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IBS-KIAS JOINT WORKSHOP ON PARTICLE PHYSICS, AND COSMOLOGY

LOCAL B-L: A PLAYGROUND FOR NEW PHYSICS

ZHAOFENG KANG, KIAS, 2/6/2017
BASED ON PUBLICATIONS WITH JUN GUO, KUNIO KANETA, JIN-MIAN LI, HYESUNG LEE, P. KO AND YUTA ORIKASA

Outline

$U(1)_{B\text{-}L}$ and hierarchy problem

$U(1)_{B\text{-}L}$ as a playground for DM

$U(1)_{B\text{-}L}$ as a playground for collider physics

Conclusions

Local $U(1)_{B\text{-}L}$ extension to SM

- Where does new physics stand? Says:

Hierarchy problem
Neutrino mass
Dark matter

→

extra gauge boson
extra Higgs boson
extra fermions

- Local $U(1)_{B\text{-}L}$ provides a playground for all of them. In particular, it is the simplest framework to understand neutrino masses via the seesaw mechanism

It explains the origin and structure of three right-handed neutrinos (RHNs) following the gauge principle

	q_L	u_R	d_R	l_L	e_R	ν_R	H	Φ
$SU(3)_c$	3	3	3	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	1
$U(1)_Y$	1/6	2/3	-1/3	-1/2	-1	0	1/2	0
$U(1)_{B-L}$	1/3	1/3	1/3	-1	-1	-1	0	2

$$\mathcal{L} = V(H,\Phi) + \left(\frac{1}{2}\lambda_{N,i}\Phi\bar{N}_i^c N_i + Y_{N,ij}\bar{\ell}H^\dagger N + h.c.\right) + \mathcal{L}_{\rm SM}$$

$U(1)_{B-L}$ and hierarchy problem

- Classical scale invariance (CSI) rescues naturalness

CSI might protect a light scalar from quadratic divergency

W. A. Bardeen, FERMILAB-CONF-95-391-T, C95-08-27.3 (1995)

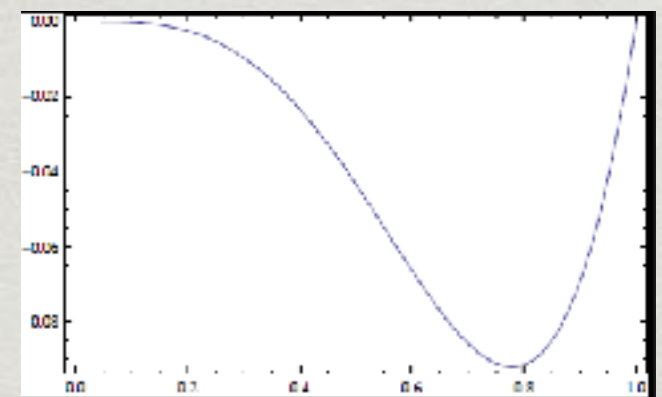
CSI is radiatively broken by the Coleman-Weinberg (CW) mechanism, due to CSI anomaly. Scalar QED example:

$$V_0 = \frac{\lambda}{2}|\Phi|^4$$

$$V_{\rm eff} = A\phi_{\rm cl}^4 + B\phi_{\rm cl}^4 \ln\frac{\phi_{\rm cl}^2}{Q^2},$$

$$A = \frac{\lambda}{8} + \frac{1}{64\pi^2}\sum_P n_P g_P^4\left(-A_P + \ln g_P^2\right),$$

$$B = \frac{1}{64\pi^2}\sum_P n_P g_P^4,$$



encode quantum effect

positive PGSB requires $B>0$

CSI CANNOT be realized within SM due to heavy top quarks, which renders a negative B

$U(1)_{B\text{-}L}$ and hierarchy problem

- Weak scale from the scale invariant *B-L* (SIBL) sector

$$V(H,\Phi) = \frac{\lambda_h}{2}|H|^4 - \lambda_{h\phi}|H|^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$$

Induce EWSB ← Make <Φ>~10 TeV via CW mechanism

The local B-L leads to the extension to SM by a scalar QED, implementing the CW mechanism in the hidden sector

The Higgs portal term can mediate CSI breaking to the SM sector as long as it has a negative coupling, which leads to the negative Higgs mass term as in the conventional EWSB

S. Iso, N. Okada and Y. Orikasa, Phys. Rev. D 80, 115007 (2009);
E. J. Chun, S. Jung and H. M. Lee, Phys. Lett. B 725, 158 (2013)

$U(1)_{B\text{-}L}$ as a playground for DM

- SIBL accommodates accidental dark matter

Matter stability is not trivial !!

J. Guo, Z. Kang, P. Ko and Y. Orikasa, Phys. Rev. D 91, no. 11, 115017 (2015).

In the visible world, baryon is accidentally stable as a consequence of the spacetime and gauge symmetries & renormalizability & matter content in the SM

Similar mechanism applies to DM? The real singlet DM can be accidentally stable in SIBL:

$$\mathcal{L}_{DM} = \frac{1}{2}\lambda_{sh} S^2 (H^\dagger H) + \frac{1}{2}\lambda_{s\phi} S^2 (\Phi^\dagger \Phi) + \frac{\lambda_s}{4} S^4.$$

Unify DM interactions and mass origin

Address DM mass origin: the bare mass term is forbad by CSI and DM mass is dynamically

$U(1)_{B-L}$ as a playground for DM

- *B-L* charged case: Accidental Z_3

J. Guo, Z. Kang, P. Ko and Y. Orikasa, Phys. Rev. D 91, no. 11, 115017 (2015).

Scalar S_X with peculiar charge like X=1.1 will not be considered

The only nontrivial case has charge ±2/3, leading to an accidental Z_3 remanent :

$$\mathcal{L}_{Z_3} = \lambda_1 |S_X|^2|\Phi|^2 + \left(\frac{\lambda_3}{3}\Phi S_X^3 + c.c.\right) + \lambda_2 |S_X|^2 |H|^2 + V(H,\Phi).$$

- Importance of $S_X^3\Phi$ dynamics

Separating DM mass generation from annihilation

Z' is irrelevant in DM annihilating, because of the LHC constraint on Z'

$$\left\langle \sigma_{SS^*\to Z'\to f\bar{f}} v \right\rangle \sim \frac{v^2}{64\pi}\frac{g_{B-L}^4}{m_{Z'}^4} m_{\rm DM}^2 < 10^{-3}\left(\frac{m_{\rm DM}}{1\rm TeV}\right)^2 \rm pb$$

semi-annihilation is not suppressed by large VEV <Φ>

$$\left\langle \sigma_{SS\to S^*+{\rm PGSB}} v \right\rangle \sim \frac{1}{64\pi}\frac{\lambda_3^2}{m_S^2}$$

$U(1)_{B-L}$ as a playground for DM

- Economical seesaw: RHN as DM candidate

In seesaw, the lightest RHN N_1 is neutral under QED & QCD and thus CAN be DM candidate if it is sufficiently long-lived

seesaw with 2 RHNs is enough!!

For N_1 with mass M_1~O(10) keV, longevity is accidental

$$\Gamma_{N_1\to\nu\gamma} \simeq \frac{9G_F^2\alpha M_1^5}{256\pi^4} \times \sin^2\theta \simeq 1.62\times10^{-28}s^{-1}\left(\frac{\sin^2 2\theta}{7\times10^{-11}}\right)\left(\frac{M_1}{7\mathrm{keV}}\right)^5$$

tiny neutrino mass forces θ<<1 in seesaw

BUT, correct relic density is a big issue!

X-ray observation & Lyman-α forest data kill the oscillation mechanism except for abnormally large lepton asymmetry

→ gauge B-L makes a real difference!

$U(1)_{B\text{-}L}$ as a playground for DM

- new forces of RHN comes to the rescue

In the local B-L N_1 is not sterile, coupling to $Z_{B\text{-}L}$ and B-L Higgs

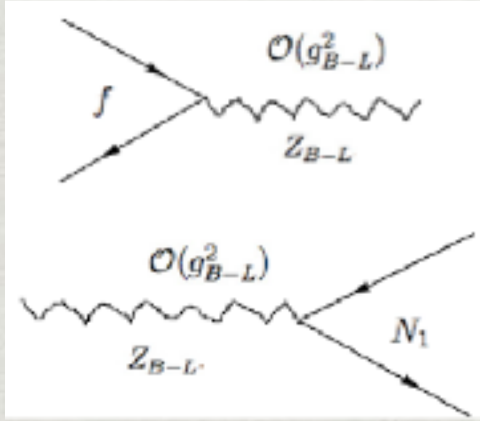
sizable gauge coupling $g_{B\text{-}L}$ can thermalize N_1 and leads to too much relic after freezing-out

$$\Omega_{N_1} h^2 = \frac{s_0 M_{N_1}}{\rho_c h^{-2}} \times \frac{n_{N_1}}{s}\Big|_{T^{\rm dec}_{N_1}} \simeq 110 \times \left[\frac{M_{N_1}}{10\,{\rm keV}}\right]\left[\frac{10.75}{g_*(T^{\rm dec}_{N_1})}\right]$$

Kunio Kaneta, Zhaofeng Kang and Hye-Sung Lee, 1606.09317

freeze-in production of N_1 in the $g_{B\text{-}L}$<<1 limit

- M_{N1}<$M_{B\text{-}L}$ /2: Freeze-in via the decay of frozen-in $Z_{B\text{-}L}$



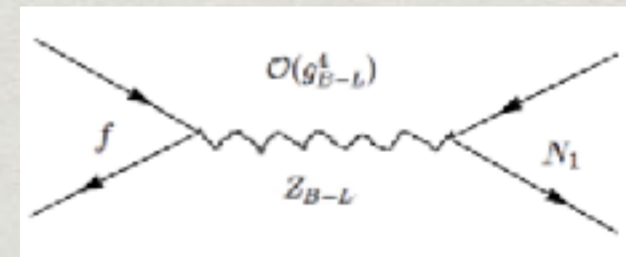
$$\Omega_N h^2 \simeq 0.12 \times \left[\frac{100}{g_*}\right]^{3/2}\left[\frac{g_{B-L}}{5.1\times 10^{-12}}\right]^2\left[\frac{7}{C_f}\right]\left[\frac{f(\tau)}{0.19}\right]$$

$f(\tau) = \tau(1-\tau^2)^{3/2}$ with $\tau = 2M_{N_1}/M_{Z'}$ taking $0 < \tau < 1$

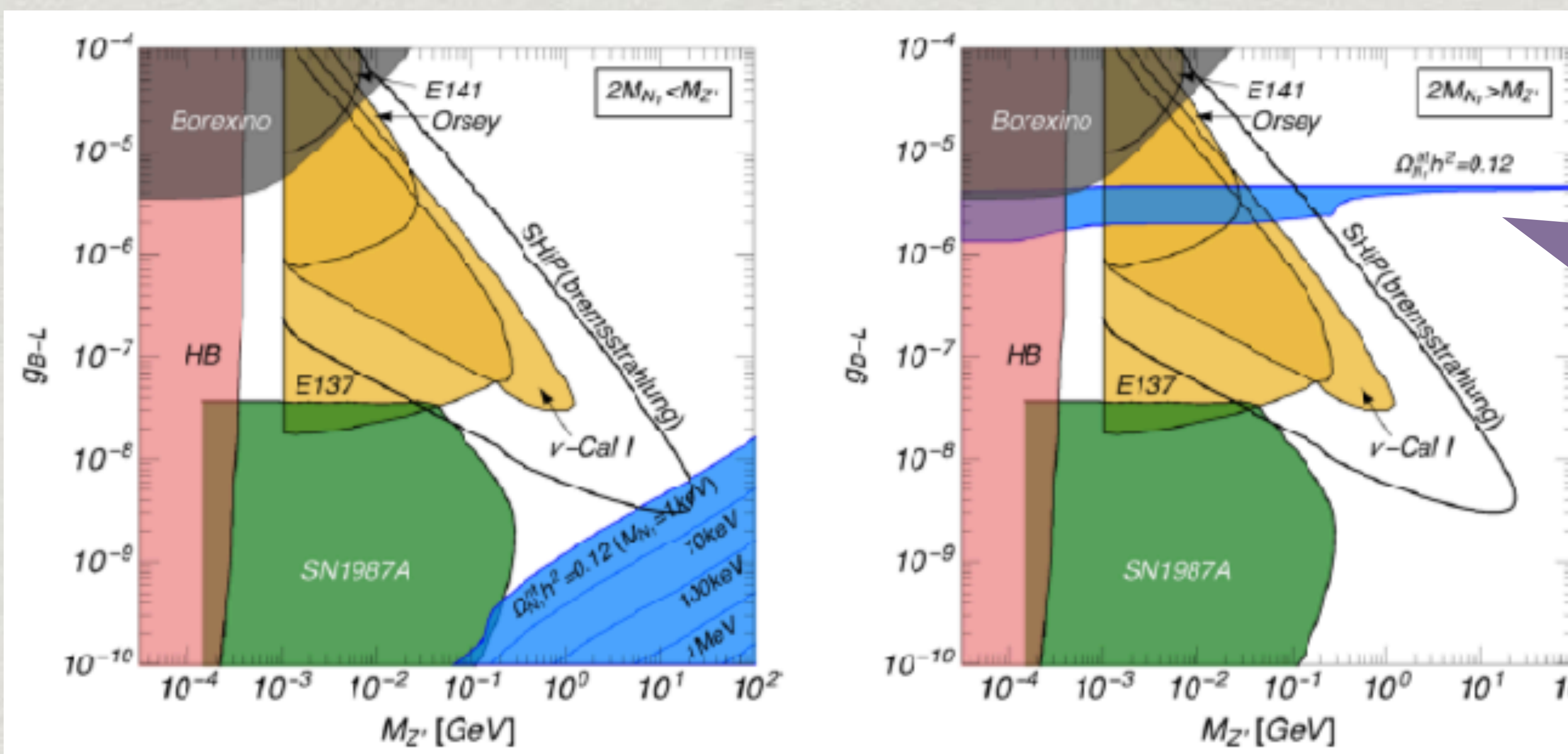
$U(1)_{B-L}$ as a playground for DM

- $M_{N1} > M_{B-L}/2$: Freeze-in via scattering

$$\Omega^{\rm nt}_{N_1} h^2 \simeq 0.12 \times \left(\frac{100}{g_*}\right)^{3/2} \left(\frac{g_{B-L}}{4.5\times 10^{-6}}\right)^4$$



- The results:



(a) (b)

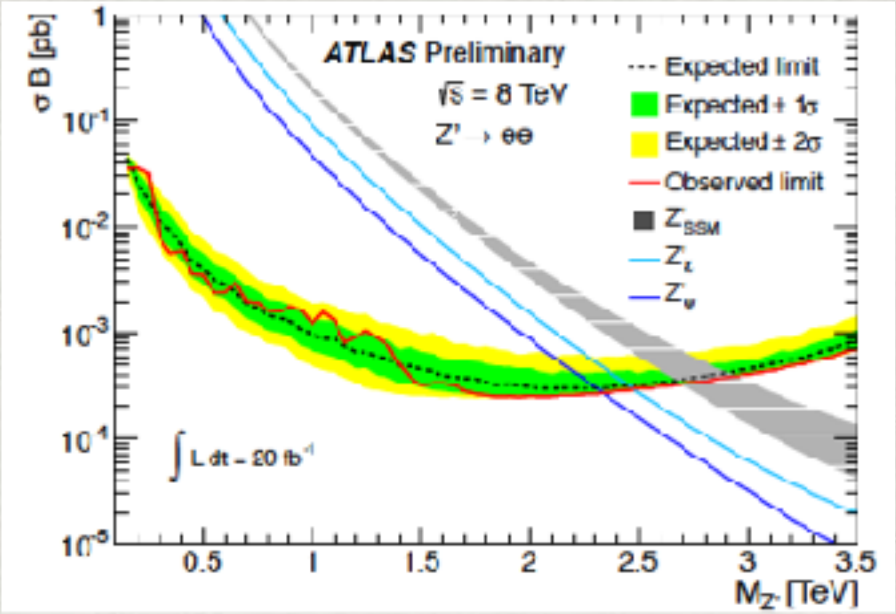
a complete study, including tests/constraints on light particles from cosmology and laboratory

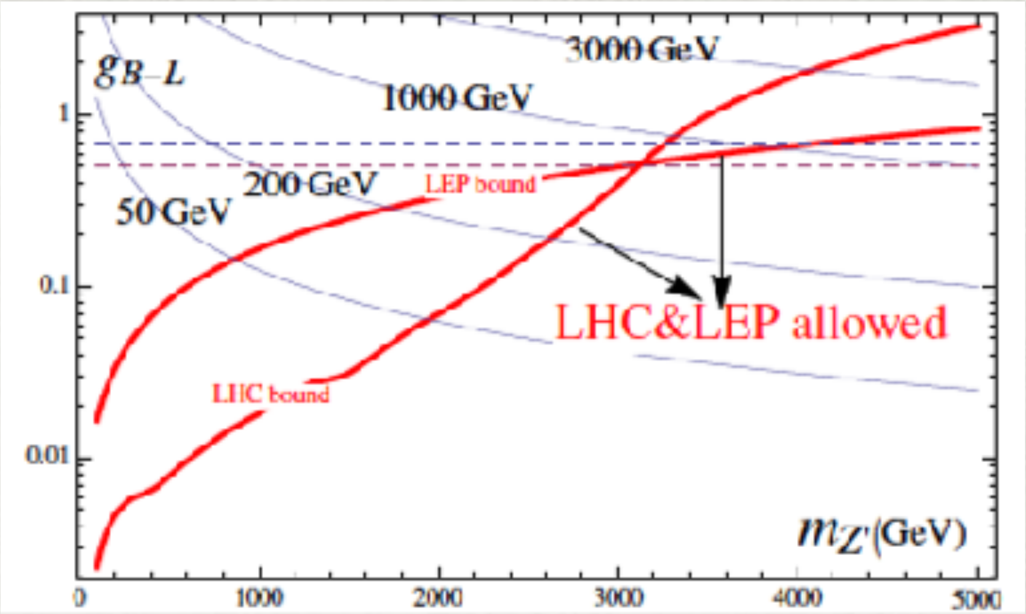
$U(1)_{B-L}$ as a playground for collider

- Smoking gun: heavy di-lepton resonance signature

Z_{B-L} couples to quarks and leptons simultaneously, thus abundantly producing $pp \to Z_{B-L} \to e^+e^-/\mu^+\mu^-$ at the LHC, with little backgrounds

di-lepton resonance receives much attention at LHC and the current data gives a strong constraint on (M_{B-L}, g_{B-L}) plane





$U(1)_{B\text{-}L}$ as a playground for colliders

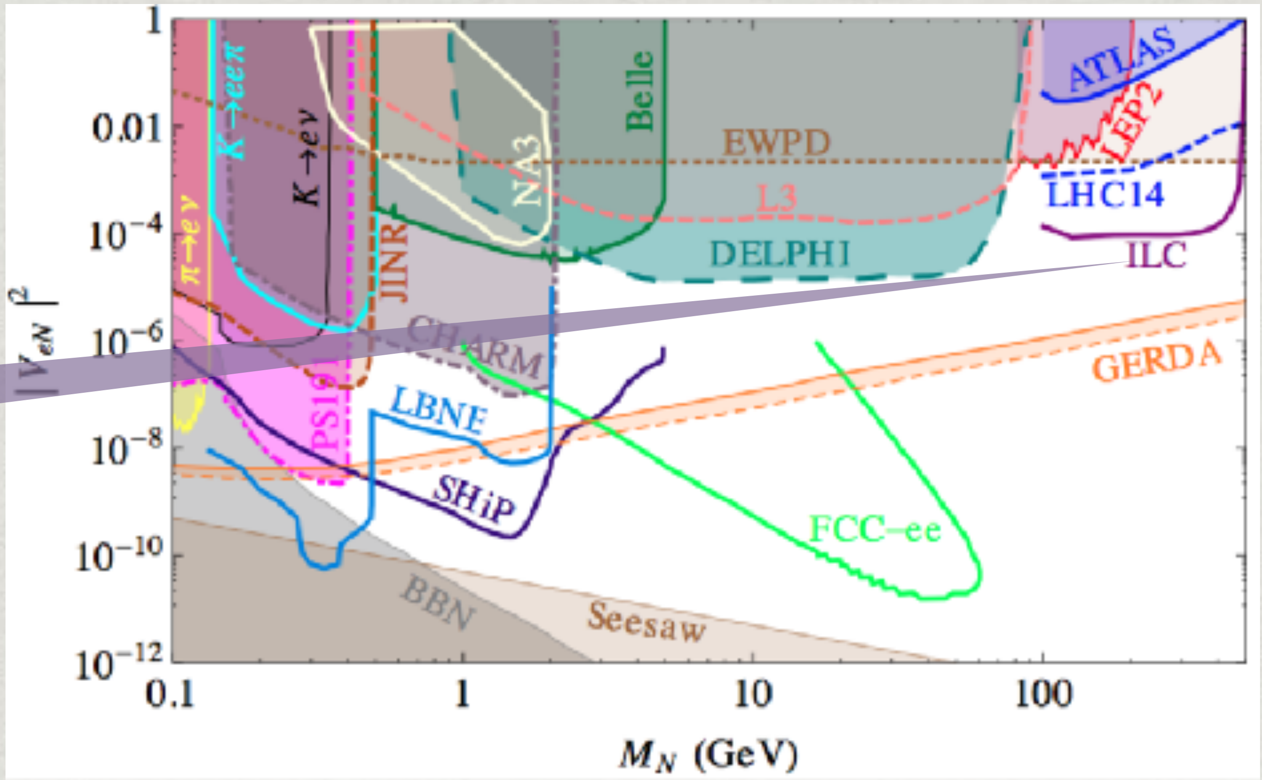
- New opportunity for higher scale seesaw

Conventionally, RHN searches rely on sizable sterile-active mixing, which gives rise to same-sign dilepton at LHC: pp'→W^+→e^+N→e^+e^+jj

But this mixing angle is supposed to be very small

$$V_{iN} \simeq \sqrt{m_\nu/M_N} \quad (i = e, \mu, \tau)$$

Searching for heavy RHN is particularly difficult, even ILC just reaches mixing with electron~10^{-2} for RHN~100GeV



Not Mentioning to TeV scale RHN!!!

$U(1)_{B-L}$ as a playground for colliders

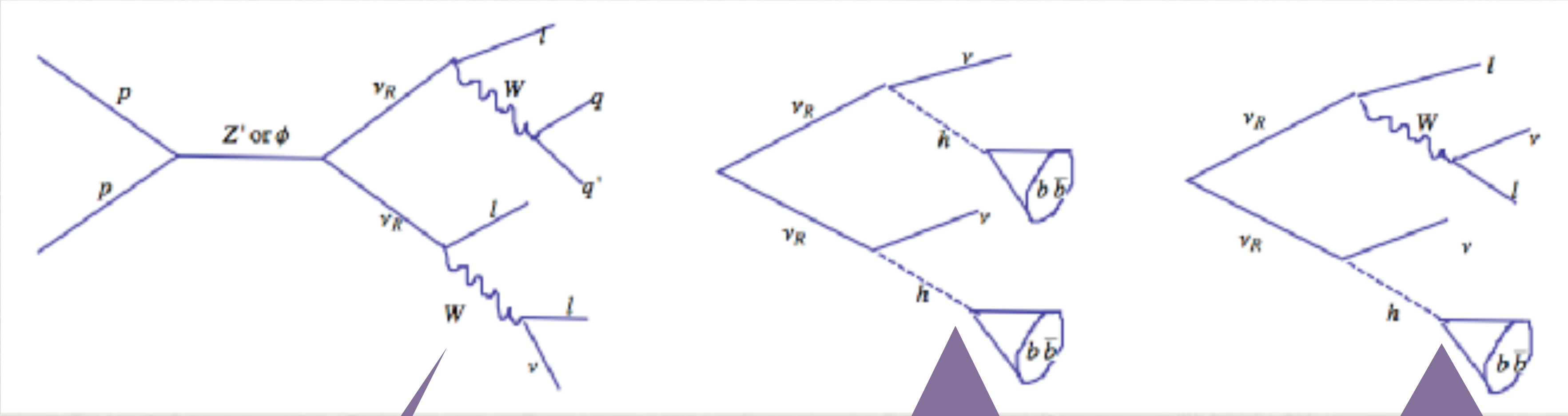
- Enter into TeV scale seesaw

In local $U(1)_{B-L}$: RHN pairly couples to new heavy resonances

Z. Kang, P. Ko and J. Li, Phys. Rev. D 93, no. 7, 075037 (2016)

RHN pair production with resonant enhancement

works even in the absence of sterile-active mixing!



trilepton+jets

boosted di-Higgs+MET

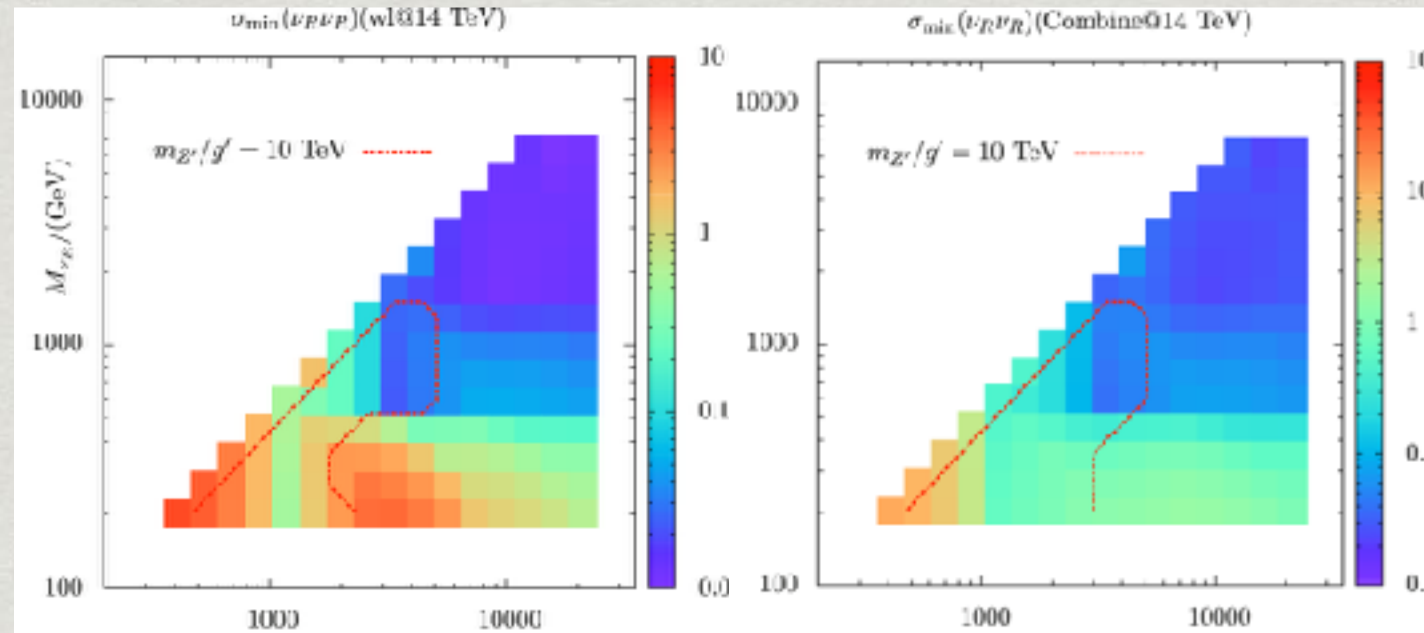
boosted Higgs+dilepton

Z. Kang, P. Ko and J. Li, Phys. Rev. Lett. 116, no. 13, 131801 (2016)

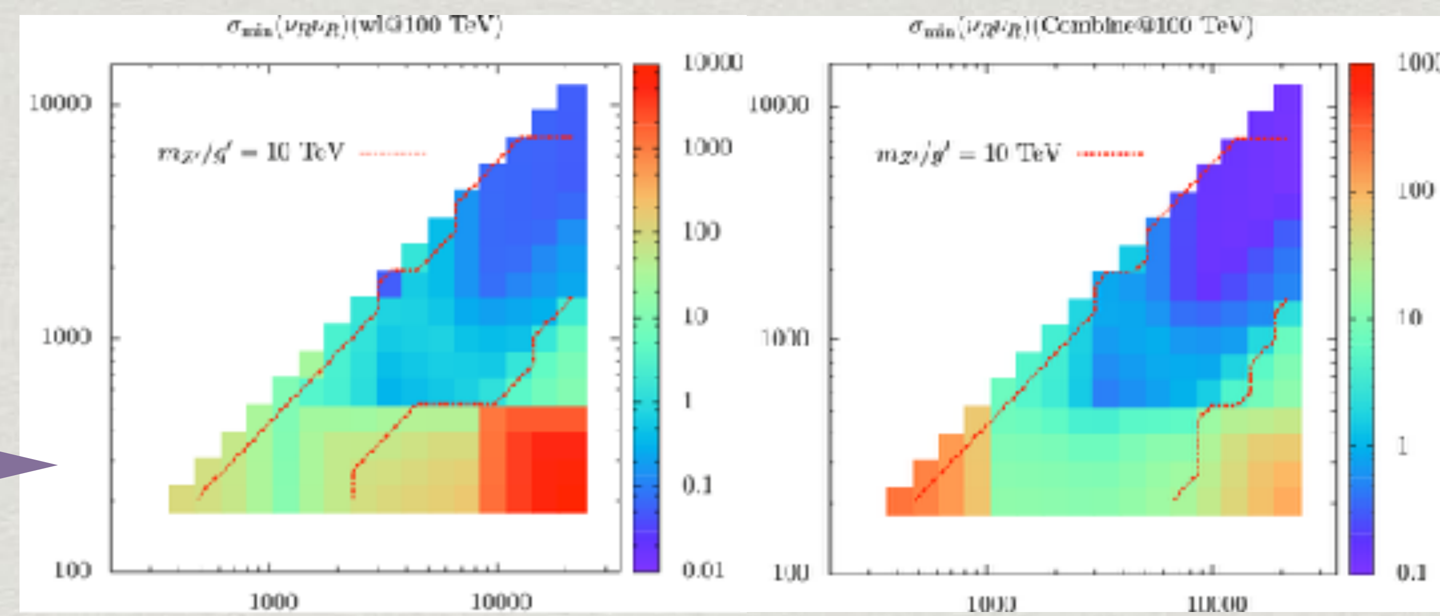
$U(1)_{B-L}$ as a playground for colliders

- Enter into TeV scale seesaw: results

@ the end of 14 TeV, combine three channels (the di-*W* and *hW* channels dominate).



@ the 100 TeV collider with 3000/fb



NWA approximation breaks down for Z' above 6TeV

Conclusions

* Local B-L is well motivated to understand neutrinos, but its role in new physics is much beyond it:

It offers a simple model to understand weak scale origin in the scale invariance framework

It furnishes a playground for dark matter physics, including accidental DM and right-handed neutrino DM

It leaves remarkable signature at colliders, and in particular offers chance for probing TeV scale seesaw via pair RHN

Thanks!