Possibility of a general U(1) extended theory and its implications

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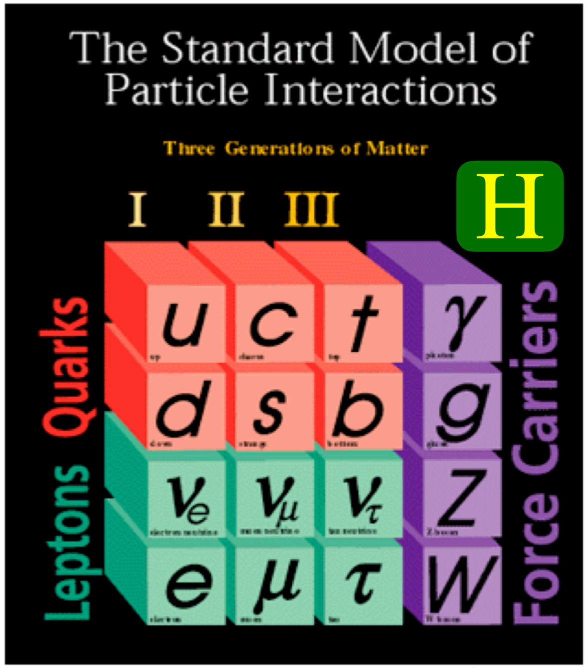
Introduction



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 → Neutrino oscillation experiment : SNO, Super – K, etc .

Relic abundance of dark matter . . .

Unkown ←
- Nature : Majorana/ Dirac
- Ordering : Normal/Inverted
- Nature of the mixing between the mass and the flavor eigenstates

SM can not explain them

Particle Content

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

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

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

$$m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h \qquad m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

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

Seesaw mechnism

Higgs potential

$$V = m_h^2(H^\dagger H) + \lambda(H^\dagger H)^2 + m_\Phi^2(\Phi^\dagger\Phi) + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda'(H^\dagger H)(\Phi^\dagger\Phi)$$

$U(1)_X$ breaking Electroweak breaking

$$\langle\Phi\rangle = \frac{v_\Phi + \phi}{\sqrt{2}} \qquad \langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v+h \\ 0 \end{pmatrix} \qquad v \simeq 246\,\mathrm{GeV},\, v_\Phi >> v_h$$

Mass of the neutral gauge boson Z'

$$M_{Z'} = g'\sqrt{4v_\Phi^2 + \frac{1}{4}x_H^2 v_h^2} \simeq 2g' v_\Phi.$$

Neutrino masss

$$\mathscr{L}^{\mathrm{mass}} = -Y_\nu^{\alpha\beta}\overline{\ell_L^\alpha} H N_R^\beta - Y_N^\alpha \Phi \overline{N_R^{\alpha c}} N_R^\alpha + \mathrm{h.c.}$$

$$m_{N_\alpha} = \frac{Y_N^\alpha}{\sqrt{2}} v_\Phi, \quad m_D^{\alpha\beta} = \frac{Y_\nu^{\alpha\beta}}{\sqrt{2}} v. \quad m_\nu^{\mathrm{mass}} = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix} \qquad m_\nu \simeq -m_D m_N^{-1} m_D^T$$

seesaw

Interaction between the quarks and Z′ $\mathcal{L}^q = -g'(\overline{q}\gamma_\mu q^q_{x_L} P_L q + \overline{q}\gamma_\mu q^q_{x_R} P_R q) Z'_\mu$

Interaction between the leptons and Z′ $\mathcal{L}^\ell = -g'(\overline{\ell}\gamma_\mu q^\ell_{x_L} P_L \ell + \overline{e}\gamma_\mu q^\ell_{x_R} P_R e) Z'_\mu$

Partial decay width

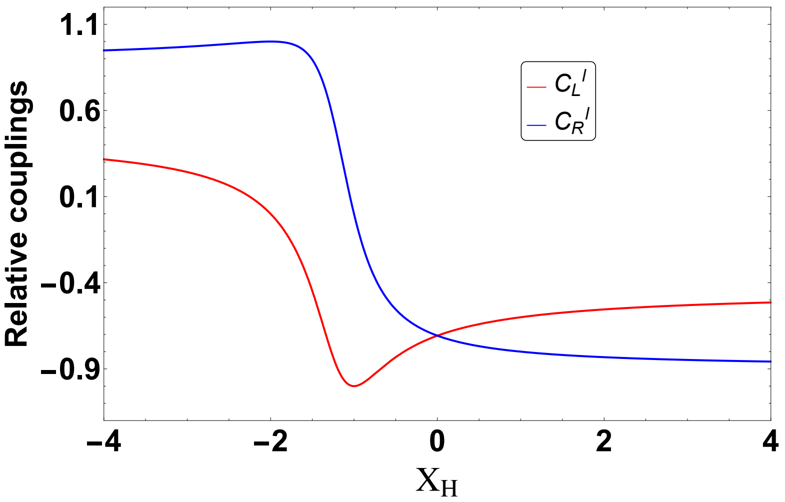
Charged fermions $\Gamma(Z' \to 2f) = N_c \frac{M_{Z'}}{24\pi} \left(g^f_L\Big[g', x_H, x_\Phi\Big]^2 + g^f_R\Big[g', x_H, x_\Phi\Big]^2 \right)$

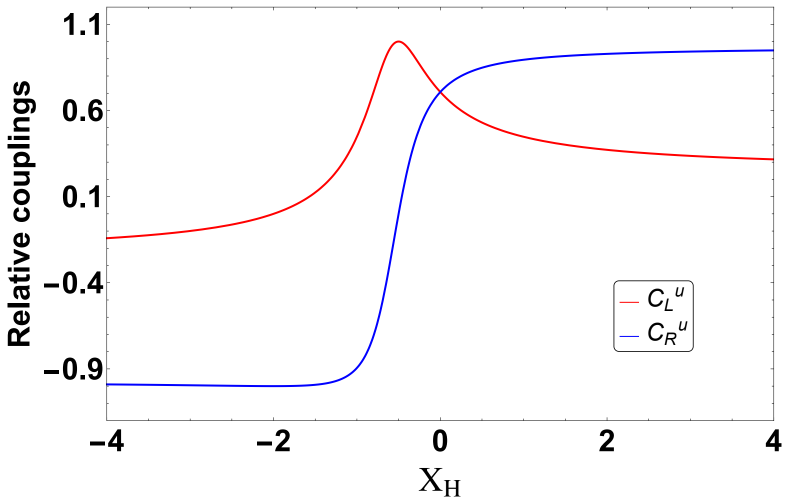
light neutrinos $\Gamma(Z' \to 2\nu) = \frac{M_{Z'}}{24\pi}\; g^\nu_L\Big[g', x_H, x_\Phi\Big]^2$

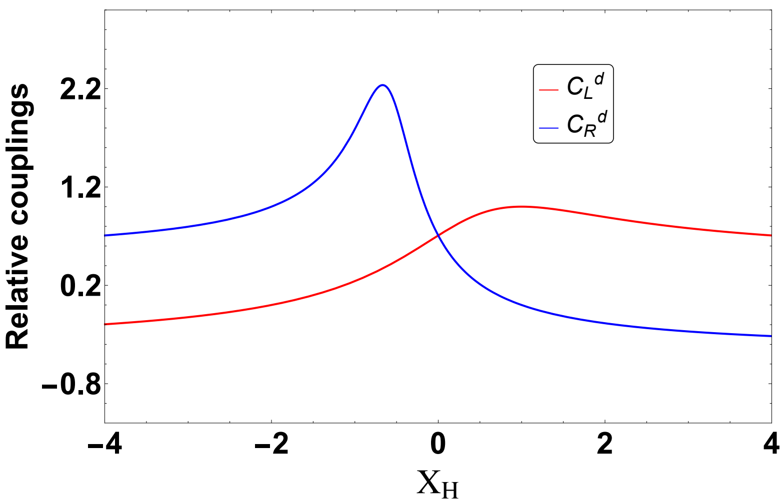
heavy neutrinos $\Gamma(Z' \to 2N) = \frac{M_{Z'}}{24\pi}\; g^N_R\Big[g', x_\Phi\Big]^2 \left(1 - 4\frac{m_N^2}{M_{Z'}^2}\right)^{\frac{3}{2}}$

We define the relative coplings $C_L^f = \frac{g_L^f[g', x_H, x_\Phi]}{\sqrt{g_L^f[g', x_H, x_\Phi]^2 + g_R^f[g', x_H, x_\Phi]^2}}$, $C_R^f = \frac{g_R^f[g', x_H, x_\Phi]}{\sqrt{g_L^f[g', x_H, x_\Phi]^2 + g_R^f[g', x_H, x_\Phi]^2}}$

$x_\Phi = 1$

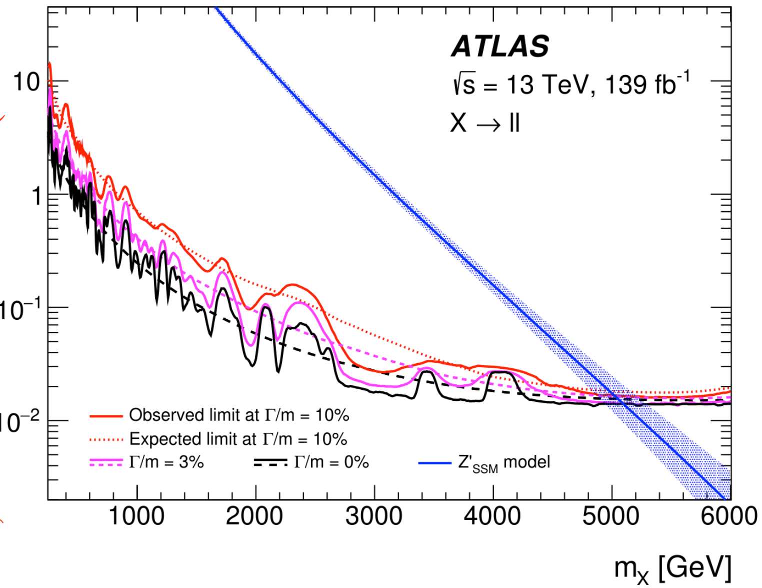




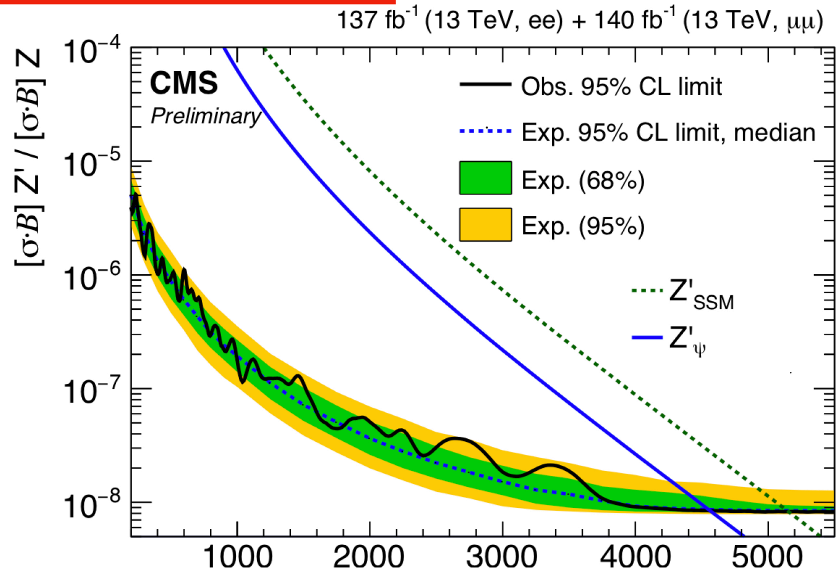


Recent bounds on the heavy Z' from dilepton channel

2ℓ, ATLAS : 1903.06248 (139 fb^{-1})

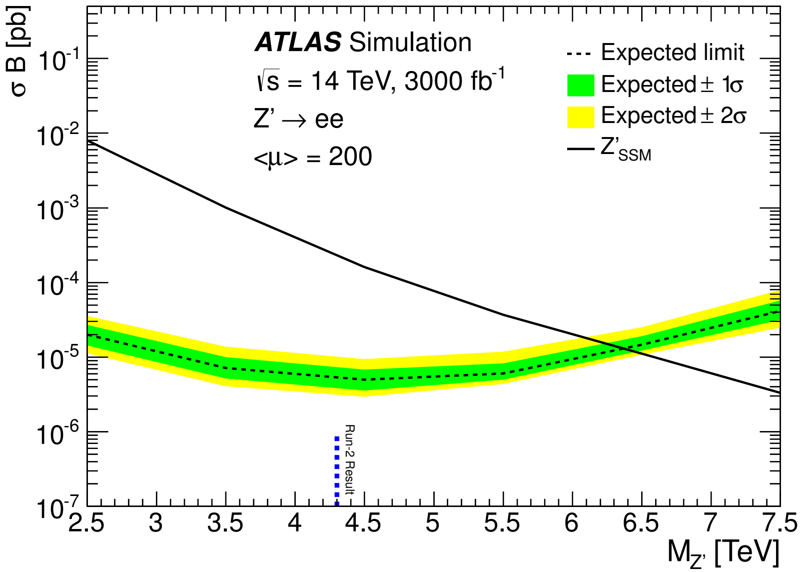


$$g' = \sqrt{\frac{\sigma^{\text{Observed}}_{\text{ATLAS/CMS}}}{\frac{\sigma_{\text{Model}}}{g^2_{\text{Model}}}}}$$

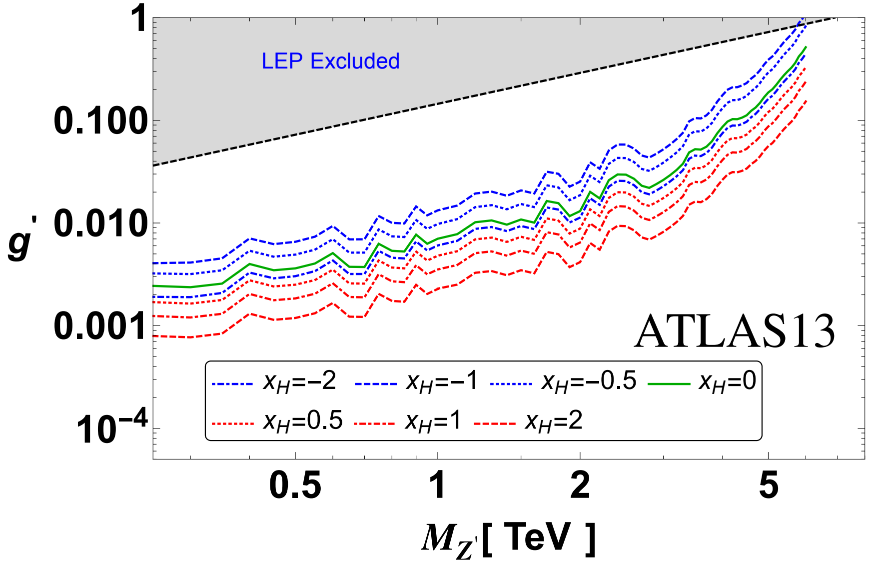


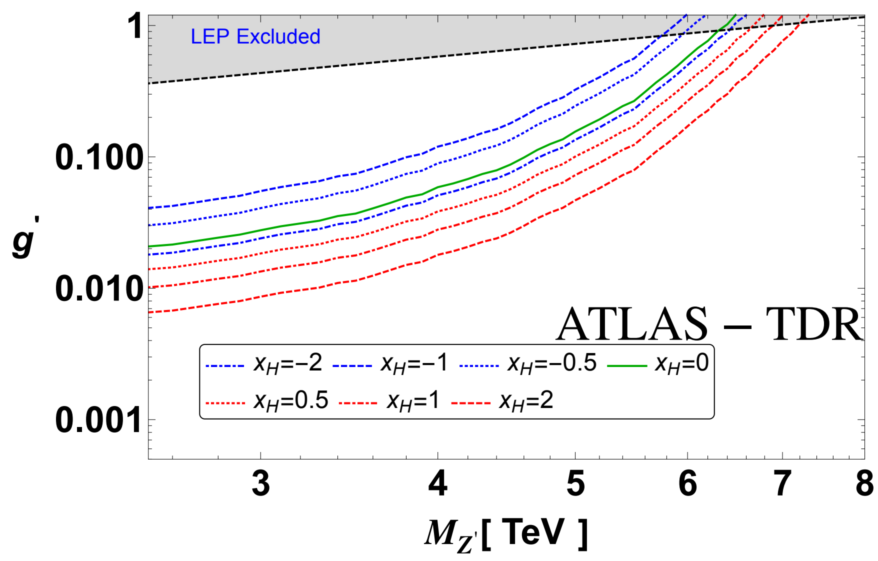
CMS PAS EXO − 19 − 019
ee(137 fb^{-1}) + $\mu\mu$(140 fb^{-1})

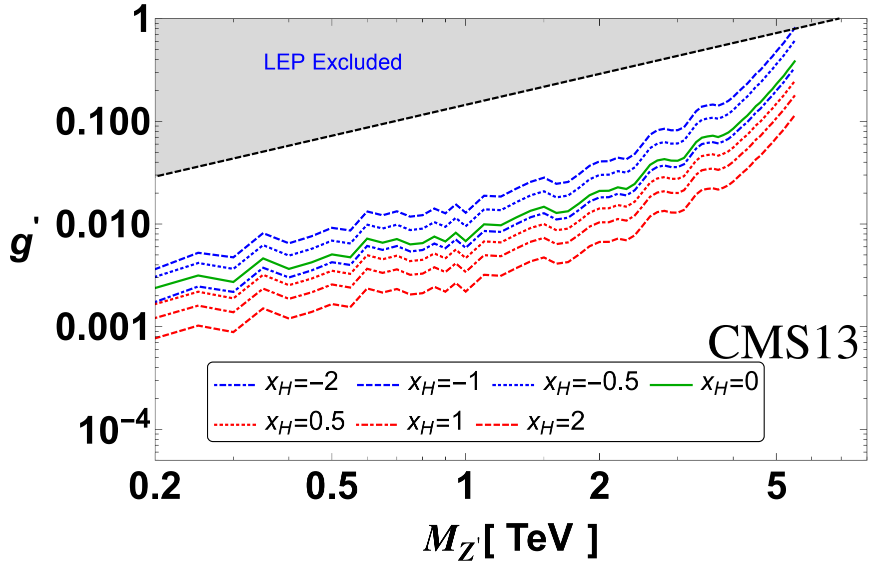
ATLAS − TDR − 027
ee (Prospective)



Limits on $g' - M_{Z'}$ plane







$$g' = \sqrt{\frac{\sigma^{\text{Observed}}_{\text{ATLAS/CMS}}}{\frac{\sigma_{\text{Model}}}{g^2_{\text{Model}}}}}$$

CMS PAS EXO − 19 − 019

ee(137 fb^{-1}) + $\mu\mu$(140 fb^{-1})

ATLAS : 1903.06248 (139 fb^{-1})

ATLAS − TDR − 027

LEP − II : arXiv : 1302.3415 [hep − ex]

Implications of the choices of x_H

No interaction with e_R

No interaction with d_R

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	-2 $U(1)_R$	-1	-0.5	0 B−L	0.5	1	2
q_L^i	**3**	**2**	$\frac{1}{6}$	$x'_q = \frac{1}{6}x_H + \frac{1}{3}x_\Phi$	0	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{5}{12}$	$\frac{1}{2}$	$\frac{1}{3}$
u_R^i	**3**	**1**	$\frac{2}{3}$	$x'_u = \frac{2}{3}x_H + \frac{1}{3}x_\Phi$	-1	$-\frac{1}{3}$	0	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{5}{3}$
d_R^i	**3**	**1**	$-\frac{1}{3}$	$x'_d = -\frac{1}{3}x_H + \frac{1}{3}x_\Phi$	1	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$	0	$-\frac{1}{3}$
ℓ_L^i	**1**	**2**	$-\frac{1}{2}$	$x'_\ell = -\frac{1}{2}x_H - x_\Phi$	0	$-\frac{1}{2}$	$-\frac{3}{4}$	-1	$\frac{5}{4}$	$-\frac{3}{2}$	-2
e_R^i	**1**	**1**	-1	$x'_e = -x_H - x_\Phi$	1	0	$-\frac{1}{2}$	-1	$-\frac{3}{2}$	-2	-3
N_R^i	**1**	**1**	0	$x'_\nu = -x_\Phi$	-1	-1	-1	-1	-1	-1	-1
H	**1**	**2**	$-\frac{1}{2}$	$-\frac{x_H}{2} = -\frac{x_H}{2}$	1	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{4}$	$\frac{1}{4}$	1
Φ	**1**	**1**	0	$2x_\Phi = 2x_\Phi$	2	2	2	2	2	2	2

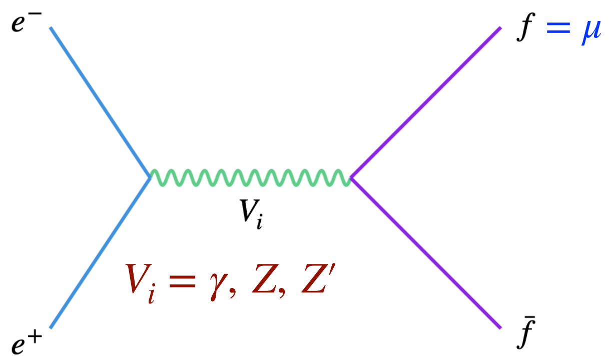
No interaction with left handed fermions

No interaction with u_R

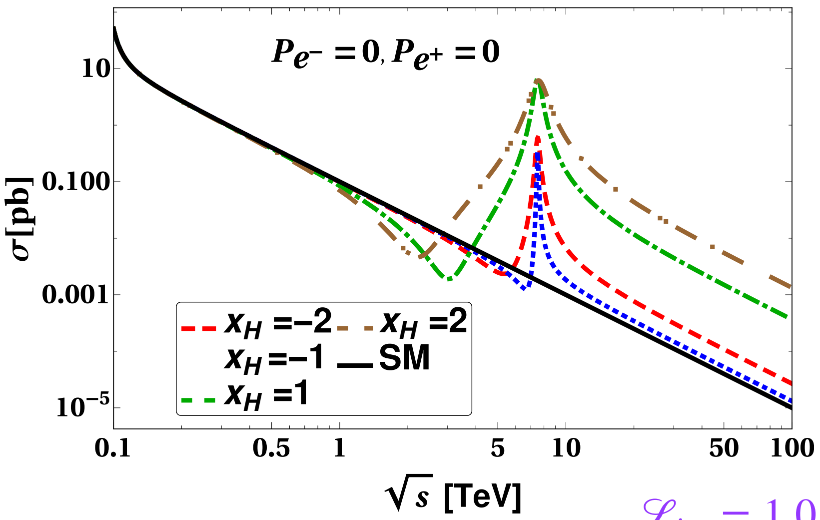
Fermion pair production at the e^-e^+ collider

$M_{Z'} = 7.5$ TeV

2103/4.XXXXX

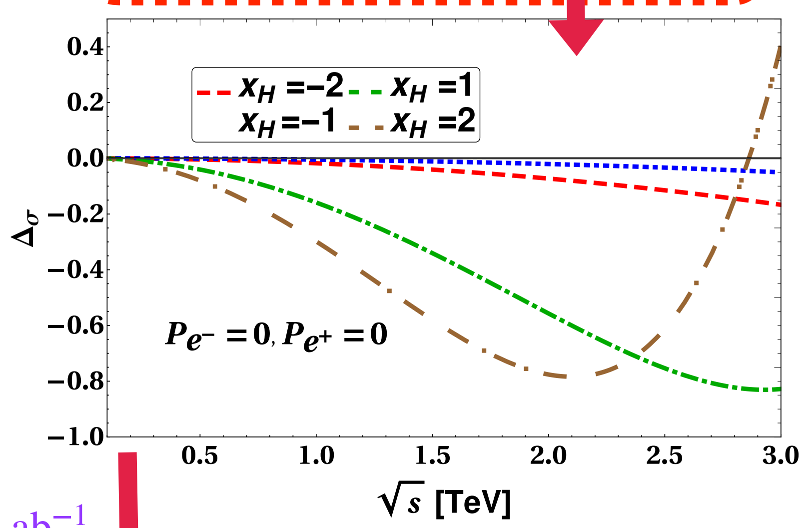


Total cross section

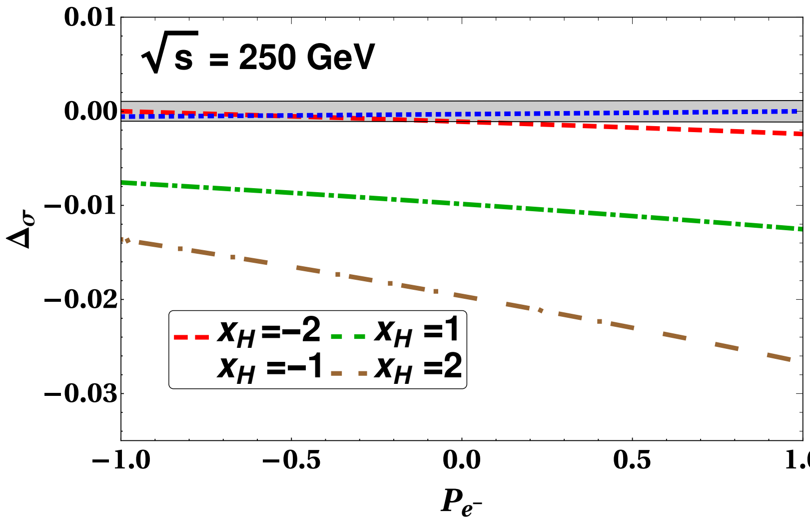


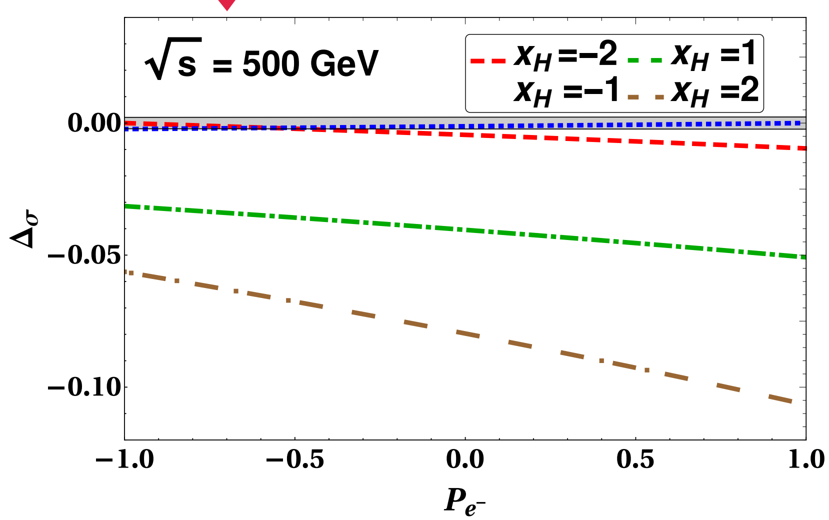
Deviation in cross section

$$\Delta_\sigma\left(P_{e^-}, P_{e^+}\right) = \frac{\sigma^{U(1)_X}}{\sigma^{\rm SM}}(P_{e^+}, P_{e^-}) - 1$$



$\mathscr{L}_{\rm int} = 1.0$ ab^{-1}

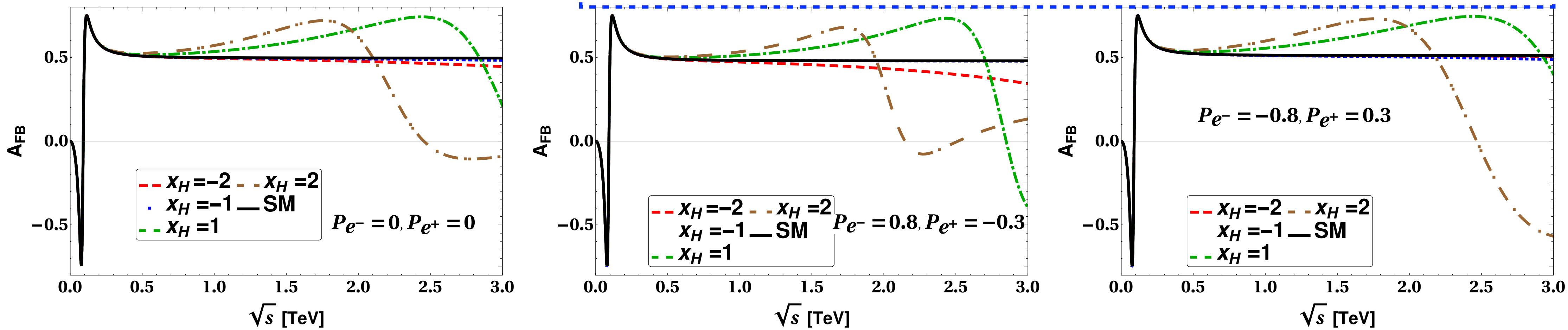




Forward backward scattering

$$\mathcal{A}_{FB}(P_{e^-},P_{e^+}) = \frac{\sigma_F(P_{e^-},P_{e^+})-\sigma_B(P_{e^-},P_{e^+})}{\sigma_F(P_{e^-},P_{e^+})+\sigma_B(P_{e^-},P_{e^+})}$$

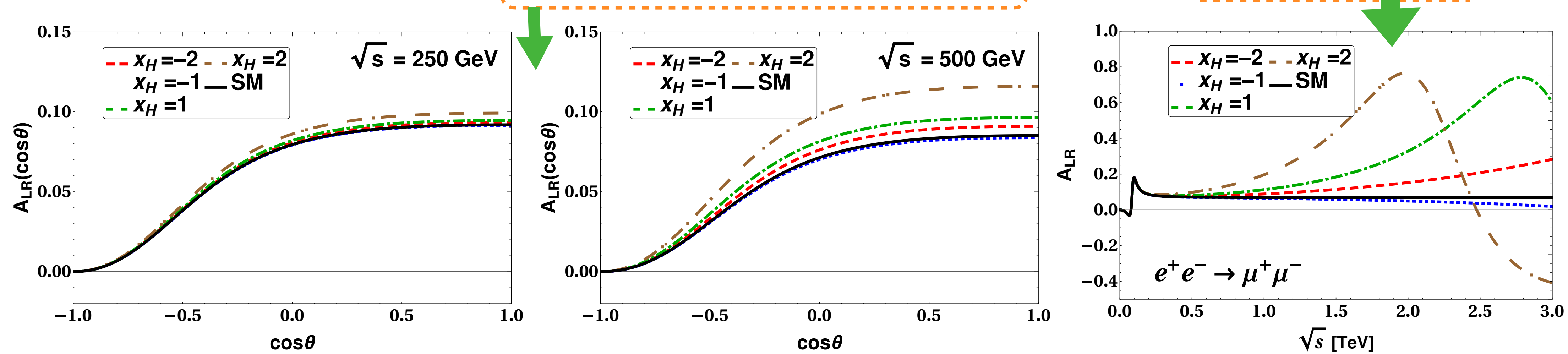
$$\sigma_F(P_{e^-},P_{e^+}) = \sigma(P_{e^-},P_{e^+},[0,+\cos\theta_{\max}]) \quad \sigma_B(P_{e^-},P_{e^+}) = \sigma(P_{e^-},P_{e^+},[-\cos\theta_{\max},0])$$



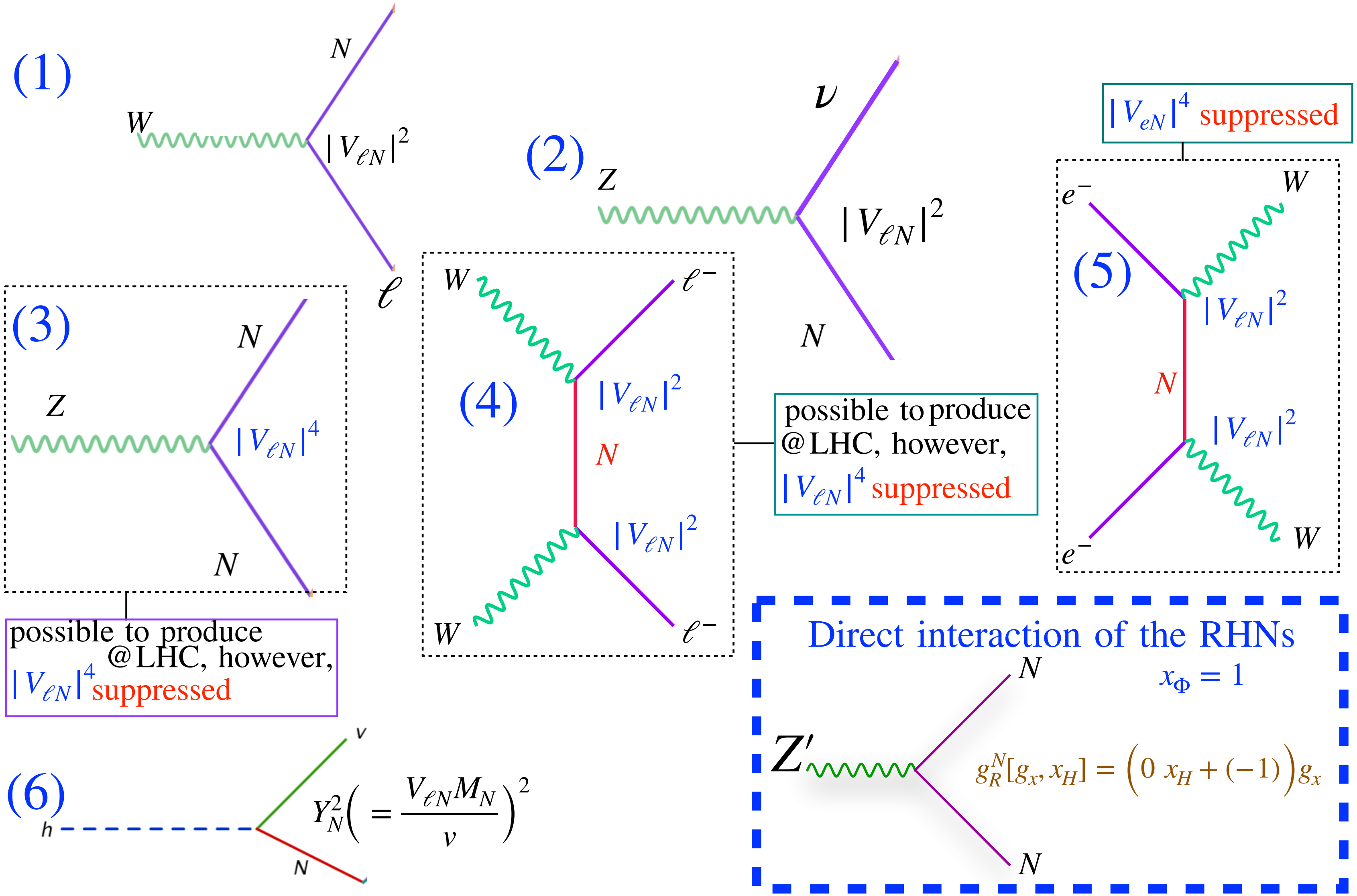
Left – Right asymmetry

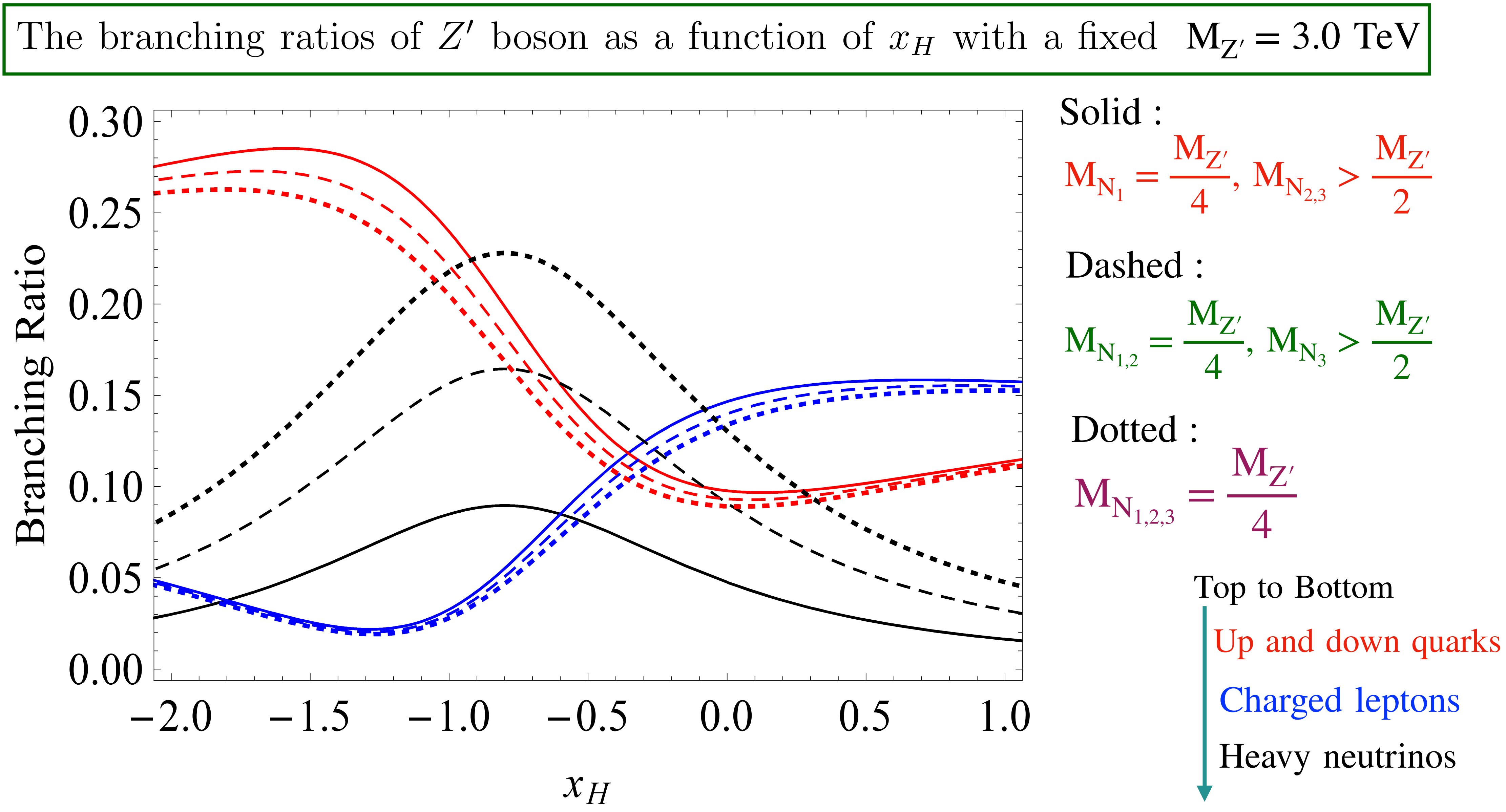
$$\mathcal{A}_{\rm LR}(\cos\theta) = \frac{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) - \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) + \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}$$

$$\mathcal{A}_{LR} = \frac{\sigma^{LR}-\sigma^{RL}}{\sigma^{LR}+\sigma^{RL}}$$



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

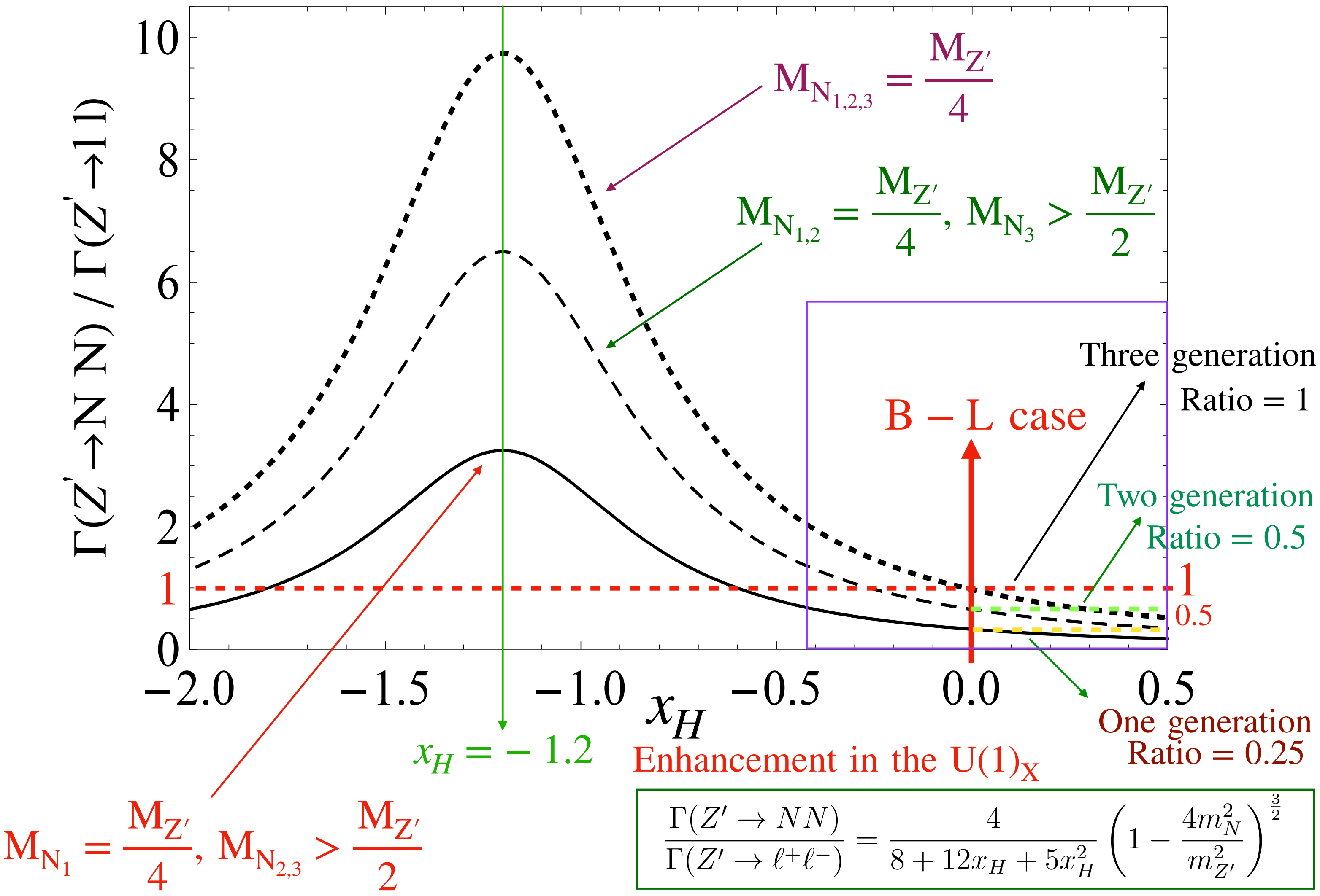




The branching ratios of Z' boson as a function of x_H with a fixed $M_{Z'} = 3.0$ TeV
Branching Ratio
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
x_H
Solid :
$M_{N_1} = \frac{M_{Z'}}{4}, M_{N_{2,3}} > \frac{M_{Z'}}{2}$
Dashed :
$M_{N_{1,2}} = \frac{M_{Z'}}{4}, M_{N_3} > \frac{M_{Z'}}{2}$
Dotted :
$M_{N_{1,2,3}} = \frac{M_{Z'}}{4}$
Top to Bottom
Up and down quarks
Charged leptons
Heavy neutrinos

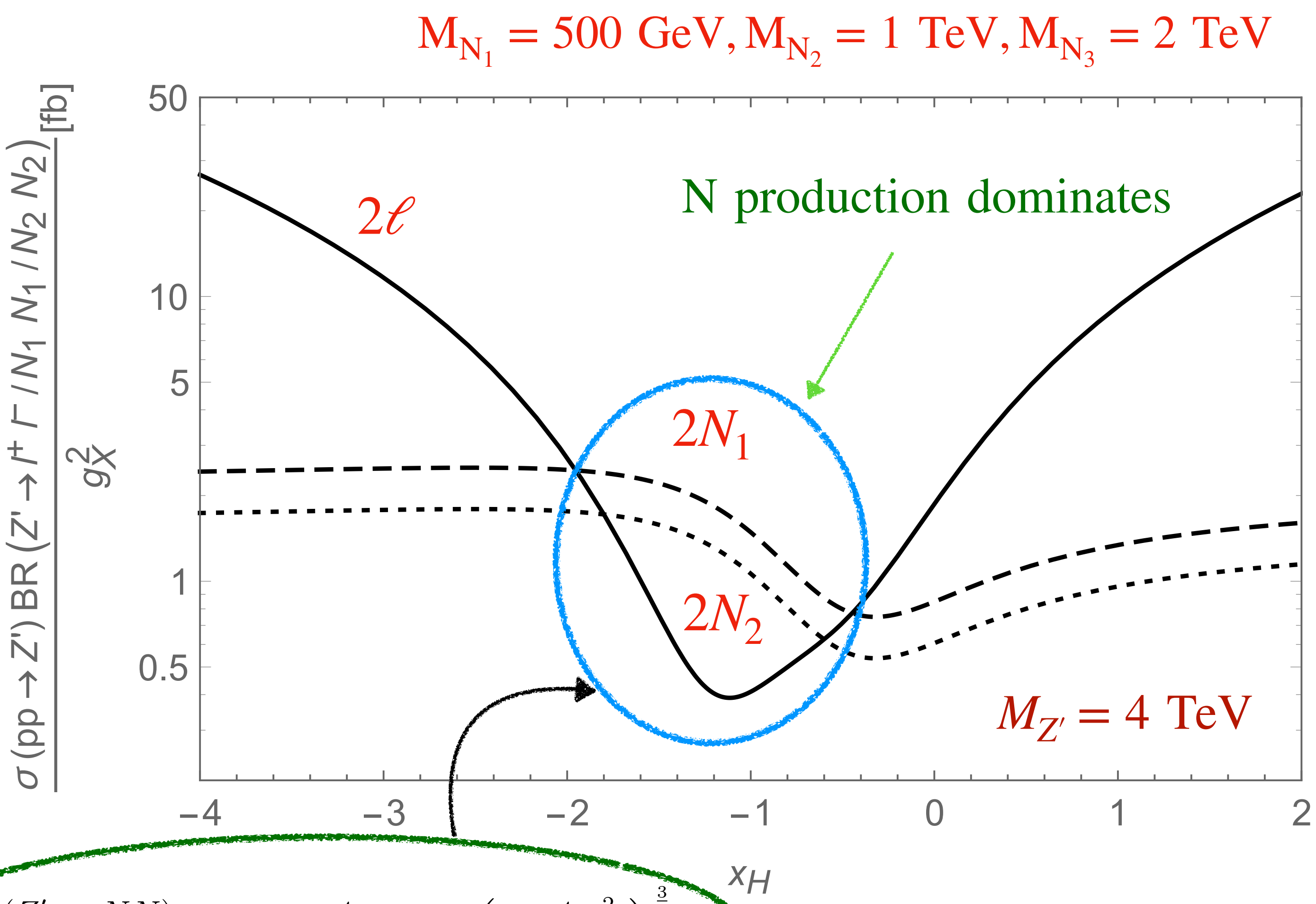
The ratio of the partial decay widths of Z' boson into RHNs and dilepton final states as a function of x_H

1710.03377



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

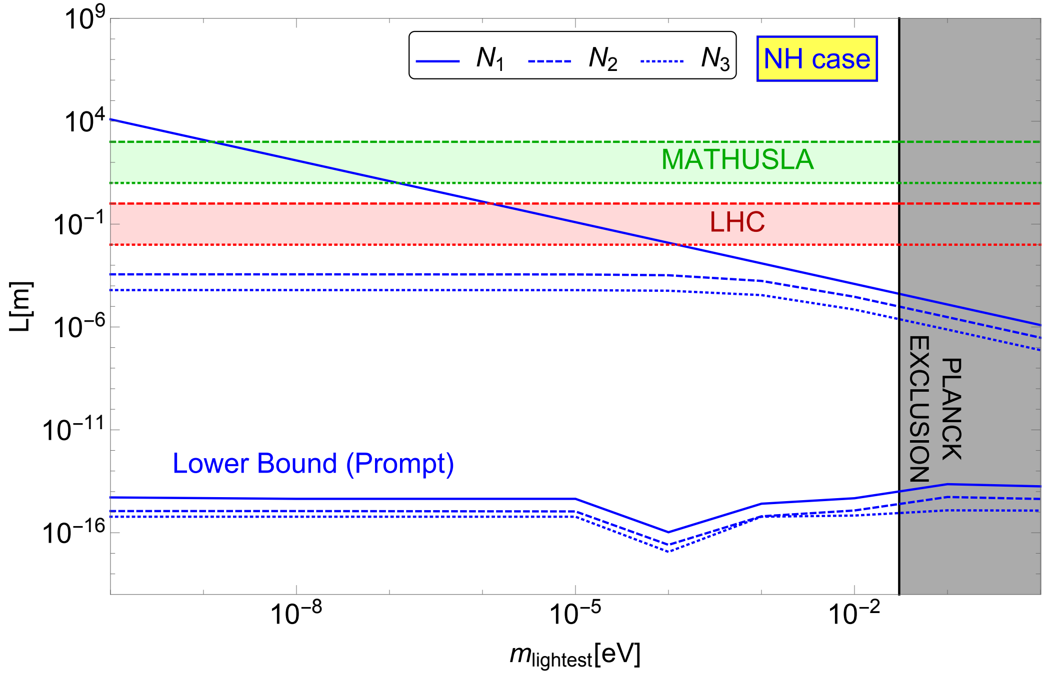
Pair Production of the RHNs as function of x_H



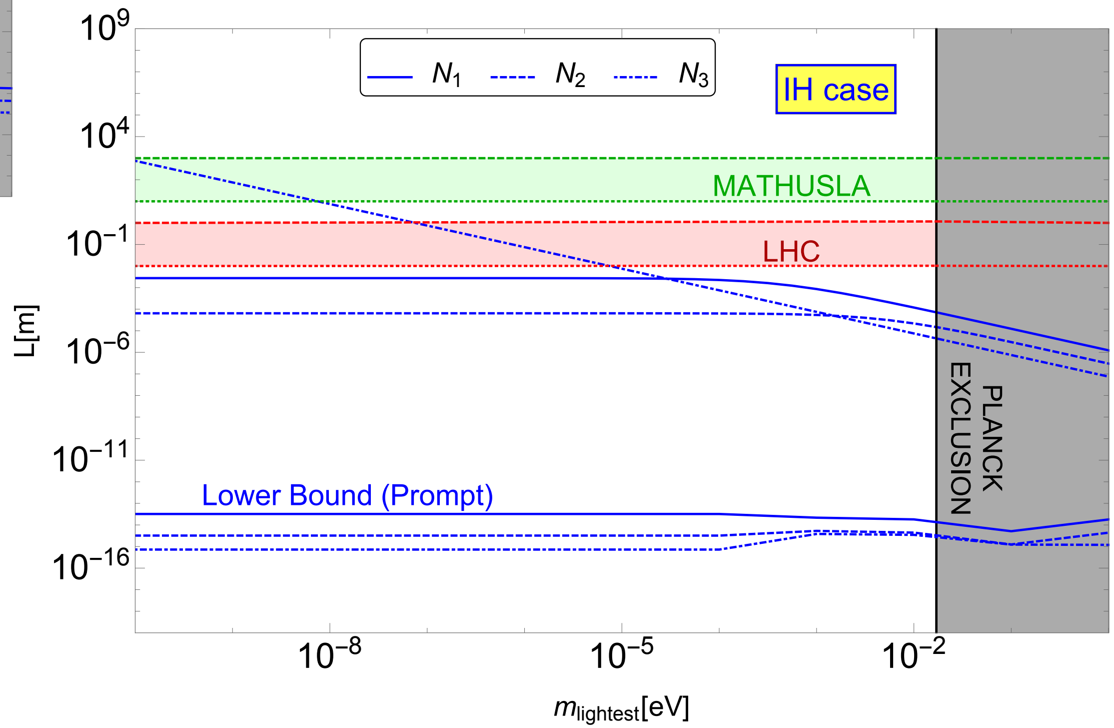
$$\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \ell^+\ell^-)} = \frac{4}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{\frac{3}{2}}$$

RHN decay length vs . m_{lightest}

1906.04132 1908.09838 $M_{N_1} = 500$ GeV $M_{N_2} = 1$ TeV $M_{N_3} = 2$ TeV



Fitting neutrino oscillation data
Generalizing the Dirac Yukawa : Y_D
Using the nonunitarity constraints

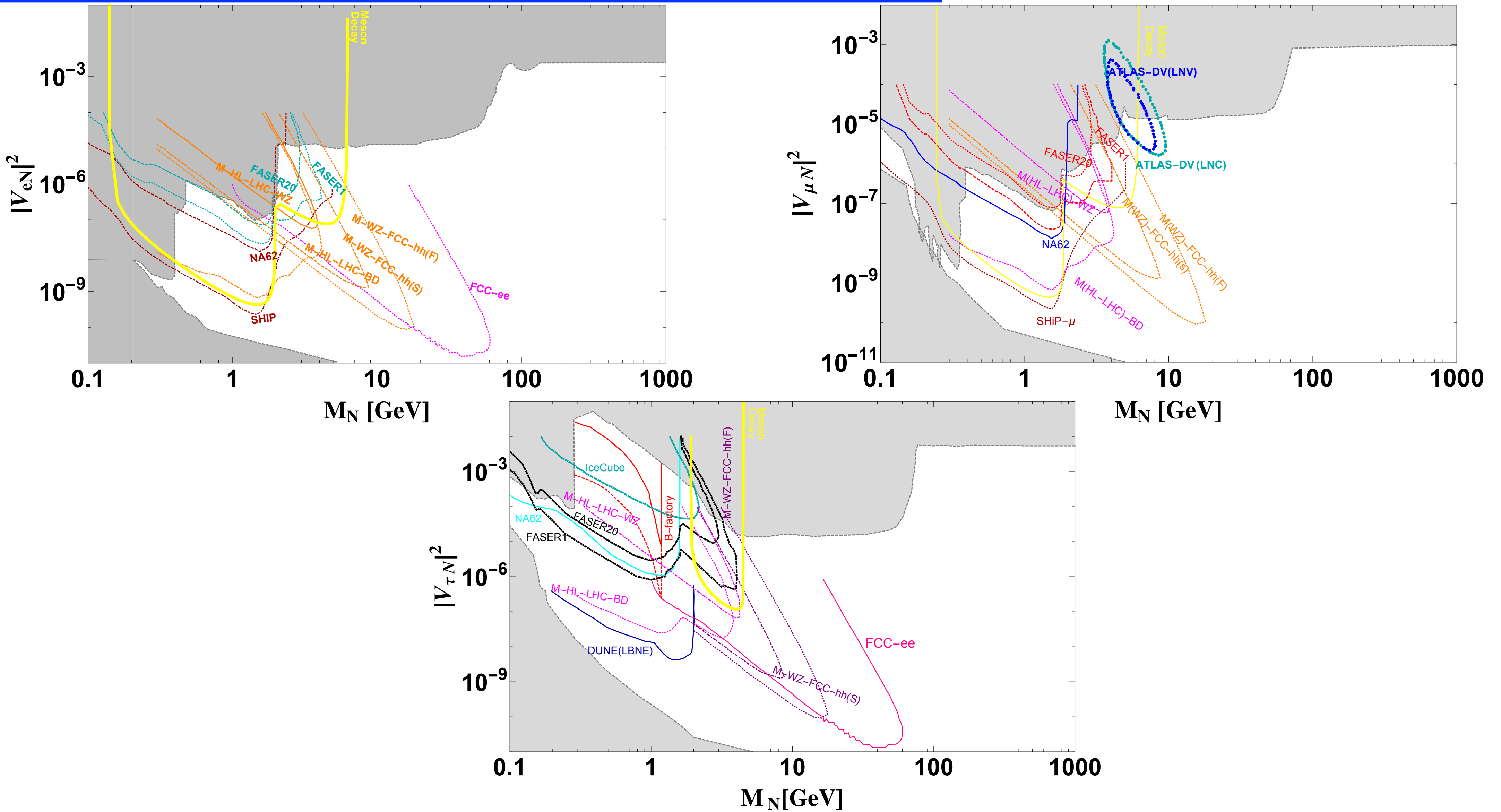


The decay length

$$L_i^{\text{NH/IH}} = \frac{1.97 \times 10^{-13}}{\Gamma_{N_i}^{\text{NH/IH}}[\text{GeV}]} \quad [\text{mm}].$$

Existing and prospective bounds on the mixings

1502.06541 1805.00070 1908.09562



Conclusions :

We are looking for a scenario where which can explain a variety of beyond the SM sceanrios.

The proposal for the generation of the tiny neutrino mass, from the seesaw mechanism, under investigation at the energy frontier. We study $\mathscr{A}_{\rm FB}$, $\mathscr{A}_{\rm LR}$, $\mathscr{A}_{\rm LR,\,FB}$.
The asymmetries are sizable at 250 GeV and 500 GeV $e^{-}e^{+}$ colliders.
Prospective DM candidates can also be sudited in this scenario.

The motovation of these works is to find a new particle, a new force carrier as a part of the of the new physics search including various BSM aspects.