Probing the Seesaw Mechanism at the 250 GeV ILC

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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

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Gauged B-L extension of the Standard Model

---- For neutrino mass generation -----

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

If B-L symmetry breaking is @ TeV, we have a good chance to observe new particles (Z' boson & RHNs) at high energy colliders in the future

Gauged B-L Extension of the SM

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

Particle Contents (SM particles)

i=1,2,3

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$
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
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0

With only the SM fermions, the model is anomalous:
gauge & mixed gauge-gravitation

New Particle Contents

Anomalies are canceled out in the presence of 3 RHNs

Minimal B-L Model

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
N_R^i	1	1	0	-1
Φ	1	1	0	$+2$

i=1,2,3

$$\mathcal{L}_Y = -\sum_{i,j=1}^{3} Y_D^{ij} \overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{k=1}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \mathrm{h.c.}$$

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Alternative B-L Model

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$N_R^{1,2}$	$\mathbf{1}$	$\mathbf{1}$	0	-4
N_R^3	$\mathbf{1}$	$\mathbf{1}$	0	$+5$
H_ν	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	3
Φ_A	$\mathbf{1}$	$\mathbf{1}$	0	$+8$
Φ_B	$\mathbf{1}$	$\mathbf{1}$	0	-10

$$\begin{aligned}\mathcal{L}_Y &= -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^i} H_\nu N_R^j \\ &\quad - \frac{1}{2}\sum_{k=1}^{2} Y_N^k \Phi_A \overline{N_R^{k\,c}} N_R^k \\ &\quad - \frac{1}{2} Y_N^3 \Phi_B \overline{N_R^{3\,c}} N_R^3 + \text{h.c.}.\end{aligned}$$

After B-L & Electroweak symmetry breaking

Minimal Model | Alternative Model

B-L gauge boson mass

$$m_{Z'} = 2\, g_{BL}\, v_\phi$$

$$\simeq g_{BL}\sqrt{64 v_A^2 + 100 v_B^2}$$

RHN Majorana mass

$$m_{N^j} = \frac{Y_N^j}{\sqrt{2}} v_\phi$$

$$m_{N^{1,2}} = \frac{Y_N^{1,2}}{\sqrt{2}} v_A, \quad m_{N^3} = \frac{Y_N^3}{\sqrt{2}} v_B$$

Neutrino Dirac mass

3X3 matrix

$$m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v$$

3x2 matrix

Seesaw with 3 RHNs

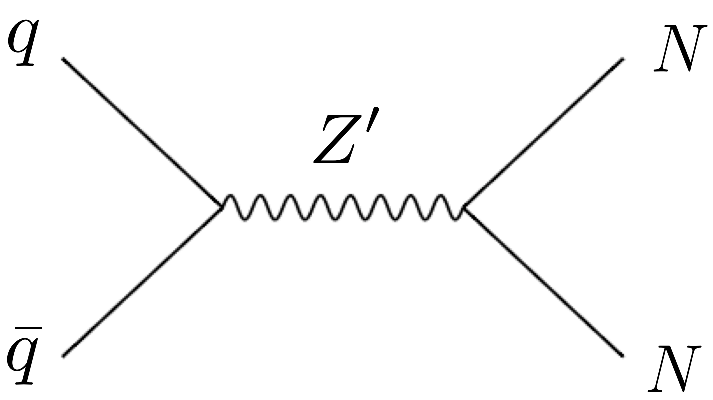
Minimal Seesaw w/ 2 RHNs

How to probe Seesaw Mechanism at Colliders?

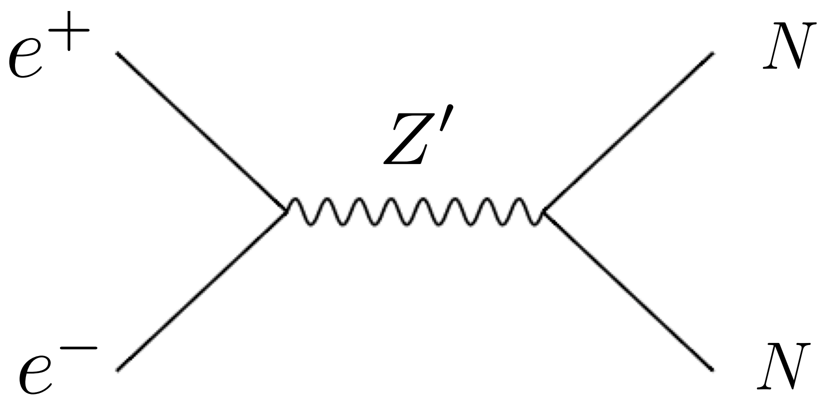
- RHN production

  Although RHN is SM-singlet, Z’ boson as a probe of RHN productions

Hadron collider



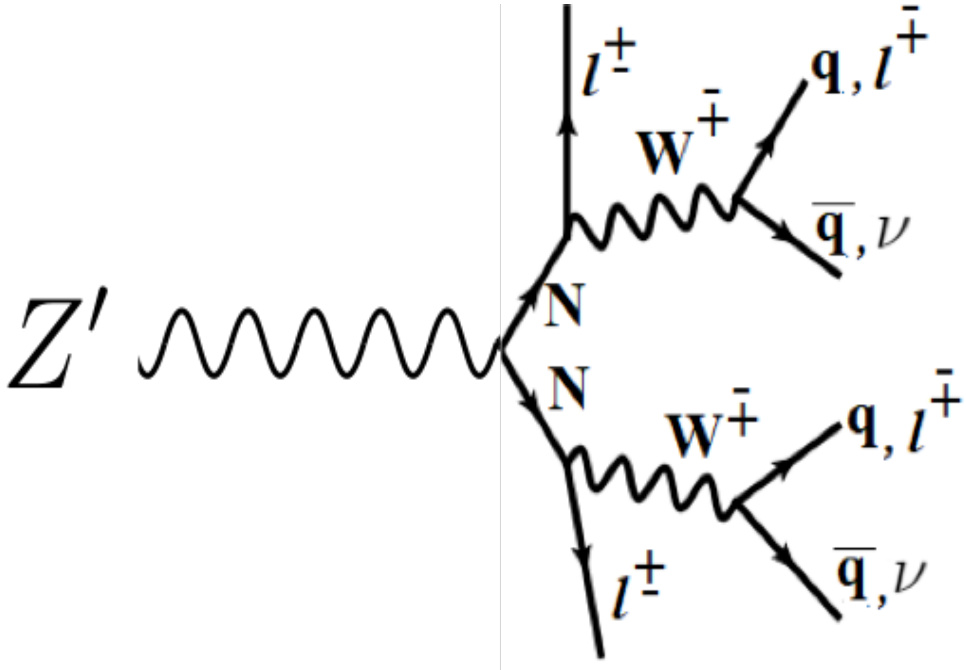
Lepton collider



How to probe Seesaw Mechanism at Colliders?

- Lepton number violating RHN decay

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



Same sign dilepton+jets

~background free

Prospect of

(i) Probing Seesaw Mechanism at HL-LHC?

Study in the B-L model context:

Das, N.O & Raut, PRD 97 (2018) 115023
Das, N.O & Raut, EPJC 78 (2018) 696

Long-lived RHN production in the B-L model:

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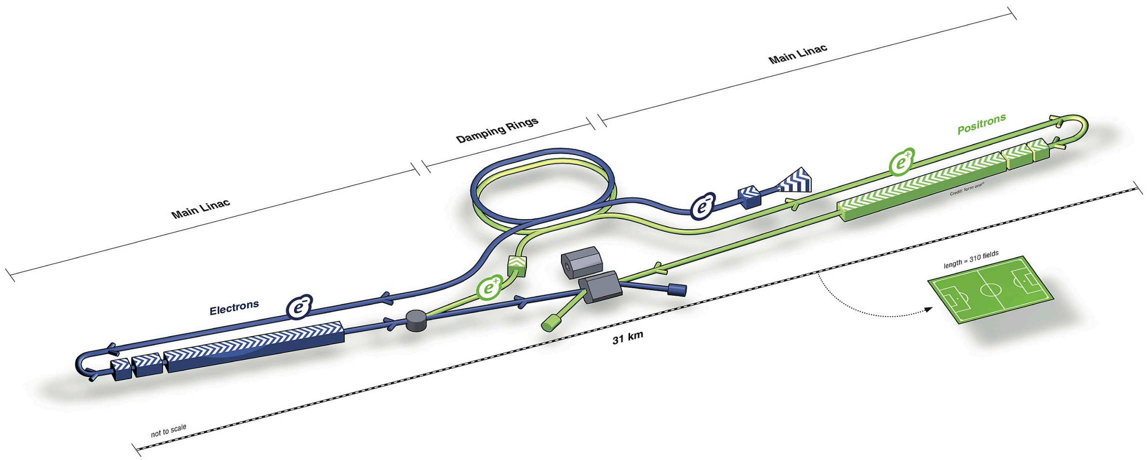
(ii) Probing Seesaw Mechanism at ILC?

Future Lepton Collider Projects

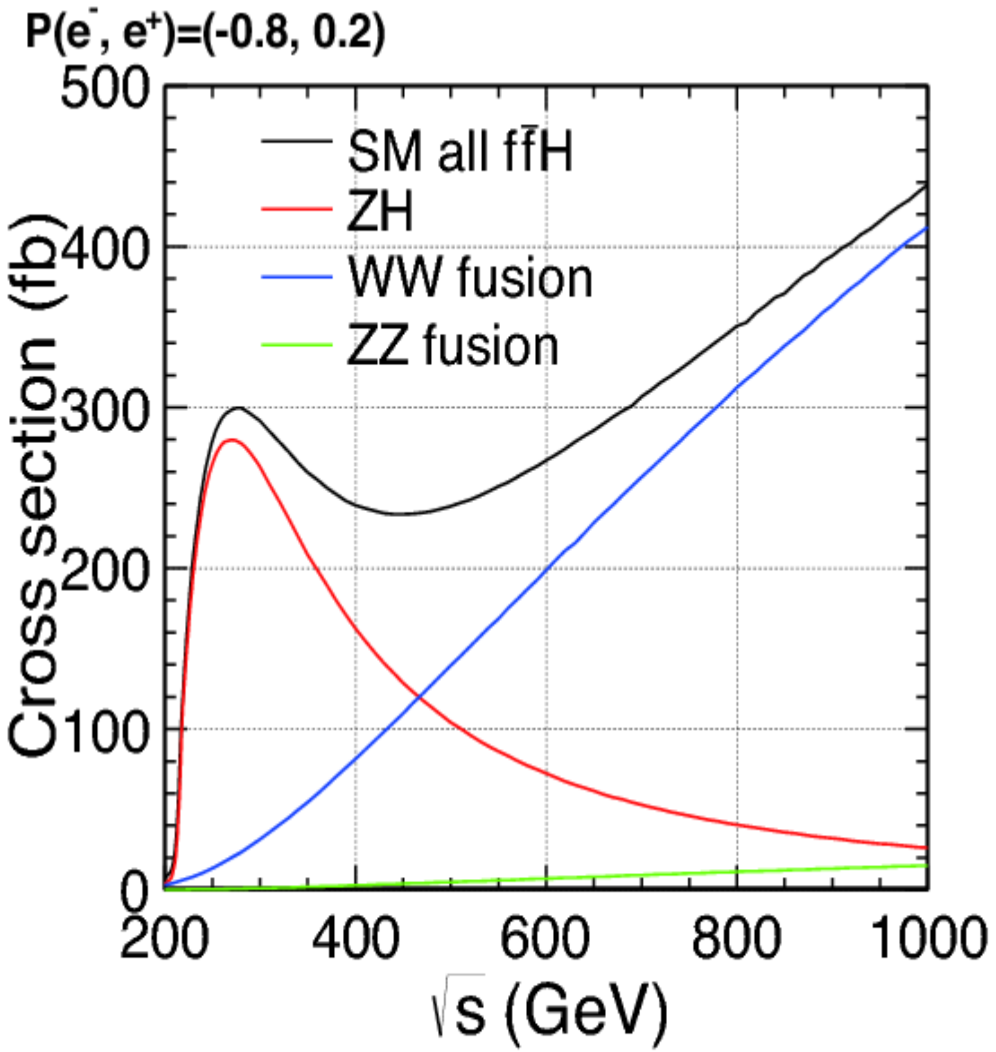
International Linear Collider (ILC)



- ➢ Japan is most likely the host
- ➢ Japanese government plans to make a decision soon?
- ➢ Cost: \$5 billion → ILC energy with 250 GeV

What can we do with the 250 GeV ILC?

- Higgs Factory
- Precise measurements of Higgs boson properties
  →
  New physics effects related to the SM Higgs sector



Can we probe Seesaw Mechanism

at the 250 GeV ILC

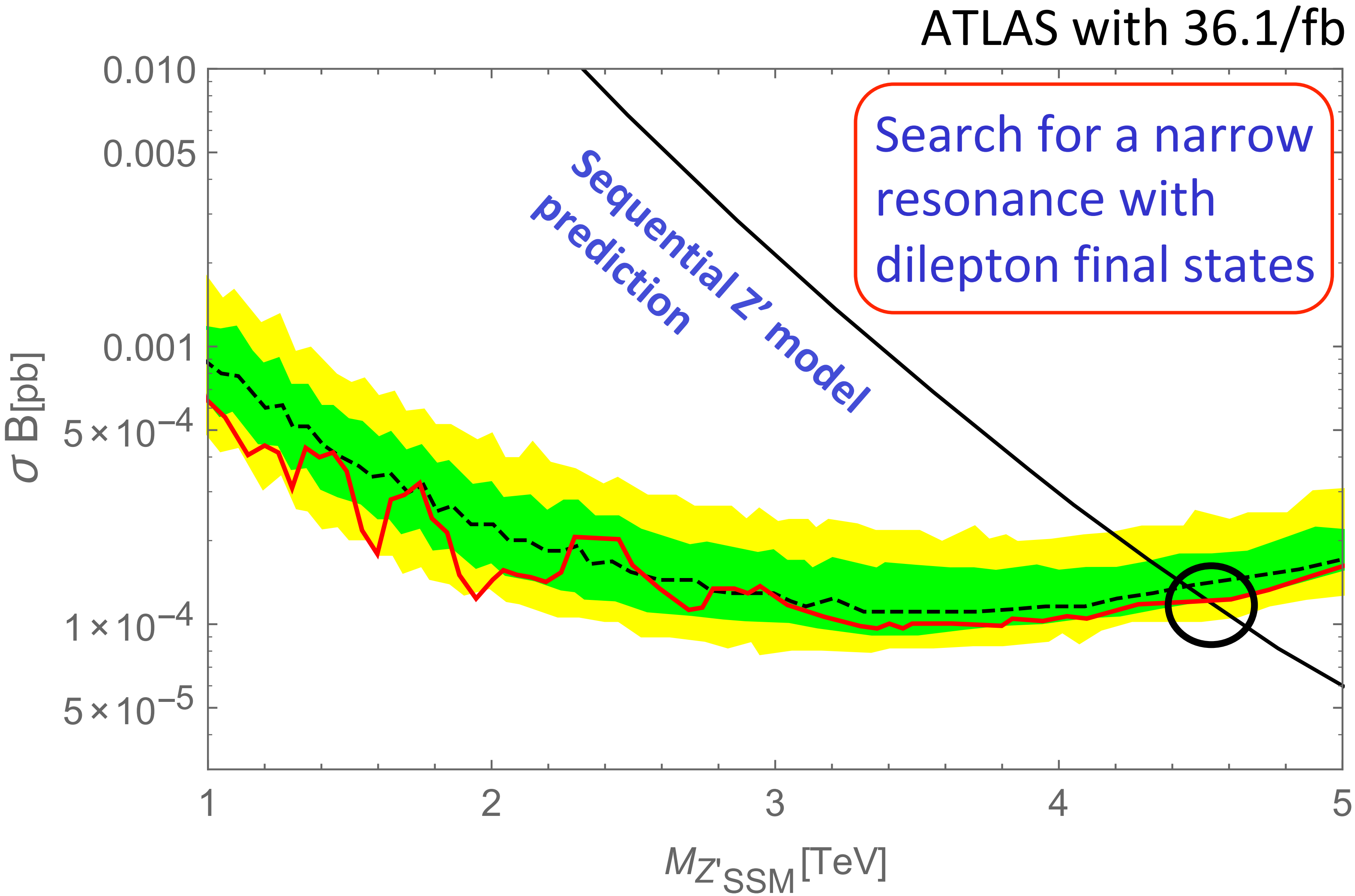
after HL-LHC?

Can we probe Seesaw Mechanism
at the 250 GeV ILC
after HL-LHC?

Worst case scenario

Can we probe Seesaw Mechanism at the 250 GeV ILC in the worst case scenario that HL-LHC data would show no evidence?

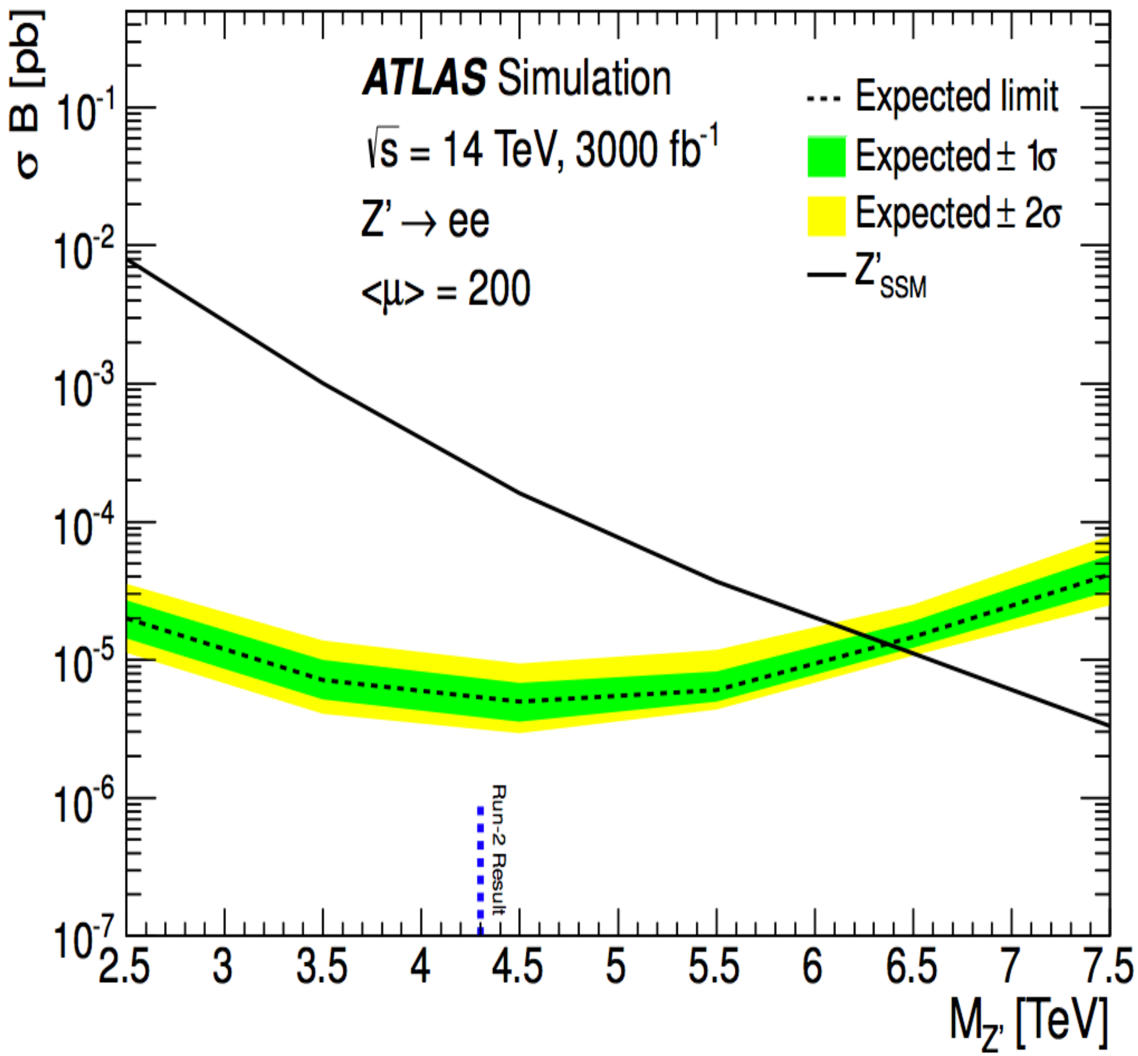
Current Status: LHC Run 2 constraints



*CMS collaboration has similar results

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

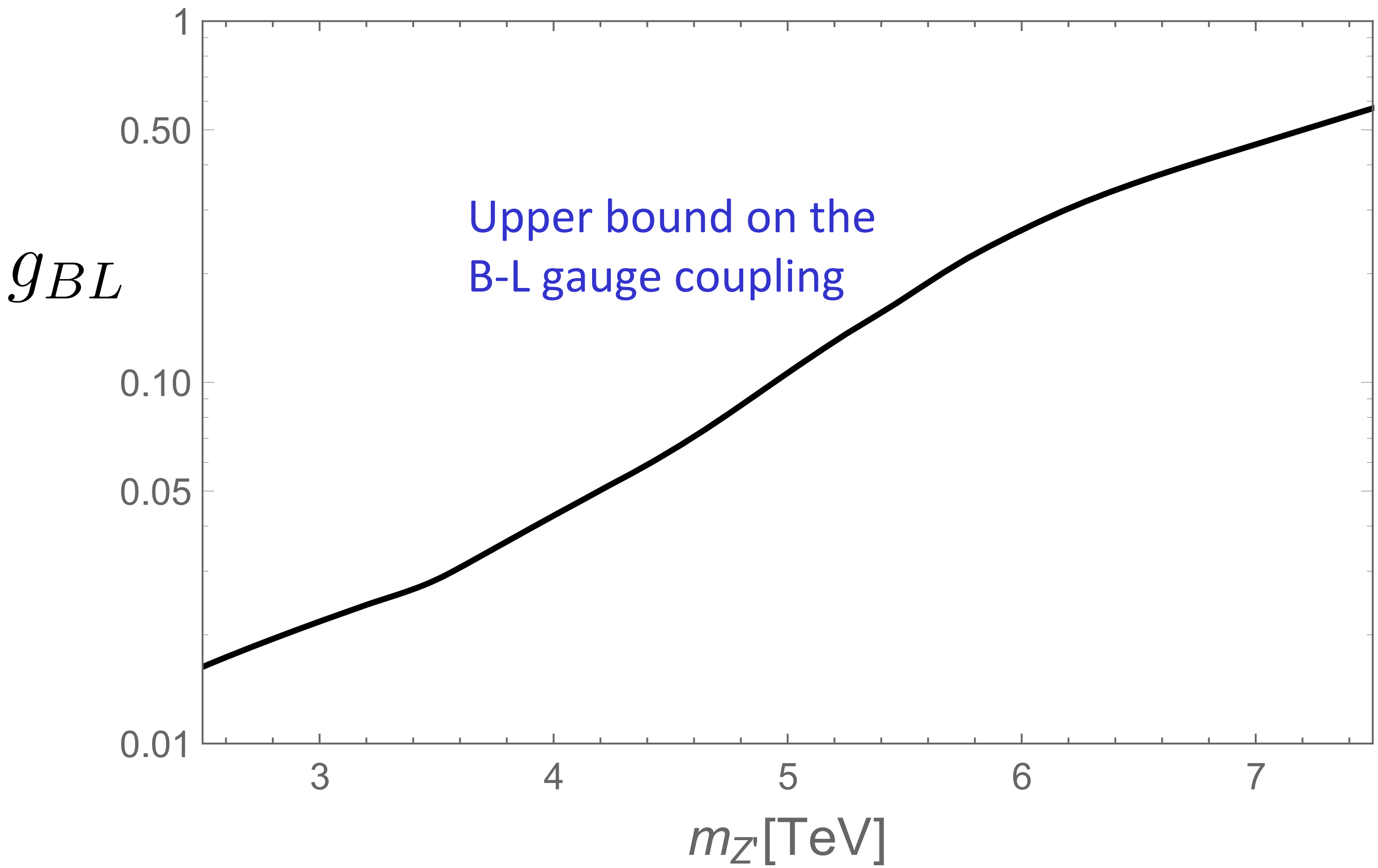
Future High-Luminosity LHC prospects (ATLAS TDR 2018)



HL-LHC will constrain the model more severely (if no Z' boson evidence)

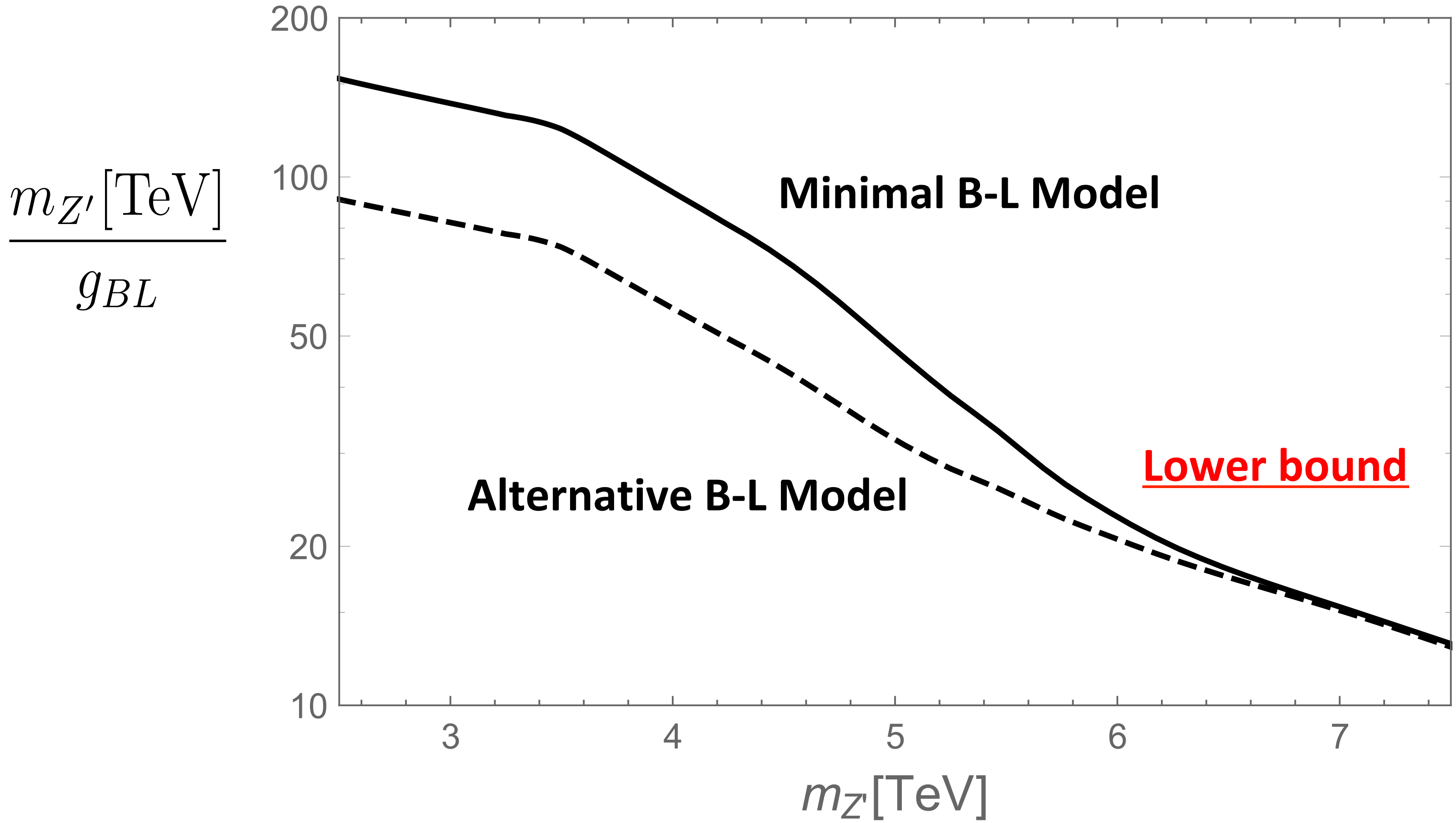
Goal:
SSM Z' mass > 6.5 TeV

Interpretation of the prospective HL-LHC into the minimal B-L model



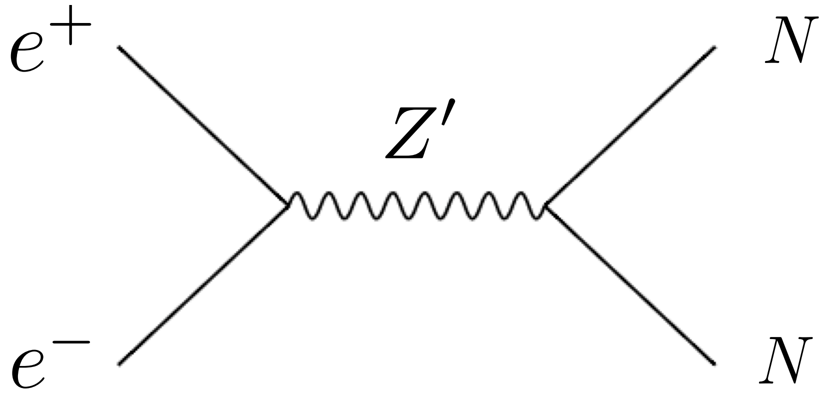
It turns out that for Z’ mass =7.5 TeV, the upper bound on the B-L gauge coupling can be as large as O(1)

HL-LHC prospective bound in terms of $\boxed{m_{Z'}/g_{BL}}$



Lower bound on $\frac{m_{Z'}[\mathrm{TeV}]}{g_{BL}}$ is dramatically reducing!

RHN pair production at the 250 GeV ILC



$$E_{\mathrm{ILC}} \ll m_{Z'}$$

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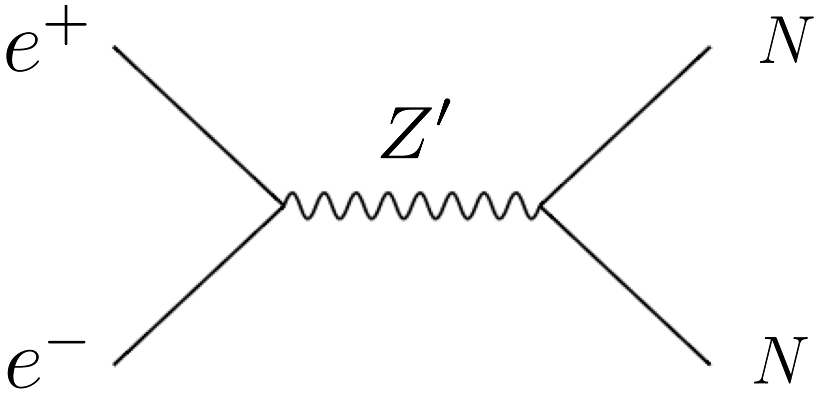

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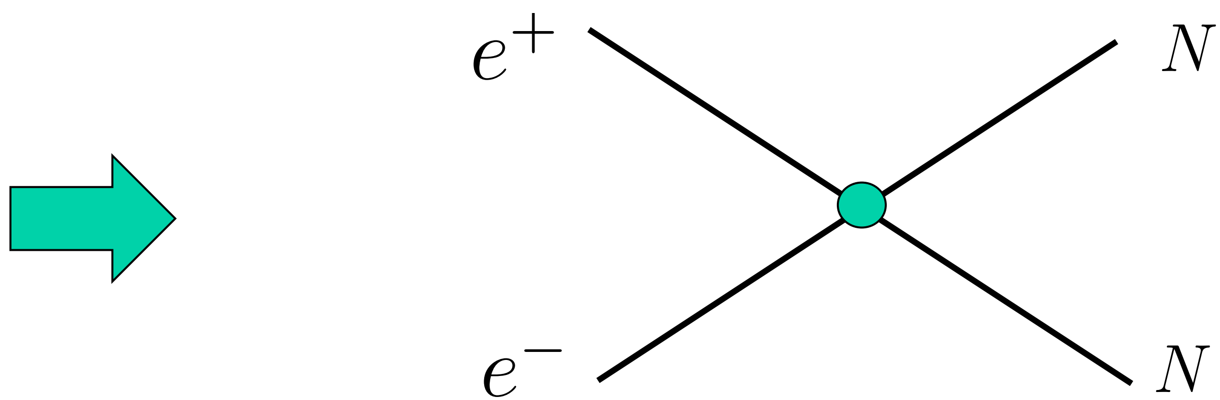
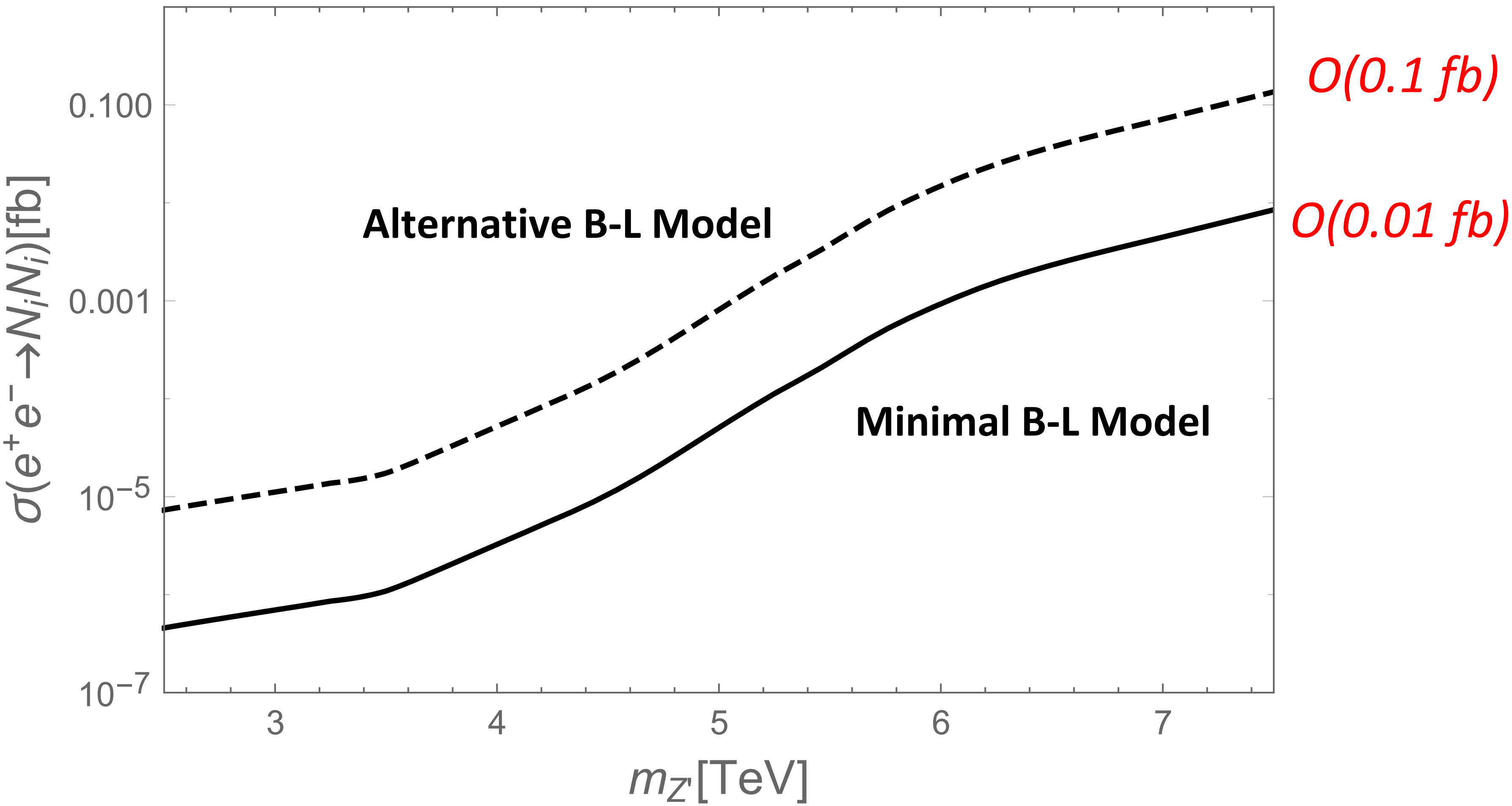


$$\boxed{Q_e Q_N \left(\frac{g_{BL}}{m_{Z'}} \right)^2}$$

RHN pair production at the 250 GeV ILC

Along the HL-LHC prospective bounds

$m_{N^i} = 50 \text{ GeV}$



For $m_{Z'} = 7.5$ TeV,

Minimal: $\sum_{i=1}^{3} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.026$ fb

Alternative: $\sum_{i=1}^{2} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.29$ fb

while satisfying the prospective HL-LHC bounds

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while satisfying the prospective HL-LHC bounds

Branching ratio of $N^i N^i \to \ell^\pm \ell^\pm jjjj$ is about 20%

while reproducing the neutrino oscillation data

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Number of events of same-sign dileptons @ the 250 GeV ILC with 2000/fb luminosity

Minimal:	10
Alternative:	116

Summary

- We have considered the Minimal/Alternative U(1) B-L extended SM

- Toward probing the Seesaw Mechanism at colliders, we have discussed a RHN pair production at the 250 GeV ILC through Z' boson

- Although the current LHC constraints/HL-LHC prospects are very severe, we can avoid the LHC constraints by taking Z' boson mass large ~ 7.5 TeV.

- We hove found a possibility to observe the smoking-gun signature of the Majorana RHN production at the 250 GeV ILC