New light gauge boson in low and high energy experiments

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HPNP2025, 9 – 13 June, 2025 Osaka University

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

Other sourses of beyond the SM scenario

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

Is there any role of Higgs boson in BSM physics?

Some simple examples of neutrino mass generation mechanism

Tree level particle extension of SM

SM + SM – singlet RHNs seesaw : Majorana RHN

inverse seesaw
linear seesaw
pseudo – Dirac
Mohapatra, Yanagida, Valle, Minkowski

SM + SU(2) triplet scalar : type – II seesaw

SM + SU(2) triplet fermion : type – III seesaw
Schechter, Cheng, Li, Foot, Joshi, et . al .

Quantum level : 1, 2, 3 – loop : Ma, Zee – Babu, Babu Nandi Tavartkiladze, . . . MORE

Higher dimensional operators : Dim(5), Dim(6), . . Babu, Leung : 9309223, 0106054

Gauge extension of SM

$SU(2)_R$ extension : $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$: many possibilities Mohapatra, Senjanovic, et . al .

U(1) textension : $SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_{B-L}$, $SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_X$

$L_i - L_j$: Leptonic flavored scenarios : quarks are uncharged U(1) gauge . . . many more

Our area of interest is to study a general U(1) extension of the SM

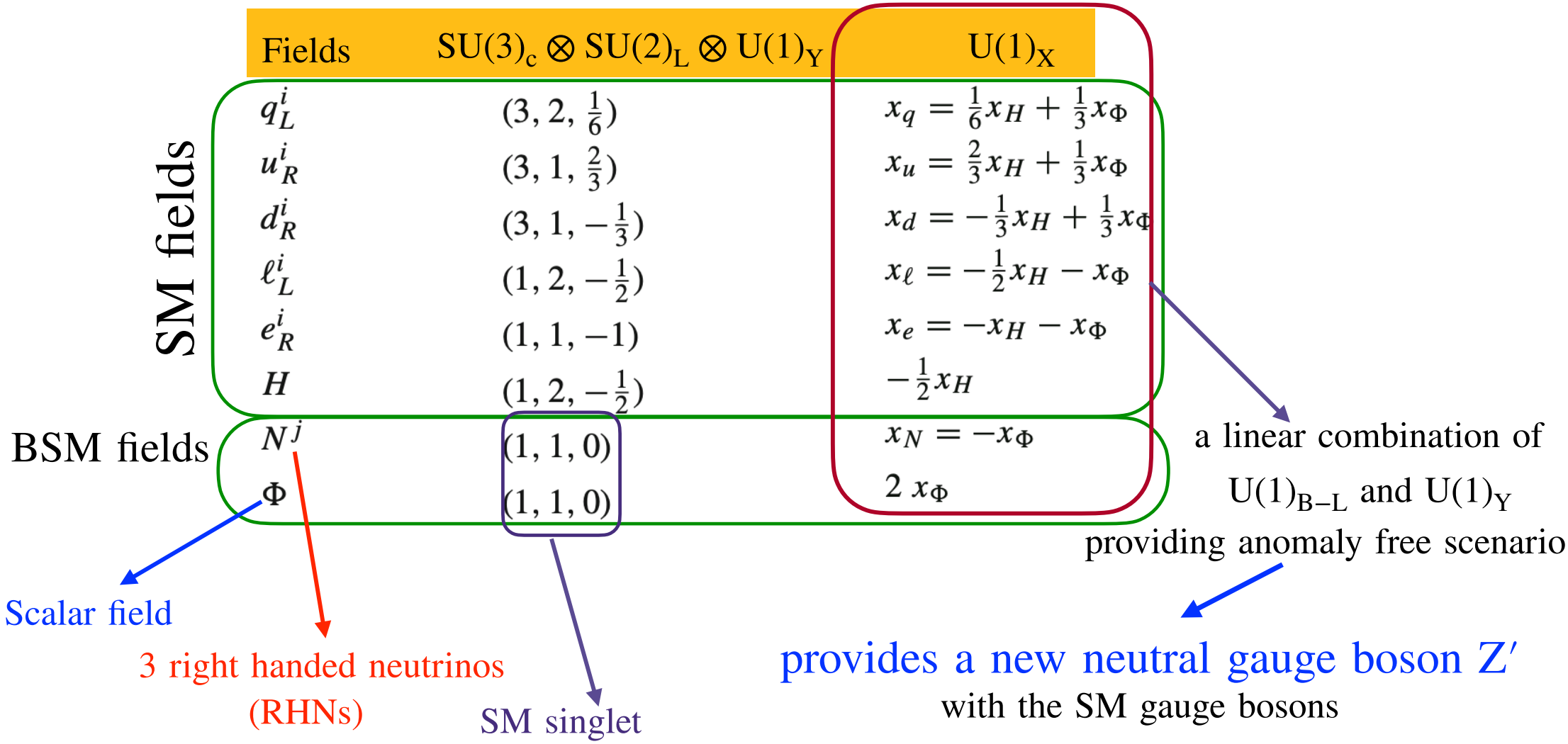
Different frontiers

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 .

A general U(1) extension of the Standard Model



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

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

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

Dirac mass : $m_D = \frac{Y_\nu v}{\sqrt{2}}$

Majorana mass : $m_N = \frac{Y_N v_\Phi}{\sqrt{2}}$

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

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

Bounds from different experiments

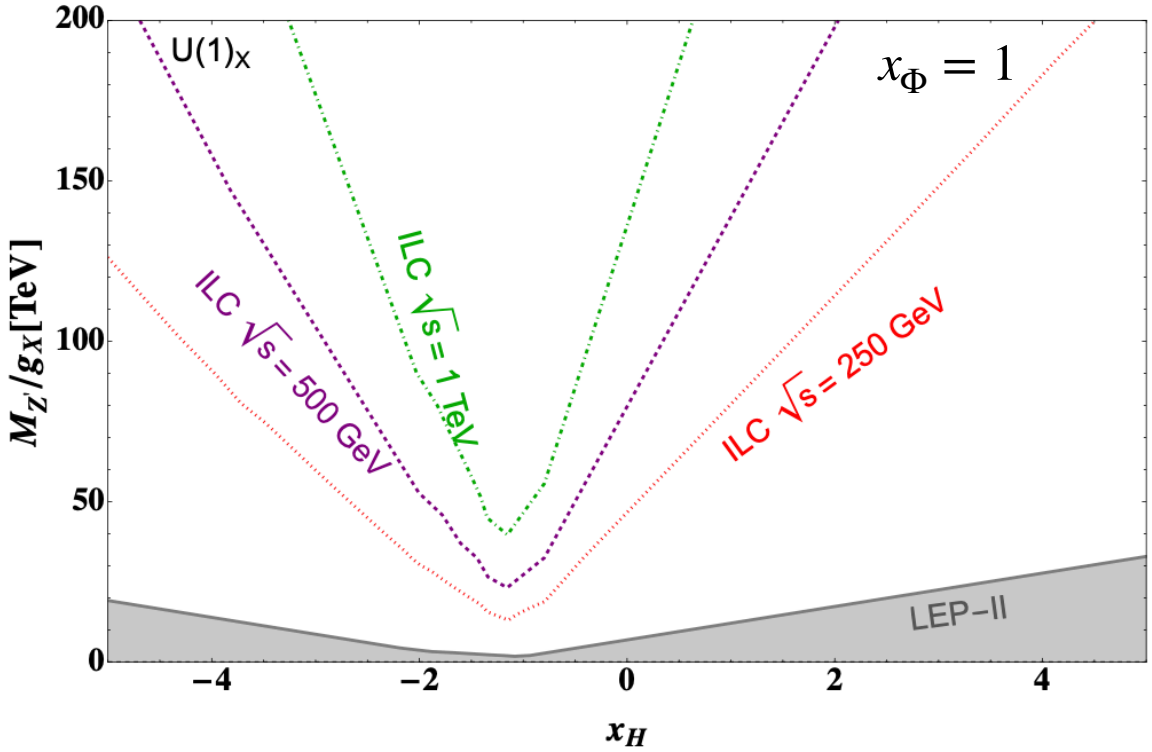
Interaction between Z′ and fermions $\mathcal{L}^f = -g_X(\overline{f_L}\gamma^\mu q_{f_L} f_L + \overline{f_R}\gamma^\mu q_{f_R} f_R)Z'_\mu$.

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

$\Lambda_{XX}^{f\pm}$: 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

Scattering experiments : ν − e (Borexino, Tenono, GEMMA, CHARM − II), ν − N (COHERENT)

$e^\pm$ beam dump(BD) : NA64, E774, Orsay, KEK

p^+ BD : LSND, PS191, NOMAD, CHARM

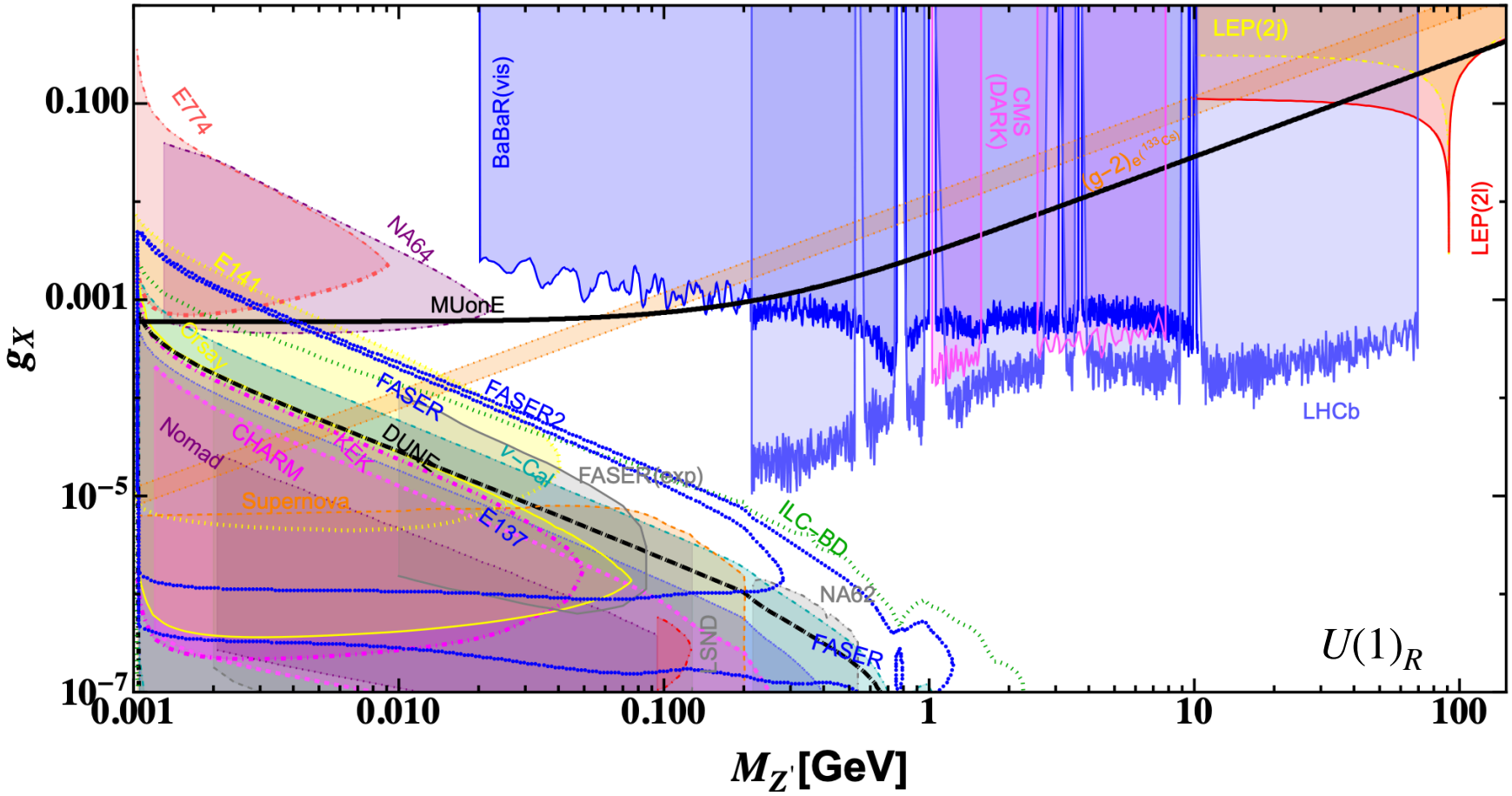
Existing(shaded) and propspective bounds

$e\mu$ scattering : MUonE, e^-e^+scatterimng : LEP, $e-\nu$scattering : DUNE, JSNS2

$\nu-$N scattering : FASERν, SND@LHC $e^{\pm}$ BD : ILC(BD), p^+BD : FASER(2), DUNE

Drark photon search : LHCb, CMS($Z' \to \mu^+\mu^-$), BaBar($Z' \to$ leptons, light mesons)

$x_H = -2,\ x_\Phi = 1$: No interaction between left handed fermion doublets and Z'

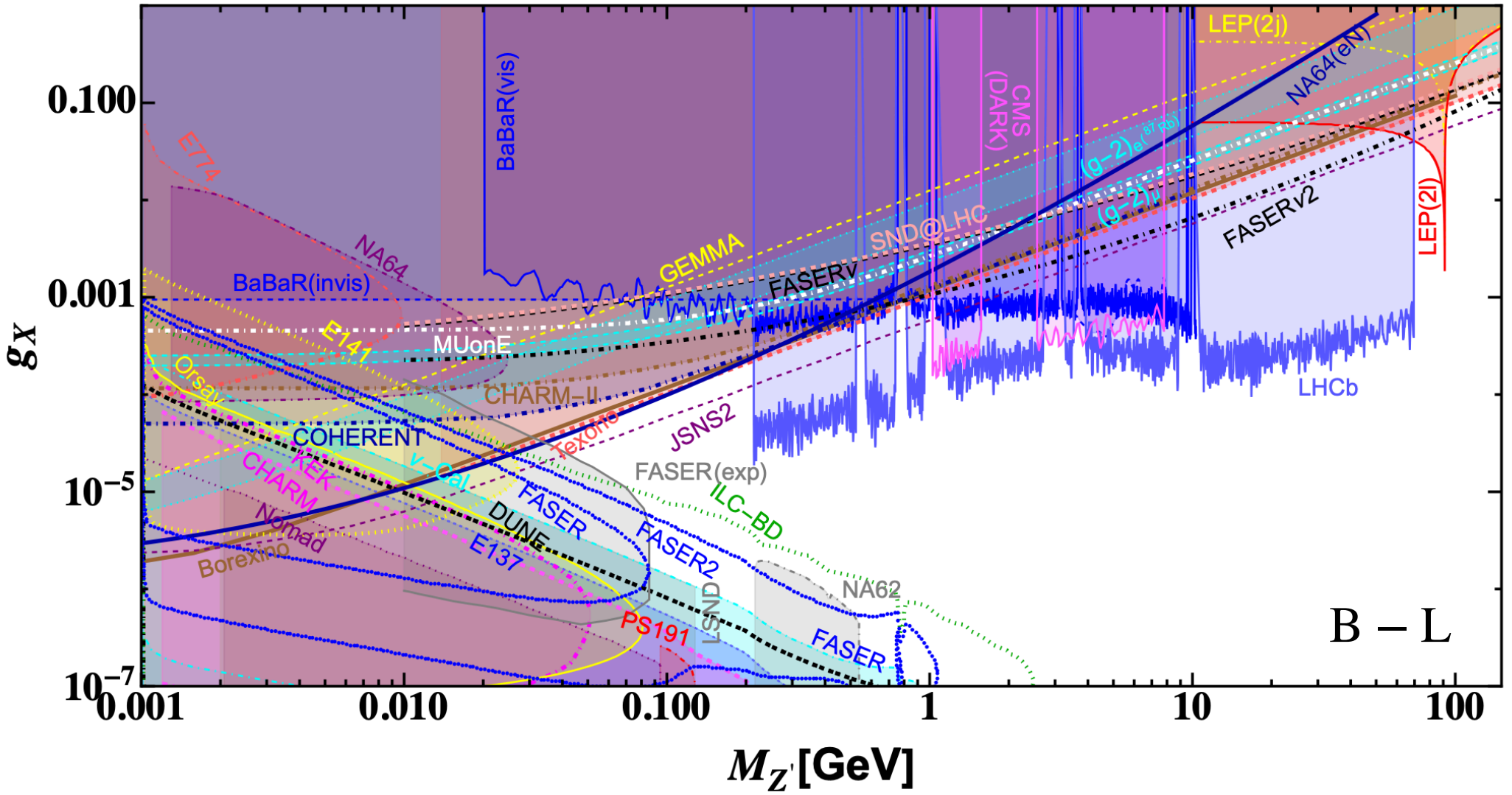


Complete BD analyses : 2206.12676

Scattering experiments : 2307.09737

$\nu-$DM scattering : 2308.14483

$x_H = 0,\ x_\Phi = 1$: left and right handed fermions interact with Z'



$\nu-$ scattering provides strong bounds up to $g_X \leq \mathcal{O}(10^{-4})$ for $M_{Z'} \leq 60$ GeV

Scalar interactions with Z′ and RHNs

$$\mathscr{L}^{\text{Yukawa}} \supset \; - Y_\nu^{\alpha\beta}\overline{\ell_L^\alpha} H N_R^\beta - \frac{1}{2} Y_N^\alpha \Phi \overline{(N_R^\alpha)^c} N_R^\alpha + \text{h.c.}$$

In this theory : $M_{Z'} = 2 g_X v_\Phi \quad M_N = \dfrac{Y_N v_\Phi}{\sqrt{2}}$

RHNs couple directly with Z' and Φ

$M_N < M_{Z'/\phi}/2$: RHN can be produced in pair from Z' and ϕ in low and high energy experiments

RHNs mix with light neutrinos through the seesaw mechanism

RHNs interact with $W^\pm$, Z and h though mixing vertices are mixing suppressed

SM Higgs doublet (H) and $U(1)_X$ scalar mix with eachother : $V \supset \quad \lambda'(H^\dagger H)(\Phi^\dagger \Phi)$

through the scaler mixing SM Higgs can provide a signature of RHN pair if $M_N < 62.5$ GeV

vertex will be proportional to $\sin\theta$ (scalar mixing) $\quad H \supset \dfrac{v + h_1}{\sqrt{2}}, \quad \Phi \supset \dfrac{v_\Phi + \phi_1}{\sqrt{2}}$

If $x_H \neq 0$, SM Higgs couples with Z' originated from $\mathscr{L}_{\text{kin}} \supset (\mathscr{D}_\mu h)^\dagger (\mathscr{D}^\mu h)$

Φ interacts with Z' through $\mathscr{L}_{\text{kin}} \supset (\mathscr{D}_\mu \phi)^\dagger (\mathscr{D}^\mu \phi)$

We consider 4μ final state to compare $h \to Z'Z'$ process followed by $Z' \to 4\mu$ at the LHC

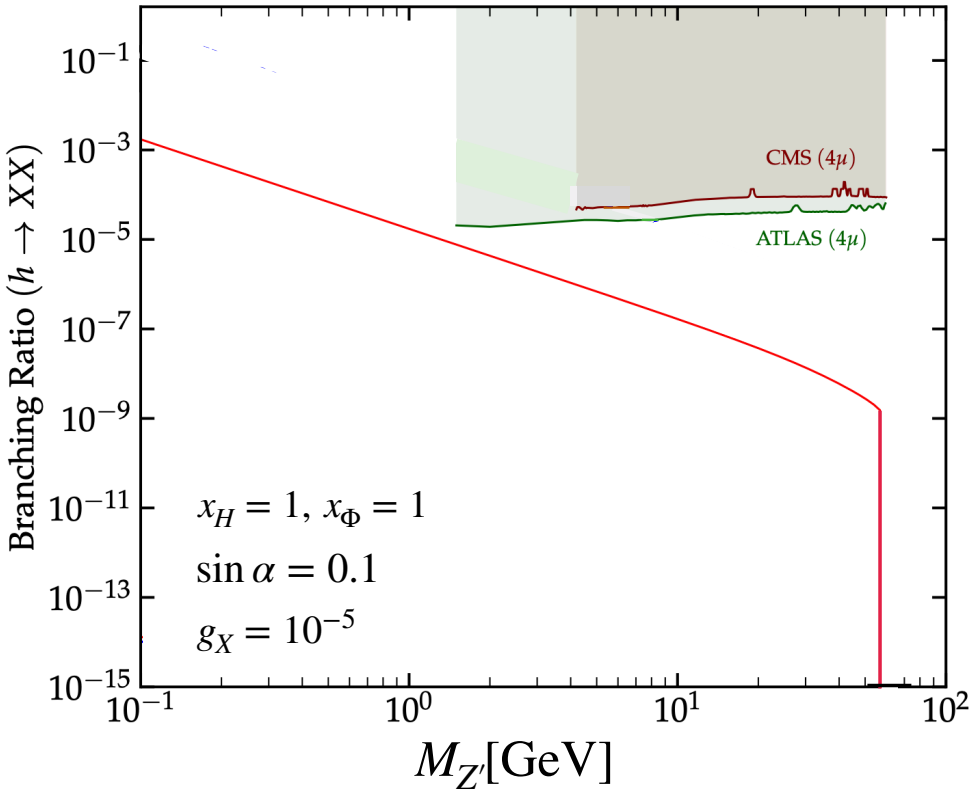
$\Gamma(h \to Z'Z') \sim \frac{m_h^3 s_\alpha^2}{32\pi v_\Phi^2}$, $\mathrm{BR}(h \to ZZ') < 10^{-9}$ suppressed by g_X^2 $\mathrm{BR}(h \to Z'\gamma)$: suppressed by g_X^2 and loop factor

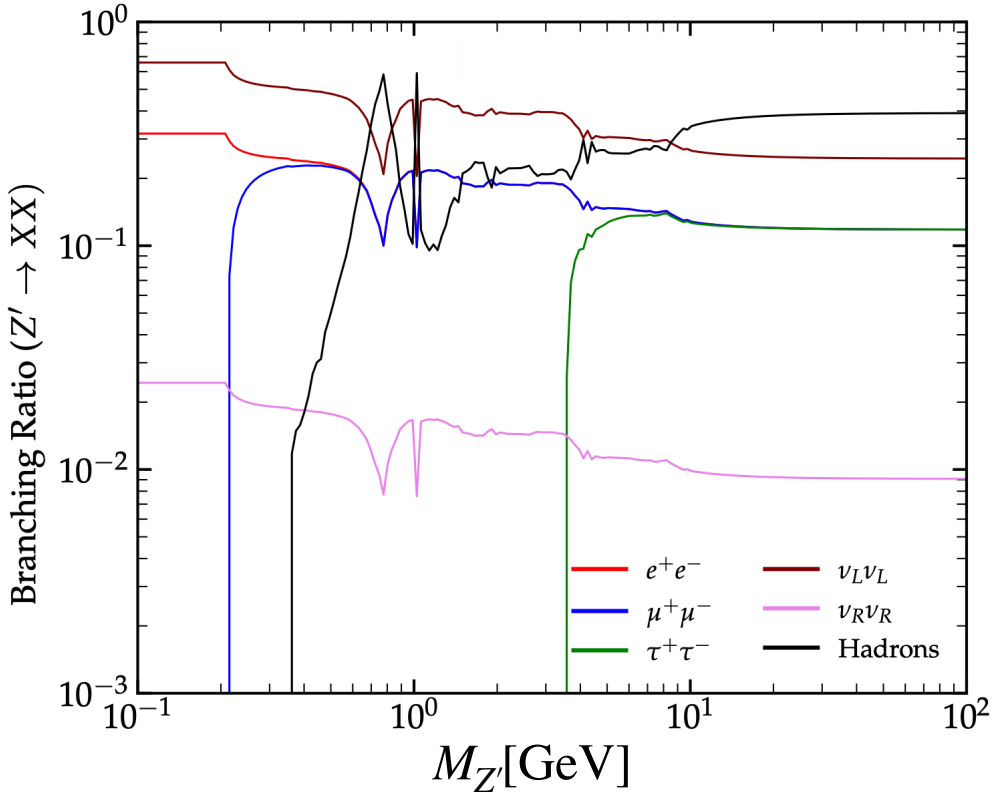
$(m_\phi \gg m_h)$

$\sigma_{4\mu} = \sigma_h^{\mathrm{SM}} \times \cos^2\alpha \times \mathrm{BR}(h \to Z'Z') \times \mathrm{BR}(Z' \to \mu\mu)^2$ 2402.00392

$\sigma^{\mathrm{SM}} \simeq 55.73$ pb at 13 TeV 2004.03447

$\sin\alpha = 0.1$ 2202.01443

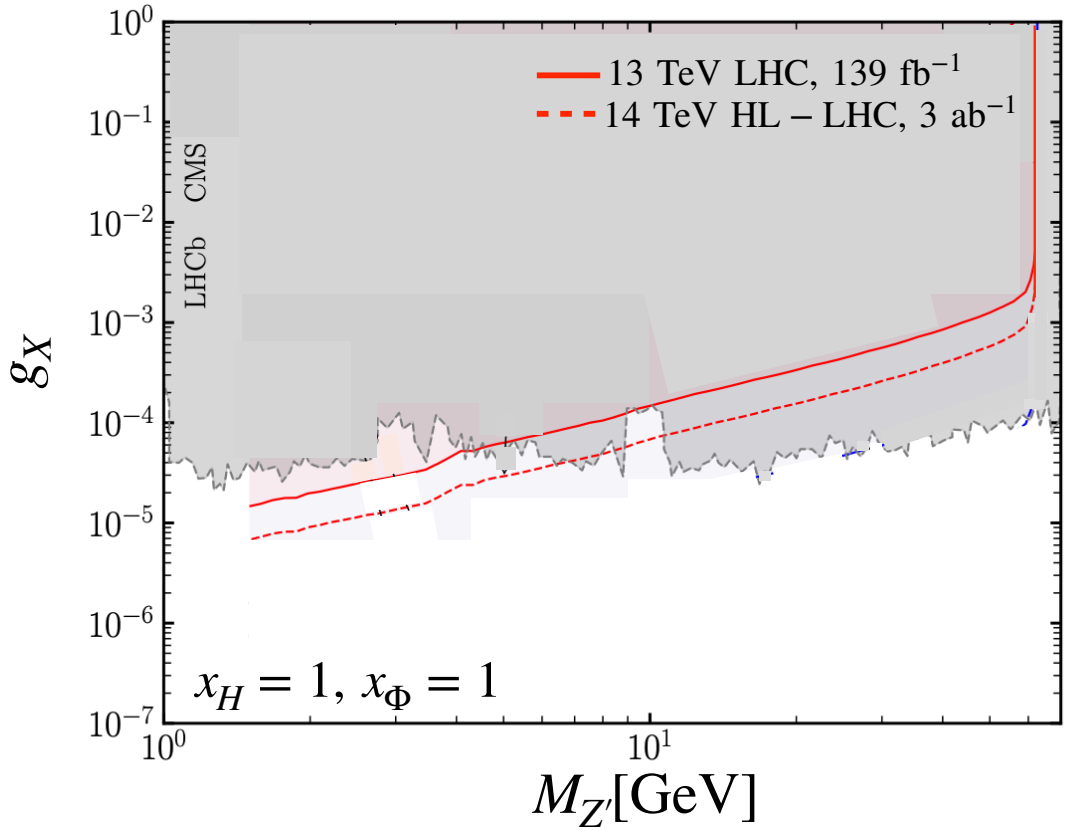




$\sigma_{4\mu}^{\mathrm{ATLAS,CMS}} = 0.05$ fb, 0.03 fb 2110.13673 (ATLAS), 2111.01299 (CMS)

$\sigma_{4\mu}^{\mathrm{HL-LHC}} = \sigma_{4\mu}^{\mathrm{Run-II}} \sqrt{139/3000}$

Limits on $g_X - M_{Z'}$ from 4μ final state



Wraping up . . .

We wanted to probe Z' interactions from a scenario which can study different BSM aspects involving neutrino, electron, nucleons and Higgs . We find that $M_{Z'} \leq 0.1$ GeV istighly constrained by beam dump expriments and $M_{Z'} \geq 0.1$ GeV is constrained by scattering experiments . Future beam dump experiments could provide stronger constraints .

We have a simple approach to study a scenario that explains neutrino mass generation mechanism
For heavy neutrino searches in this sceanrio at high energy collioders
1710.03377, 1906.04132, 1908.09838, 1812.11931, 2202.13358

Heavy neutrino searches in forward physics facility will appear soon
with : Shivasankar K . Arunachalam (grad student @ HU)
Souvik Das (MS project : IISER, Kolkata → grad student @ TEXAS A & M)
Sanjoy Mandal, PD @ KIAS, South Korea