ILC signatures of the minimal U(1)x extended Standard Model

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Work in progress in collaboration with

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Problems of the Standard Model

Although the Standard Model (SM) is the best theory so far, New Physics beyond SM is strongly suggested by both experimental & theoretical points of view

What is missing?

1. Neutrino masses and flavor mixings
2. Dark matter candidate
3. and more

New Physics must supplement the missing pieces

A simple gauge extension of the SM for neutrino masses

Minimal gauged B-L extension of the Standard Model

- B-L is the unique anomaly free global symmetry in the SM
- Gauging the global B-L symmetry may be natural
- Anomaly free requirement → 3 right-handed neutrinos
- Seesaw mechanism is automatically implemented

In terms of high energy collider physics,
we focus on the gauged U(1) extended model @ TeV

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

i=1,2,3

		$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
	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

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

Particle Contents

i=1,2,3

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

Model properties & Phenomenology

New particles: Z' boson
Heavy Majorana neutrinos
U(1)x Higgs boson

Phenomenology

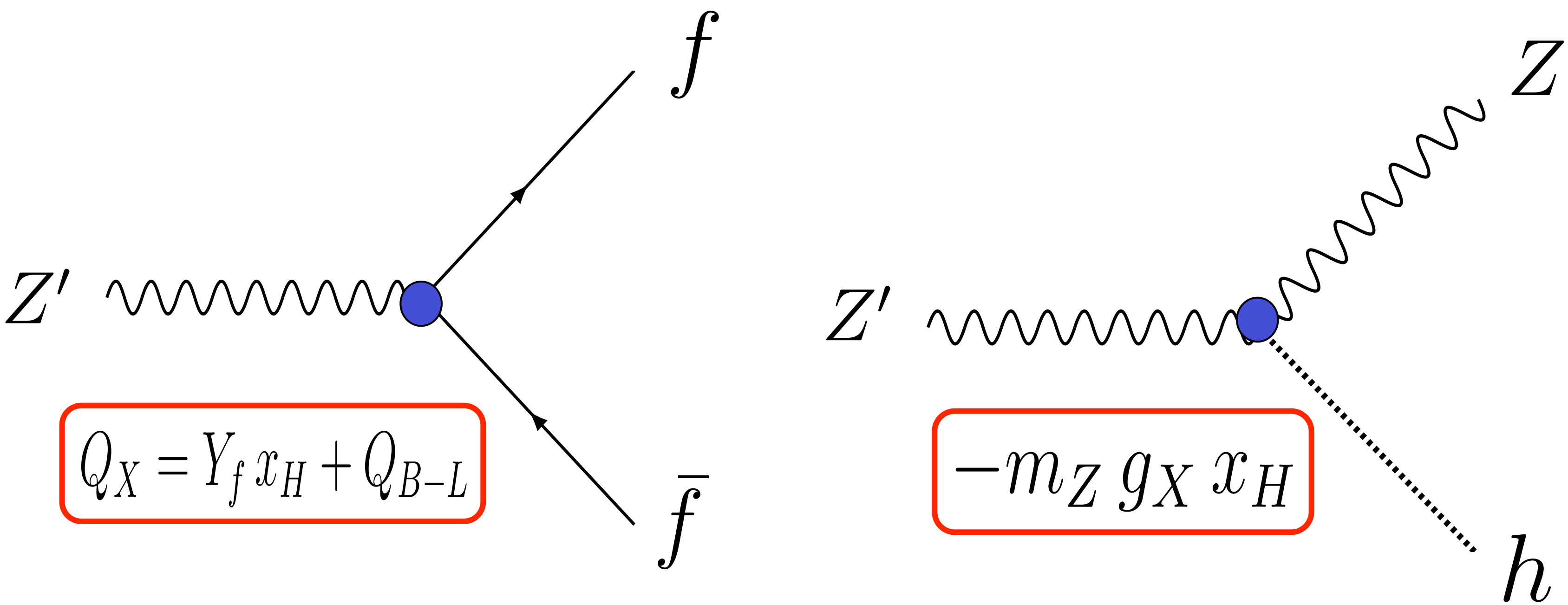
- Z' boson production & decay
- Z' boson mediated processes
- Heavy neutrino production
- U(1)x Higgs boson phenomenology
- more

Since U(1)x Higgs boson phenomenology is included in SM singlet Higgs phenomenology, we focus on Z' boson & heavy neutrino phenomenology.

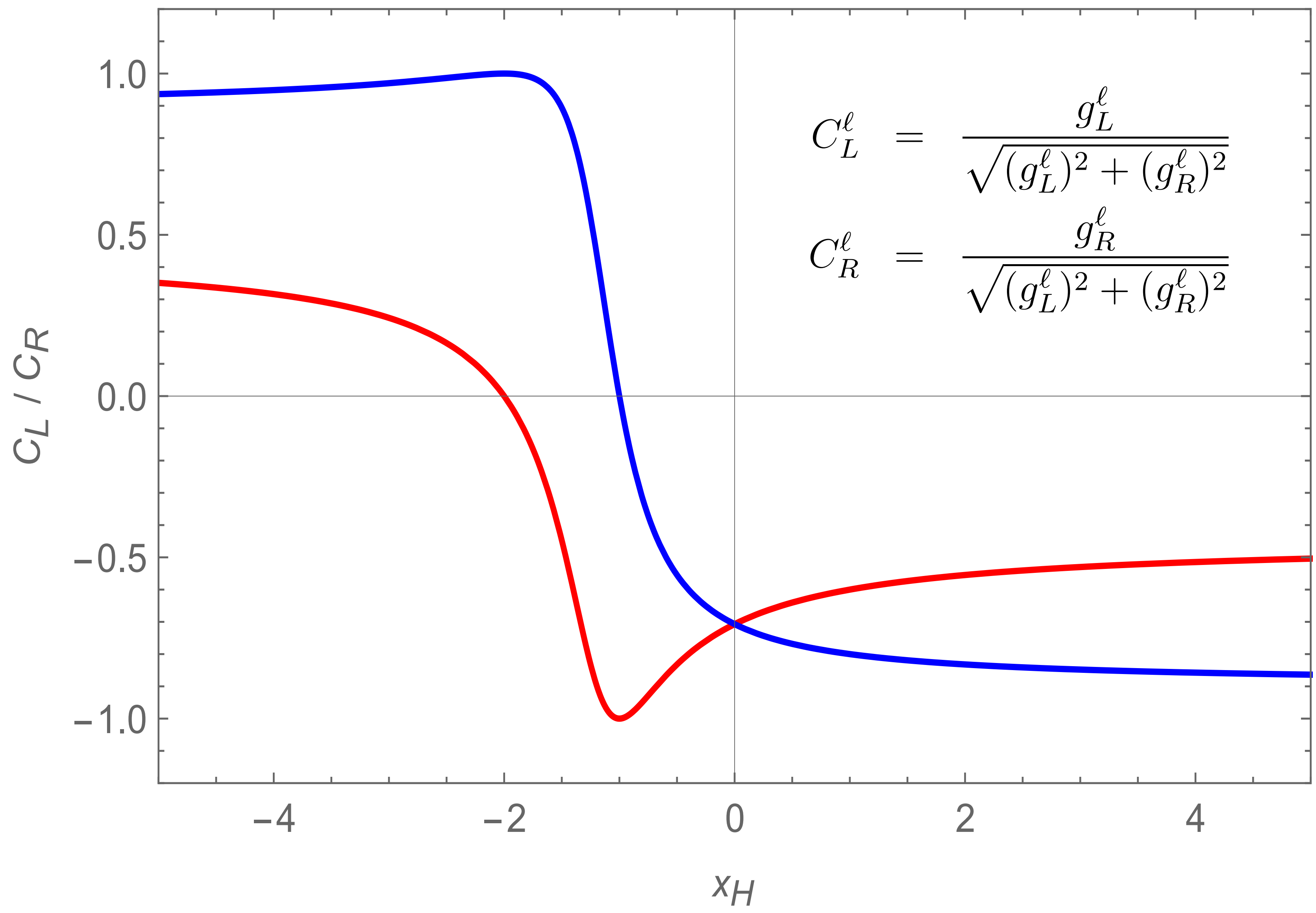
Z’ boson phenomenology

Properties: electrically neutral heavy vector boson

Couplings with SM particles

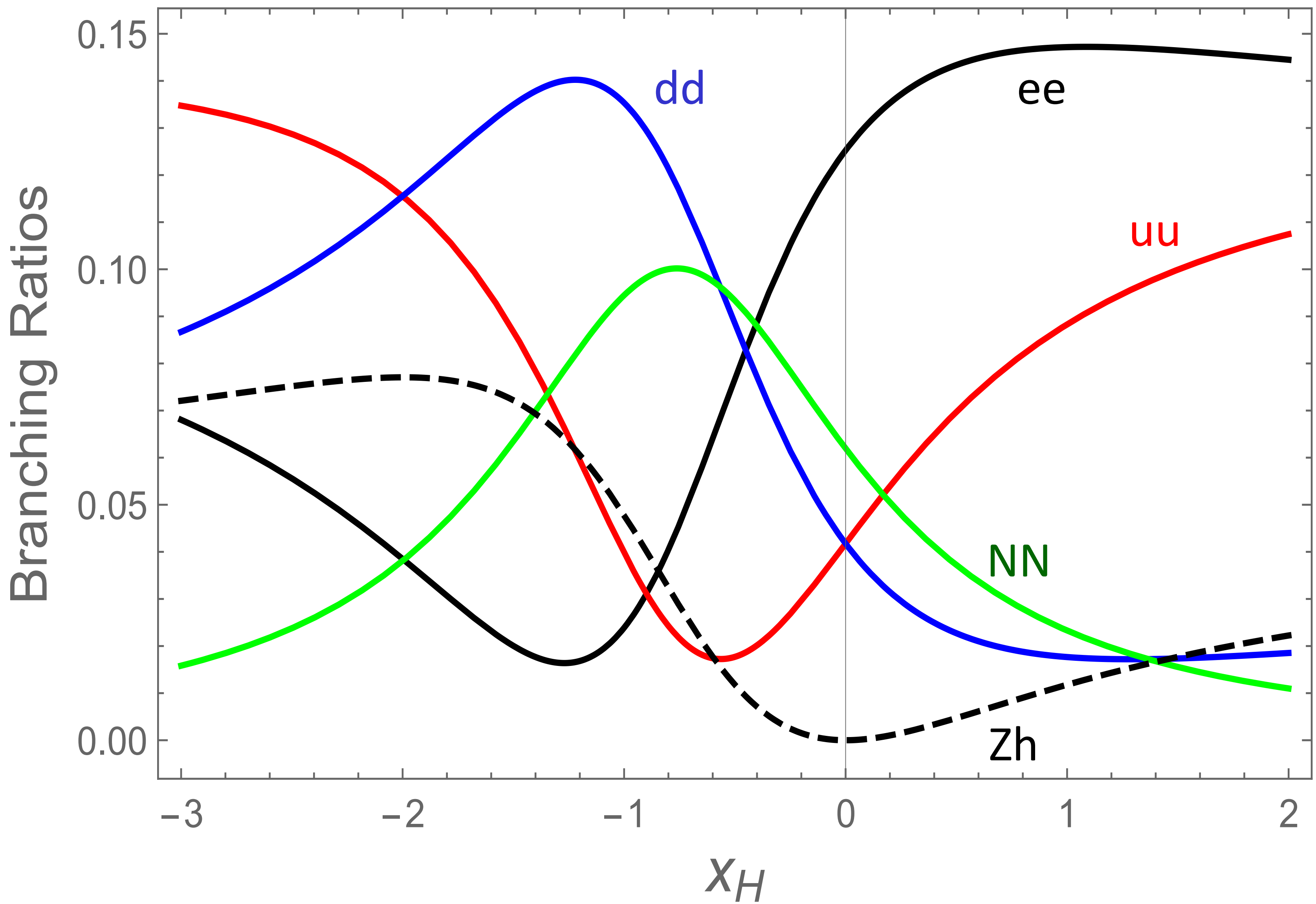


Left/right-handed lepton couplings



Z’ boson branching ratios

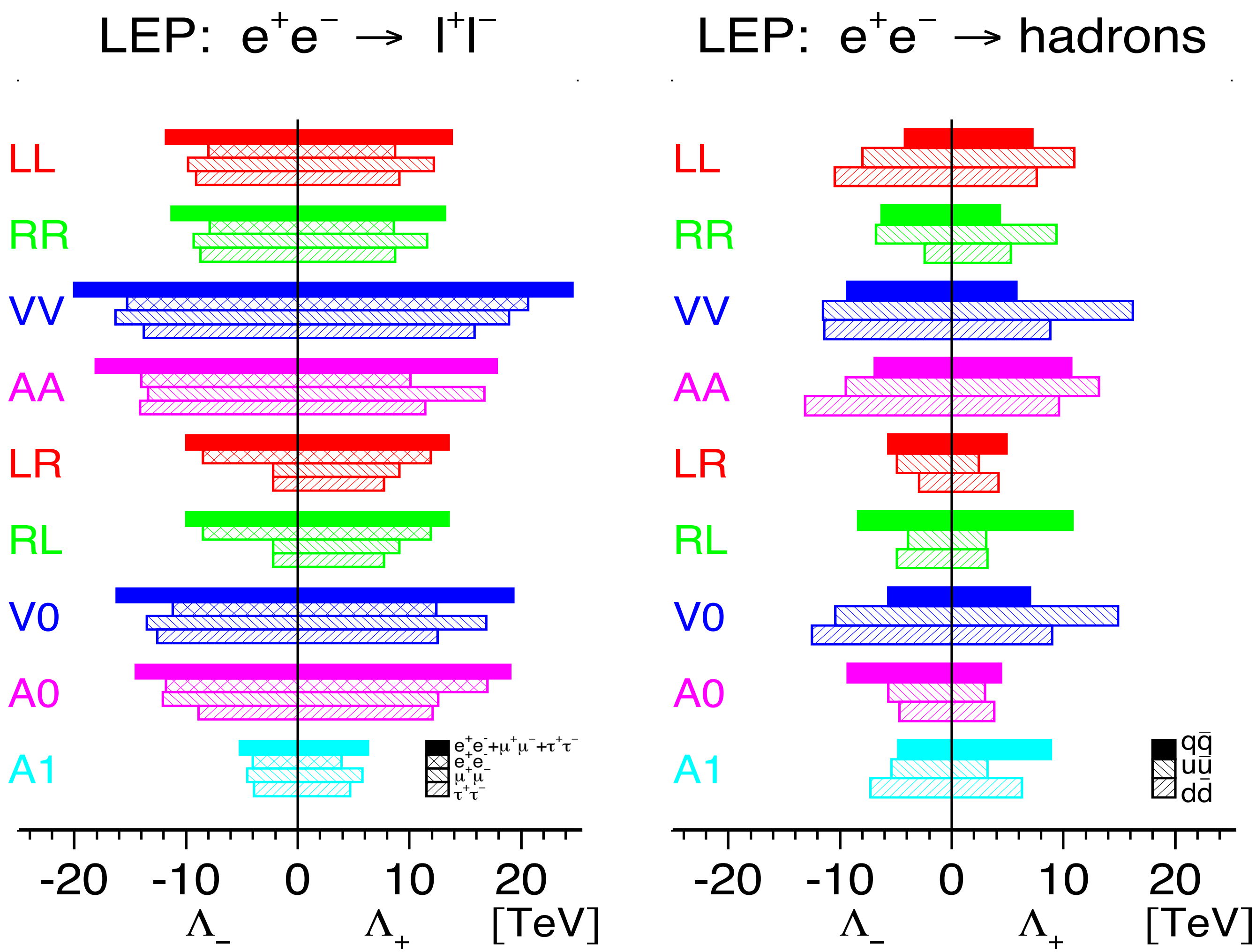
$m_{Z'} \gg m_f, m_h$



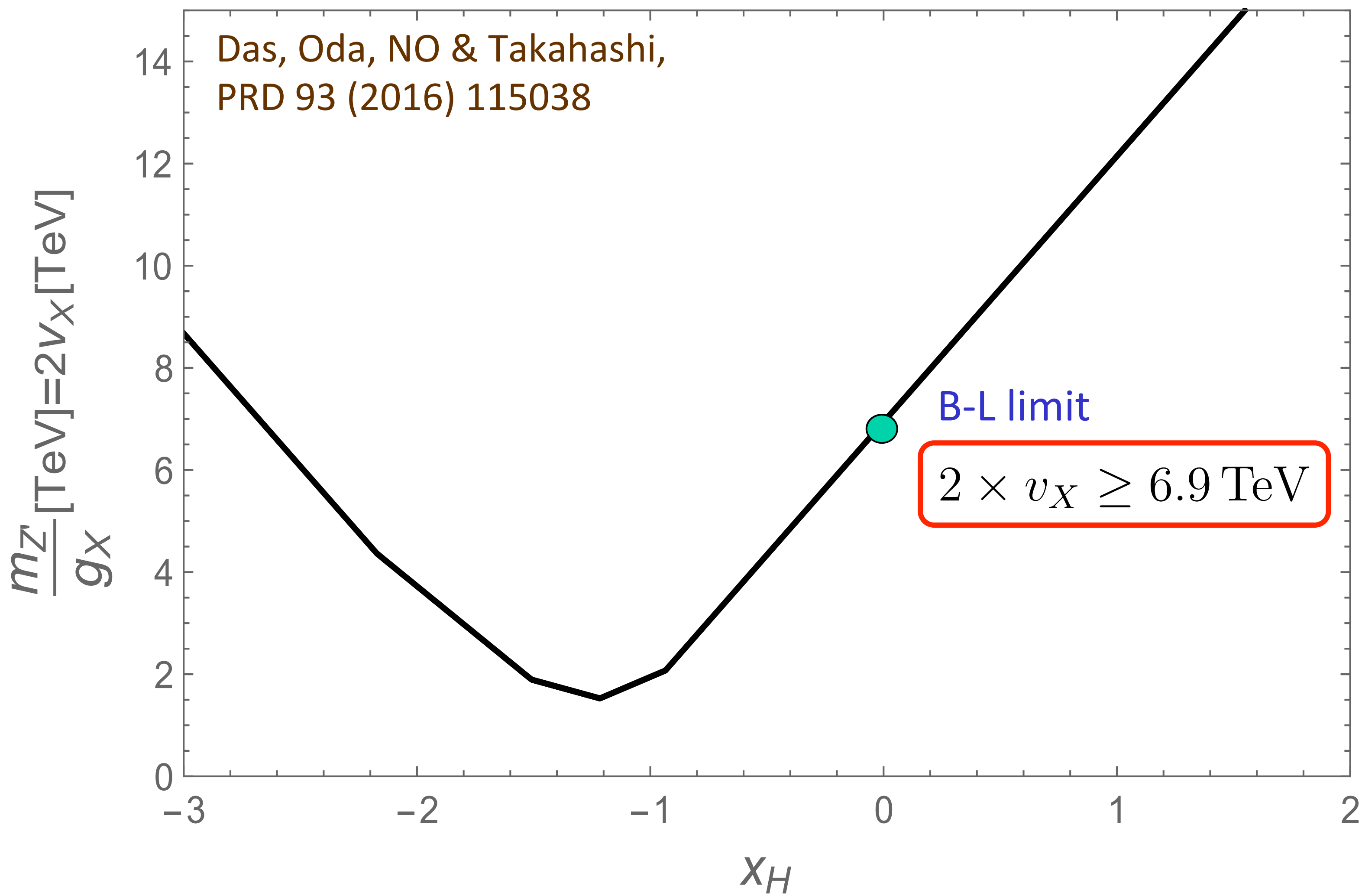
Current Status I: LEP constraints

The LEP Electroweak Working Group, arXiv: 1302.3415

Constraints on 4-Fermi operators

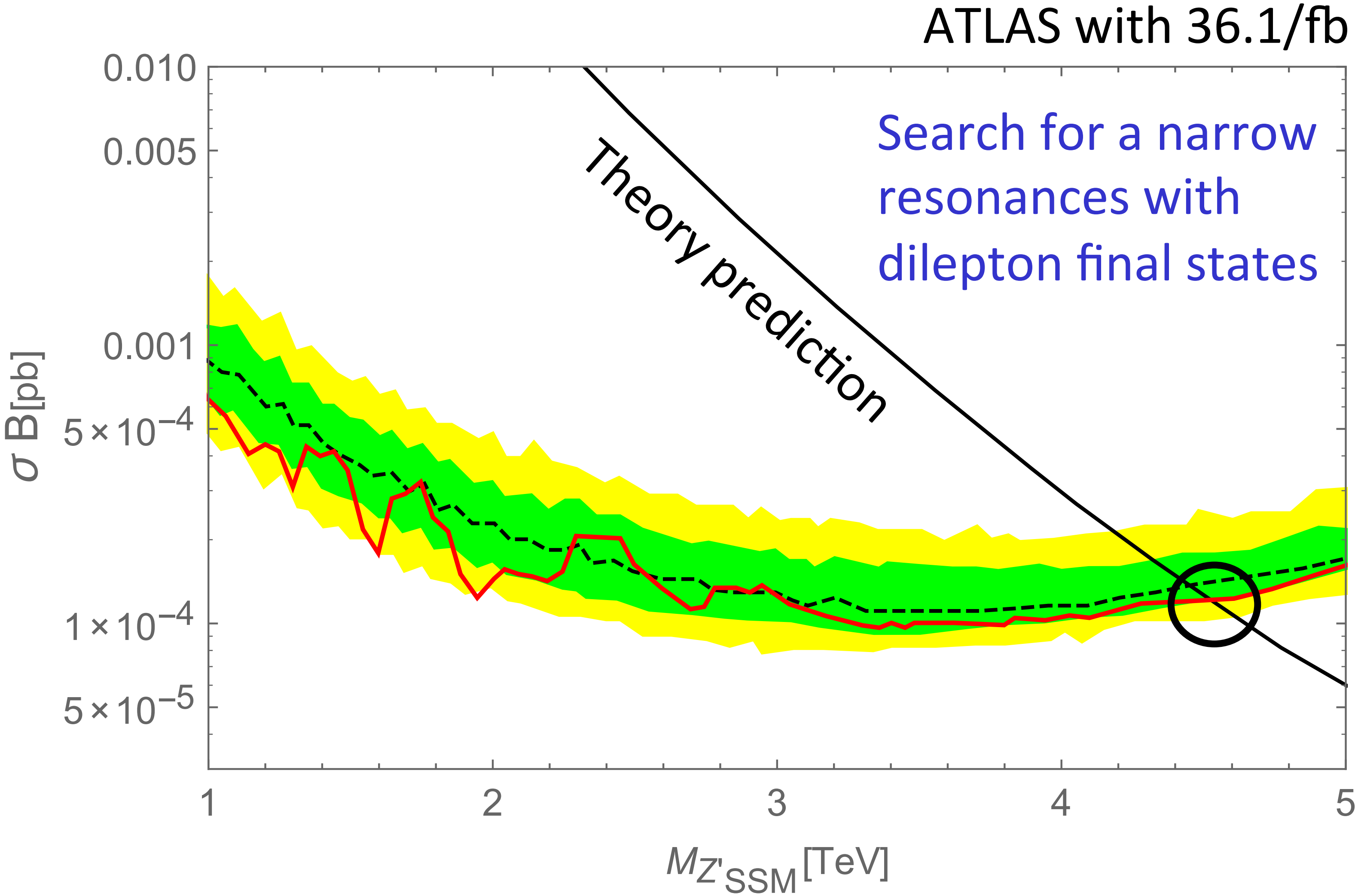


Interpretation of the LEP constraints into U(1)x Z' boson



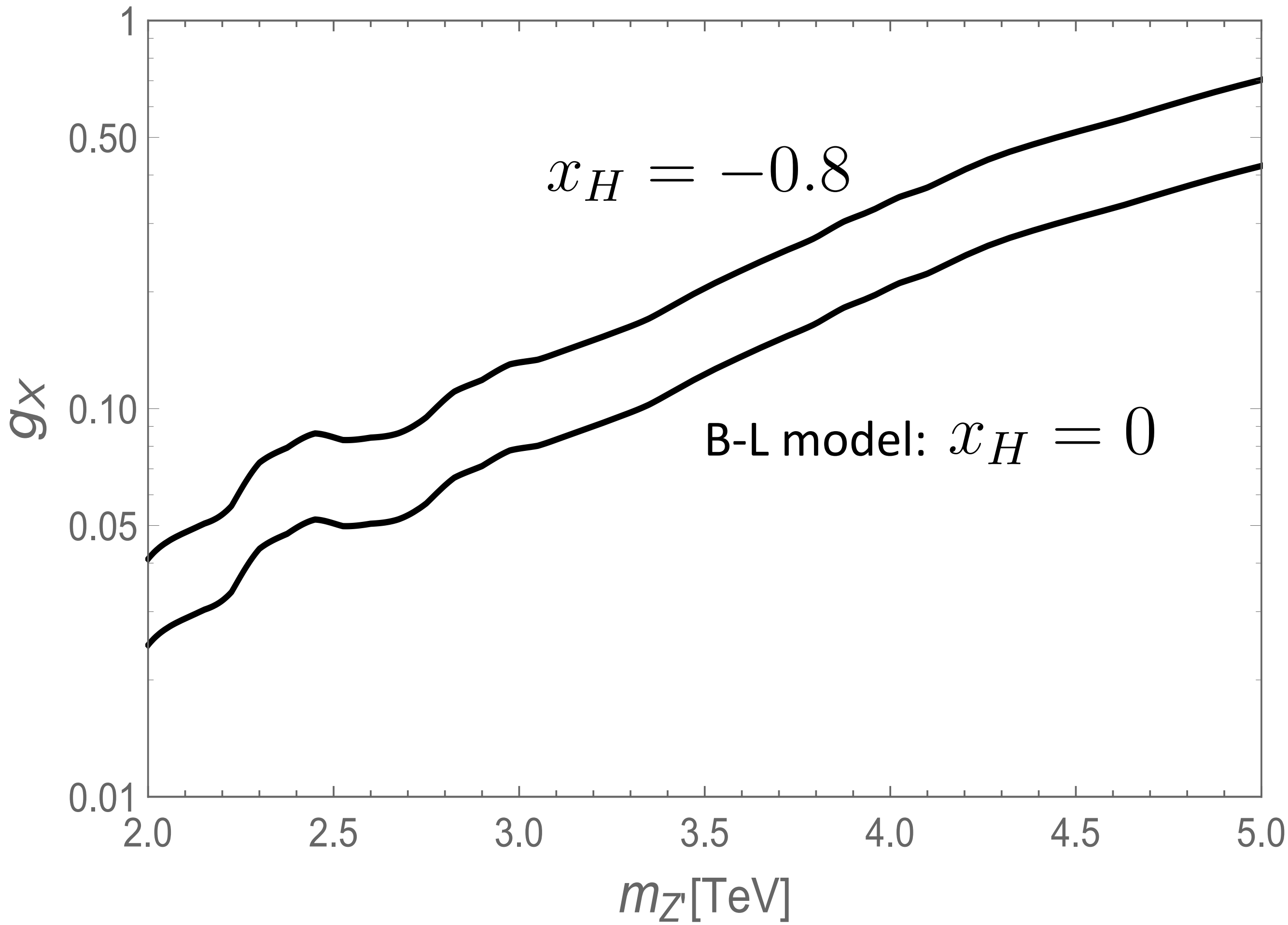
U(1)x symmetry breaking VEV can be as low as 1 TeV

Current Status II: LHC constraints



LHC constraints are already very severe (for sequential Z' boson)

Interpretation of the ATLAS 2017 constraints into U(1)x Z' boson



NO, S.Okada & D. Raut, PLB 780 (2018) 422

Current LHC constraints on U(1)x Z' boson are even stronger than sequential Z' boson

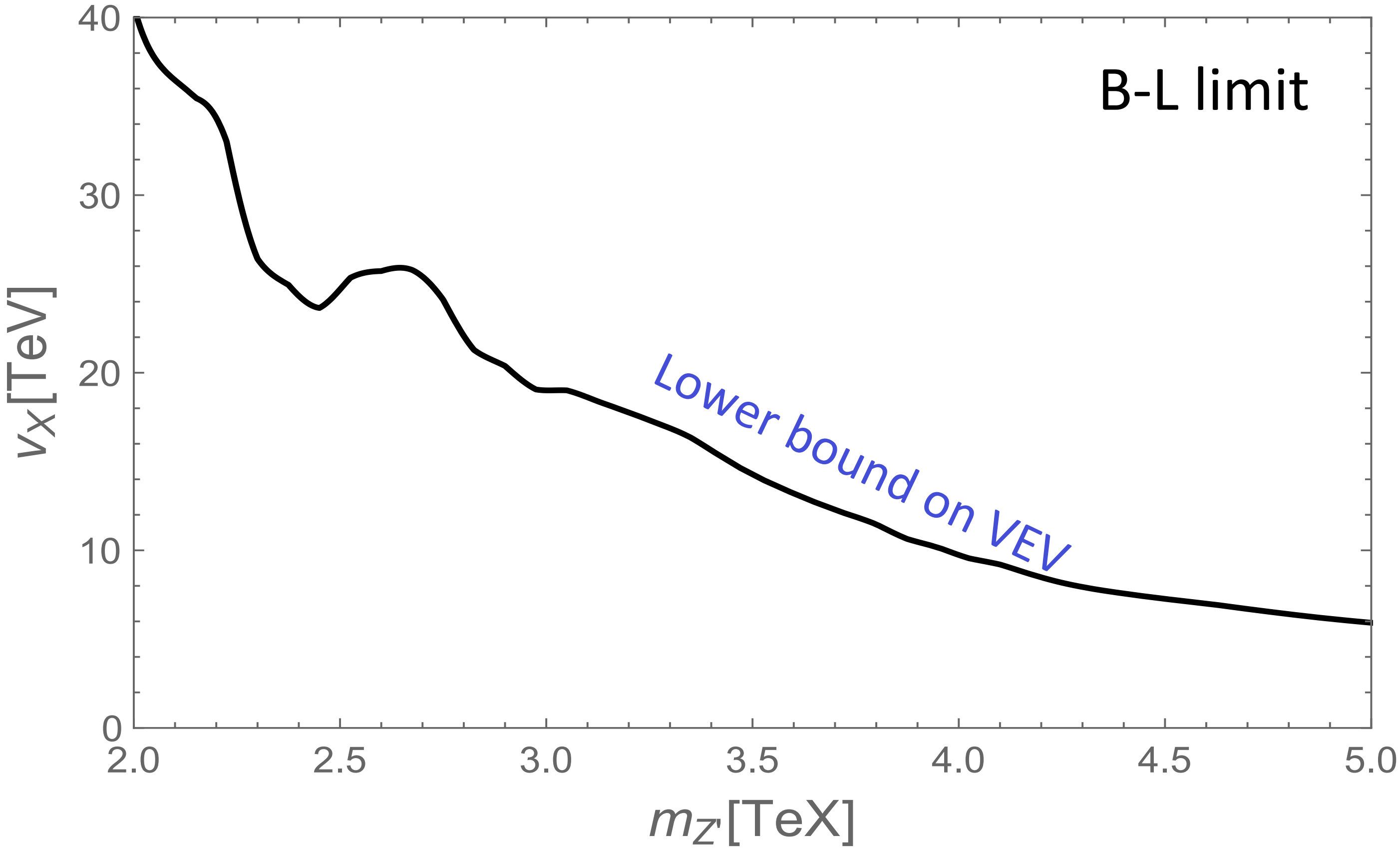
- LHC constraints are already very severe for U(1)x Z’ boson.
- If we take Z’ boson mass around a few TeV, gauge coupling is very small < 0.1.
- This is a quite tough situation for Future Linear Collider to see Z’ boson effects.
- Future LHC results (if there is no evidence of Z’ boson) make this situation worth.

Is there any way for Future Linear Collider to be more powerful than LHC?

Is there anything for Future Linear Collider to say under the very severe LHC constraints?

Interpretation of the ATLAS 2017 constraints into U(1)x Z' boson

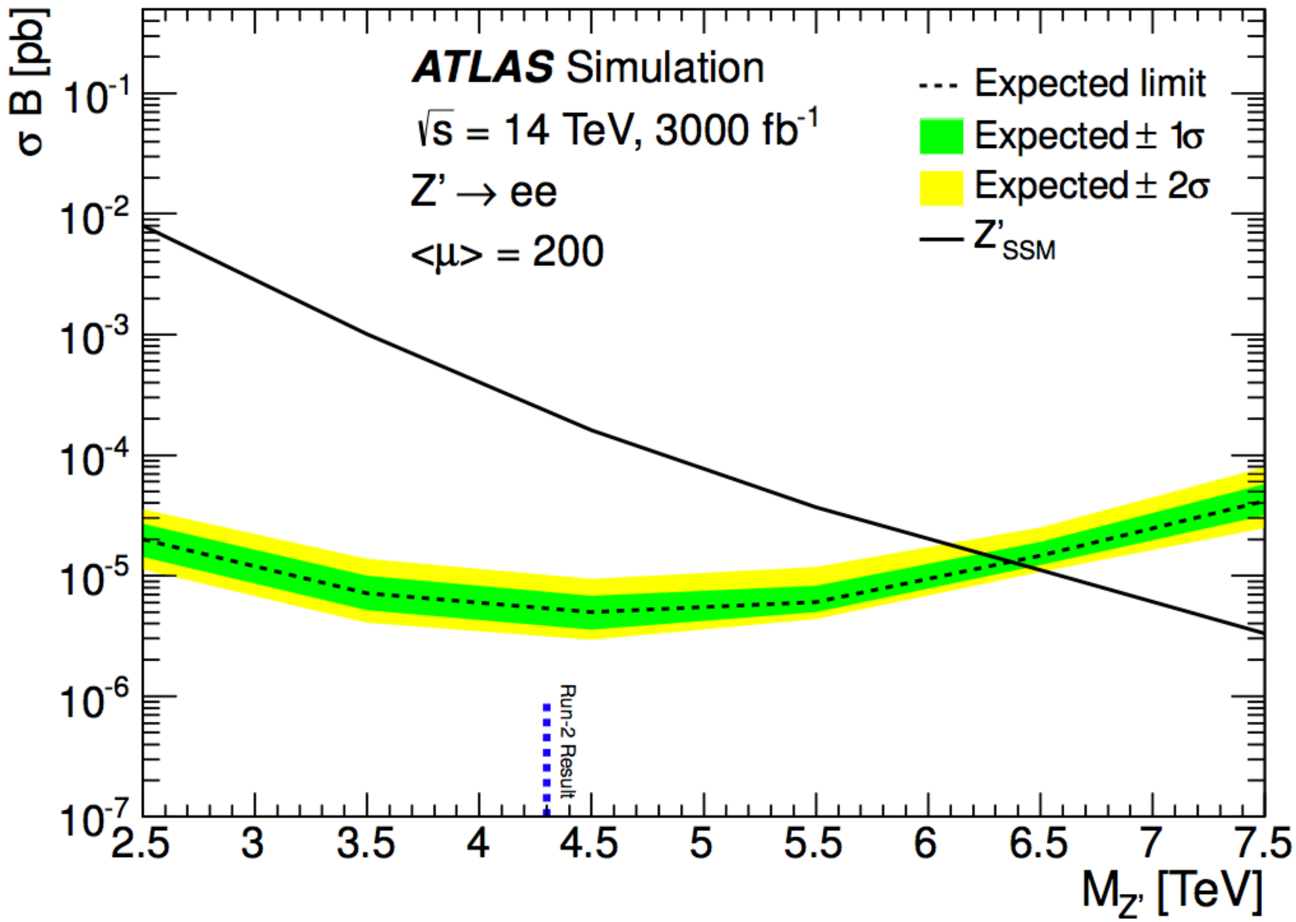
U(1)x Higgs VEV versus Z' boson mass $\quad m_{Z'} = 2\, g_X\, v_X$



Even for 5 TeV Z' mass, the LHC bound is more severe than LEP. However, the lower bound on Higgs VEV is dramatically reducing as Z' boson mass is increasing

Future prospect on Z' boson bound from HL-LHC

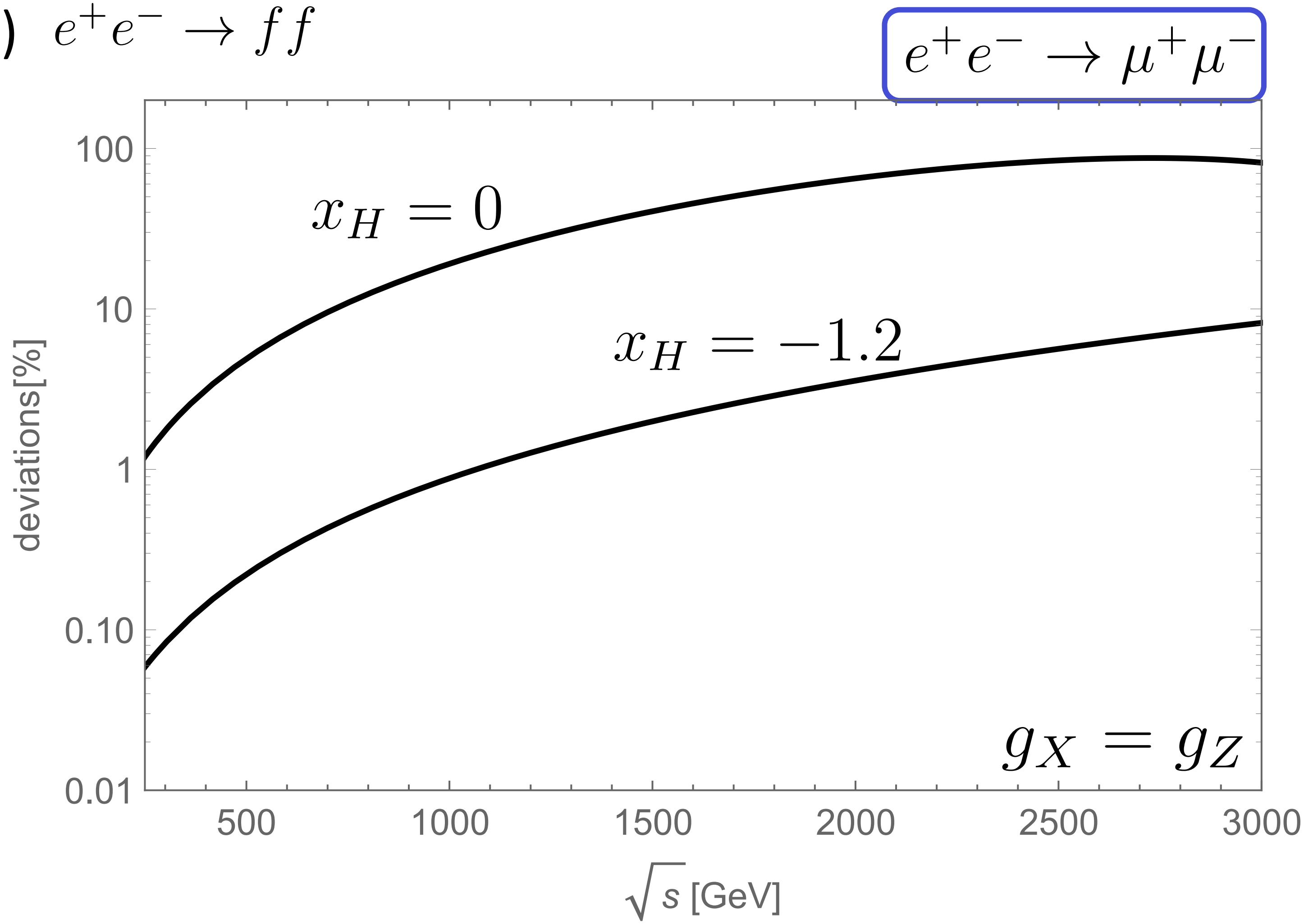
See Talk by Keith Ulmer at this workshop



Roughly, we can avoid LH-LHC constraints by taking, say, 7 TeV Z' boson mass

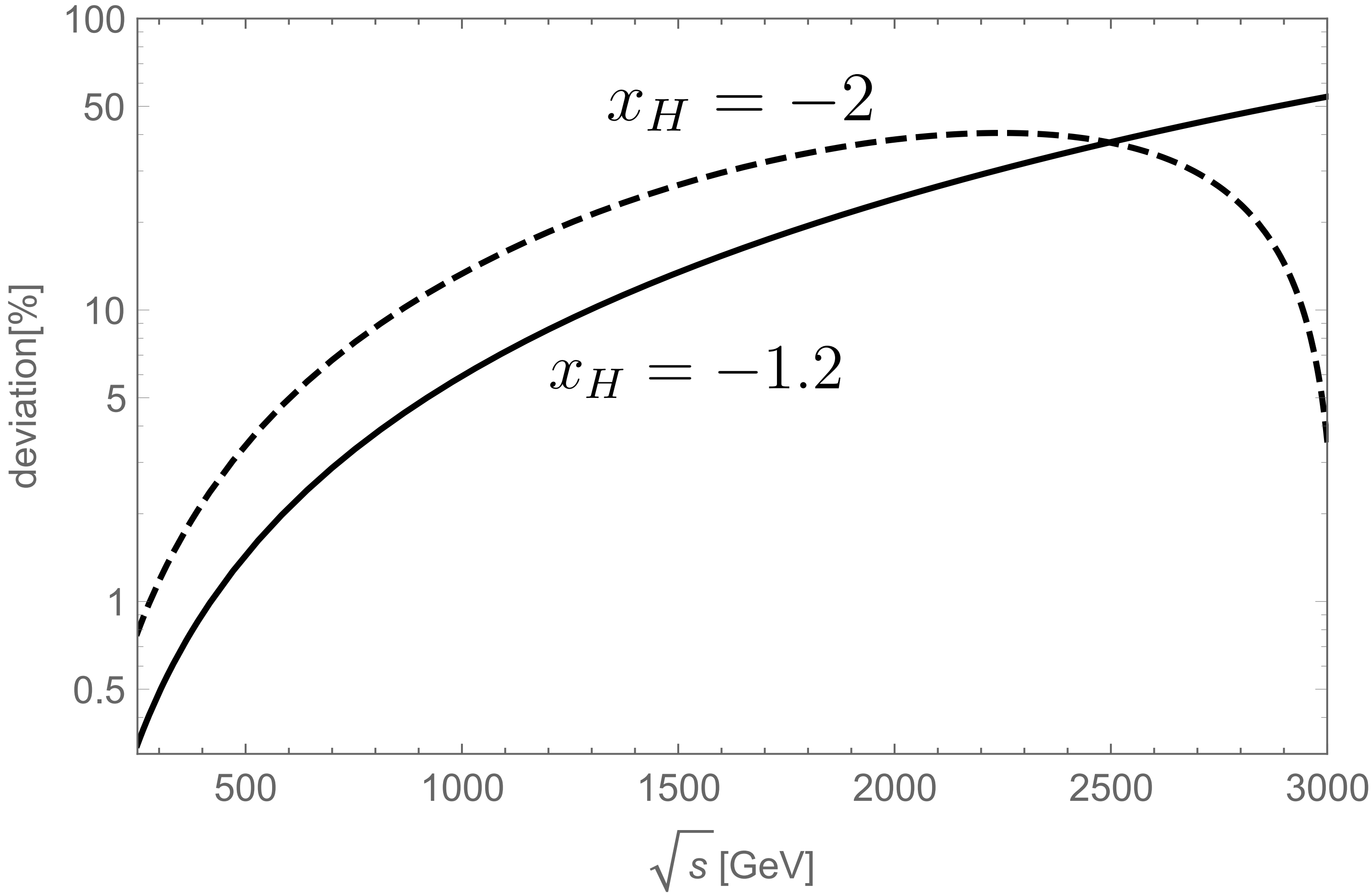
Future Linear Collider study with Z' mass=7 TeV

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



Deviations $\left|\frac{\sigma}{\sigma_{SM}} - 1\right|$ can be as large as 10% for xH=0 at 1 TeV ILC

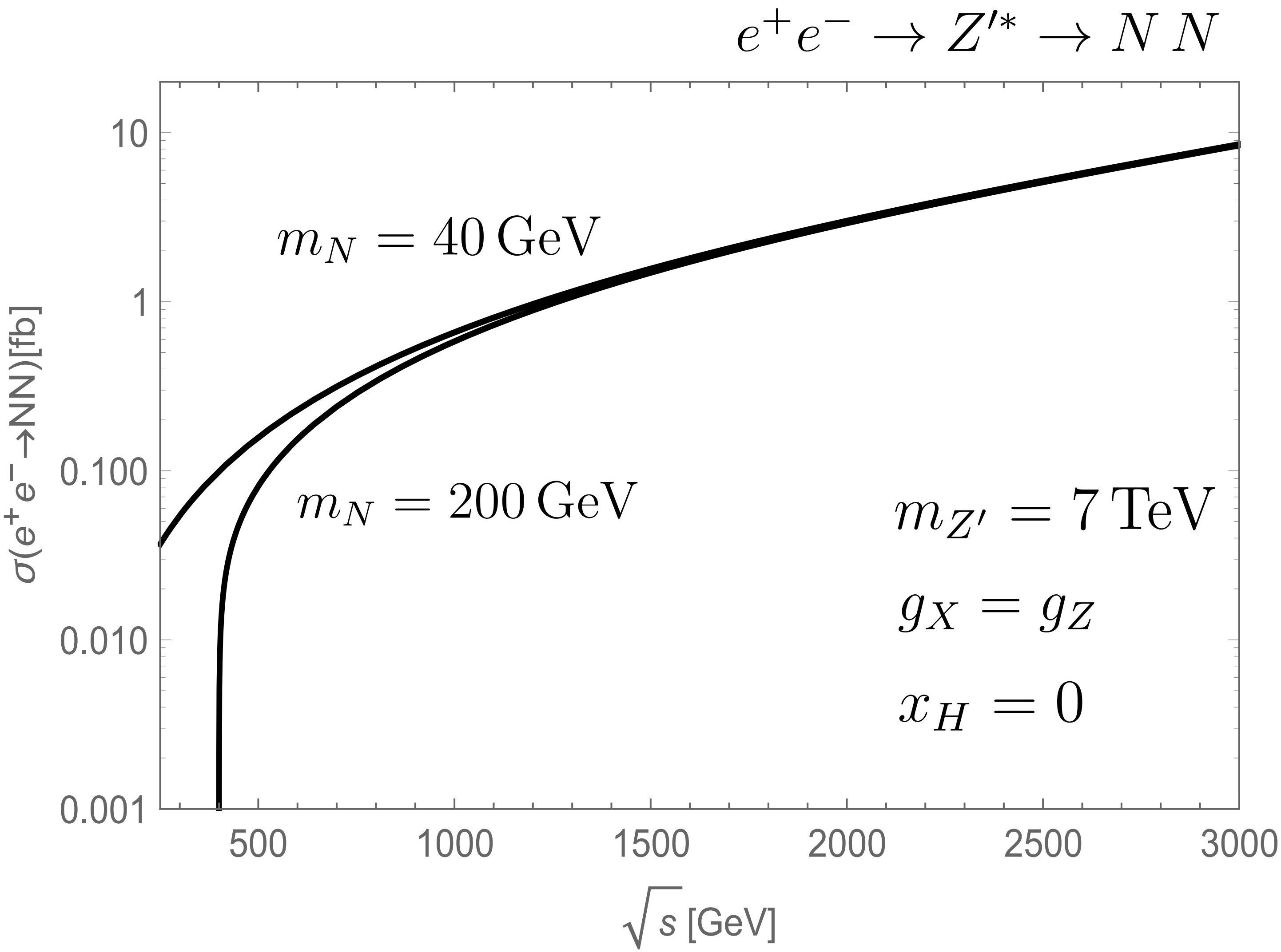
(2) $e^+e^- \to Z\,h$



Deviation can be as large as 5% for xH=-1.2 at 1 TeV ILC

Note that Z' contribution is vanishing for the B-L limit

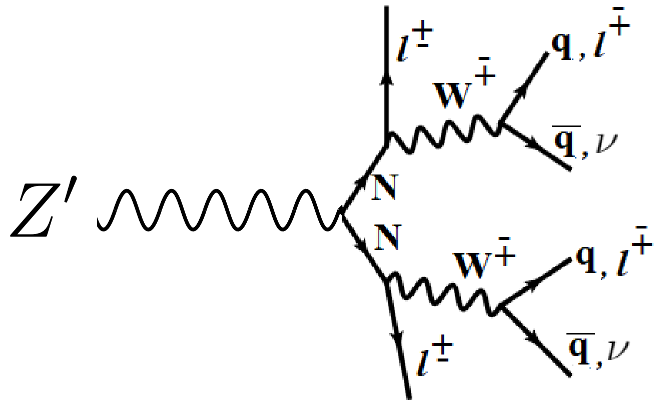
(3) Heavy Majorana Neutrino production



~0.5 fb cross section at 1 TeV ILC

Signatures of heavy Majorana neutrino

- ``Smoking-gun'' signature of the Majorana nature: same sign dilepton final states

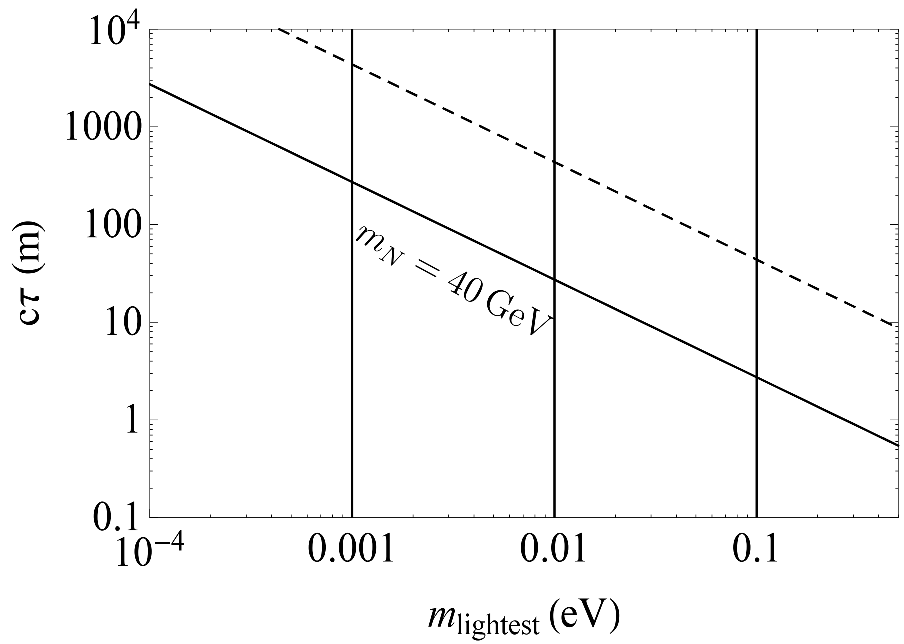


Same sign dilepton+jets

- Displaced vertex signature

N can be long lived when lightest neutrino is very light

Jana, NO & Raut, PRD 98 (2018) 035023



Summary

- We have considered the minimal U(1)x extended SM
- We have discussed Z’ boson signatures with a variety of final stets, such as lepton pair, Zh and heavy neutrino pair at Future Linear Collider
- Although the current LHC constraints (HL-LHC prospects) are very severe, we can avoid the LHC constraints by taking Z’ boson mass > 7 TeV.
- The Z’ boson mass is very high, but 1 TeV ILC can explore the U(1)x model

Thank you

for your attention!