Neutrino Mass Models: Roadmap for Collider and Cosmology

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Outline:

Origin of Neutrino Masses, Mixings and Discovery Prospects

Focussing on a subset

Heavy Neutral Lepton

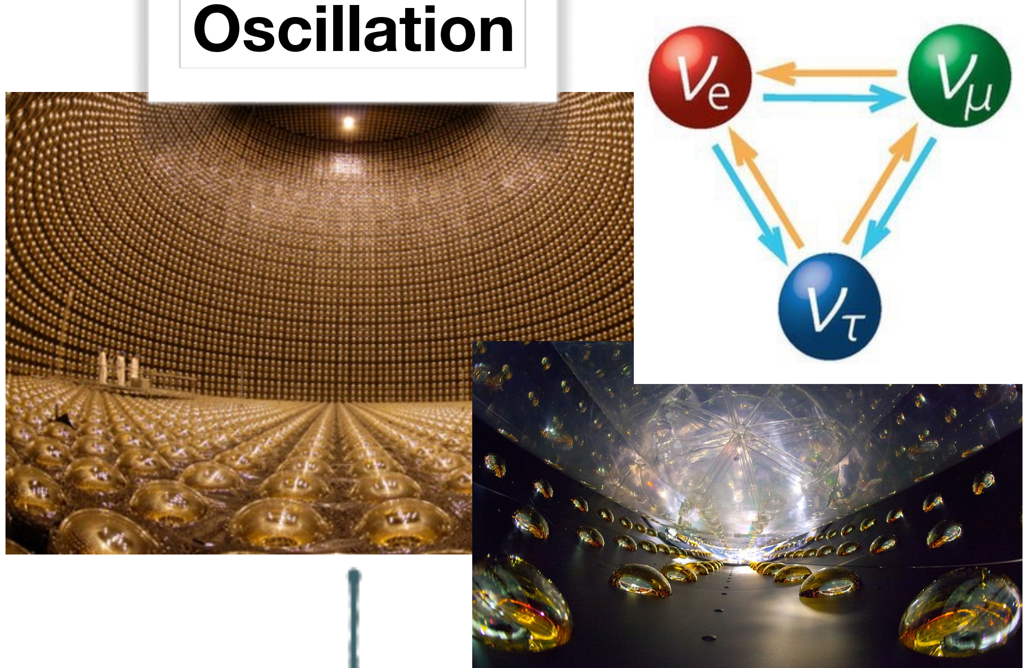
- ***Collider searches***
- **Astroparticle physics - Dark Matter**

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

$$\Delta m^2_{21} = (7.05 - 8.14) \times 10^{-5}\ \mathrm{eV}^2$$

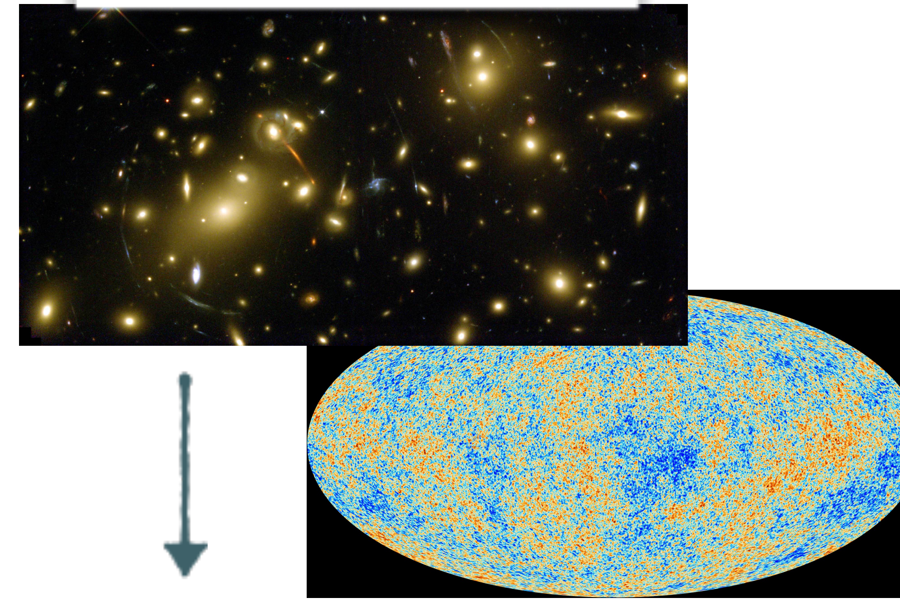
$$|\Delta m^2_{31}| = (2.41 - 2.60) \times 10^{-3}\ \mathrm{eV}^2$$

Large angle $\theta_{12} \sim 33^\circ, \theta_{23} \sim 49^\circ$

Non-zero $\theta_{13} \sim 8.41^\circ$ (DAYA BAY, RENO)

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

Non-Oscillation



Sum of neutrino masses

Bound from cosmology

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

(Planck Collaboration, arXiv 1807.06209)

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)

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

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

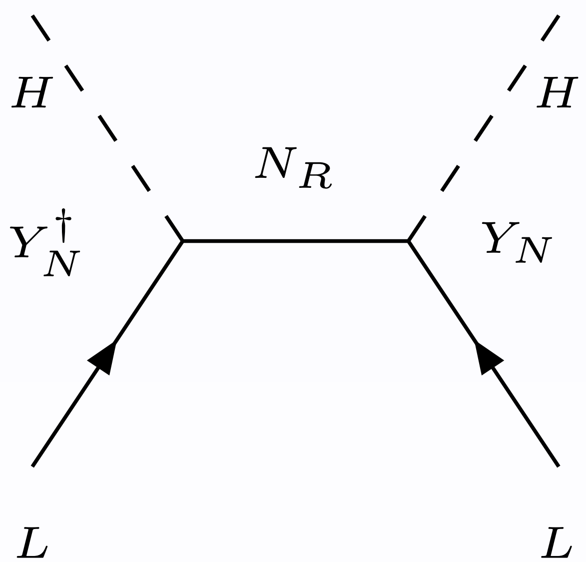
UV Completion

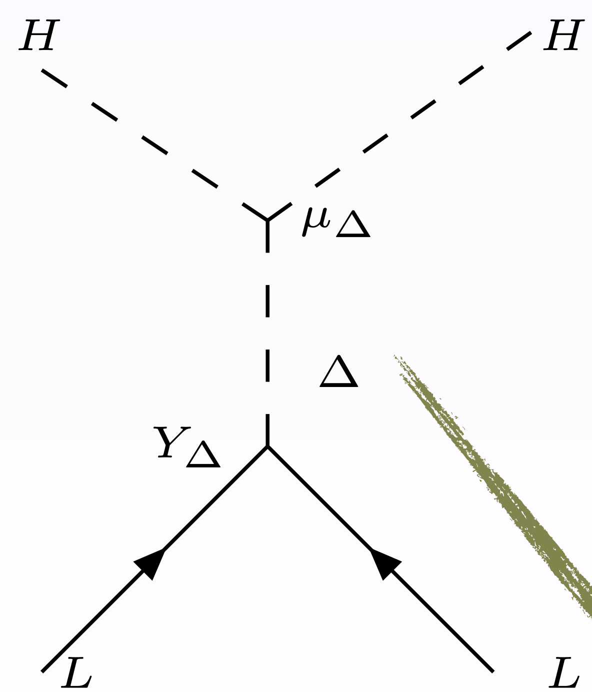
- **Type-I,II,III**
- **Inverse Seesaw**
- **Gauged B-L and Left Right Symmetric Model**
- **Scotogenic model**

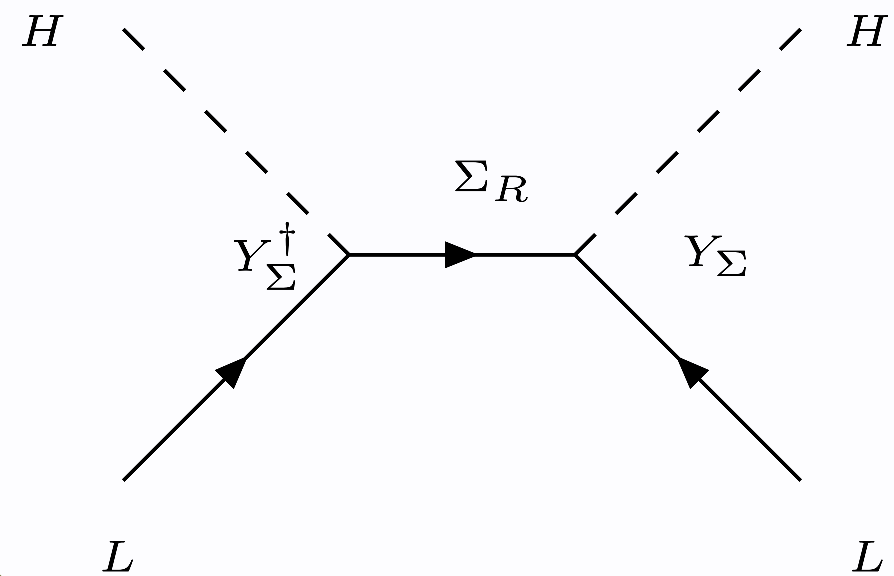
Contd:

Type-I	**Type-II**	**Type-III**
SM gauge singlet	$SU(2)$ Triplet, $Y = 2$	$SU(2)$ Triplet, $Y = 0$

Σ_R → Gauge interaction



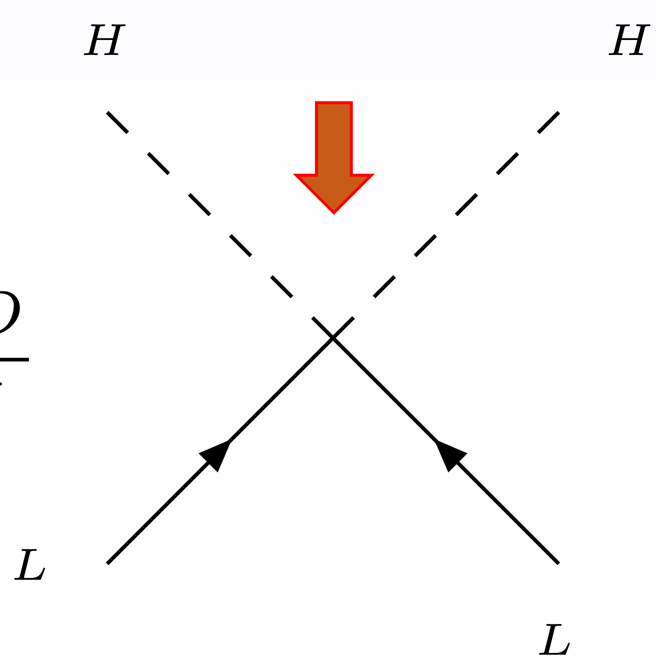




interaction of N with other SM particles is proportional to the active-sterile mixing

V_{lN} → $\frac{m_D}{M}$

Suppressed



H^{++} Doubly charged Higgs

Heavy modes integrate out

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

Inverse Seesaw

Quasi-degenerate neutrinos

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

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

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)

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 $\tan 2\alpha = \dfrac{v v_{BL} \lambda_3}{v^2 \lambda_1 - v_{BL}^2 \lambda_2}.$
- 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 $\rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

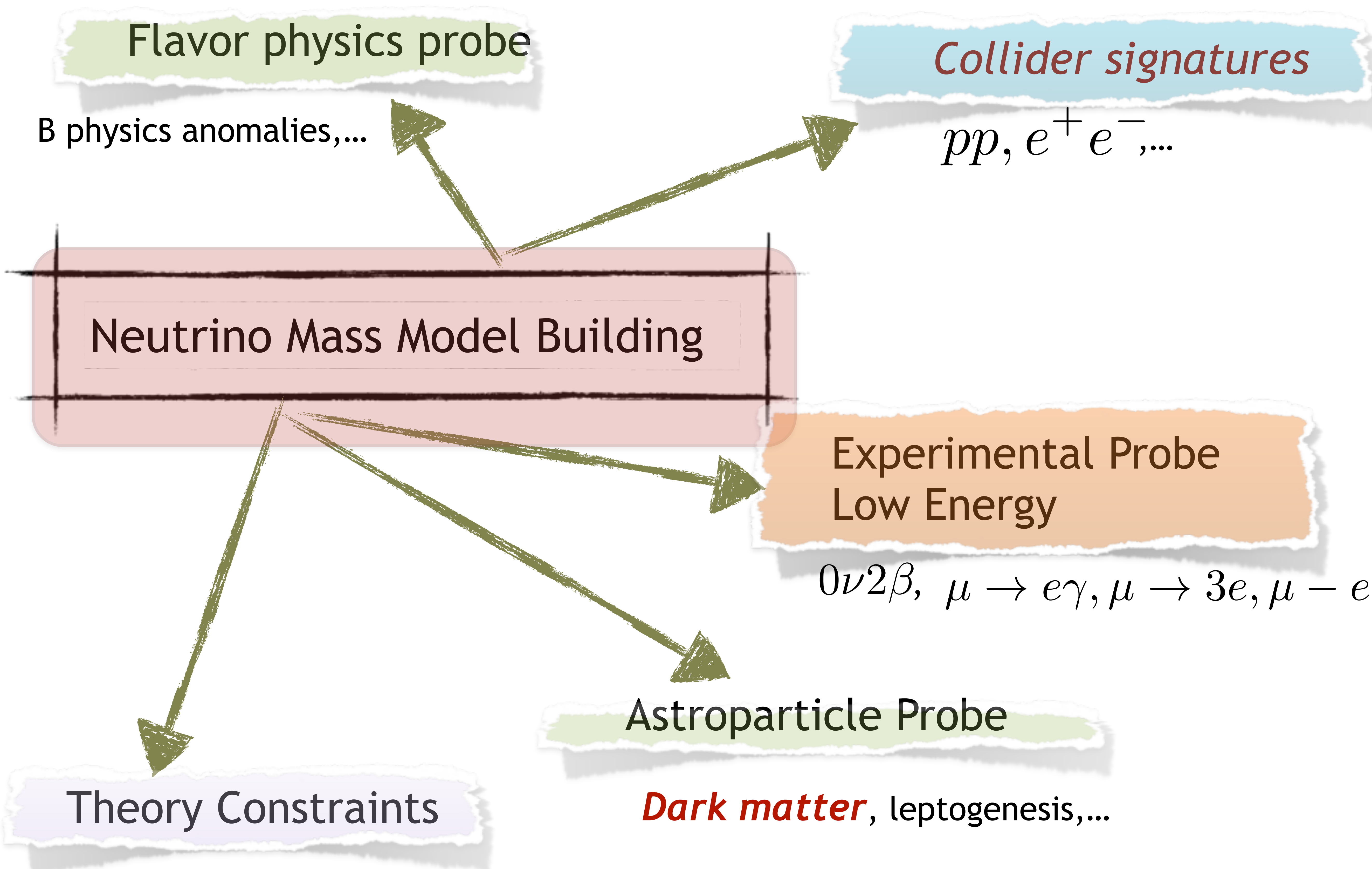
Parity symmetric theory $\rightarrow$ parity violating SM

- 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

Experimental probe:



Heavy Neutral Lepton:

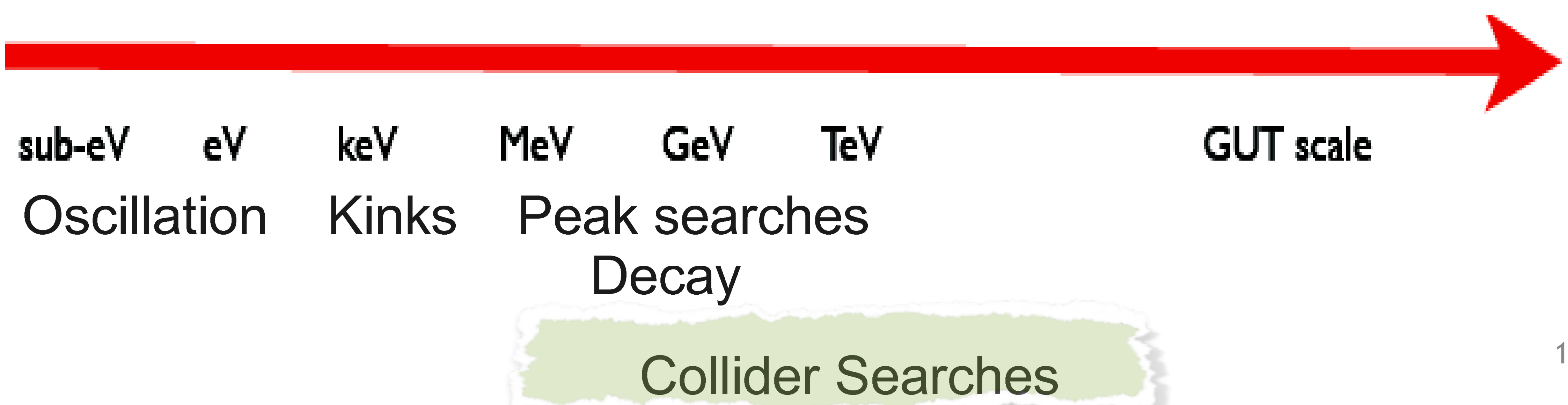
Heavy Neutrino N

↓

Key ingredients behind neutrino mass generation

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

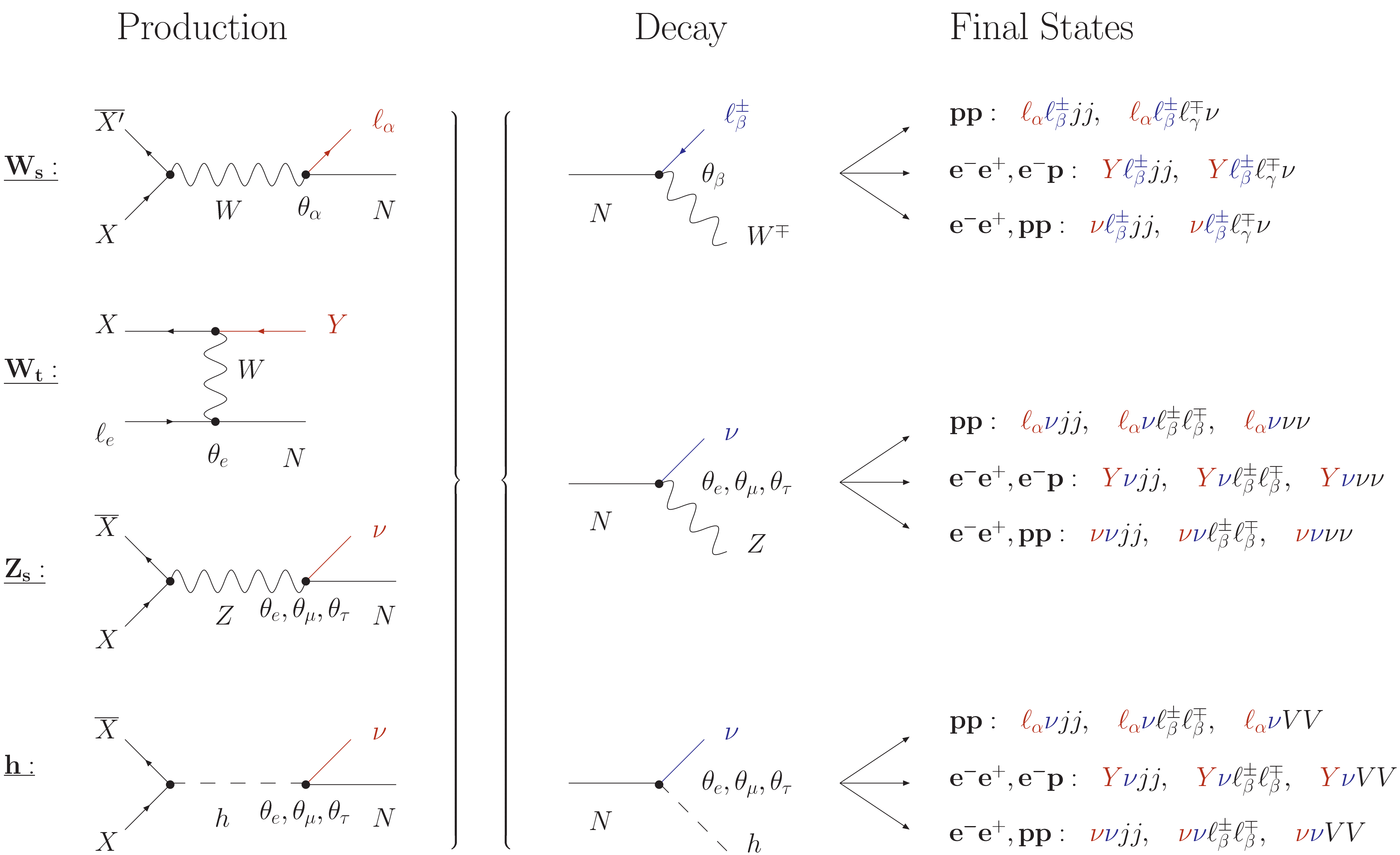
- Detection $\rightarrow$ Collider, Oscillation, Peak searches, Kink, $(\beta\beta)_{0\nu}$-decay,...
- And $\rightarrow$ LFV processes, Non-unitary effect,...



HNL at Colliders (single production from SM particles):

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 $\frac{gM}{2M_w}\bar{\nu}\theta_{\alpha}N_R H$

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



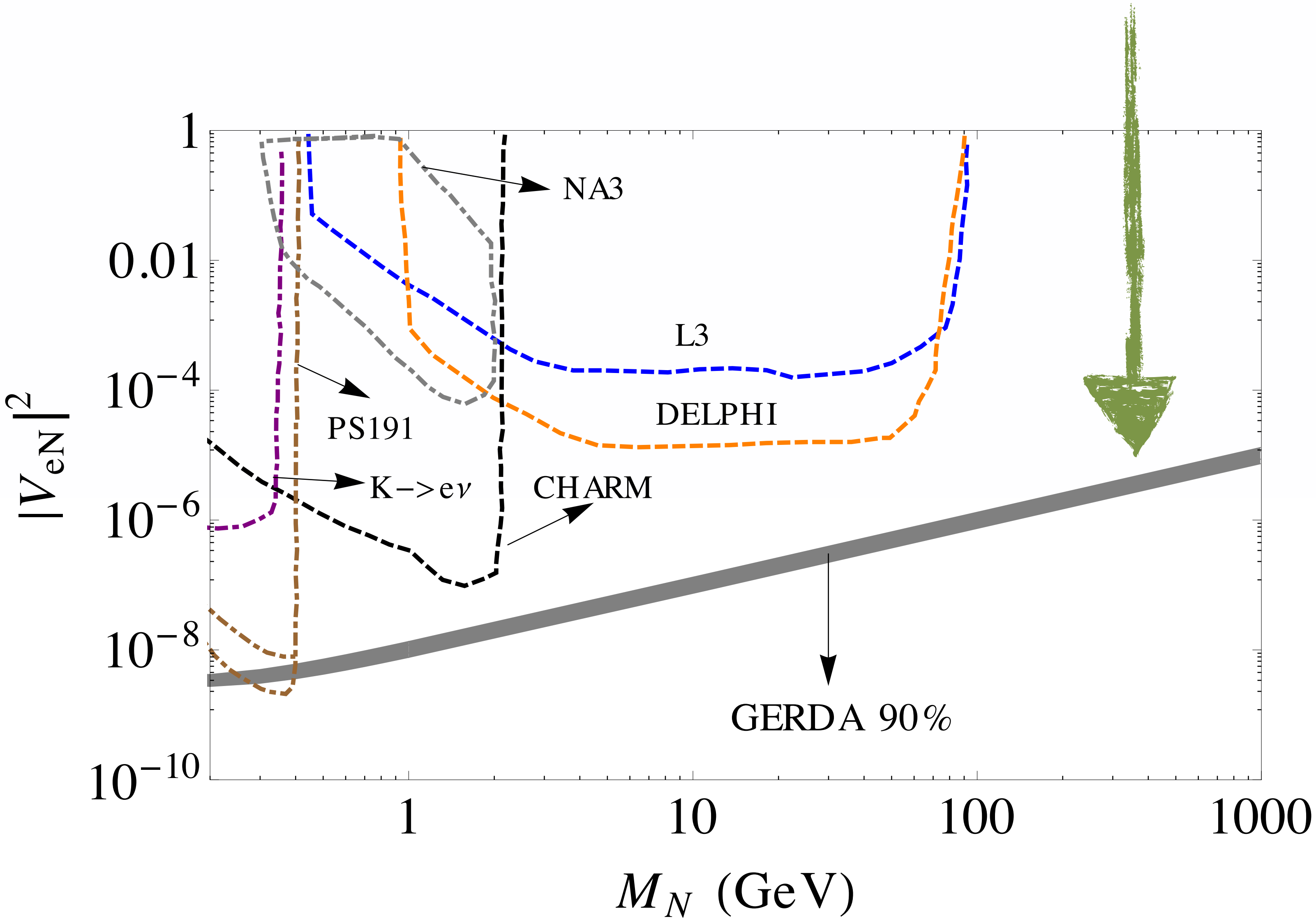
Multilepton, multijet final states

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

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, $V \sim 10^{-6} \to$ extremely small
- Experimental constraints $\to (\beta\beta)_{0\nu}$-decay, beam dump experiments. $(\beta\beta)_{0\nu}$-decay $\to$ stringent.



Mitra, Pascoli, Wong, 2013 ;

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

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

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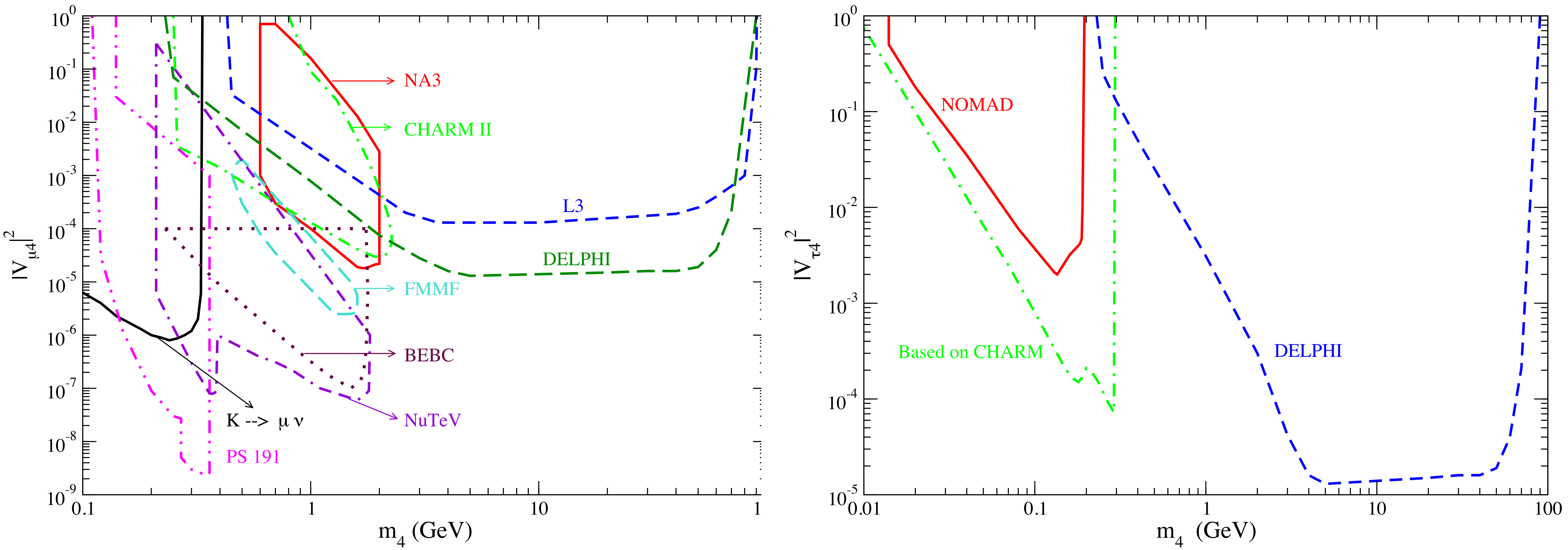
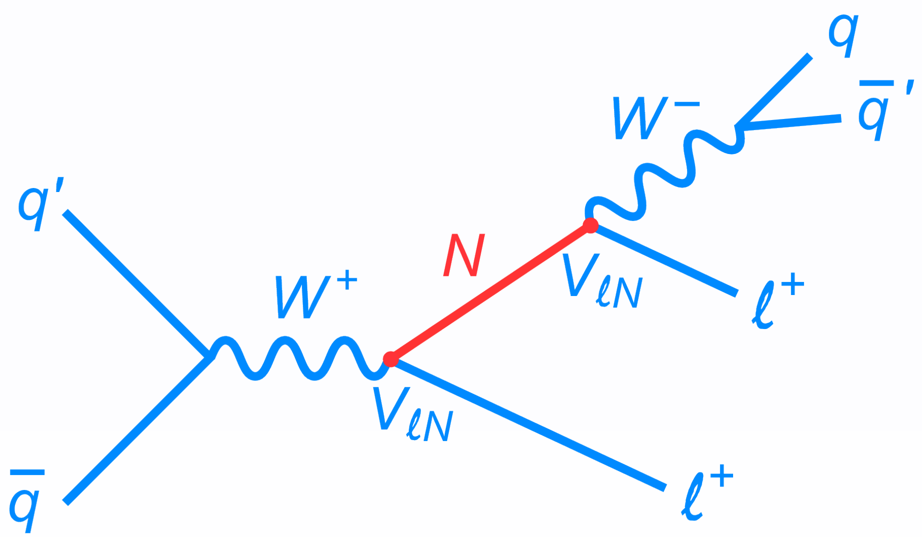
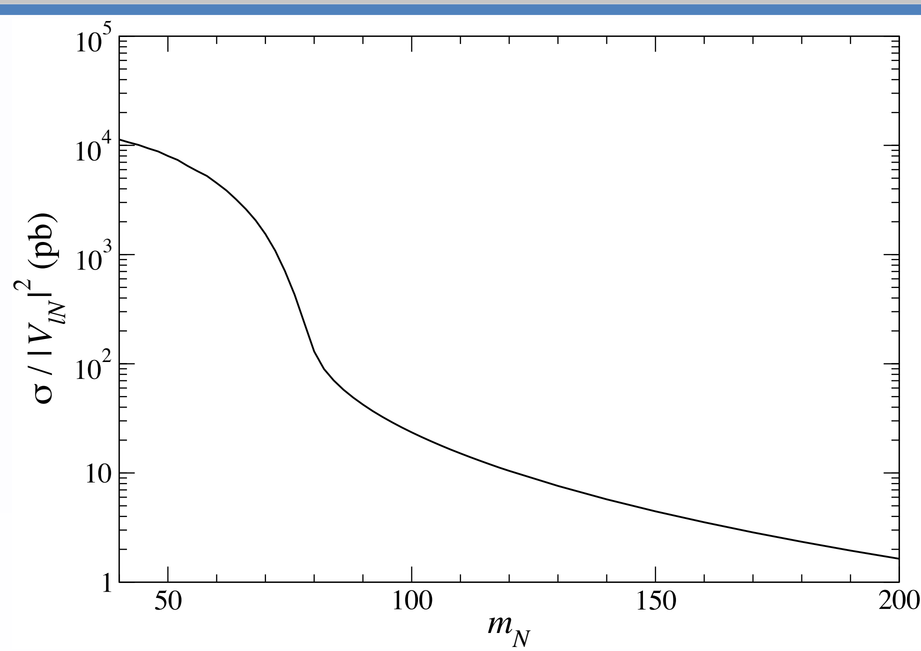


Atre et al., JHEP **0905**, 030 (2009)

- Severe constraint from light neutrino mass → 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 → collider prospect

Collider Searches (LHC)



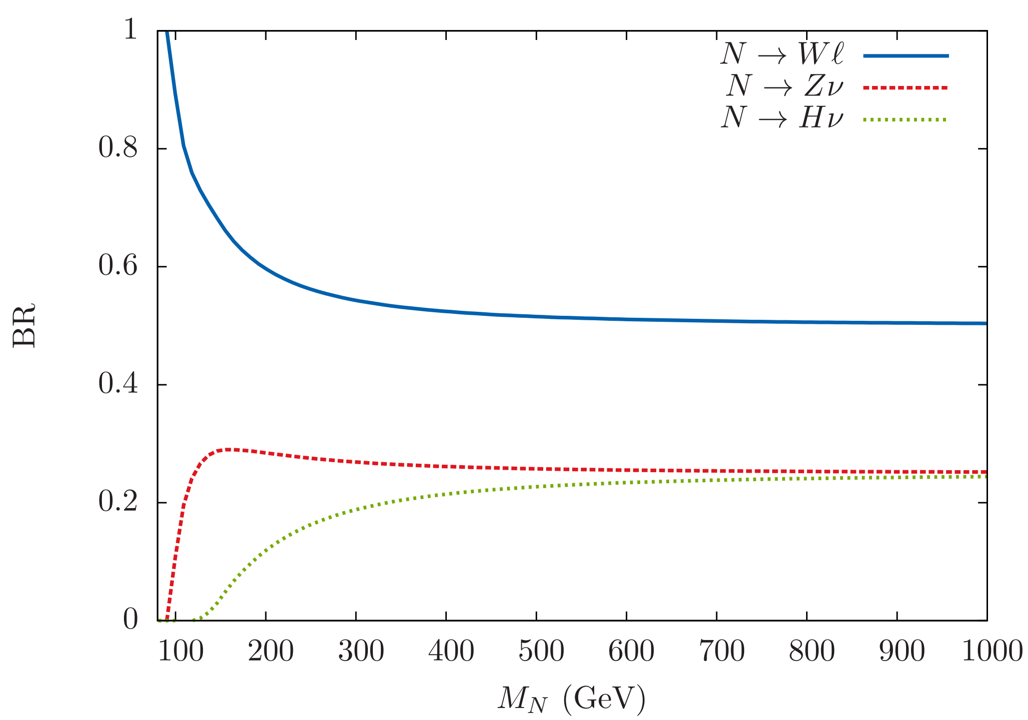


$$pp \to l^{\pm} N$$

$m_N \sim 100$ 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*** $N \to lW$
- ***Other decay modes has branching ~ 20%***

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

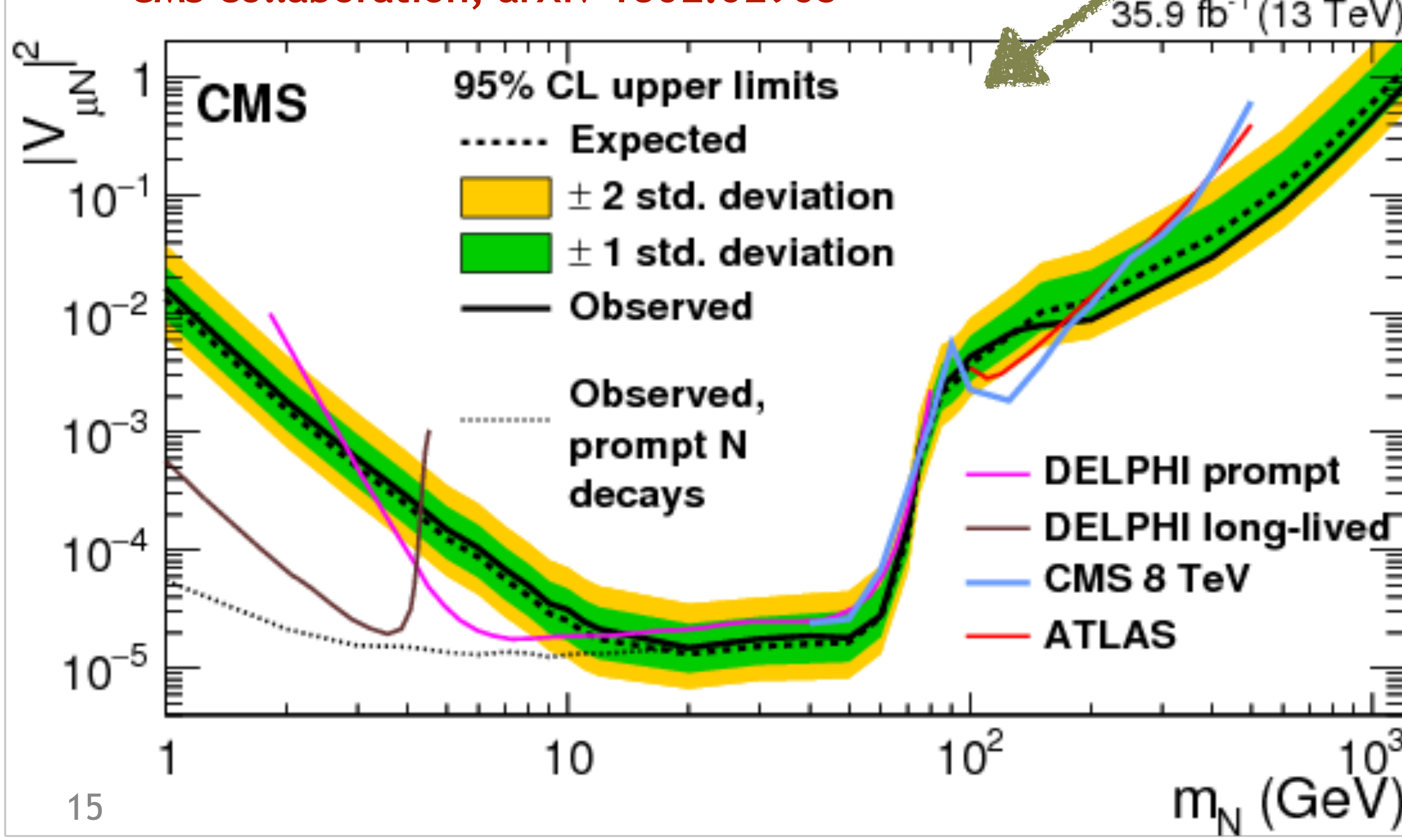
Atre et al., JHEP **0905**, 030 (2009); Aguila et al., NPB **813**, 2009; Aguila et al., 2007; Aguila et al., PLB **672**, 2009; Arhib et al., 2010, ...

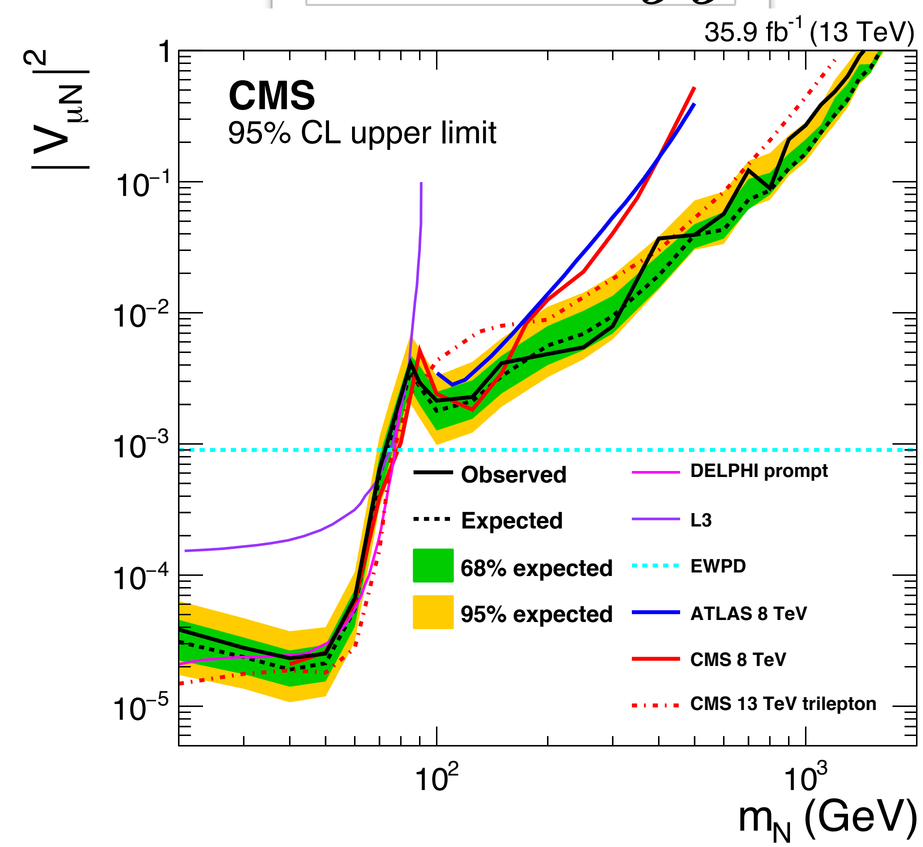
3l+X search

Low sensitivity in high mass regime

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

CMS collaboration, arXiv 1802.02965



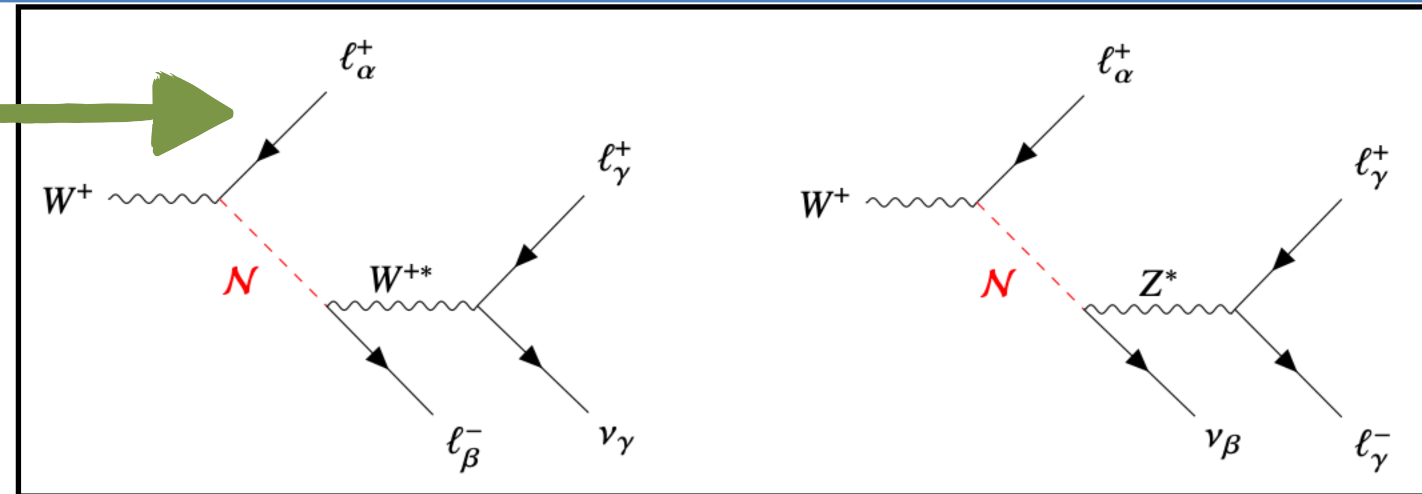


CMS collaboration, 1603.02248

CMS collaboration, arXiv 1806.10905

Displaced HNL Search:

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

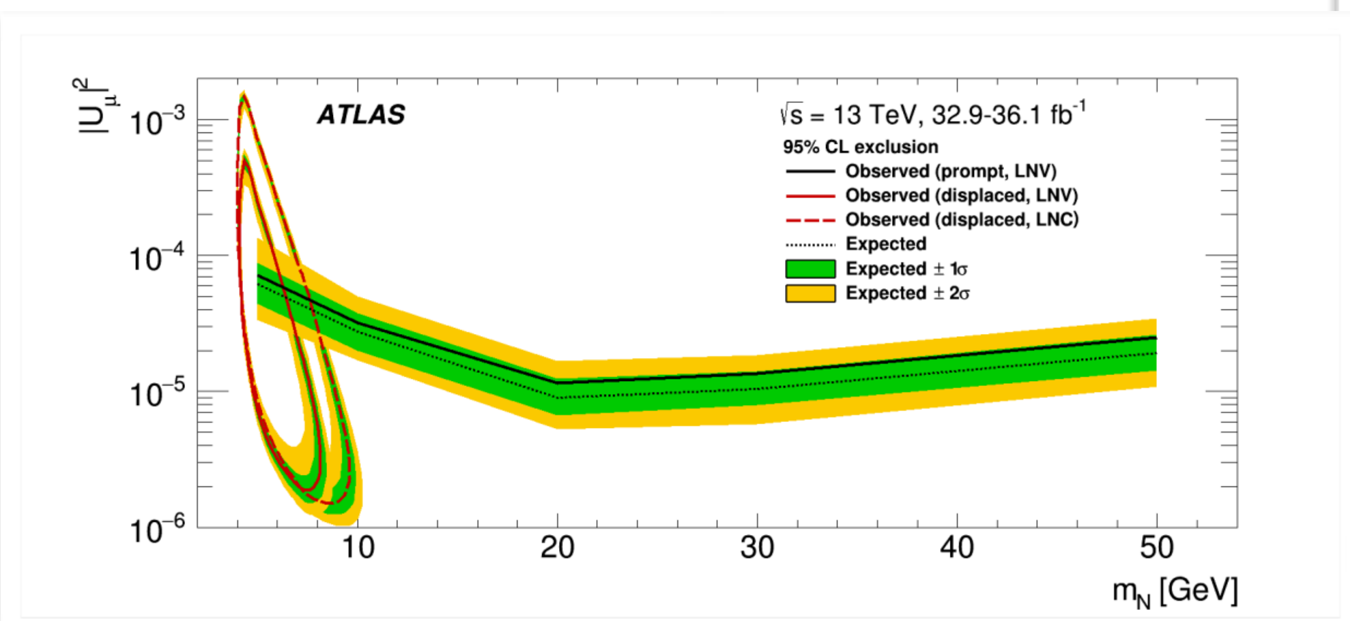


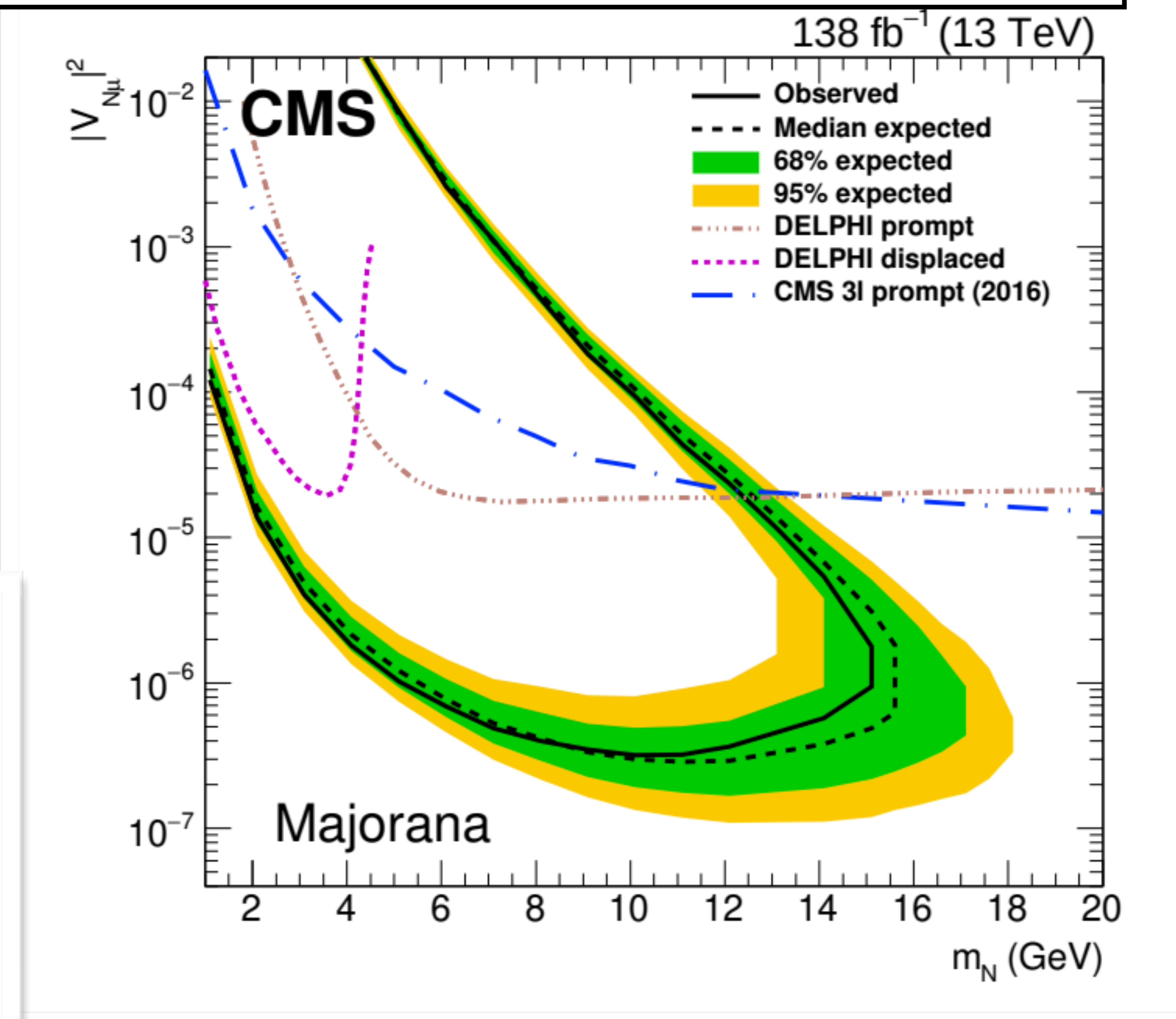
Active-sterile mixing is constrained from light neutrino mass measurement

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

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

Decay length can be substantial ~ mm to meter





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

Displaced decay of RHN

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

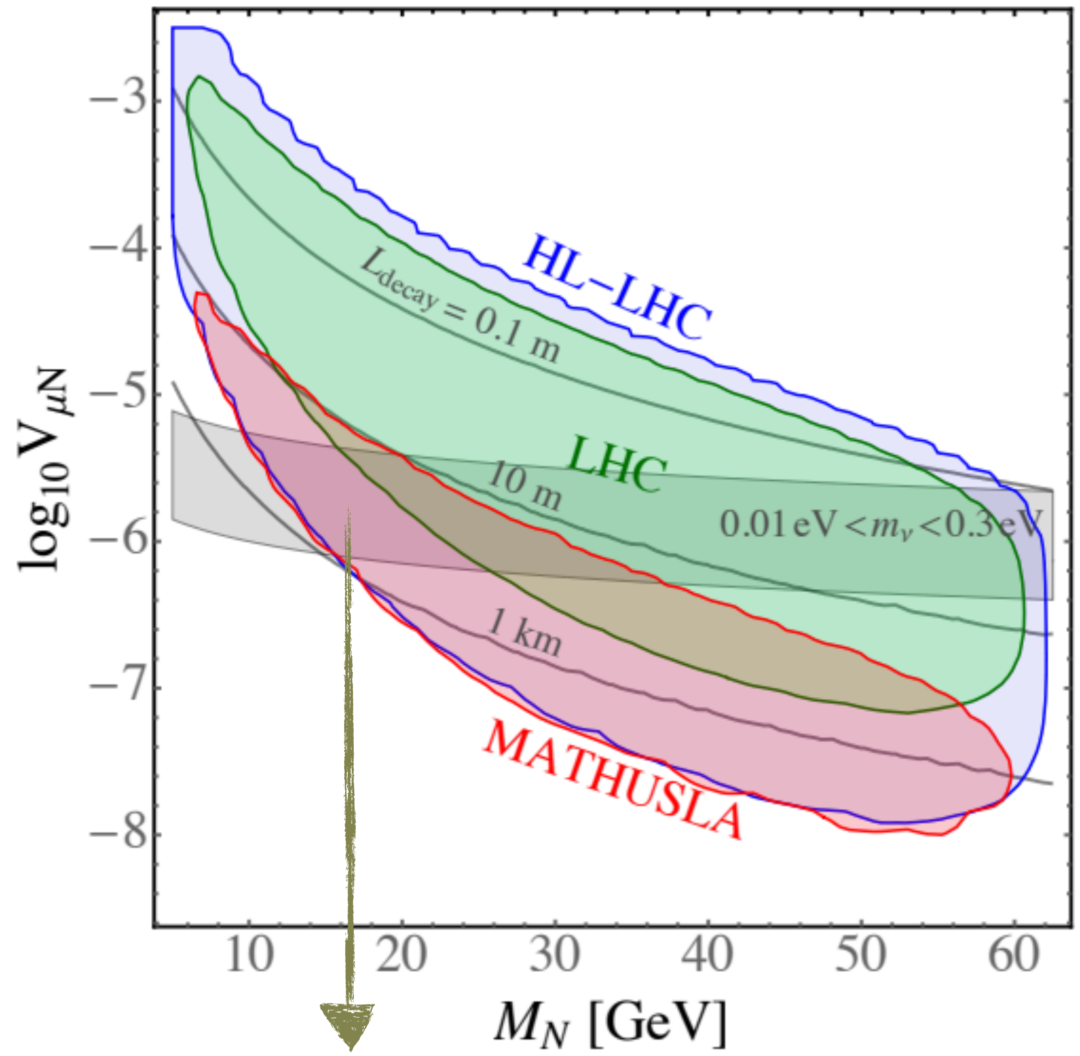
Gauged B-L model

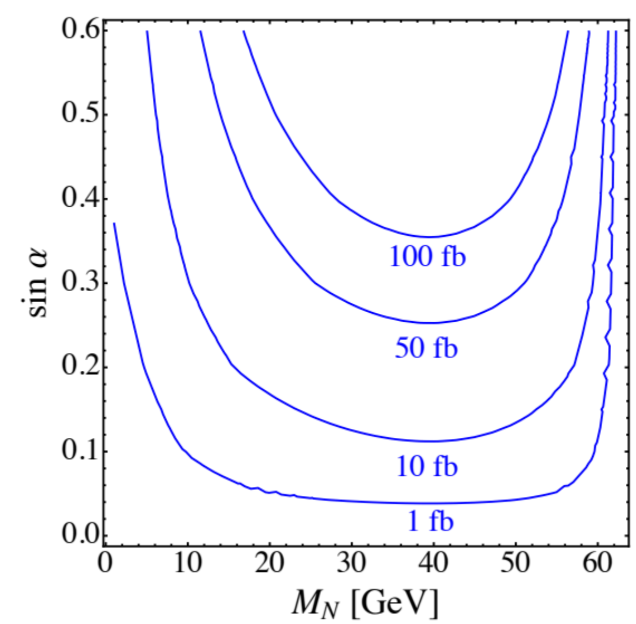
Scalar S

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

↓

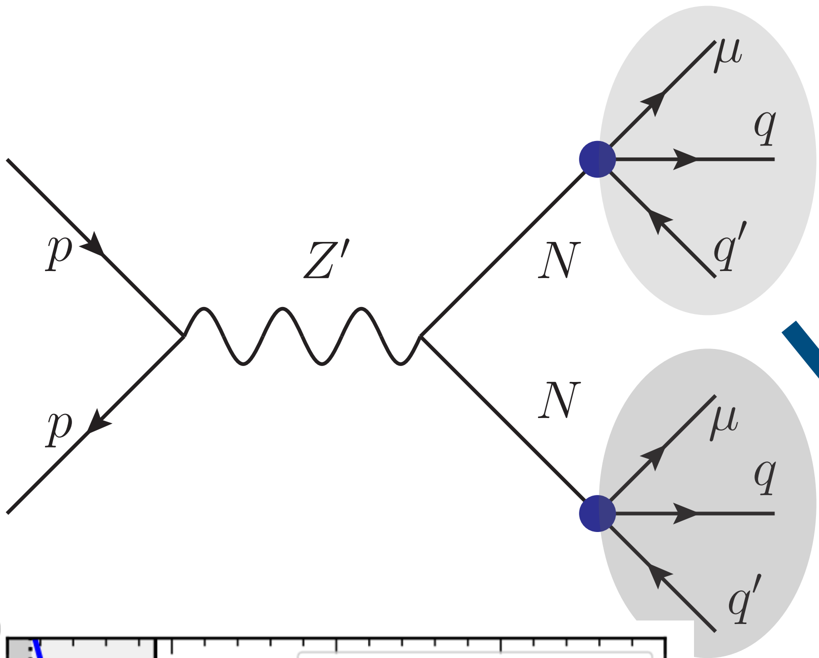
Depends on active-sterile mixing

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

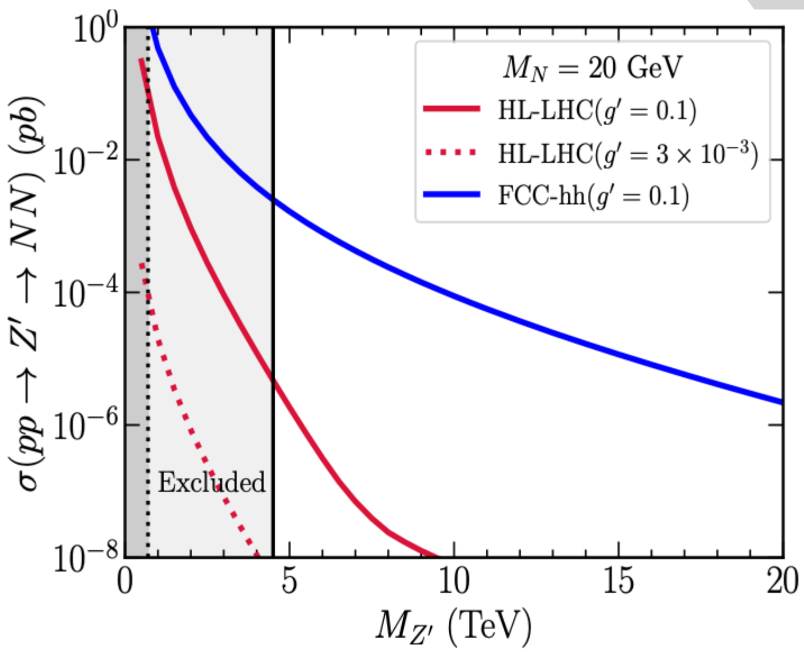
Seesaw favoured region can be accessed at the LHC/HL-LHC

Displaced 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



- 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

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

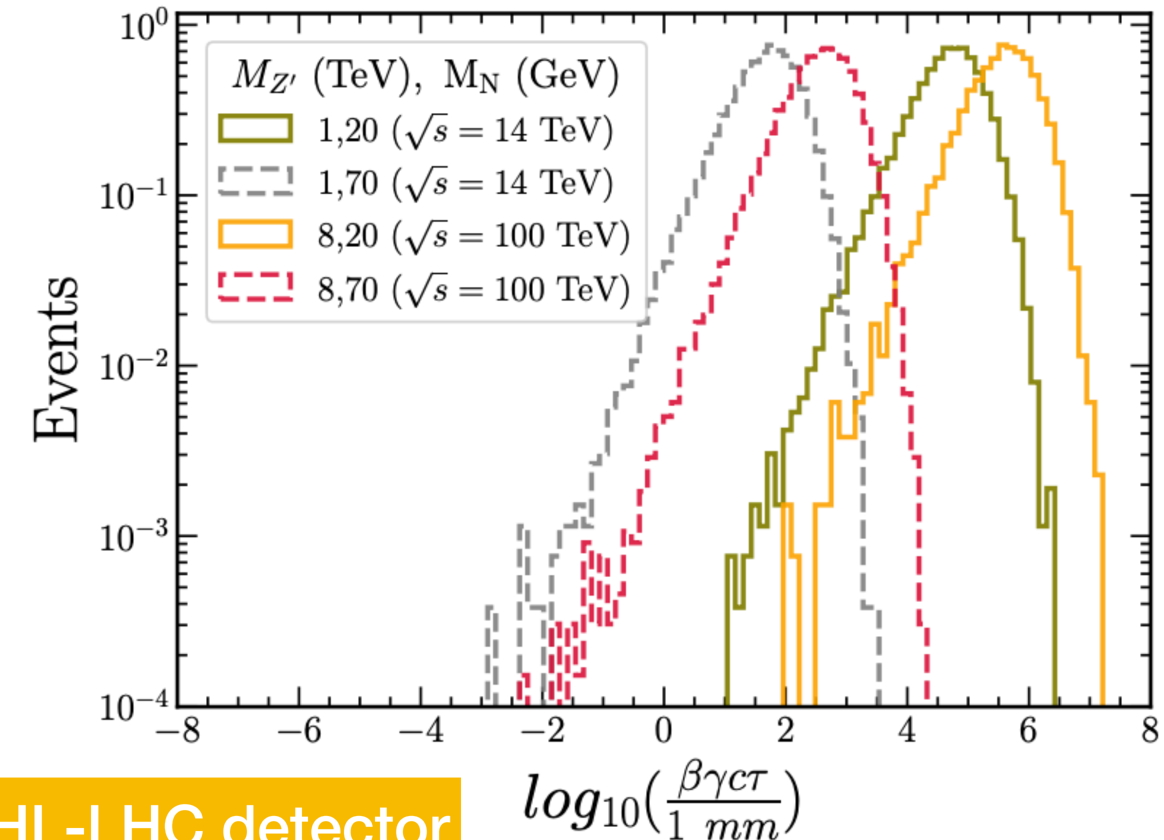
Deppisch, Padhan, Kulkarni and Mitra, Eur.Phys.J.C 82 (2022) 10, 858

Displaced and boosted decay of RHN

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

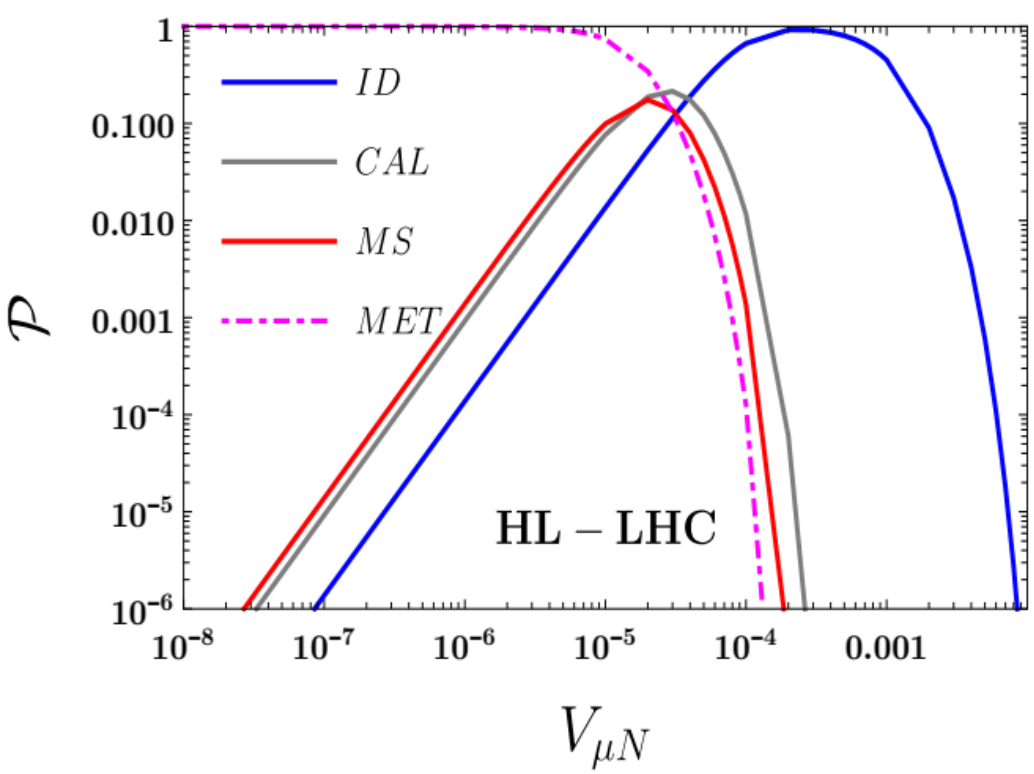
$$\Gamma(N \to l_\alpha^- \nu_\beta l_\beta^+) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{192\pi^3} \mathcal{I}(x_{l_\alpha}, x_{l_\beta}, x_{\nu_\beta})$$

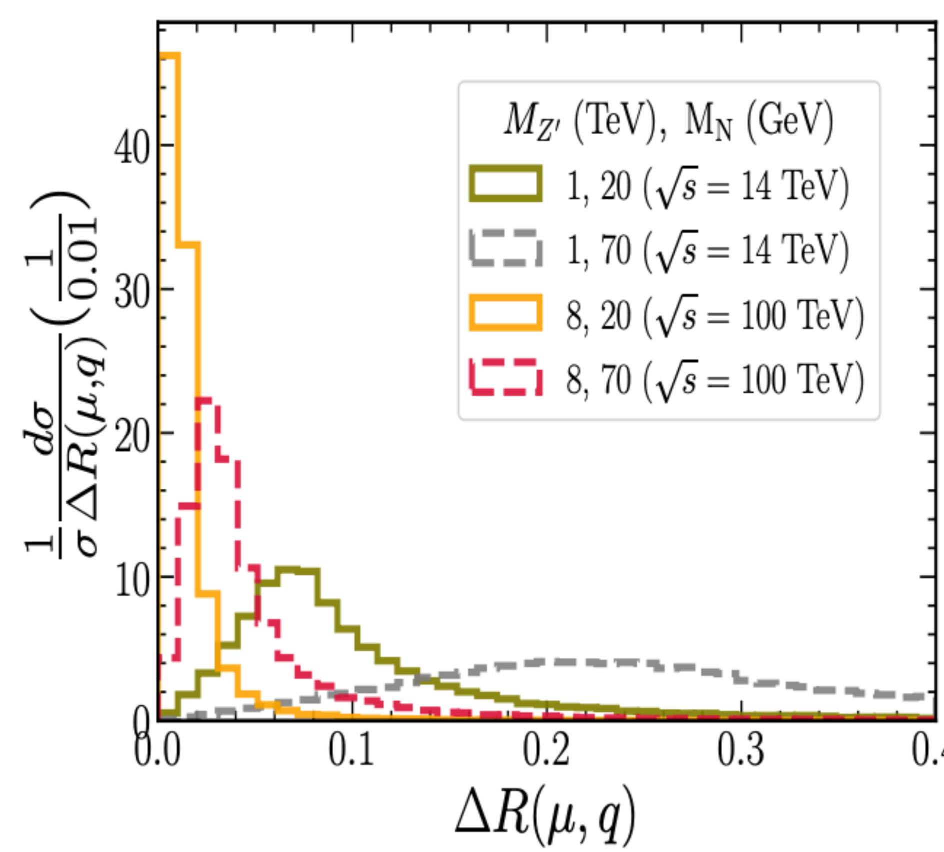
$$\Gamma(N \to \nu\nu\nu) = |V_\alpha|^2 \frac{G_F^2 M_N^5}{96\pi^3}$$



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

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

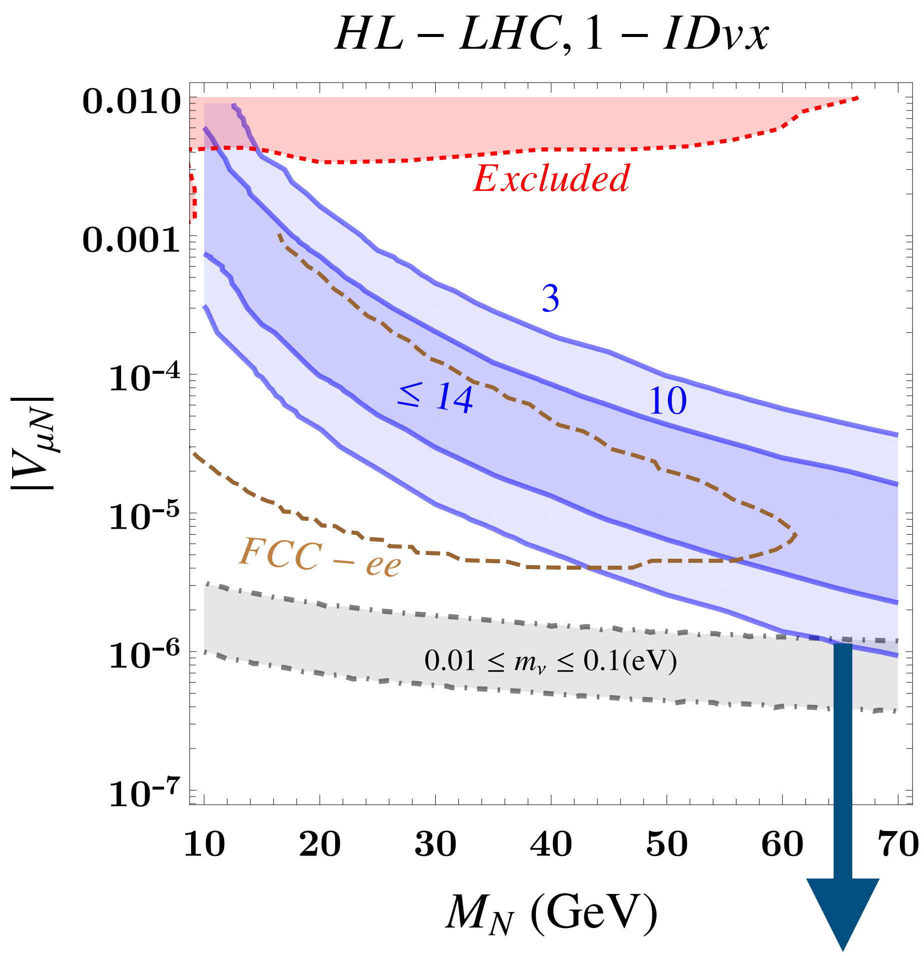


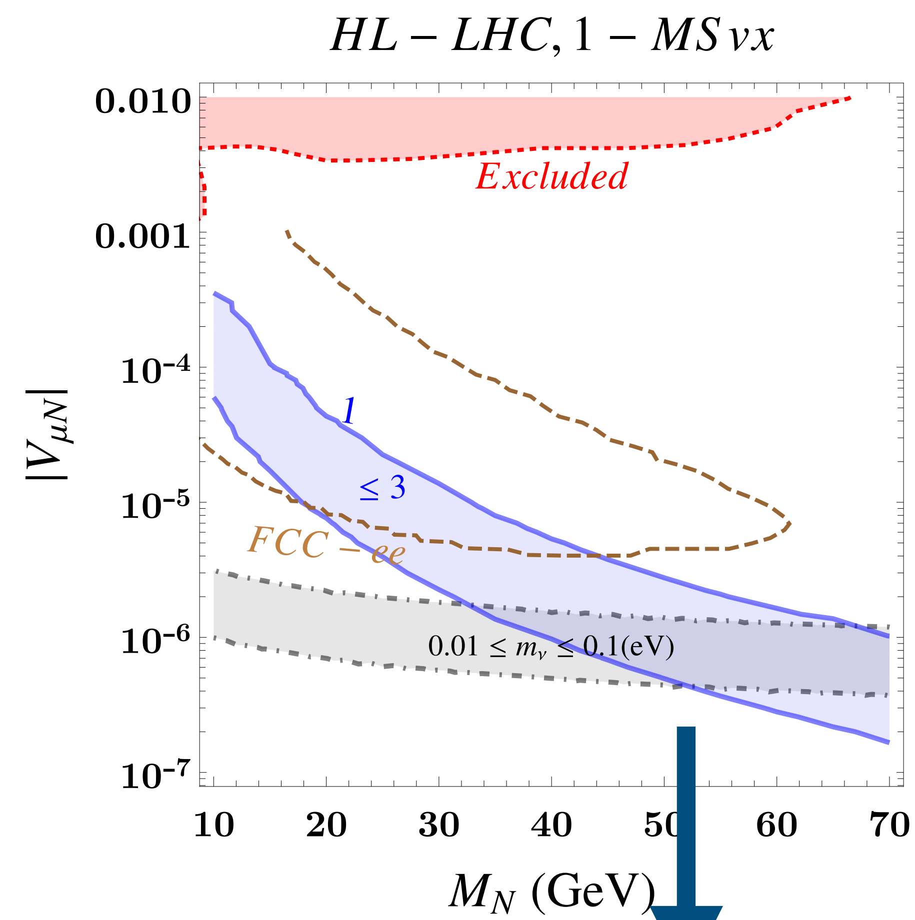


Displaced fat-jet signature

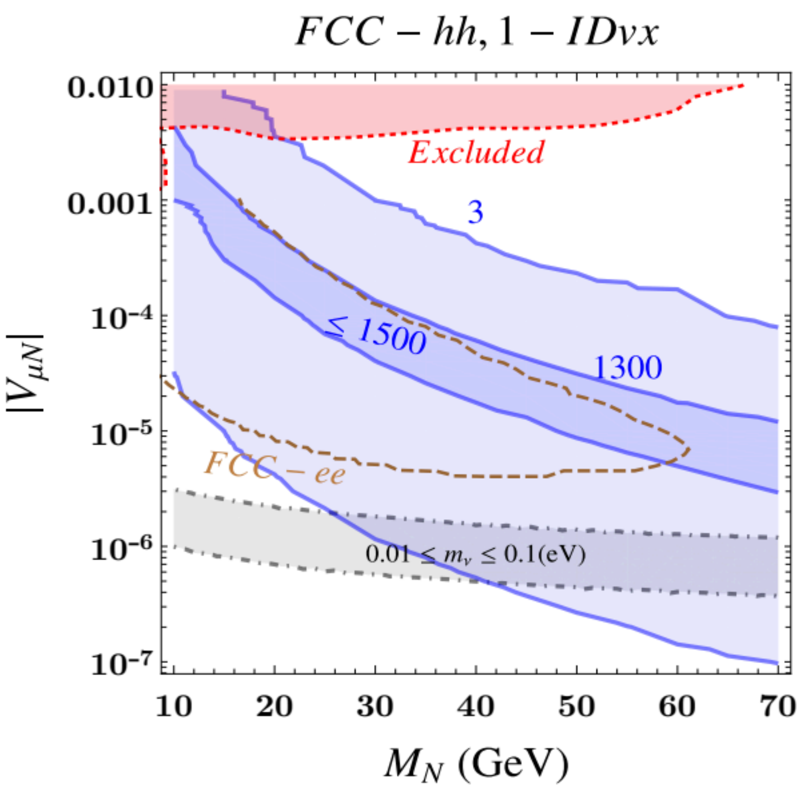
- *Eur.Phys.J.C 82 (2022) 10, 858*

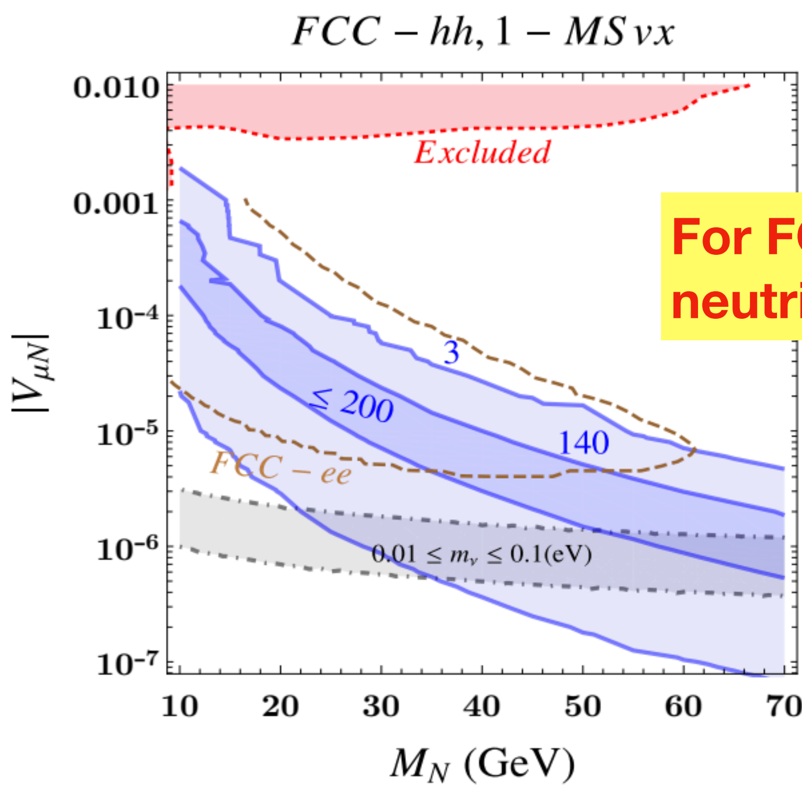
Hits/Tracks in MS





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

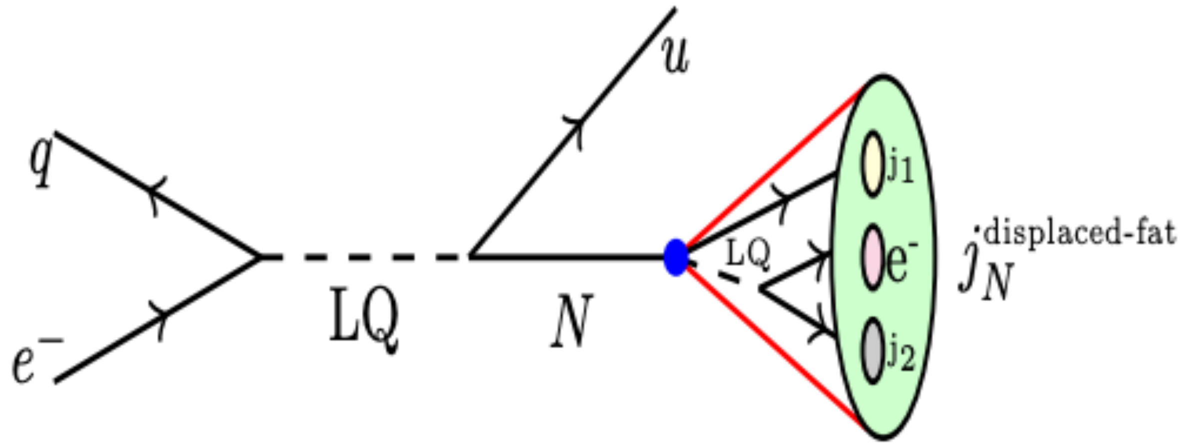




For FCC-hh, a wide range of light neutrino mass is accessible

Displaced and boosted decay of RHN

Another important probe of RHN is displaced fat-jet signature



- Occurs when N is boosted
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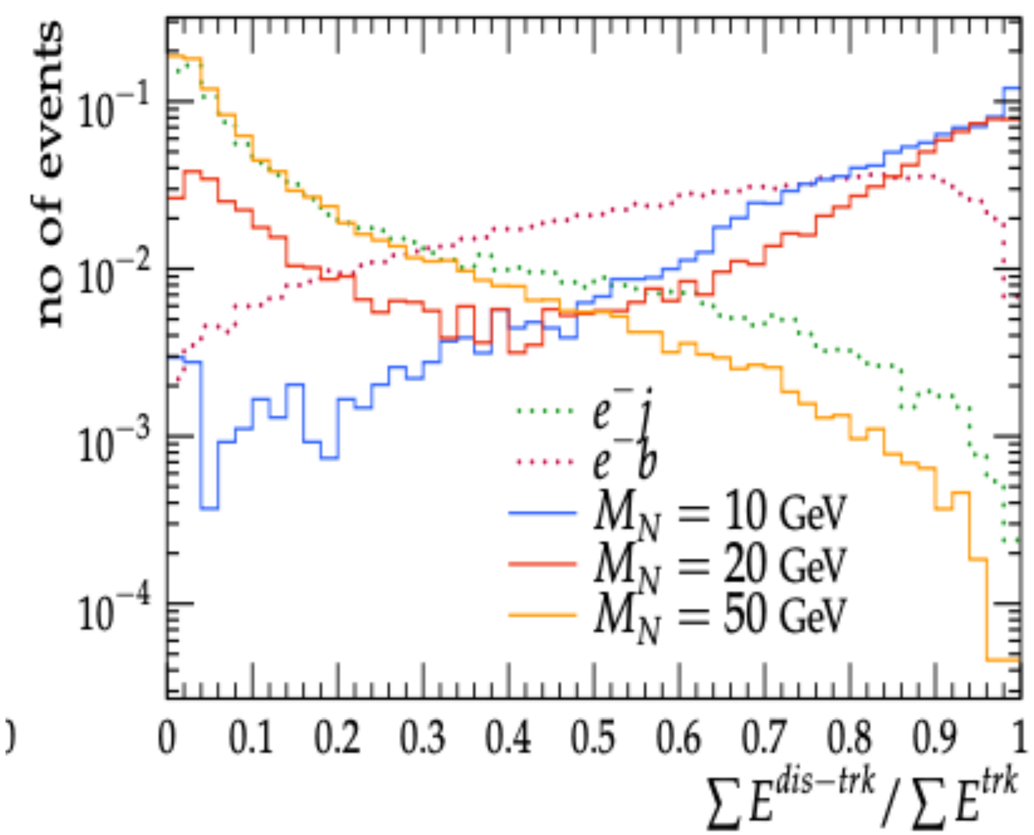
For a leptoquark model with RHN



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

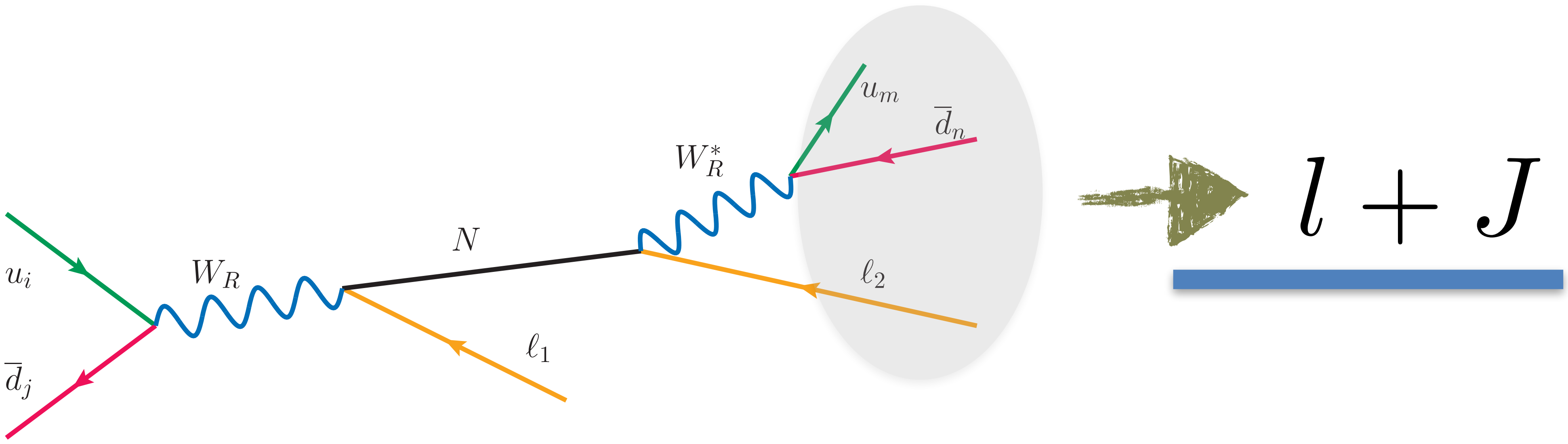
M_N [GeV]	n_σ	$\mathcal{L}$ [fb^{-1}]	$\mathcal{Y}^{ex}$
10	6.0 (41.5)	34.0 (0.7)	0.067 (0.035)
20	4.7 (39.7)	56.8 (0.8)	0.059 (0.017)
30	3.3 (30.4)	116.6 (1.3)	0.047 (0.013)

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

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

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

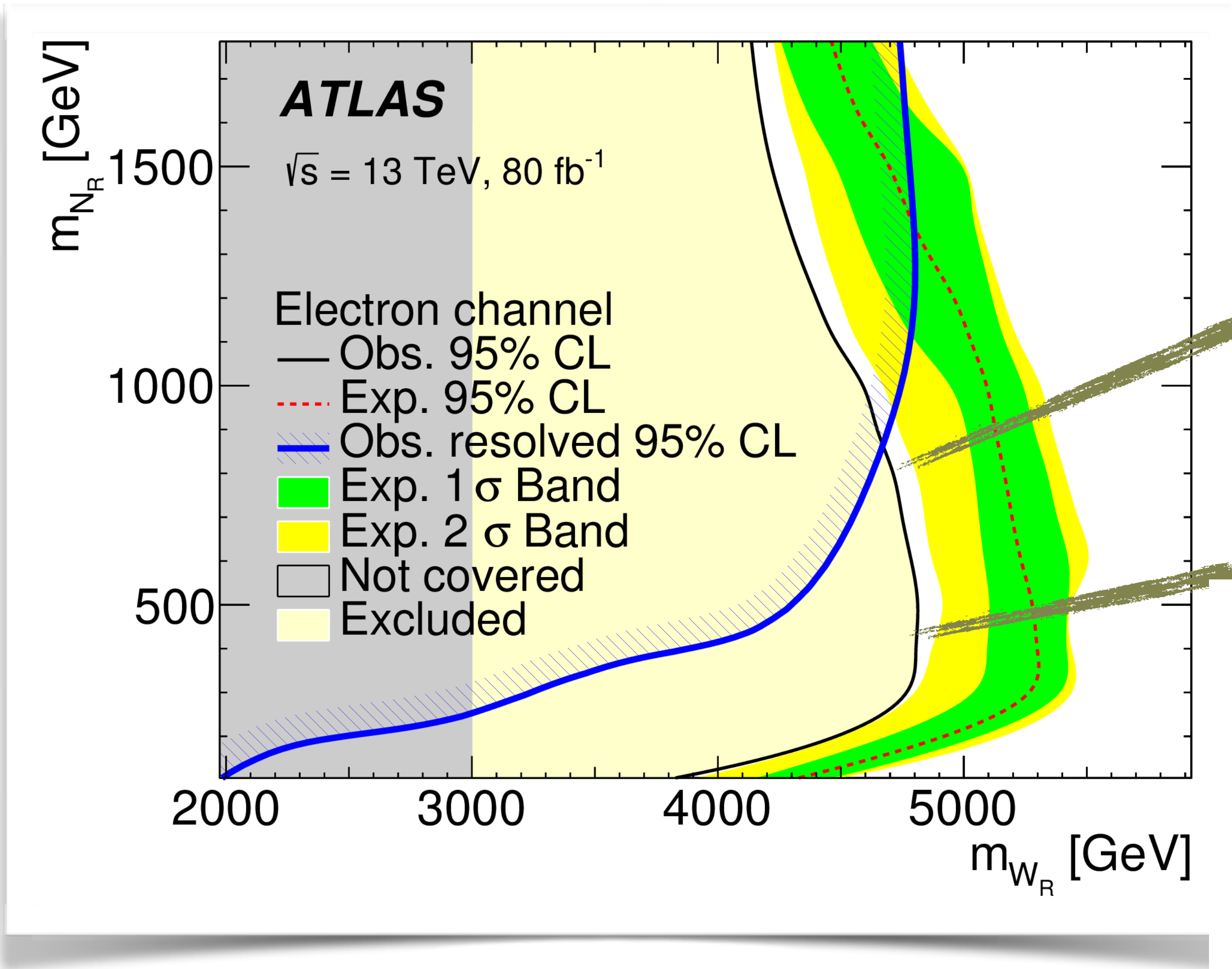
Manimala Mitra, Richard Ruiz, Darren J. Scott, and Michael Spannowsky - PRD 94, 095016, 2016



Simple 2 body topology

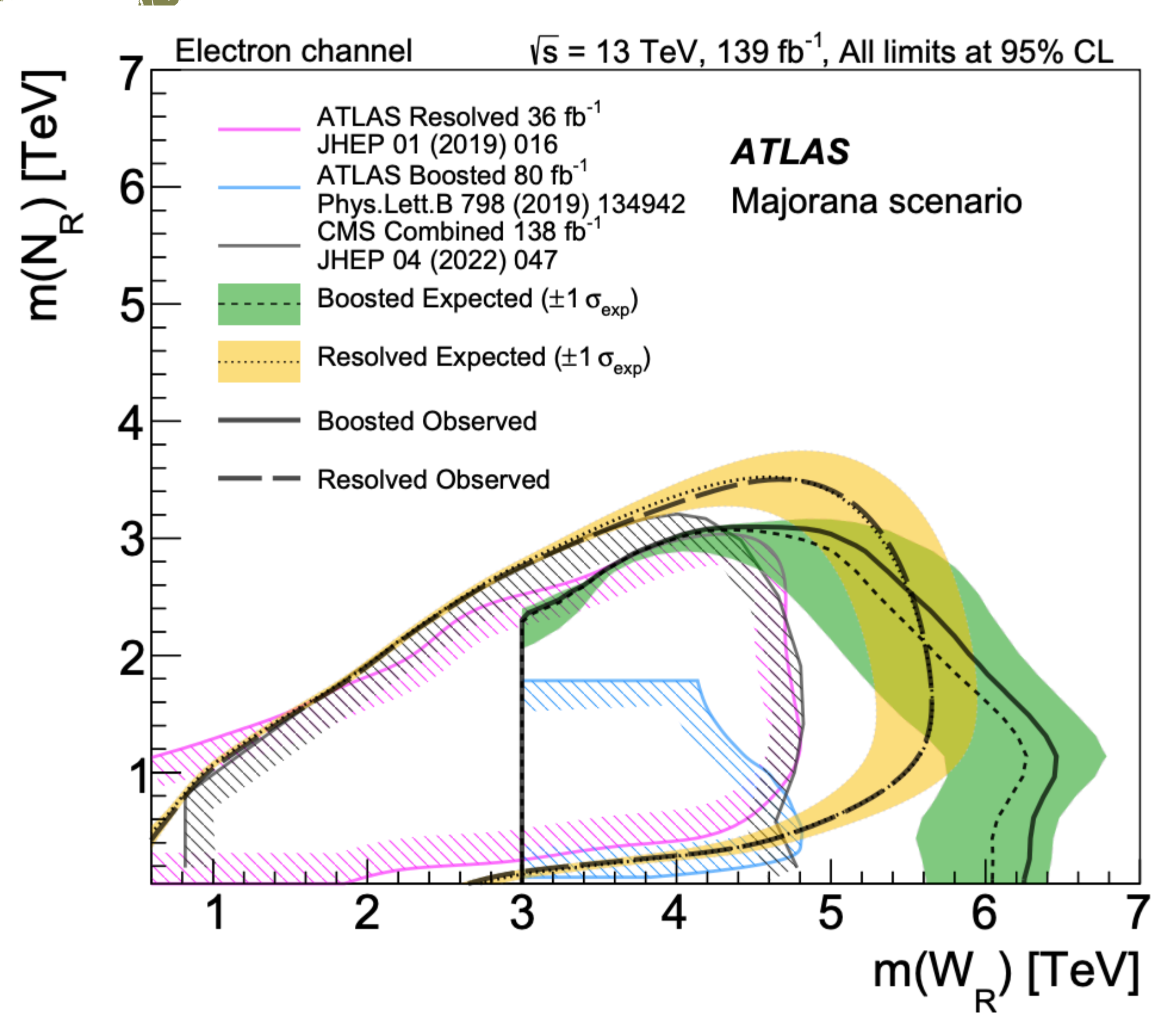
- **The transverse momentum** $p_T(l, j_{\text{fat}}) \sim M_{W_R}/2$
- **The separation between** l_2 **and** q, q' **will be small.**

Boosted RHN in LRSM:



Resolved analysis di-lepton+di-jet

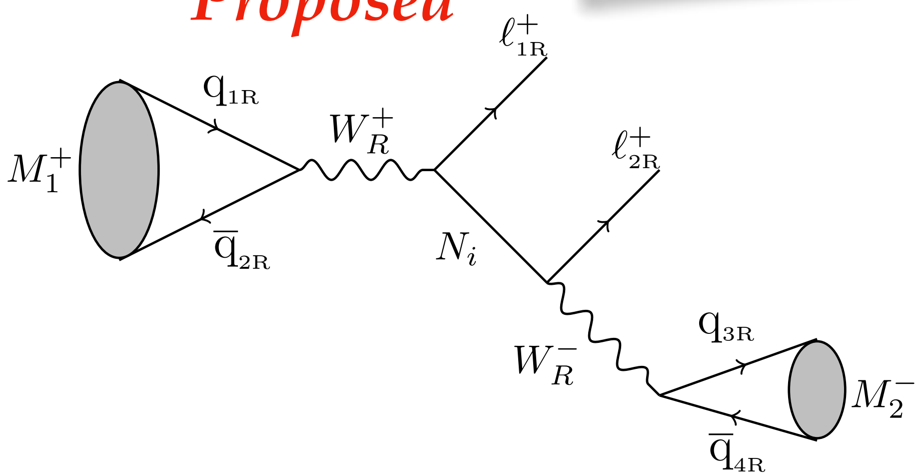
Boosted heavy neutrino search



ATLAS Collaboration,
[Phys. Lett. B 798 (2019) 1349]
arXiv:2304.09553

Lepton Number Violating Meson Decays

Proposed

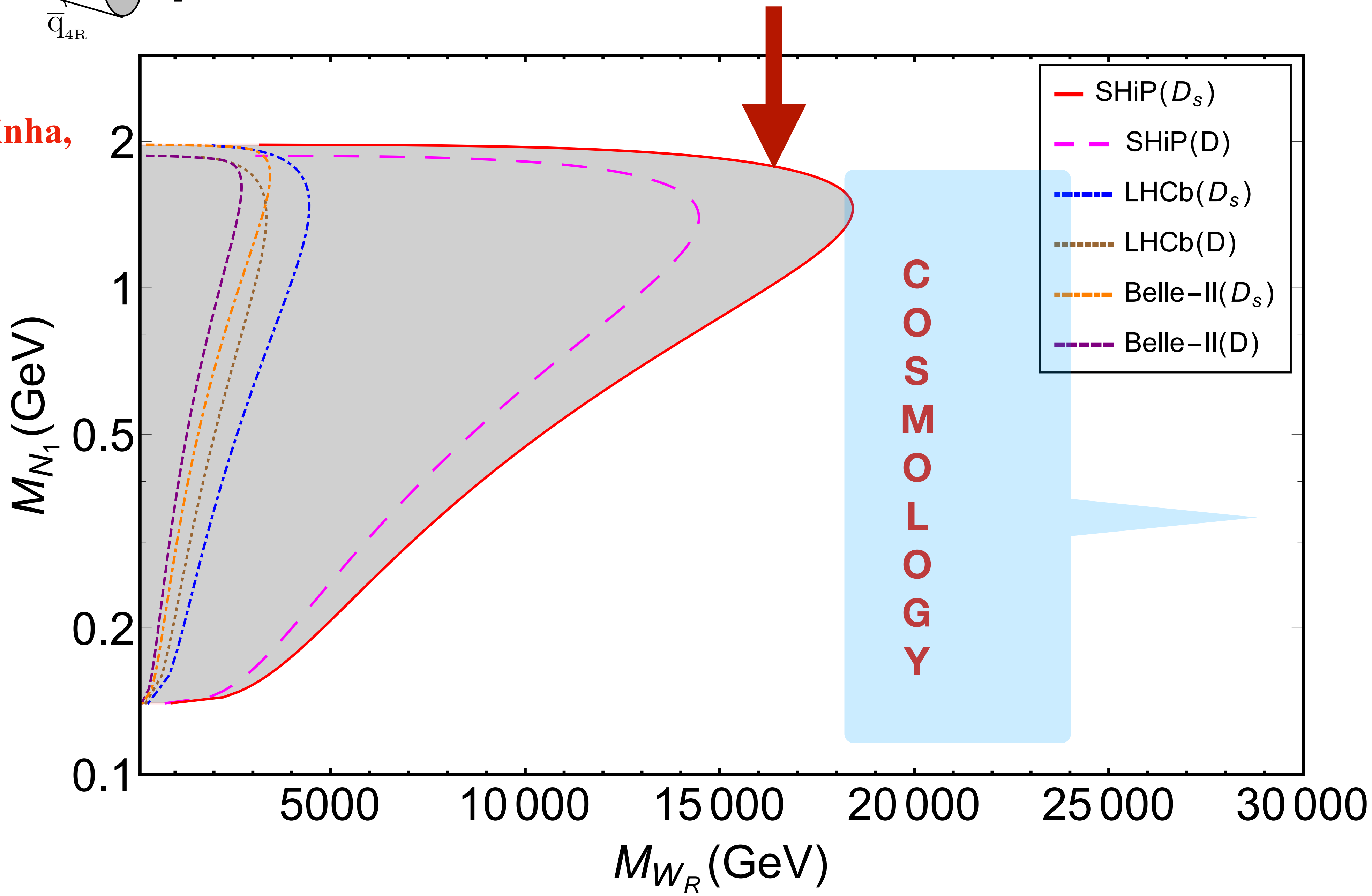


$$M^+ \to e^+ e^+ \pi^-$$

Sensitive to Sub-GeV Neutrino

Sensitive to a very high mass WR

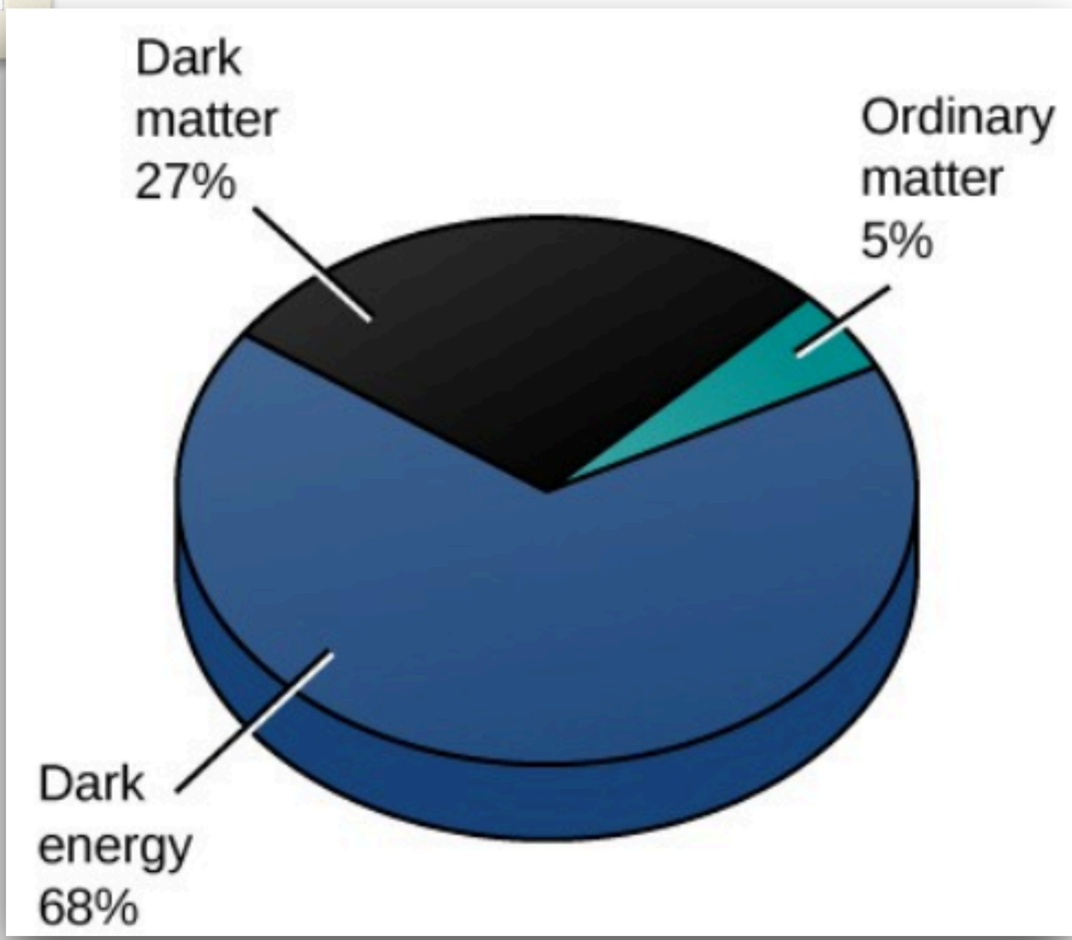
S. Mandal, M. Mitra, N. Sinha, PRD 96 (2017) 3, 035023



LHC search and LNV meson decays are complimentary probes

Major Questions in Modern Particle Physics ?

Dark Matter?



Relic density

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

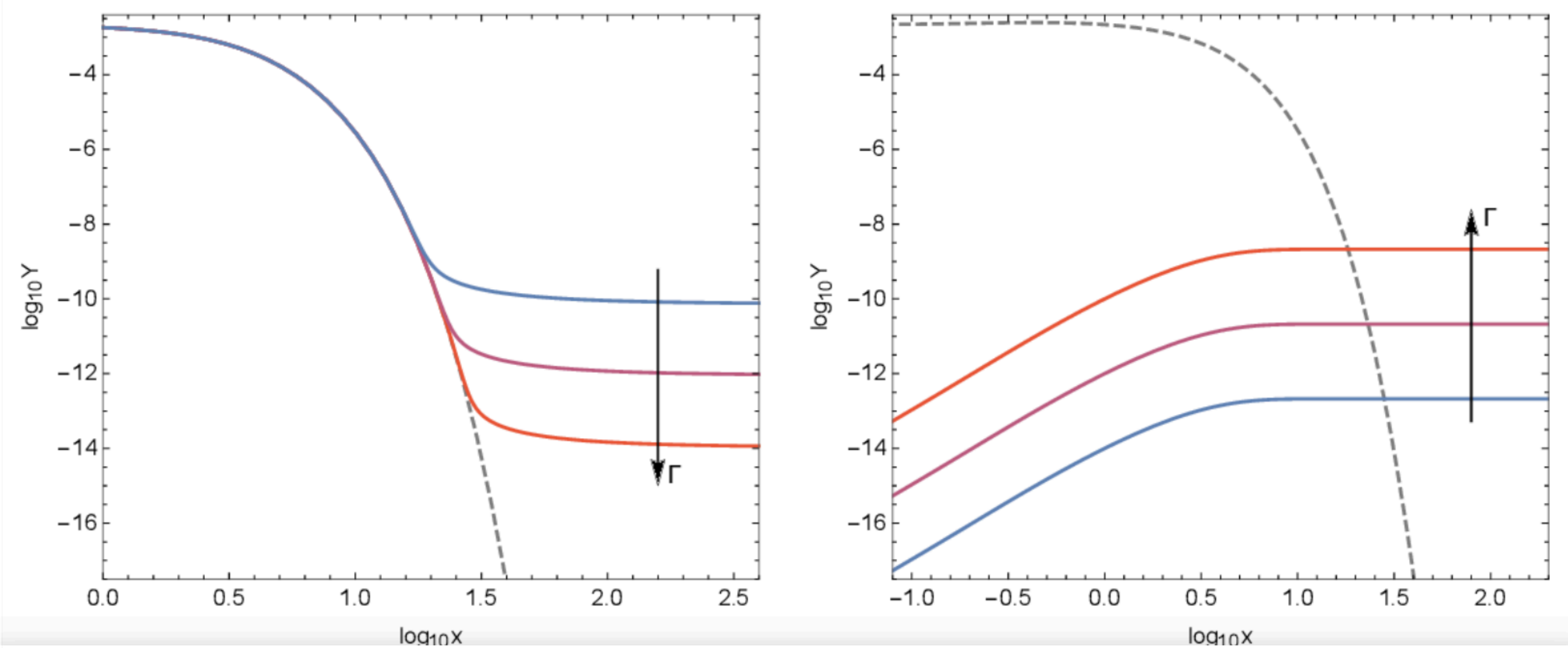
- Weakly interacting massive particle
- Feebly interacting massive particle
- Other production mechanisms, such as conversion driven freeze out

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

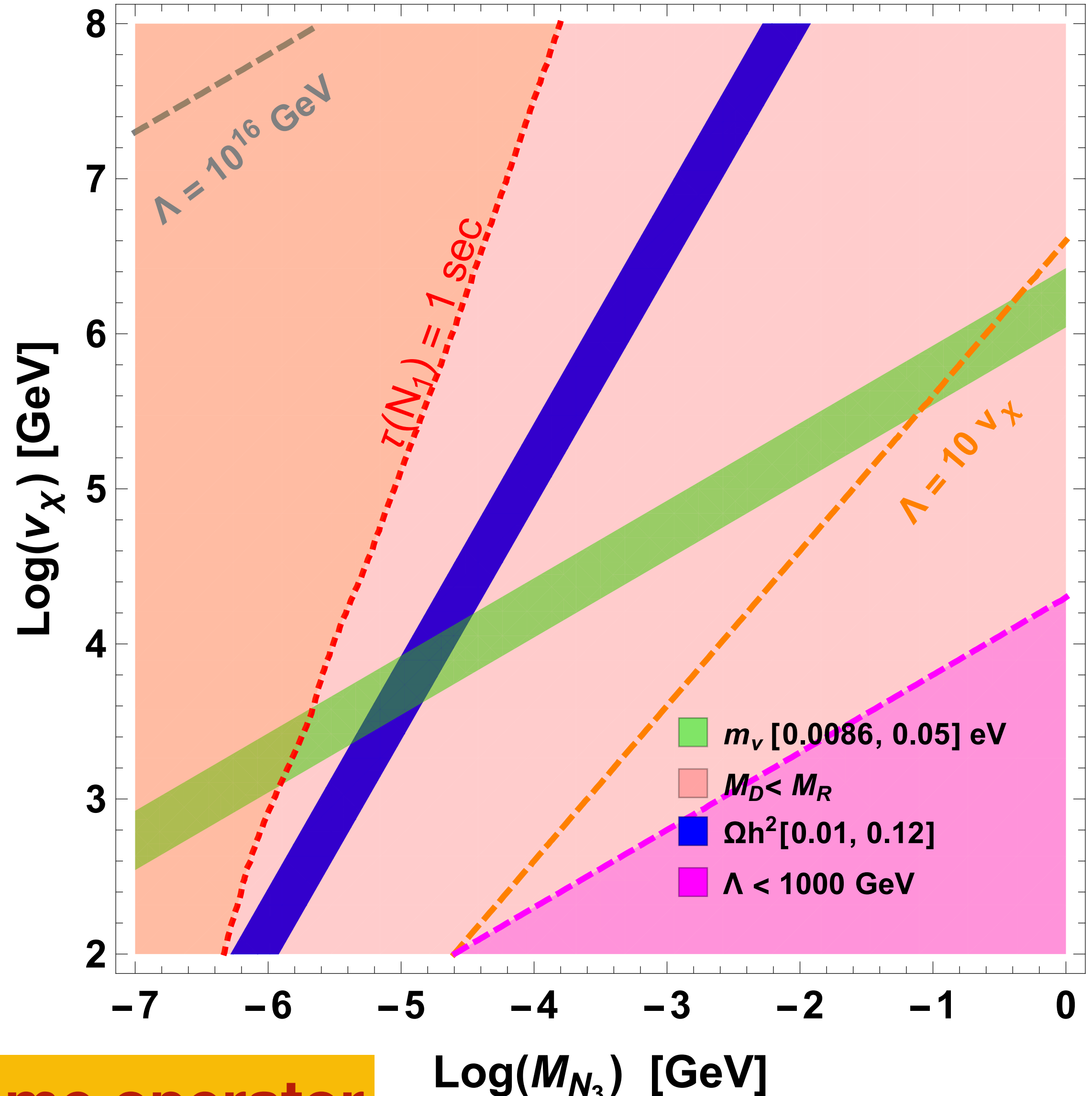
Right handed neutrinos, TeV scale BSM neutral Higgs boson, and FIMP dark matter in an EFT framework

$$\mathcal{L}_{eff} = M_B N_i^T C^{-1} N_i + \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \Phi^\dagger \Phi + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + H.C.$$

$M_B = 0$

- Dimension-5 operators with RHN field (DM) N and SM gauge singlet scalar χ
- N3 is Dark Matter
- Freeze-in production of N3
- Correlation with the BSM Higgs state
- BSM Higgs mass ~ vev.

$$\langle \chi \rangle = v_\chi, \quad M_{N_3} = \frac{c}{\Lambda} v_\chi^2$$



Primery dark matter production $\chi \to N_3 N_3$

DM mass and production is governed by the same operator

BSM Higgs mass is $M_H^2 \sim v_\chi^2$

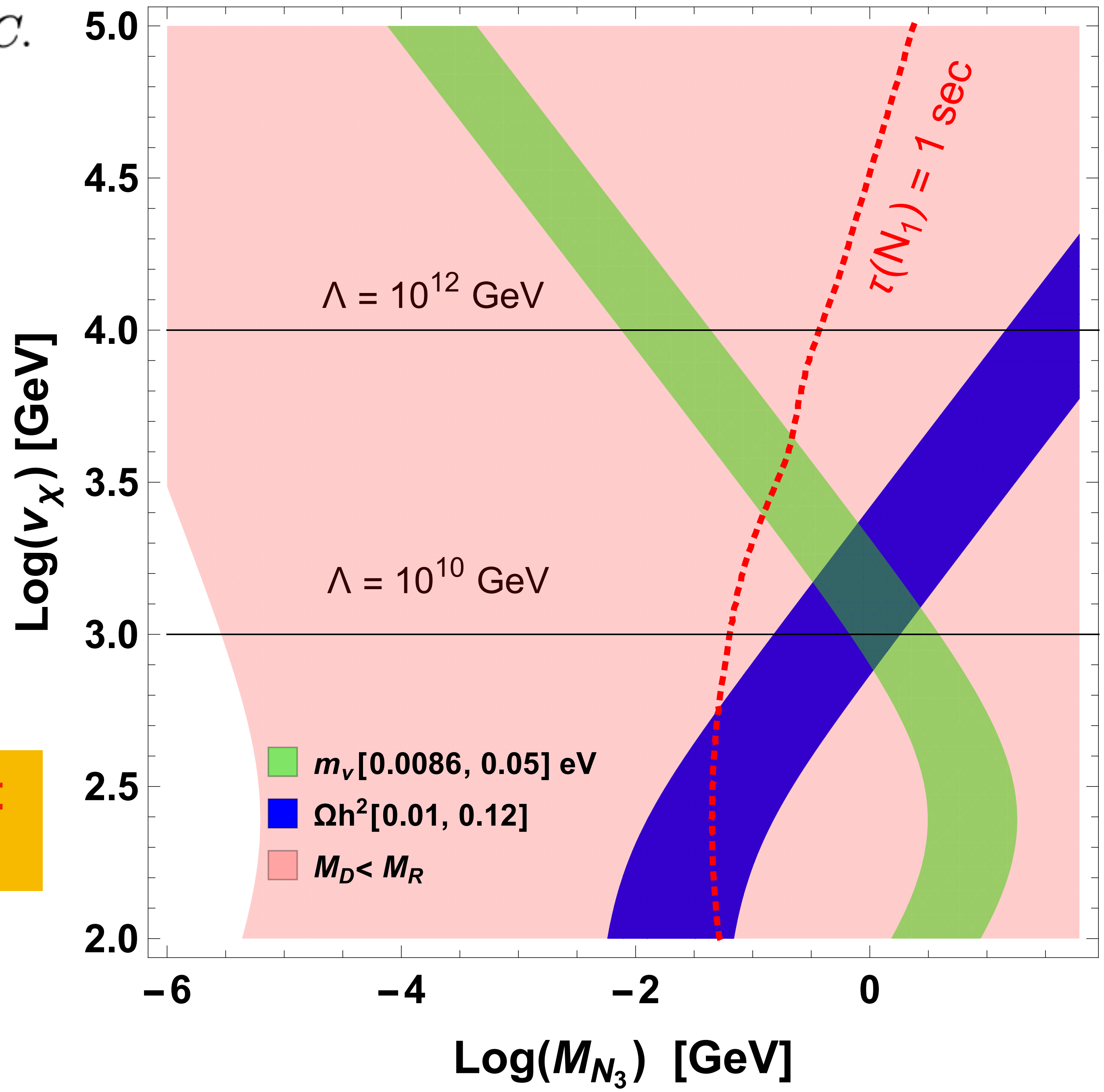
TeV scale BSM Higgs/vev requires DM in the KeV range

Belanger, Khan, Padhan, Mitra and Shil, *Phys.Rev.D 104 (2021) 5, 055047*

Right handed neutrinos, TeV scale BSM neutral Higgs boson, and FIMP dark matter in an EFT framework

$$\mathcal{L}_{eff} = M_B N_i^T C^{-1} N_i + \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \Phi^\dagger \Phi + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + H.C.$$

With a non-zero bare mass term



GeV scale DM mass is also consistent with a TeV scale BSM Higgs mass

HNL as WIMP: Dynamic Scotogenic Model with Global B-L Extension

$$-\mathcal{L}_Y \supset Y^{\ell}_{ij}\bar{L}_i\Phi\ell_{R_j} + Y^{\nu}_{ij}\,\bar{L}_i\tilde{\eta}N_j + \frac{1}{2}Y^N_{ij}\,\sigma\bar{N}^c_iN_j + h.c.,$$

Phys. Rev. D 107, 095019

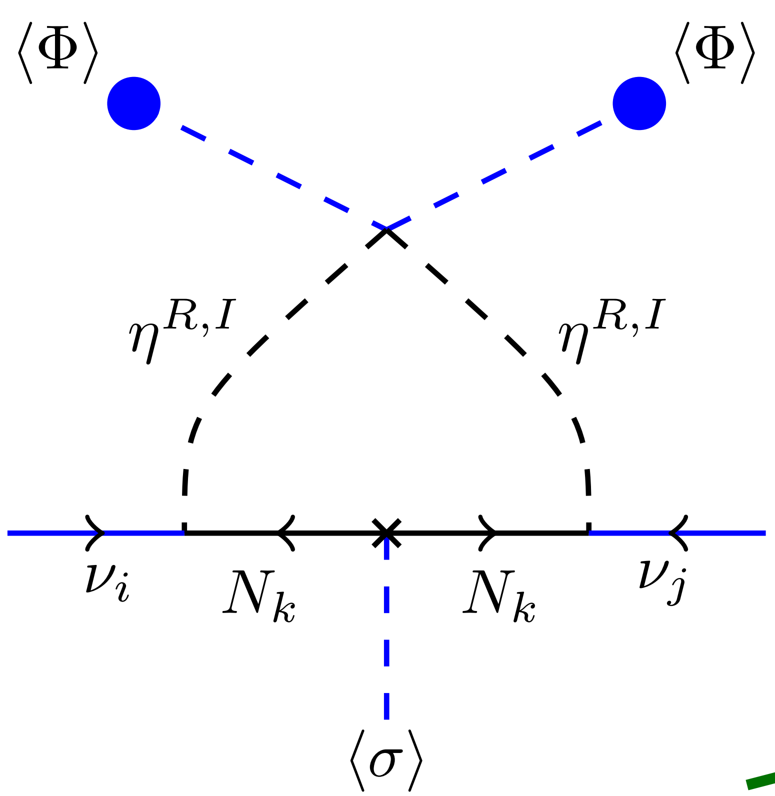
- Vev of σ breaks global B-L

Majoron state J

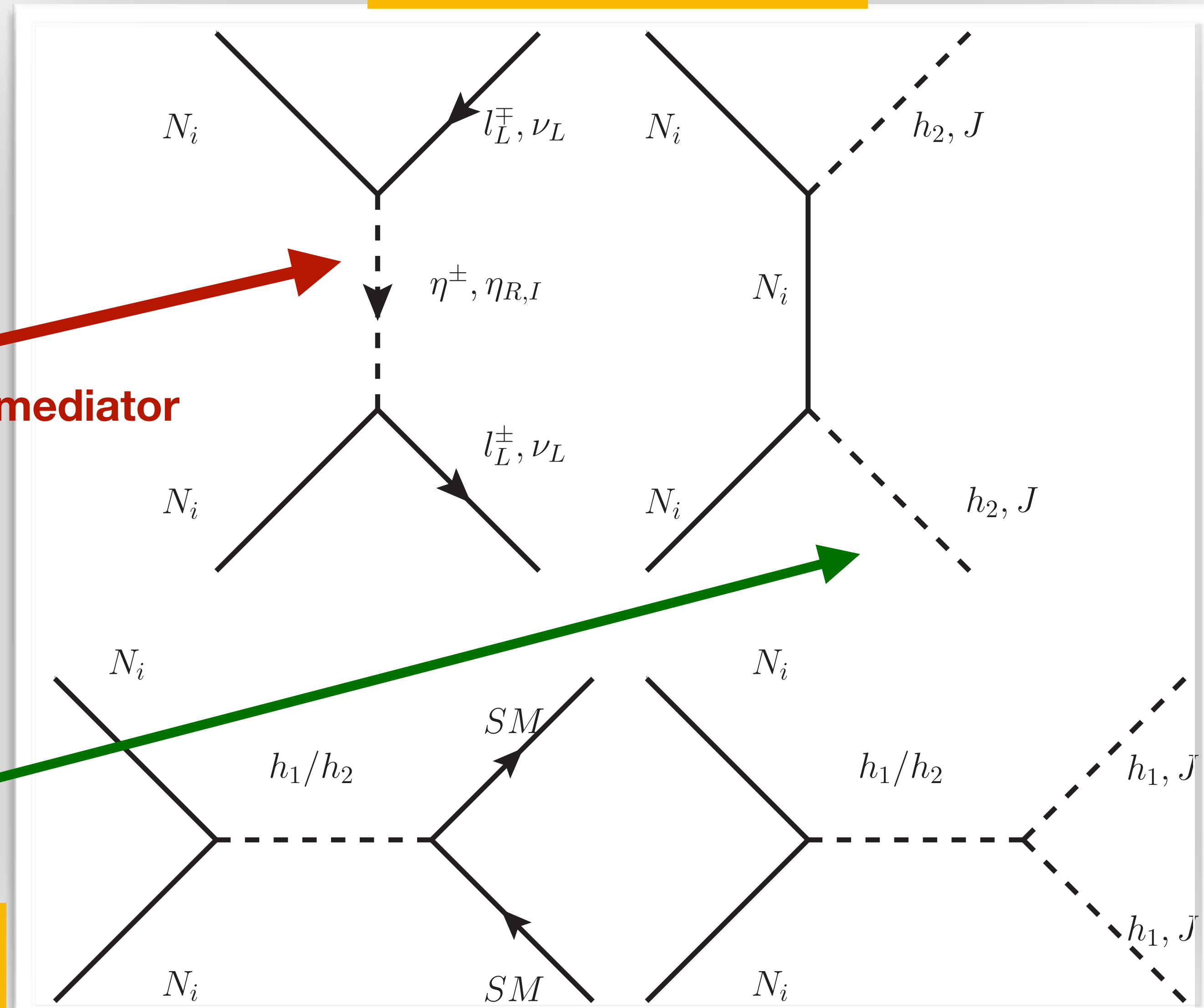
$$V = m^2_{\Phi}\Phi^\dagger\Phi + m^2_{\eta}\eta^\dagger\eta + m^2_{\sigma}\sigma^*\sigma + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_\eta(\eta^\dagger\eta)^2 + \lambda_3(\eta^\dagger\eta)(\Phi^\dagger\Phi) + \lambda_4(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$+ \frac{\lambda_5}{2}\left[(\eta^\dagger\Phi)^2 + \mathrm{h.c}\right] + \lambda_\sigma(\sigma^*\sigma)^2 + \lambda_{\Phi\sigma}(\Phi^\dagger\Phi)(\sigma^*\sigma) + \lambda_{\eta\sigma}(\eta^\dagger\eta)(\sigma^*\sigma).$$

HNL N as the DM

Neutrino mass generated in loop



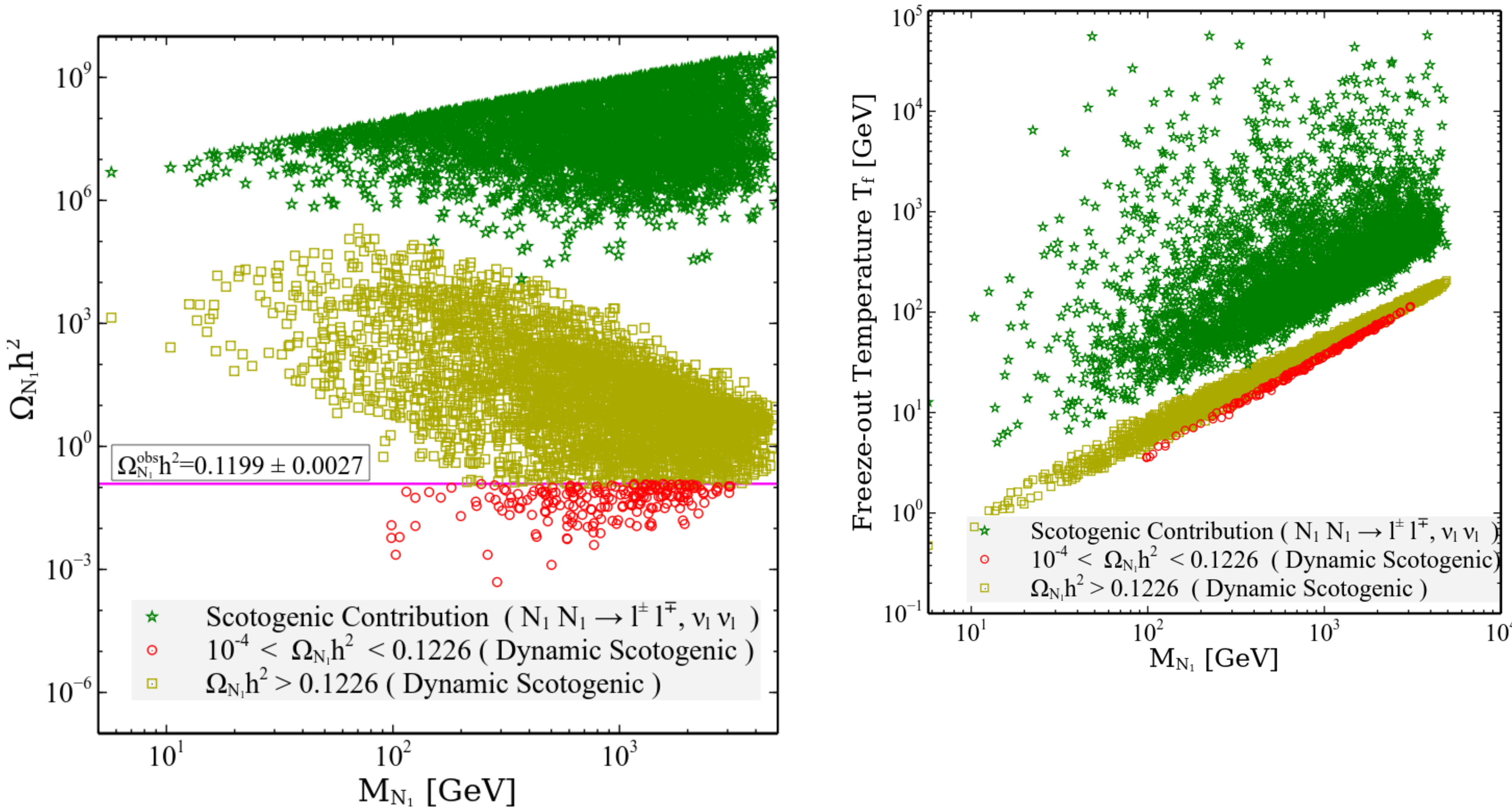
Inert doublet as mediator



DM DM annihilation to Majoron state, NN -> J J can play significant role in determining relic abundance

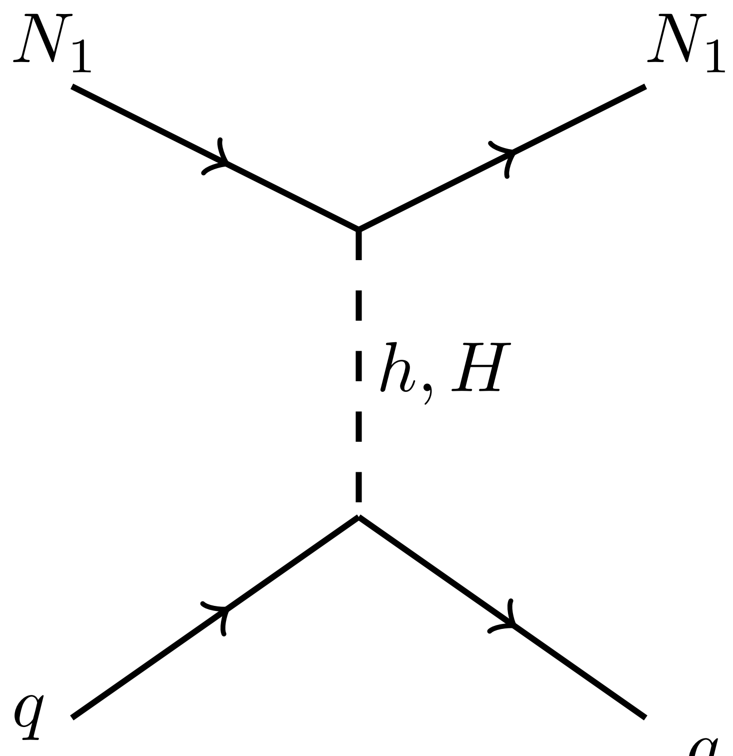
EJChun, S. Mandal, M. Mitra, A. Roy – JHEP08(2023)130

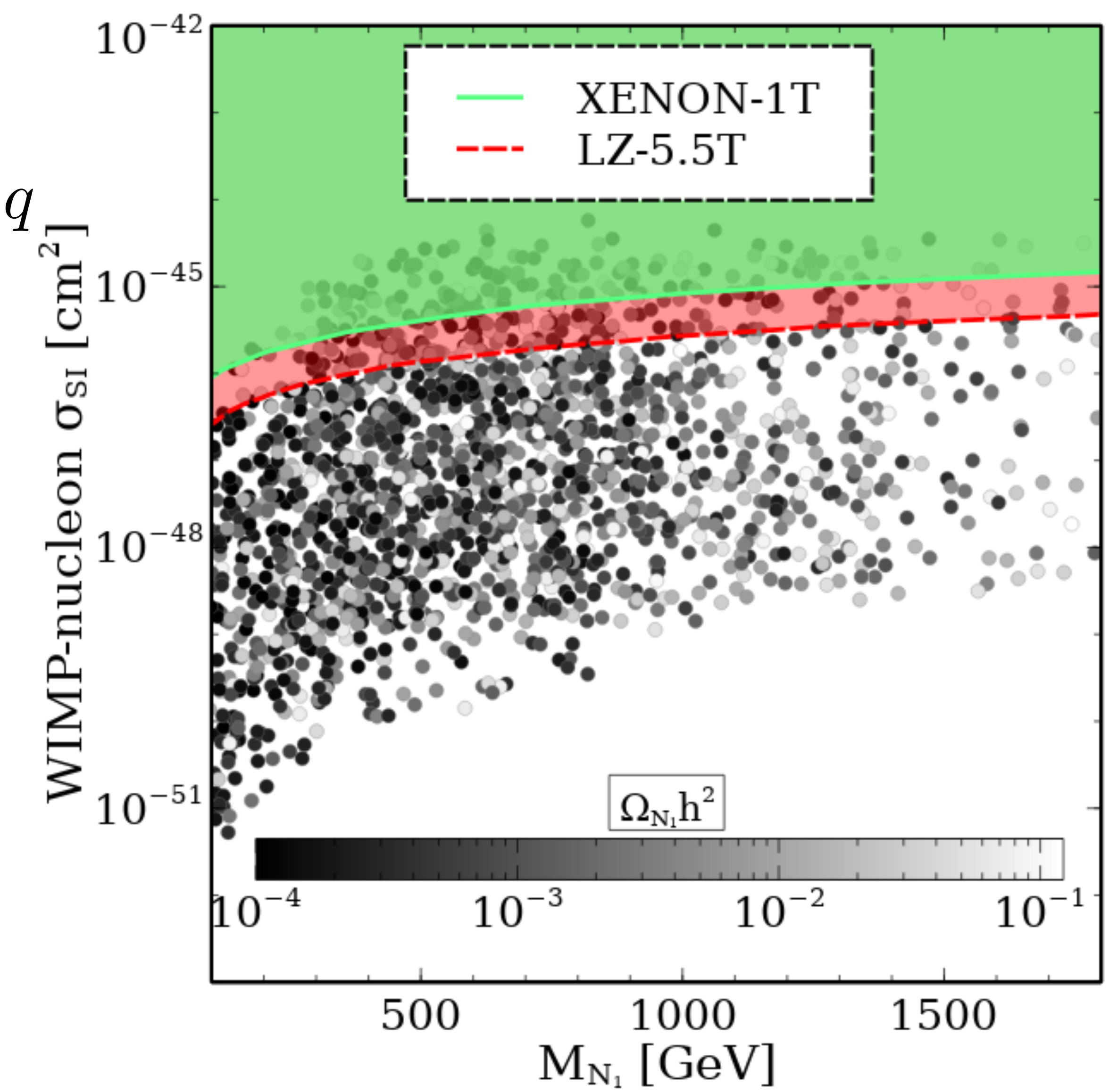
Relic abundance of DM

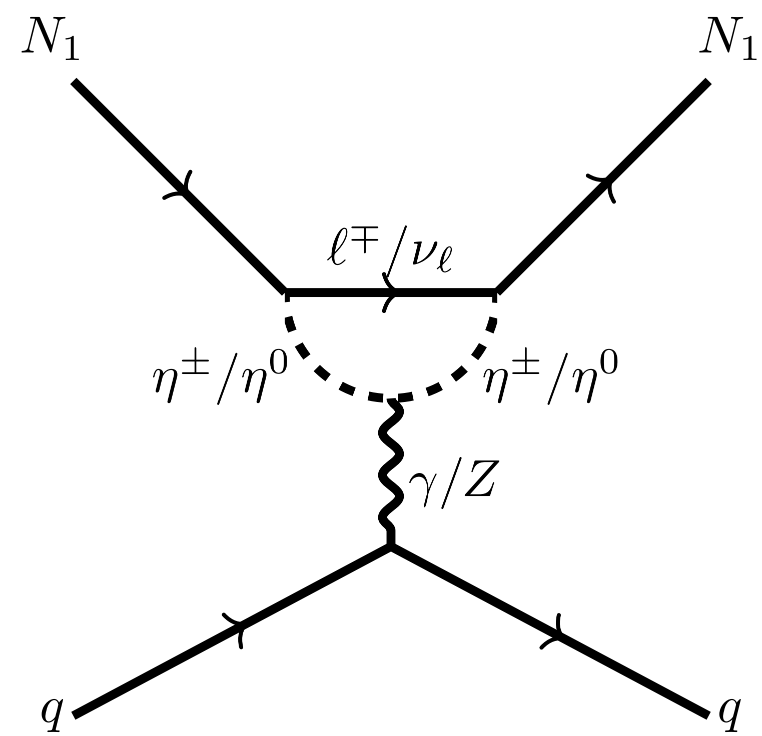


- Additional DM DM to Majoron annihilation processes can give significant contributions
- Freeze out temperature becomes smaller
- DM relic density is satisfied for a wide range of masses

Direct detection signature





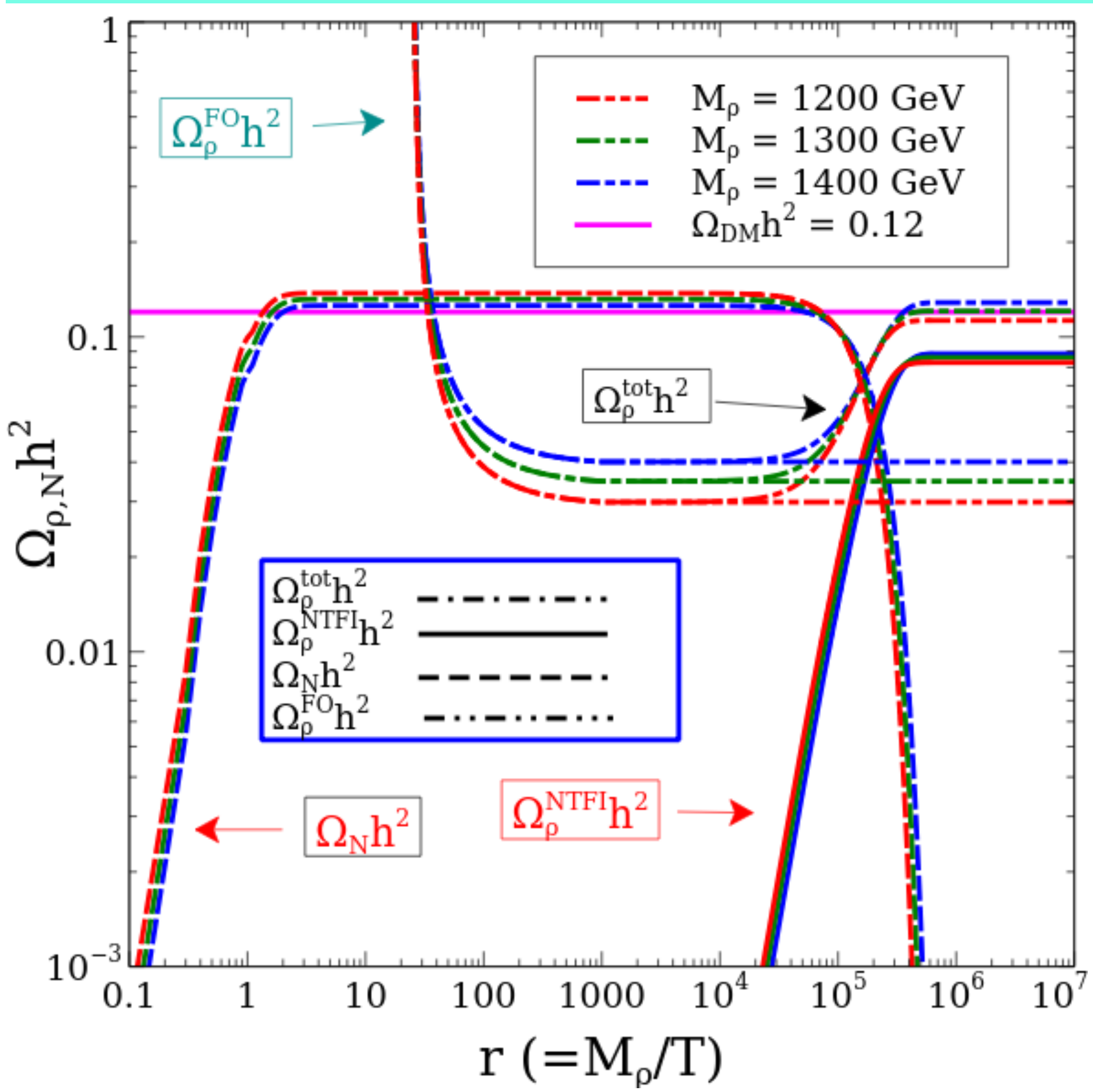


HNL as NLOP

Dark matter production for singlet-triplet fermonic model

- Model contains HNL state N and triplet state ρ, and BSM Higgs states H_2
- Triplet state ρ is WIMP dark matter. (typically for < 2 TeV mass, it will be under-abundant)
- Gauge singlet N is not in thermal bath, BSM Higgs H_2 is in thermal equilibrium
- The decay $H_2 \to \rho N$ governs the production of N
- The late decay of $N \to H_{SM}\rho$ is important in determining the relic abundance
- Since N is non-thermal, determine the distribution function

$$\hat{L} f_N = \mathcal{C}^{H_2\to N\rho} + \mathcal{C}^{AB\to N\rho} + \mathcal{C}^{N\to\ all},$$



- Boltzmann equation for ρ

$$\frac{dY_\rho}{dr} = -\sqrt{\frac{\pi}{45G}}\frac{M_{Pl}\sqrt{g_*(r)}}{r^2}\langle\sigma_{eff}|v|\rangle\left(Y_\rho^2-(Y_\rho^{eq})^2\right) + \frac{M_{Pl}\, r\,\sqrt{g_\star(r)}}{1.66\, M_{sc}^2\, g_s(r)}\left[\langle\Gamma_{H_2\to N\rho}\rangle(Y_{H_2}-Y_N Y_\rho)+\langle\Gamma_{N\to\rho A}\rangle_{NTH}\,(Y_N - Y_\rho Y_A)\right]$$

For higher triplet mass, relic density can be satisfied.

G. Belanger, S. Choubey, R. Godbole, S. Khan, M. Mitra, A. Roy, JHEP 11 (2022) 133

Late decay $N \to \rho H_{SM}$ can alter BBN

Summary

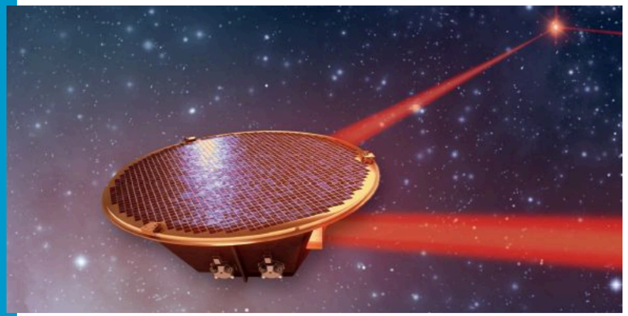
- *Few major observations in nature ~ Neutrino masses and mixings, Dark Matter, and Baryon Asymmetry in the Universe*
- **low scale neutrino mass models with heavy neutral lepton offers wide detection prospects at different terrestrial experiments, cosmic probes**
- *New signatures ~ Boosted, LLP search*
- *Astroparticle probe ~ Dark Matter, BBN*

~ Collider, precision experiments
~ Dark matter direct and indirect

Neutrino Mass Models
at
Energy, Intensity, Cosmic frontiers

GERDA

SHiP
Search for Hidden Particles



Thank You

Higher Dimensional Probe of Seesaw

Babu-Nandi-Tavartkiladze (BNT) Model

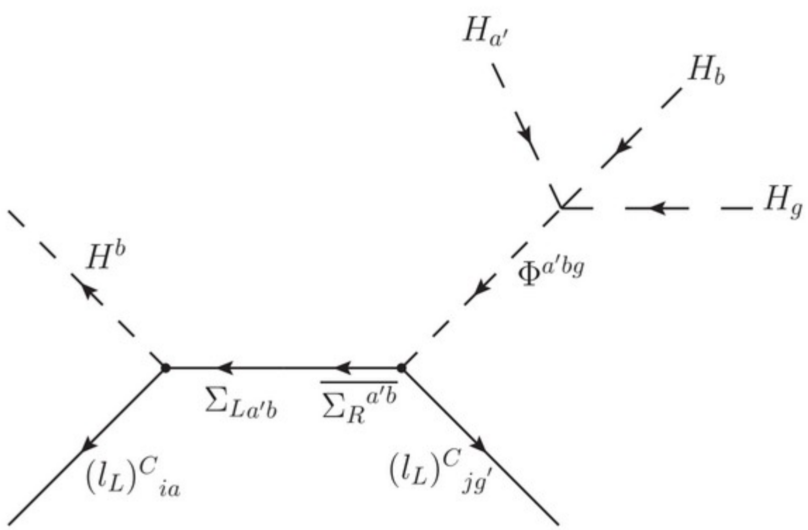
Scalar isospin 3/2 quadruplet (Φ)

$$\Phi = \begin{pmatrix} \Phi^{+++} & \Phi^{++} & \Phi^{+} & \Phi^{0} \end{pmatrix}_{Y=3}$$

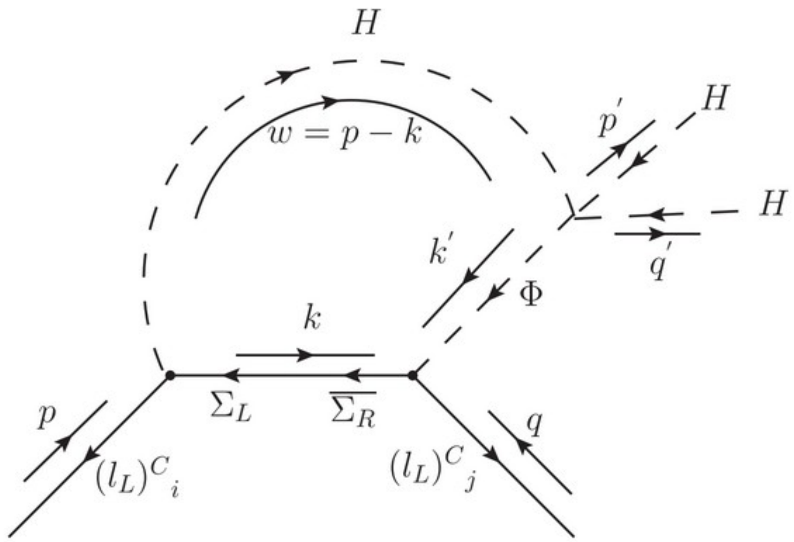
Vecor like triplet (Σ)

$$\Sigma_{R,L} = \begin{pmatrix} \Sigma^{++}_{R,L} & \Sigma^{+}_{R,L} & \Sigma^{0}_{R,L} \end{pmatrix}_{Y=2}$$

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

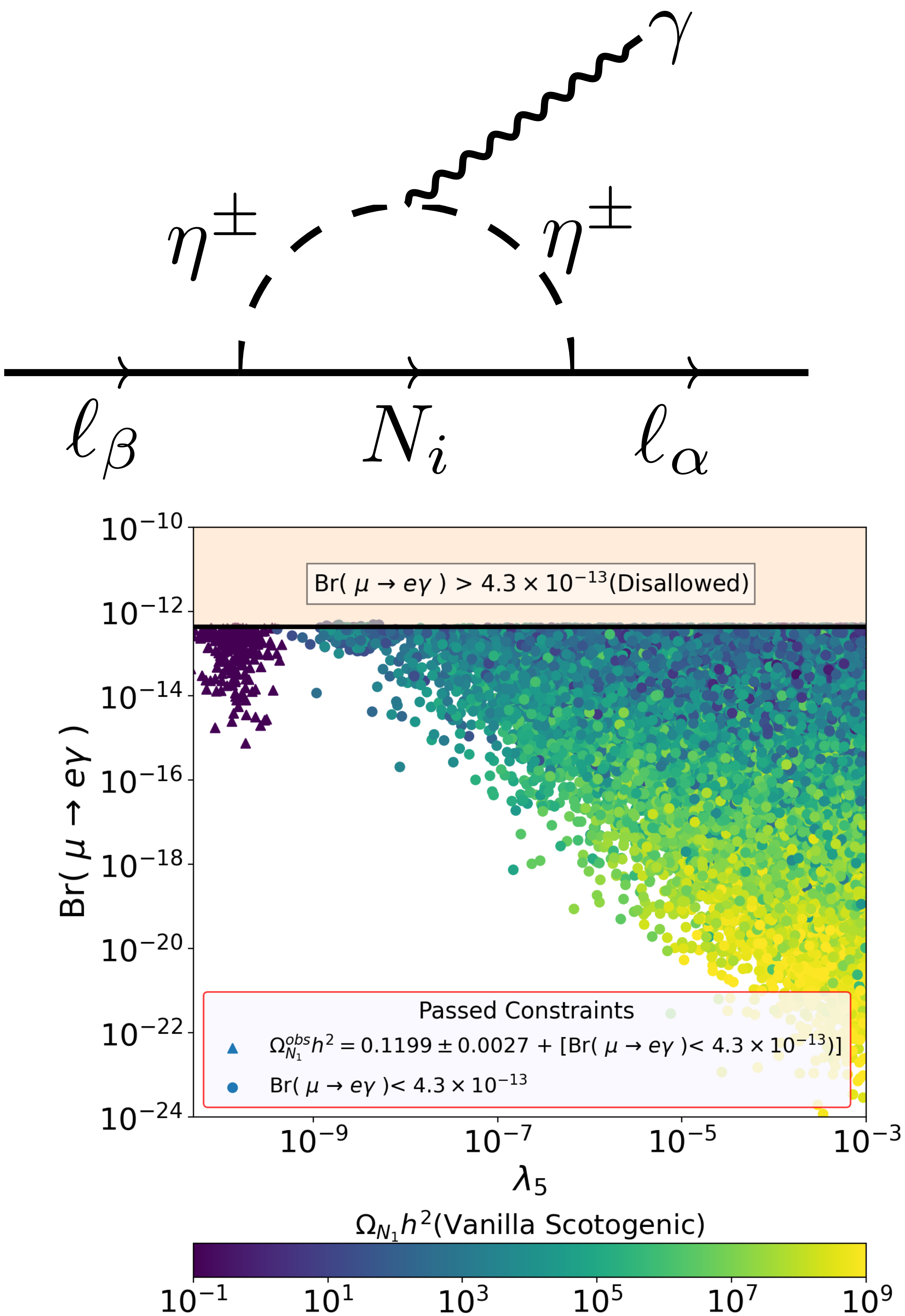
$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$
$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

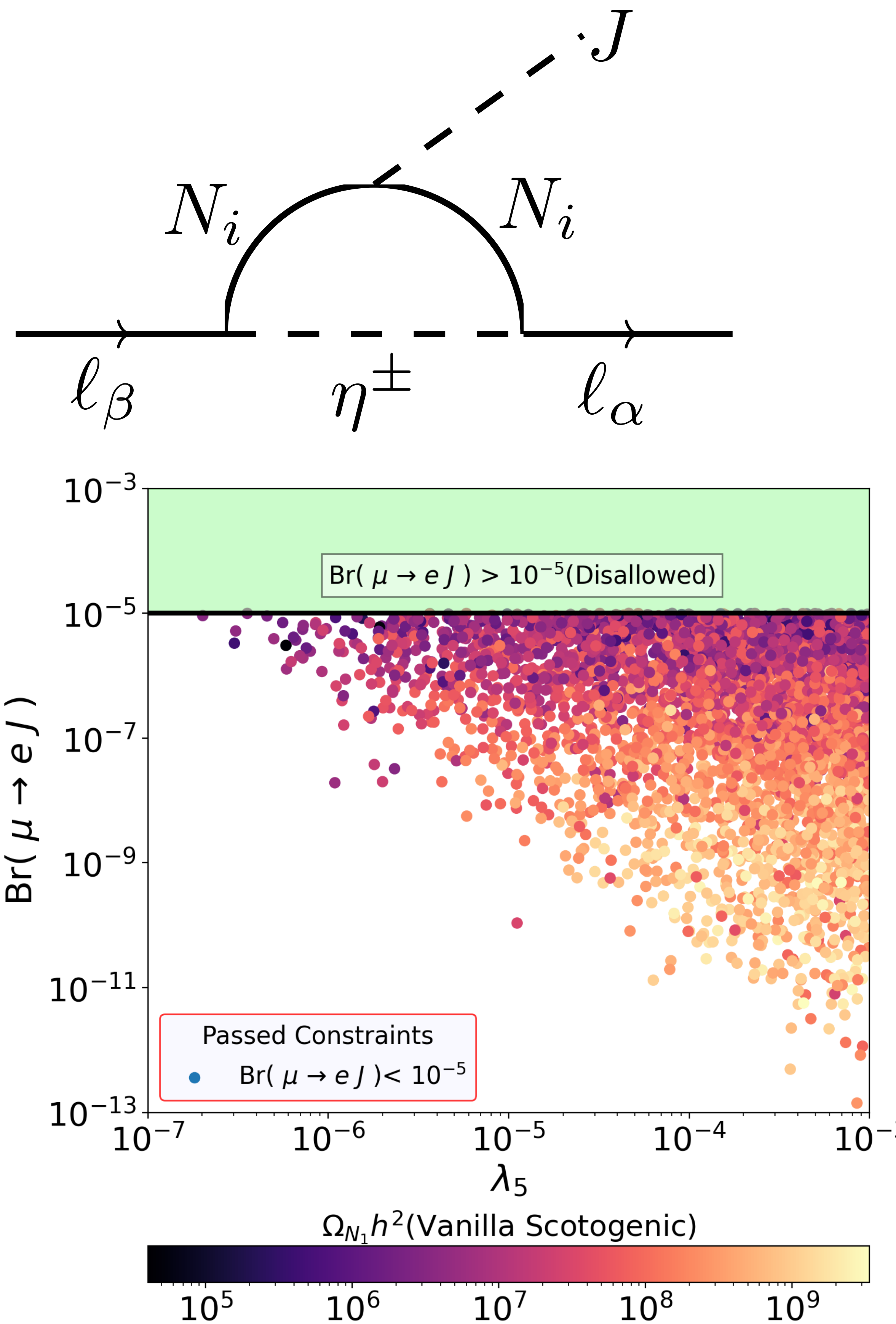
3ℓ, 4ℓ, 5ℓ and 6ℓ events
Same-sign-tri-lepton events
Lepton flavour violating (LFV) 4 lepton events

Small v_Φ

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

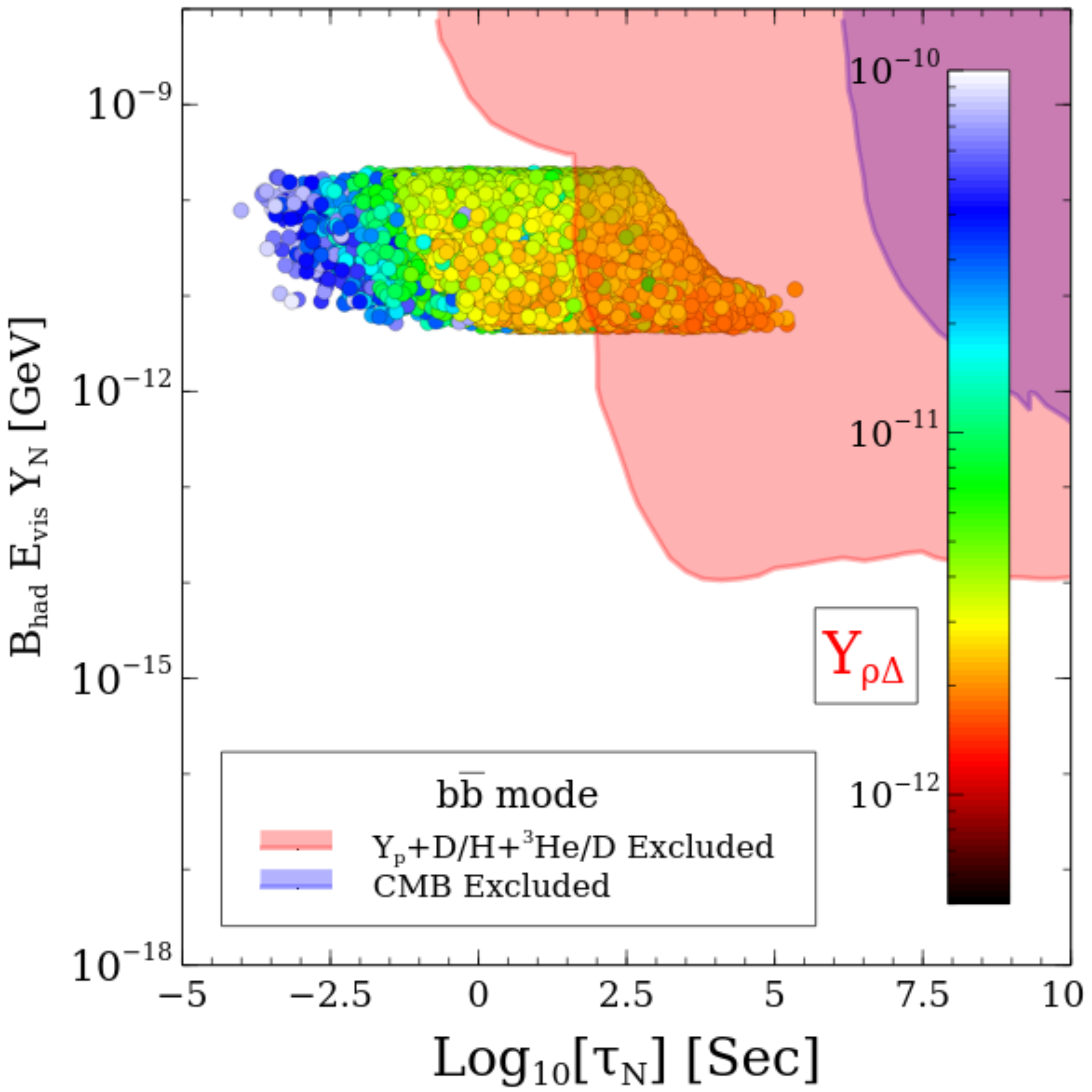
Lepton flavour violation





N as NLOP undergoes the late decay

Impact of late decay of N in BBN



Late decay $N \to \rho H_{SM}$ can alter BBN observation

Lifetime of N can be constrained