Searching for Higgs from the heavy resonce under the general $U(1)_X$ scenario

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(primarily based on : 1710.03377, 1905.00201
and work in progress with N. Okada)

Physics
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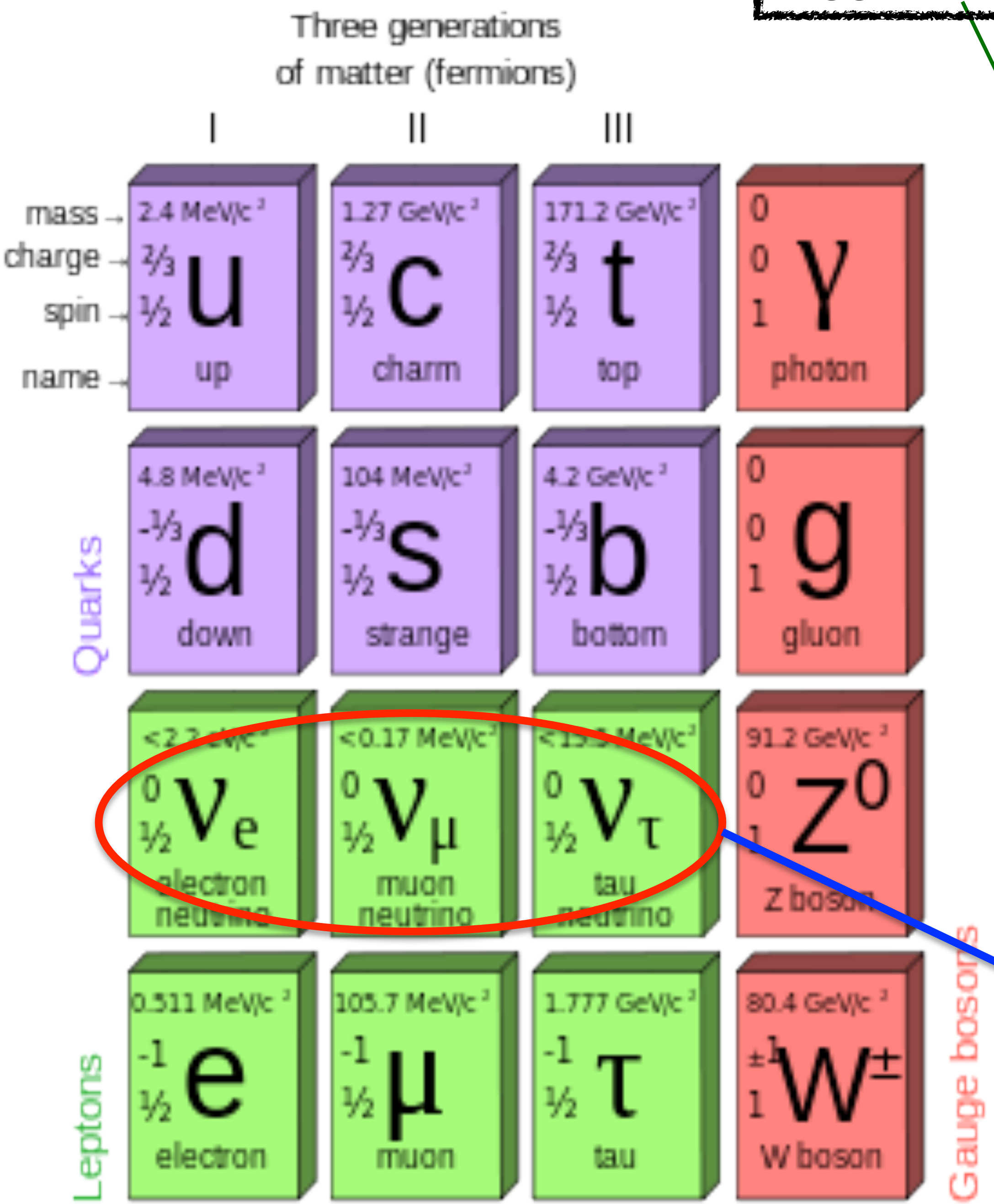
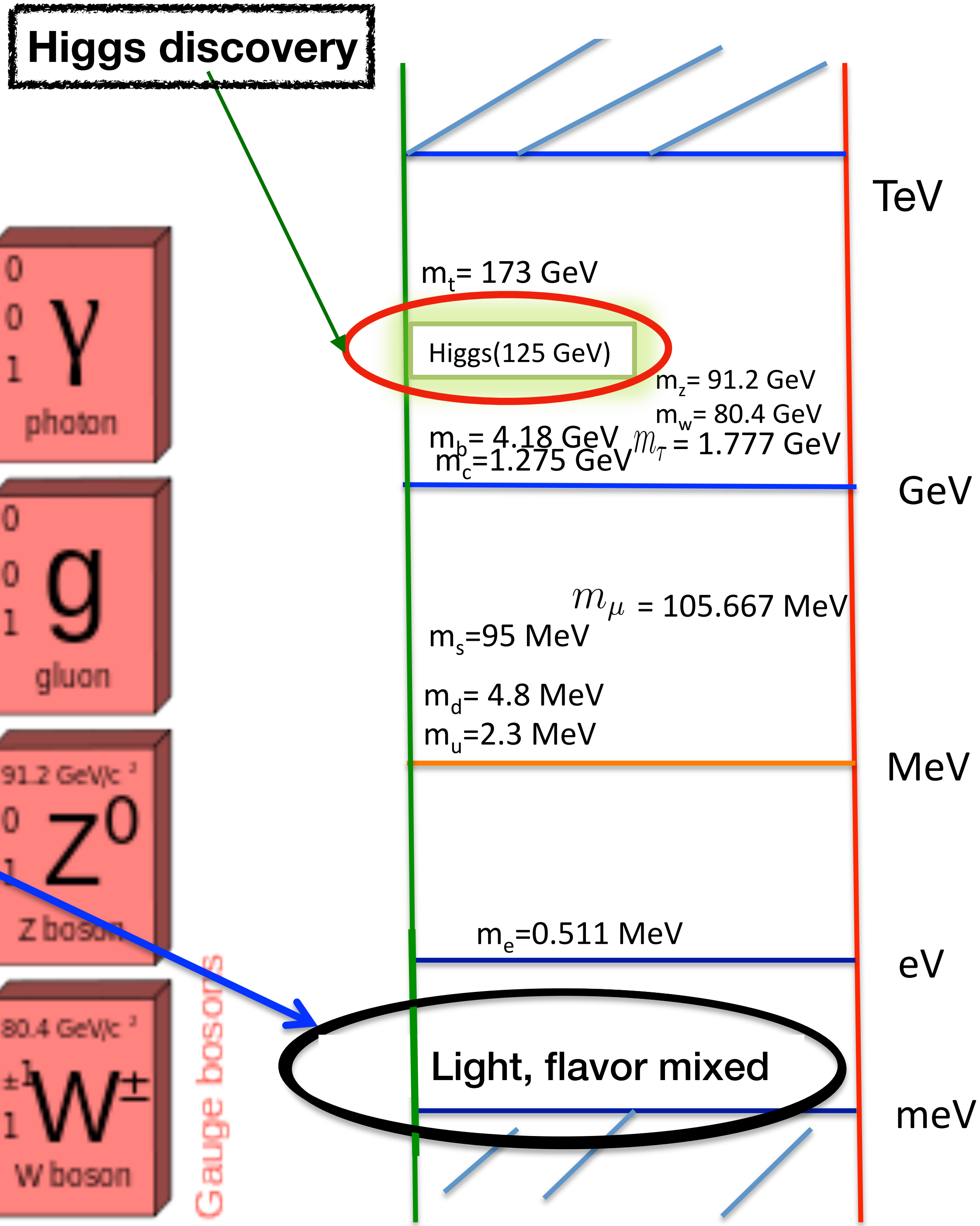
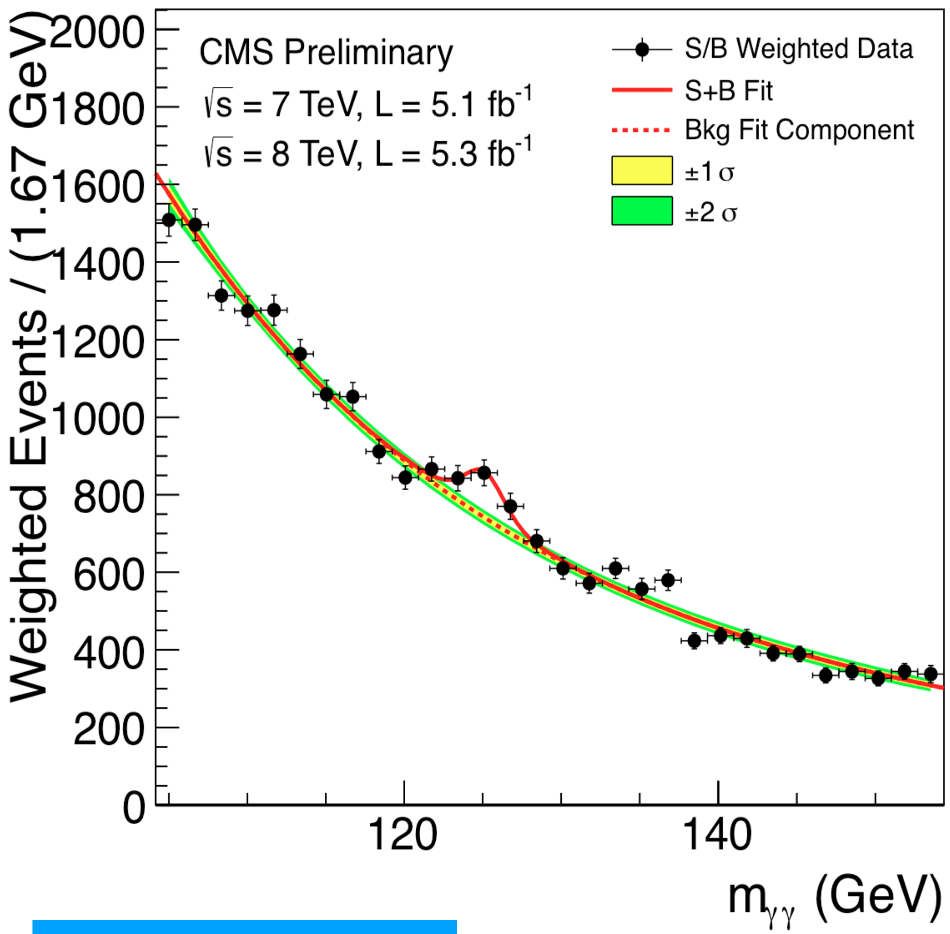
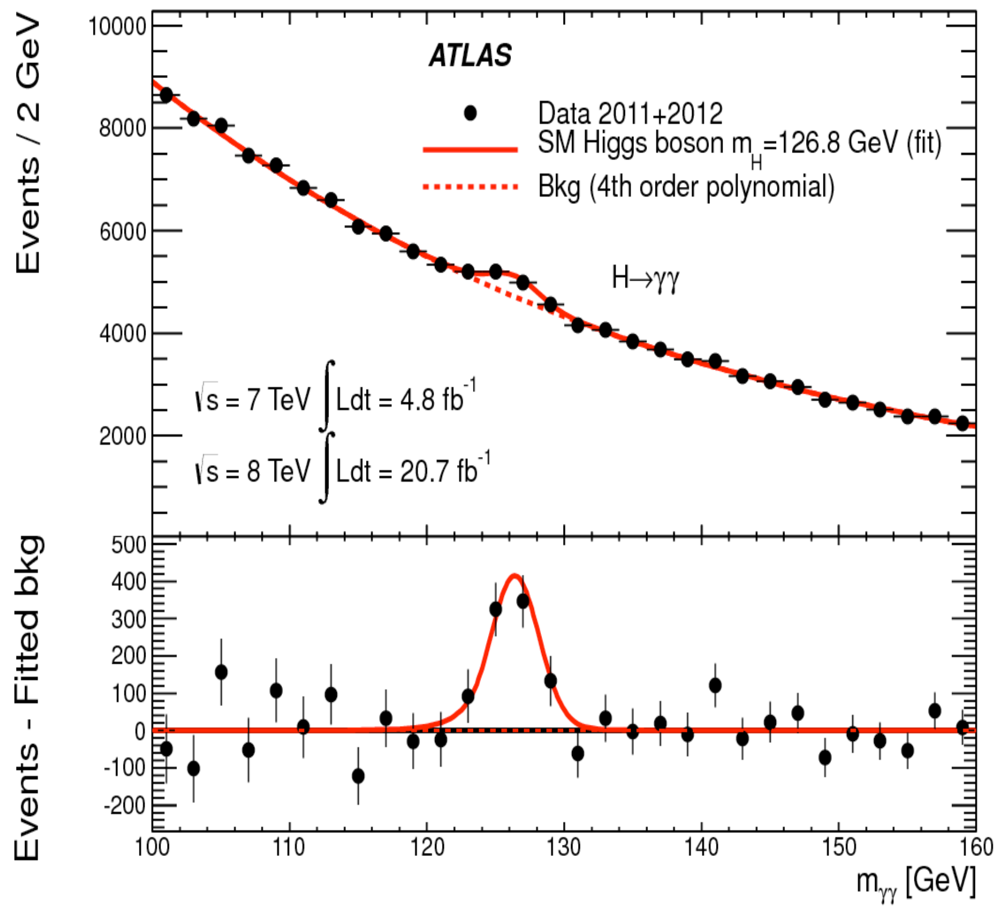
Introduction





Discovery of Higgs boson





Nobel Prize in 2013

Role in future

Higgs boson mass around 125 GeV

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	$= -\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
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	$= 2x_\Phi$

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

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

Yukawa interaction

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

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

Gauge and gravitational anomaly-free conditions

$$\mathrm{U}(1)_X \times [\mathrm{SU}(3)_C]^2 \qquad 2x_q - x_u - x_d = 0$$

$$\mathrm{U}(1)_X \times [\mathrm{SU}(2)_L]^2 \qquad 3x_q + x_\ell = 0$$

$$\mathrm{U}(1)_X \times [\mathrm{U}(1)_Y]^2 \qquad x_q - 8x_u - 2x_d + 3x_\ell - 6x_e = 0$$

$$[\mathrm{U}(1)_X]^2 \times \mathrm{U}(1)_Y \qquad x_q^2 - 2x_u^2 + x_d^2 - x_\ell^2 + x_e^2 = 0$$

$$[\mathrm{U}(1)_X]^3 \qquad 6x_q^3 - 3x_u^3 - 3x_d^3 + 2x_\ell^3 - x_\nu^3 - x_e^3 = 0$$

$$\mathrm{U}(1)_X \times [\mathrm{grav.}]^2 \qquad 6x_q - 3x_u - 3x_d + 2x_\ell - x_\nu - x_e = 0$$

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, $\mathrm{x}'_{\mathrm{H}} = \frac{1}{2}\mathrm{x}_{\mathrm{H}}$ and $\mathrm{x}'_{\Phi} = 2\mathrm{x}_{\Phi}$ we find the charges of the $\mathrm{U}(1)_{\mathrm{X}}$ sector is the linear combination of the $\mathrm{U}(1)_{\mathrm{Y}}$ and $\mathrm{U}(1)_{\mathrm{B-L}}$ charges .

One of the important aspects of the model is **Neutrino sector**

AD, Okada, Raut: 1710.03377

$U(1)_X$ breaking

EWSB

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

Dirac mass term

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

Majorana mass term

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

Seesaw mechanism to generate the light neutrino mass

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

$$m_\nu \simeq -M_D M_N^{-1} M_D^T$$

Alternatively we can have

Neutrino mass in the following way

AD, Goswami, Vishnudath, Nomura: 1905.00201

$$-L_{\rm Yukawa} = Y_e \bar{l}_L H e_R + Y_\nu \bar{l}_L \tilde{H} \nu_R + Y_u \overline{Q}_L \tilde{H} u_R + Y_d \overline{Q}_L H d_R \ + \ y_{NS} \overline{\nu}_R \Phi S + \frac{1}{2} \overline{S^c} M_\mu S \ + \ \text{h.c.}$$

EWSB

$U(1)_X$ breaking

$U(1)_X$ charge neutral

$$-L_{mass} = \overline{\nu}_L M_D \nu_R + \overline{\nu_R} M_R S \ + \ \frac{1}{2} \overline{S^c} M_\mu S \ + \ \text{h.c.}$$

$M_D = Y_\nu \langle H \rangle$

$M_R = y_{NS} \langle \Phi \rangle$

$$-L_{mass} = \frac{1}{2} (\overline{\nu_L^c} \ \ \overline{\nu}_R \ \ \overline{S^c}) \begin{pmatrix} 0 & M_D^* & 0 \\ M_D^\dagger & 0 & M_R \\ 0 & M_R^T & M_\mu \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ S \end{pmatrix} \ + \ \text{h.c..}$$

Inverse seesaw mechanism to generate the light neutrino mass

$$M_{light} \ = \ M_D^* (M_R^T)^{-1} M_\mu M_R^{-1} M_D^\dagger$$

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

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

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

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

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

$$\Gamma[Z' \to Zh] = \frac{M_{Z'} g_x^2 x_H^2}{48\pi} \sqrt{\lambda\left[1, (\frac{M_Z}{M_{Z'}})^2, (\frac{m_h}{M_{Z'}})^2\right]} \left(\lambda\left[1, (\frac{M_Z}{M_{Z'}})^2, (\frac{m_h}{M_{Z'}})^2\right] + 12\frac{M_Z}{M_{Z'}}\right)$$

Corresponding couplings

$$g_L^\nu[g_x, x_H] = \left((-\frac{1}{2})x_H + (-1)\right) g_x \qquad g_L^e[g_x, x_H] = \left((-\frac{1}{2})x_H + (-1)\right) g_x \qquad g_L^u[g_x, x_H] = \left((\frac{1}{6})x_H + (\frac{1}{3})\right) g_x$$

$$g_R^N[g_x, x_H] = \left(0\ x_H + (-1)\right) g_x \qquad g_R^e[g_x, x_H] = \left((-1)x_H + (-1)\right) g_x \qquad g_R^u[g_x, x_H] = \left((\frac{2}{3})x_H + (\frac{1}{3})\right) g_x$$

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

Important Interactions of with the particles of the model

Z' and Z

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

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

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

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

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

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

$Z - Z' - h$ coupling

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

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

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

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

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

$Z - h$ coupling

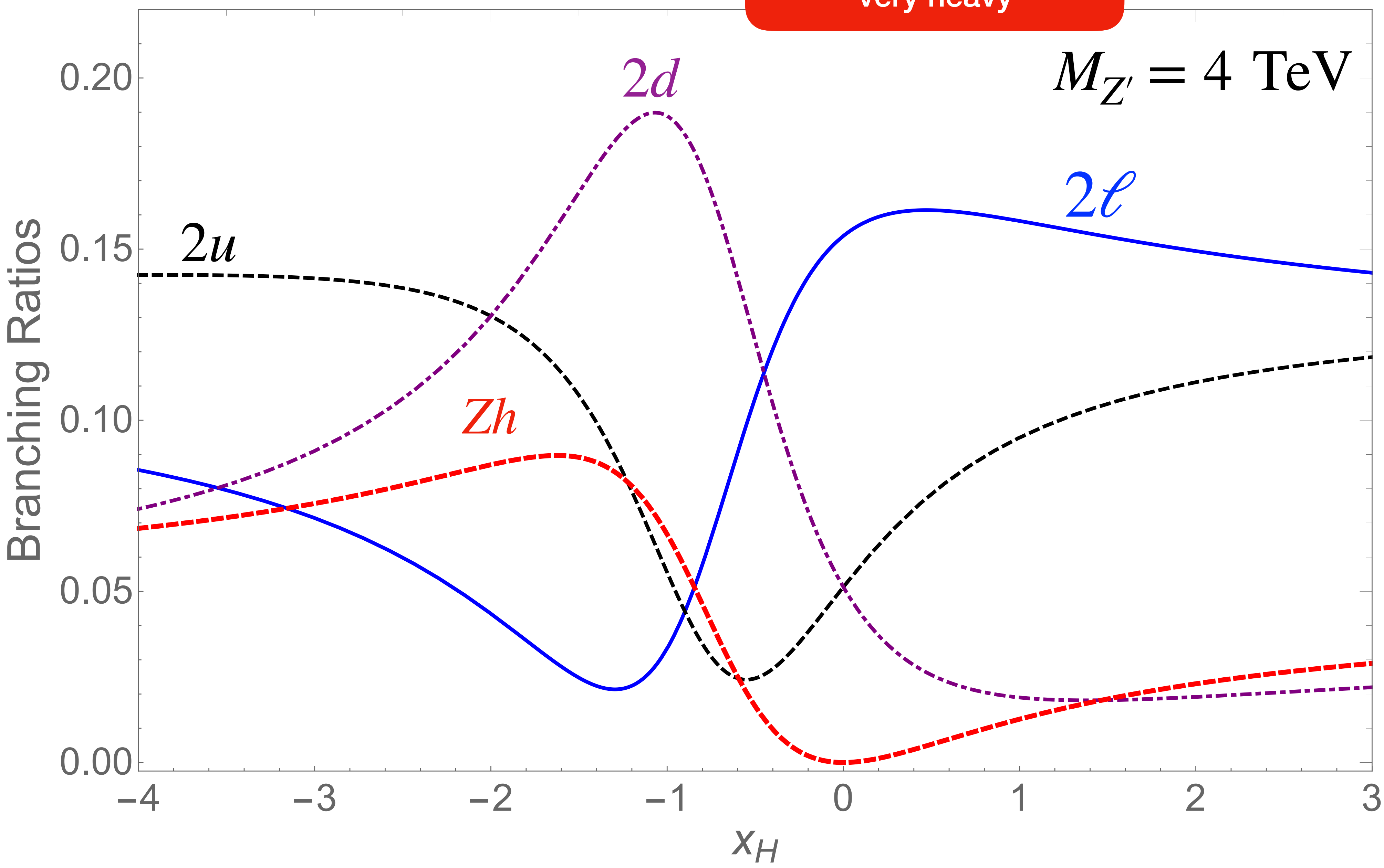
$$\mathcal{L} \supset \Big|-\frac{i}{2}g_z Z_{\mu}\frac{1}{\sqrt{2}}(v+h)\Big|^2$$

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

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

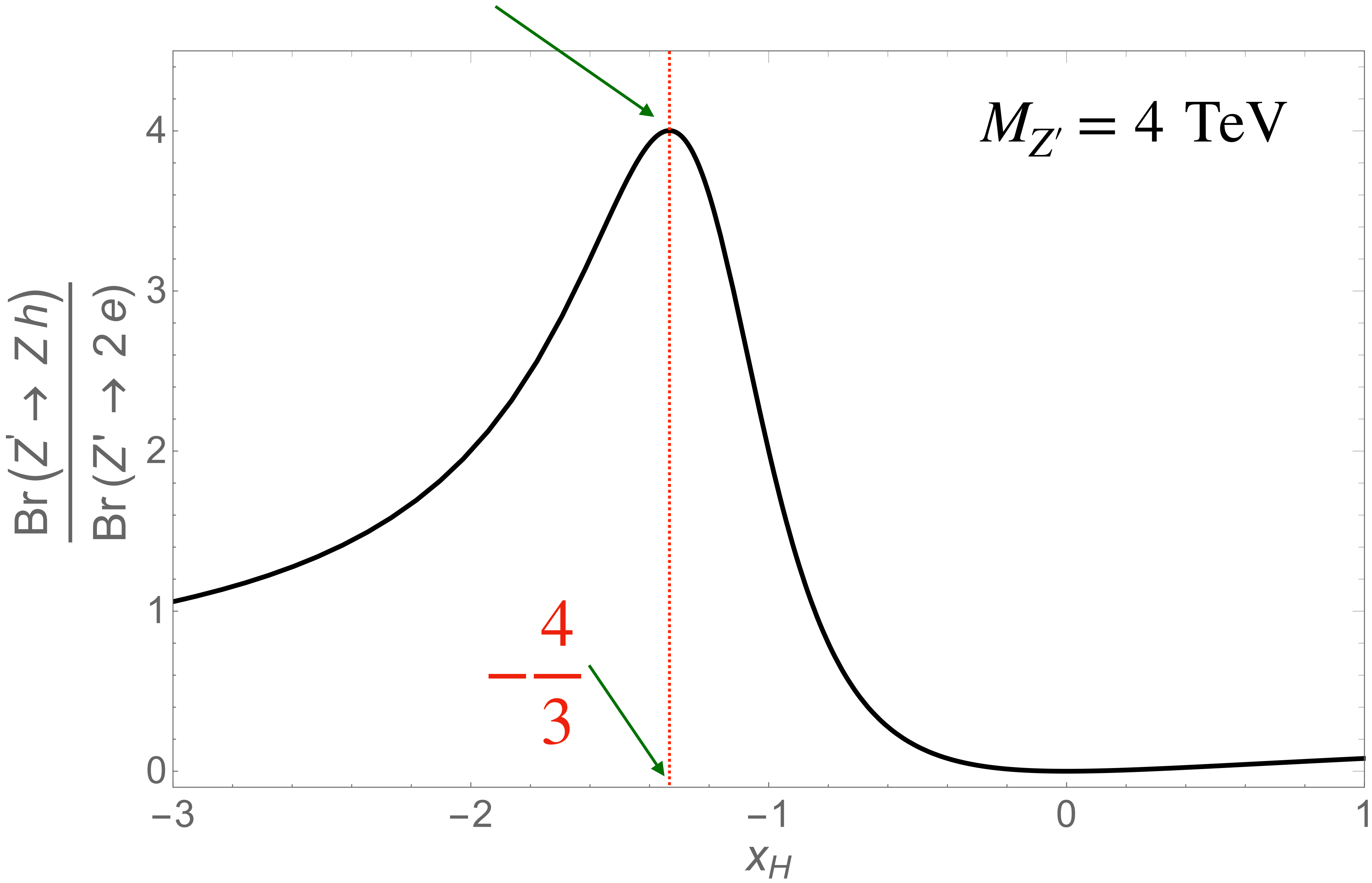
Branching ratios of $Z' \to f\bar{f}$

Right handed neutrinos are considered to be very heavy



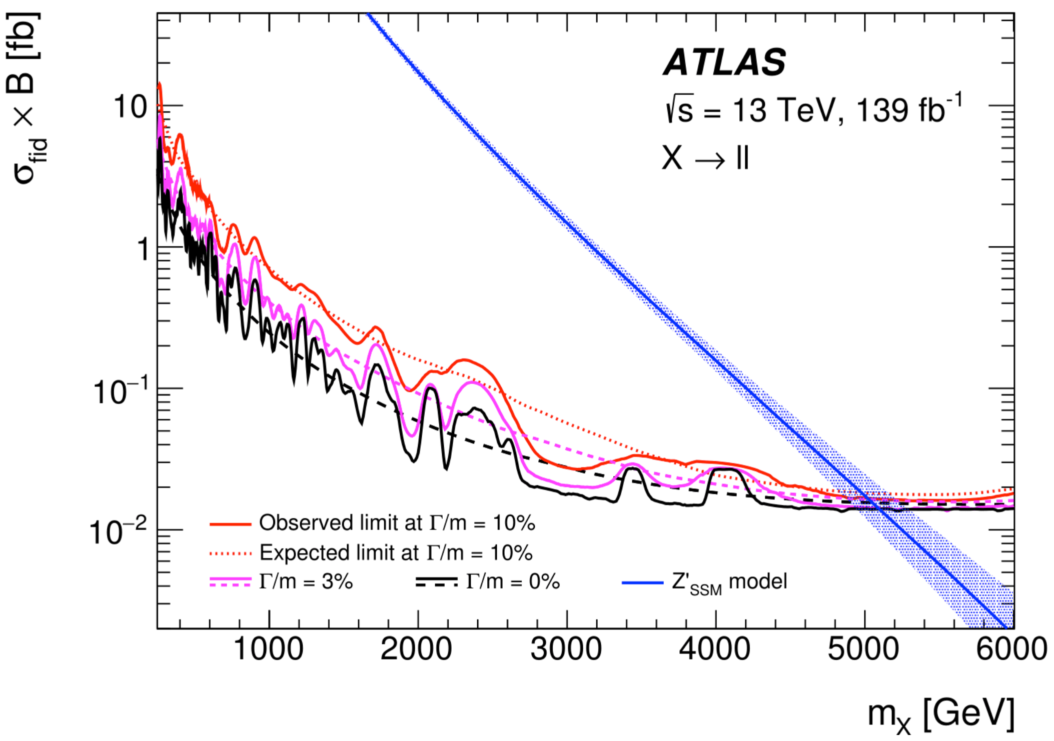
Ratio of the branching ratios $\frac{Br(Z' \to Zh)}{Br(Z' \to 2e)}$

Zh mode is 4 times larger than the 2e mode



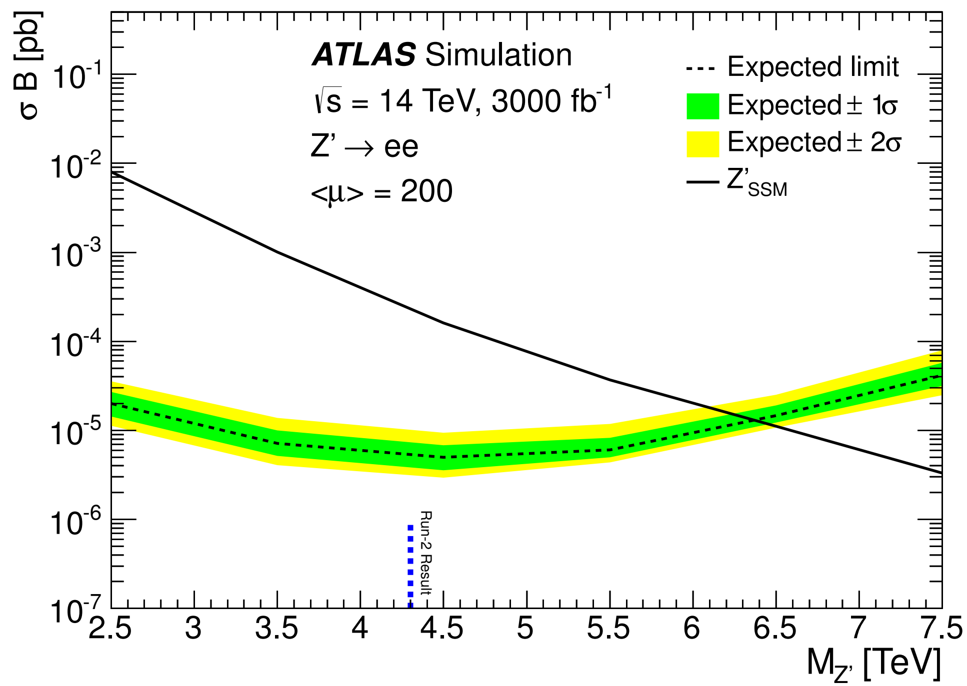
Bounds on the $U(1)_X$ gauge coupling

ATLAS: 1903.06248 (139/fb)

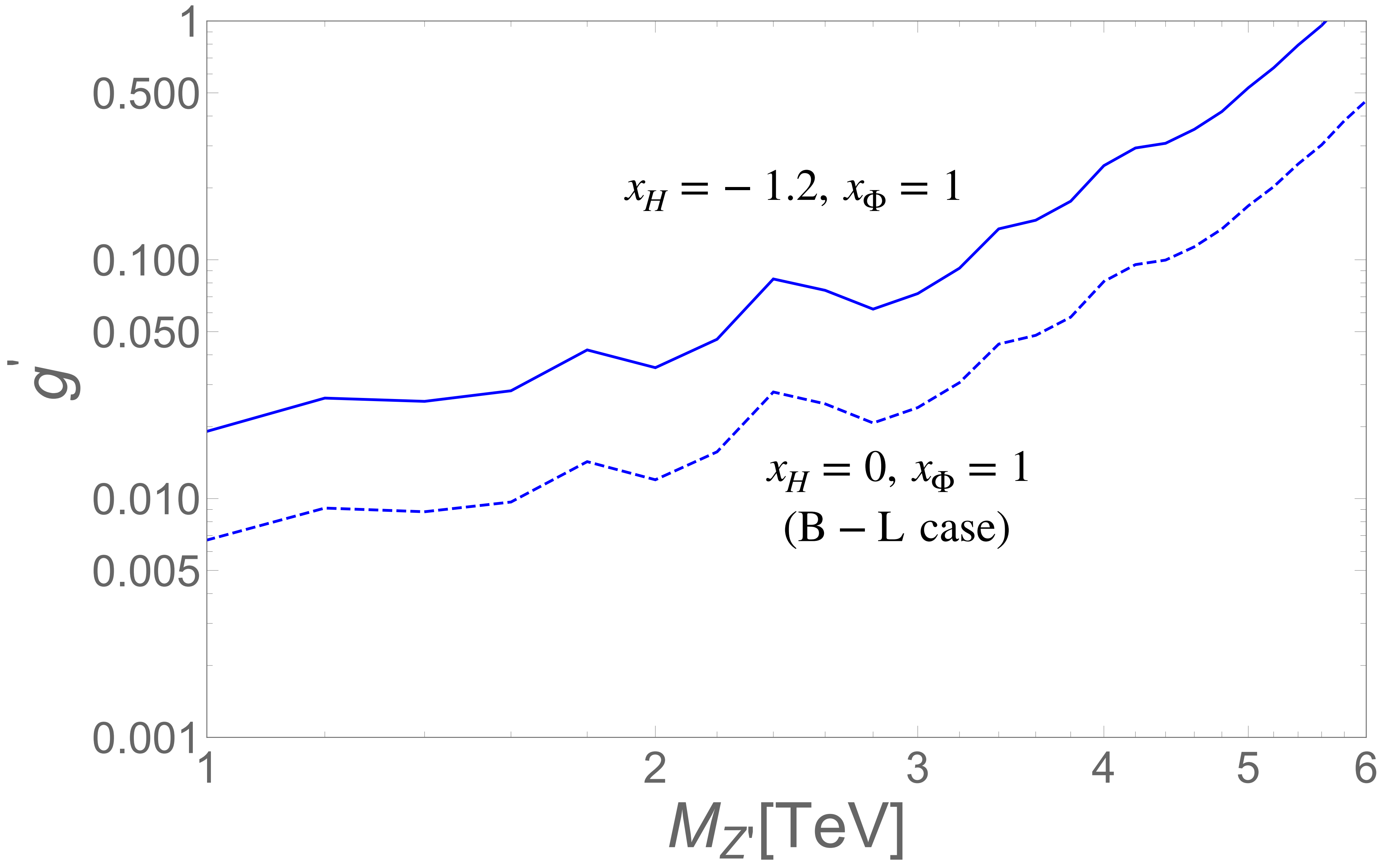


CMS (36/fb) and ATLAS (139/fb) searches at the LHC Run-1 and Run-2 respectively

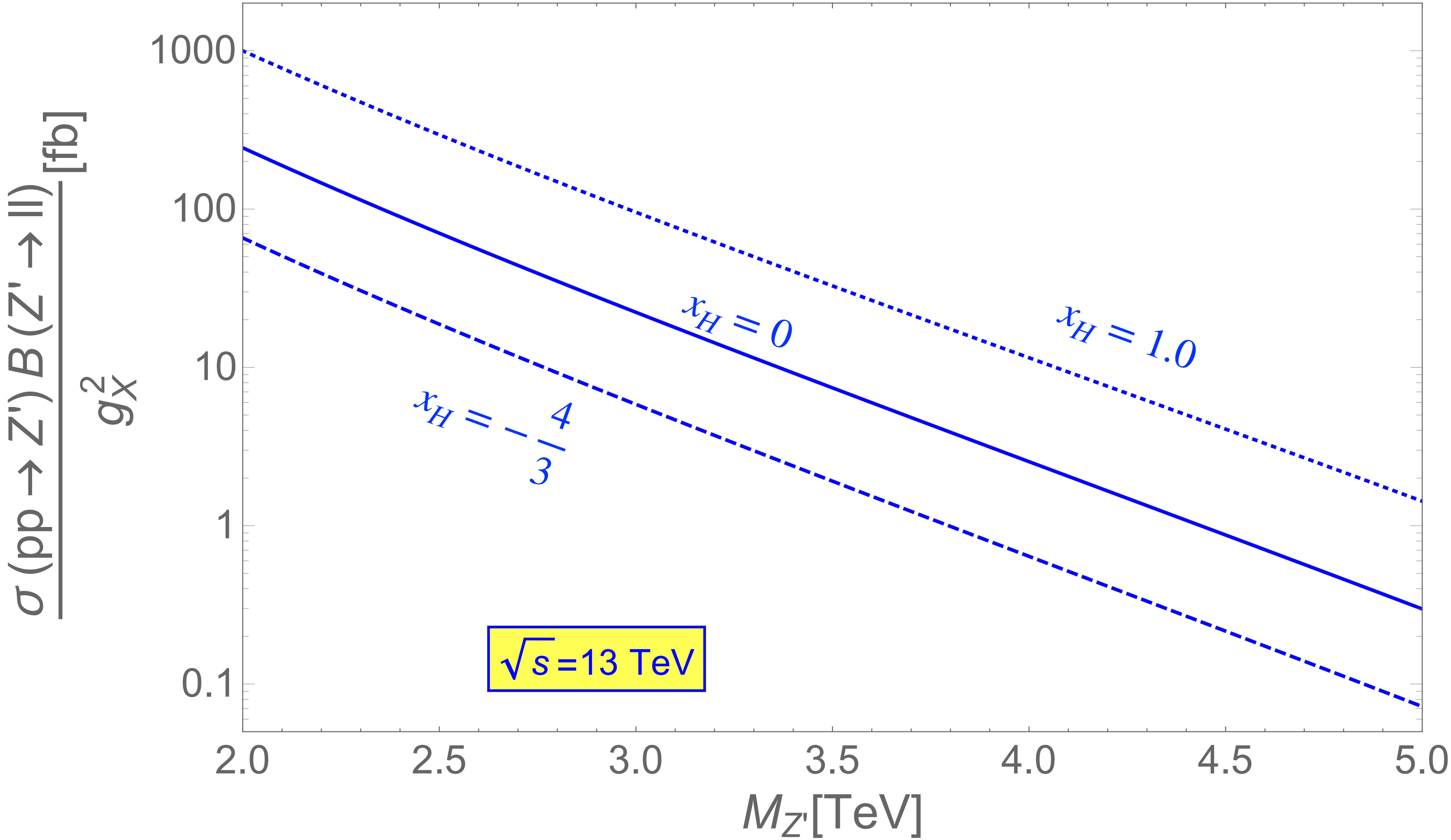
ATLAS-TDR-027 (prospective)



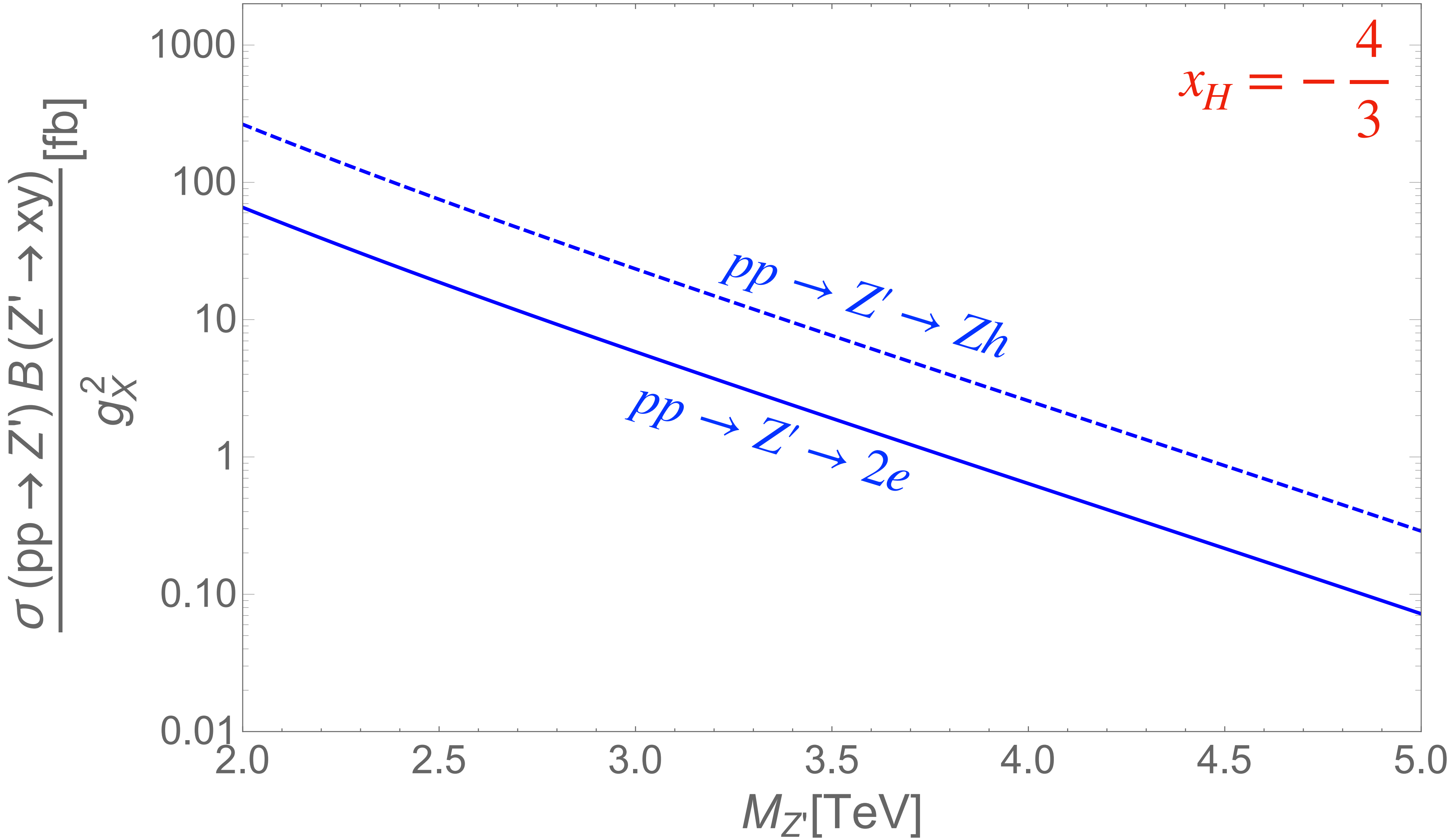
Current LHC constraints on g_x vs $M_{Z'}$ (sample)



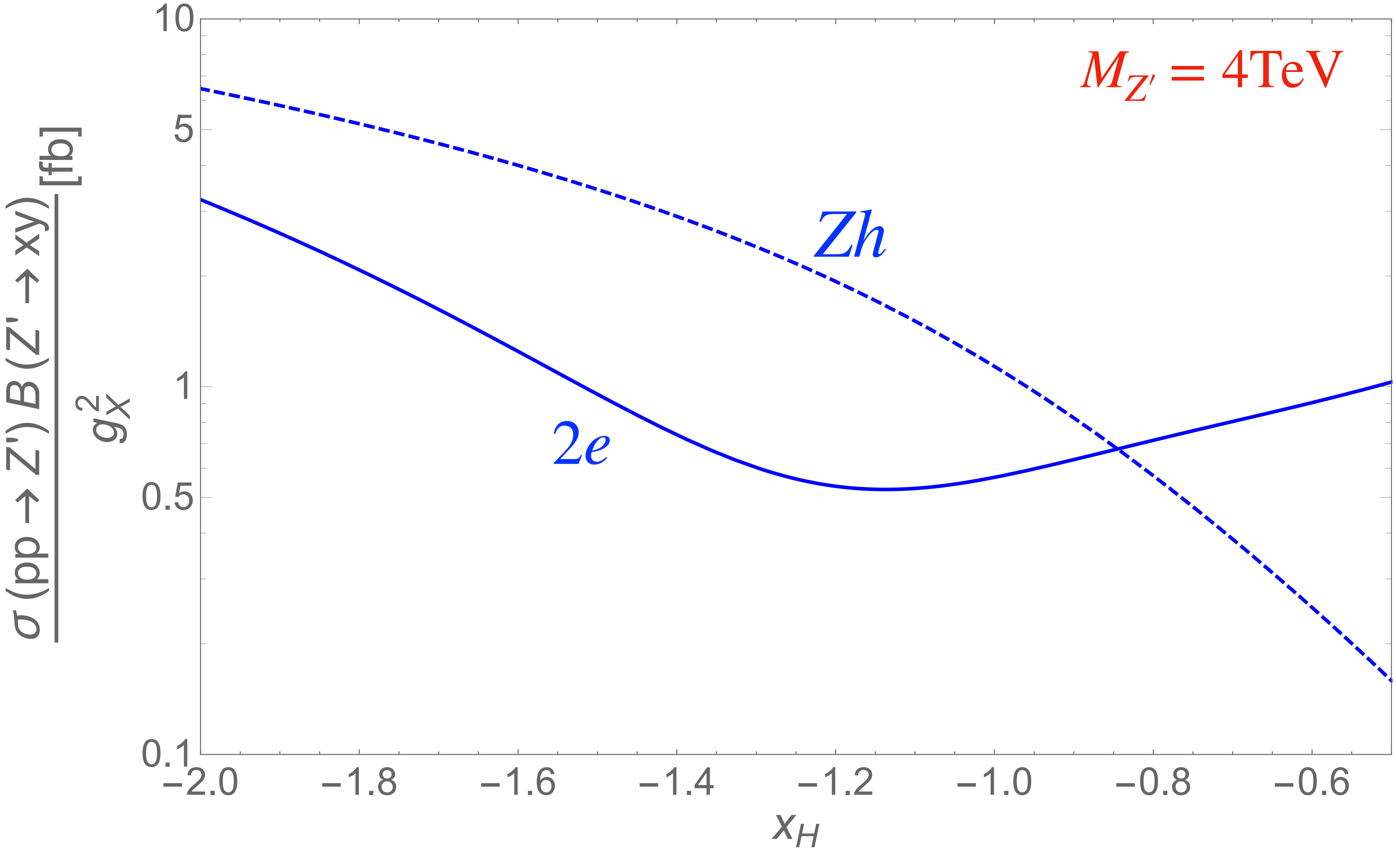
Dilepton production from the Z' at the LHC



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

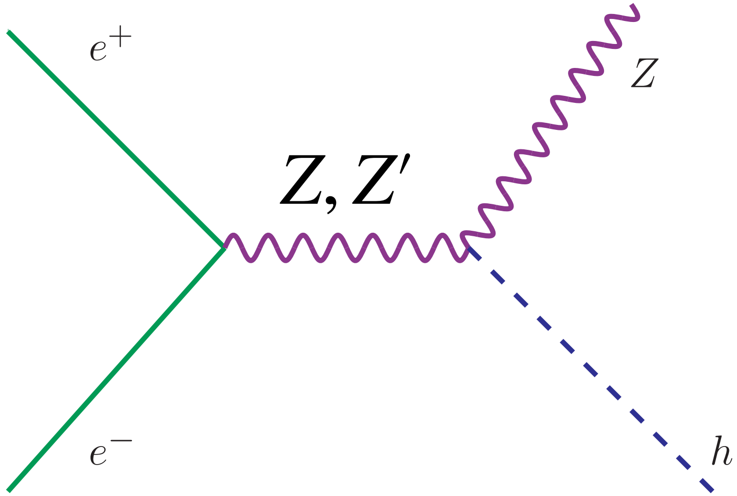


Dilepton and Zh production at the 13 TeV LHC



Production process at the linear collider

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



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

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

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

INTERFERENCE

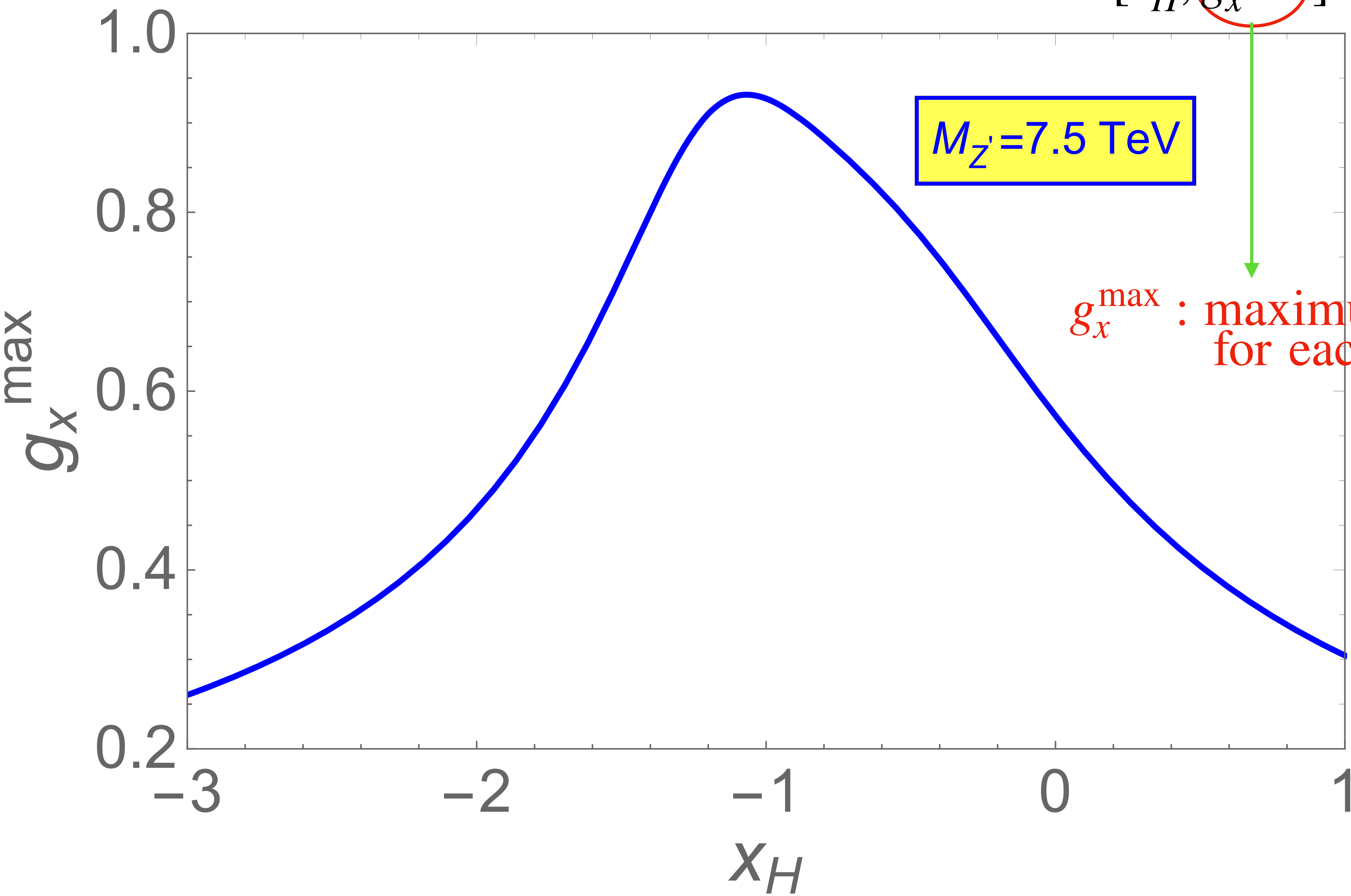
$U(1)_X$ coupling versus x_H for fixed Z' mass

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

$[X_{sce}^{\mathrm{ATLAS}}, M_{Z'}] \to \mathrm{Fixed}$

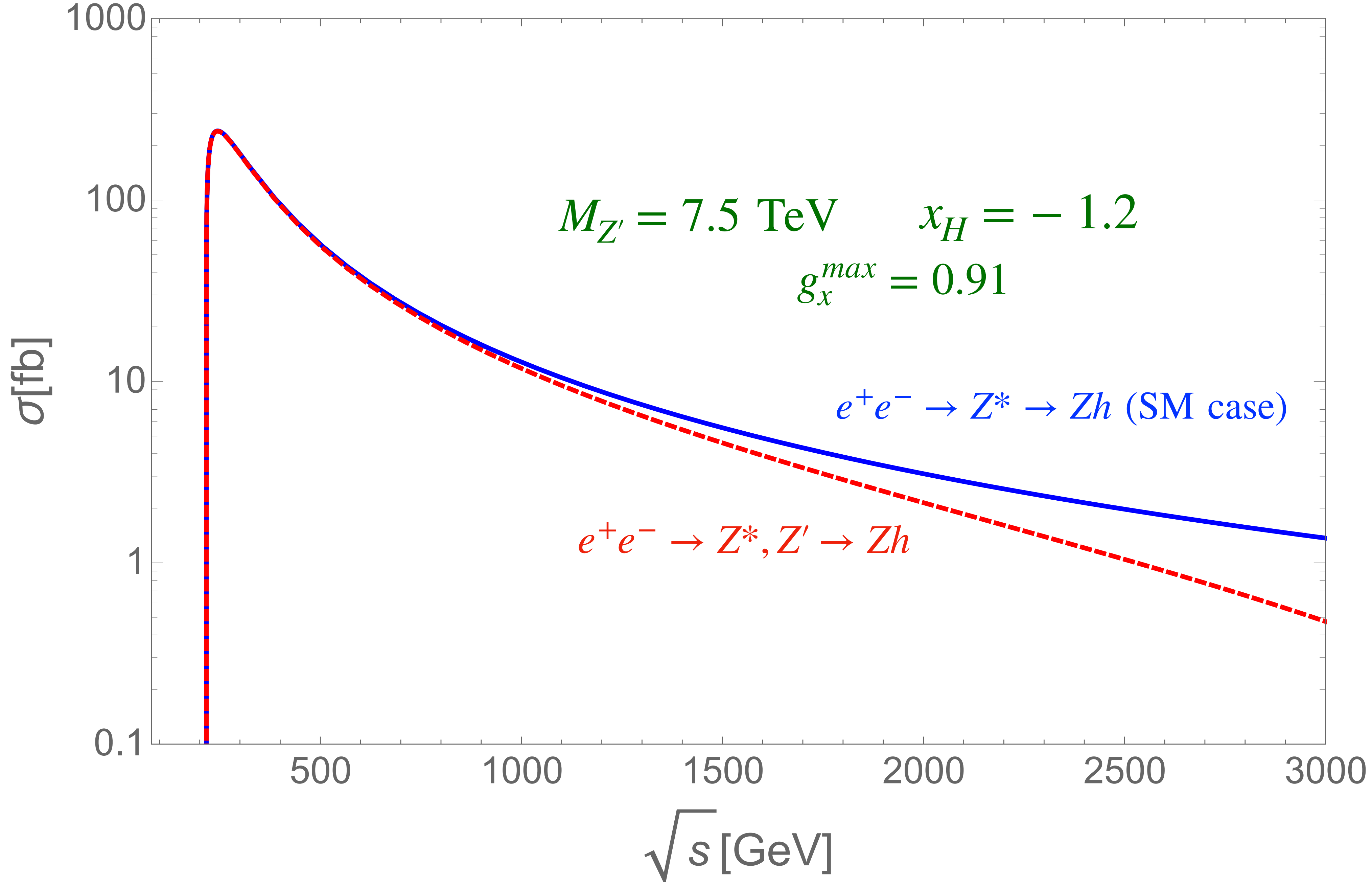
$\sigma[x_H, g_x] \leq X_{\mathrm{sce}}^{\mathrm{ATLAS}}$

$\sigma[x_H, g_x^{max}] = X_{\mathrm{sce}}^{\mathrm{ATLAS}}$

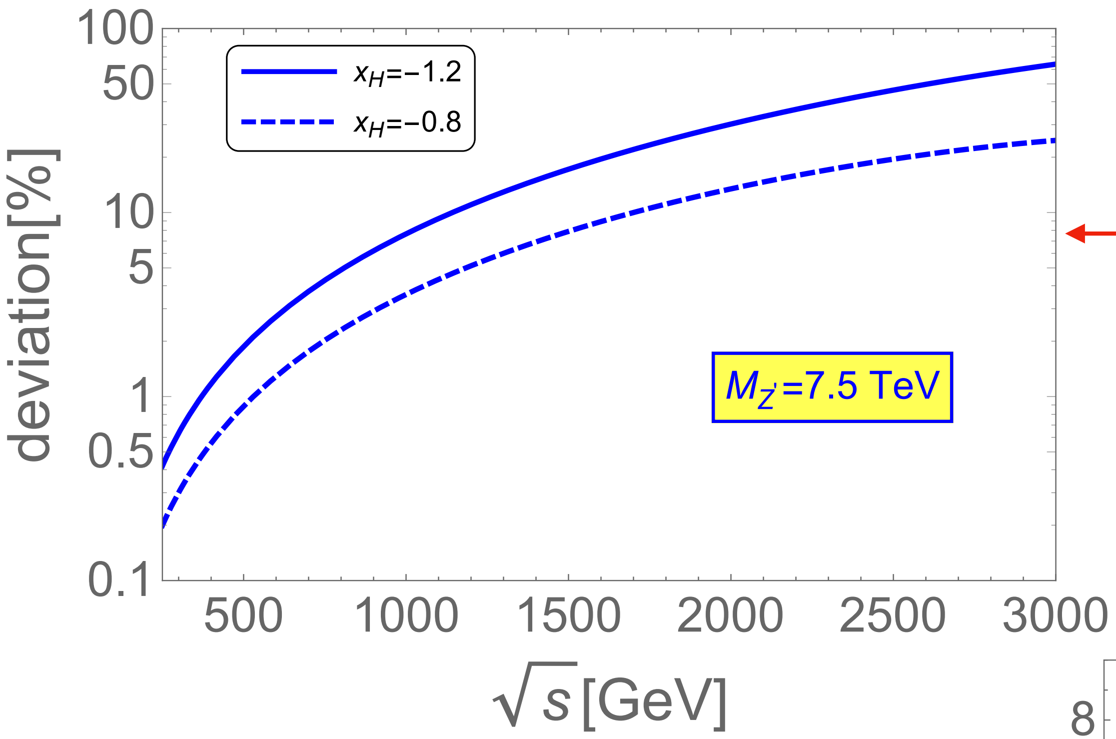


g_x^{max} : maximum value for each $\mathrm{x_H}$

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

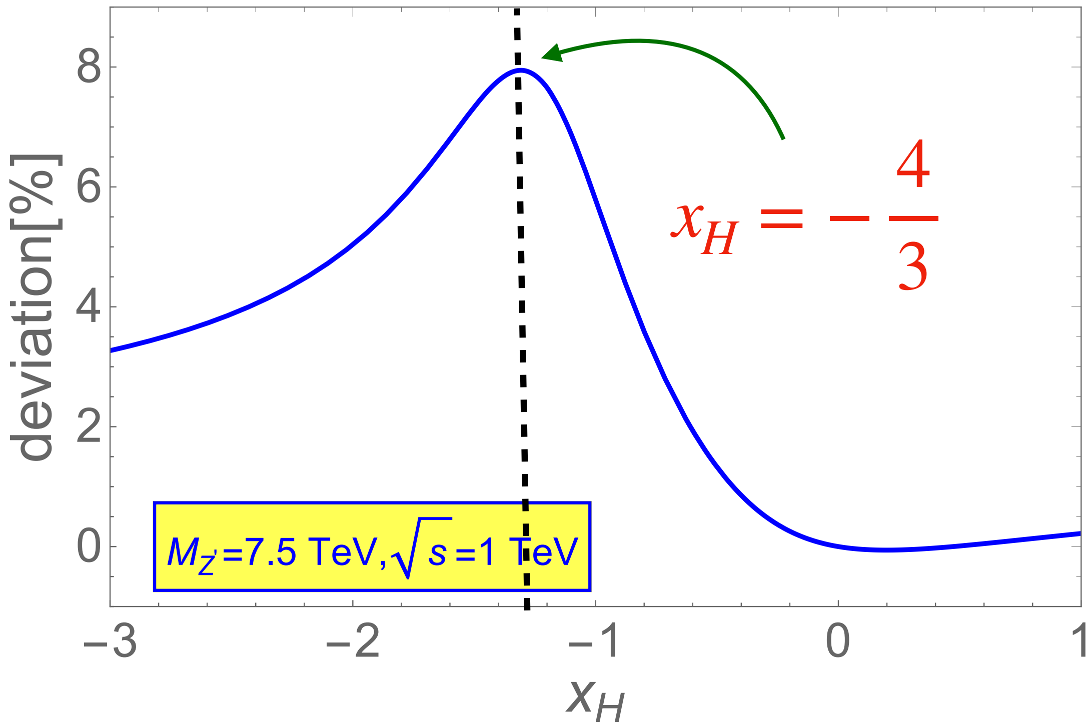


$$Deviation[\%] = Abs[1 - \frac{\sigma_{U(1)_X}[E_{CM}^{ILC}, g_x^{max}, x_H, M_{Z'}]}{\sigma_{SM}[E_{CM}]}] \times 100\%.$$



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

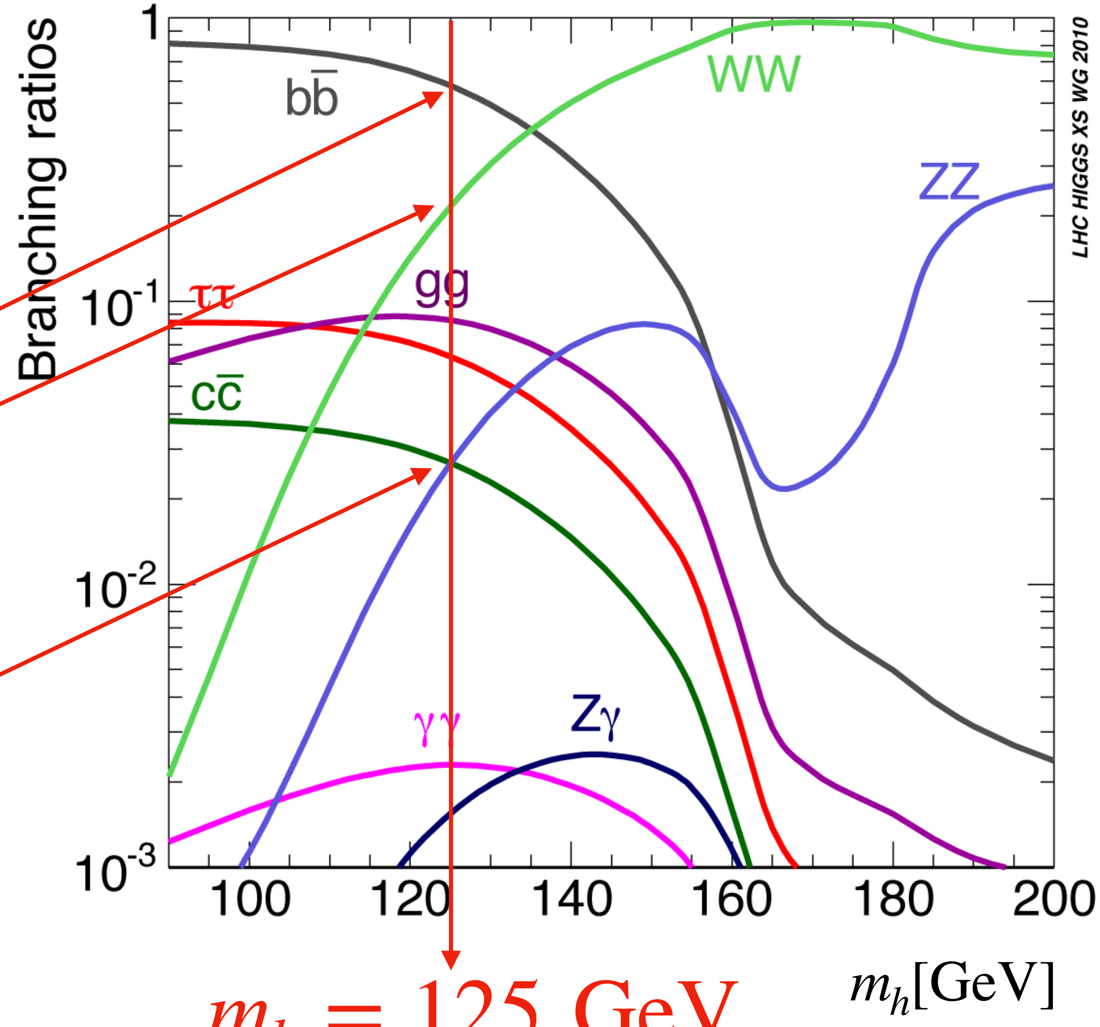
$$Zh \to 2\ell\ b\bar{b}$$

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

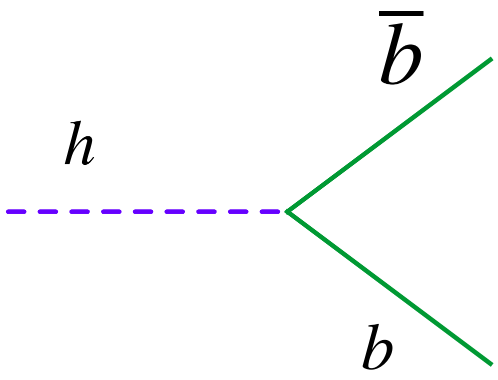
$\sim 60\ \%$

$\sim 20\ \%$

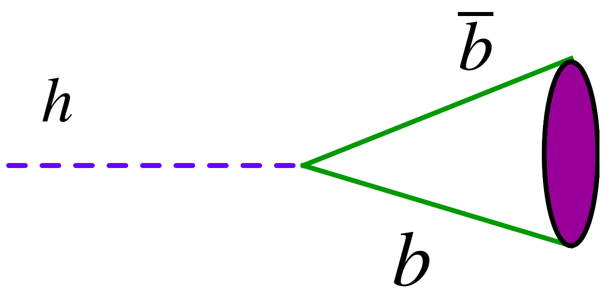
$\sim 2.5\ \%$



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



Higgs produced at rest (at the ILC)

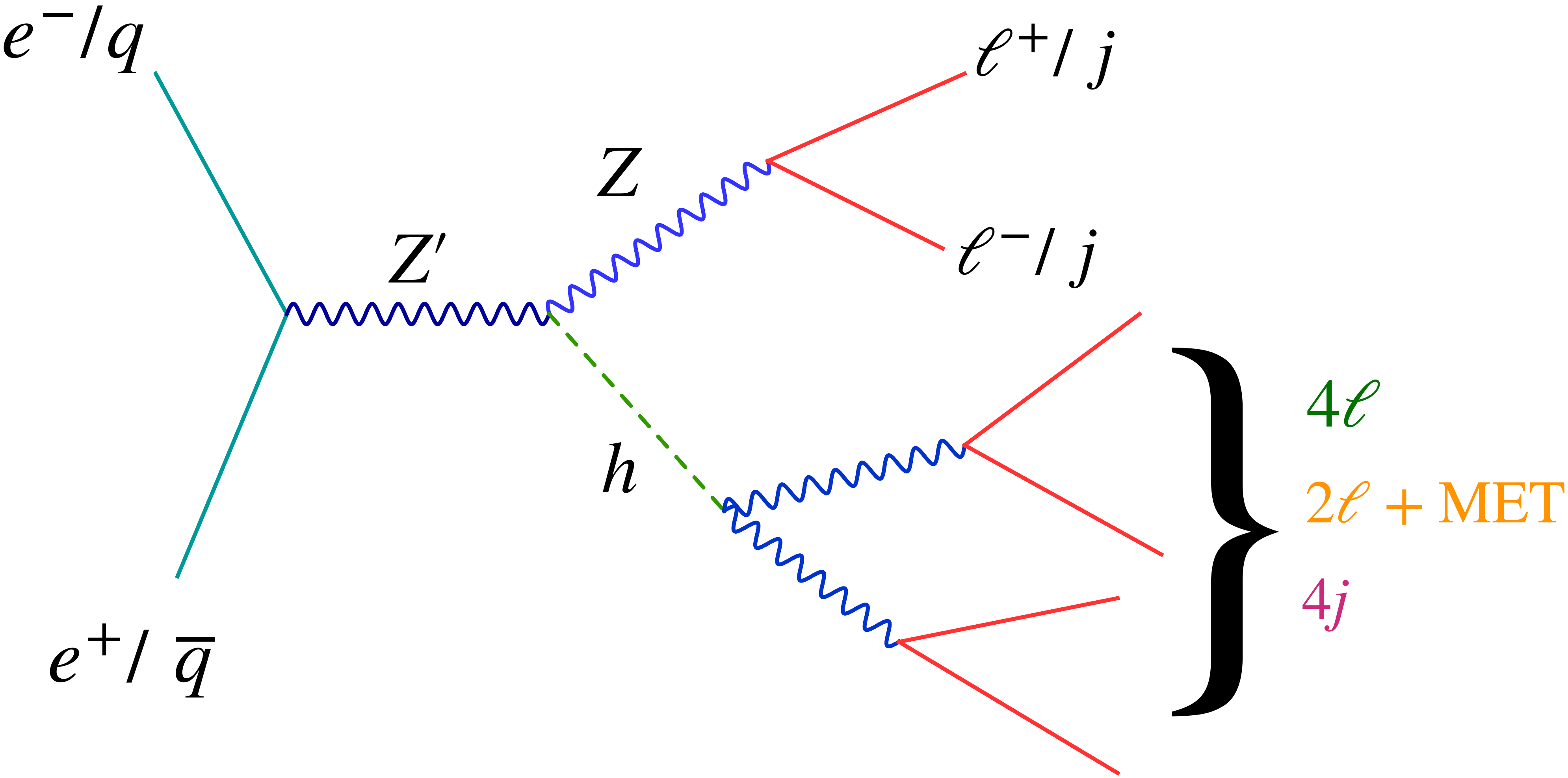


Boosted Higgs at the LHC

Analysis in progress

Multilepton-multijet channels

Analysis in progress



At the LHC, the produced Higgs could 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.

Conclusions

In this work we are studying the heavy resonance production at the colliders such as LHC and ILC. To study the heavy resonance 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, 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.

Thank you