Testing the neutrino mass generation mechanism at the future colliders

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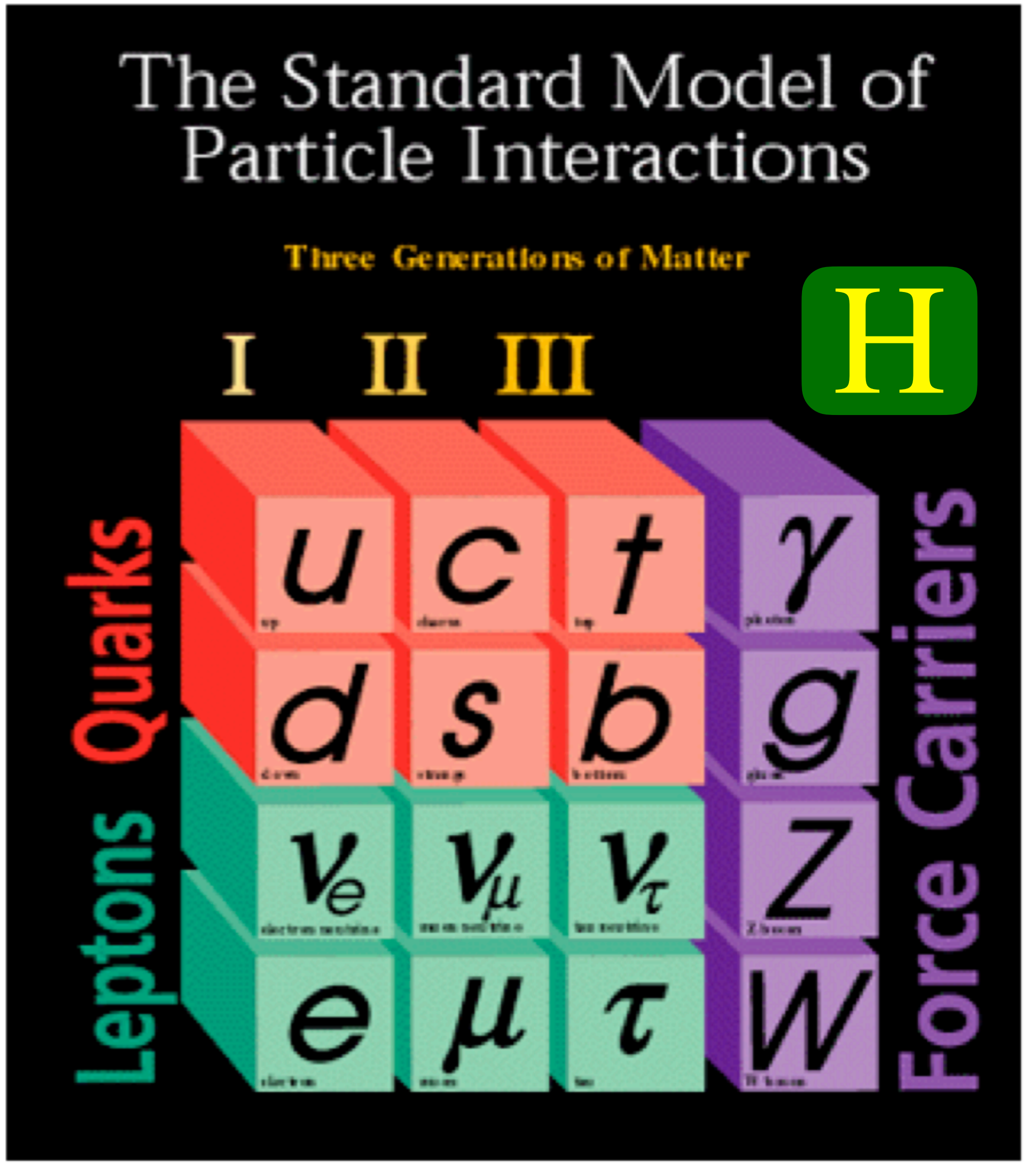


Over the decades experiments have found each and every missing pieces

Verified the facts that they belong to this family

Finally at the Large Hadron collider Higgs has been observed

→ Its properties must be verified

Strongly established with interesting shortcomings

Few of the very interesting anomalies :

Tiny neutrino mass and flavor mixings

Relic abundance of dark matter . . .

SM can not explain them

Models of Neutrino mass

There is a wide variety of neutrino mass models

The predicted models extend the SM minimally

At the tree level SM can be extended by Singlet fermions

→ Right handed neutrinos — seesaw mechanism, inverse seesaw mechanism

Minkowski, Ramond, Slansky, Yanagida, Gell – Mann, Glashow, Mohapatra, Senjanovic, Schecter, Valle,

Linear, Hybrid

Alternative ideas extending the Standard Model

→ SU(2) triplet scalar : type – II seesaw

Schecter, Valle, Lazarides, Shafi, Wetterich, Mohapatra, Senjanovic

→ SU(2) triplet fermion : type – III seesaw

Foot, Lew, He, Joshi, Ma

→ One – loop and even at 2/3 – loop models also exist

For example : Ma – model, Zee – Model, Zee – Babu model, BNT, KNT, etc .

Babu, Leung, Hirsch, King, Nasri, Volkas   Dev, Pilaftsis   AD, Nomura, Okada, Roy

→ Discrete symmetry, Effective operator approaches

Petcov, Tanimito, et . al; Volkas, et . al

→ Light neutrino induced model : νSM

Asaka, Gorbunov, Shaposhnikov

→ Gauge extended : U(1) and Left – Right

Pati, Salam; Mohapatra, Pati; Senjanovic, Mohapatra   Buchmuller, Greub; FileviezPerez, Han, Li; Heeck, Teresi;
Kang, Ko, Li; Keung, Senjanovic; Ferrari et . al . ; Nemevsek, Nesti, Senjanovic, Zhang; AD, Dev, Okada, Raut
Chen, Dev, Mohapatra; Dev, Mohapatra, Zhang; AD, Dev, Mohapatra; Deppisch, Desai, Kulkarni, Valle; Gluza

and more .

Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut;
Chiang, Cottin, AD, Mandal; AD, Takahashi, Oda, Okada AD, Dev, Okada

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	$=$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	$=$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	$=$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	$=$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	$=$	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x'_H	$=$	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	$=$	$-x_\Phi$
Φ	**1**	**1**	0	x'_Φ	$=$	$2x_\Phi$

$m_{Z'} = 2\, g_X v_\Phi$

x_H, x_Φ will appear the coupling with Z'

B − L case
$x_H = 0,\ x_\Phi = 1$

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

$U(1)_X$ breaking

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

$$m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h$$

$$m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

$$m_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \qquad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

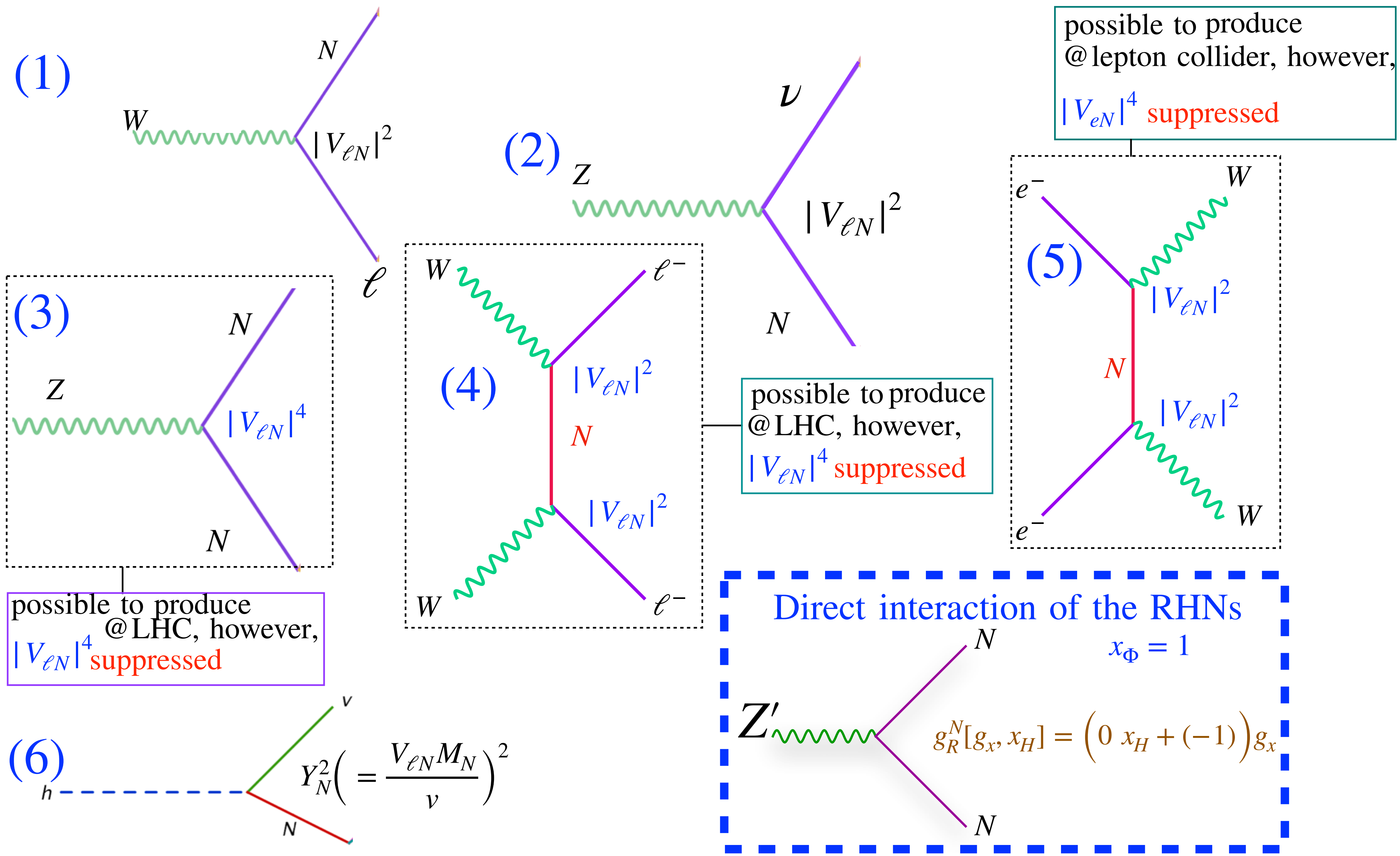
Seesaw mechnism

Production modes of the RHNs at the colliders : pp, e^-e^+, e^-p

Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \simeq U_{\ell m}\nu_m + V_{\ell n}N_n$$

PMNS matrix ($U_{\ell m}$), $M_D M_N^{-1}$ ($V_{\ell n}$)

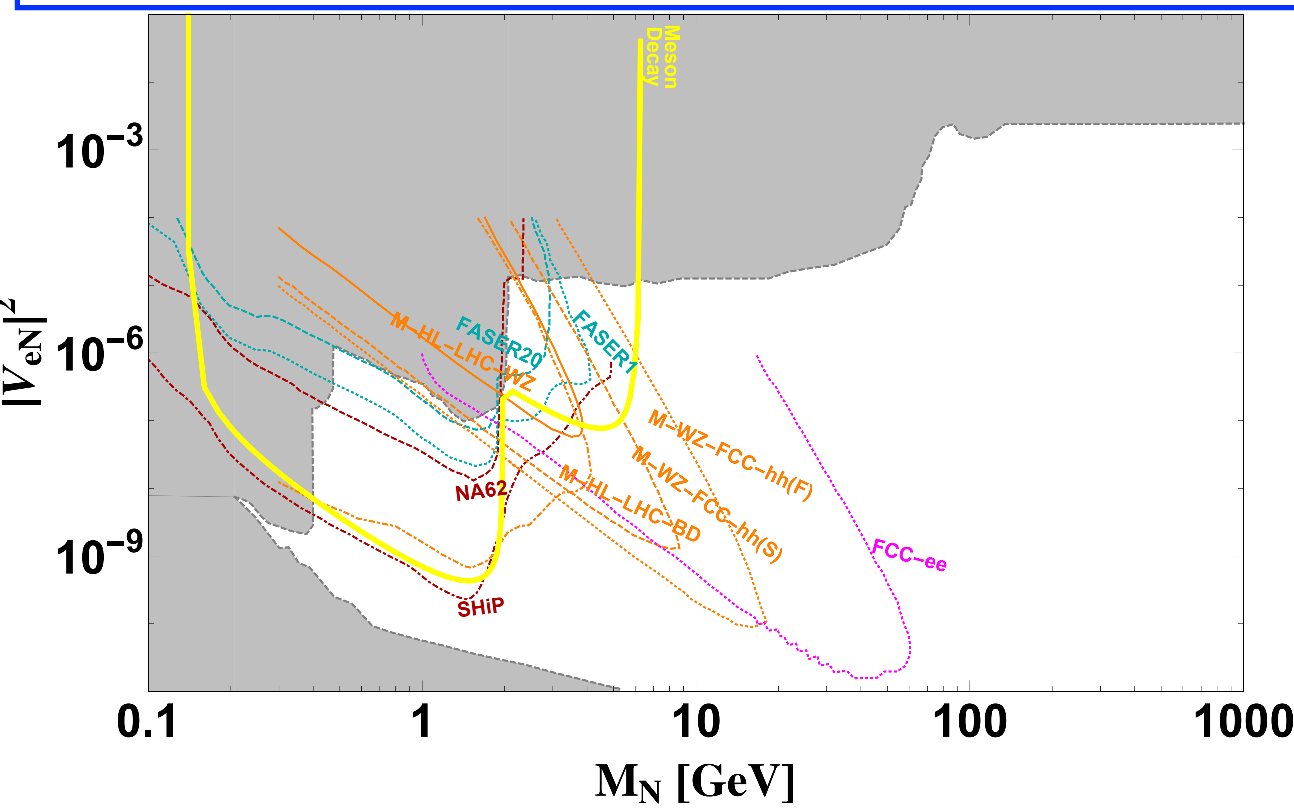


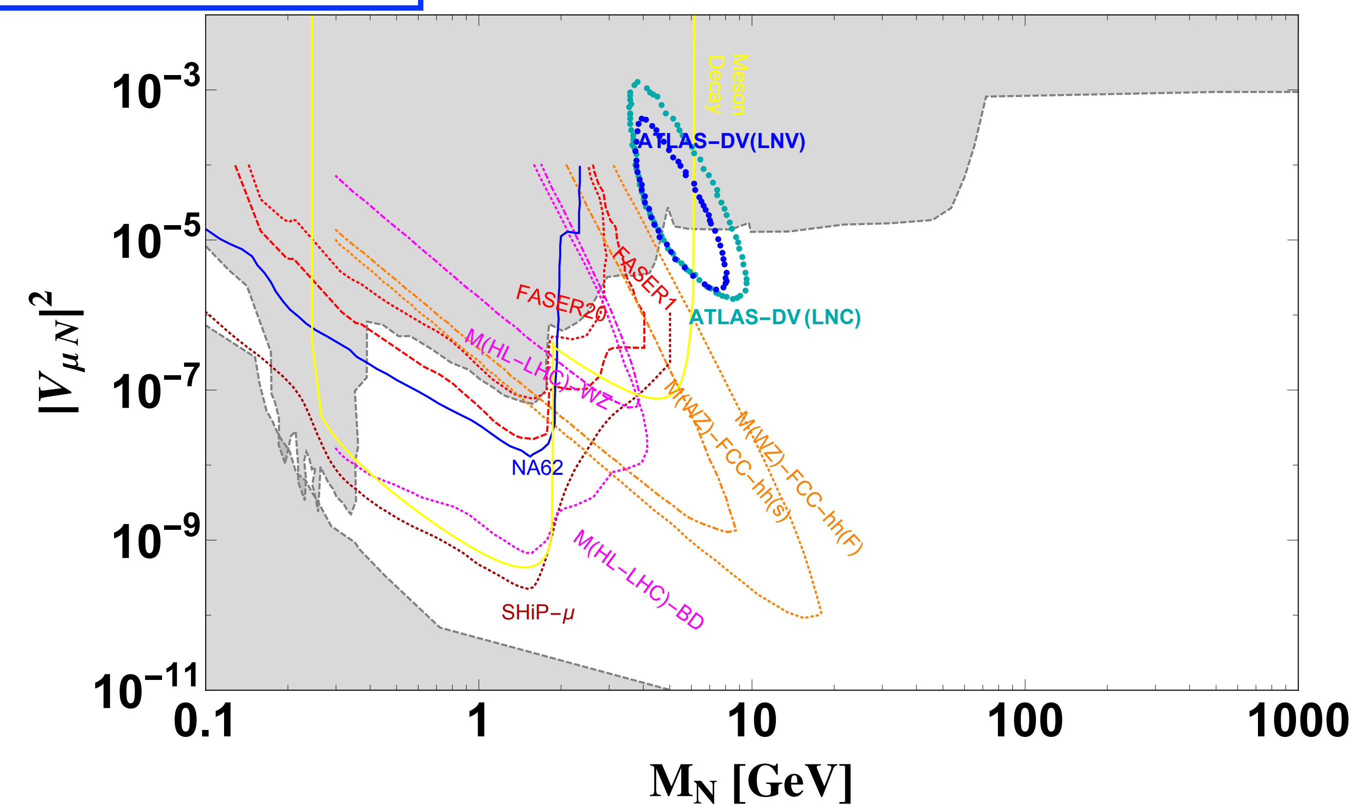
We consider $x_\Phi = 1$

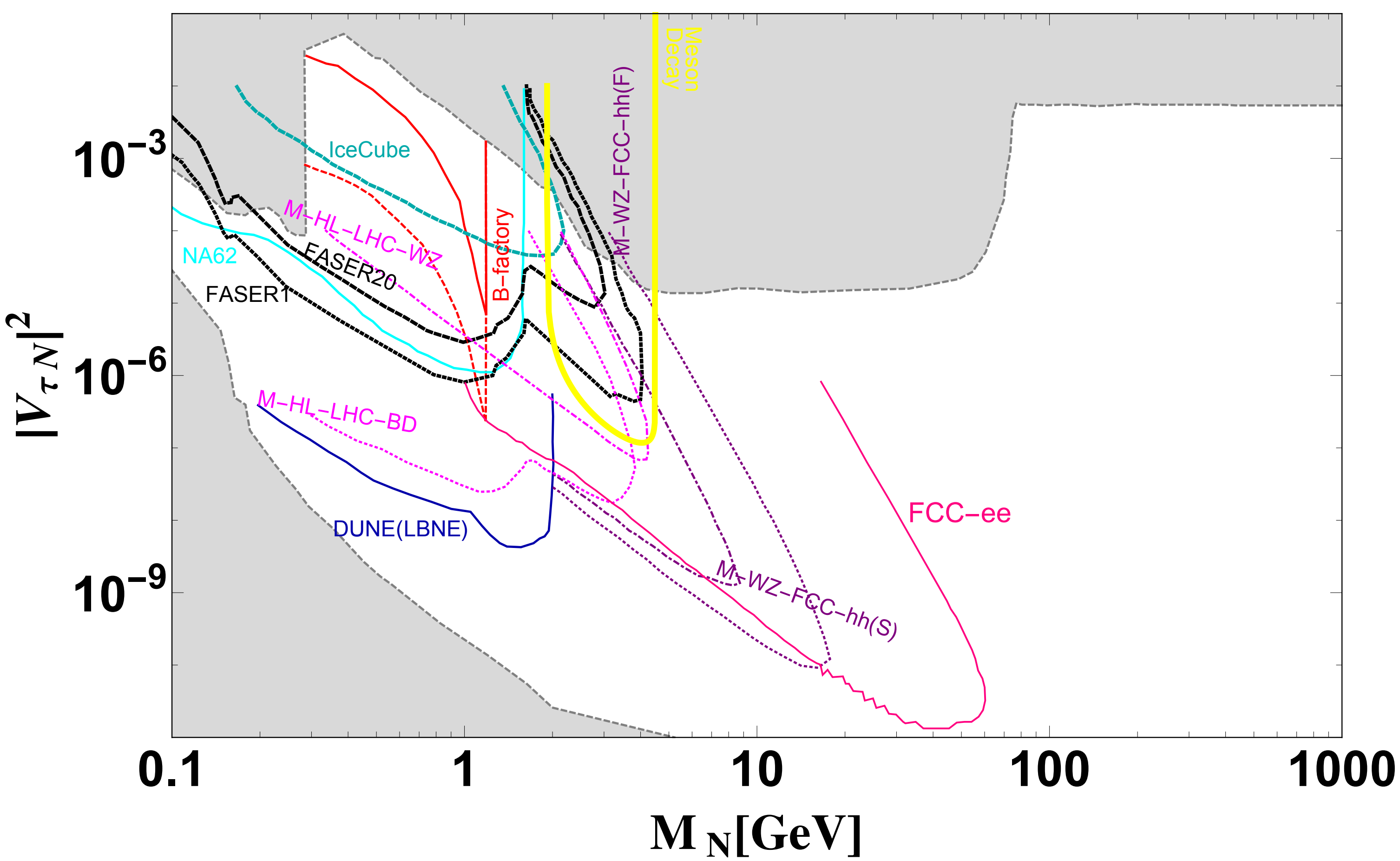
$Z \to N\ \nu$, see Andre de Gouvea's talk : Dirac – Majorana nature

Existing and prospective bounds on the mixings

1502.06541 1805.00070 1908.09562







In back – up slides

CMS $\ell^\pm \ell^\pm$ + jets
1806.10905 13 TeV, 35.9 fb^{-1}
CMS 3ℓ + MET
1802.02965 13 TeV, 35.9 fb^{-1}
ATLAS 3ℓ + MET
1905.09787, 36.1 fb^{-1}

General Yukawa structure : 1702.04668

Also : Meson decay : Julia Harz's talk

Limits on strile neutrinos from DUNE : Kevin Kelly's talk

FASERν : Tomoko Ariga's talk

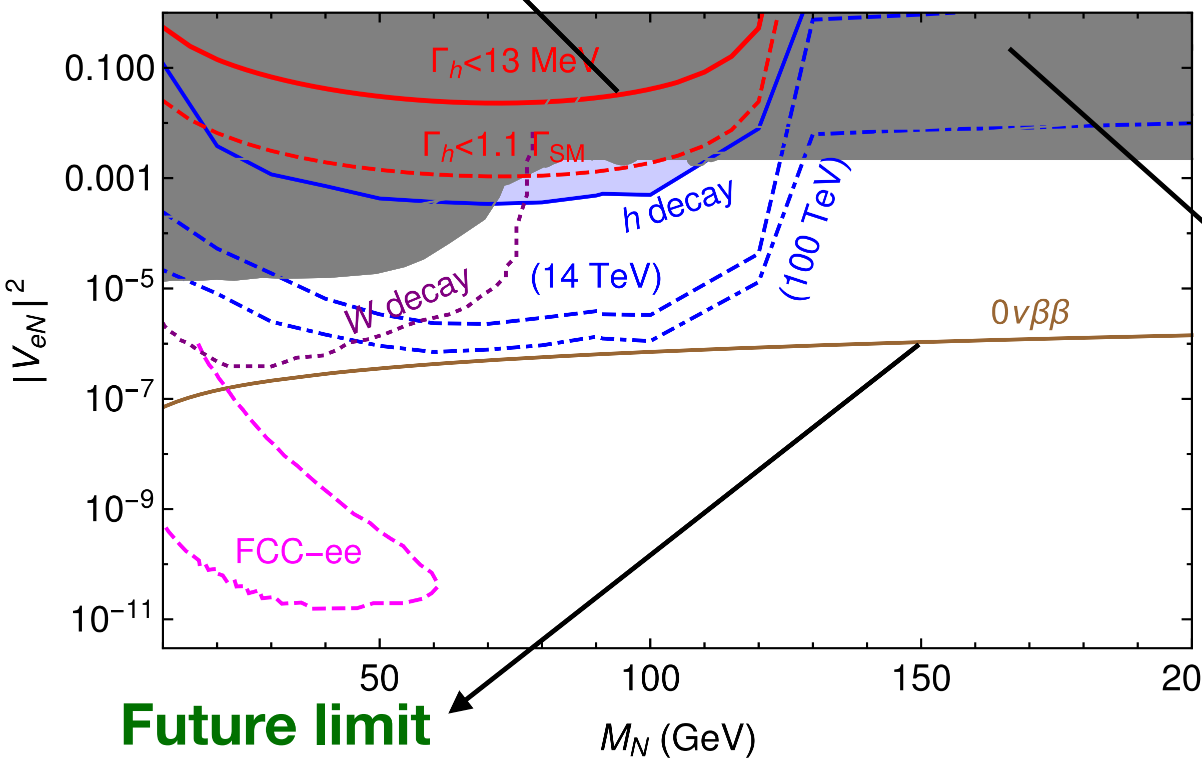
μBooNE : Pawel Guzowski's talk

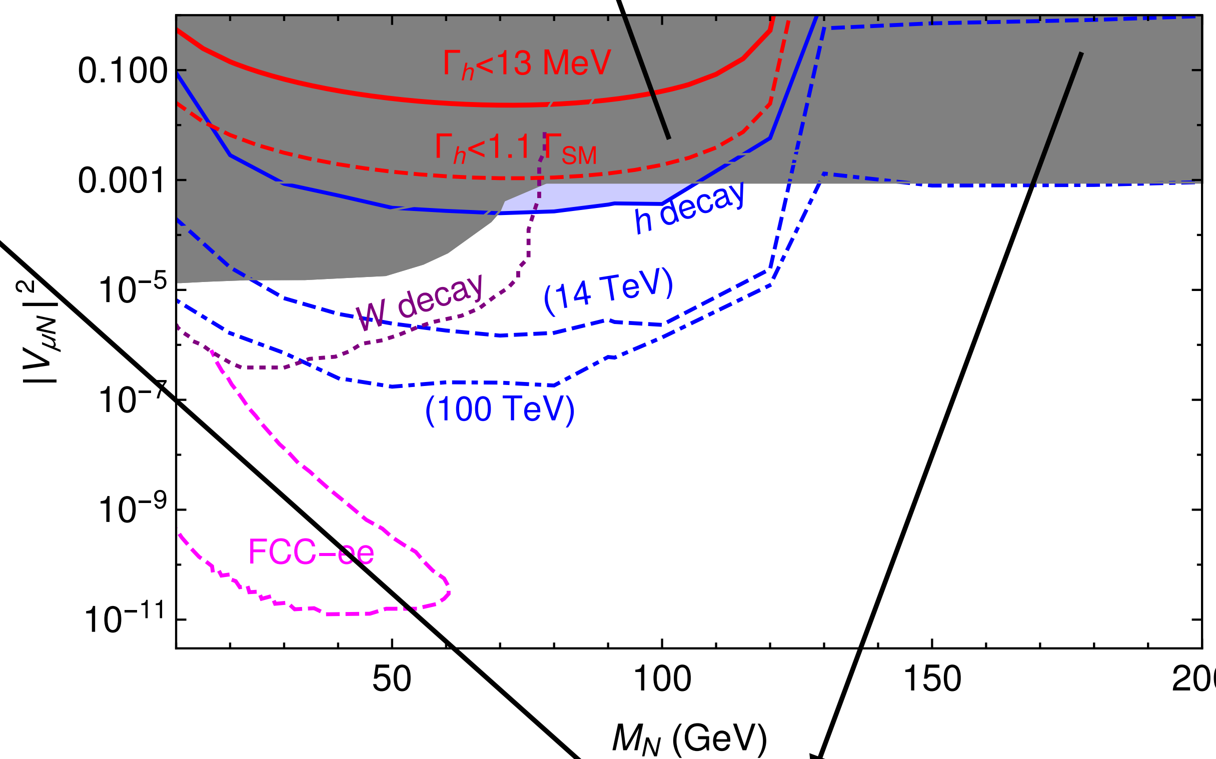
$2\ell + p_T^{\rm miss}$: bounds from the Higgs decay $(h \to N\nu, N \to 2\ell\nu)$

CMS, JHEP 09 (2016) 051: 7&8 TeV combined H $\longrightarrow$ W W*, upper limit on Yukawa as well as mixing

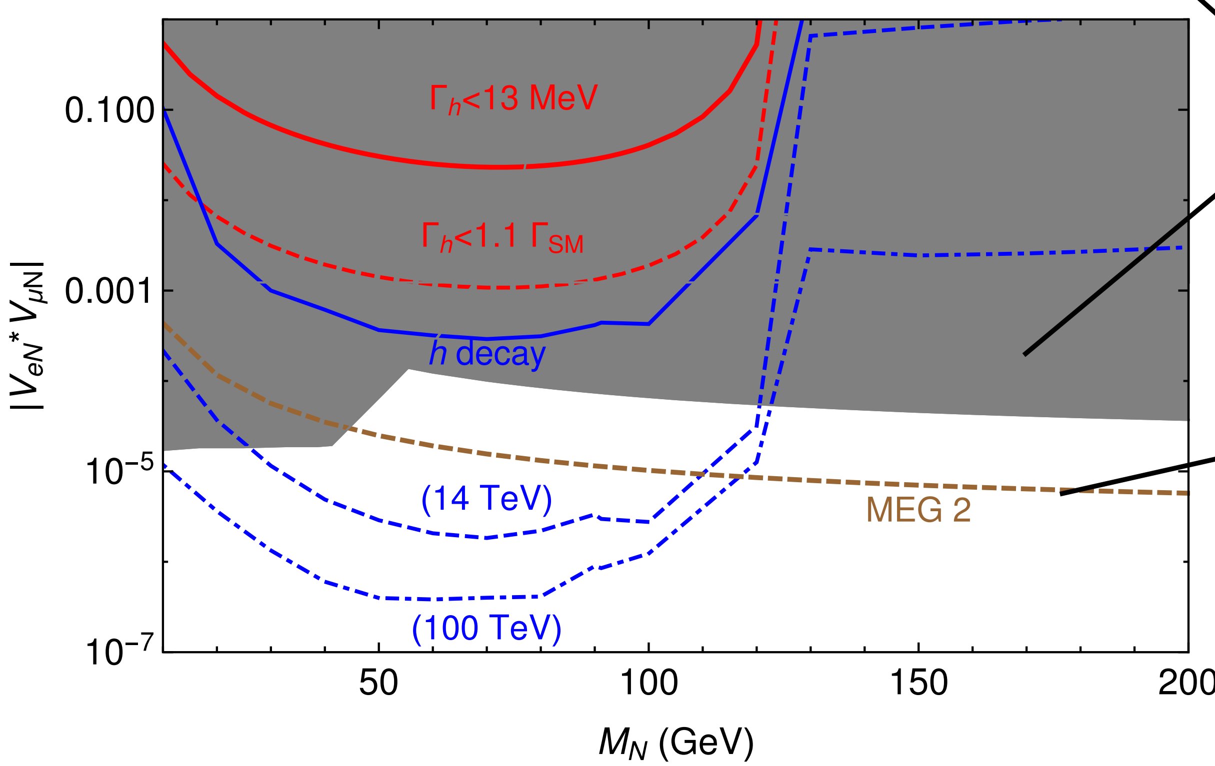
Future sensitivity can go down to 10%precise result at pp collider: arXiv:1606.09408

1704.00880
1704.00881





Future limit considering Majorana heavy neutrinos only



Excluded by LEP LHC,EWPD,

LFV limits from CMS is also included in the lower panel

$\mu \to e\gamma$

~ future branching ratio $O(10^{-15})$

FCC-ee : Limits from Z decay

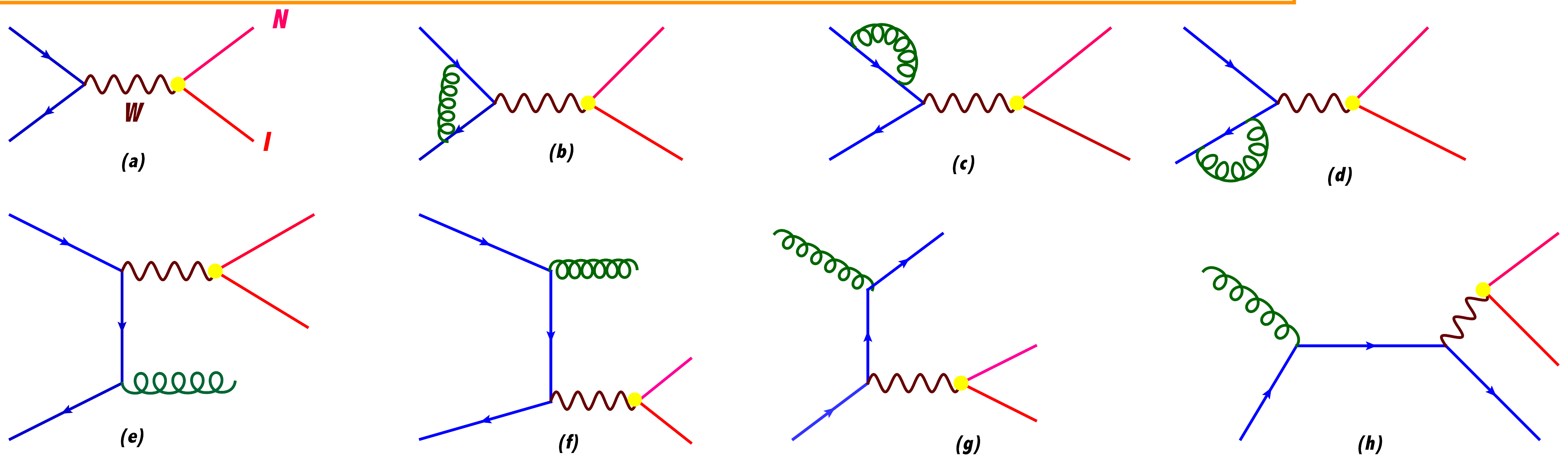
W-decay @LHC

Future limits

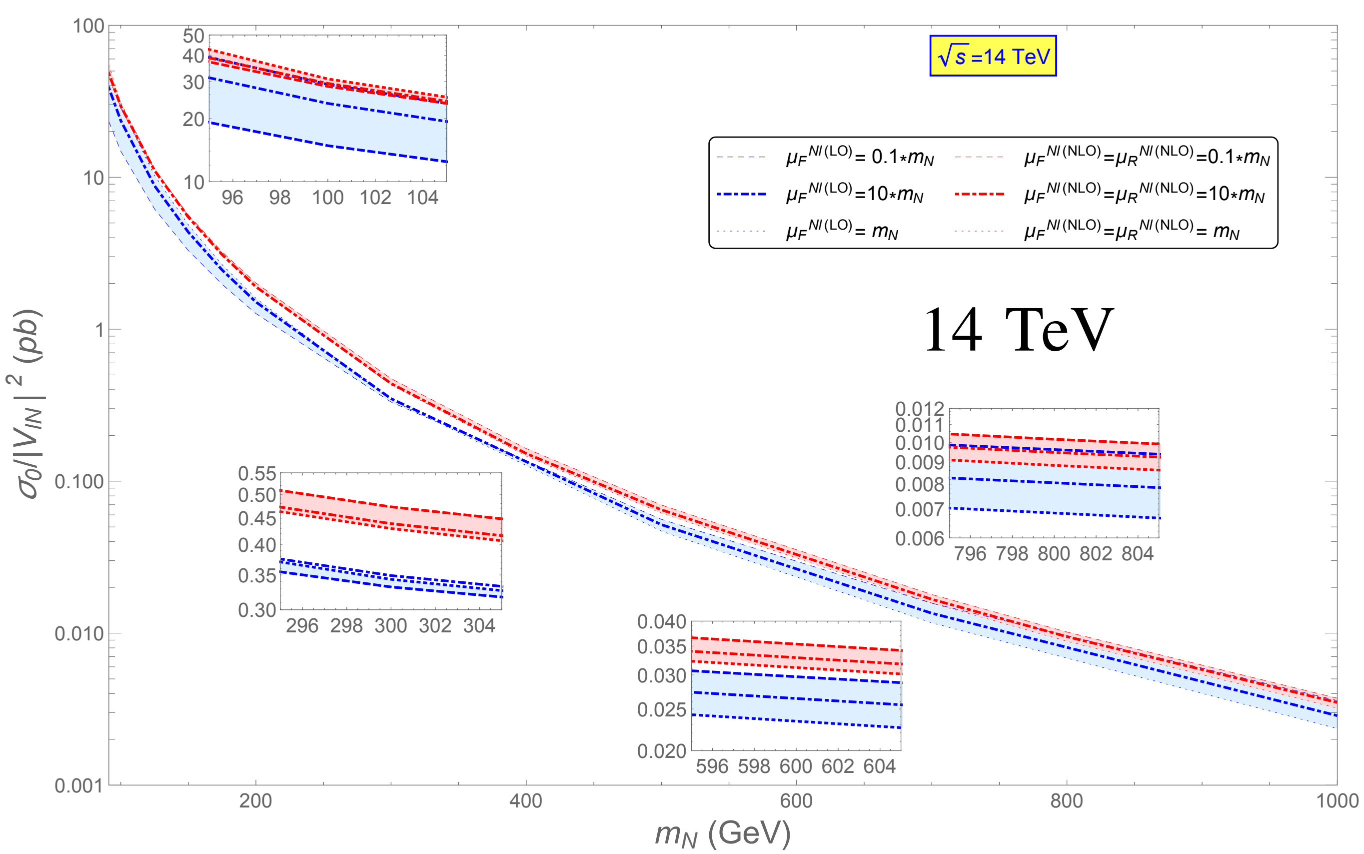
Dev, Franceschini, Mohapatra; Cely, Ibarra, Molinaro, Petcov; AD, Dev, Kim; AD, Gao, Kamon; Antusch, Fischer

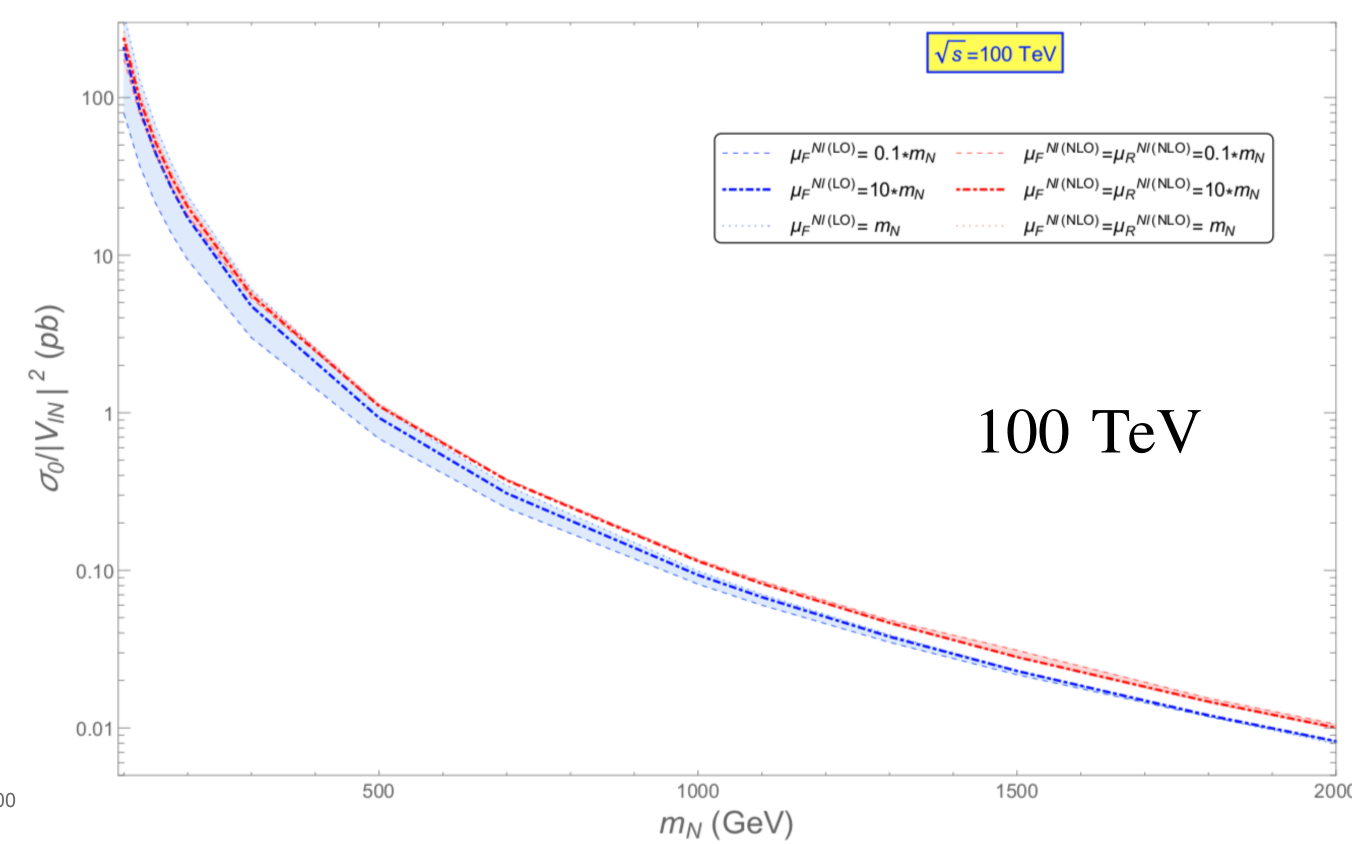
NLO – QCD production of the heavy neutrinos

1602.06957

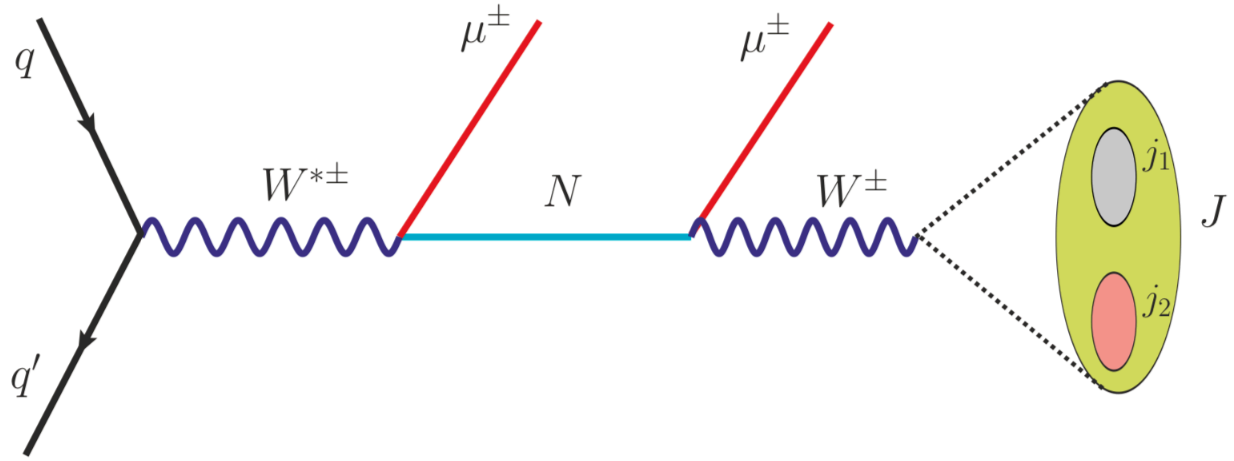


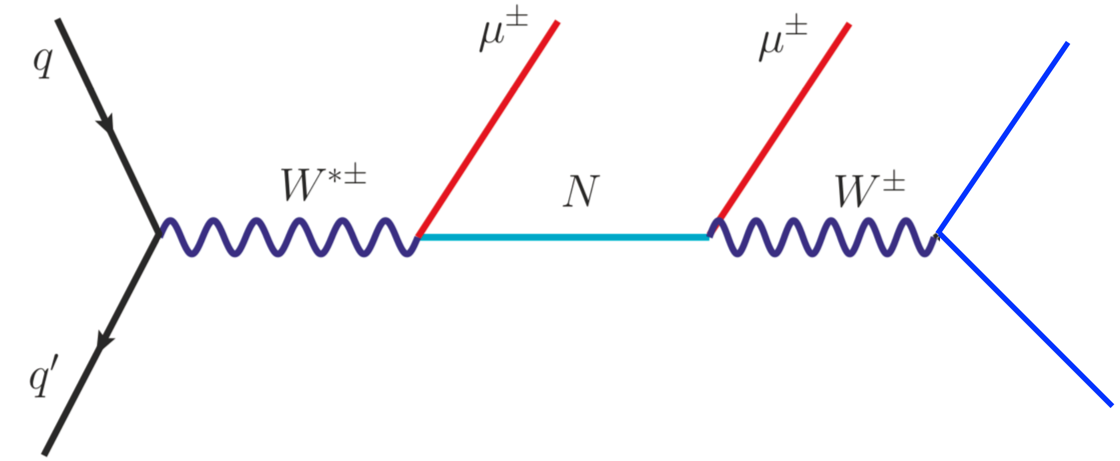
$\mu_F^{NLO} = \mu_R^{NLO} = \xi * m_N$ $\mu_F^{NLO} = m_N, \mu_R^{NLO} = \xi * m_N$ $\mu_F^{NLO} = \xi * m_N, \mu_R^{NLO} = \xi * m_N$ $0.1 \leq \xi \leq 10$





Normalized by $|V_{\ell N}|^2$



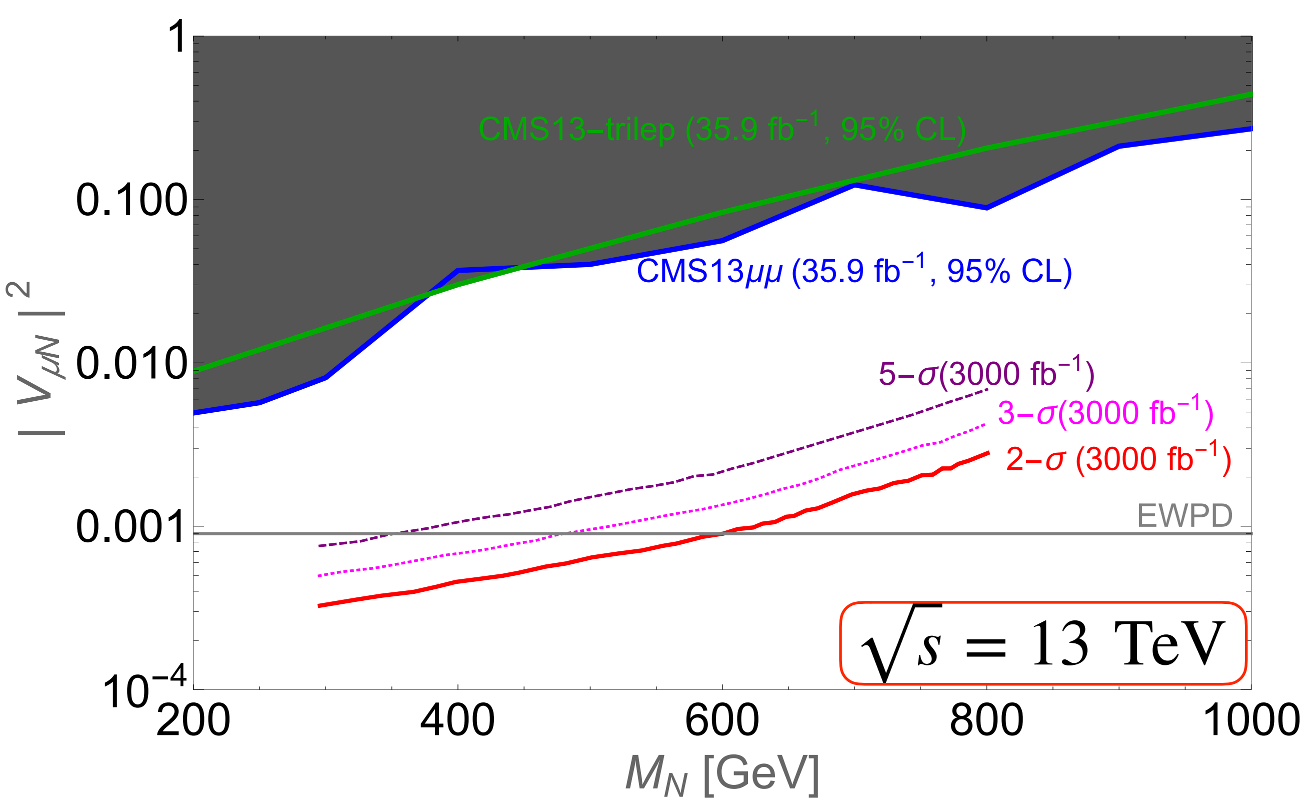


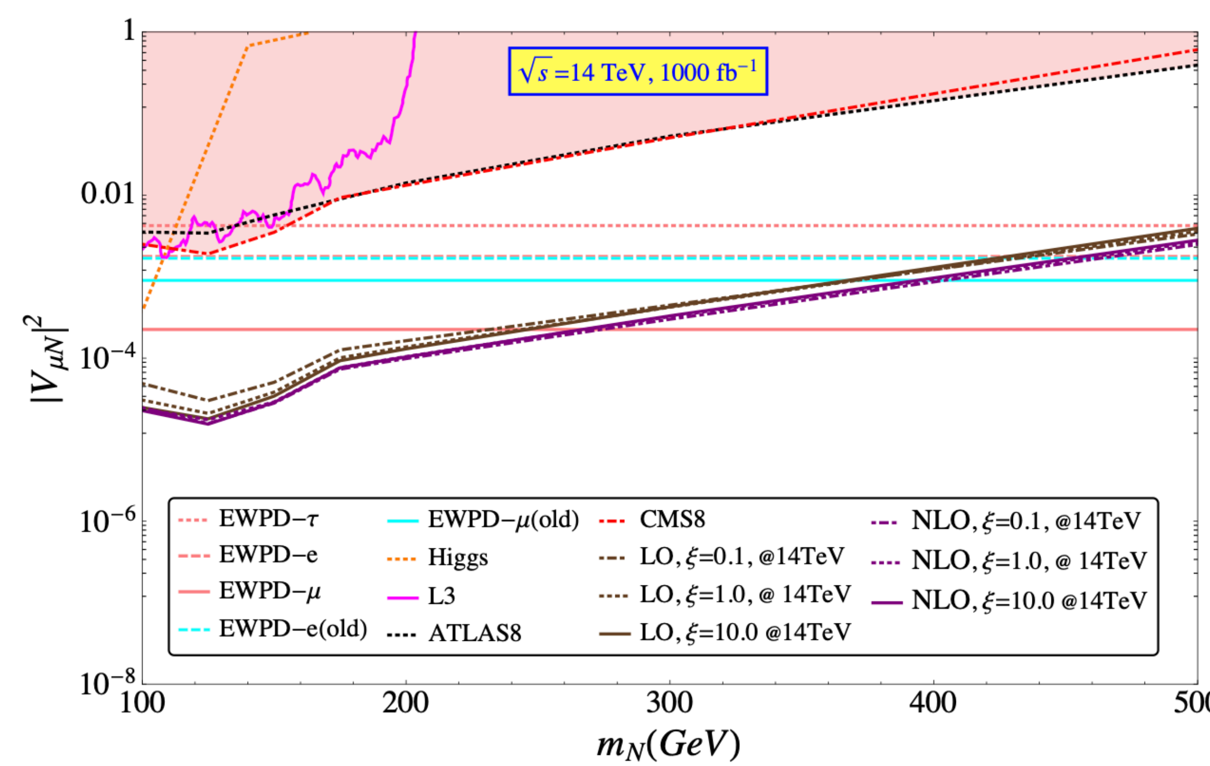
$R = 0.8,\ p_T^J\ >\ 150\ \text{GeV},\ \tau_{21}^{\mathrm{J}}\ <\ 0.5,\ \mathrm{E_T^{miss}}\ <\ 35\ \text{GeV},\ \mathrm{M^J}\ >\ 50\ \text{GeV}$

SSDL + 1 – Fat jet

SSDL + 2 – jet

Mass versus mixing plot and comparison to the current bounds





14 TeV, 1000 fb^{-1}

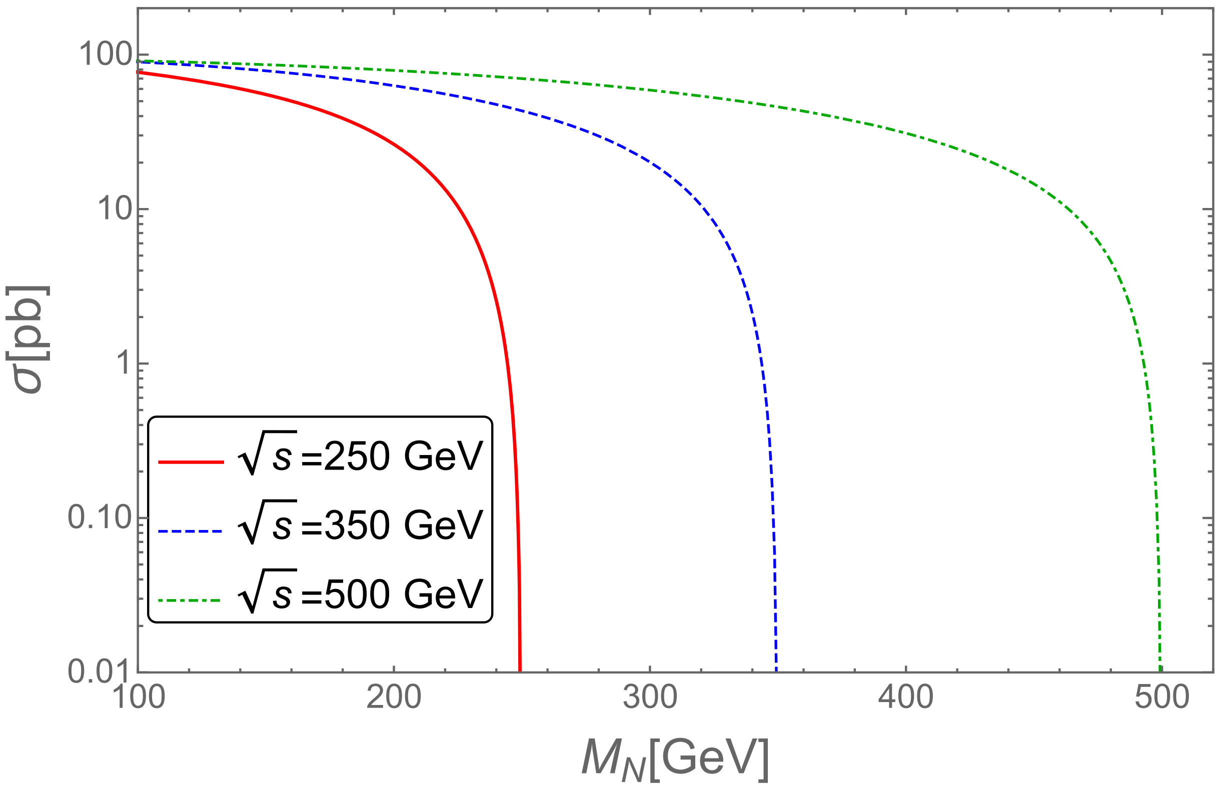
AD, Konar, Thalapillil 1709.09712

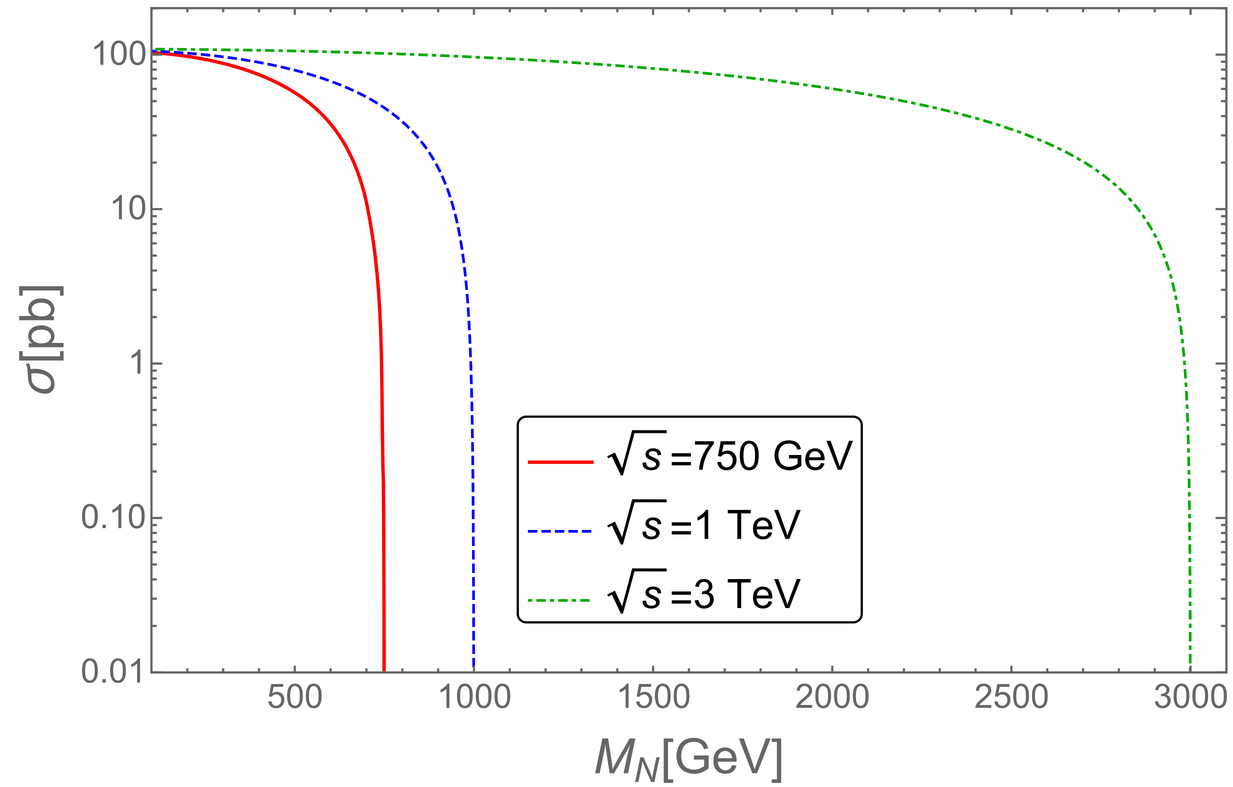
AD, Konar, Majhi 1602.06957

Production of the heavy neutrinos at the Linear Collider using fat jet

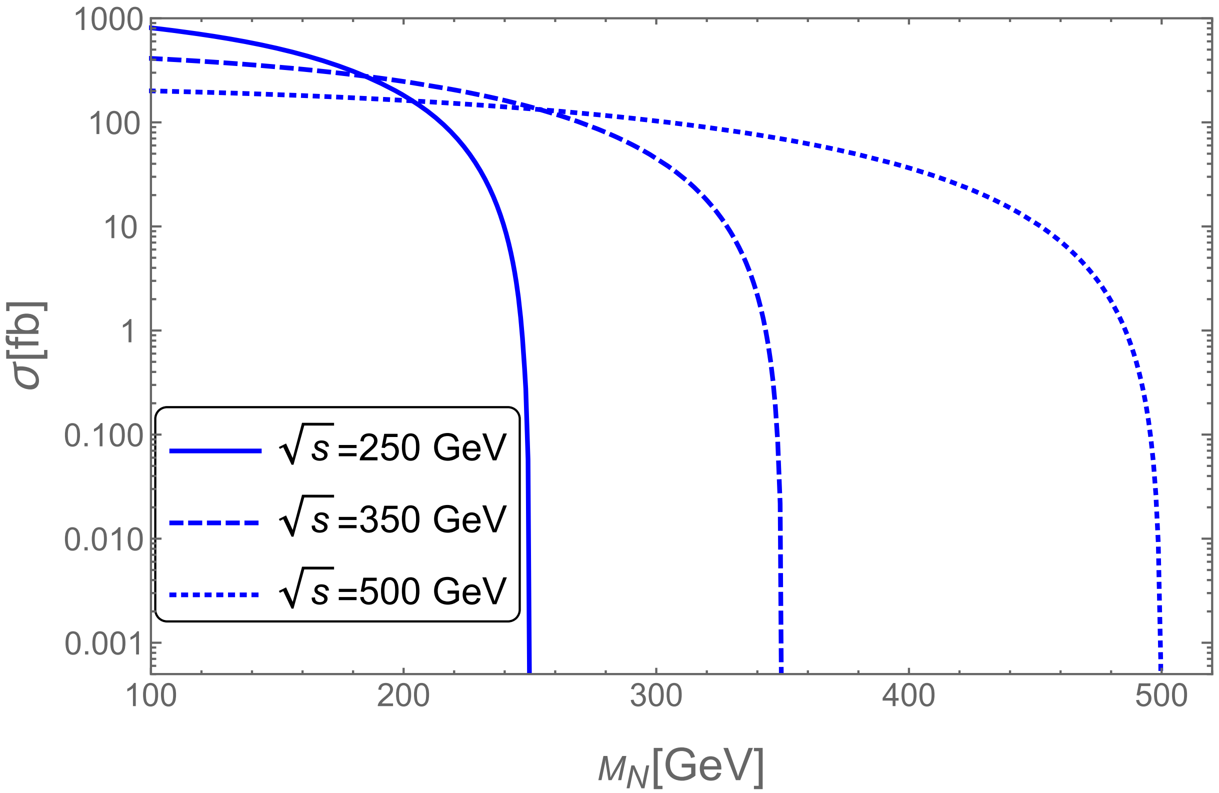
1811.04291

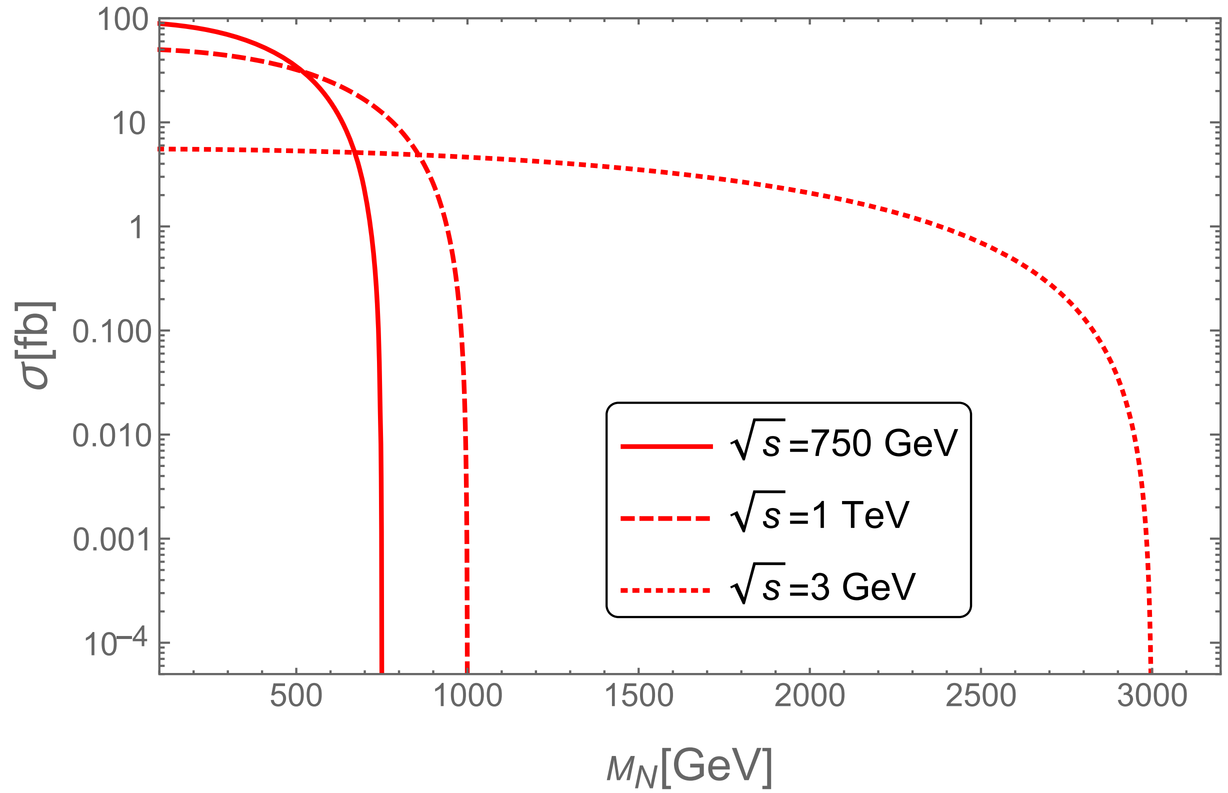
$e^+e^- \to \nu_1 N_1$ Includes s – channel and t – channel processes



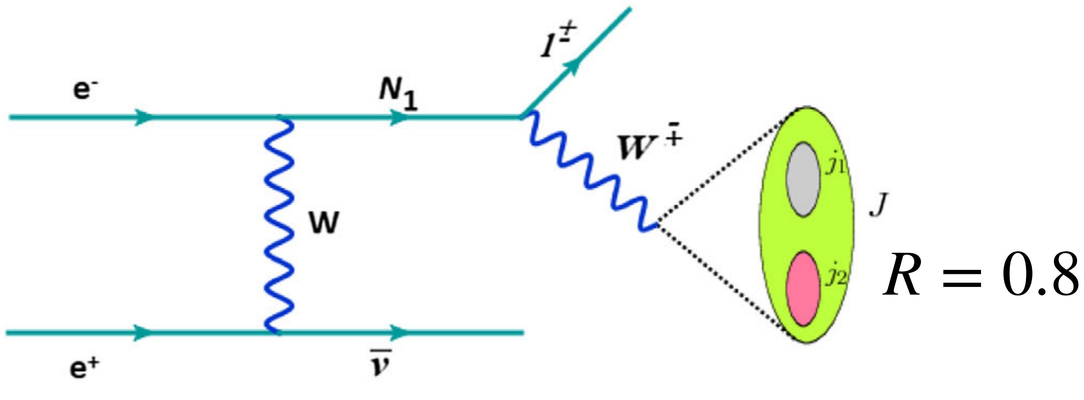


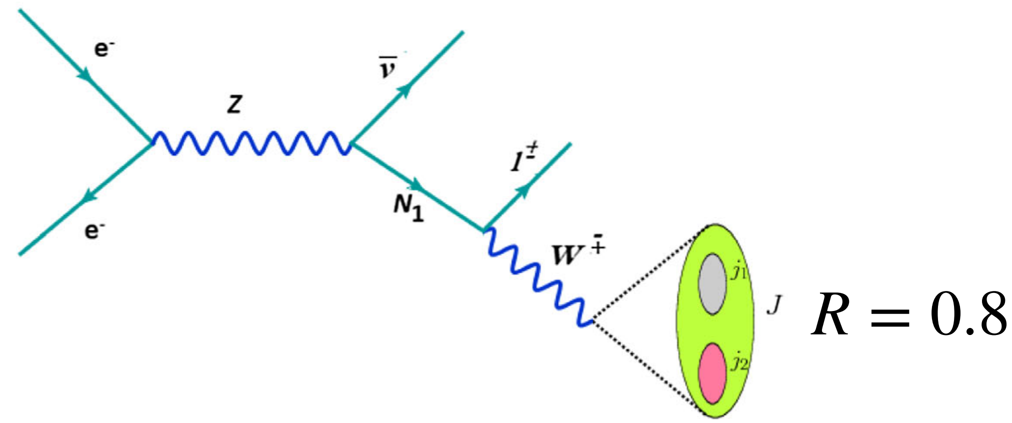
$e^+e^- \to \nu_2 N_2 / \ \nu_3 N_3$ Includes s – channel process, t – channel suppressed by off – diagonal Yukawa, away from the Z pole



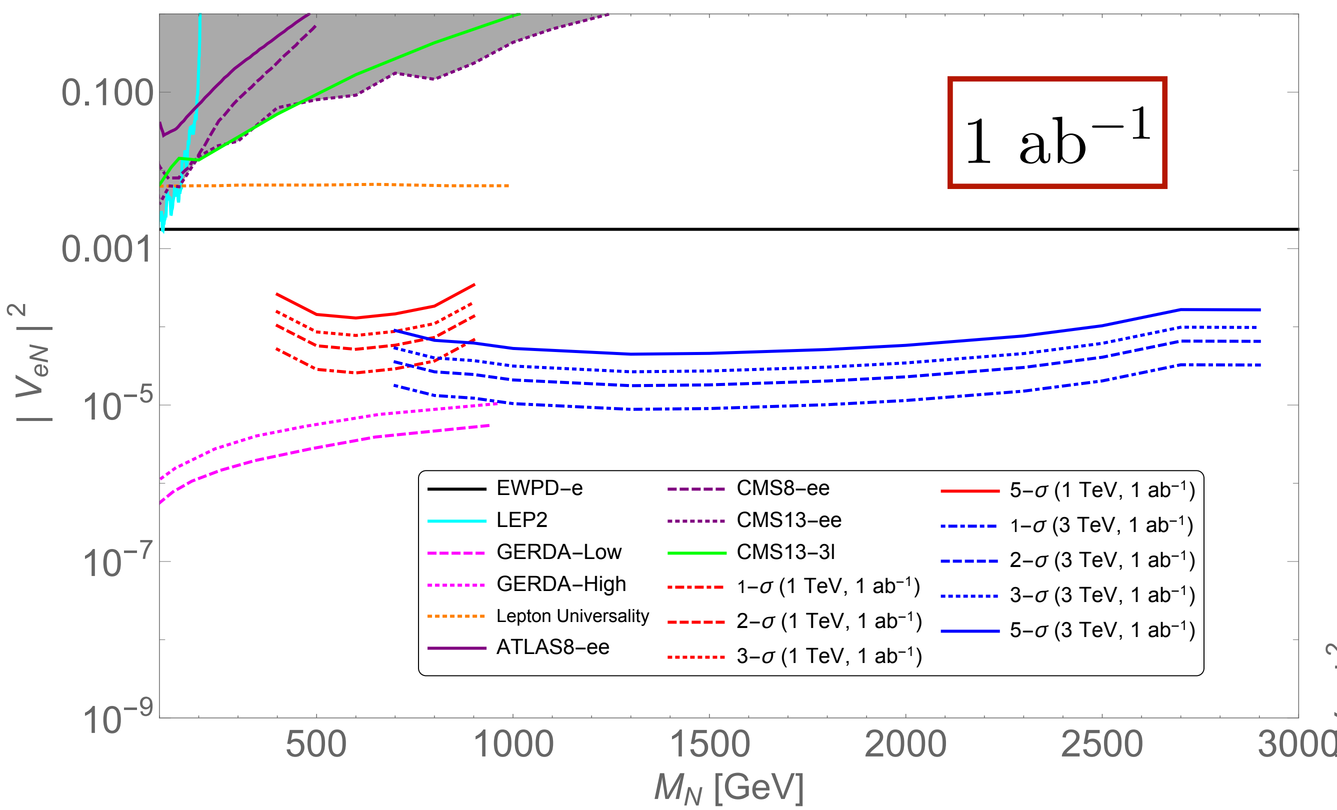


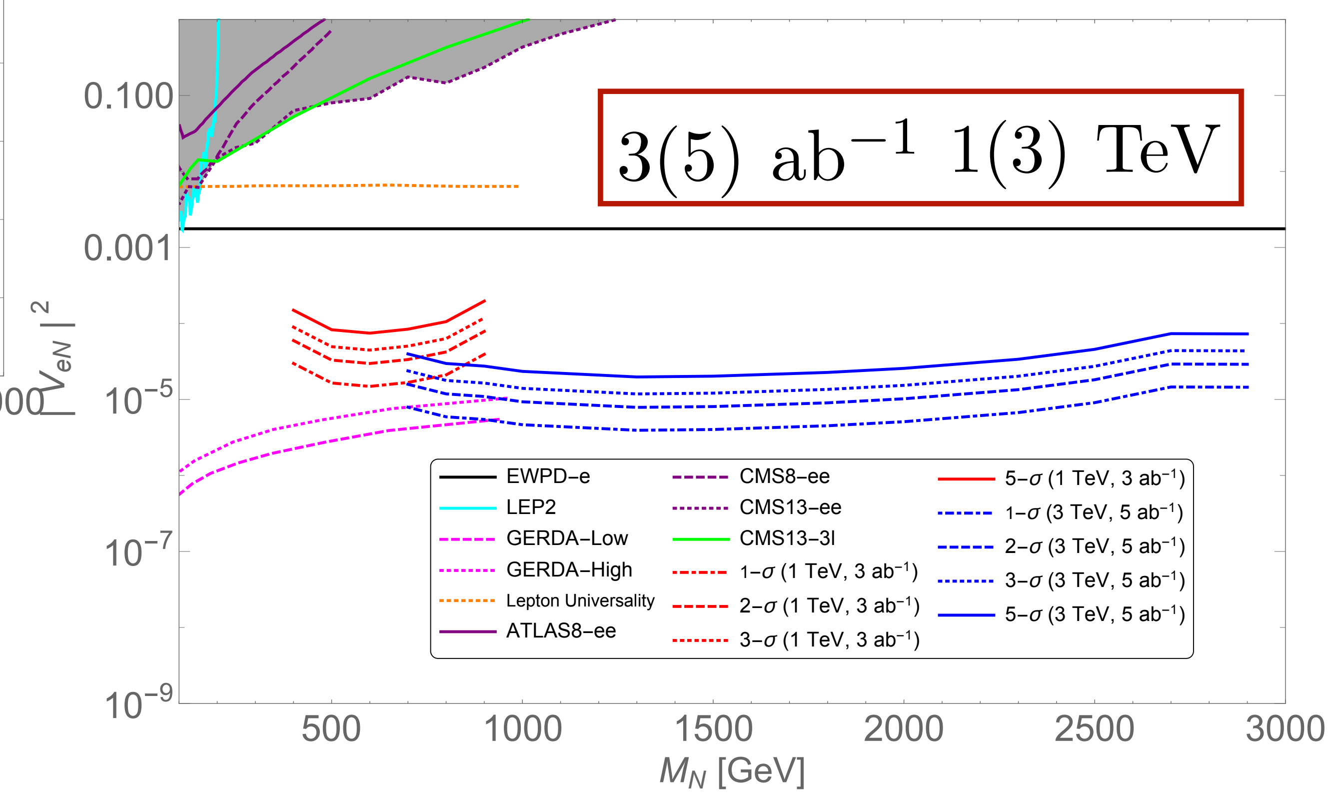
$e + J + p_T^{\text{miss}}$ final states at the linear colliders





1 TeV (red band) and 3 TeV (blue band)

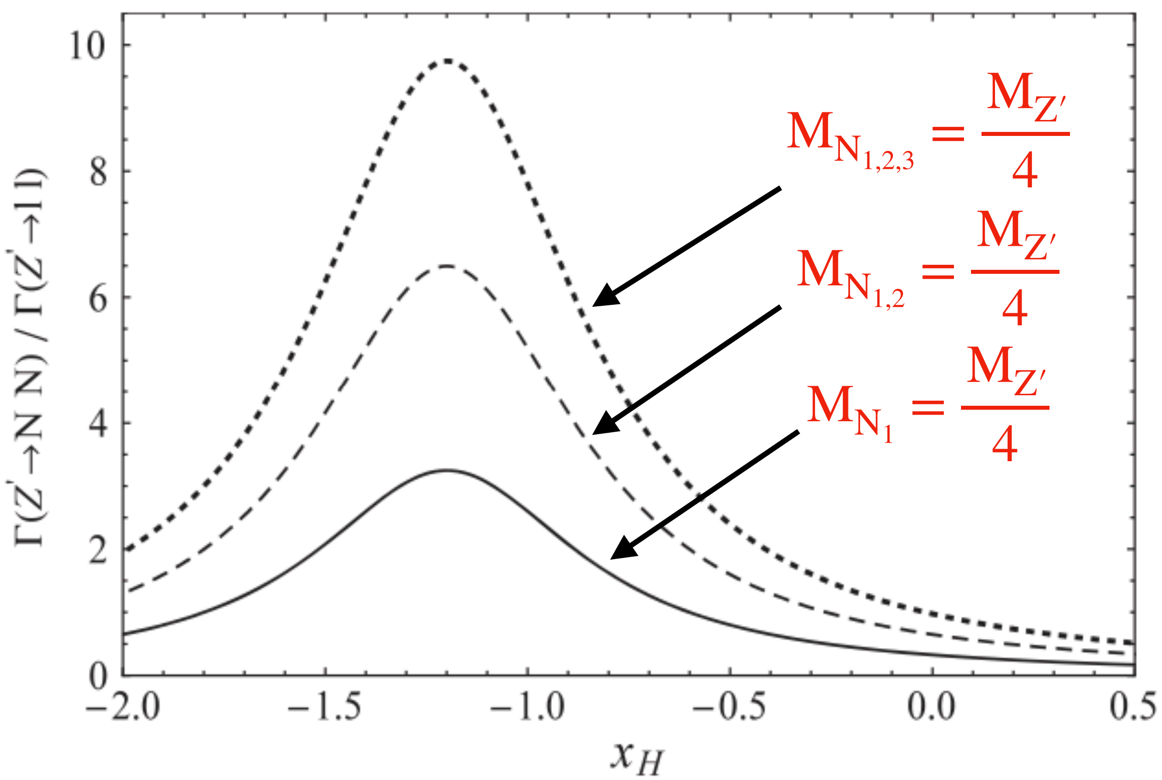




Decay length of RHNs neutrinos as a function of lightest active neutrino mass

$pp \to Z' \to NN$, under $U(1)_X$ scenario

1906.04132 1908.09838



$$\mathcal{L}^q = -g'(\bar{q}\gamma_\mu q^q_{x_L} P_L q + \bar{q}\gamma_\mu q^q_{x_R} P_R q) Z'_\mu \qquad Z' - \text{quarks}$$

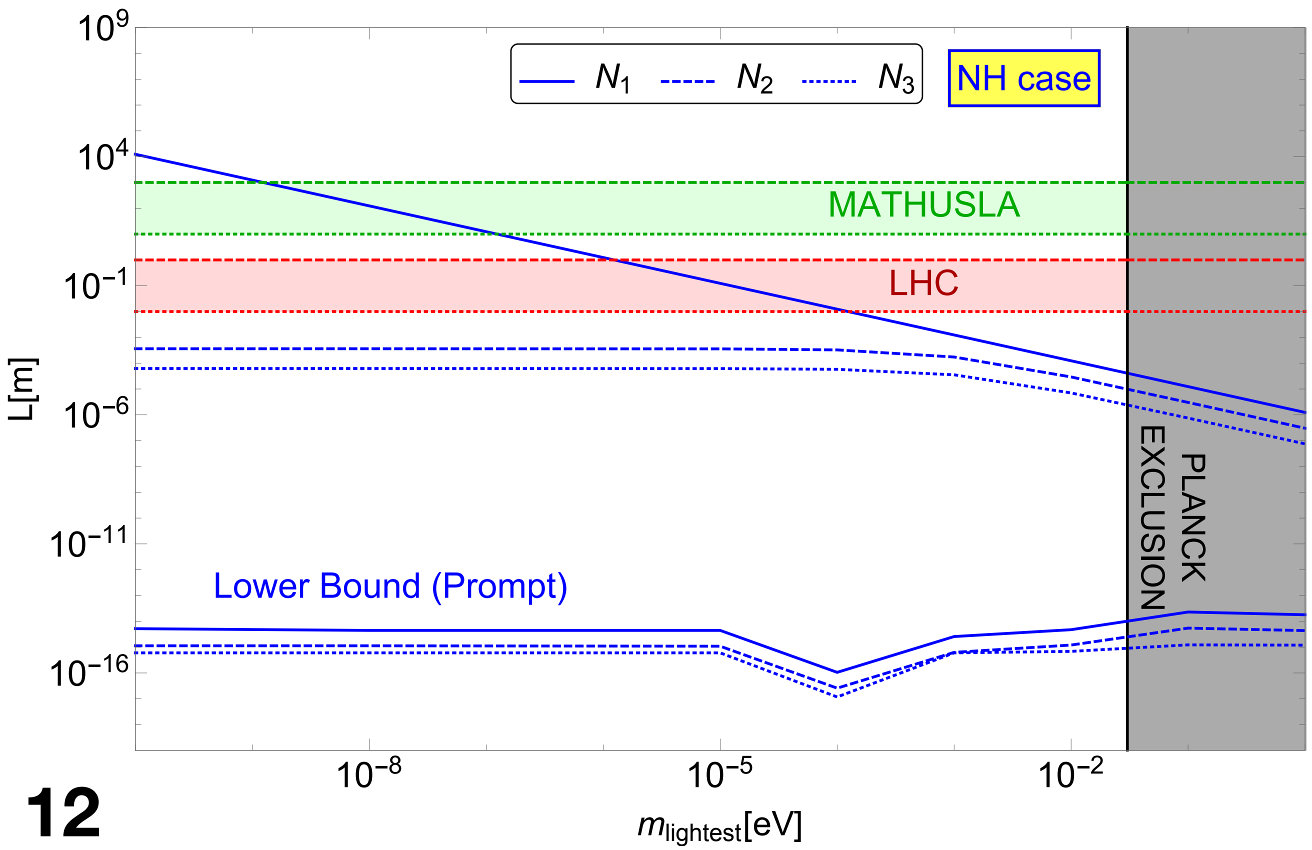
$$\mathcal{L}^\ell = -g'(\bar{\ell}\gamma_\mu q^\ell_{x_L} P_L \ell + \bar{e}\gamma_\mu q^\ell_{x_R} P_R e) Z'_\mu \qquad Z' - \text{charged leptons}$$

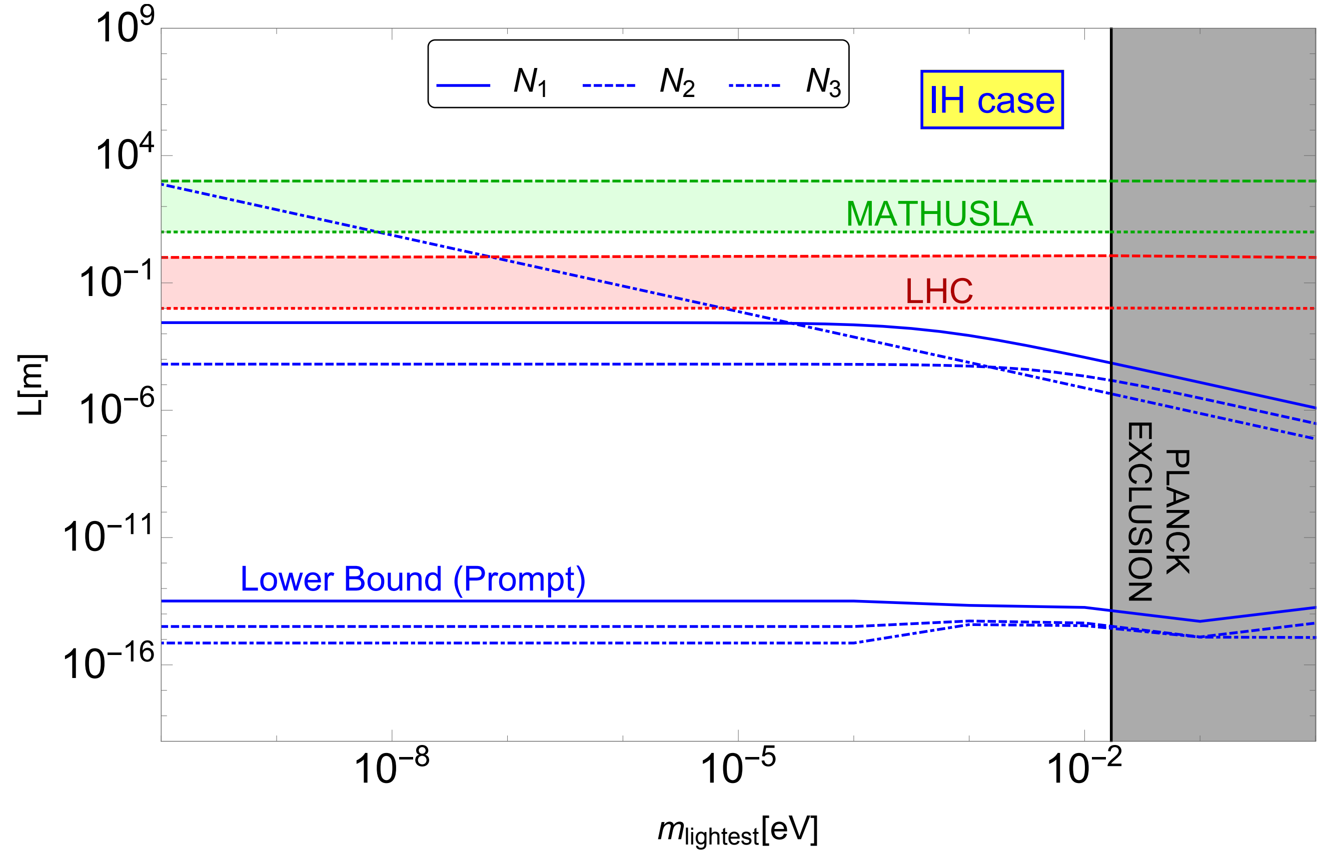
$$\Gamma(Z' \to 2f) = N_c \frac{M_{Z'}}{24\pi} \left(g^f_L\left[g', x_H, x_\Phi\right]^2 + g^f_R\left[g', x_H, x_\Phi\right]^2 \right)$$

$$\Gamma(Z' \to 2\nu) = \frac{M_{Z'}}{24\pi}\, g^\nu_L\left[g', x_H, x_\Phi\right]^2 \qquad \Gamma(Z' \to N^i N^i) = \frac{g^2}{24\pi} m_{Z'} \left(1 - \frac{4m^2_{N^i}}{m^2_{Z'}}\right)^{3/2},$$

$$\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \ell^+\ell^-)} = \frac{4}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{\frac{3}{2}}.$$

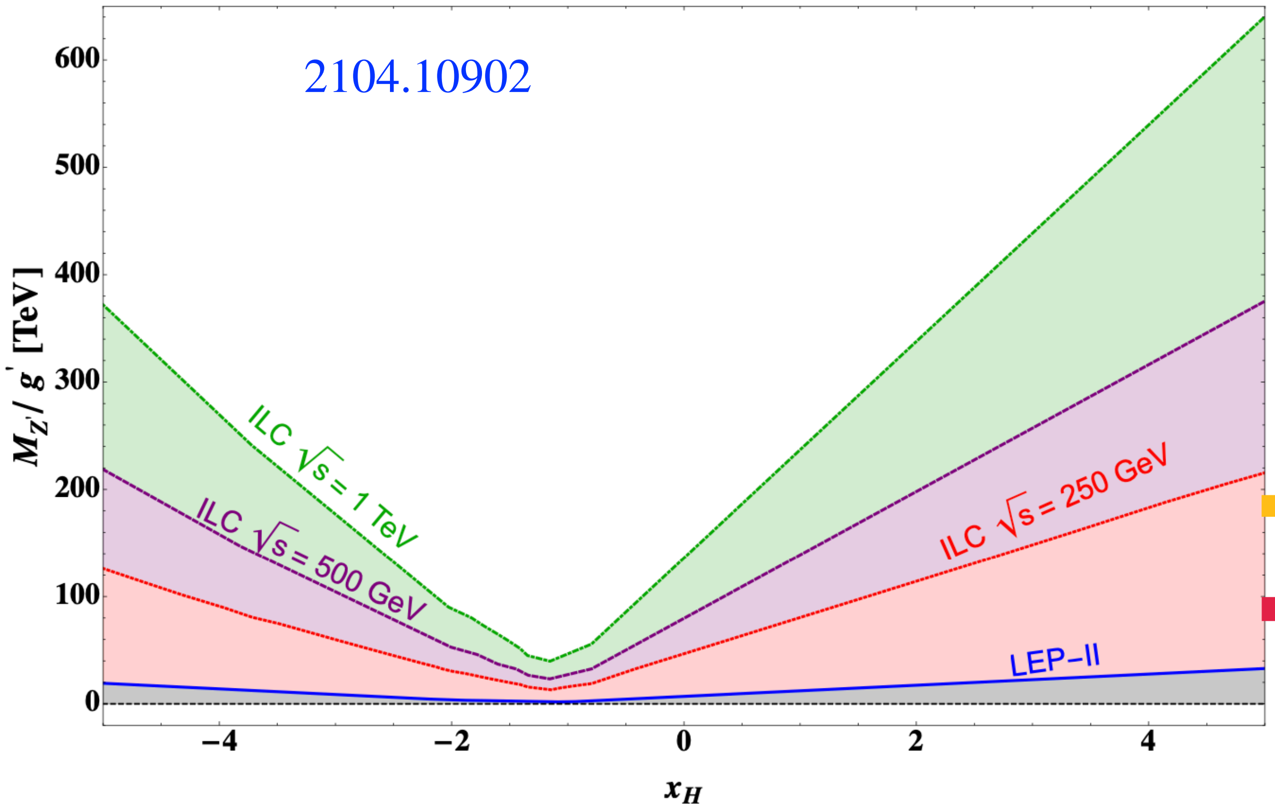
$M_{N_1} = 500$ GeV $\quad M_{N_3} = 2$ TeV $\quad M_{N_2} = 1$ TeV





Limits on the model parameters

Considering the limit $M_{Z'} >> \sqrt{s}$ and appling effective theory we find the limits on $\frac{M_{Z'}}{g'}$ using LEP – II (1302.3415) and (prospective) ILC (1908.11299) :



$$\frac{\pm 4\pi}{(1+\delta_{ef})(\Lambda_{AB}^{f\pm})^2}(\bar{e}\gamma_\mu P_A e)(\bar{f}\gamma_\mu P_B f)$$

Z' exchange matrix element for our process

$$\frac{(g')^2}{{M_{Z'}}^2 - s}[\bar{e}\gamma_\mu(x_\ell{}' P_L + x_e{}' P_R)e][\bar{f}\gamma_\mu(x_{f_L}P_L + x_{f_R}P_R)f]$$

Matching the above equations :

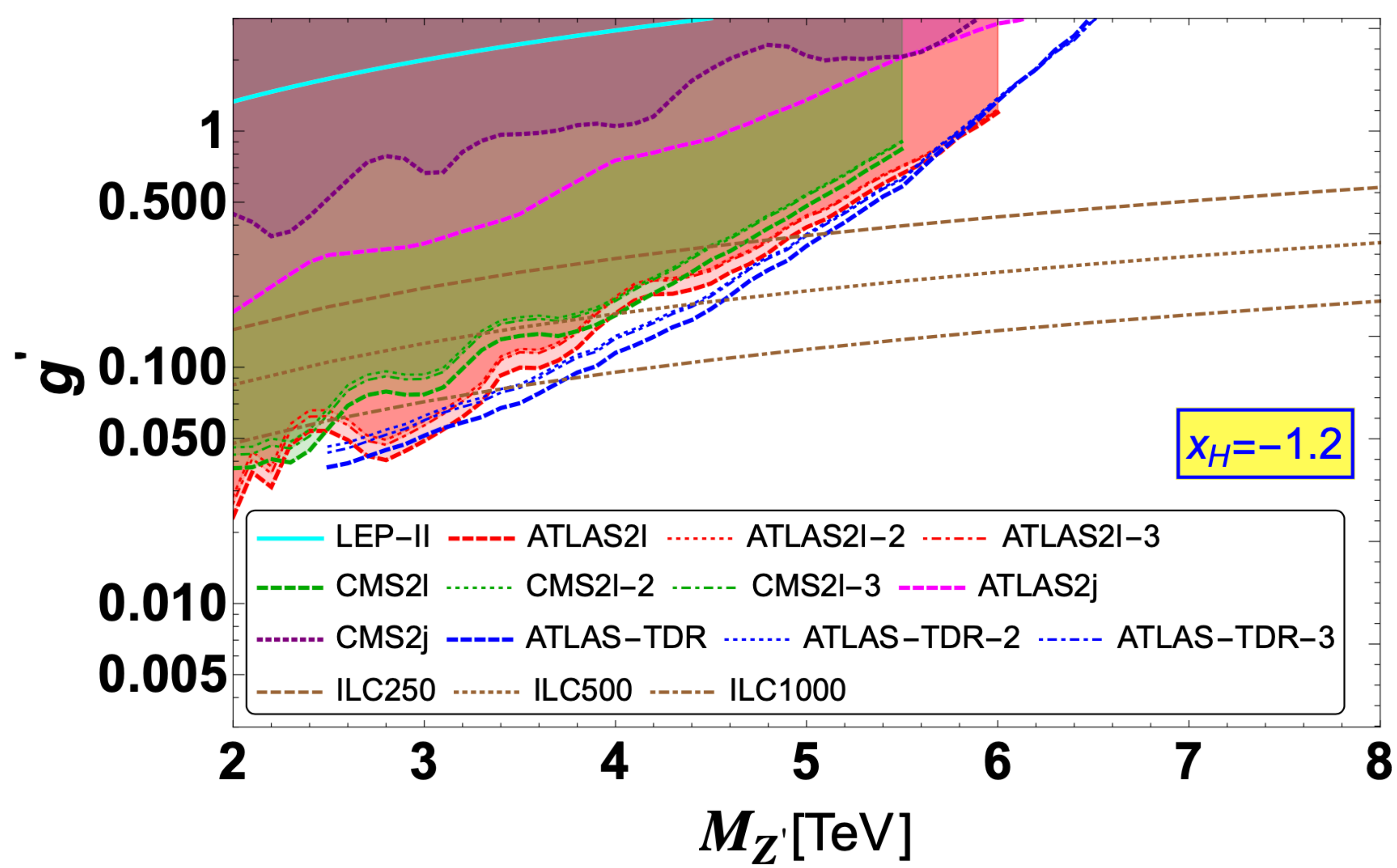
$$M_{Z'}^2 - s \geq \frac{{g'}^2}{4\pi}|x_{e_A}x_{f_B}|(\Lambda_{AB}^{f\pm})^2$$

Indicates a large VEV scale can be probed from LEP – II to ILC1000 via ILC250 and ILC500

Shows limits on $M_{Z'}$ vs g' for LEP – II, ILC250, ILC500 and ILC1000

Limits on $M_{Z'}$ and g' can also be obtained from dilepton and dijet searches at the LHC

$$g' = \sqrt{g_{\rm Model}^2\left(\frac{\sigma_{\rm ATLAS}^{\rm Obs.}}{\sigma_{\rm Model}}\right)}$$



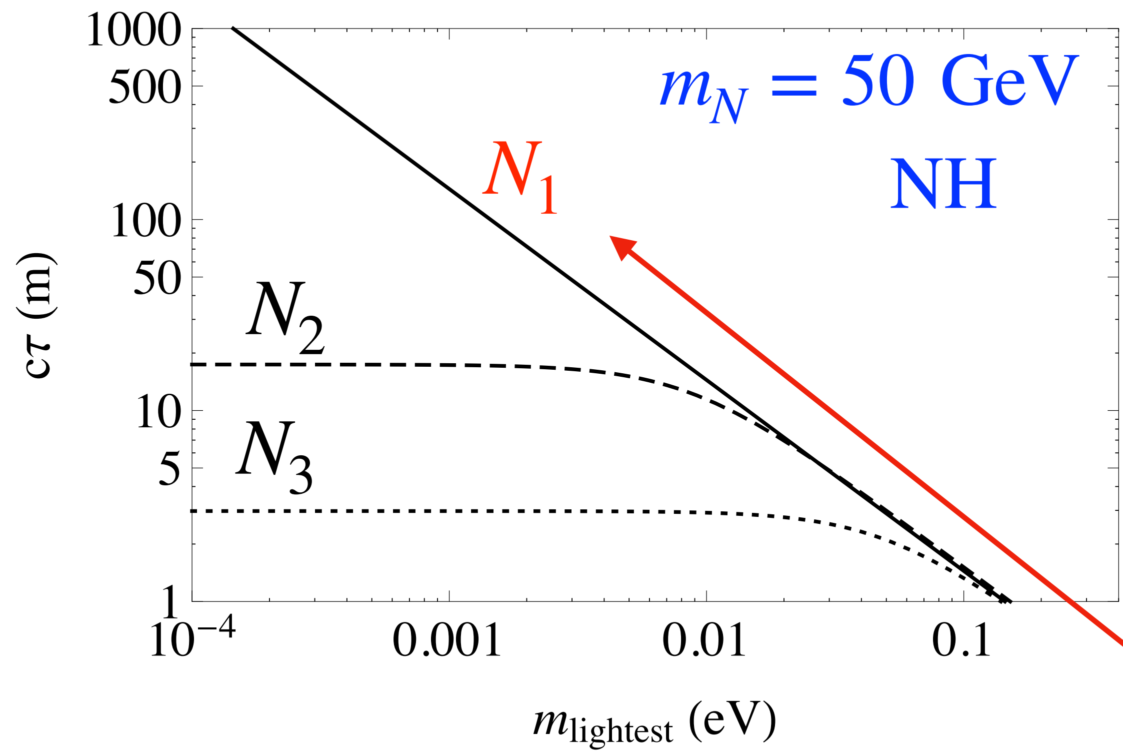
ATLAS2l/CMS2l/ATLAS – TDR : $M_N > \frac{M_{Z'}}{2}$

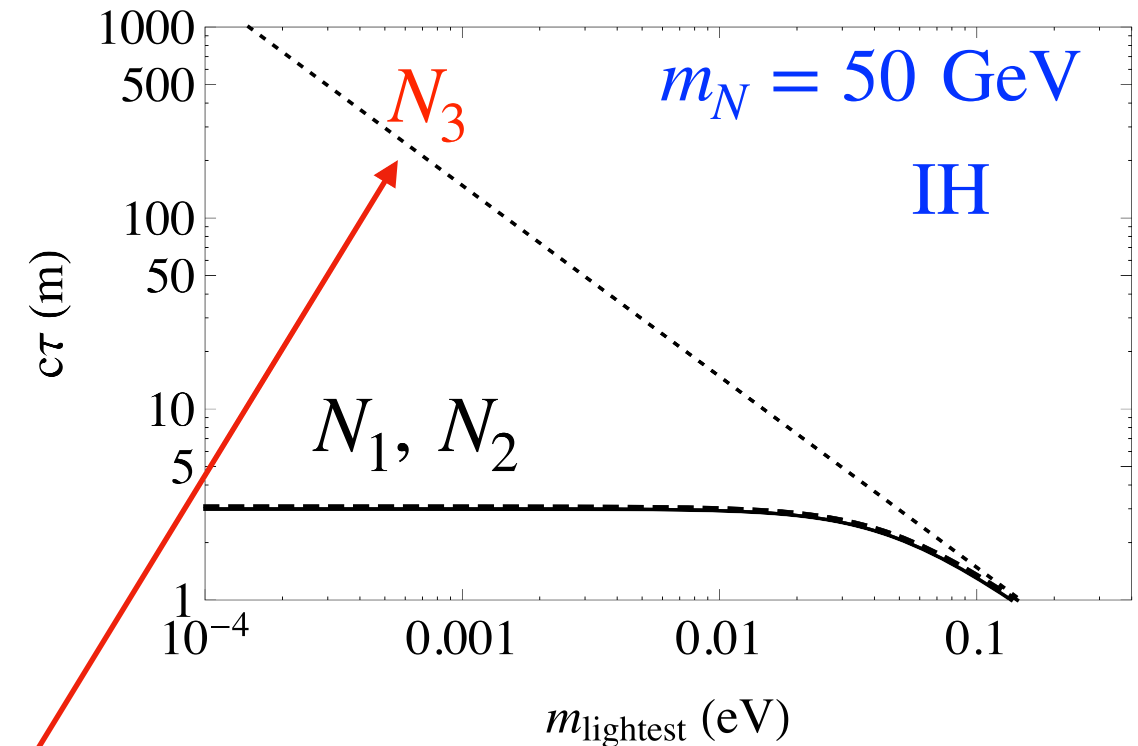
ATLAS2l – 1/CMS2l – 1/ATLAS – TDR – 1 : M_N = 500GeV

ATLAS2l – 2/CMS2l – 2/ATLAS – TDR – 2 : M_N = 1000GeV

Long lived RHNs

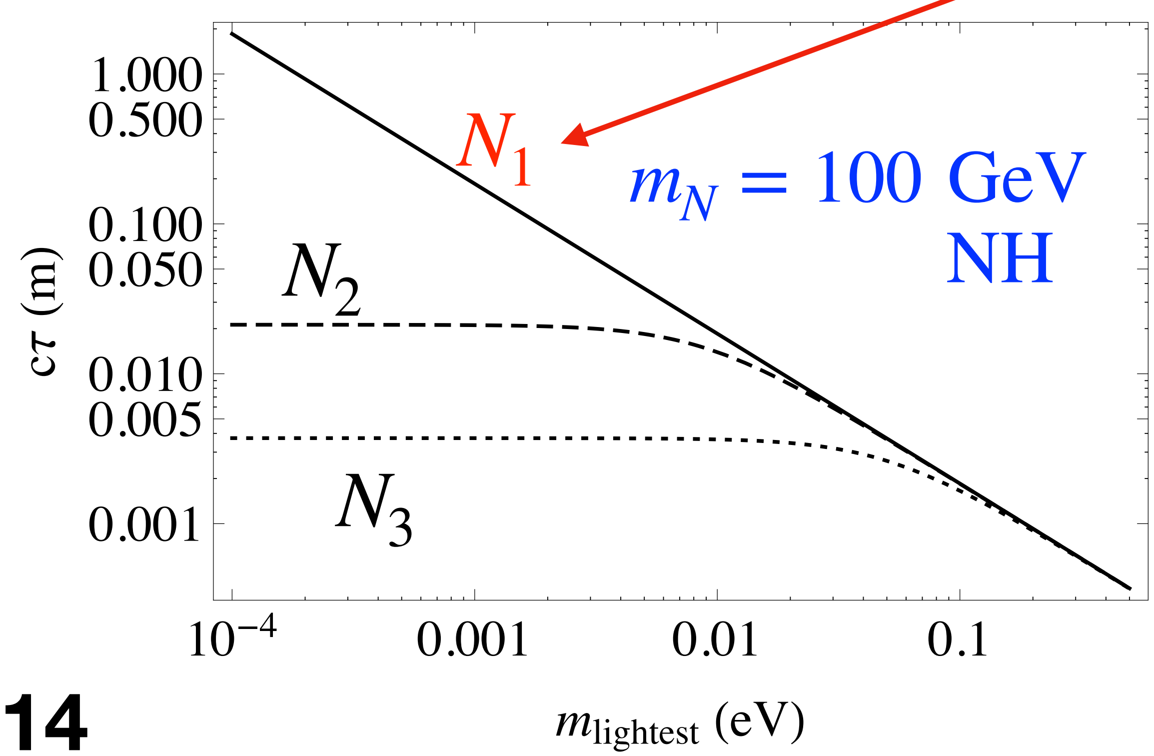
$B-L$ case, $x_H = 0$

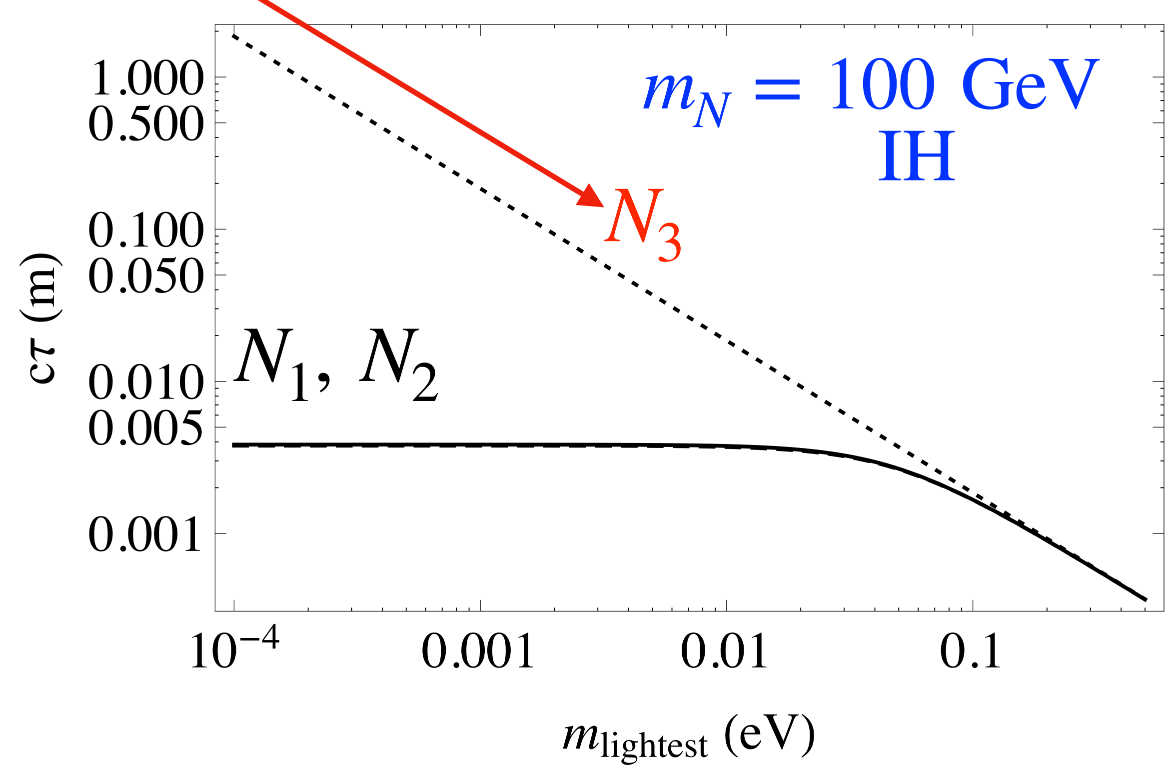




Longest lived RHN life time is inversely proportional to $m_{lightest}$

$m_{lightest} \to 0$ leads to the long lived species as a potential DM candiadte





Type – III seesaw

SM + $SU(2)_L$ triplet fermion

Franceschini, Hambye, Strumia Biggio, Bonnet
Biggio, Fernandez Martinez, Hernandez Garcia, Lopez Pavon
AD, Mandal, Modak 2005.02267 AD, Mandal 2006.04123

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}(\overline{\Psi} i\gamma^\mu D_\mu \Psi) - \frac{1}{2} M \,{\rm Tr}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - \sqrt{2}(\overline{\ell_L} Y_D^\dagger \Psi H + H^\dagger \overline{\Psi} Y_D \ell_L)$$

$$\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \text{ and } \Psi^c = \begin{pmatrix} \Sigma^{0c}/\sqrt{2} & \Sigma^{-c} \\ \Sigma^{+c} & -\Sigma^{0c}/\sqrt{2} \end{pmatrix}$$

$$-\mathcal{L}_{\rm mass} = \begin{pmatrix} \overline{e}_L & \overline{\Sigma}_L \end{pmatrix} \begin{pmatrix} m_\ell & Y_D^\dagger v \\ 0 & M \end{pmatrix} \begin{pmatrix} e_R \\ \Sigma_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\Sigma_R^0} \end{pmatrix} \begin{pmatrix} 0 & Y_D^T \frac{v}{\sqrt{2}} \\ Y_D \frac{v}{\sqrt{2}} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_R^{0c} \end{pmatrix} + h.c.$$

$$m_\nu \simeq -\frac{v^2}{2} Y_D^T M^{-1} Y_D = M_D M^{-1} M_D^T$$

$$\Gamma(\Sigma^\pm \to \nu W) = \frac{g^2 |V_{\ell\Sigma}|^2}{32\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell h) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \pi^\pm) = \frac{2 G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e) = \frac{2 G_F^2 \Delta M^5}{15\pi}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \mu \nu_\mu) = 0.12\,\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e)$$

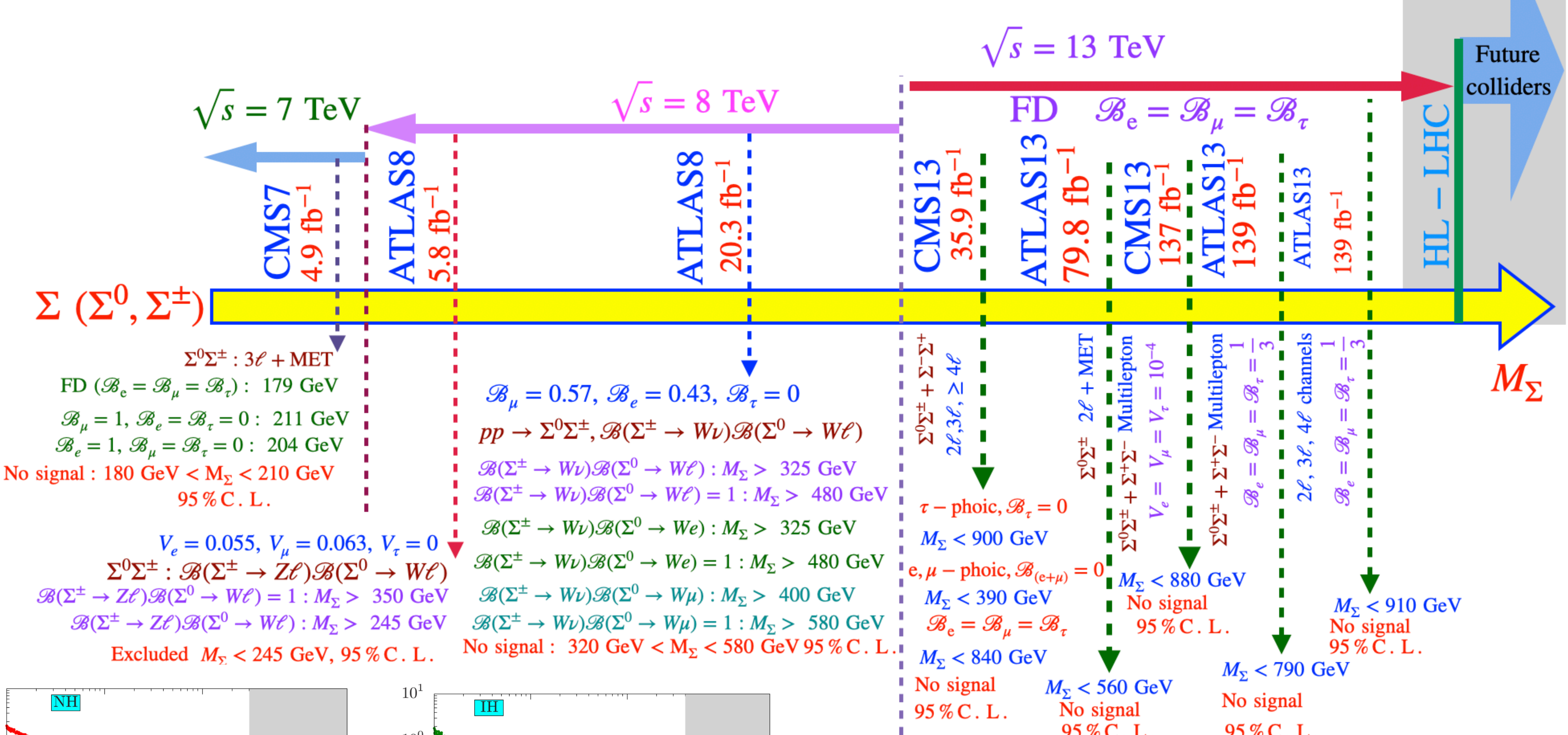
$$\Gamma(\Sigma^0 \to \ell^+ W) = \Gamma(\Sigma^0 \to \ell^- W) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

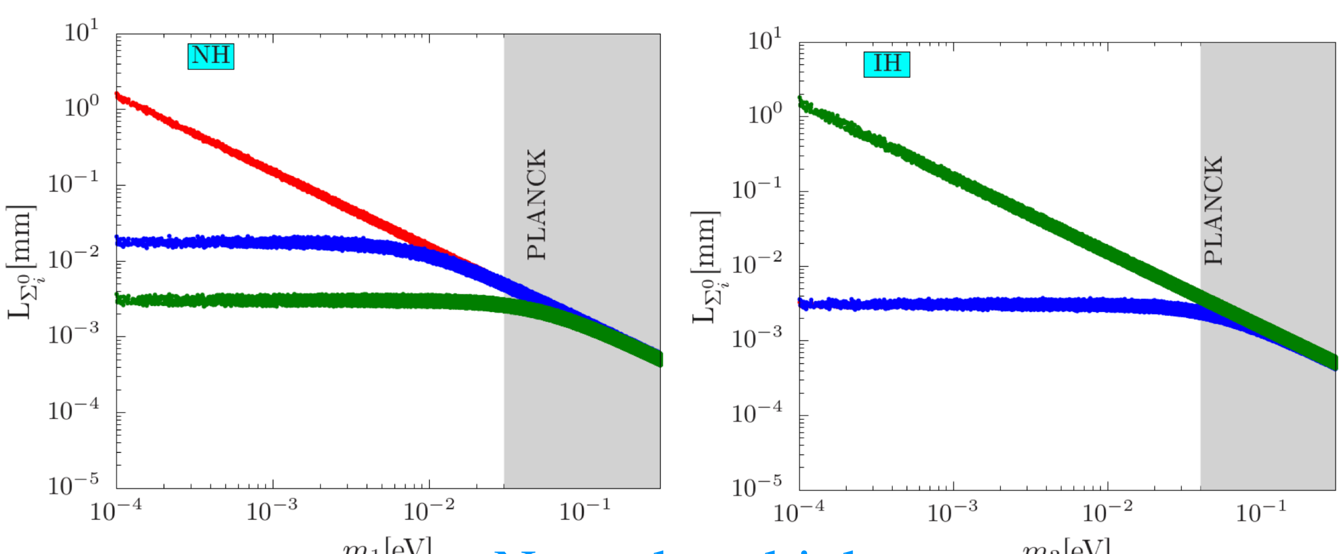
$$\Gamma(\Sigma^0 \to \nu Z) = \Gamma(\Sigma^0 \to \overline{\nu} Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^0 \to \nu h) = \Gamma(\Sigma^0 \to \overline{\nu} h) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

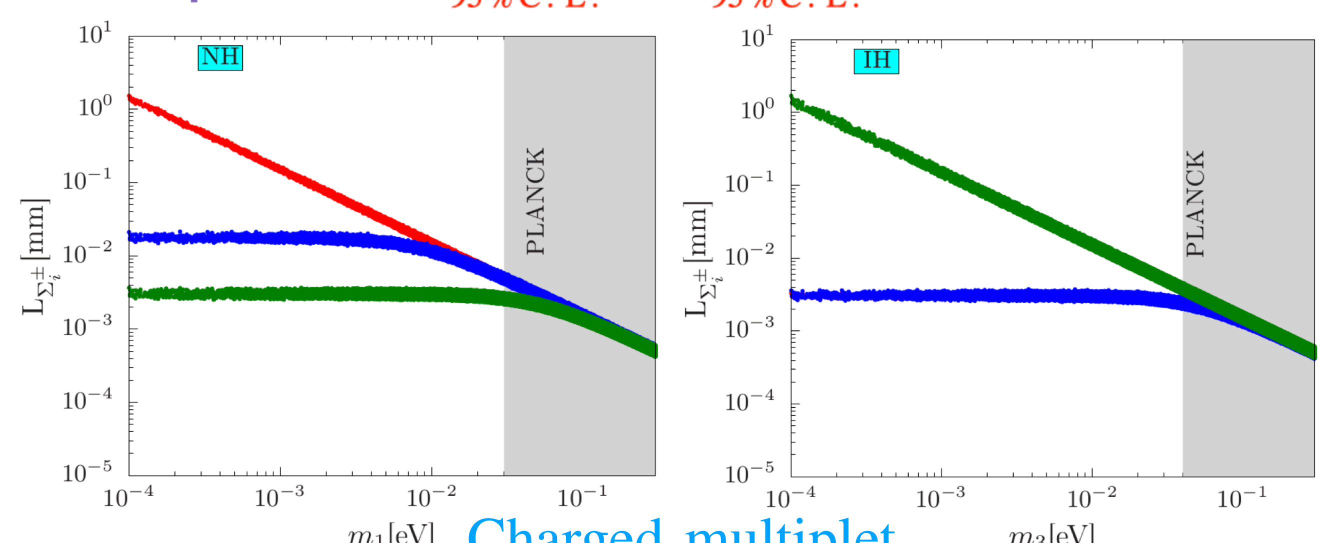
Experimental limits from ATLAS and CMS on type − III seesaw

2006.04123





Neutral multiplet

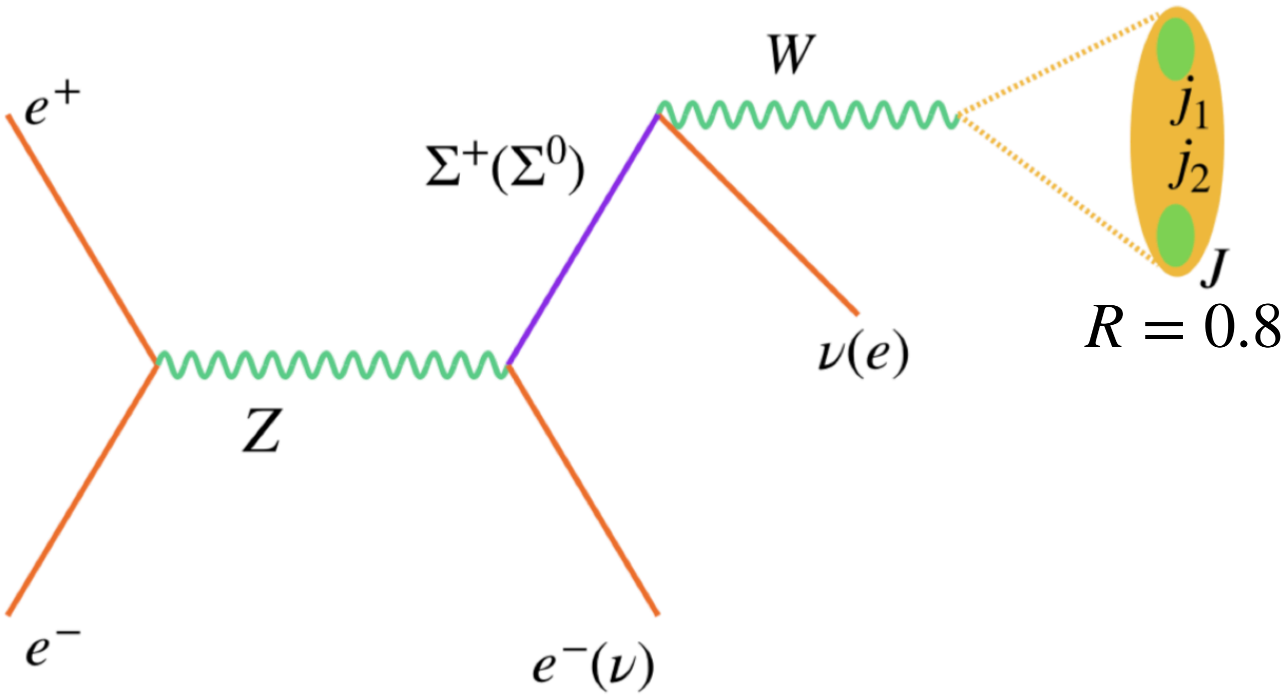


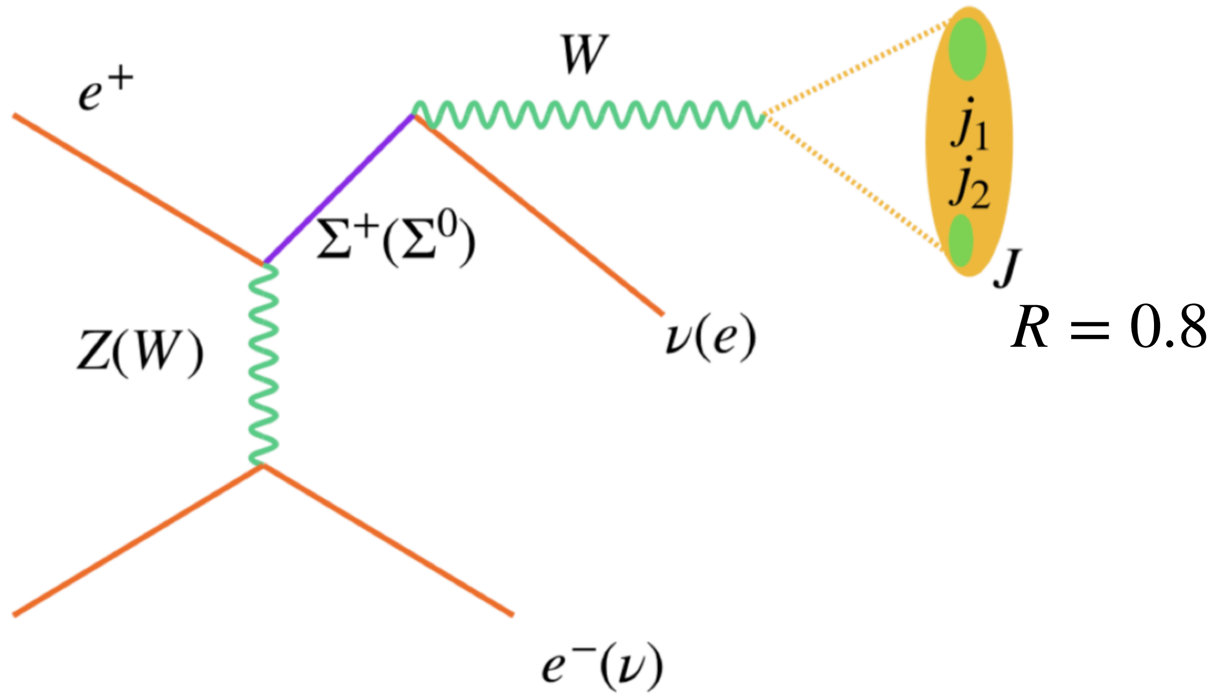
Charged multiplet

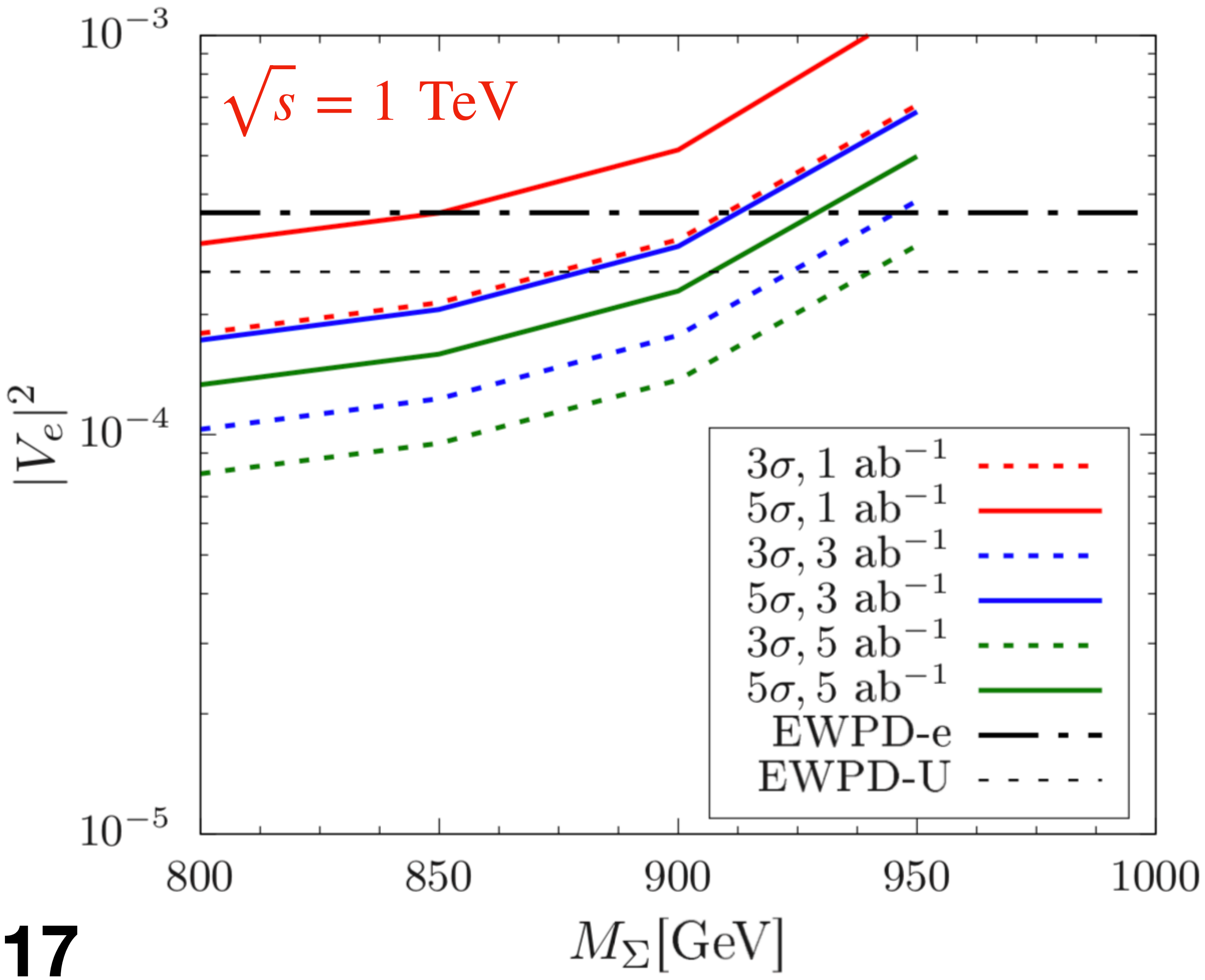
Lower in $m_{lightest}$ increases L by (1 − 2) oreders of magnitude upto a steady value .

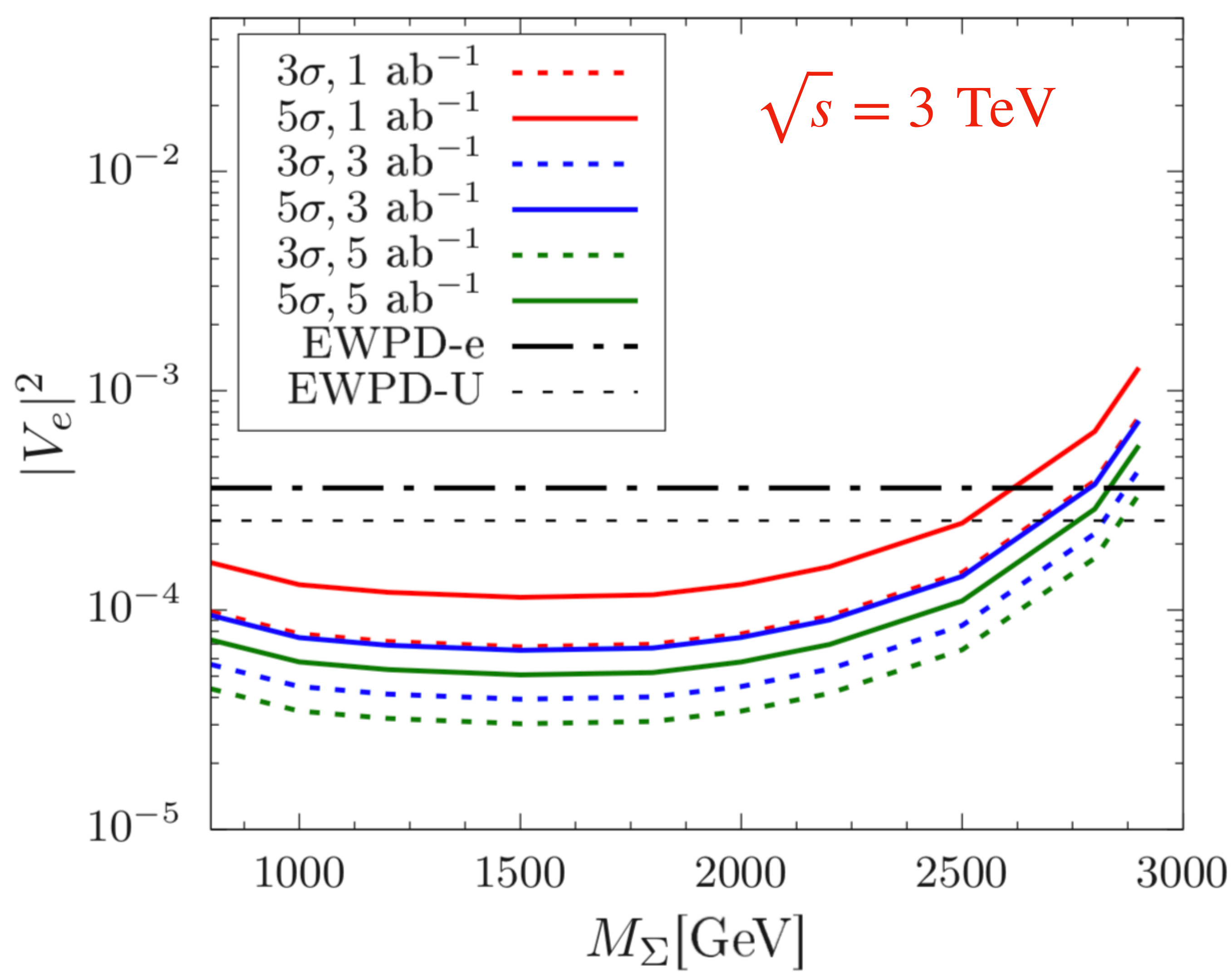
Mass-mixing limit plots

2005.02267





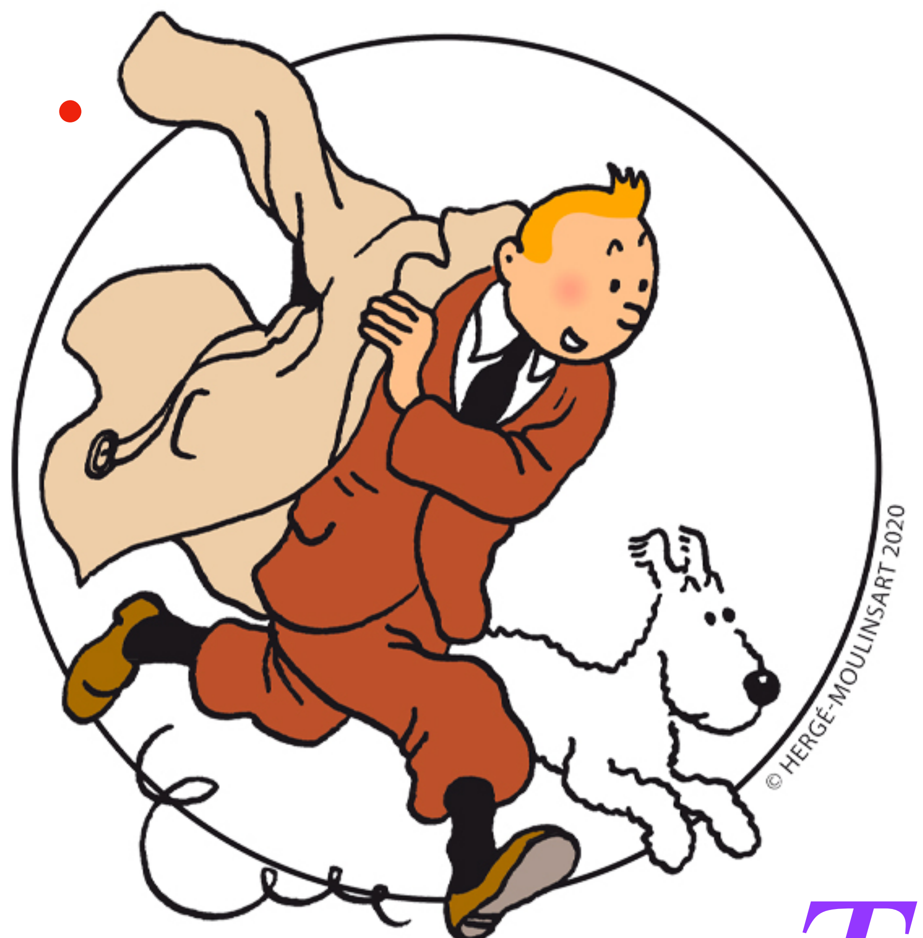




Summary

We study the models with the heavy fermions under the simple extensions of the SM where the neutrino mass is generated by the seesaw mechanism at the tree level to reproduce the neutrino oscillation data.

Stay tuned . . .

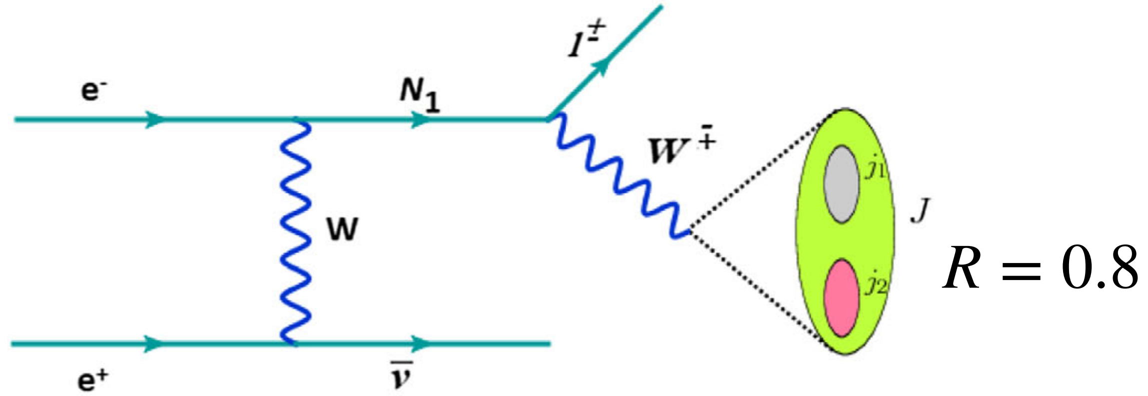


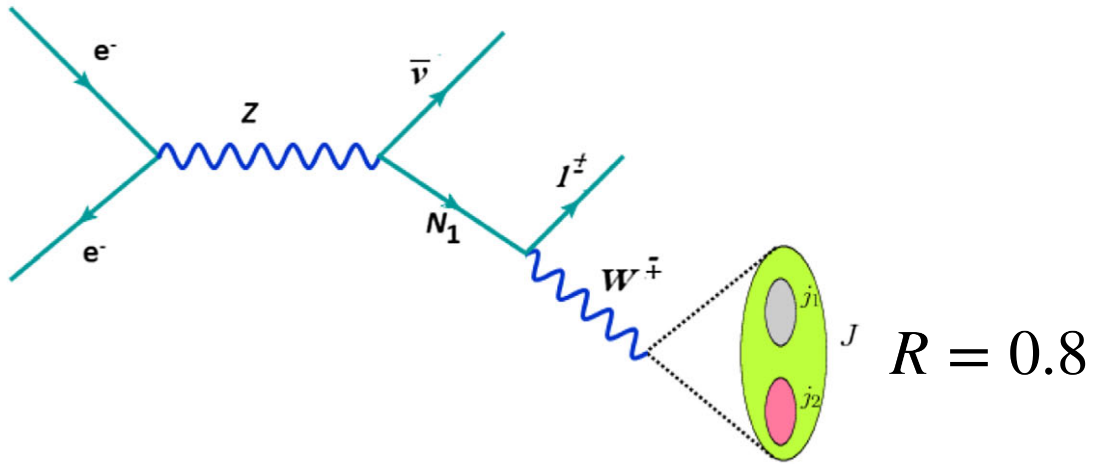
Thank You

We find that such heavy fermions can be tested at the underground experiments- at the proton-proton, electron-positron and electron-proton colliders in the near future. We have calculated the bounds on the light-heavy mixings for the electron-positron collider which could be probed in the near future.

Back – up slides

$e + J + p_T^{\rm miss}$ final states at the linear colliders.





- Transverse momentum for fat-jet $p_T^J > 150$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^J > 250$ GeV for M_N mass range 700 GeV-900 GeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 100$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^{e^\pm} > 200$ GeV for M_N mass range 700 GeV-900 GeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

1 TeV e^-e^+ collider

- Transverse momentum for fat-jet $p_T^J > 250$ GeV for the M_N mass range 700 GeV-900 GeV and $p_T^J > 400$ GeV for M_N mass range $1 - 2.9$ TeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 200$ GeV for M_N mass range $700 - 900$ GeV and $p_T^{e^\pm} > 250$ GeV for M_N mass range $1 - 2.9$ TeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

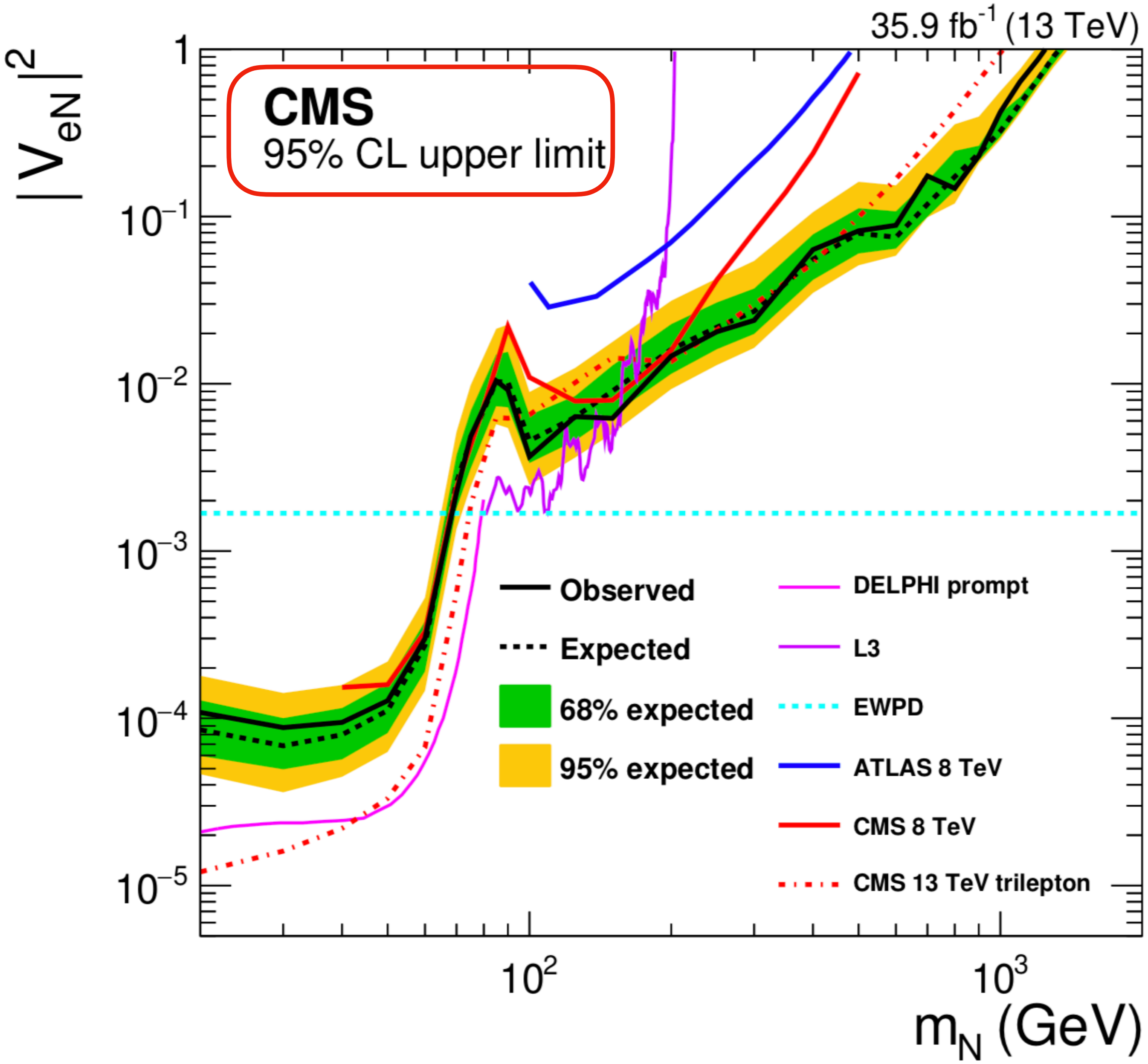
3 TeV e^-e^+ collider

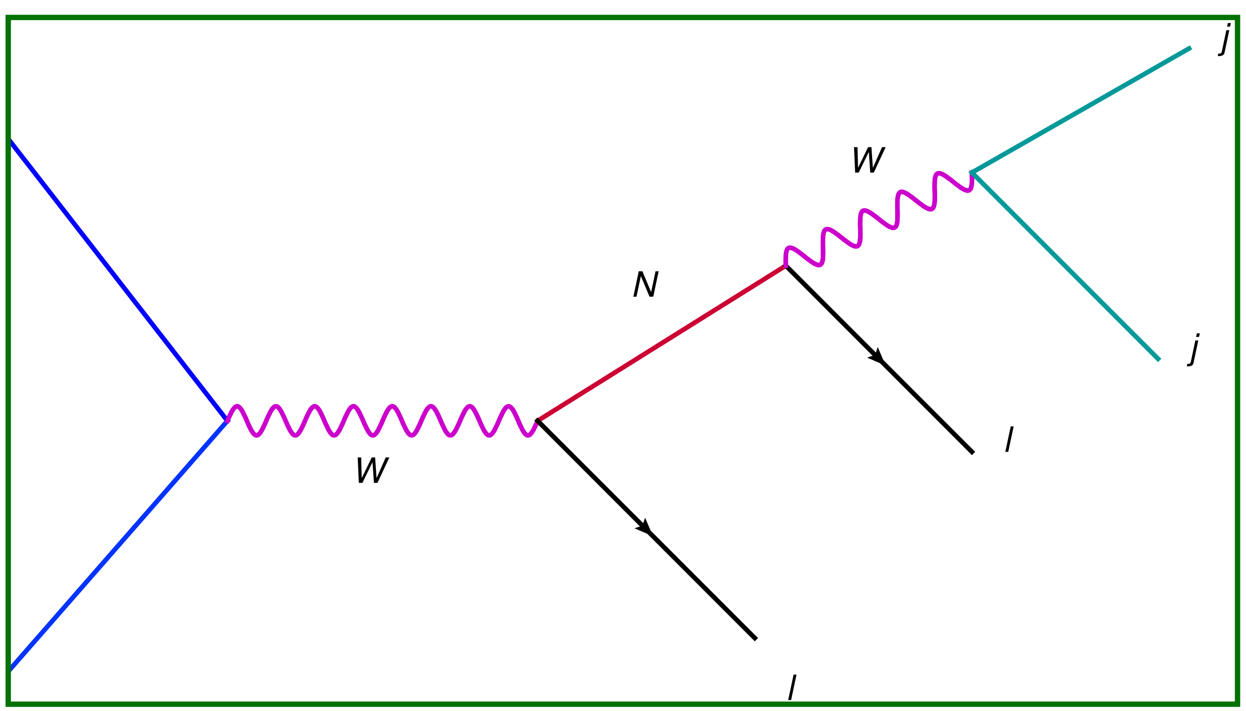
Experimental limits

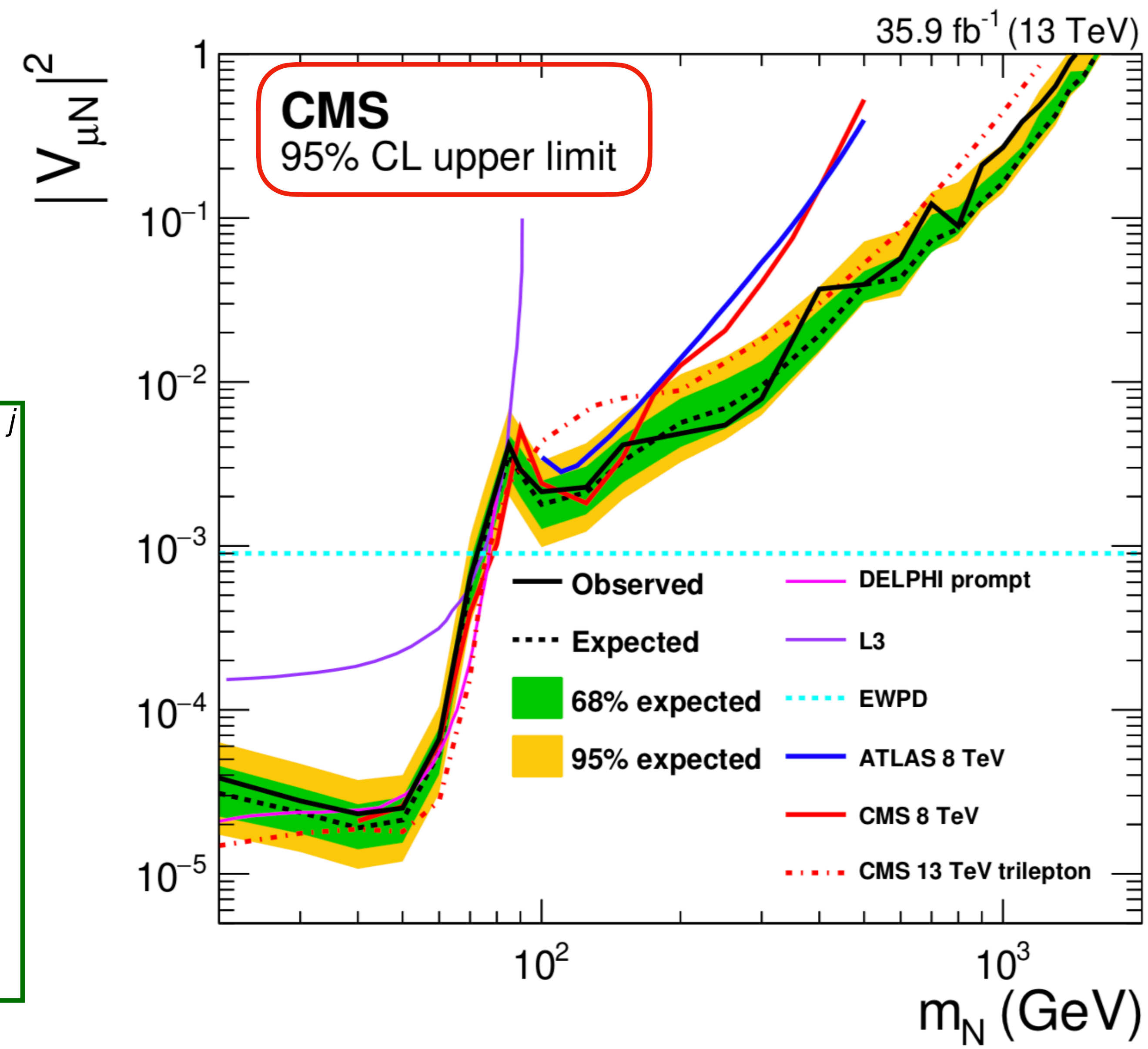
$\ell^\pm \ell^\pm + \text{jets}$

CMS

1806.10905 13 TeV, 35.9 fb^{-1}

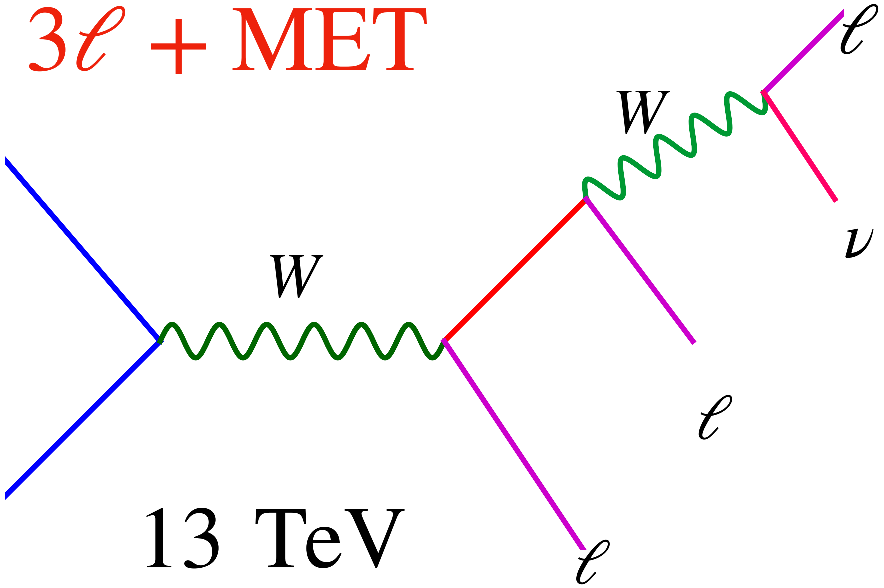




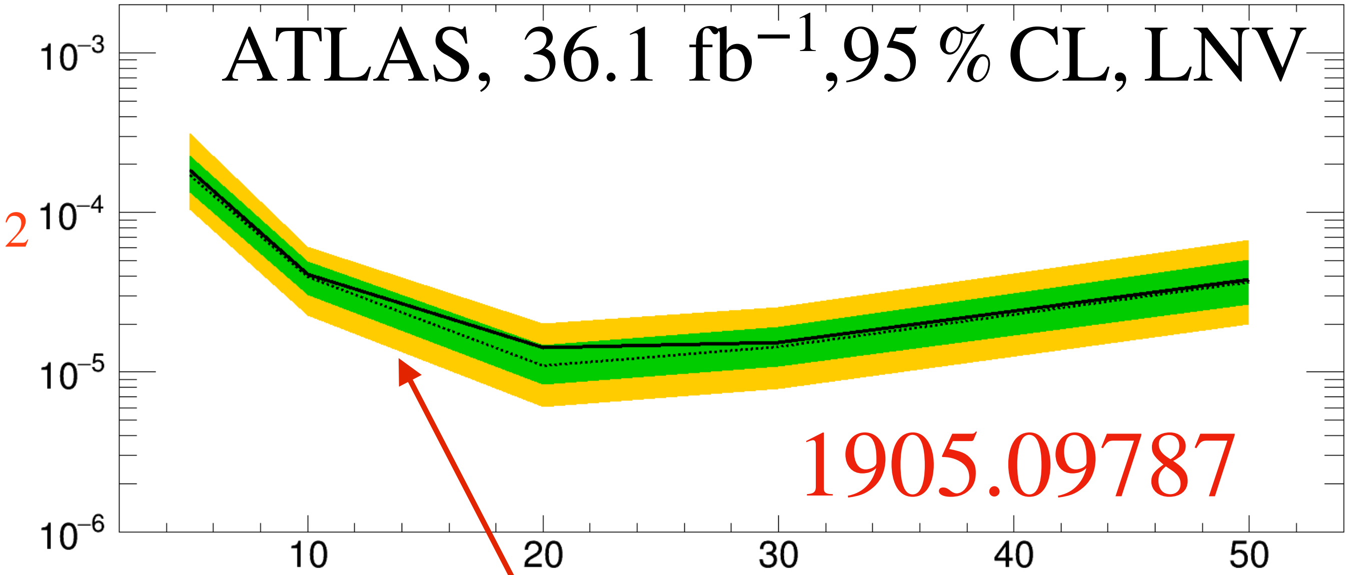


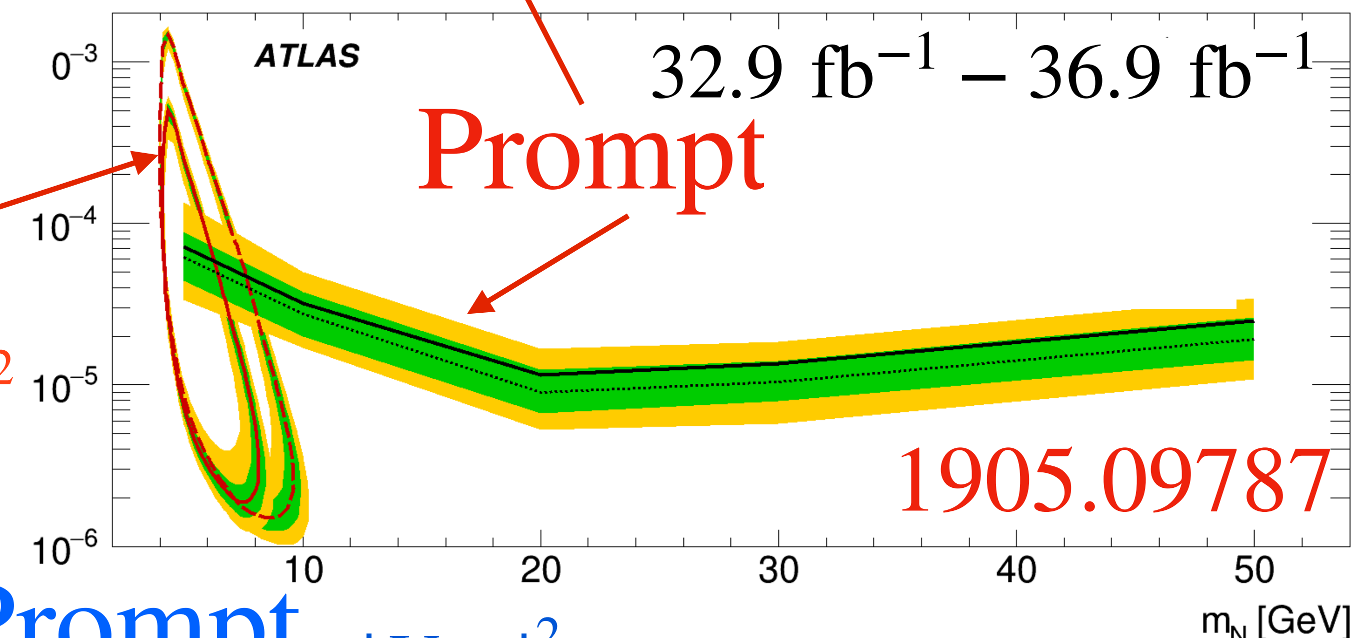
Experimental limits

3ℓ + MET



13 TeV





Prompt

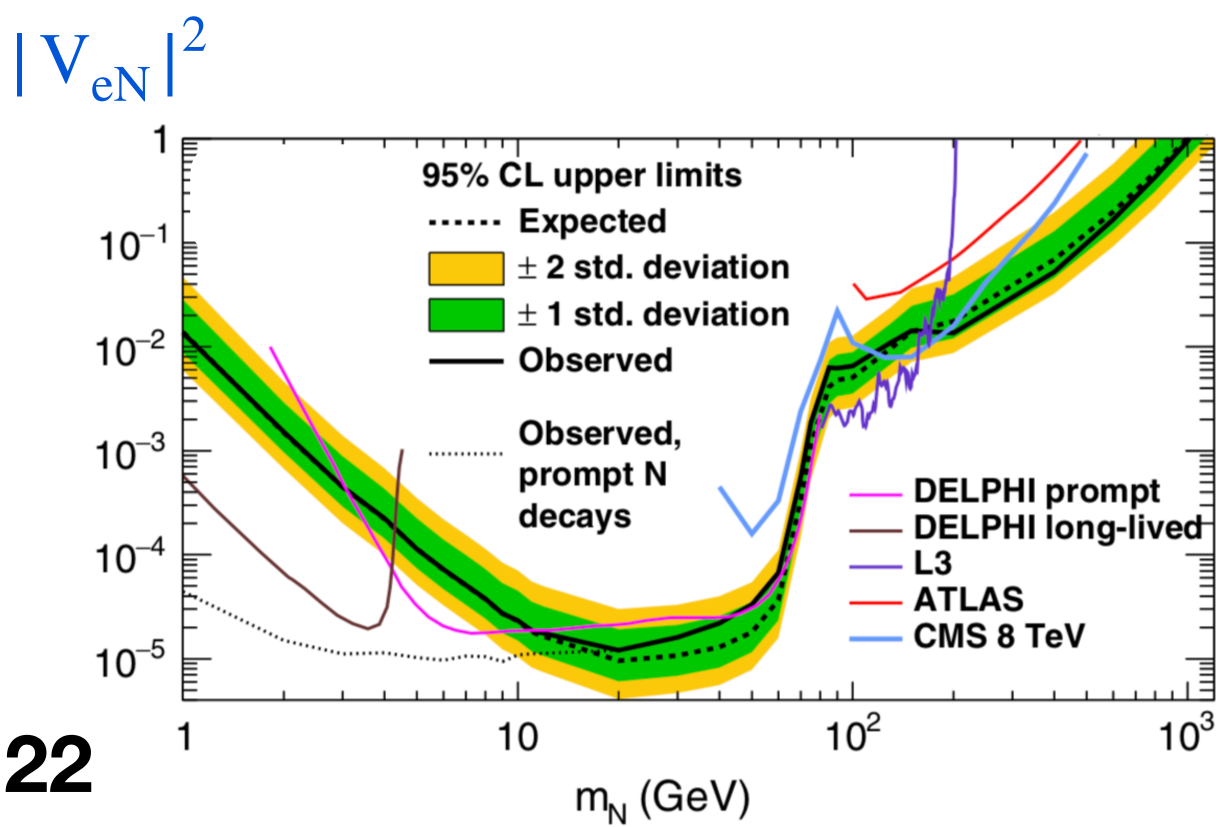
Displaced

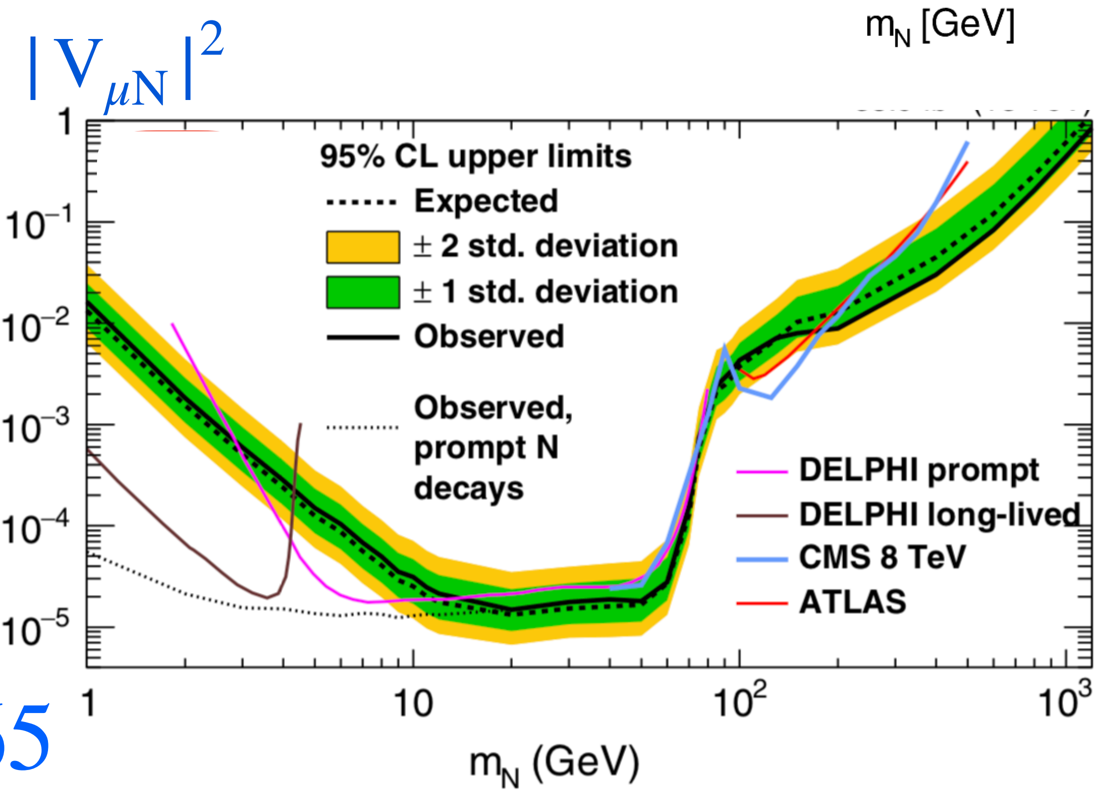
LNV

LNC

Prompt

CMS





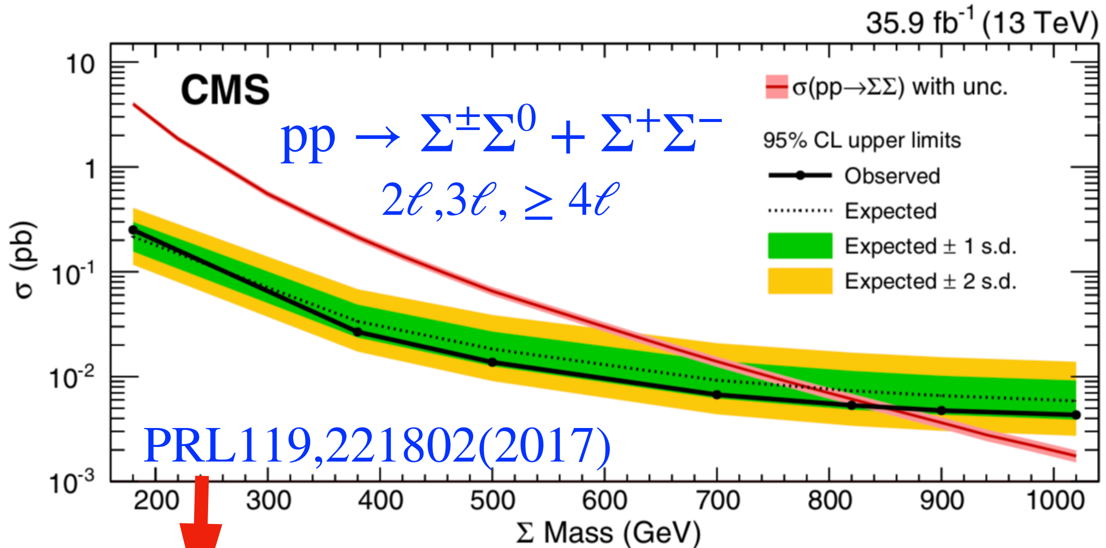
35.9 fb^{-1}

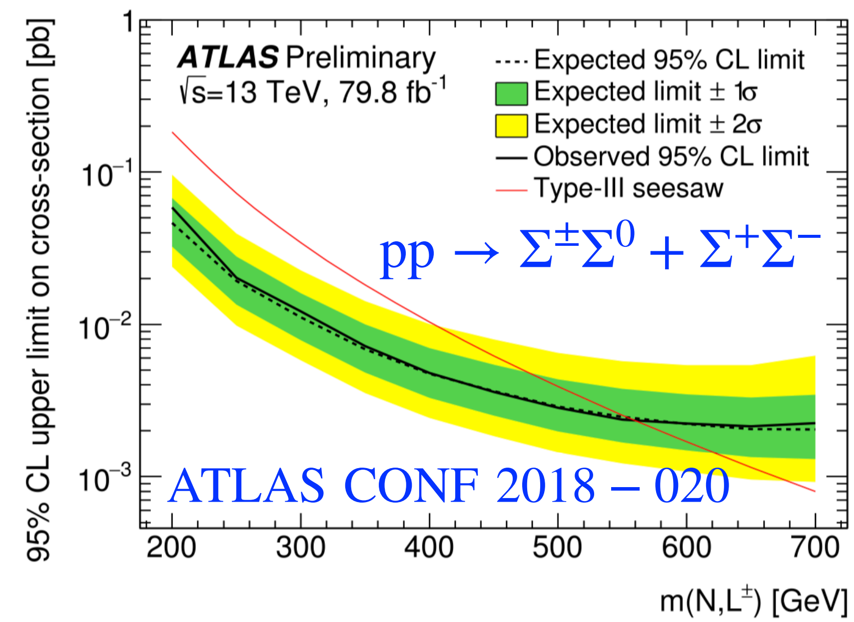
1802.02965

LHC limits

$$\mathrm{BR} = B_\ell \propto \frac{|V_\ell|^2}{|V_e|^2 + |V_\mu|^2 + |V_\tau|^2}$$

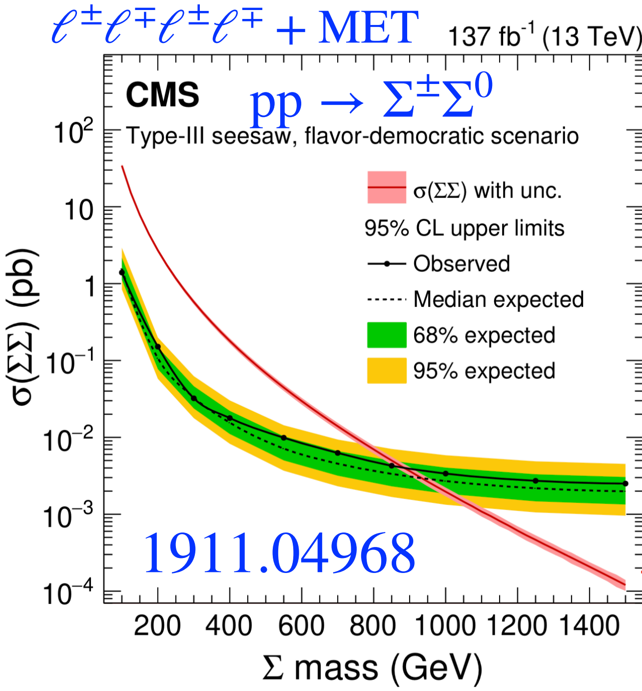
$B_e = B_\mu = B_\tau$
Flavor – democratic scenario



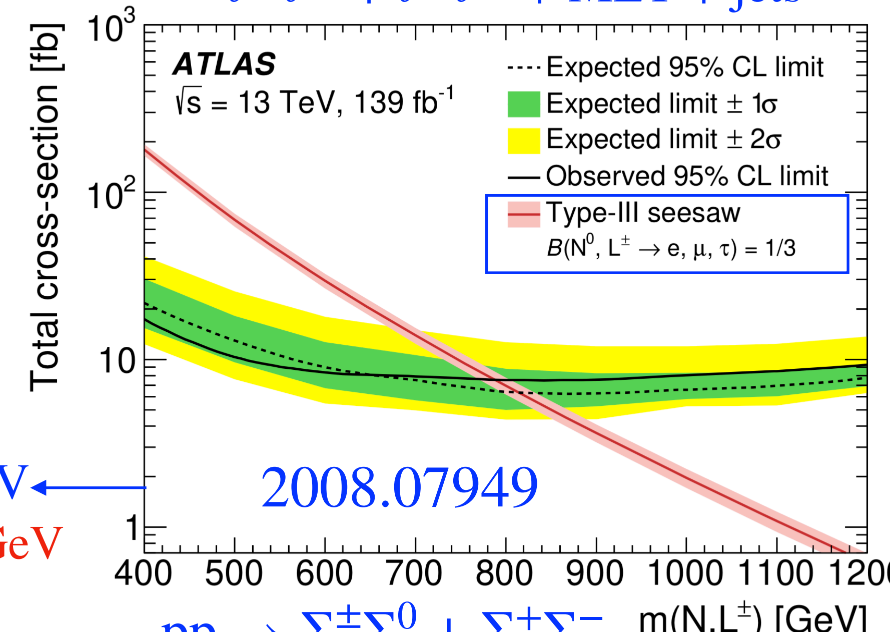


τ – phoic, $B_\tau = 0, M_\Sigma = 900$ GeV, 90 % CL
(e, μ) – phoic, $B_{e+mu} = 0, M_\Sigma = 390$ GeV, 90 % CL

$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$ + MET



$\ell^\pm\ell^\pm + \ell^\mp\ell^\pm$ + MET + jets



$M_\Sigma \leq 800$ GeV

$M_\Sigma \leq 900$ GeV

$pp \to \Sigma^\pm\Sigma^0 + \Sigma^+\Sigma^-$