Probing a minimal $U(1)_X$ model at future e^-e^+ collider via the fermion pair production channel

Based on : 2104.10902

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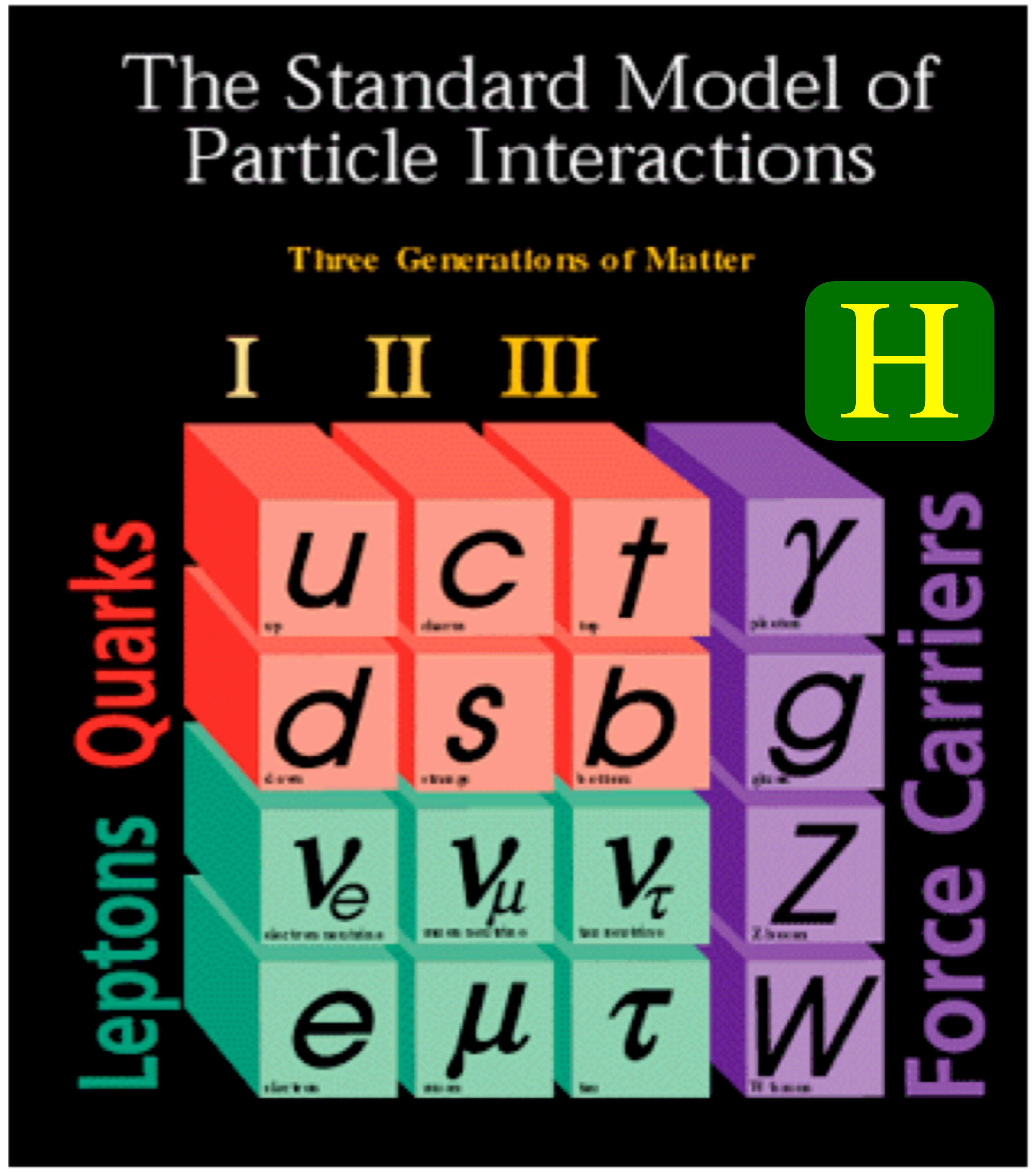
Introduction



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 . . .

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

Unkown ←

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	$=$	$2x_\Phi$

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

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**

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

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

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

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

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

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

seesaw

Z' interactions

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

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

Partial decay width

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

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

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

Implications of the choices of x_H keeping $x_\Phi = 1$

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)$_\mathrm{R}$	-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

Phenomenological aspects of the model

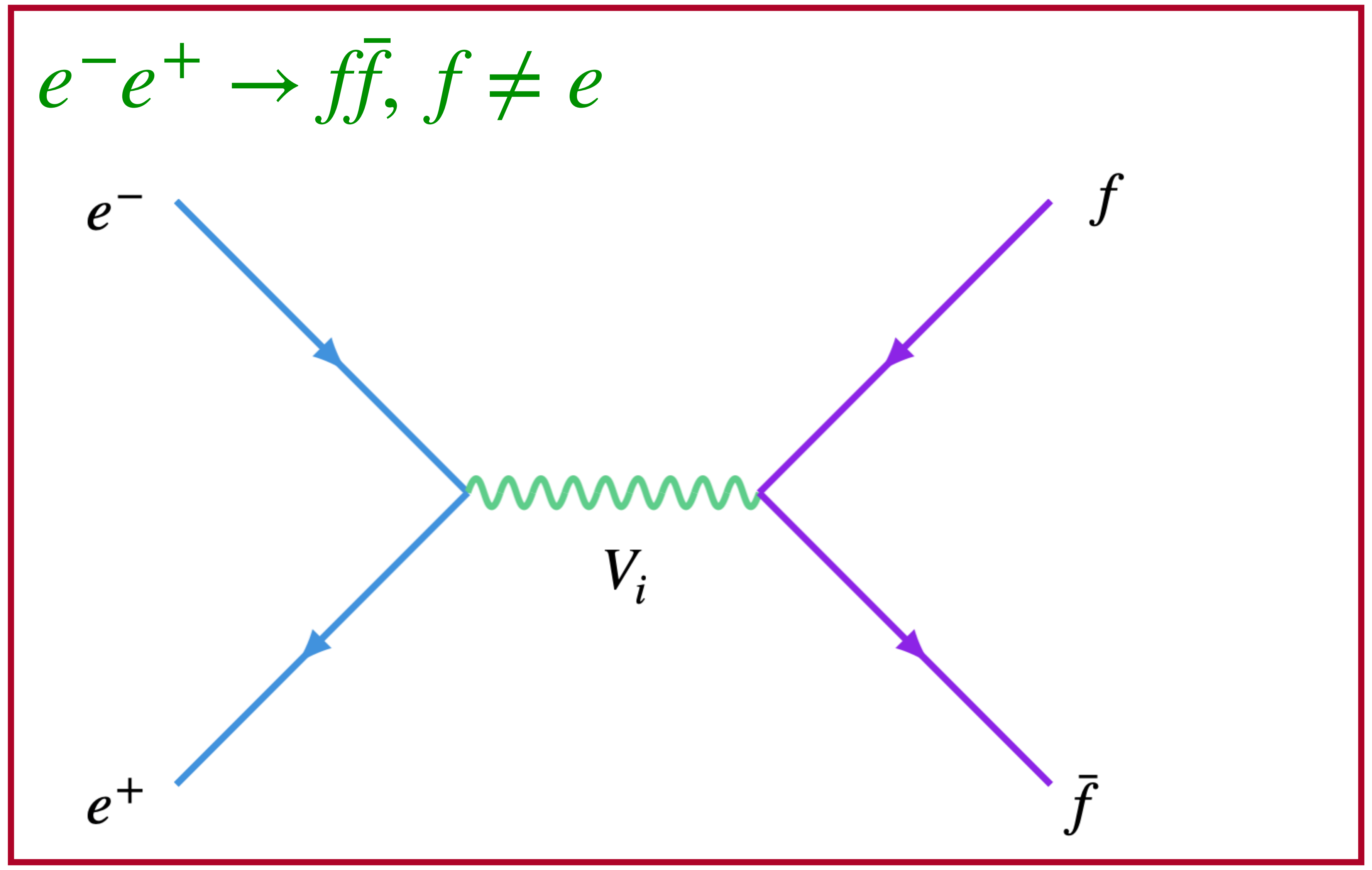
New particles Z' boson Heavy Majorana Neutrino $U(1)_X$ Higgs boson

Phenomenology Z' boson production and decay Heavy neutrino production

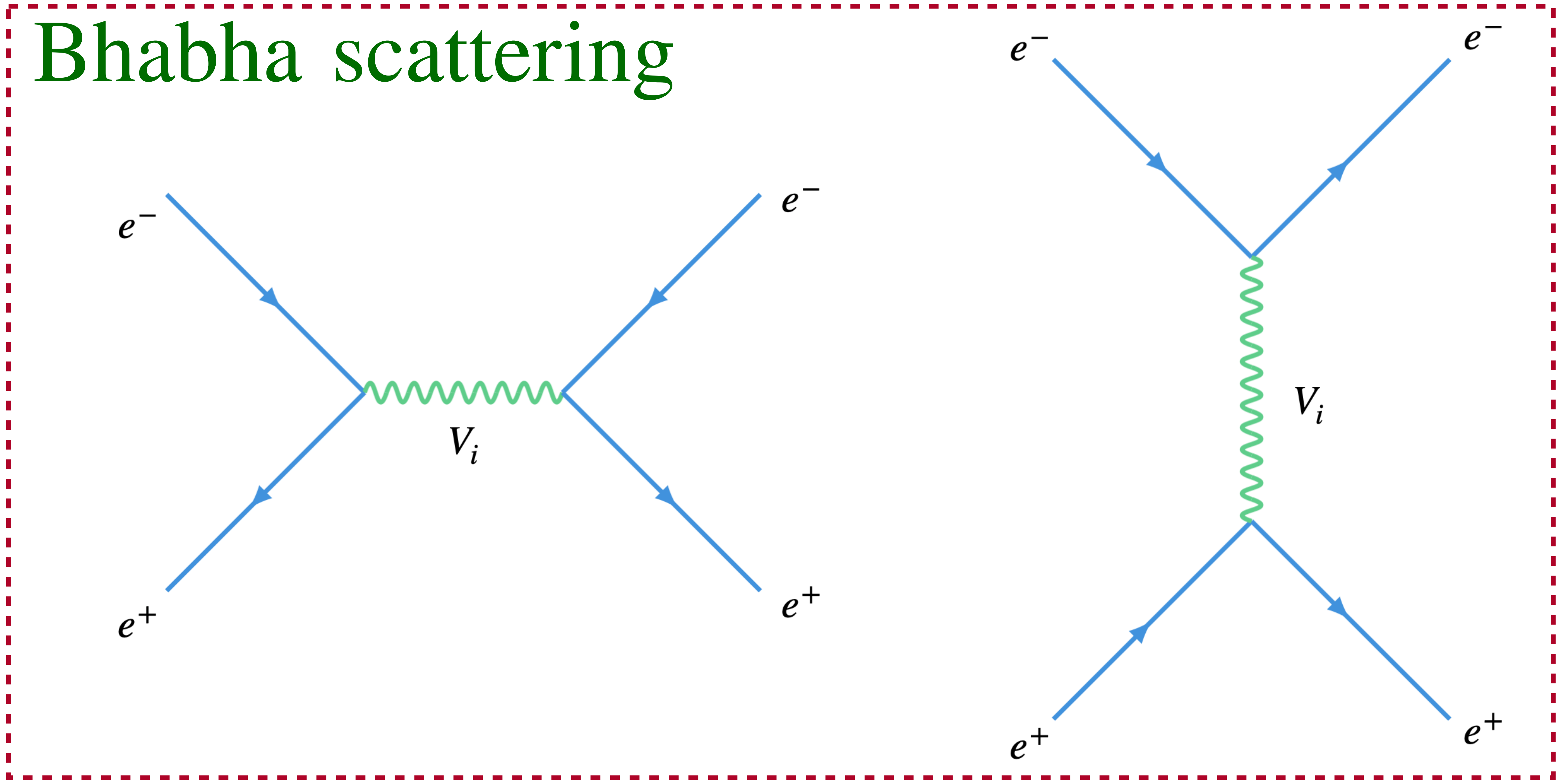
Dark Matter collider $U(1)_X$Higgs phenoemenology : Vacuum Stability

Leptogenesis and many more

Fermionic pair production form the Z′

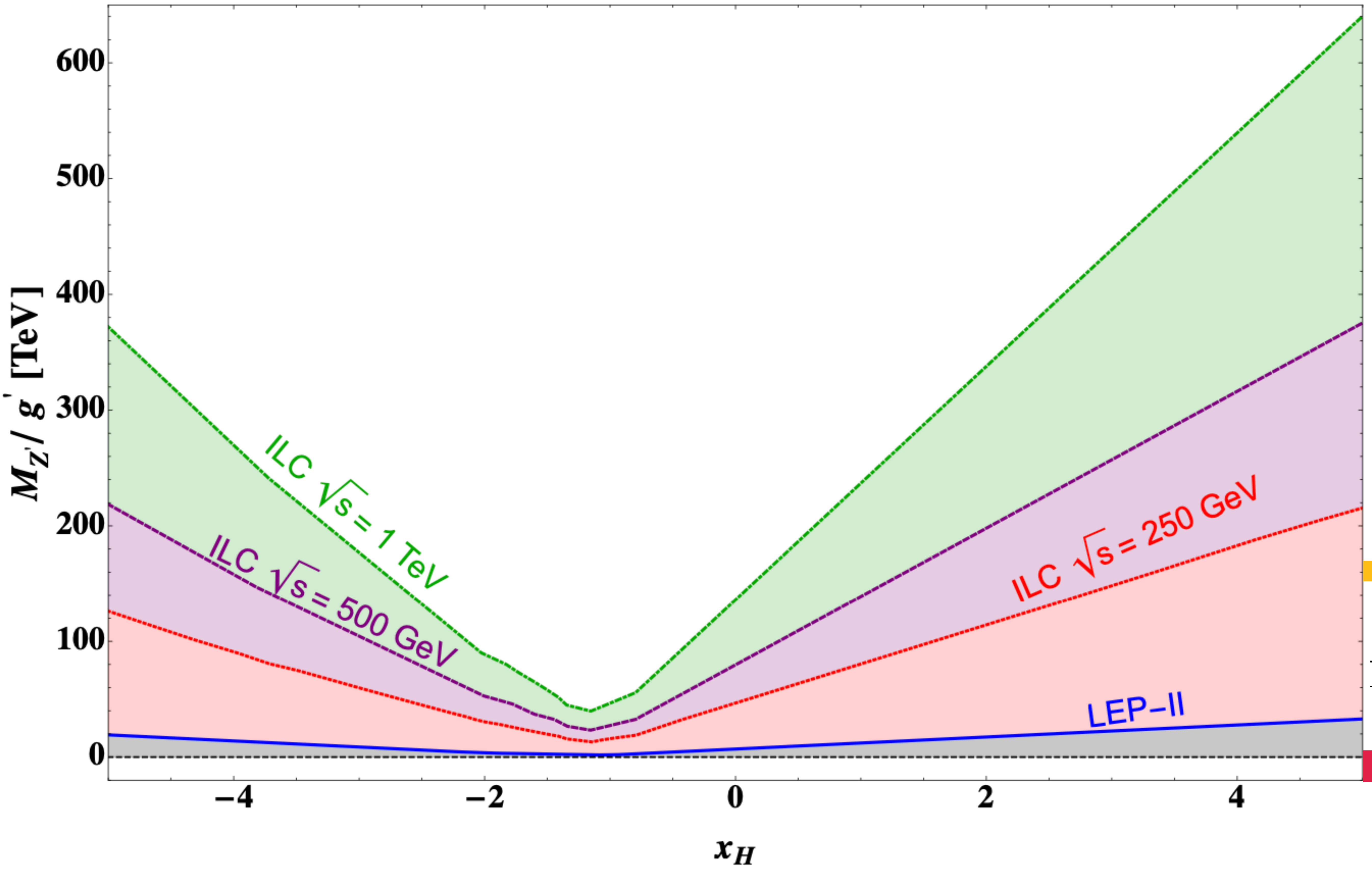


$V_i = \{\gamma, Z, Z'\}$



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) :



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

Z' exchange matrix element for our process

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

Matching the above equations we obtain

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

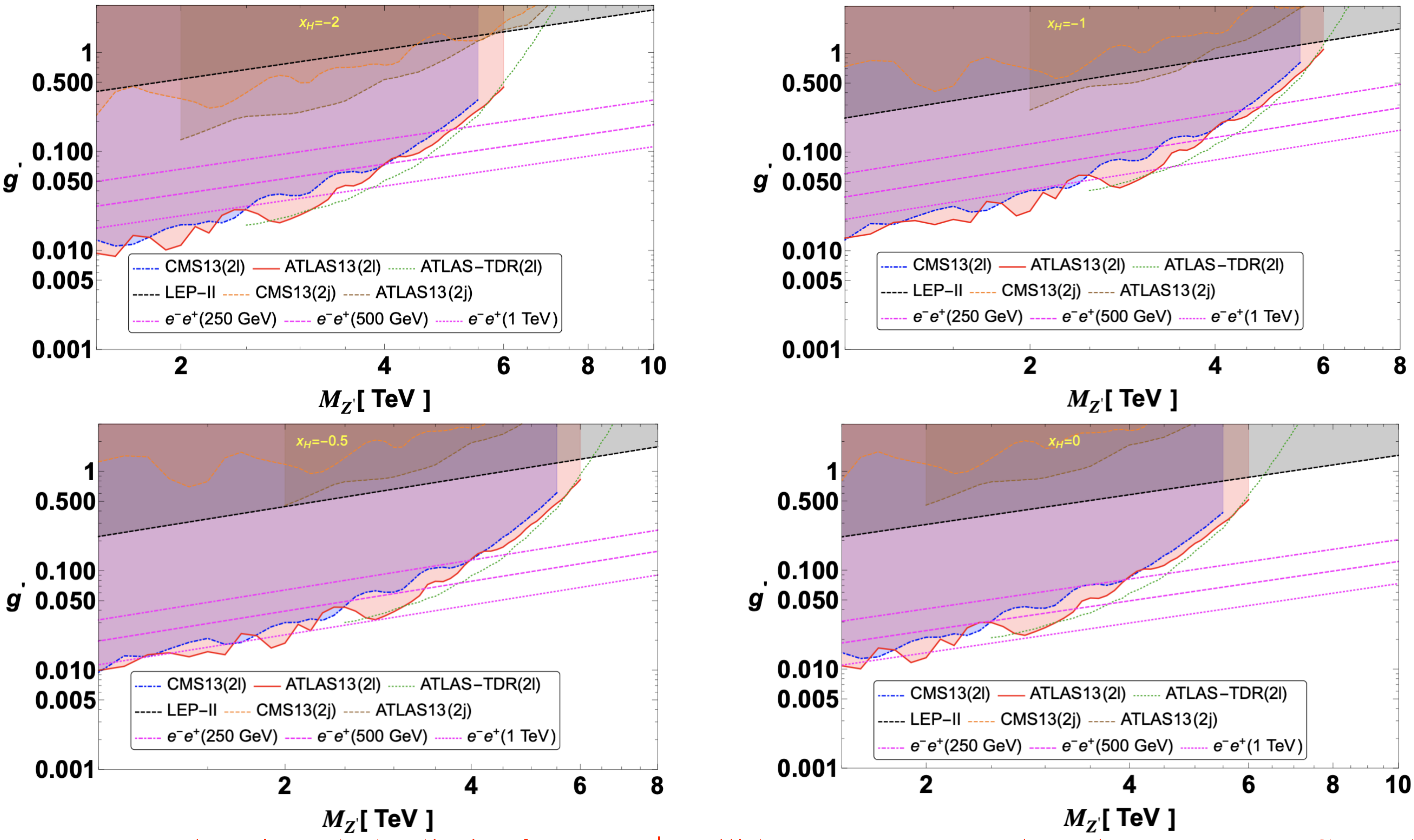
Indicates a large VEV scale can be probed from LEP – II to ILC1000 via ILC250 and ILC500

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

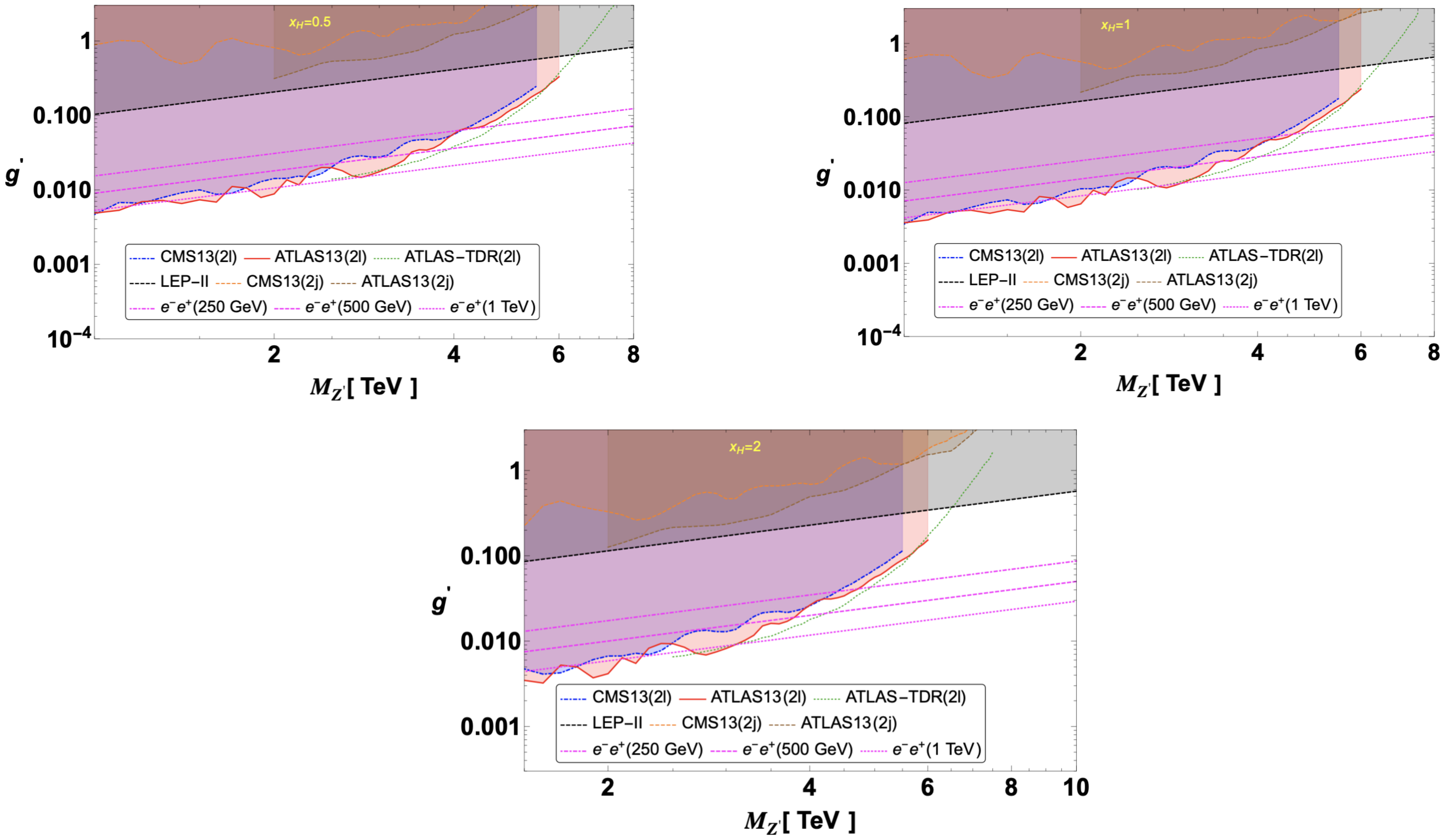
$$\boxed{g' = \sqrt{g^2_{\text{Model}}\left(\frac{\sigma^{\text{Obs.}}_{\text{ATLAS}}}{\sigma_{\text{Model}}}\right)}}$$

$x_H \leq 0$



For heavier Z', the limits from e^-e^+ colliders are stronger than the current LHC results

$x_H > 0$



For heavier Z', the limits from e^-e^+ colliders are stronger than the current LHC results

$e^-e^+ \to f\,f$

We define

$$q^{e_L f_L} = \sum_i \frac{g_L^{V_i e} g_L^{V_i f}}{s - m_{V_i}^2 + i\, m_{V_i}\Gamma_{V_i}}, \quad q^{e_L f_R} = \sum_i \frac{g_L^{V_i e} g_R^{V_i f}}{s - m_{V_i}^2 + i\, m_{V_i}\Gamma_{V_i}}$$

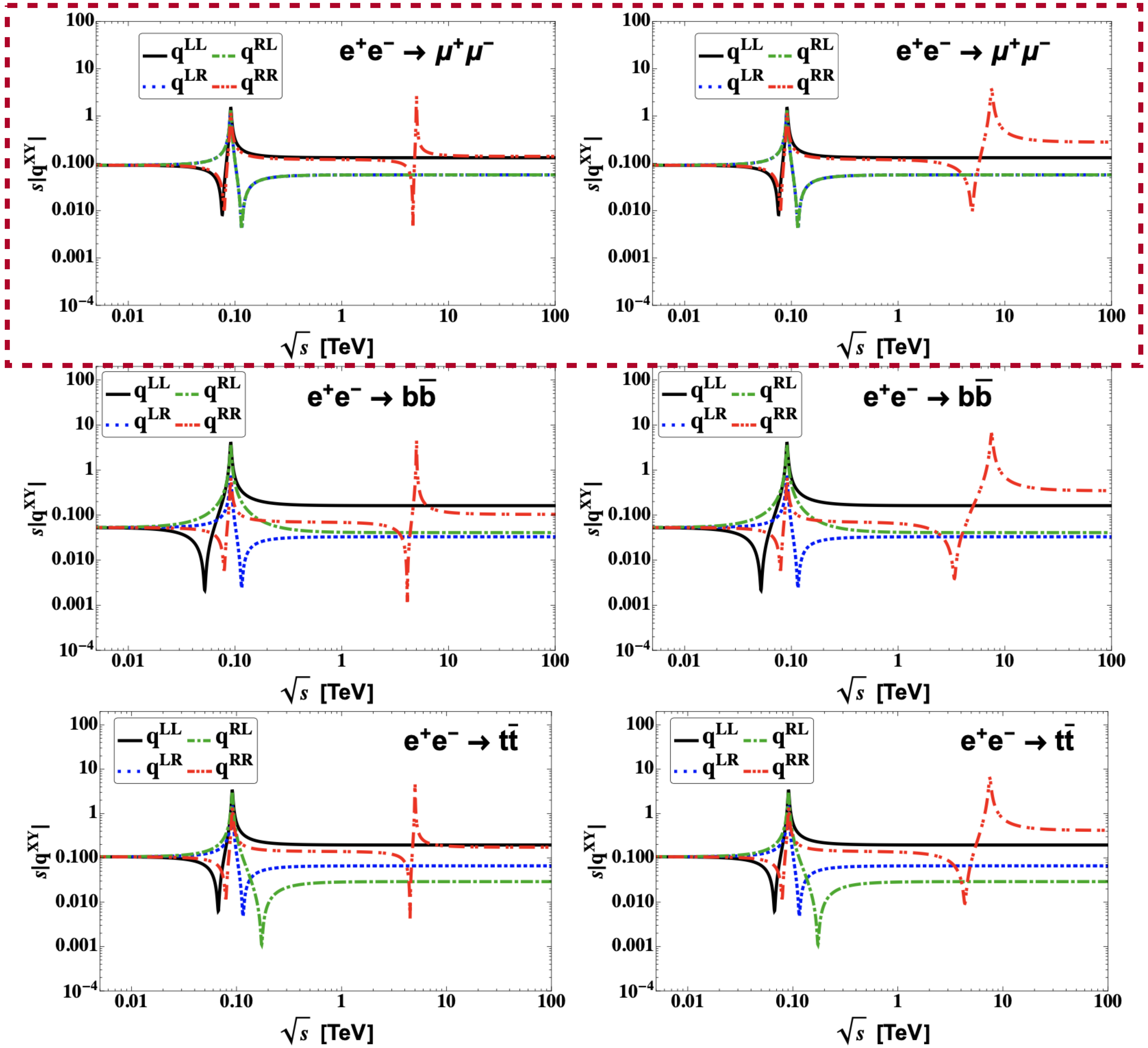
$$q^{e_R f_L} = \sum_i \frac{g_R^{V_i e} g_L^{V_i f}}{s - m_{V_i}^2 + i\, m_{V_i}\Gamma_{V_i}}, \quad q^{e_R f_R} = \sum_i \frac{g_R^{V_i e} g_R^{V_i f}}{s - m_{V_i}^2 + i\, m_{V_i}\Gamma_{V_i}}$$

$g_{L/R}^{V_i} \to$ information of charges x_H, x_Φ

No interaction with left handed fermions

$x_H = -2$

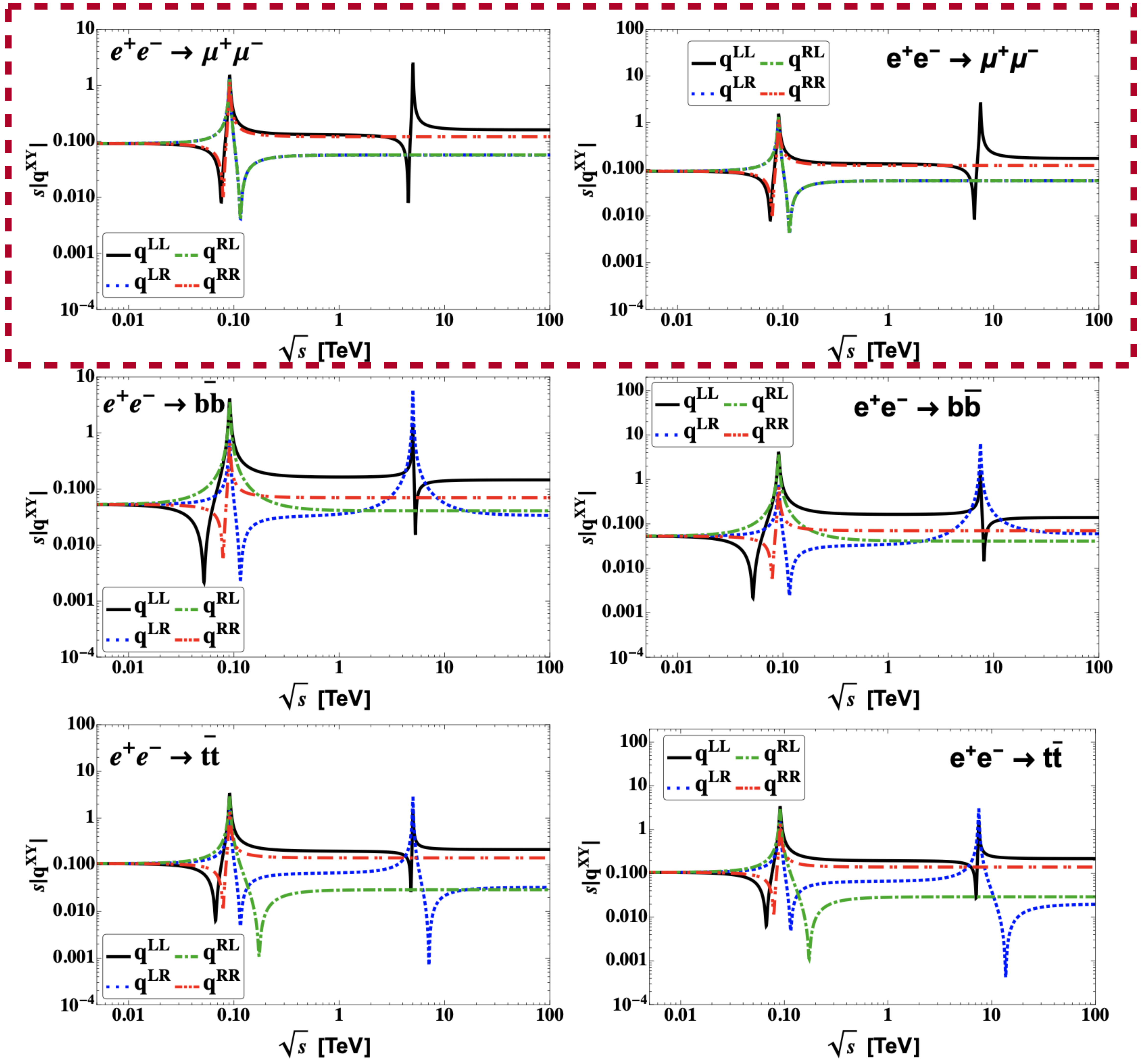
No contribution q_{LL}, q_{LR}, q_{RL} in $\mu^+\mu^-$



No interaction with e_R

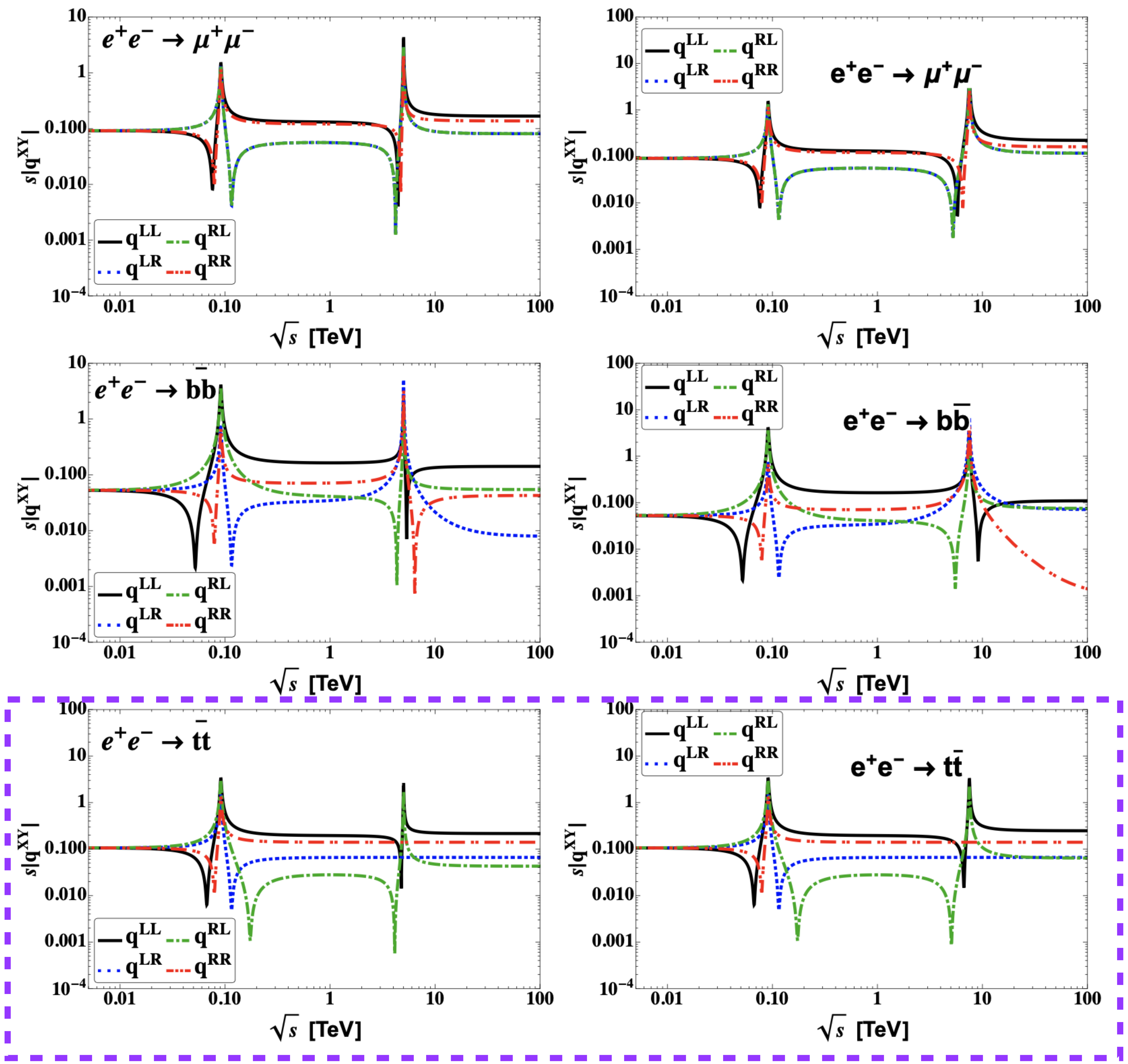
$x_H = -1$

No contribution q_{RR}, q_{LR}, q_{RL} in $\mu^+\mu^-$



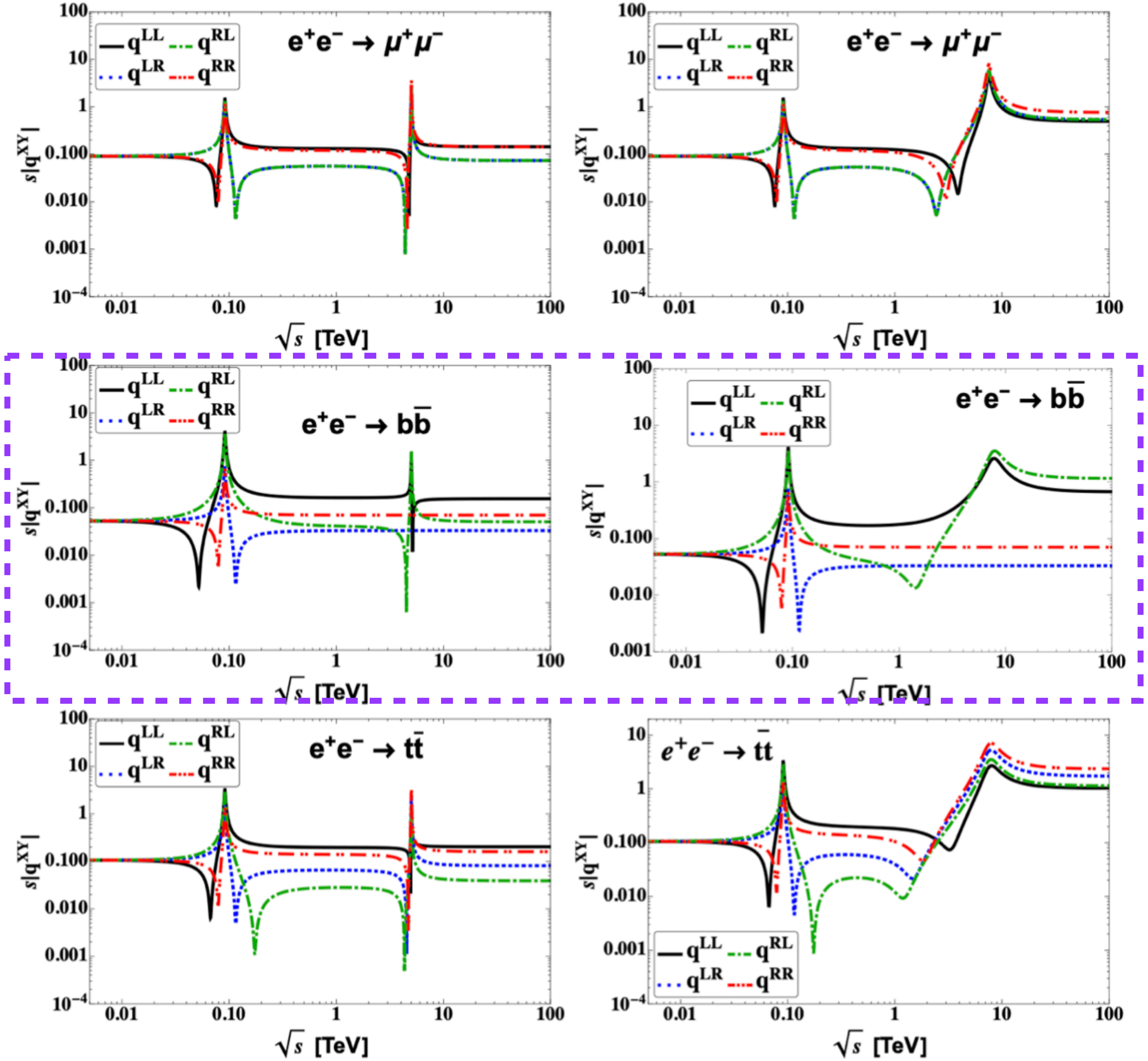
$x_H = 0.5$ No interaction with u_R

No contribution q_{RR}, q_{LR} in $t\bar{t}$



$x_H = 1$ No interaction with d_R

No contribution q_{RR}, q_{LR} in $b\bar{b}$



$e^-e^+ \to \mu^+\mu^-$

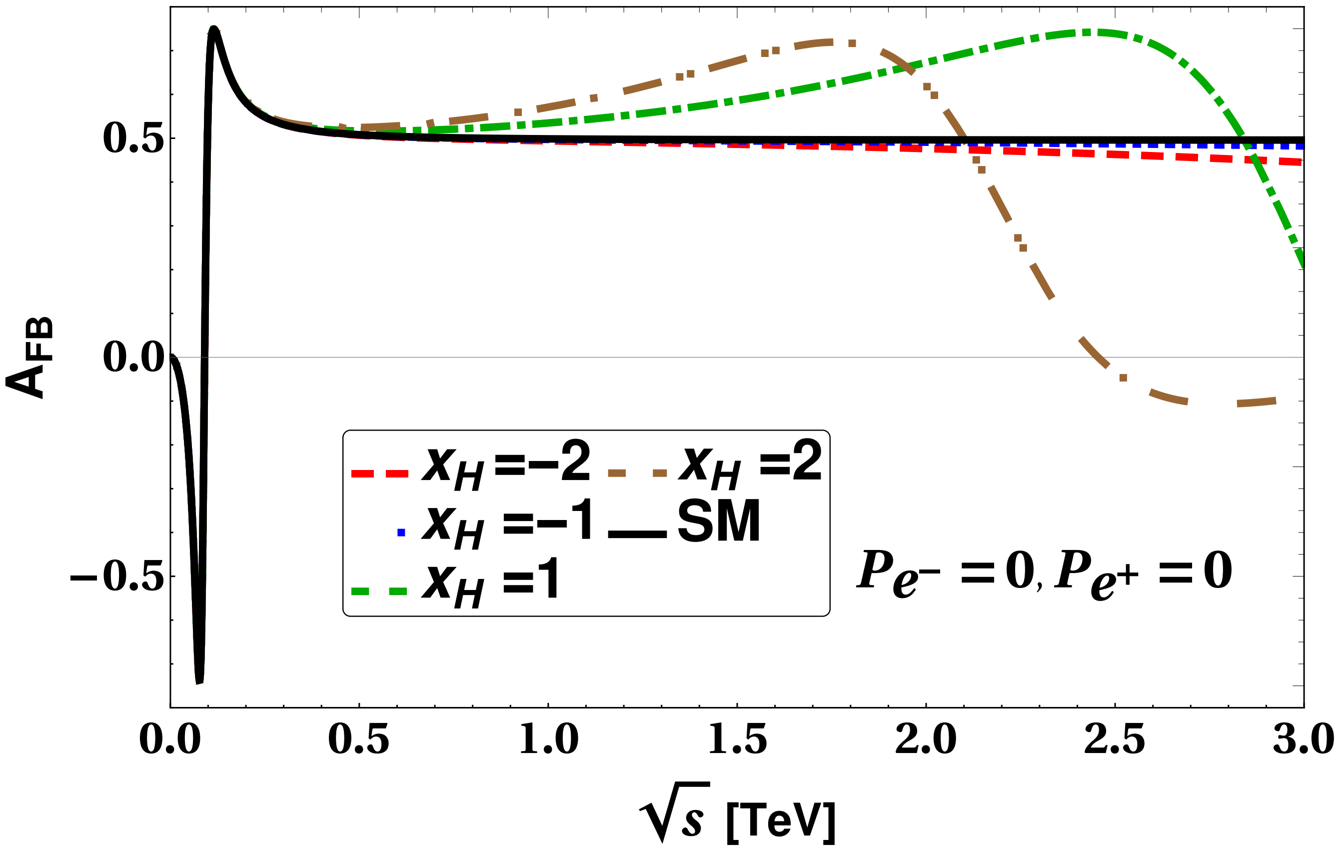
$M_{Z'} = 7.5$ TeV

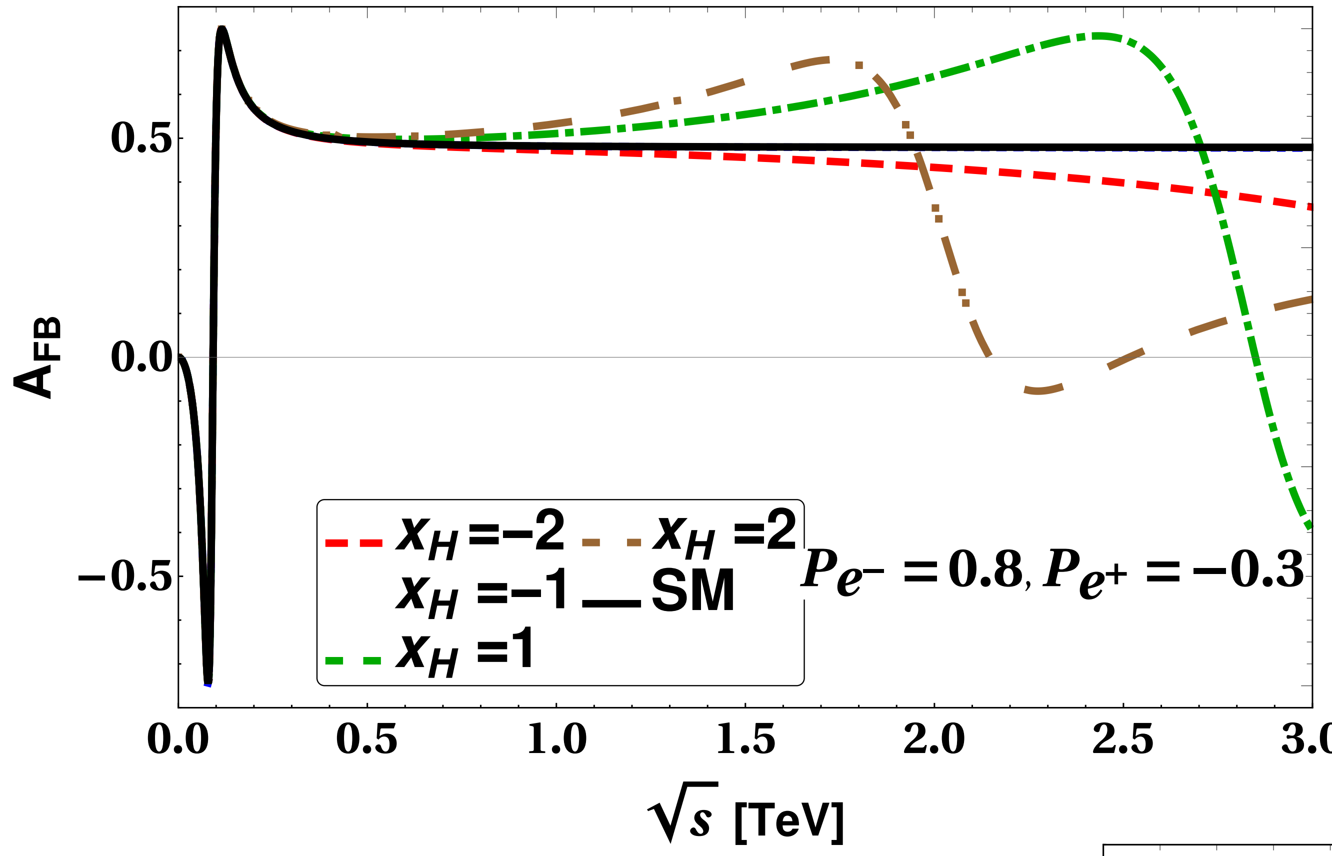
$e^-e^+ \to e^+e^-$

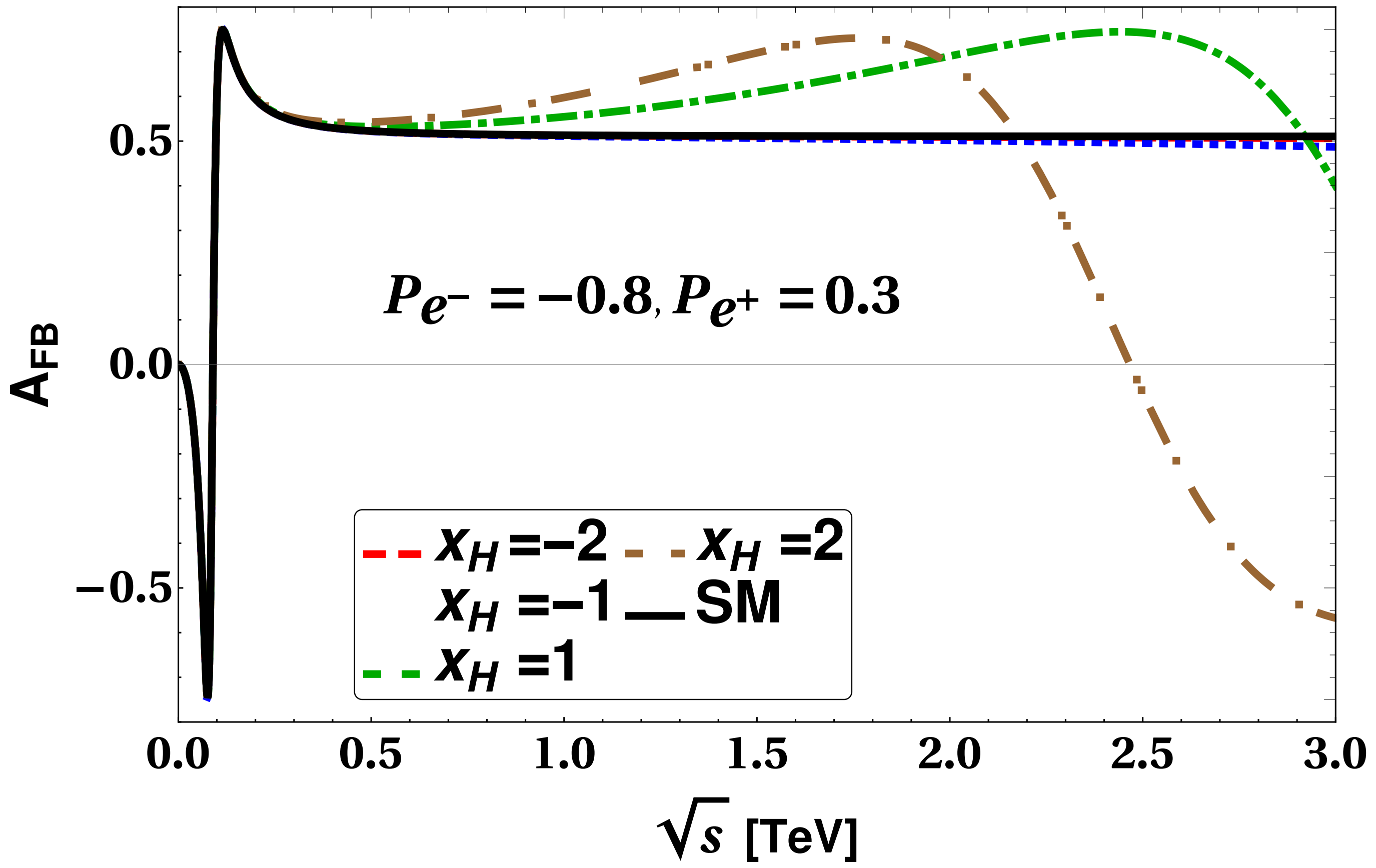
Deviations in total cross sections from SM is more than 100 % for $x_H \geq 1$ for $\sqrt{s} = 3$ TeV . For $\sqrt{s} < 3$TeV the deviation is also sizable .

Integrated Forward – Backward Asymmetry ($e^-e^+ \to \mu^-\mu^+$) : $\mathscr{A}_{\rm FB}$

$M_{Z'} = 7.5$ TeV







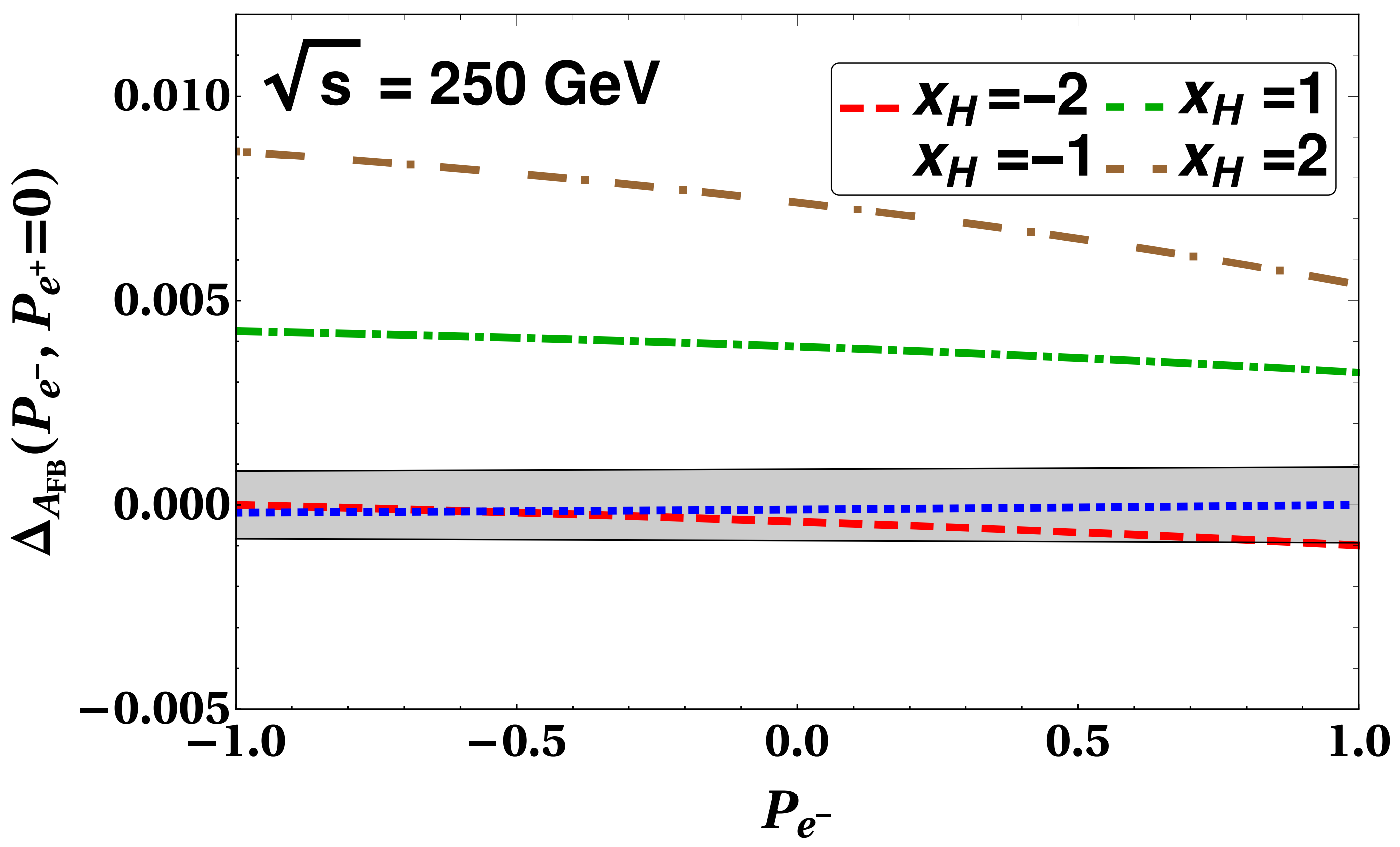
Integrated

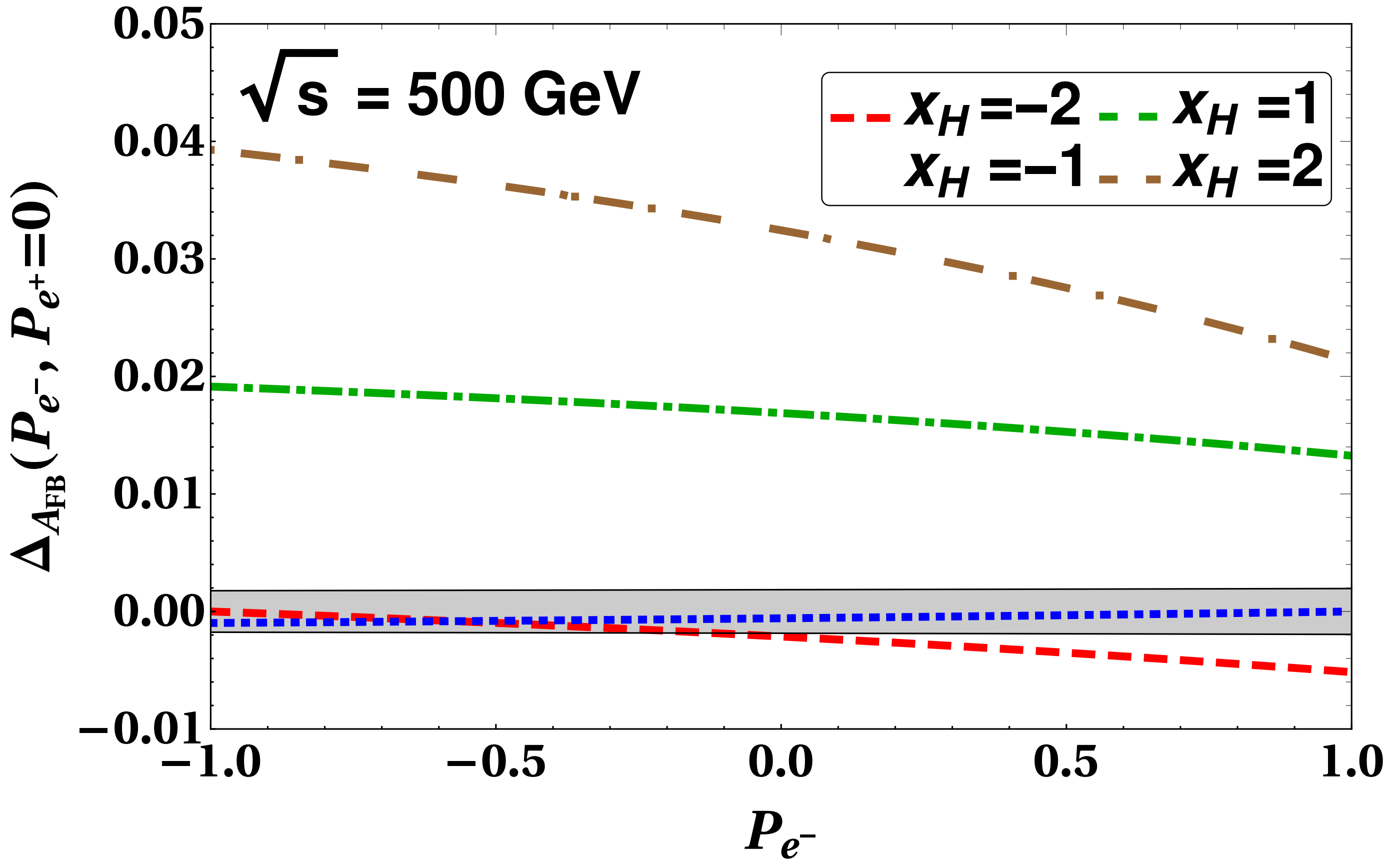
$$\mathcal{A}_{FB}(P_{e^-}, P_{e^+}) = \frac{\sigma_F(P_{e^-},P_{e^+}) - \sigma_B(P_{e^-},P_{e^+})}{\sigma_F(P_{e^-},P_{e^+}) + \sigma_B(P_{e^-},P_{e^+})}$$

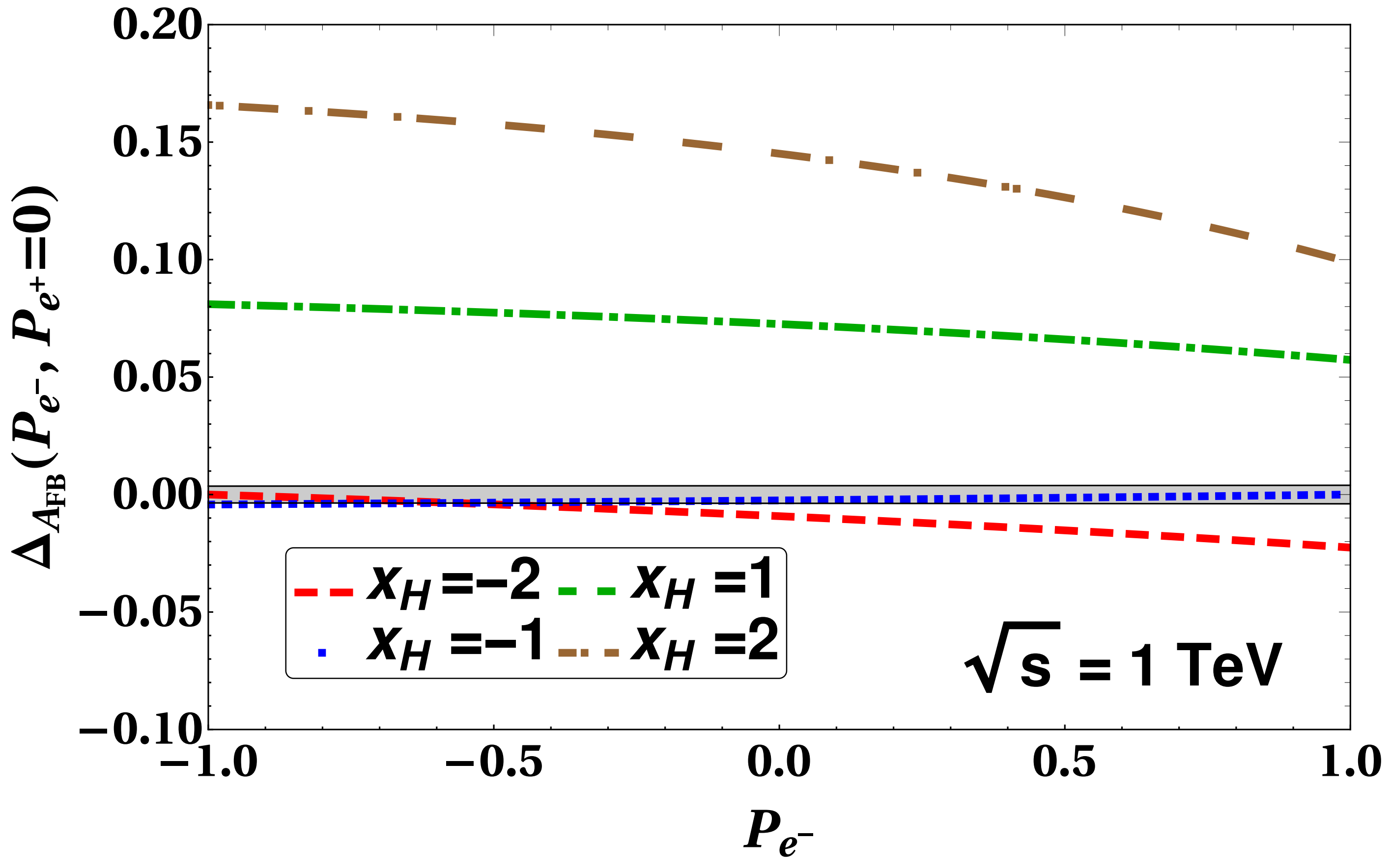
Deviation from the SM

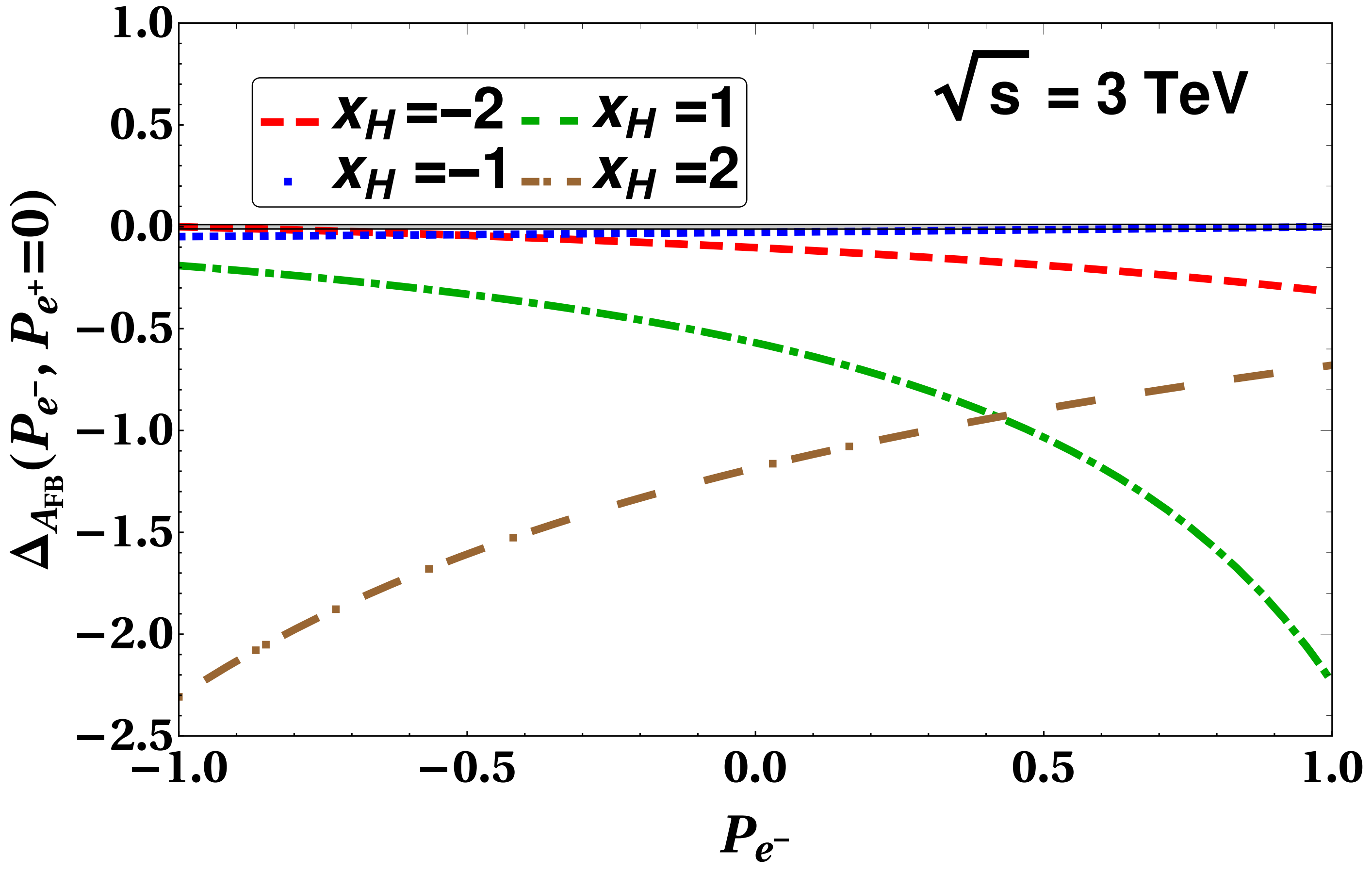
$$\Delta_{\mathcal{A}_{FB}} = \frac{\mathcal{A}_{\rm FB}^{U(1)_X}}{\mathcal{A}_{\rm FB}^{SM}} - 1.$$

$x_H = 2$: 3.8 % for $P_{e^-} = -0.8$ at 500 GeV
$x_H = 1$: 79 % for $P_{e^-} = -0.8$ at 1 TeV
$x_H = -1$: 20 % for $P_{e^-} = 0.3$ at 3 TeV







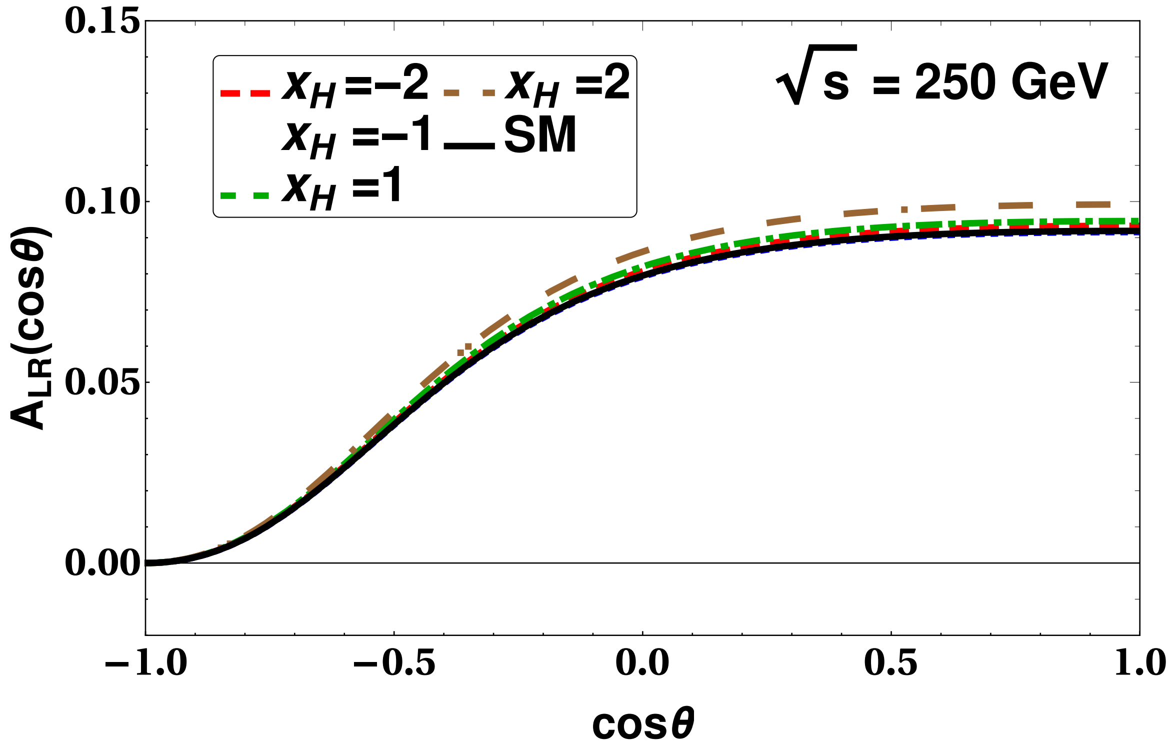


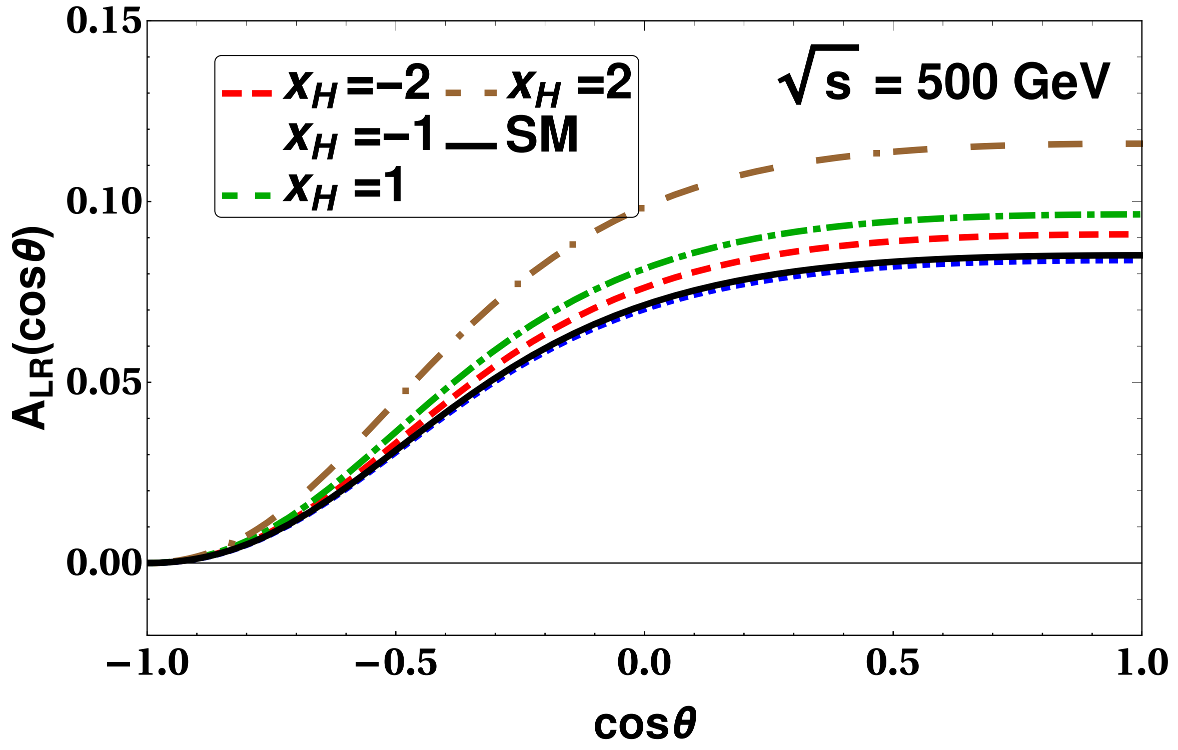
Statistical error

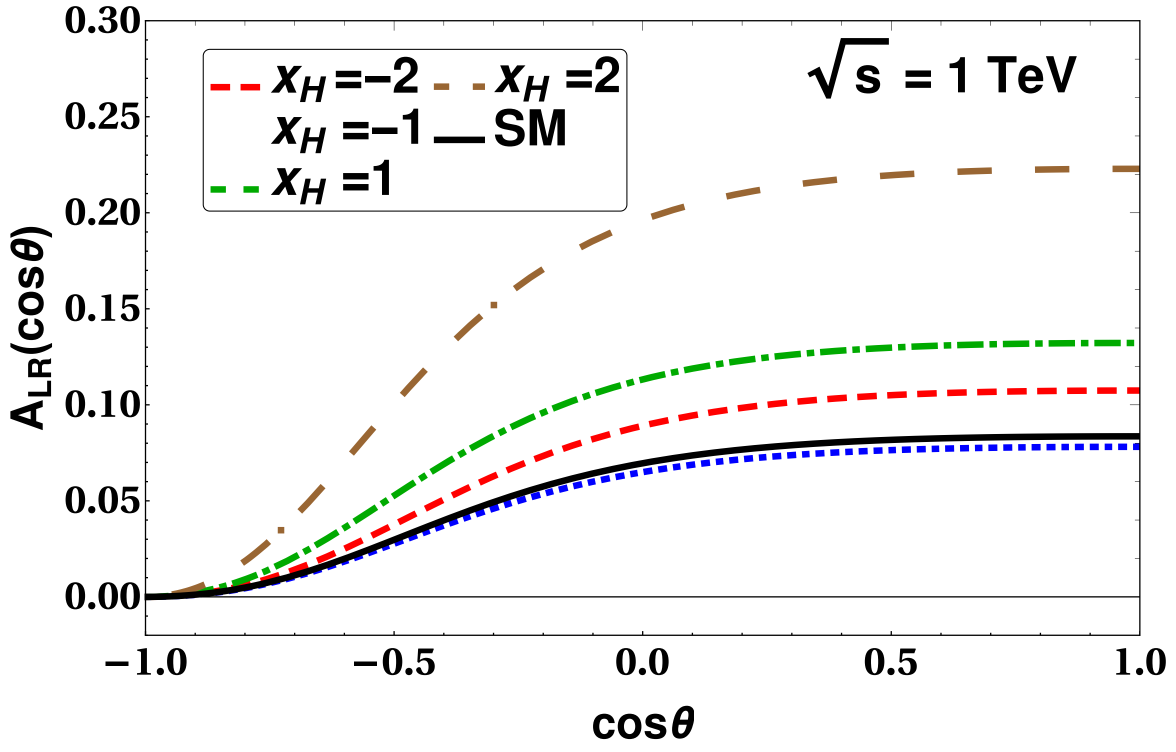
$$\Delta\mathcal{A}_{\rm FB} = 2\frac{\sqrt{n_1 n_2}\left(\sqrt{n_1} + \sqrt{n_2}\right)}{(n_1 + n_2)^2} = \frac{2\sqrt{n_1 n_2}}{(n_1 + n_2)\left(\sqrt{n_1} - \sqrt{n_2}\right)}\mathcal{A}_{FB}$$

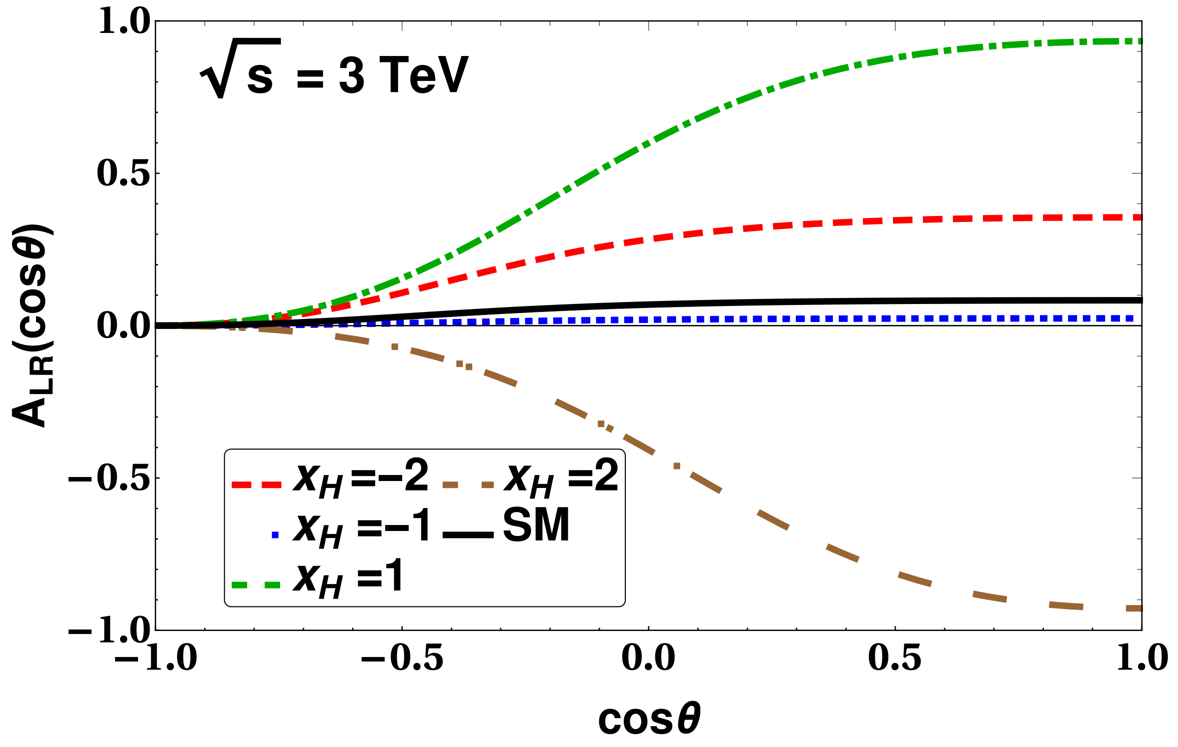
$$(n_1, n_2) = (N_F, N_B) \qquad N_{F(B)} = L_{\rm int}\sigma_{F(B)}(P_{e^-}, P_{e^+})$$

Differenial and integarted Left – Right Asymmetry ($e^-e^+ \to \mu^-\mu^+$) : $\mathscr{A}_{\rm LR}$ $M_{Z'} = 7.5$ TeV









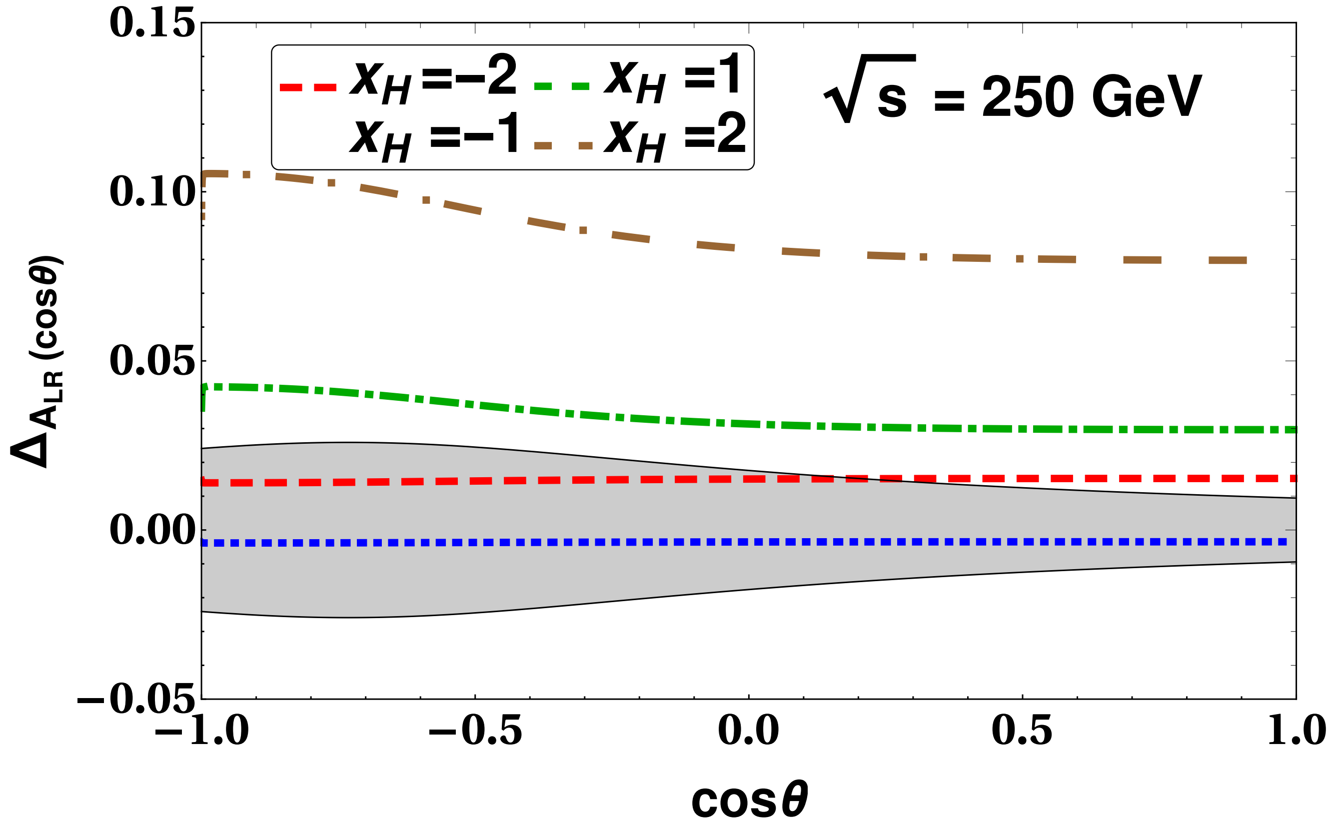
Differential

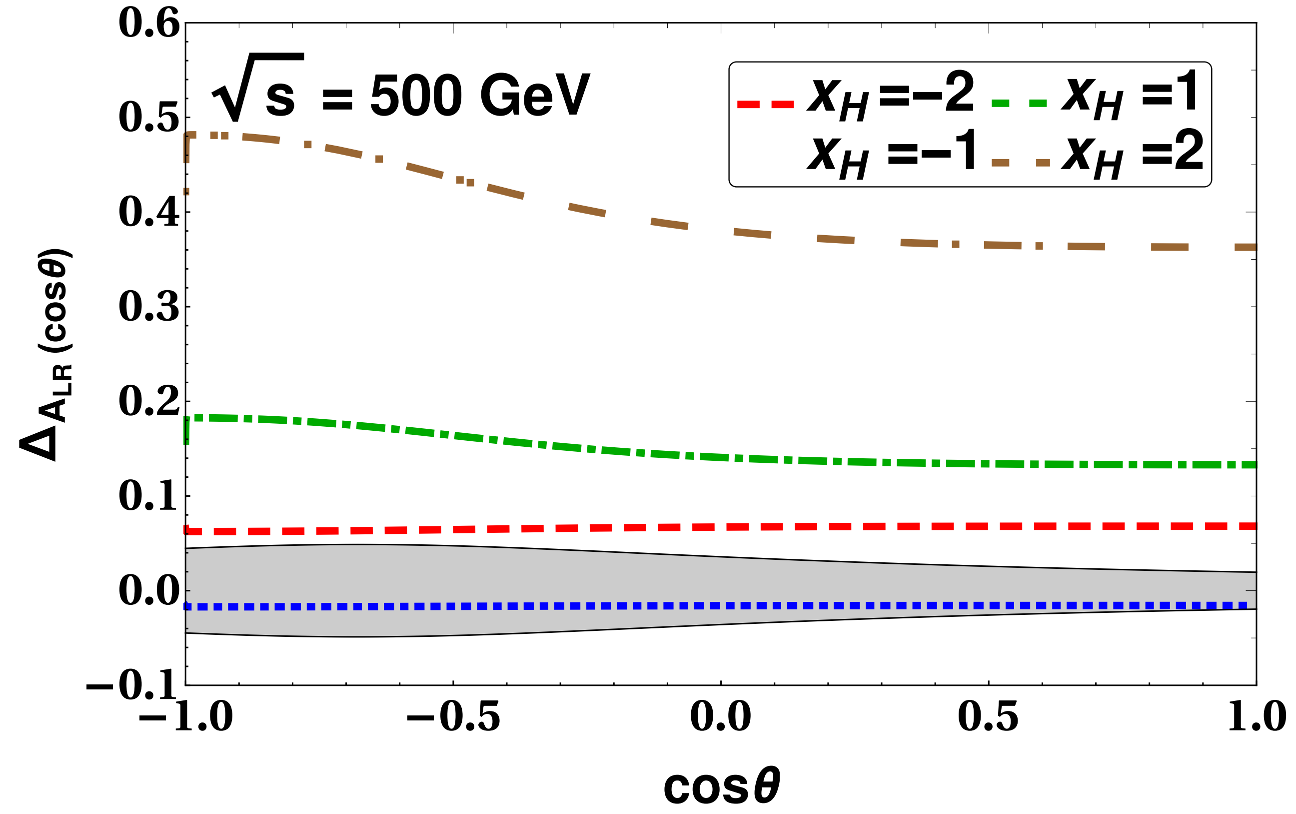
$$\mathcal{A}_{\rm LR}(\cos\theta) = \frac{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) - \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) + \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}$$

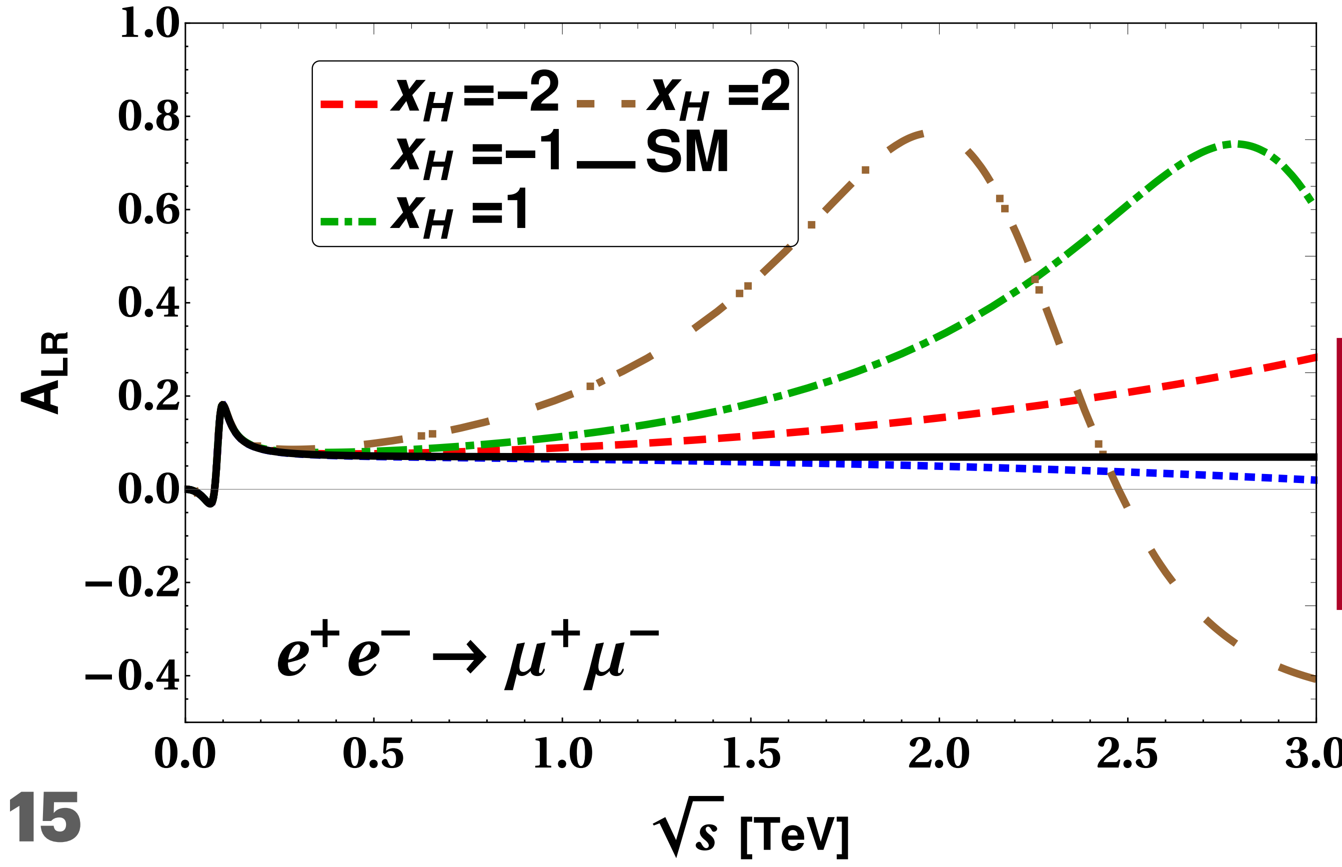
Deviation from the SM

$$\Delta_{\mathcal{A}_{LR}}(\cos\theta) = \frac{\mathcal{A}_{LR}^{U(1)_X}(\cos\theta)}{\mathcal{A}_{LR}^{\rm SM}(\cos\theta)} - 1$$

$x_H = 2$: 10 % for at 250 GeV
$x_H = 1$: 20 % for at 500 GeV
$x_H = -2$: 8 % for at 500 GeV

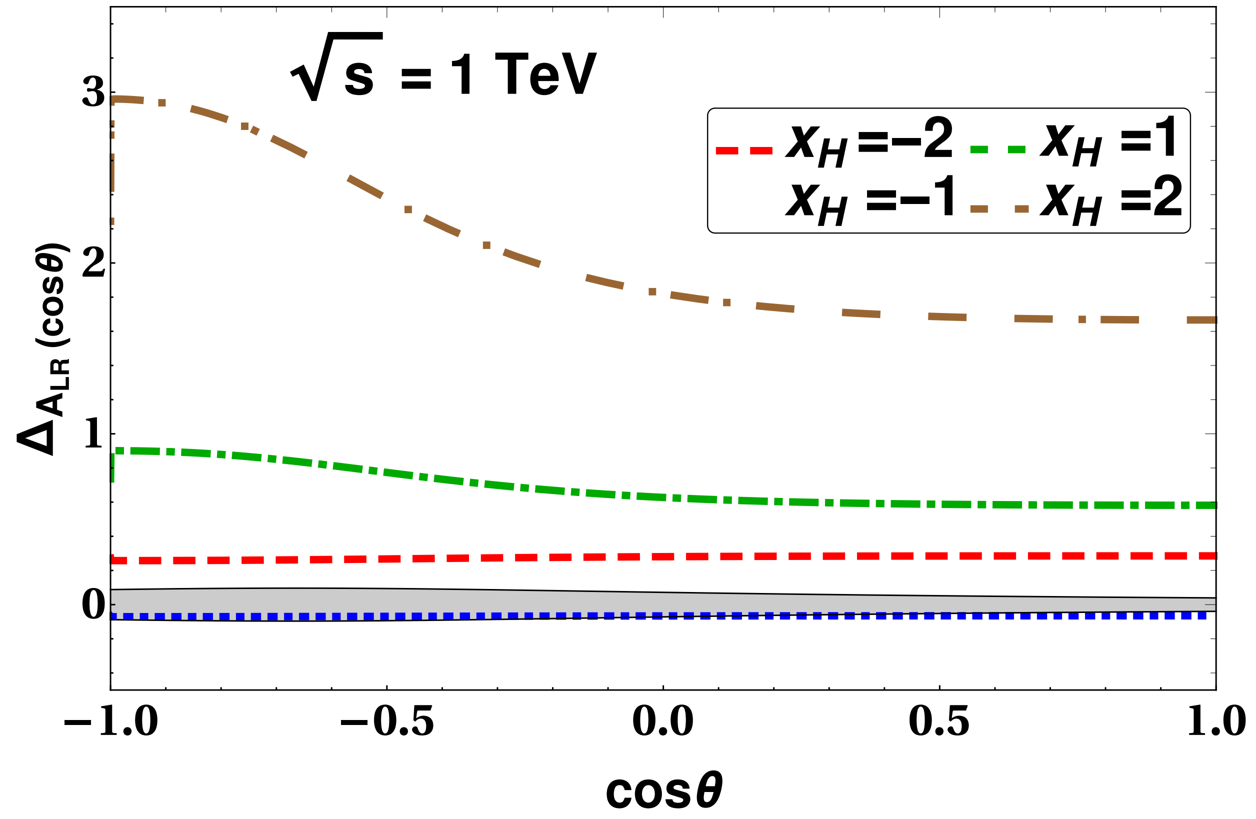


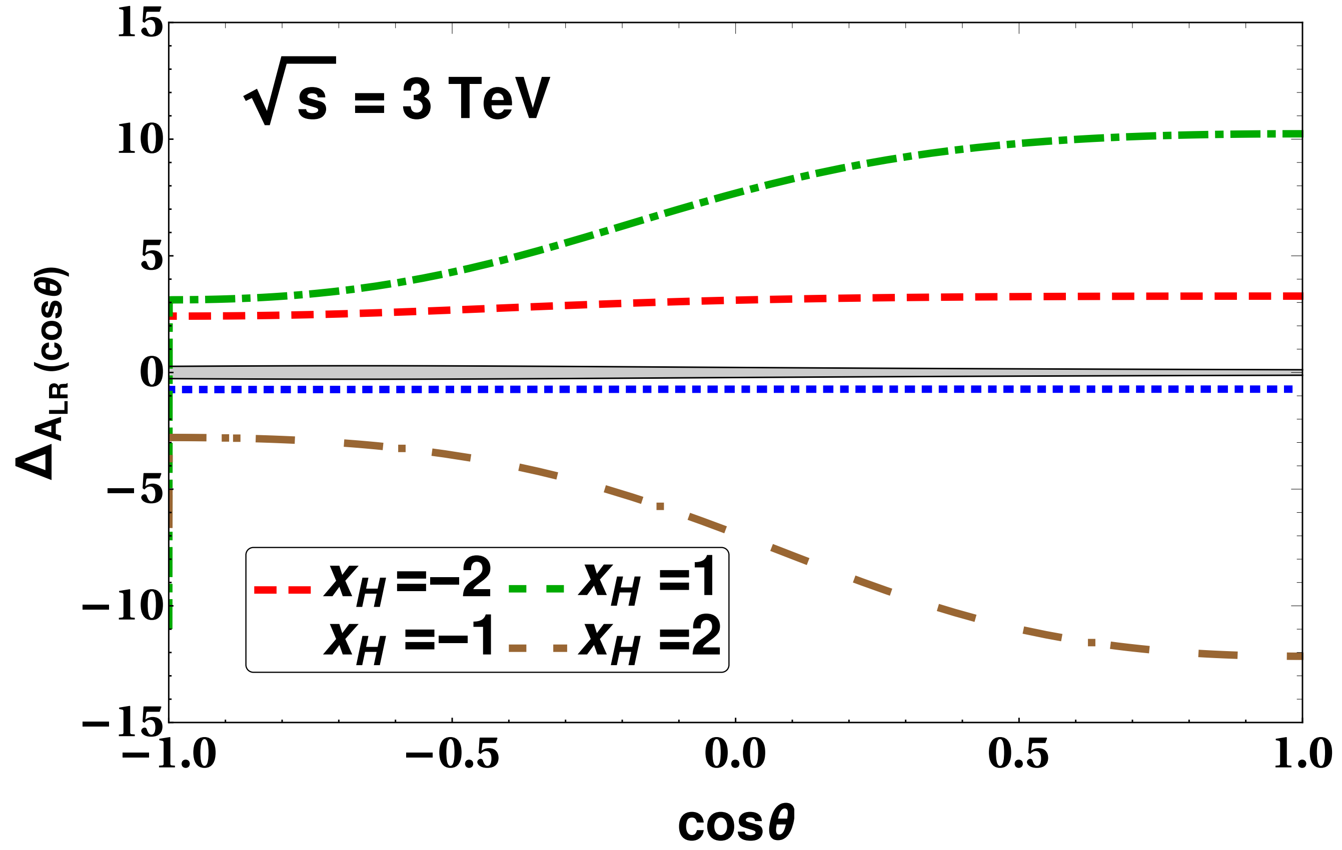




Integral

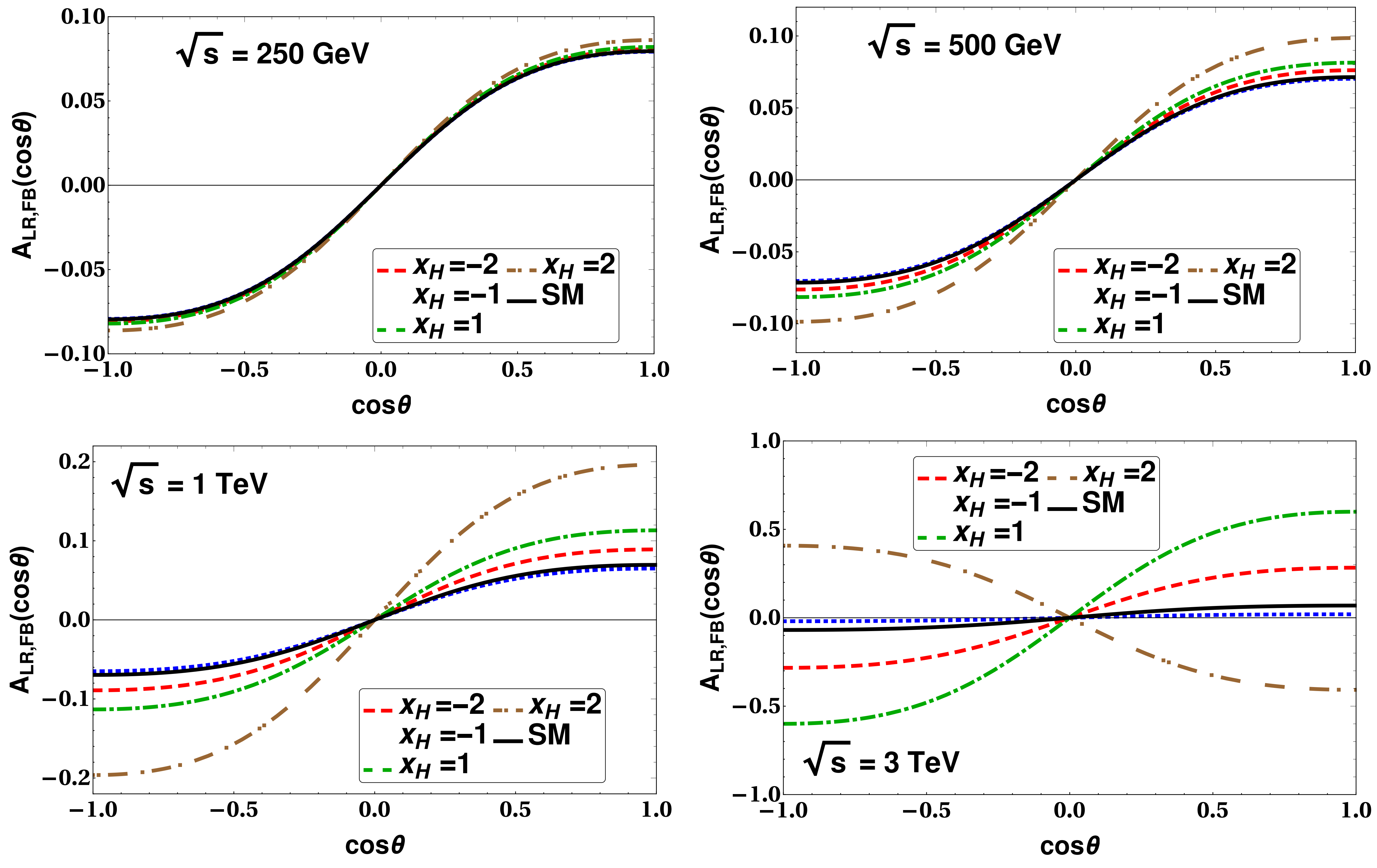
$$\mathcal{A}_{LR} = \frac{\sigma^{LR} - \sigma^{RL}}{\sigma^{LR} + \sigma^{RL}}.$$





Differential Left – Right, Forward – Backward Asymmetry ($e^-e^+ \to \mu^-\mu^+$) : $\mathscr{A}_{\mathrm{LR,\,FB}}$

$M_{Z'} = 7.5$ TeV



Differential

$$\mathcal{A}_{LR,FB}(\cos\theta) = \frac{[\sigma_{\rm LR}(\cos\theta) - \sigma_{\rm RL}(\cos\theta)] - [\sigma_{\rm LR}(-\cos\theta) - \sigma_{\rm RL}(-\cos\theta)]}{[\sigma_{\rm LR}(\cos\theta) + \sigma_{\rm RL}(\cos\theta)] + [\sigma_{\rm LR}(-\cos\theta) + \sigma_{\rm RL}(-\cos\theta)]}$$

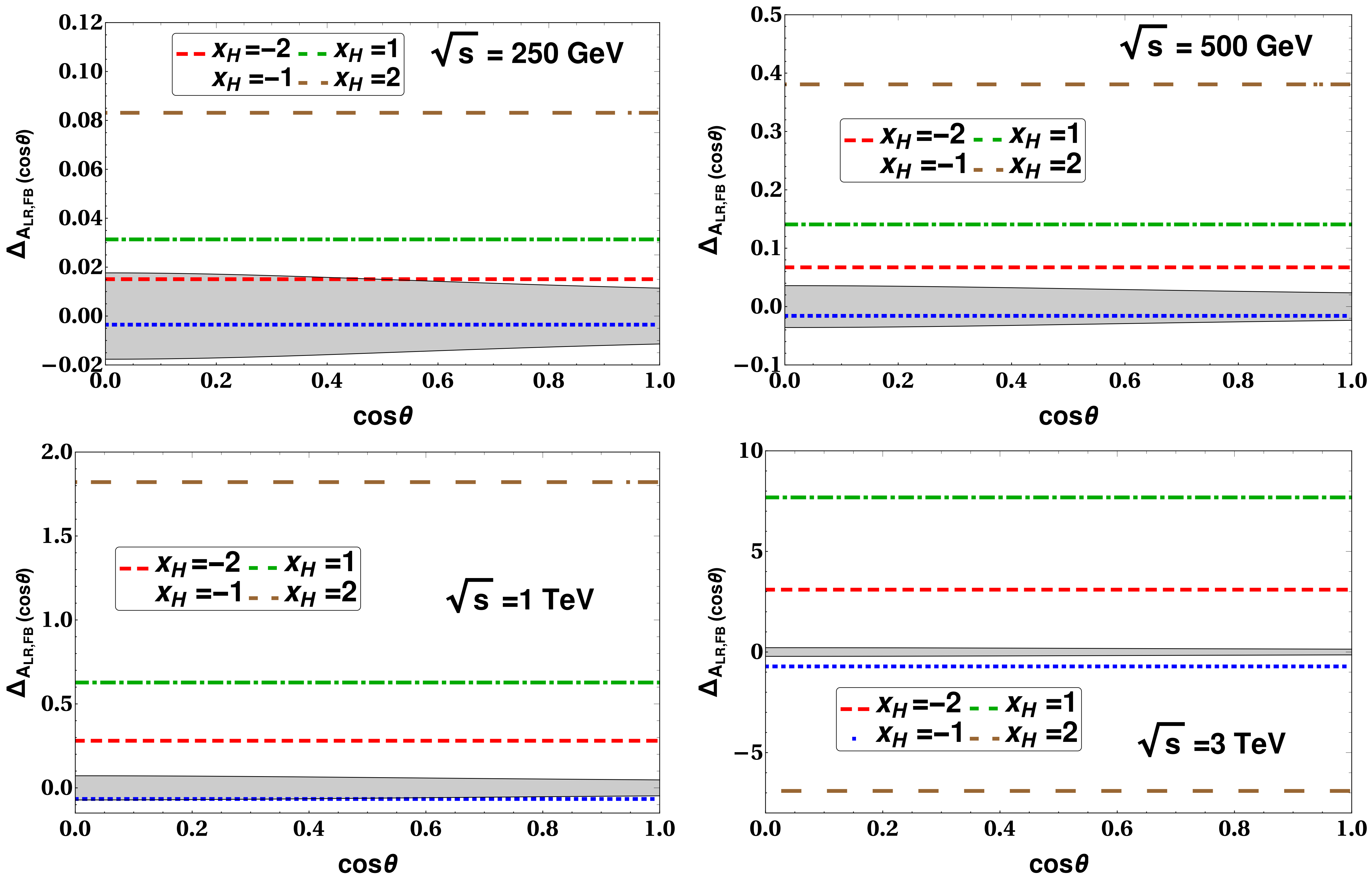
Deviation from the SM

$$\Delta_{\mathcal{A}_{LR,FB}}(\cos\theta) = \frac{\mathcal{A}_{LR,FB}{}^{\mathrm{U(1)_X}}(\cos\theta)}{\mathcal{A}_{LR,FB}{}^{\mathrm{SM}}(\cos\theta)} - 1$$

$x_H = 2$: 8.2 % for at 250 GeV

$x_H = 1$: 15 % for at 500 GeV

$x_H = -2$: 7.5 % for at 500 GeV

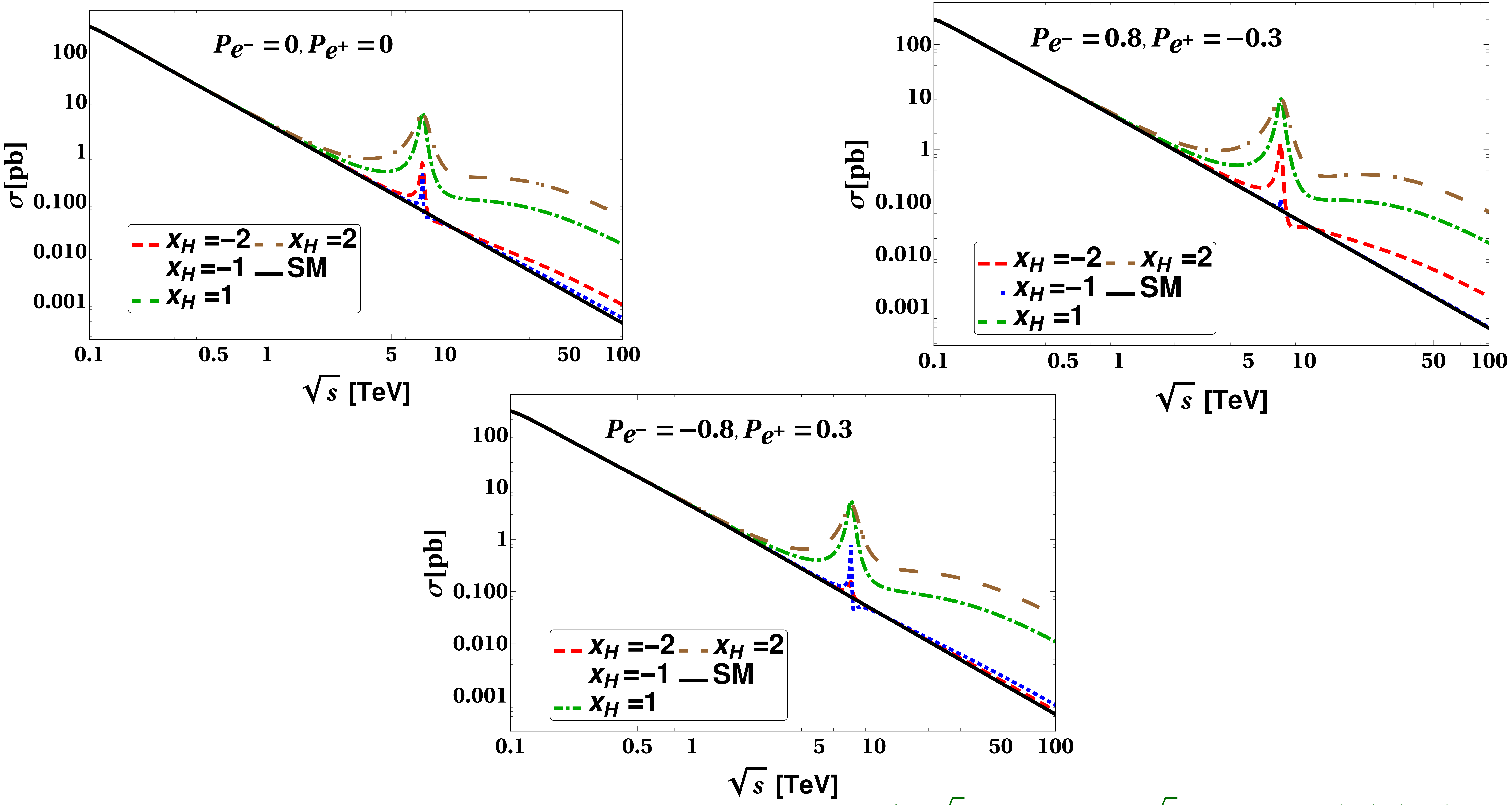


Statistical error

$$\Delta\mathcal{A}_{LR,FB} = 2\frac{(n_3+n_2)\left(\sqrt{n_1}+\sqrt{n_4}\right) + (n_1+n_4)\left(\sqrt{n_3}+\sqrt{n_2}\right)}{(n_1+n_4)^2 - (n_3+n_2)^2} A_{LR,FB}$$

Bhabha scattering

$e^- e^+ \to e^+ e^-$



 Deviations in total cross sections from SM is more than 100 % for $x_H \geq 1$ for $\sqrt{s} = 3$ TeV . For $\sqrt{s} < 3$TeV the deviation is also sizable .

We define

$g'_{L/R}$ → information of charges x_H, x_Φ

$$q_s(s)^{\rm LL} = \frac{e^2}{s} + \frac{g_L^2}{s - M_Z^2 + iM_Z\Gamma_Z} + \frac{{g'_L}^2}{s - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$
$$q_s(s)^{\rm RR} = \frac{e^2}{s} + \frac{g_R^2}{s - M_Z^2 + iM_Z\Gamma_Z} + \frac{{g'_R}^2}{s - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$
$$q_s(s)^{\rm LR} = q_s(s)^{\rm RL} = \frac{e^2}{s} + \frac{g_L g_R}{s - M_Z^2 + iM_Z\Gamma_Z} + \frac{g'_L g'_R}{s - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$

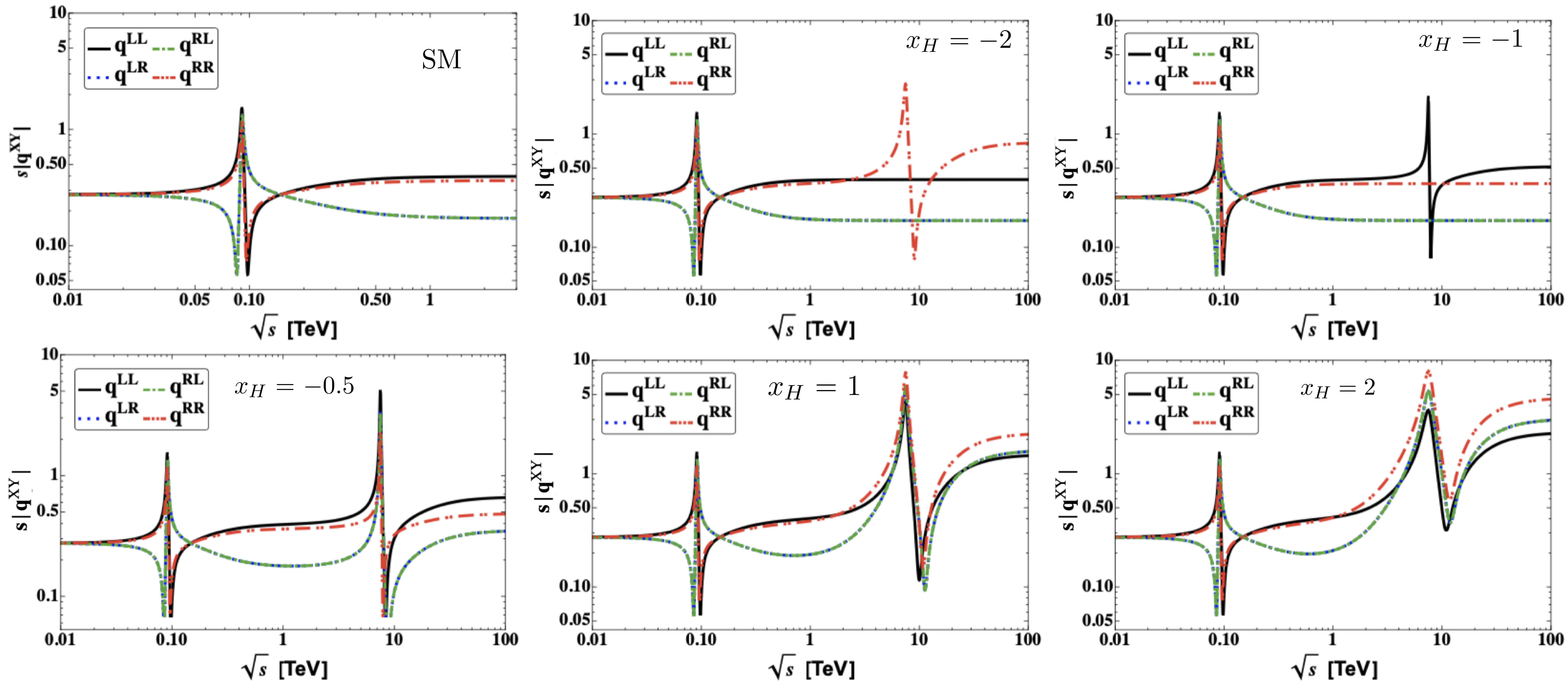
s – channel

$$q_t(s,\theta)^{\rm LL} = \frac{e^2}{t} + \frac{g_L^2}{t - M_Z^2 + iM_Z\Gamma_Z} + \frac{{g'_L}^2}{t - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$
$$q_t(s,\theta)^{\rm RR} = \frac{e^2}{t} + \frac{g_R^2}{t - M_Z^2 + iM_Z\Gamma_Z} + \frac{{g'_R}^2}{t - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$
$$q_t(s,\theta)^{\rm LR} = q_t(s,\theta)^{\rm RL} = \frac{e^2}{t} + \frac{g_L g_R}{t - M_Z^2 + iM_Z\Gamma_Z} + \frac{g'_L g'_R}{t - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$

t – channel

$$s|q^{\rm LL}| = s|q_s(s)^{\rm LL} + q_t(s,\theta)^{\rm LL}|$$
$$s|q^{\rm LR}| = s|q_s(s)^{\rm LR} + q_t(s,\theta)^{\rm LR}|$$
$$s|q^{\rm RL}| = s|q_s(s)^{\rm RL} + q_t(s,\theta)^{\rm RL}|$$
$$s|q^{\rm RR}| = s|q_s(s)^{\rm RR} + q_t(s,\theta)^{\rm RR}|$$

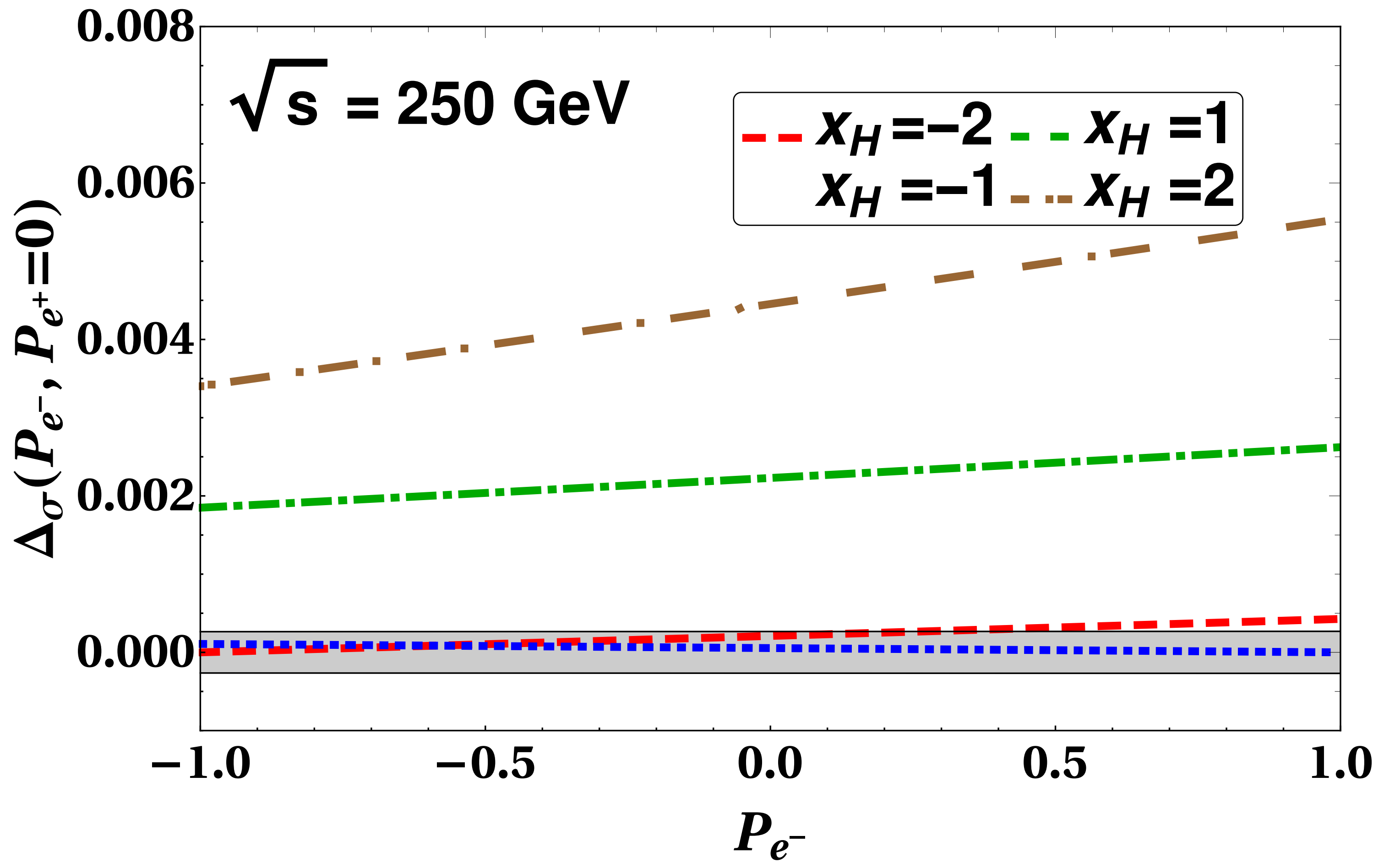
combined

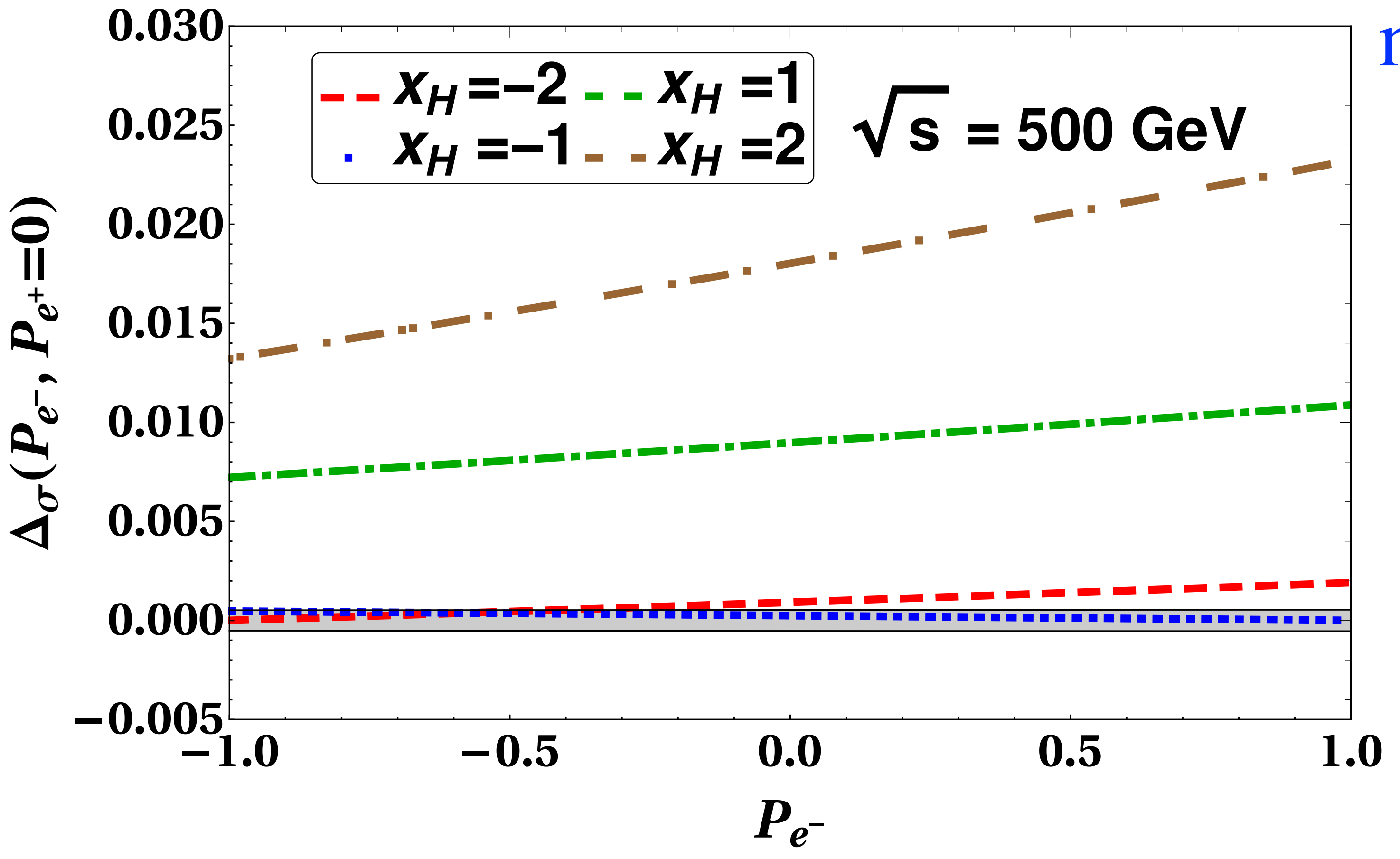


Deviation in differential scattering cross section

$M'_Z = 7.5$ TeV

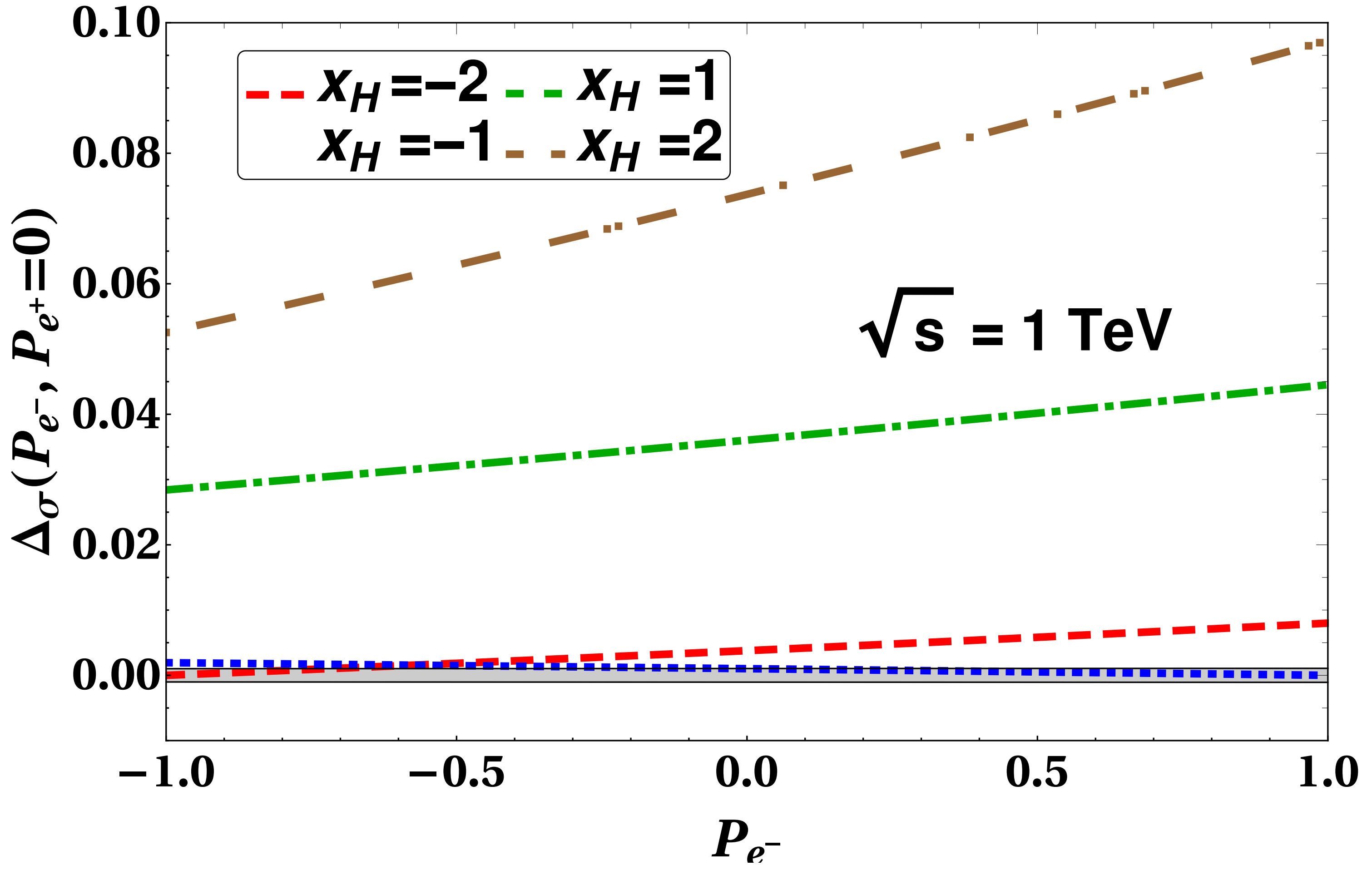
maximum deviation $0.6\,\%$

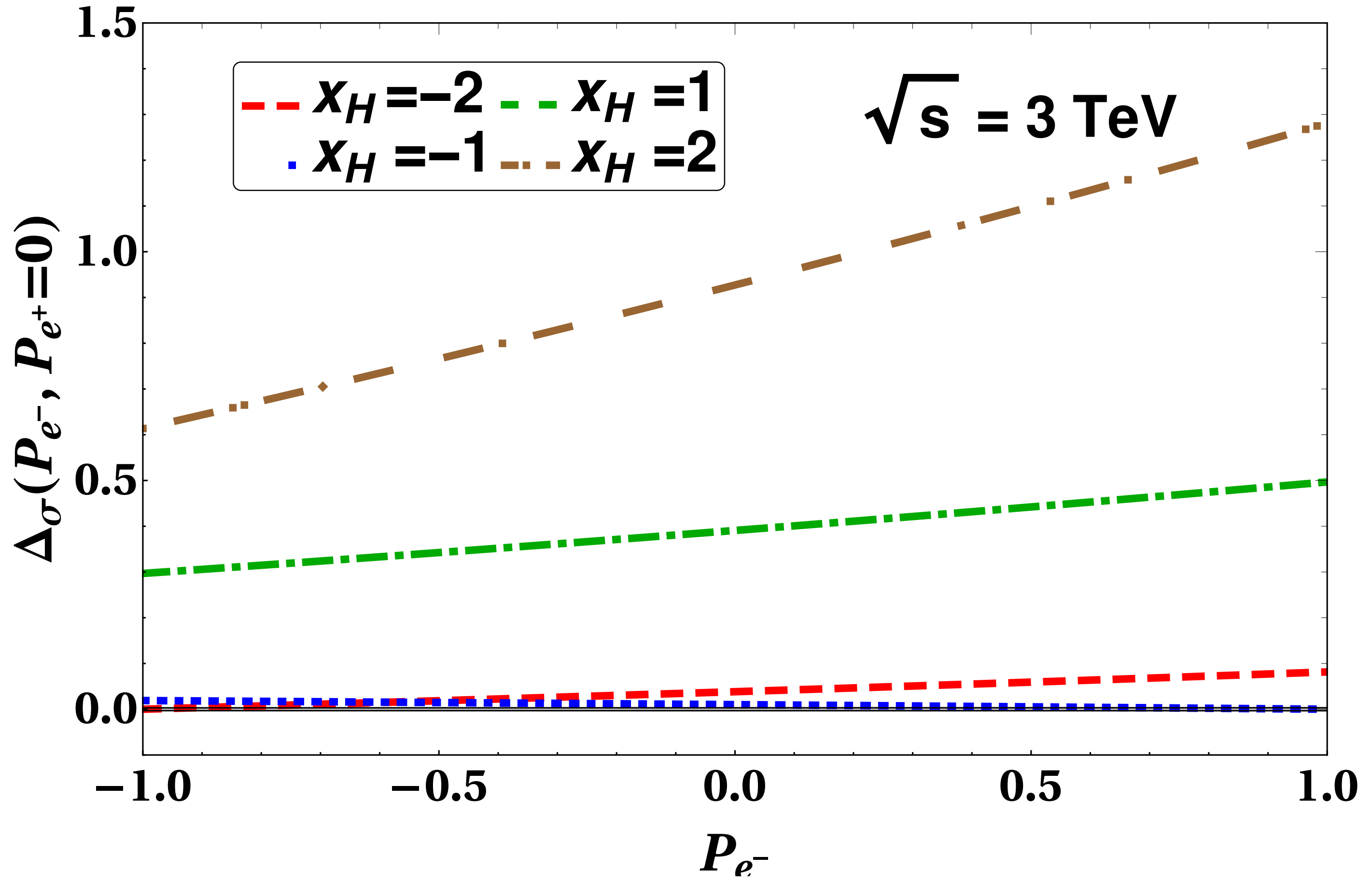




maximum deviation $2.3\,\%$

maximum deviation $10\,\%$





$> 100\,\%$

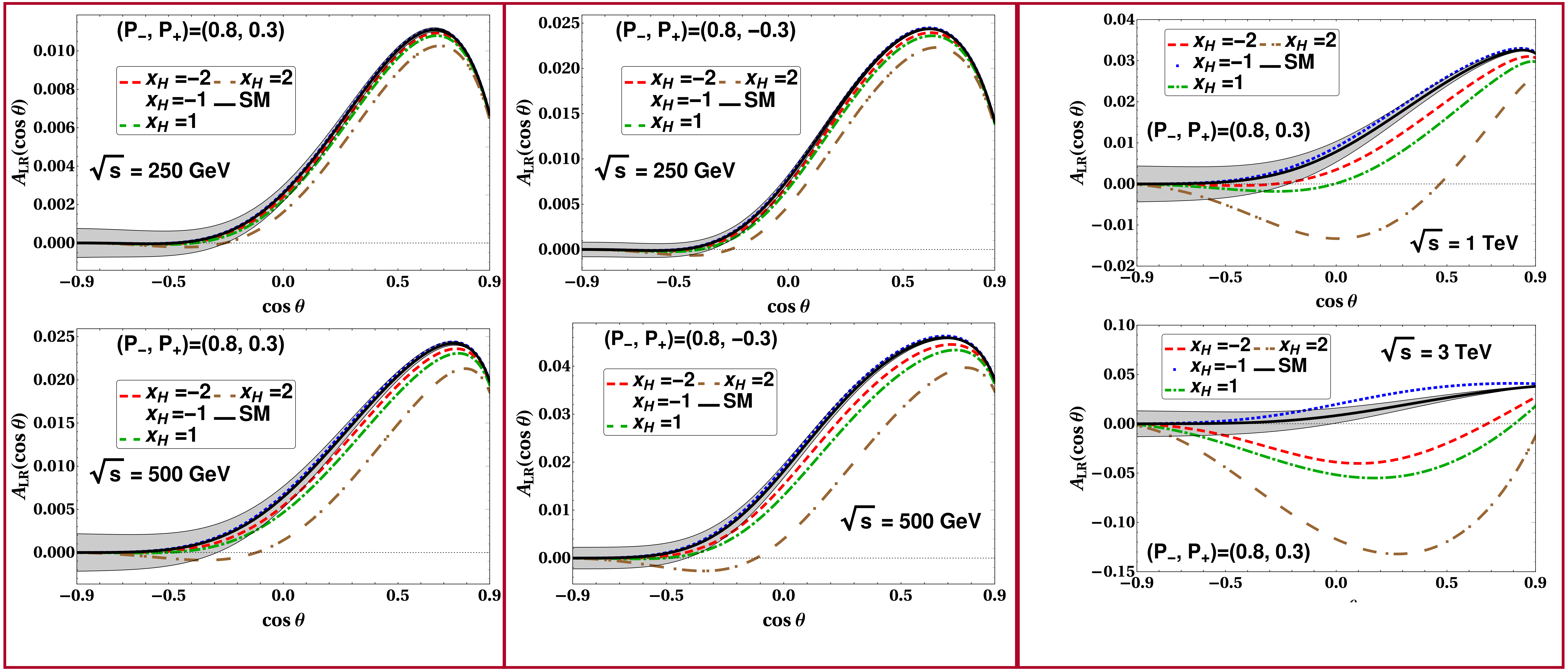
Differential LR asymmetry

$M'_Z = 7.5$ TeV $g' = 0.4$

maximum deviation 1 – 2 % $\sqrt{s} = 250$ GeV

maximum deviation 2.3 – 4.3 % $\sqrt{s} = 500$ GeV

maximum deviation 12 – 13 % $\sqrt{s} = 1$ TeV



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 the 250 GeV and 500 GeV e^-e^+ colliders or higher in the near future.

Such a model can be studied at muon colliders with high CM energy. This allows us to probe heavier Z'.

The motovation of this work is to find a new particle and/or a new force carrier as a part of the of the new physics searches including a variety of BSM aspects.