Direct and Indirect Probes of Seesaw

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Anomalies2020, IIT Hyderabad

Outline:

Origin of Neutrino Masses, Mixings and Discovery Prospects

- Beyond Standard Models (Heavy neutrinos- Type-I/ Inverse, Type-II And Left-Right Symmetry)

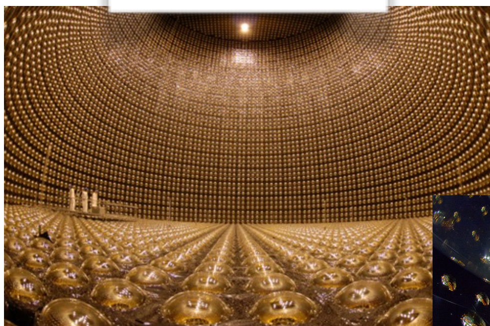
↓

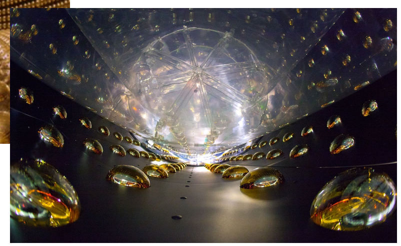
- Collider searches
- Non-collider searches

Neutrino Masses and Mixings ?

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

Oscillation





Mass square differences and mixings

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

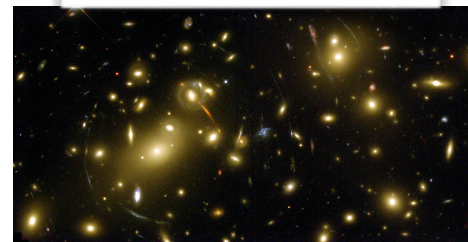
$$|\Delta m^2_{31}| = (2.41 - 2.60) \times 10^{-3}\,\mathrm{eV}^2$$

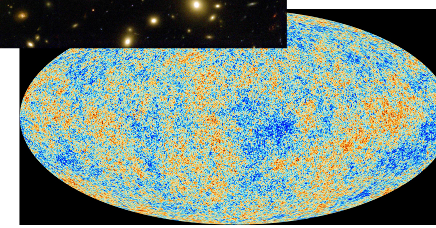
Large angle $\theta_{12} \sim 34.5^\circ, \theta_{23} \sim 47.7^\circ$

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

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

Non-Oscillation





Sum of neutrino masses

Bound from cosmology

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

(Planck Collaboration, arXiv 1502.01589)

Can not be explained with SM without adding any additional particle

Neutrinos and Beyond Standard Model Physics

Neutrinos masses, and mixings

Key Questions

- **Underlying theory of neutrino mass generation!**
  At present no experimental evidence

- Neutrinos are electromagnetic charge neutral
  → **Dirac or Majorana ?** Majorana particle → it's own antiparticle.

Experimental Tests

Large Hadron Collider, CERN

Image credit: CERN.

Neutrinoless Double Beta Decay

Rare meson decays

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)

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

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

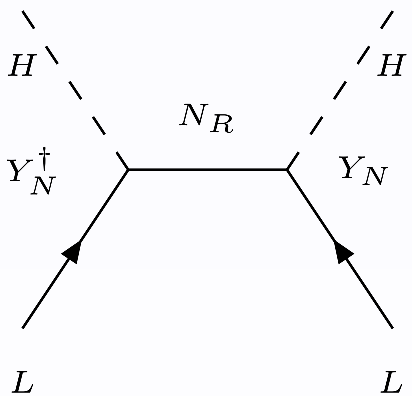
UV Completion

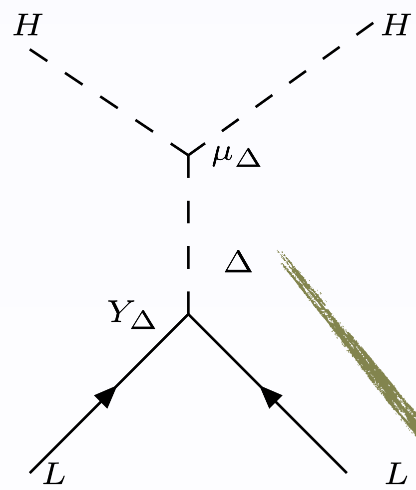
- Type-I,II,III
- Inverse Seesaw
- Left Right Symmetric Model
- Scotogenic model

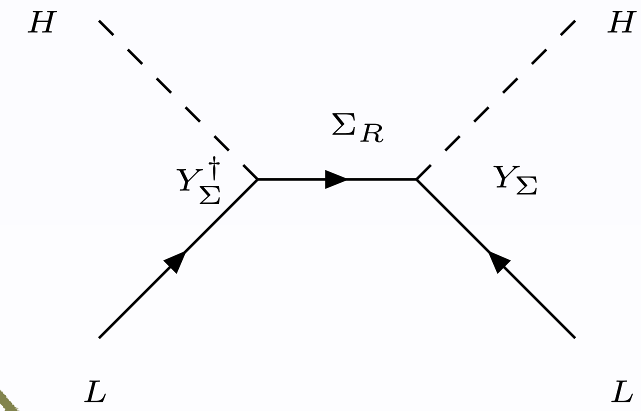
Contd:

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

Σ_R → Gauge interaction



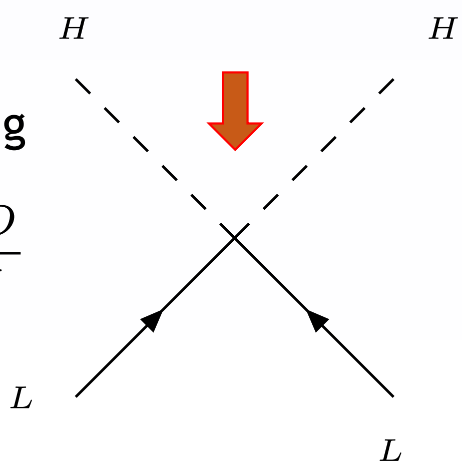




interaction of N with other SM particles is proportional to the active-sterile mixing

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

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

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

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

Unsuppressed mixing $\frac{m_D}{M} \rightarrow \sigma$ large

Mohapatra, Valle, 1986

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

$\mu \sim 0$

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 $\Delta_L = (3,1,2)$, $\Delta_R = (1,3,2)$.

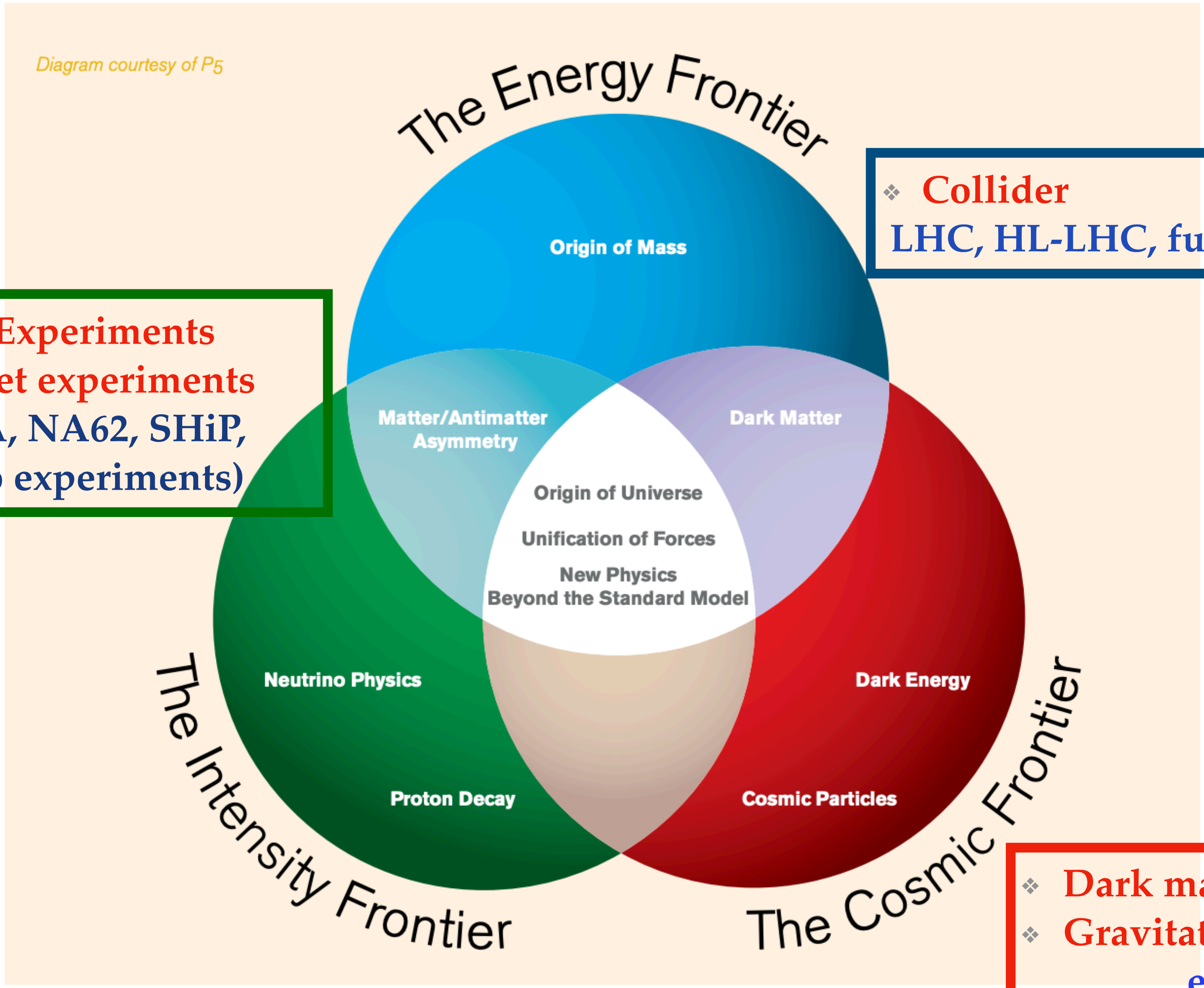
  $\langle\Delta_R\rangle$ **breaks the** $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$
- Sterile neutrino N is part of the gauge multiplet $\begin{pmatrix} N \\ e \end{pmatrix}_R$
- Additional gauge bosons W_R and Z'. $M_{W_R} \propto \langle\Delta_R\rangle$

Natural way to embed the sterile neutrinos

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

Detection Prospects

Wide detection prospects at direct and indirect search experiments



- Collider
  LHC, HL-LHC, future

- Precision Experiments
- Fixed target experiments
  (GERDA, NA62, SHiP, neutrino experiments)

- Dark matter
- Gravitational wave
  eLISA

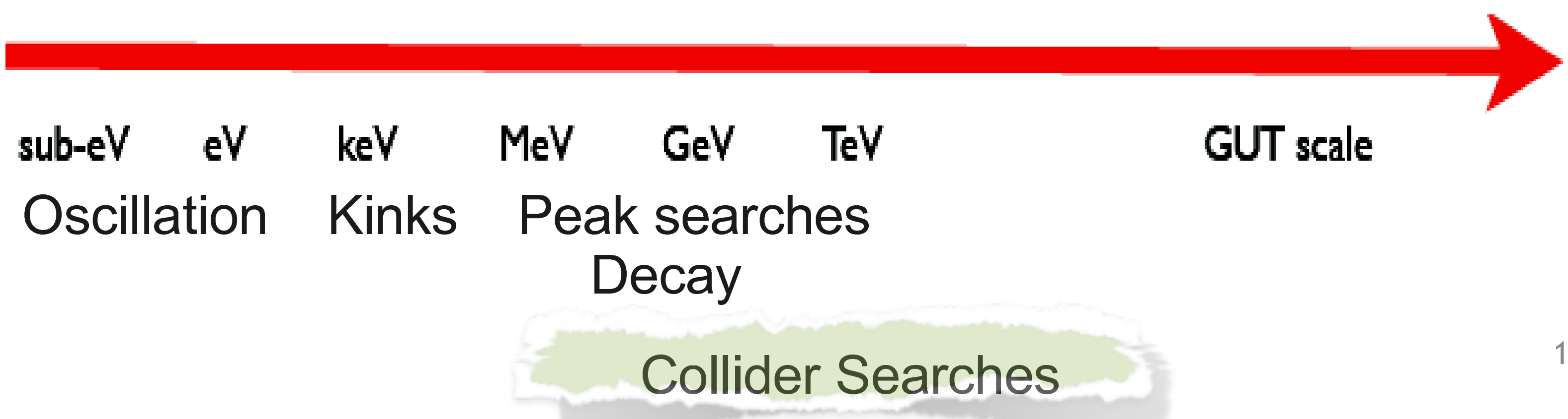
Heavy Neutrino:

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,...

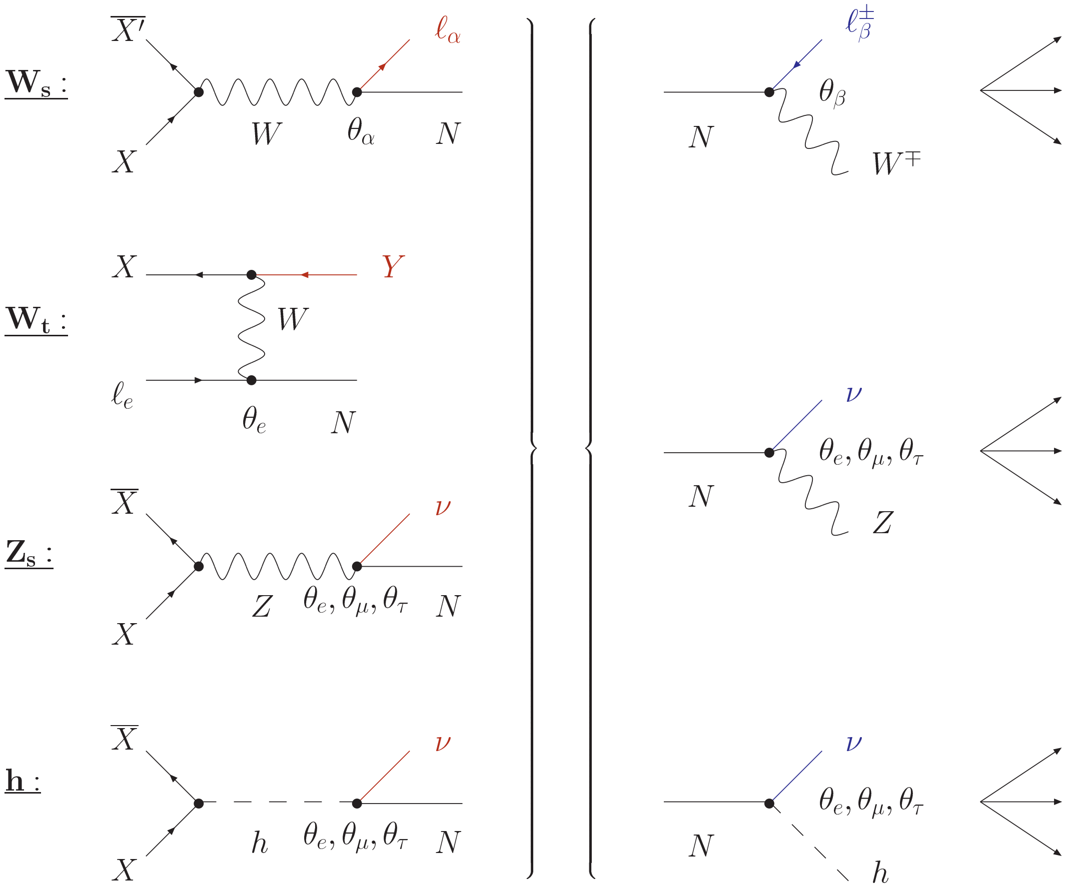


Sterile Neutrino:

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



Final states (W decay):

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

Final states (Z decay):

- 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 : $\nu\nu jj$, $\nu\nu\ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu\nu\nu$

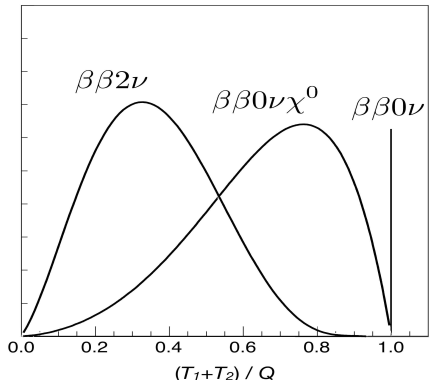
Final states (h decay):

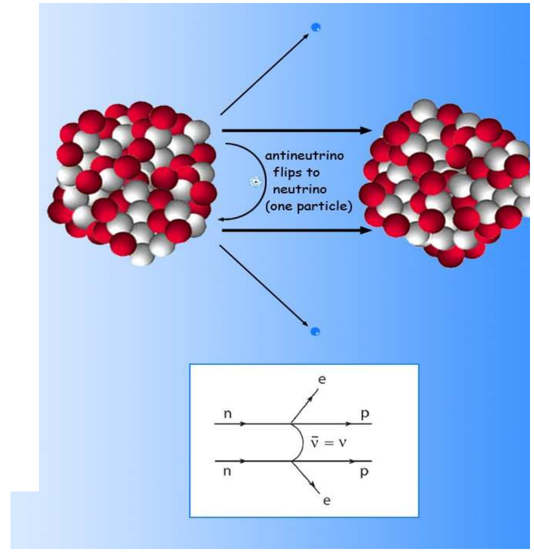
- pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu VV$
- e⁻e⁺, e⁻p : $Y\nu jj$, $Y\nu\ell_\beta^\pm \ell_\beta^\mp$, $Y\nu VV$
- e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu\ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu VV$

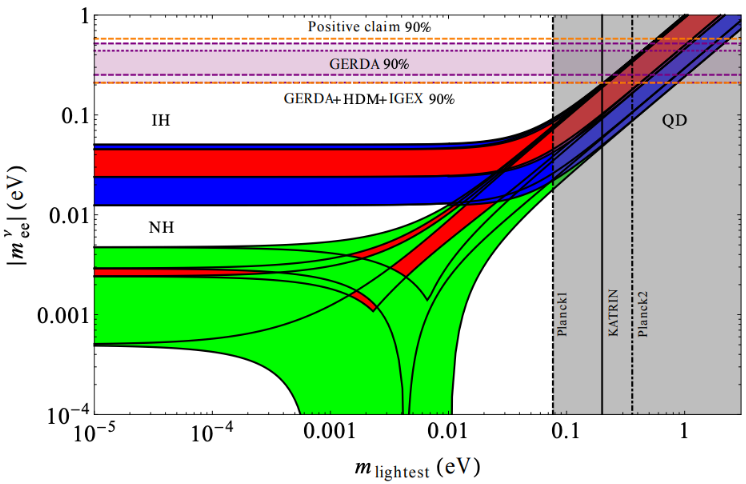
Multilepton, multijet final states

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

Neutrinoless double beta decay







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

G Racah 1937; W. H. Furry

Probing lepton number violation

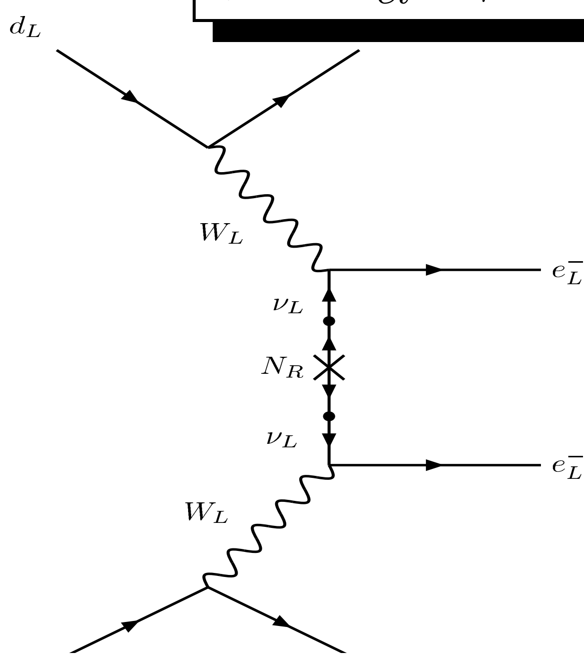
Sterile Neutrino Contribution

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

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

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

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



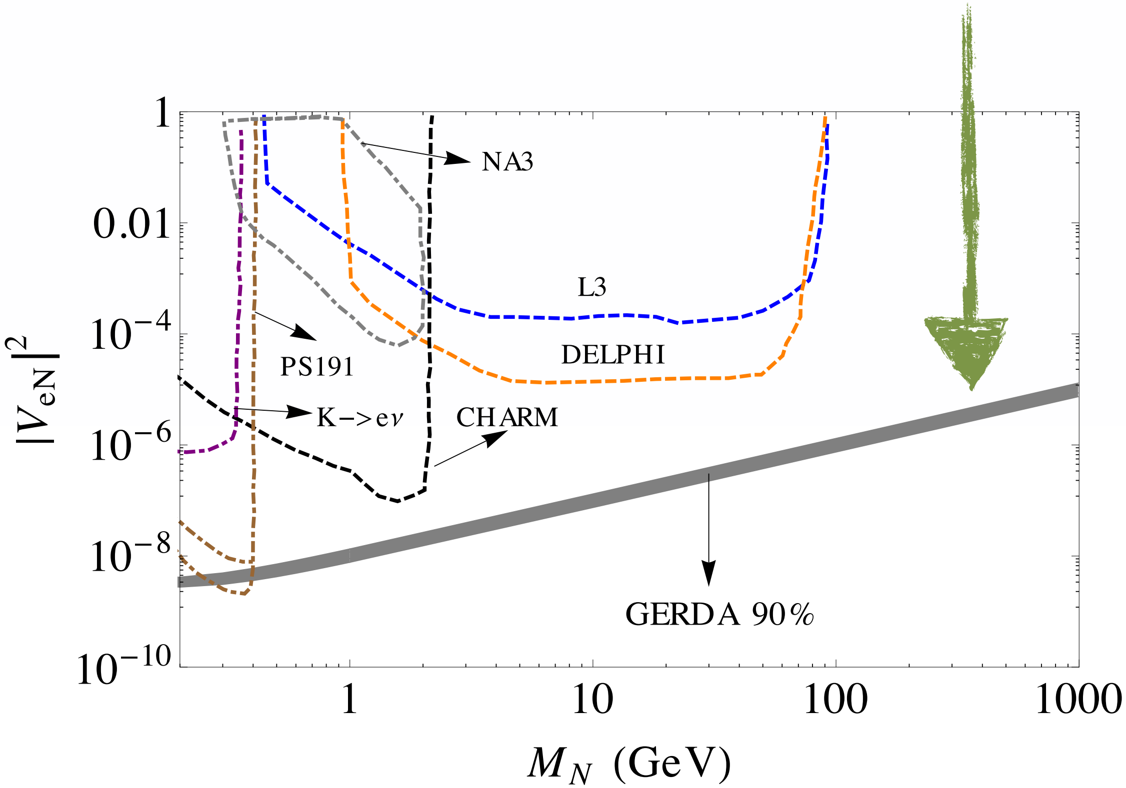
$M_i^2 > p^2 \sim (200)^2 \text{MeV}^2$; $p \to$ intermediate momentum

Controlled by V and M

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.

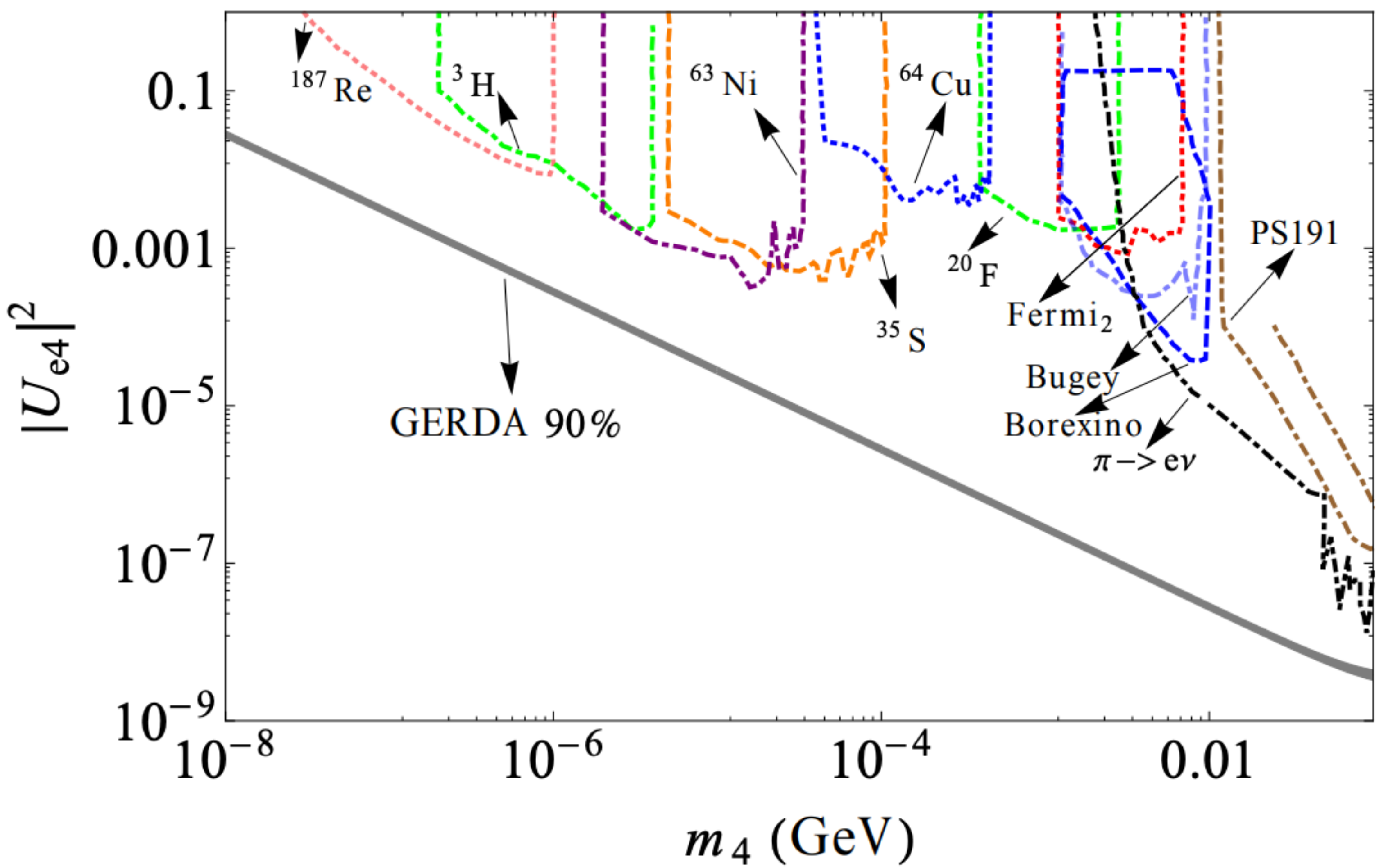


Mitra, Pascoli, Wong, 2013 ;

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

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

Light Sterile Neutrinos:



M. Mitra, S. Pascoli, S. Wong, *Phys.Rev.D* 90 (2014) 9, 093005

Collider signatures → lepton channels

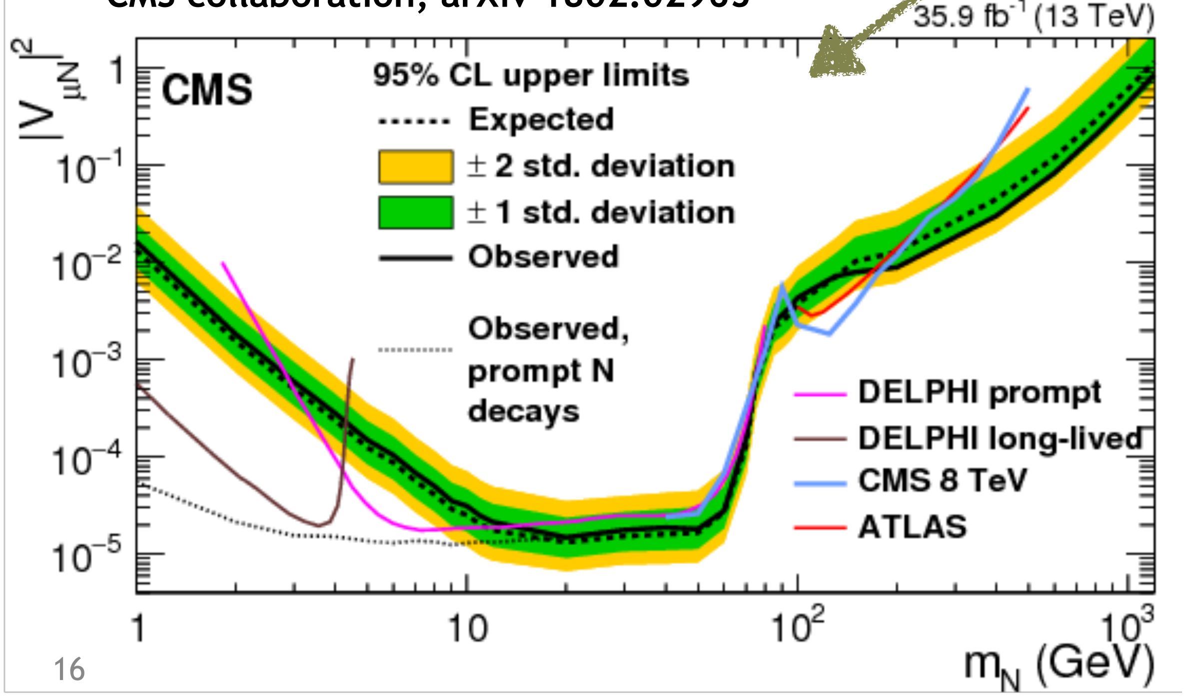
- Like sign/ different flavor diliptons $l^\pm l^\pm / l^\pm l'^\mp + 2j$
- Trilepton channels $l^\pm l^\mp l^\pm$ → For Dirac neutrinos N_R
- Lepton number violating $l^\pm l^\pm$ → Proof of heavy Majorana neutrinos N_R

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

Poor sensitivity in low and high mass regime

CMS collaboration, arXiv 1802.02965



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

Similar constraints

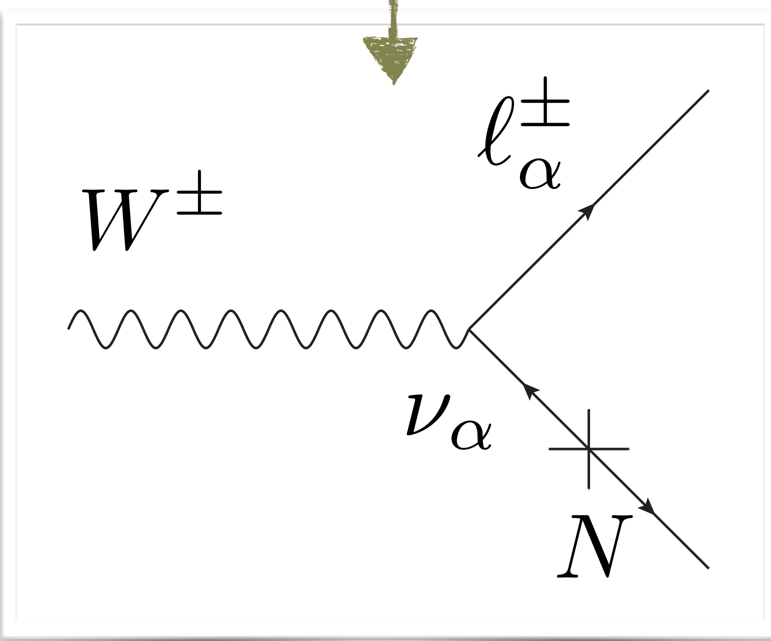
CMS collaboration, 1603.02248

CMS collaboration, arXiv 1806.10905

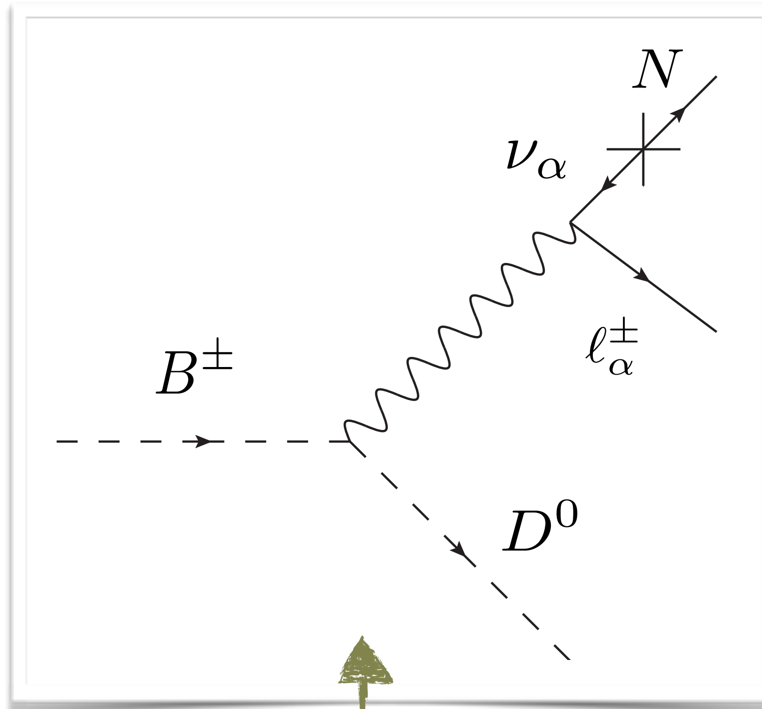
Low Mass Sterile Neutrino - Boosted Regime:

Boosted RH neutrino N

$$m_N < M_W$$



Production from meson decay



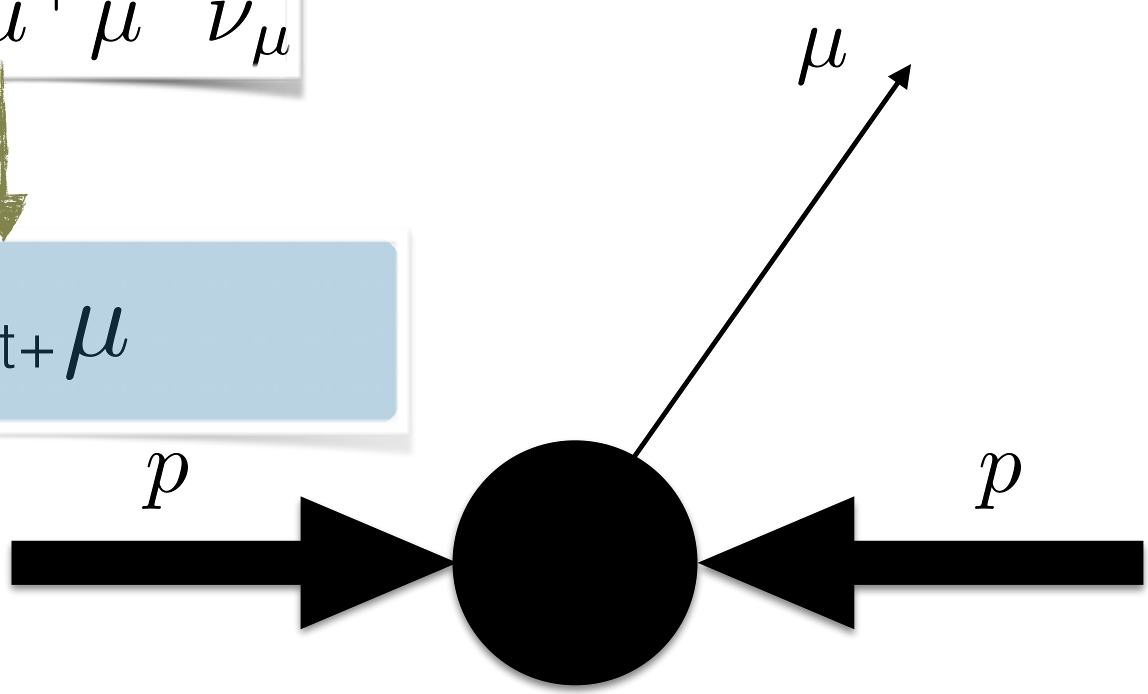
$$m_N < B^\pm$$

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

Lepton Jet:

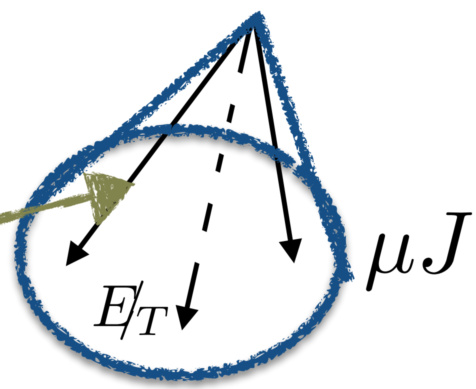
$N \to \mu^+\mu^-\nu_\mu$

Lepton jet+μ



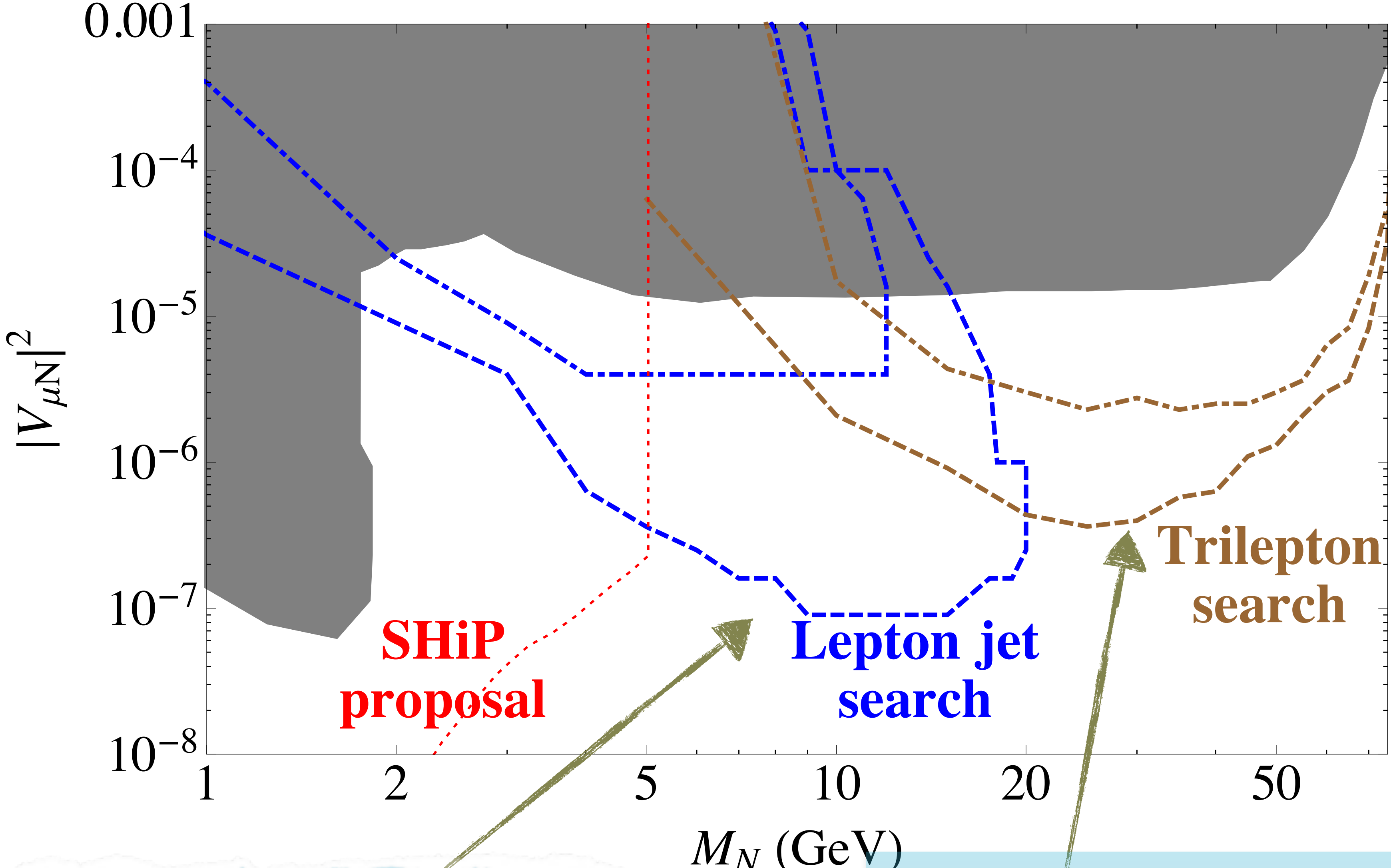
Collimated $\mu^+\mu^-$

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

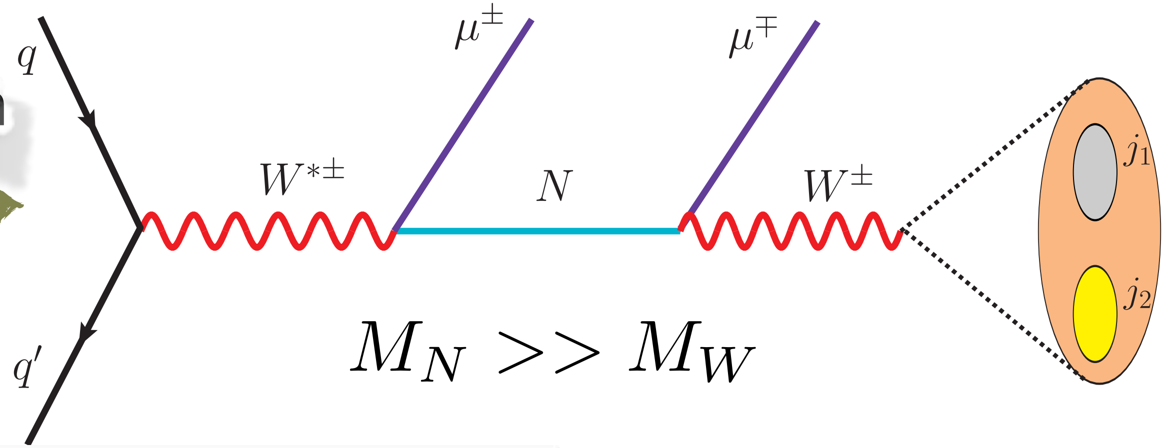
High Mass Sterile Neutrino:

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

Opposite charged lepton

+ Fat-jet

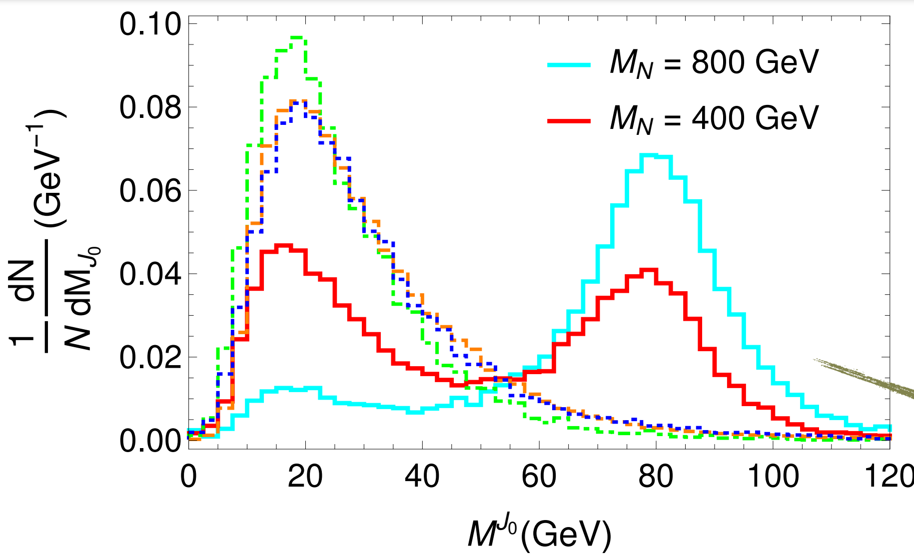
Bharadwaj et al., arXiv 1801.00797



$$M_N >> M_W$$

Most challenging corner due to large backgrounds

$$Z + j, t\bar{t}, VV + j$$

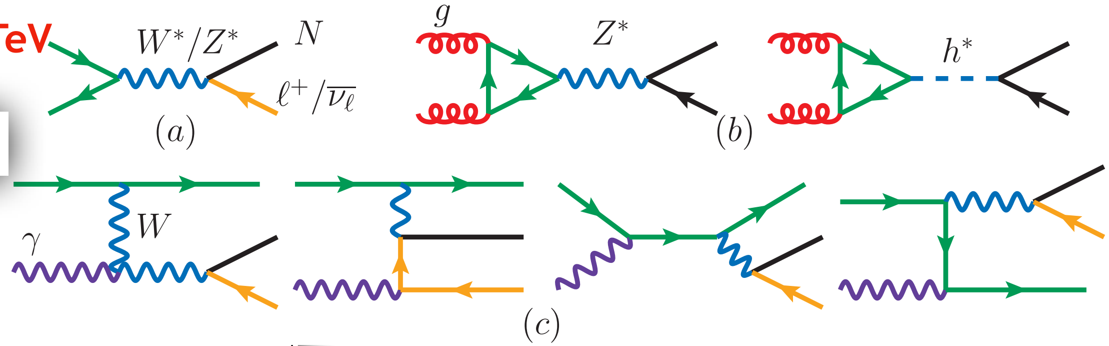


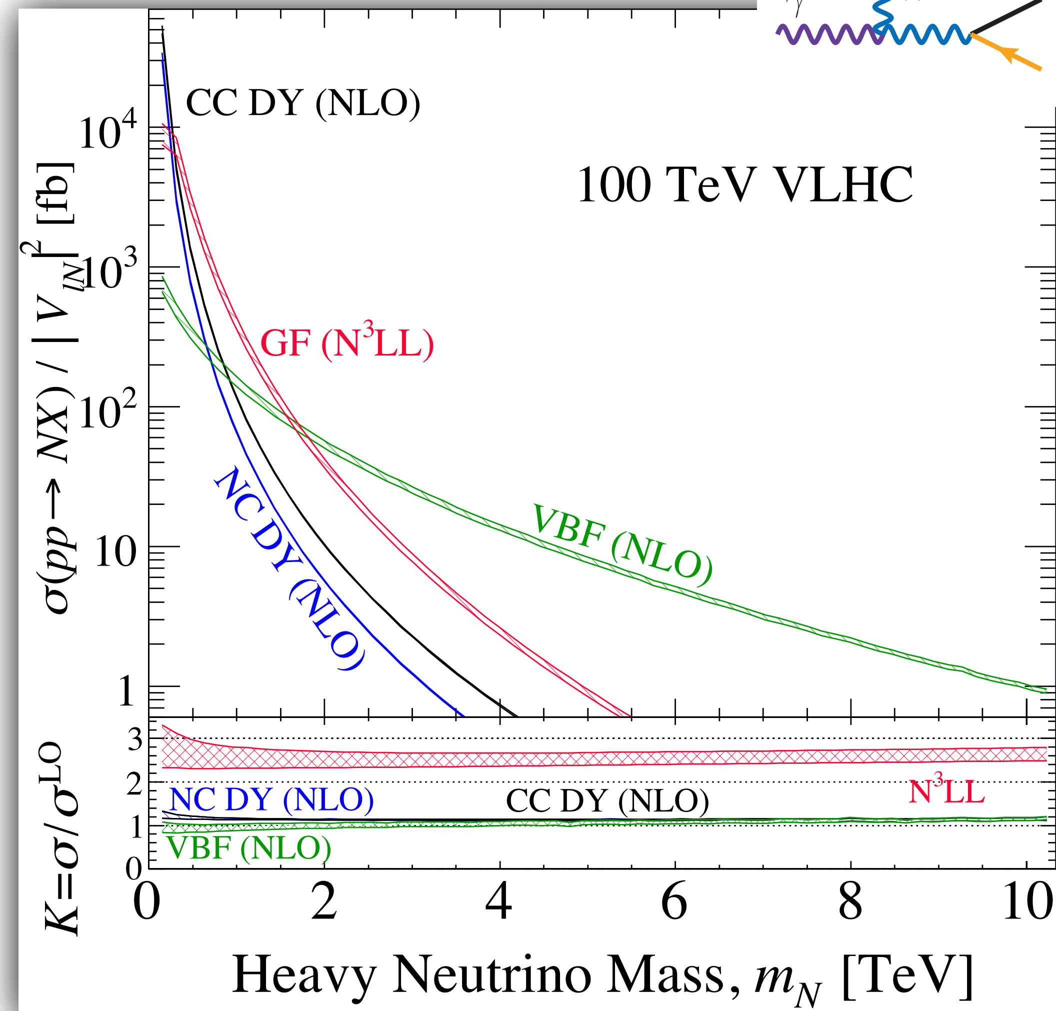
substructure variable

VLHC Prediction

Very heavy mass can be probed at 100 TeV

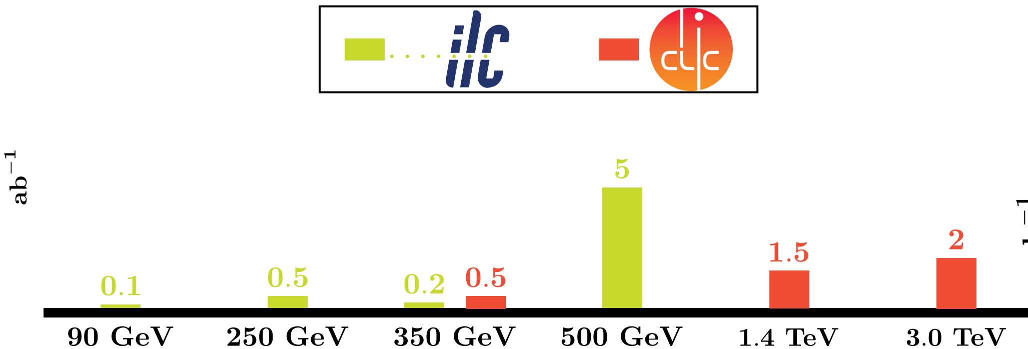
Large contribution from GF, VBF channels

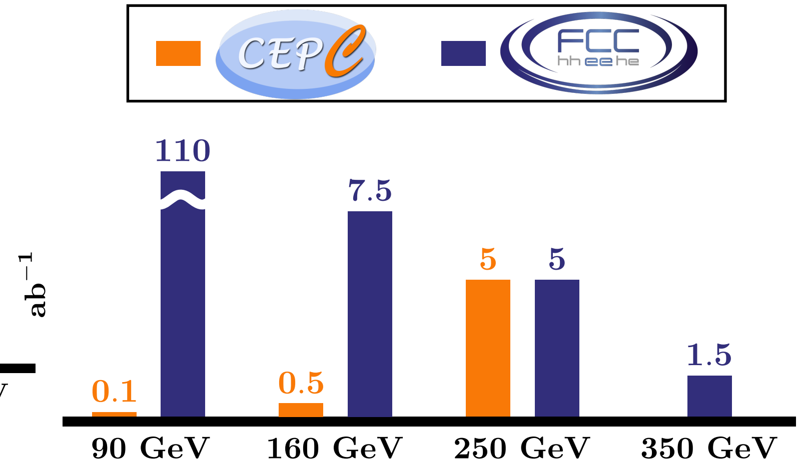


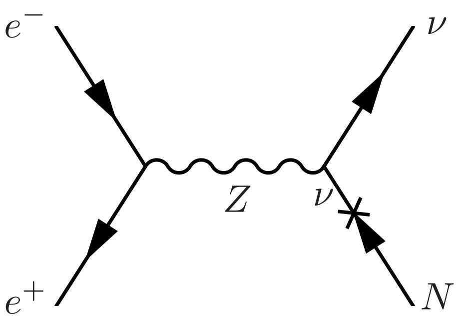


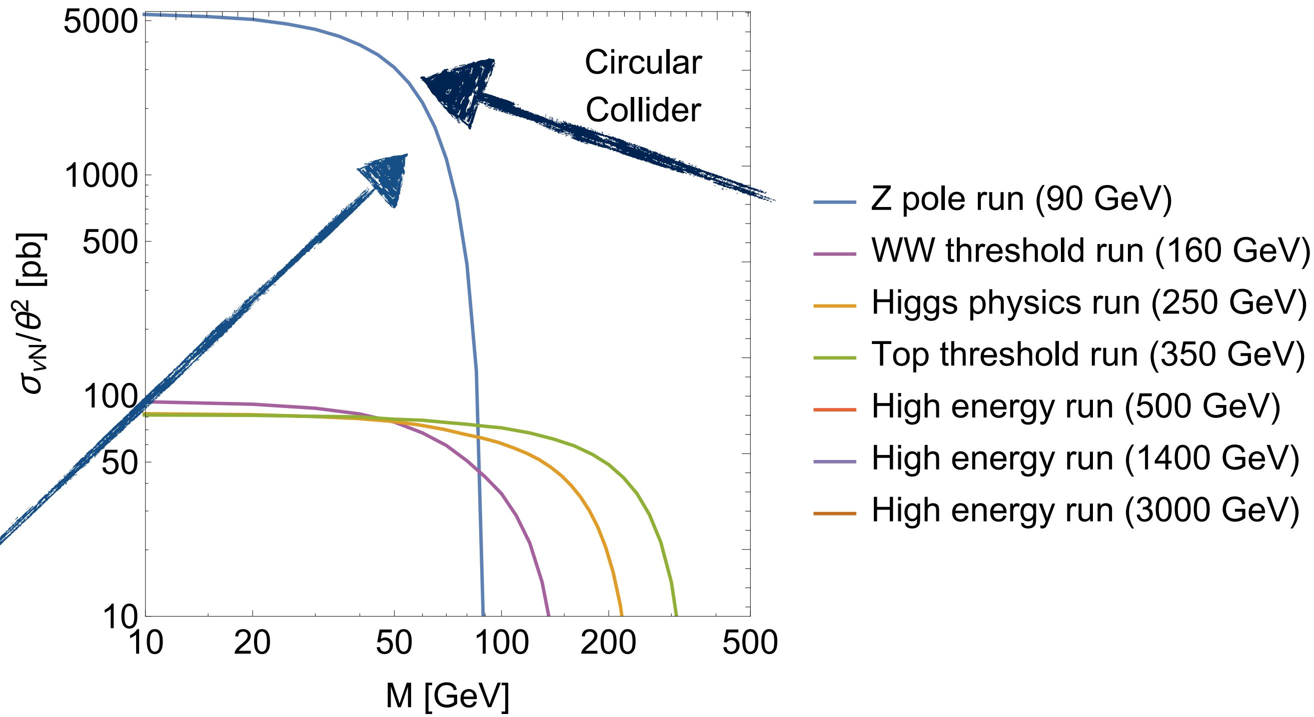
S. Pascoli, R. Ruiz, C. Weiland-*JHEP* 06 (2019) 049

Future Lepton Collider









Limited by kinematics

$M_N < M_Z$

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

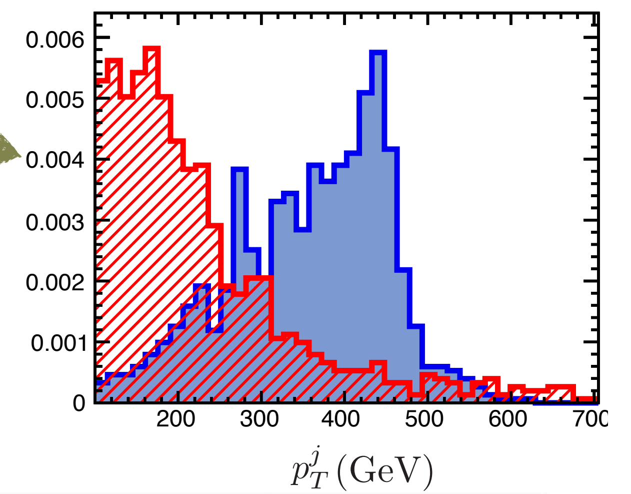
Even more massive N $M_N \sim TeV$

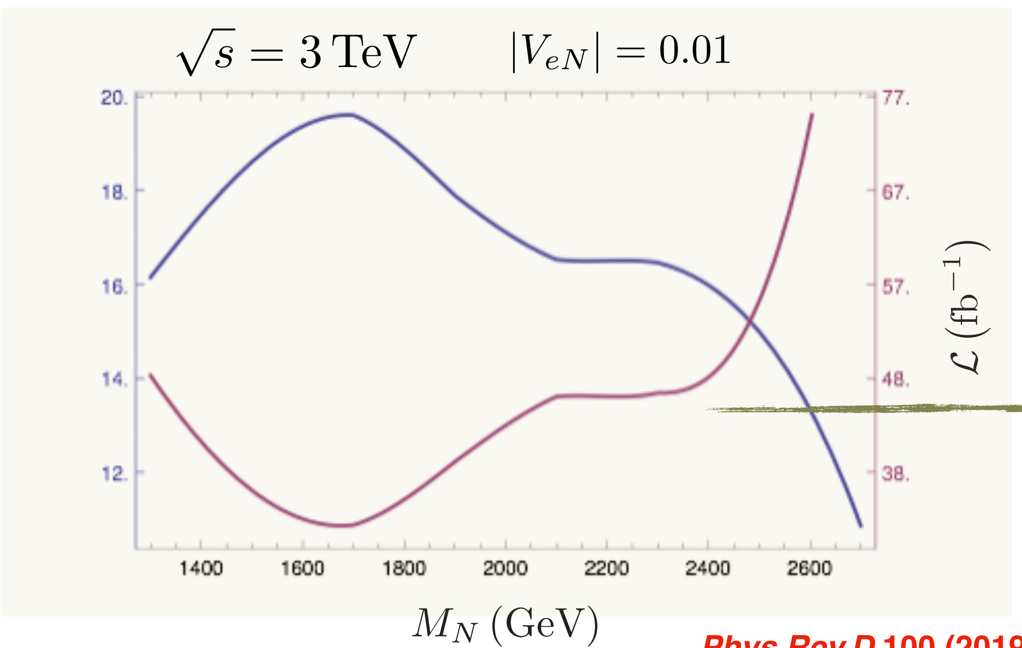
Model signature → $e^+e^- \to \nu N \to lW\nu \to lJ_{Fat} + \not{E}$

Boosted W → Collimated decay products

High Mass of N=900 GeV

High p_T





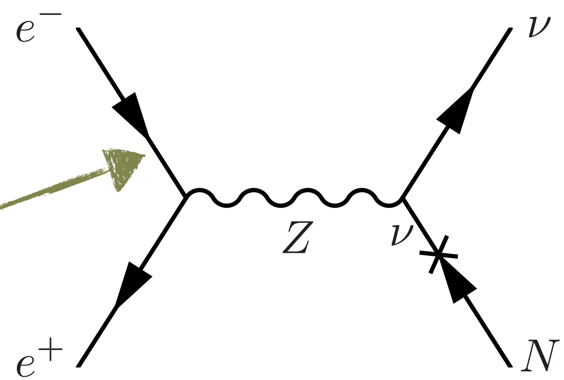
Required luminosity

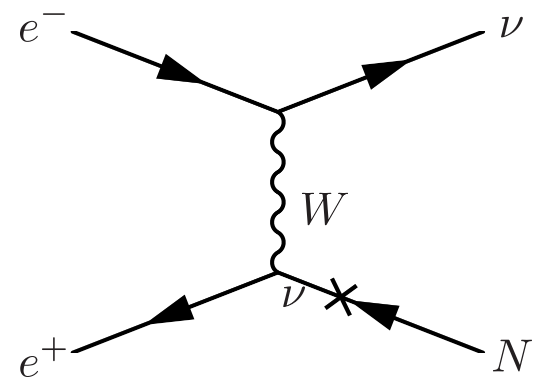
$$\mathcal{L} < 38\,\text{fb}^{-1}$$

Phys.Rev.D 100 (2019) 1, 015012, S. Chakraborty, S. Shil and M. Mitra

Collider Search:

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



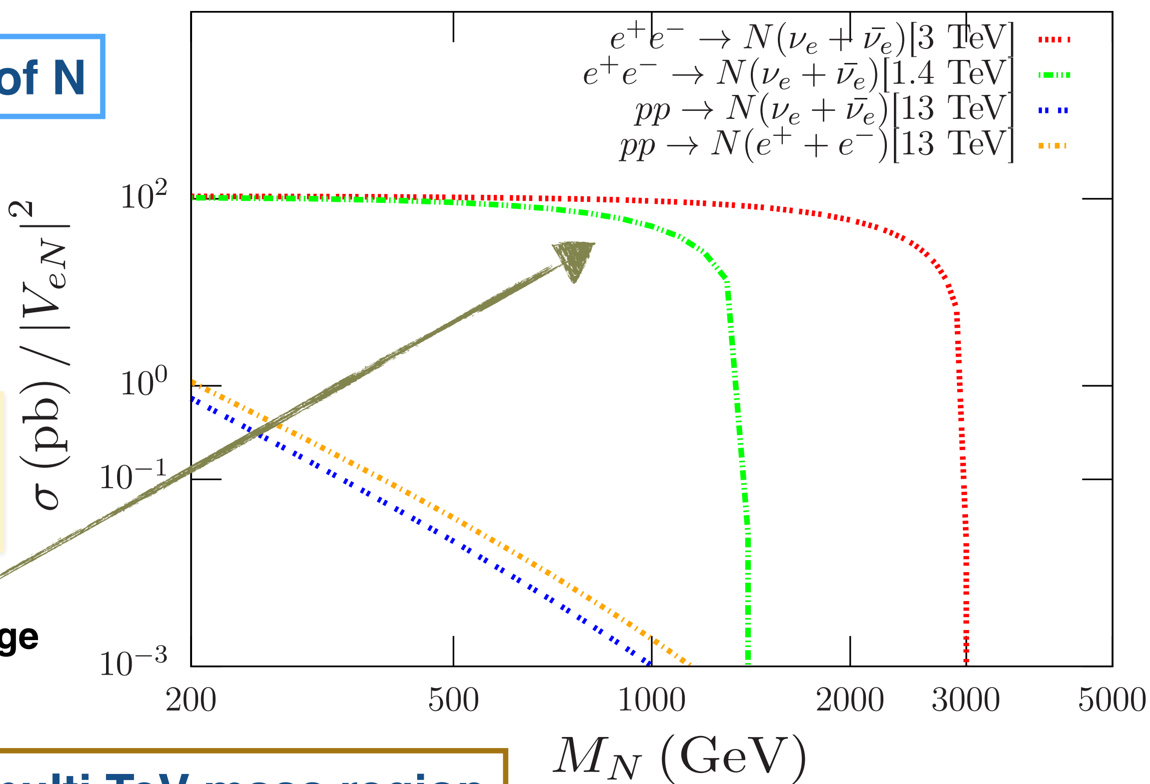


Followed by decay of N

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

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

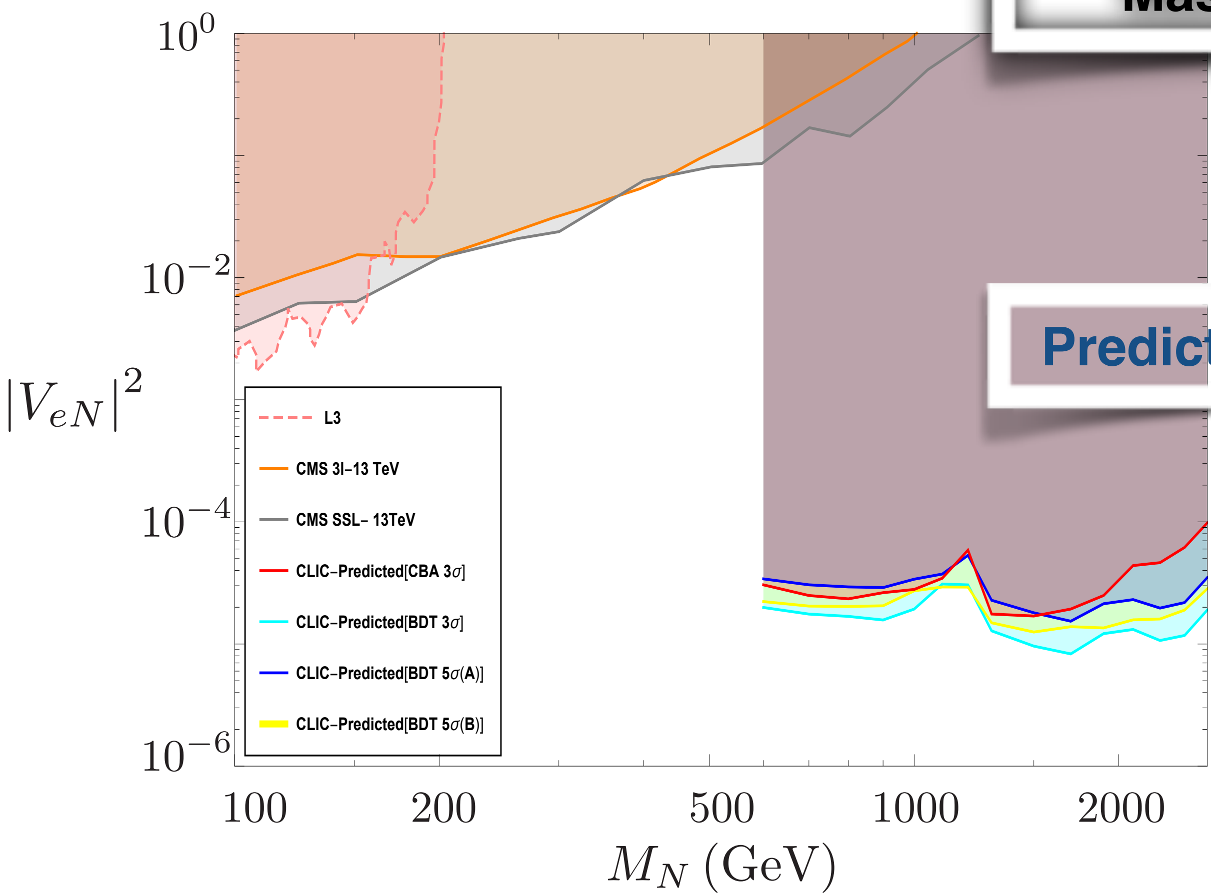
Cross-section is large

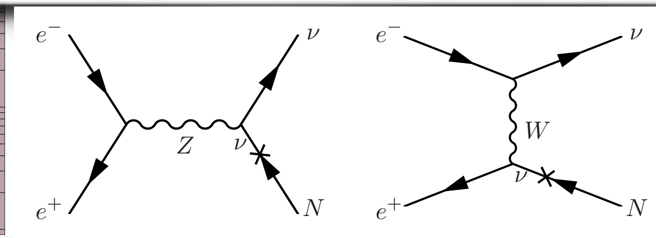


Large cross section in multi TeV mass region

Phys.Rev.D 100 (2019) 1, 015012, S. Chakraborty, S. Shil and M. Mitra

Mass vs active-sterile mixing

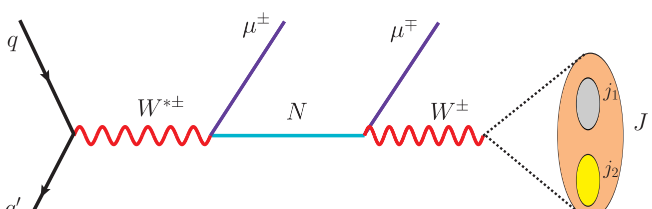




Prediction for CLIC

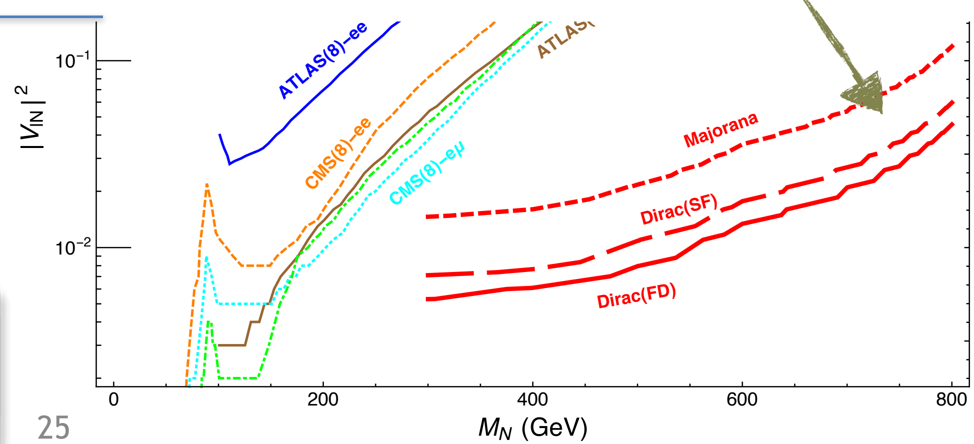
$$|V_{eN}|^2 \sim 10^{-5}$$

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



Bharadwaj et al., arXiv 1801.00797

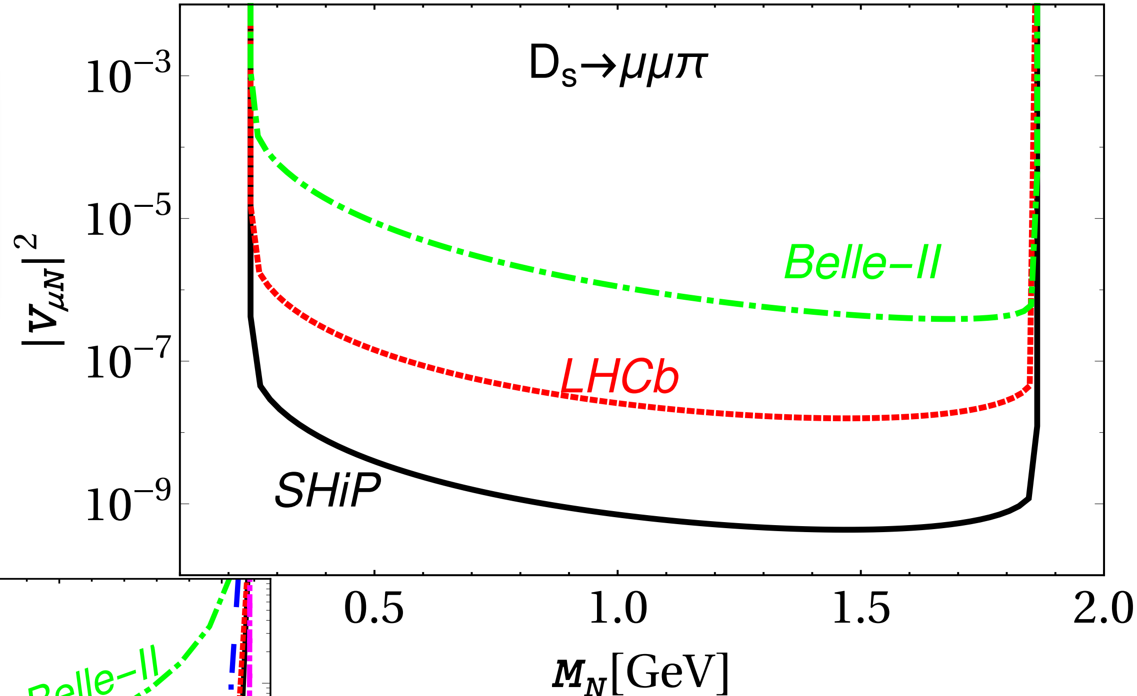
HL-LHC

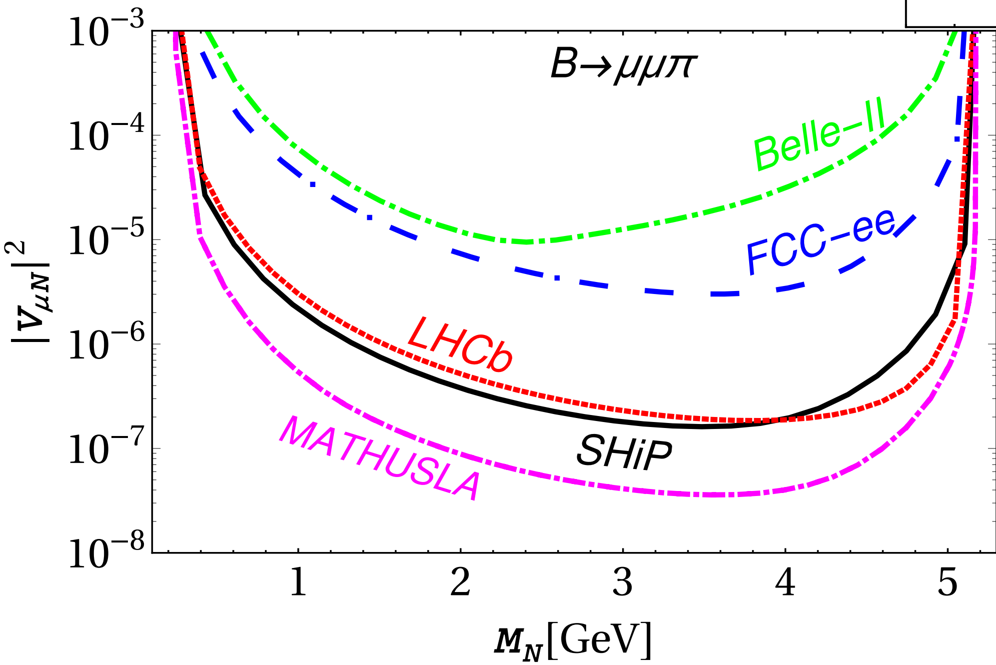


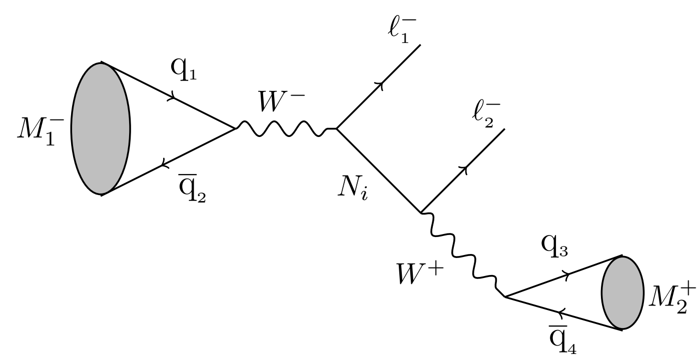
High sensitivity for active-sterile mixing in large mass regime at e+ e-

Low Mass Sterile Neutrino - 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

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'

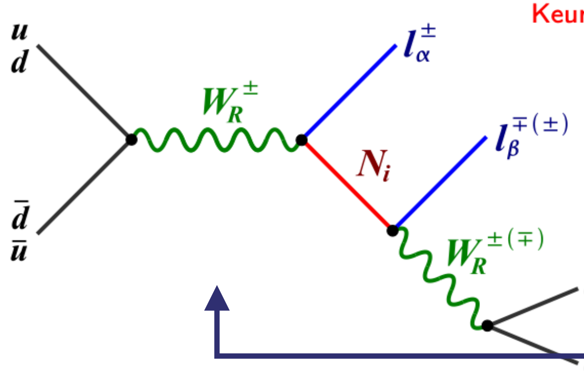
Left-Right symmetry $\rightarrow$ production via W_R

Two Higgs doublet model $\rightarrow$ Large Yukawa

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

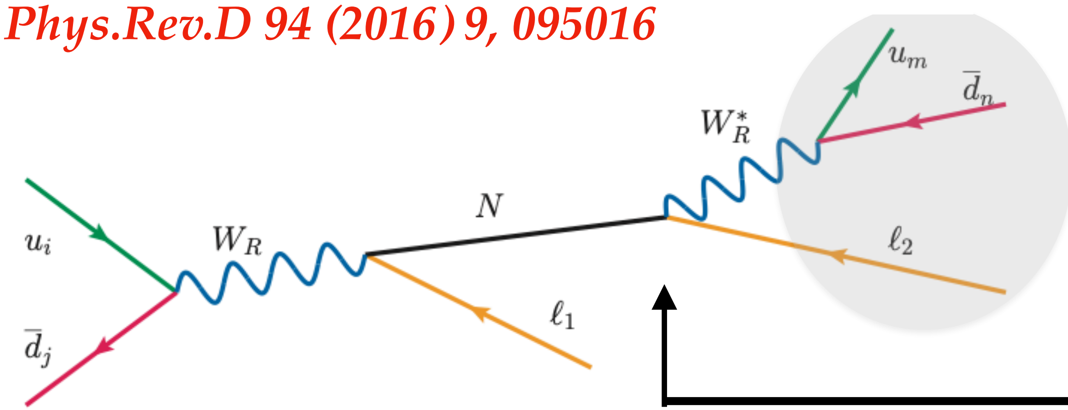
Alternate signal topology → $l + j_{\mathrm{fat}}$

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

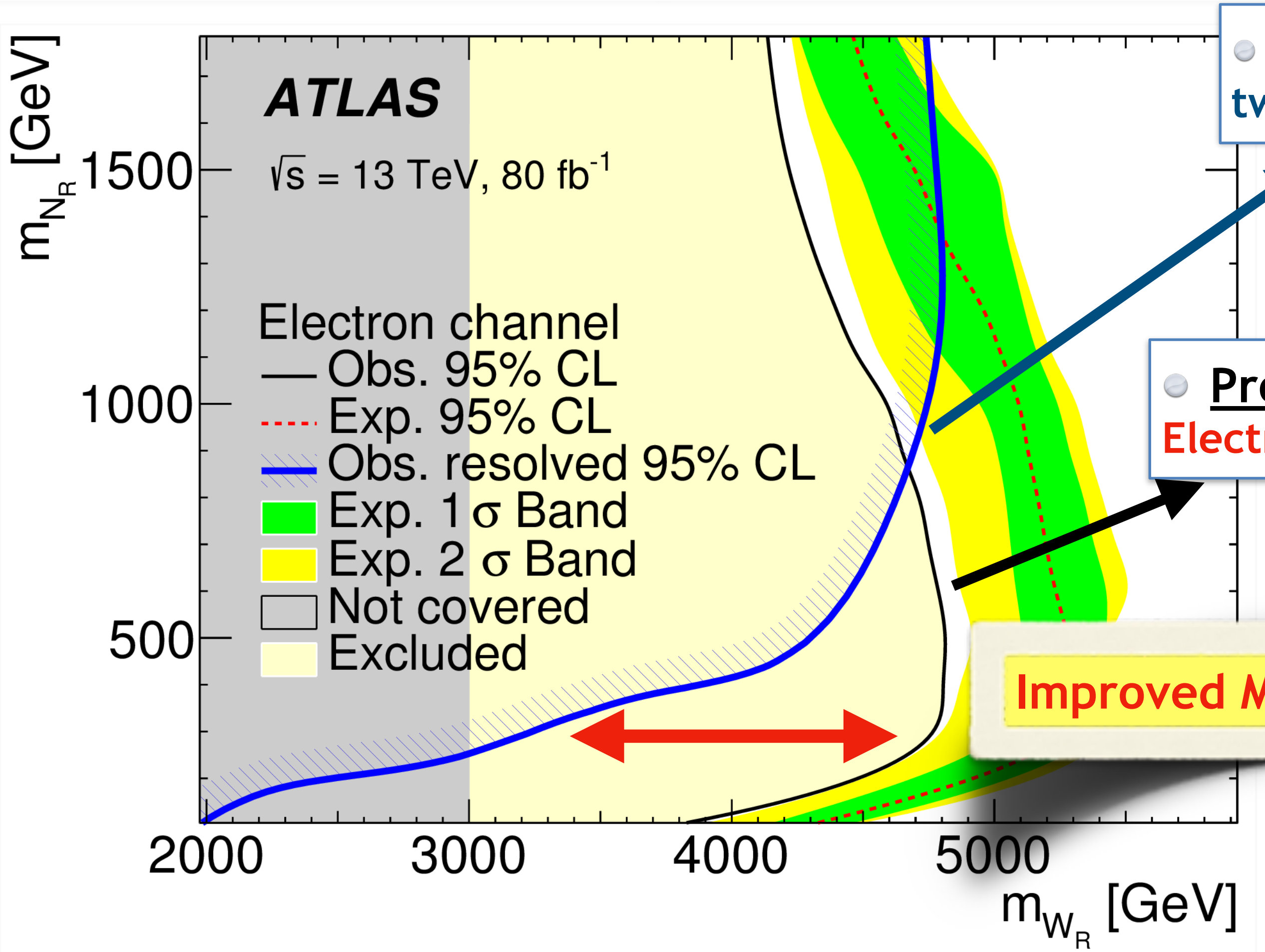


Electron with a large radius jet

ATLAS-LHC Search for Electron+Fat Jet

Search has been performed by the LHC-ATLAS collaboration

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



- **Conventional search**
two electrons+di-jet

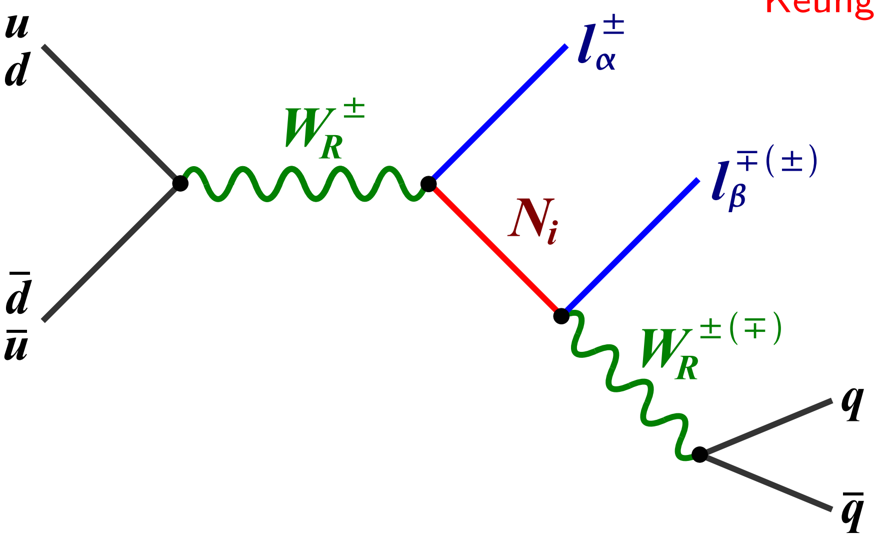
- **Proposed search**
Electron+Fat Jet

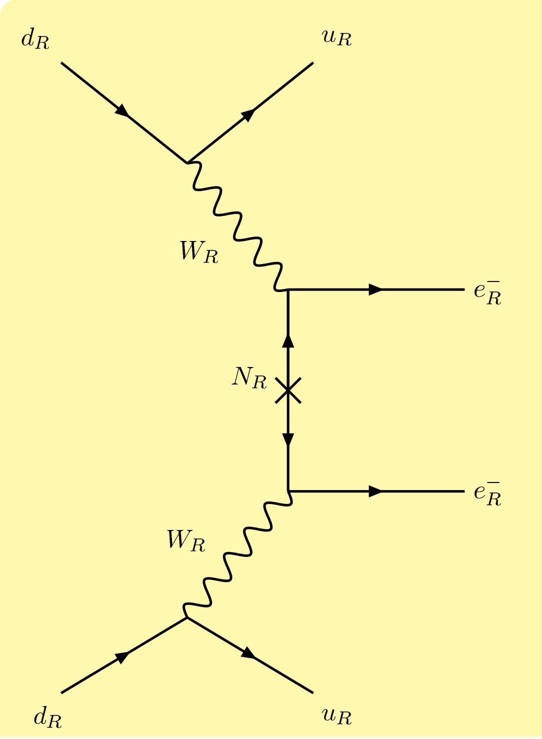
Improved Mass Limit of WR

Left Right Symmetry

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

Keung, Senjanović, PRL, 83



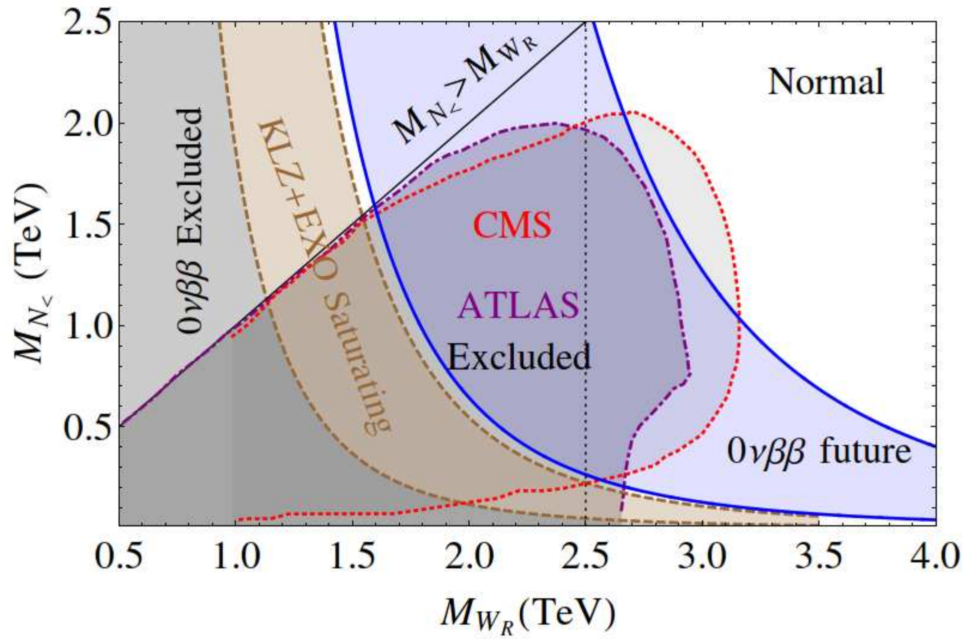


Complementarity to LHC

J. Chakrabortty, H. Zeen Devi, S. Goswami, *JHEP* 08 (2012) 008

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

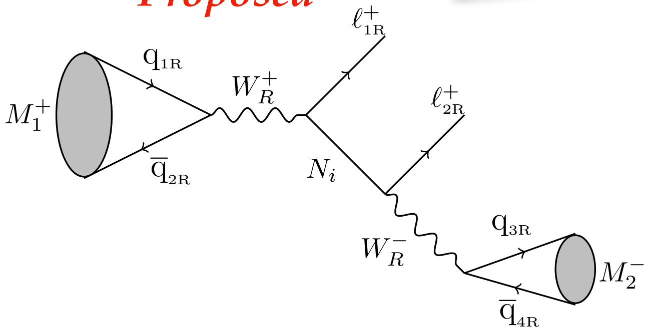
- Future $0\nu\beta\beta \to m^N_{ee} = 0.1 - 0.01$ eV.

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

However, LHC puts stringent bound in the TeV range

Lepton Number Violating Meson Decays

Proposed

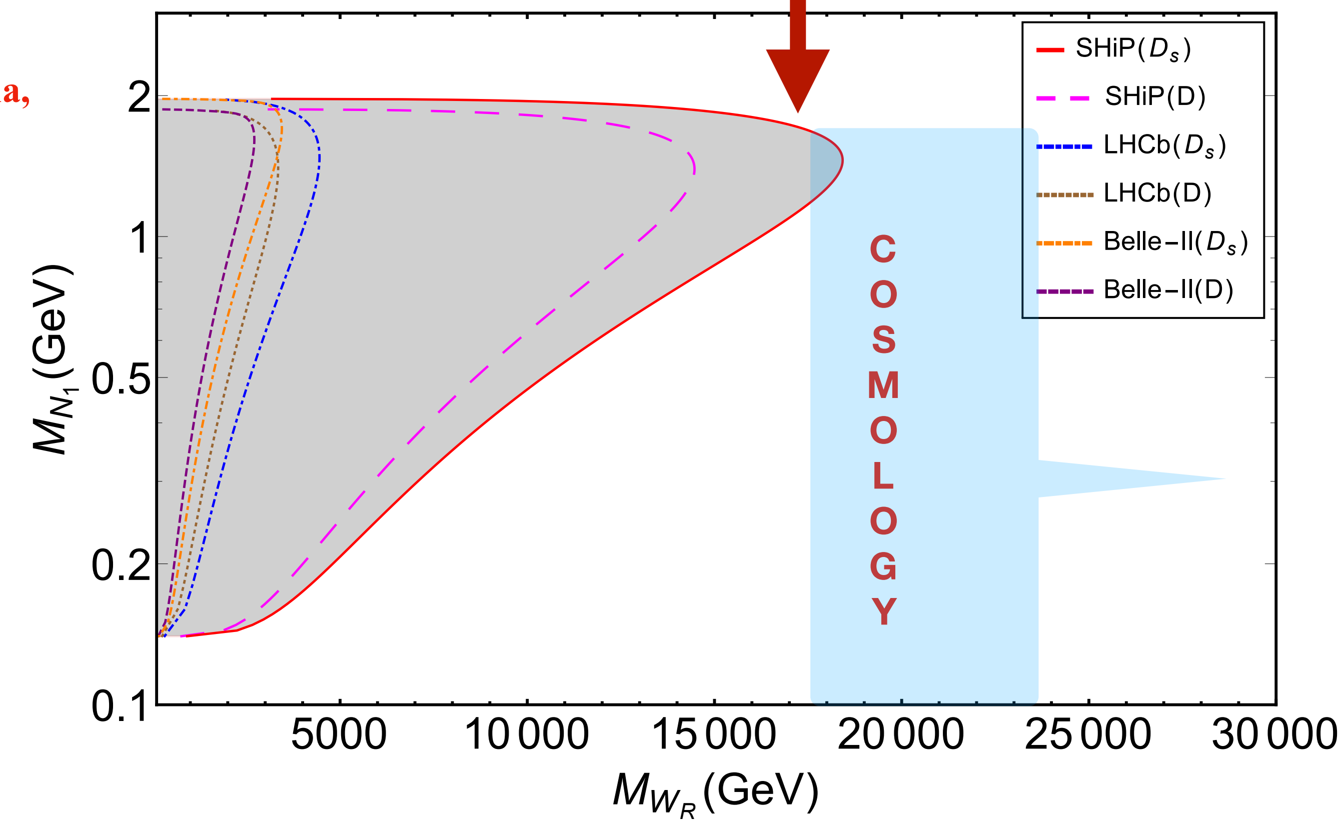


$$M^+ \to e^+ e^+ \pi^-$$

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

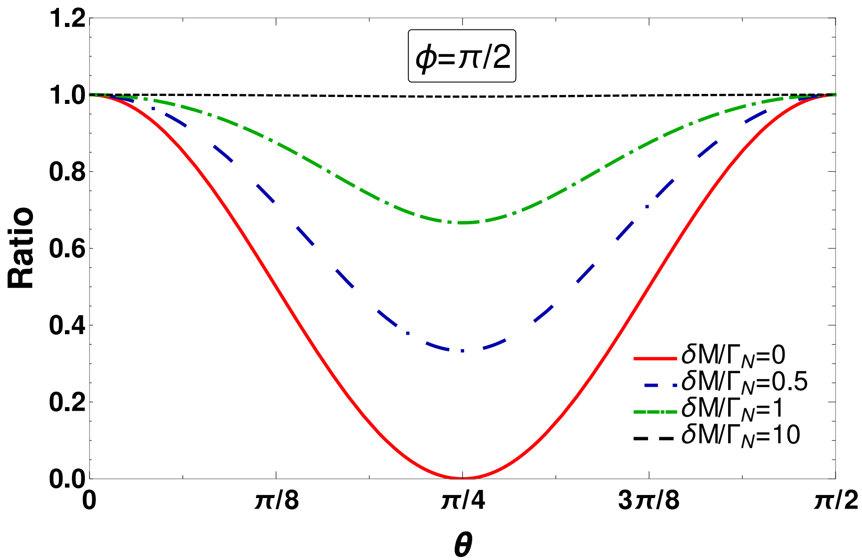
Interference Effect in Lepton Number Violating Meson Decays

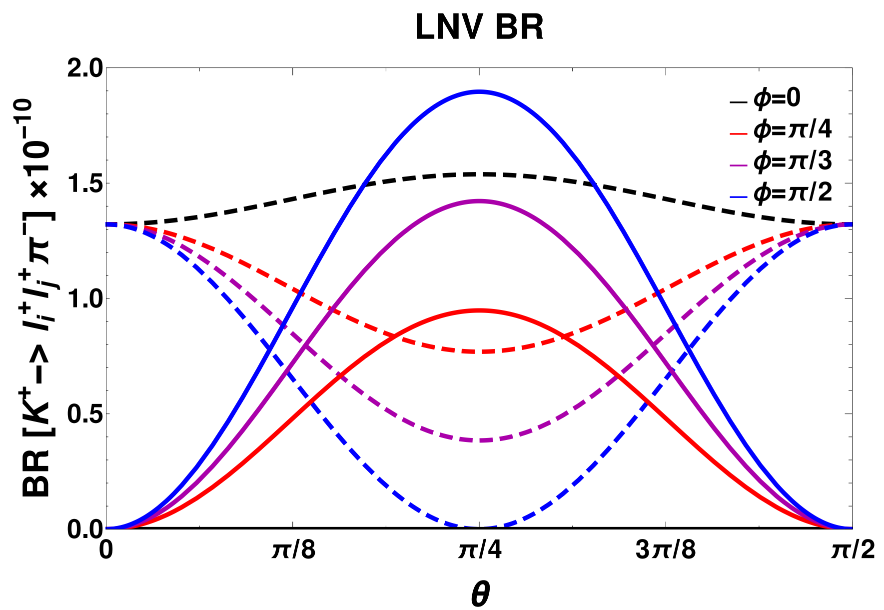
Presence of almost de-generate heavy neutrino states

↓

Interference between the N1 and N2 contributions in LNV process

$$|\mathcal{M}^{\rm LNV}|^2 = \sum_{a,b=1;\, b>a}^{3} \Big(|\mathcal{M}_{ij}^{{\rm LNV},a}|^2 + |\mathcal{M}_{ji}^{{\rm LNV},a}|^2 + 2{\rm Re}\Big[(\mathcal{M}_{ij}^{{\rm LNV},a})^\dagger (\mathcal{M}_{ij}^{{\rm LNV},b}) \Big] + 2{\rm Re}\Big[(\mathcal{M}_{ji}^{{\rm LNV},a})^\dagger (\mathcal{M}_{ji}^{{\rm LNV},b}) \Big] \Big)$$





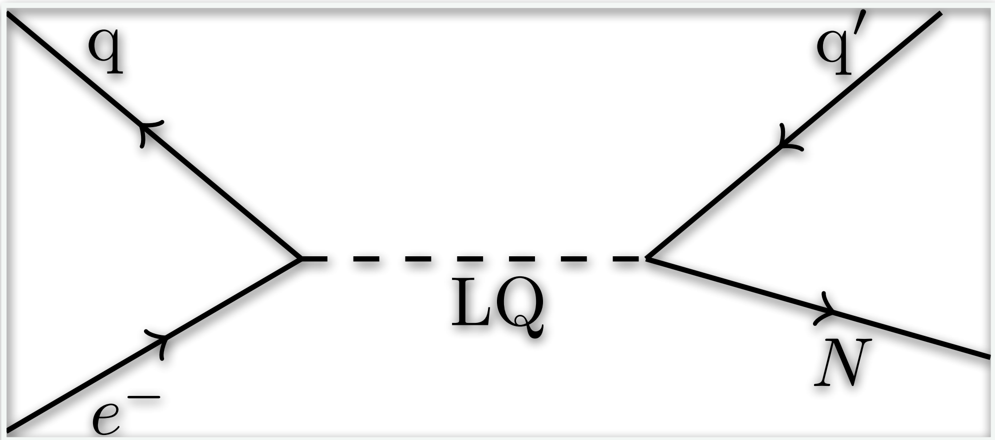
- **Branching ratio changes**
- **Ratio of LNV and LNC differ from unity**

arXiv: 2008.05467, R. M. Godbole, S. P. Maharathy, S. Mandal, M. Mitra and N. Sinha

Collider- J. Gluza and T. Jelinski, Phys. Lett. B 748 (2015); P. S. Bhupal Dev, R. N. Mohapatra, Y. Jhang, *JHEP* 11 (2019) 137, Arindam Das et al., *J.Phys.G* 47 (2020) 1, 015001, S. Antusch et al., *Mod.Phys.Lett.A* 34 (2019) 07n08, 1950061

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



$\tilde{R}_2$ Leptoquark

In preparation with
Rojalin Padhan,
Sanjoy Mandal

Rojalin's talk

Other heavy neutrino signatures at colliders

Arindam's talk

Displaced Decays, Fat Jet Signatures, Lepton Flavor Violation, and others

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

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

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** $\to y_\Delta, \mu_\Delta$
- eV light neutrino mass $\to y_\Delta \sim \mathcal{O}(1)$, $v_\Delta = 1$ eV

$\mu_\Delta \to 0 \to v_\Delta \to 0$

Massless neutrino

y_Δ, μ_Δ

The Yukawa $y_\Delta = M_\nu / v_\Delta = U_{PMNS}^T M_d^\nu U_{PMNS}^* / v_\Delta$

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

fixed from the PMNS mixing and neutrino mass

Large y_Δ → lepton flavor violation

Higgs triplet:

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

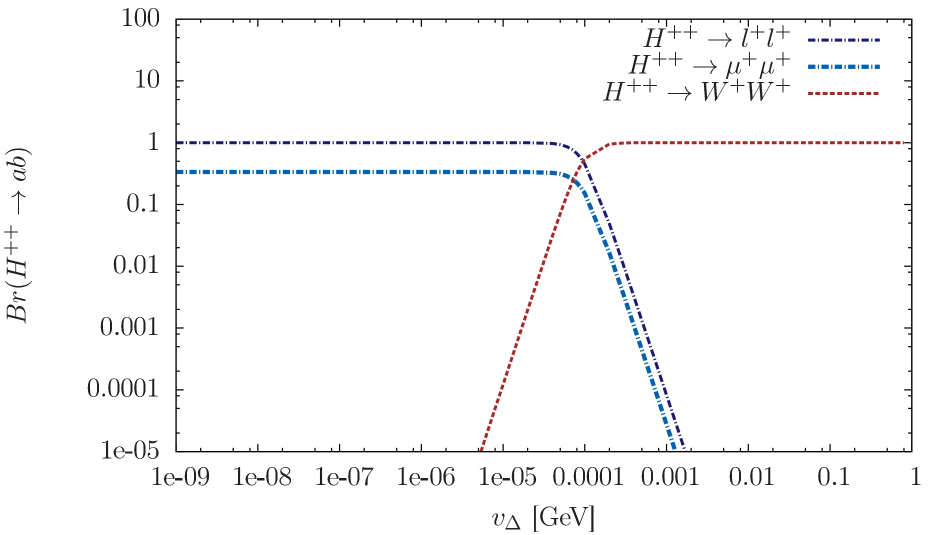
$LL\Delta \to$ Light neutrino mass $M_\nu = y_\Delta v_\Delta$. $\boxed{H^{++} l^- l^- \sim M_\nu / v_\Delta}$.

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

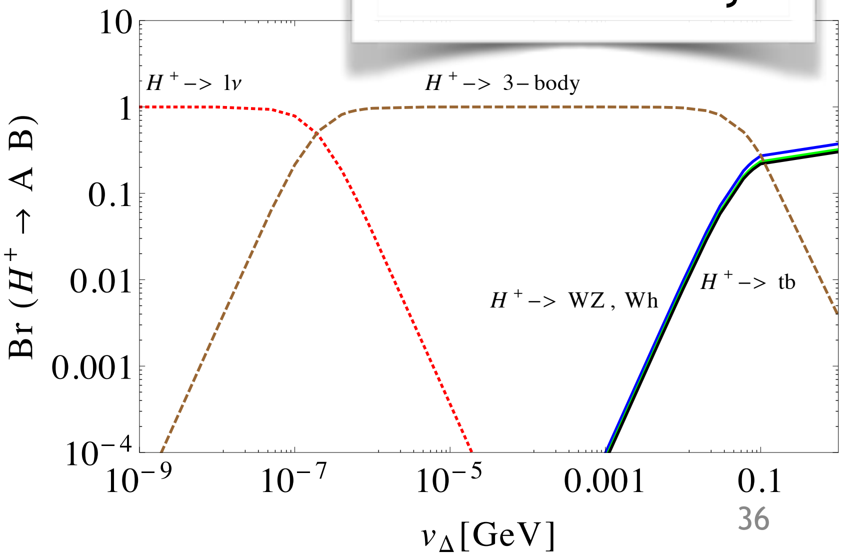
$$\Gamma\left(H^{++} \to W^+ W^+\right) = \frac{v_\Delta^2 M_{H^{++}}^3}{4\pi v_0^4} \left(1 - \frac{4M_W^2}{M_{H^{++}}^2}\right)^{1/2} \left(1 - \frac{2M_W^2}{M_{H^{++}}^2}\right)^2$$

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

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



Dominant 3 body



Decays of doubly charged Higgs →

$H^{\pm\pm} \to l^{\pm} l^{\pm}$ for $v_\Delta < 10^{-4}\,\mathrm{GeV}$

$H^{\pm\pm} \to W^{\pm} W^{\pm}$ for $v_\Delta > 10^{-4}\,\mathrm{GeV}$

- **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** $pp \to H^{\pm\pm} H^{\mp\mp} \to W^+ W^+ W^- W^-$

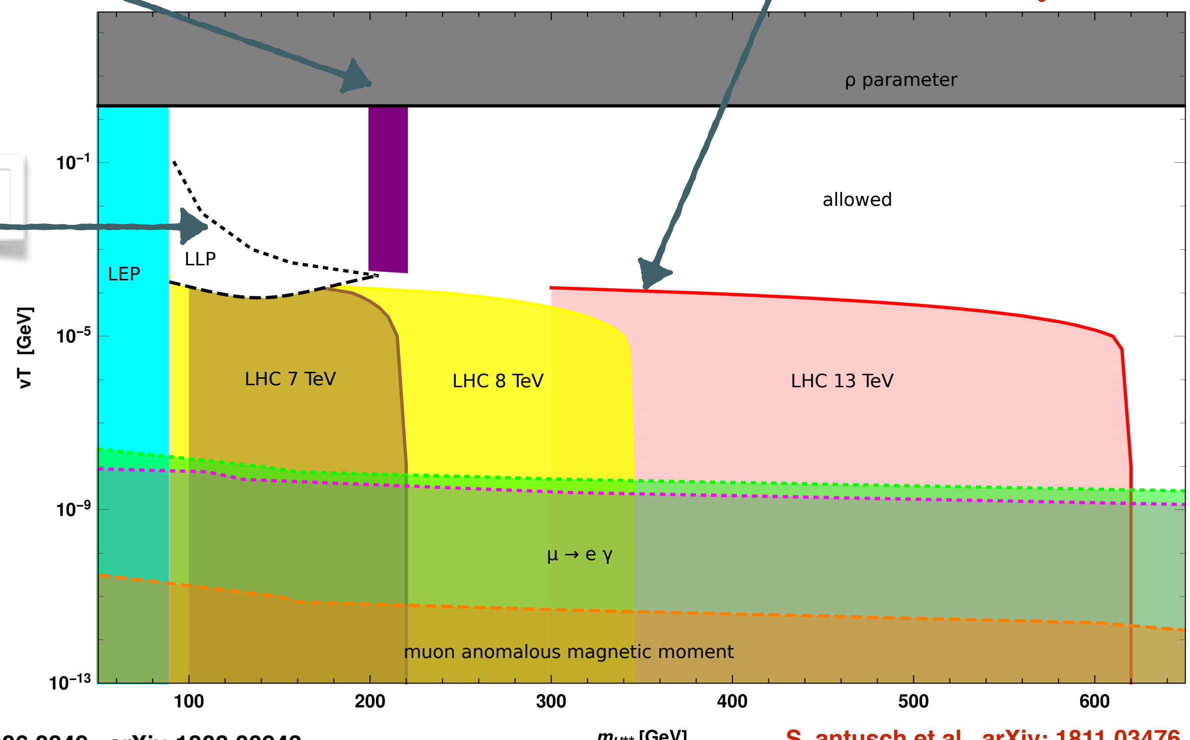
arXiv: 1808.01899

- 200-220 GeV excluded

Unconstrained

Long lived → Displaced vertex

High mass and large vev is unconstrained



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

S. antusch et al., arXiv: 1811.03476

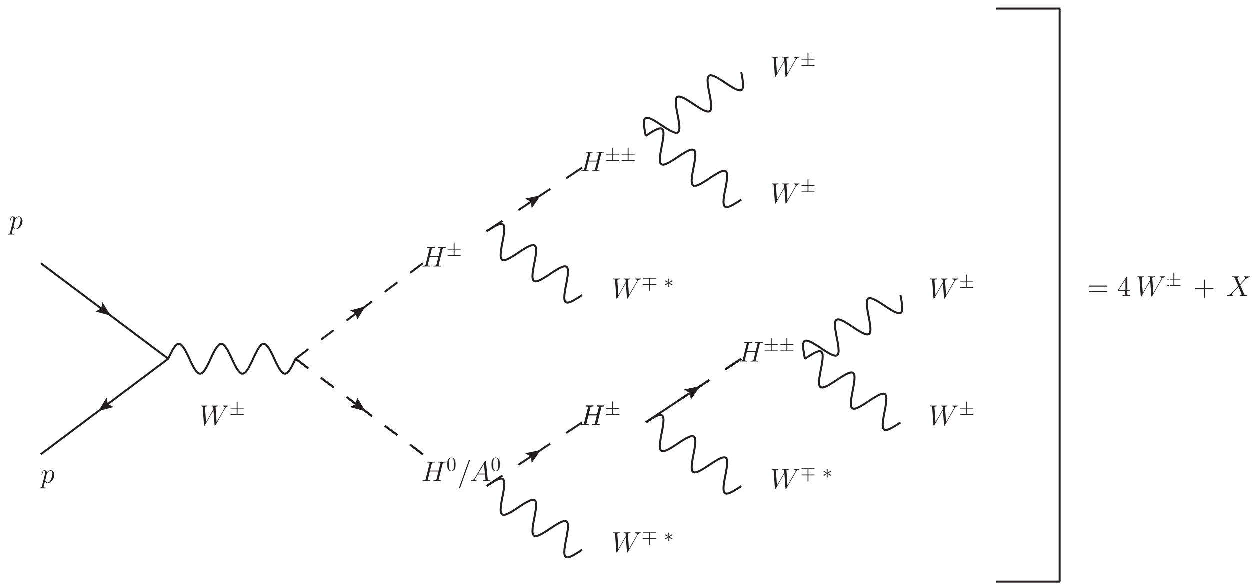
Other searches:

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

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

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

$l^\pm l^\pm l^\pm l^\pm + X$



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

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

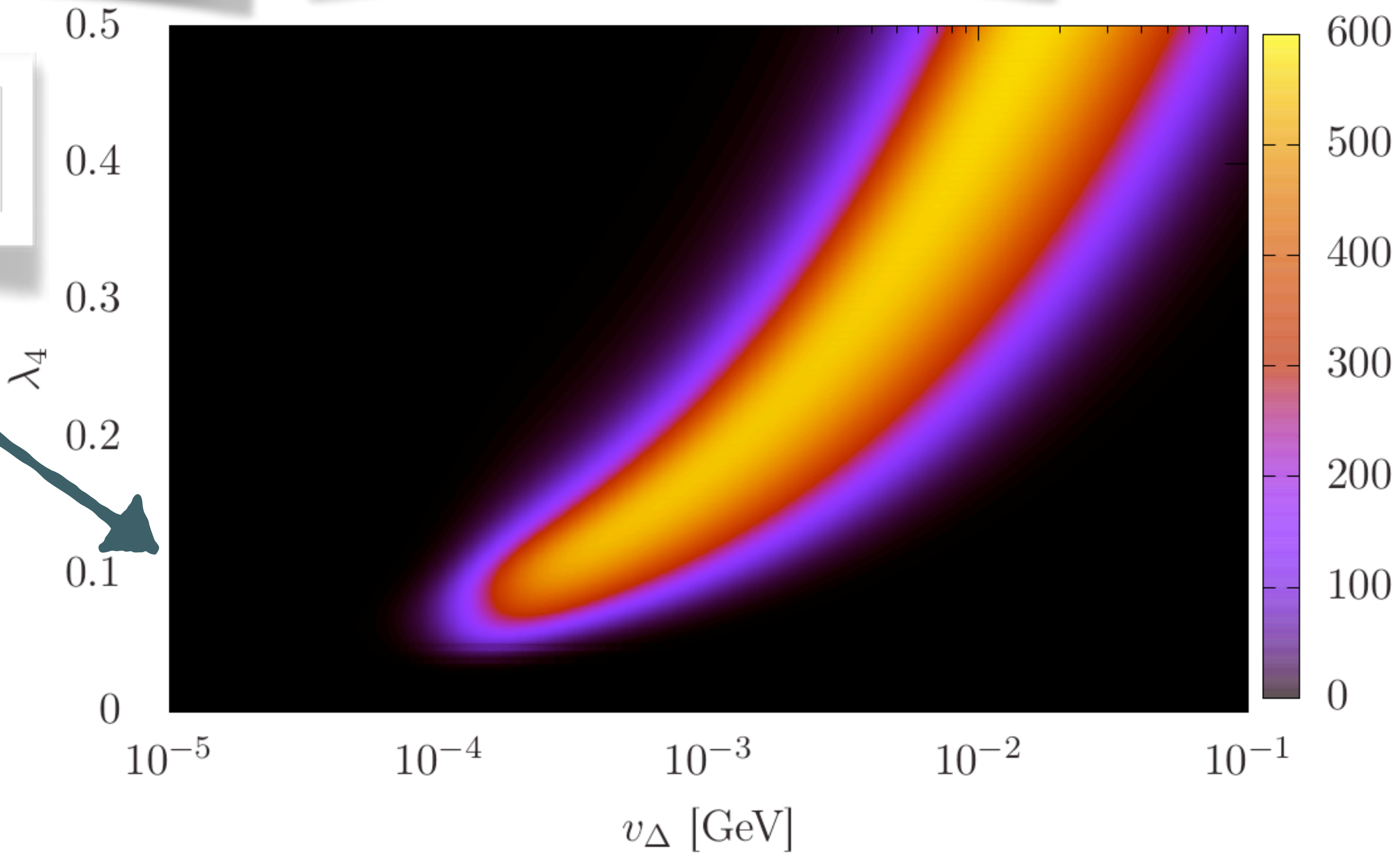
Discovery prospect at 14 TeV:

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, *Phys.Rev.D* 101 (2020) 7, 075008

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

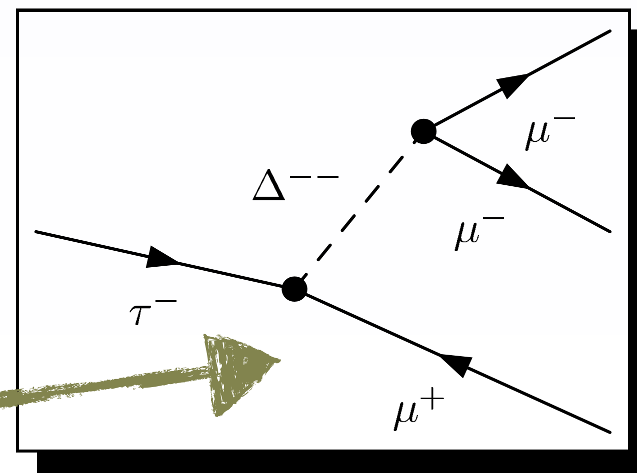
- Branching ratio of $\mu \to 3e \leq 10^{-12}$
- Branching ratio of $\mu \to e\gamma \leq 5.7 \times 10^{-13}$

Tightly constrained

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

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

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

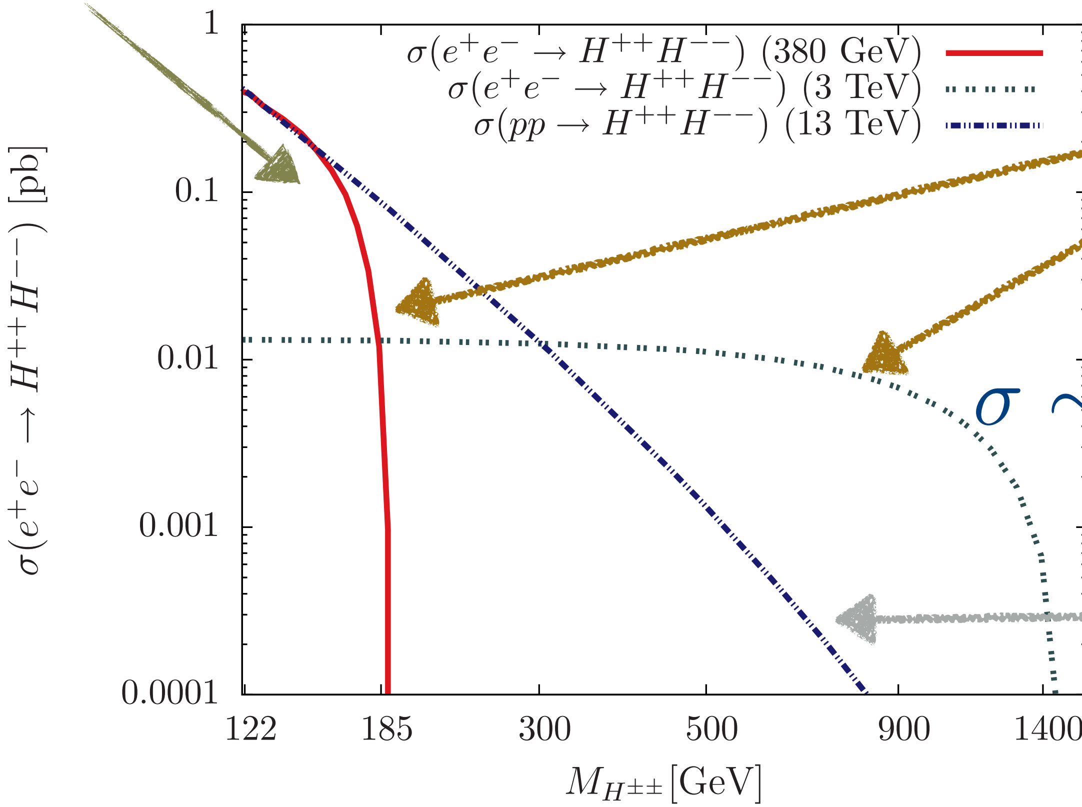


Higgs triplet

G. Mohanty's talk

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:

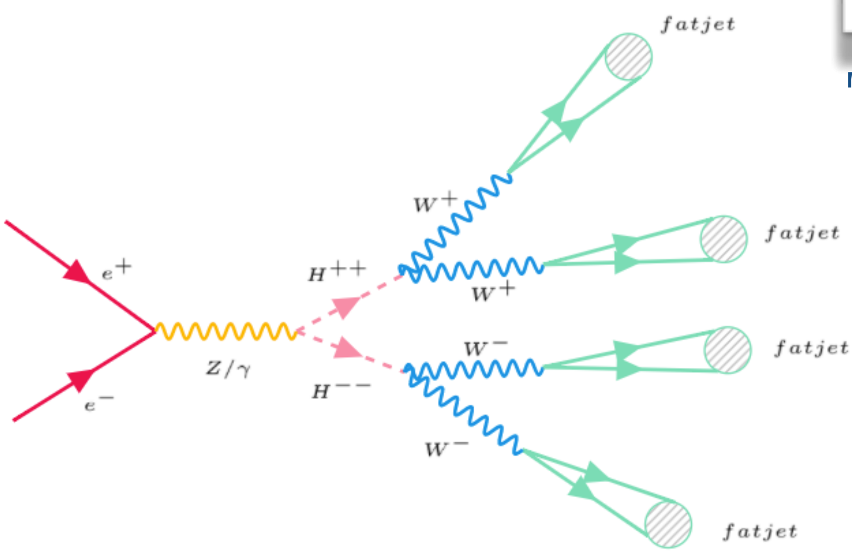
Higher c.m.energy → 3 TeV

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

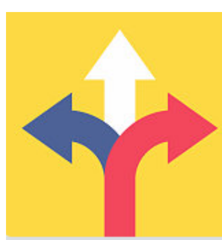


$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to Nj_{\rm fat}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500\,\mathrm{fb}^{-1}$)	$\mathcal{L}(\mathrm{fb}^{-1})$(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15

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

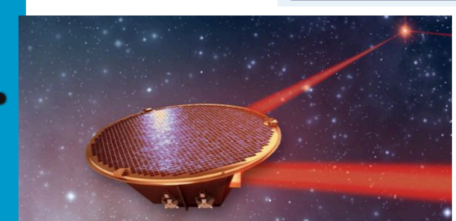
Summary

- *Major observations in nature ~ Neutrino masses and mixings*
- *Low scale neutrino mass models*
- *Wide detection prospects at different direct and indirect experiments*
- *Collider searches, neutrinoless double beta decay, meson decays*
- *New signatures ~ Boosted Topology, Long lived particle search*
- *Challenging corners to probe*



GERDA

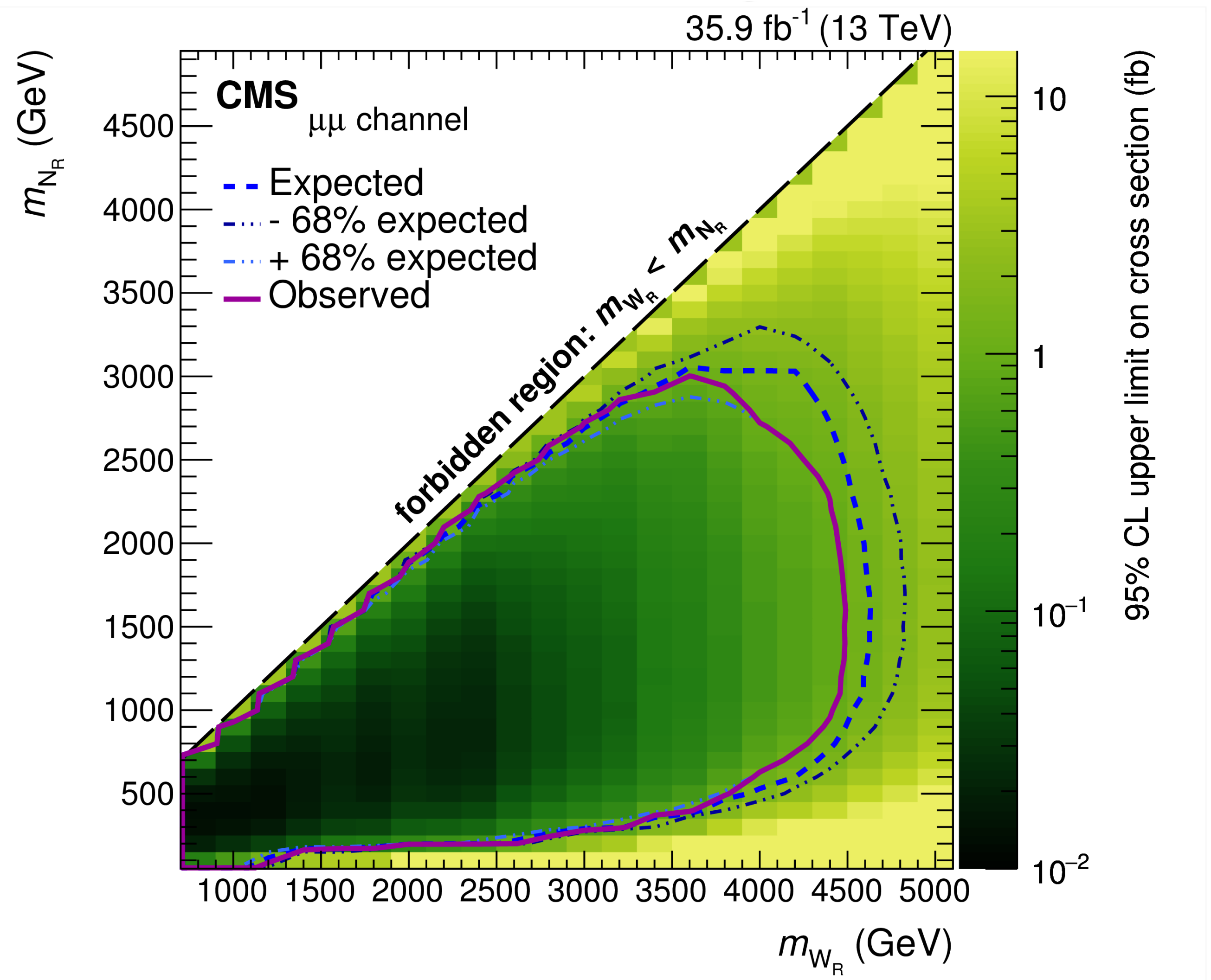
SHiP
Search for Hidden Particles



Thank You

13 TeV Result:

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

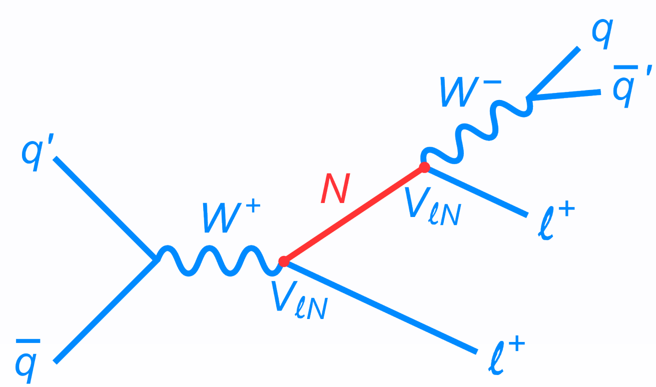


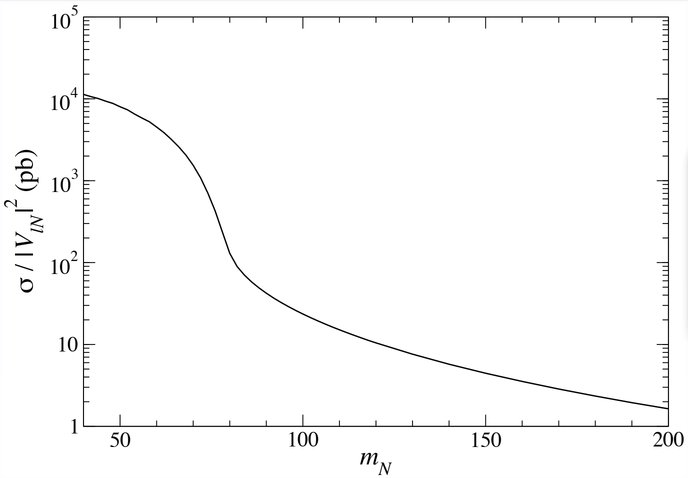
Same flavour,
OS+SS combined

CMS-PAS-EXO-17-011

4.4 TeV

Collider Searches (LHC)



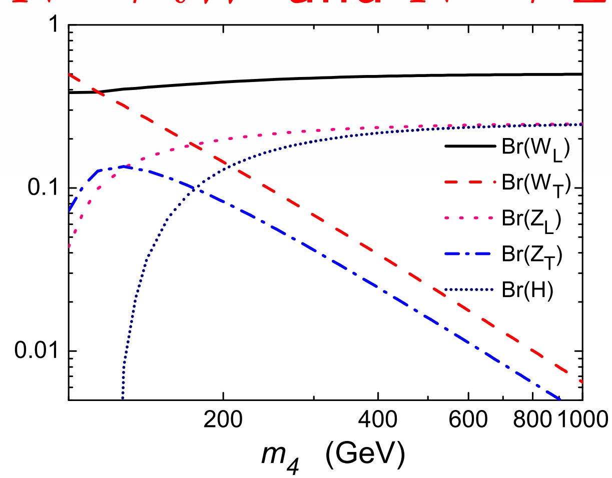


$$pp \to l^{\pm} N$$

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

Heavy Majorana Decay

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



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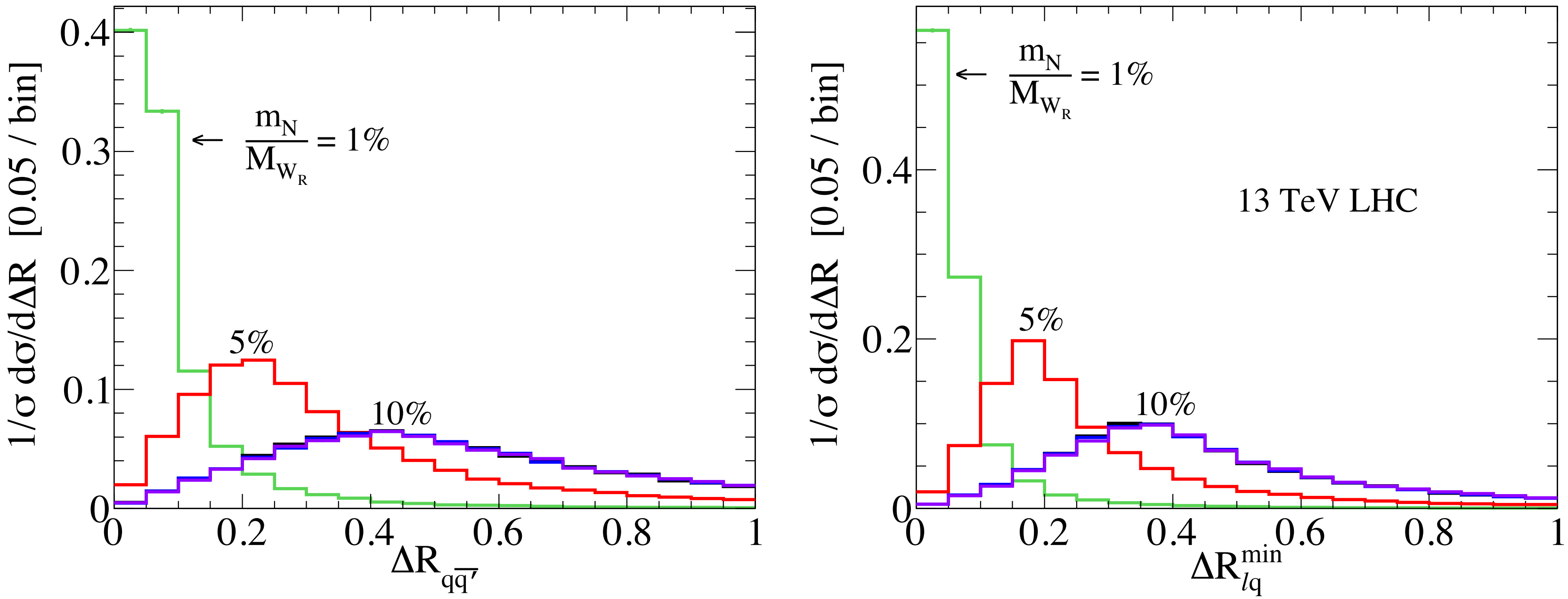
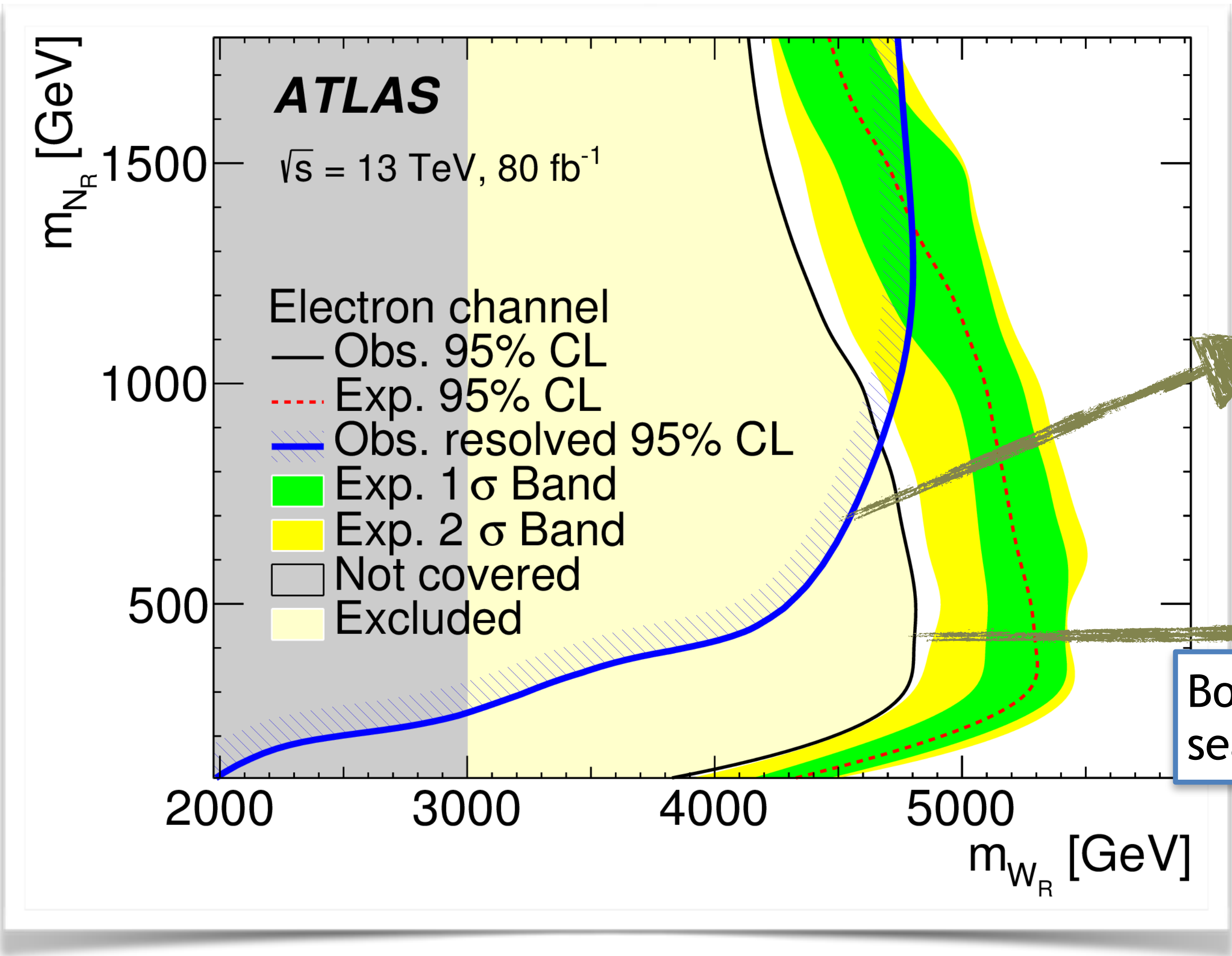


$$\frac{M_N}{M_{W_R}} \sim 1\% \rightarrow \Delta R < 0.3$$

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

Boosted RHN:

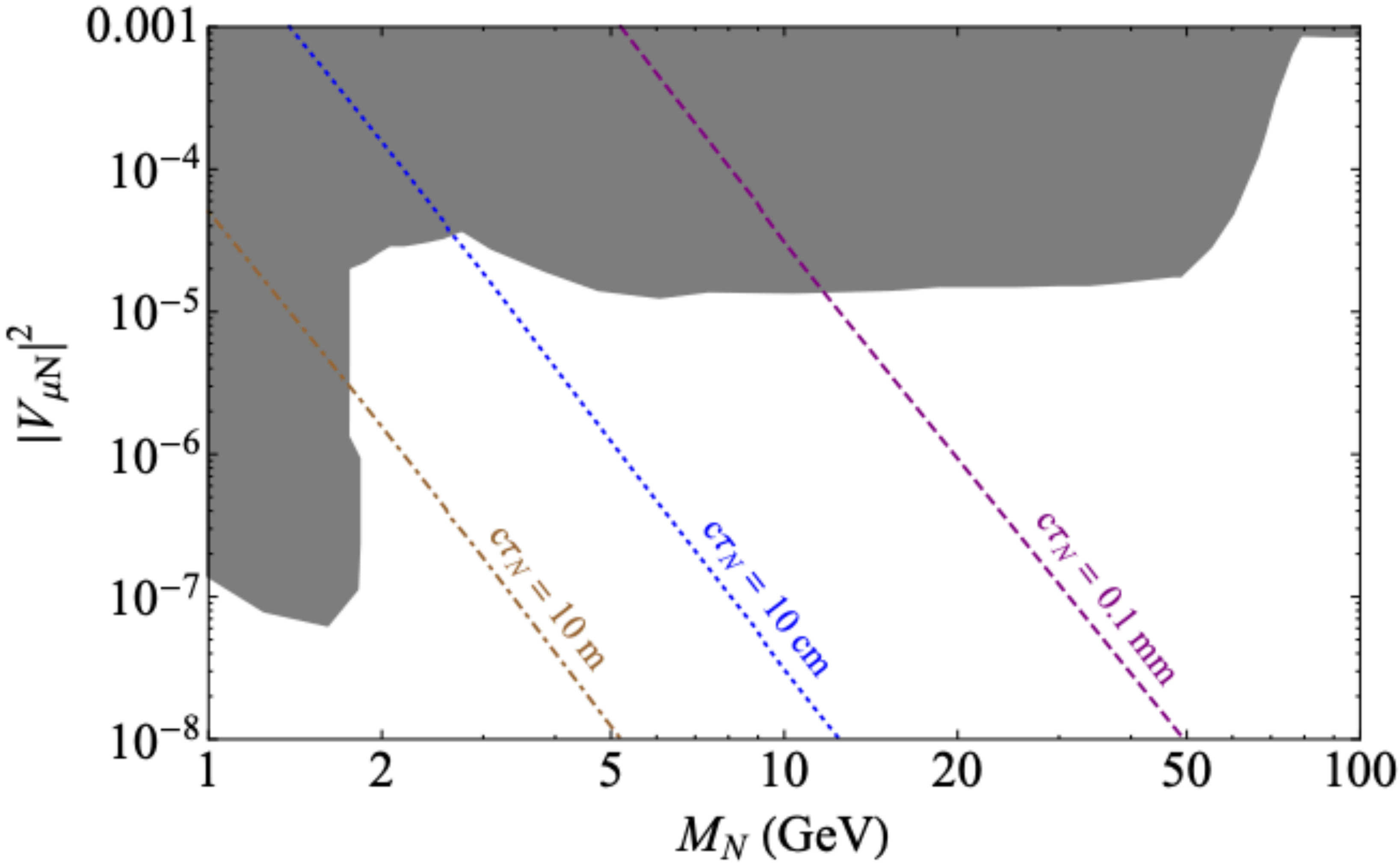


Resolved analysis di-lepton+di-jet

Boosted heavy neutrino search

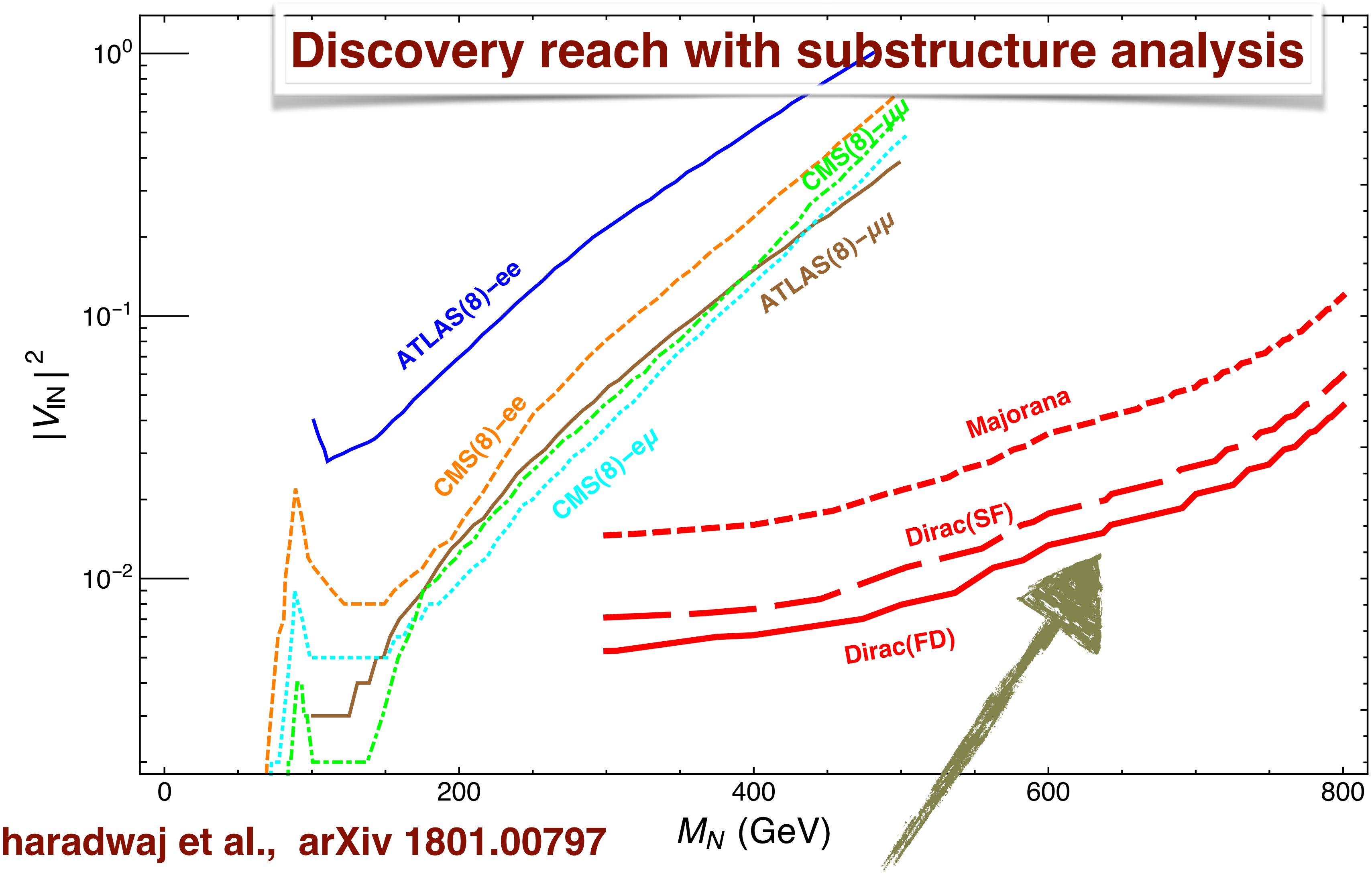
ATLAS Collaboration,
Phys. Lett. B 798 (2019) 134942

RHN Searches via Displaced Decays?



Discovery Reach:

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



Bharadwaj et al., arXiv 1801.00797

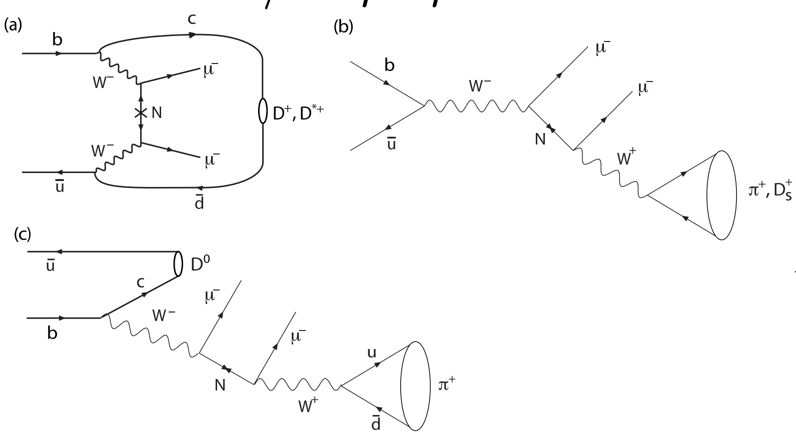
High mass range $M_N >> M_W$

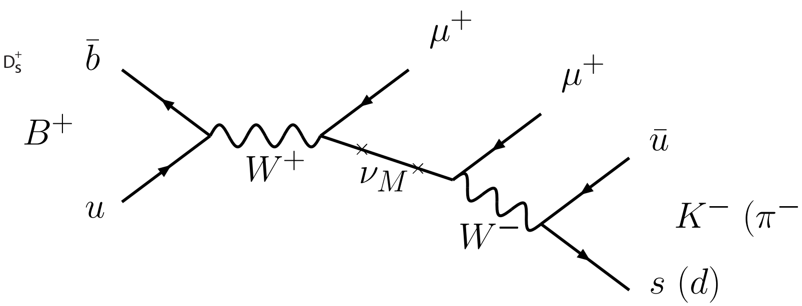
Other LNV Searches:

Meson decay and Collider Searches

Lepton number violation in meson system

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





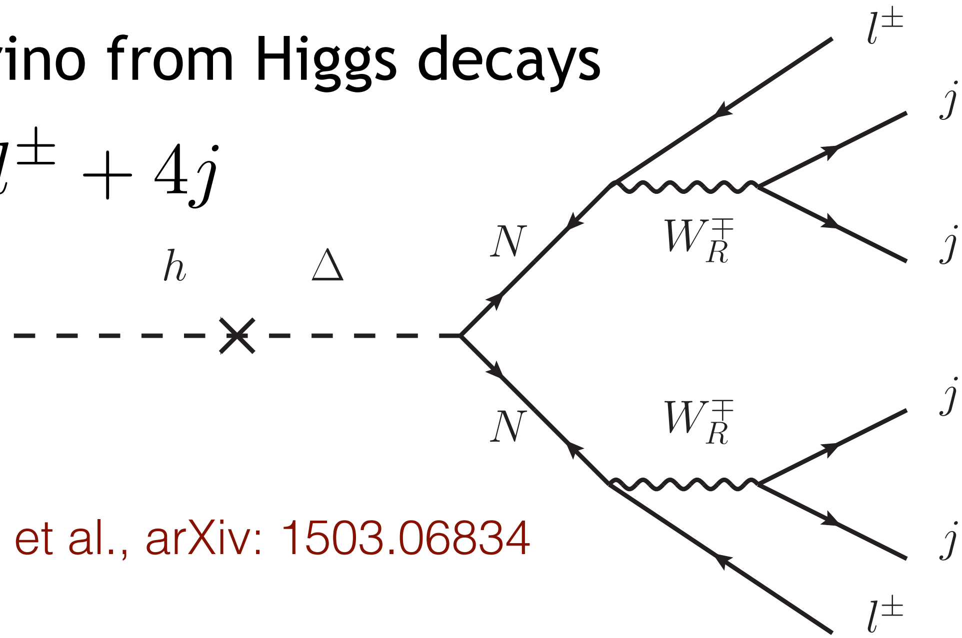
LHCb collaboration, 2012; LHCb collaboration, 2011; BELLE collaboration, O. Seon et al., 2011.

Also lepton number violating τ decays by BABAR, LHCb

LNV Higgs decays:

Heavy neutrino from Higgs decays

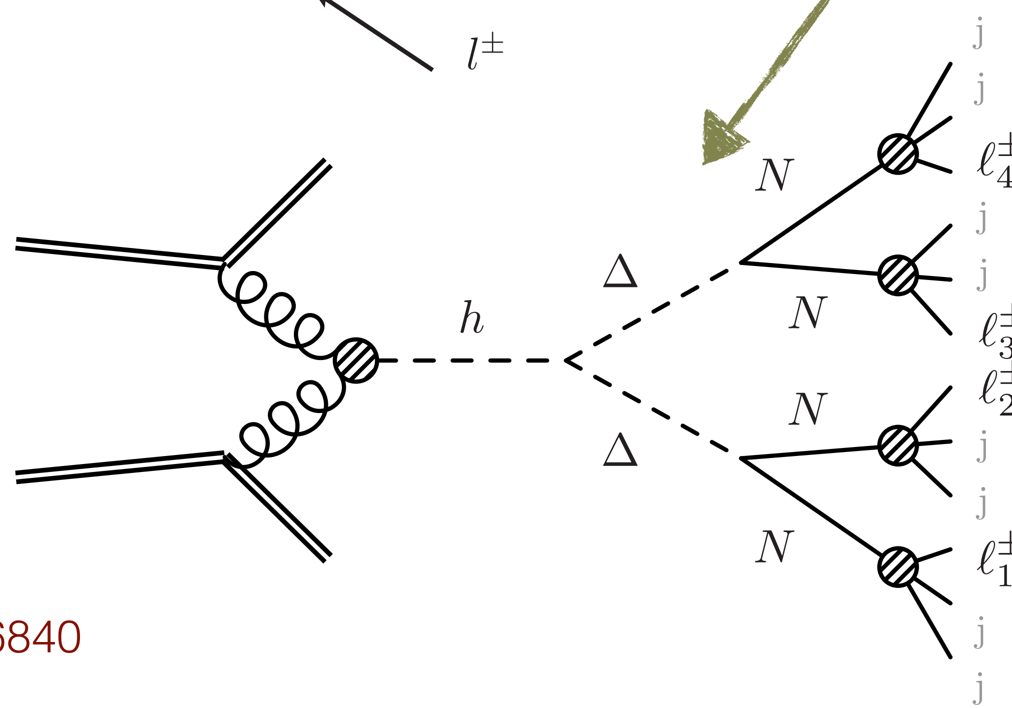
$$pp \to l^{\pm} l^{\pm} + 4j$$



A. Maiezza et al., arXiv: 1503.06834

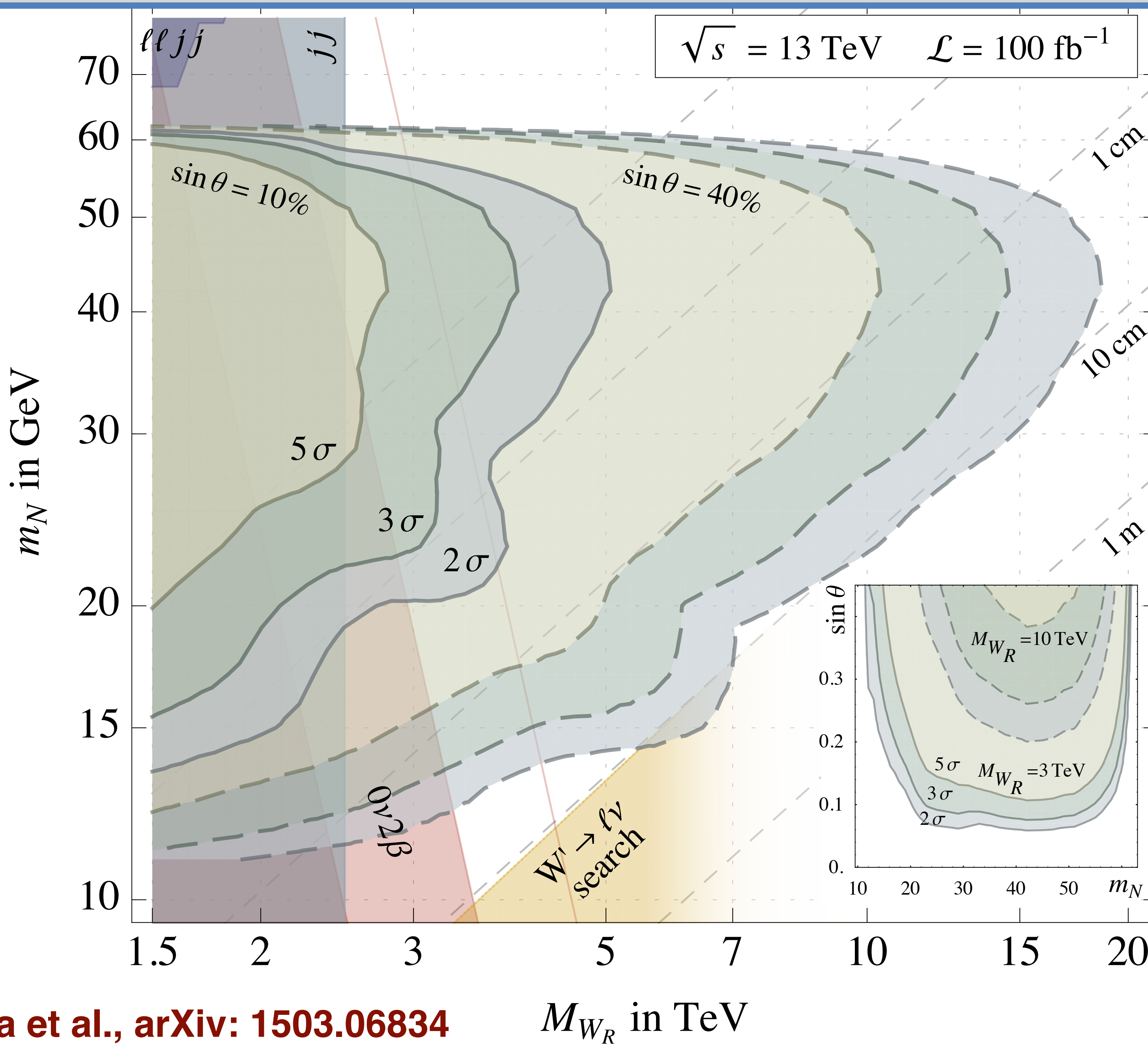
LNV signal

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



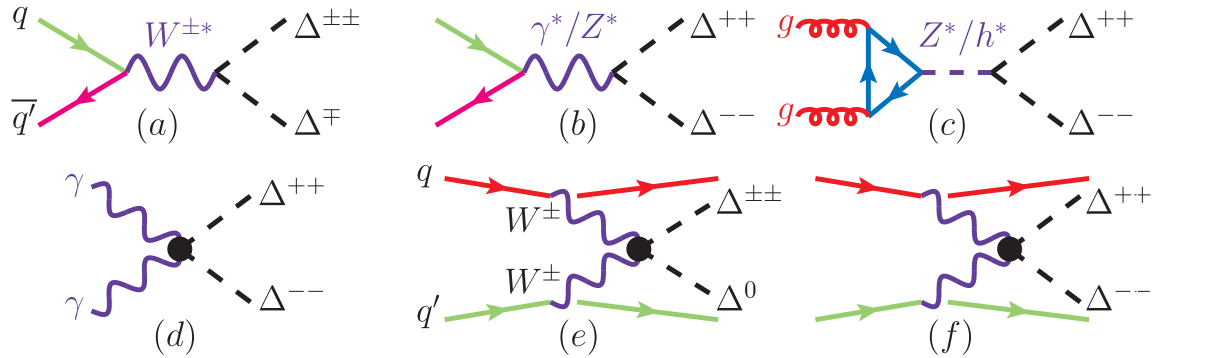
M. Nemevsek, arXiv: 1612.06840

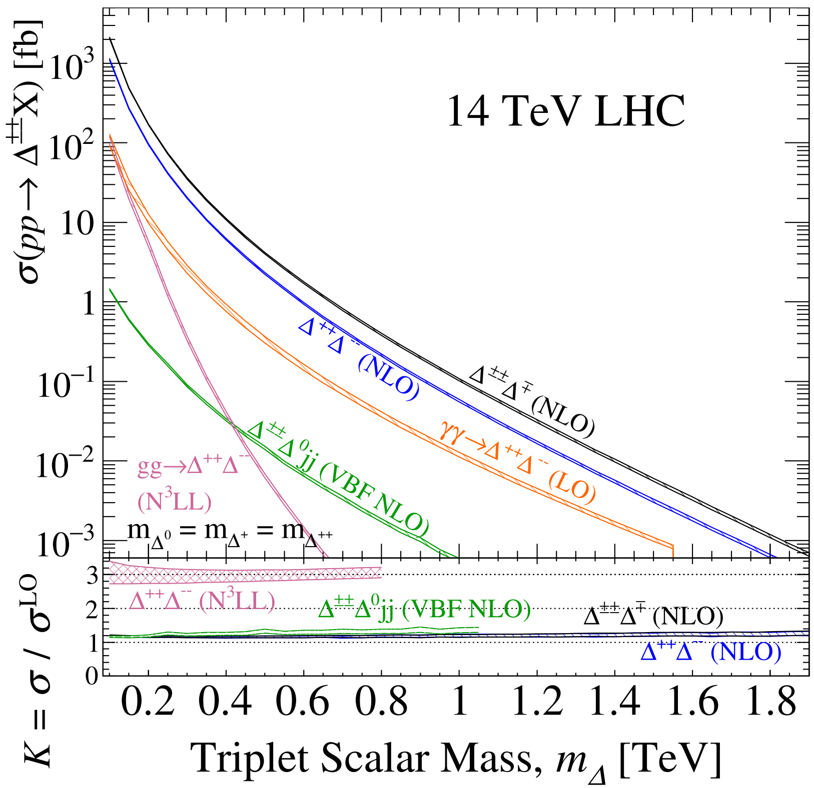
Discovery Reach:

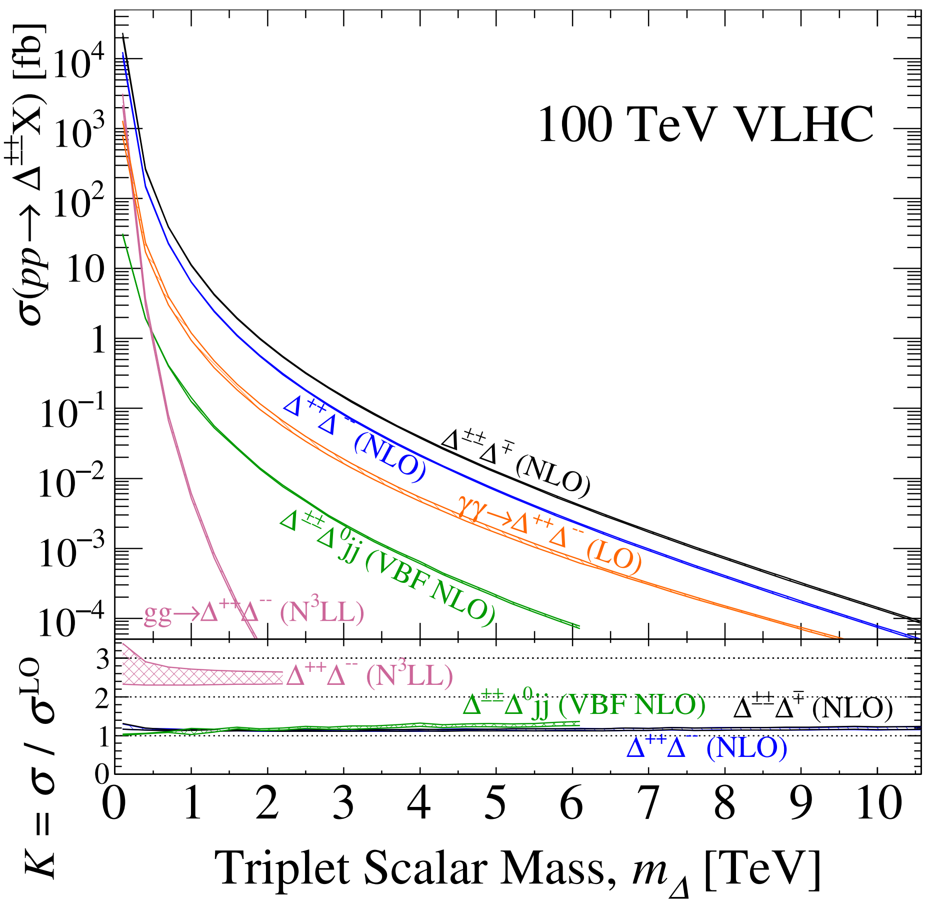


A. Maiezza et al., arXiv: 1503.06834

VLHC Prediction







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

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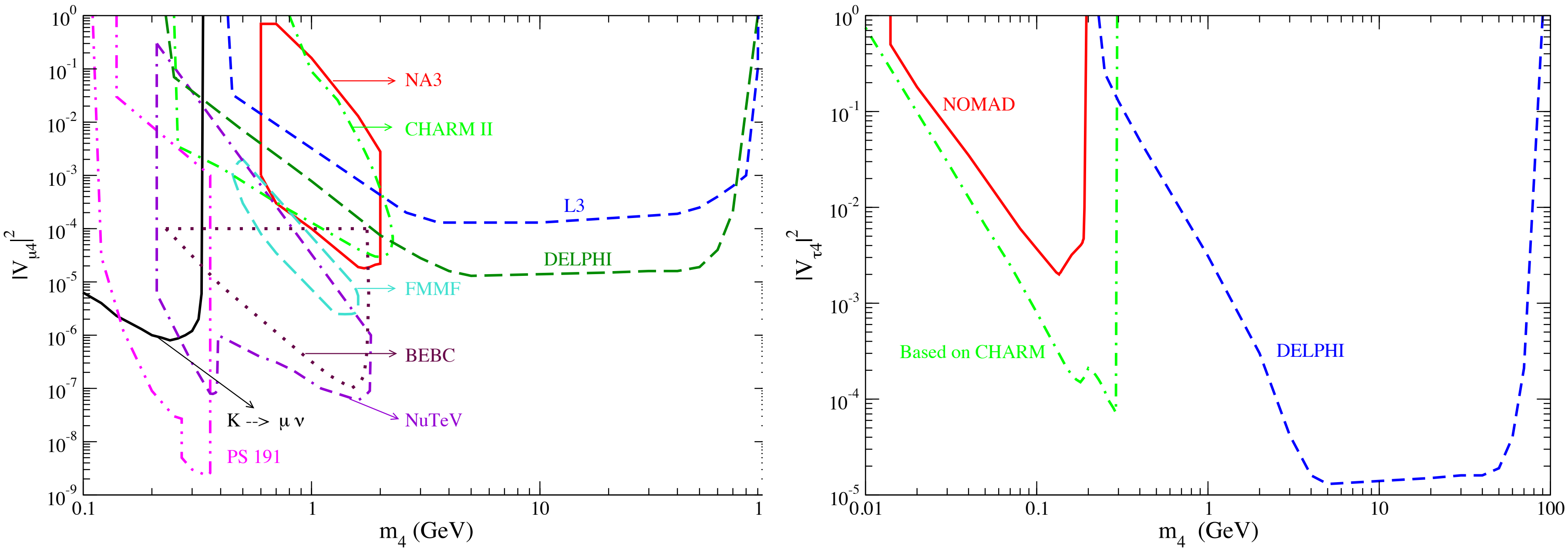


Atre et al., JHEP **0905**, 030 (2009)

- 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

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

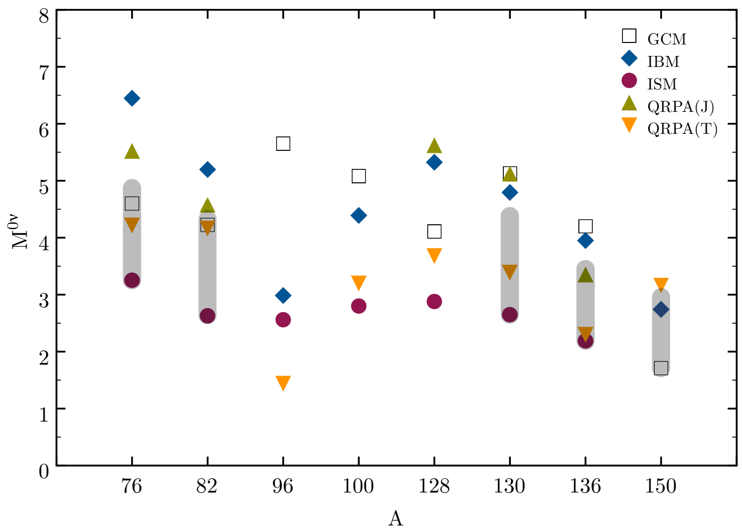
- Direct evidence of BSM models

Collider → Limited by kinematics

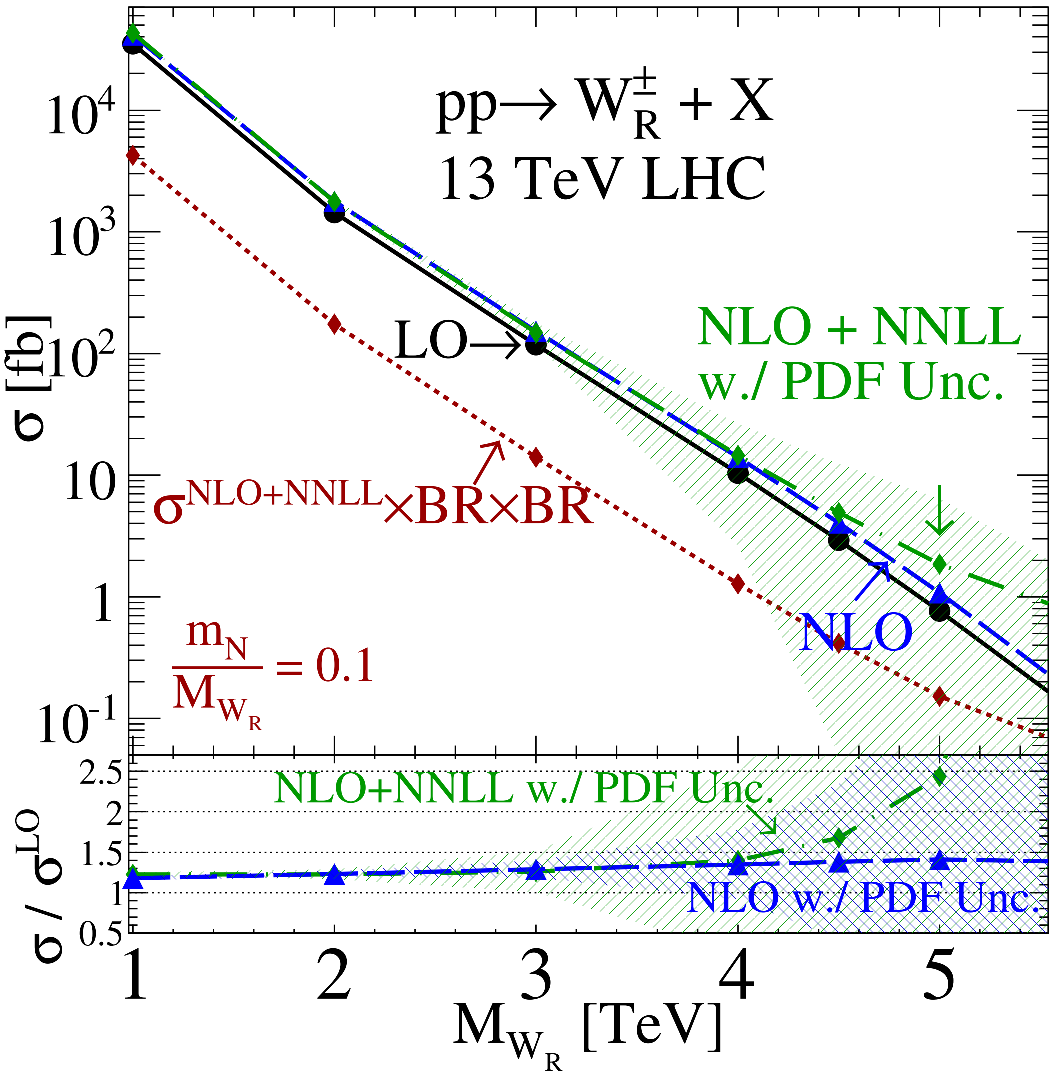
$0\nu\beta\beta$

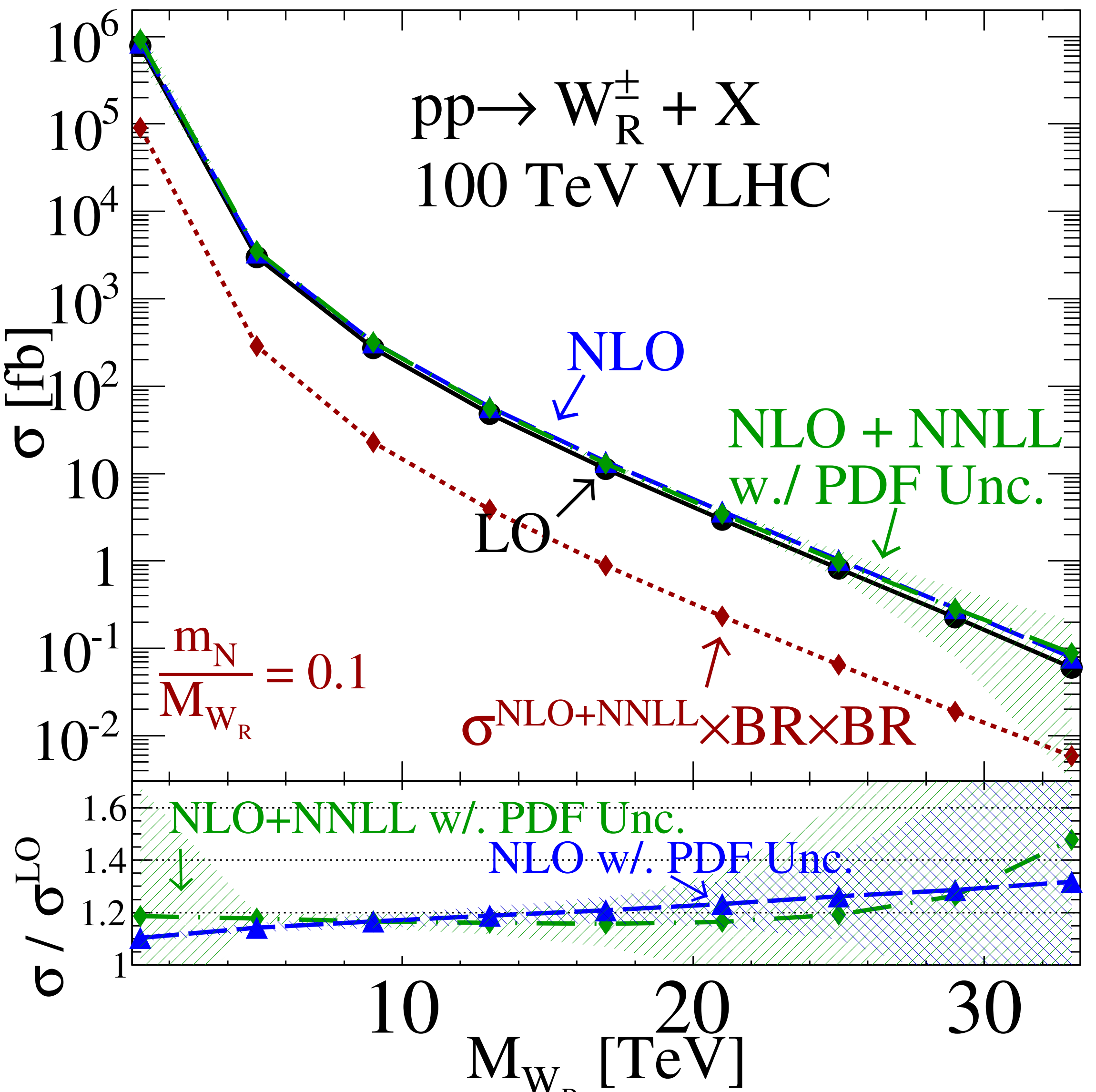
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} |\mathcal{M}(A,Z)\,\eta|^2$$

To extract η, need information about NME.

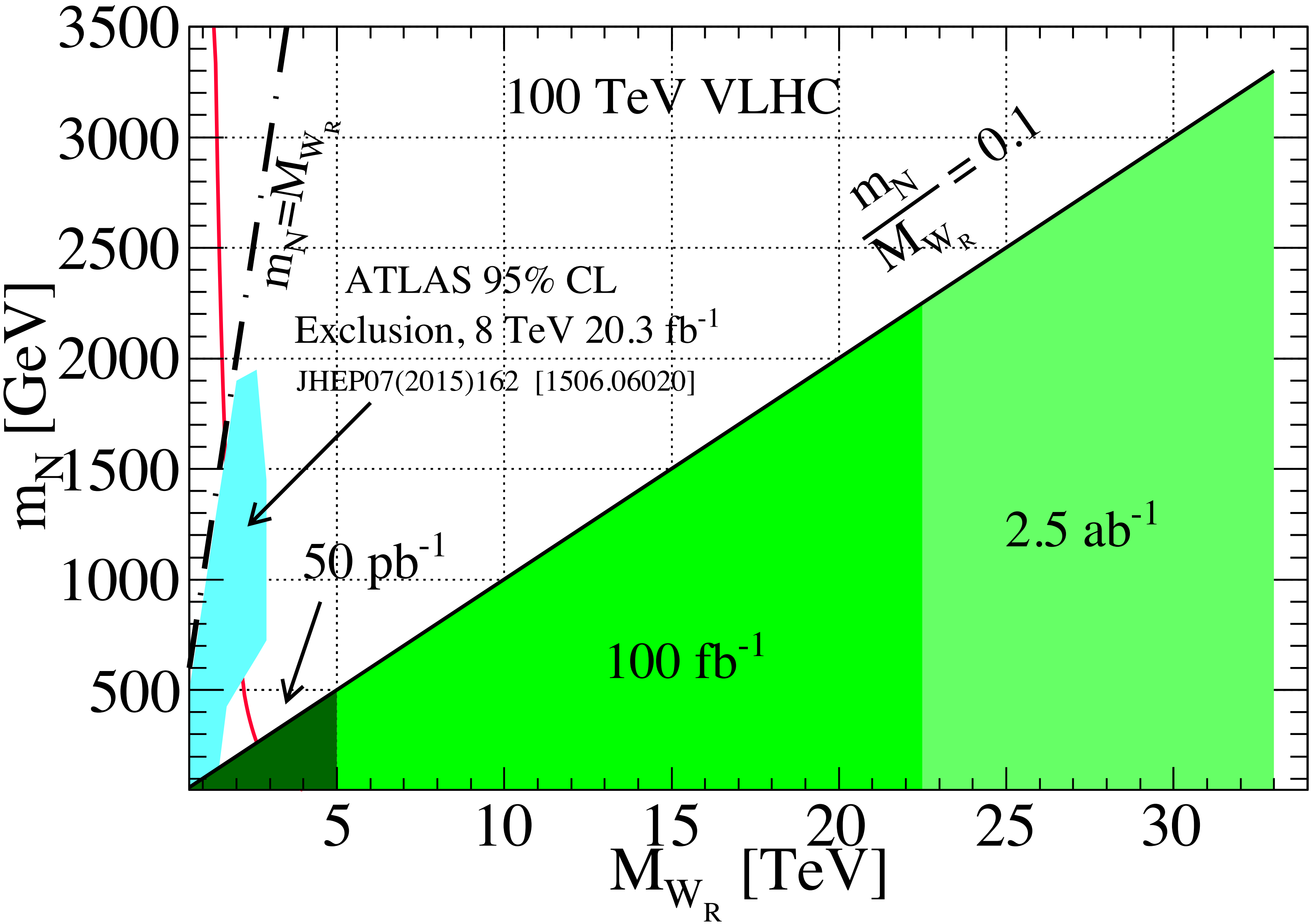


Limited by NME uncertainty


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



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}
m_N [GeV]
M_{W_R} [TeV]
3500
3000
2500
2000
1500
1000
500
5
10
15
20
25
30