Searching for beyond the standard model physics from heavy resonance at the linear collider

Arindam Das
Osaka University

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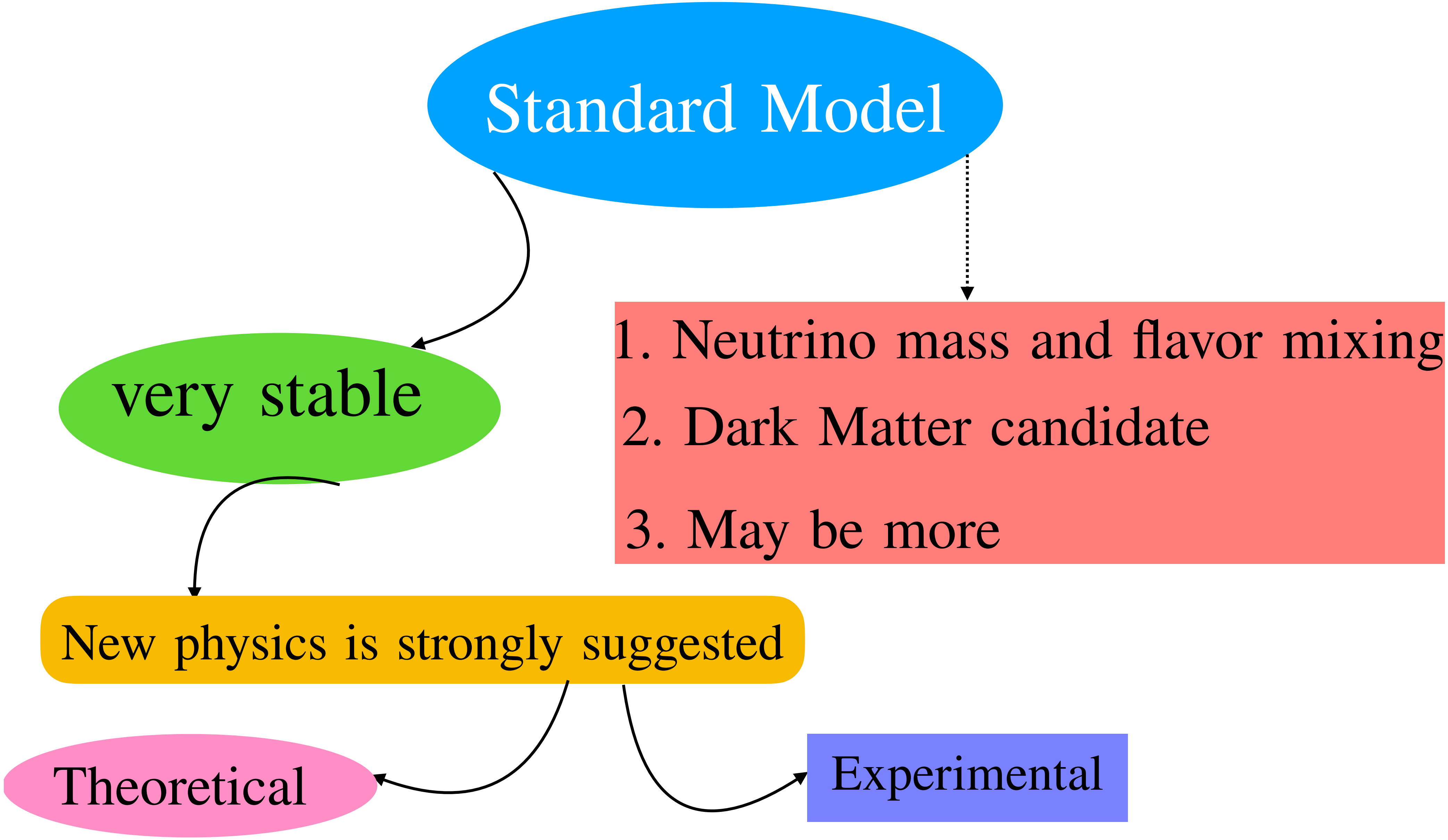


We definitely need new physics to provide missing pieces

Particle content of the model

x_H, x_Φ will appear in the coupling with Z'

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$		
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	$=$	$2x_\Phi$

$U(1)_X$ breaking

$$< \Phi > = \frac{v_\Phi}{\sqrt{2}}$$

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

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

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

Yukawa interaction

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

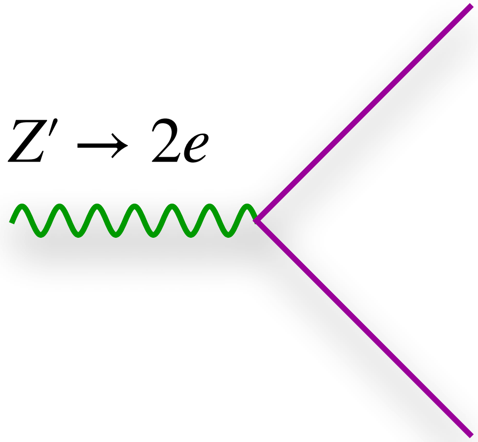
$$\mathcal{L}_Y = -\sum_{\alpha,\beta=1}^{3} Y_u^{\alpha\beta}\overline{q_L^\alpha}\tilde{H}u_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_d^{\alpha\beta}\overline{q_L^\alpha}H d_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_e^{\alpha\beta}\overline{\ell_L^\alpha}H e_R^\beta - \sum_{\alpha,\beta=1}^{3} Y_D^{\alpha\beta}\overline{\ell_L^\alpha}\tilde{H}N_R^\beta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

Interaction of Z' with the Higgs

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

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

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

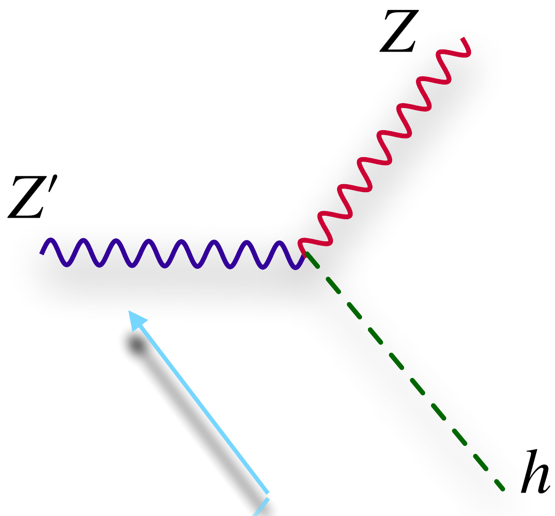


$Z - Z' - h$ coupling

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

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

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



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

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

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

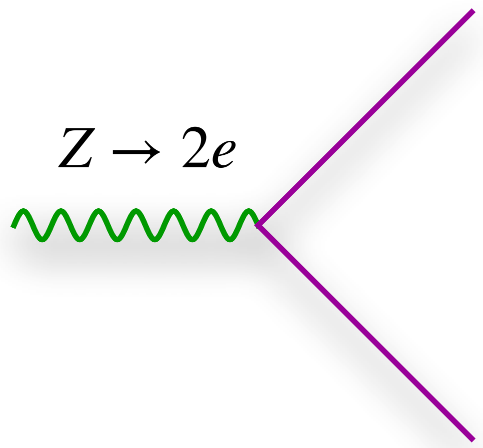
$$\Big(\lambda\Big[1,(\frac{M_Z}{M_{Z'}})^2,(\frac{m_h}{M_{Z'}})^2\Big] + 12\frac{M_Z}{M_{Z'}}\Big)$$

Interaction of Z with the Higgs

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

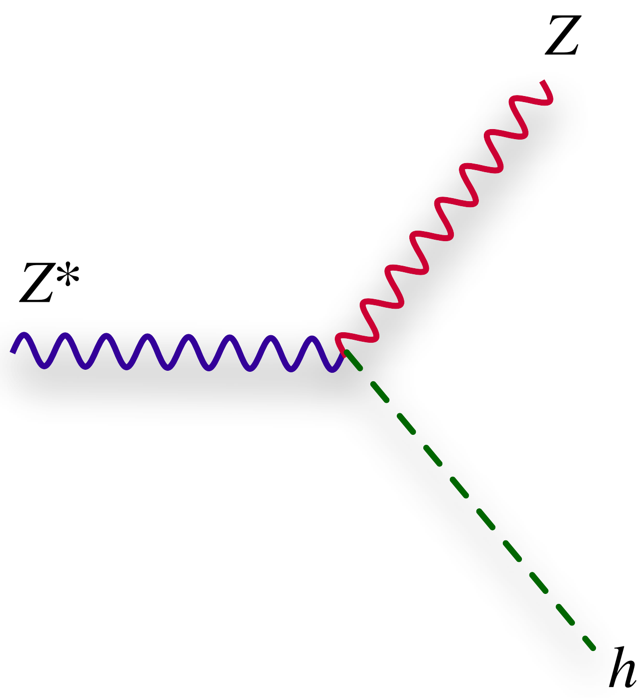
$$C_V = g_z\Big(-\tfrac{1}{4} + \sin^2\theta_W\Big)$$

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



$Z - h$ coupling

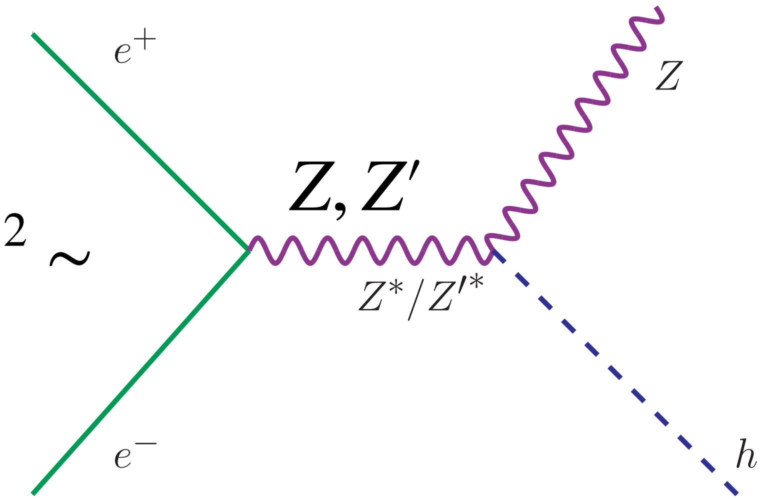
$$\begin{aligned}\mathcal{L} &\supset \left| -\frac{i}{2} g_z Z_\mu \frac{1}{\sqrt{2}}(v+h)\right|^2 \\ &= \frac{g_z^2}{8} Z_\mu Z^\mu (v^2 + 2vh + h^2) \\ &\supset \frac{M_Z^2}{v} h Z_\mu Z^\mu\end{aligned}$$



Production process at the linear collider

with N. Okada (appear soon)

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



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

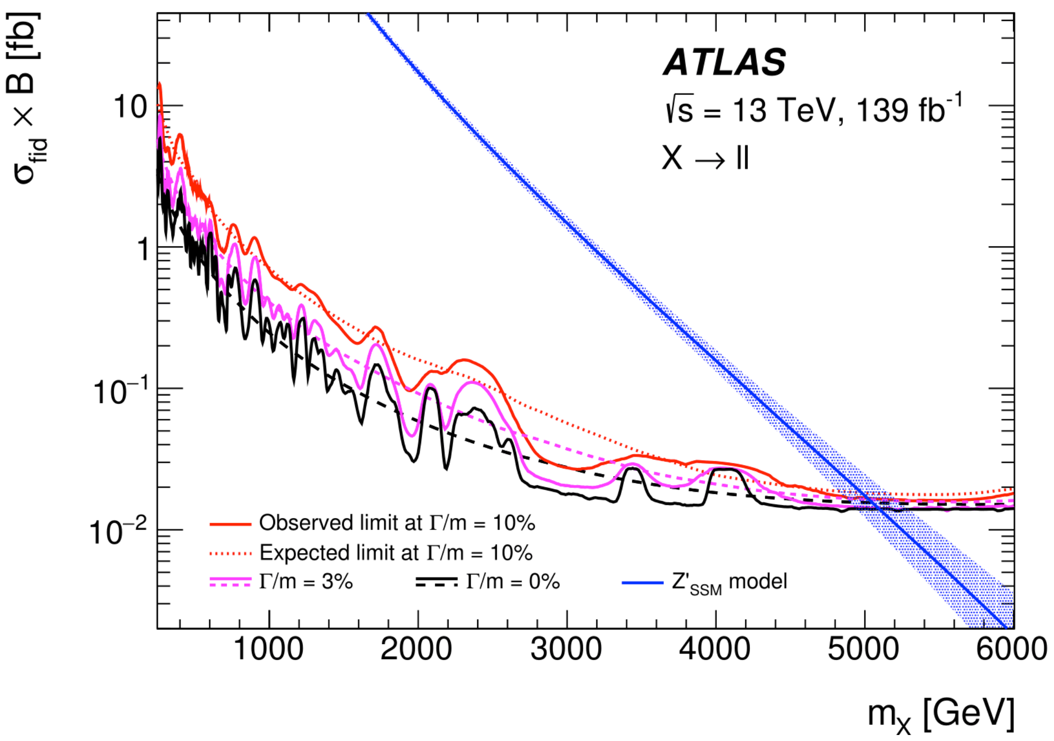
$$C_Z = 2\left(\frac{M_Z^2}{v}\right)\frac{1}{s - M_Z^2 + i\Gamma_Z M_Z}$$

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

INTERFERENCE

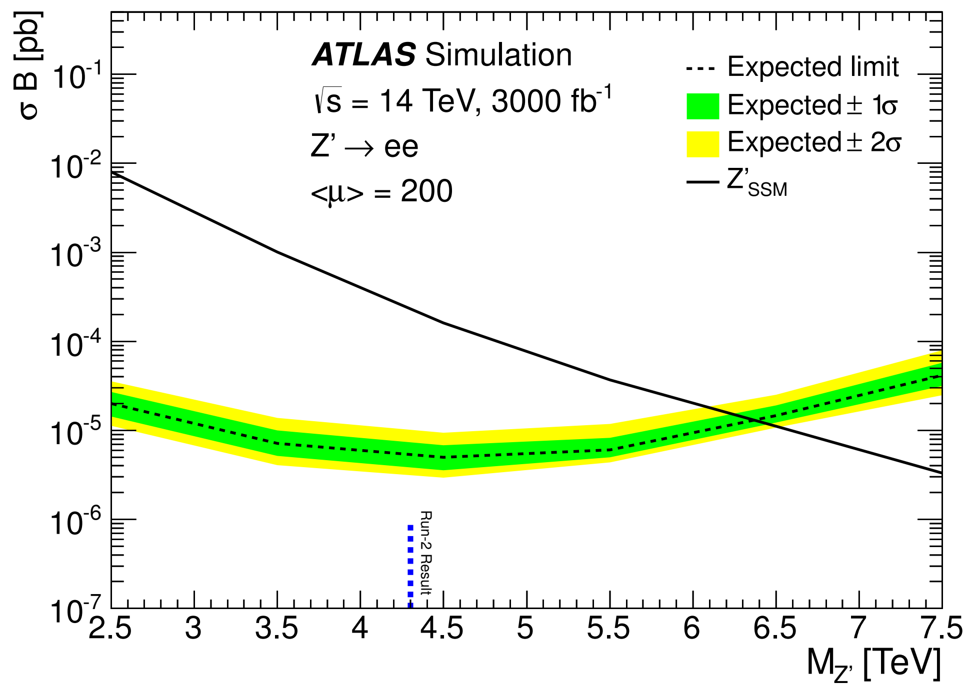
Bounds on the $U(1)_X$ gauge coupling

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)

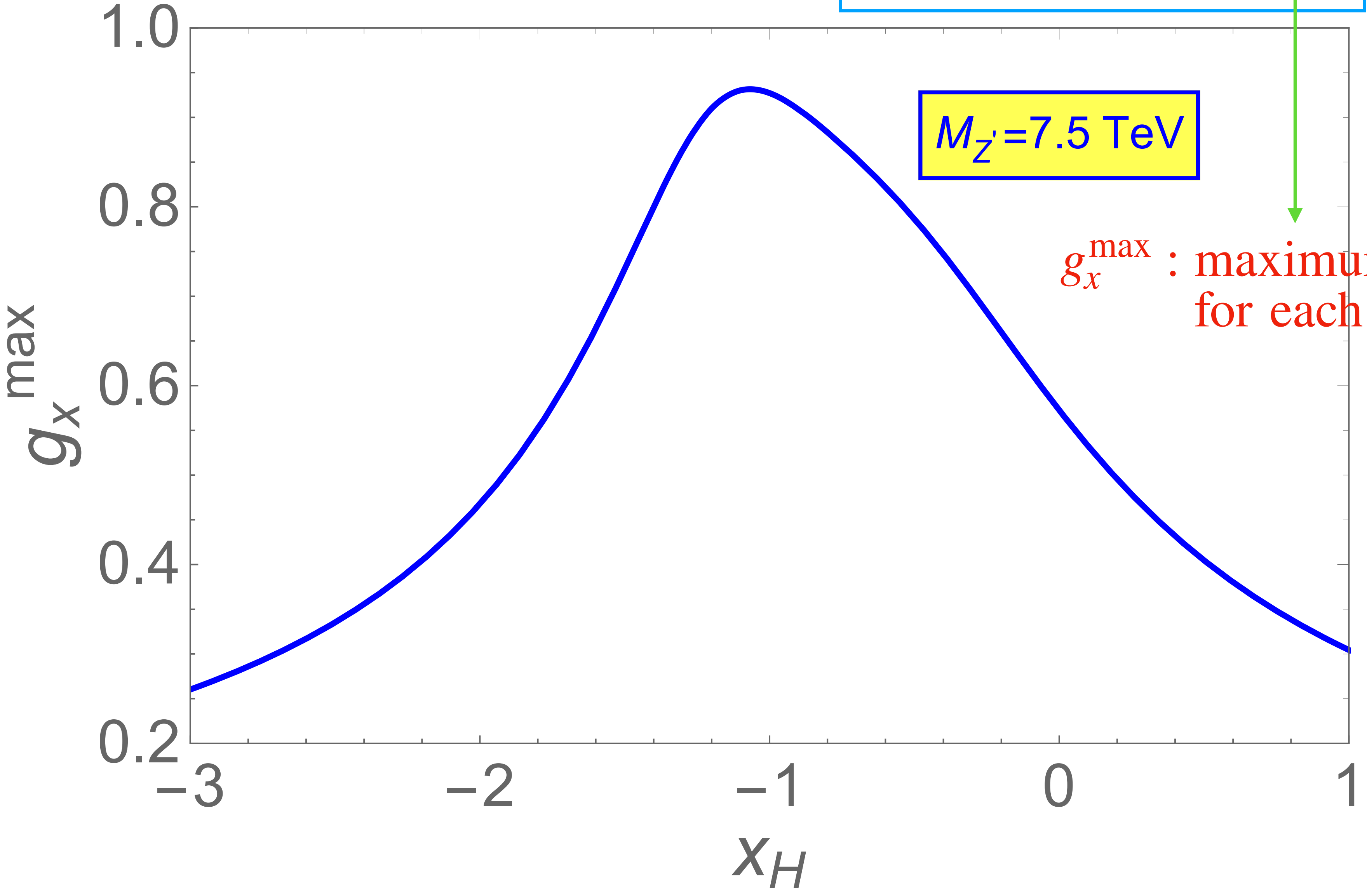


$U(1)_X$ coupling versus x_H for fixed Z' mass

ATLAS-TDR-027 (prospective)

$\sigma[g_x, x_H, M_{Z'}] = \mathrm{X}_{\mathrm{sec}}^{\mathrm{ATLAS-TDR}}$

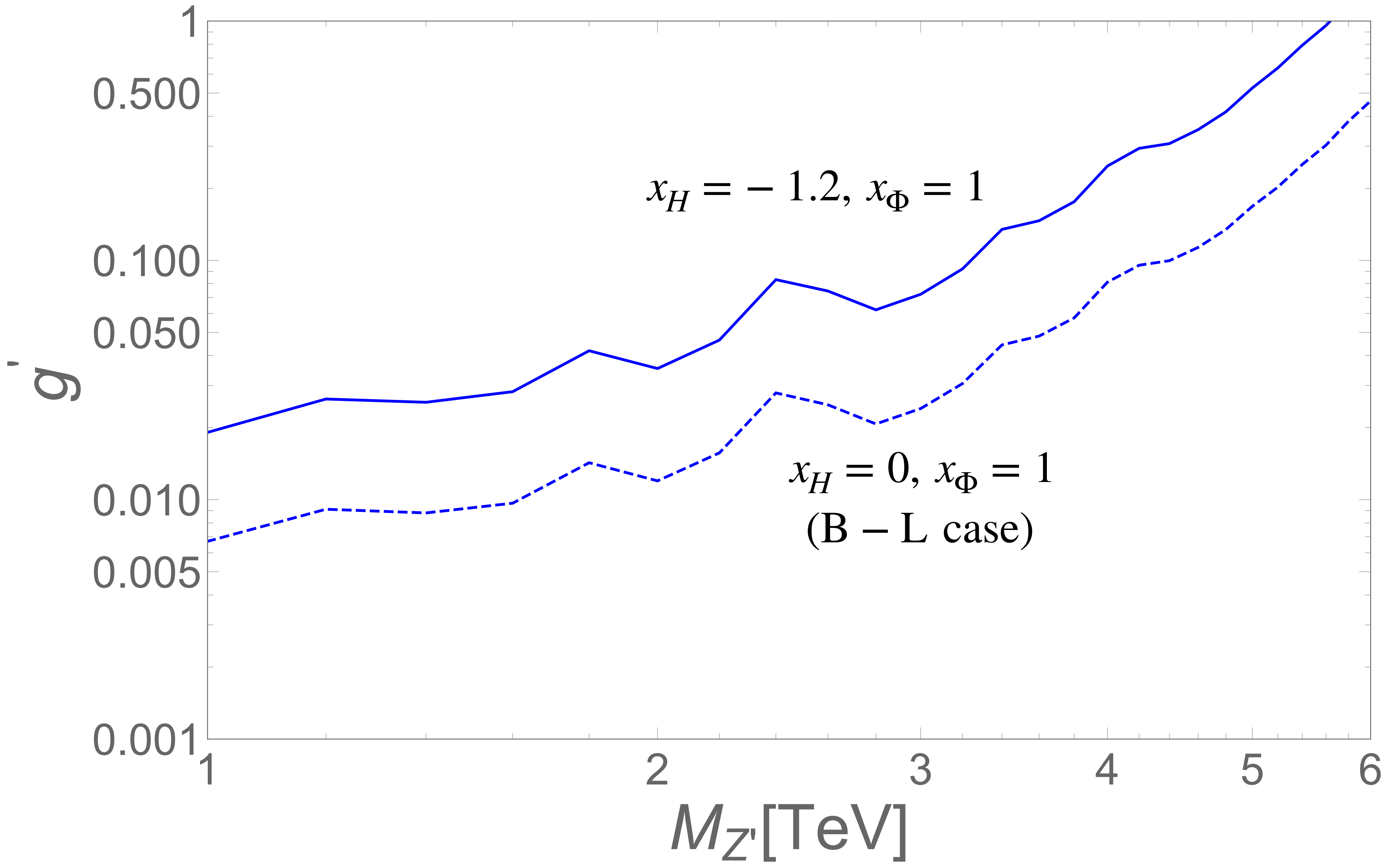
$[x_H, M'_Z] \to \mathrm{Fix} : \{\mathrm{X}_{\mathrm{sec}}, \mathrm{g}_{\mathrm{x}}\}$



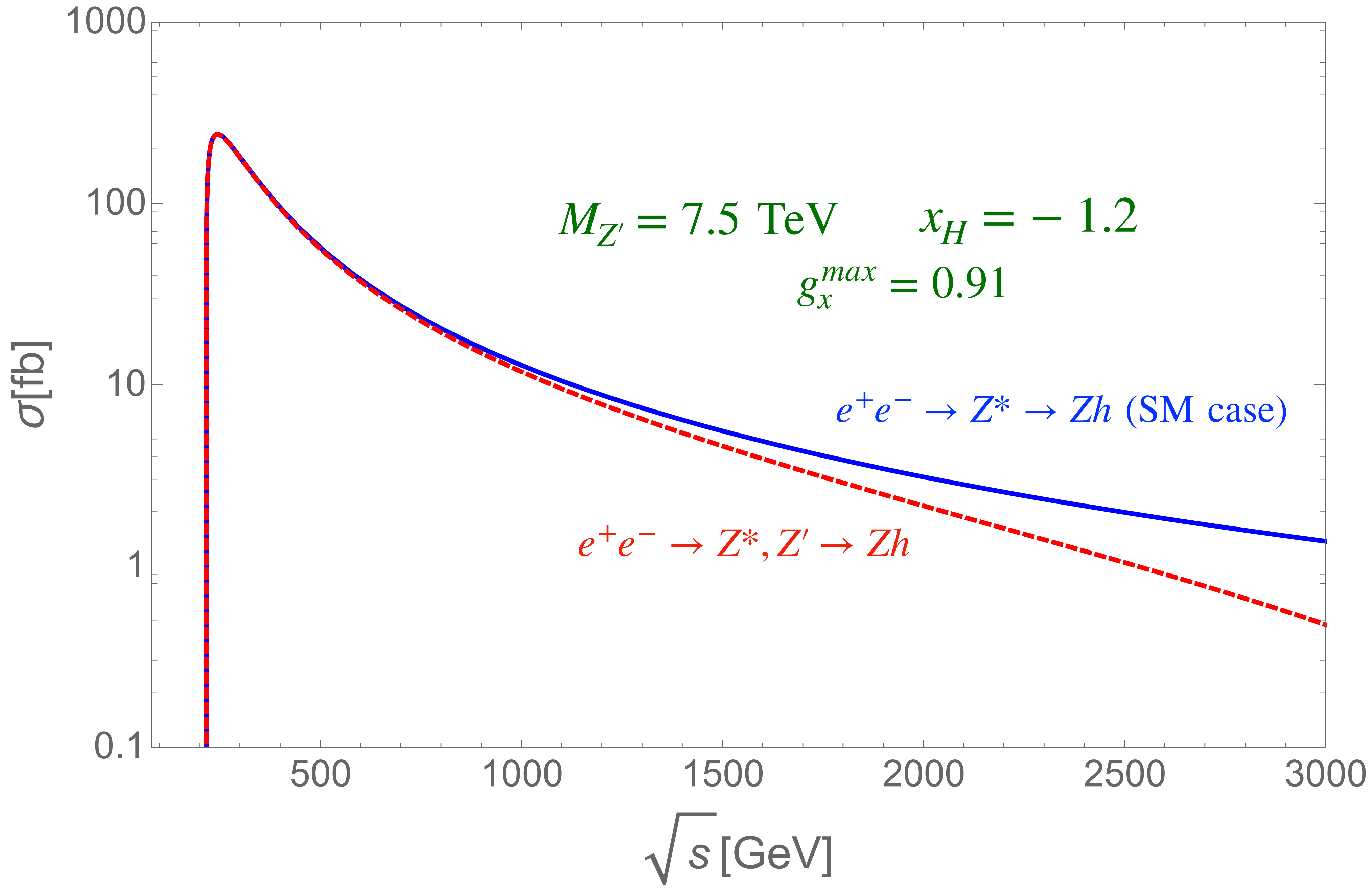
$g_x^{\max}$: maximum value for each x_{H}

Current LHC constraints on g_x vs $M_{Z'}$ (sample)

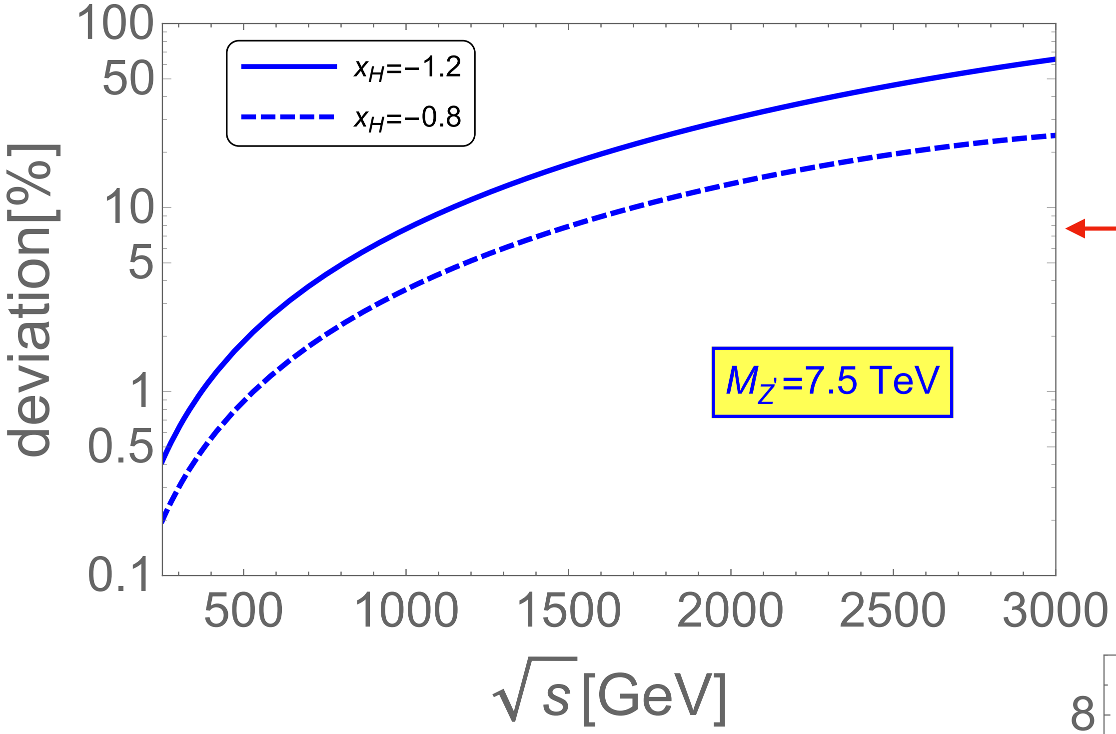
ATLAS: 1903.06248 (139/fb)



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

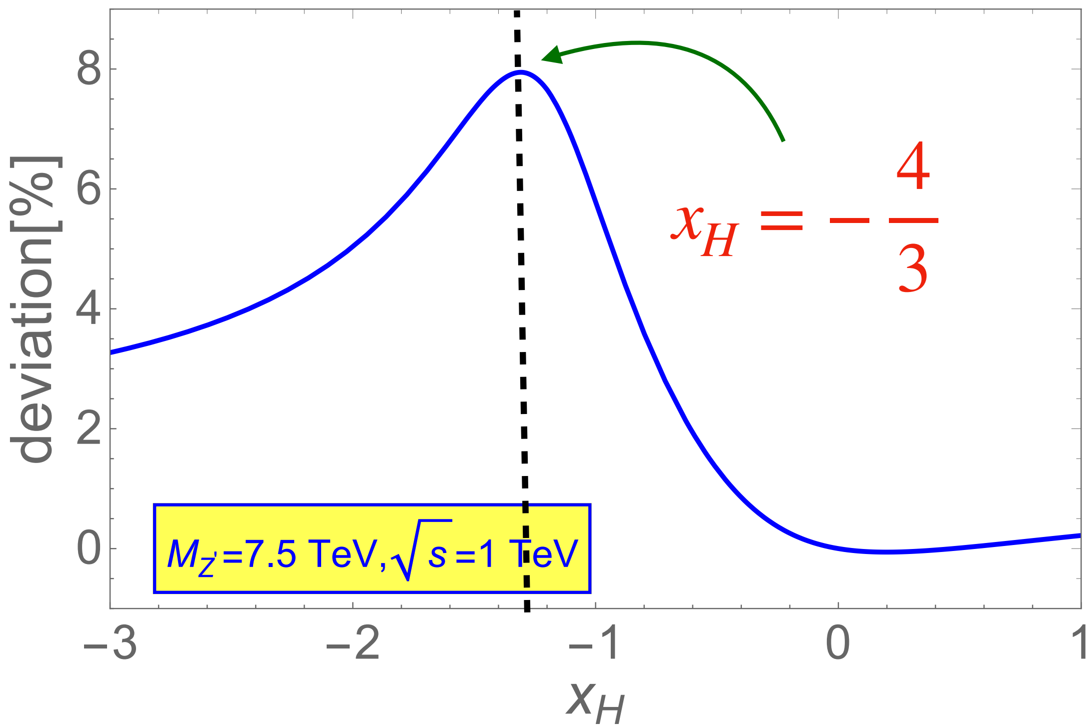


$$Deviation[\%] = Abs[1 - \frac{\sigma_{U(1)_X}[E_{CM}^{ILC}, g_x^{max}, x_H, M_{Z'}]}{\sigma_{SM}[E_{CM}]}] \times 100\%.$$



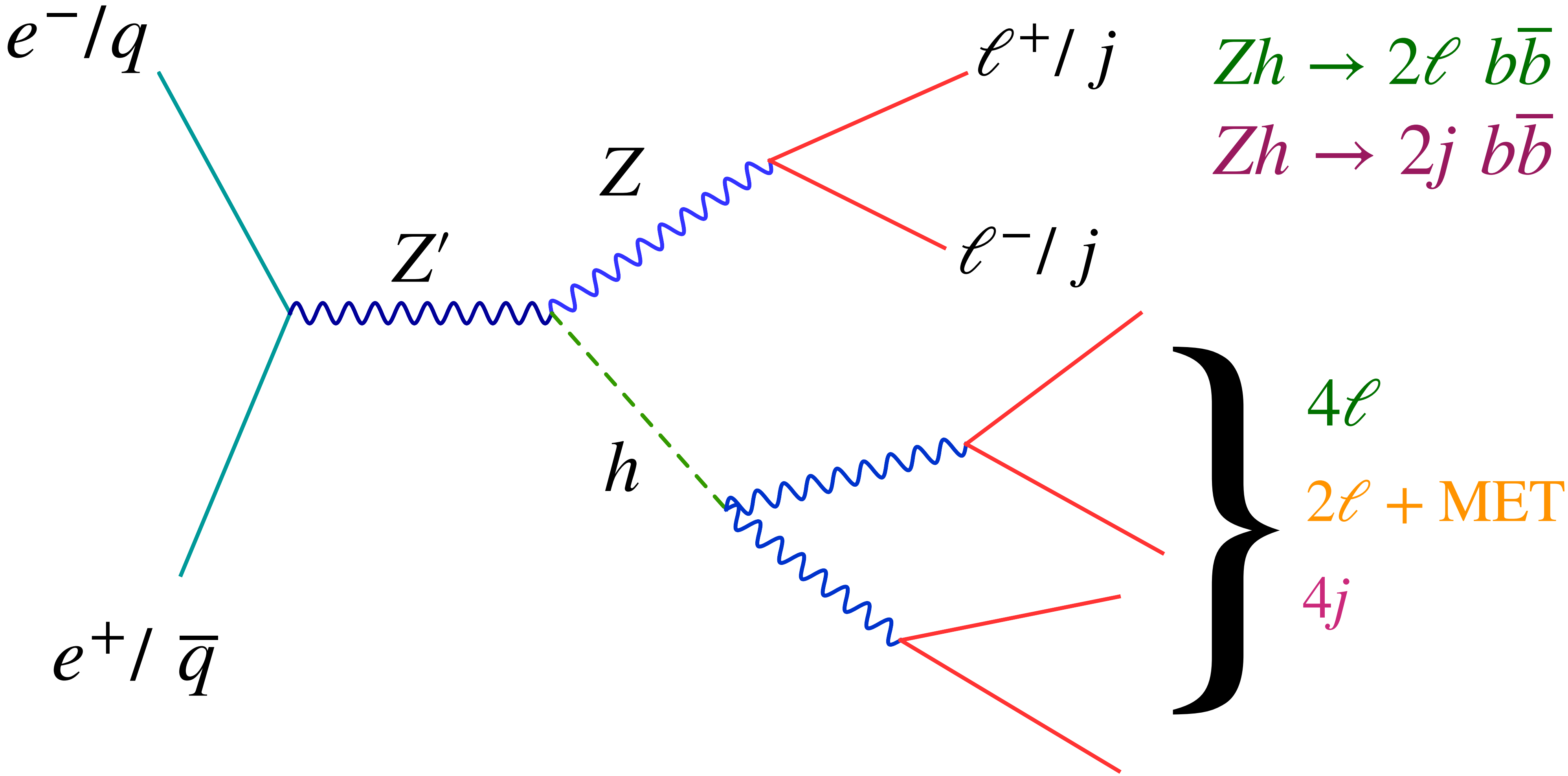
Deviation for different x_H at a fixed Z' mass as a function of the center of mass energy of the linear collider

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



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.

Alternative scenario under $U(1)_X$

1812.11931

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_{L_i}	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$(1/6)x_H + (1/3)$
u_{R_i}	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$(2/3)x_H + (1/3)$
d_{R_i}	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$-(1/3)x_H + (1/3)$
ℓ_{L_i}	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H - 1$
e_{R_i}	$\mathbf{1}$	$\mathbf{1}$	-1	$-x_H - 1$
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H$
$N_{R_{1,2}}$	$\mathbf{1}$	$\mathbf{1}$	0	-4
N_{R_3}	$\mathbf{1}$	$\mathbf{1}$	0	$+5$
H_E	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H + 3$
Φ_A	$\mathbf{1}$	$\mathbf{1}$	0	$+8$
Φ_B	$\mathbf{1}$	$\mathbf{1}$	0	-10
Φ_C	$\mathbf{1}$	$\mathbf{1}$	0	-3

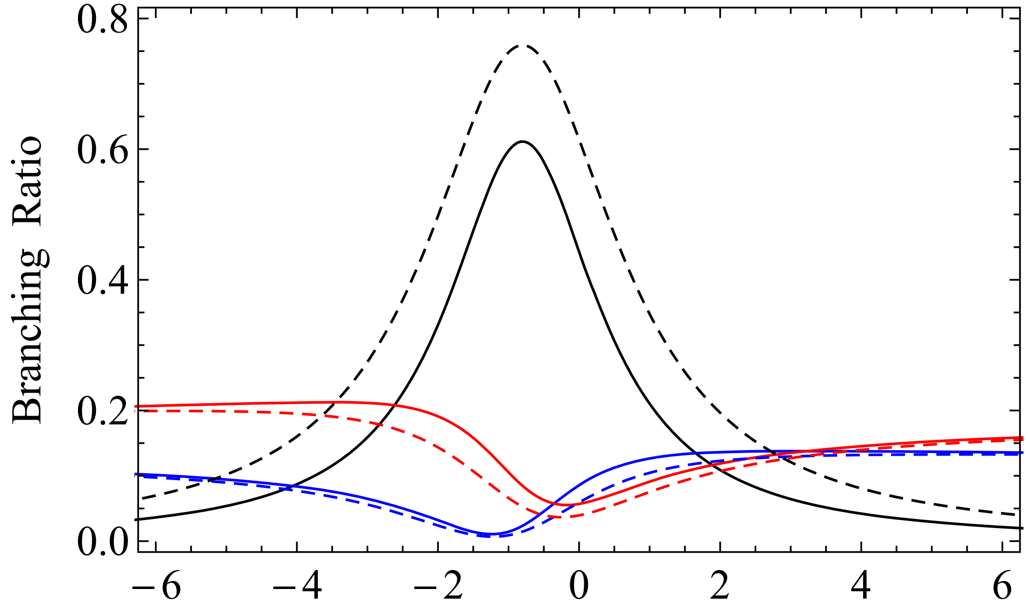
Possible alternative B – L, with $x_H = 0$

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

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

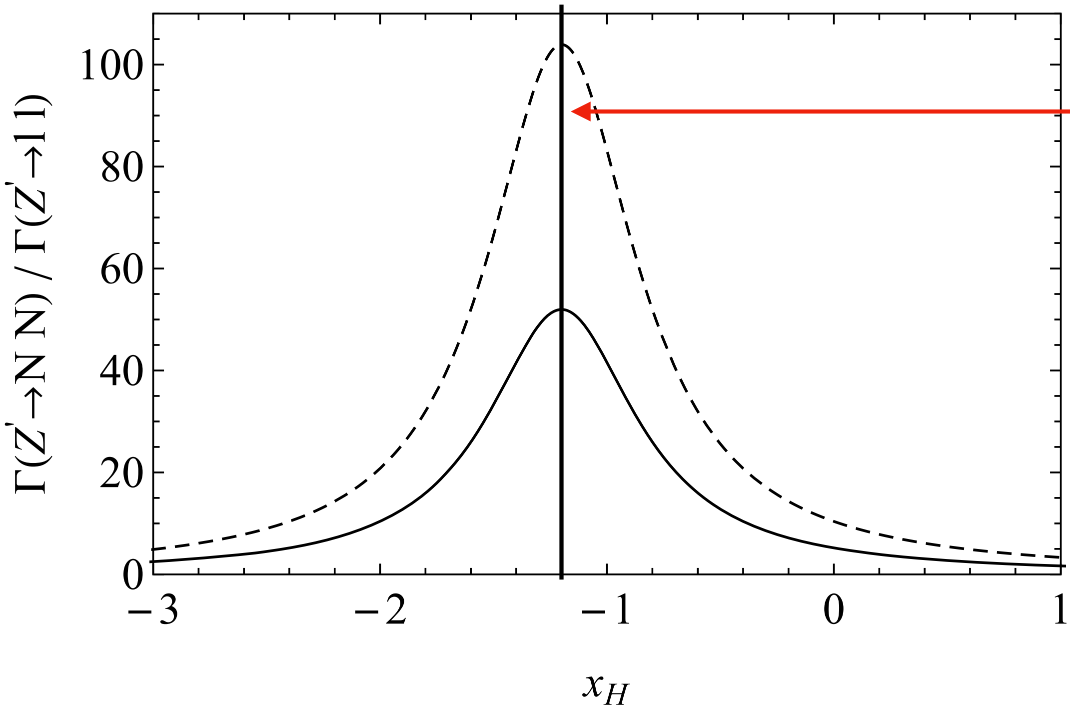
$m_{N^2} > m_{Z'}/2$,

Dashed

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

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

Up and down quarks Heavy neutrinos Charged leptons

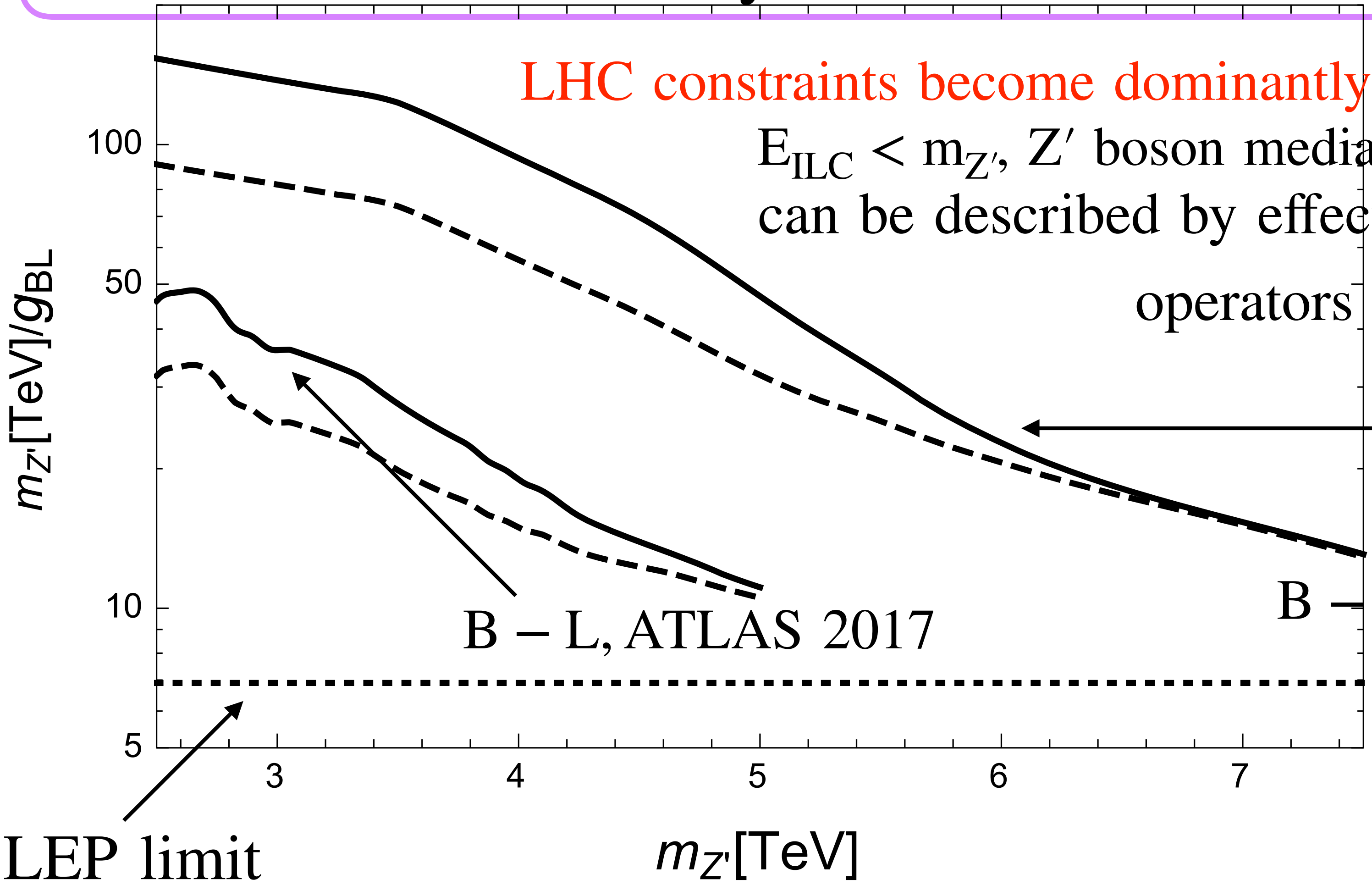


$x_H = -1.2$

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



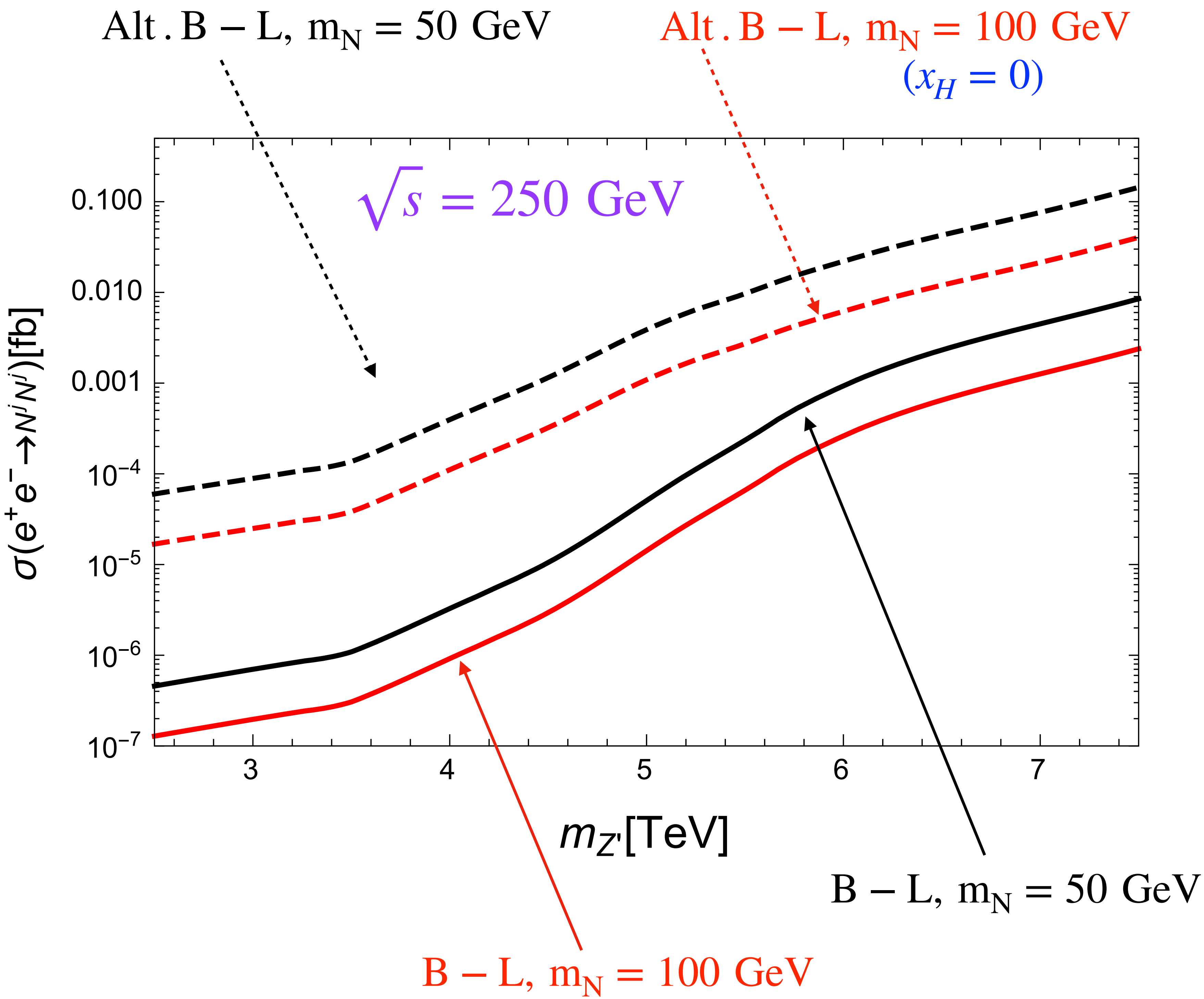
LHC constraints become dominantly weaker with heavier Z'

$E_{ILC} < m_{Z'}$, 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)
$\sqrt{s}$ = 250 GeV
$\sigma(e^+e^- \to N^jN^j)$[fb]
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
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

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

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

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 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 at the ILC to probe Majorana nature. Let's find the branching ratios after the neutrino data fitting through the light heavy mixing in the heavy neutrino decay width.

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

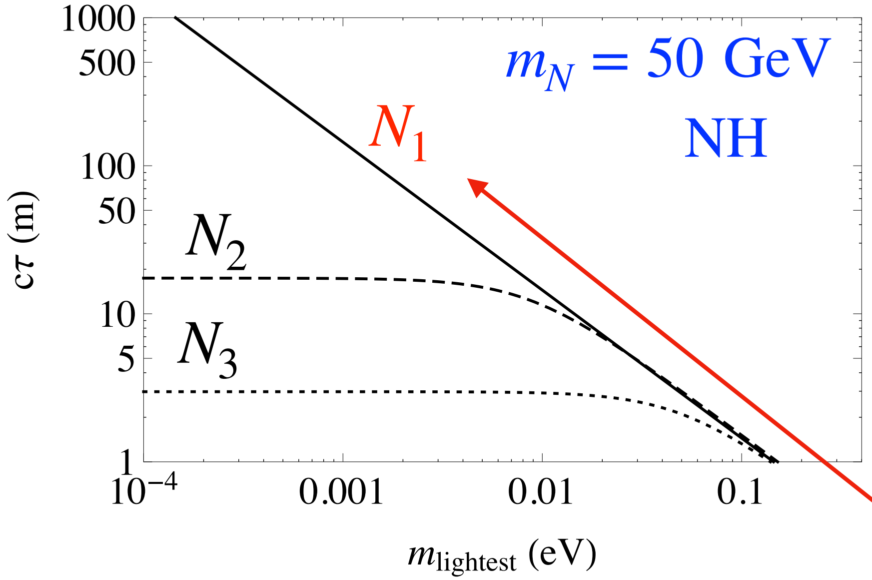
IH case

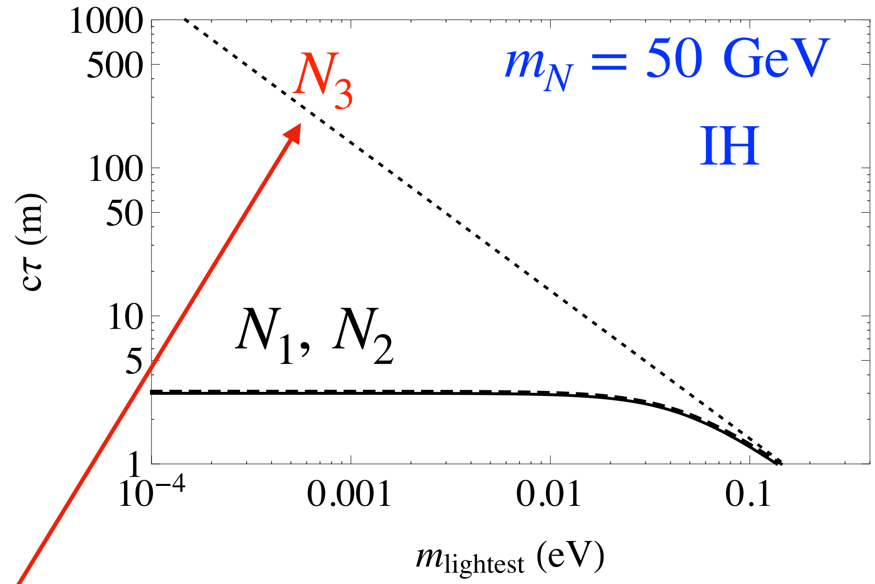
$m_N = 50$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.412	0.104	0.104
N^2	0.204	0.224	0.224

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

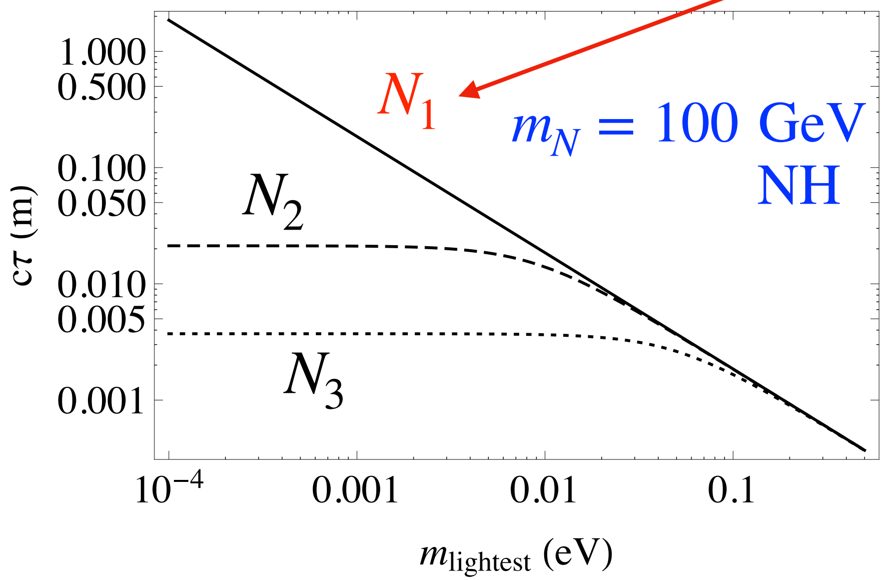
Finally NN $\rightarrow 2\ell^{\pm}4$j will dominantly be between 16% – 34 % for the final results for the B – L $\rightarrow$ Alt . B – Lscenario .

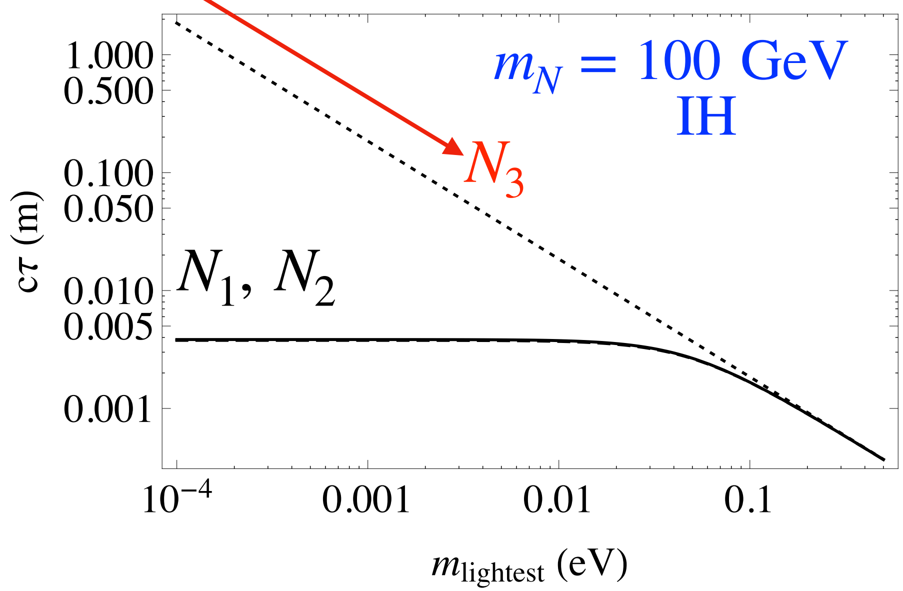
Long lived RHNs   B − L case





Longest lived RHN life time is inversely proportional to m_{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 the 250 GeV linear collider can be a promising machine to probe BSM physics apart from considering it as a Higgs factory.

Thank you