Direct and Indirect Probes of Seesaw

Manimala Mitra

Institute of Physics (IOP), Bhubaneswar

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LAPTh, Annecy

Outline:

Origin of Neutrino Masses, Mixings and Discovery Prospects

- Beyond Standard Models (Type-I, Type-II Seesaw, And Left-Right Symmetry)

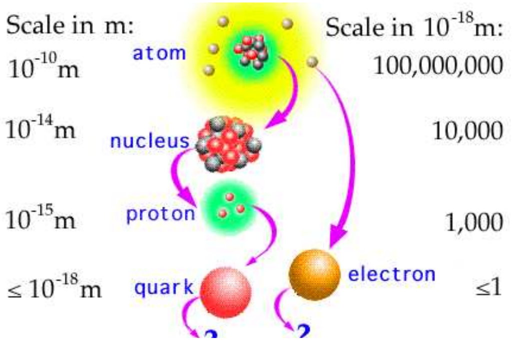
↓

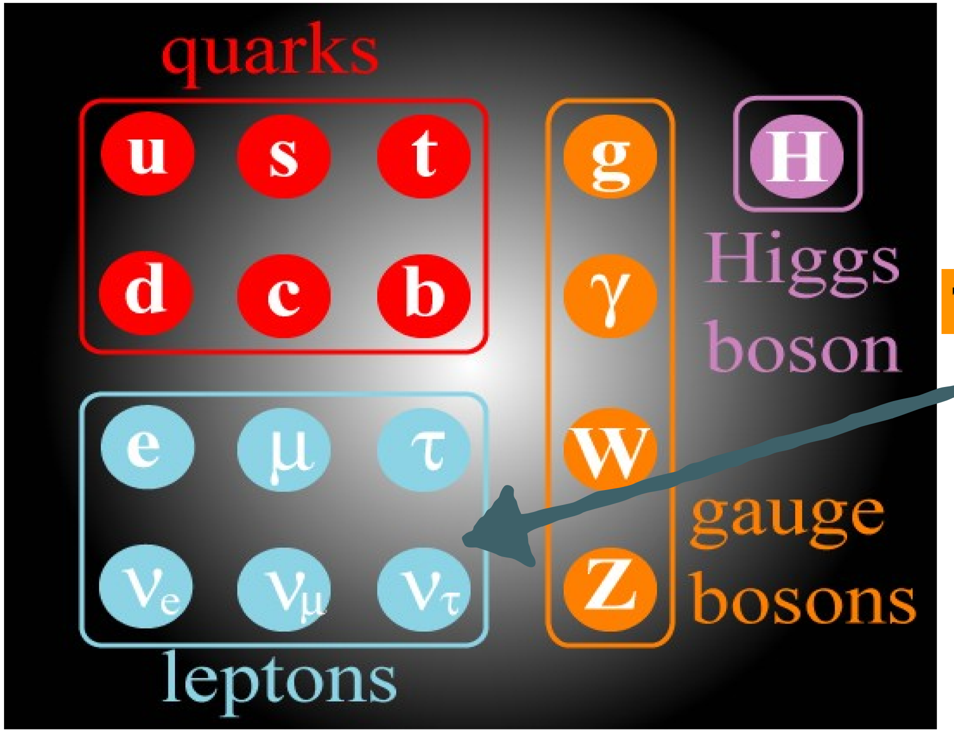
- Collider searches
- Non-collider searches

Standard Model of particle physics

Glashow 61; Weinberg, Salam 67.

Gauge group $\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$





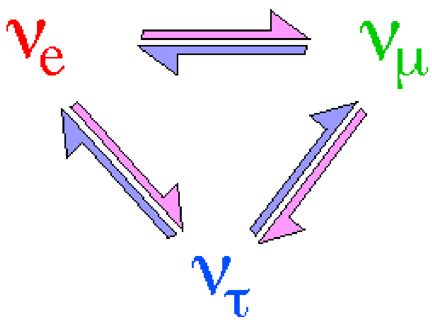
Three generation of neutrinos

Electroweak interaction

Neutrino Oscillation $\nu_\alpha \rightarrow \nu_\beta$

Bruno Pontecorvo, 1957
Solar, atmospheric, reactor, long-baseline

Neutrinos of a specific flavor oscillates into a different flavor while propagating over a distance.



- Three families $\rightarrow \nu_e,\ \nu_\mu,\ \nu_\tau$ in standard model flavor basis

$$|\psi_f\rangle = U \times |\psi_m\rangle$$

Two neutrino scenario $\rightarrow$ flavor state $|\psi_f\rangle = (\nu_e, \nu_\mu)^T$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mass eigenstate $|\psi_m\rangle = (\nu_1, \nu_2)^T$

Oscillation probability $P(\nu_e \rightarrow \nu_\mu) \simeq \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 L}{4E}$

Non-zero probability

Mass and mixing non-zero

Extend two generation to three generation $\rightarrow (\nu_e, \nu_\mu, \nu_\tau)^T$

More parameter involved

- Three mixing angles θ_{12}, θ_{13}, θ_{23}
- Two mass square differences Δm^2_{21}, $|\Delta m^2_{31}|$
- Three phases Dirac phase-δ, Majorana phases-α and β

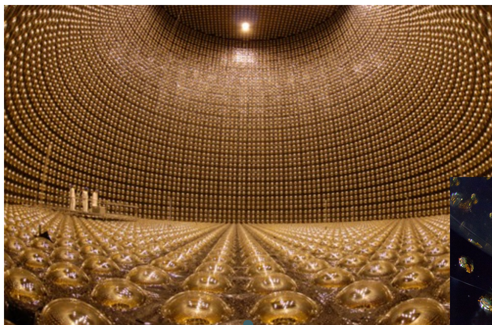
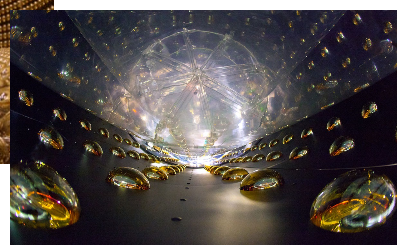
Mixing matrix is $U_{PMNS} =$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

Neutrino Mass and Mixing:

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

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

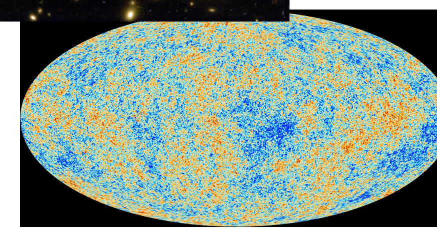
$$|\Delta m^2_{31}| = (2.41 - 2.60) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.273 - 0.379, \sin^2\theta_{23} = 0.445 - 0.599$$

Large angle $\theta_{12} \sim 34.5^\circ, \theta_{23} \sim 47.7^\circ$

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

P. F. de. Salas et al., arXiv: 1708.01186

Bound from cosmology

$$\Sigma m_i < \mathcal{O}(0.17 - 0.72)$$

(Planck Collaboration, arXiv 1502.01589)

Relaxed bound from β decay

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.3\ \mathrm{eV}$$

(Mainz, Troitzk)

$m_\nu < 1.1\,eV$ **By KATRIN, 2019**

Why BSM?

The experimental observation of neutrino mass and mixing demands Beyond Standard Model physics

Neutrinos could be Dirac or Majorana

$m_d\bar{\psi}_L\psi_R$

$m\nu^T C^{-1}\nu$

Dirac mass

Majorana mass

ψ_R is missing in the Standard Model

Not gauge invariant

Major Puzzles

Beyond The Standard Model (BSM) theory is necessary

- **Underlying theory of neutrino mass generation!**

  At present no experimental evidence

- Neutrinos are electromagnetic charge neutral

  $\rightarrow$ **Dirac or Majorana ?** Majorana particle $\rightarrow$ it's own antiparticle.

Neutrino Oscillation

- Normal vs Inverted Mass hierarchy $\longrightarrow$ ν_1/ν_3 Lightest state
- CP violation (T2K?), Ambiguity in θ_{23}

Origin of Neutrino Mass

Seesaw

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

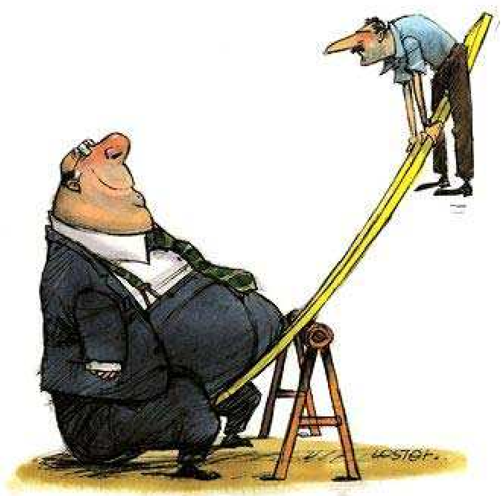
Yanagida 1979, Mohapatra, Senjanovic 1980

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

Seesaw:

Neutrinos $\sim$ eV mass??

Majorana mass from d=5 operator



Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980

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

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

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

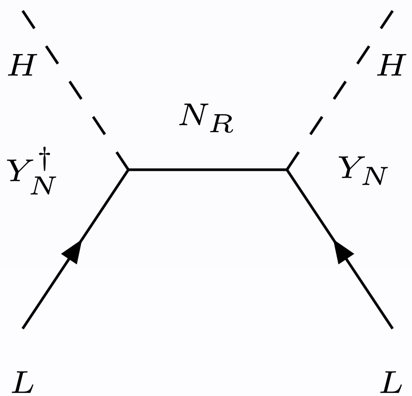
$$\frac{y^2 LL\langle H\rangle\langle H\rangle}{M} \Rightarrow m_\nu = \nu^T C^{-1} \nu$$

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

Contd:

Type-I | **Type-II** | **Type-III**

SM gauge singlet

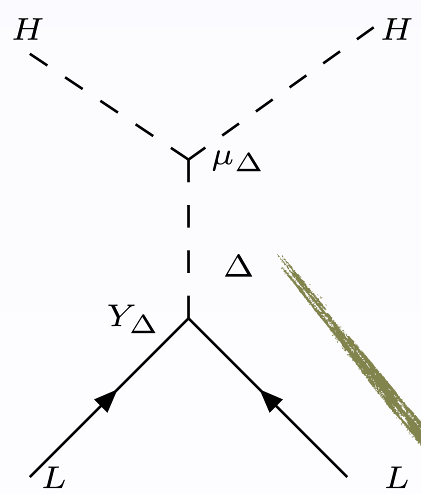


interaction of N with other SM particles is proportional to the active-sterile mixing

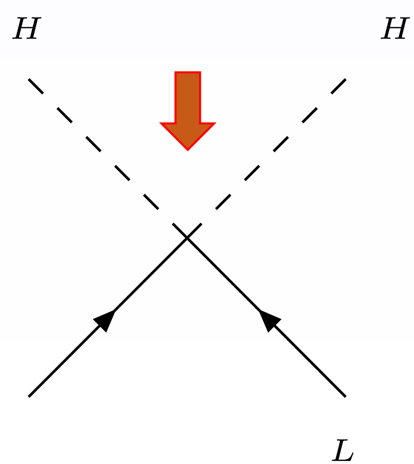
$V_{lN} \rightarrow \frac{m_D}{M}$

Suppressed

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

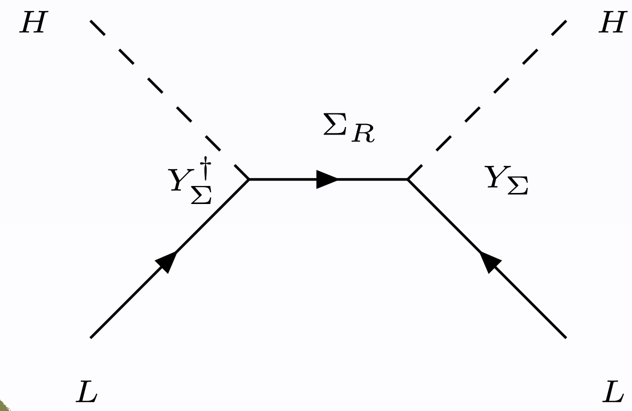


H^{++} Doubly charged Higgs



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

$\Sigma_R \rightarrow$ 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)

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^{++} → Phenomenology

Higher Dimensional Probe of Seesaw

Babu-Nandi-Tavartkiladze (BNT) Model

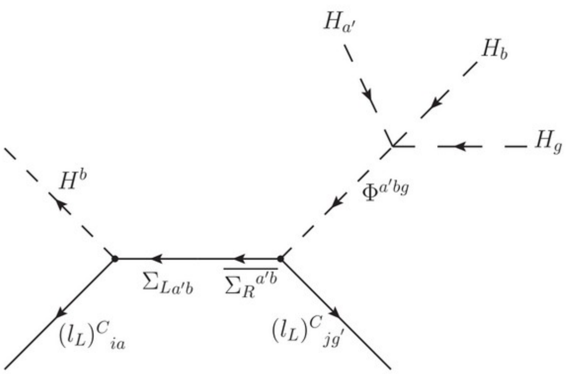
Scalar isospin 3/2 quadruplet (Φ)

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

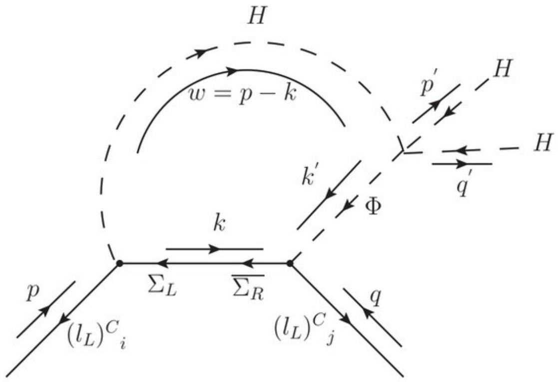
Vecor like triplet (Σ)

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

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

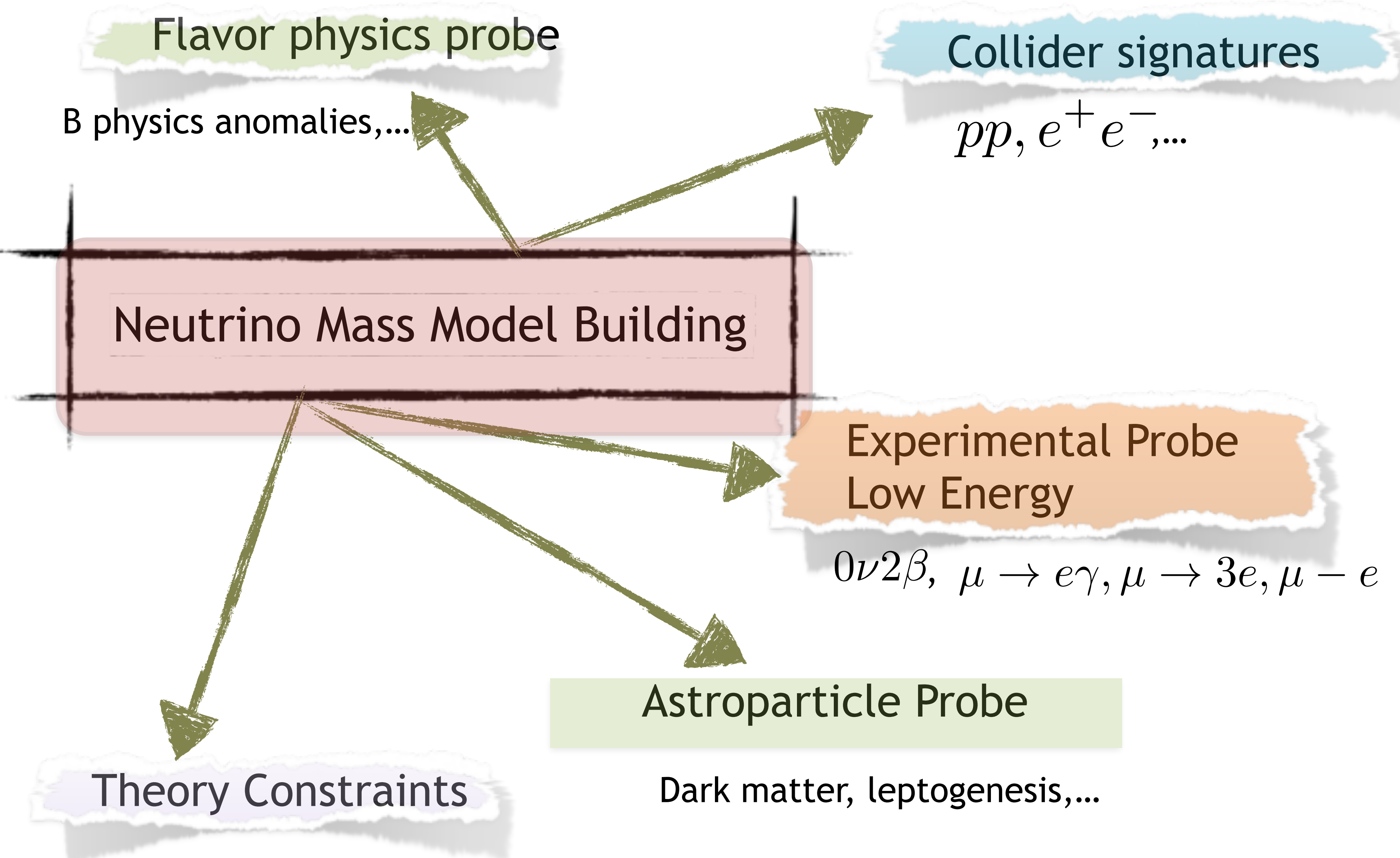
$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$
$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

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)

Experimental probe:



Sterile Neutrino:

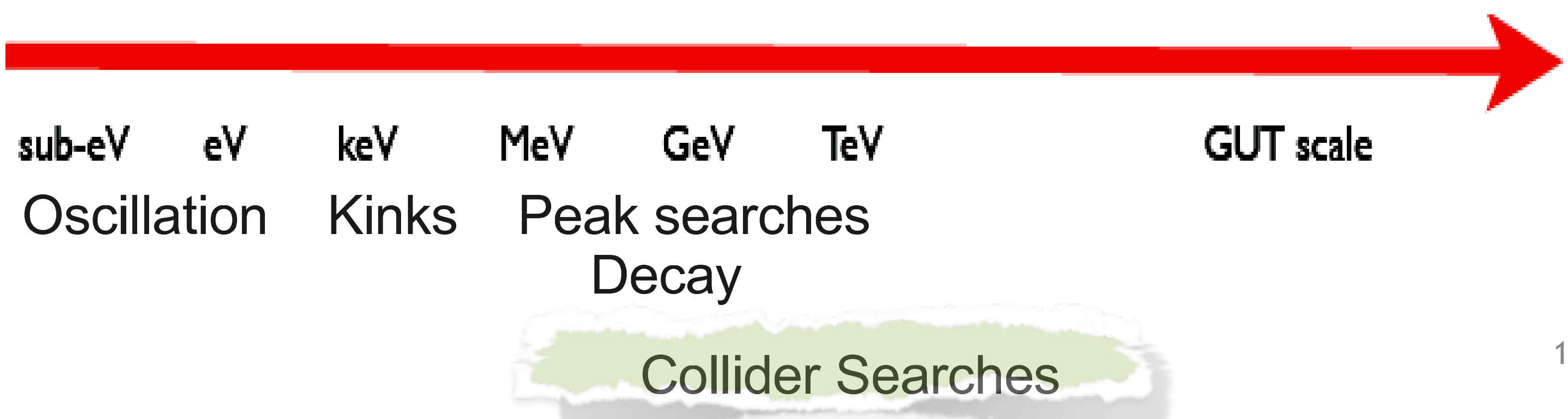
Heavy Neutrino N

⬇

Key ingredients behind neutrino mass generation

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

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

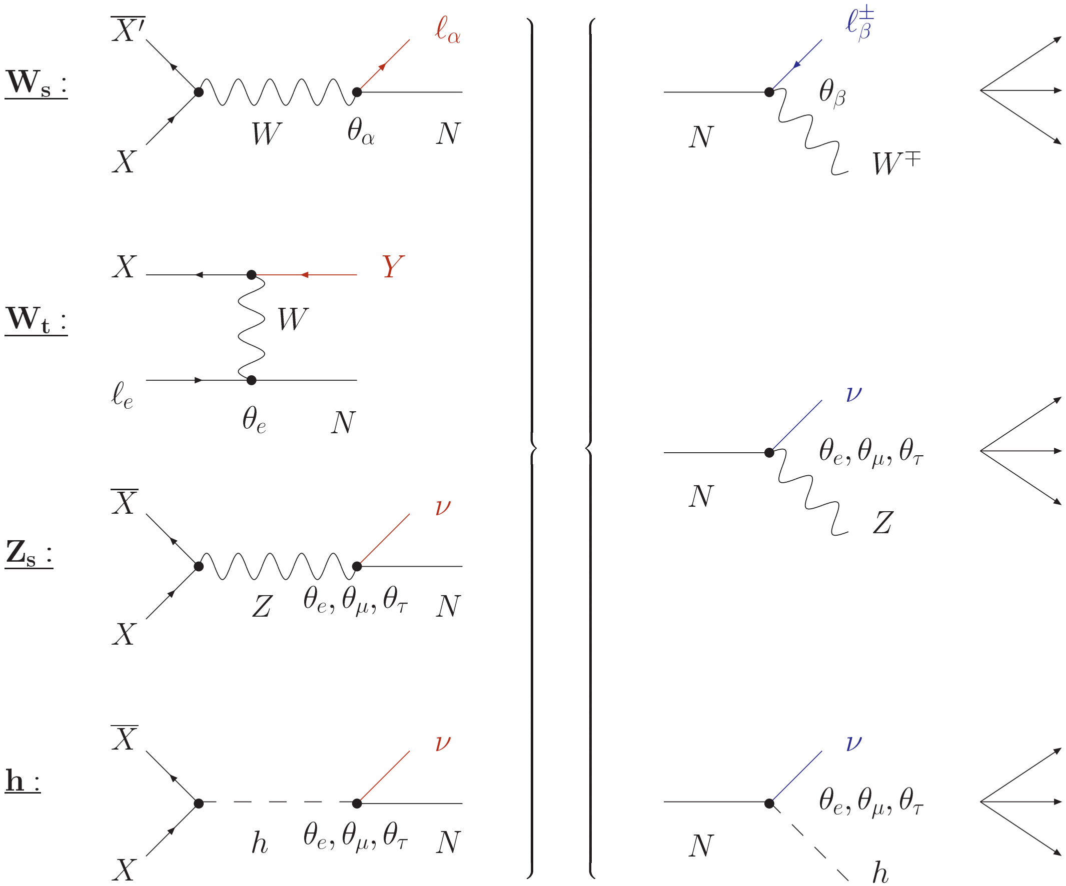


Sterile Neutrino:

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 . → $\frac{m_D}{M}$

Production Decay Final States



pp : $\ell_\alpha \ell_\beta^\pm jj$, $\ell_\alpha \ell_\beta^\pm \ell_\gamma^\mp \nu$

e⁻e⁺, e⁻p : $Y\ell_\beta^\pm jj$, $Y\ell_\beta^\pm \ell_\gamma^\mp \nu$

e⁻e⁺, pp : $\nu\ell_\beta^\pm jj$, $\nu\ell_\beta^\pm \ell_\gamma^\mp \nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu\nu\nu$

e⁻e⁺, e⁻p : $Y\nu jj$, $Y\nu\ell_\beta^\pm \ell_\beta^\mp$, $Y\nu\nu\nu$

e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu\ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu\nu\nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu VV$

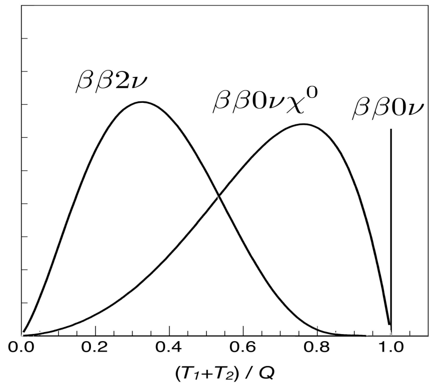
e⁻e⁺, e⁻p : $Y\nu jj$, $Y\nu\ell_\beta^\pm \ell_\beta^\mp$, $Y\nu VV$

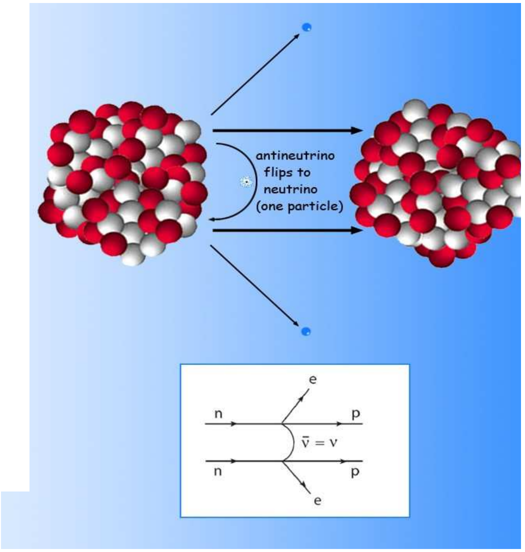
e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu\ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu VV$

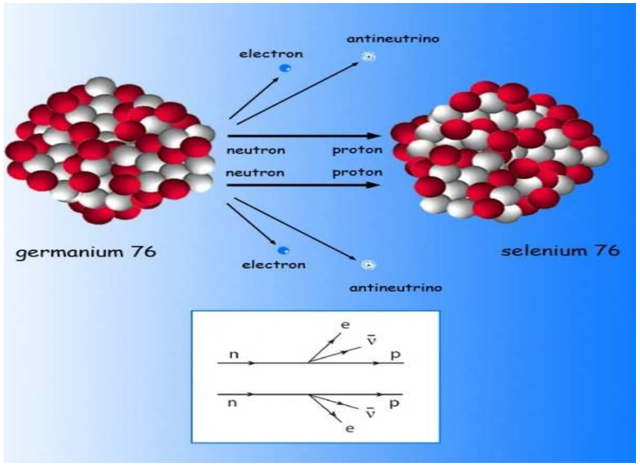
Multilepton, multijet final states

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

Neutrinoless double beta decay







The process is $(A, Z) \rightarrow (A, Z + 2) + 2e^-$

G Racah 1937; W. H. Furry

Probing lepton number violation

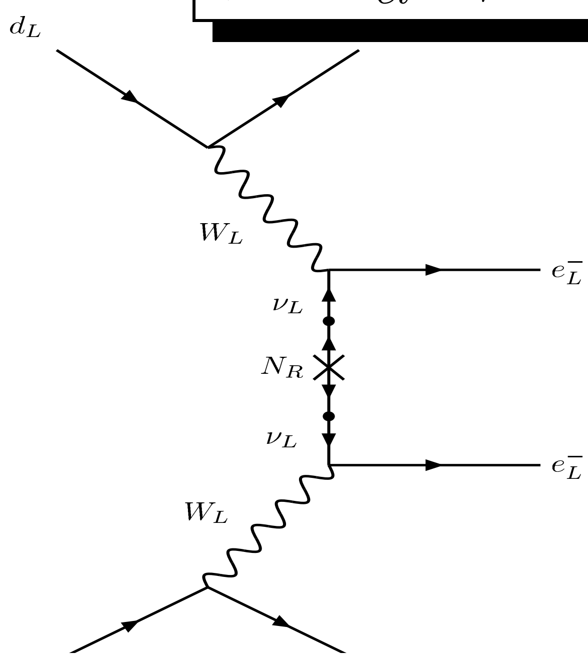
Sterile Neutrino Contribution

N Mix with light SM neutrino ν with mixing V and mass M

(**Mitra, Senjanović and Vissani, Nucl Phys B856 (2012) 26-73**)

Half-life $\frac{1}{T_{1/2}} = G_{0\nu} \left|\mathcal{M}_\nu \eta_\nu + \mathcal{M}_N \eta_N\right|^2$

$\eta_\nu = U_{ei}^2 m_i/m_e$, $\eta_N = V^2 m_p/M$



$M_i^2 > p^2 \sim (200)^2 \text{MeV}^2$; $p \to$ intermediate momentum

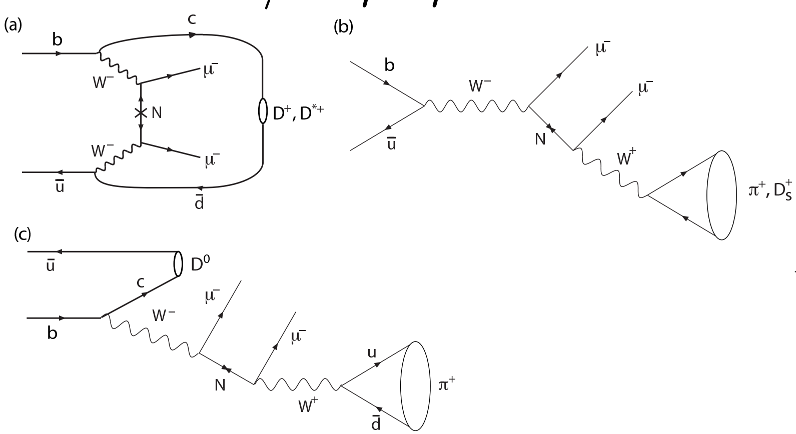
Controlled by V and M

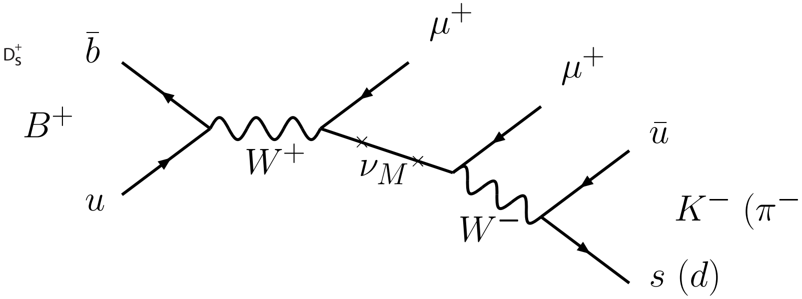
Other LNV Searches:

Meson decay and Collider Searches

Lepton number violation in meson system

$B^- \to D^+/\pi^+\mu^-\mu^-$, $B^- \to D^{*+}\mu^-\mu^-$, $B^- \to D^0\pi^+\mu^-\mu^-$, $B^+ \to K^-/\pi^-\mu^+\mu^+$





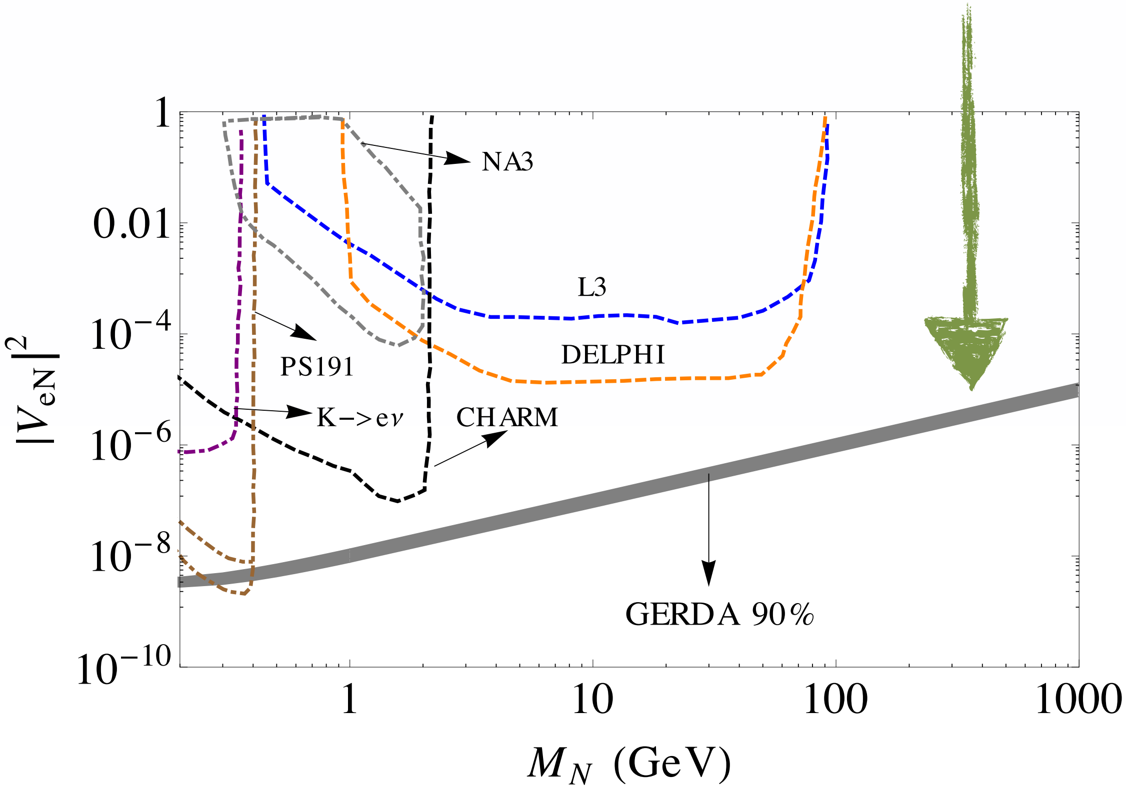
LHCb collaboration, 2012; LHCb collaboration, 2011; BELLE collaboration, O. Seon et al., 2011.

Also lepton number violating τ decays by BABAR, LHCb

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.



Mitra, Pascoli, Wong, 2013 ;

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

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

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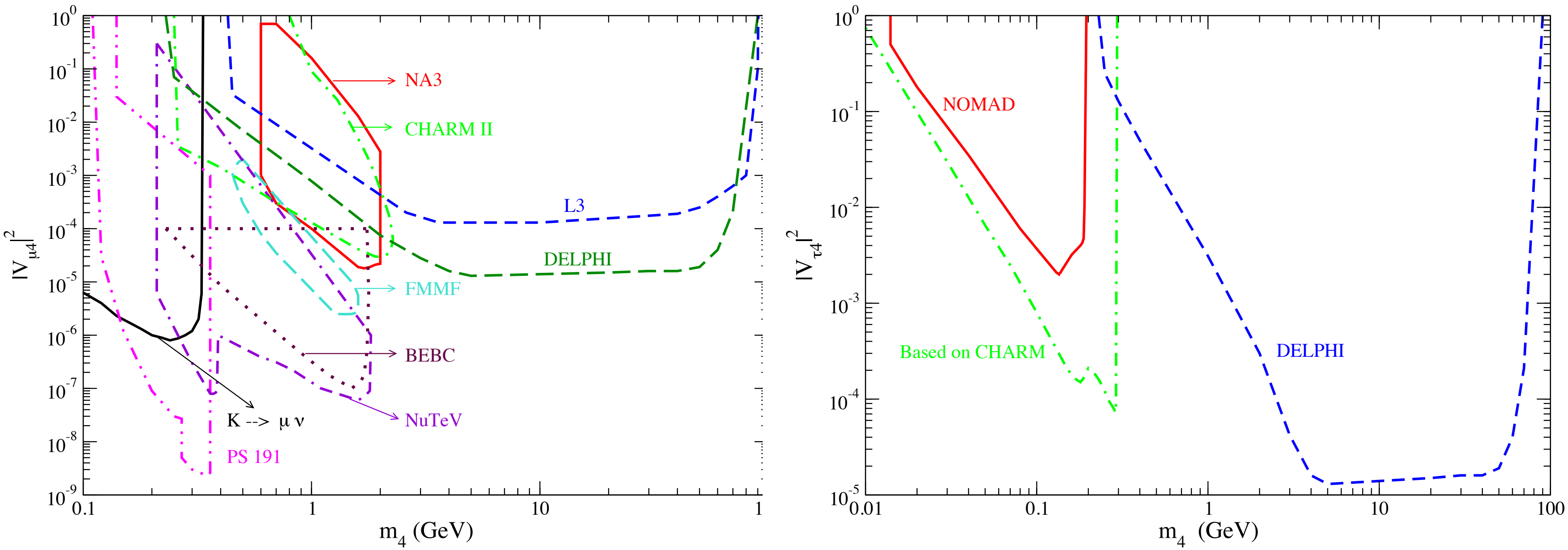
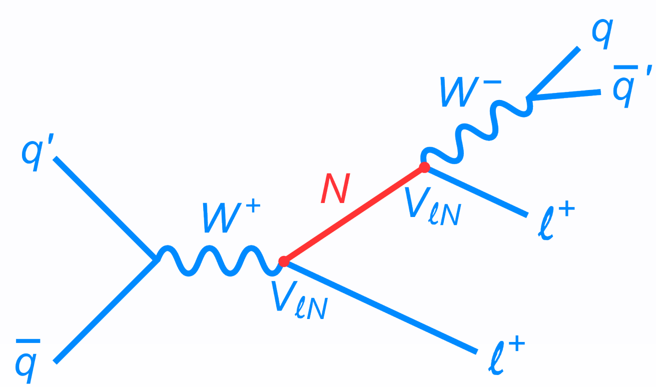
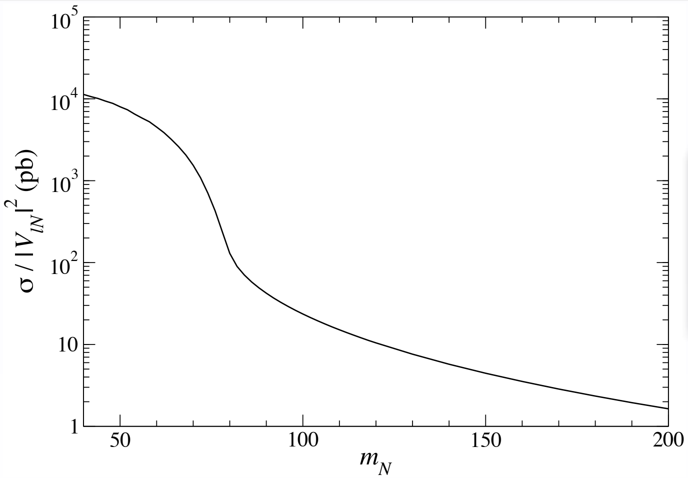


Atre et al., JHEP **0905**, 030 (2009)

- 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)



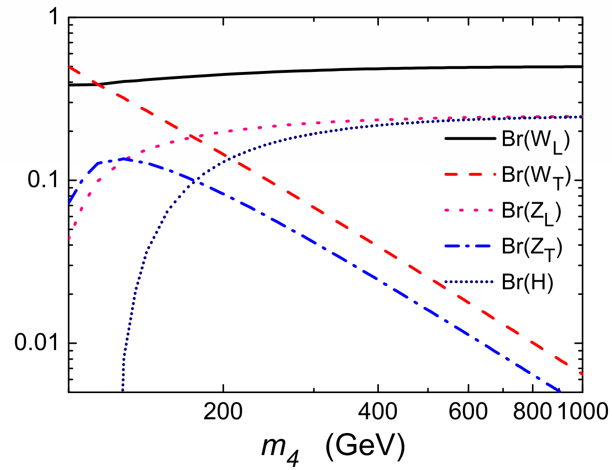


$$pp \to l^{\pm} N$$

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

Heavy Majorana Decay

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



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

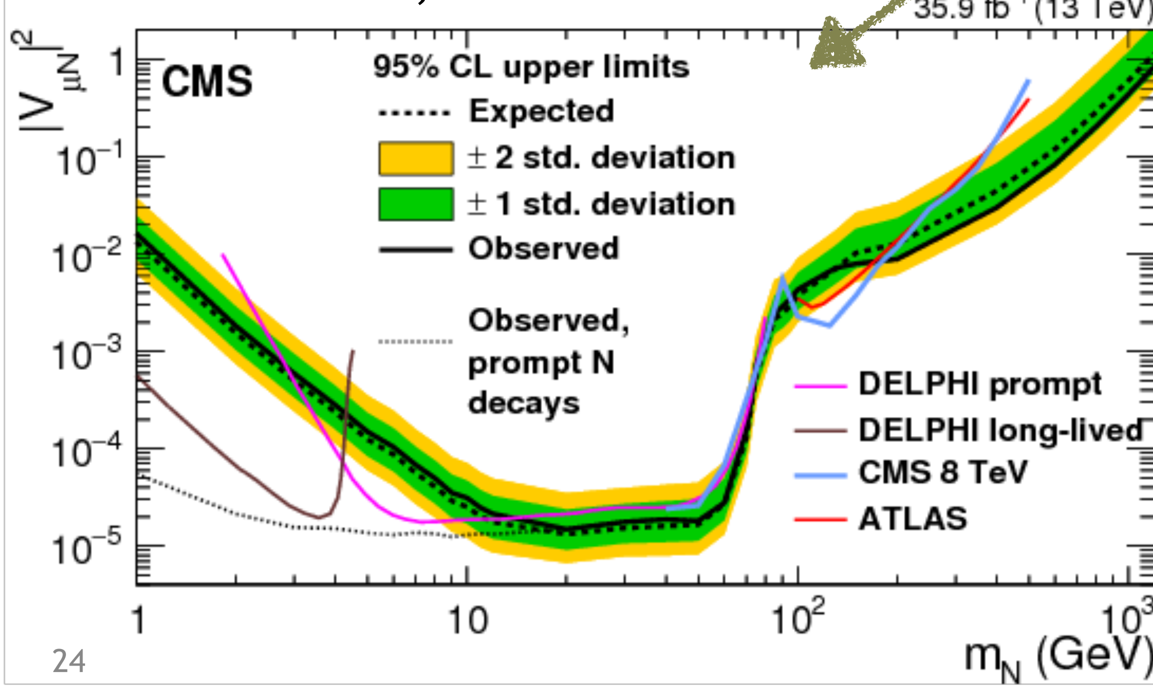
Atre et al., JHEP **0905**, 030 (2009); Aguila et al., NPB **813**, 2009; Aguila et al., 2007; Aguila et al., PLB **672**, 2009; Arhib et al., 2010, ...

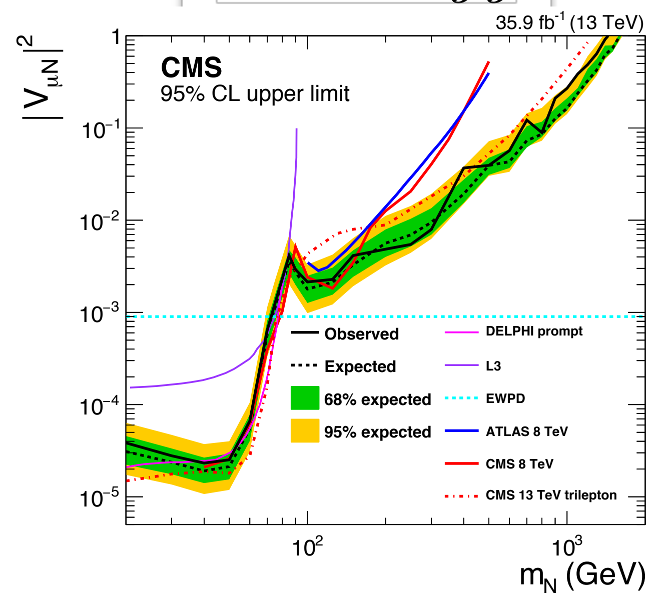
3l+X search

Low sensitivity in high mass regime

$l^\pm l^\pm + jj$

CMS collaboration, arXiv 1802.02965





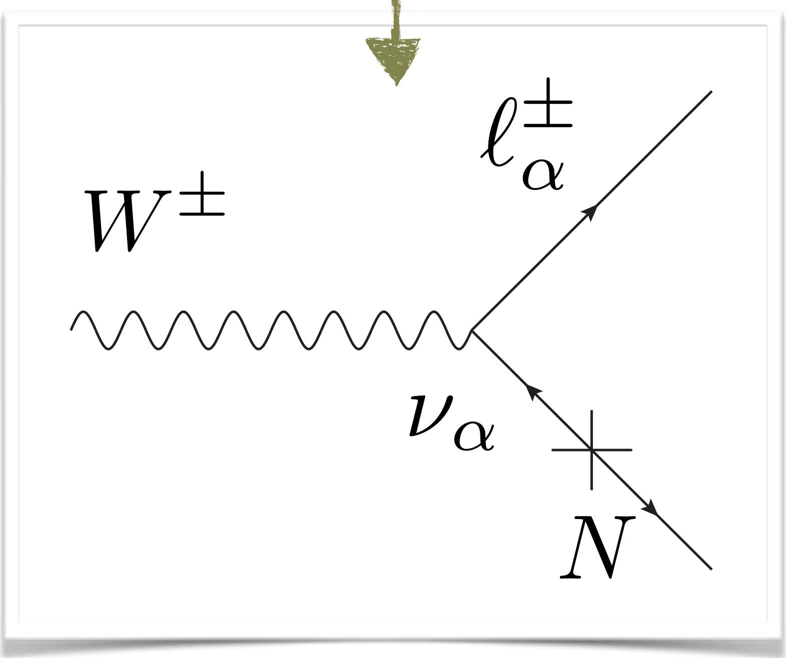
CMS collaboration, 1603.02248

CMS collaboration, arXiv 1806.10905

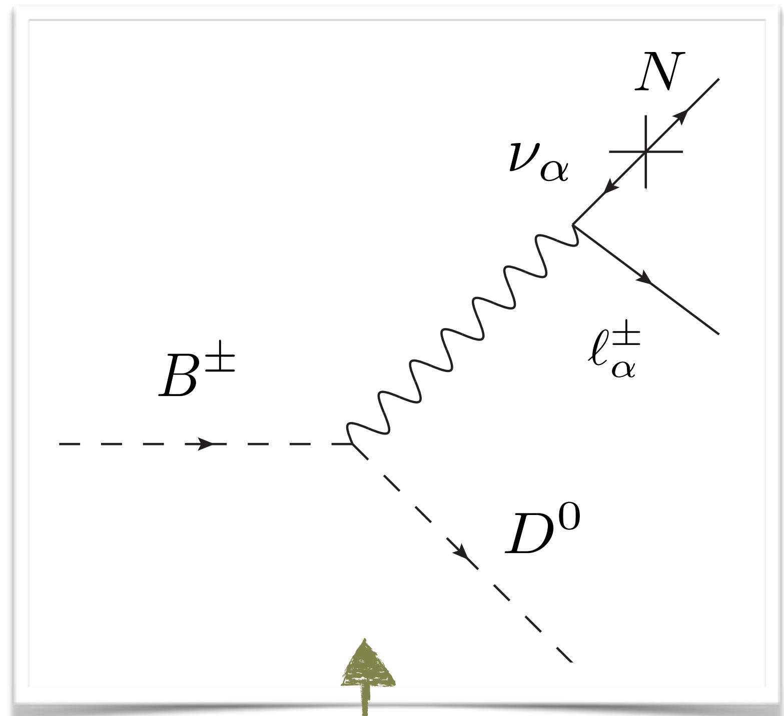
Boosted regime:

Boosted RH neutrino N

$$m_N < M_W$$



Production from meson decay



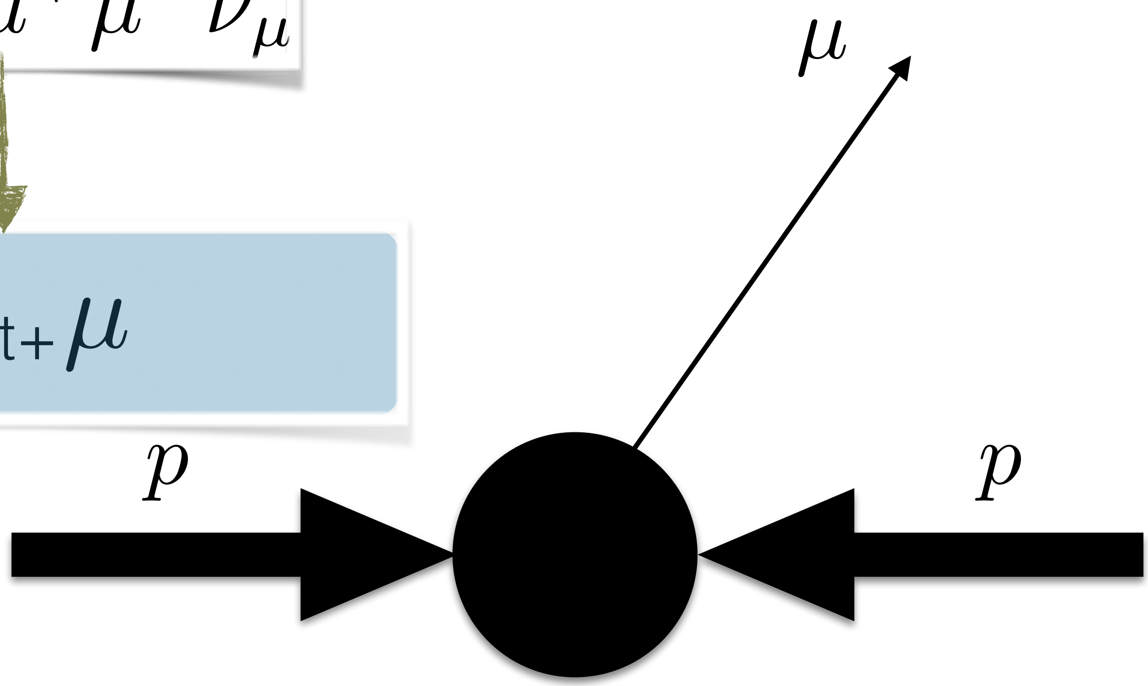
$$m_N < B^{\pm}$$

Three body decays of N to $ljj, l^+l^-\nu$

Lepton Jet:

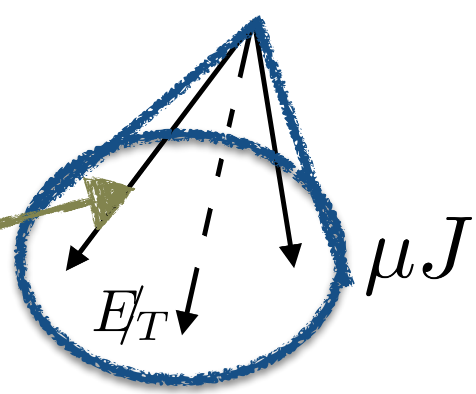
$$N \to \mu^+ \mu^- \nu_\mu$$

Lepton jet+μ



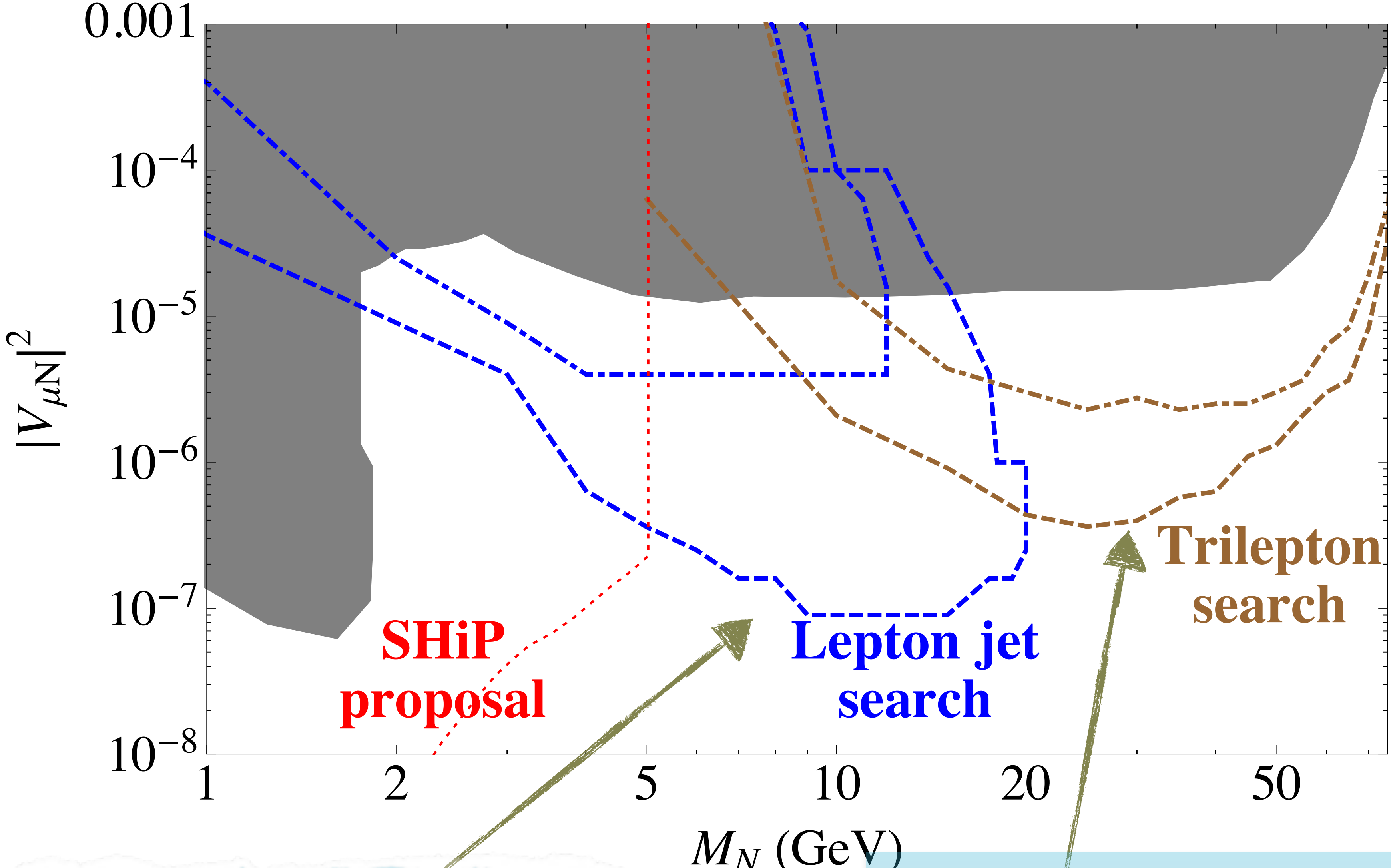
Collimated $\mu^+ \mu^-$

Lepton jet



Brian Shuve et al., 1504.02470
Sourabh Dube et al., 1707.00008

Discovery Reach:



Displaced lepton jet search

Prompt trilepton search

LHC 13 TeV → $m_N < M_W$

Brian Shuve et al., 1504.02470

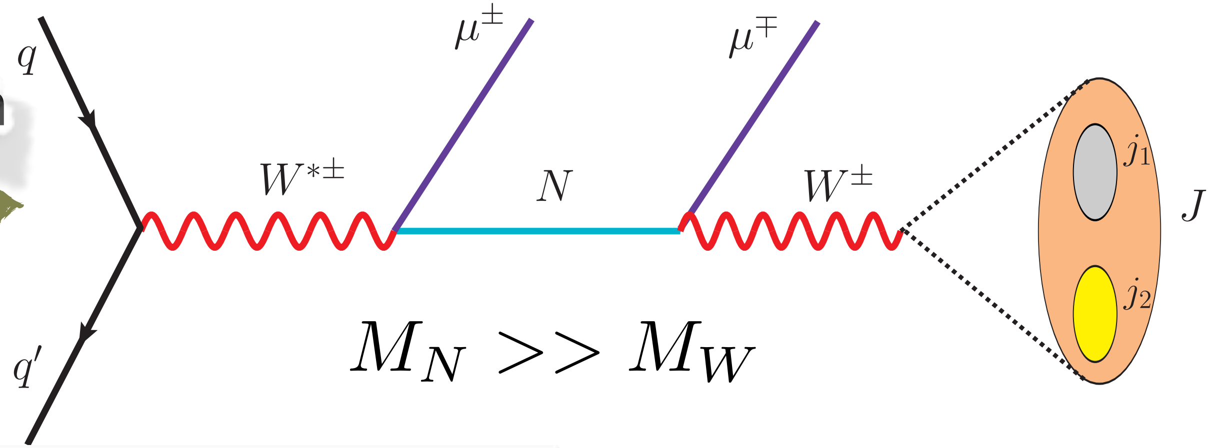
High Mass Sterile Neutrino:

$$pp \to W^{\pm *} \to \mu^{\pm} N, N \to \mu^{\mp} W^{\pm}, W^{\pm} \to J$$

Opposite charged lepton

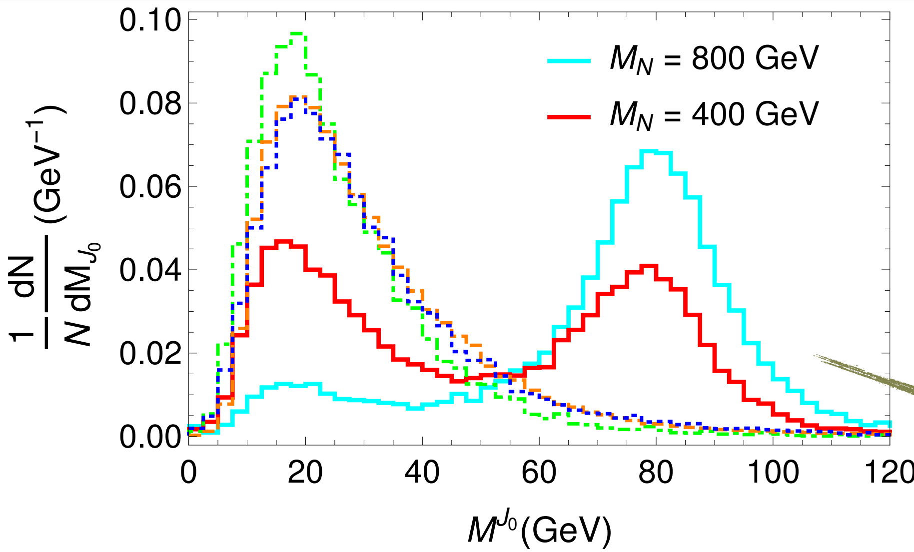
+ Fat-jet

Bharadwaj et al., arXiv 1801.00797



$$M_N >> M_W$$

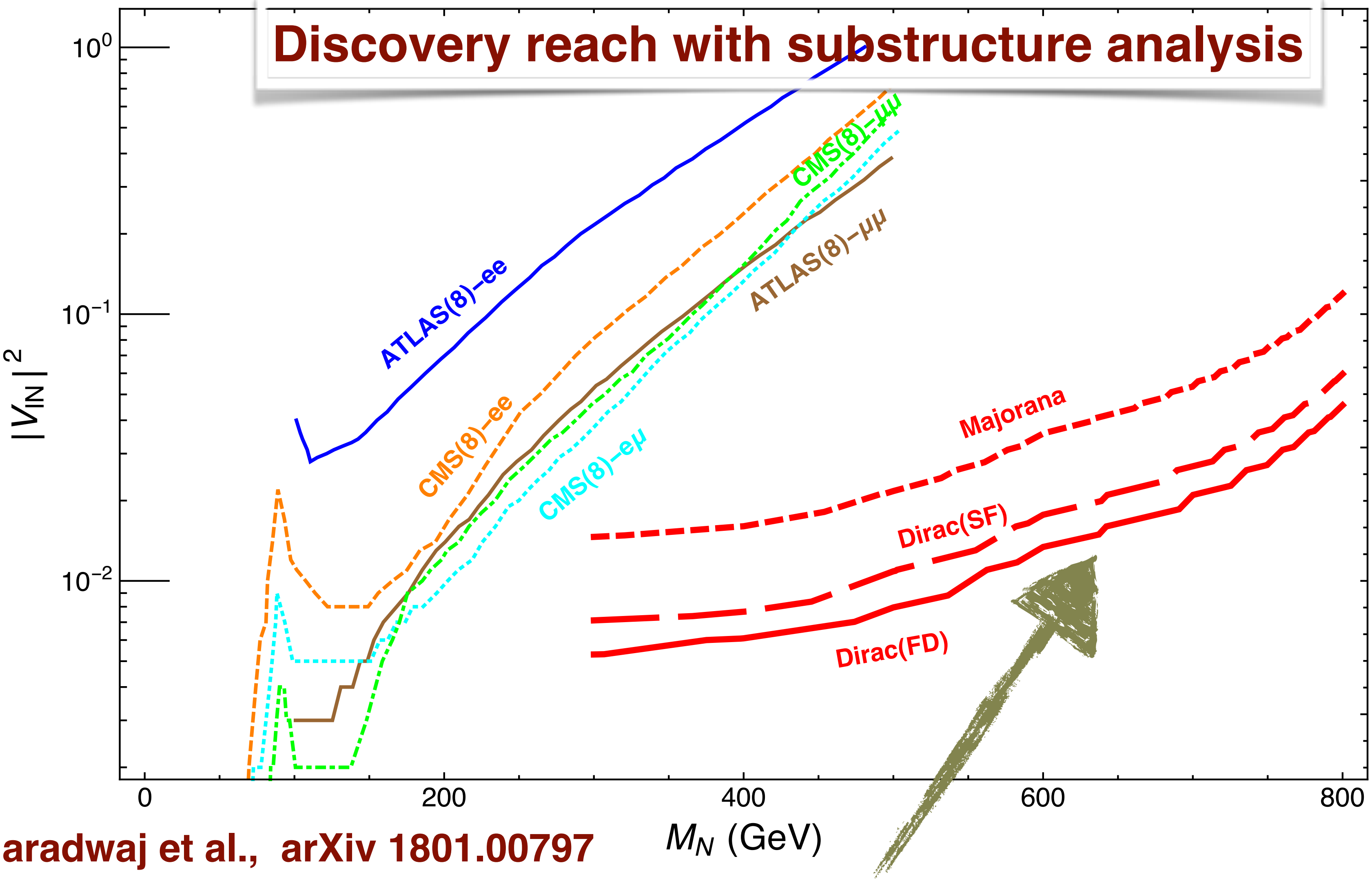
Most challenging corner due to large backgrounds → $Z + j, t\bar{t}, VV + j$



substructure variable

Discovery Reach:

LHC 13 TeV $3000\,\mathrm{fb}^{-1}$



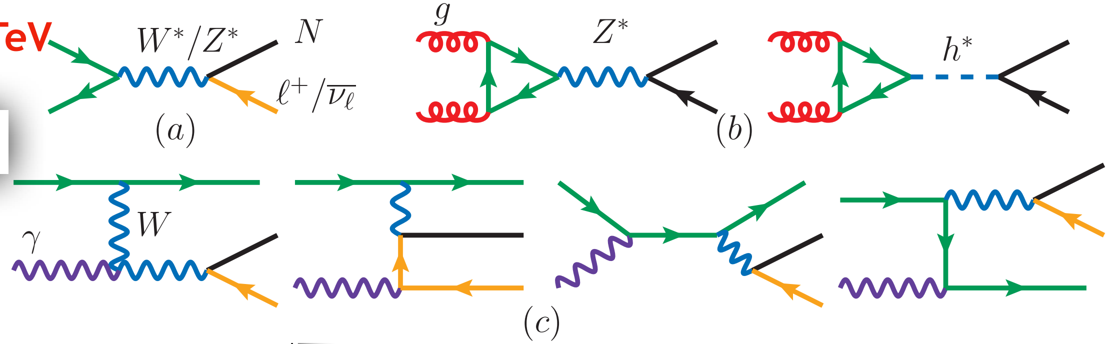
Bharadwaj et al., arXiv 1801.00797

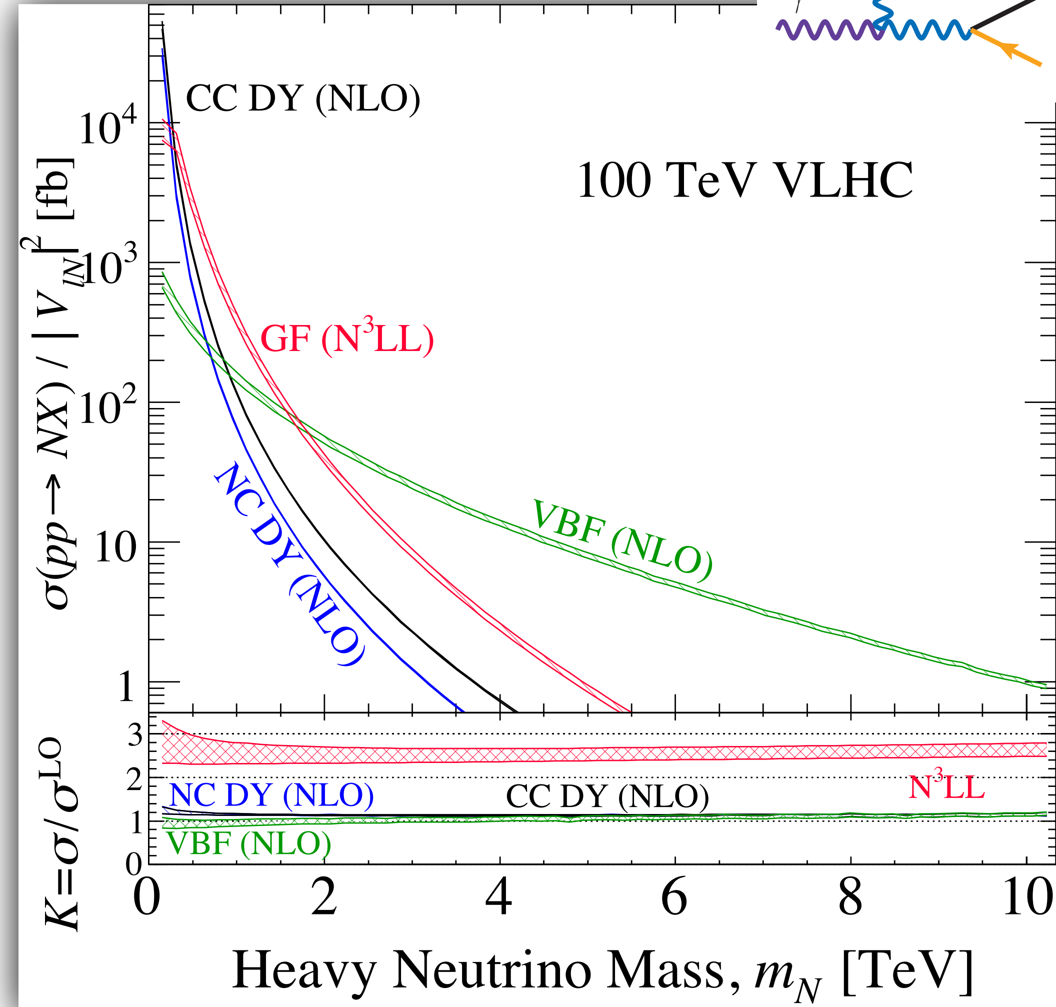
High mass range $M_N >> M_W$

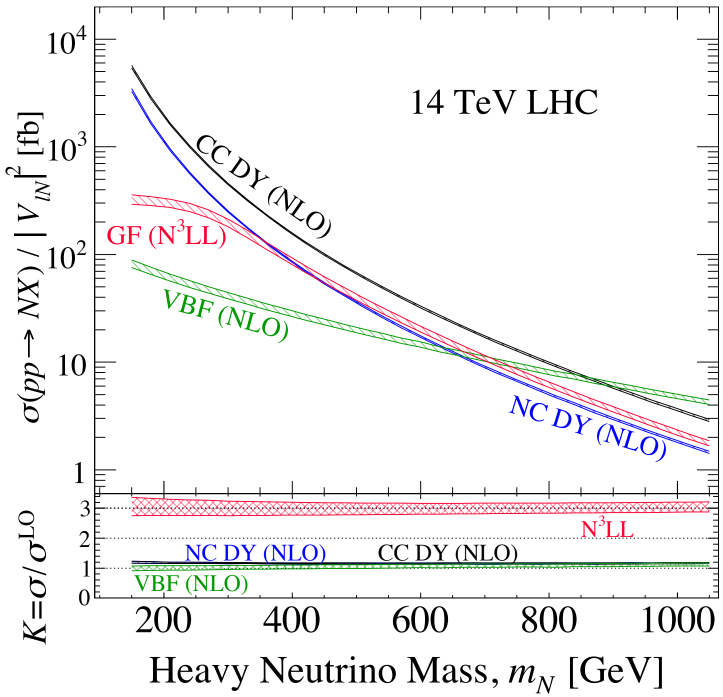
VLHC Prediction

Very heavy mass can be probed at 100 TeV

Large contribution from GF, VBF channels

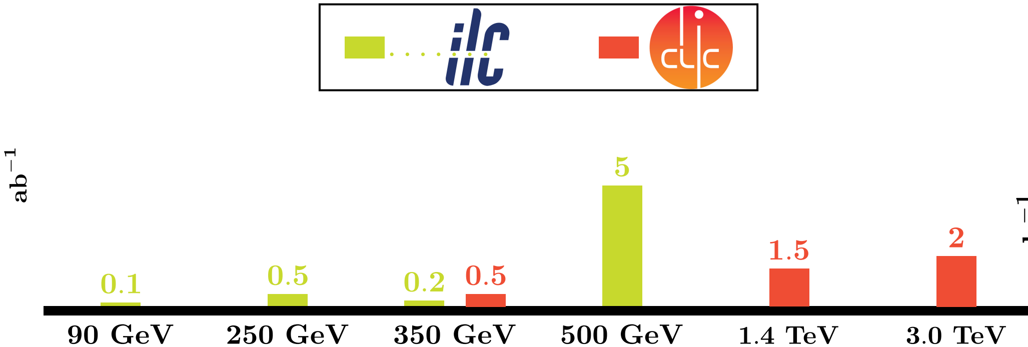


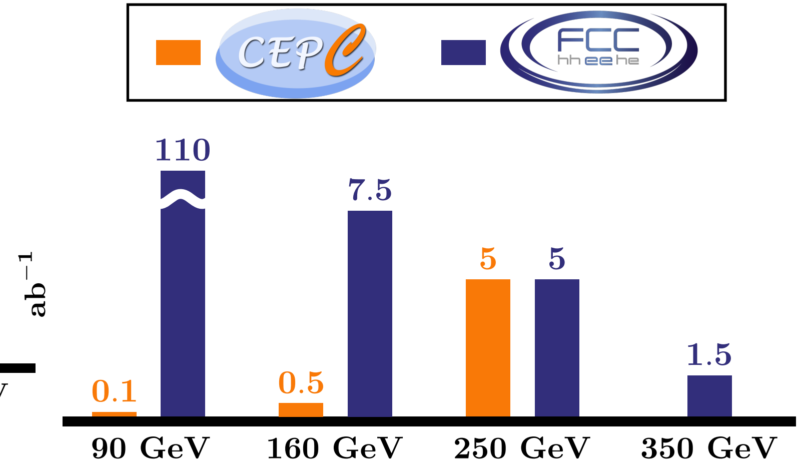


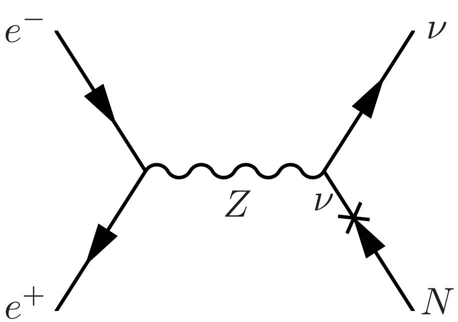


S. Pascoli, R. Ruiz, C. Weiland-*JHEP* 06 (2019) 049

Future Lepton Collider

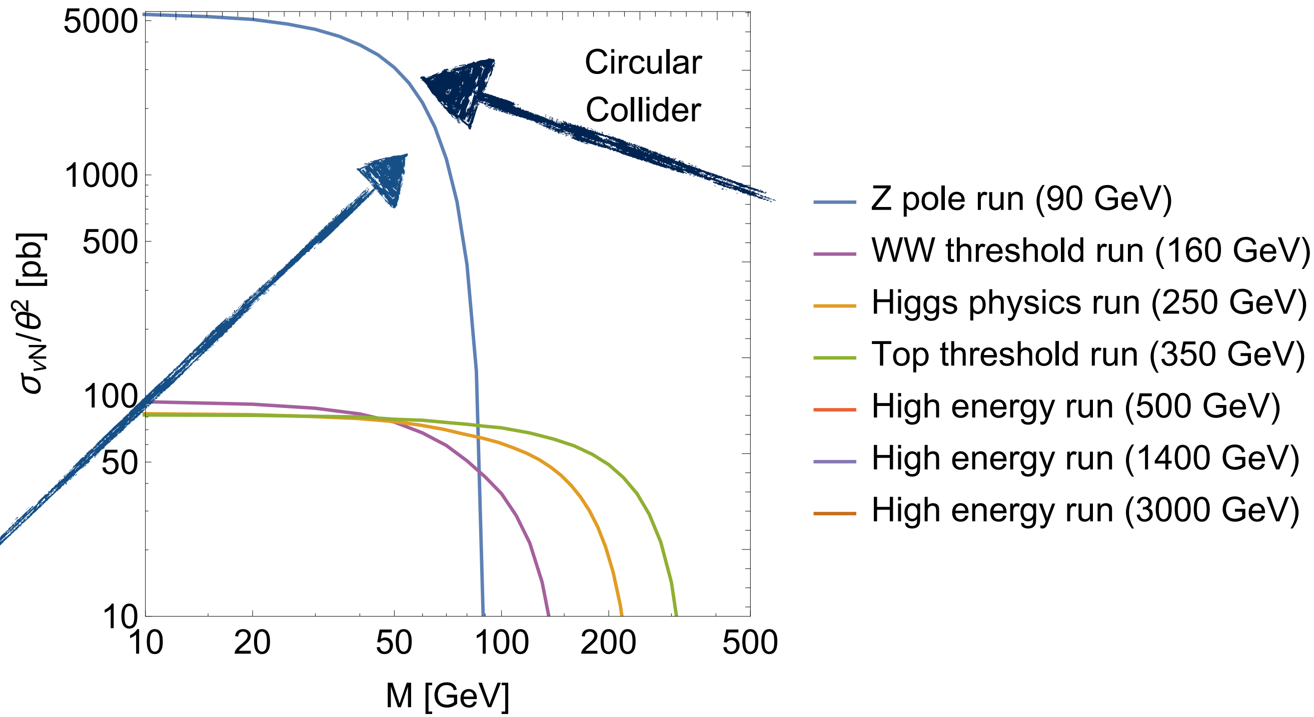






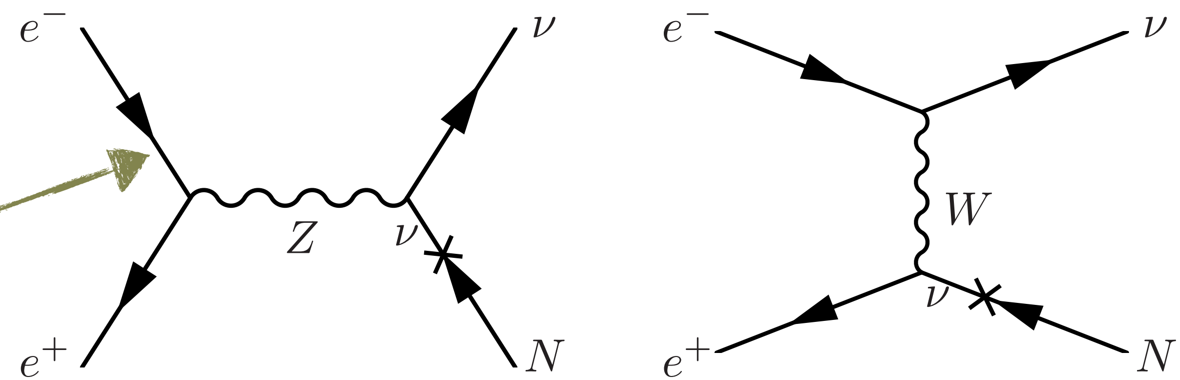
Limited by kinematics

$M_N < M_Z$



Antusch et al., Int.J.Mod.Phys. A32 (2017) no.14, 1750078

Collider Search:



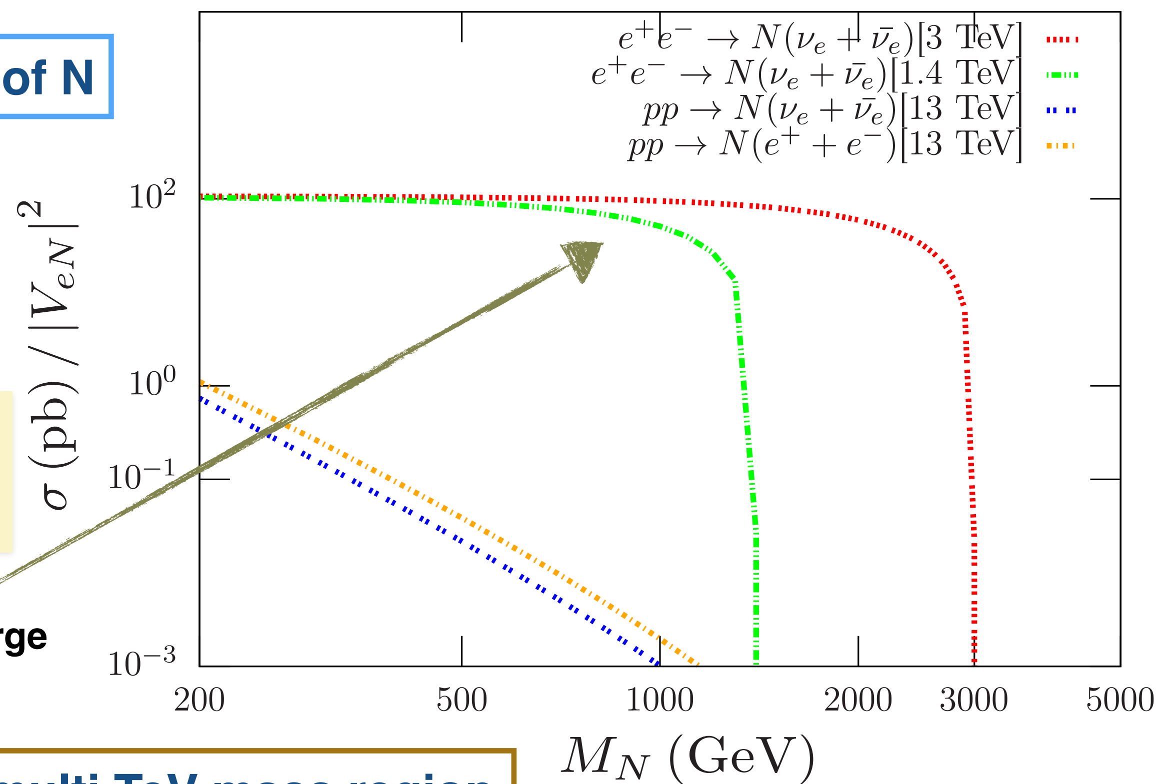
$$e^+e^- \to \nu N$$

Followed by decay of N

$$N \to lW, \nu Z, \nu h$$

$$\frac{\sigma}{|V_{eN}|^2} \sim 10^2$$

Cross-section is large



Large cross section in multi TeV mass region

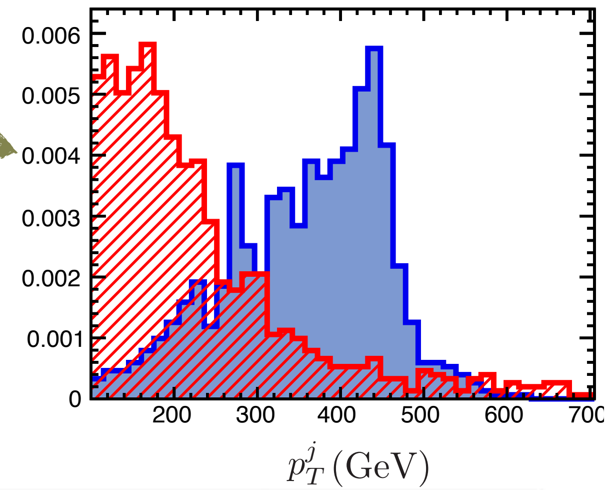
Even more massive N $M_N \sim TeV$

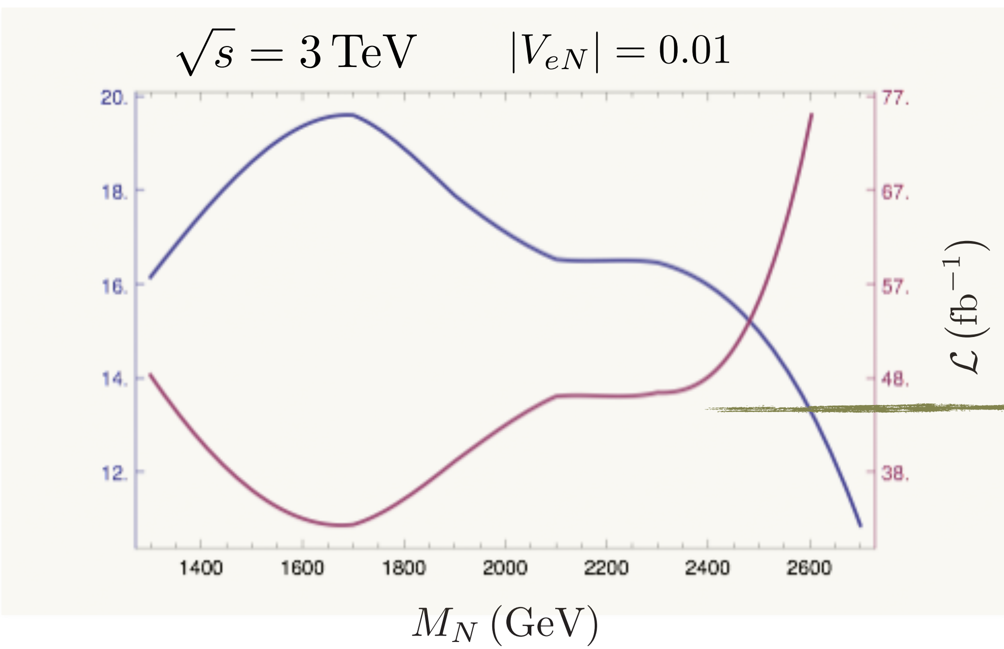
Model signature → $e^+e^- \to \nu N \to lW\nu \to lJ_{Fat} + \not{E}$

Boosted W → **Collimated decay products**

High Mass of N=900 GeV

High p_T





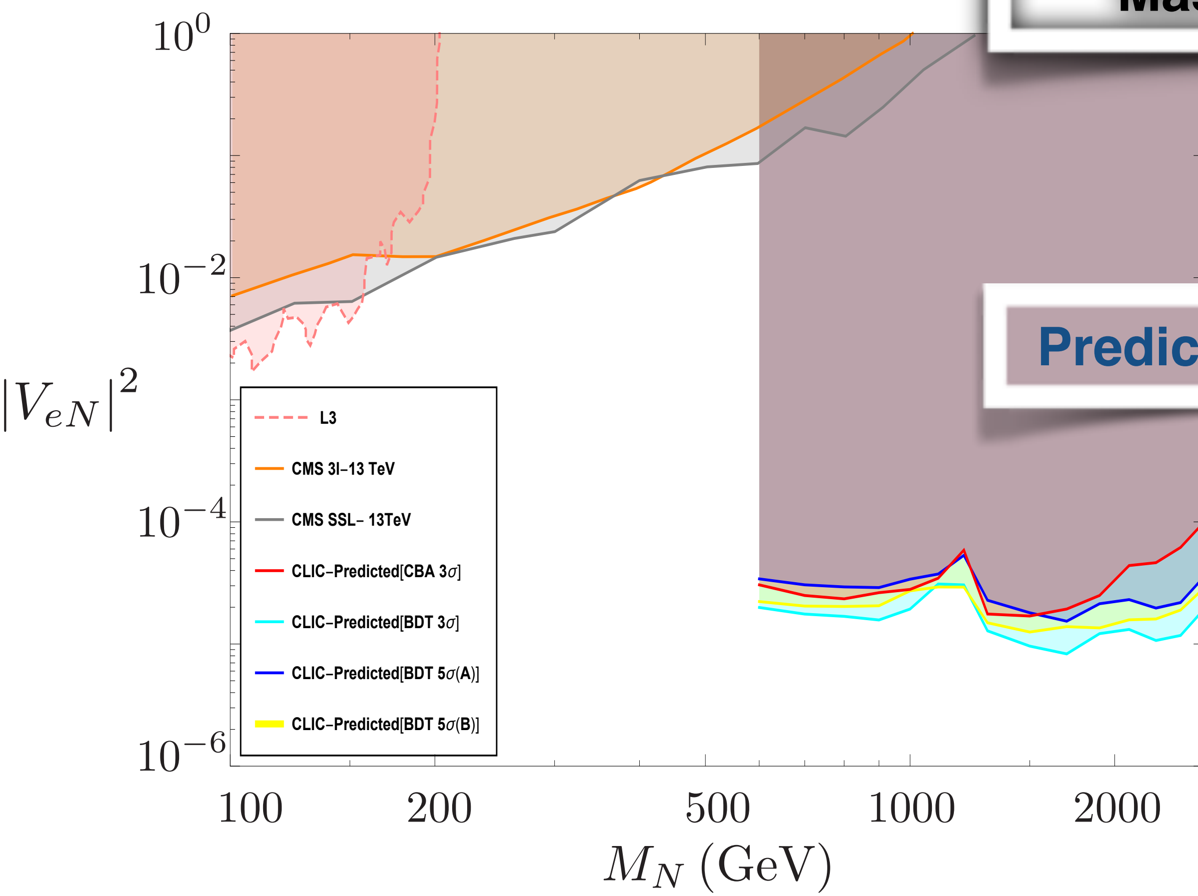
Required luminosity

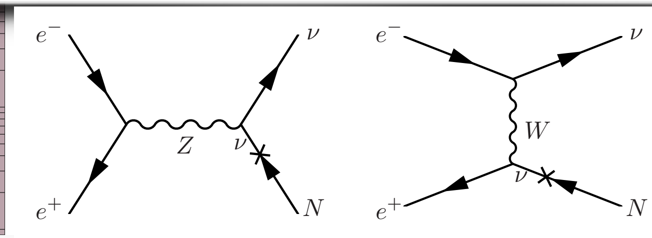
$$\mathcal{L} < 38\,\text{fb}^{-1}$$

arXiv:1810.08970, Sabyasachi Chakraborty, Sujay Shil and M. Mitra

arXiv:1810.08970, S. Chakraborty, S. Shil and M. Mitra

Mass vs active-sterile mixing

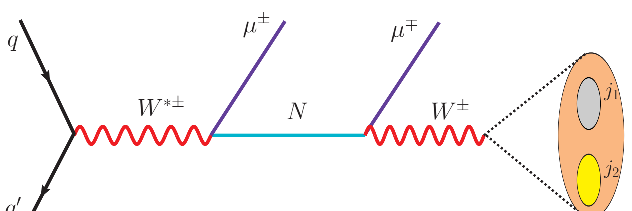




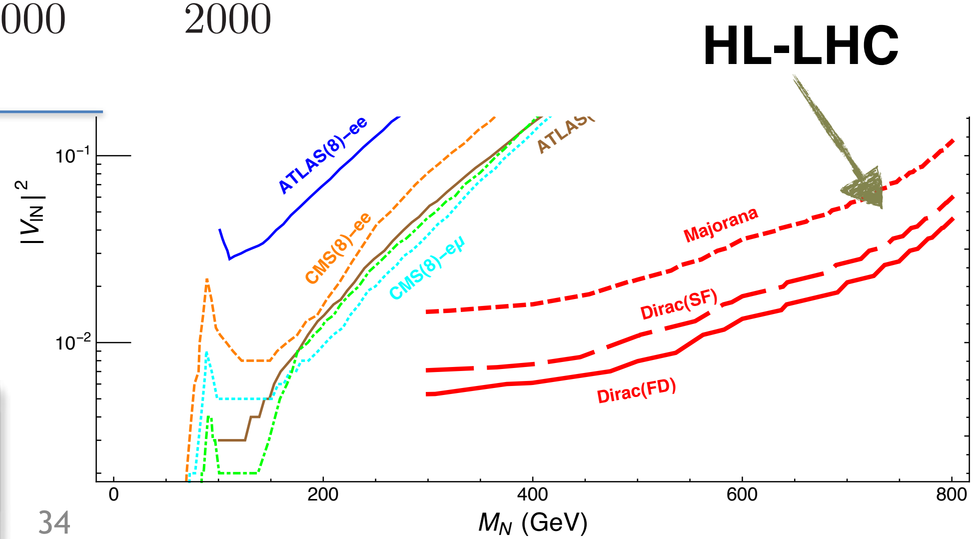
Prediction for CLIC

$$|V_{eN}|^2 \sim 10^{-5}$$

- Competitive to neutrinoless double beta decay
- order of magnitude improvement compared to HL-LHC



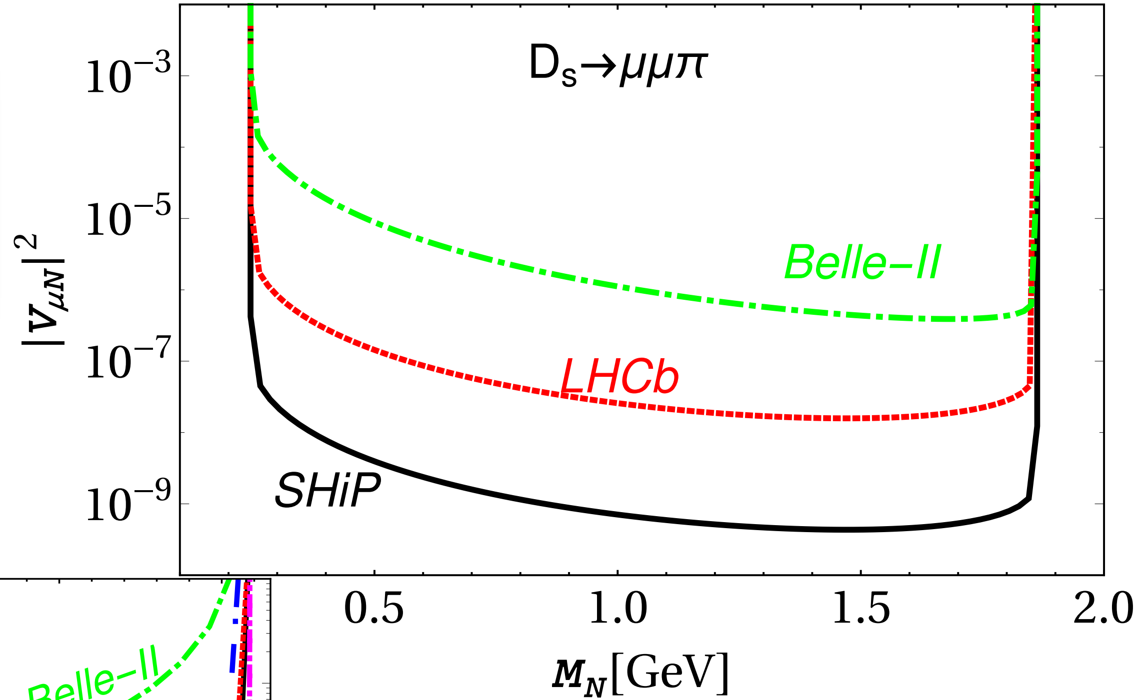
Bharadwaj et al., arXiv 1801.00797

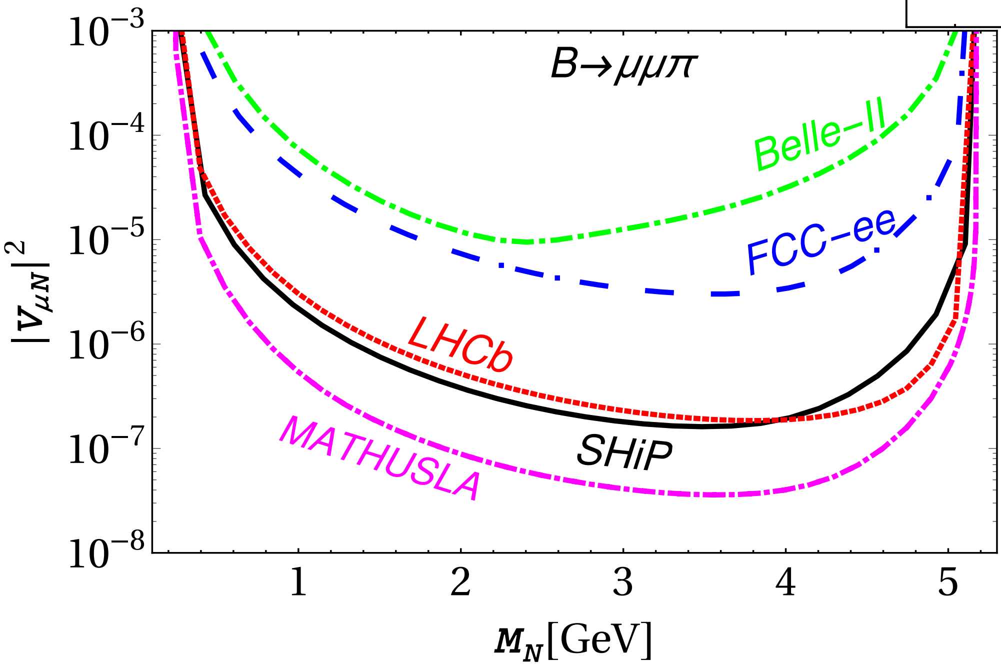


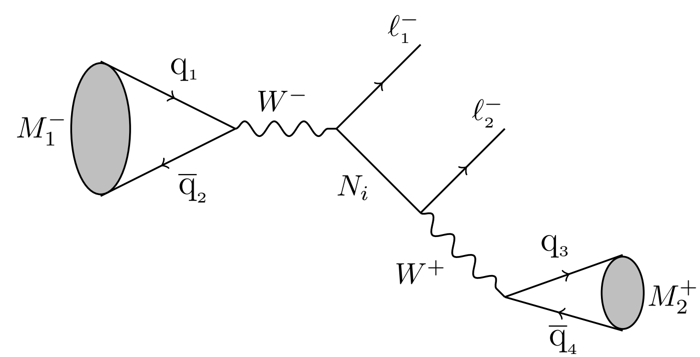
High sensitivity for active-sterile mixing in large mass regime at e+ e-

LNV Meson Decays:

Lower mass range ~100 MeV-5 GeV can be probed in rare decays of mesons.

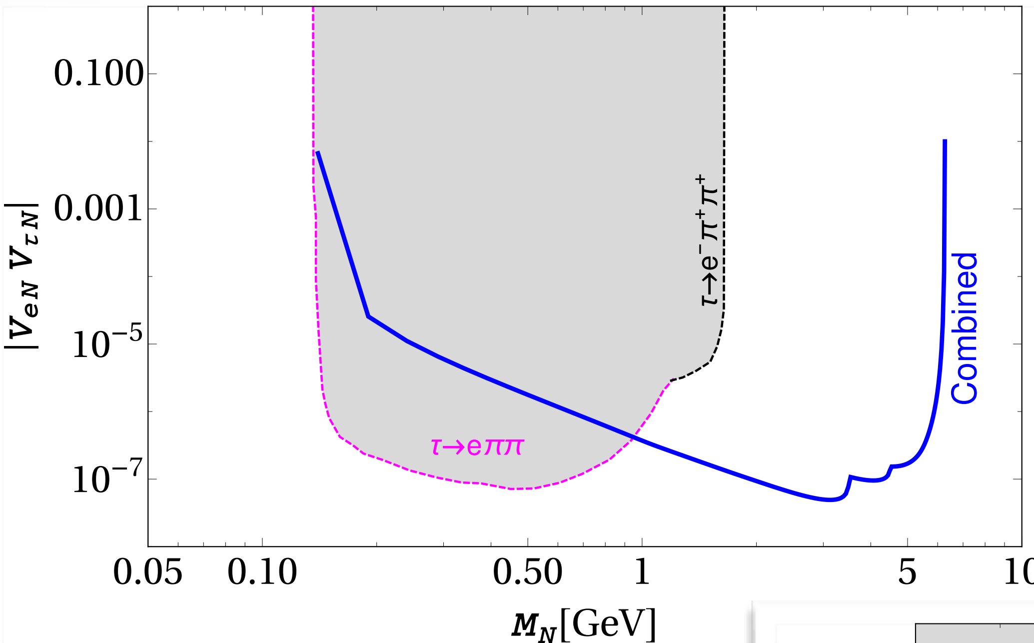


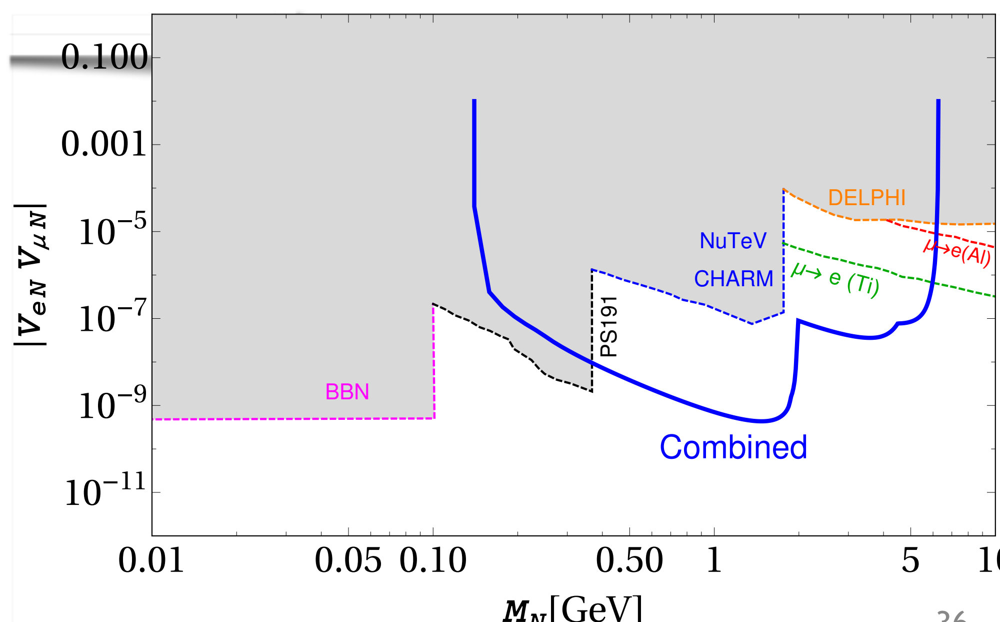




E. J. Chun, A. Das, S. Mandal, M. Mitra, and N. Sinha-PRD 100 (2019) 9, 095022

LNV Meson Decays:





E. J. Chun, A. Das, S. Mandal, M. Mitra, and N. Sinha-PRD 100 (2019) 9, 095022

Alternate Theories

- The basic framework is simple, but conservative. Production and decay of heavy neutrinos through active-strile neutrino mixing.
- Stringent constraints on the mixing parameter
- A large mixing requires cancellation in the light neutrino mass matrix

Models with extended gauge sectors or particle contents

Higgs triplet

Gauged B-L $\rightarrow$ production via z'

Left-Right symmetry $\rightarrow$ production via W_R

Two Higgs doublet model $\rightarrow$ Large Yukawa

Higgs triplet:

Higgs triplet, Δ (3,2)

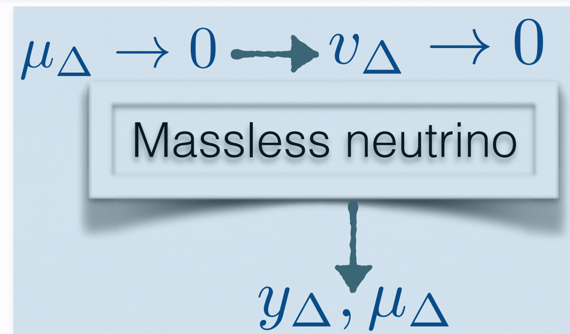
$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

The gauge invariant Lagrangian

$$-\mathcal{L}_Y = y_\Delta L_L^T C i\tau_2 \Delta L_L + \mu_\Delta H^T i\tau_2 \Delta^\dagger H + \quad M_\Delta Tr(\Delta^\dagger \Delta) + \text{h.c} + \ldots$$

Magg, Wetterich, PLB 94, 61, 1980

- **Light neutrino mass** $M_\nu \propto y_\Delta v_\Delta$
- $v_\Delta = v^2 \frac{\mu_\Delta}{M_\Delta^2}$.
- **Lepton number violation** $\rightarrow y_\Delta, \mu_\Delta$
- eV light neutrino mass $\rightarrow y_\Delta \sim \mathcal{O}(1)$, $v_\Delta = 1$ eV



The Yukawa $y_\Delta = M_\nu / v_\Delta = U^T_{PMNS} M^\nu_d U^*_{PMNS} / v_\Delta$

$$y_\Delta = f(\theta_{12}, \theta_{13}, \theta_{23}, m_i, \delta, \alpha_1, \alpha_2, v_\Delta)$$

fixed from the PMNS mixing and neutrino mass

Large y_Δ → lepton flavor violation

Higgs triplet:

$$\Delta(3,2) \to H^{++}, H^{+}, A^0, H_2^0, H_1^0$$

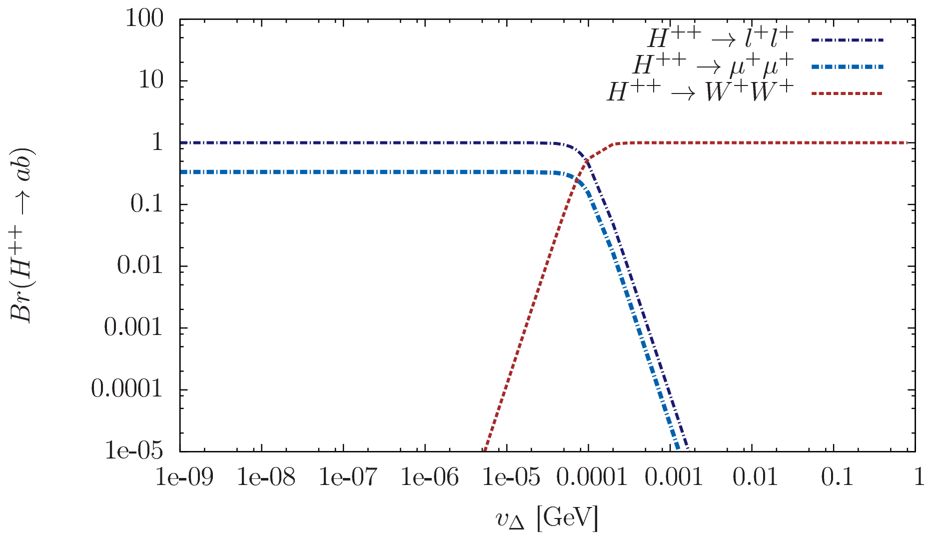
$LL\Delta \to$ Light neutrino mass $M_\nu = y_\Delta v_\Delta$. $\boxed{H^{++}l^-l^- \sim M_\nu/v_\Delta}$.

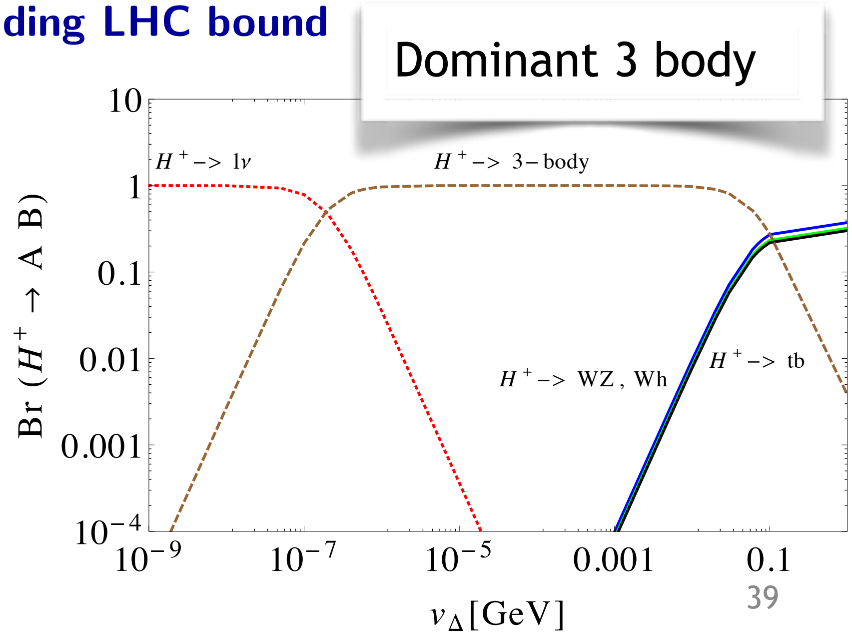
$$\Gamma\left(H^{++} \to e_i^+ e_j^+\right) = \frac{|M_\nu^{ij}|^2}{8\pi(1+\delta_{ij})v_\Delta^2} M_{H^{++}}$$

$$\Gamma\left(H^{++} \to W^+W^+\right) = \frac{v_\Delta^2 M_{H^{++}}^3}{4\pi v_0^4}\left(1 - \frac{4M_W^2}{M_{H^{++}}^2}\right)^{1/2}\left(1 - \frac{2M_W^2}{M_{H^{++}}^2}\right)^2$$

Different $v_\Delta \to$ distinctive H^{++}, H^+ branching

$v_\Delta \geq 10^{-4}$ **GeV** $\to H^{++} \to W^+W^+ \to$ **evading LHC bound**





Decays of doubly charged Higgs

$$H^{\pm\pm} \to l^{\pm}l^{\pm} \quad \text{for} \quad v_\Delta < 10^{-4}\,\text{GeV}$$
$$H^{\pm\pm} \to W^{\pm}W^{\pm} \quad \text{for} \quad v_\Delta > 10^{-4}\,\text{GeV}$$

- CMS search for same sign di-lepton $pp \to H^{\pm\pm}H^{\mp\mp} \to l^{\pm\pm}l^{\mp\mp}$

HIG-PAS-16-036

- ATLAS search for same sign W $pp \to H^{\pm\pm}H^{\mp\mp} \to W^{+}W^{+}W^{-}W^{-}$

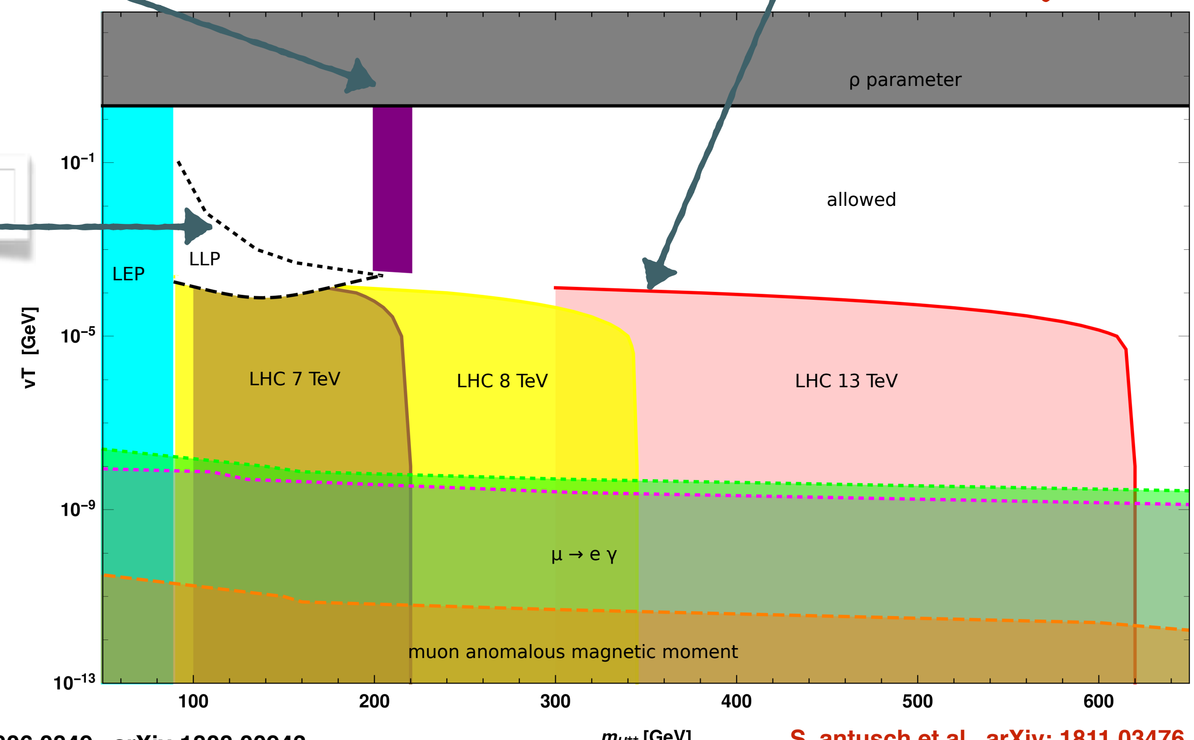
arXiv: 1808.01899

- 200-220 GeV excluded

Unconstrained

Long lived → Displaced vertex

High mass and large vev is unconstrained



S. antusch et al., arXiv: 1811.03476

LHC and 100 TeV -> P.S.Bhupal Dev et al., arXiv:1806.0849, arXiv:1808.00943, Yong Du et al., arXiv:1810.09450

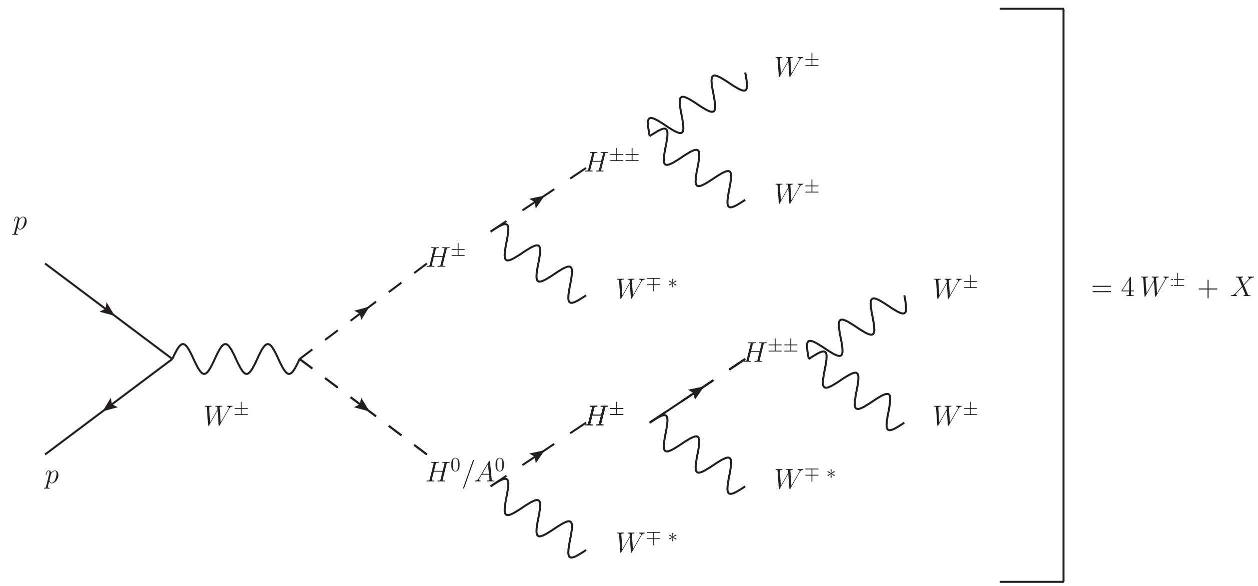
Other searches:

Same sign tetra lepton $pp \to l^{\pm}l^{\pm}l^{\pm}l^{\pm} + X$

$$pp \to W^* \to H^{\pm}H^0/A^0; pp \to Z^* \to H^0A^0$$

$$H^{\pm} \to H^{\pm\pm}W^{\mp *}, H^0/A^0 \to H^{\pm}W^{\mp *}$$

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



$M_{H^{\pm\pm}} - M_{H^{\pm}}$

Eung Jin Chun et al., arXiv: 1206.6278, 1911.00971

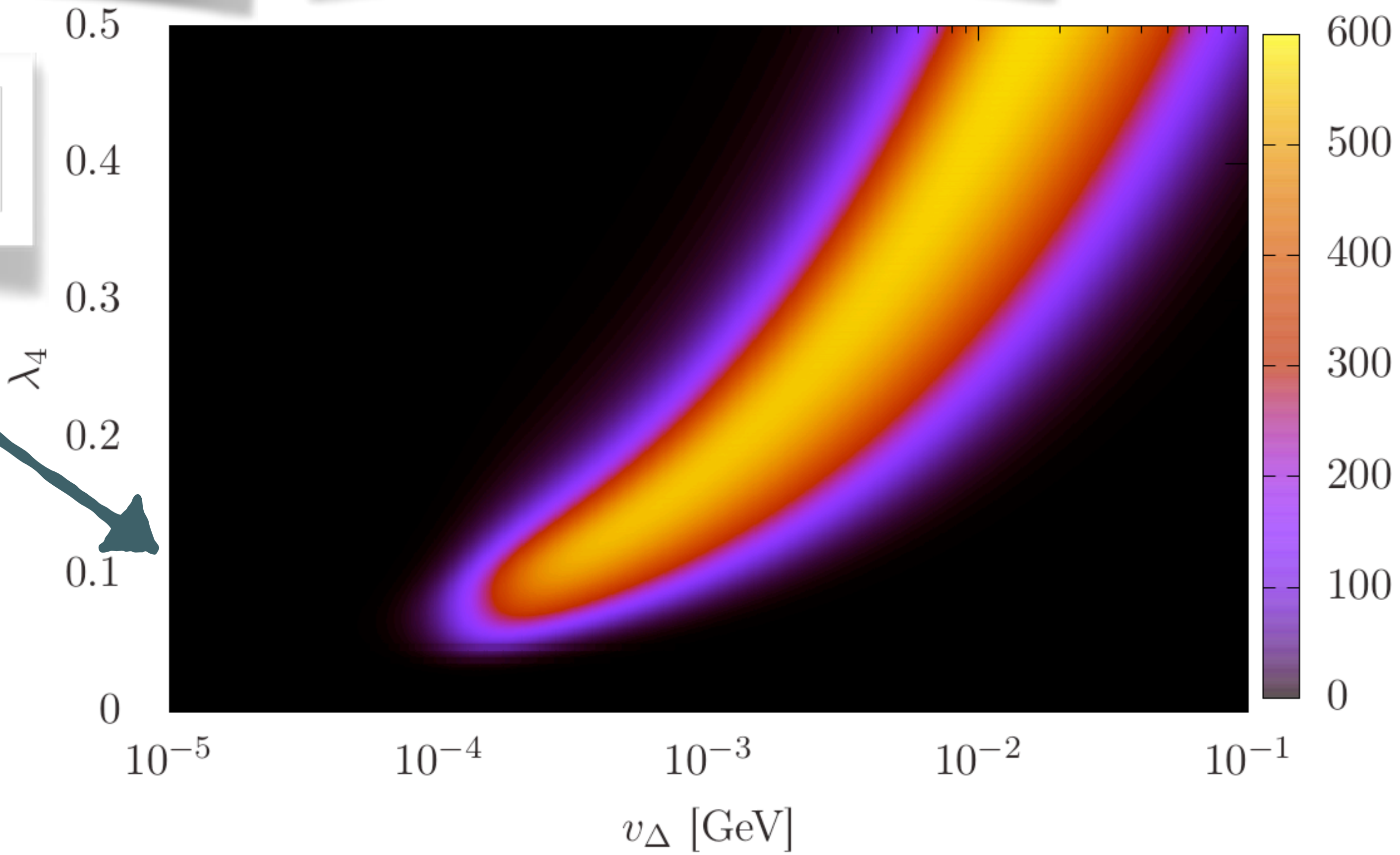
Discovery prospect at 14 TeV:

Same sign tetra lepton events for lighter charged Higgs

$M_{H^0/A^0} = 253\, GeV$

$M_{H^+} - M_{H^{++}} = 15\, GeV$

Probe quartic coupling

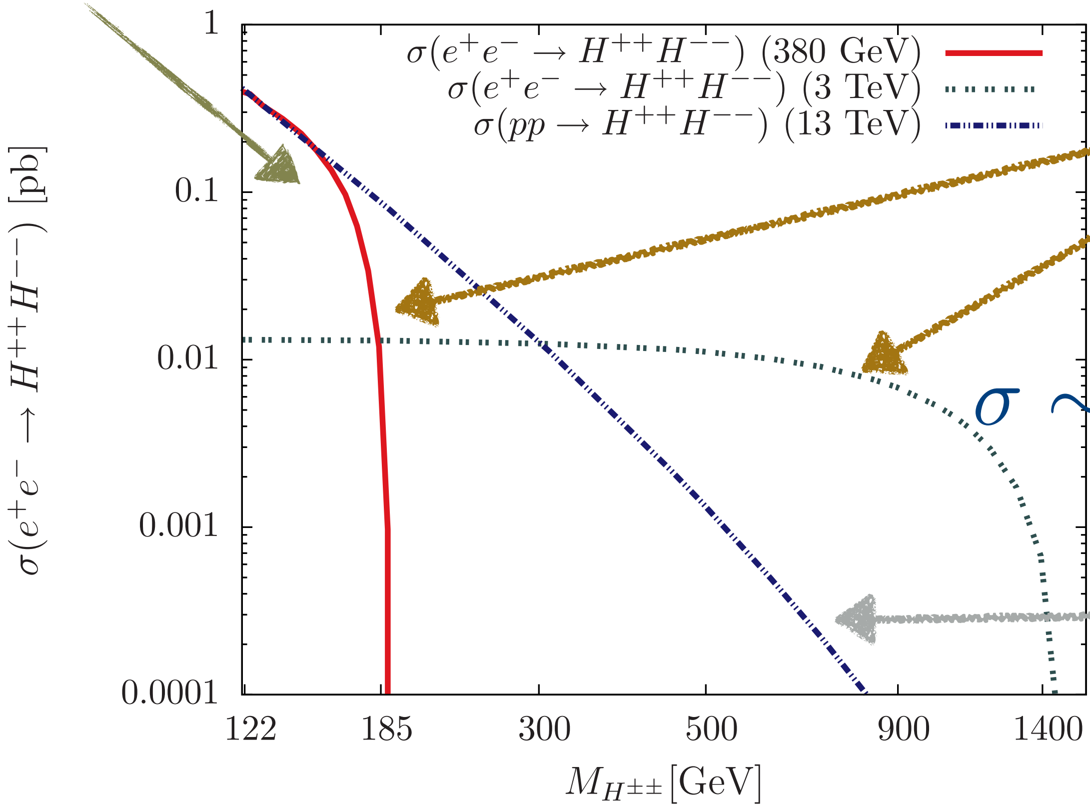


Triplet vev

E. J. Chun, S. Khan, S. Mandal, M. Mitra, S. Shil, arXiv: 1911.00971

Cross-sections:

$\sigma \sim 100 - 400\,\text{fb}$



CLIC

380 GeV, 3 TeV

$\sigma \sim 10\,\text{fb}$

LHC 13 TeV

LHC cross-section is low for higher masses $\sigma \sim 0.004\,\text{fb for } \mathrm{M_{H^{\pm\pm}}} = 1.3\,\text{TeV}$

For high mass and large vev, lepton collider is more suitable

Two mass ranges

Light Higgs, large vev (CLIC with 380 GeV c.m.energy)
Heavy Higgs, large vev (CLIC with 3 TeV c.m.energy)

Phys.Rev. D98 (2018) no.1, 015024 , P. Agrawal, M. Mitra, S. Shil, S. Niyogi and M. Spannowsky

Heavy Higgs at 3 TeV:

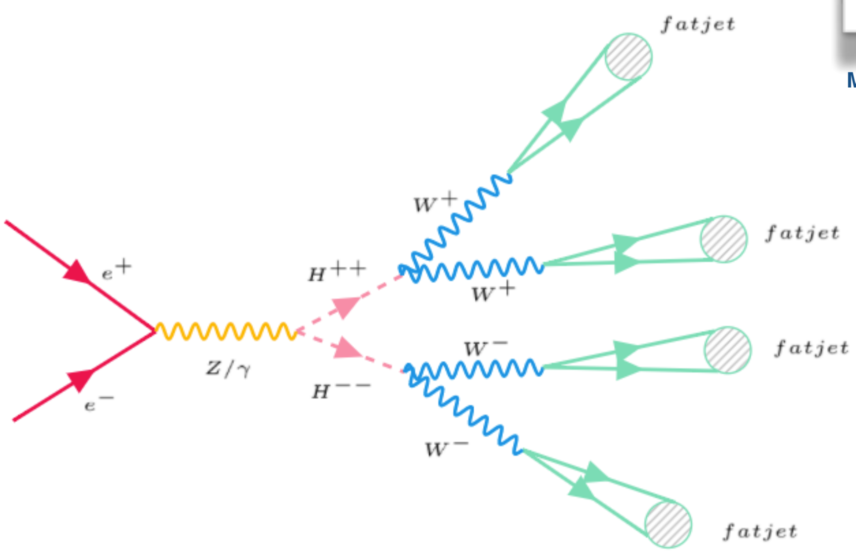
Higher c.m.energy → 3 TeV

Heavy Higgs upto 1.5 TeV

Boosted W → Fat jets

- $e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to W^\pm W^\mp W^\pm W^\mp \to 4\,\mathrm{fat-jet}.$

MadGraph5_aMC@NLO, Pythia8, Cambridge-Achen algorithm in FastJet-3.0.0, jet radius R=1.0



$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to Nj_{\mathrm{fat}}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500\,\mathrm{fb}^{-1}$)	$\mathcal{L}(\mathrm{fb}^{-1})$(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15

$M_{H^{\pm\pm}} =$ 800 GeV-1120 GeV discovery with $\mathcal{L} = 39 - 94\,\mathrm{fb}^{-1}$

LFV signatures $\mu \to 3e, \mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$

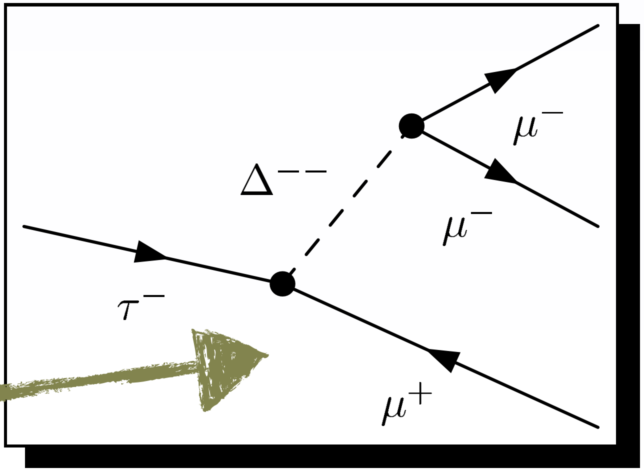
- Branching ratio of $\mu \to 3e \leq 10^{-12}$
- Branching ratio of $\mu \to e\gamma \leq 5.7 \times 10^{-13}$

Tightly constrained

τ sector is less constrained $\tau \to 3\mu, e\mu\mu, e\gamma, \mu\gamma$.

$$\tau \to 3\mu, e\mu\mu \sim 10^{-8}$$

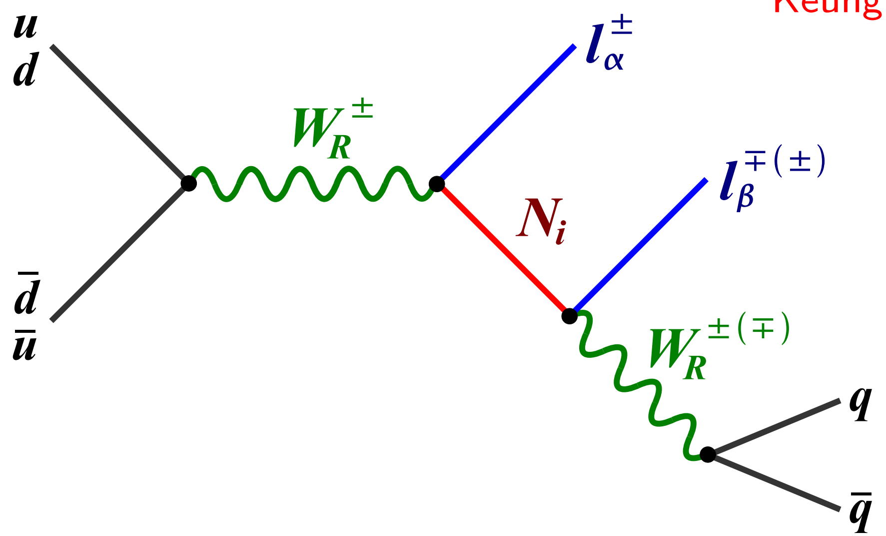
- $\Gamma(\tau^{\mp} \to \mu^{\pm}\mu^{\mp}\mu^{\mp}) = \frac{m_\tau^5}{192\pi^3}|C_{\tau\mu\mu\mu}|^2$
- $C_{\tau\mu\mu\mu} = \frac{Y_{\tau\mu}Y_{\mu\mu}}{m^2_{\Delta^{\pm\pm}}} = \frac{M_\nu(\tau,\mu)M_\nu(\mu,\mu)}{2v_\Delta^2 m^2_{\Delta^{\pm\pm}}}$



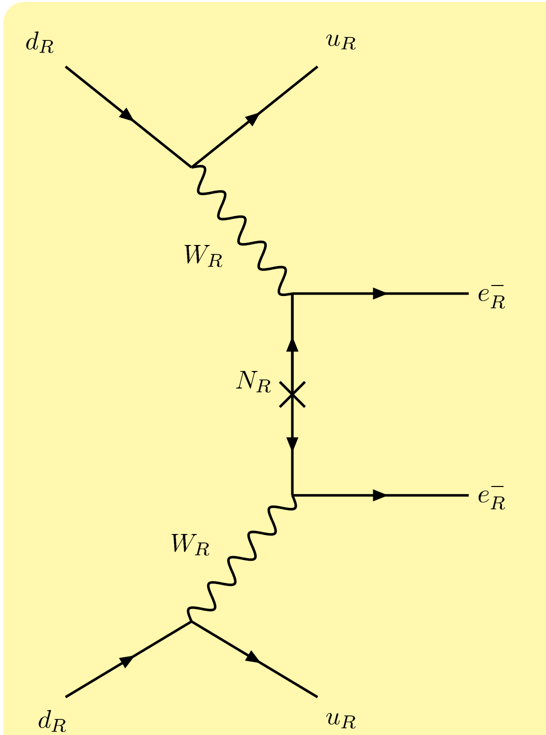
Higgs triplet

Left Right Symmetry

- Collider
- Neutrinoless Double Beta Decay
- Meson Decays
- charged lepton flavor violation



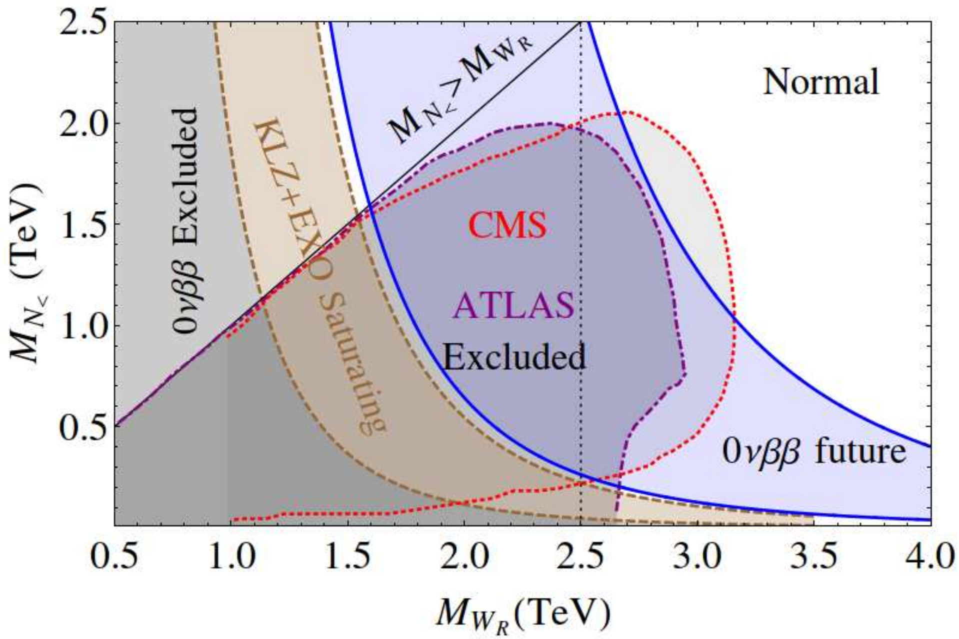
Keung, Senjanović, PRL, 83



Complementarity to LHC

P. S. Bhupal Dev, S. Goswami, M. Mitra and W. Rodejohann, Phys. Rev. D 88, 091301 (2013)

R.Awasthi, A. Dasgupta and M. Mitra, arXiv: 1607.03504)



The contour is $M_{N_<} = \frac{p^2}{M^4_{W_R}} \frac{\Phi(\text{oscillation parameters})}{\sqrt{m^{\nu}_{exp} - m^{\nu}_{ee}}}$

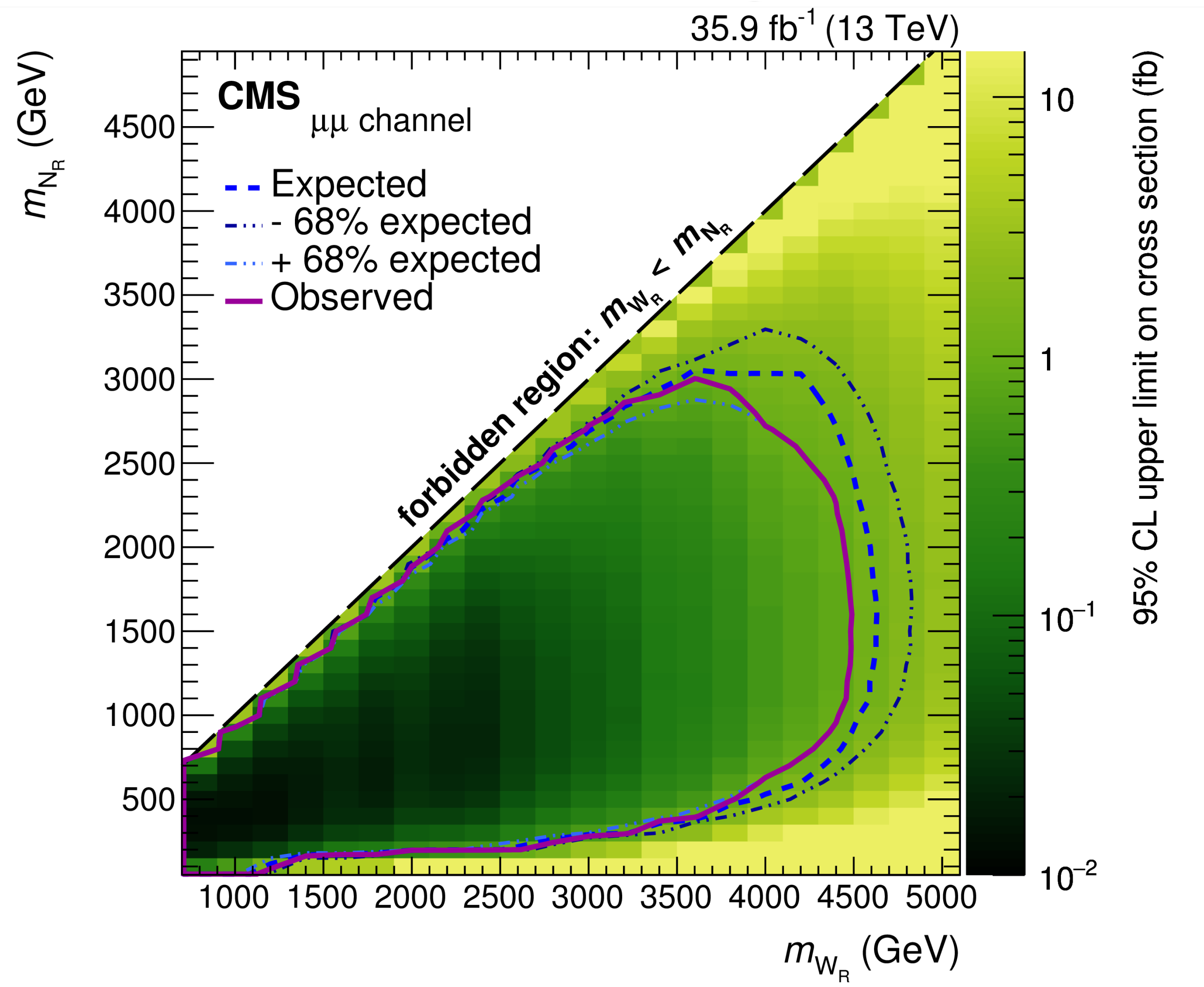
- Future $0\nu\beta\beta \to m^N_{ee} = 0.1 - 0.01$ eV.

$0\nu\beta\beta \to$ **Complementary to LHC**

However, LHC puts stringent bound in the TeV range

13 TeV Result:

$$pp \rightarrow W_R \rightarrow l^{\pm} N \rightarrow l^{\pm} l^{\pm} jj$$



Same flavour,
OS+SS combined

CMS-PAS-EXO-17-011

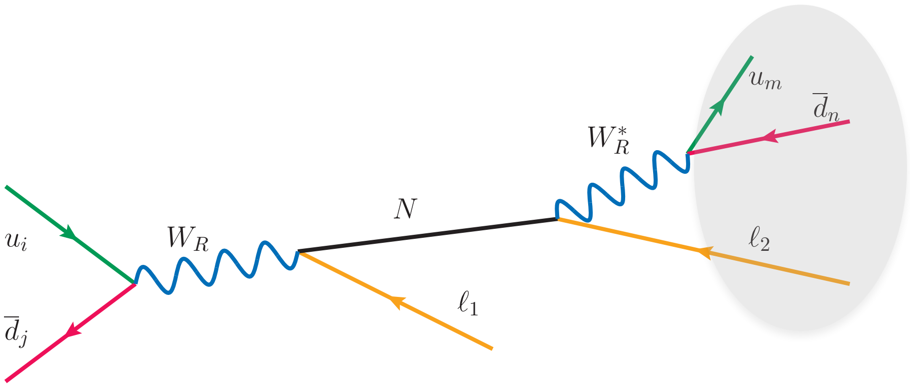
4.4 TeV

Contd:

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

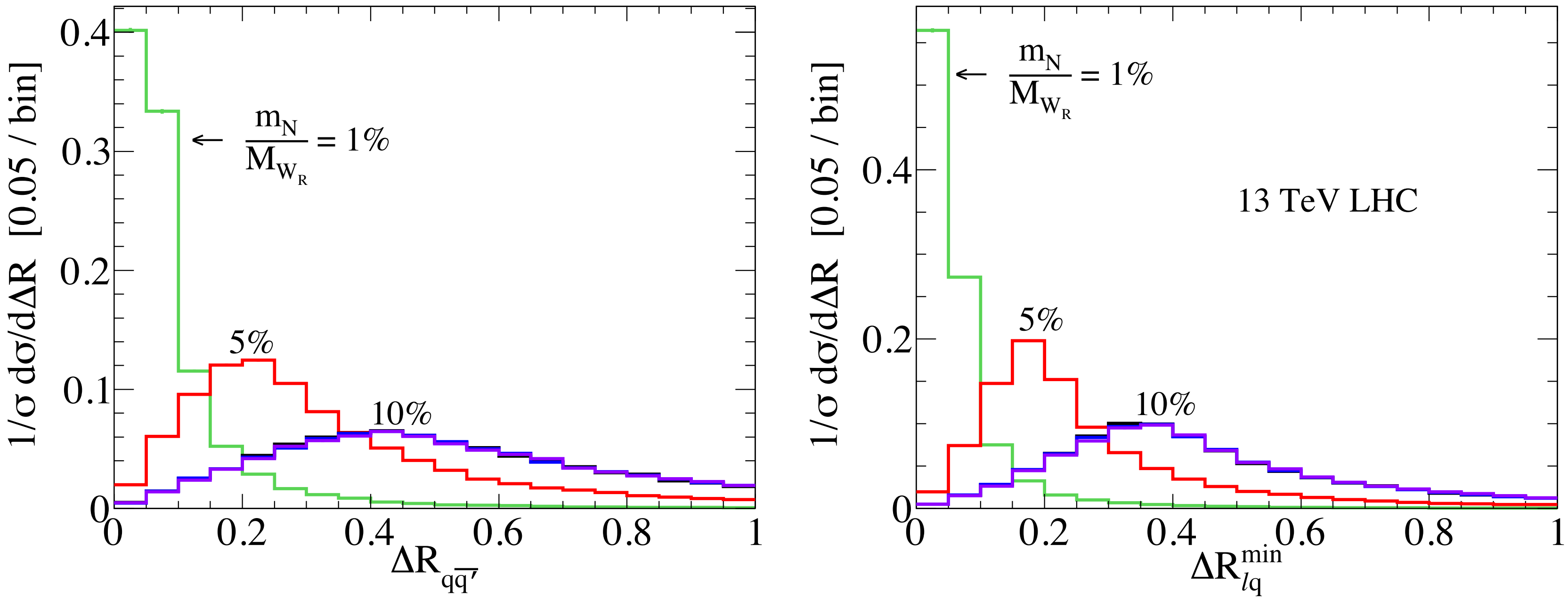


$l + J$

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.**

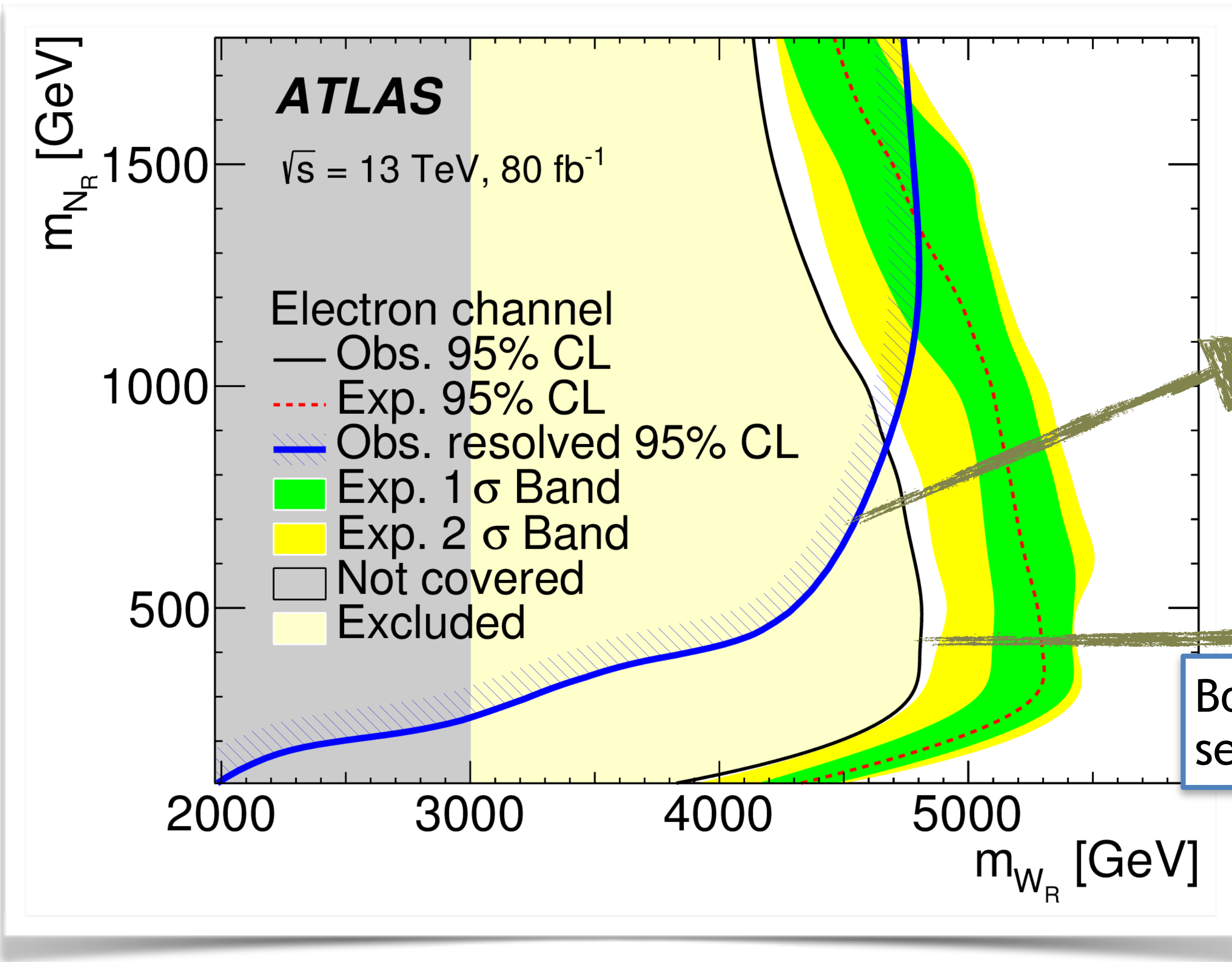
Contd:



$$\frac{M_N}{M_{W_R}} \sim 1\% \rightarrow \Delta R < 0.3$$

ATLAS 13 TeV search with $\Delta R > 0.3$ for $l^{\pm}l^{\pm}jj$ is not applicable

Boosted RHN:

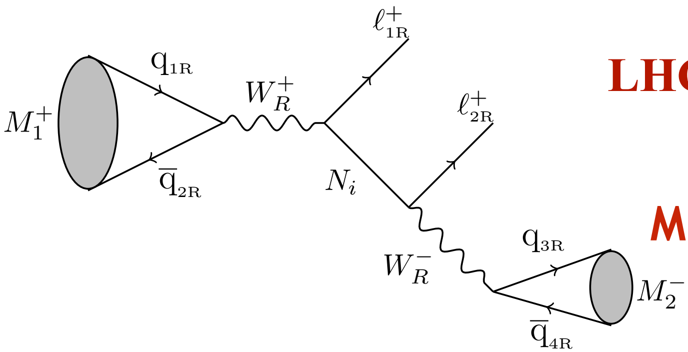


Resolved analysis di-lepton+di-jet

Boosted heavy neutrino search

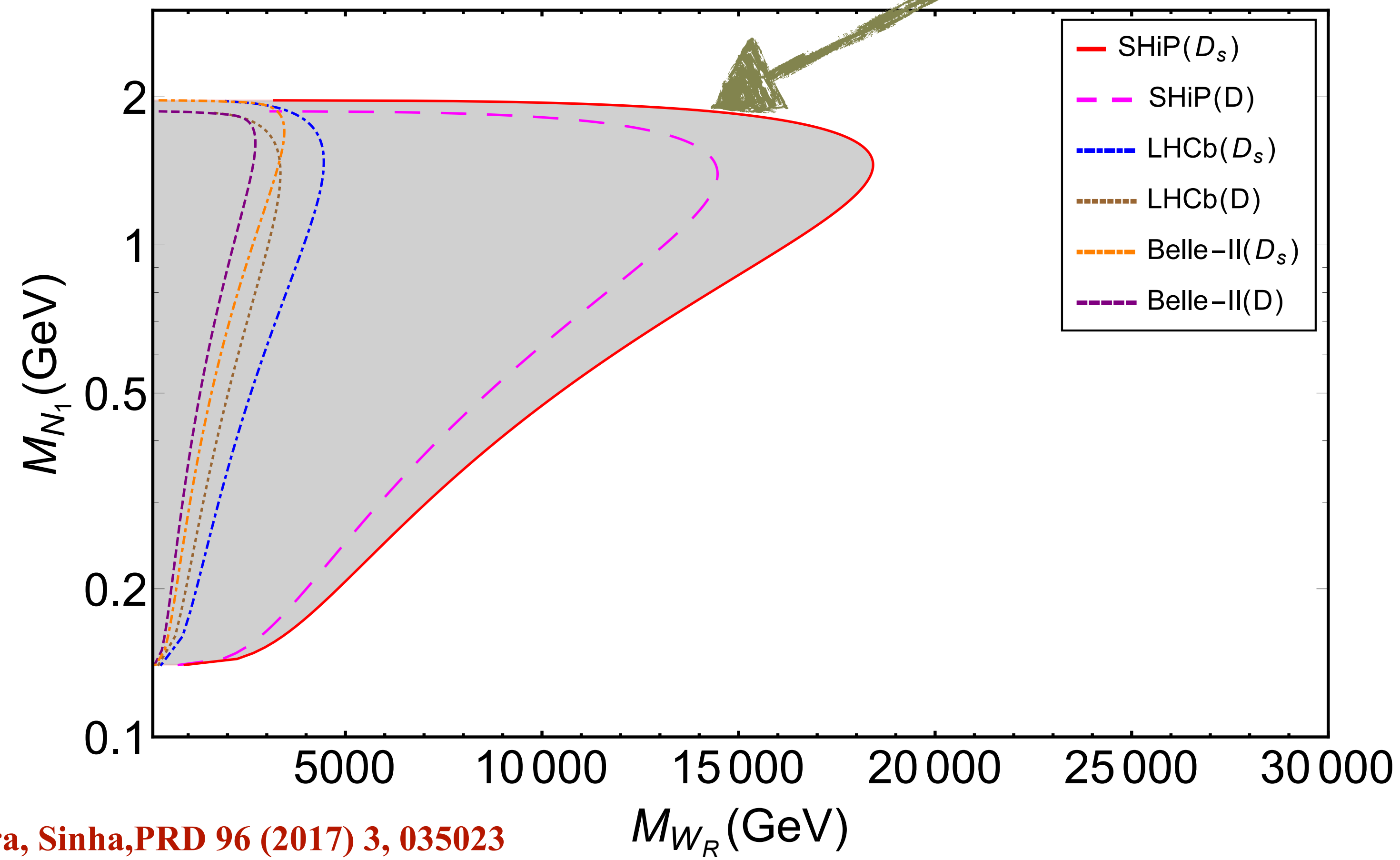
ATLAS Collaboration,
Phys. Lett. B 798 (2019) 134942

LNV Meson Decays:



LHC and LNV Meson decays are complimentary

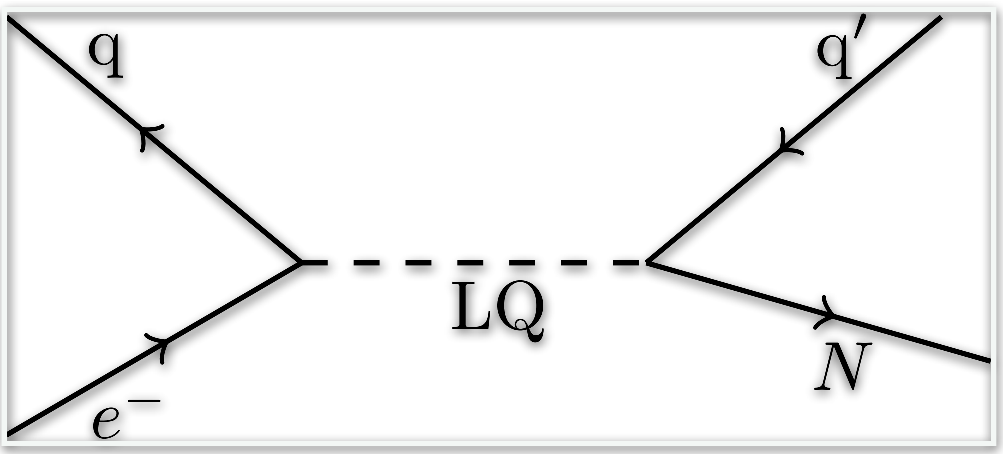
MN mass in 100 MeV range, WR mass 18 TeV



Mandal, Mitra, Sinha,PRD 96 (2017) 3, 035023

Heavy Neutrino Production from Leptoquark

S. Mandal, M. Mitra, N. Sinha *Phys.Rev.D* 98 (2018) 9, 095004,
D. Das, M. Mitra, S. Mondal, K. Ghosh, *Phys.Rev.D* 97 (2018) 1, 015024



In preparation with
Rojalin Padhan,
Sanjoy Mandal

Displaced Decays, Lepton Flavor Violation, muon-electron conversion, and others

Summary

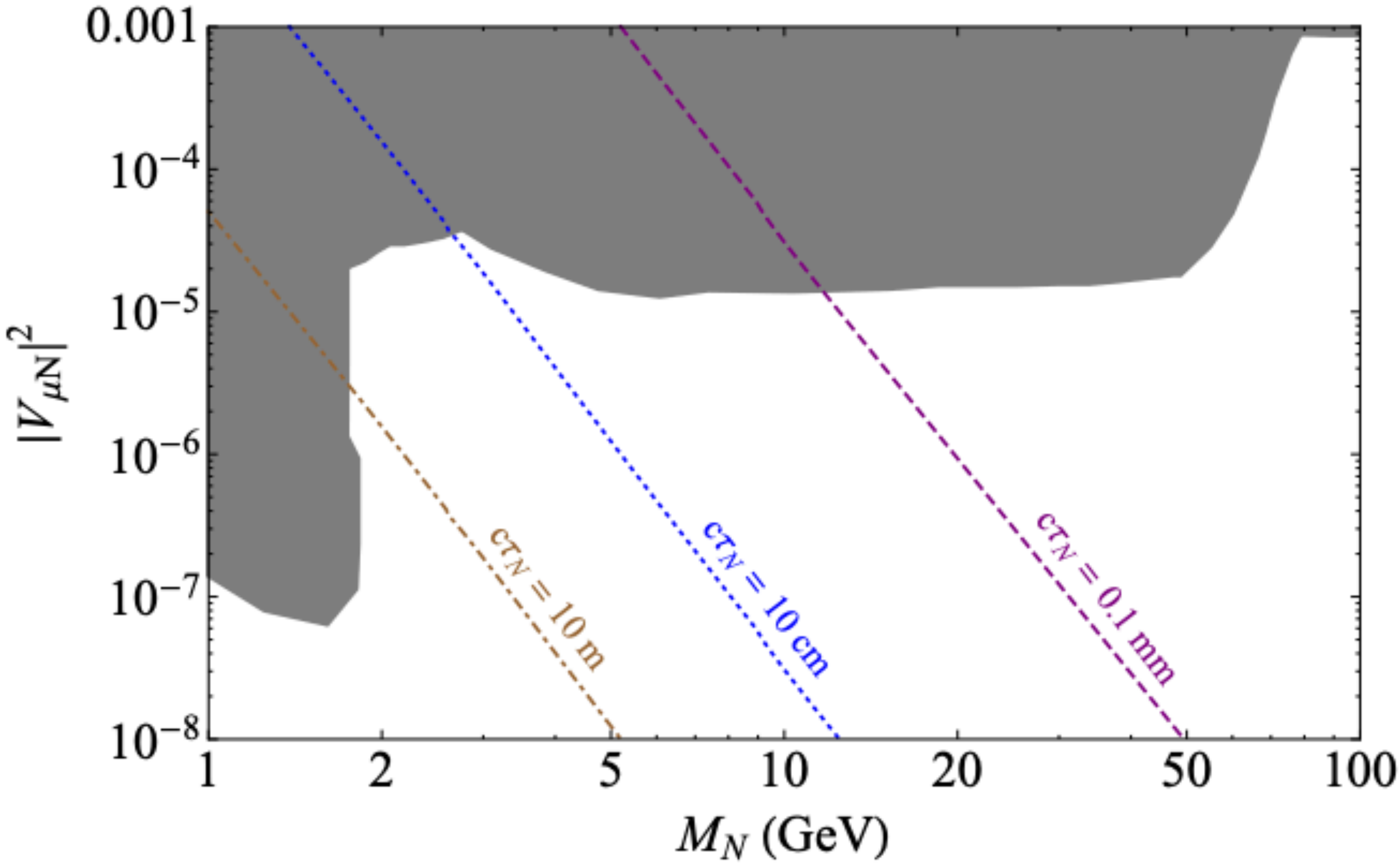
Simplest sterile neutrino can be tested in low energy, collider experiments → 1 GeV-1000 GeV constrained from LHC

Higgs triplet, bound exists upto 820 GeV on doubly charged Higgs, more on LFV searches.

Left-right symmetry, RH neutrino, RH gauge bosons, Higgs triplet → LNV signals

Challenging corners to probe

RHN Searches via Displaced Decays?

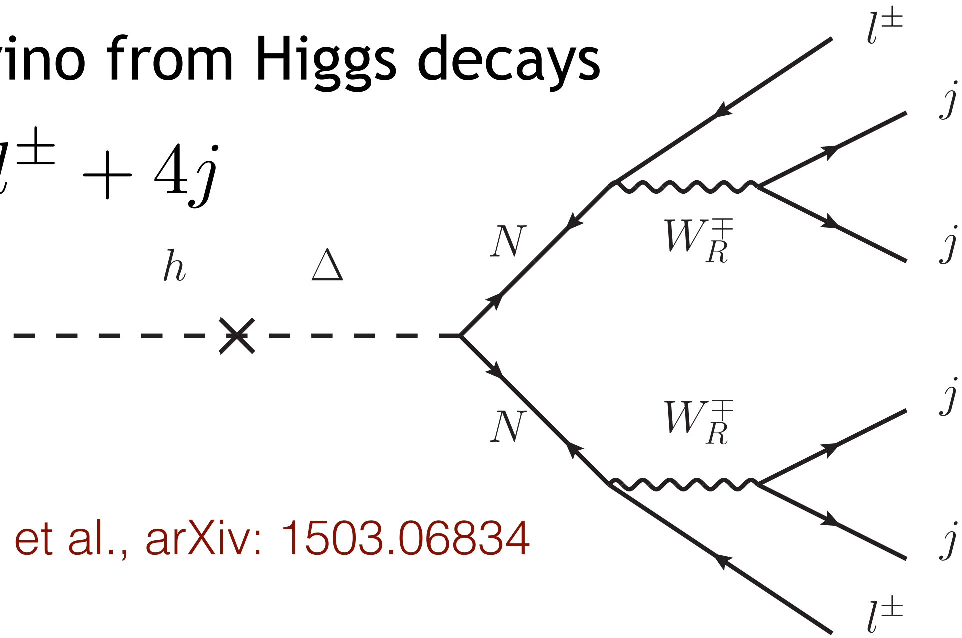


Thank You

LNV Higgs decays:

Heavy neutrino from Higgs decays

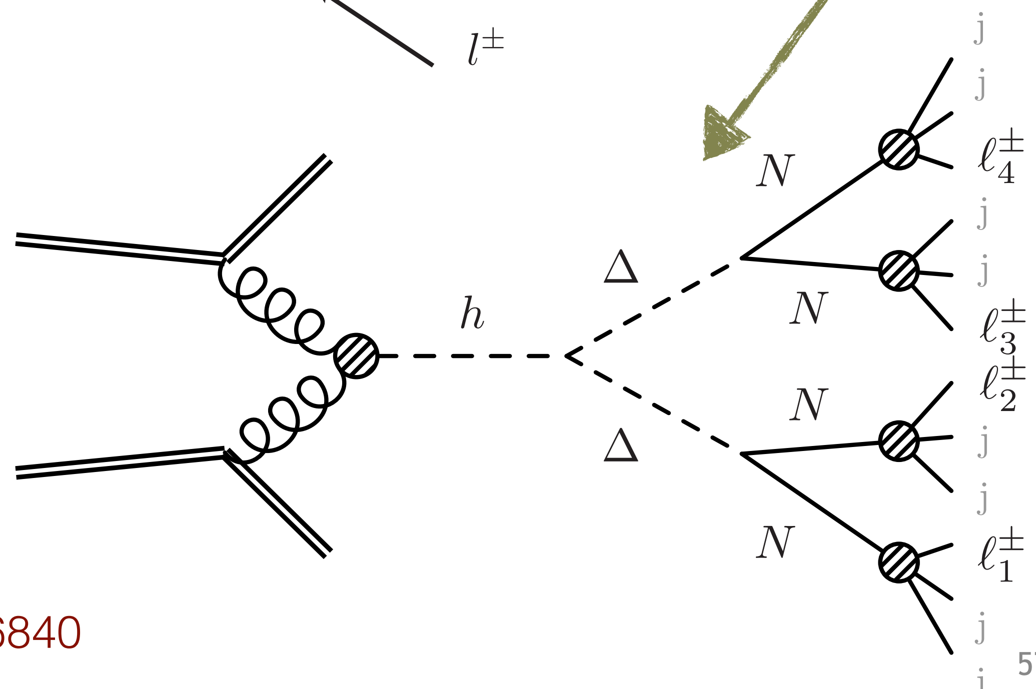
$$pp \to l^{\pm}l^{\pm} + 4j$$



A. Maiezza et al., arXiv: 1503.06834

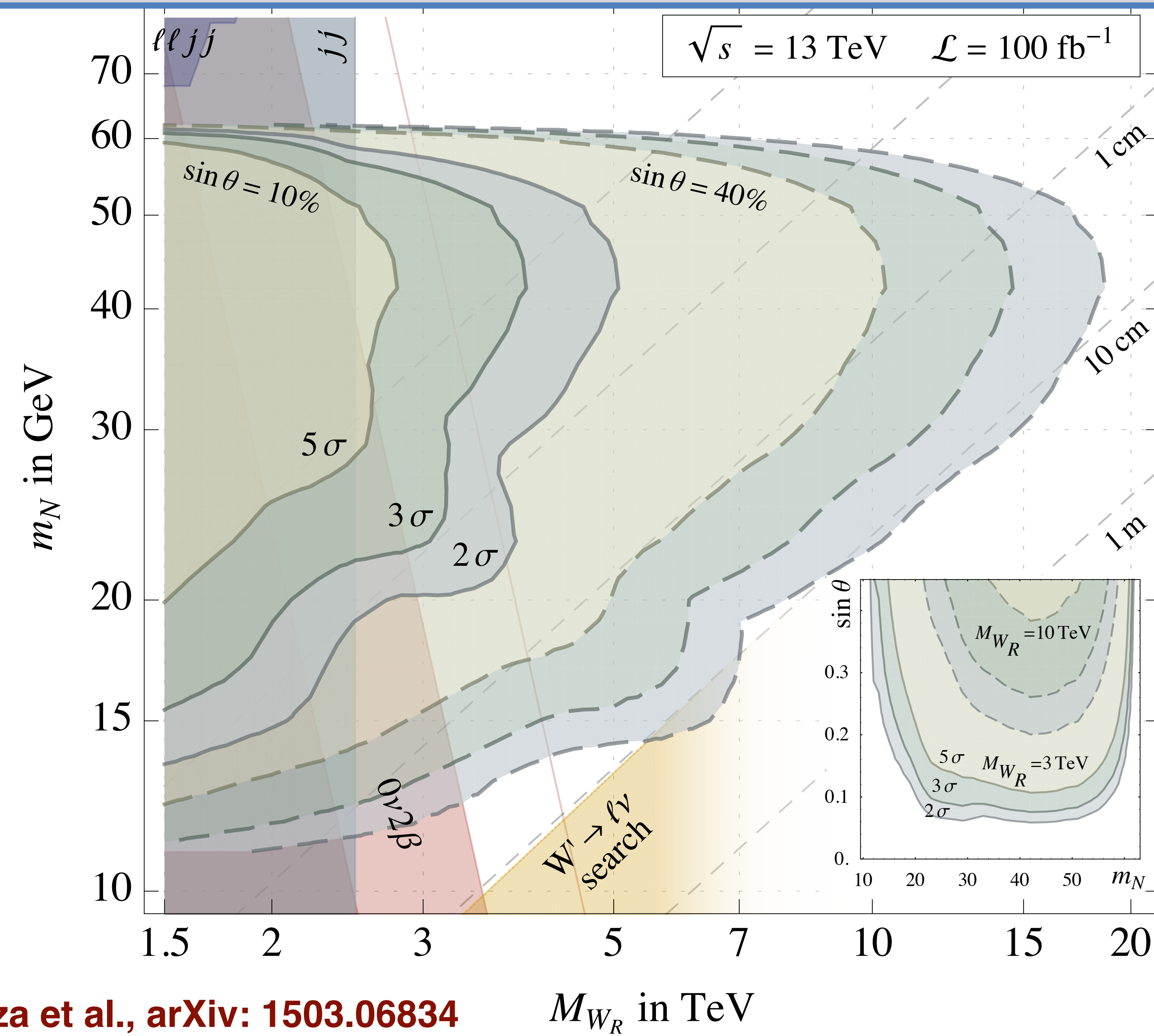
LNV signal

$$pp \to l^{\pm}l^{\pm}l^{\pm}l^{\pm} + nj$$



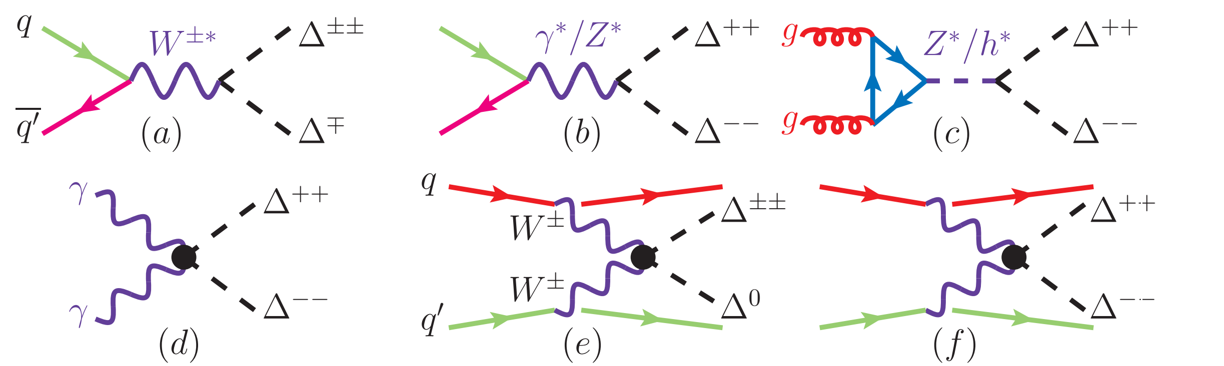
M. Nemevsek, arXiv: 1612.06840

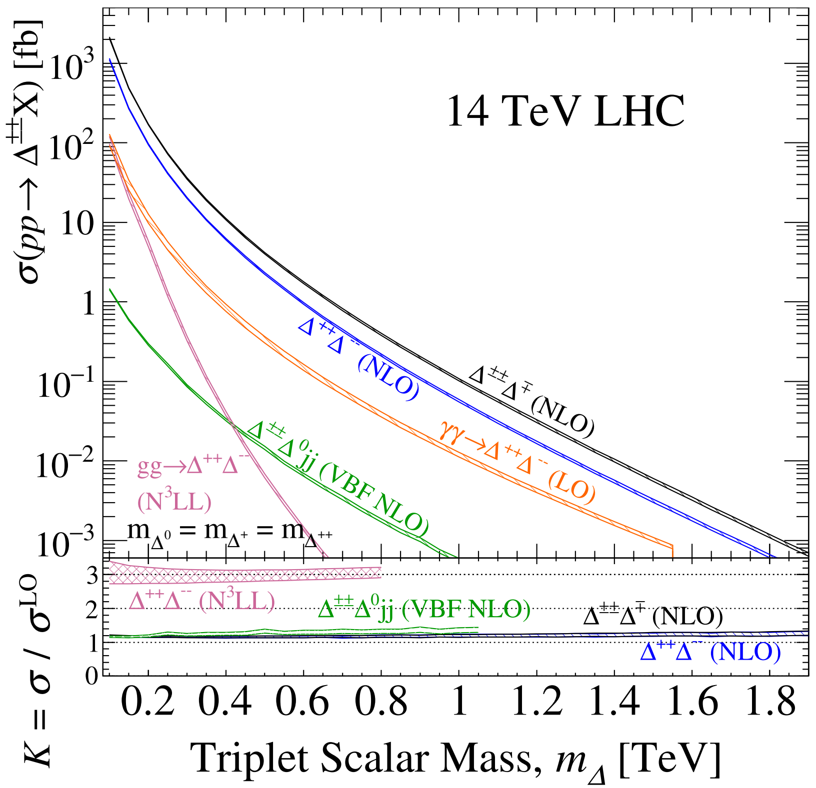
Discovery Reach:

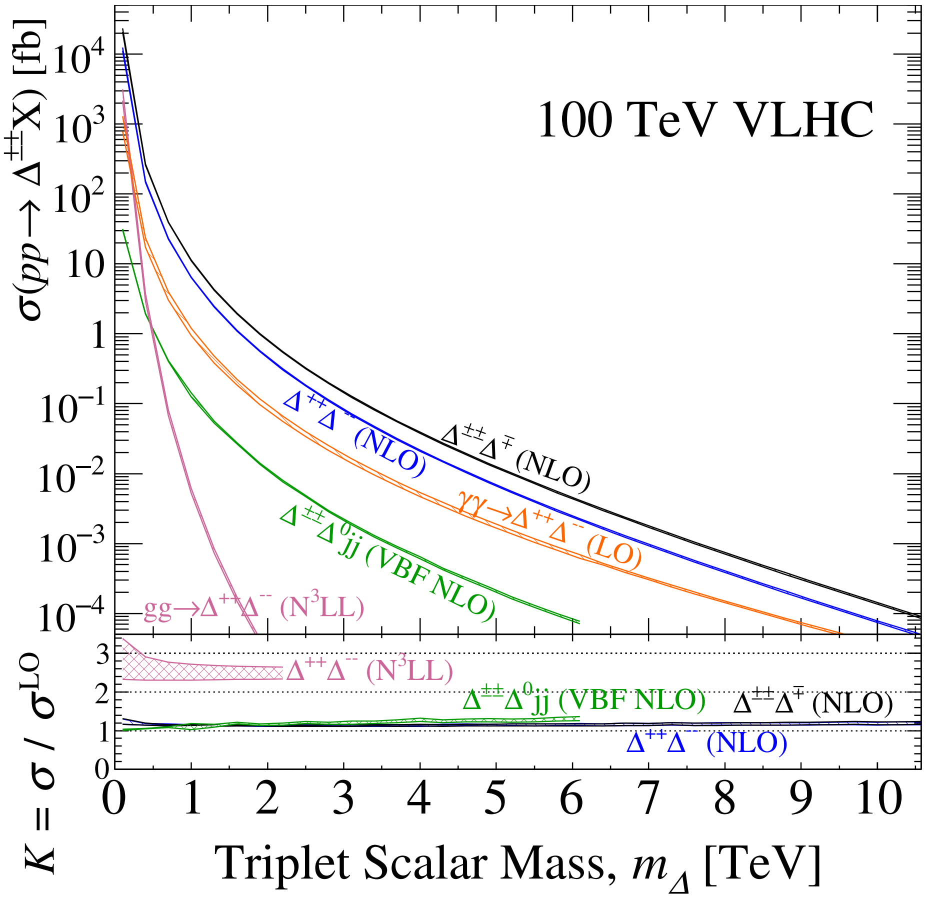


A. Maiezza et al., arXiv: 1503.06834

VLHC Prediction







B. Fuks et al., *Phys.Rev.D* 101 (2020) 7, 075022

Contd:

$$\tau^\pm \to \mu^\pm \mu^\mp \mu^\mp$$

Experiment	Current	Projected
Belle	2.1×10^{-8}	$(4.7-10) \times 10^{-10}$
BaBar	3.3×10^{-8}	–
FCC-ee	–	$(5-10) \times 10^{-12}$
LHCb	4.6×10^{-8}	$(1.5-11) \times 10^{-9}$
ATLAS	3.8×10^{-7}	$(1.8-8.1) \times 10^{-9}$
FCC-hh	–	$(3-30) \times 10^{-10}$

$$\tau^\pm \to e^\mp \mu^\pm \mu^\pm$$

	$\tau^\mp \to e^\pm \mu^\mp \mu^\mp$		$\tau^\mp \to e^\mp \mu^\mp \mu^\pm$	
Experiment	Current	Projected	Current	Projected
Belle	1.7×10^{-8}	$(3.4-5.1) \times 10^{-10}$	2.7×10^{-8}	$(5.9-12) \times 10^{-10}$
BaBar	2.6×10^{-8}	–	3.2×10^{-8}	–
FCC-ee	–	$(5-10) \times 10^{-12}$	–	$(5-10) \times 10^{-12}$

The present limit $\sim 10^{-8}$. LHCb limit similar to Belle. The future sensitivity $\sim 10^{-10} - 10^{-12}$. 13 TeV LHC can give stringent limit.

LHC limits $\to$ 8 TeV. Future limits with 13 TeV, 3 ab^{-1} for ATLAS and 50 ab^{-1} with LHCb.

Direct vs Indirect:

Neutrinoless Double Beta Decay

- Indirect evidence of BSM models

Large Hadron Collider

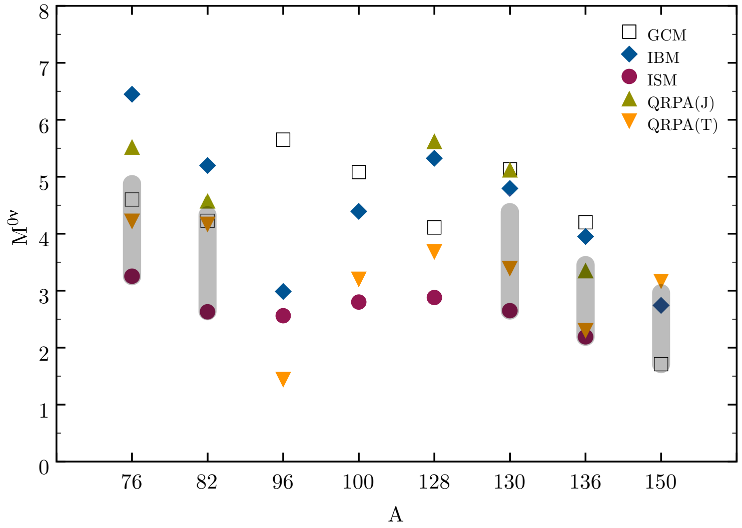
- Direct evidence of BSM models

Collider → Limited by kinematics

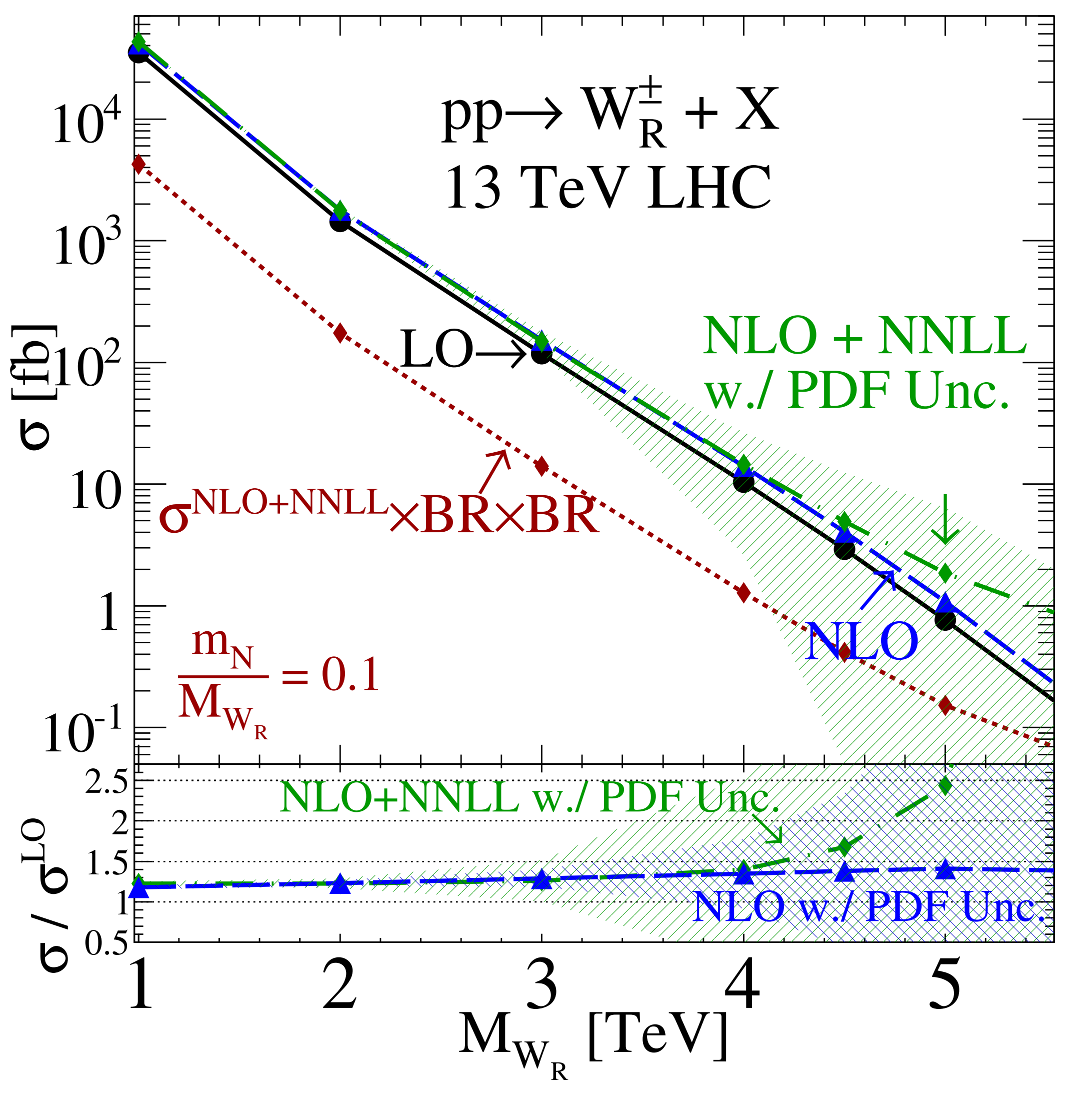
$0\nu\beta\beta$

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}(A,Z)\,\eta|^2$$

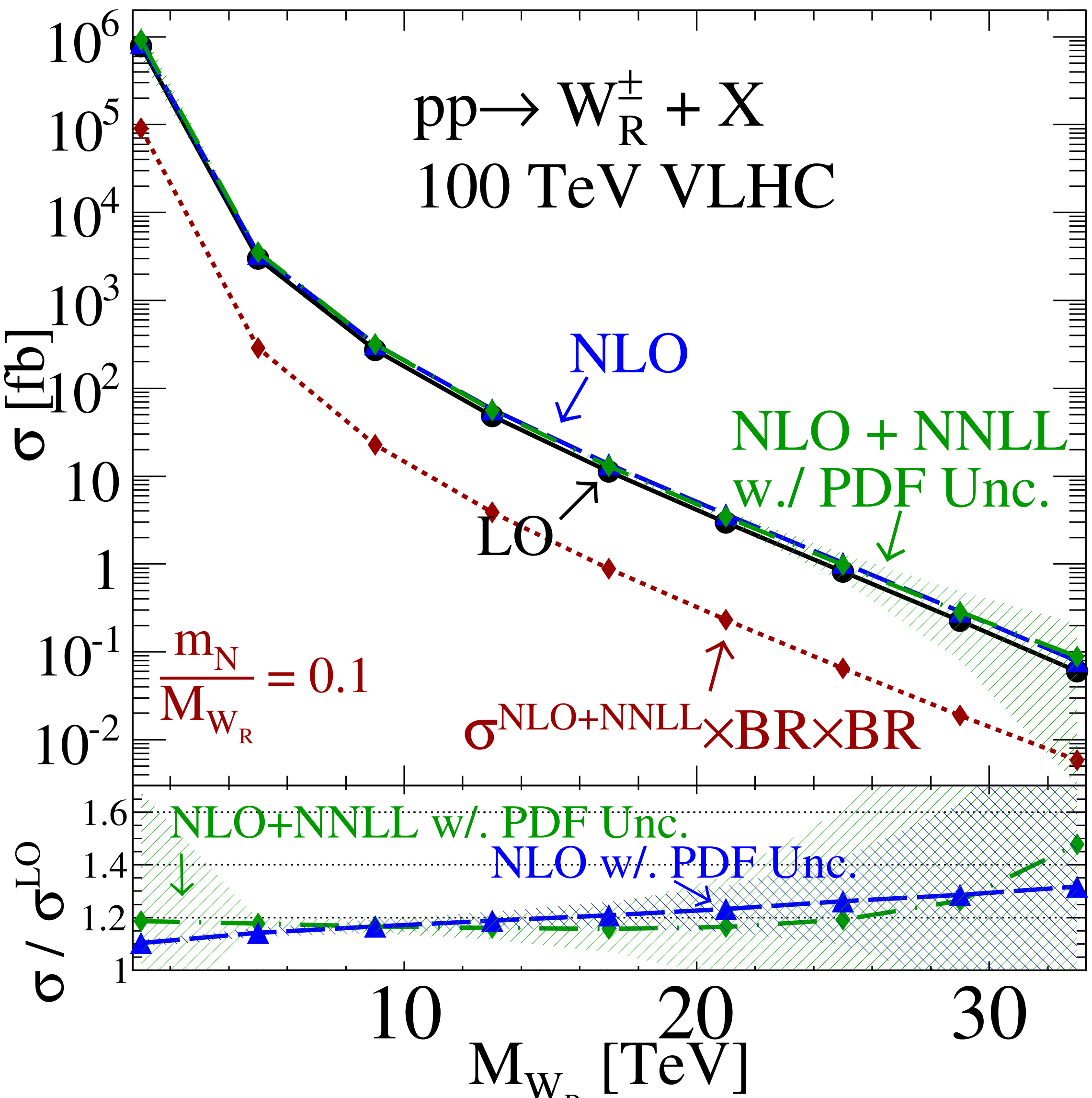
To extract η, need information about NME.



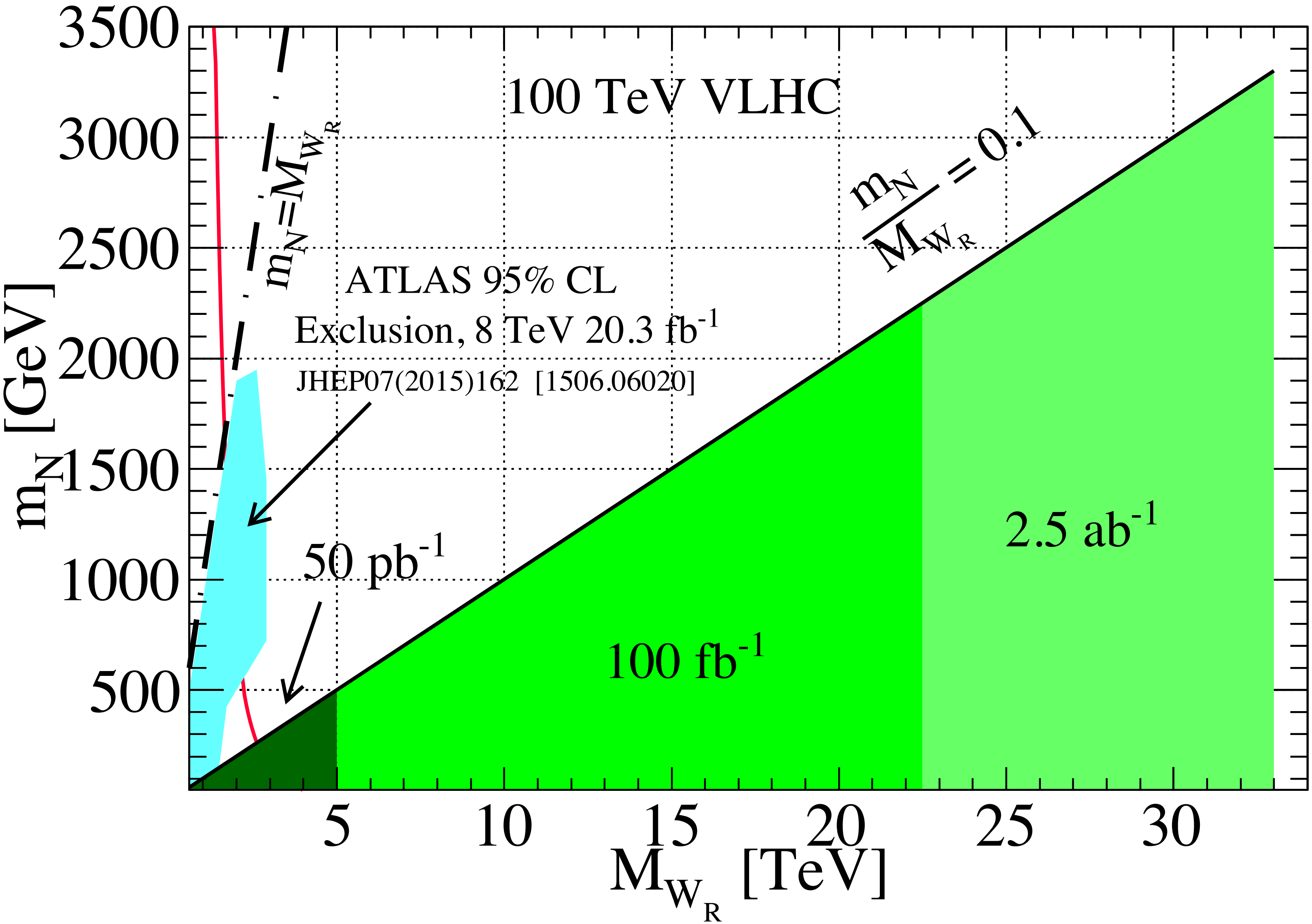
Limited by NME uncertainty



pp→ W$^{\pm}_{R}$ + X
13 TeV LHC
LO→
NLO + NNLL
w./ PDF Unc.
σ$^{NLO+NNLL}$×BR×BR
NLO
$\frac{m_N}{M_{W_R}}$ = 0.1
σ [fb]
NLO+NNLL w./ PDF Unc.
NLO w./ PDF Unc.
σ / σ^{LO}
M_{W_R} [TeV]



pp→ $W_R^{\pm}$ + X
100 TeV VLHC
NLO
NLO + NNLL
w./ PDF Unc.
LO
$\frac{m_N}{M_{W_R}} = 0.1$
$\sigma^{NLO+NNLL}\times BR\times BR$
NLO+NNLL w/. PDF Unc.
NLO w/. PDF Unc.
σ [fb]
σ / σ^{LO}
M_{W_R} [TeV]
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
1.6
1.4
1.2
1
10
20
30



100 TeV VLHC
$m_N = M_{W_R}$
$\frac{m_N}{M_{W_R}} = 0.1$
ATLAS 95% CL
Exclusion, 8 TeV 20.3 fb^{-1}
JHEP07(2015)162 [1506.06020]
50 pb^{-1}
100 fb^{-1}
2.5 ab^{-1}
3500
3000
2500
2000
1500
1000
500
m_N [GeV]
5
10
15
20
25
30
M_{W_R} [TeV]