Phenomenology of an $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model

Takaaki Nomura (KIAS)

Based on: arXiv: 1606.03084 C.H.Chen, T.N.,
& works in progress

2016-10-24 The 6th KIAS Workshop on Particle Physics and Cosmology/
The 2nd Durham-KEK-KIPMU-KIAS Joint Workshop

Non-Abelian gauge extension is interesting

→ **Inducing Z' and $W'^{\pm}$ bosons**

Ex)

Left right symmetric model $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- ❖Left(right)-handed fermions belong to $SU(2)_{L(R)}$ doublets
- ❖Scalar sector with bi-doublet + triplets $\Delta_{L,R}$
- ❖SSB: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_{EM}$
- ❖Z' mass should be > 3 TeV by LHC constraints

It is worth considering SU(2)×SU(2) model

with more simple Higgs sector

$SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model with 2 Higgs doublets

→ Higgs fields with $SU(2)_1$ and $SU(2)_2$ doublets

- Z'(W') masses can be lighter than LR model
- $SU(2)_2$ multiplet fermion is required for W' decay
- "4th generation" fermion with new SU(2) doublet is possible
- Only one new heavy neutral Higgs

Collider physics will be interesting

Flavor physics will be also interesting

(It will not be discussed in this talk)

1. Introduction
2. Model
3. Collider physics
4. Summary

The structure of The model

❖ $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ gauge symmetry

❖ Particle contents

	Fermions					Scalar	
	Q_L	u_R	d_R	L_L	e_R	H_1	H_2
SU(3)	**3**	**3**	**3**	**1**	**1**	**1**	**1**
$SU(2)_1$	**2**	**1**	**1**	**2**	**1**	**2**	**1**
$SU(2)_2$	**1**	**1**	**1**	**1**	**1**	**1**	**2**
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	1/2	1/2

SM fermions + scalar

	Fermions					
	Q'_L	u'_R	d'_R	L'_L	e'_R	ν_R
SU(3)	**3**	**3**	**3**	**1**	**1**	**1**
$SU(2)_1$	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_2$	**2**	**1**	**1**	**2**	**1**	**1**
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0

"4th generation "

➢ $SU(2)_2$ doublet fermion is required to make W' to decay

$W_\mu^{1,2,3}$: $SU(2)_1$ gauge fields $W'^{1,2,3}_\mu$: $SU(2)_2$ gauge fields

2.Model

Scalar sector

$$H_1 = \begin{pmatrix} G_1^+ \\ (v_1 + \rho_1 + iG_1)/\sqrt{2} \end{pmatrix} \qquad H_2 = \begin{pmatrix} G_2^+ \\ (v_2 + \rho_2 + iG_2)/\sqrt{2} \end{pmatrix}$$

$SU(2)_1$ doublet **$SU(2)_2$ doublet**

$$V = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2 + \lambda_{12} H_1^\dagger H_1 H_2^\dagger H_2$$

$\rho_2(\rho_1) \sim H(h_{SM})$ (Small mixing)

Yukawa coupling

$$\mathcal{L}_Y = y_U^{ai} \bar{Q}_L^a u_R^i \tilde{H}_1 + y_D^{ai} \bar{Q}_L^a d_R^i H_1 + y_E^{ai} \bar{L}^a e_R^i H_1 + y_N^a \bar{L}_L^a \nu_R \tilde{H}_1$$
$$+ Y_U^i \bar{Q}'_L u_R^i \tilde{H}_2 + Y_D^i \bar{Q}'_L d_R^i H_2 + Y_E^i \bar{L}'_L e_R^i H_2 + Y_N \bar{L}' \nu_R \tilde{H}_2 + h.c.$$

(i=1-4, a=1-3)

Heavy fermion mass with H_2 VEV : $m_F \approx \frac{y_F}{\sqrt{2}} v_2$

Yukawa coupling

$$\mathcal{L}_Y = y_U^{ai}\bar{Q}_L^a u_R^i \tilde{H}_1 + y_D^{ai}\bar{Q}_L^a d_R^i H_1 + y_E^{ai}\bar{L}^a e_R^i H_1 + y_N^a \bar{L}_L^a \nu_R \tilde{H}_1$$
$$+ Y_U^i \bar{Q}'_L u_R^i \tilde{H}_2 + Y_D^i \bar{Q}'_L d_R^i H_2 + Y_E^i \bar{L}'_L e_R^i H_2 + Y_N \bar{L}' \nu_R \tilde{H}_2 + h.c.$$

(i=1-4, a=1-3)

Heavy fermion mass with H_2 VEV : $m_F \approx \frac{y_F}{\sqrt{2}} v_2$

- ✓ Mixing between SM fermion and heavy fermions is induced
- ✓ In this talk, we assume mixing is sufficiently small
- ✓ A Heavy fermion decays like U → W^- d^i etc. via mixing effect

Gauge bosons

❖Charged gauge boson W' (W)

No mixing at tree level

$$W'^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(W'^{1}_{\mu} \mp W'^{2}_{\mu}), \quad W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(W^{1}_{\mu} \mp W^{2}_{\mu})$$

$$m_{W'} = \frac{g_2}{2} v_2, \quad m_W = \frac{g}{2} v_1$$

❖Neutral gauge boson + photon

$$\begin{pmatrix} W'^{3}_{\mu} \\ W^{3}_{\mu} \\ B_{\mu} \end{pmatrix} = \begin{pmatrix} c_X c_Z + s_X s_W s_Z & c_X s_Z - s_X s_W c_Z & s_X c_W \\ -c_W s_Z & c_W c_Z & s_W \\ -s_X c_Z + c_X s_W s_Z & -s_X s_Z - c_X s_W c_Z & c_X c_W \end{pmatrix} \begin{pmatrix} Z'_{\mu} \\ Z_{\mu} \\ A_{\mu} \end{pmatrix}$$

Mass eigenstates

$$c_X \equiv \cos\theta_X = \frac{g_2}{\sqrt{g_2^2 + g_Y^2}}, \quad s_X \equiv \sin\theta_X = \frac{g_Y}{\sqrt{g_2^2 + g_Y^2}} \quad g' = \frac{g_Y}{c_X}$$

$c_Z(s_Z)=\cos\theta_Z(\sin\theta_Z)$: mixing for Z-Z'

❖Z' couplings to fermions (θ_Z<< 1)

$$L \supset \bar{F}\left(\frac{g_2}{c_X}(T_3^{(2)} - s_X^2 Q_F)\right)\gamma^{\mu} Z'_{\mu} F + \bar{f}\left(\frac{g_2}{c_X} s_X^2 (T_3^{(1)} - Q_F)\right)\gamma^{\mu} Z'_{\mu} f$$

"4G" SM

Gauge bosons

❖Z,Z' boson masses

$$M^2_{Z_1Z_2} = \begin{pmatrix} \frac{v_1^2}{4}(g^2+g'^2) & \frac{v_1^2 g'^2}{4}\sqrt{\frac{g^2+g'^2}{g_2^2-g'^2}} \\ \frac{v_1^2 g'^2}{4}\sqrt{\frac{g^2+g'^2}{g_2^2-g'^2}} & \frac{v_2^2 g_2^4 + v_1^2 g'^4}{4(g_2^2-g'^2)} \end{pmatrix} \equiv \begin{pmatrix} m^2_{Z_1} & m^2_{Z_1Z_2} \\ m^2_{Z_1Z_2} & m^2_{Z_2} \end{pmatrix}$$

$$\Rightarrow \begin{cases} m^2_{Z/Z'} = \frac{m^2_{Z_1}+m^2_{Z_2}}{2} \pm \frac{1}{2}\sqrt{(m^2_{Z_2}-m^2_{Z_1})+4m^4_{Z_1Z_2}} \\ \sin 2\theta_Z = \frac{2m^2_{Z_1Z_2}}{m^2_{Z'}-m^2_Z} \end{cases}$$

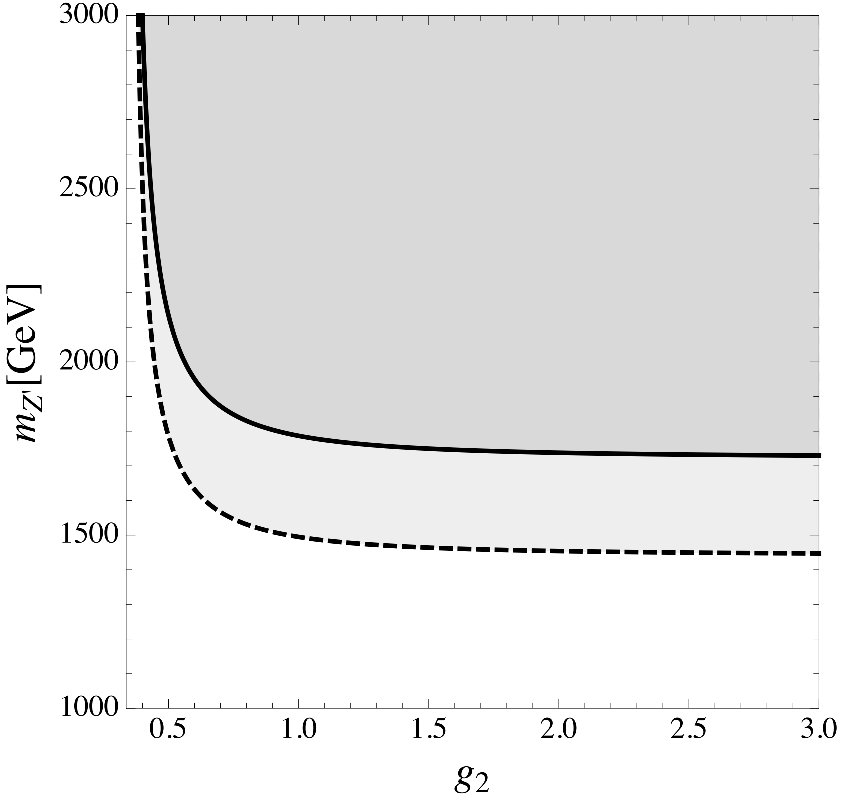
❖Constraint from ρ parameter

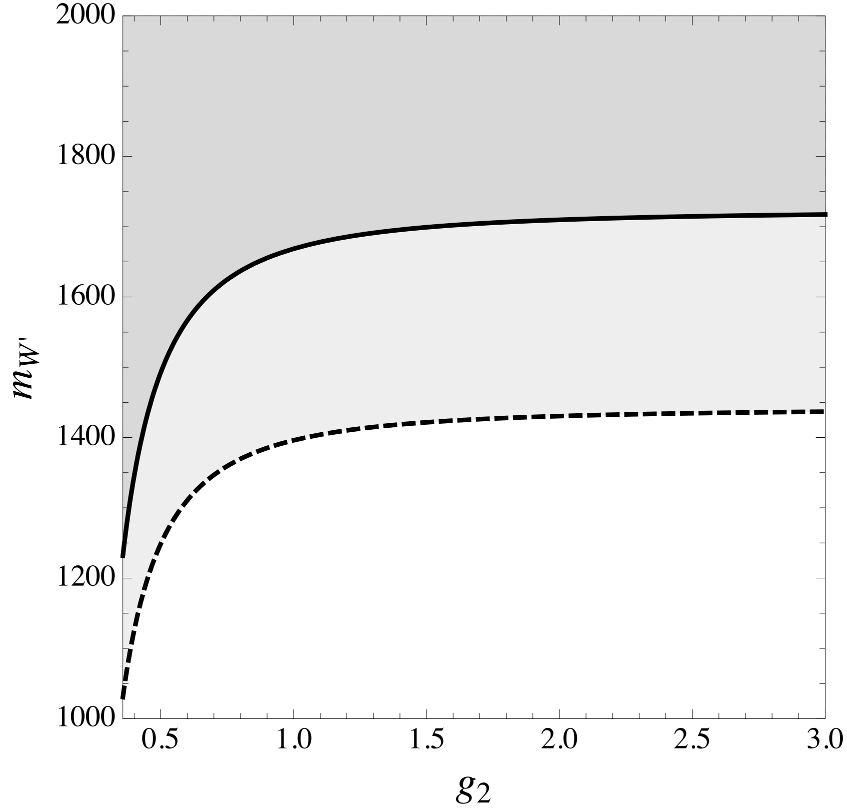
$$\rho^{\exp} = 1.00040^{+0.0003}_{-0.0004} \Rightarrow m_{Z'} > \sqrt{\frac{1}{4}+\frac{g'^4}{g_2^2-g'^2}}\,\frac{m_Z}{\sqrt{7\times 10^{-4}}}$$

1. Introduction
2. Model
3. Collider physics
4. Summary

Collider physics for Z’ boson

Constraint of Z'(W') mass from ρ parameter

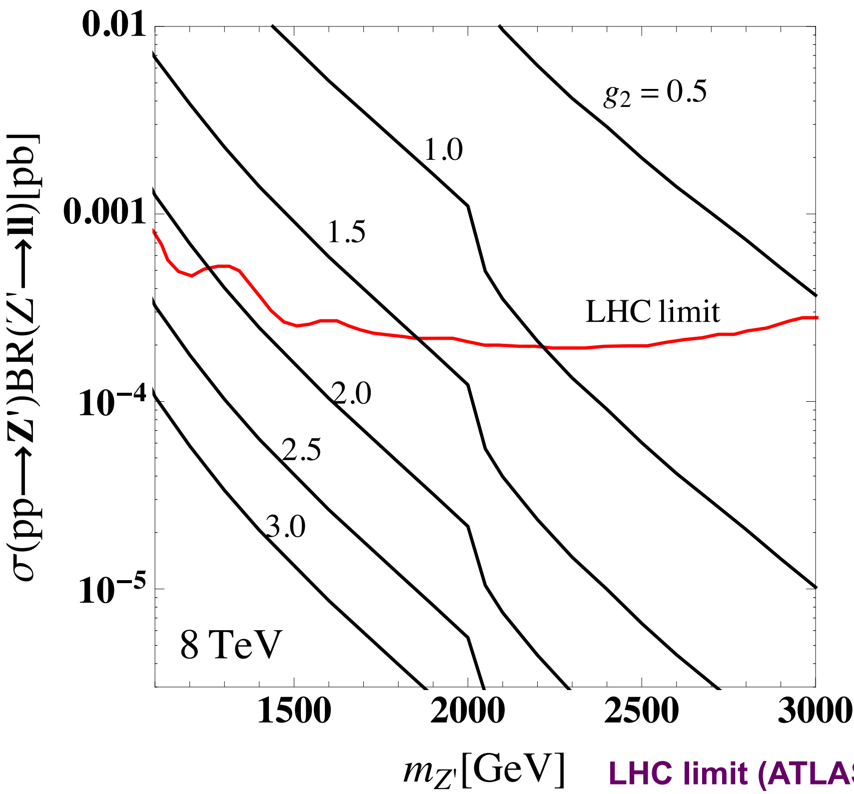




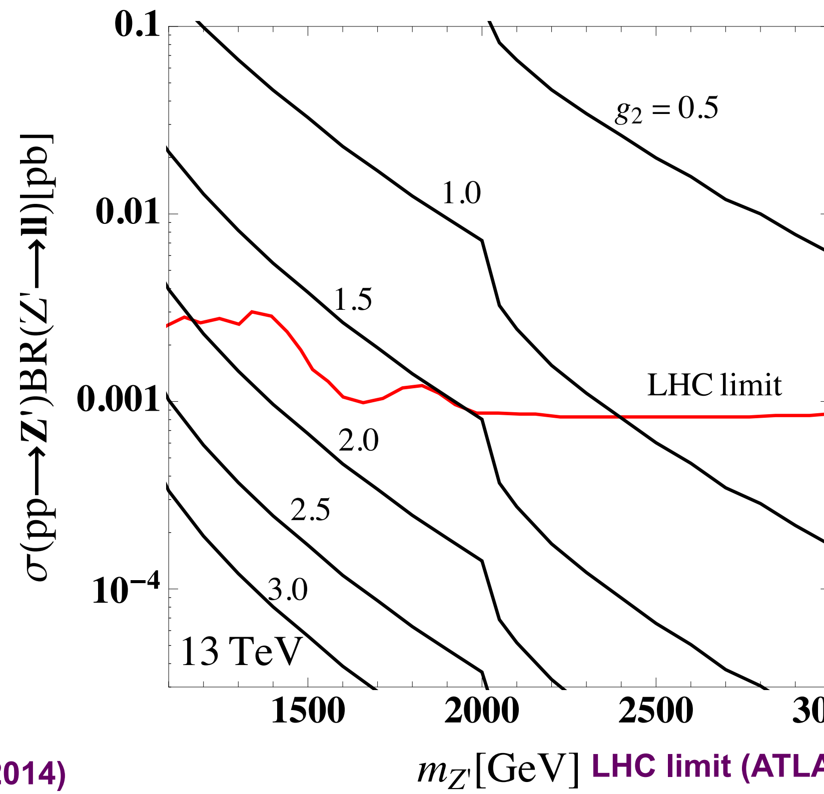
- ✓ Z' should be heaver than ~1.7(1.5) TeV from 1(2)σ level constraint of ρ
- ✓ W' is slightly lighter than Z'

Constraints from Z' to dilepton

$$m_{E'} = m_{N'} = 400\ GeV, \quad m_{U'} = m_{D'} = 1\ TeV$$



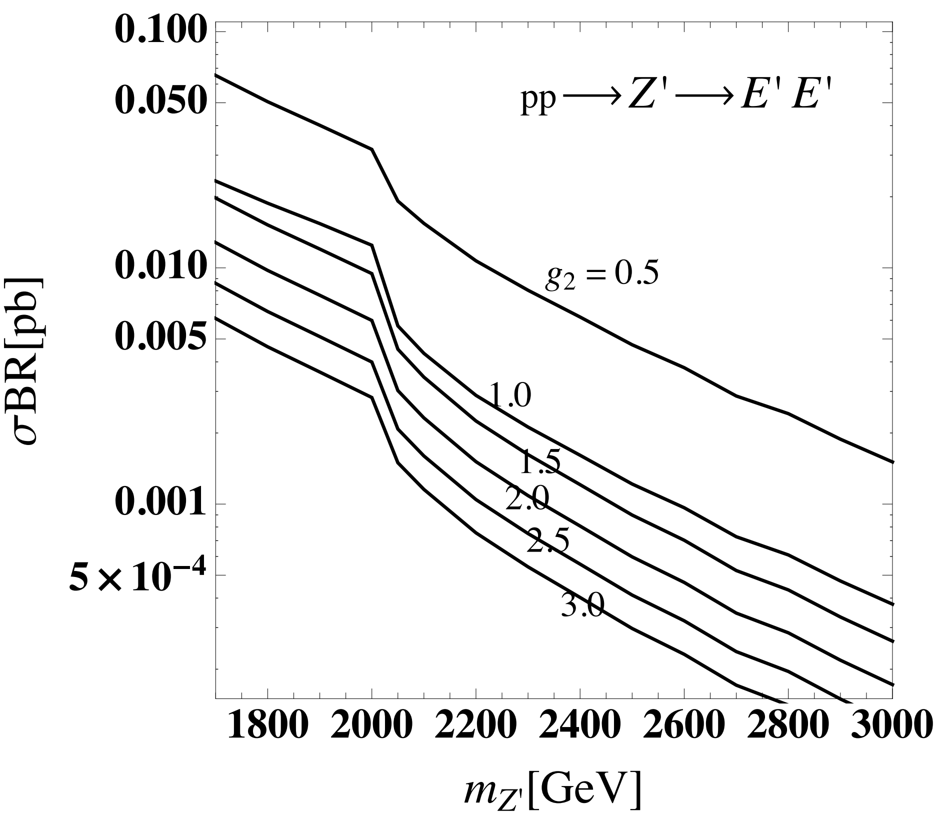
LHC limit (ATLAS 2014)

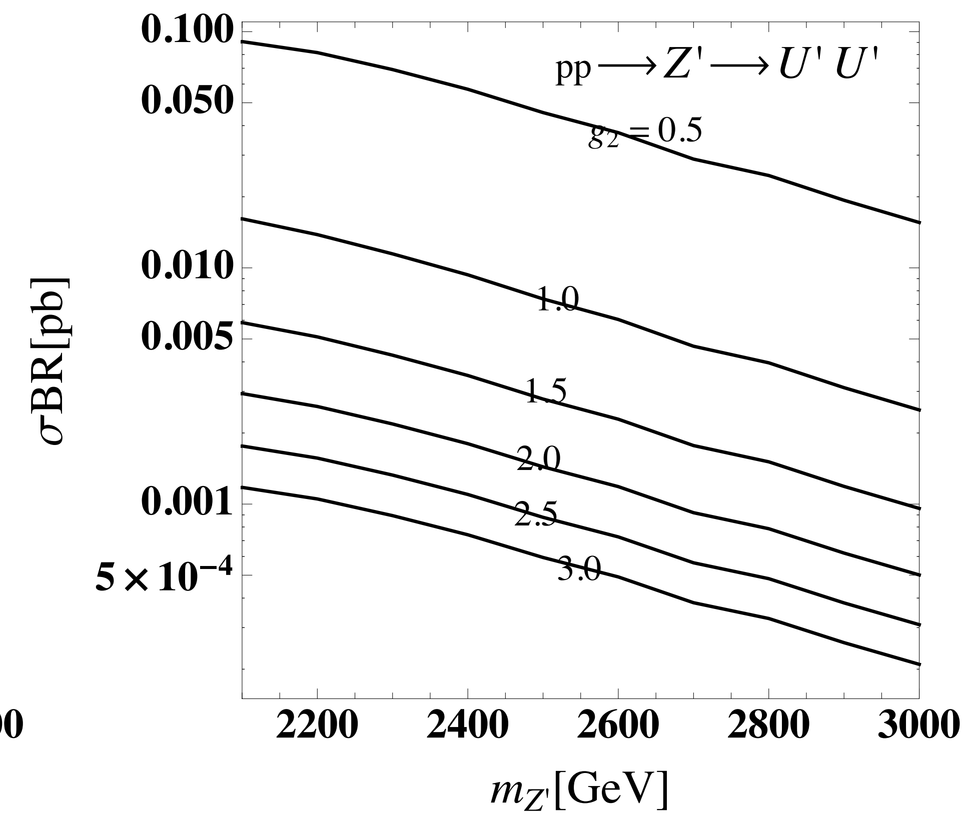


LHC limit (ATLAS 2015)

- ✓ Constraints are stronger for smaller g_2
- ✓ For $g_2>2$, ρ parameter constraint is stronger

New fermion generation via Z’





- ✓ O(1)~O(10)fb cross sections can be obtained considering the constraints
- ✓ E’,U’ are decay into SM leptons and quarks respectively

Collider physics for heavy Higgs

Gluon fusion production of heavy Higgs

❖Effective Lagrangian for gluon fusion

$$L_{sgg} = \frac{\alpha_s}{8\pi}\left(\sum_{q'} \frac{g_2}{4c_X m_{Z'}} A_{1/2}(\tau_{q'})\right) H G^{a\mu\nu} G^a_{\mu\nu}$$

$$\left(m_{q'} = \frac{y_{q'}}{\sqrt{2}} v_2, \quad m_{Z'} \approx \frac{g_2 v_2}{2c_X} \right)$$

❖Decay channel of H

$$\Gamma(H \to gg) = \frac{\alpha_s m_H^3}{32\pi^3} \left| \sum_{q'} \frac{g_2}{4c_X m_{Z'}} A_{1/2}(\tau_{q'}) \right|^2$$

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha m_H^3}{256\pi^3} \left| -\sum_f \frac{g_2 Q_f^2 N_c}{4c_X m_{Z'}} A_{1/2}(\tau_f) + \frac{g_2}{2m_{W'}} A_1(\tau_{W'}) \right|^2$$

$$\Gamma\left(H \to F\bar{F}\right) = \frac{y_F^2}{16\pi} m_H \sqrt{1 - \frac{4m_F^2}{m_H^2}}$$

$$\left(y_F \approx \frac{g_2 m_F}{\sqrt{2} m_{Z'} c_X} \right)$$

Cross section & BRs for some BPs

❖ m_H=500 GeV $m_{E'} = m_{N'} = 400\, GeV, \quad m_{U'} = m_{D'} = 1\, TeV, \quad m_{Z'} = 2\, TeV$

	$\sigma(pp \to H)$	$BR(H \to gg)$	$BR(H \to \gamma\gamma)$	$BR(H \to E'E')$	$BR(H \to U'U'(D'D'))$
$g_2 = 1.0$	3.5 fb	0.96	0.039	0	0
$g_2 = 1.5$	7.3 fb	0.96	0.042	0	0
$g_2 = 2.0$	13. fb	0.96	0.043	0	0
$g_2 = 2.5$	20. fb	0.96	0.044	0	0

- ✓ O(10) fb production cross section for large g_2
- ✓ H mainly decay into gg channel
- ✓ Two photon BR is sizable
- ✓ $H \to \gamma\gamma$ would be tested by sufficient luminosity

Cross section & BRs for some BPs

❖ m_H=1.0 TeV

	$\sigma(pp \to H)$	$BR(H \to gg)$	$BR(H \to \gamma\gamma)$	$BR(H \to E'E')$	$BR(H \to U'U'(D'D'))$
$g_2 = 1.0$	0.45 fb	3.5×10^{-3}	1.4×10^{-4}	0.66	0
$g_2 = 1.5$	0.94 fb	3.5×10^{-3}	1.5×10^{-4}	0.66	0
$g_2 = 2.0$	1.6 fb	3.5×10^{-3}	1.5×10^{-4}	0.66	0
$g_2 = 2.5$	2.5 fb	3.5×10^{-3}	1.5×10^{-4}	0.66	0

- ✓ O(1) fb production cross section for large g_2
- ✓ H mainly decay into heavy charged leptons
- ✓ ~33% BR for heavy neutrino channel
- ✓ H→E’E’→SM leptons + W/Z would be tested

Summary and Discussions

- ✧ **We consider a $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model**
- ✧ **Scalar sector is simple with $SU(2)_{1,2}$ doublets**
- ✧ **Z' and W' boson can be < 2 TeV**
- ✧ **We analyzed Heavy Higgs production and signature**
- ✧ **More detailed analysis will be carried out**
- ✧ **Flavor physics: in progress**

Thanks for listening !

Appendix

Decay width of Z'

$$\bar{f}\gamma^{\mu}(C_L^{ff'}P_L + C_R^{ff'}P_R)f'Z'_{\mu},$$

$$\begin{aligned}
\Gamma_{Z'\to\bar{f}f'} =& \frac{m_{Z'}}{24\pi}\lambda(m_f^2/m_{Z'}^2, m_{f'}^2/m_{Z'}^2) \\
&\times\left[\left((C_L^{ff'})^2+(C_R^{ff'})^2\right)\left(2-\frac{m_f^2+m_{f'}^2}{m_{Z'}^2}-\frac{(m_f^2-m_{f'}^2)^2}{m_{Z'}^4}\right)+12\frac{m_f m_{f'}}{m_{Z'}^2}C_L^{ff'}C_R^{ff'}\right] \\
=& \frac{m_{Z'}}{12\pi}\lambda(m_f^2/m_{Z'}^2, m_{f'}^2/m_{Z'}^2) \\
&\times\left[\left((C_V^{ff'})^2+(C_A^{ff'})^2\right)\left(2-\frac{m_f^2+m_{f'}^2}{m_{Z'}^2}-\frac{(m_f^2-m_{f'}^2)^2}{m_{Z'}^4}\right)+6\frac{m_f m_{f'}}{m_{Z'}^2}\left((C_V^{ff'})^2-(C_A^{ff'})^2\right)\right]
\end{aligned}$$

$$\lambda(x,y) = \sqrt{1+x^2+y^2-2x-2y-2xy}.$$

Z’ production cross section at LHC 13 TeV