Probing U(1) extended Standard Models at ILC

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Based on collaborations with

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Problems/Mysteries in the Standard Model

- Origin of Neutrino Masses?
- Dark Matter?
- Origin of the Electroweak symmetry breaking?
- Cosmic Inflation before Big Bang?
- Origin of Matter-Antimatter asymmetry in the Universe?
- Strong CP problem
- More

Need to go beyond the SM for solving the problems!

BSM candidate: gauged U(1) extended SMs

Gauge group: $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)$

The most popular scenario: the minimal B-L model

1. B-L (Baryon number minus Lepton number) is unique anomaly free global symmetry in the SM

2. Why not gauging the U(1) B-L?

We may follow the history:

Before the SM
- SU(2) isospin
- U(1) hypercharge
- SU(3)

gauging →

The SM

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Minimal Gauged B-L Extension of the SM

Mohapatra & Marshak; Wetterich; others

The model is based on $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

Particle Contents

		$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
i=1,2,3	q_L^i	$\mathbf{3}$	$\mathbf{2}$	$+1/6$	$+1/3$
	u_R^i	$\mathbf{3}$	$\mathbf{1}$	$+2/3$	$+1/3$
	d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$+1/3$
	ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
New fermions:	N_R^i	$\mathbf{1}$	$\mathbf{1}$	0	-1
	e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
	H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
New scalar:	Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

More general U(1) extended SM

Appelquist, Dobrescu & Hopper, PRD 68 (1998) 035012

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$$

Particle Contents

i=1,2,3

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$	
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$(1/6)x_H$	$+1/3$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$(2/3)x_H$	$+1/3$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$(-1/3)x_H$	$+1/3$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H$	-1
N_R^i	$\mathbf{1}$	$\mathbf{1}$	0		-1
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	$(-1)x_H$	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$(-1/2)x_H$	*0*
Φ	$\mathbf{1}$	$\mathbf{1}$	0		$+2$

- U(1)x charge: $Q_X = Y_f x_H + Q_{B-L}$
- B-L limit: $x_H \to 0$

New Yukawa terms in Lagrangian

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

U(1)x symmetry breaking via $\langle \Phi \rangle = \frac{v_X}{\sqrt{2}}$

➡ U(1)x gauge boson (Z' boson) mass

$$m_{Z'} = 2\, g_X\, v_X$$

Mass scale is controlled by U(1)x Sym. Br. scale

Heavy Majorana neutrino mass

$$M_{N^i} = \frac{Y_N^k}{\sqrt{2}} v_X$$

U(1)x sym breaking also generates RHN mass

➡ Seesaw mechanism after EW sym. breaking

U(1) Higgs sector could be the origin of EWSB

U(1) Higgs model and Coleman-Weinberg mechanism

Toy model:

Field	Symbol	U(1)
Higgs Scalar	Φ	$+2$
Weyl Fermion	Ψ	-1

* General picture. This can be a part of the B-L model

We impose Classical Conformal symmetry

$$V_{tree} = \lambda_\Phi (\Phi^\dagger \Phi)^2$$

* defining this theory as ``Massless Theory"

Yukawa coupling is allowed:

$$\mathscr{L}_Y = Y \Phi \Psi \Psi + \mathrm{h.c.}$$

Coleman-Weinberg mechanism

Coleman & Weinberg, PRD 7 (1973) 1888

$$V_{CW} = V_{tree} + V_{1-loop}$$

$$= \frac{\lambda_\Phi}{4}\phi^4 + \frac{\beta_\Phi}{8}\phi^4\left(\ln\left[\frac{\phi^2}{v_\phi^2}\right] - \frac{25}{6}\right),$$

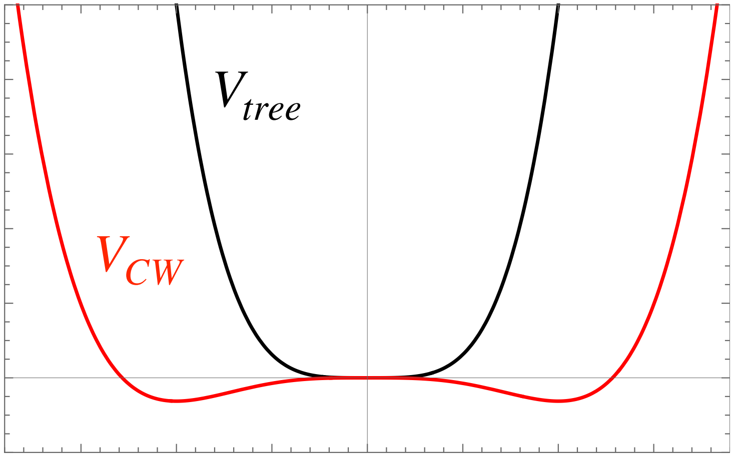
where $\Phi = \frac{1}{\sqrt{2}}(\phi + i\chi)$, $\beta_\Phi = \frac{1}{16\pi^2}\left(96g^4 - Y^4\right)$

- Radiative U(1) symmetry breaking at $\phi = v_\phi$
- Parameter relations: $\lambda_\Phi = \frac{11}{6}\beta_\Phi$

$$m_\phi^2 = \lambda_\Phi v_\phi^2$$

Interesting properties:

- ➢ Origin of gauge symmetry breaking?
  quantum corrections (QM system knows where to be)



- ➢ Predictability

  Relation between Higgs mass and U(1) gauge boson mass

- ➢ Yukawa coupling must be sub-dominant,

$$\beta_\Phi = \frac{1}{16\pi^2}\left(96g^4 - Y^4\right) > 0,$$

otherwise unstable vacuum

Application to the Standard Model

Induced EW symmetry breaking

Iso, NO & Orikasa,
PLB 676 (2009) 81;
PRD 80 (2009)11007

Classically conformal U(1) extended SM

$$V = \lambda_h \left(H^\dagger H\right)^2 - \lambda_{mix} \left(H^\dagger H\right) \left(\Phi^\dagger \Phi\right) + V_{CW}(\Phi^\dagger \Phi)$$

Negative Higgs mass squared is induced by Phi VEV!

$$m_H^2 = -\lambda_{mix} | \langle \Phi \rangle |^2$$

The origin of EWSB is the radiative U(1) symmetry breaking!

Probing U(1) extended Standard Models at ILC

Properties & Phenomenology of U(1) extended SMs

New Particles:

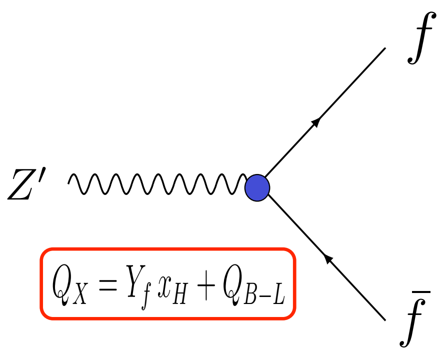
- Z' boson
- Heavy Majorana neutrinos for the seesaw mechanism
- SM-singlet U(1) Higgs

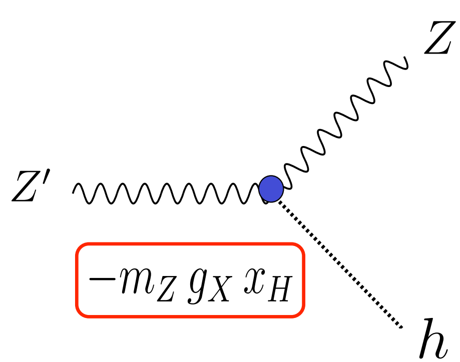
Phenomenology:

- Z' boson production & decay
- Z' boson mediated processes
- Heavy neutrino production
- U(1) Higgs boson phone

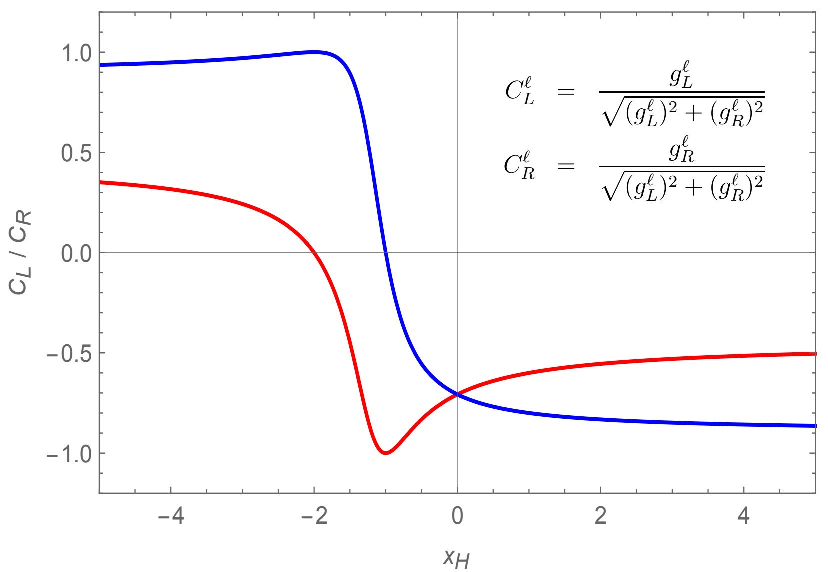
I. Phenomenology involving Z' boson

U(1)x Z' boson

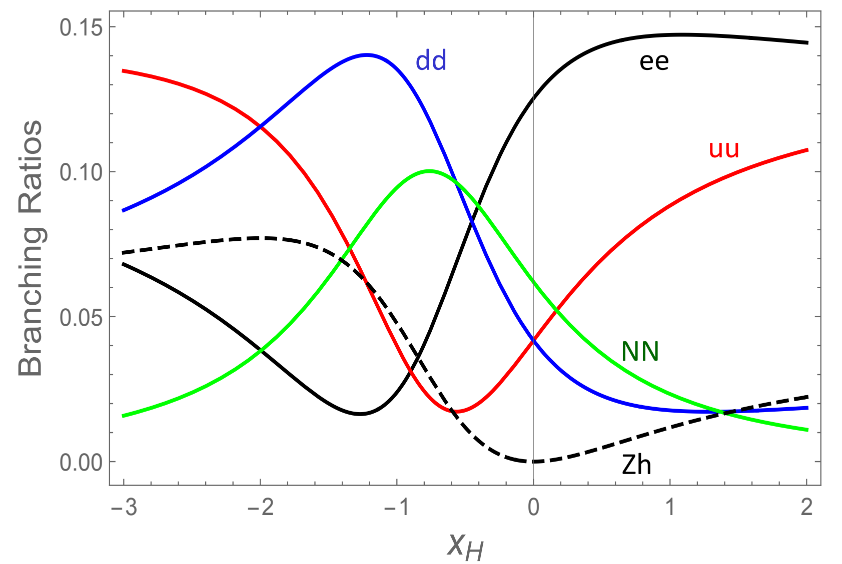




L/R coupling

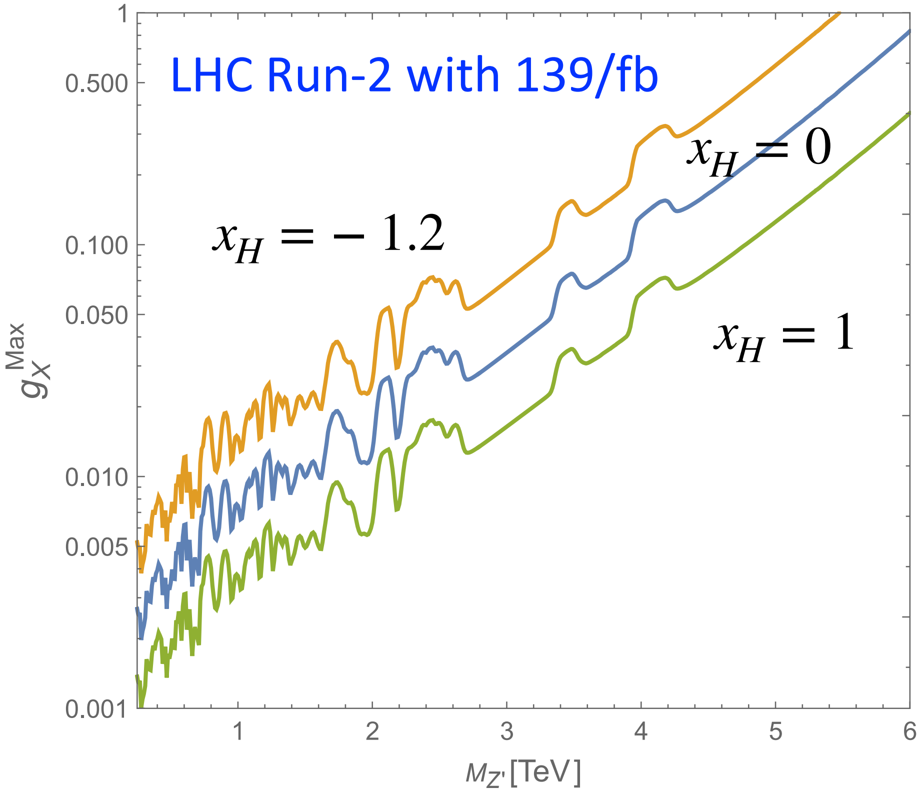


Branching raitos



For ILC studies, we need to consider the current LHC constraints whenever Z' couples to u & d quarks

Das, Bhupal & NO, PLB 799 (2019) 135052



Very severe constraints from the resonance search at LHC Run-2

$$pp \to Z' \to e^+e^-/\mu^+\mu^-$$

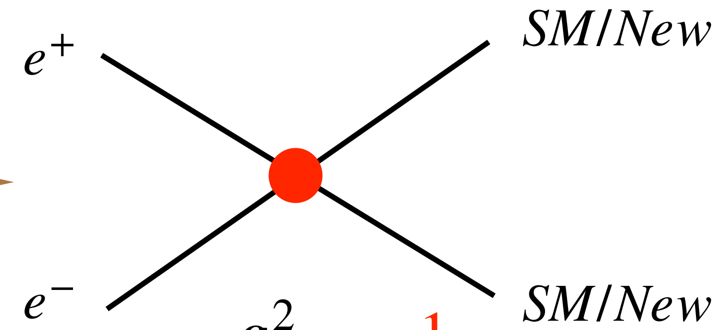
Interpretation to the upper bound on the U(1) gauge coupling as a function of Mz'

ILC energy is expected to be

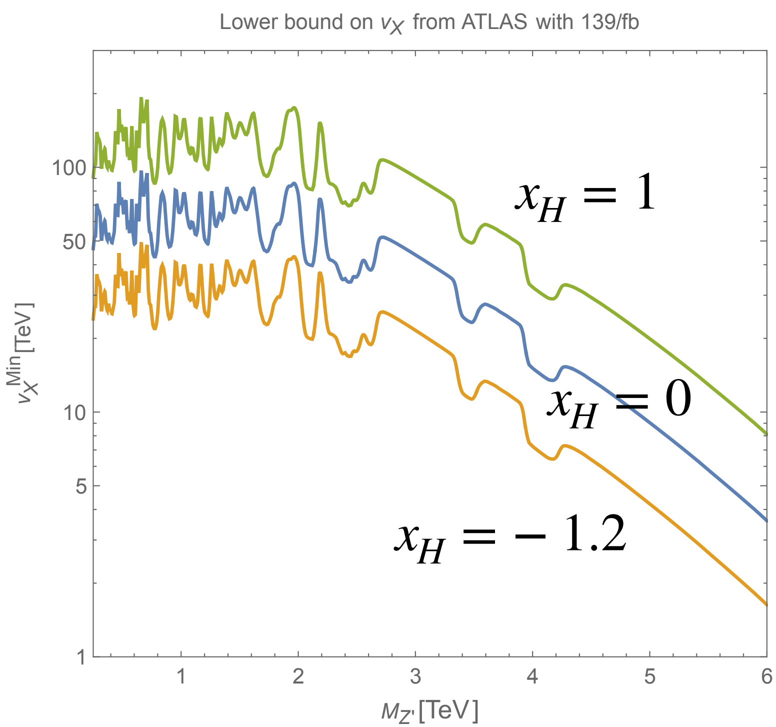
$$\sqrt{S_{\rm ILC}} \ll M_{Z'}$$

ILC studies for the processes involving Z' boson

Z' boson mediated processes with $\sqrt{S_{\rm ILC}} \ll M_{Z'}$



$$\propto 4\frac{g_X^2}{M_{Z'}^2} = \frac{1}{v_X^2}$$

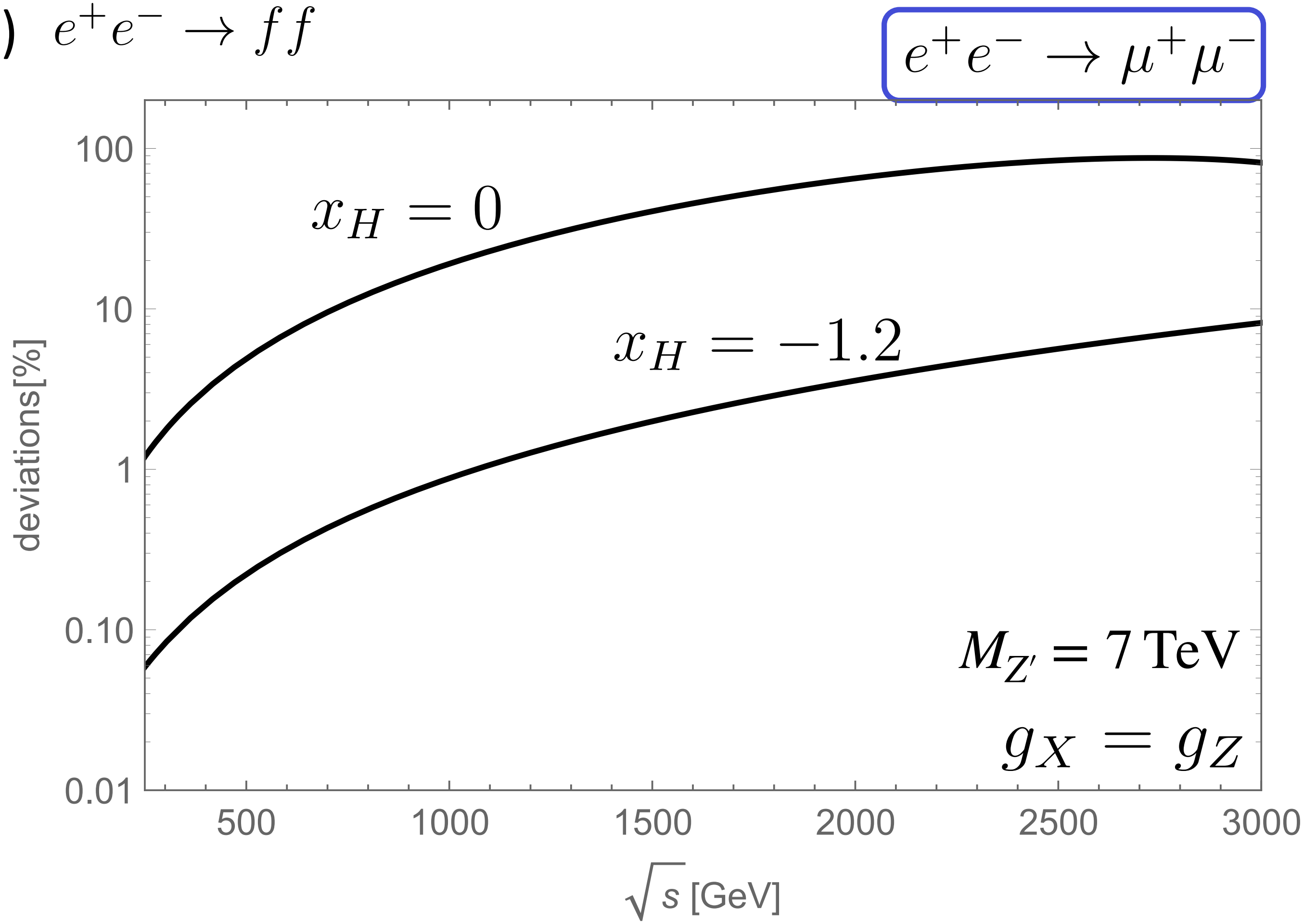


$$M_{Z'} \gtrsim 6\,{\rm TeV} \rightarrow v_X^{\rm Min} \lesssim \mathcal{O}(1\,{\rm TeV})$$

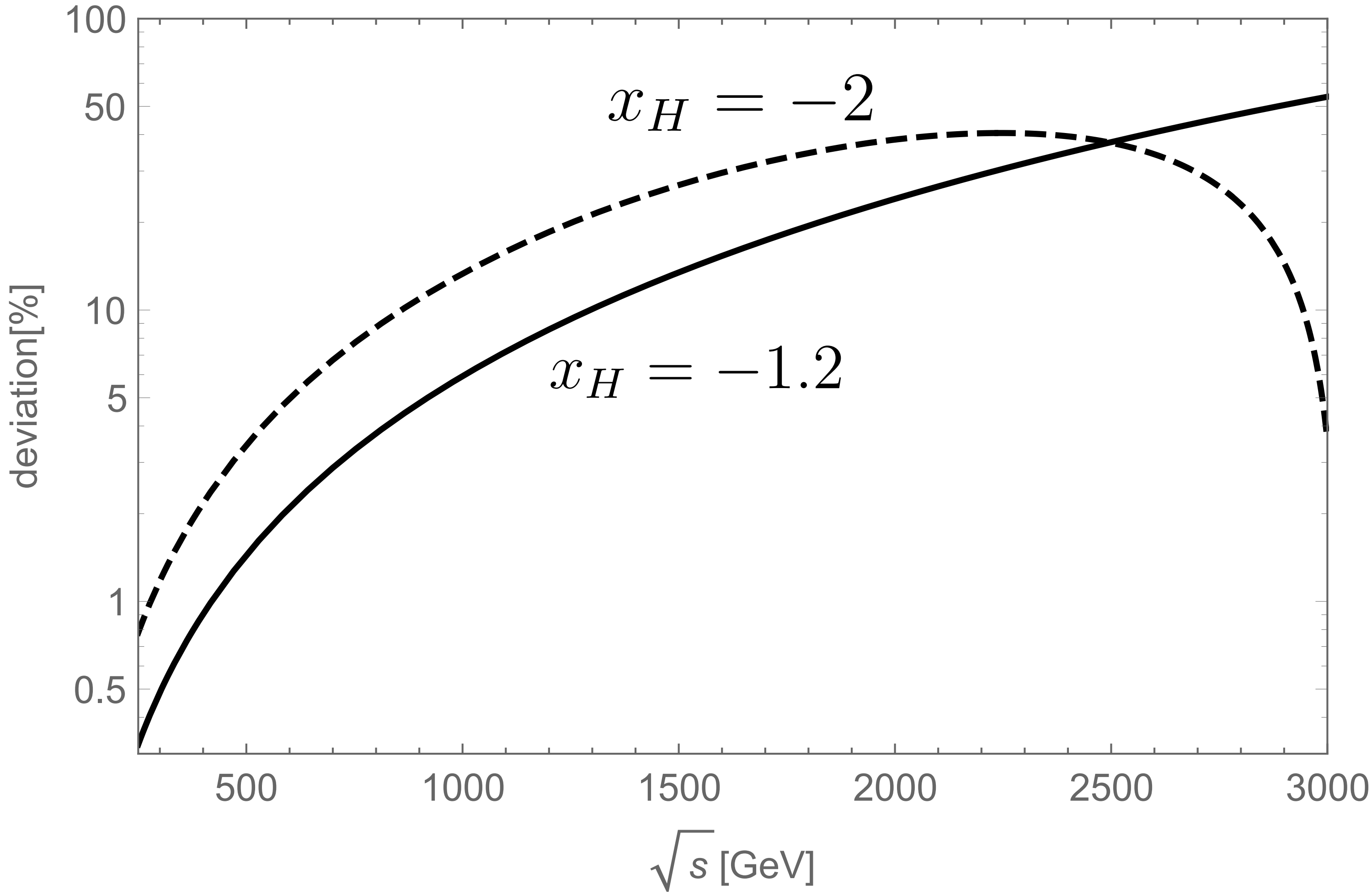
The ILC is more powerful for heavier Z' boson!

Sample ILC studies

(1) $e^+e^- \to f\bar{f}$

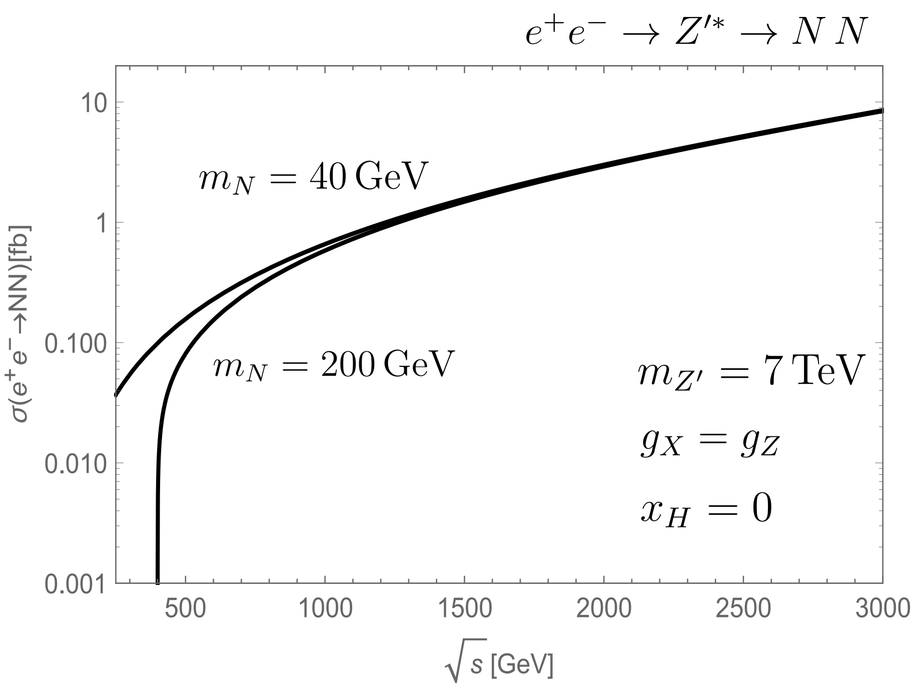


(2) $e^+e^- \to Z\,h$



* For detailed analysis, see Das &NO, arXiv: 2008.04023

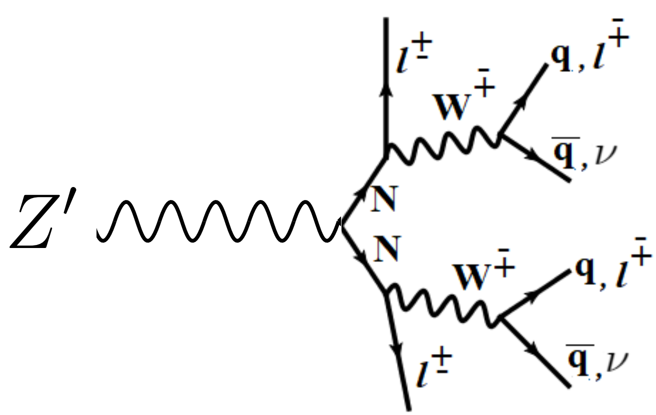
(3) Heavy Majorana neutrino pair production at ILC



Das, NO, Okada & Raut
PLB 797 (2019) 134849

The production cross section can be sizable, while satisfying the LHC constrains

The ILC can be HMN factory!



Same-sign dilepton final states as ``Smoking-gun” signature of Majorana nature

HMN can be long-lived

ILC to explore the Seesaw Mechanism

II. Exploring EWSB origin at ILC

Conventional:

$$V = \frac{\lambda_h}{4}(h^2 - v_h^2)^2 + \frac{\lambda_\phi}{4}(\phi^2 - v_\phi^2)^2 - \frac{\lambda_{mix}}{4}(h^2 - v_h^2)(\phi^2 - v_\phi^2)$$

EW symmetry is broken w/o λ_{mix}

CW system:

$$V = \frac{\lambda_h}{4}h^4 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\beta_\phi}{8}\phi^4\left(\ln\left[\frac{\phi^2}{v_\phi^2}\right] - \frac{25}{6}\right) - \frac{\lambda_{mix}h^2\phi^2}{4}$$

The radiative U(1) symmetry breaking and $\lambda_{mix} > 0$ are crucial for the EW symmetry breaking

Potential analysis

Mass matrix: $M_{sq} = \begin{pmatrix} \partial_h^2 V & \partial_h \partial_\phi V \\ \partial_\phi \partial_h V & \partial_\phi^2 V \end{pmatrix}\Bigg|_{h=v_h,\phi=v_\phi} = \begin{pmatrix} m_h^2 & M^2 \\ M^2 & m_\phi^2 \end{pmatrix}$

Mass eigenstates: $\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$

Express the potential in terms of mass eigenstates

We set $\theta \ll 1$, which means $h_1 \simeq h$, $h_2 \simeq \phi$

$$m_{h_1} = 125\,\mathrm{GeV}$$
$$m_{h_2} < \frac{m_{h_1}}{2}$$

SM-like Higgs coupling analysis

We have found an interesting difference:

Conventional: $$g_{h_1h_2h_2} \simeq \frac{m_h^2}{v_h}\left(1+2\frac{m_\phi^2}{m_h^2}\right)\theta^2$$

CW system: $$g_{h_1h_2h_2} \simeq -\frac{m_\phi^2}{v_h}\left(1-4\frac{m_\phi^2}{m_h^2}\right)\theta^2$$

For the triple scalar coupling, we naively expect

$$g_{h_1h_2h_2} \sim \lambda_{mix} v_h$$

This is right in the conventional Higgs potential case,

but in the CW system, it is found to be very suppressed!

How to confirm the symmetry breaking structure?

1. Measuring Anomalous SM-like Higgs couplings

Higgs-like particle is NOT 100% the SM Higgs boson

$$\frac{C_{NP}}{C_{SM}} = \cos(\theta) < 1$$

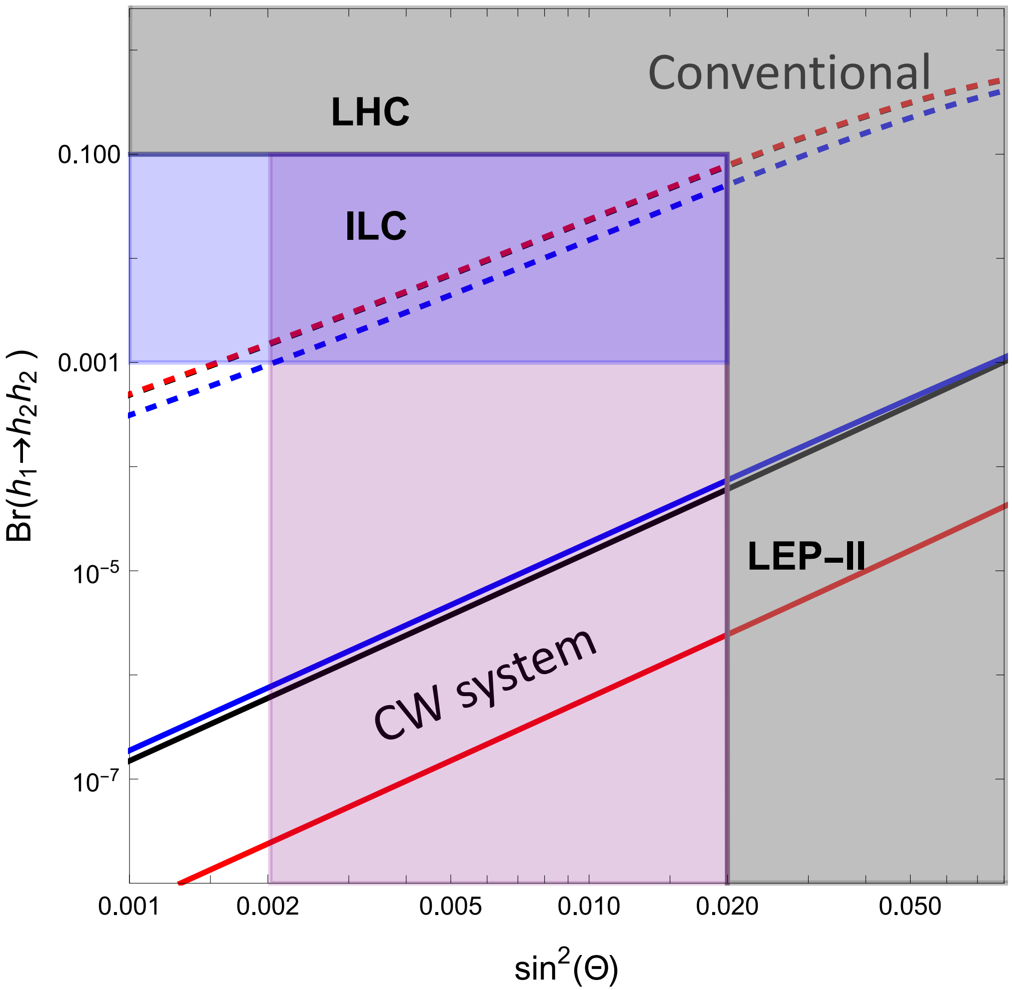
Same for Conventional/CW system

2. Searching for Anomalous Higgs decay: $h_1 \to h_2 h_2$

Conventional	VS.	CW system
$\mathrm{BR}(h_1 \to h_2 h_2)$	$\gg$	$\mathrm{BR}(h_1 \to h_2 h_2)$

How to confirm the symmetry breaking structure?

Baules & NO, in preparation



$M_{h_2} = 10$ (red), 25 (black), and 50 GeV (Blue)

Best case scenario

✓ Anomalous Higgs couplings

✓ Observation of $h_1 \to h_2 h_2$

Yes or No

Summary

- Gauged U(1) extended SMs are interesting BSM candidate.
- Toward probing the U(1) extended SMs, ILC studies (simple theoretical analysis) are presented.
- To show the ILC feasibility, detailed analysis (realistic detector simulations) are necessary.