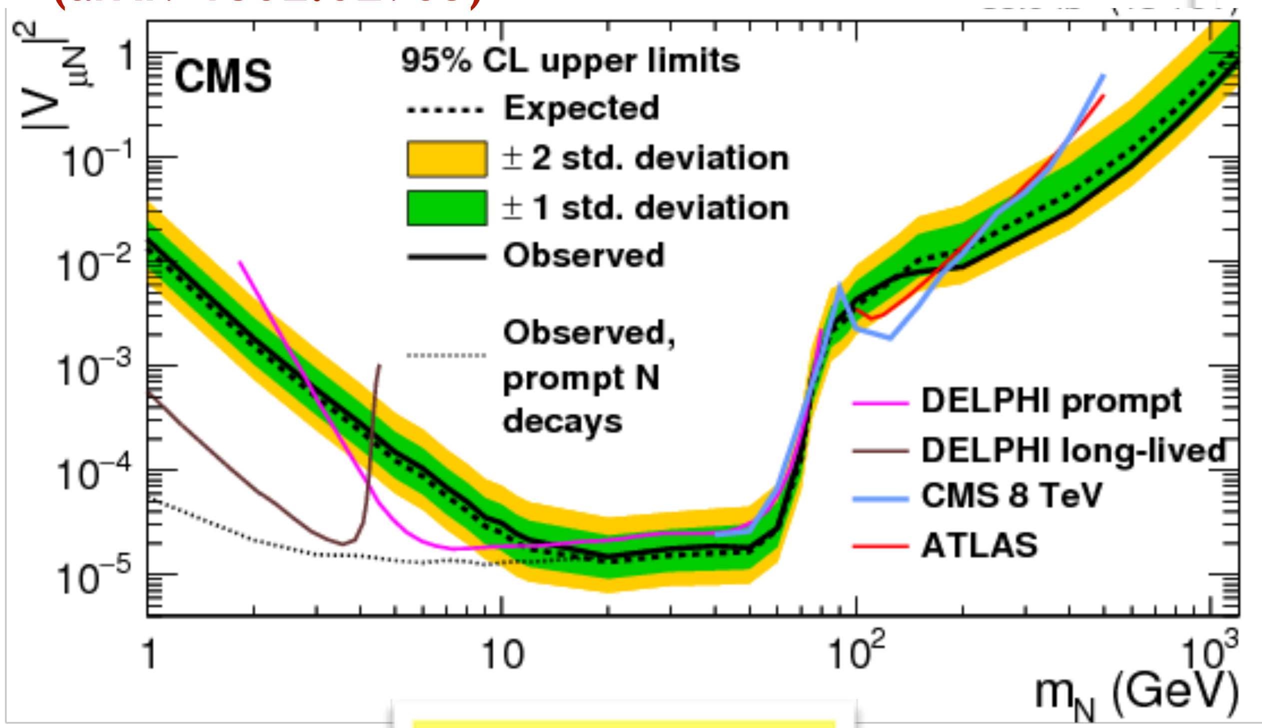
- **Large $\sigma(pp \to Nl)$ for a large four-Fermi operator $\mathcal{O}_{duNe}$**
- **Branching ratio of N is heavily dependent on $\mathcal{O}_{duNe}$ and $\mathcal{O}_{HNe}$ Wilson coefficients along with the active-sterile mixing**

$\mathcal{O}_{duNe}$ alters the kinematics of N, hence cuts proposed in CMS HNL searches for tri-lepton+MET is not efficient

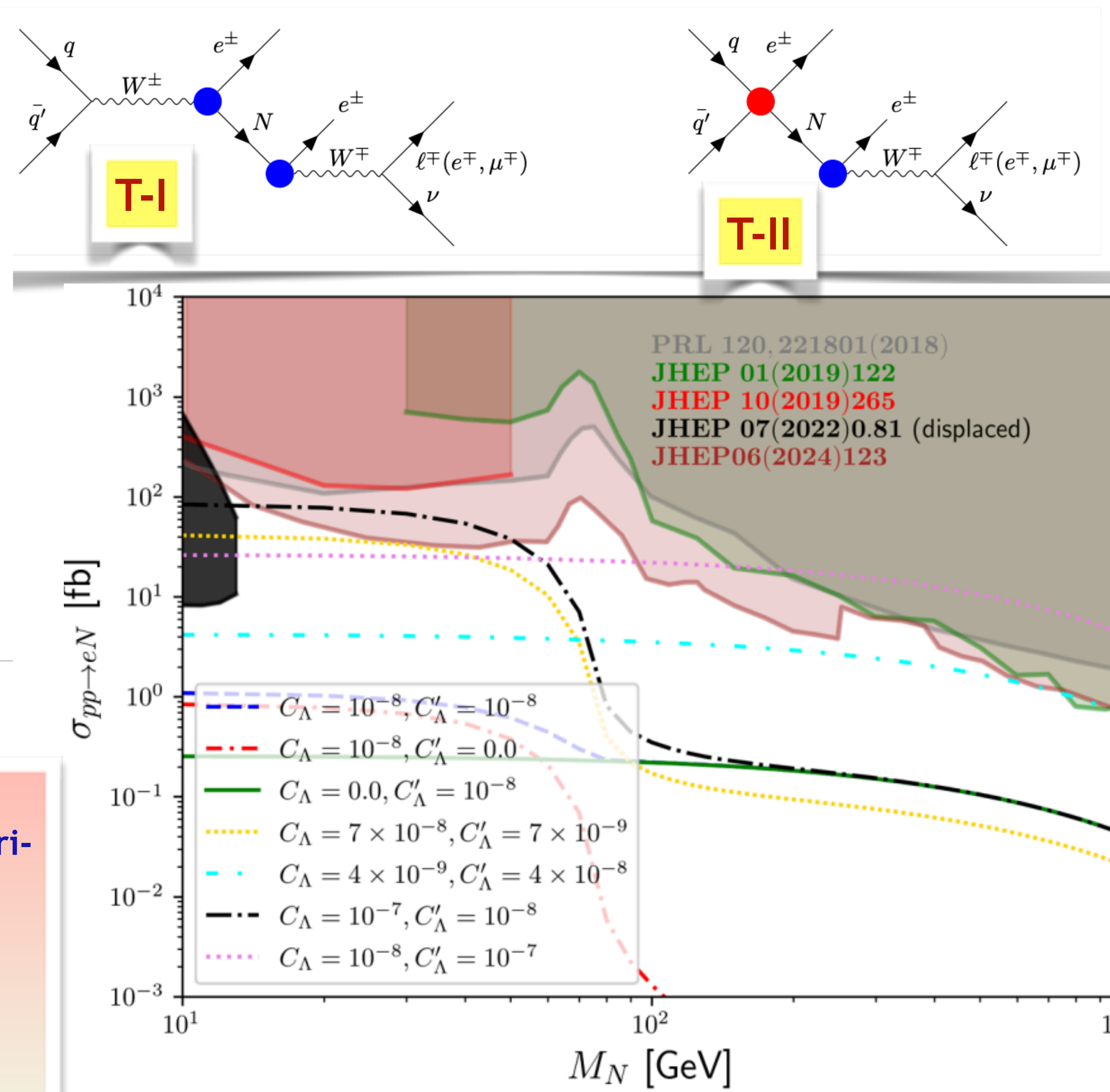
- J. Wudka et al., Physics Letters B 670 no. 4, (2009) 399–402
- H. L. Li et al., JHEP 11 (2021) 003
- M. Chala et al., *Phys.Rev.D* 100 (2019) 11, 115019; *Eur.Phys.J.C* 80 (2020) 8, 743,
- P. Hernandez et al., *JHEP* 03 (2021) 117,
- R. Padhan et al/, *Phys.Rev.D* 106 (2022) 11, 113008, *Phys.Rev.D* 109 (2024) 11, 115002
- G. Cottin et al., *JHEP* 01 (2022) 044, *JHEP* 01 (2023) 015
- R. Beltran et al., e-Print: 2501.09065 [hep-ph]
- P. D. Bolton et al., arXiv 2502.06972

Reinterpretation of LHC constraint for HNL search (conservative approach?)

CMS collaboration, *PRL*120 (2018) 22, 221801 (arXiv 1802.02965)



Road Block??



- HEP data files, distributions, cut-efficiencies are not available for the above CMS search and the previous tri-lepton+MET HNL searches
- JHEP 06 (2024) 123 involves information about cut-efficiencies for few mass points. For high mass, more informations required. Informations about distributions Fig 2,3,4 not available and validation is difficult.

Derive limit for T-I

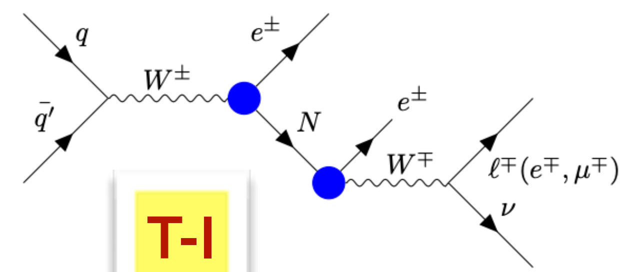
Naive reinterpretation (although not most optimal!)

Active-sterile mixing from arXiv 1802.02965

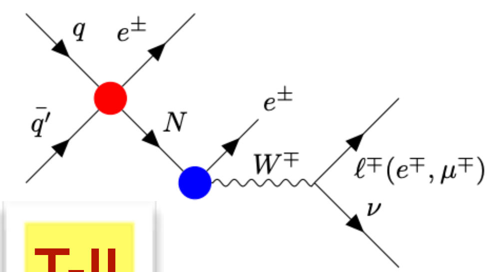
Effect of cuts used in 3l+MET is missing

Effect of selection cuts for HL-LHC

Selection cuts from *PRL*120 (2018) 22, 221801, CMS collaboration



T-I



T-II

A. $M_N < M_W, C_\Lambda > C'_\Lambda$

B. $M_N < M_W, C_\Lambda < C'_\Lambda$

C. $M_N > M_W, C_\Lambda > C'_\Lambda$

D. $M_N > M_W, C_\Lambda < C'_\Lambda$

Benchmark values of mass and couplings

$M_N = 50$ GeV and $C_\Lambda = 4\times10^{-9}$ (7×10^{-8}), $C'_\Lambda = 4\times10^{-8}$ (7×10^{-9})

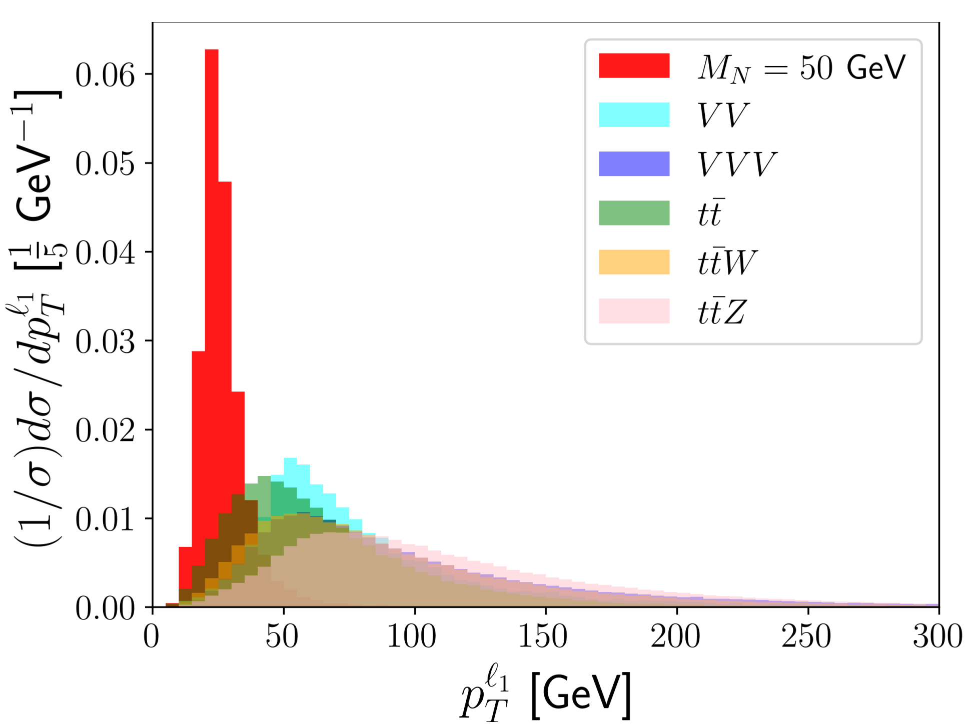
$M_N = 450$ GeV, $C_\Lambda = 4\times10^{-9}$ (7×10^{-8}), and $C'_\Lambda = 4\times10^{-8}$ (7×10^{-9})

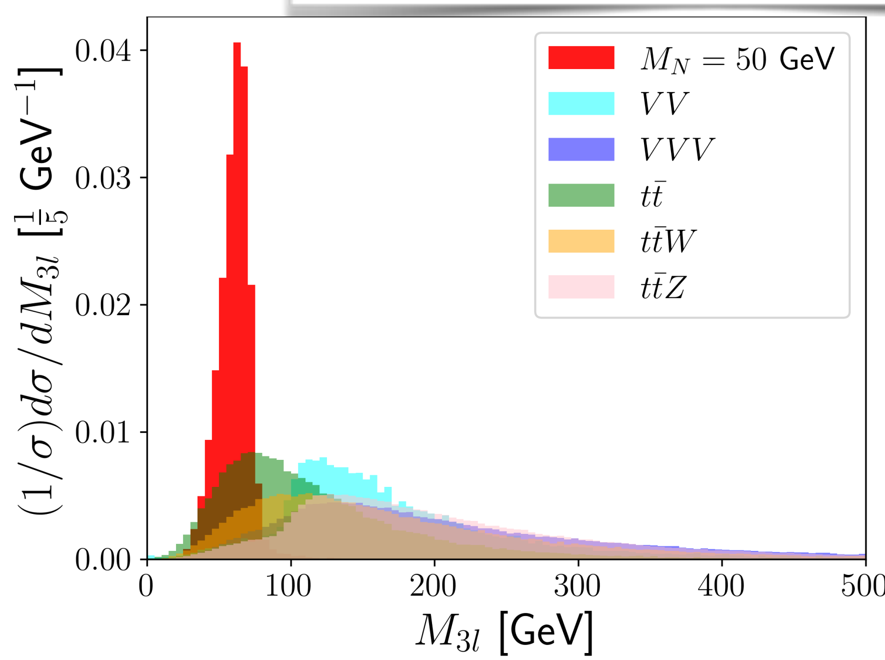
Low mass region

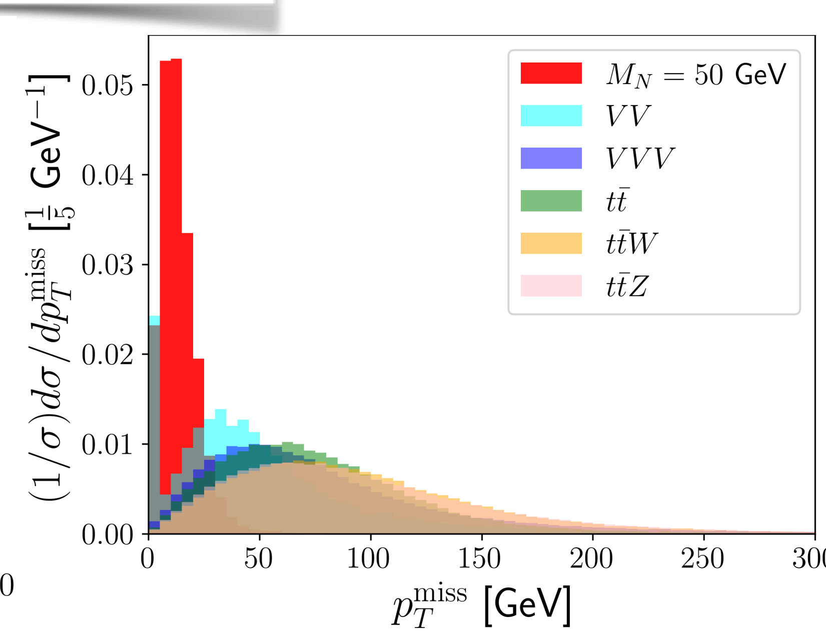
High mass region

Relevant kinematic variables

$C_\Lambda > C'_\Lambda$



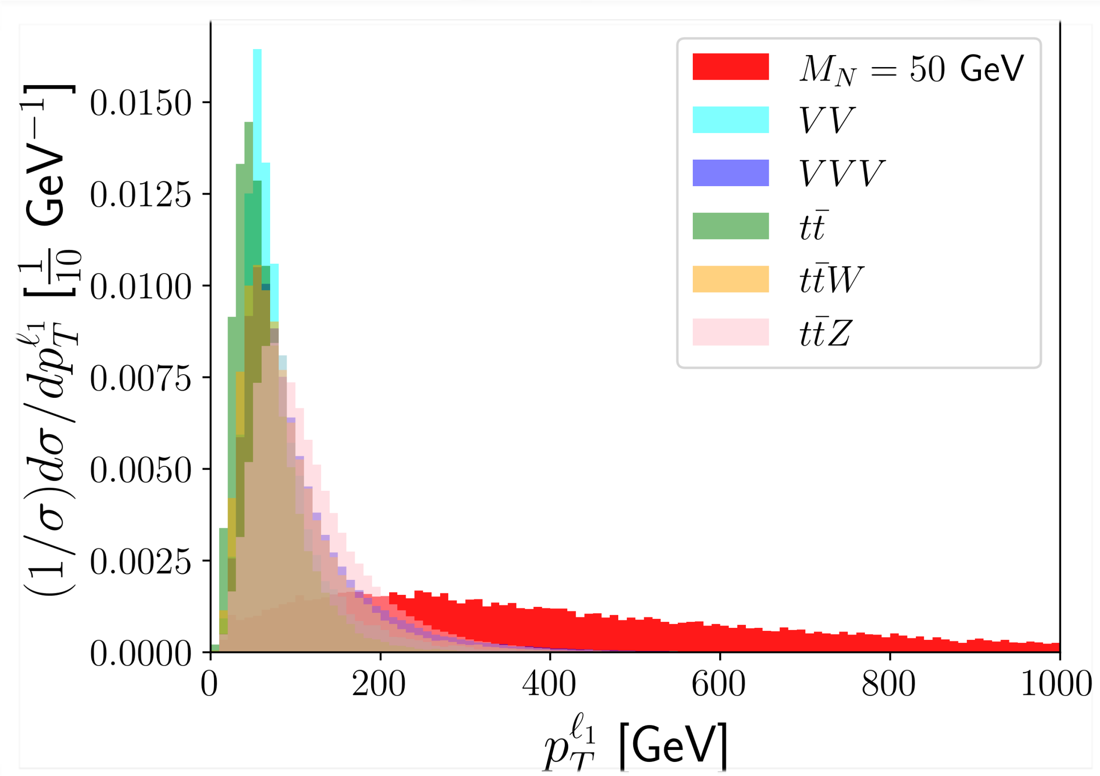


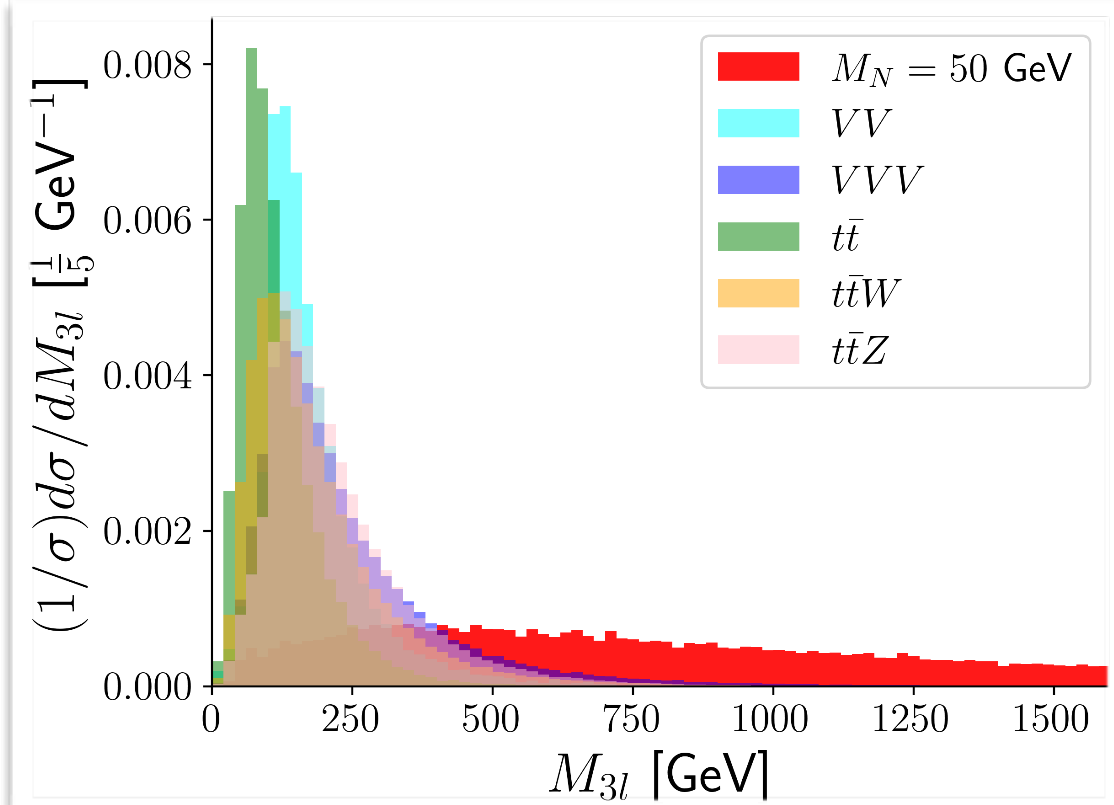


Effect of selection cuts

Low mass region

$M_N = 50\,\text{GeV} \;\; C_\Lambda < C'_\Lambda$





	no. bjets = 0	no. $\ell^{\pm} = 3$	$M_{3\ell} < 80$ GeV	$\lvert M_{\ell^{\pm}\ell^{\mp}} - M_Z\rvert > 15$ GeV	$p_T^{\text{miss}} < 75$ GeV	σ_{eff}[fb]	η_s
50 GeV($C_\Lambda > C'_\Lambda$) [6.59 fb]	6.59	1.34	1.30	1.30	1.29	1.29	26.86
50 GeV($C_\Lambda < C'_\Lambda$) [2.25 $\times 10^{-2}$ fb]	2.24 $\times 10^{-2}$ [a]	3.94 $\times 10^{-3}$	9.93 $\times 10^{-5}$	9.93 $\times 10^{-5}$	9.89 $\times 10^{-5}$	9.89 $\times 10^{-5}$	2.23$\times 10^{-3}$
VV [9847 fb]	9847	277.29	2.19	1.70	1.22	1.22	
VVV [5.53 fb]	5.53	1.22	5.74 $\times 10^{-2}$	4.29 $\times 10^{-2}$	2.76 $\times 10^{-2}$	2.76 $\times 10^{-2}$	
$t\bar{t}$ [51170 fb]	11289.56	92.18	11.57	8.72	4.35	4.35	
$t\bar{t}W^{\pm}$ [13.22 fb]	2.29	4.83 $\times 10^{-1}$	3.16 $\times 10^{-2}$	2.31 $\times 10^{-2}$	9.26 $\times 10^{-3}$	9.26 $\times 10^{-3}$	
$t\bar{t}Z$ [7.26 fb]	1.31	3.99 $\times 10^{-1}$	8.67 $\times 10^{-3}$	6.66 $\times 10^{-3}$	2.87 $\times 10^{-3}$	2.87 $\times 10^{-3}$	

Following arXiv 1802.02965 (*PRL*120 (2018) 22, 221801)

- $M_{3l} < 80\,\text{GeV}$ **reduces signal for a higher** C'_Λ **and not suitable, although MN is low**

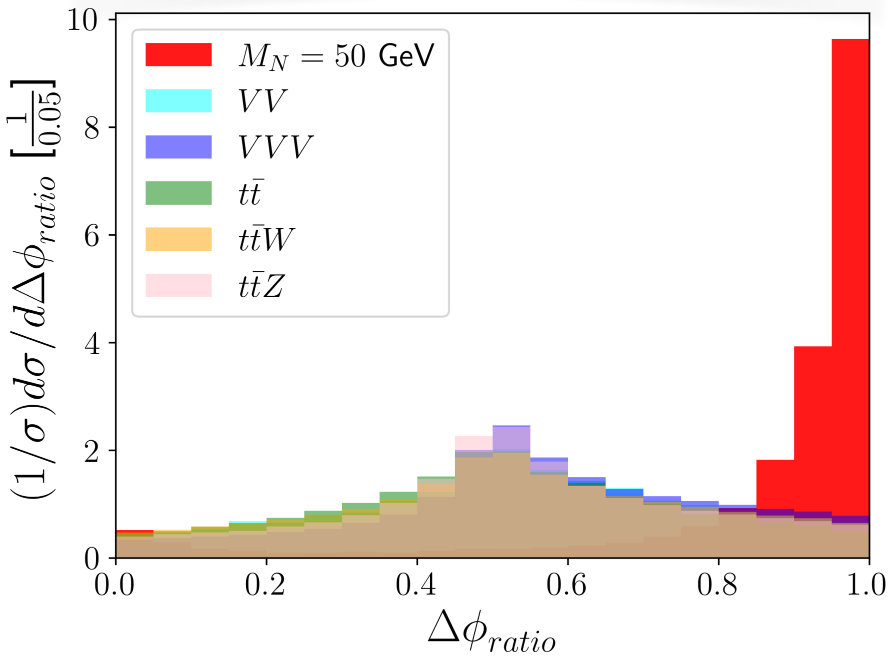
- $P_T^{miss} < 75\,\text{GeV}$ **is not most optimal for higher** C'_Λ

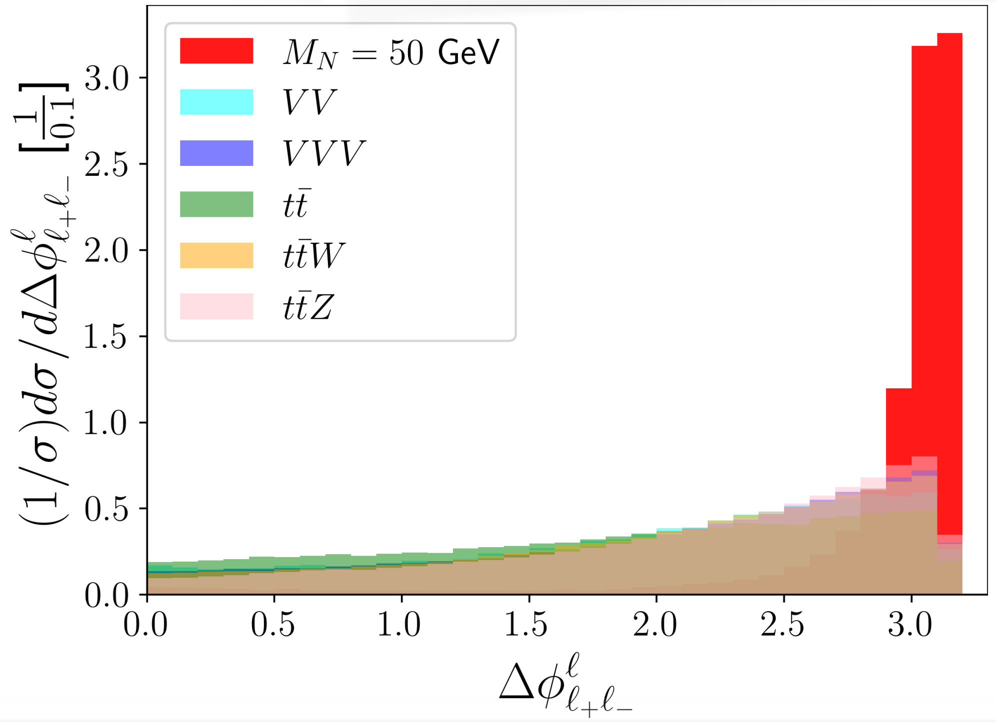
Low mass region

$M_N = 50\,\text{GeV} \quad C_\Lambda < C'_\Lambda$

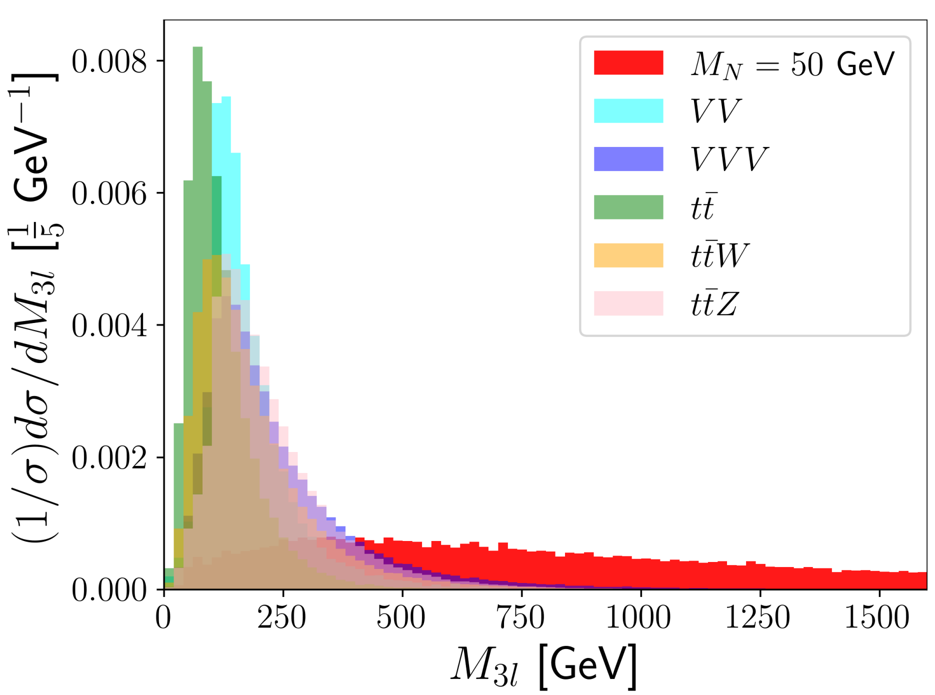
$N(l^\pm) \geq 3,\ N(e^\pm) \geq 2$
$P_T(l_1) > 220\,\text{GeV} \quad P_T(l_2) > 80\,\text{GeV}$

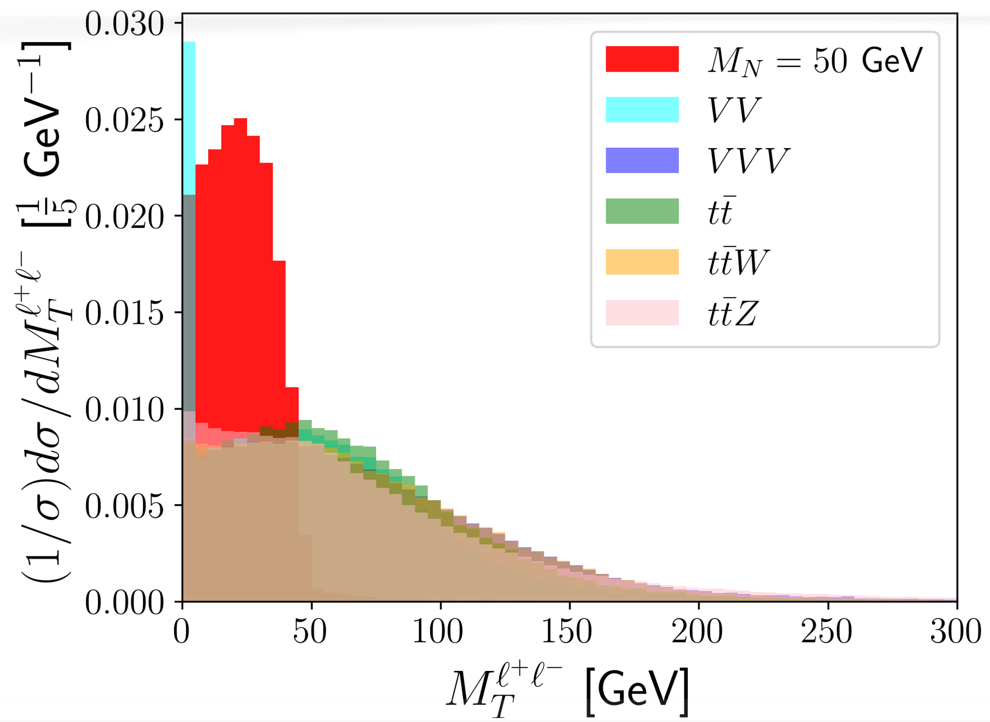
$\Delta\phi_{ratio} = \Delta\phi_{\ell_1}^{p_T^{miss}} / (\Delta\phi_{\ell_1}^{p_T^{miss}} + \Delta\phi_{\ell_2}^{p_T^{miss}})$





Maximum azimuthal angle between the di-lepton system in $M_T^{l^+l^-}$ and rest of leptons





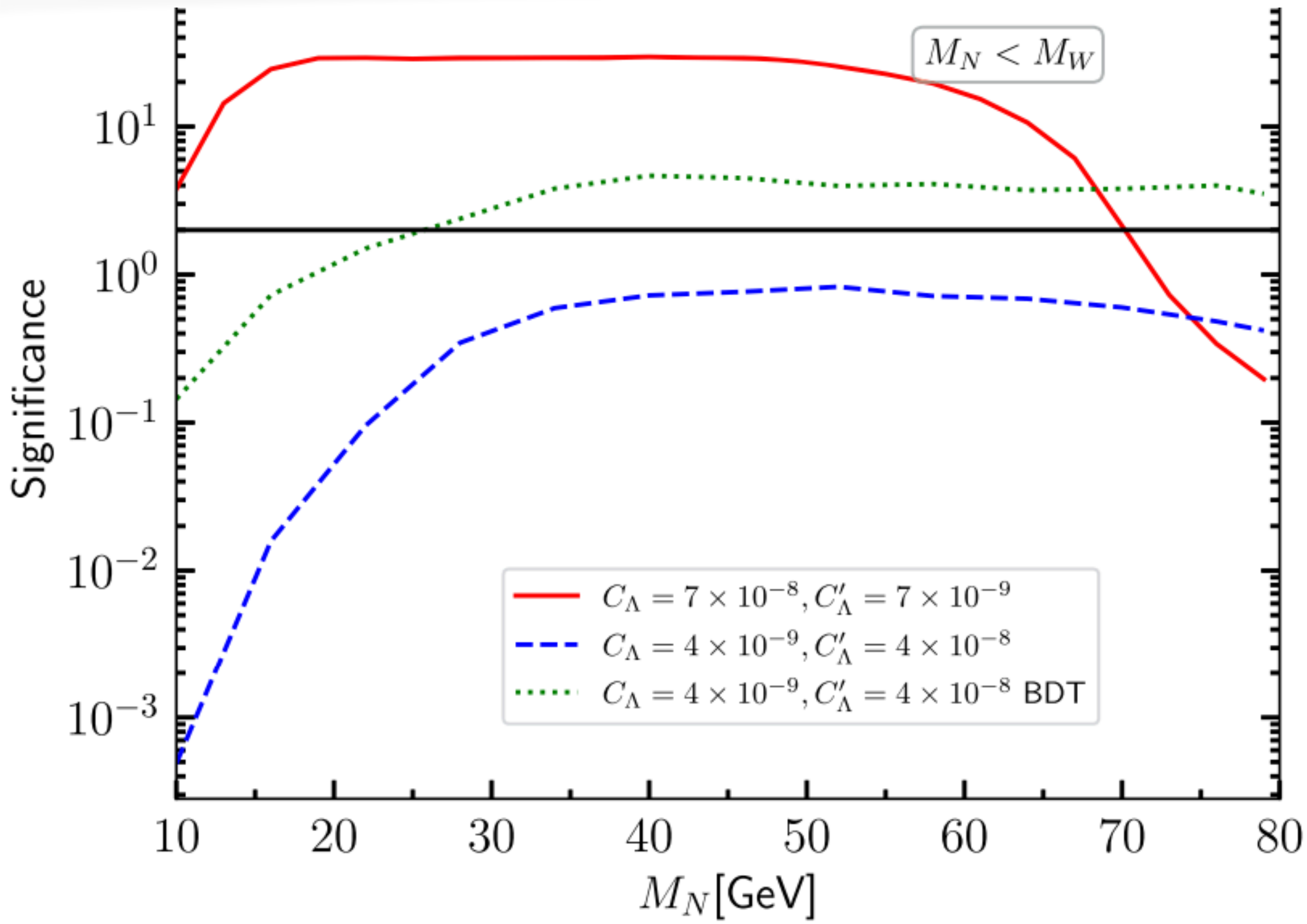
Transverse mass of opposite sign di-lepton system closest to MN

New sets of kinematic variables

Low mass region

	No. b jets $=0$	No. $\ell^{\pm} \geq 3$	$M_{3\ell} > 550$	$\Delta\phi_{\rm ratio} > 0.8$	$\Delta\phi^{\ell}_{\ell_+\ell_-} > 2.5$	$M_T^{\ell} > 5.0$	$M_T^{\ell^+\ell^-} < 55.0$	$\lvert M_{\ell^\pm\ell^\mp} - M_Z\rvert > 50$	$\sigma_{\rm eff}$[fb]	η_s
50 GeV ($C_\Lambda < C'_\Lambda$) [2.23×10^{-2} fb]	2.22×10^{-2}[a]	9.25×10^{-3}	8.37×10^{-3}	7.73×10^{-3}	7.57×10^{-3}	6.73×10^{-3}	6.71×10^{-3}	6.34×10^{-3}	6.34×10^{-3}	7.78×10^{-1}
VV[9847 fb]	9847	3.95	1.19	4.31×10^{-1}	2.40×10^{-1}	2.04×10^{-1}	1.35×10^{-1}	9.89×10^{-2}	9.89×10^{-2}	
VVV [5.53 fb]	5.53	5.87×10^{-2}	3.51×10^{-2}	1.48×10^{-2}	1.23×10^{-2}	1.18×10^{-2}	6.61×10^{-3}	4.21×10^{-3}	4.21×10^{-3}	
$t\bar{t}$ [51170 fb]	11289.56	5.78	1.09	4.35×10^{-1}	2.30×10^{-1}	1.84×10^{-1}	1.23×10^{-1}	9.21×10^{-2}	9.21×10^{-2}	
$t\bar{t}W^{\pm}$ [13.22 fb]	2.29	1.46×10^{-2}	6.24×10^{-3}	2.27×10^{-3}	1.88×10^{-3}	1.77×10^{-3}	1.03×10^{-3}	6.35×10^{-4}	6.35×10^{-4}	
$t\bar{t}Z$ [7.26 fb]	1.31	3.22×10^{-2}	9.13×10^{-3}	3.24×10^{-3}	2.06×10^{-3}	1.94×10^{-3}	1.29×10^{-3}	5.08×10^{-4}	5.08×10^{-4}	

$\Delta\phi_{ratio}, M_{3l}, \Delta\phi^{l}_{l^+l^-}, M_T^{l^+l^-}$ - useful variable to suppress background and optimise signal sensitivity $C_\Lambda < C'_\Lambda$



More than 2σ significance for a large C'_Λ

Effect of selection cuts

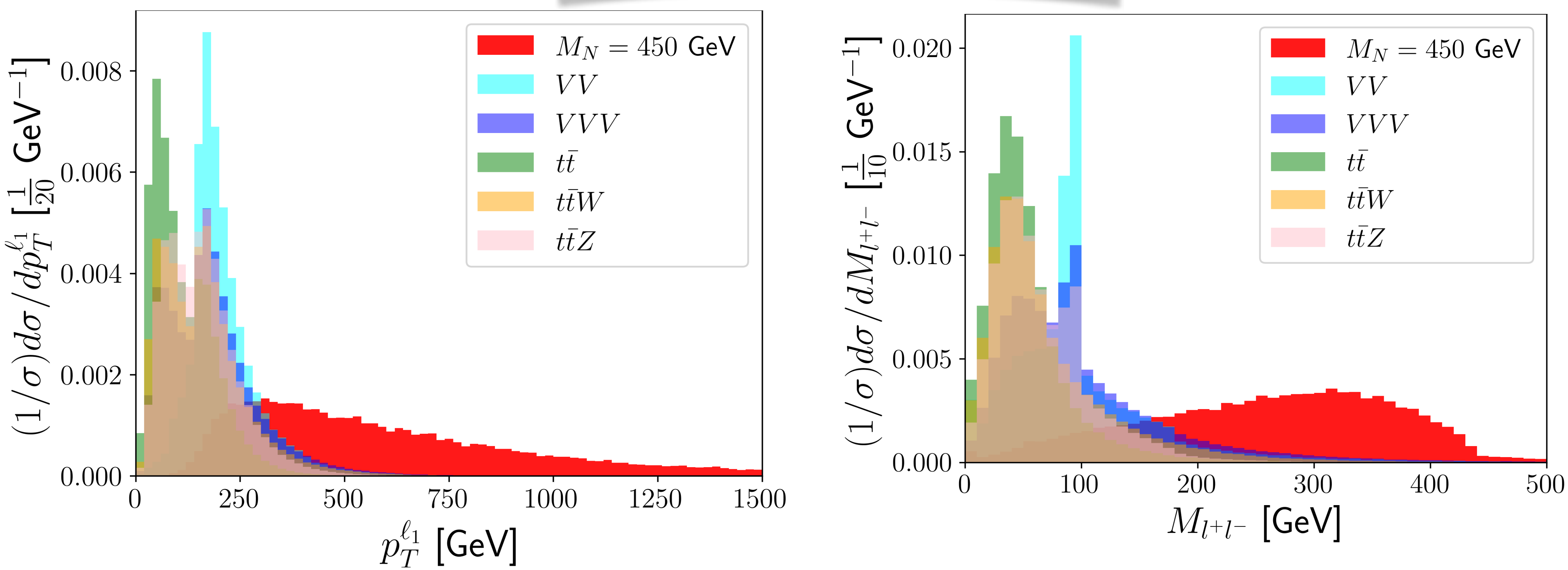
High mass region

$M_N = 450\,GeV$

	no. bjets = 0	no. $\ell^{\pm} = 3$	$\lvert M_{\ell^{\pm}\ell^{\mp}} - M_Z \rvert > 15$ GeV	$p_T^{\rm miss} > 50$ GeV	$\sigma_{\rm eff}$[fb]	η_s
450 GeV($C_\Lambda > C'_\Lambda$) [2.2 $\times10^{-2}$ fb]	2.2 $\times10^{-2}$	1.17 $\times10^{-2}$	1.15 $\times10^{-2}$	8.96 $\times10^{-3}$	8.96 $\times10^{-3}$	5.7 $\times10^{-2}$
450 GeV($C_\Lambda < C'_\Lambda$) [7.6 $\times10^{-2}$ fb]	7.6 $\times10^{-2}$	4.02 $\times10^{-2}$	3.96 $\times10^{-2}$	3.08 $\times10^{-2}$	3.08 $\times10^{-2}$	1.96 $\times10^{-1}$
VV [9847 fb]	9847	202.31	115.07	50.95	50.95	
VVV [5.53 fb]	5.53	9.27 $\times10^{-1}$	5.53 $\times10^{-1}$	3.84 $\times10^{-1}$	3.84 $\times10^{-1}$	
$t\bar{t}$ [51170 fb]	11289.56	55.94	31.43	21.66	21.66	
$t\bar{t}W^{\pm}$ [13.22 fb]	2.29	3.85 $\times10^{-1}$	2.29 $\times10^{-1}$	1.79 $\times10^{-1}$	1.79 $\times10^{-1}$	
$t\bar{t}Z$ [7.26 fb]	1.31	3.50 $\times10^{-1}$	1.79 $\times10^{-1}$	1.41 $\times10^{-1}$	1.41 $\times10^{-1}$	

Following arXiv 1802.02965 (*PRL*120 (2018) 22, 221801)

Relevant kinematic variables $C_\Lambda < C'_\Lambda$



Background suppression should be more to have optimal signal sensitivity

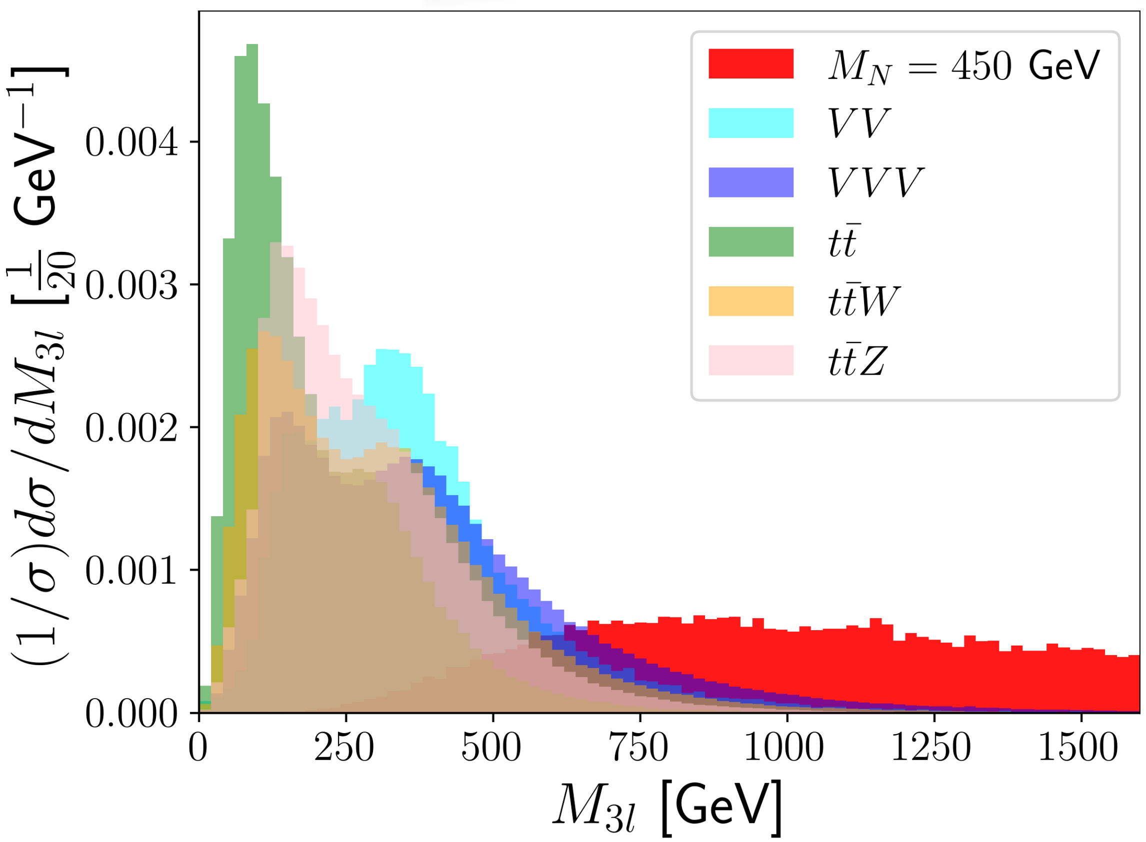
New sets of kinematic variables for HL-LHC - proposal

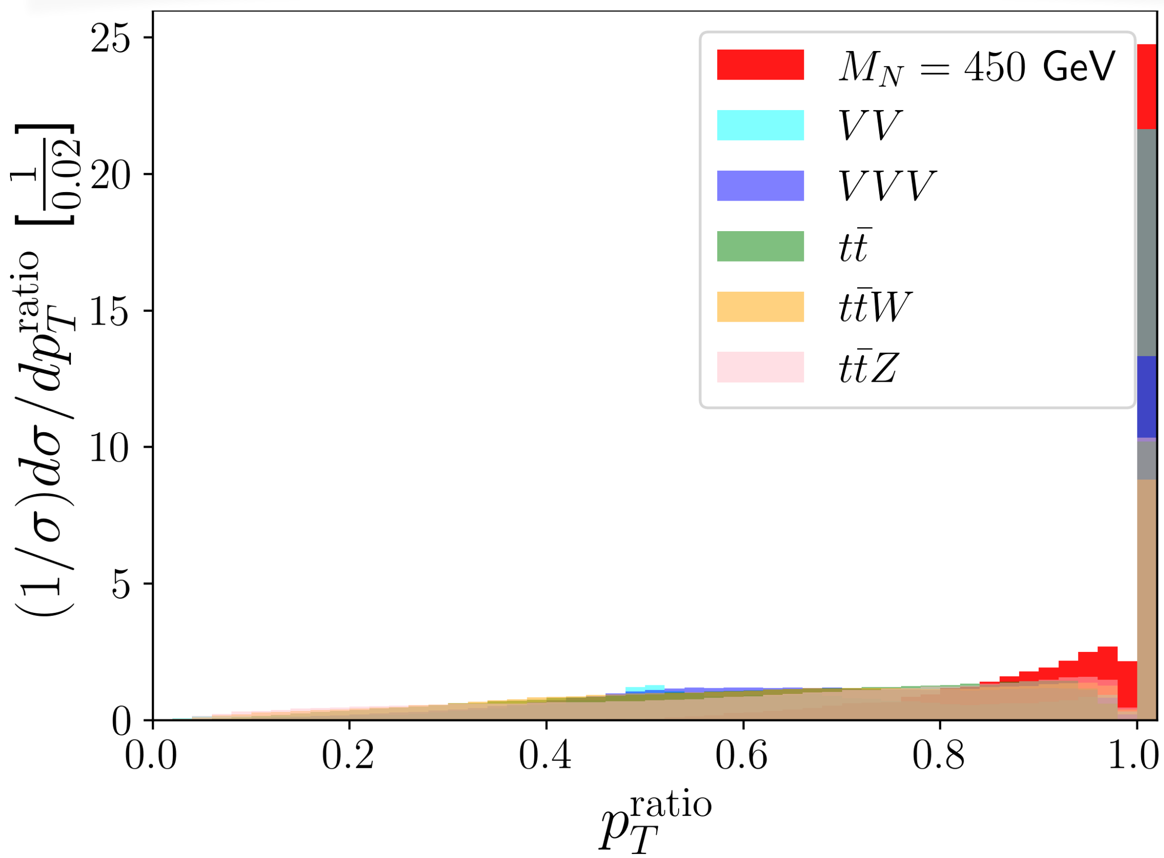
High mass region $M_N = 450\,GeV \quad C_\Lambda < C'_\Lambda$

$p_T^{ratio} = \Sigma_i p_T(e_i^\pm)/\Sigma_j p_T(l_j^\pm)$

$N(l^\pm) \geq 3,\ N(e^\pm) \geq 2$

$P_T(l_1) > 350\,GeV \quad P_T(l_2)(l_3) > 150(50)\,GeV$





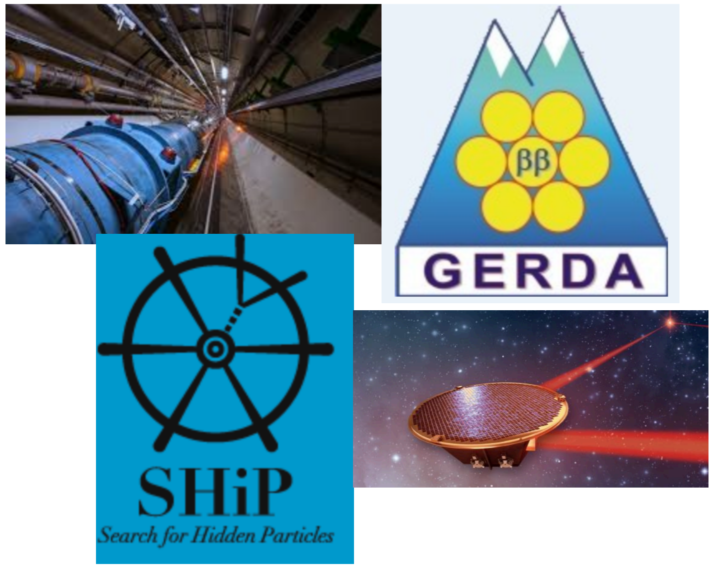
	no. bjets = 0	no. $\ell^\pm \geq 3$	$M_{\ell^\pm\ell^\mp} > 100$	$M_{3\ell} > 550$	$p_{T_{\rm ratio}} > 0.75$	$\sigma_{\rm eff}$[fb]	η_s
450 GeV ($C_\Lambda > C'_\Lambda$) [2.2 $\times 10^{-2}$ fb]	2.2 $\times 10^{-2}$	6.58 $\times 10^{-3}$	6.52 $\times 10^{-3}$	6.52 $\times 10^{-3}$	5.98 $\times 10^{-3}$	5.98 $\times 10^{-3}$	1.45
450 GeV ($C_\Lambda < C'_\Lambda$) [7.6 $\times 10^{-2}$ fb]	7.6 $\times 10^{-2}$	2.28 $\times 10^{-2}$	2.27 $\times 10^{-2}$	2.26 $\times 10^{-2}$	2.08 $\times 10^{-2}$	2.08 $\times 10^{-2}$	4.49
VV [9847 fb]	9847	2.18 $\times 10^{-1}$	9.54 $\times 10^{-2}$	7.16 $\times 10^{-2}$	4.26 $\times 10^{-2}$	4.26 $\times 10^{-2}$	
VVV [5.53 fb]	5.53	7.55 $\times 10^{-3}$	3.98 $\times 10^{-3}$	3.85 $\times 10^{-3}$	2.01 $\times 10^{-3}$	2.01 $\times 10^{-3}$	
$t\bar{t}$ [51170 fb]	11279.98	0	0	0	0	0	
$t\bar{t}W^\pm$ [13.22 fb]	2.30	5.55 $\times 10^{-4}$	4.76 $\times 10^{-4}$	4.76 $\times 10^{-4}$	1.85 $\times 10^{-4}$	1.85 $\times 10^{-4}$	
$t\bar{t}Z$ [7.26 fb]	1.31	1.23 $\times 10^{-3}$	5.52 $\times 10^{-4}$	3.92 $\times 10^{-4}$	1.89 $\times 10^{-4}$	1.89 $\times 10^{-4}$	

More than 4σ significance for a large C'_Λ

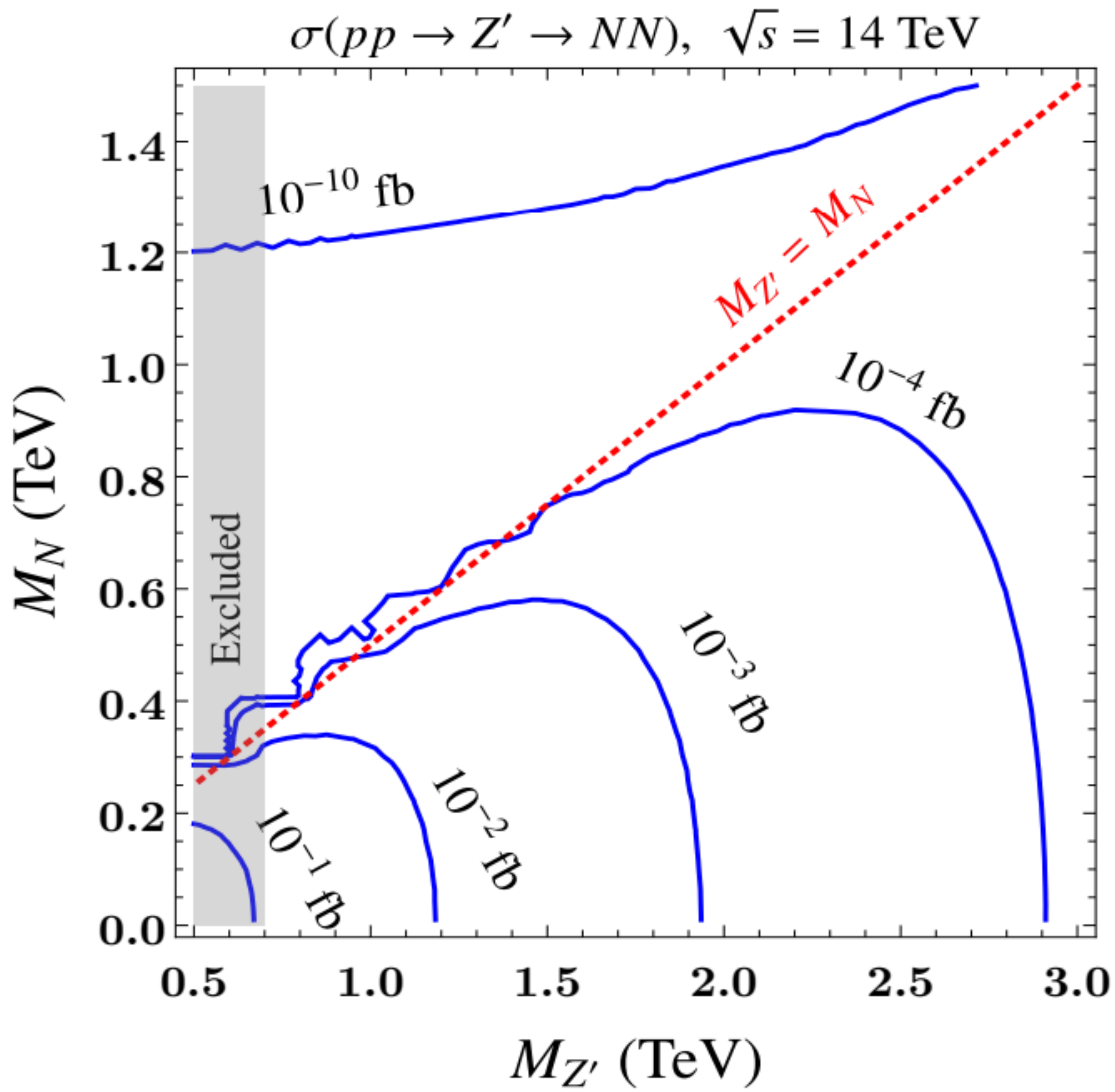
Summary

- *Low scale neutrino mass models with heavy neutral lepton offer wide detection prospects at different terrestrial experiments*
- *Non canonical signatures at collider ~ Boosted, LLP searches can probe relatively smaller masses of HNL and canonical Type-I seesaw preferred active-sterile mixing*
- *Separation of production and decay mode of HNL facilitate to achieve enhance sensitivity*
- ***NR-EFT operators such as $\mathcal{O}_{duNe}$ can enhance the HNL production cross-section.***
- ***The distributions of kinematic variables for a large Wilson coefficient of $\mathcal{O}_{duNe}$ operator is distinct from the conventional Drell-Yan topology which is investigated in LHC searches.***
- ***We propose some of the other variables $\Delta\phi_{ratio}, M_{3l}, \Delta\phi^{l}_{l^+l^-}, M_T^{l^+l^-}$ for $M_N < M_W, C_\Lambda < C'_\Lambda$, which are useful.***

Neutrino Mass Models
at
Energy, Intensity, Cosmic frontiers



Thank You

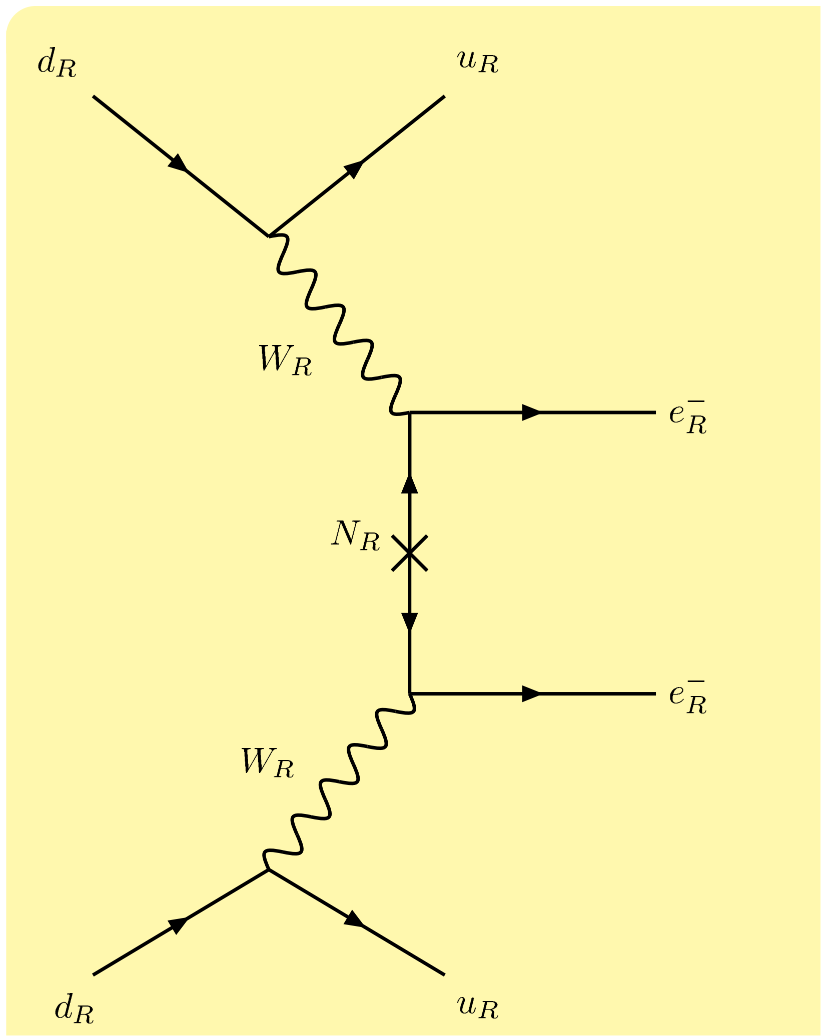


Detector Geometry		
	HL-LHC	FCC-hh
Inner detector (ID)	(2-300) mm	(25-1550) mm
Calorimeter (CAL)	(2000-4000) mm	(2700-4700) mm
Muon Spectrometer (MS)	(4000-7000) mm	(6000-9000) mm

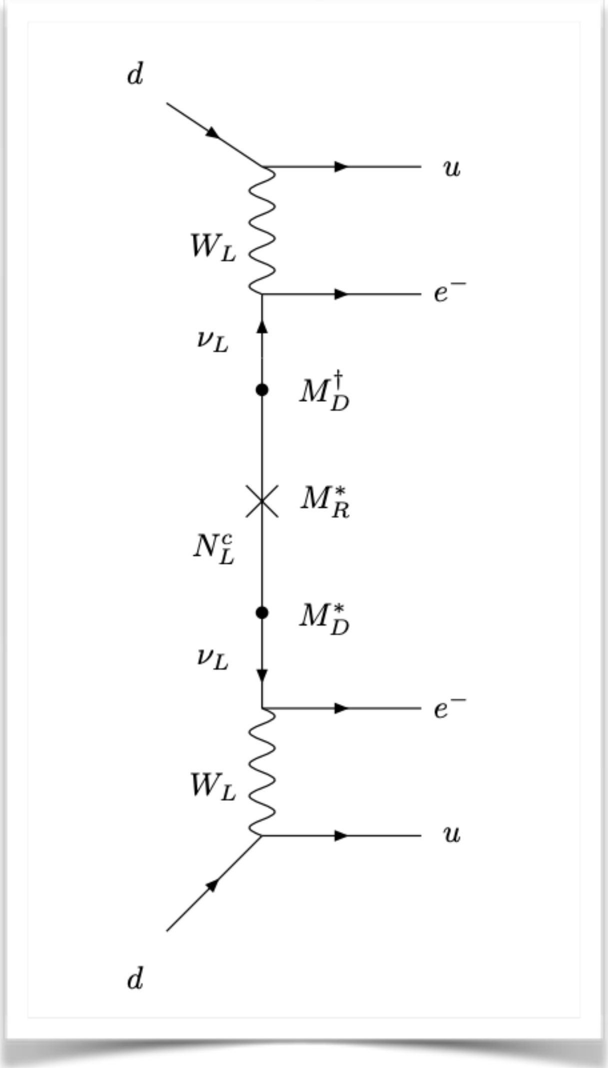
Table 1: Coverage of geometric acceptance of various sub-detectors of the HL-LHC and FCC-hh.

BSM Physics

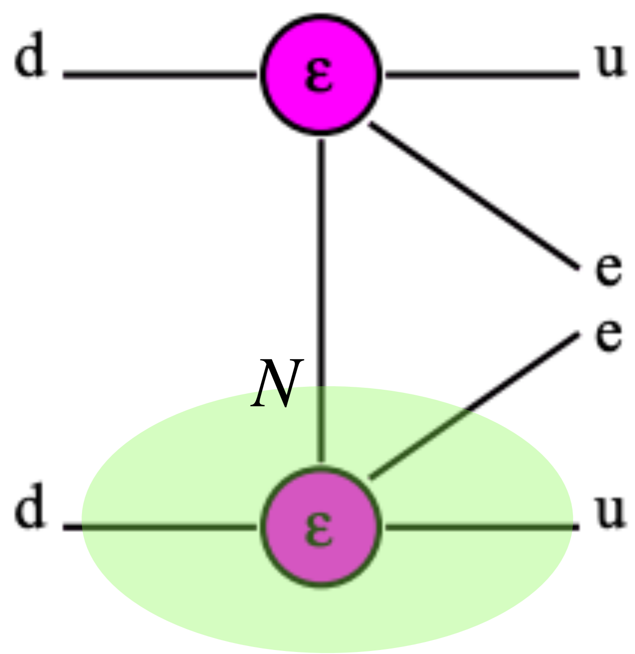
Left Right Symmetry



Lighter HNL



EFT with HNL



$$\mathcal{O}_{duNe} = \frac{\alpha}{\Lambda^2}(\bar{d}_R\gamma^\mu u_R)(\bar{e}_R\gamma_\mu N_R)$$

- Different BSM models can induce non-conventional contribution in NDBD
- Correlation with collider searches?

- *Phys.Rev.Lett.* 106 (2011) 151801
- *Nucl.Phys.B* 856 (2012) 26-73
- *JHEP* 05 (2009) 030
- *J.Phys.G* 39 (2012) 124007
- arXiv: 2212.14690
- *JHEP* 09 (2013) 153
- And many more…..

Collider signatures → lepton channels

- Like sign/ different flavor diliptons $l^{\pm}l^{\pm}/l^{\pm}l'^{\mp} + 2j$
- Trilepton channels $l^{\pm}l^{\mp}l^{\pm}$ → For Dirac neutrinos N_R
- Lepton number violating $l^{\pm}l^{\pm}$ → Proof of heavy Majorana neutrinos N_R

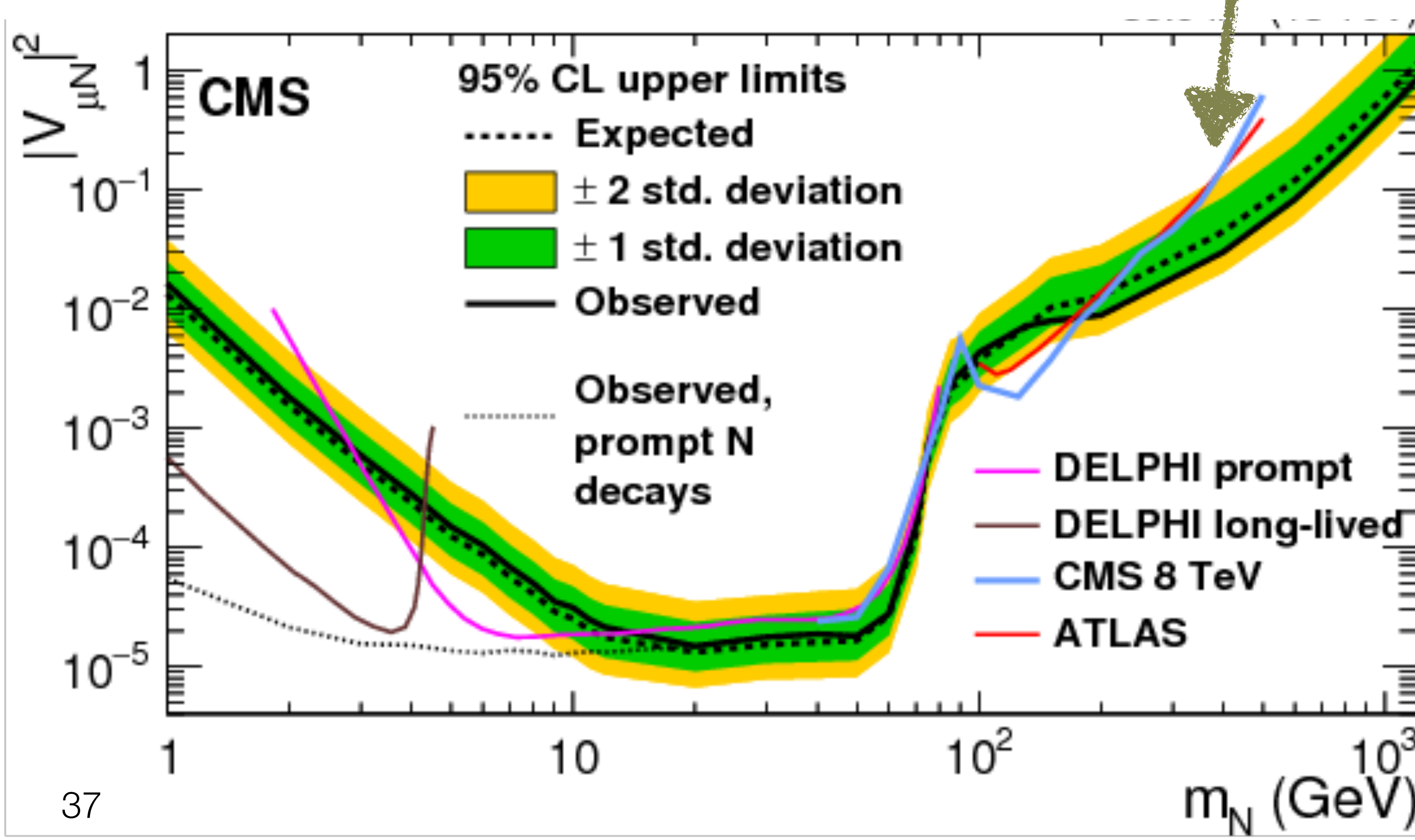
Atre et al., JHEP **0905**, 030 (2009); Aguila et al., NPB **813**, 2009; Aguila et al., 2007; Aguila et al., PLB **672**, 2009; Arhib et al., 2010, ...

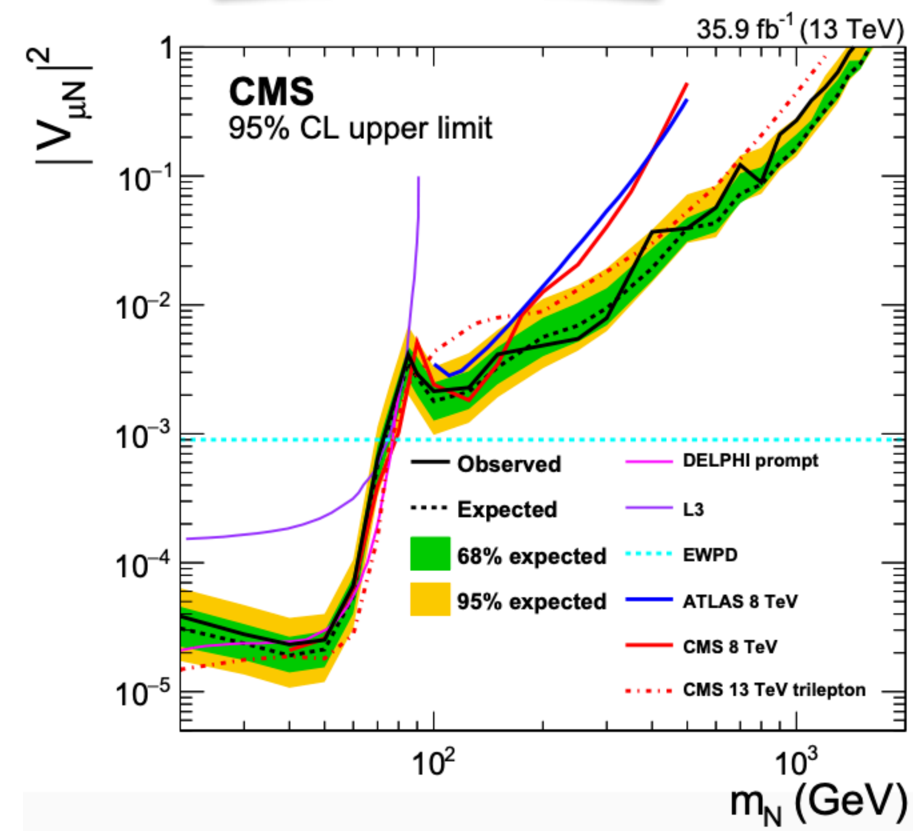
3l+X search

Low sensitivity in high mass regime

$l^{\pm}l^{\pm} + jj$

CMS collaboration, arXiv 1802.02965, ATLAS- JHEP06(2024)123



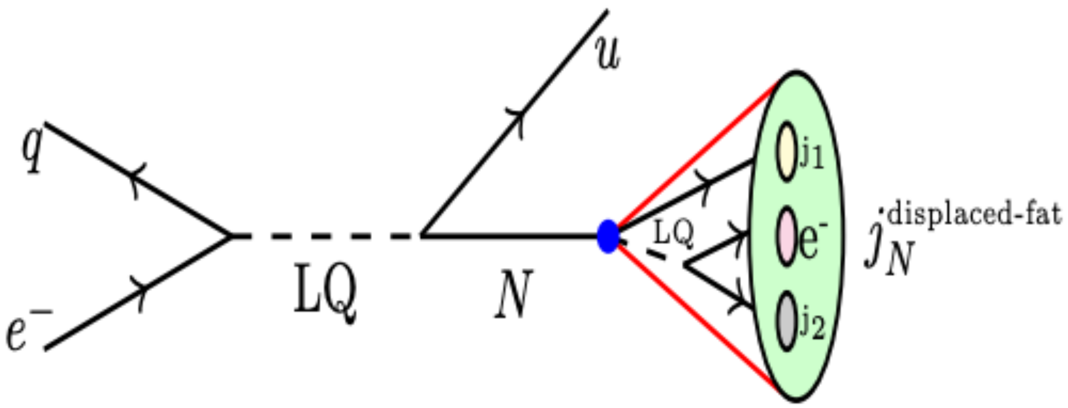


CMS collaboration, 1603.02248

CMS collaboration, *JHEP* 01 (2019) 122

Displaced decay of boosted HNL at ep collider

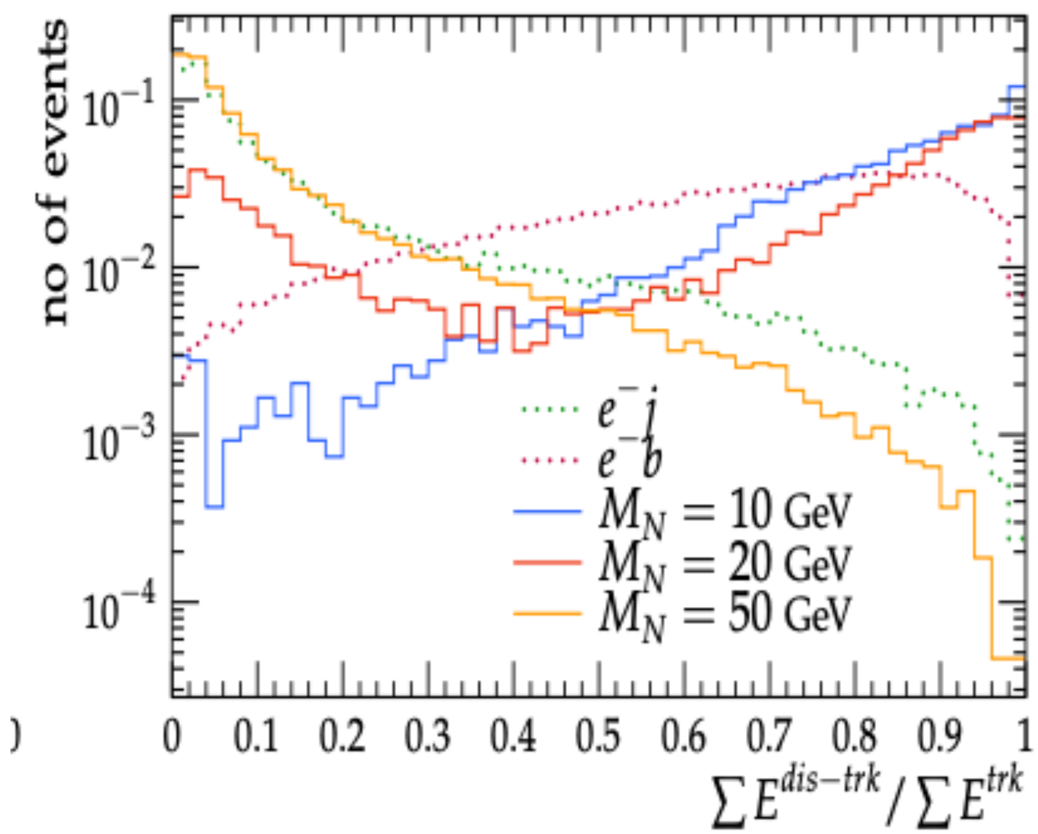
Production from a LQ, and three body decay via off-shell LQ



Displaced fat-jet signature of HNL

- Occurs when N is displaced and boosted
- Decay products are collimated
- All the decay products can not be separately identified
- Appear as a fat-jet

G. Cottin, O. Fischer, S. Mandal, M. Mitra, R. Padhan JHEP 06 (2022) 168



M_N [GeV]	n_σ	$\mathcal{L}$ [fb^{-1}]	$\mathcal{Y}^{ex}$
10	6.0 (41.5)	34.0 (0.7)	0.067 (0.035)
20	4.7 (39.7)	56.8 (0.8)	0.059 (0.017)
30	3.3 (30.4)	116.6 (1.3)	0.047 (0.013)

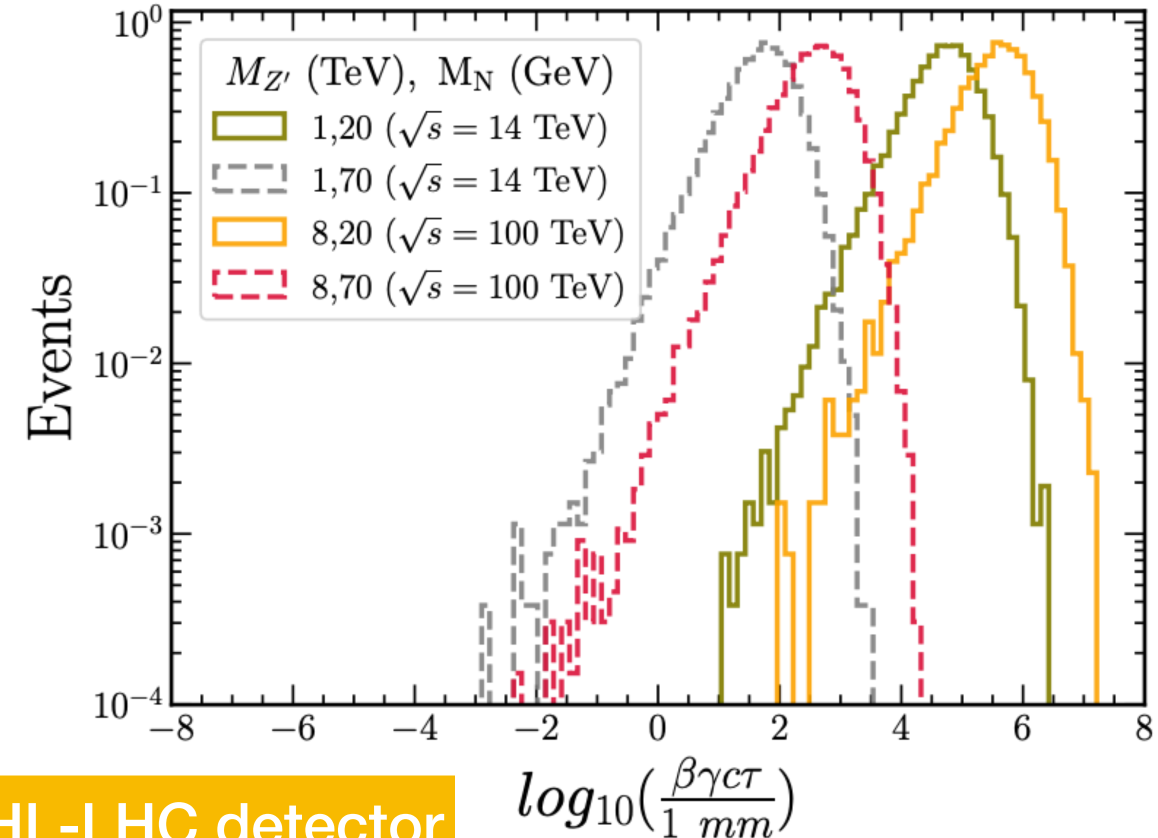
$\mathscr{L} < 100\,\text{fb}^{-1}$ can probe a leptoquark of mass 1 TeV and RHN ~ 10 GeV mass

Displaced and boosted decay of RHN

$$\Gamma(N \to l_\alpha^- u \bar{d}) = N_c |V_{ud}^{CKM}|^2 |V_\alpha|^2 \frac{G_F^2 M_N^5}{192\pi^3} \mathcal{I}(x_u, x_d, x_l)$$

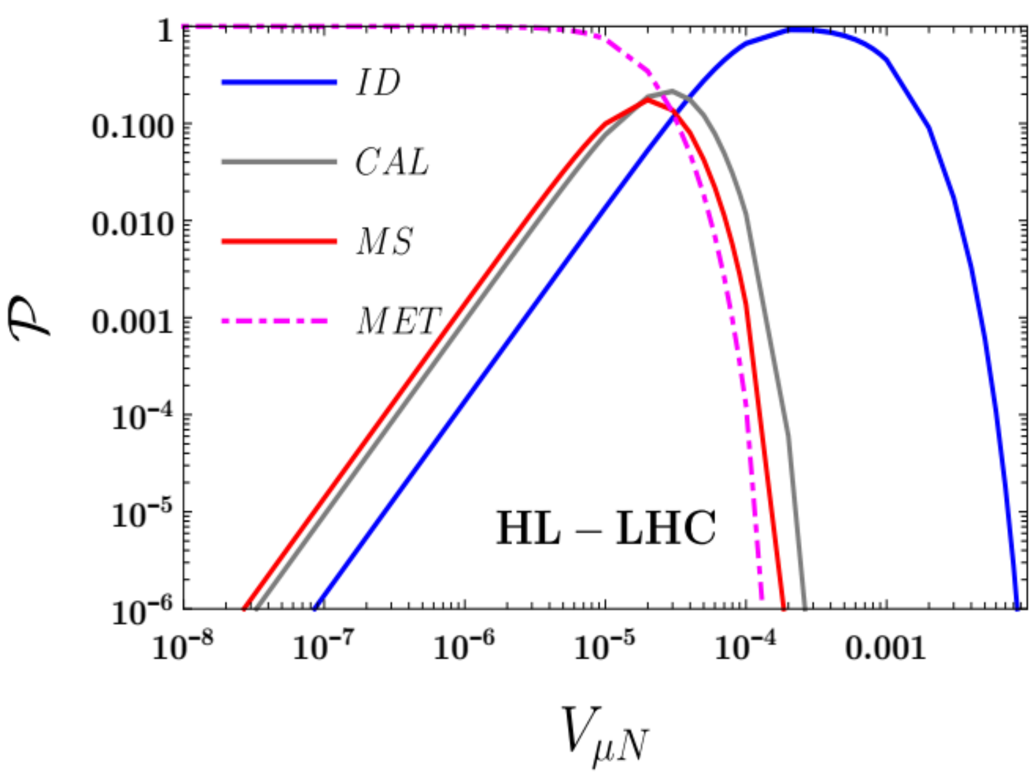
$$\Gamma(N \to l_\alpha^- \nu_\beta l_\beta^+) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{192\pi^3} \mathcal{I}(x_{l_\alpha}, x_{l_\beta}, x_{\nu_\beta})$$

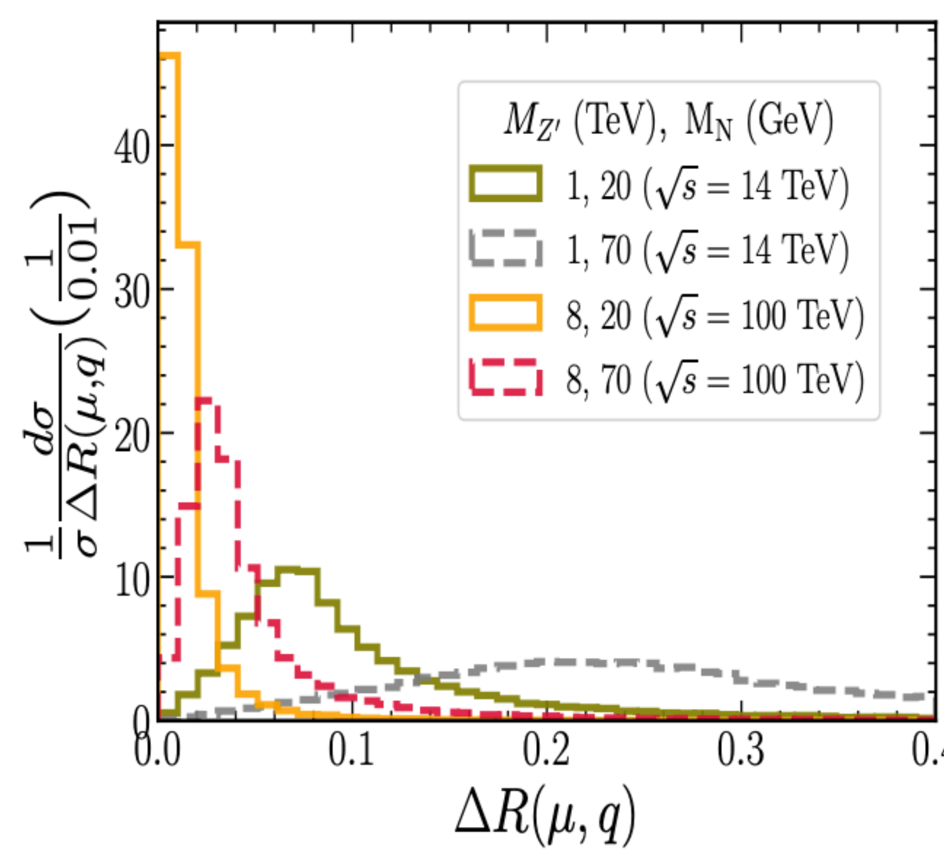
$$\Gamma(N \to \nu\nu\nu) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{96\pi^3}$$



Probability of RHN to decay at different parts of the HL-LHC detector

$$\mathcal{P}(L_1, L_2, \sqrt{s}, M_N, M_{Z'}, \theta) = \int db_1 db_2\ f(\sqrt{s}, M_N, M_{Z'}, b_1, b_2) \prod_{i=1}^{2} \left[e^{\frac{-L_1}{b_i c\tau(\theta)}} - e^{\frac{-L_2}{b_i c\tau(\theta)}} \right]$$

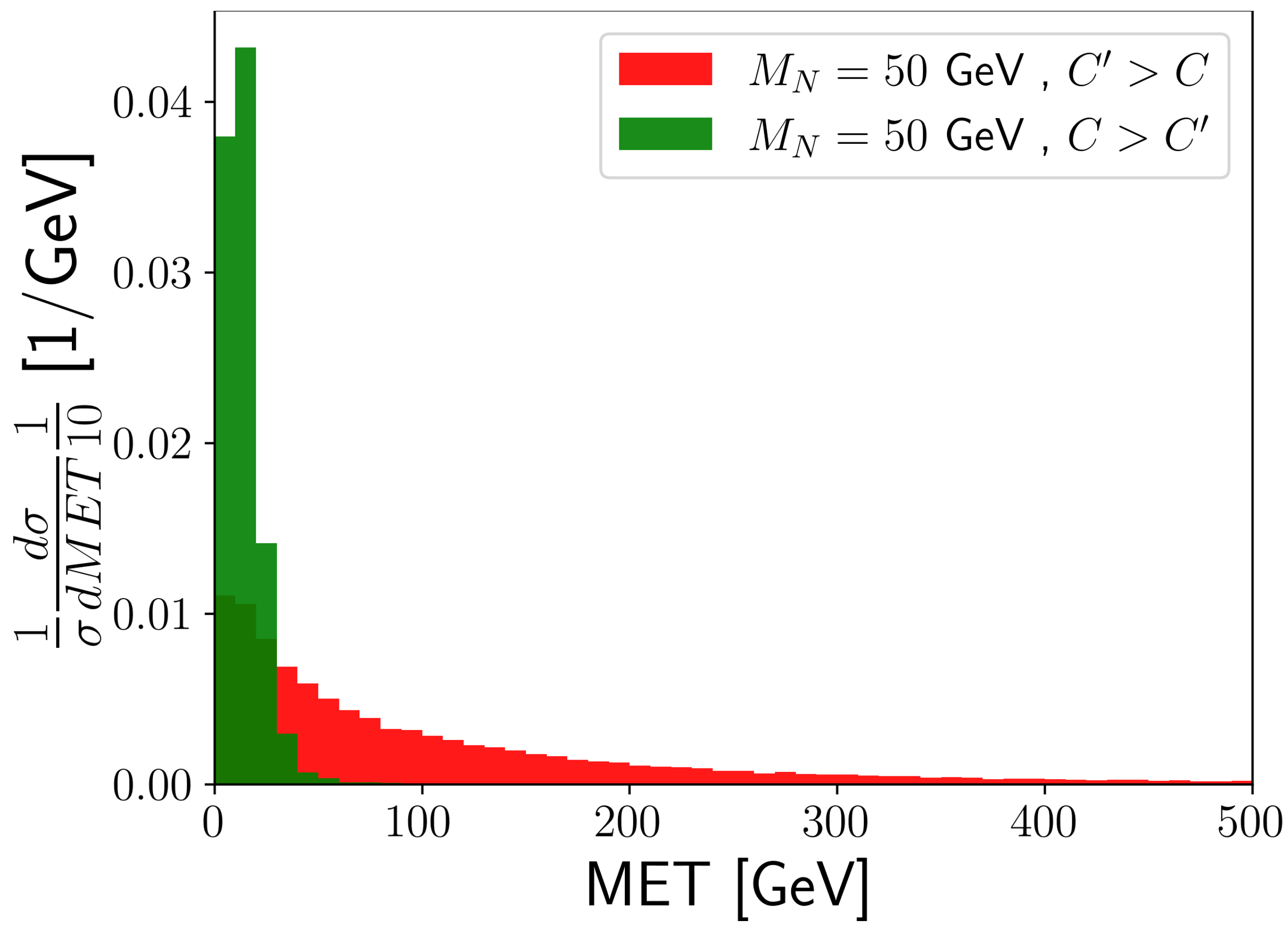




Effect of selection cuts

Low mass region

$M_N = 50\,GeV \quad C_\Lambda < C'_\Lambda$



	no. bjets = 0	no. $\ell^\pm = 3$	$M_{3\ell} < 80$ GeV	$\lvert M_{\ell^\pm\ell^\mp} - M_Z\rvert > 15$ GeV	$p_T^{miss} < 75$ GeV	σ_{eff}[fb]	η_s
50 GeV($C_\Lambda > C'_\Lambda$) [6.59 fb]	6.59	1.34	1.30	1.30	1.29	1.29	26.86
50 GeV($C_\Lambda < C'_\Lambda$) [2.25 $\times 10^{-2}$ fb]	2.24 $\times 10^{-2}$ [a]	3.94 $\times 10^{-3}$	9.93 $\times 10^{-5}$	9.93 $\times 10^{-5}$	9.89 $\times 10^{-5}$	9.89 $\times 10^{-5}$	2.23$\times 10^{-3}$
VV [9847 fb]	9847	277.29	2.19	1.70	1.22	1.22	
VVV [5.53 fb]	5.53	1.22	5.74 $\times 10^{-2}$	4.29 $\times 10^{-2}$	2.76 $\times 10^{-2}$	2.76 $\times 10^{-2}$	
$t\bar{t}$ [51170 fb]	11289.56	92.18	11.57	8.72	4.35	4.35	
$t\bar{t}W^\pm$ [13.22 fb]	2.29	4.83 $\times 10^{-1}$	3.16 $\times 10^{-2}$	2.31 $\times 10^{-2}$	9.26 $\times 10^{-3}$	9.26 $\times 10^{-3}$	
$t\bar{t}Z$ [7.26 fb]	1.31	3.99 $\times 10^{-1}$	8.67 $\times 10^{-3}$	6.66 $\times 10^{-3}$	2.87 $\times 10^{-3}$	2.87 $\times 10^{-3}$	

Following arXiv 1802.02965 (*PRL*120 (2018) 22, 221801)

$P_T^{miss} < 75\,GeV$ is not most optimal for this scenario

Effect of selection cuts

High mass region

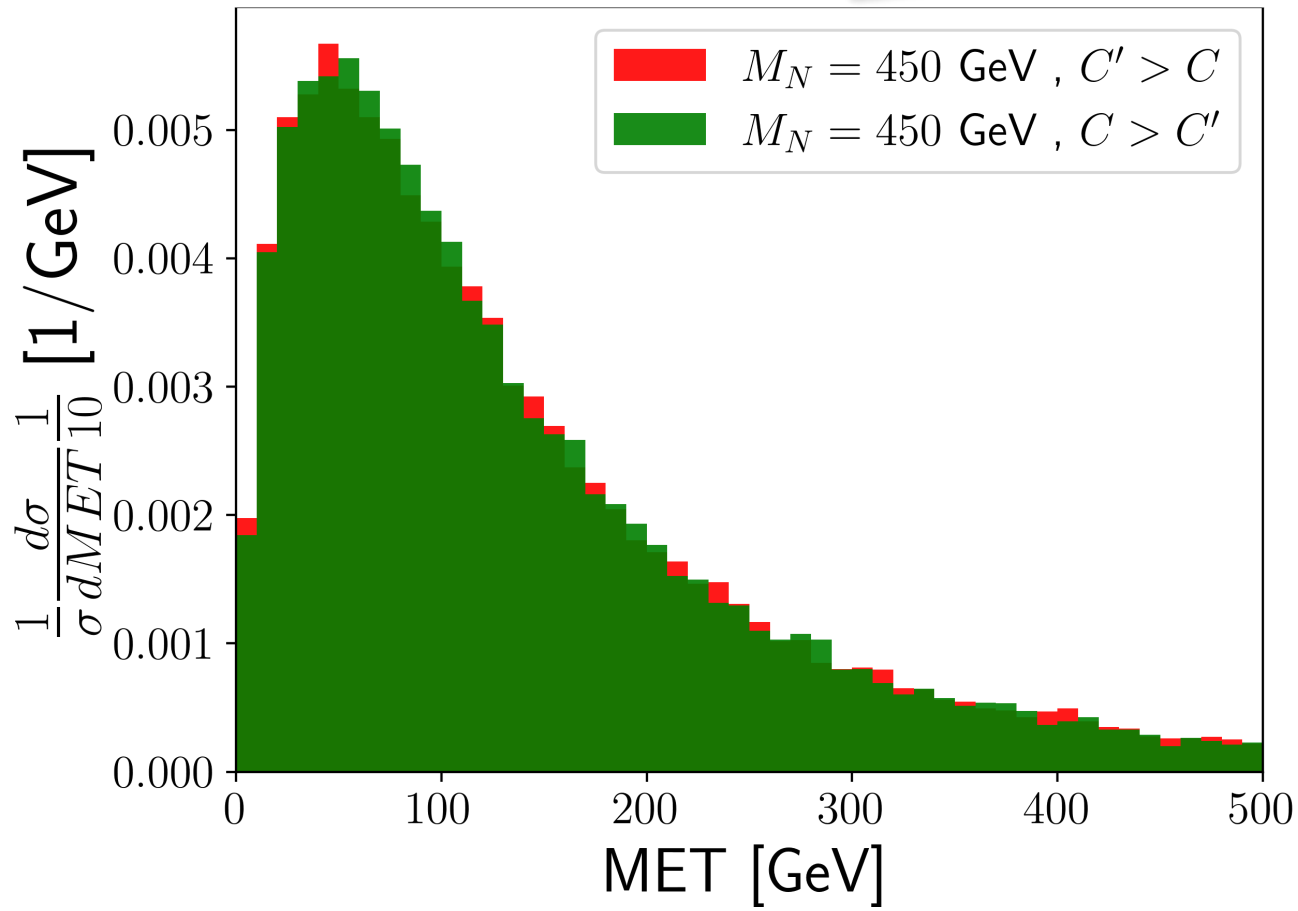
$M_N = 450\,GeV$

	no. bjets = 0	no. $\ell^{\pm} = 3$	$\lvert M_{\ell^{\pm}\ell^{\mp}} - M_Z \rvert > 15$ GeV	$p_T^{\rm miss} > 50$ GeV	$\sigma_{\rm eff}$[fb]	η_s
450 GeV($C_\Lambda > C'_\Lambda$) [2.2 $\times 10^{-2}$ fb]	2.2 $\times 10^{-2}$	1.17 $\times 10^{-2}$	1.15 $\times 10^{-2}$	8.96 $\times 10^{-3}$	8.96 $\times 10^{-3}$	5.7 $\times 10^{-2}$
450 GeV($C_\Lambda < C'_\Lambda$) [7.6 $\times 10^{-2}$ fb]	7.6 $\times 10^{-2}$	4.02 $\times 10^{-2}$	3.96 $\times 10^{-2}$	3.08 $\times 10^{-2}$	3.08 $\times 10^{-2}$	1.96 $\times 10^{-1}$
VV [9847 fb]	9847	202.31	115.07	50.95	50.95	
VVV [5.53 fb]	5.53	9.27 $\times 10^{-1}$	5.53 $\times 10^{-1}$	3.84 $\times 10^{-1}$	3.84 $\times 10^{-1}$	
$t\bar{t}$ [51170 fb]	11289.56	55.94	31.43	21.66	21.66	
$t\bar{t}W^{\pm}$ [13.22 fb]	2.29	3.85 $\times 10^{-1}$	2.29 $\times 10^{-1}$	1.79 $\times 10^{-1}$	1.79 $\times 10^{-1}$	
$t\bar{t}Z$ [7.26 fb]	1.31	3.50 $\times 10^{-1}$	1.79 $\times 10^{-1}$	1.41 $\times 10^{-1}$	1.41 $\times 10^{-1}$	

Following arXiv 1802.02965 (*PRL*120 (2018) 22, 221801)

Relevant kinematic variables

$C_\Lambda < C'_\Lambda$



Outline of the talk:

Origin of Neutrino Masses, Mixings and Discovery Prospects

Focussing on a subset

Heavy Neutral Lepton

- ***Collider searches (and non-collider searches)***

Broad spectra of neutrino mass models:

Neutrino Mass Models, UV completed and renormalisable models

Based on SM gauge group and extended particle content

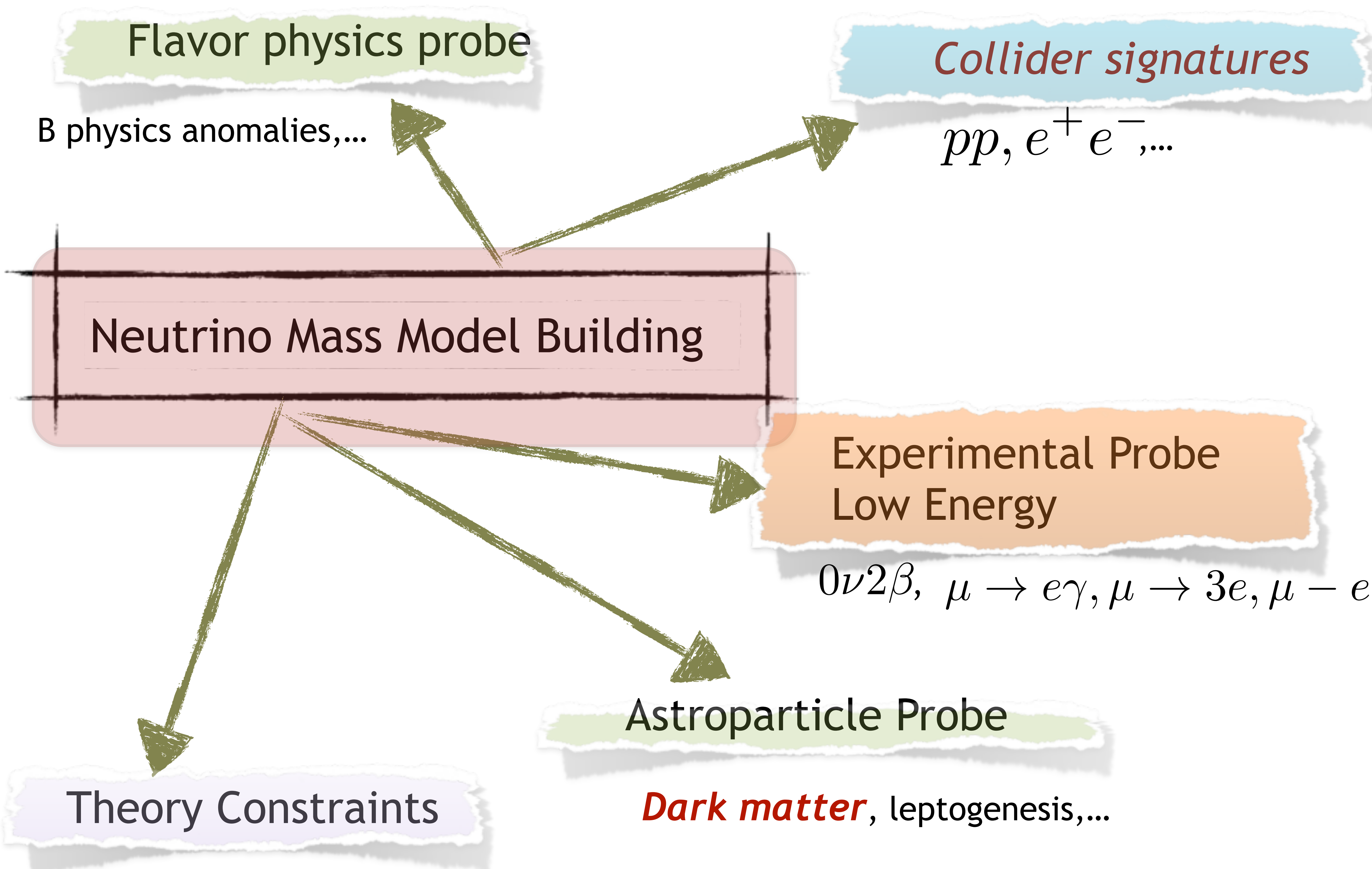
Extended symmetry and particle content

- Majorana or Dirac mass of light neutrinos
- Tree level or loop level mass generation
- Up to 3 loop realisation in the literature

Recent reviews

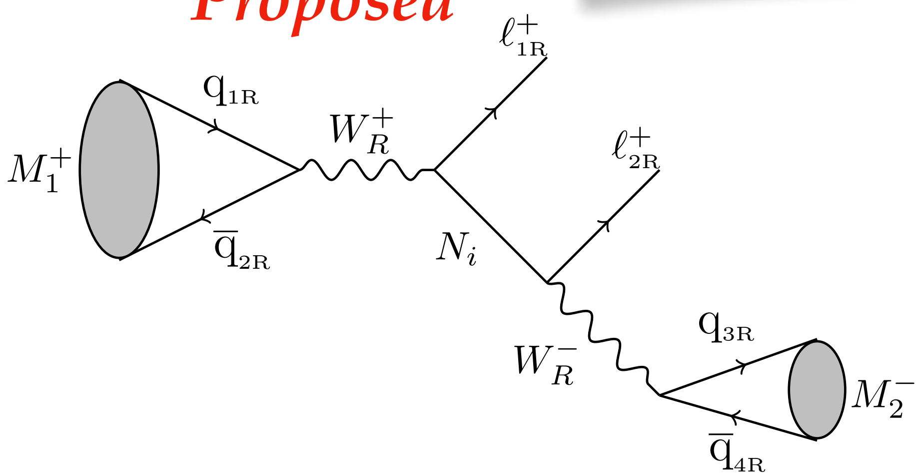
- Carolina Arbeláez *et al., JHEP* 08 (2022) 023
- Y. Cai et al., Front.in Phys. 5 (2017) 63
- Phys. Rev. D 101, 075032 (2020)
- A. Vicente et al., arXiv:2005.00015

Experimental probe:



Lepton Number Violating Meson Decays

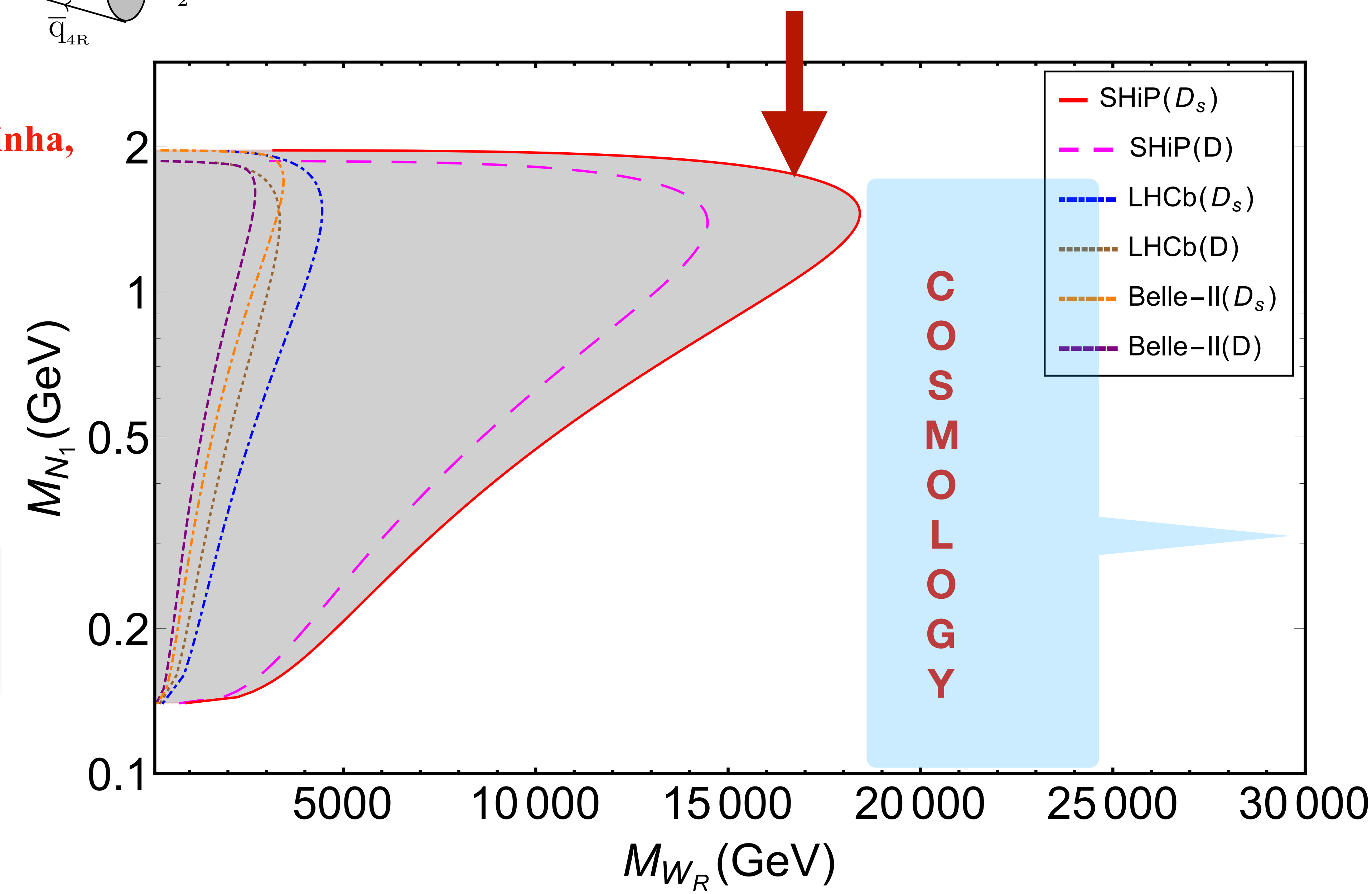
Proposed



$$M^+ \to e^+ e^+ \pi^-$$

Sensitive to Sub-GeV Neutrino

Sensitive to a very high mass WR



S. Mandal, M. Mitra, N. Sinha, PRD 96 (2017) 3, 035023

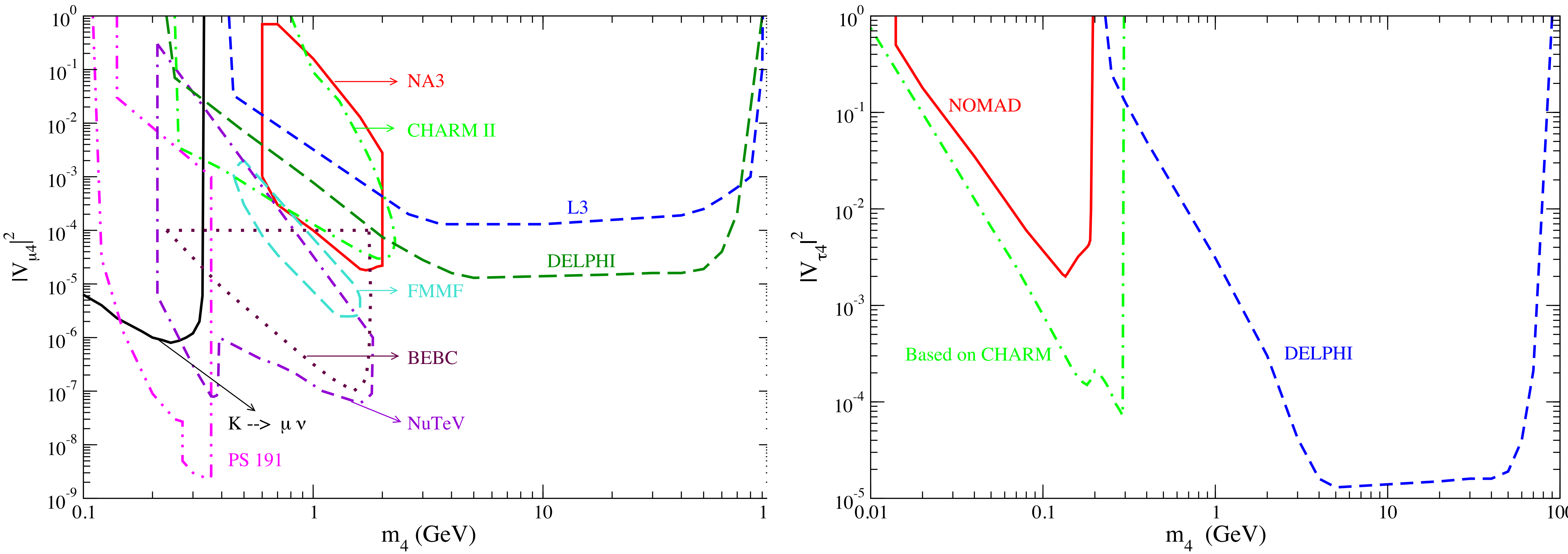
- **M. Mitra et al., *Phys.Rev.D* 100 (2019) 9, 095022, *Phys.Rev.D* 104 (2021) 9, 095009**

LFV processes?

$\mu \to e\gamma, \mu \to 3e$ and others

LHC search and LNV meson decays are complimentary probes

Contd:

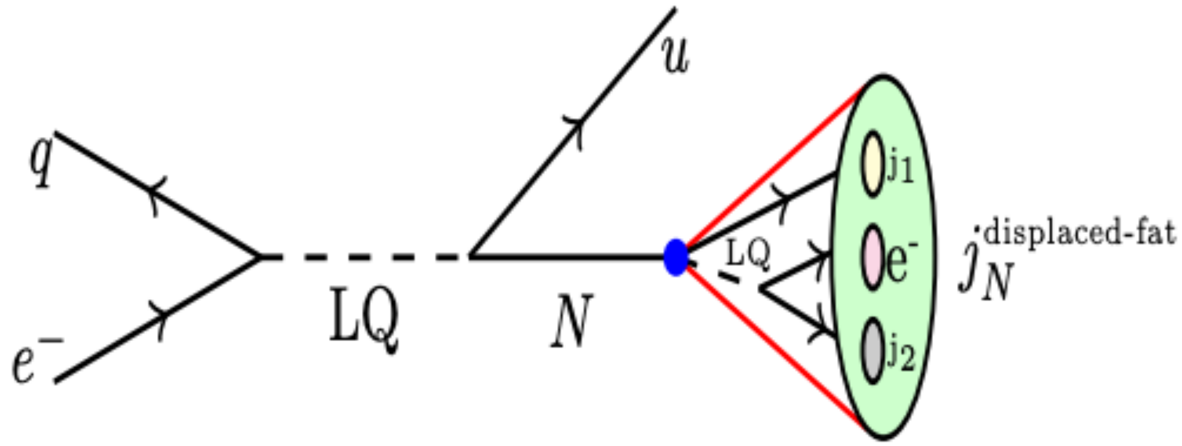


Atre et al., JHEP **0905**, 030 (2009)

- Severe constraint from light neutrino mass $\rightarrow$ possible to escape in presence of cancellation in neutrino mass matrix $M_\nu = M_D^T M_R^{-1} M_D$ or enhanced global symmetry.
- V_{eN} is tightly constrained from $(\beta\beta)_{0\nu}$-decay upto TeV scale
- The muon and tau sector are less constrained $\rightarrow$ collider prospect

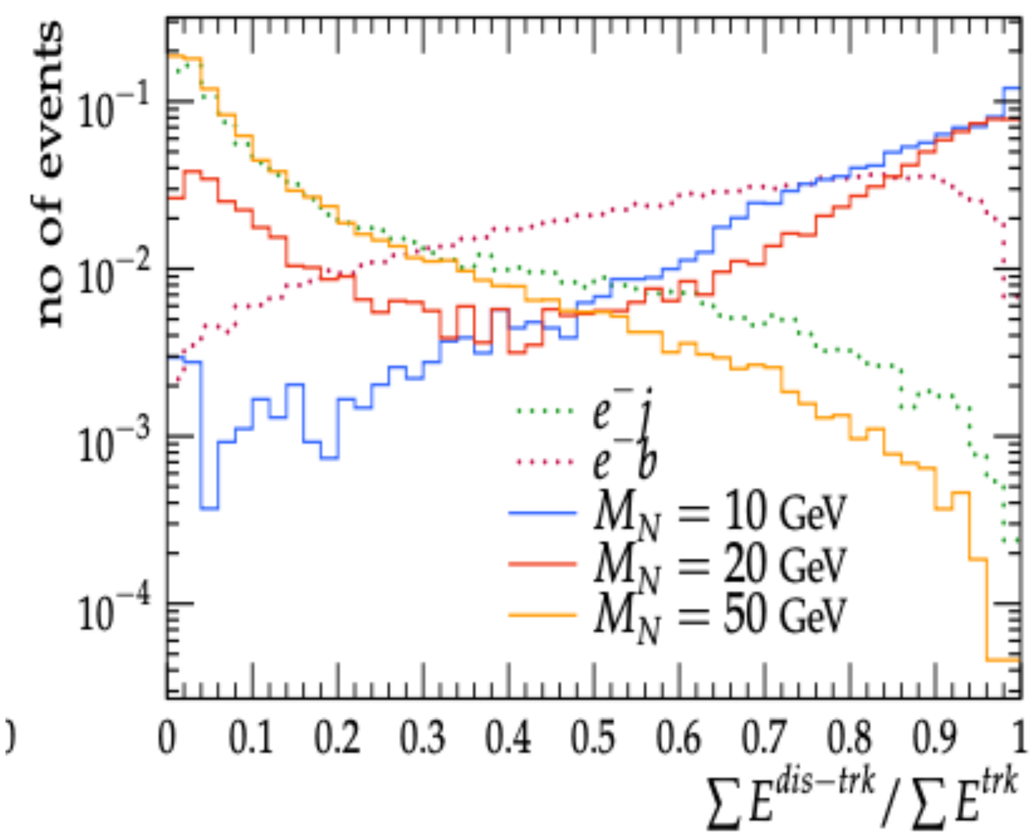
Displaced and boosted decay of RHN

Another important probe of RHN is displaced fat-jet signature



- Occurs when N is boosted
- Decay products are collimated
- All the decay products can not be separately identified
- Appear as a fat-jet

For a leptoquark model with RHN



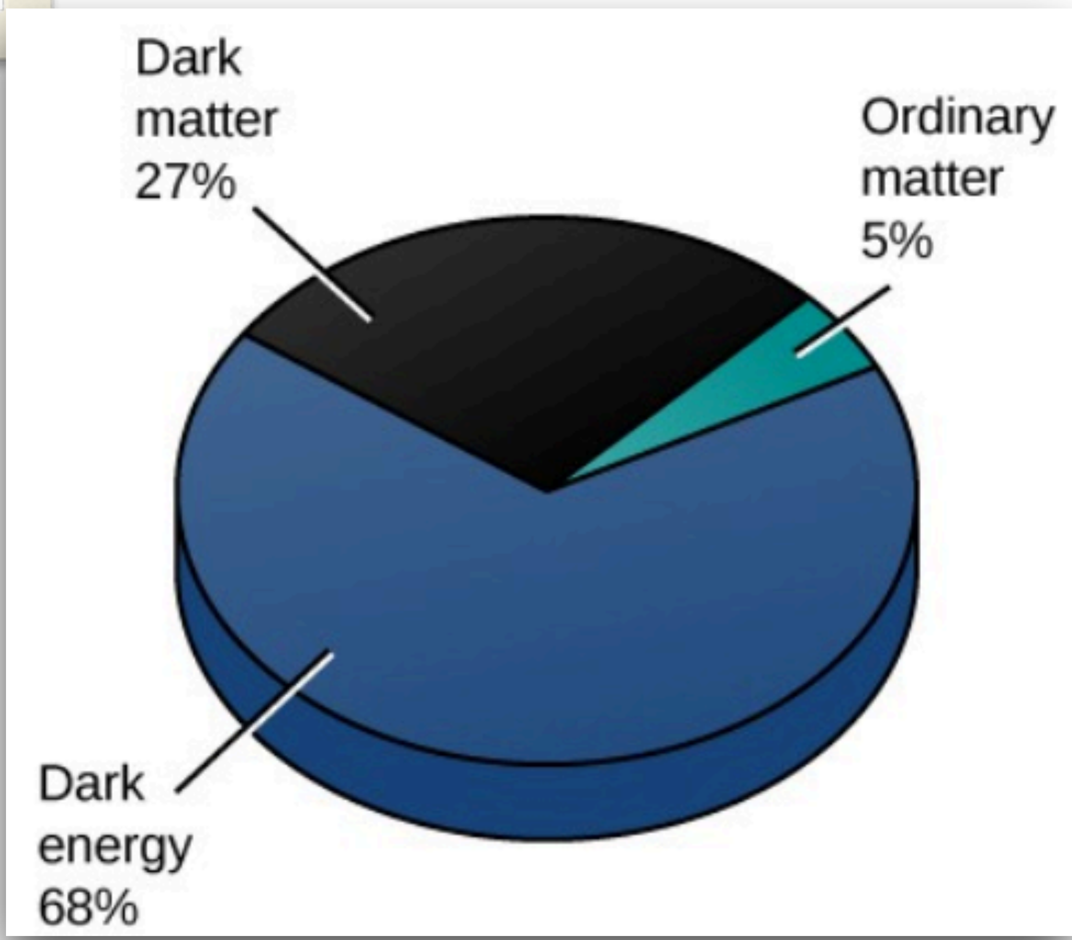
G. Cottin, O. Fischer, S. Mandal, M. Mitra, R. Padhan
JHEP 06 (2022) 168

M_N [GeV]	n_σ	$\mathcal{L}$ [fb^{-1}]	$\mathcal{Y}^{ex}$
10	6.0 (41.5)	34.0 (0.7)	0.067 (0.035)
20	4.7 (39.7)	56.8 (0.8)	0.059 (0.017)
30	3.3 (30.4)	116.6 (1.3)	0.047 (0.013)

can probe a leptoquark of mass 1 TeV and RHN ~ 10 GeV mass

Major Questions in Modern Particle Physics ?

Dark Matter?



Relic density

$$\Omega h^2 = 0.1186 \pm 0.0020$$

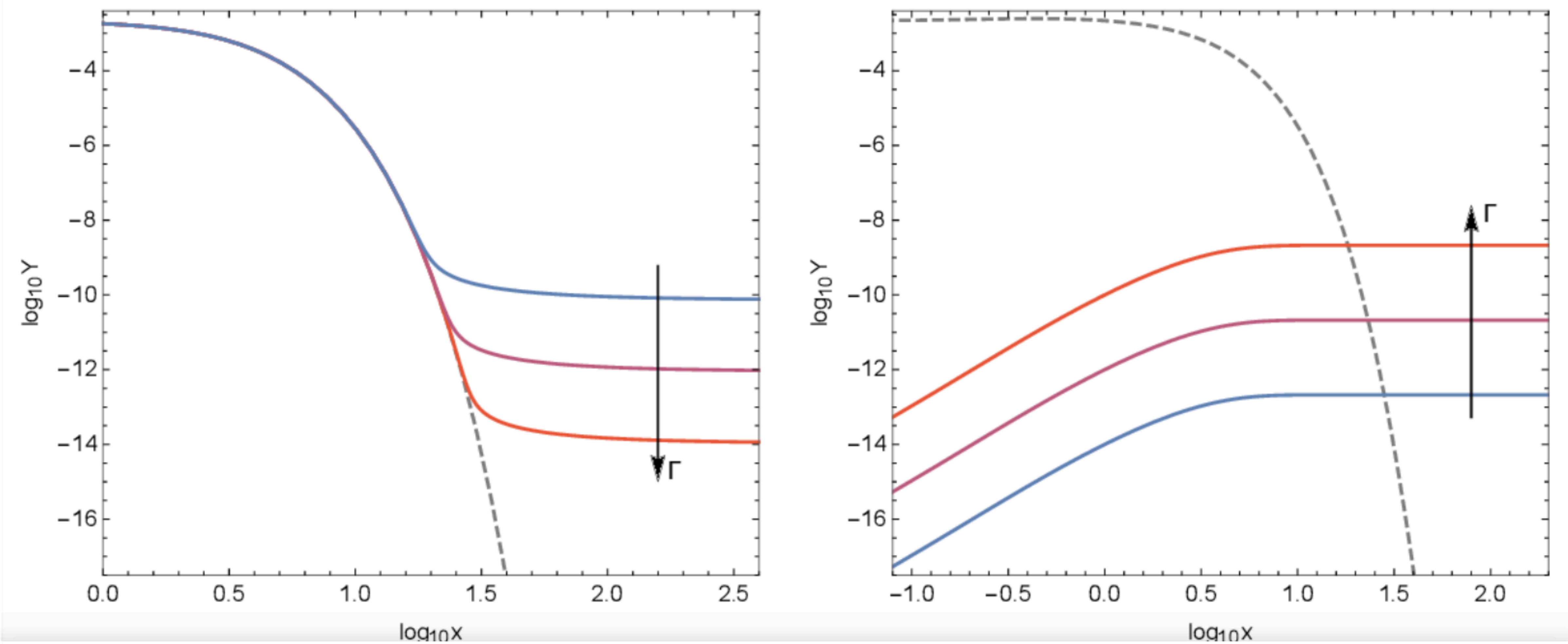
- Weakly interacting massive particle
- Feebly interacting massive particle
- Other production mechanisms, such as conversion driven freeze out

Theoretical description

Testing BSM descriptions in experiments

DarkMatter Production

- Weakly interacting massive particle
- Feebly interacting massive particle



- **HNL as a FIMP**

N is produced from decay or annihilation of thermal bath particles

- **HNL as a WIMP**

N N -> SM SM, BSM BSM generates the relic abundance

- **HNL as a NLOP and a SuperWimp**

Late decay of N into DM + X contributes significantly to DM relic abundance

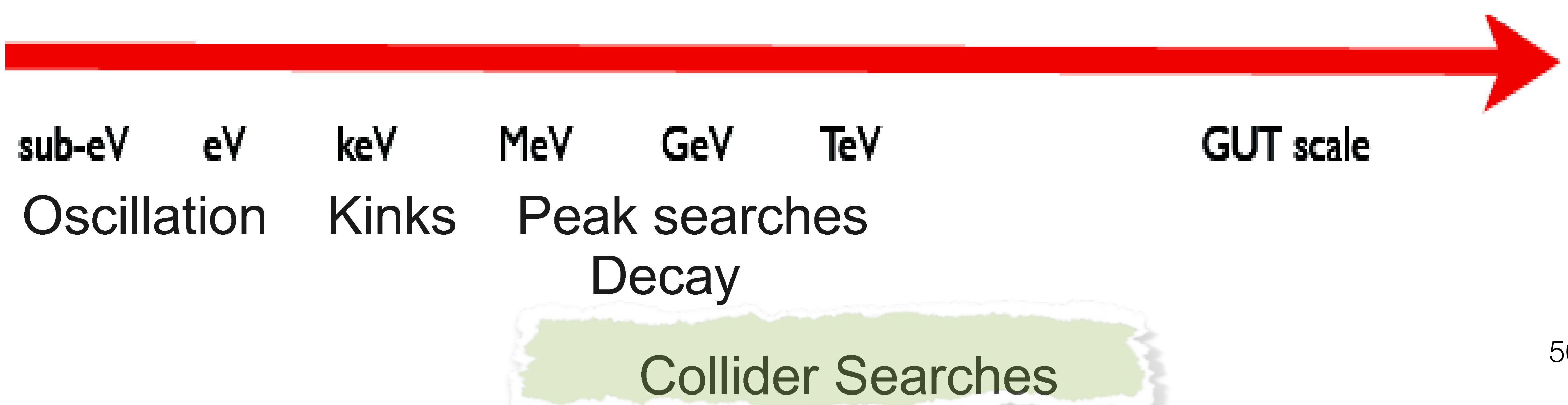
Heavy Neutral Lepton:

Heavy Neutrino N

Key ingredients behind neutrino mass generation

Heavy neutrino mass $M \sim$ eV- GUT scale

- Detection $\rightarrow$ Collider, Oscillation, Peak searches, Kink, $(\beta\beta)_{0\nu}$-decay,...
- And $\rightarrow$ LFV processes, Non-unitary effect,...



Babu-Nandi-Tavartkiladze (BNT) Model

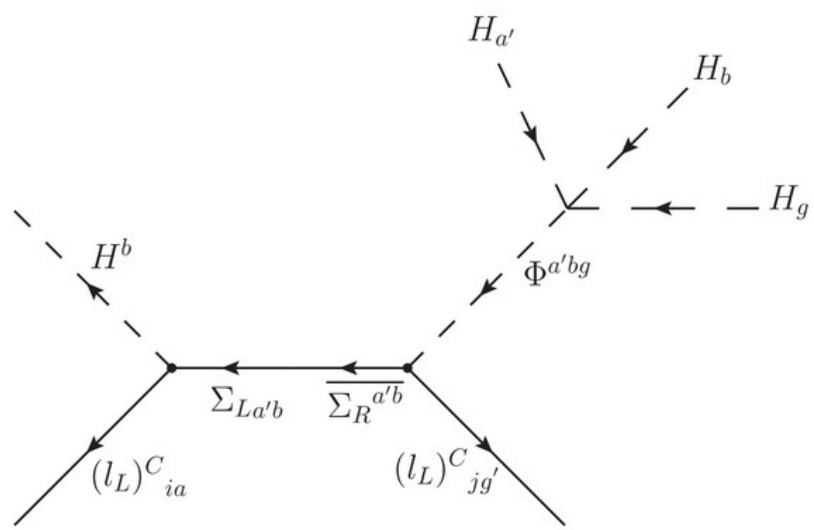
Scalar isospin 3/2 quadruplet (Φ)

$$\Phi = \left(\Phi^{+++} \quad \Phi^{++} \quad \Phi^{+} \quad \Phi^{0} \right)_{Y=3}$$

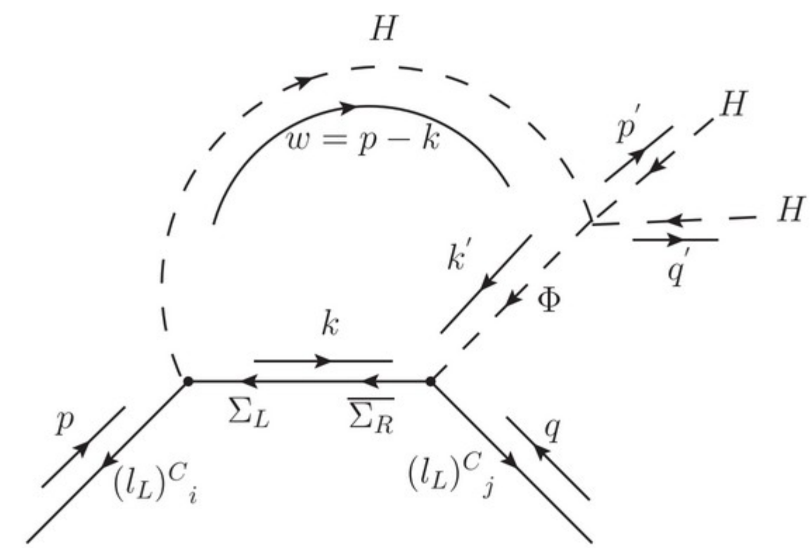
Vecor like triplet (Σ)

$$\Sigma_{R,L} = \left(\Sigma^{++}_{R,L} \quad \Sigma^{+}_{R,L} \quad \Sigma^{0}_{R,L} \right)_{Y=2}$$

Tree level (d=7)



1-loop level (d=5)



$$V = \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger \Phi)^2$$
$$+ \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi)$$
$$+ \{\lambda_5 H^3 \Phi^* + \text{H.c.}\},$$

$$(m_\nu)_{ij} = -\frac{\lambda_5 (Y_i Y_j' + Y_i' Y_j) v^4}{(M_\Sigma M_{\Phi^0}^2)}$$

Rich Phenomenology with **"Multi-lepton"** final states

$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$

$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

3ℓ, 4ℓ, 5ℓ and 6ℓ events

Same-sign-tri-lepton events

Lepton flavour violating (LFV) 4 lepton events

Small v_Φ

K. S. Babu, S. Nandi, and Zurab Tavartkiladze, PRD (Rap Comm) 80, 071702(R) (2009)

Loop Generated Dirac Neutrino Mass (Gauge extension)

An alternate version of Left-Right extension:

S.P.Maharathy, M. Mitra, A. Sarkar, *Eur.Phys.J.C* 83 (2023) 6, 480

Ernest Ma et al., Phys. Lett. B764 (2017) 142–144

Multiplets	$SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$
Φ_L	$(1,1,2,1)$
Φ_R	$(1,2,1,1)$
ζ_L	$(1,1,2,3)$
ζ_R	$(1,2,1,3)$
χ^+	$(1,1,1,2)$

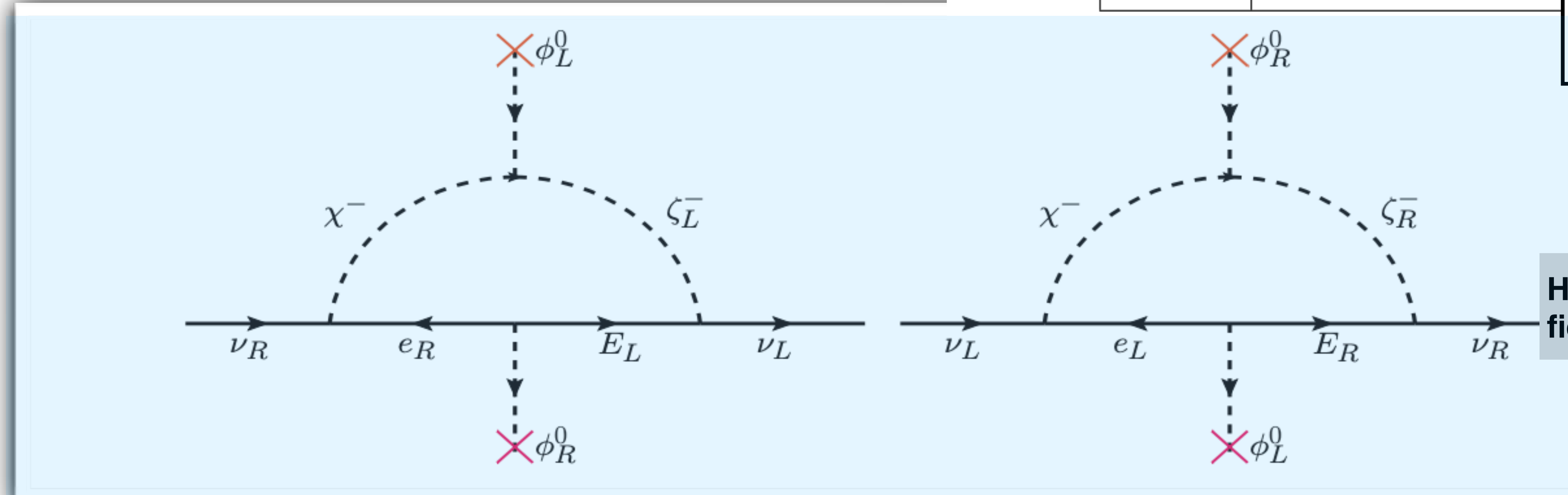
$$\zeta_L = \begin{bmatrix} \zeta_L^{++} \\ \zeta_L^{+} \end{bmatrix}, \quad \zeta_R = \begin{bmatrix} \zeta_R^{++} \\ \zeta_R^{+} \end{bmatrix}, \quad \chi^{\pm}$$

Contains two doublets with B-L=3

Multiplets	$SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$
Quarks	$Q_L^i(3,1,2,\frac{1}{3}) = \begin{bmatrix} u_L^i \\ d_L^i \end{bmatrix}$ $Q_R^i(3,2,1,\frac{1}{3}) = \begin{bmatrix} u_R^i \\ d_R^i \end{bmatrix}$ $U_{L,R}^i(3,1,1,\frac{4}{3})$ $D_{L,R}^i(3,1,1,\frac{-2}{3})$
Leptons	$L_{Li}(1,1,2,-1) = \begin{bmatrix} \nu_{L_i} \\ e_{L_i} \end{bmatrix}$ $L_{Ri}(1,2,1,-1) = \begin{bmatrix} \nu_{R_i} \\ e_{R_i} \end{bmatrix}$ $E_{L,R_i}(1,1,1,-2)$

$$U_{L,R}^i, \quad D_{L,R}^i, \quad E_{L,R}^i$$

Heavy fermionic fields



Dirac Neutrino Mass

Classic way to generate Dirac mass of light neutrino

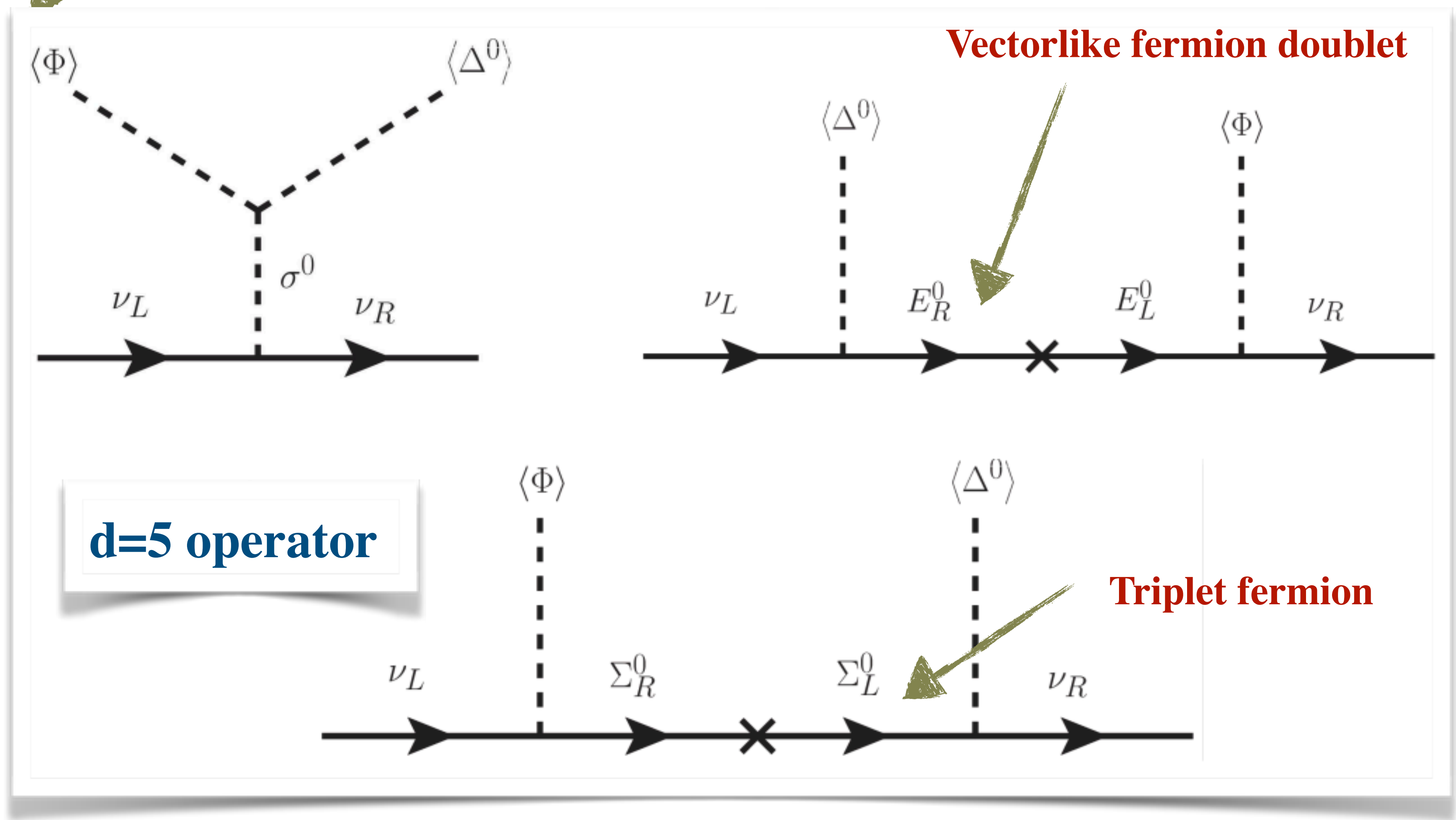
$\mathscr{L} = y\bar{L}\phi N_R$

$\mathscr{L}_m \sim M_D \bar{\nu}_L N_R$

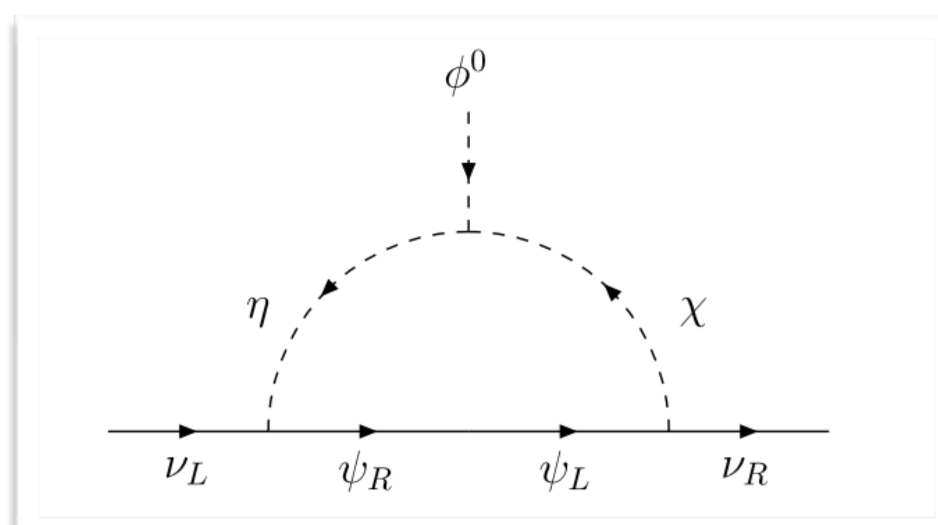
$m_\nu = yv$

eV mass of light neutrino require $y \sim \mathcal{O}(10^{-12})$

eV Dirac neutrino mass can instead be generated radiatively, or via symmetry breaking with BSM Higgs



S.S.Chulia et al., PLB ‘18



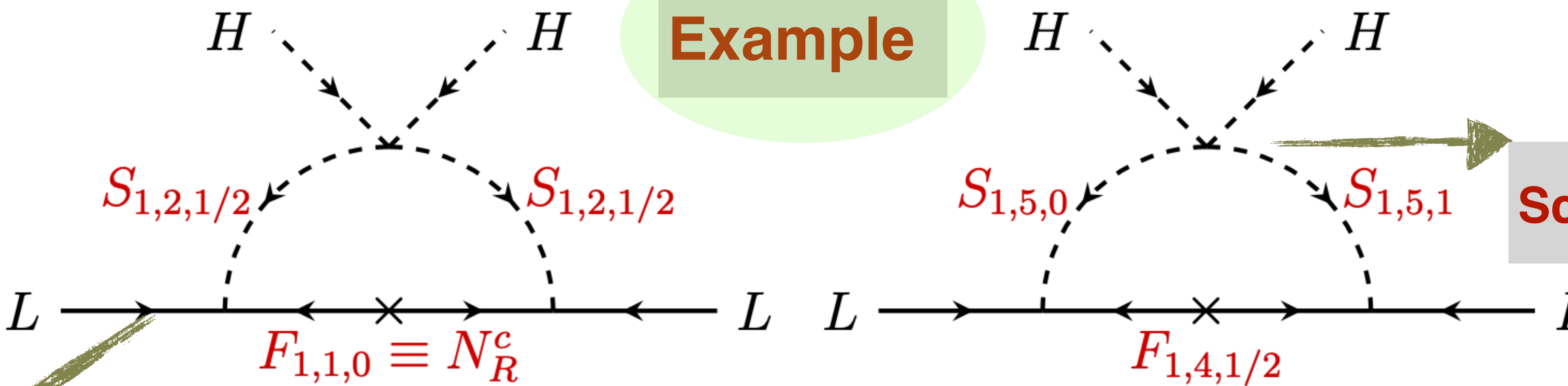
Alternate option is via loop

Ernest Ma et al., Phys. Lett. B764 (2017) 142–144

Loop Generated Neutrino Mass (Weinberg operator)

The d=5 Weinberg operator can be generated

Example



Scalar+Fermion

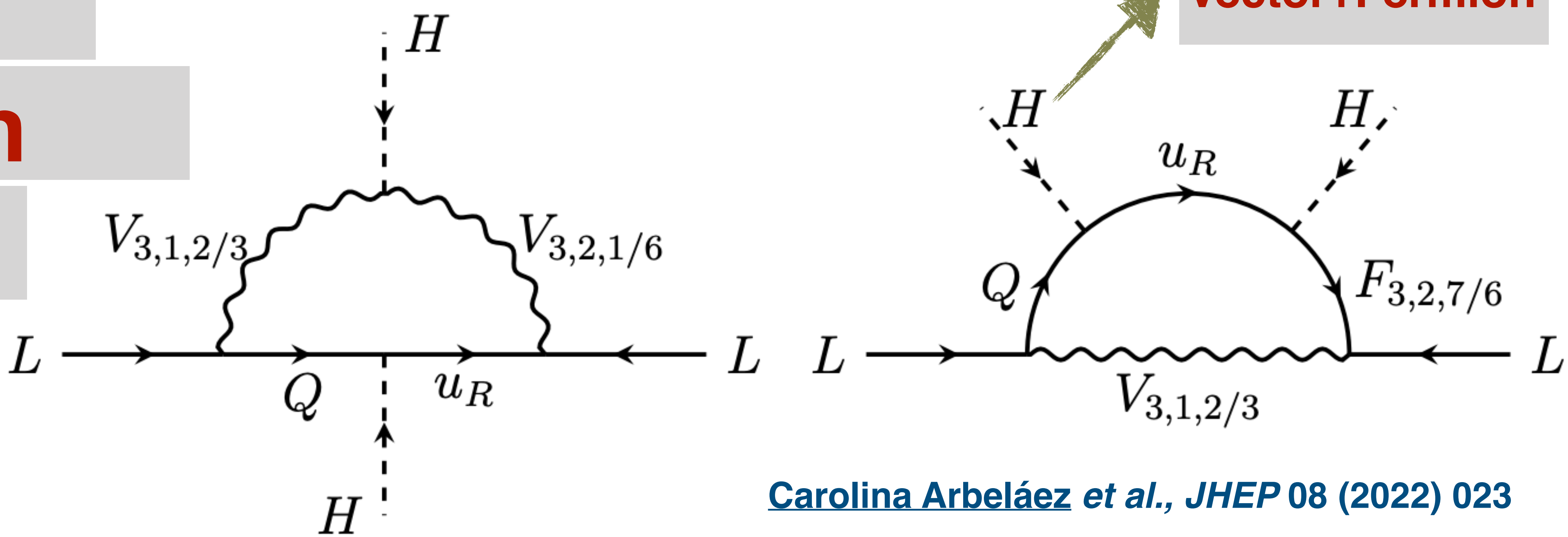
Ernest Ma et al., *Phys.Lett.B* 642 (2006) 18-23

Scotogenic

Contain

Provide

Vector+Fermion



Carolina Arbeláez *et al.*, *JHEP* 08 (2022) 023

Non-trivial SU(2) or SU(3) multiplets (scalar/gauge bosons,