# Phenomenology of the anomaly free general U(1) extended Standard Model

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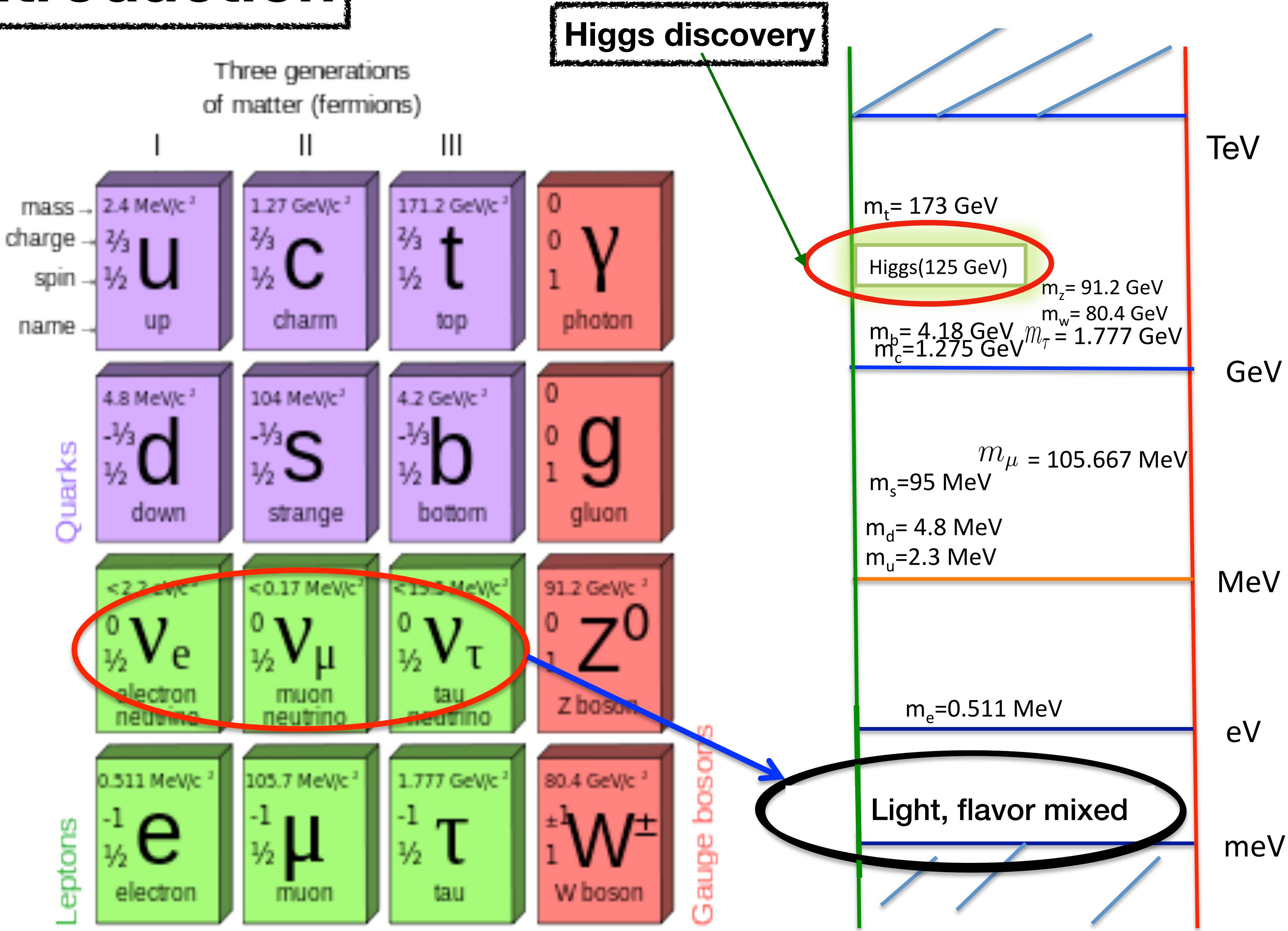
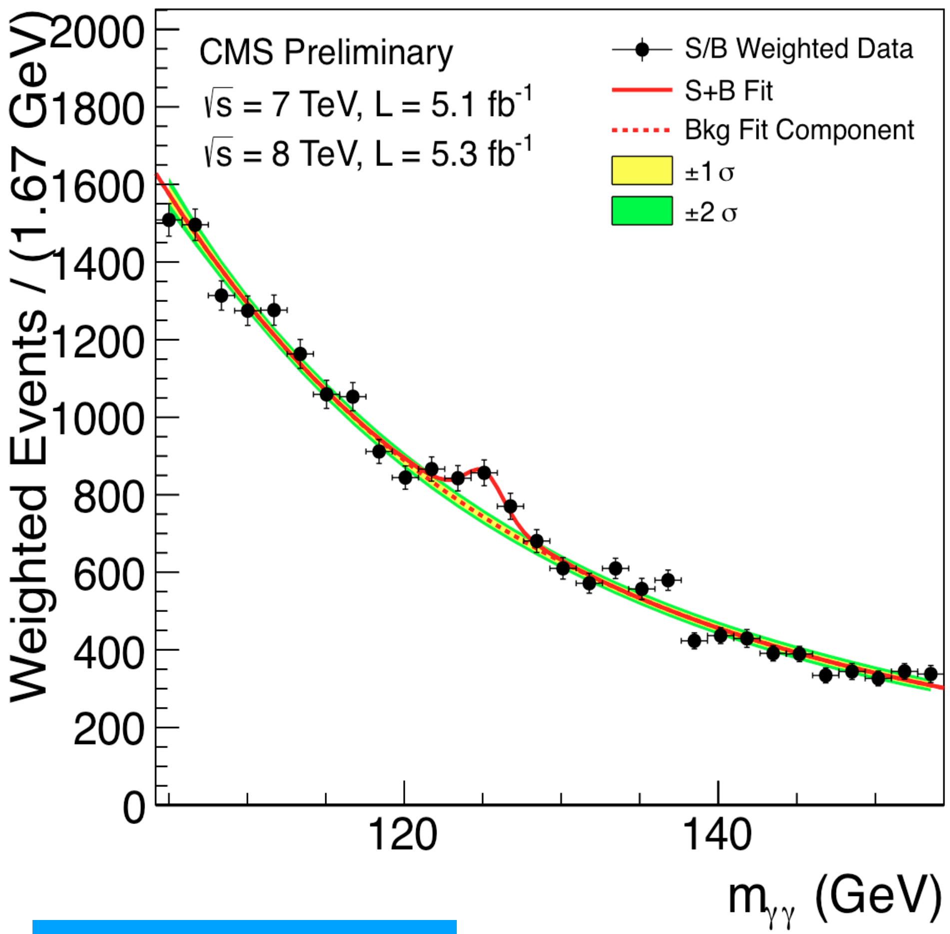
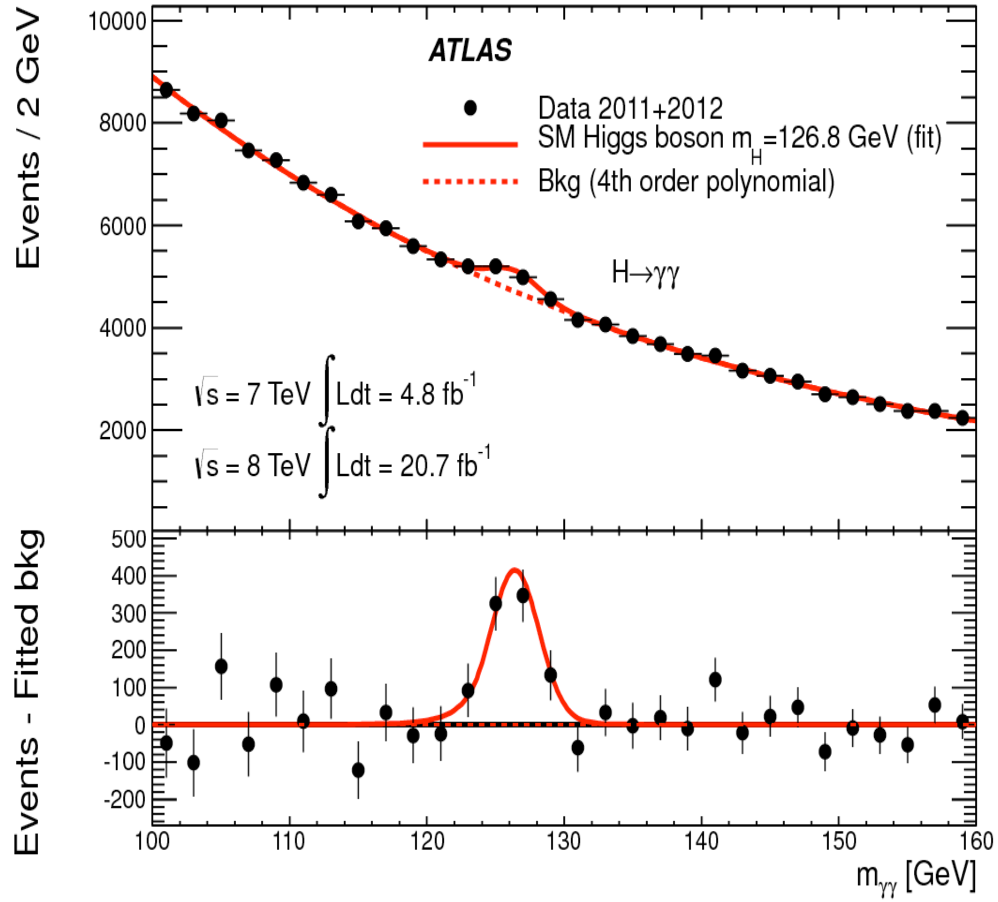
# Introduction



# Discovery of Higgs boson




Nobel Prize in 2013

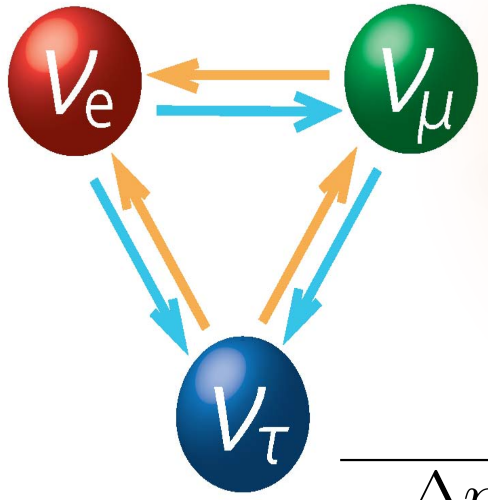
**Role in future**

Higgs boson mass around 125 GeV

# Some interesting results in the neutrino sector

Super- Kamiokande, Sudbury Neutrino Observatory 1999 ,
Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special

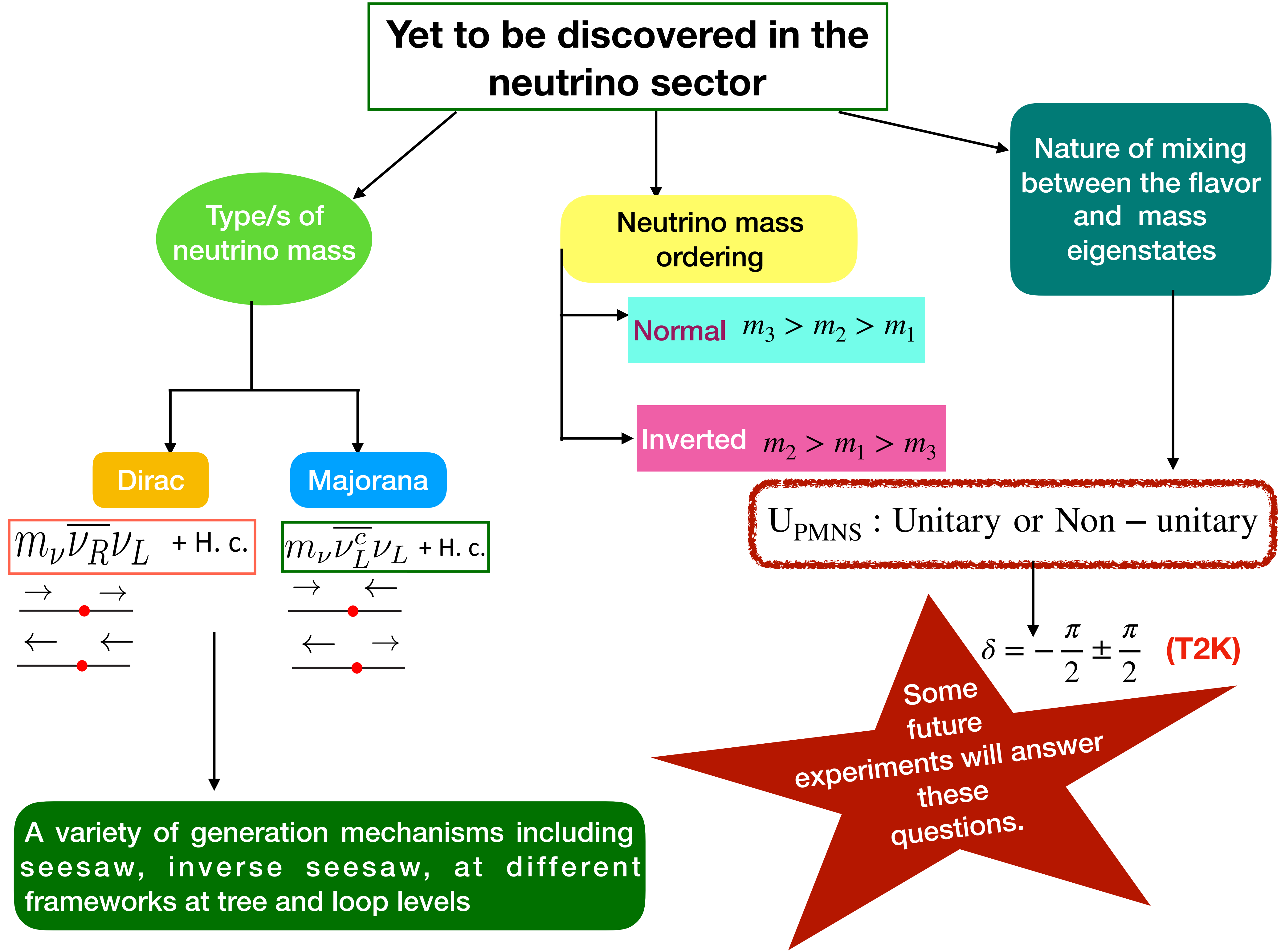



Physics Nobel Prize 2015

$\nu$

Neutrino oscillation data

| | | |
|---|---|---|
| $\Delta m^2_{21}$ | $7.6 \times 10^{-5} \mathrm{eV}^2$ | SNO |
| $\lvert \Delta m_{31} \rvert^2$ | $2.4 \times 10^{-3} \mathrm{eV}^2$ | Super − K |
| $\sin^2 2\theta_{12}$ | 0.87 | KamLAND, SNO |
| $\sin^2 2\theta_{23}$ | 0.999 | T2K |
| | 0.90 | MINOS |
| $\sin^2 2\theta_{13}$ | 0.084 | DayaBay2015 |
| | 0.1 | RENO |
| | 0.09 | DoubleChooz |



Yet to be discovered in the neutrino sector
Type/s of neutrino mass
Neutrino mass ordering
Nature of mixing between the flavor and mass eigenstates
Normal $m_3 > m_2 > m_1$
Inverted $m_2 > m_1 > m_3$
Dirac
Majorana
$m_\nu \overline{\nu_R} \nu_L$ + H. c.
$m_\nu \overline{\nu_L^c} \nu_L$ + H. c.
$U_{PMNS}$ : Unitary or Non − unitary
$\delta = -\frac{\pi}{2} \pm \frac{\pi}{2}$ (T2K)
Some future experiments will answer these questions.
A variety of generation mechanisms including seesaw, inverse seesaw, at different frameworks at tree and loop levels

# Some of the Recent results and future

Neutrino oscillations experiments confirm the existence of the tiny neutrinos mass and flavor mixing

Standard Model (SM) can not explain such observation

Extension of the SM is necessary through an SM singlet Right Handed Neutrino

Discovery of Higgs

INVISIBLE DECAY

Beyond the SM signature

Can relate

Seesaw mechanism

Explains the tiny neutrino mass

Can be tested @Collider/s in future

# In a nutshell we need a scenario which can efficiently include

The Standard Model is
not a complete one

The long – standing question of the
origin of the
neutrino mass and flavor mixing
are yet – to – be fixed

nature of the neutrino mass

discovery potential of
the heavy SM – singlet
neutrinos

Prompt/ Long lived particle

Higgs vacuum stability
Stable/ metastable/ unstable :
needs to be fixed

Invisible decay of the Higgs boson

can not explain the exsitance
of the Dark Matter relic abandance
and the nature of the Dark Matter

Several other beyond the Standard Model scenarios
e.g. Flavor physics

# Particle content of the model

| | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_X$ | | |
|---|---|---|---|---|---|---|
| $q_L^i$ | **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** | $-1/3$ | $x_d$ | $=$ | $-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$ |
| $\ell_L^i$ | **1** | **2** | $-1/2$ | $x_\ell$ | $=$ | $-\frac{1}{2}x_H - x_\Phi$ |
| $e_R^i$ | **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** | $0$ | $x_\nu$ | $=$ | $-x_\Phi$ |
| $\Phi$ | **1** | **1** | $0$ | $x'_\Phi$ | $=$ | $2x_\Phi$ |

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

**Charges before the anomaly cancellations**

**Charges after Imposing the anomaly cancellations**

Yukawa interaction

$$\tilde{H} \equiv i\tau^2 H^*$$

$$\mathcal{L}_Y = -\sum_{\alpha,\beta=1}^{3} Y_u^{\alpha\beta}\overline{q_L^\alpha}\tilde{H}u_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_d^{\alpha\beta}\overline{q_L^\alpha}Hd_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_e^{\alpha\beta}\overline{\ell_L^\alpha}He_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_D^{\alpha\beta}\overline{\ell_L^\alpha}\tilde{H}N_R^\beta - \sum_{\alpha=1}^{3} Y_N^\alpha \Phi\overline{N_R^{\alpha C}}N_R^\alpha + \text{h.c.}$$

## Gauge and gravitational anomaly-free conditions

| | |
|---|---|
| $U(1)_X \times [SU(3)_C]^2$ | $2x_q - x_u - x_d = 0$ |
| $U(1)_X \times [SU(2)_L]^2$ | $3x_q + x_\ell = 0$ |
| $U(1)_X \times [U(1)_Y]^2$ | $x_q - 8x_u - 2x_d + 3x_\ell - 6x_e = 0$ |
| $[U(1)_X]^2 \times U(1)_Y$ | $x_q^2 - 2x_u^2 + x_d^2 - x_\ell^2 + x_e^2 = 0$ |
| $[U(1)_X]^3$ | $6x_q^3 - 3x_u^3 - 3x_d^3 + 2x_\ell^3 - x_\nu^3 - x_e^3 = 0$ |
| $U(1)_X \times [\text{grav.}]^2$ | $6x_q - 3x_u - 3x_d + 2x_\ell - x_\nu - x_e = 0$ |

## Yukawa interactions

$$x'_H = -x_q + x_u = x_q - x_d \qquad x'_H = -x_\ell + x_\nu = x_\ell - x_e \qquad x'_\Phi = -2x_\nu$$

Using the above equations, $x'_H = \frac{1}{2}x_H$ and $x'_\Phi = 2x_\Phi$ we find the charges of the $U(1)_X$ sector is the linear combination of the $U(1)_Y$ and $U(1)_{B-L}$ charges.

$$\mathscr{L} = \mathscr{L}_{\text{scalar}} + \mathscr{L}_{\text{YM}} + \mathscr{L}_{\text{f}} + \mathscr{L}_{\text{Y}}$$

Scalar

$$\mathscr{L}_{\text{YM}}^{\text{Abel.}} + \mathscr{L}_{\text{YM}}^{\text{Non Abel.}}$$

$$\sum \left( i\overline{q_L}\gamma_\mu D^\mu q_L + i\overline{u_R}\gamma_\mu D^\mu u_R + i\overline{d_R}\gamma_\mu D^\mu d_R + i\overline{\ell_L}\gamma_\mu D^\mu \ell_L + i\overline{e_R}\gamma_\mu D^\mu e_R \right)$$

$$\mathcal{L}_Y = -\sum_{\alpha,\beta=1}^{3} Y_u^{\alpha\beta}\overline{q_L^\alpha}\tilde{H}u_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_d^{\alpha\beta}\overline{q_L^\alpha}Hd_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_e^{\alpha\beta}\overline{\ell_L^\alpha}He_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_D^{\alpha\beta}\overline{\ell_L^\alpha}\tilde{H}N_R^\beta - \sum_{\alpha=1}^{3} Y_N^\alpha \Phi \overline{N_R^{\alpha C}} N_R^\alpha + \text{h.c.}$$

$$D_\mu = \partial_\mu + ig_s T^\alpha G_\mu^\alpha + igT^a W_\mu^a + ig_1 y B_\mu + g' y_x B'_\mu$$

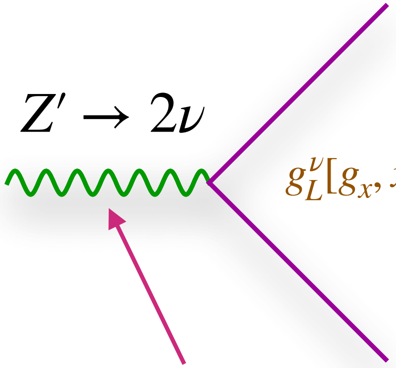
Another important aspect of these model is the existence of a heavy neutral gauge boson $Z'$ which interacts with the particles of the model

After the symmetry breaking

$$m_{Z'} = g_X\sqrt{4v_\Phi^2 + \frac{1}{4}x_H^2 v^2} \simeq 2g_X v_\Phi \qquad v_\Phi^2 \gg v^2 \qquad x_\Phi = 1$$

## Couplings and the partial decay widths of $Z'$

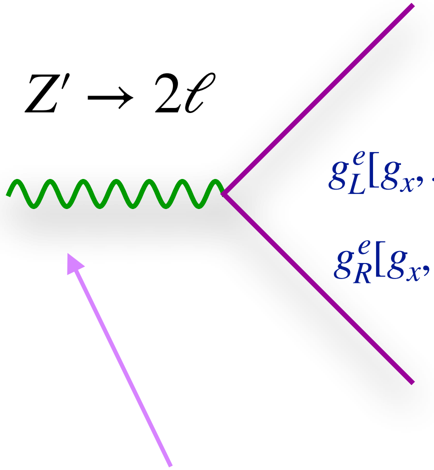
$Z' \to 2\nu$



$$g_L^{\nu}[g_x, x_H] = \left((-\frac{1}{2})x_H + (-1)\right)g_x$$

$$\Gamma[Z' \to 2\nu] = \frac{M_{Z'}}{24\pi} g_L^{\nu}[g_x, x_H]^2$$

$Z' \to 2\ell$

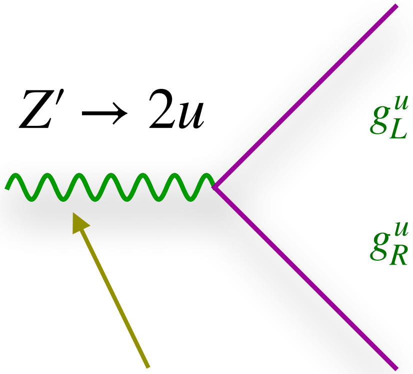


$$g_L^{e}[g_x, x_H] = \left((-\frac{1}{2})x_H + (-1)\right)g_x$$

$$g_R^{e}[g_x, x_H] = \left((-1)x_H + (-1)\right)g_x$$

$$\Gamma[Z' \to 2\ell] = \frac{M_{Z'}}{24\pi}(g_L^{e}[g_x, x_H]^2 + g_R^{e}[g_x, x_H]^2)$$

$Z' \to 2u$

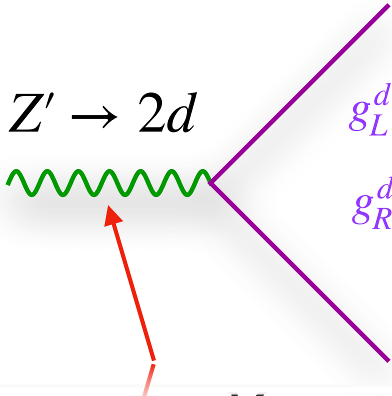


$$g_L^{u}[g_x, x_H] = \left((\frac{1}{6})x_H + (\frac{1}{3})\right)g_x$$

$$g_R^{u}[g_x, x_H] = \left((\frac{2}{3})x_H + (\frac{1}{3})\right)g_x$$

$$\Gamma[Z' \to 2u] = \frac{M_{Z'}}{24\pi}(g_L^{u}[g_x, x_H]^2 + g_R^{u}[g_x, x_H]^2)$$

$Z' \to 2d$



$$g_L^{d}[g_x, x_H] = \left((\frac{1}{6})x_H + (\frac{1}{3})\right)g_x$$

$$g_R^{d}[g_x, x_H] = \left((-\frac{1}{3})x_H + (\frac{1}{3})\right)g_x$$

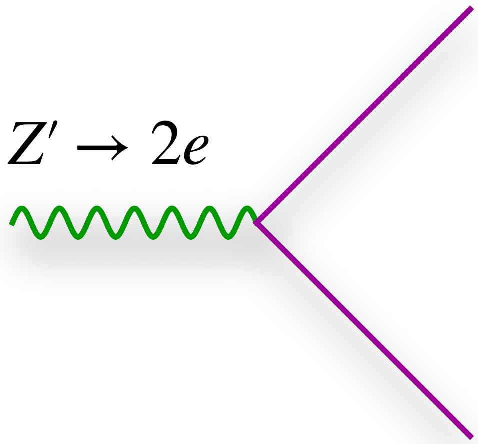
$$\Gamma[Z' \to 2d] = \frac{M_{Z'}}{24\pi}(g_L^{d}[g_x, x_H]^2 + g_R^{d}[g_x, x_H]^2)$$

# Interaction of $Z'$ with the Higgs

$$\mathcal{L}_{int}^{Z'} = \bar{e}\gamma^{\mu}\Big(C'_V + C'_A\gamma_5\Big)eZ'_{\mu}$$

$$C'_V = g_x\Big(-\tfrac{3}{4}x_H - 1\Big)$$

$$C'_A = g_x\Big(-\tfrac{1}{4}x_H\Big)$$

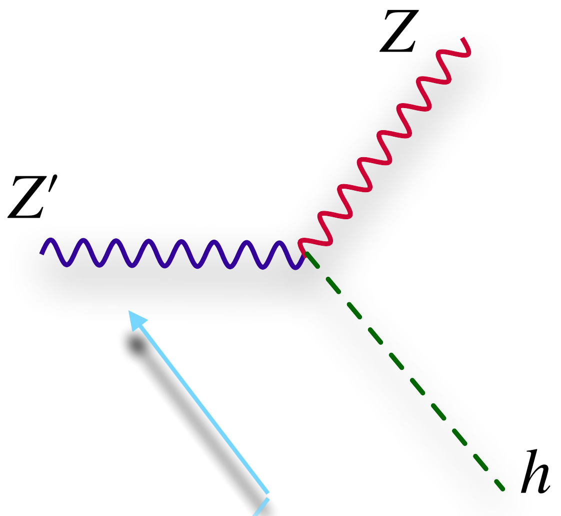



**$Z - Z' - h$ coupling**

$$\mathcal{L} \supset \left|\left\{-\frac{i}{2}g_z Z_{\mu} - ig_x Z'_{\mu}(-\frac{1}{2}x_H)\right\}\frac{1}{\sqrt{2}}(v+h)\right|^2$$

$$= \frac{1}{8}\Big(g_z^2 Z_{\mu}Z^{\mu} + g_x^2 x_H^2 Z'_{\mu}Z'^{\mu} - 2g_z\Big(g_x x_H\Big)Z_{\mu}Z'_{\mu}\Big)$$

$$v^2\Big(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\Big)$$




$$\mathcal{L} \supset -\frac{1}{2}g_z(g_x x_H)vhZ^{\mu}Z'_{\mu}$$

$$= -m_Z\Big(g_x x_H\Big)hZ^{\mu}Z'_{\mu}$$

$$\Gamma[Z' \to Zh] = \frac{M_{Z'}g_x^2 x_H^2}{48\pi}\sqrt{\lambda\Big[1,(\frac{M_Z}{M_{Z'}})^2,(\frac{m_h}{M_{Z'}})^2\Big]}$$

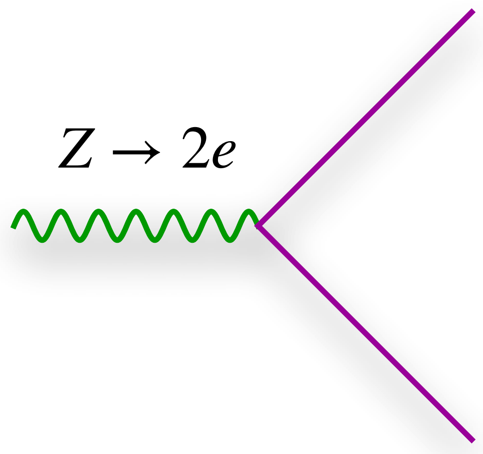
$$\Big(\lambda\Big[1,(\frac{M_Z}{M_{Z'}})^2,(\frac{m_h}{M_{Z'}})^2\Big] + 12\frac{M_Z}{M_{Z'}}\Big)$$

# Interaction of $Z$ with the Higgs

$$\mathcal{L}_{int}^{Z} = g_Z \bar{e} \gamma^{\mu} \Big( C_V + C_A \gamma_5 \Big) e Z_{\mu}$$

$$C_V = g_z \Big( -\tfrac{1}{4} + \sin^2 \theta_W \Big)$$

$$C_A = \frac{g_z}{4}$$

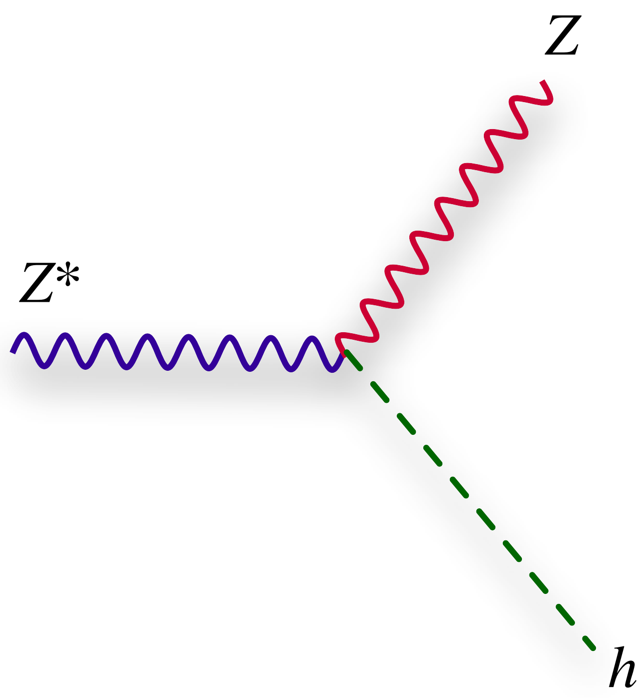



**$Z - h$ coupling**

$$\mathcal{L} \supset \Big| -\frac{i}{2} g_z Z_\mu \frac{1}{\sqrt{2}} (v+h) \Big|^2$$

$$= \frac{g_z^2}{8} Z_\mu Z^\mu (v^2 + 2vh + h^2)$$

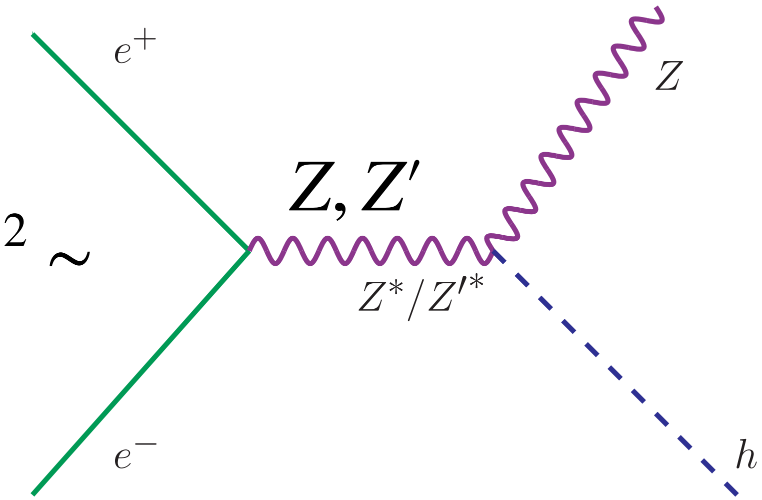
$$\supset \frac{M_Z^2}{v} h Z_\mu Z^\mu$$



# Production process at the linear collider

with N. Okada (appear soon)

$$|M_Z + M_{Z'}|^2 \sim$$




$$\frac{d\sigma}{d\cos\theta} = \frac{3.89 \times 10^8}{32\pi}\sqrt{\frac{E_Z^2 - M_Z^2}{s}}\left[\left|C_Z\right|^2\left(C_V^2 + C_A^2\right) + |C'_Z|^2\left(C'_V{}^2 + C'_A{}^2\right) + \left(C_Z^* C'_Z + C_Z C'_Z{}^*\right)\left(C_V C'_V + C_A C'_A\right)\right] \times \left\{1 + \cos^2\theta + \frac{E_Z^2}{M_Z^2}\left(1 - \cos^2\theta\right)\right\}$$

$$C_Z = 2\left(\frac{M_Z^2}{v}\right)\frac{1}{s - M_Z^2 + i\Gamma_Z M_Z}$$

$$C'_Z = \frac{-M_Z g_x x_H}{s - M'_Z{}^2 + i\Gamma_{Z'} M_{Z'}}$$

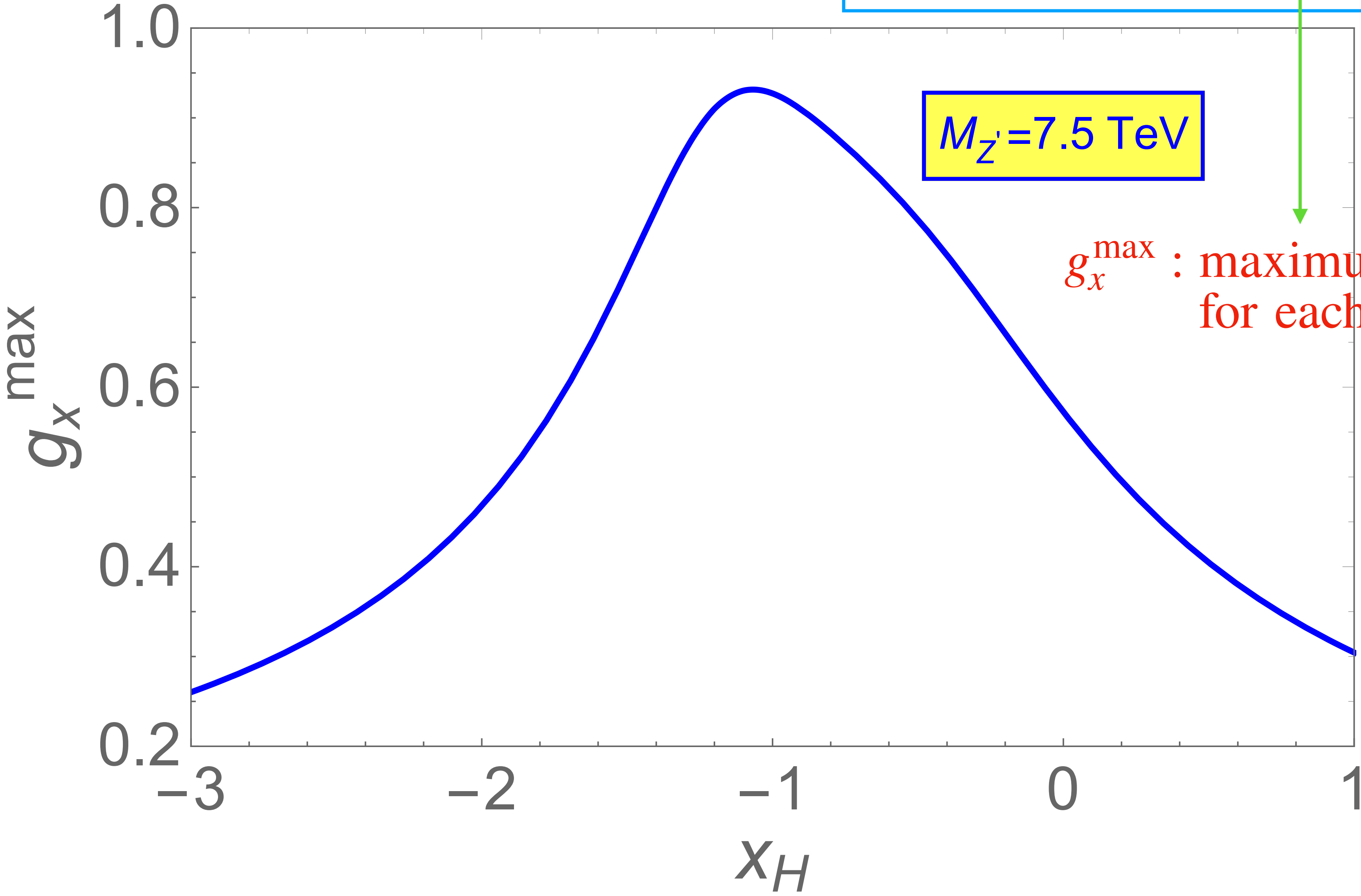
**INTERFERENCE**

# $U(1)_X$ coupling versus $x_H$ for fixed $Z'$ mass

$\sigma[g_x, x_H, M_{Z'}] = X_{\rm sec}^{\rm ATLAS-TDR}$

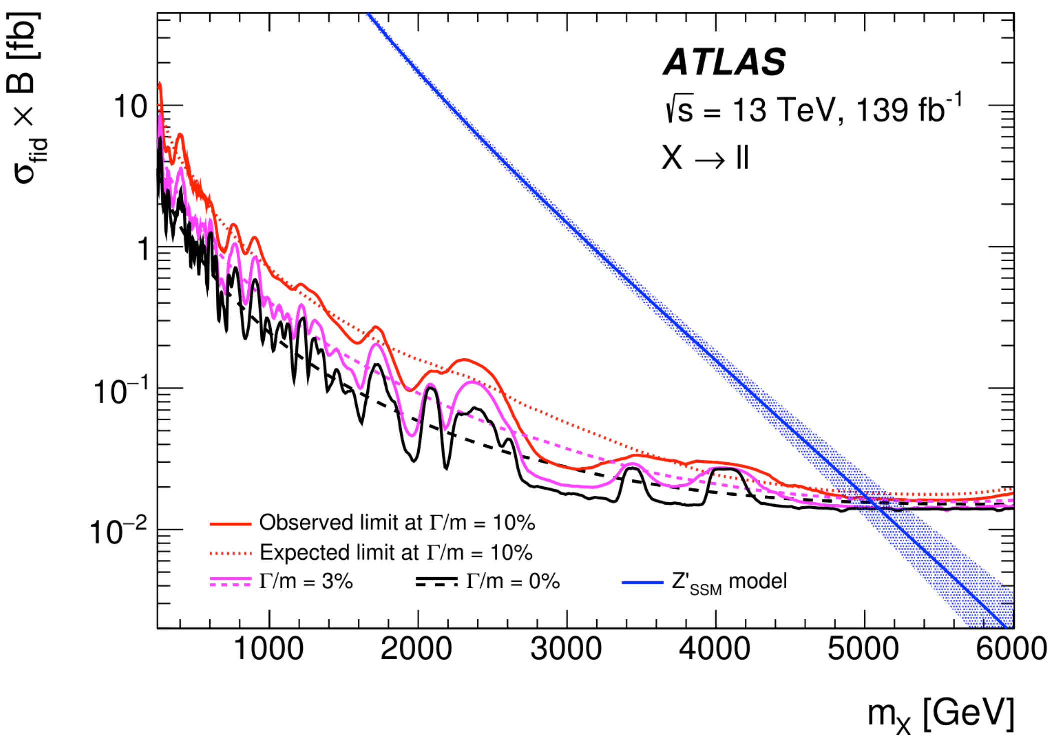
$[x_H, M'_Z] \to \text{Fix} : \{X_{\rm sec}, g_x\}$

$g_x^{\rm max}$ : maximum value for each $x_H$



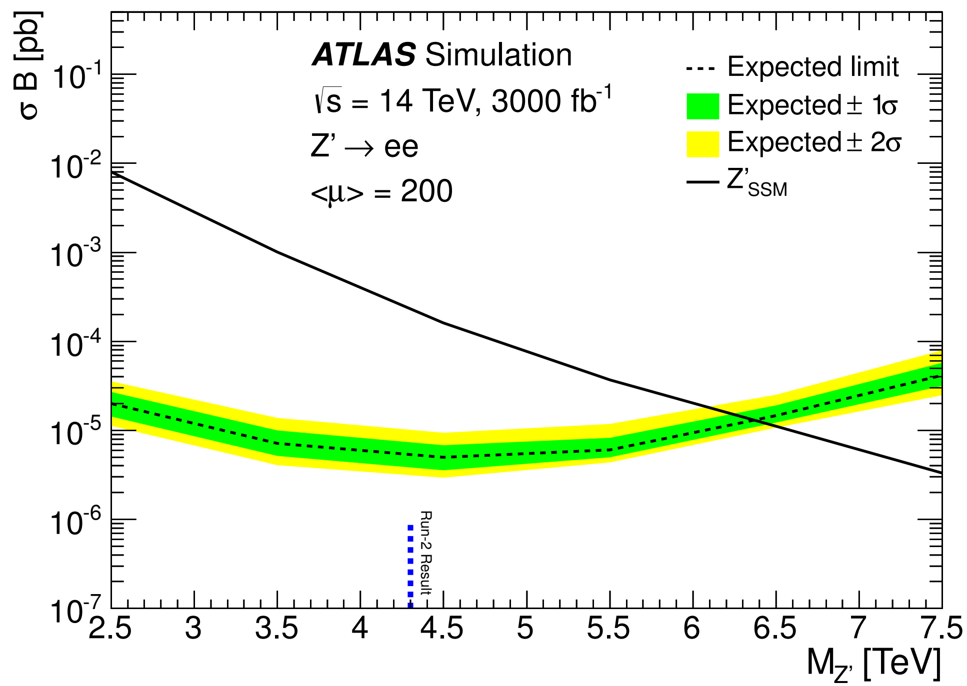
# Bounds on the $U(1)_X$ gauge coupling

**ATLAS: 1903.06248 (139/fb)**

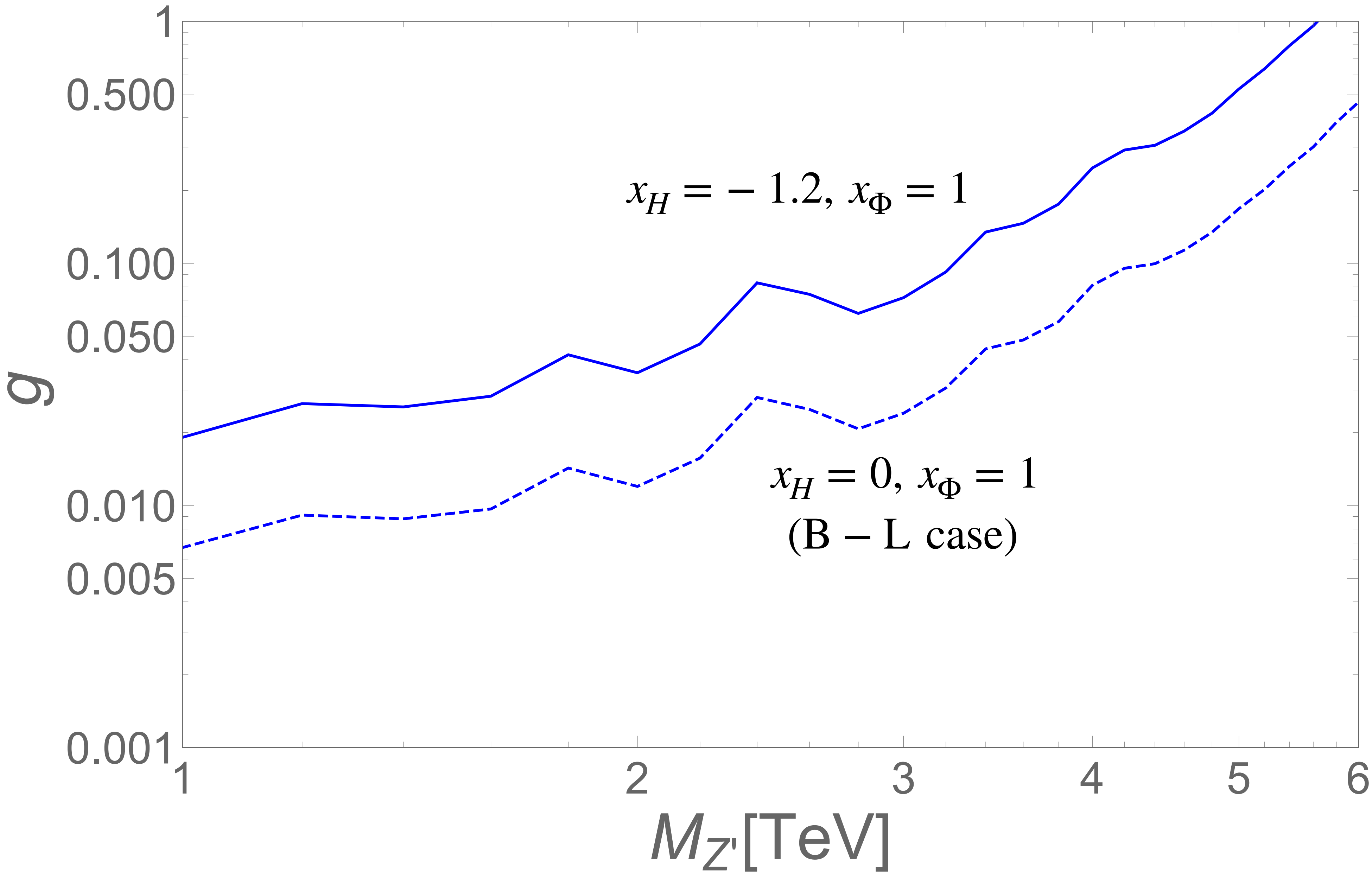



CMS (36/fb) and ATLAS (139/fb) searches at the LHC Run-1 and Run-2 respectively

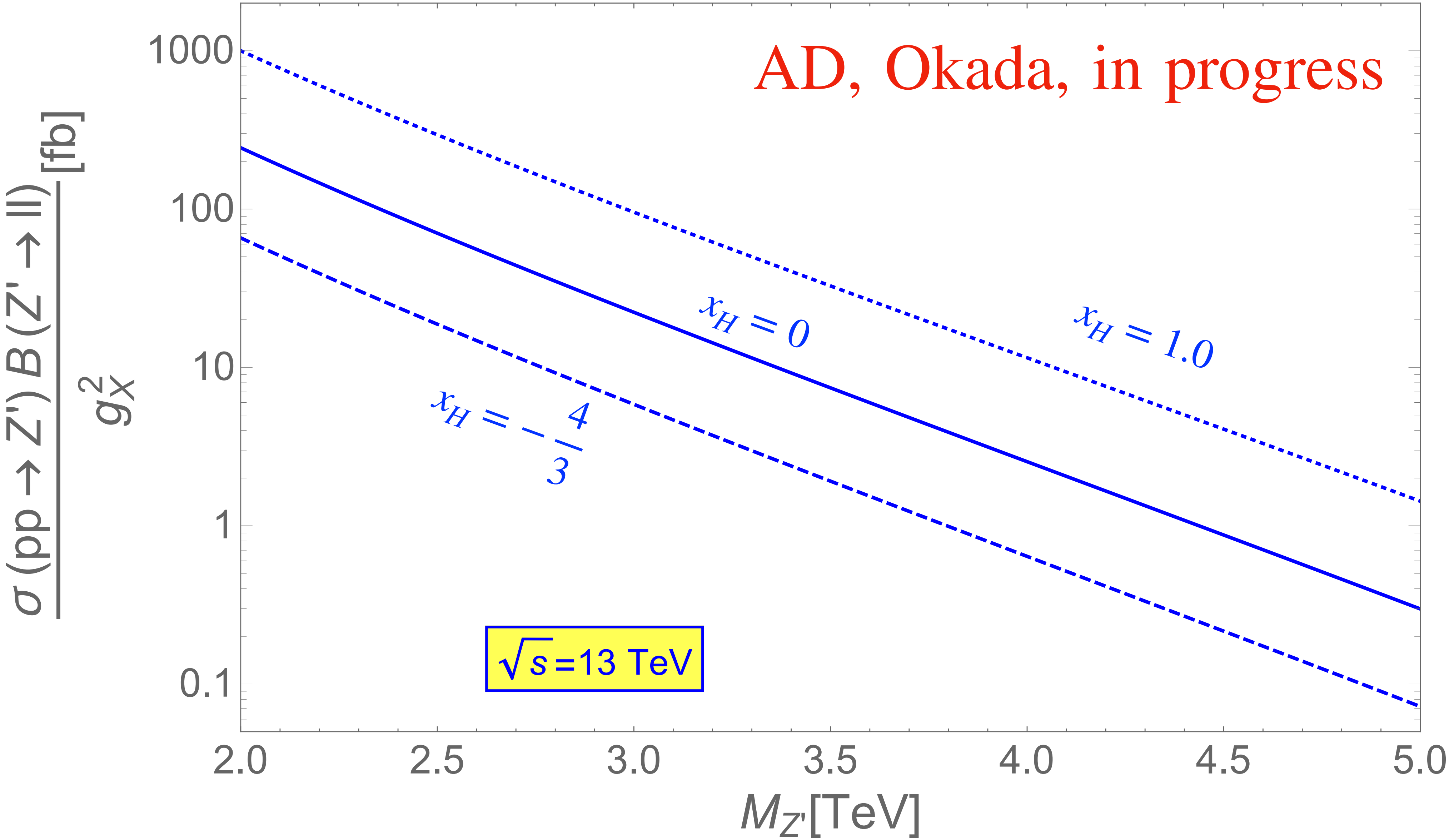
**ATLAS-TDR-027 (prospective)**



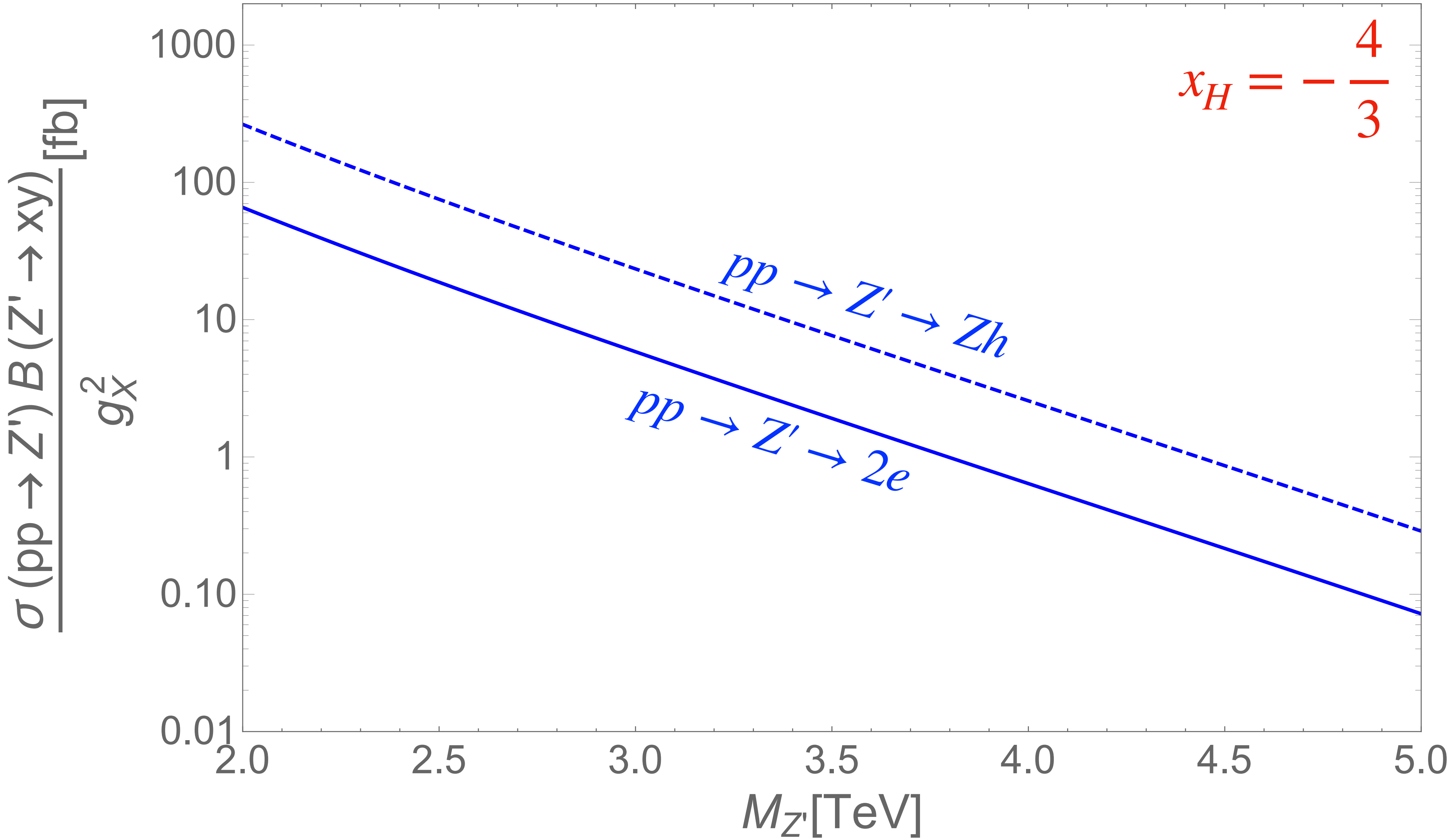
# Current LHC constraints on $g_x$ vs $\mathrm{M}_{Z'}$ (sample)



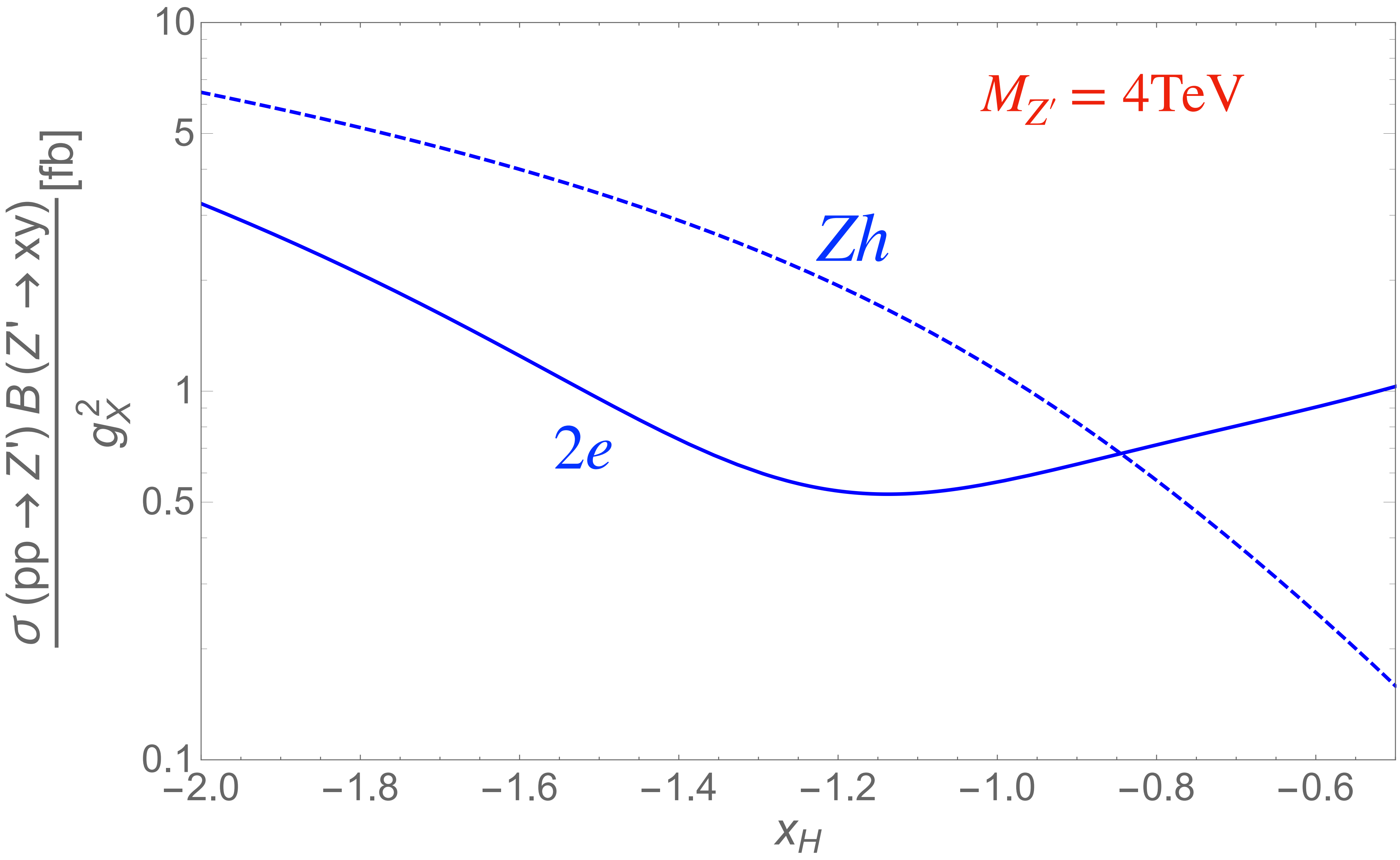
# Dilepton production from the $Z'$ at the LHC



# Dilepton and the $Zh$ production from the $Z'$ at the 13 TeV LHC

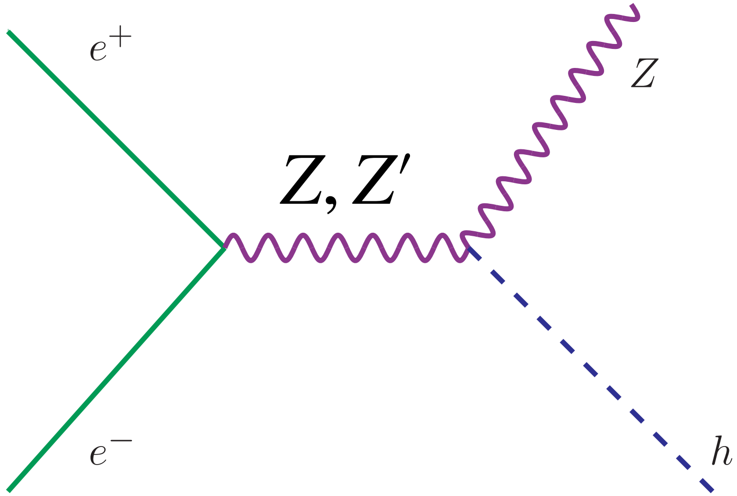


# Dilepton and $Zh$ production at the 13 TeV LHC



# Production process at the linear collider

$$|M_Z + M_{Z'}|^2 \sim$$



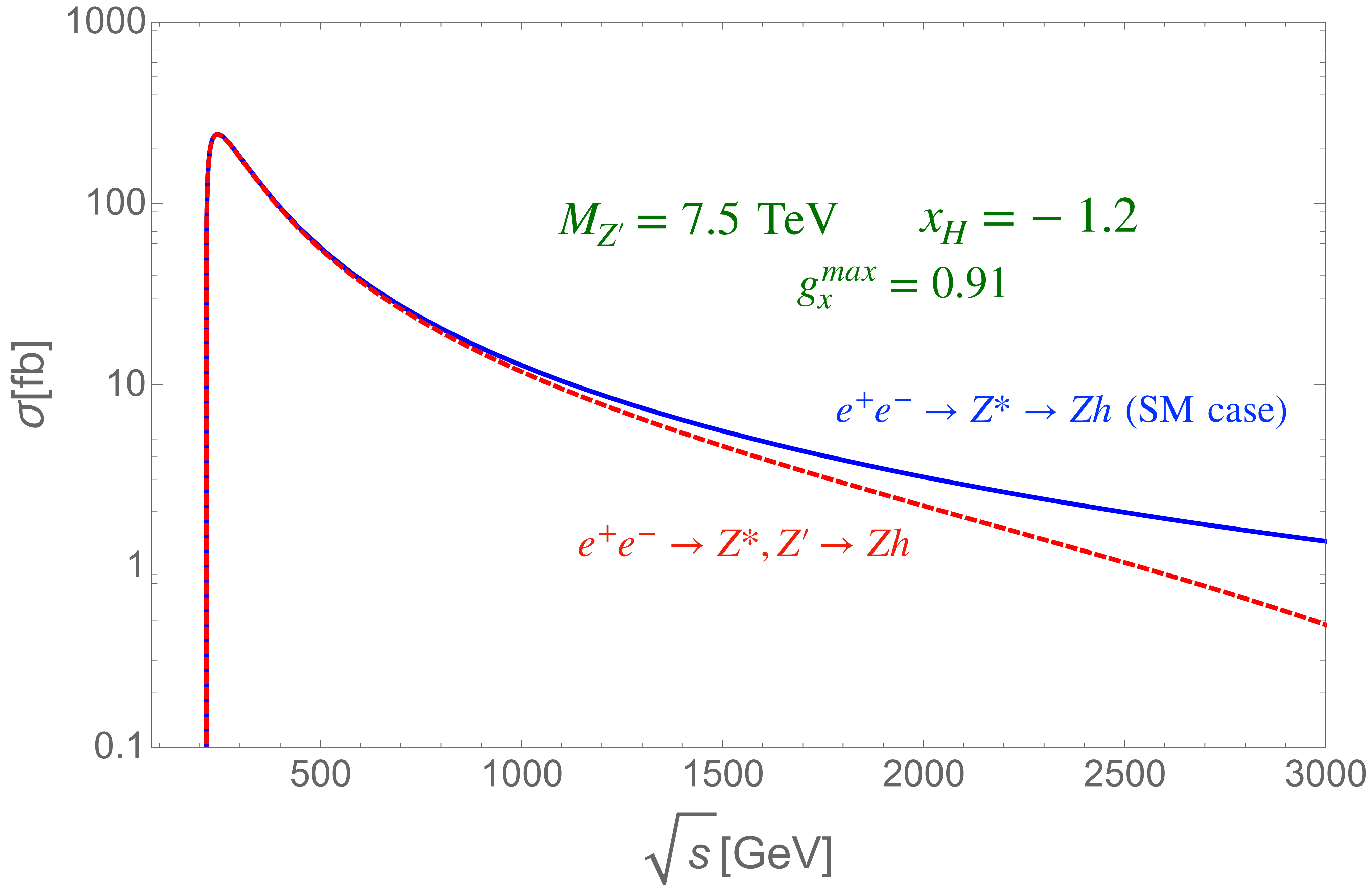

$$\frac{d\sigma}{d\cos\theta} = \frac{3.89\times 10^8}{32\pi}\sqrt{\frac{E_Z^2 - M_Z^2}{s}}\Big[\left|C_Z\right|^2\left(C_V^2 + C_A^2\right) + |C'_Z|^2\left(C'_V{}^2 + C'_A{}^2\right) + \left(C_Z^* C'_Z + C_Z C'_Z{}^*\right)\left(C_V C'_V + C_A C'_A\right)\Big] \times \left\{1 + \cos^2\theta + \frac{E_Z^2}{M_Z^2}\left(1 - \cos^2\theta\right)\right\}$$

$$C_Z = 2\left(\frac{M_Z^2}{v}\right)\frac{1}{s - M_Z^2 + i\Gamma_Z M_Z}$$

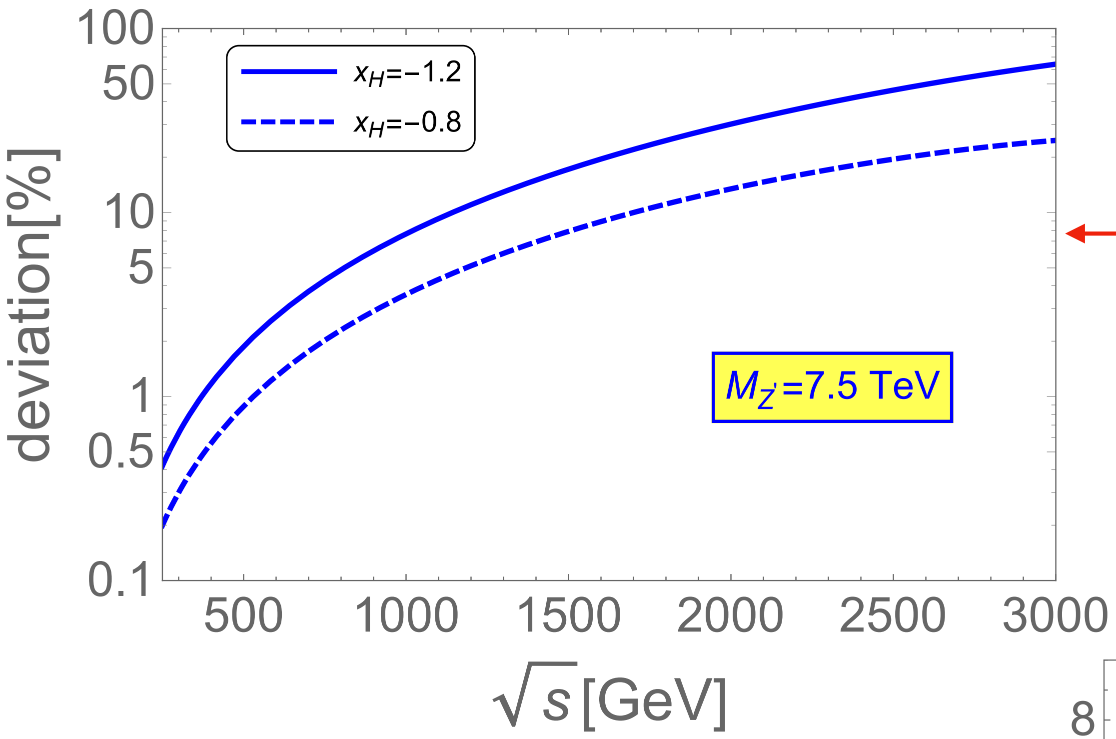
$$C'_Z = \frac{-M_Z g_x x_H}{s - M'_Z{}^2 + i\Gamma_{Z'} M_{Z'}}$$

**INTERFERENCE**

# Cross section as a function of the center of mass energy of the ILC

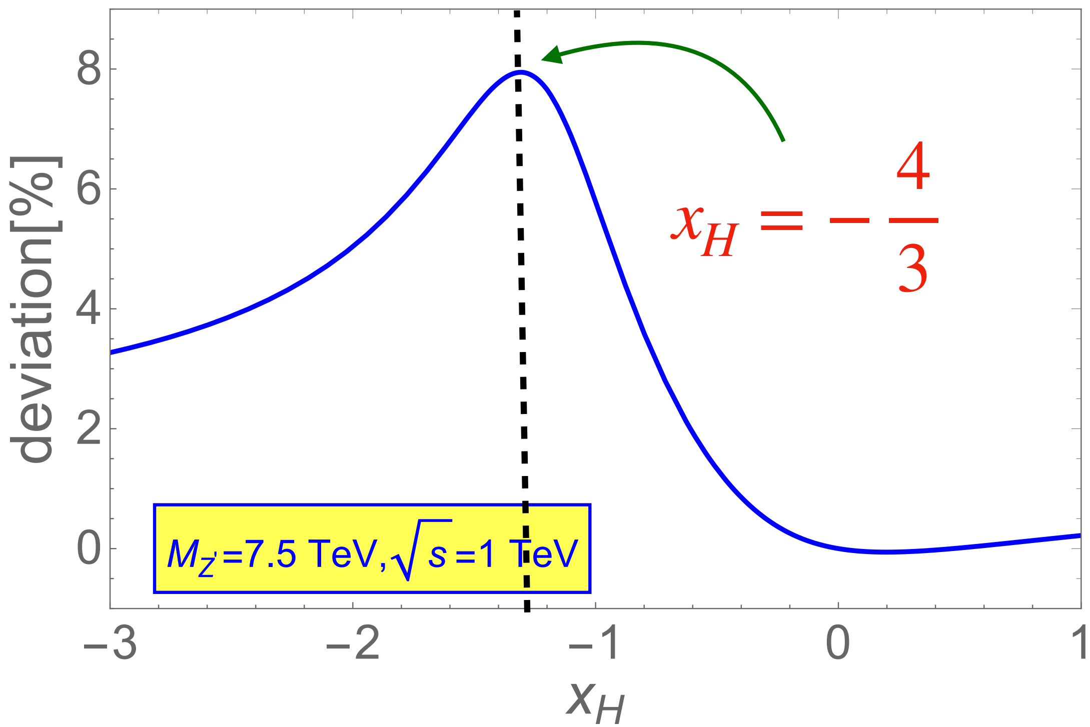


$$Deviation[\%] = Abs[1 - \frac{\sigma_{U(1)_X}[E_{CM}^{ILC}, g_x^{max}, x_H, M_{Z'}]}{\sigma_{SM}[E_{CM}]}] \times 100\%.$$




Deviation for different $x_H$ at a fixed $Z'$ mass as a function of the center of mass energy of the linear collider

Deviation for a fixed center of mass energy of the linear collider for a fixed value of the $Z'$ mass and varying $x_H$



# Final sate signals

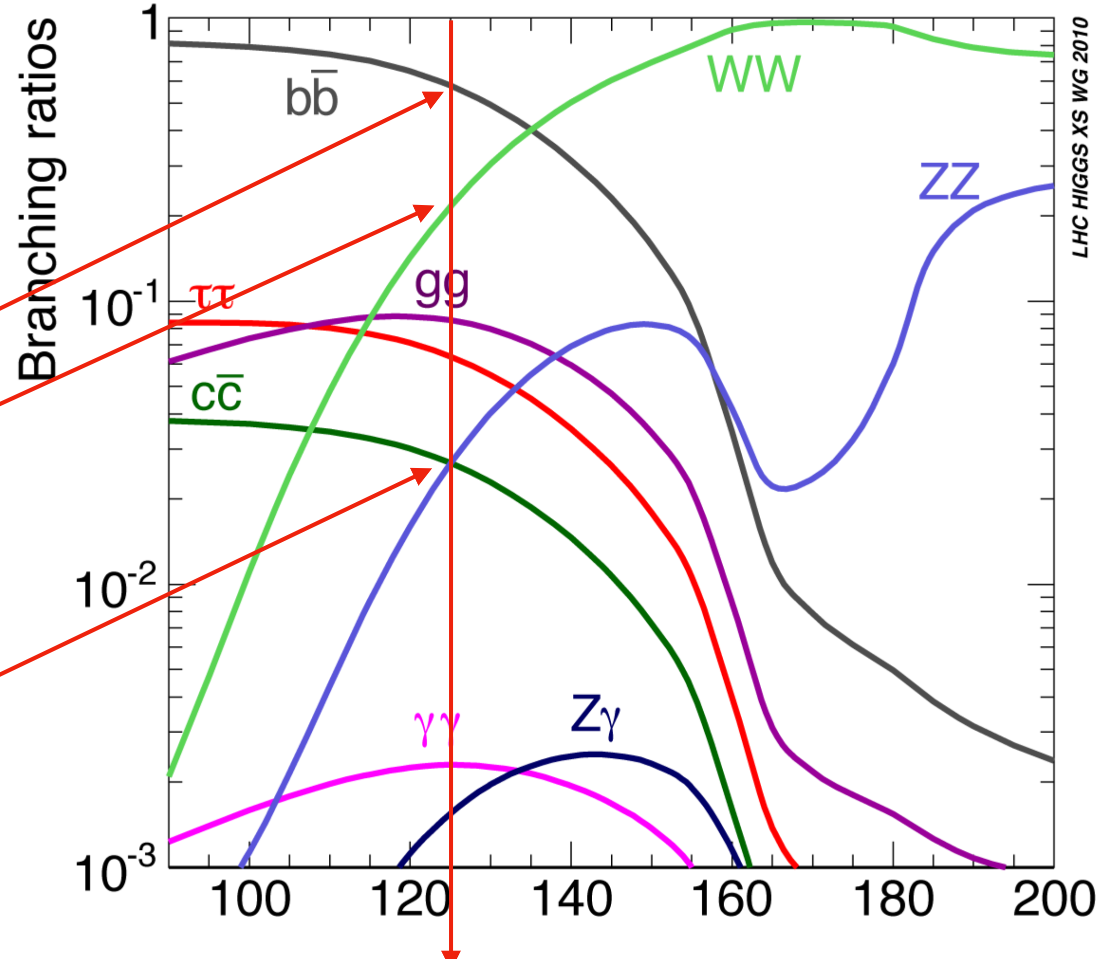
$$Zh \to 2\ell\ b\bar{b}$$

$$Zh \to 2j\ b\bar{b}$$

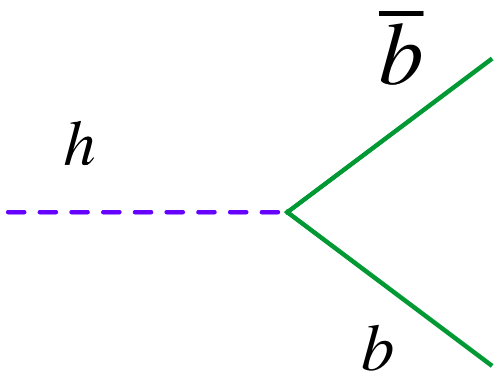
~ 60 %

~ 20 %

~ 2.5 %

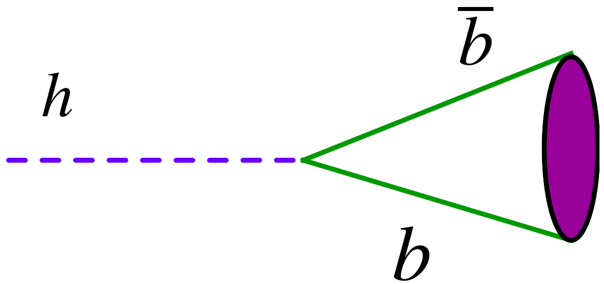



$$m_h = 125\ \text{GeV}$$




Higgs produced at rest (at the ILC)

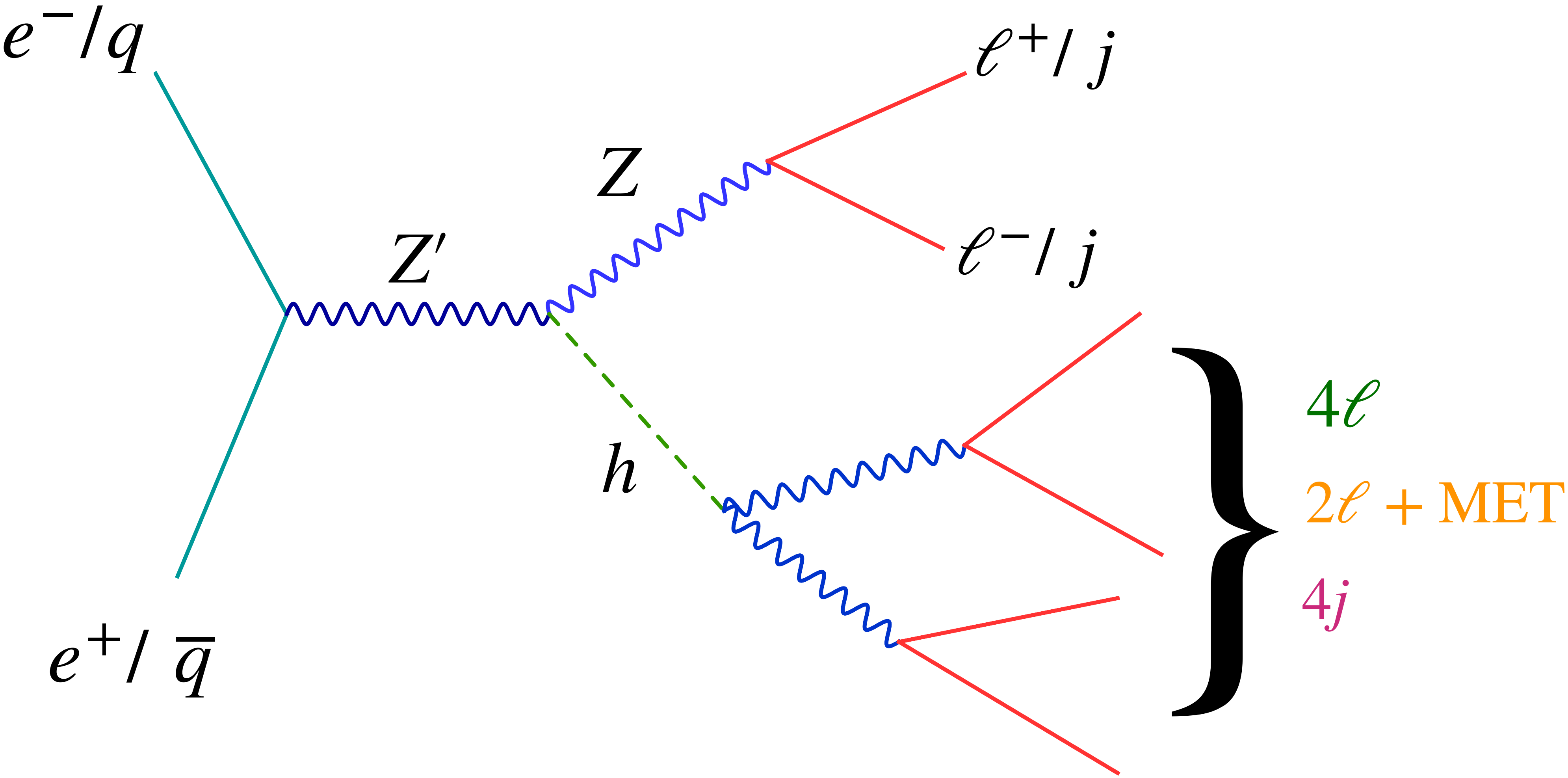
Appear soon




Boosted Higgs at the LHC

# Multilepton-multijet channels

Appear soon

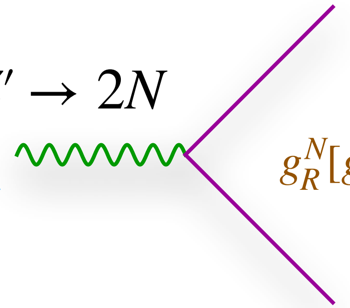



At the LHC, the produced Higgs will be boosted (also the associated Z). In such a case 4 leptons from Higgs will be collimated in such a way so that it can produce a lepton-jet like scenario.

# Right handed neutrino pair production

1906.04132

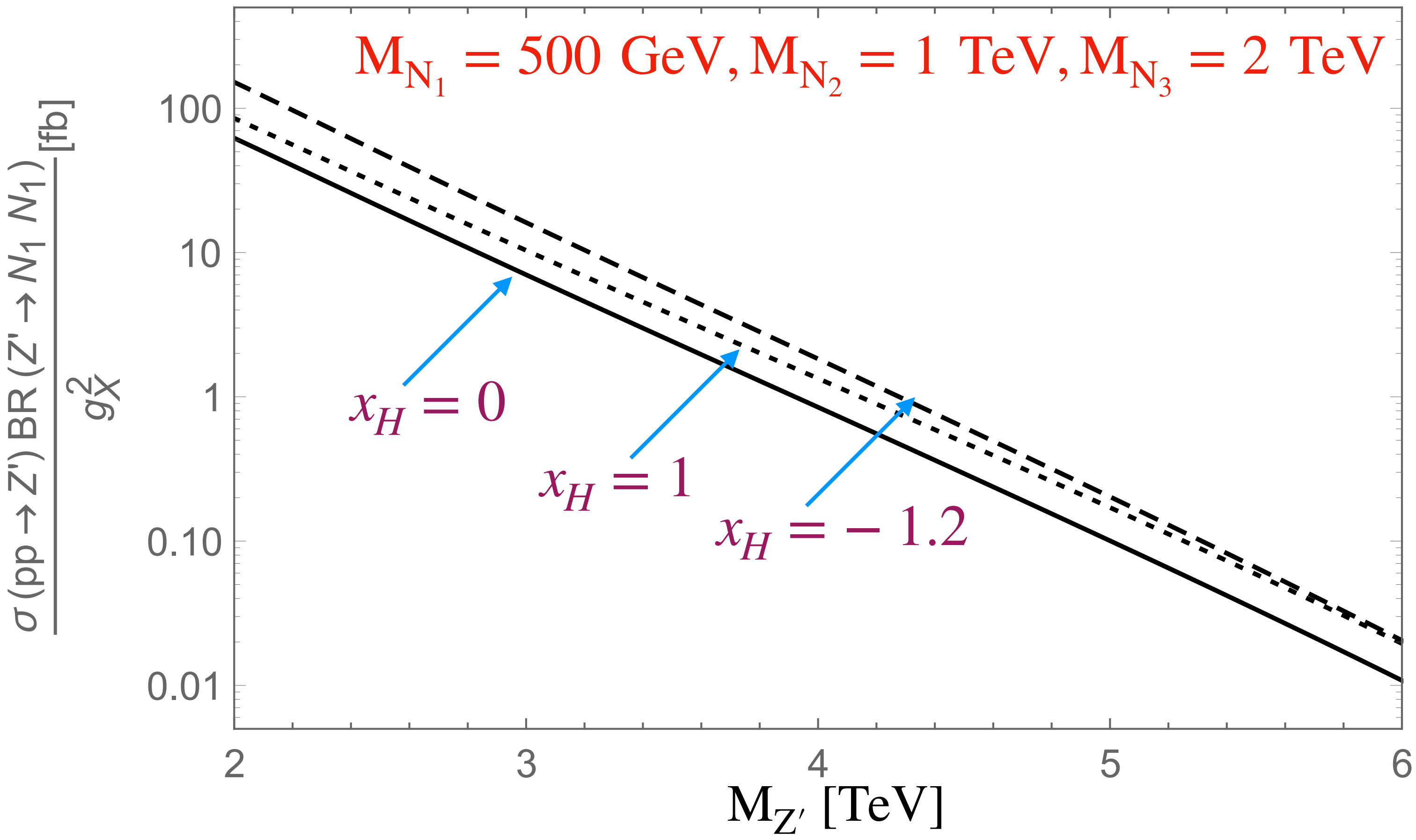
$M_{Z'} > 2M_N$ (at least)



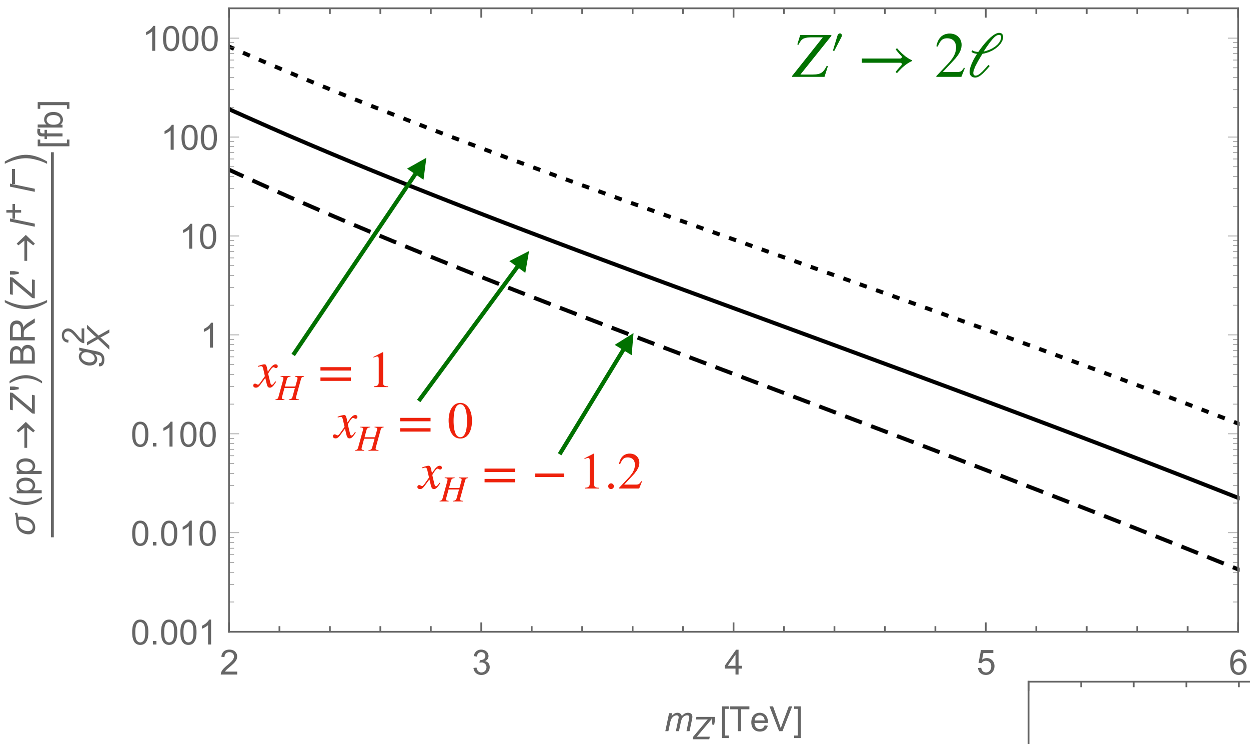

$$g_R^N[g_x, x_H] = \Big(0\; x_H + (-1)\Big) g_x$$

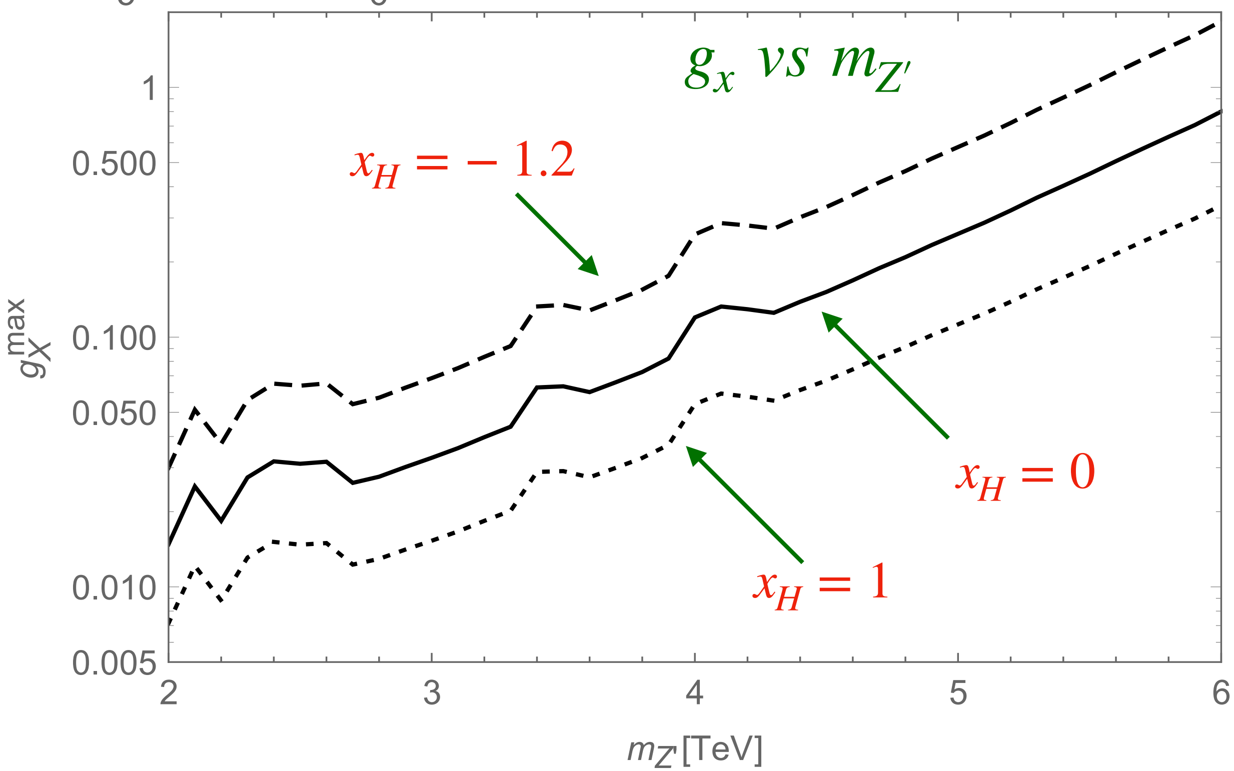
$$M_N = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

$$\Gamma[Z' \to 2N_i] = \frac{M_{Z'}}{24\pi} g_R^N[g_x, x_H]^2 \left(1 - 4\frac{M_{N_i}^2}{M_{Z'}^2}\right)^{\frac{3}{2}}$$



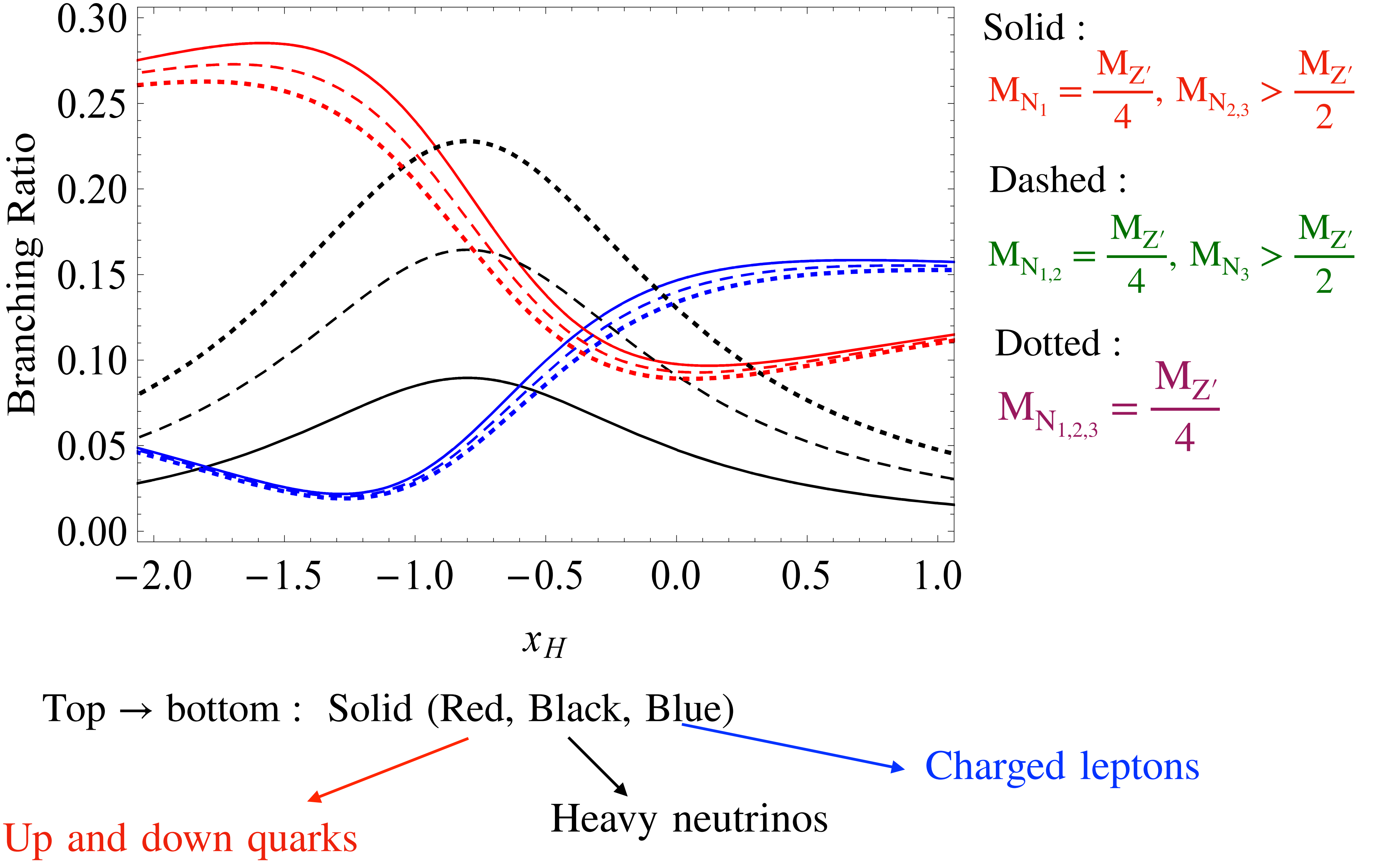
# Performance at the LHC



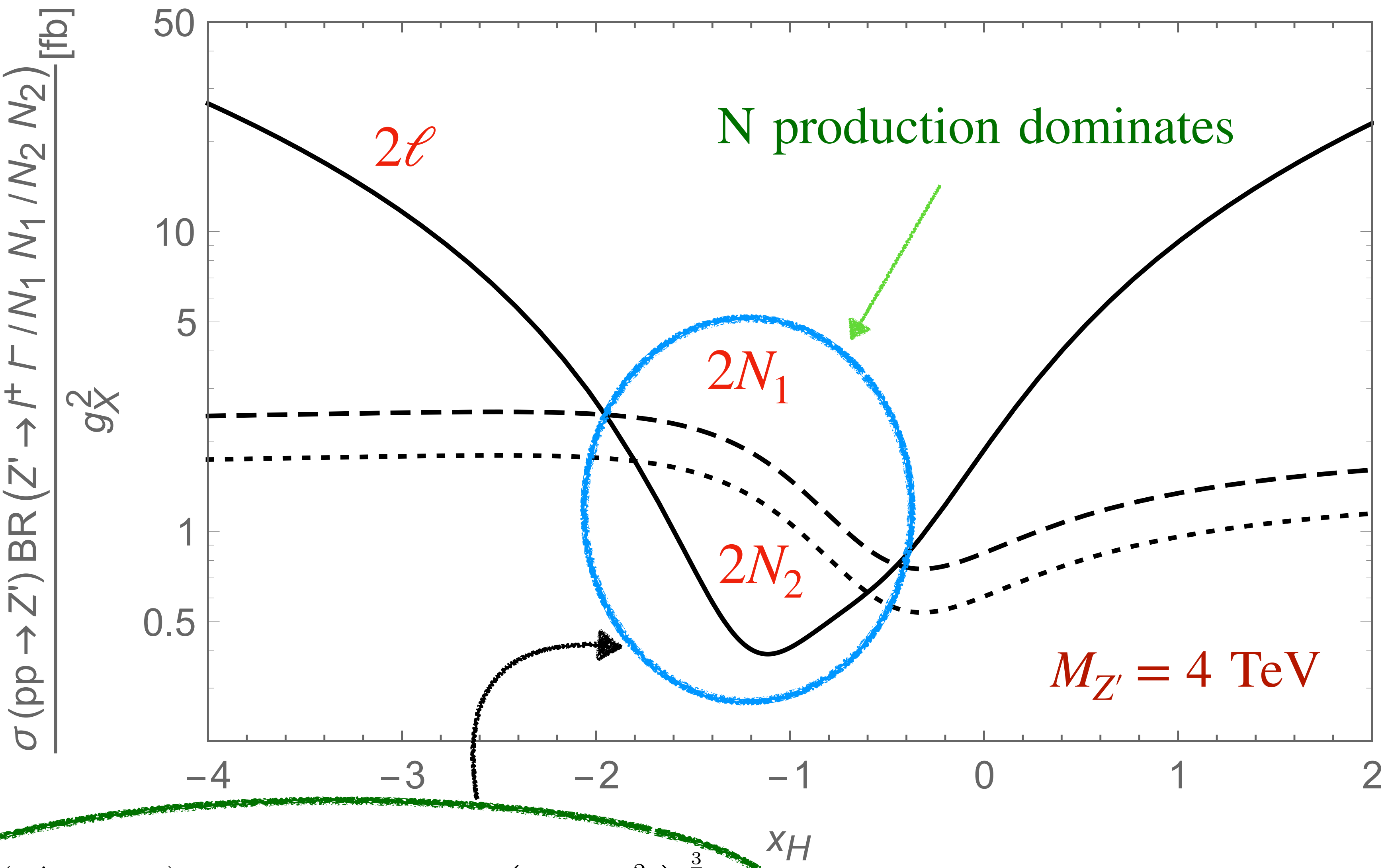
The branching ratios of $Z'$ boson as a function of $x_H$ with a fixed $M_{Z'} = 3.0$ TeV

1710.03377



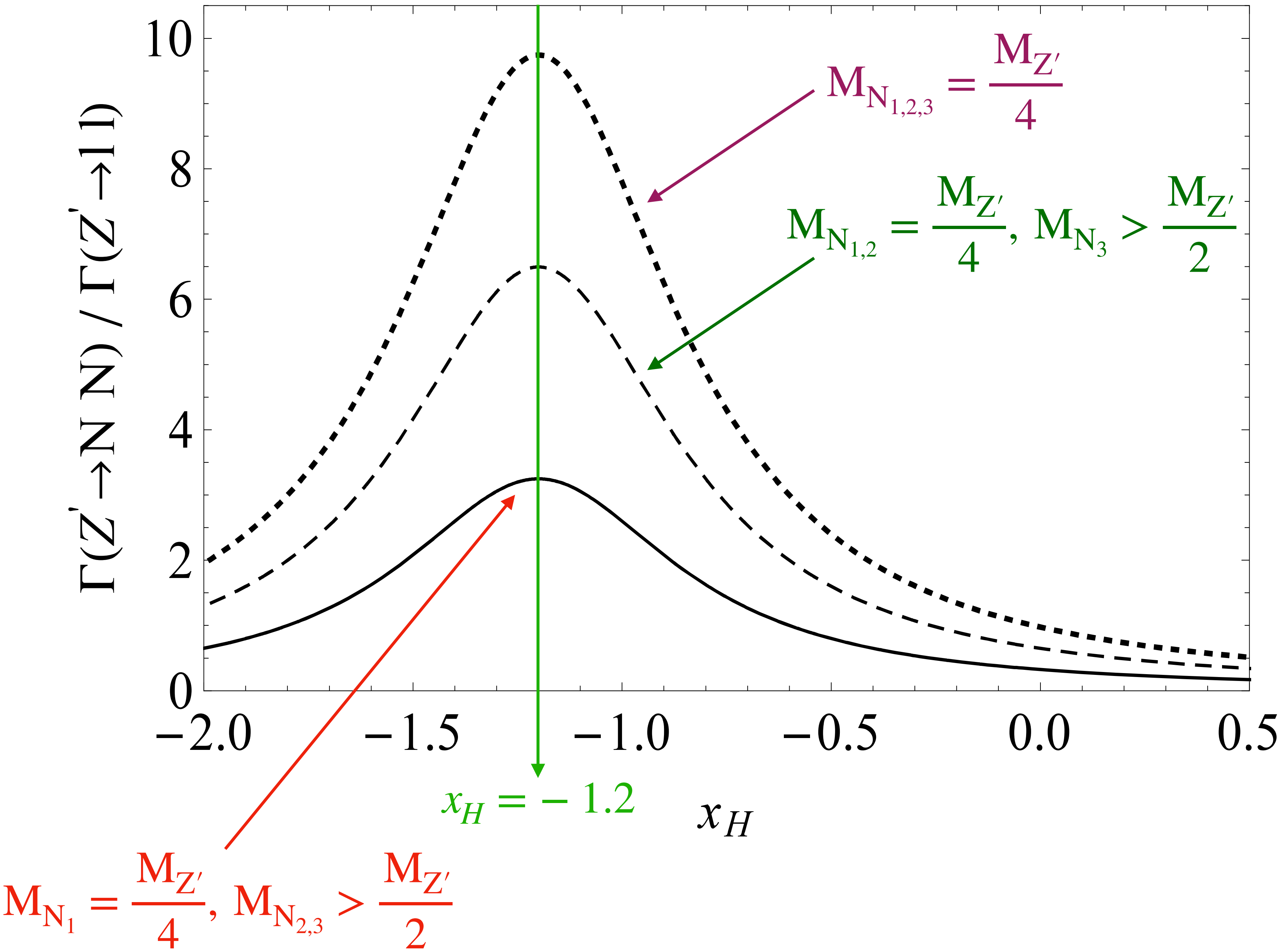
# Pair Production of the RHNs as function of $x_H$

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




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

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



# Long lived RHNs

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

Diagonalizing

$$m_\nu \simeq -m_D m_N^{-1} m_D^T$$

$$\epsilon = \mathcal{R}^* \mathcal{R}^T$$

$$\mathcal{N} = \left(1 - \tfrac{1}{2}\epsilon\right) U_{\rm PMNS} \qquad \mathcal{R} = m_D m_N^{-1}$$

Flavor to mass eigenstates

$$\nu_\alpha = \mathcal{N}_{\alpha i}\nu_i + \mathcal{R}_{\alpha i} N_i$$

$$U_{\rm PMNS}^T m_\nu U_{\rm PMNS} = {\rm diag}(m_1, m_2, m_3).$$

In the presence of $\epsilon$, the mixing matrix $\mathcal{N}$ is not unitary, namely $\mathcal{N}^\dagger \mathcal{N} \neq 1$

**Charged Current**

$$-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} W_\mu \overline{\ell_\alpha} \gamma^\mu P_L \left(\mathcal{N}_{\alpha j}\nu_j + \mathcal{R}_{\alpha j} N_j\right) + {\rm H.c.}$$

**Neutral Current**

$$-\mathcal{L}_{\rm NC} = \frac{g}{2\cos\theta_w} Z_\mu \left[\overline{\nu_i}\gamma^\mu P_L (\mathcal{N}^\dagger\mathcal{N})_{ij}\nu_j + \overline{N_i}\gamma^\mu P_L(\mathcal{R}^\dagger\mathcal{R})_{ij} N_j + \left\{\overline{\nu_i}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{R})_{ij} N_j + {\rm H.c.}\right\}\right]$$

# Generalizing the mixing parameter

$$\mathcal{R}^{\rm NH/IH} = U^*_{\rm PMNS}\sqrt{D^{\rm NH/IH}}\,O\,\sqrt{m_N^{-1}}$$

general orthogonal matrix

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos x & \sin x \\ 0 & -\sin x & \cos x \end{pmatrix} \begin{pmatrix} \cos y & 0 & \sin y \\ 0 & 1 & 0 \\ -\sin y & 0 & \cos y \end{pmatrix} \begin{pmatrix} \cos z & \sin z & 0 \\ -\sin z & \cos z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Normal hierarchy

$$D^{\rm NH} = {\rm diag}\left(m_{\rm lightest}, m_2^{\rm NH}, m_3^{\rm NH}\right)$$

$$m_2^{\rm NH} = \sqrt{\Delta m^2_{12} + m^2_{\rm lightest}}$$

$$m_3^{\rm NH} = \sqrt{\Delta m^2_{23} + (m_2^{\rm NH})^2}$$

Inverted hierarchy

$$D^{\rm IH} = {\rm diag}\left(m_1^{\rm IH}, m_2^{\rm IH}, m_{\rm lightest}\right)$$

$$m_2^{\rm IH} = \sqrt{\Delta m^2_{23} + m^2_{\rm lightest}}$$

$$m_1^{\rm IH} = \sqrt{(m_2^{\rm IH})^2 - \Delta m^2_{12}}.$$

$$m_N = {\rm diag}\left(m_{N_1}, m_{N_2}, m_{N_3}\right)$$

## Neutrino oscillation data

$$\Delta m^2_{12} = m^2_2 - m^2_1 = 7.6 \times 10^{-5}\ \text{eV}^2$$

$$\Delta m^2_{23} = |m^2_3 - m^2_2| = 2.4 \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{12} = 0.87 \qquad \sin^2 2\theta_{23} = 1.0$$

$$\sin^2 2\theta_{13} = 0.092$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\rho_1} & 0 \\ 0 & 0 & e^{i\rho_2} \end{pmatrix}$$

$$\delta = \frac{3\pi}{2}$$ NO$\nu$A, T2K

## Partial decay width of RHN

$$\Gamma(N_i \to \ell_\alpha W)^{\text{NH/IH}} = \frac{|\mathcal{R}^{\text{NH/IH}}_{\alpha i}|^2}{16\pi} \frac{(m^2_{N_i} - m^2_W)^2 (m^2_{N_i} + 2m^2_W)}{m^3_{N_i} v^2},$$

$$\Gamma(N_i \to \nu^\alpha Z)^{\text{NH/IH}} = \frac{|\mathcal{R}^{\text{NH/IH}}_{\alpha i}|^2}{32\pi} \frac{(m^2_{N_i} - m^2_Z)^2 (m^2_{N_i} + 2m^2_Z)}{m^3_{N_i} v^2},$$

$$\Gamma(N_i \to \nu^\alpha h)^{\text{NH/IH}} = \frac{|\mathcal{R}^{\text{NH/IH}}_{\alpha i}|^2}{32\pi} \frac{(m^2_{N_i} - m^2_h)^2}{m_{N_i} v^2}$$

$$\Gamma^{\text{NH/IH}}_{N_i} = \sum_{\alpha=e,\mu,\tau} \left[\Gamma(N_i \to \ell_\alpha W)^{\text{NH/IH}} + \Gamma(N_i \to \nu_\alpha Z)^{\text{NH/IH}} + \Gamma(N_i \to \nu_\alpha h)^{\text{NH/IH}}\right]$$

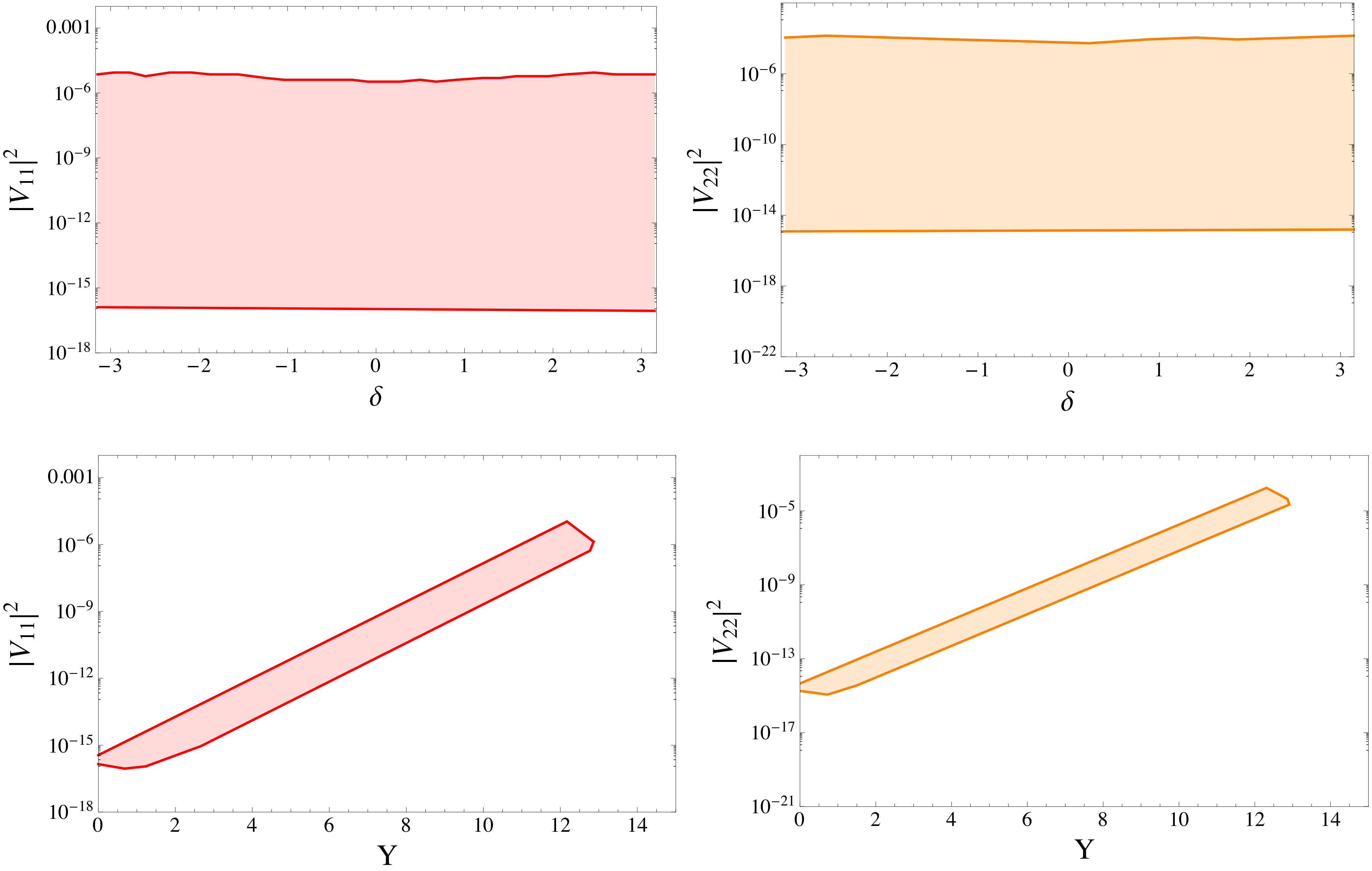
## Decay length of RHN

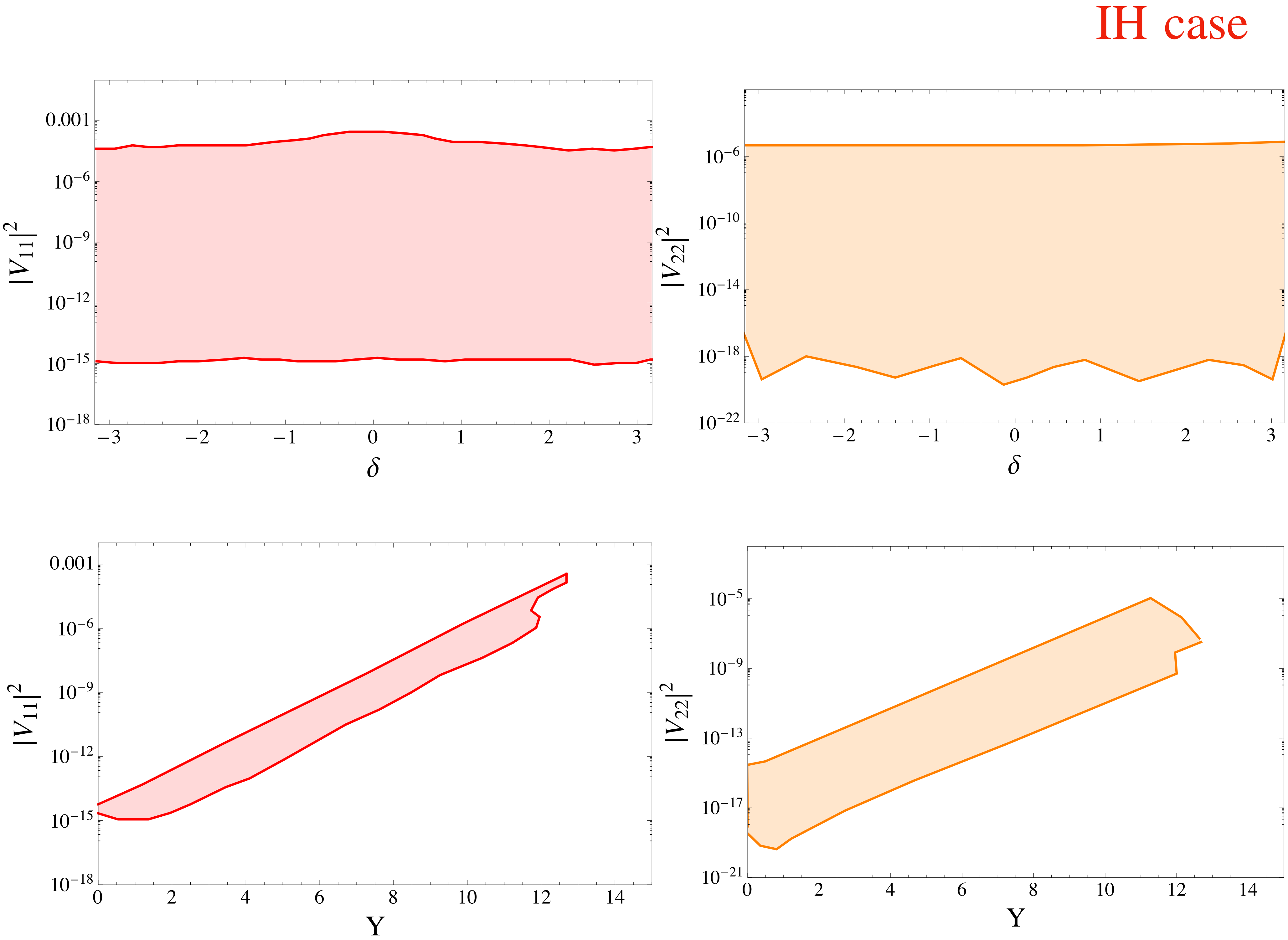
$$L^{\text{NH/IH}}_i = \frac{1.97 \times 10^{-13}}{\Gamma^{\text{NH/IH}}_{N_i}[\text{GeV}]}\ [\text{mm}].$$

# Mixing angle reach for the two generations of RHN

1702.04668

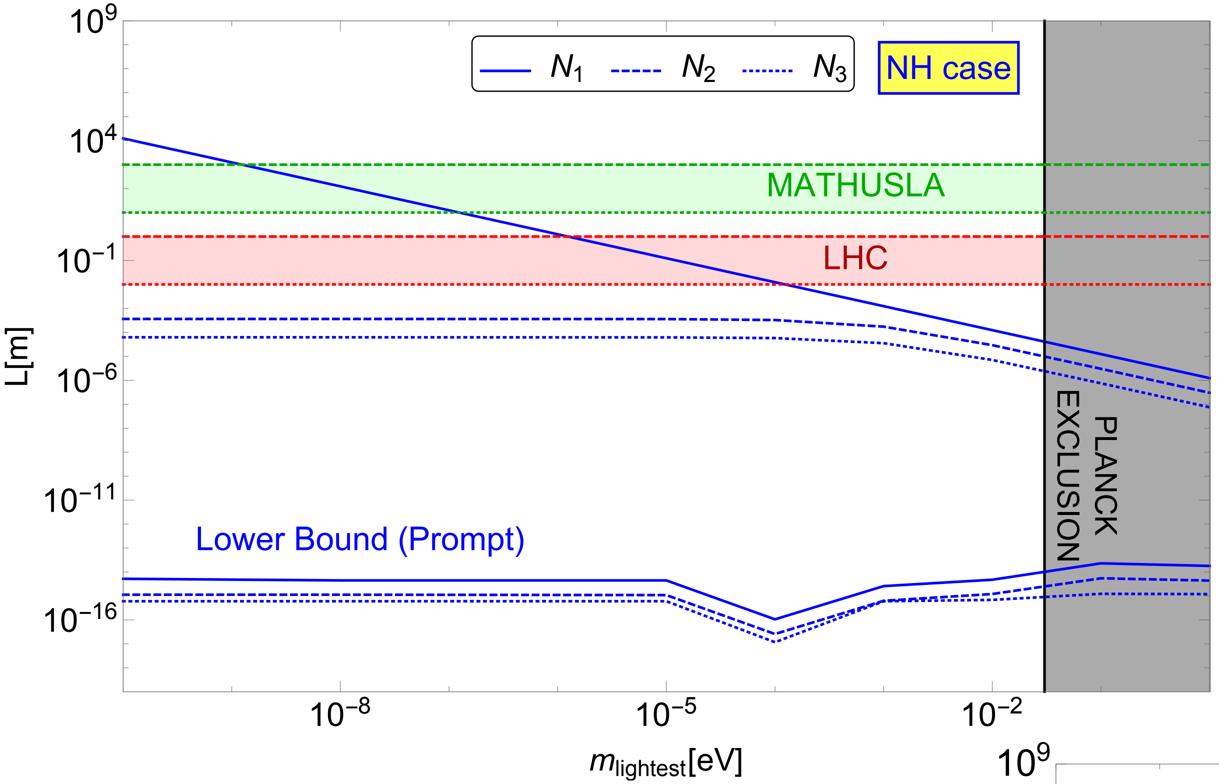
## NH case





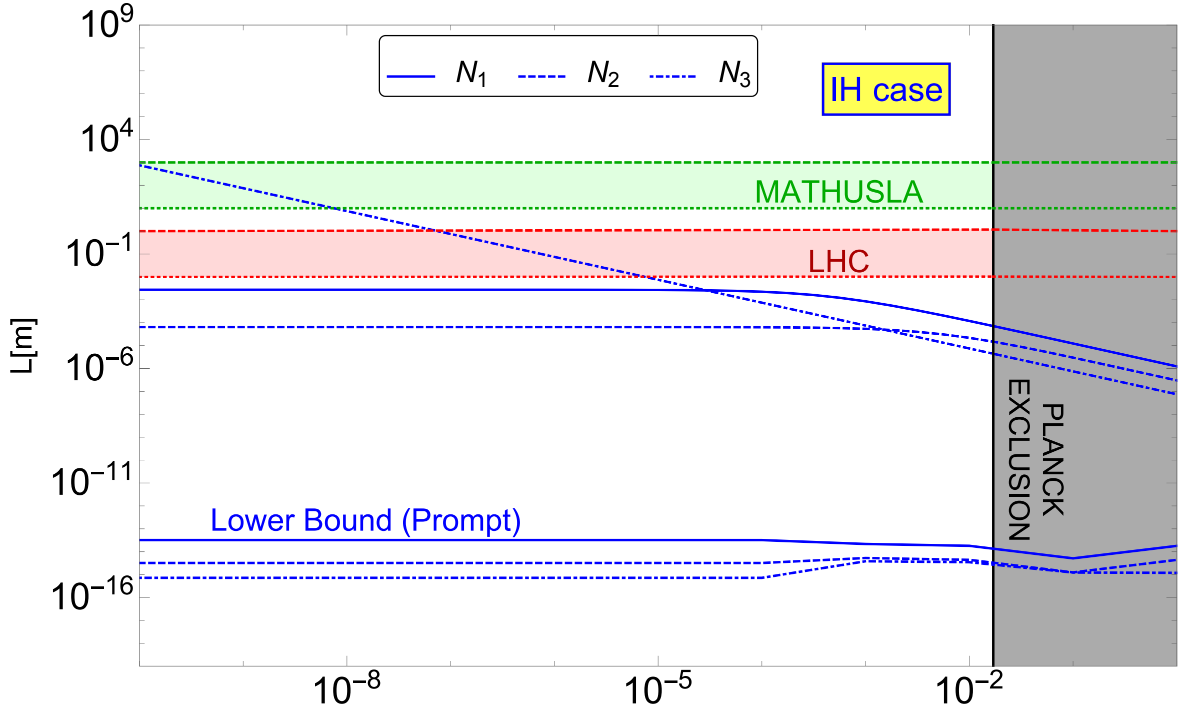
IH case
0.001
$10^{-6}$
$10^{-9}$
$10^{-12}$
$10^{-15}$
$10^{-18}$
$|V_{11}|^2$
$\delta$
$10^{-6}$
$10^{-10}$
$10^{-14}$
$10^{-18}$
$10^{-22}$
$|V_{22}|^2$
−3
−2
−1
0
1
2
3
Y
0
2
4
6
8
10
12
14
$10^{-5}$
$10^{-9}$
$10^{-13}$
$10^{-17}$
$10^{-21}$

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



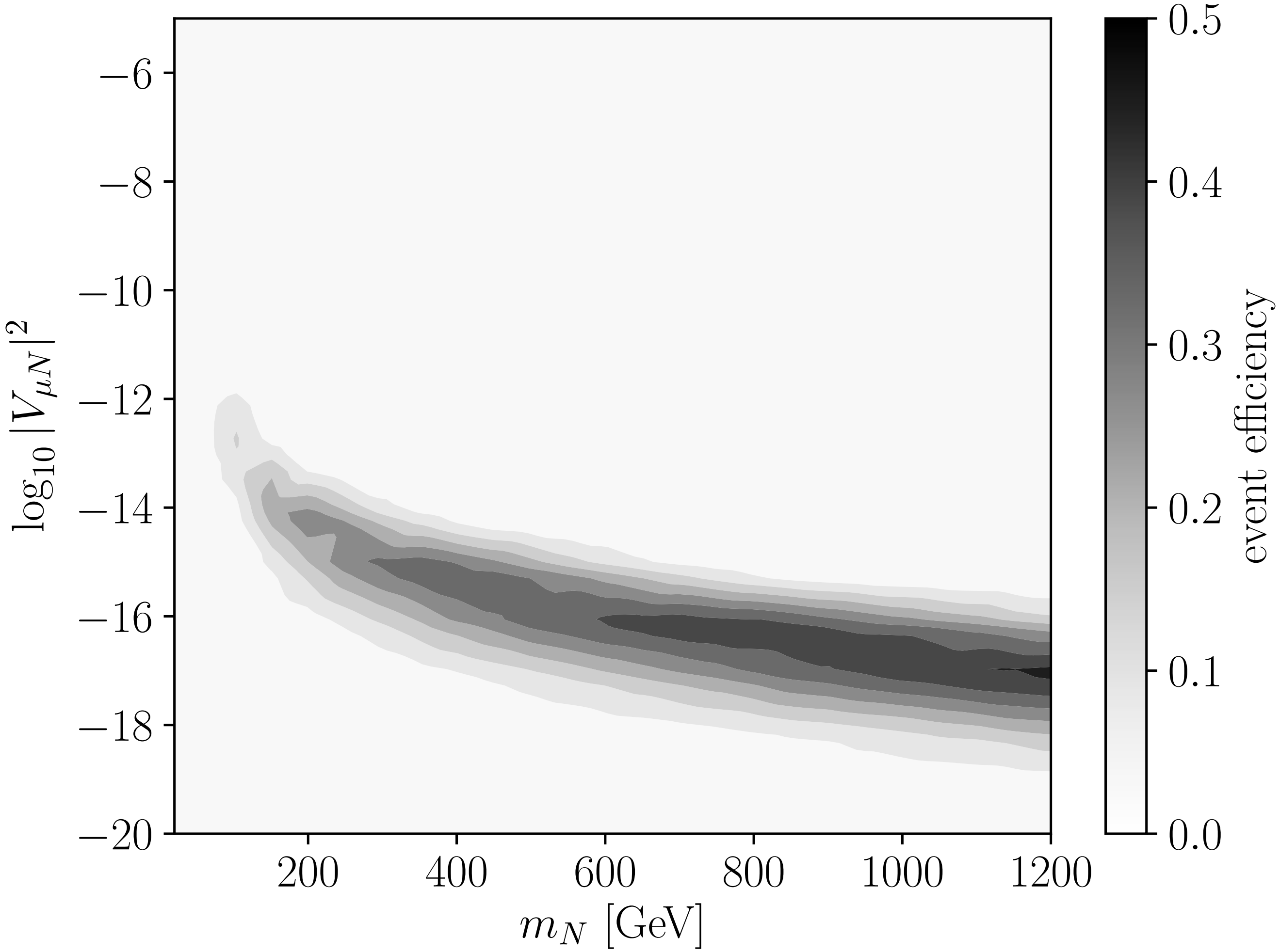

$M_{N_1} = 500$ GeV $M_{N_2} = 1$ TeV

$M_{N_3} = 2$ TeV



# ATLAS – 1DV 1908.09838

| | |
|---|---|
| Trigger | Muon: $\lvert\eta\rvert < 1.07$ and $p_T > 55$ GeV |
| | Electron: $\lvert\eta\rvert < 2.47$ and $p_T > 120$ GeV |
| DV region | DV within 4 mm $< r_{DV} <$ 300 mm and $\lvert z_{DV}\rvert <$ 300 mm |
| DV selection | Made from tracks with $\lvert d_0\rvert > 2$ mm and with $p_T > 1$ GeV |
| | DV track multiplicity $N_{trk} \geq 4$ and invariant mass $m_{DV} \geq 5$ GeV |

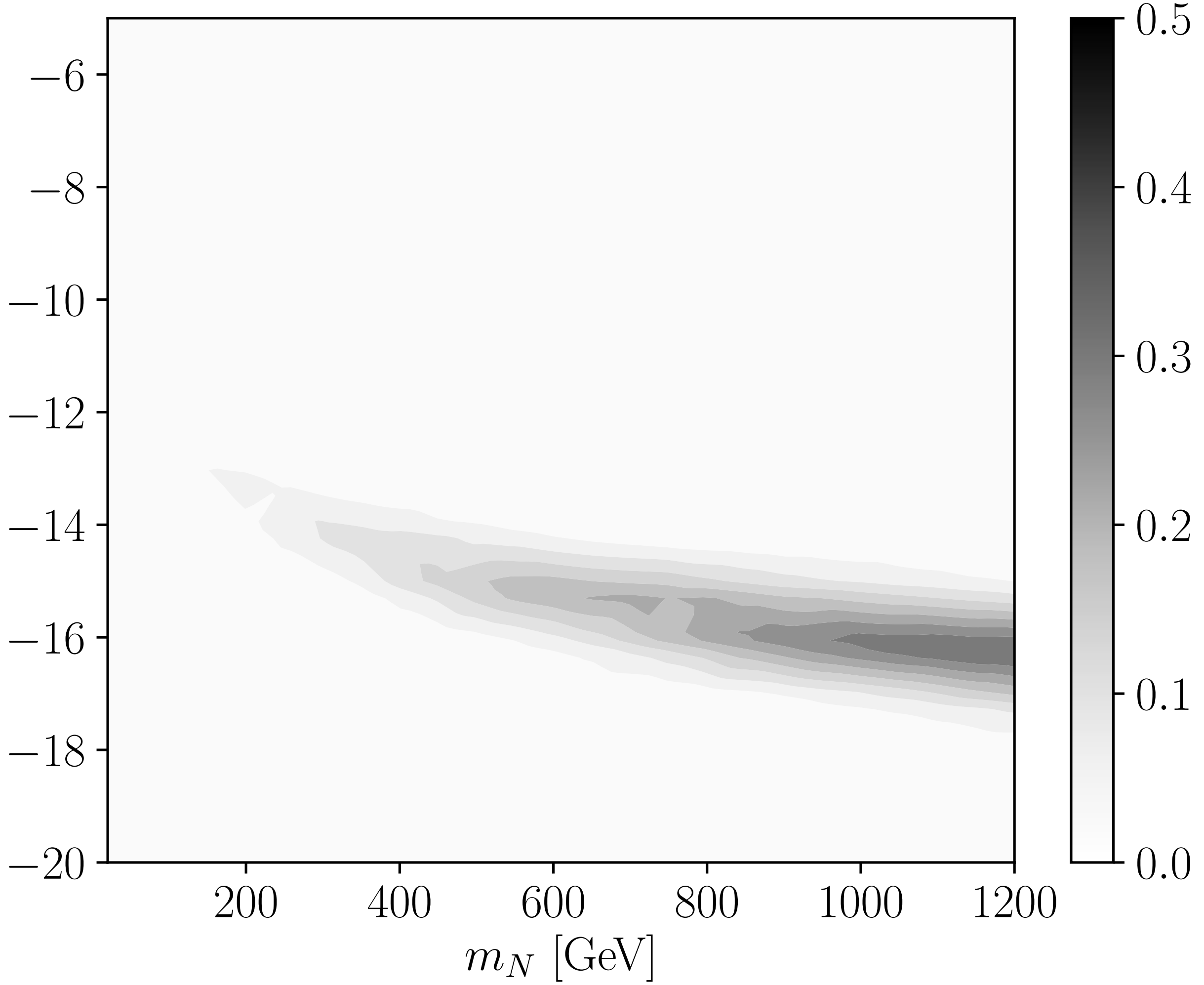



Large efficiency
at heavier RHNs

# CMS – 2DV

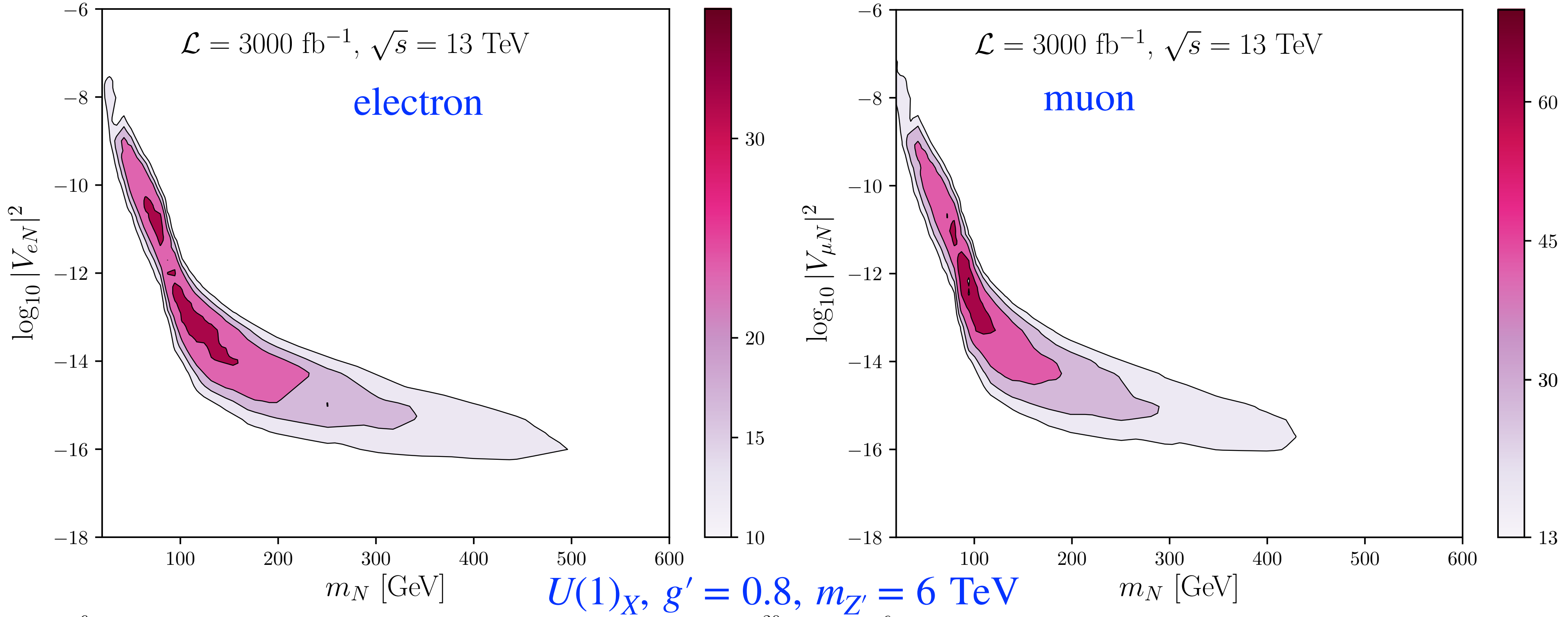
| | |
|---|---|
| Trigger | $H_T > 1000$ GeV |
| Jet selection | At least 4 jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$ |
| DV region | 2 DVs within 0.1 mm $< r_{DV} <$ 20 mm and $d_{VV} >$ 0.4 mm |
| DV selection | Made from tracks with $\|d_0\| \geq 0.1$ mm, $p_T > 20$ GeV and $\|\eta\| < 2.5$. |
| | $\sum p_T \geq 350$ GeV, correcting for $b$ quarks. |

Large efficiency at heavier RHNs

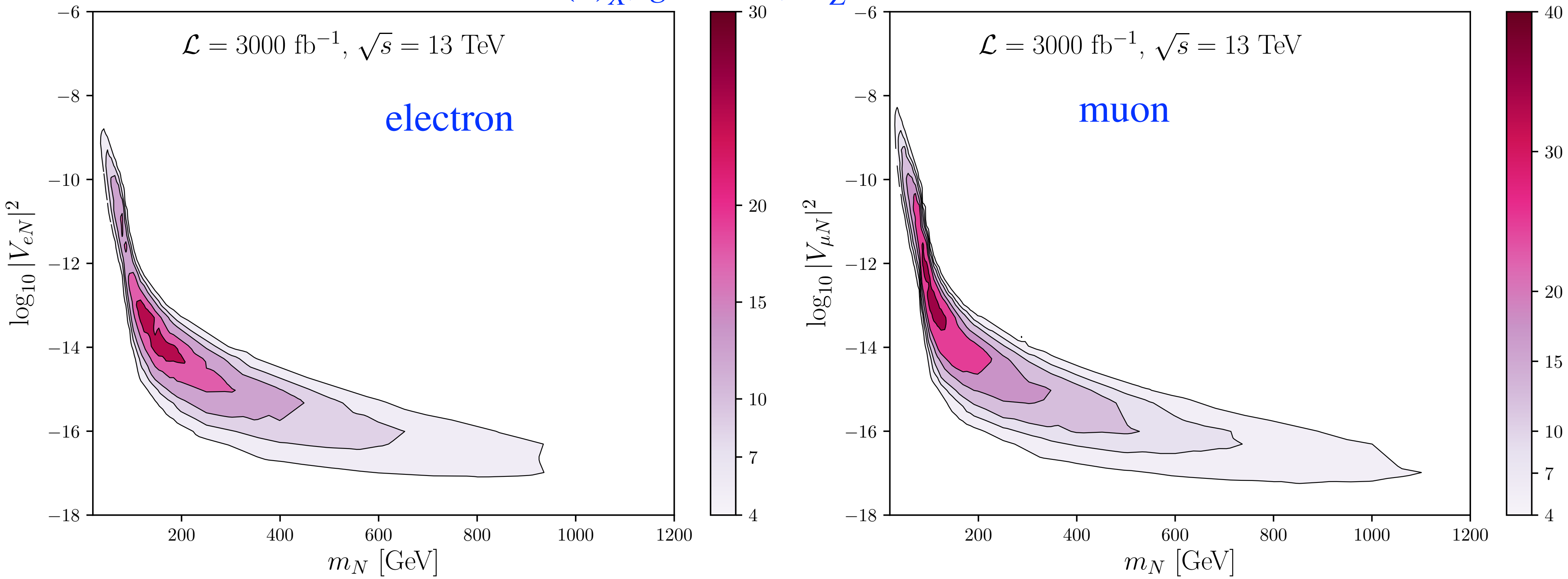


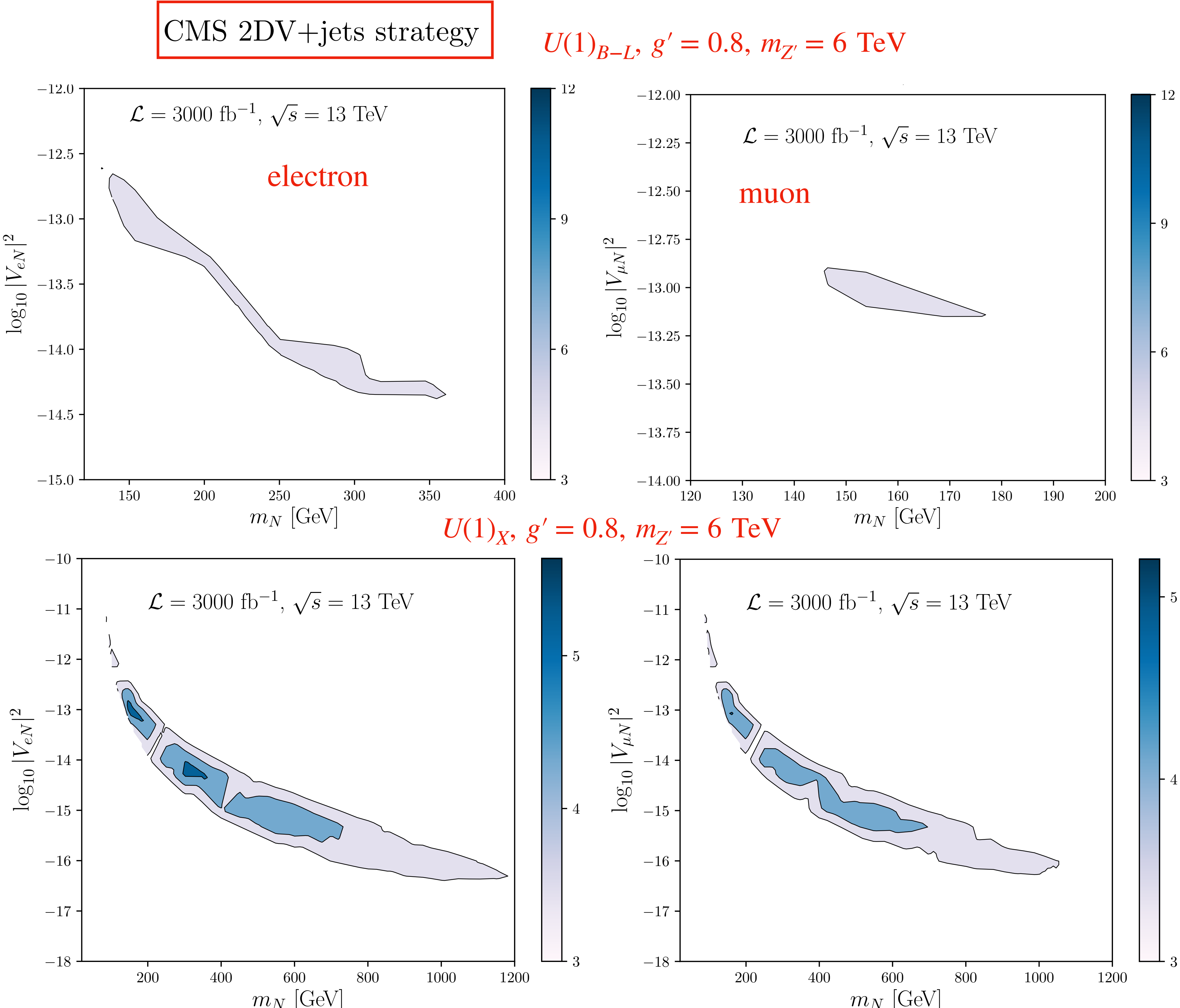
$\sqrt{s} = 13$ TeV expected in $\mathcal{L} = 3000$ fb$^{-1}$ with the ATLAS 1DV ID

$U(1)_{B-L}$, $g' = 0.8$, $m_{Z'} = 6$ TeV




$U(1)_X$, $g' = 0.8$, $m_{Z'} = 6$ TeV





CMS 2DV+jets strategy
$U(1)_{B-L}$, $g' = 0.8$, $m_{Z'} = 6$ TeV
$\mathcal{L} = 3000$ fb$^{-1}$, $\sqrt{s} = 13$ TeV
electron
muon
$\log_{10}|V_{eN}|^2$
$\log_{10}|V_{\mu N}|^2$
$m_N$ [GeV]
$U(1)_X$, $g' = 0.8$, $m_{Z'} = 6$ TeV

# Alternative scenario under $U(1)_X$

1812.11931

| | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_X$ |
|---|---|---|---|---|
| $q_{L_i}$ | **3** | **2** | $1/6$ | $(1/6)x_H + (1/3)$ |
| $u_{R_i}$ | **3** | **1** | $2/3$ | $(2/3)x_H + (1/3)$ |
| $d_{R_i}$ | **3** | **1** | $-1/3$ | $-(1/3)x_H + (1/3)$ |
| $\ell_{L_i}$ | **1** | **2** | $-1/2$ | $(-1/2)x_H - 1$ |
| $e_{R_i}$ | **1** | **1** | $-1$ | $-x_H - 1$ |
| $H$ | **1** | **2** | $-1/2$ | $(-1/2)x_H$ |
| $N_{R_{1,2}}$ | **1** | **1** | $0$ | $-4$ |
| $N_{R_3}$ | **1** | **1** | $0$ | $+5$ |
| $H_E$ | **1** | **2** | $-1/2$ | $(-1/2)x_H + 3$ |
| $\Phi_A$ | **1** | **1** | $0$ | $+8$ |
| $\Phi_B$ | **1** | **1** | $0$ | $-10$ |
| $\Phi_C$ | **1** | **1** | $0$ | $-3$ |

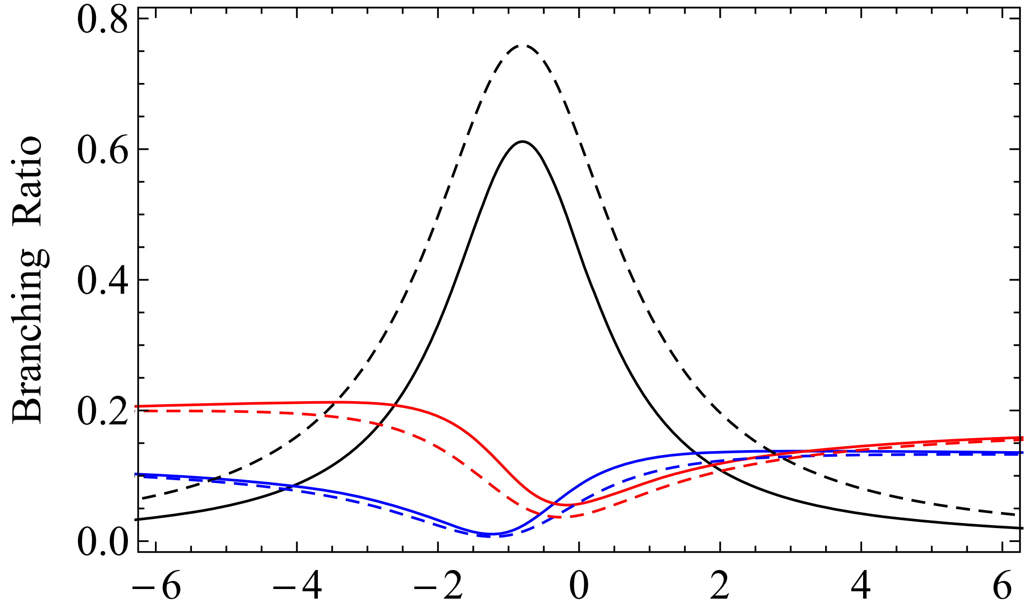
Possible alternative $B - L$, with $x_H = 0$

Detailed scalar sector study

**In Progress**

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

$x_H = -1$




$m_{Z'} = 3$ TeV.

Solid

$m_{N^1} = m_{Z'}/4$

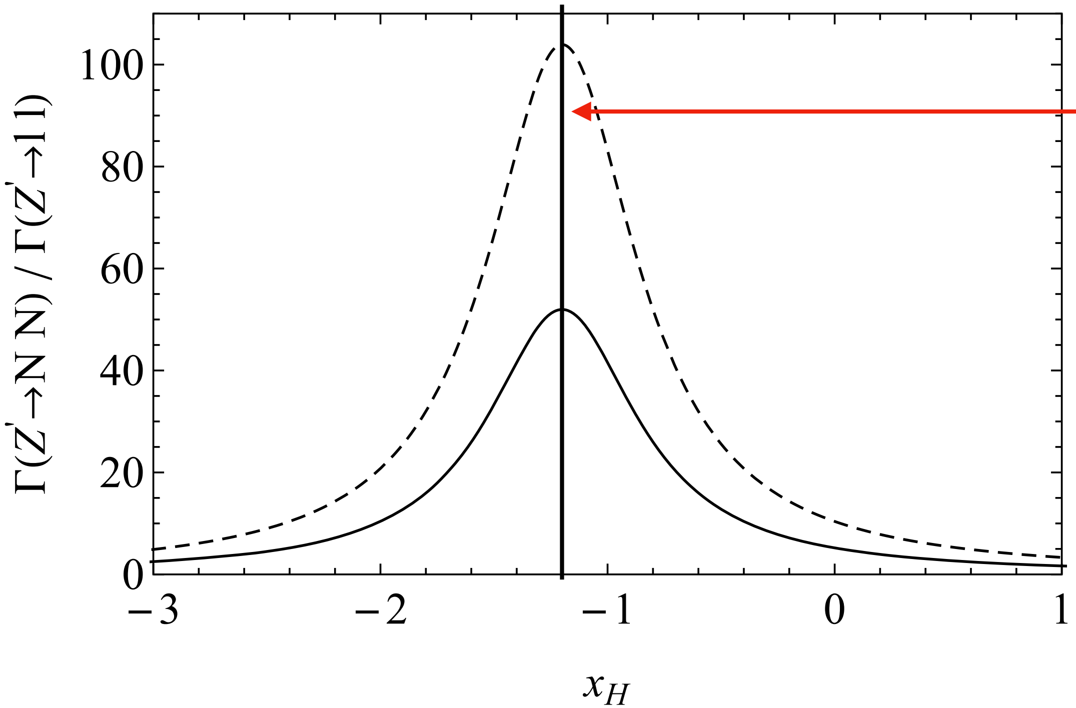
$m_{N^2} > m_{Z'}/2,$

Dashed

$m_{N^{1,2}} = m_{Z'}/4.$

Top → bottom : Solid (Red, Black, Blue)

Up and down quarks  Heavy neutrinos  Charged leptons

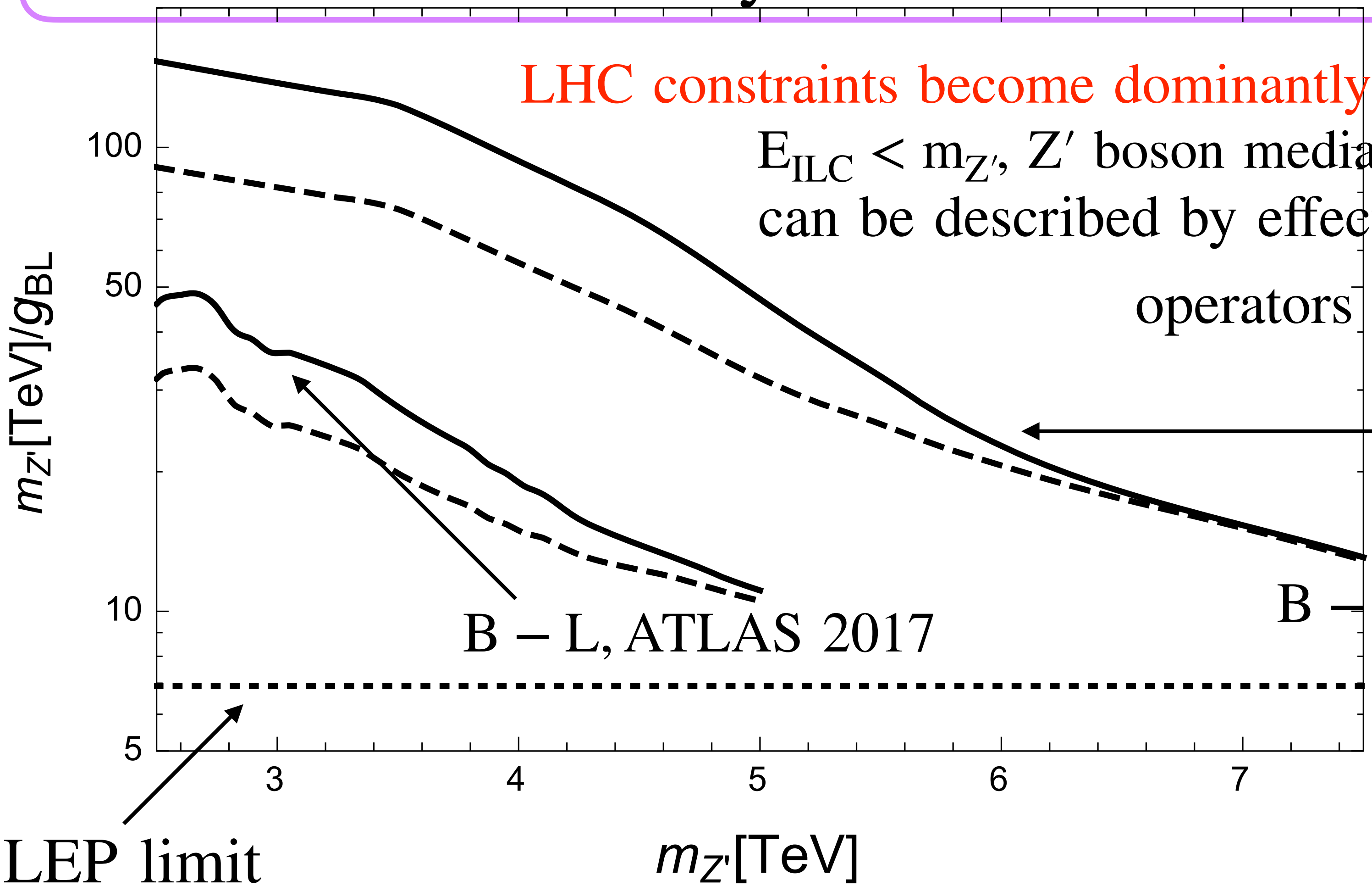



$x_H = -1.2$

Solid $m_{N^1} = m_{Z'}/4$ $m_{N^2} > m_{Z'}/2,$

Dashed $m_{N^{1,2}} = m_{Z'}/4.$

# Production of the heavy neutrino at the ILC



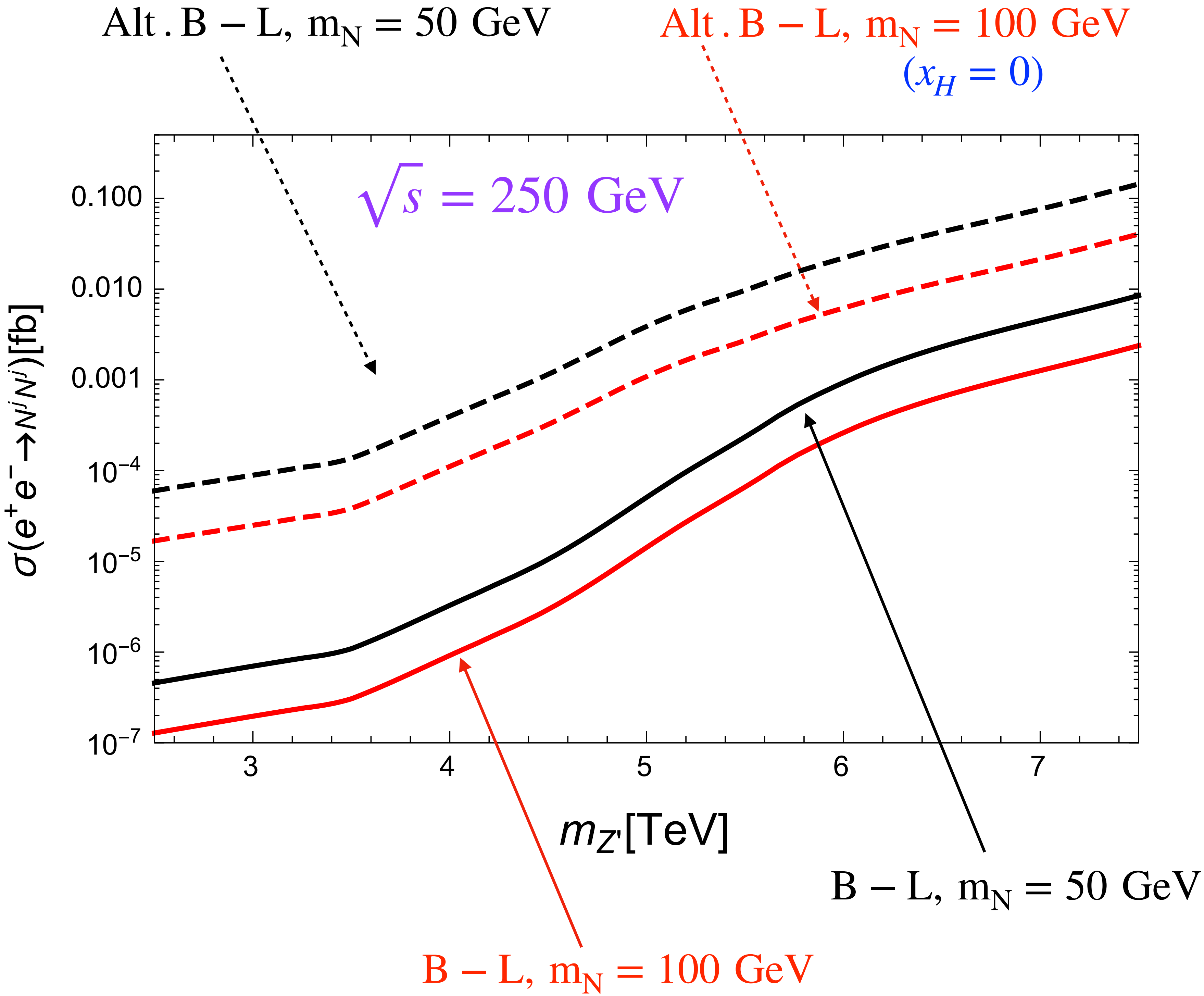

LHC constraints become dominantly weaker with heavier $Z'$

$E_{ILC} < m_{Z'}$, $Z'$ boson mediated processes at the ILC can be described by effective higher dimensional operators $\propto \left(\frac{m_{Z'}}{g_{BL}}\right)^2$

Dashed lines represent the Atl. B – L case

$$\sigma(e^+e^- \to Z'^* \to N^i N^i) \simeq \frac{(Q_{N^i})^2}{24\pi} s \left(\frac{g_{BL}}{m_{Z'}}\right)^4 \left(1 - \frac{4m_{N^i}^2}{m_{Z'}^2}\right)^{\frac{3}{2}}.$$

As a result ILC is a powerful machine to probe $Z'$ beyond HL – LHC



Alt . B − L, m_N = 50 GeV
Alt . B − L, m_N = 100 GeV
(x_H = 0)
√s = 250 GeV
0.100
0.010
0.001
10^−4
10^−5
10^−6
10^−7
σ(e^+e^− → N^j N^j)[fb]
3
4
5
6
7
m_Z'[TeV]
B − L, m_N = 50 GeV
B − L, m_N = 100 GeV

$m_{Z'} = 7.5$ TeV $\sqrt{s} = 250$ GeV

$$\sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.0085 \text{ fb (B − L)}$$
$$= 0.14 \text{ fb (Alt. B − L)}$$

$m_{N1,2,3} = 50$ GeV and $m_{N1,2} = 50$ GeV

degenerate RHNs @ $\sum_{i=1}^{3} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.026$ fb (B − L)

$\sum_{i=1}^{2} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.29$ fb (Alt. B − L)

Luminosity = 2000 $\text{fb}^{-1}$ 52 and 576 events respectively

satisfying constraints from the HL − LHC

Majorana RHNs will show $\ell^\pm \ell^\pm 4j$ signal which can be a smoking gun signature data fitting.
at the ILC to probe Majorana nature. Let's find the branching ratios after the neutrino

# B – L

| $m_N = 50$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.412 | 0.104 | 0.104 |
| $N^2$ | 0.204 | 0.224 | 0.224 |
| $N^3$ | 0.0154 | 0.310 | 0.310 |

| $m_N = 100$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.587 | 0.148 | 0.148 |
| $N^2$ | 0.276 | 0.304 | 0.304 |
| $N^3$ | 0.0208 | 0.431 | 0.431 |

# Alt . B – L

NH case

| $m_N = 50$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.194 | 0.213 | 0.213 |
| $N^2$ | 0.0154 | 0.318 | 0.318 |

| $m_N = 100$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.276 | 0.304 | 0.304 |
| $N^2$ | 0.0208 | 0.431 | 0.431 |

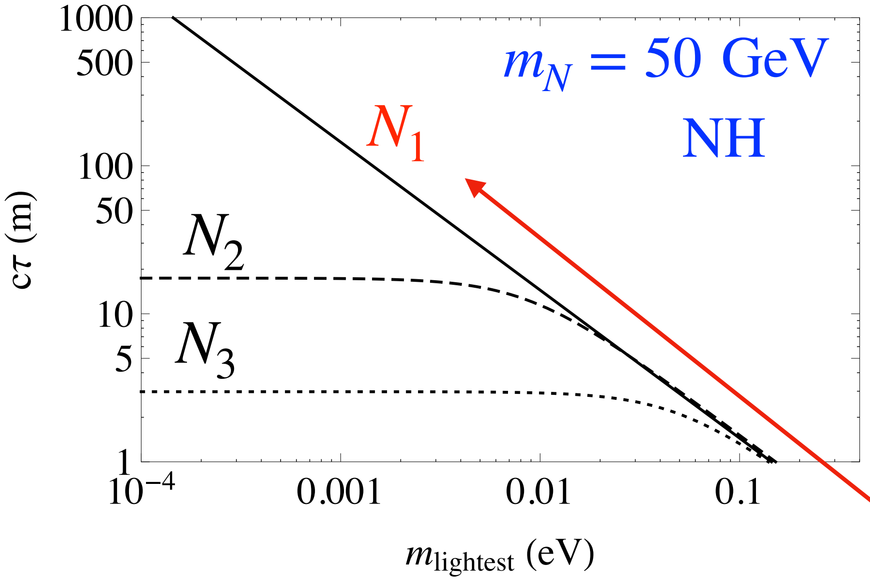
IH case

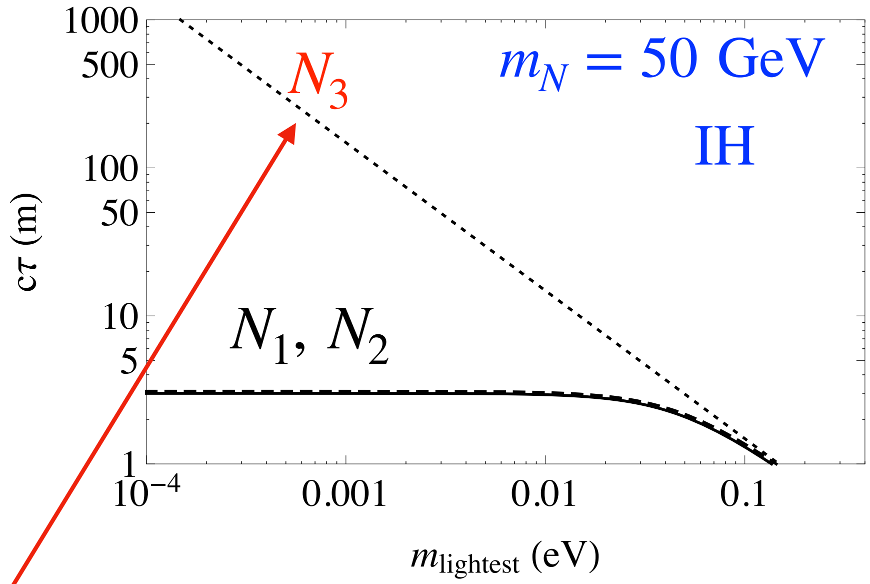
| $m_N = 50$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.412 | 0.104 | 0.104 |
| $N^2$ | 0.204 | 0.224 | 0.224 |

| $m_N = 100$ GeV | $e + jj$ | $\mu + jj$ | $\tau + jj$ |
|---|---|---|---|
| $N^1$ | 0.587 | 0.148 | 0.148 |
| $N^2$ | 0.276 | 0.304 | 0.304 |

Finally NN $\rightarrow 2\ell^{\pm}4j$ will dominantly be between 16% – 34 % for the final results for the B – L $\rightarrow$ Alt . B – Lscenario .

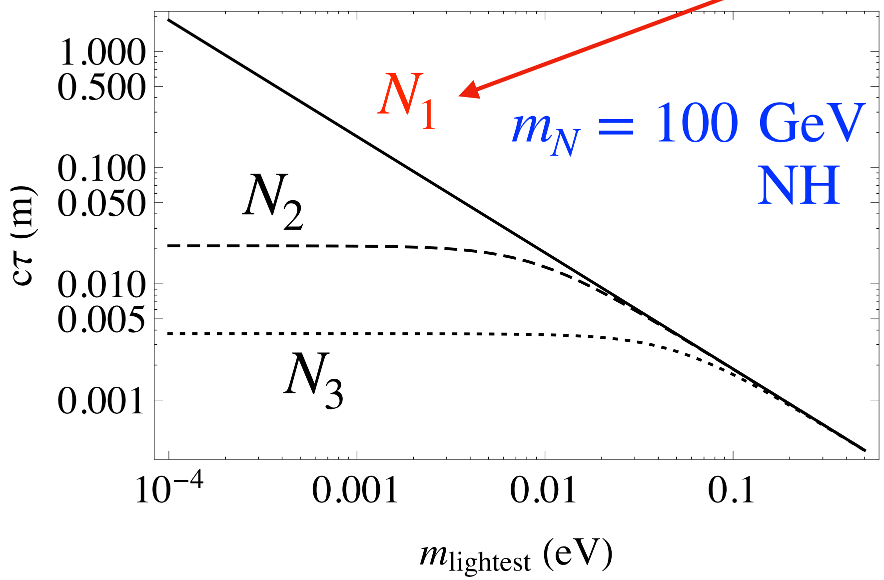
## Long lived RHNs  B − L case

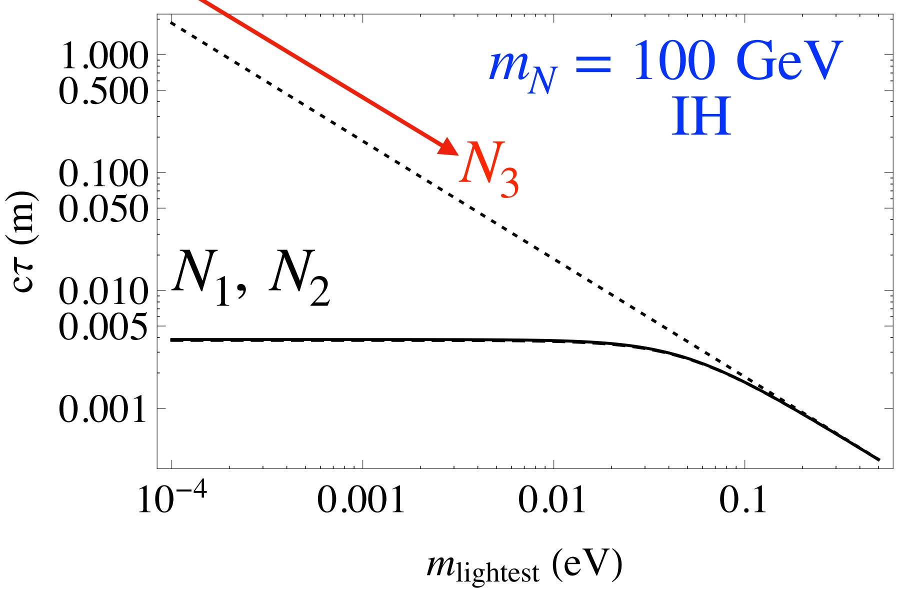



Longest lived RHN life time is inversely proportional to $m_{\text{lightest}}$

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



# Conclusions

In this work we are studying the Higgs production at the ILC from the heavy resonance. To study such a scenario we have used a general U(1) extension of the Standard Model where the Higgs production is enhanced by the additional U(1) charges obtained after the anomaly cancellations.

This model is extremely useful for the further study of the various properties of the beyond the standard model physics such as the pair production of the heavy neutrinos, displaced vertex searches for the long lived particles, dark matter physics (both of the scalar and fermion) and vacuum stability. Such studies have been performed in a variety of past literatures and also will be done in some future articles.

Finally a 250 GeV ILC can be an promising machine to probe BSM physics apart from considering it as a Higgs factory.

Thank you