

Testing tree level TeV scale seesaw scenarios in μ TRISTAN

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Standard Model of elementary particles and Beyond the Standard Model



Higgs (H) → proposed in 60s and observed in 2012 by LHC

Neutrinos → proposed to be massless, however, **neutrino oscillation and flavor mixing** confirm the presence of tiny neutrino mass

SM needs to be extended

Several proposals

1. Tree level
2. Quantum level
3. Gauge extension
4. Higher dimensional operators

ν — mass

Other sources of beyond the SM scenario

- Dark Matter relic abundance
- Baryon asymmetry of the universe
- Strong CP problem

Some (interesting) unknown facts about the neutrinos

Nature of the neutrinos : Dirac/ Majorana \Rightarrow Lepton number conserving/ violating

The origin of tiny neutrino mass \Rightarrow The mechanism of neutrino mass generation

Neutrino mass hierarchy \Rightarrow Normal hierarchy/Inverted hierarchy

Type of neutrino mixing matrix :

U_{PMNS} : unitary/non – unitary

values of Dirac/ Majorana CP phases

Neutrino interactions \Rightarrow how do the neutrinos interact?

any involvements of BSM physics

Birth of a new idea : generation of neutrino mass

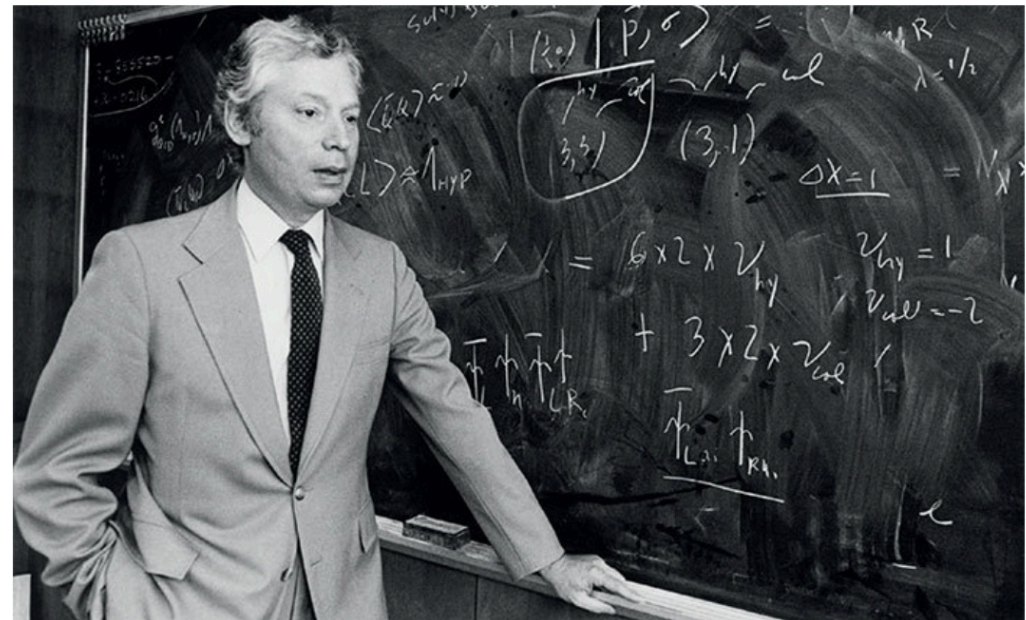
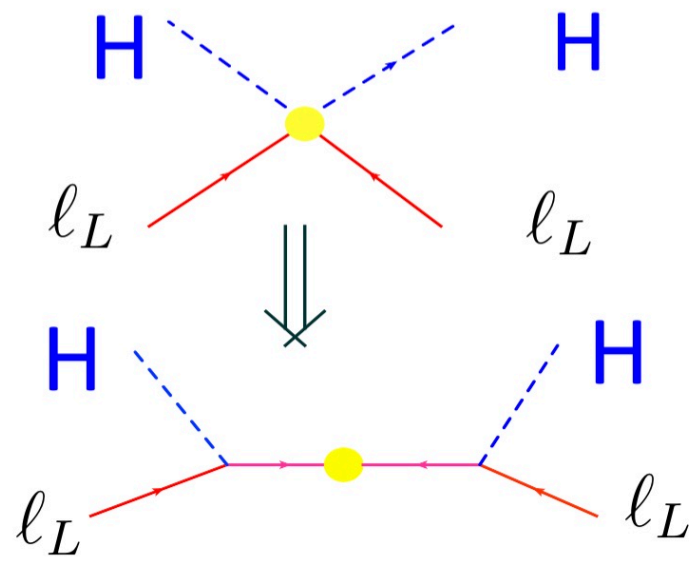
Weinberg Operator in SM ($d=5$), PRL 43, 1566(1979)

$$\frac{\overline{\ell}_L H \overline{\ell}_L^c H}{M}$$

within the Standard Model

Steven Weinberg : 1933 – 2021

The dimension 5 operator can be realized in the following ways



Majorana mass term is generated by the breaking of the lepton numbers by 2 units.

Seesaw scenario

SM + at least two generations of Majorana type Right Handed Neutrinos

$$\mathcal{L} \supset -Y_D^{\alpha\beta} \bar{\ell}_L^\alpha H N_R^\beta - \frac{1}{2} m_N^{\alpha\beta} \overline{N_R^{\alpha C}} N_R^\beta + H.c.$$

	SU(3)	SU(2)	U(1) _Y
$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
e_R	1	1	-1
$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$	1	2	$-\frac{1}{2}$
N_R	1	1	0

Dirac mass after electroweak symmetry breaking

$$M_D = \frac{Y_D v}{\sqrt{2}}$$

Neutrino mass matrix $M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix}$

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

as a result light and heavy neutrino mass eigenstates are mixed

$$\nu \simeq \mathcal{N} \nu_m + V N_m, \quad V \simeq M_D m_N^{-1}$$

modified charged (CC) and neutral (NC) current interactions of the lepton sector

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu \bar{e} \gamma^\mu P_L (\mathcal{N} \nu_m + V N_m) + h.c.$$

$$\mathcal{L}_{NC} = -\frac{g}{2c_w} Z_\mu \left[\bar{\nu}_m \gamma^\mu P_L (\mathcal{N}^\dagger \mathcal{N}) \nu_m + \bar{N}_m \gamma^\mu P_L (V^\dagger V) N_m + \{ \bar{\nu}_m \gamma^\mu P_L (\mathcal{N}^\dagger V) N_m + h.c. \} \right]$$

Another interesting aspect : U(1) extension of the SM

	Fields	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_X$
SM fields	q_L^i	$(3, 2, \frac{1}{6})$	$x_q = \frac{1}{6}x_H + \frac{1}{3}x_\Phi$
	u_R^i	$(3, 1, \frac{2}{3})$	$x_u = \frac{2}{3}x_H + \frac{1}{3}x_\Phi$
	d_R^i	$(3, 1, -\frac{1}{3})$	$x_d = -\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
	ℓ_L^i	$(1, 2, -\frac{1}{2})$	$x_\ell = -\frac{1}{2}x_H - x_\Phi$
	e_R^i	$(1, 1, -1)$	$x_e = -x_H - x_\Phi$
	H	$(1, 2, -\frac{1}{2})$	$-\frac{1}{2}x_H$
BSM fields	N^j	$(1, 1, 0)$	$x_N = -x_\Phi$
	Φ	$(1, 1, 0)$	$2x_\Phi$

a linear combination of $U(1)_{B-L}$ and $U(1)_Y$ providing anomaly free scenario

provides a new neutral gauge boson Z' with the SM gauge bosons carry information of $\{x_H, x_\Phi\}$

Scalar field

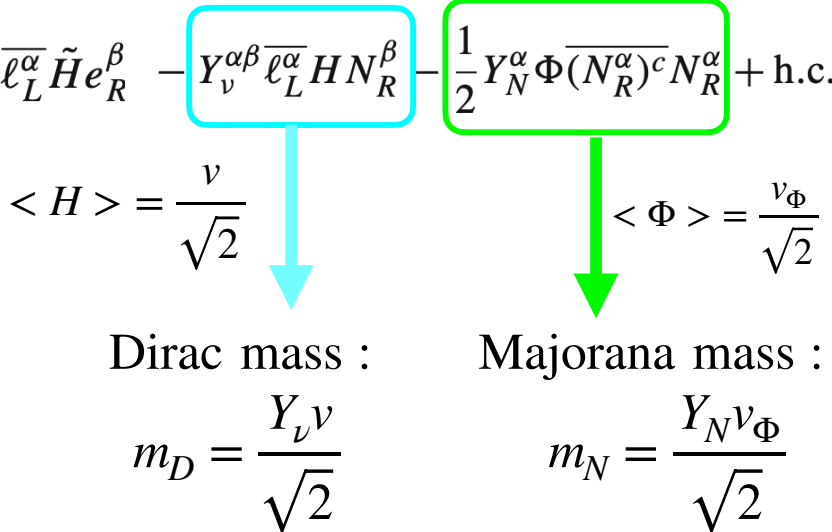
3 right handed neutrinos (RHNs)

SM singlet

The renormalizable scalar potential $V = m_h^2(H^\dagger H) + \lambda_H(H^\dagger H)^2 + m_\Phi^2(\Phi^\dagger \Phi) + \lambda_\Phi(\Phi^\dagger \Phi)^2 + \lambda'(H^\dagger H)(\Phi^\dagger \Phi)$

The Yukawa interaction $\mathcal{L}^{\text{Yukawa}} = -Y_u^{\alpha\beta} \bar{q}_L^\alpha H u_R^\beta - Y_d^{\alpha\beta} \bar{q}_L^\alpha \tilde{H} d_R^\beta - Y_e^{\alpha\beta} \bar{\ell}_L^\alpha \tilde{H} e_R^\beta - Y_\nu^{\alpha\beta} \bar{\ell}_L^\alpha H N_R^\beta - \frac{1}{2} Y_N^\alpha \Phi \overline{(N_R^\alpha)^c} N_R^\alpha + \text{h.c.}$

After the $U(1)_X$ and electroweak symmetries are broken



Neutrino mass matrix

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

light neutrino mass

$$-m_D m_N^{-1} m_D^T$$

Seesaw mechanism

After the breaking of $U(1)_X$ symmetry mass of Z' is generated

$$M_{Z'} = 2g_X v_\Phi x_\Phi \quad g_X \text{ is } U(1)_X \text{ coupling}$$

we consider $x_\Phi = 1$ in our analysis

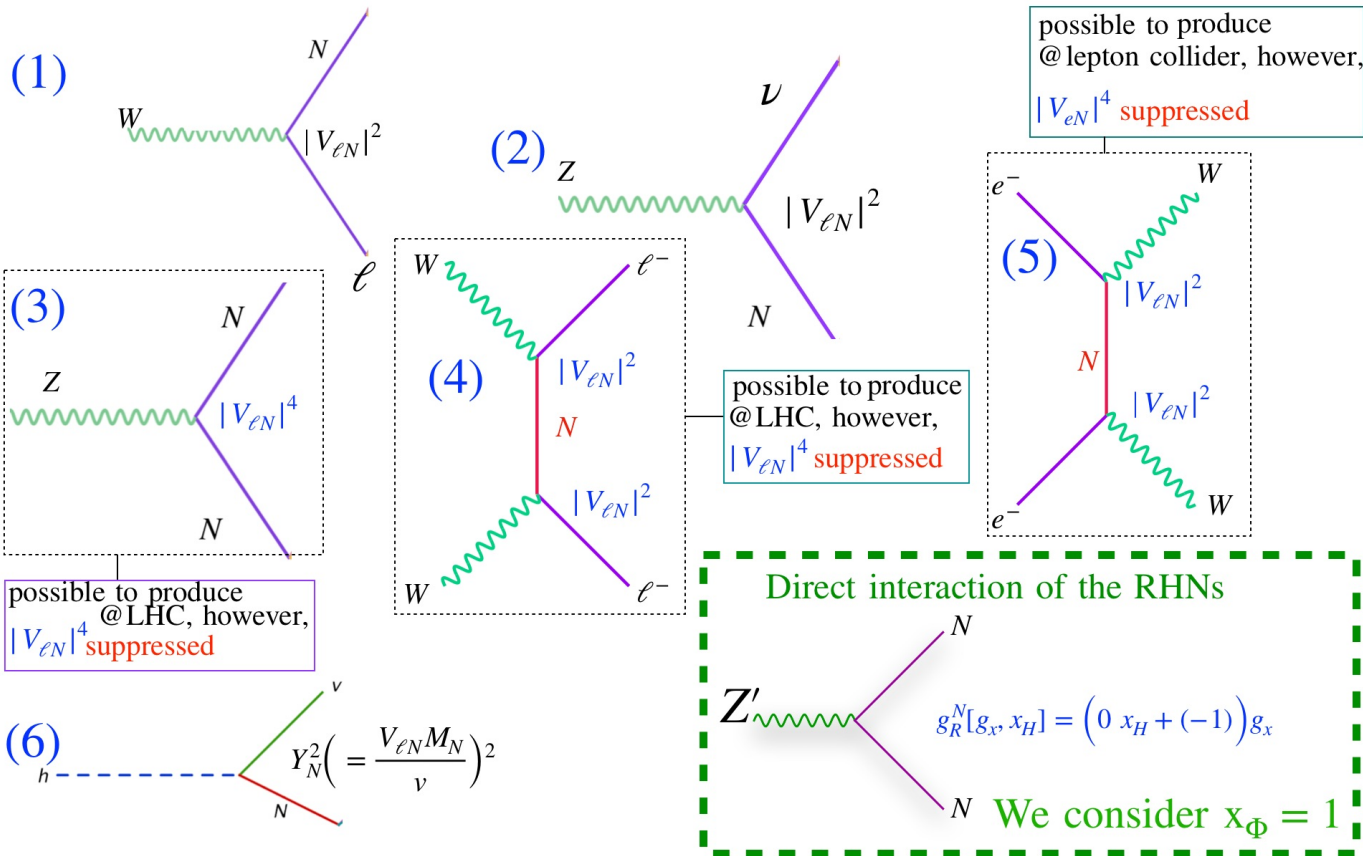
Production modes of the RHNs at the colliders

Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \approx U_{\ell m} \nu_m + V_{\ell n} N_n$$

PMNS matrix

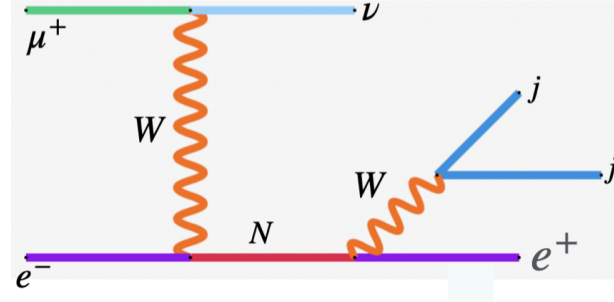
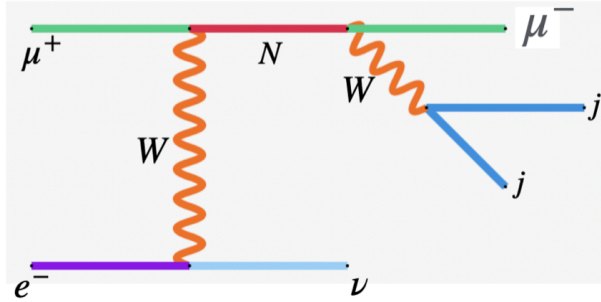
$M_D M_N^{-1}$



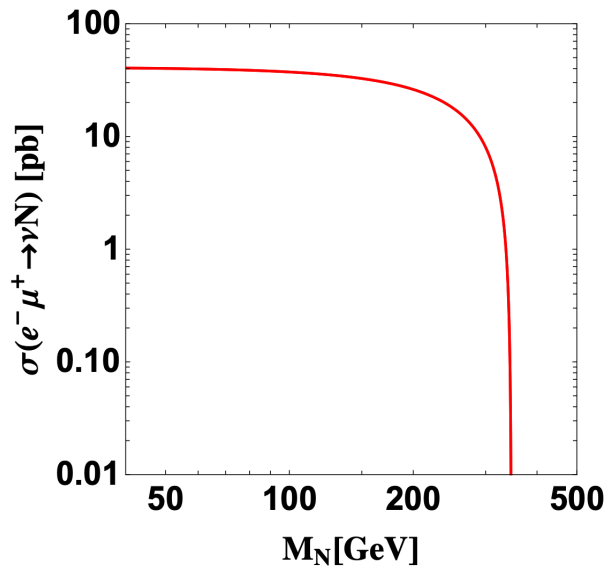
diagrams proportional to 4th power of mixing are strongly suppressed

Production and decay of heavy neutrinos

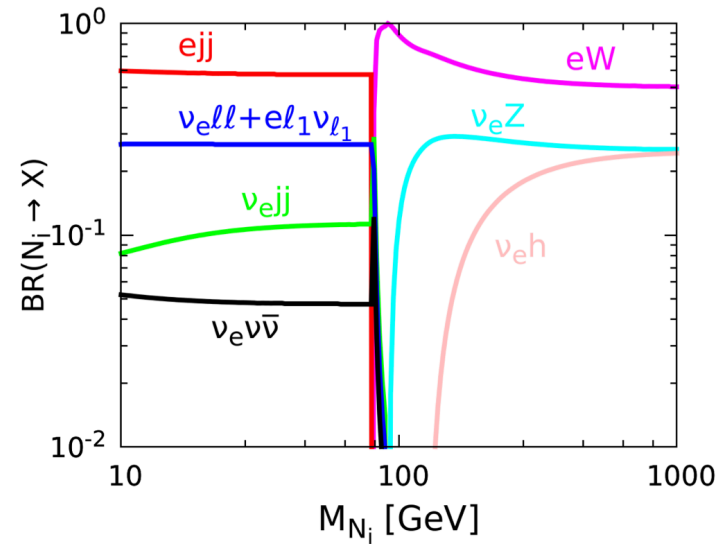
$\sqrt{s} = 346 \text{ GeV}$, 1 ab^{-1} luminosity



Cross section normalized by mixing



branching ratios



combined generic backgrounds : $\ell^+ 2j + 3\nu$, $\ell^\pm 2j + \nu/\bar{\nu}$

$p_T^j > 20 \text{ GeV}$, $|\eta| < 4.5$, $p_T^\ell > 20 \text{ GeV}$, $|\eta| < 2.5$, $E_T^{\text{miss}} < 60 \text{ GeV}$

$m_{jj} \in [70, 90] \text{ GeV}$ $m_{\ell jj} \in [M_N - 20, M_N + 20] \text{ GeV}$

Signal and backgrounds before and after cuts

\sqrt{s} (GeV)	M_{N_1} (GeV)	Signal (S)		Background (B)	
		before cuts (pb)	after cuts (fb)	before cuts (fb)	after cuts (fb)
346	45	24.62	3.7	0.0988	5.525×10^{-3}
	68	23.6	71.1	0.0988	9.375×10^{-4}
	97	23.5	137.3	0.0988	9.023×10^{-4}
	184	11.5	430.2	0.0988	2.780×10^{-4}
	300	2.9	363.24	0.0988	3.776×10^{-4}
\sqrt{s} (GeV)	M_{N_2} (GeV)	Signal		Background	
		before cuts (pb)	after cuts (fb)	before cuts (fb)	after cuts (fb)
346	45	24.62	767.4	0.213	3.681×10^{-4}
	68	23.6	1242.6	0.213	6.519×10^{-4}
	97	23.5	697.6	0.213	1.089×10^{-3}
	184	11.5	1675.0	0.213	8.560×10^{-4}
	300	2.9	582.1	0.213	3.473×10^{-4}

Z' induced scenarios : bounds from different experiments

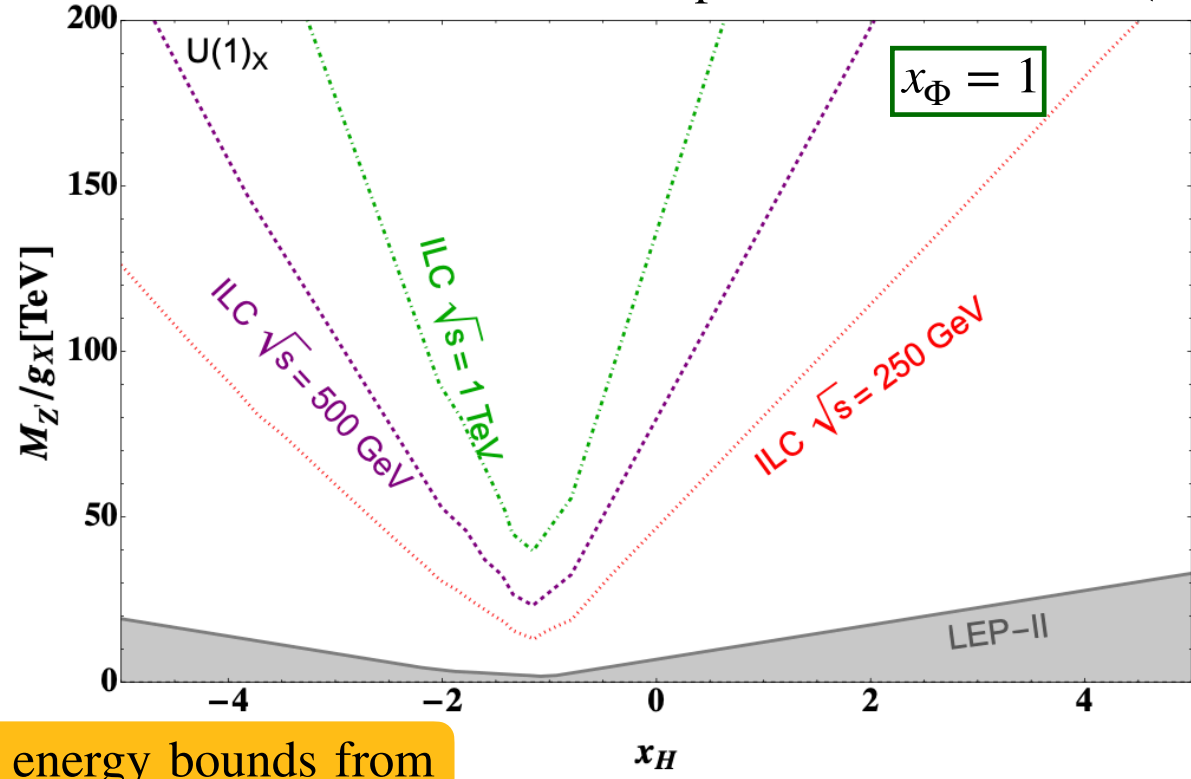
Interaction between Z' and fermions $\mathcal{L}^f = -g_X(\bar{f}_L \gamma^\mu q_{f_L} f_L + \bar{f}_R \gamma^\mu q_{f_R} f_R) Z'_\mu$.

Limits on U(1) coupling from $e^-e^+ \rightarrow f\bar{f}$ considering $M_{Z'} \gg \sqrt{s}$ (= 209 GeV)

$\Lambda_{XX}^{f\pm}$: effective scale obtained from lepton collider studies (LEP – II, ILC)

$$M_{Z'}^2 \geq \frac{g_X^2}{4\pi} |q_{e_{L/R}} q_{f_{L/R}}|^2 (\Lambda_{XX}^{f\pm})^2$$

$$q_{f_{L,R}} = f(x_H, x_\Phi)$$



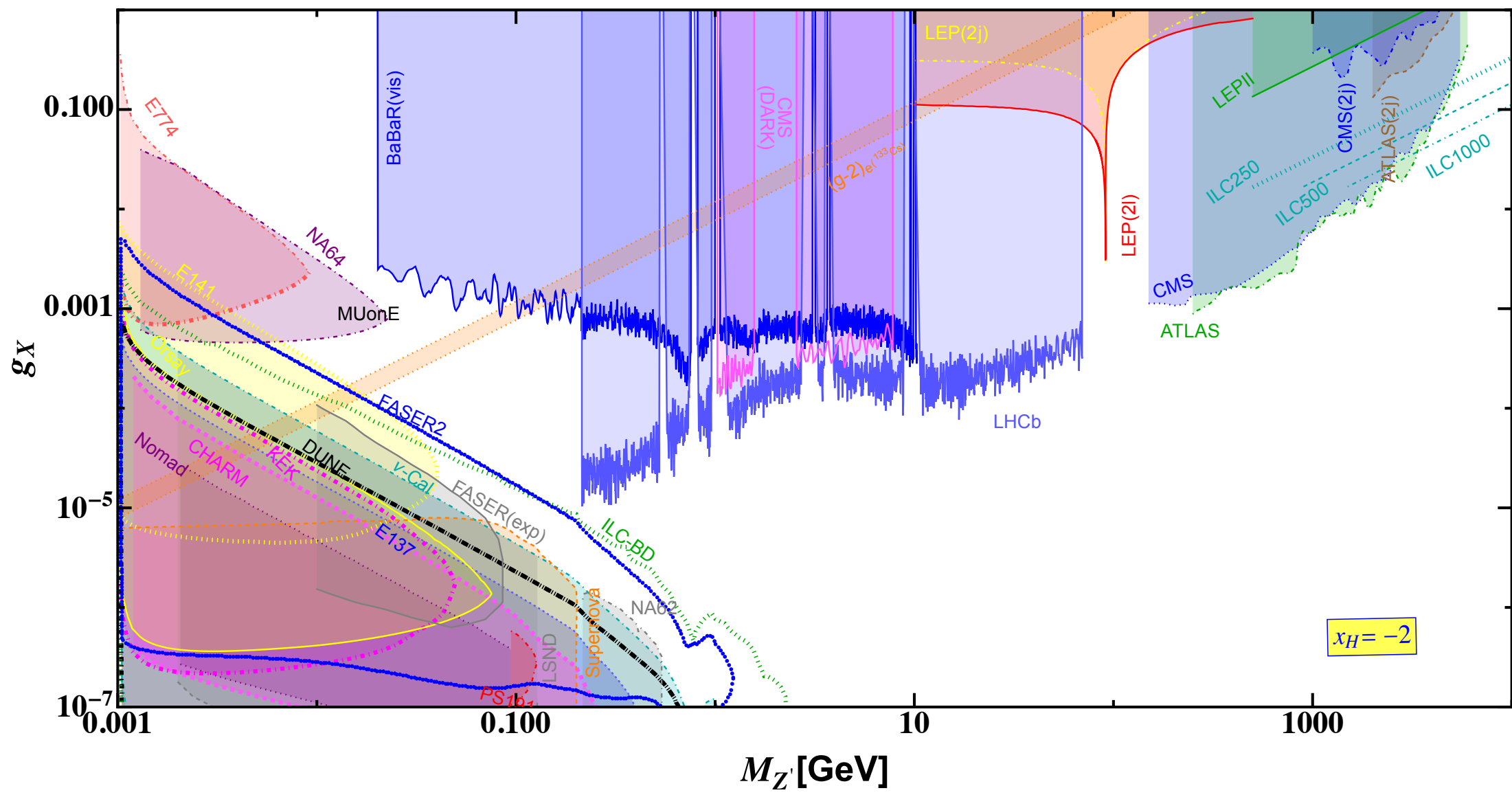
High energy scattering

LEP – II, LHC(dilepton, dijet), ILC
2104.10902

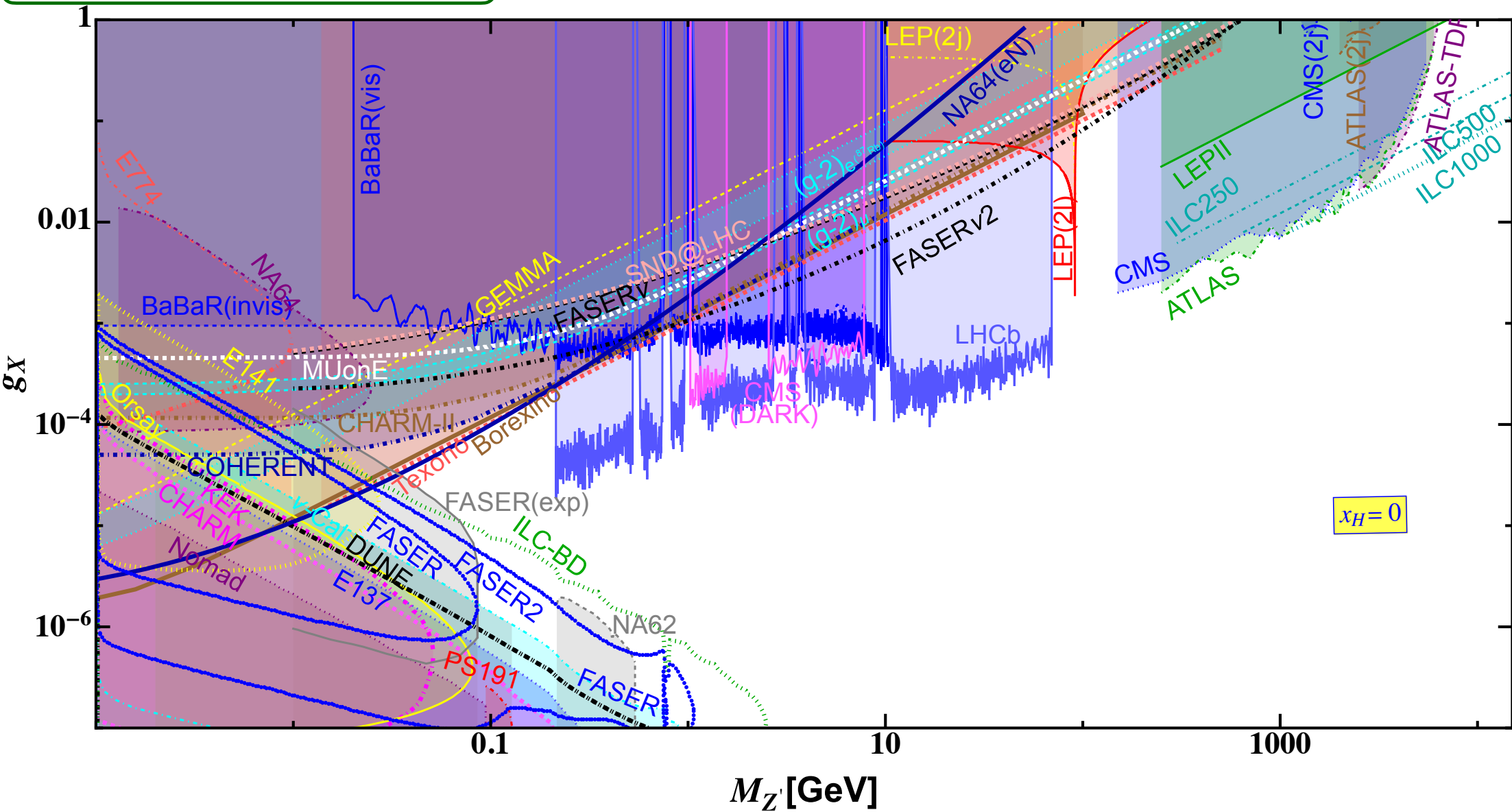
Low energy bounds from

Scattering experiments : $\nu - e$ (Borexino, Tenono, GEMMA, CHARM – II), $\nu - N$ (COHERENT)
 e^\pm beam dump(BD) : NA64, E774, Orsay, KEK p^+ BD : LSND, PS191, NOMAD, CHARM

Current constraints (1) $x_H = -2, x_\Phi = 1 : U(1)_R$ case



(2) $x_H = 0, x_\Phi = 1 : U(1)_{B-L}$ case

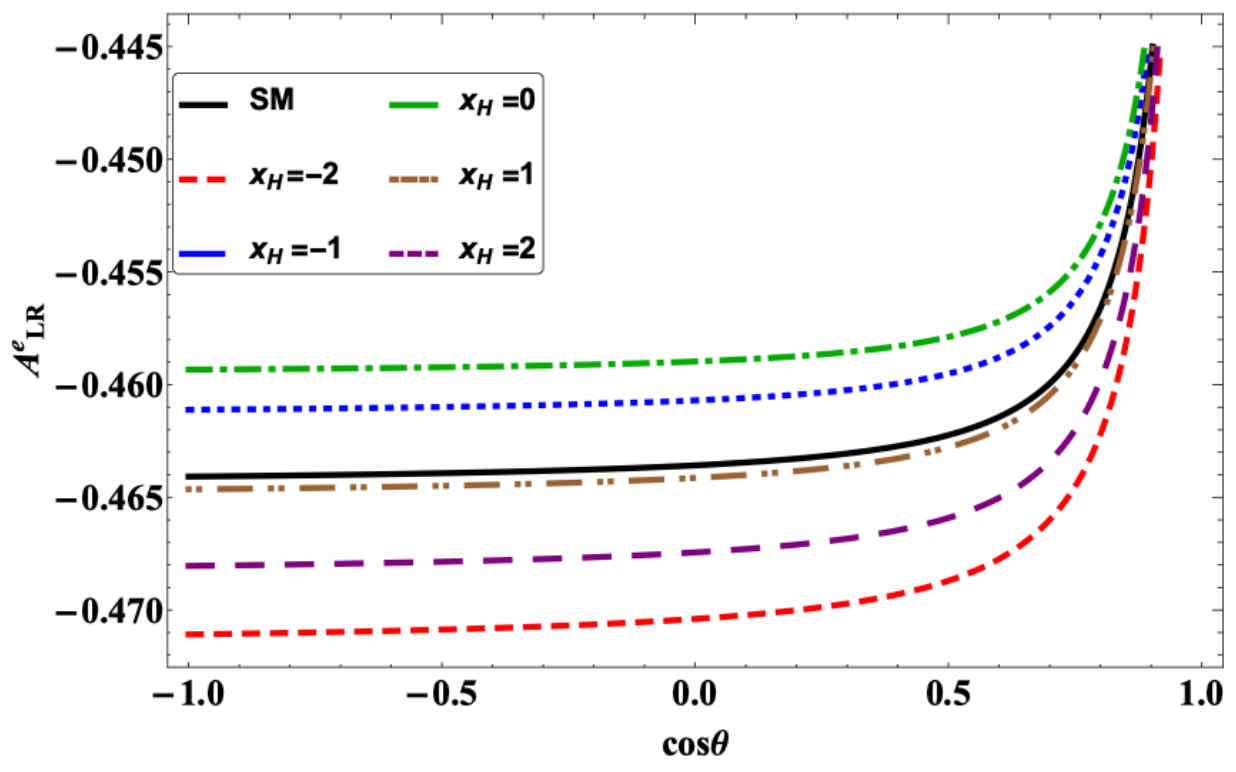
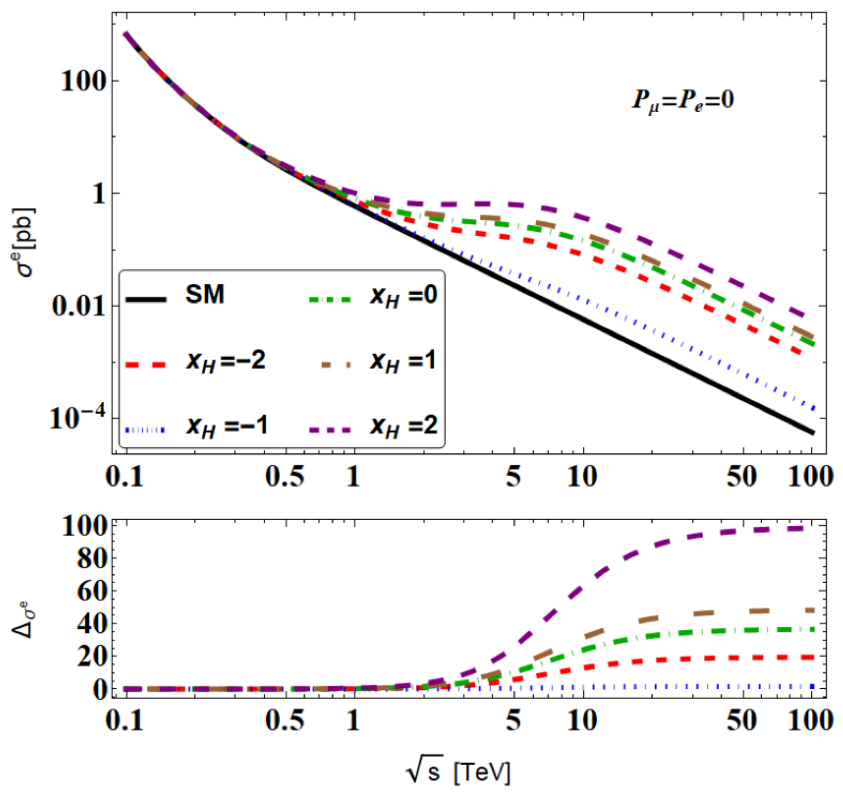
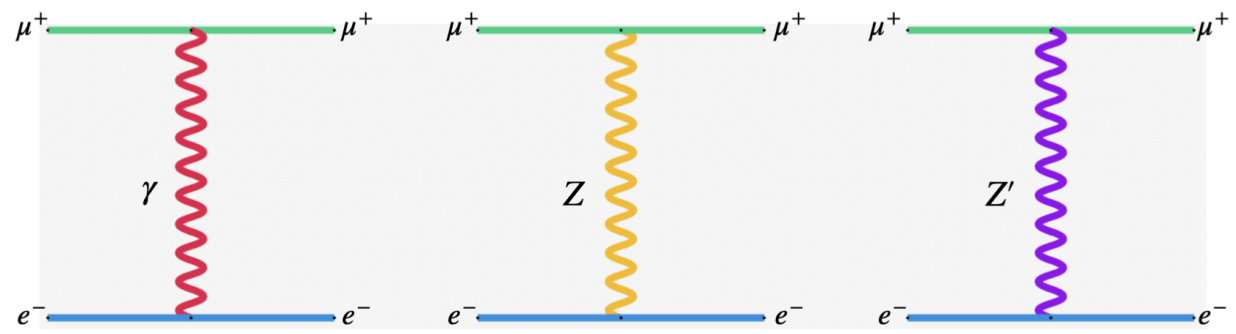


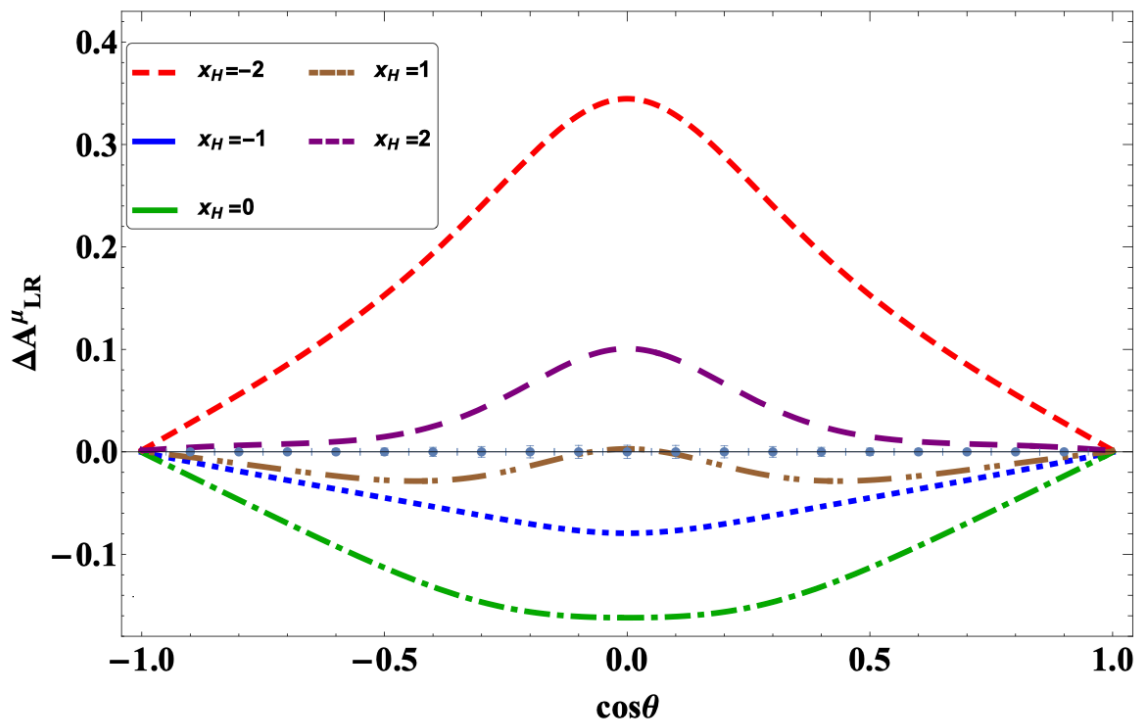
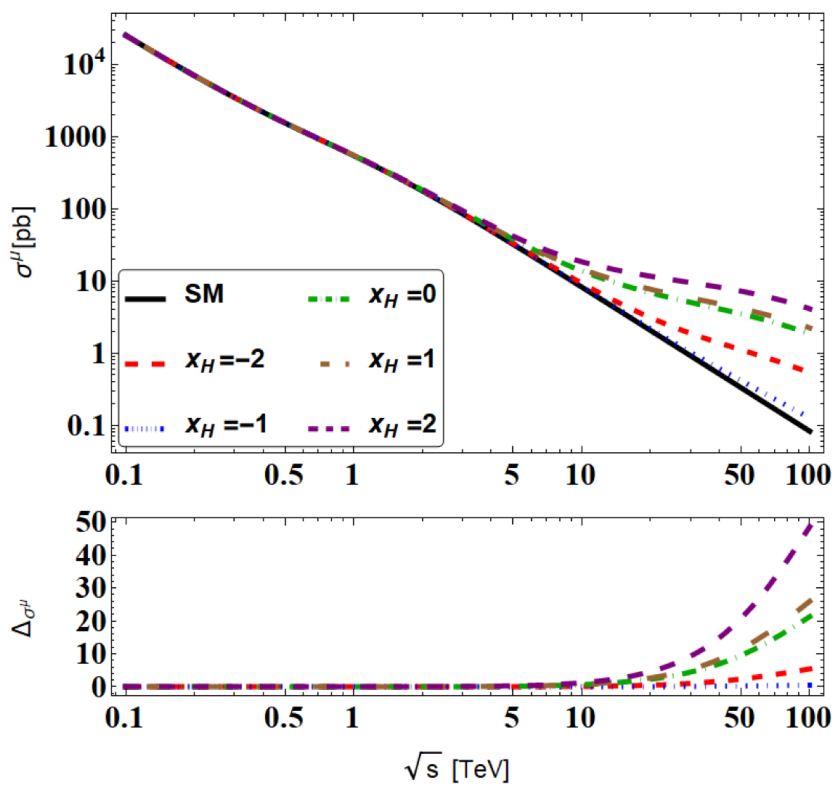
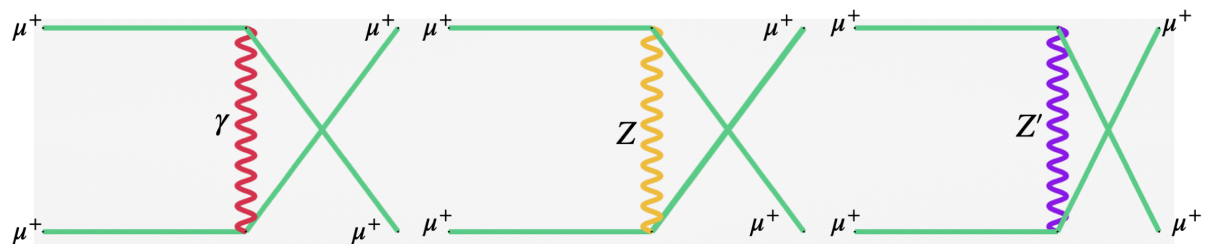
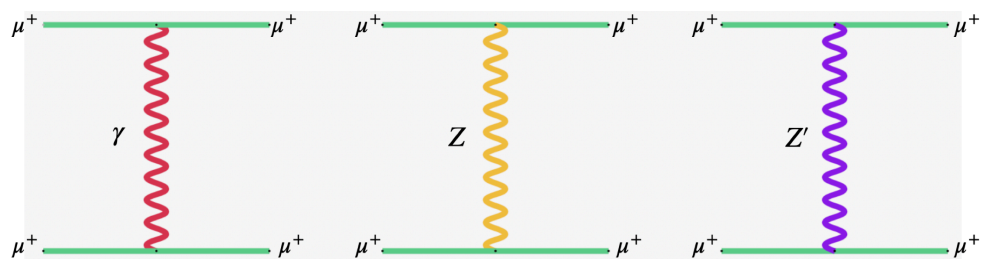
Interesting aspects of Z' induced scenarios in μ TRISTAN

2401.00696

$\mu^+e^- \rightarrow \mu^+e^-$

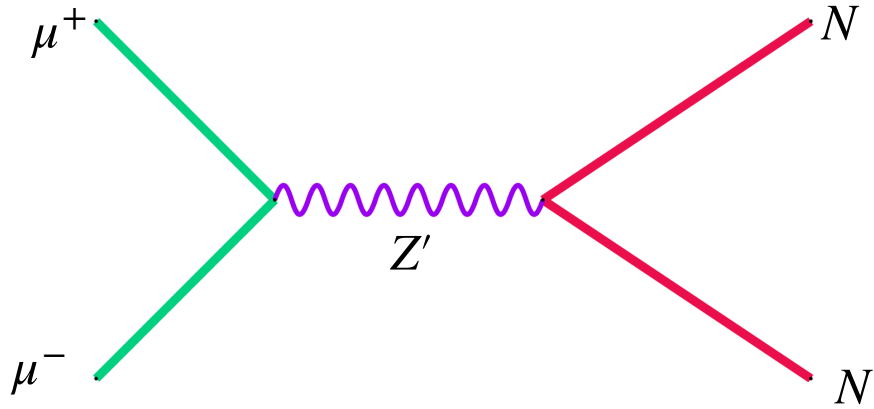
$\sqrt{s} = 346 \text{ GeV}$



$\mu^+\mu^+ \rightarrow \mu^+\mu^+$ $\sqrt{s} = 2 \text{ TeV}$ 

Heavy neutrino pair production in muon collider (in progress)

$$\sqrt{s} < M_{Z'}$$

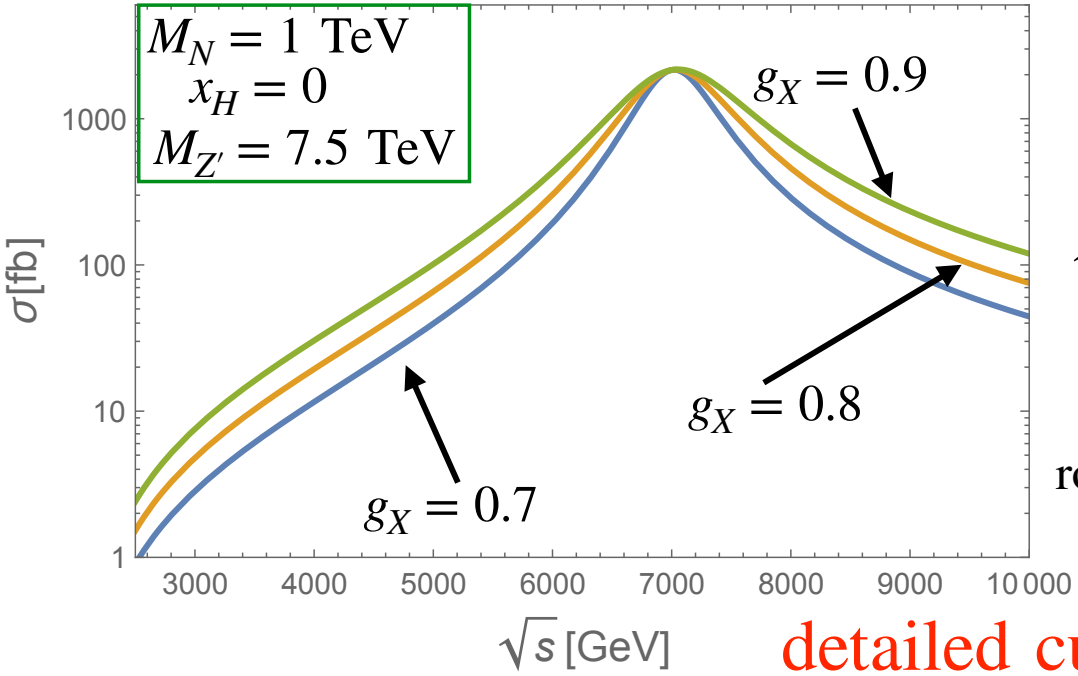


$$\propto \frac{g_X^4}{(s - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2} \approx \frac{g_X^4}{M_{Z'}^4 + \Gamma_{Z'}^2 M_{Z'}^2}$$

Lepton number violating signature

$\sqrt{s} = 3 \text{ TeV} : \sigma(\text{NN}) = 3 \text{ fb}, 5 \text{ fb}, 8 \text{ fb}$
 $(\text{BR}(N \rightarrow \ell W) \times W \rightarrow jj)^2 \times 1 \text{ ab}^{-1} :$

roughly 100 – 500 same sign dilepton plus two jet events



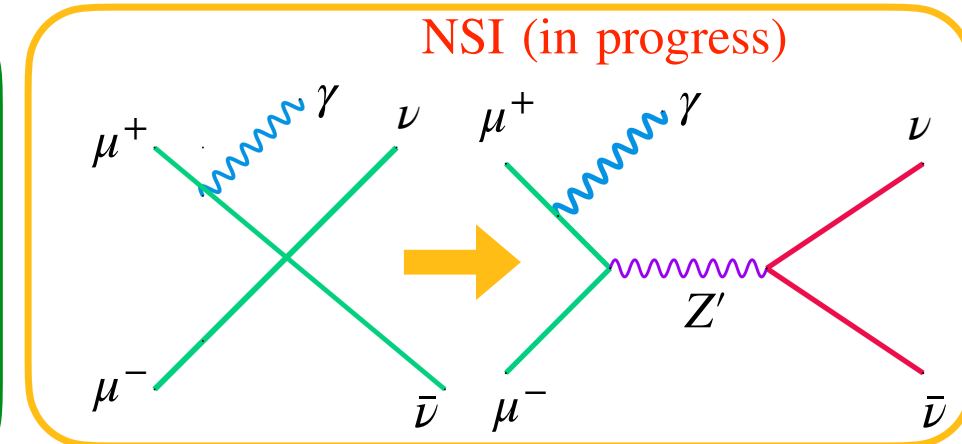
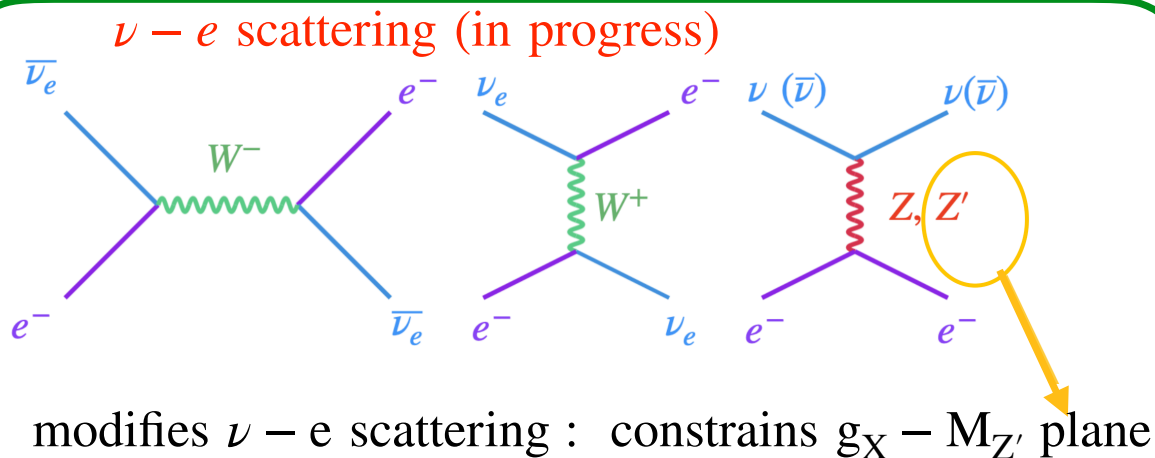
detailed cut based analysis will appear soon

Conclusions and future prospects of μ TRISTAN and muon colliders in search of BSM physics

1. We studied heavy neutrino production at μ TRISTAN and proposed a viable parameter region which could be probed in this collider.
2. We propose the possibility to study left – right asymmetry through Z' the same context.
3. Heavy neutrino pair production in muon collider through Z' : NOT suppressed by $|V|^4$, manifests lepton number violating signature.

Future direction

1. $\mu^+ e^- \rightarrow N \nu$: long lived heavy neutrinos in forward direction
2. Neutrinos@ μ colliders : a possible signature of BSM physics $\nu - e$ scattering and neutrino NSI



4. Muon beam dump (Z' , heavy neutrino production), muon ion scattering (MuSIC), etc

Thank You

