The minimal B-L model naturally realized at TeV scale

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Introduction

In this talk, we will revisit the Coleman-Weinberg Mechanism, i.e. radiative symmetry breaking, for the electroweak symmetry.
It is well known that CW mechanism does not work in SM, and an extension of SM is inevitable.

↓

We will show that CW mechanism works beautifully in the TeV scale Minimal B-L extended SM

B-L (baryon minus lepton) number is a unique anomaly free global symmetry that SM possesses, and can be easily gauged.

Minimal B-L extended standard model is a phenomenologically viable model that realizes CW type breaking of the electroweak symmetry.

Contents

2 CW mechanism in SM

I will explain why it does not work in SM.

CW mechanism in SM

$$V_{eff} = \frac{\lambda h^4}{4} + Bh^4\left(\ln\left(\frac{h^2}{<h>^2}\right) - \frac{25}{6}\right) \qquad B = \frac{3}{64\pi^2}\left(\frac{1}{16}\left(3g^4 + 2g^2g'^2 + g'^4\right) - Y_t^4\right)$$

The extremum condition

$$\frac{dV_{eff}}{dH} = 0 \;\Rightarrow\; \lambda \sim \frac{44}{3}B$$

CW mechanism occurs under balance between the tree-level quartic coupling and the terms generated by quantum correction.

The stability condition

$$\frac{d^2V_{eff}}{dH^2} > 0 \;\Rightarrow\; \frac{1}{16}\left(2g^2m_W^2 + \left(g^2 + g'^2\right)m_Z^2\right) - Y_t^2m_t^2$$

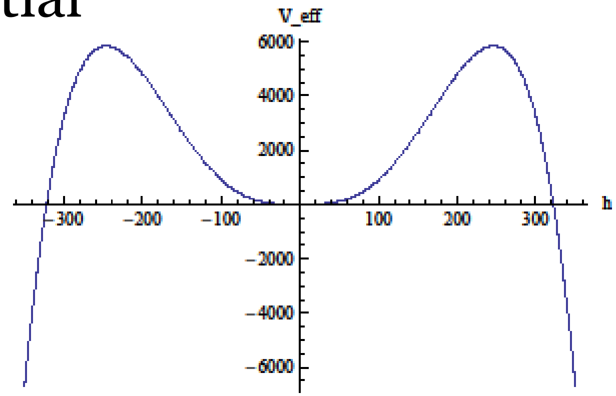
$$= \frac{2}{v^2}\left(\frac{1}{8}(2m_W^4 + m_Z^4) - m_t^4\right) > 0 \quad ?$$

However, top quark is heavy, so the stability condition is not satisfied .

$$\frac{2}{v^2}\left(\frac{1}{16}(2m_W^4+m_Z^4)-m_t^4\right)<0$$

$$\begin{aligned} m_W &= 80.4GeV, \\ m_Z &= 91.2GeV, \\ m_t &= 171.3GeV \end{aligned}$$

The effective potential is not stabilized.



In the classically conformal SM, due to the large top mass the effective potential is rendered unstable, and CW mechanism does not work.

3 Coleman Weinberg mechanism in Minimal B-L extended Standard Model

We will show that CW mechanism does work in minimal B-L extended standard model.

B-L extended SM

- **Gauge symmetry**

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

- **New particles**

ν_R right-handed neutrino

Three generations of right-handed neutrinos are necessarily introduced to make the model free from all the gauge and gravitational anomalies.

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

ϕ SM singlet scalar

The SM singlet scalar works to break the U(1)B-L gauge symmetry by its VEV.

$U(1)_{B-L}$ gauge field

- **Yukawa sector**

$$\mathcal{L} \supset -Y_D^{ij}\overline{\nu_R^i}H^\dagger l_L^j - \frac{1}{2}Y_N^i \Phi \overline{\nu_R^{ic}}\nu_R^i + h.c.$$

Dirac Yukawa Majorana Yukawa

⇒ See-saw mechanism

- **Potential**

$$V(H,\phi) = \lambda_H \left(H^\dagger H\right)^2 + \lambda \left(\phi^\dagger \phi\right)^2 + \lambda' \left(\phi^\dagger \phi\right)\left(H^\dagger H\right)$$

No mass terms are introduced.

B-L symmetry breaking

If the mixing term of SM doublet Higgs and singlet Higgs is very small, we can treat SM sector and singlet Higgs (B-L) sector separately.

$$V(H,\phi) = \lambda_H \left(H^\dagger H\right)^2 + \lambda \left(\phi^\dagger \phi\right)^2 + \lambda' \left(\phi^\dagger \phi\right) \left(H^\dagger H\right)$$

small

First, we analyze effective potential of B-L sector.

1-loop CW potential

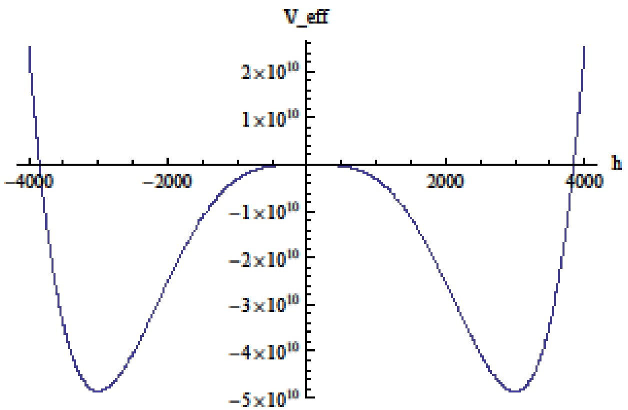
$$V_{eff}(\phi) = \frac{\lambda}{4}\phi^4 + B\phi^4\left(\ln\left(\frac{\phi^2}{<\phi>^2}\right) - \frac{25}{6}\right)$$

$$B = \frac{1}{4}\left(10\alpha_\lambda^2 + 48\alpha_{B-L}^2 - \frac{1}{2}\Sigma\alpha_N^2\right)$$

$$\alpha_\lambda = \frac{\lambda}{4\pi},\ \alpha_{B-L} = \frac{g_{B-L}^2}{4\pi},\ \alpha_N = \frac{Y_N^2}{4\pi}$$

In our model, if majorana Yukawa coupling is small, the stability condition is satisfied.

$$\alpha_{B-L}^2 - \frac{1}{96}\sum\alpha_N^{i2} > 0$$



The potential has non-trivial minimum.

B-L symmetry is broken by CW mechanism.

Electroweak symmetry breaking

Once the B-L symmetry is broken, SM Higgs doublet mass is generated through the mixing term between H and Φ in the scalar potential.

$$V(h,\phi) \sim \frac{\lambda_H}{4} h^4 + \frac{\lambda'}{4} h^2 < \phi >^2$$

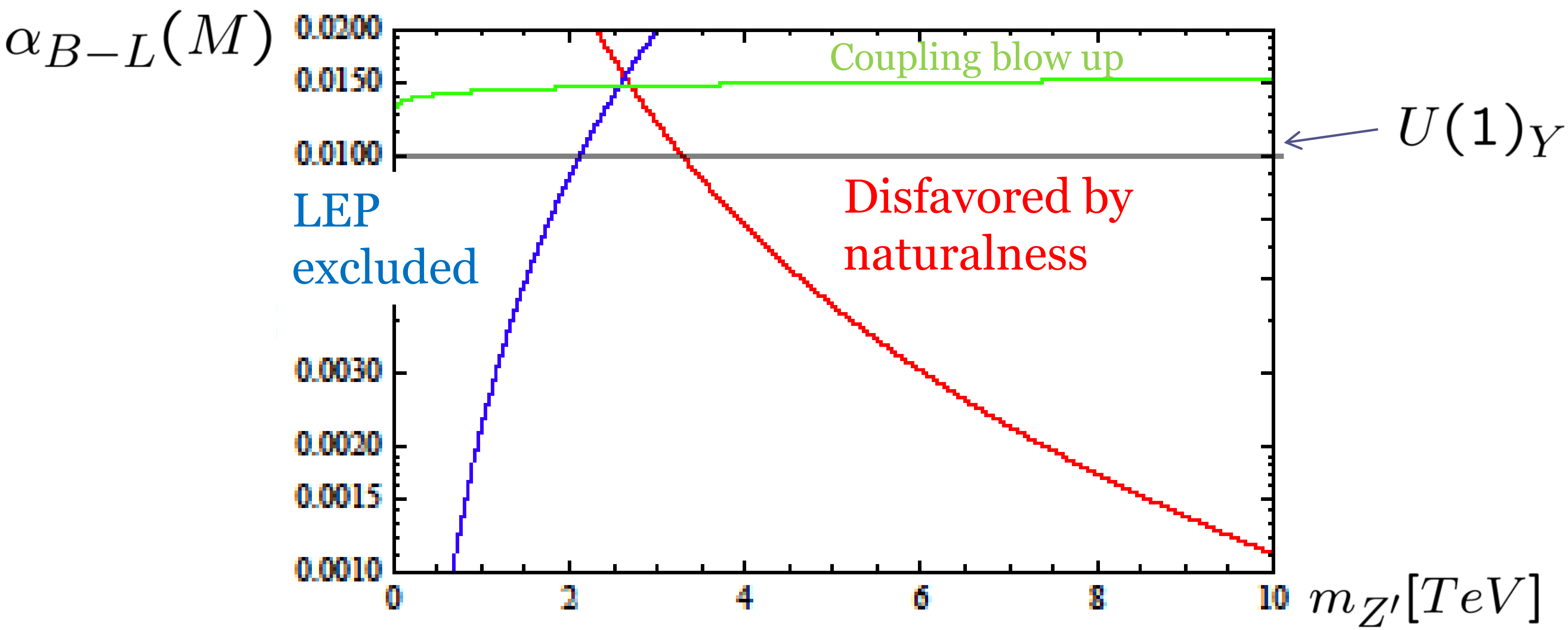
Φ has VEV M.

$$V(h) \sim \frac{\lambda_H}{4} h^4 + \frac{\lambda'}{4} M^2 h^2$$

Effective tree-level mass squared is induced, and if λ' is negative, EW symmetry breaking occurs as usual in SM.

4 Phenomenological bound for parameters

phenomenological bound



The figure indicates that if the B-L gauge coupling in not much smaller than the SM gauge couplings, Z' boson mass is around a few TeV.

Naturalness constraint

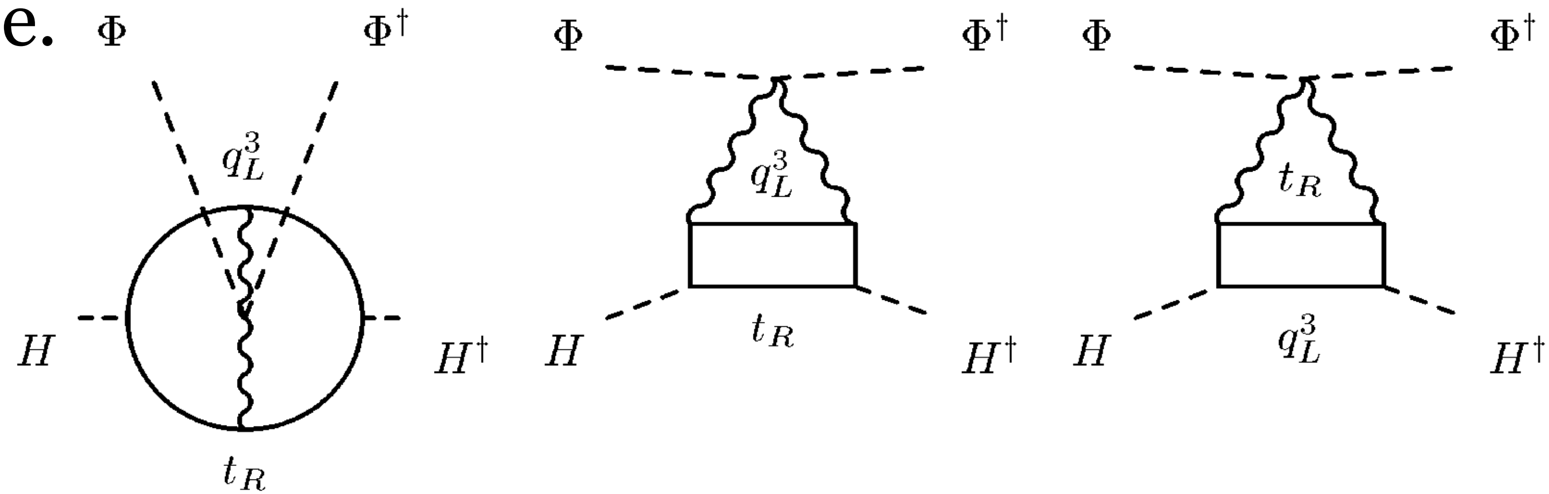
Once B-L symmetry is broken,
radiative corrections by heavy states (ν_R, Z')
may give large contribution to Higgs boson mass.

Here we calculate loop corrections of these heavy states on the Higgs boson mass
and give a severe constraint of B-L breaking scale.

Naturalness constraint

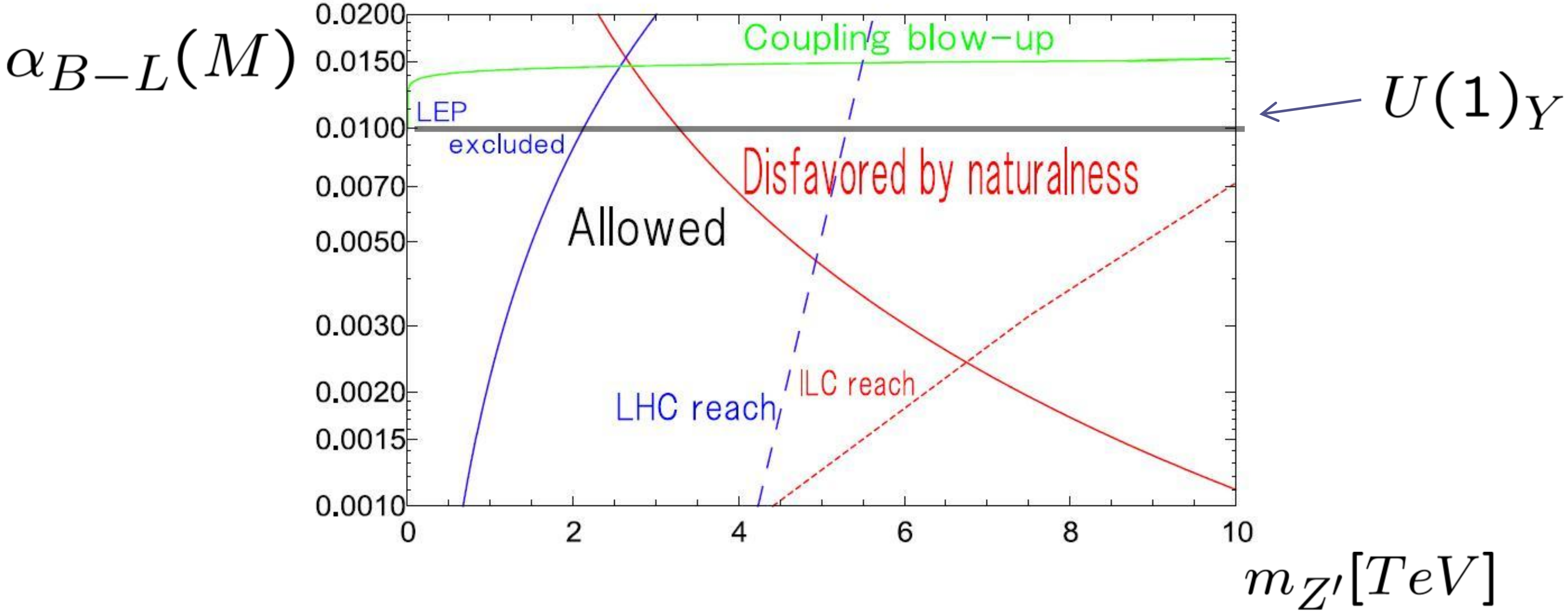
The dominant contribution comes from 2-loop effect involving the top-quarks and the Z' boson, because of the large top Yukawa coupling.

This contribution should be smaller than the EW scale.



$$\Delta m_h^2 = \frac{g_{B-L}^2 Y_t^2 m_{Z'}^2}{32\pi^4} \log \frac{m_{pl}^2}{m_{Z'}^2} \lesssim (174GeV)^2$$

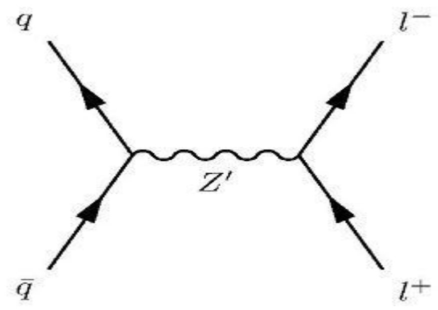
Allowed parameter region together with search reach at future colliders



The figure indicates that if the B-L gauge coupling is not much smaller than the SM gauge couplings, mass of Z' is predicted to be **a few TeV** and **Z' gauge boson can be discovered by near future collider experiments.**

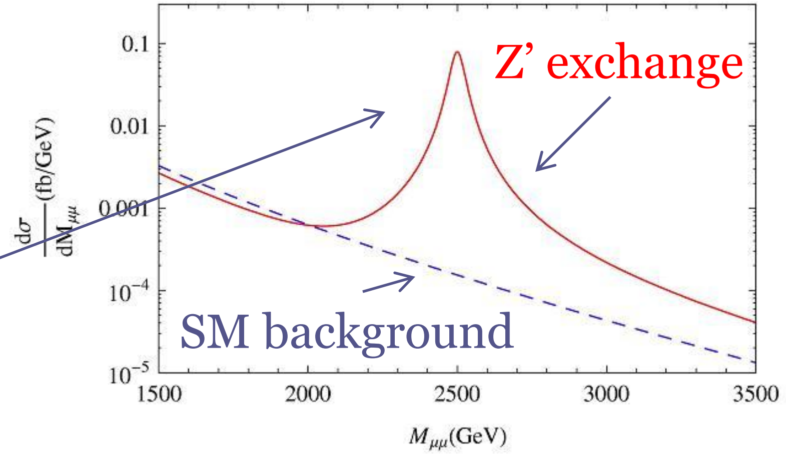
Z' boson at LHC

We calculate the dilepton production cross section through the Z' boson exchange together with the SM processes mediated by Z boson and photon.



$$\frac{d\sigma(pp\to \ell^+\ell^- X)}{dM_{ll}} = \sum_{a,b}\int_{-1}^{1} d\cos\theta \int_{\frac{M_{ll}^2}{E_{\rm CMS}^2}}^{1} dx_1 \frac{2M_{ll}}{x_1 E_{\rm CMS}^2} f_a(x_1,Q^2) f_b\left(\frac{M_{ll}^2}{x_1 E_{\rm CMS}^2}, Q^2\right) \frac{d\sigma(\bar{q}q\to \ell^+\ell^-)}{d\cos\theta}$$

$$E_{CMS} = 14TeV$$



A clear peak of Z' resonance

$$\alpha_{B-L} = 0.008$$
$$m_{Z'} = 2.5TeV$$

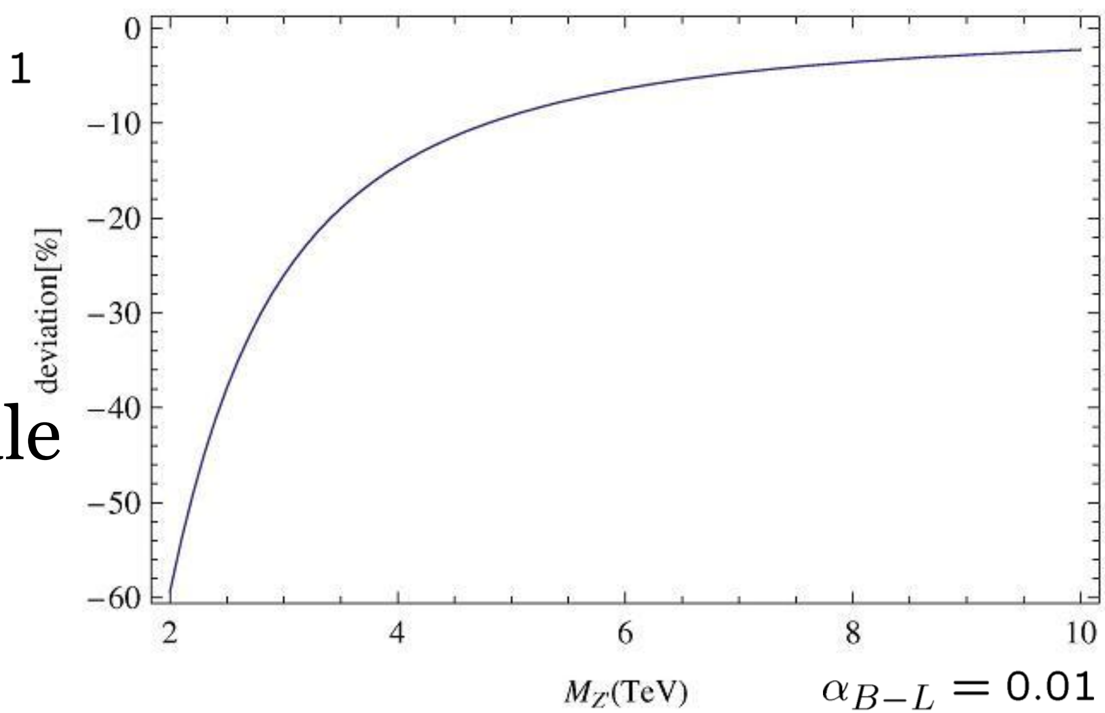
Z' boson at ILC (International Linear Collider)

We calculate the cross section of the process $e^+e^- \to \mu^+\mu^-$ at the ILC with a collider energy $\sqrt{s}$ =1 TeV.

Deviation of cross section in our model from the SM one is shown as a function of Z' boson mass.

$$\frac{\sigma(e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-)}{\sigma_{SM}(\sigma(e^+e^- \to \gamma, Z \to \mu^+\mu^-)} - 1$$

Assuming the ILC is accessible to 1% deviation, the TeV scale Z' boson can be discovered at ILC.



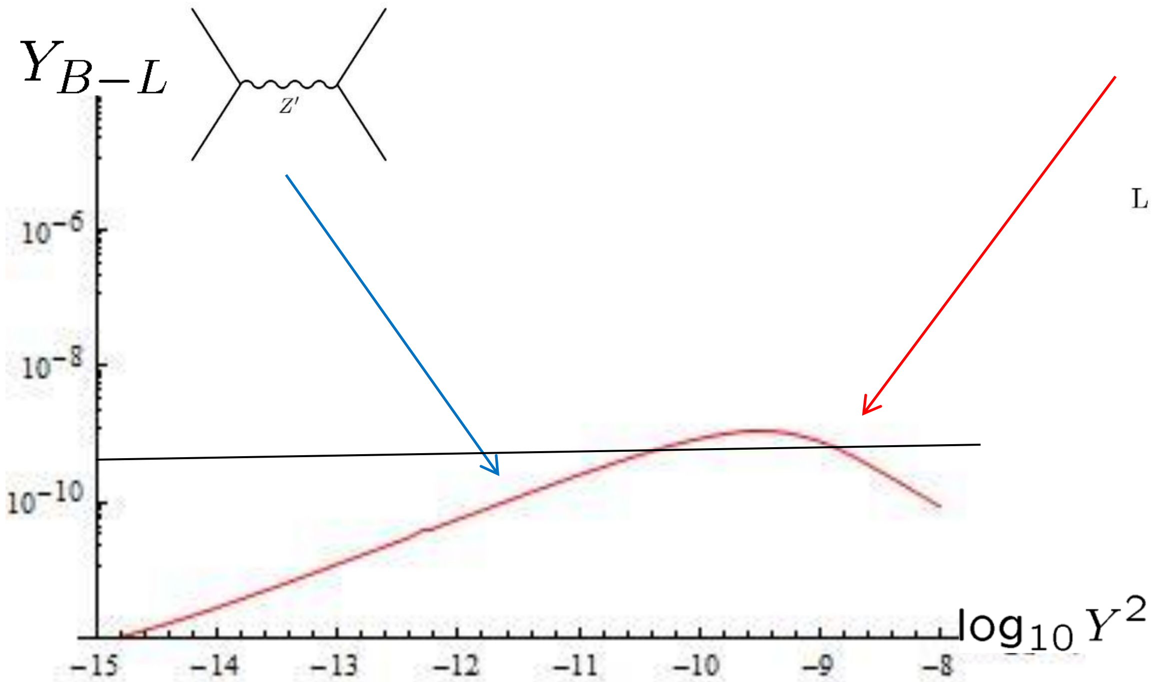
Conclusions

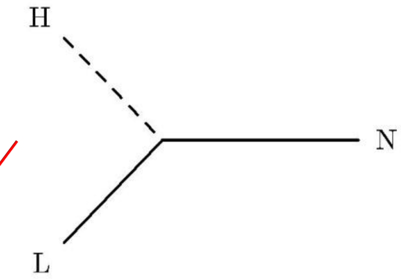
- CW mechanism does not work in classically conformal SM since the large top Yukawa coupling destabilizes the effective Higgs potential. SM needs to be extended.
- **B-L symmetry and EW symmetry are broken by CW mechanism.**
- Our model naturally predicts B-L breaking scale at TeV. Z' boson can be discovered in the near future.

TeV scale leptogensis

Suppression of Z' exchange process

Wash out for inverse decay





$$m_{Z'} = 2.5TeV$$
$$m_N = 1TeV$$
$$\alpha_{B-L} = 0.008$$
$$\varepsilon = 0.01$$

We estimate the Yukawa coupling by neutrino oscillation.

➡ $Y^2 \sim 10^{-11}$