Probing BSM neutral gauge boson in high and low energy experiments

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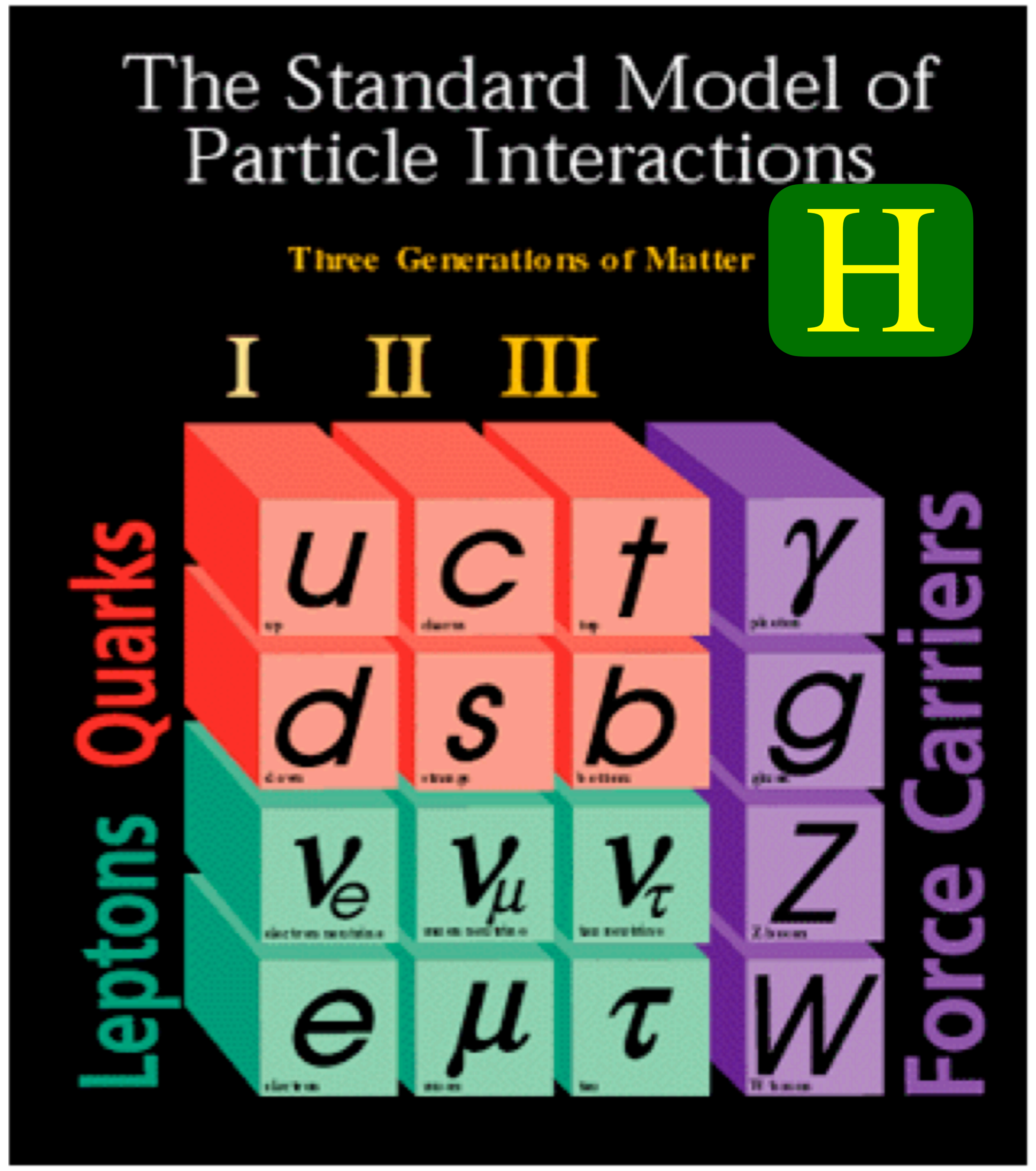
The University of Tokyo

Arindam Das
Hokkaido University

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
Relic abundance of dark matter . . .

SM can not explain them

Different frontiers

Energy frontier : Scientists build partcile acclerators to explore high energy scale to explore new phenomena after the subatomic collisions .

Intensity frontier : Highly intense beams from accelerators are used to to investigate the ultra rare processes of nature .

Cosmic frontier : Astrophysicists use the cosmos as the laboratory to investigate the fundamental laws of physics from a complementary point of view of particle accelerator .

Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut;
Chiang, Cottin, AD, Mandal; AD, Takahashi, Oda, Okada AD, Dev, 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	=	$2x_\Phi$

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

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

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

x_H, x_Φ will appear the coupling with Z'

B – L case

$x_H = 0,\ x_\Phi = 1$

$U(1)_X$ breaking

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

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

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

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

Seesaw mechnism

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

$q^f_{x_L} \neq q^f_{x_R}$ affects the phenomenology

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

Properties of the model and phenomenology

New particles Z' boson Heavy Majorana Neutrino(RHN)

$U(1)_X$ Higgs boson

Phenomenology

Z' boson production and decay

Z' boson mediated processes Heavy neutrino production

$U(1)_X$Higgs phenoemenology : Vacuum Stability

BSM scalar production, decay into RHN pair

Dark Matter Collider phenomenology

Dev, Pilaftsis; Iso, Okada, Orikasa
Orikasa, Okada, Yamada; Dev, Mohapatra, Zhang

Leptogenesis and many more

Z' boson production and heavy neutrino phenomenology

$\nu - \mathcal{N}$, $\nu - \mathrm{e}$, $\mathrm{e}^-\mathrm{e}^+$ scattering; proton, electron beam dump and dark photon search

2307.09737

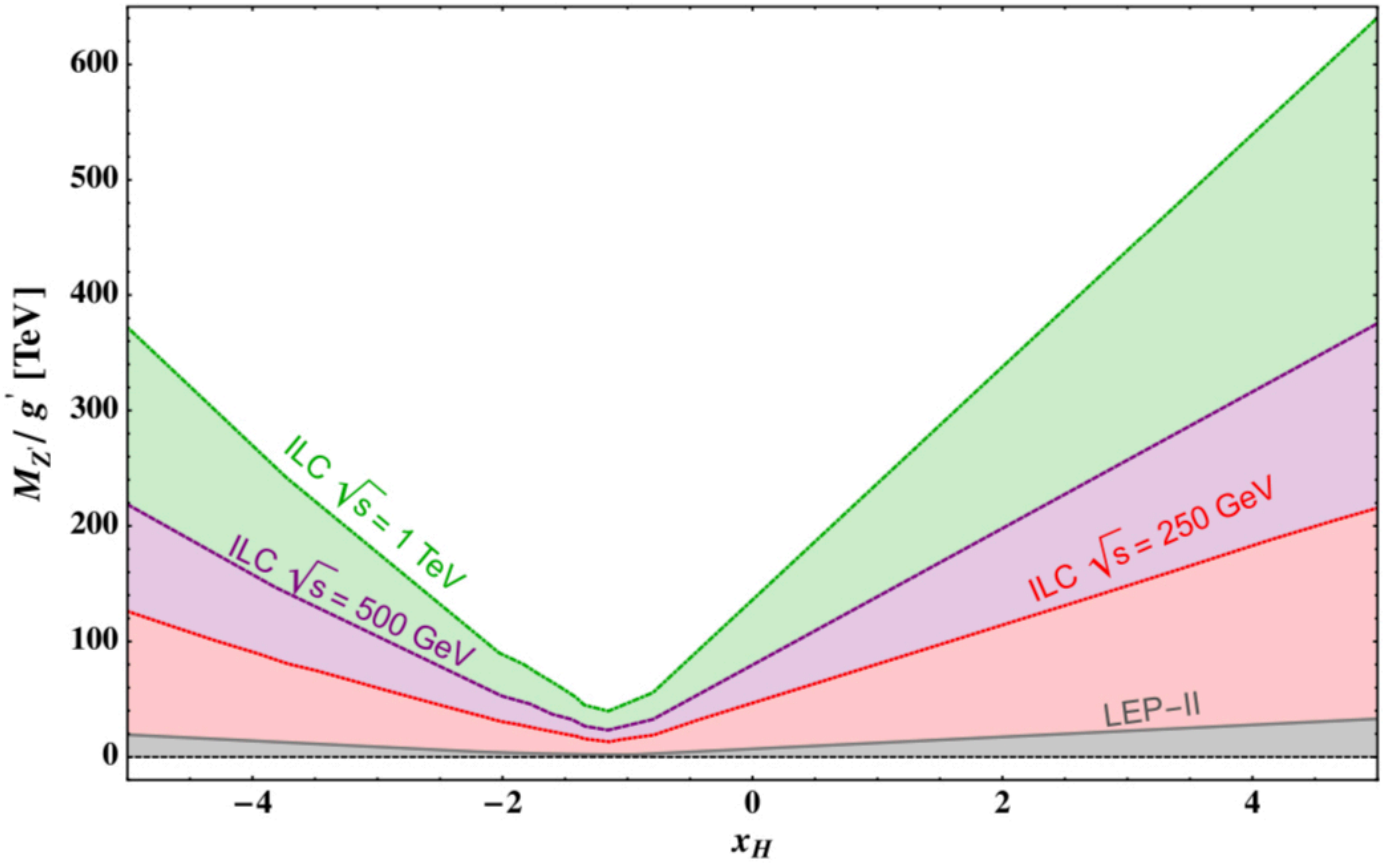
Fermionic pair production form the Z' : $\mathcal{A}_{\mathrm{FB,\,LR,\,FB-LR}}$

Bhabha scattering

2104.10902

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) :



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

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

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

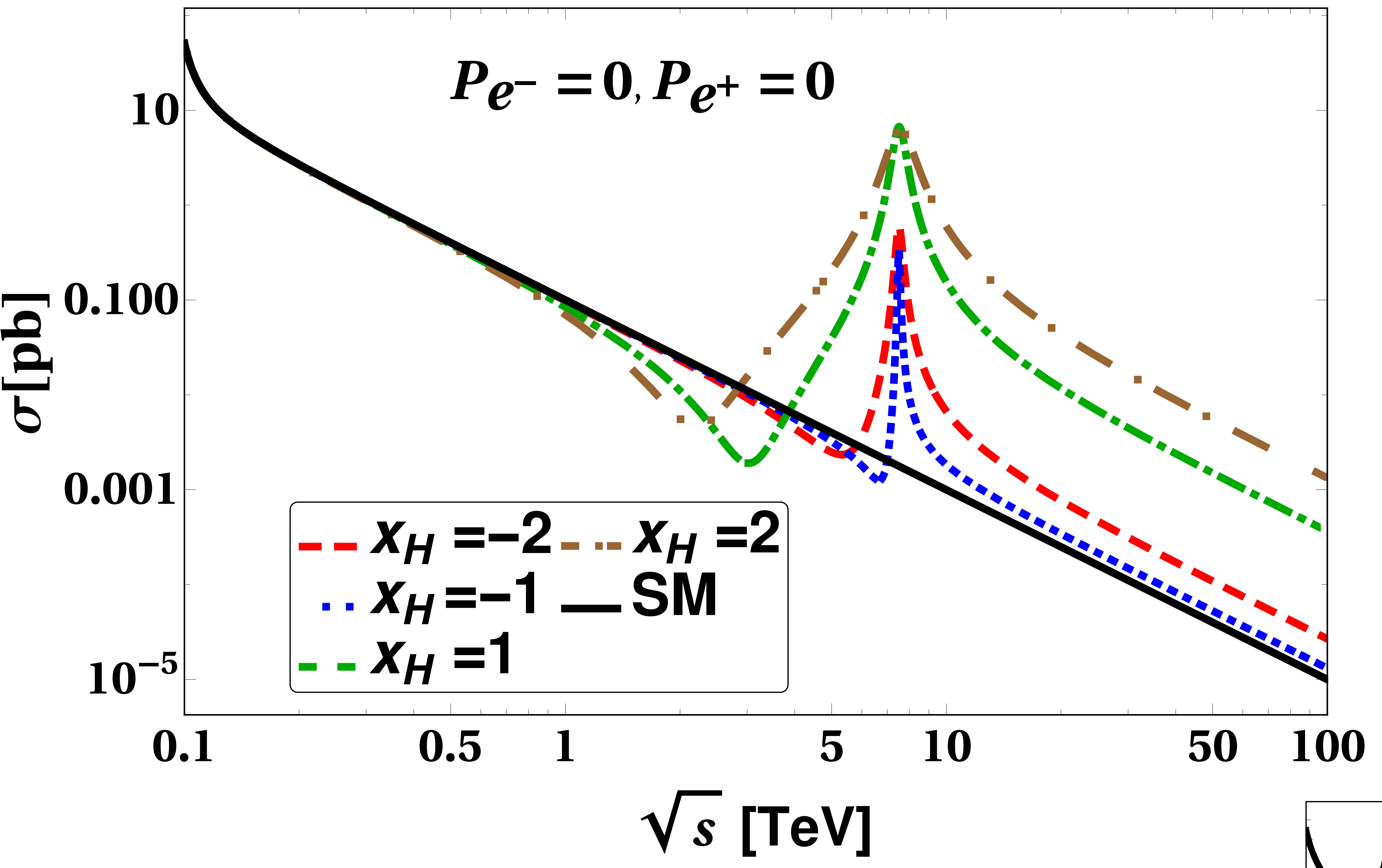
Indicates a large VEV scale can be probed from LEP – II to ILC1000 via ILC250 and ILC500

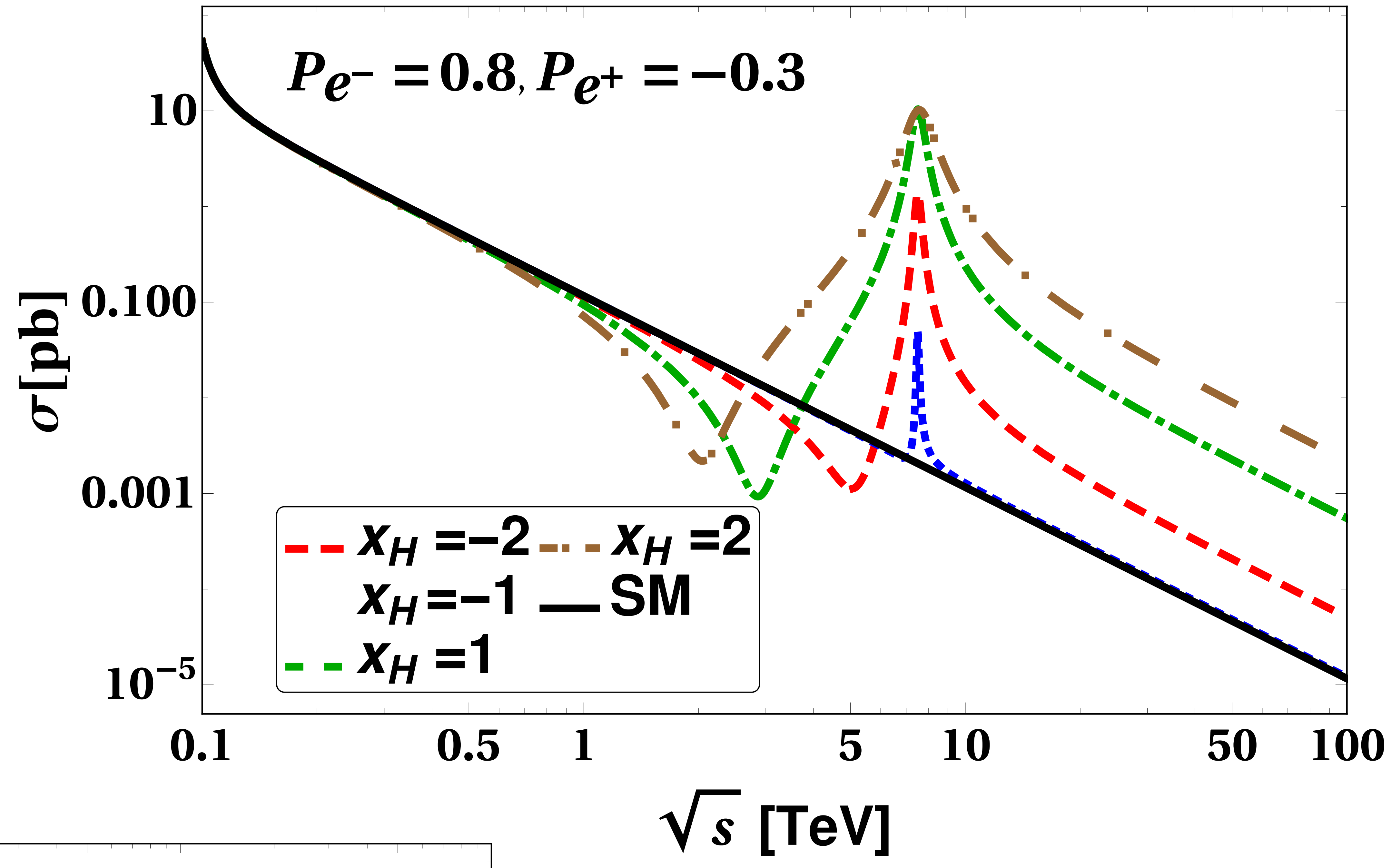
Shows limits on $M_{Z'}$ vs g' for LEP – II, ILC250, ILC500 and ILC1000

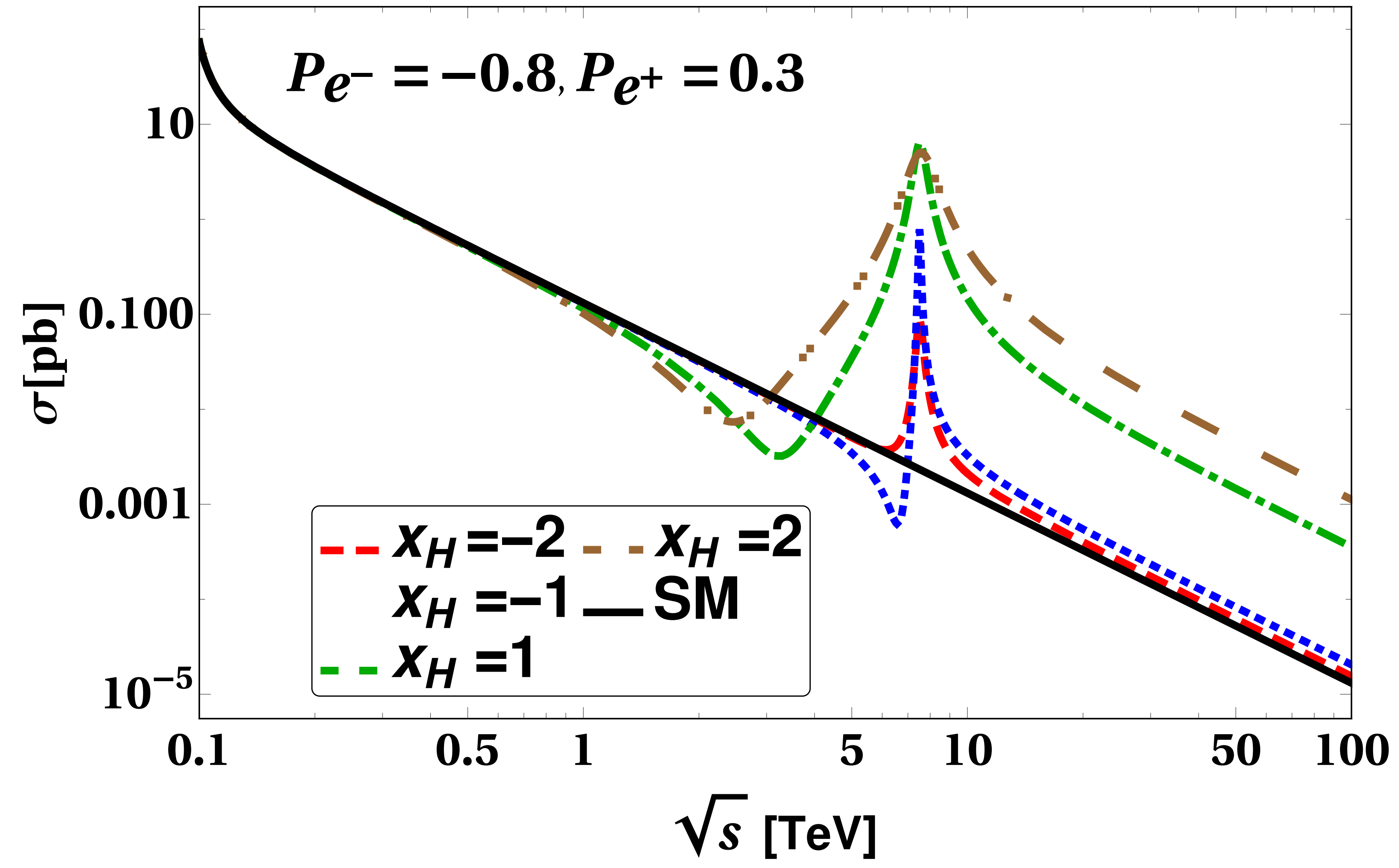
Limits on $M_{Z'}$ and g' can also be obtained from dilepton and dijet searches at the LHC

$$g' = \sqrt{g_{\rm Model}^2\left(\frac{\sigma_{\rm ATLAS}^{\rm Obs.}}{\sigma_{\rm Model}}\right)}$$

$e^-e^+ \to \mu^+\mu^-$ $M_{Z'} = 7.5$ TeV



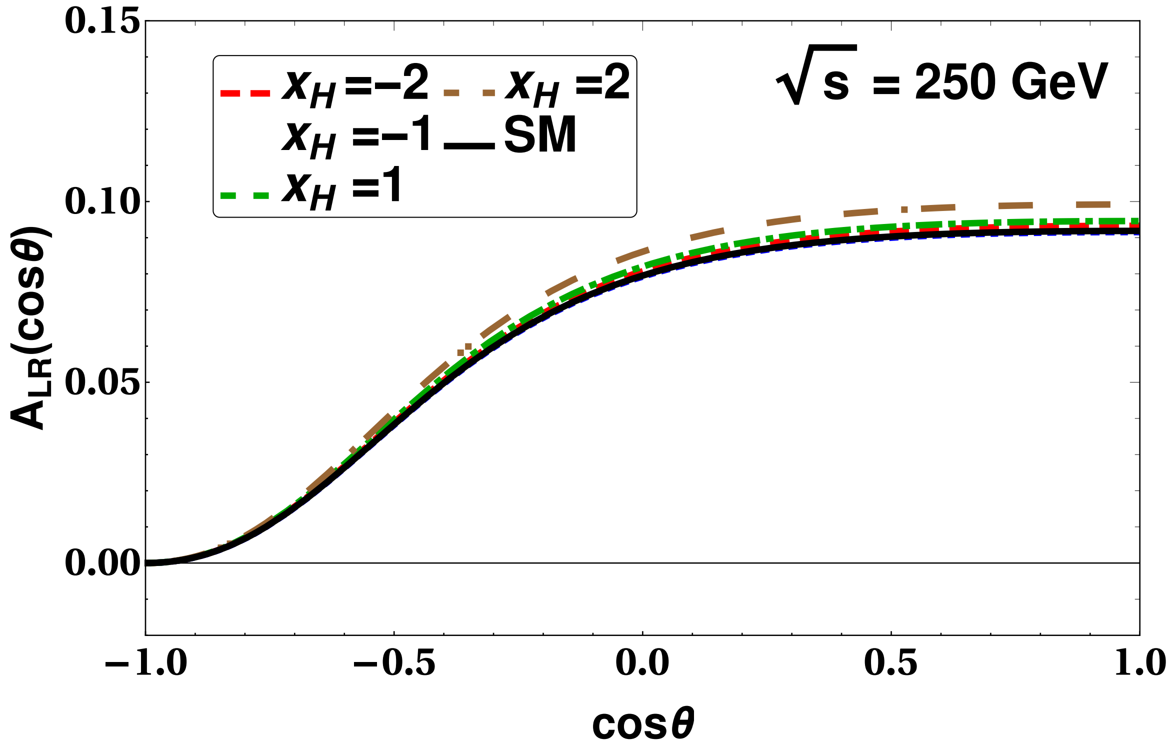


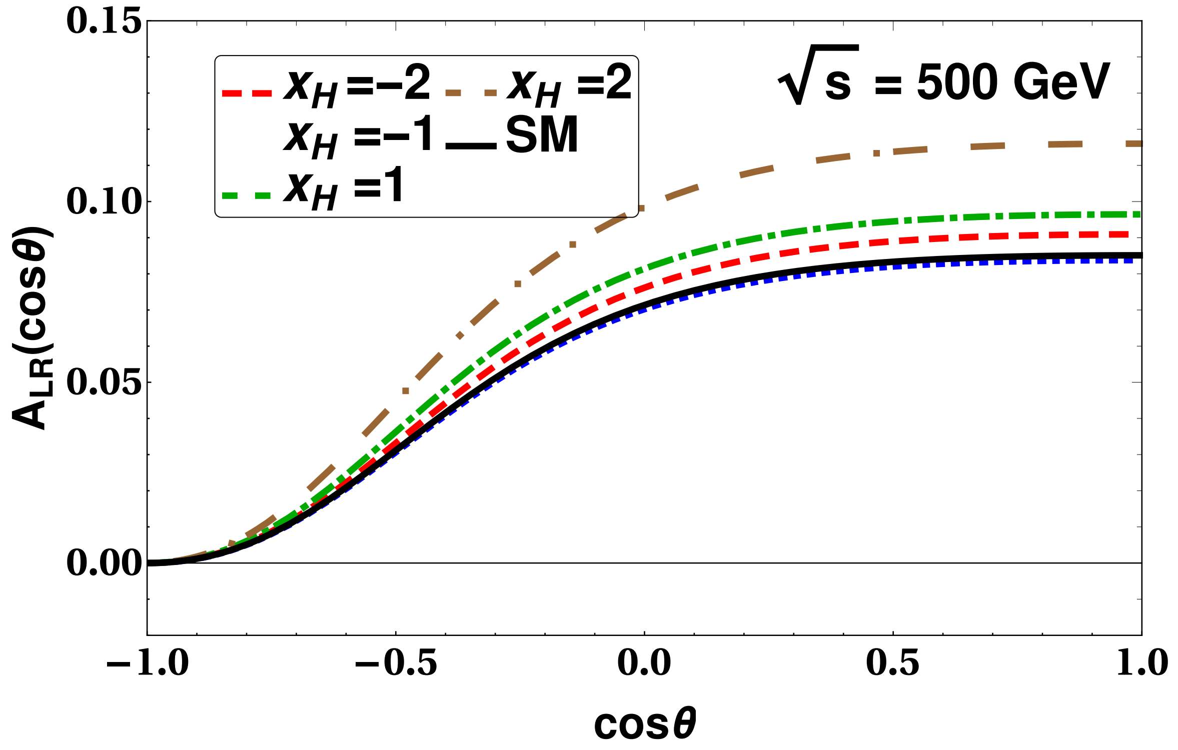


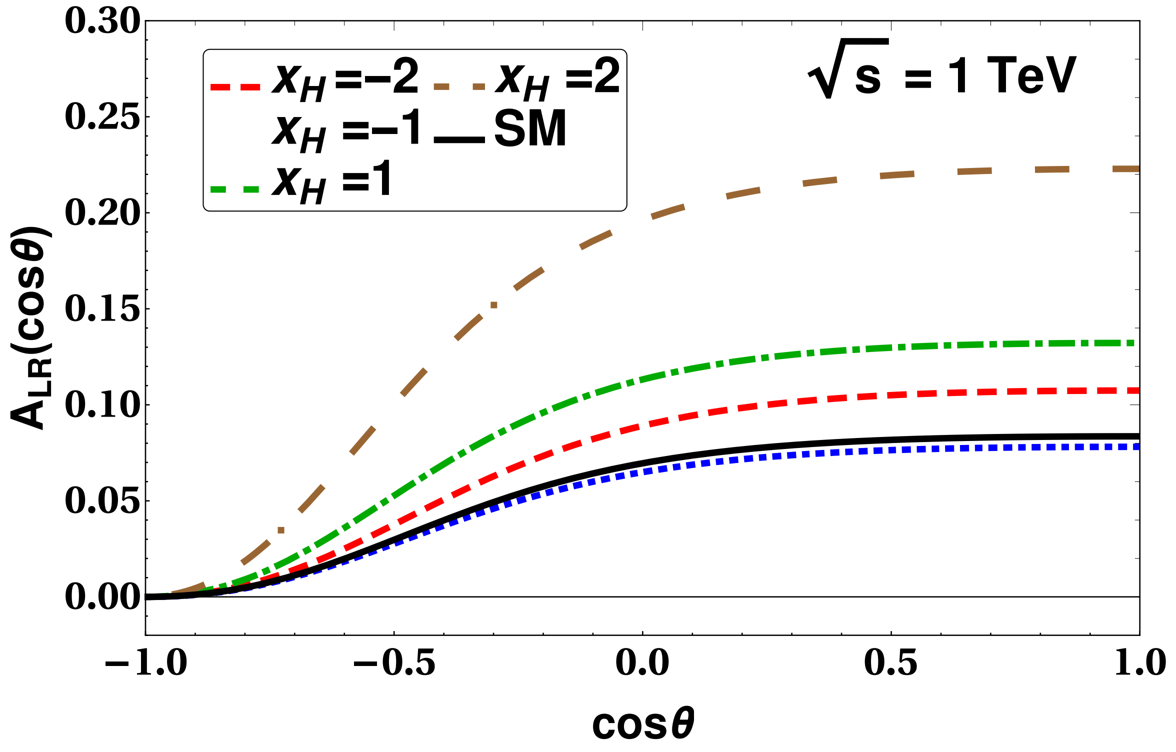
Deviations in total cross sections from SM is more than 100% for $x_H \geq 1$ for $\sqrt{s} = 3$ TeV. For $\sqrt{s} < 3$TeV the deviation is also sizable.

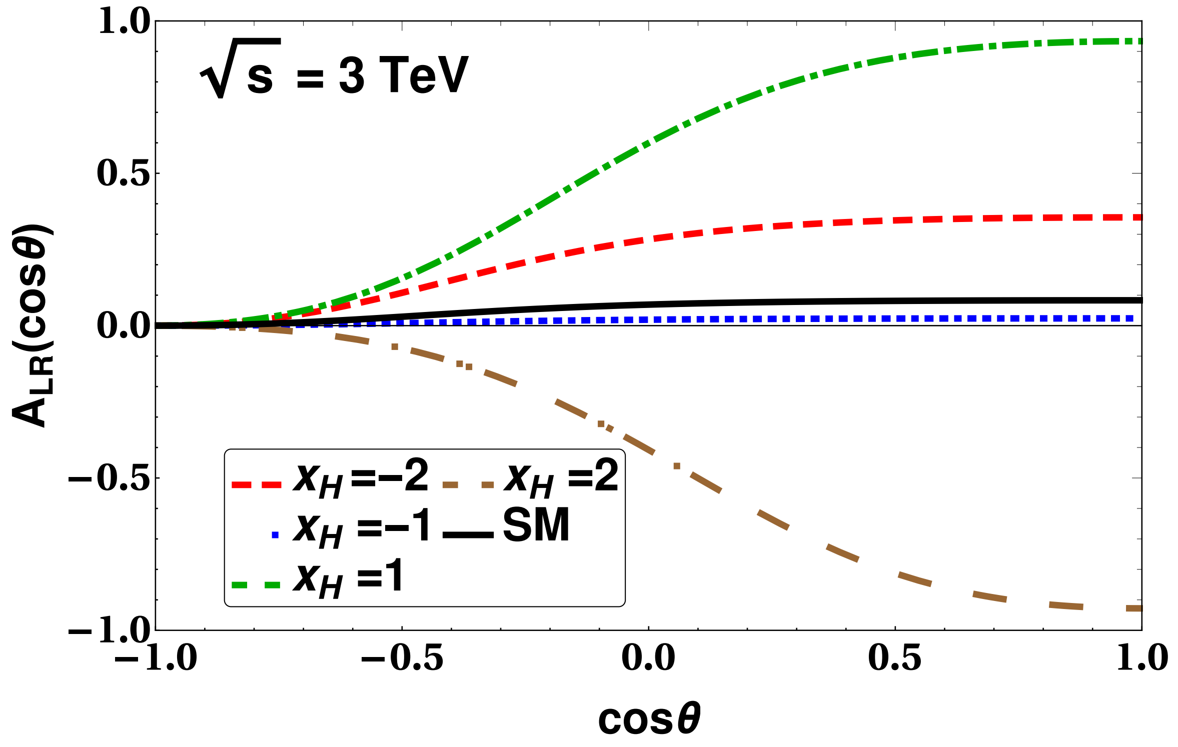
Differenial and integarted Left – Right Asymmetry ($e^-e^+ \to \mu^-\mu^+$) : $\mathscr{A}_{\rm LR}$

$M_{Z'} = 7.5$ TeV









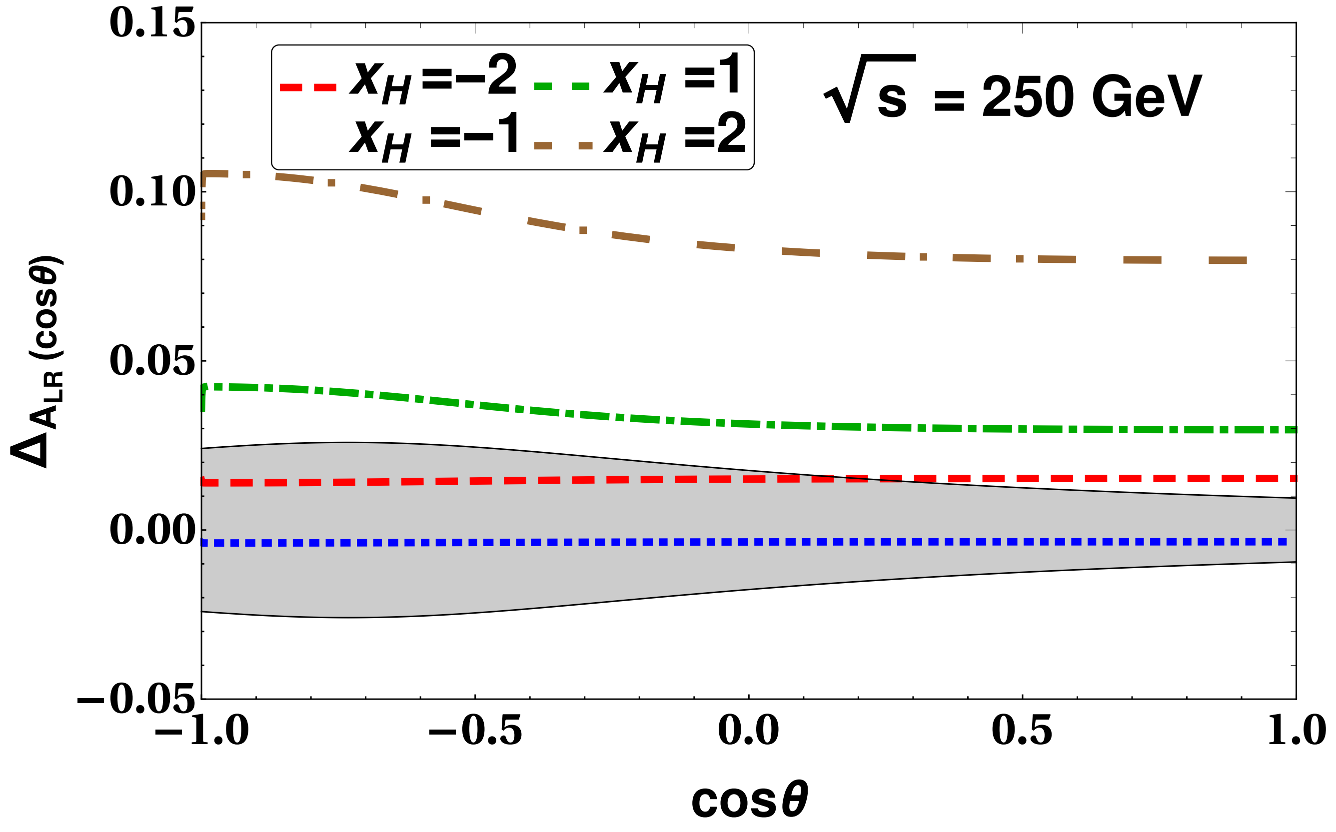
Differential

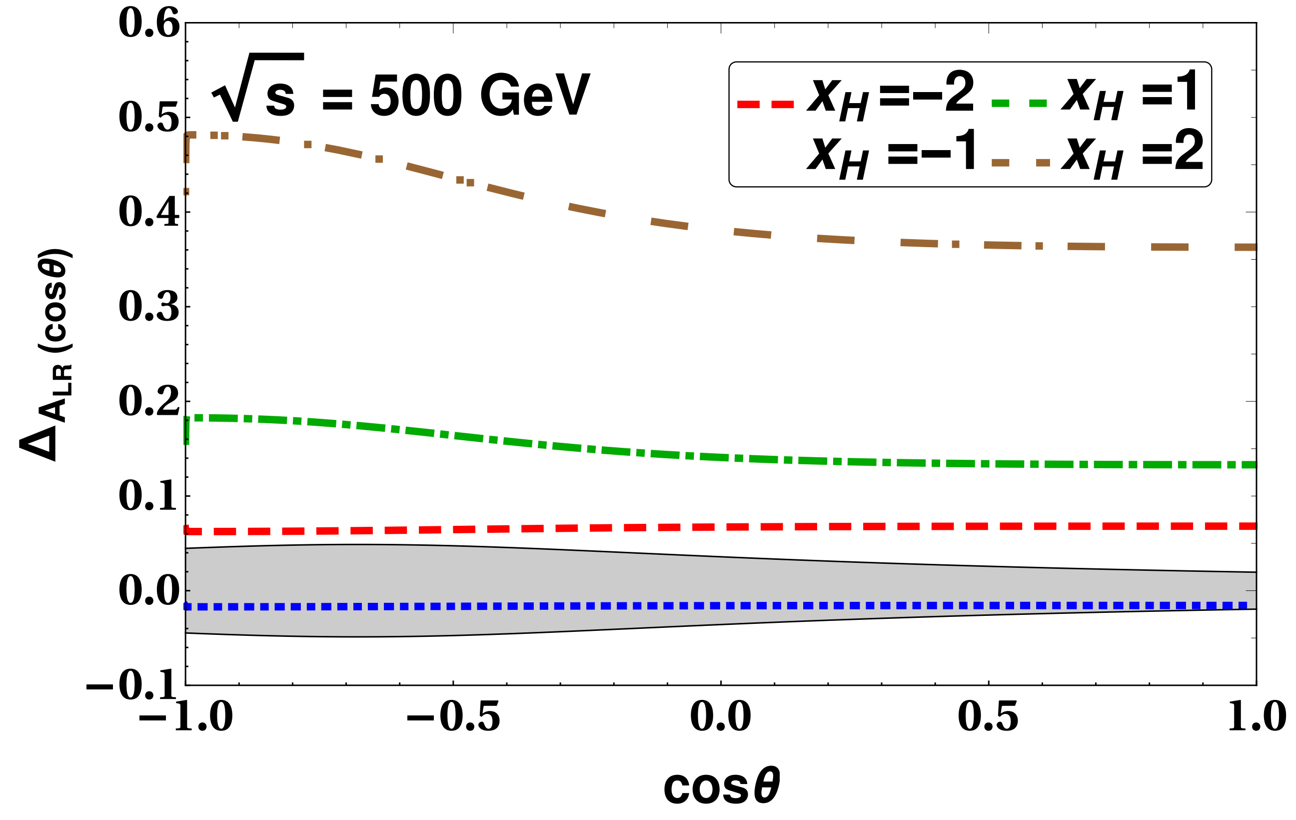
$$\mathcal{A}_{\rm LR}(\cos\theta) = \frac{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) - \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}{\frac{d\sigma_{\rm LR}}{d\cos\theta}(\cos\theta) + \frac{d\sigma_{\rm RL}}{d\cos\theta}(\cos\theta)}$$

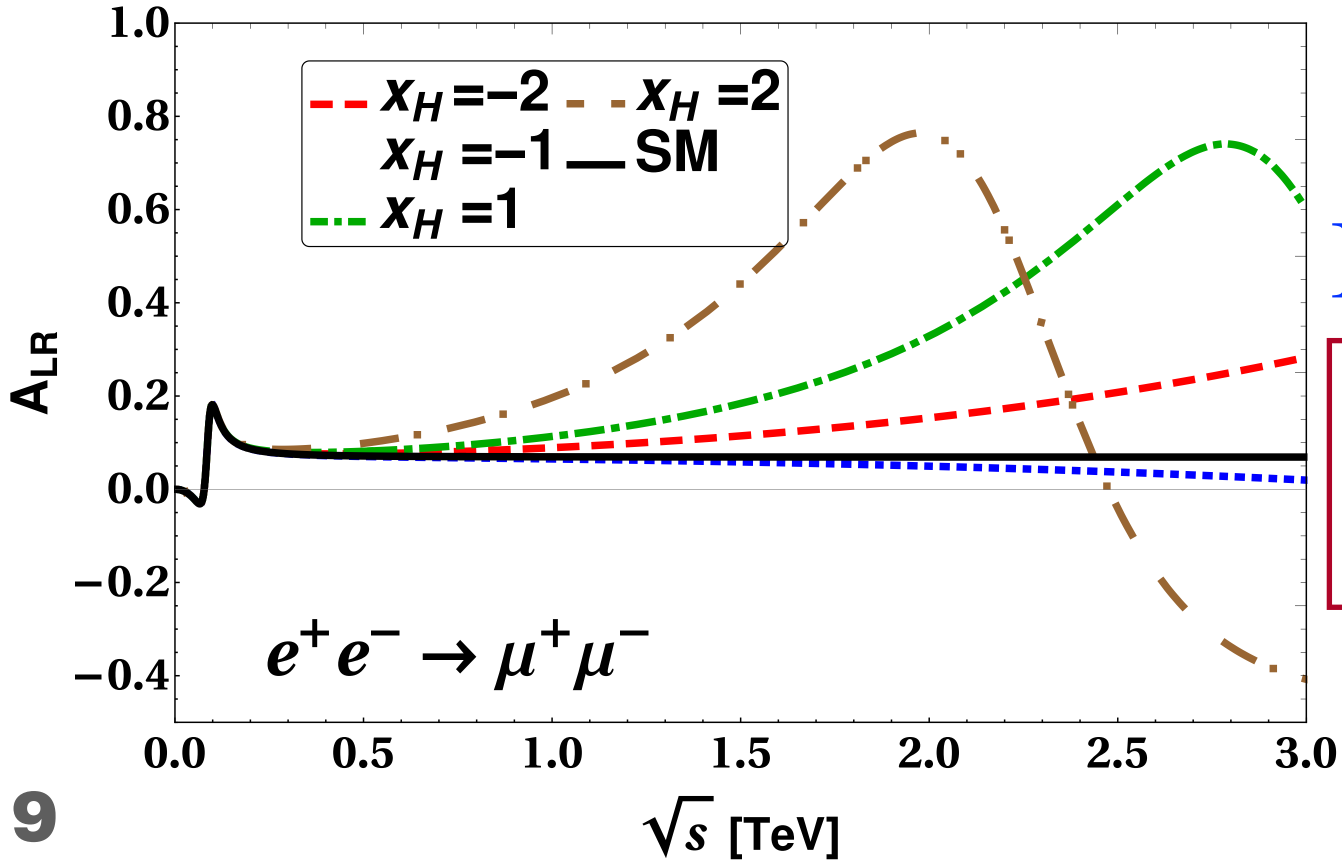
Deviation from the SM

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

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

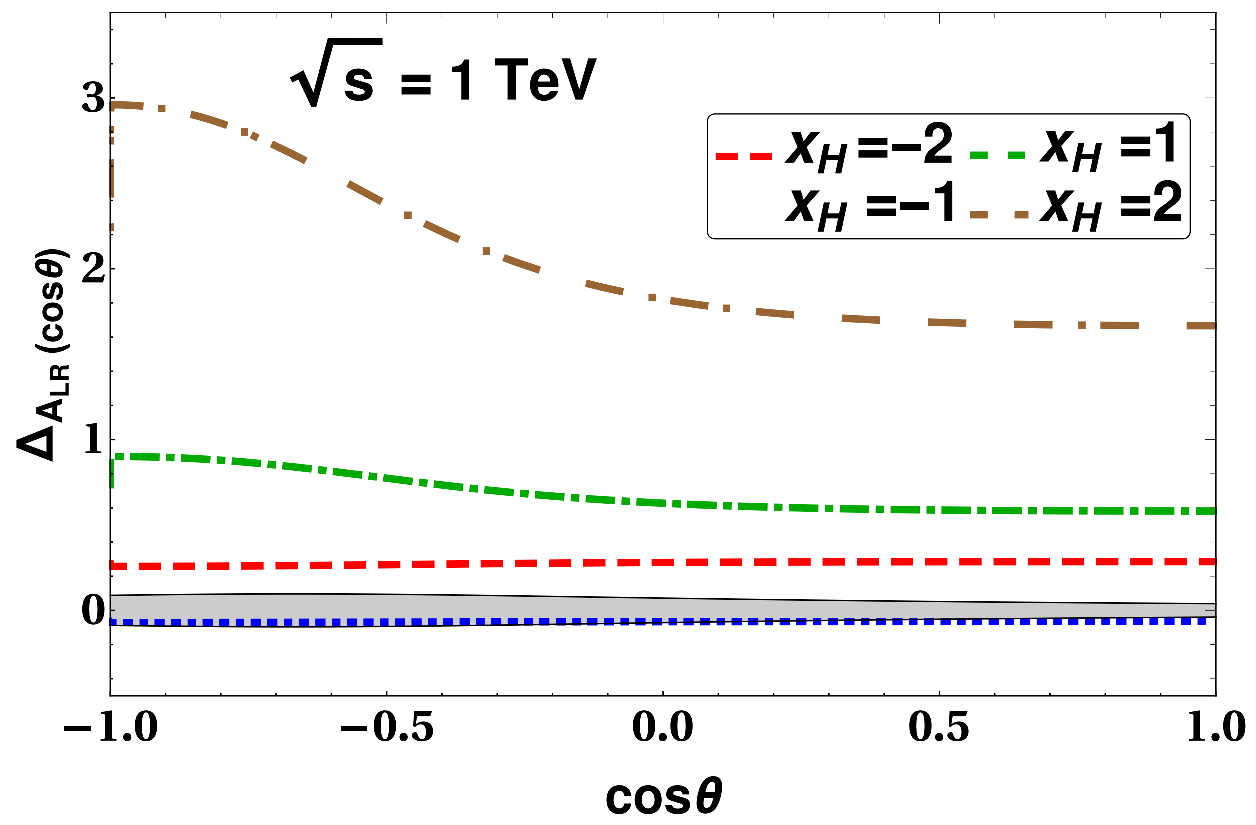


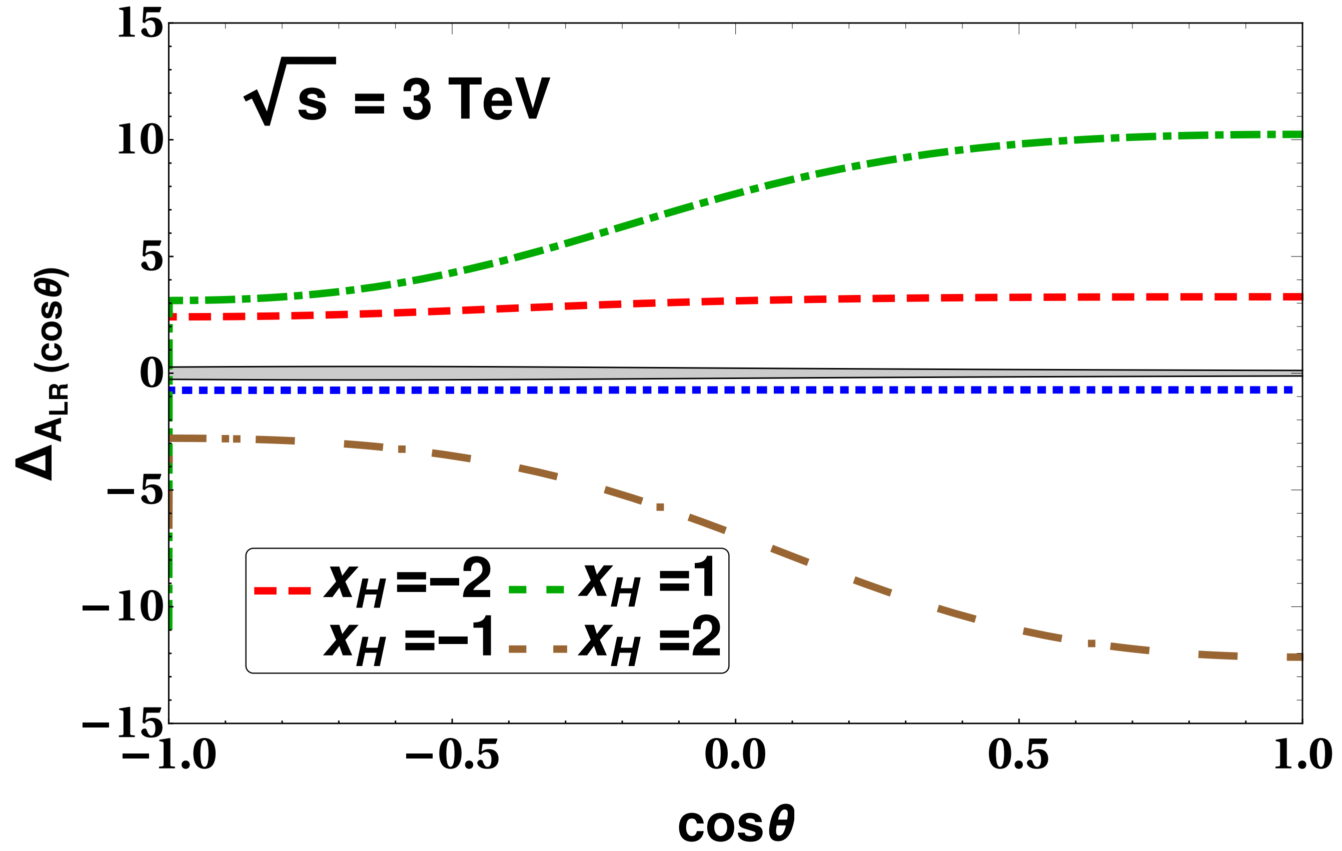




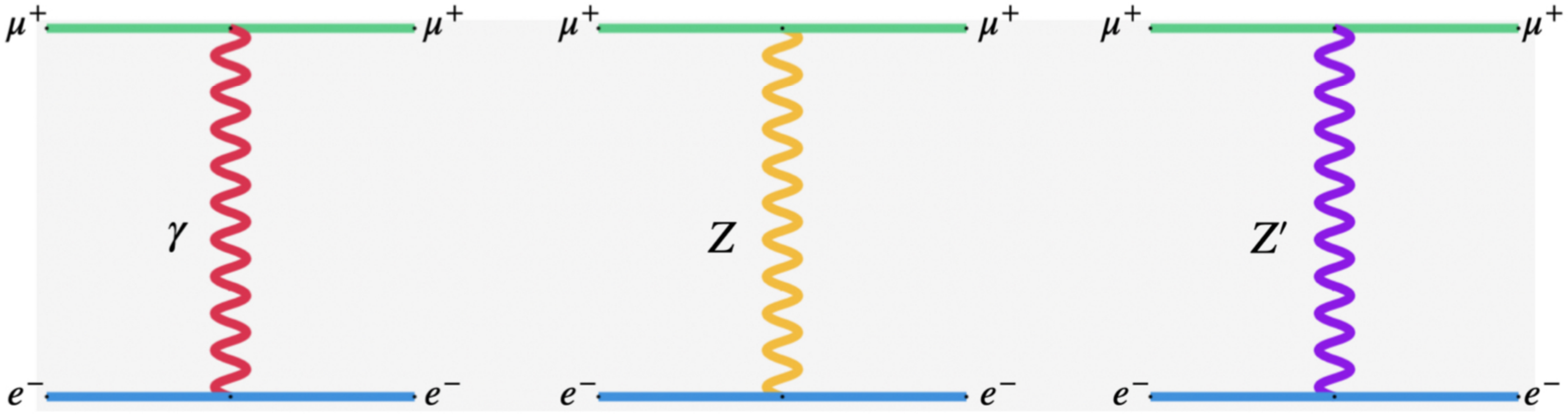
Integral

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



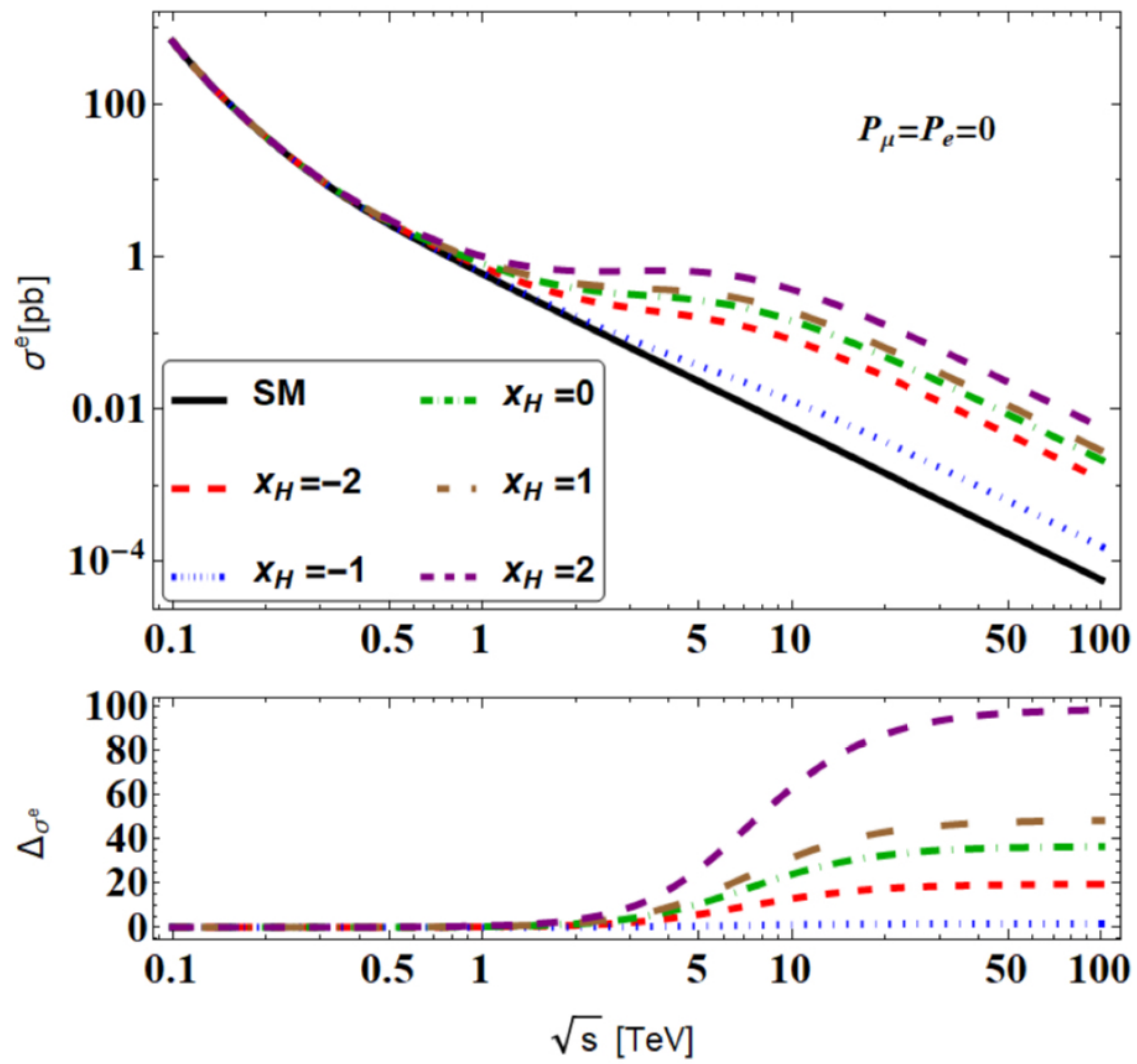


$\mu^+ e^- \to \mu^+ e^-$

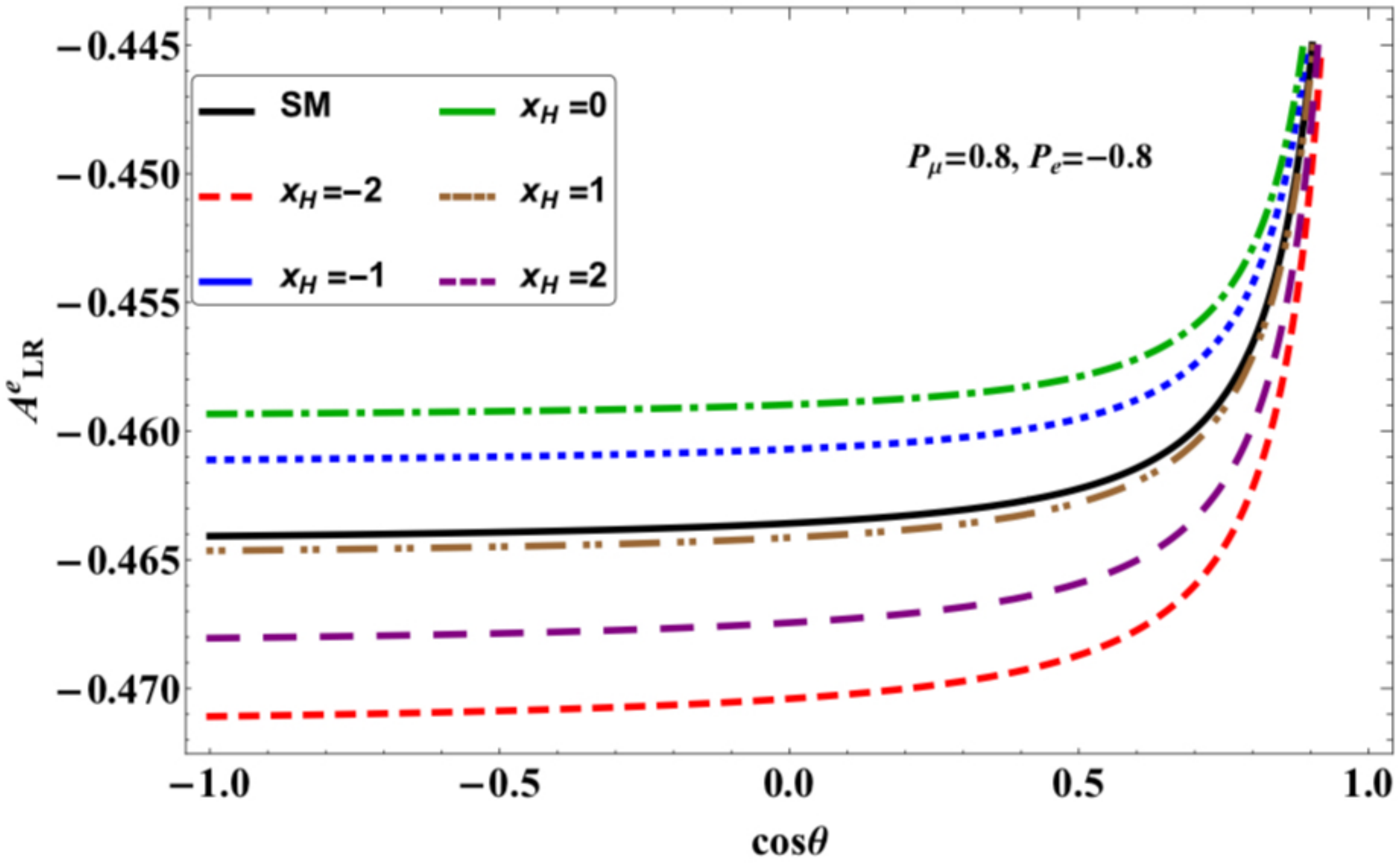


$M_{Z'} = 7.5$ TeV

Figure 3. Photon, Z and Z' mediated $\mu^+ e^- \to \mu^+ e^-$ processes in $t-$channel at μTRISTAN experiment with $\sqrt{s} = 346$ GeV where muon beam energy is 1 TeV and electron beam energy is 30 GeV.



Differential LR asymmetry



$\mu^+\mu^+ \to \mu^+\mu^+$

$M_{Z'} = 7.5$ TeV

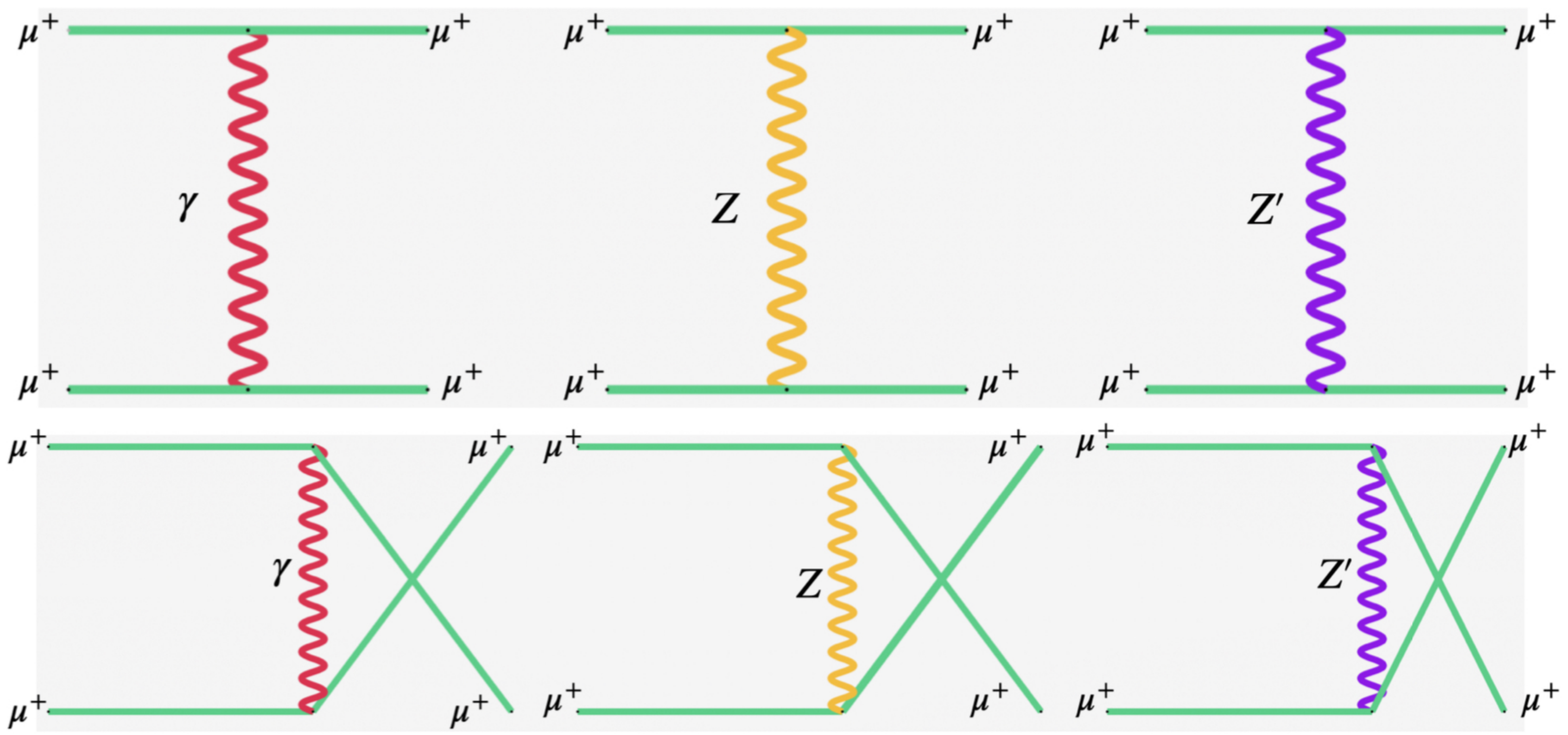
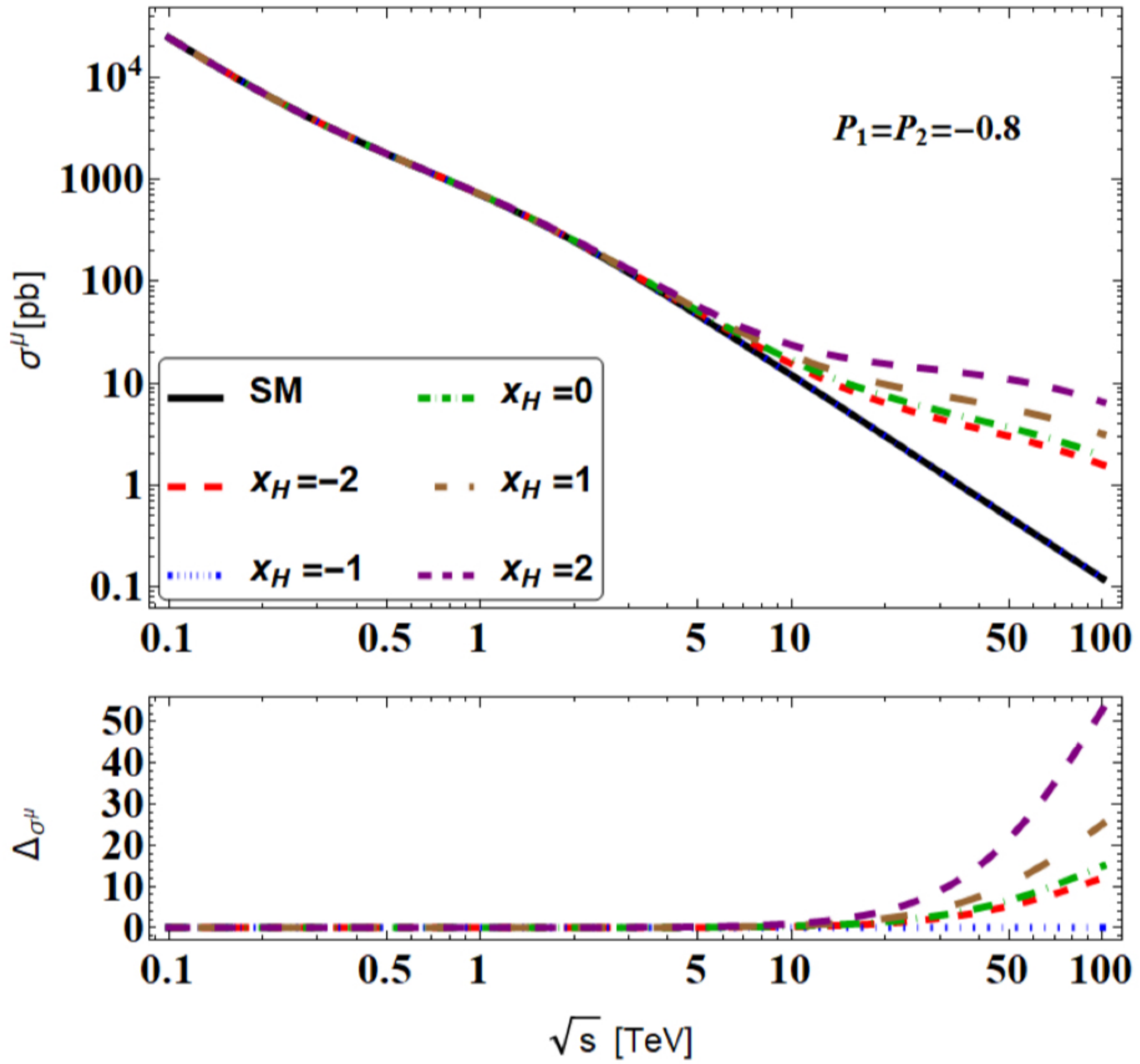
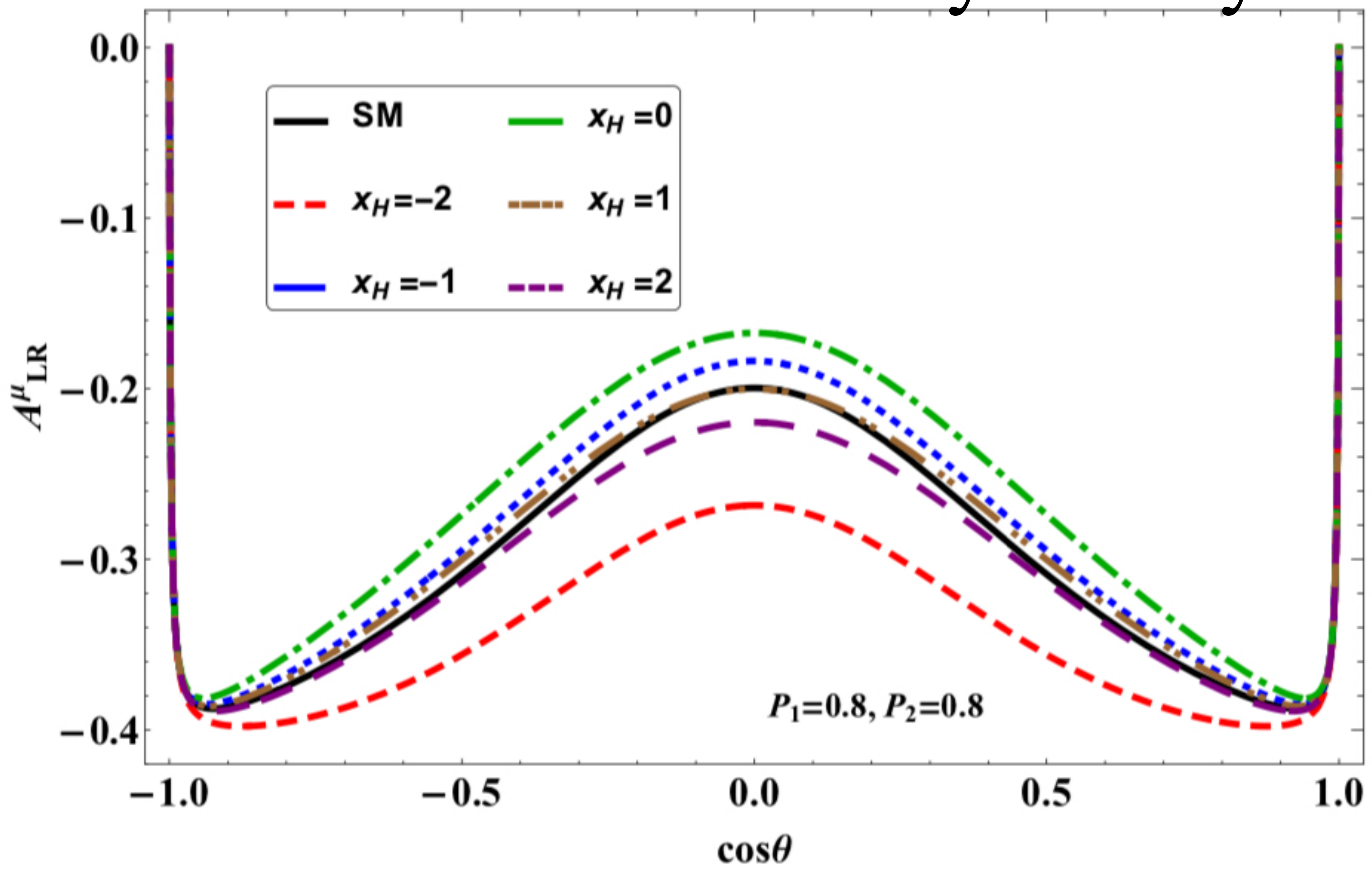


Figure 7. Photon, Z and Z' mediated $\mu^+\mu^+ \to \mu^+\mu^+$ processes in $t-$channel (upper panel) and $u-$channel (lower panel) at μTRISTAN experiment with $\sqrt{s} = 2$ TeV.



Differential LR asymmetry

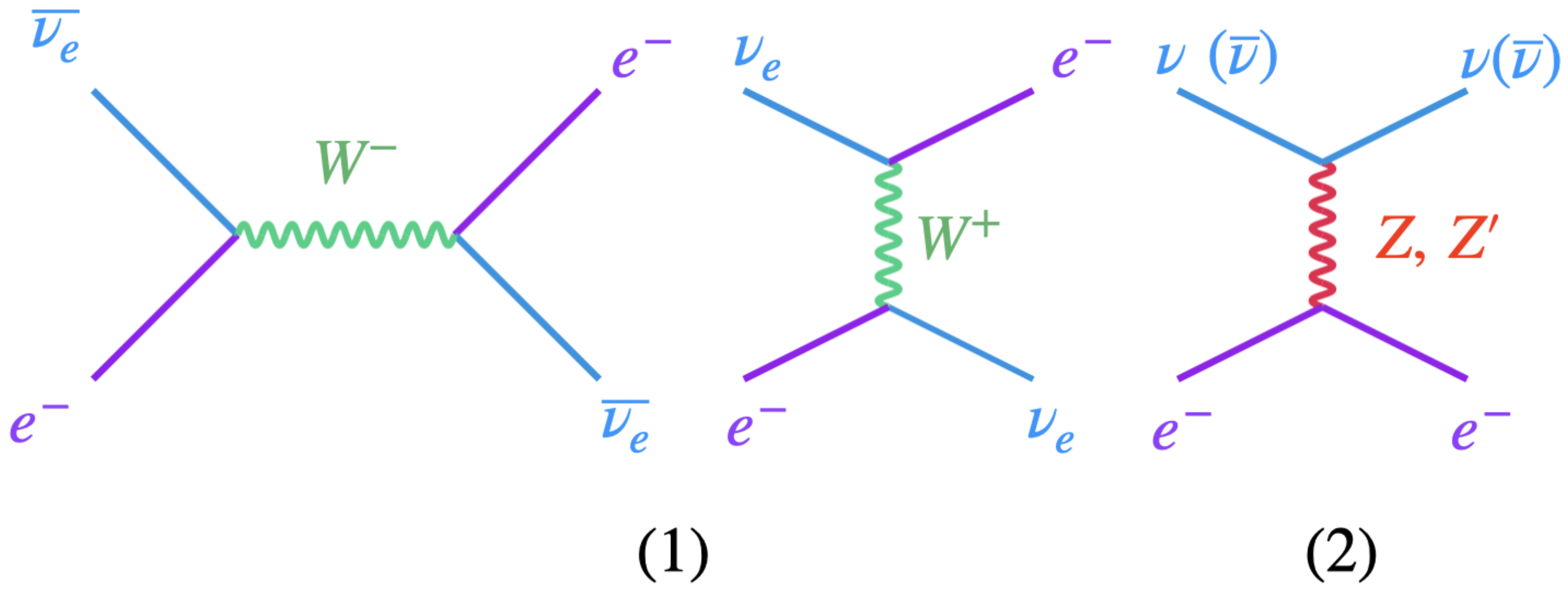


Neutrino electron scattering

2111.08767

The interactions between charged leptons and Z′

	ℓ_{L_i}	e_{R_i}	N_{R_α}	H	Φ
$\mathrm{SU(2)_L}$	**2**	**1**	**1**	**2**	**1**
$\mathrm{U(1)_Y}$	$-1/2$	-1	0	$1/2$	0
$\mathrm{U(1)}_X$	$-\frac{1}{2}x_H - x_\Phi$	$-x_H - x_\Phi$	$-x_\Phi$	$\frac{1}{2}x_H$	$2x_\Phi$



$$-\mathcal{L}^{\ell}_{\rm int} = g_X(\overline{\ell_L}Q^{\ell}_X\gamma^\mu Z'_\mu \ell_L + \overline{\ell_R}Q^{e_R}_X\gamma^\mu Z'_\mu \ell_R)$$

SM : The interactions of the leptons with Z and W bosons

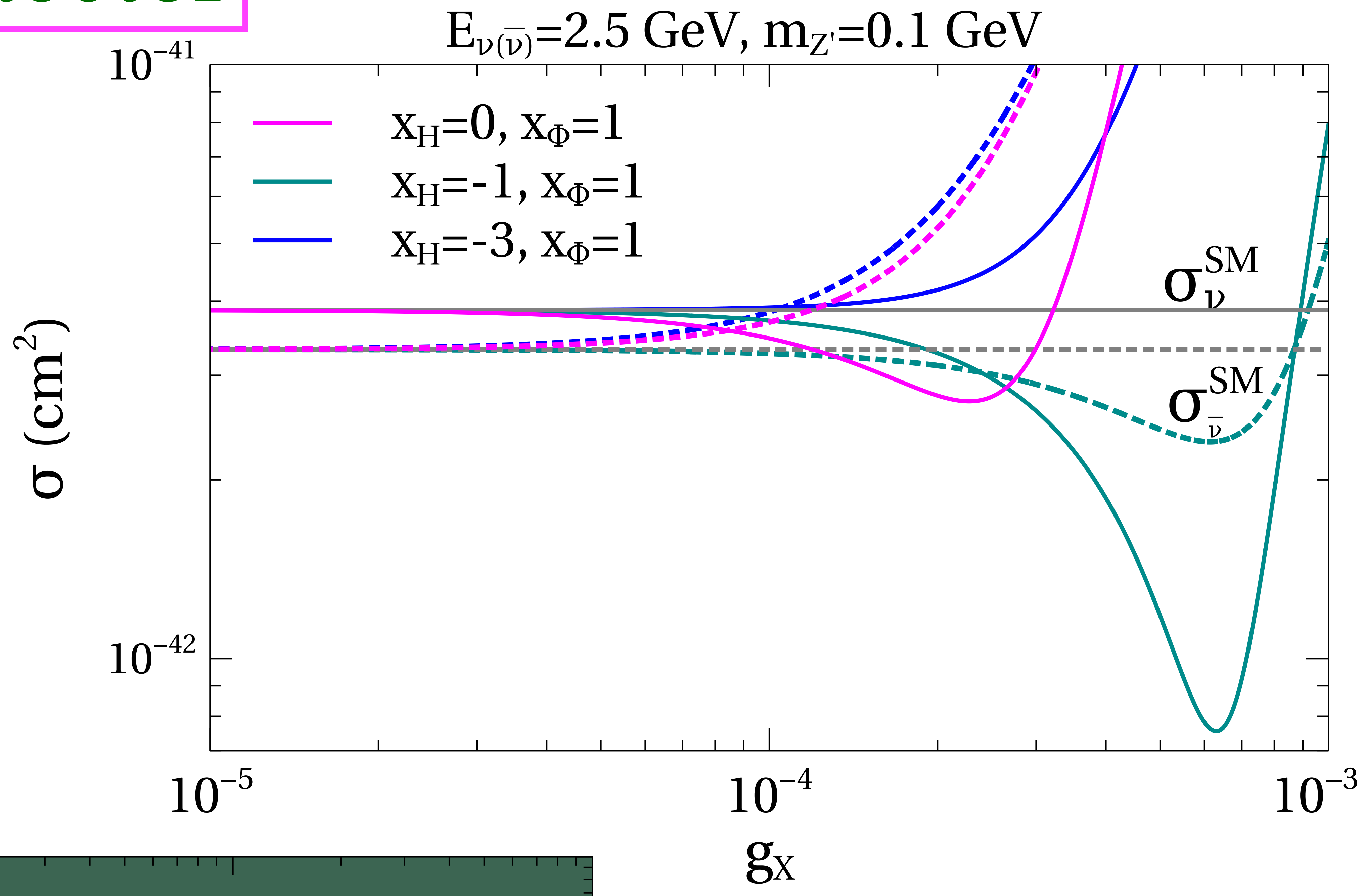
Scattering Process	a_1	a_2
$\nu_e e \to \nu_e e$	$\sin^2\theta_w + 1/2$	$\sin^2\theta_w$
$\bar{\nu}_e e \to \bar{\nu}_e e$	$\sin^2\theta_w$	$\sin^2\theta_w + 1/2$
$\nu_\beta e \to \nu_\beta e$	$\sin^2\theta_w - 1/2$	$\sin^2\theta_w$
$\bar{\nu}_\beta e \to \bar{\nu}_\beta e$	$\sin^2\theta_w$	$\sin^2\theta_w - 1/2$

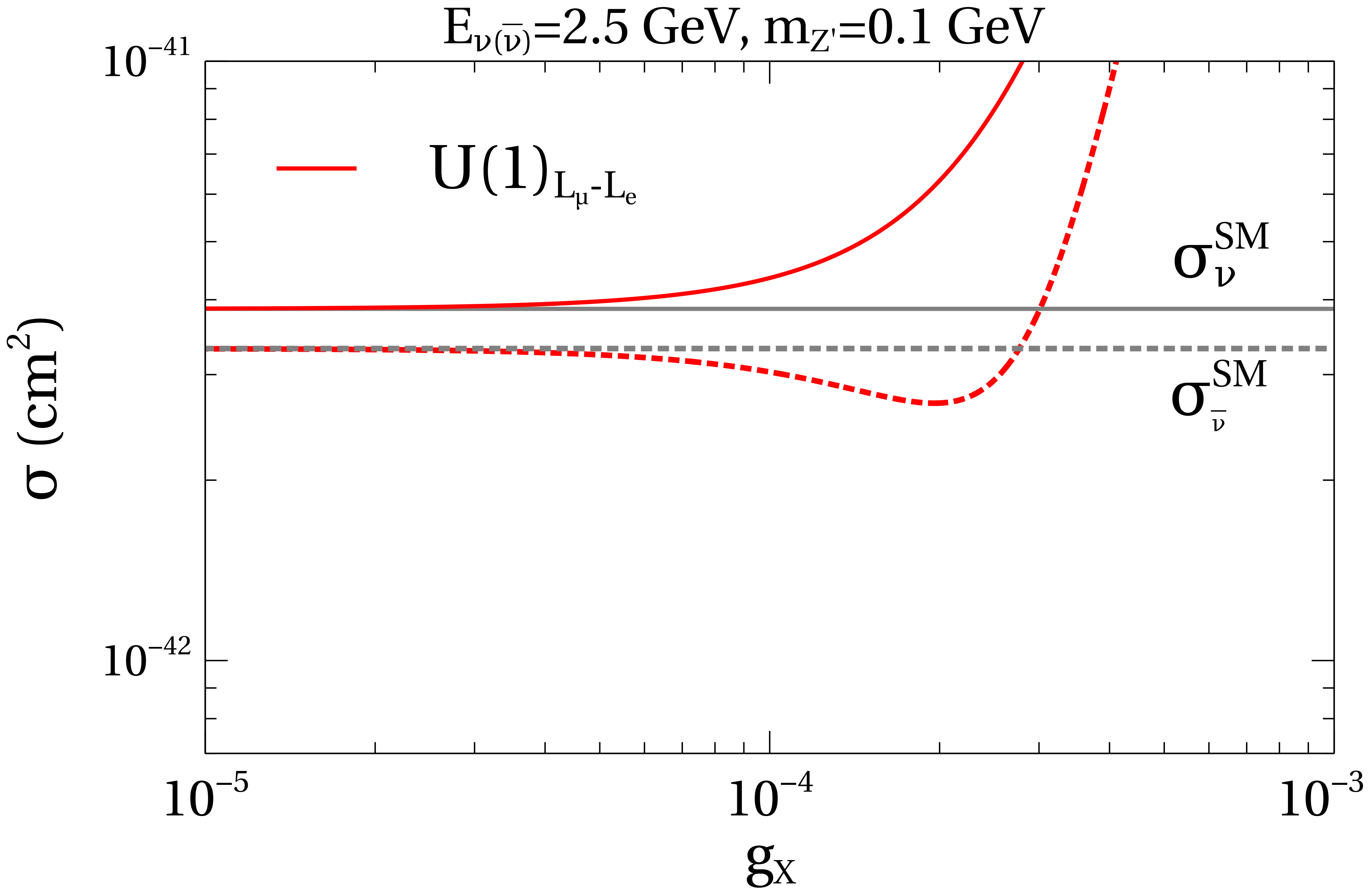
$$\frac{d\sigma(\nu e)}{dT} = \frac{d\sigma(\nu e)}{dT}\bigg|_{\rm SM} + \frac{d\sigma(\nu e)}{dT}\bigg|_{\rm Z'} + \frac{d\sigma(\nu e)}{dT}\bigg|_{\rm int}$$

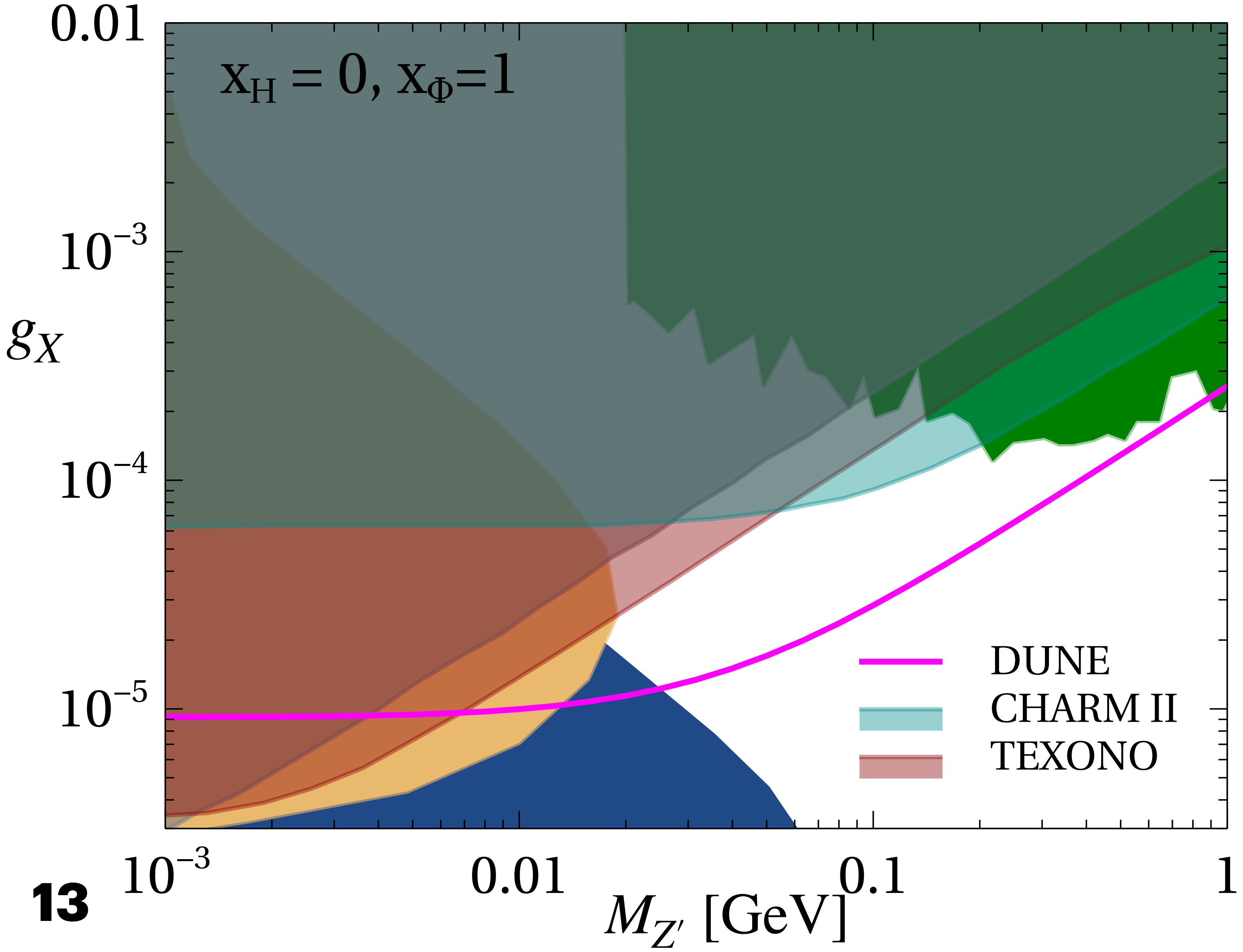
$$c_1 = -1/2 + 2\sin^2\theta_W,\ c_2 = -1/2$$

T : KE of out going electron

DUNE near detector







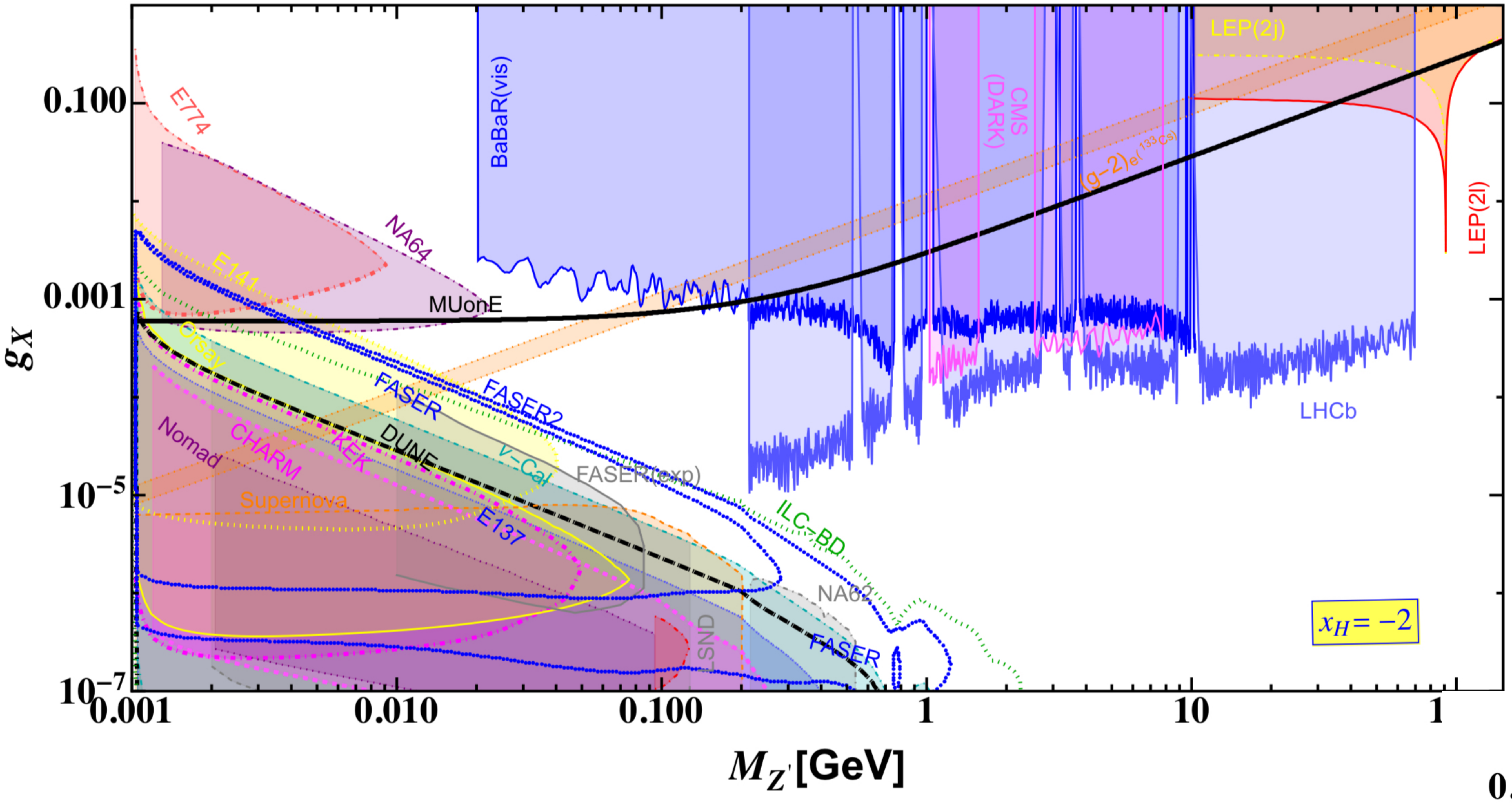
Total cross section of $\overset{(-)}{\nu}_\mu - e$ scattering for SM and U(1).

ν_μ : Solid, $\overline{\nu_\mu}$: Dashed

2111.08767 (DUNE), 2206.12676 (Beam dump)

Limits on $g_X - M_{Z'}$ plane for different charges

2206.12676, 2307.09737



e$^{\pm}$ beam dump experiments :

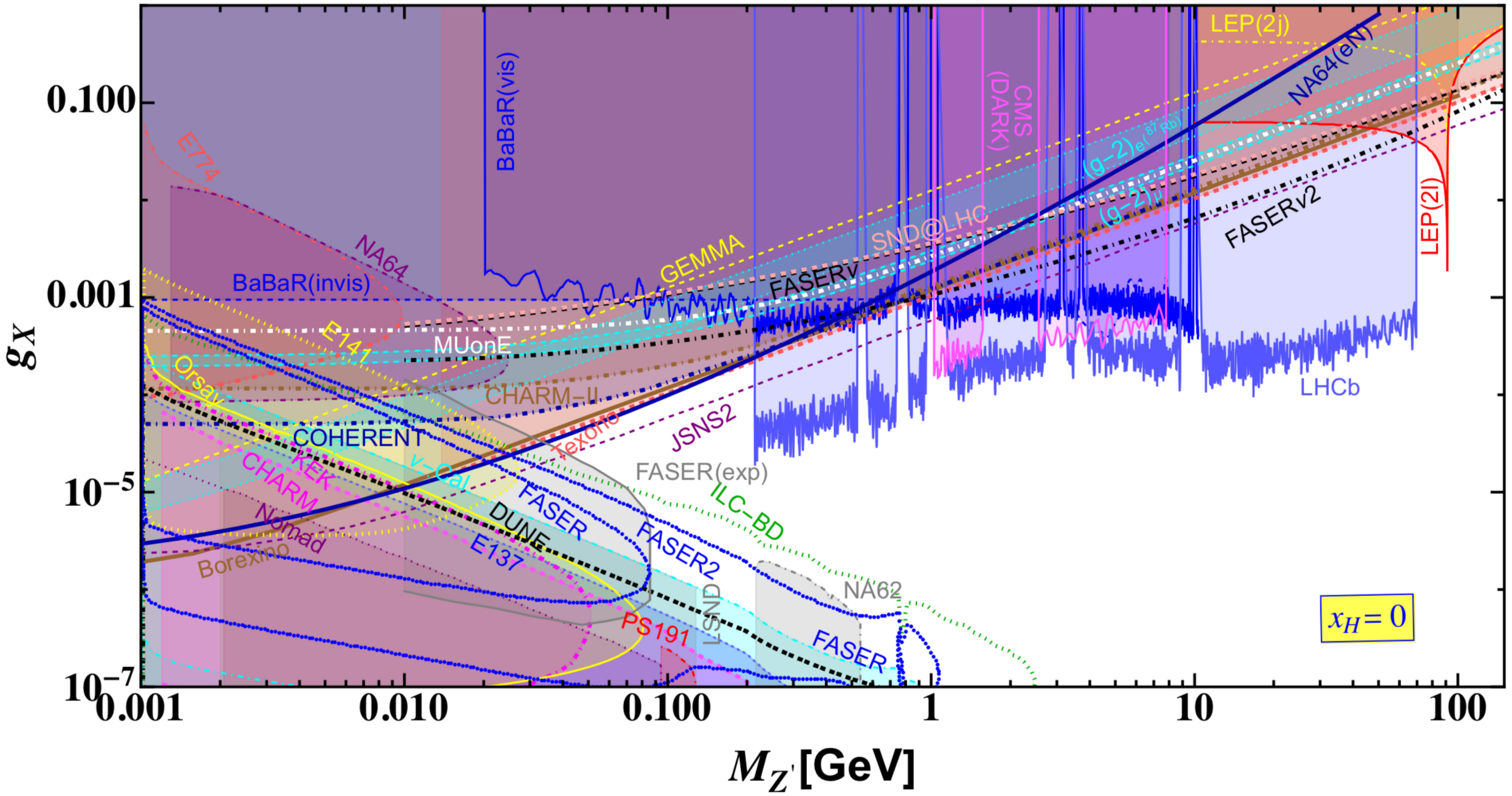
Orsay, NA64, KEK, E141, E137, E774

ILC – BD

Proton beam dump experiments :

ν – cal, CHARM, Nomad

FASER, FASER2, DUNE



Scattering experiments :

$\nu - e$: TEXONO, BOREXINO, JSNS2, DUNE

Dark photon search : BaBar, LHCb, CMS Dark

$\nu - N$: CHARM – II, COHERENT, FASERν, NA64

LEP, MUonE

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 .

Mnay aspects can be addressed in these scenarios which could connect three interesting frontiers of physics

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