LHC Phenomenology of Z' and Z'' bosons in the $SU(4)_L \times U(1)_X$ model

Soo-hyeon Nam

National Institute of Supercomputing and Networking
Korea Institute of Science and Technology Information

in collaboration with Prof. K.Y. Lee

based on
arXiv:1412.1541
Phys.Rev. D82 (2010) 105027

January 29, 2015

< YongPyong-High1 2015 Joint Winter Conference>

Outline

Introduction

Earlier studies on the models with $SU(4)_L \times U(1)_X$ gauge group

- Electroweak unification could be obtained with its subgroup $SU(2)_L \times SU(2)_R \times U(1)$ and $\sin^2\theta_W = 1/4$ in the left-right symmetry limit. (Fayyazuddin and Riazuddin, 1984, 2004)
- Hypothetical large neutrino magnetic moment around 10^{-11} of the Bohr magneton is naturally compatible with acceptably small neutrino mass of a few eV. (Voloshin, 1988)
- Explain why we only observe three families of fermions in nature, in a sense that anomaly cancellation is achieved when $N_f = N_c = 3$. (Pleitez, 1988; Foot, Hoang, Tran, 1994; Pisano, Pleitez, 1995)
- Little Higgs mechanism has been implemented in $SU(4)_L \times U(1)_X$ gauge group as an alternative solution to the hierarchy and fine-tuning issues. (Kaplan and Schmaltz, 2003)
- and more...

Introduction

Why study Z'?

- Existence of an extra neutral gauge boson Z' is a common feature of many new physics (NP) models beyond the standard model (SM).
- Therefore, the LHC has been pushing ahead on the neutral heavy resonances in various NP models.
- Recently, CMS and ATLAS collaborations have reported the search results for the Z' through the dilepton channels at $\sqrt{s}=$7 and 8 TeV with the data up to 20 fb^{-1}, and also through $t\bar{t}$, $\tau^+\tau^-$, and dijet channels with similar or less integrated luminosities
- In this talk, we consider the LHC Phenomenology of Z' and Z'' bosons appeared in the $SU(4)_L \times U(1)_X$ model with little Higgs mechanism by embedding anomaly-free set of fermions.
- Still, our result can be applicable to the models with regular Higgs mechanism as well.

$SU(4)_L \times U(1)_X$ model with little Higgs

One possible parametrization of the non-linear sigma model fields Φ_i with general f_i ($SU(4)$ breaking is not aligned):

$$\Phi_1 = e^{+i\mathcal{H}_u \frac{f_2}{f_1}} \begin{pmatrix} 0 \\ 0 \\ f_1 \\ 0 \end{pmatrix} \qquad \Phi_2 = e^{-i\mathcal{H}_u \frac{f_1}{f_2}} \begin{pmatrix} 0 \\ 0 \\ f_2 \\ 0 \end{pmatrix}$$

$$\Phi_3 = e^{+i\mathcal{H}_d \frac{f_4}{f_3}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f_3 \end{pmatrix} \qquad \Phi_4 = e^{-i\mathcal{H}_d \frac{f_3}{f_4}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f_4 \end{pmatrix}$$

where

$$\mathcal{H}_u = \begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & h_u & \begin{matrix} 0 \\ 0 \end{matrix} \\ h_u^\dagger & 0 & 0 \\ \begin{matrix} 0 & 0 \end{matrix} & 0 & 0 \end{pmatrix} / f_{12} \qquad \mathcal{H}_d = \begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} & h_d \\ \begin{matrix} 0 & 0 \end{matrix} & 0 & 0 \\ h_d^\dagger & 0 & 0 \end{pmatrix} / f_{34}$$

$$f_{ij} = \sqrt{f_i^2 + f_j^2}, \qquad \langle h_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_u \\ 0 \end{pmatrix}, \qquad \langle h_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_d \end{pmatrix}$$

$SU(4)_L \times U(1)_X$ model with little Higgs

- Neutral Gauge Boson Masses:

$$M_Z^2 = \frac{g^2 v^2}{4c_W^2}\left(1 - \frac{t_W^4}{4}\frac{v^2}{f^2}\right), \quad M_{Z'}^2 = (g^2 + g_X^2)f^2 - M_Z^2, \quad M_{Z''}^2 = \frac{1}{2}g^2 f^2$$

where

$$c_W \equiv \cos\theta_W = \sqrt{(g^2 + g_X^2)/(g^2 + 2g_X^2)},$$

$$v_1^2 \equiv v_u^2 - \frac{v_u^2}{3f^2}\left(\frac{f_2^2}{f_1^2} + \frac{f_1^2}{f_2^2} - 1\right), \quad v_2^2 \equiv v_d^2 - \frac{v_d^2}{3f^2}\left(\frac{f_4^2}{f_3^2} + \frac{f_3^2}{f_4^2} - 1\right),$$

$$f_{12} = f_{34} = f \gg \; v^2 = v_1^2 + v_2^2 \; \gg \triangle v^2 = v_1^2 - v_2^2,$$

$$\text{(In general,} \quad f_{12} \neq f_{34}, \quad f_{12}^2 - f_{34}^2 = \left(v_1^2 - v_2^2\right)\left(1 + O(v^2/f^2)\right) \ll f_{ij}^2\text{)}$$

$SU(4)_L \times U(1)_X$ model with little Higgs

- Neutral Current

$$\mathcal{L}_{NC} = -eQ\,(\bar{\psi}\gamma^{\mu}\psi)\,A_{\mu} + \frac{g}{4\sqrt{2}}\,(\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi)\,Z''_{\mu} - \frac{g}{2c_W}\left[(\bar{\psi}\gamma^{\mu}(g_V - g_A\gamma_5)\psi)\,Z_{\mu} + (\bar{\psi}\gamma^{\mu}(g'_V - g'_A\gamma_5)\psi)\,Z'_{\mu}\right]$$

ψ	g_V	g_A	g'_V	g'_A
t	$\frac{1}{2} - \frac{4}{3}s_W^2 + \frac{5r}{6}s_W s_\theta$	$\frac{1}{2} - \frac{r}{2}s_W s_\theta$	$\left(\frac{1}{2} - \frac{4}{3}s_W^2\right)s_\theta - \frac{5r}{6}s_W$	$\frac{1}{2}s_\theta + \frac{r}{2}s_W$
b	$-\frac{1}{2} + \frac{2}{3}s_W^2 - \frac{r}{6}s_W s_\theta$	$-\frac{1}{2} + \frac{r}{2}s_W s_\theta$	$\left(-\frac{1}{2} + \frac{2}{3}s_W^2\right)s_\theta + \frac{r}{6}s_W$	$-\frac{1}{2}s_\theta - \frac{r}{2}s_W$
ν	$\frac{1}{2} - \frac{r}{2}s_W s_\theta$	$\frac{1}{2} - \frac{r}{2}s_W s_\theta$	$\frac{1}{2}s_\theta + \frac{r}{2}s_W$	$\frac{1}{2}s_\theta + \frac{r}{2}s_W$
e	$-\frac{1}{2} + 2s_W^2 - \frac{3r}{2}s_W s_\theta$	$-\frac{1}{2} + \frac{r}{2}s_W s_\theta$	$\left(-\frac{1}{2} + 2s_W^2\right)s_\theta + \frac{3}{2}rs_W$	$-\frac{1}{2}s_\theta - \frac{r}{2}s_W$

$$r = g_X/g, \quad s_\theta = t_W^2\sqrt{1 - t_W^2 v^2/(2c_W f^2)}$$

$SU(4)_L \times U(1)_X$ model with regular Higgs

- Achieve the symmetry breaking by introducing the four SM type Higgs scalar fields with VEVs aligned as:

$$\langle \phi_1^T \rangle = (v_u, 0, 0, 0) \sim [1, 4, -1/2], \qquad \langle \phi_2^T \rangle = (0, 0, V_u, 0) \sim [1, 4, -1/2],$$
$$\langle \phi_3^T \rangle = (0, v_d, 0, 0) \sim [1, 4, 1/2], \qquad \langle \phi_4^T \rangle = (0, 0, 0, V_d) \sim [1, 4, 1/2],$$

where $V_u(V_d)$ corresponds to $f_{12}(f_{34})$ in the LHM.

- Neutral Gauge Boson Masses:

$$M_Z^2 = \frac{g^2 v_4^2}{c_W^2}\left(1 - t_W^4 \frac{v_4^2}{V_4^2}\right), \quad M_{Z'}^2 = (g^2+g_X^2)V_4^2 - r^2 s_W^2 M_Z^2, \quad M_{Z''}^2 = \frac{1}{2} g^2 (V_4^2 + v_4^2)$$

where $V_u = V_d \equiv V_4$ and $v_u = v_d \equiv v_4$

- Mass relation (same as the LHM case):

$$M_{Z'}^2 = 2(1 + r^2) M_{Z''}^2 - M_Z^2.$$

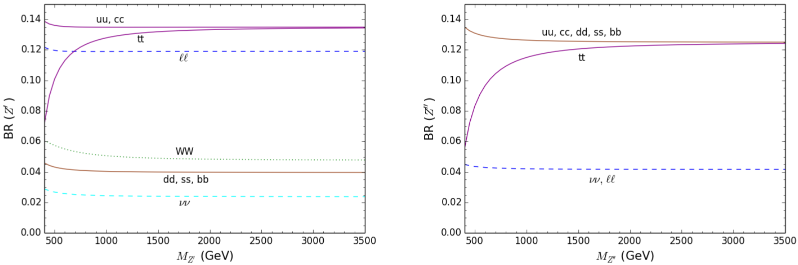
Branching Fractions

Z' decay rates:

$$\begin{aligned}
\Gamma(Z' \to \psi\bar{\psi}) &= N_c \frac{G_F}{6\sqrt{2}\pi} M_Z^2 M_{Z'} \left[\left(g_V'^2 + g_A'^2 \right) \left(1 - \frac{M_\psi^2}{M_{Z'}^2} \right) + 3 \left(g_V'^2 - g_A'^2 \right) \frac{M_\psi^2}{M_{Z'}^2} \right] \\
&\quad \times \left(1 - 4 \frac{M_\psi^2}{M_{Z'}^2} \right)^{1/2} , \\
\Gamma(Z' \to W^+W^-) &= \frac{G_F}{24\sqrt{2}\pi} c_W^4 s_\theta^2 M_Z^2 M_{Z'} \left(\frac{M_{Z'}^4}{M_W^4} + 20 \frac{M_{Z'}^2}{M_W^2} + 12 \right) \left(1 - 4 \frac{M_W^2}{M_{Z'}^2} \right)^{3/2} , \\
\Gamma(Z' \to ZH) &= \frac{G_F}{6\sqrt{2}\pi} s_\theta^2 M_Z^2 M_{Z'} \left[2 \frac{M_Z^2}{M_{Z'}^2} + \frac{1}{4} \left(1 + \frac{M_Z^2}{M_{Z'}^2} - \frac{M_H^2}{M_{Z'}^2} \right)^2 \right] \\
&\quad \times \left[1 - \left(\frac{M_Z^2}{M_{Z'}^2} + \frac{M_H^2}{M_{Z'}^2} \right)^2 \right]^{1/2} \left[1 - \left(\frac{M_Z^2}{M_{Z'}^2} - \frac{M_H^2}{M_{Z'}^2} \right)^2 \right]^{1/2}
\end{aligned}$$

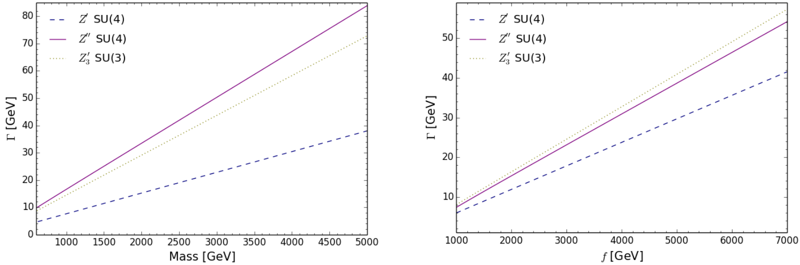
Branching Fractions

Branching Fractions of Z' and Z'' as a function of their masses.



Decay Widths

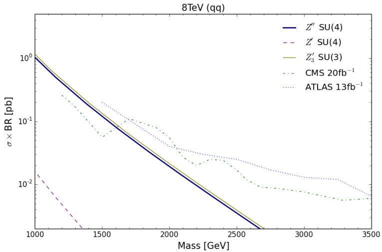
Decay widths of Z', Z'', and Z_3' as a function of their masses and the scale parameter f.

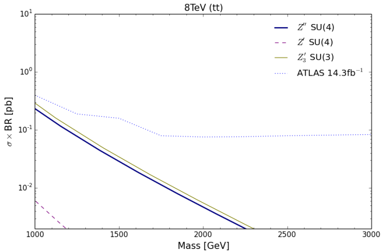


If Z' or Z'' decays into new heavy fermion pairs, the slope of each curve increases from the resonance masses of the new fermions. But the decreases of the Z' and Z'' cross-section times the SM fermion branching ratios should be very small due to the small fermion mixing.

Current bounds at $\sqrt{s} = 8$ TeV

Observed upper cross-section times branching ratio ($\sigma \times BR$) limits at 95% CL for Z', Z'', and Z_3' bosons in the diquark channels.

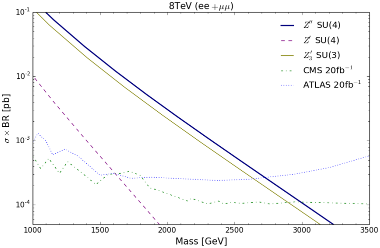


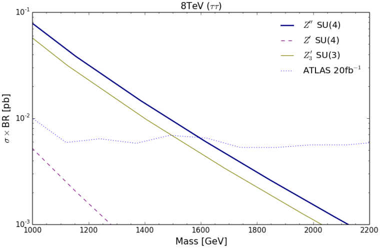


1. Z' and Z'' cross-section times branching ratios ($\sigma \times BR$) are calculated within a range of $\pm 3\Gamma$ around the Z' and Z'' pole masses as done similarly by Dittmar et al.
2. $\sigma \times BR$ for Z' are depicted as a function of the Z'' mass since the Z' and Z'' masses are dependent each other and determined by a single parameter f.

Current bounds at $\sqrt{s} = 8$ TeV

Observed upper cross-section times branching ratio ($\sigma \times BR$) limits at 95% CL for Z', Z'', and Z'_3 bosons in the dilepton channels.

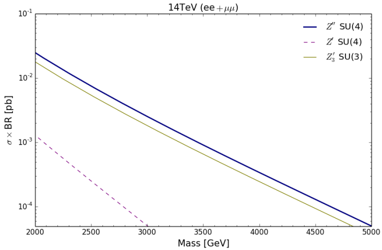


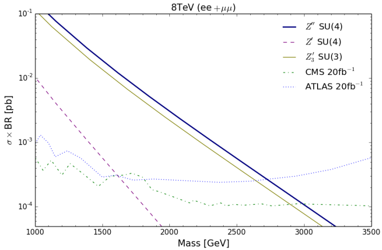


CMS limit in CMS-PAS-EXO-12-061 was given on the production ratio R_σ of cross-section times branching fraction for Z' bosons to the same quantity for Z bosons, but we converted it to $\sigma \times BR$ using the Z cross-section obtained within the range of 60-120 GeV, for a clear comparison with the other measurements.

Discovery potentials at $\sqrt{s} = 14$ TeV

Total cross-sections for the processes $pp \to Z''(Z', Z_3') \to \ell^+\ell^-$ as a function of the Z'' and Z_3' masses at $\sqrt{s}$ =14 TeV, compared with those obtained at 8 TeV.

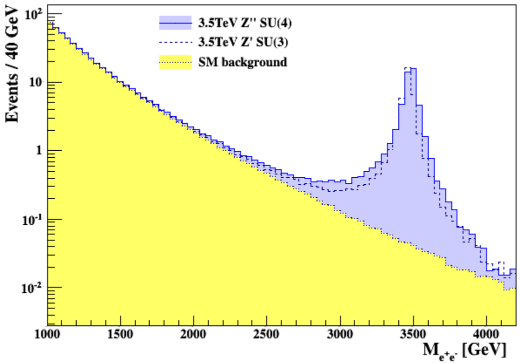




Depending on the masses of $Z''(Z', Z_3')$, the cross-sections increase by a factor of 10 to 10^2 at 14 TeV in comparison with their values at 8 TeV.

Discovery potentials at $\sqrt{s} = 14$ TeV

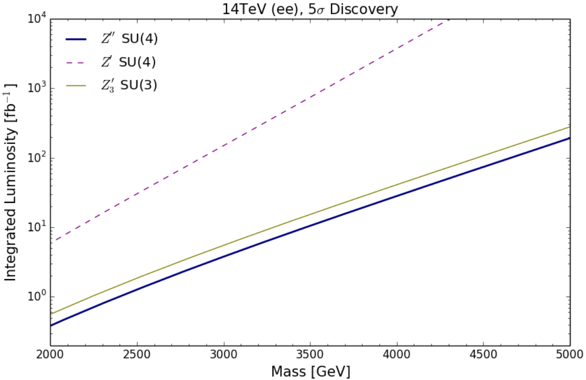
Invariant mass distributions in the electron channel for the new exotic neutral gauge bosons with their masses set to 3.5 TeV using a luminosity of 100 fb^{-1} data at $\sqrt{s}$ =14 TeV.



The contribution of the other backgrounds is less than 30% of the DY cross-section and can be heavily suppressed by isolation cuts at high masses.

Discovery potentials at $\sqrt{s} = 14$ TeV

Integrated luminosity needed for 5σ discovery of $Z''(Z', Z'_3) \to e^+e^-$ as a function of the Z'' and Z'_3 masses at $\sqrt{s}$ =14 TeV.



For more realistic study, we consider an overall efficiency of 73% for the electron channel as determined by the ATLAS experiment.

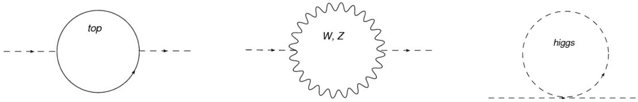
Summary

- Z'' boson is lighter than Z' boson, and their masses are determined by the single scale parameter f.
- The CMS result from the analysis of the production ratio R_σ excludes Z'' boson with mass below 2980 GeV while the ATALS result from the analysis of $\sigma \times BR$ excludes Z'' boson with mass below 2730 GeV.
- Exclusion limit of the Z_3' mass is about 100 GeV lower than that of the Z'' mass.
- For $M_{Z''} \sim 3.5$ TeV, it is required to have about 12 fb^{-1} data to discover this new heavy state, while about 5 fb^{-1} more data are needed to observe Z_3' boson with the same mass.
- With a luminosity of 100 fb^{-1} data, one can search for $Z''(Z_3')$ boson with mass up to about 4650(4450) GeV in the electron channel.

Backup

Fine-tuning issue of Higgs mass

- Due to quantum corrections, the Higgs mass is quadratically sensitive to the cutoff scale: $\sim \Lambda^2$ ($\rightarrow$ naturalness problem?)



$$
\begin{aligned}
m_h^2 &= m_{H^0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \\
(200\ \mathrm{GeV})^2 &= m_{H^0}^2 + \left[-(2\ \mathrm{TeV})^2 + (700\ \mathrm{GeV})^2 + (500\ \mathrm{GeV})^2 \right] \left(\frac{\Lambda}{10\ \mathrm{TeV}} \right)^2 \\
&\Rightarrow \quad \Lambda \sim 1\ \mathrm{TeV} \quad \rightarrow \quad \text{Fine-Tuning Issue}
\end{aligned}
$$

- Note that cutoff Λ for non-renormalizable operators such as $|H^\dagger D_\mu H|^2/\Lambda^2$ should be greater than about 5 TeV.

Little Higgs approach

- As an alternative solution to the naturalness problem (and the fine-tuning issue), little Higgs models (LHM) has been recently introduced.
  (Arkani-Hamed, Cohen, and Georgi 2001)
- LHMs adopts the early idea that Higgs can be considered as a Nambu Goldstone boson from global symmetry breaking at some higher scale $\Lambda \sim 4\pi f$.
  (Dimopoulos, Preskill 1982; Georgi, Kaplan 1984; Banks 1984)
- Higgs acquires a mass radiatively through symmetry breaking at the EW scale v, by collective breaking.
- Consequently, quadratic divergences absent at one-loop level $\Rightarrow$ cancellation among same spin states!

Symmetry Breaking Pattern in the LHM

- Start from a non-linear sigma model $[SU(4)/SU(3)]^4$ with four complex quadruplets scalar fields Φ_i $(i = 1, 2, 3, 4)$

  $\Longrightarrow$ Diagonal $SU(4)$ is gauged.

- Gauge symmetry breaking: $SU(4)_L \times U(1)_X \to SU(2)_L \times U(1)_Y$

  $\Longrightarrow$ 12 new gauge bosons with masses of order the scale f.

- Global symmetry breaking: $[SU(4)]^4 \to [SU(3)]^4$

  $\Longrightarrow$ 12 of the 28 degrees of freedom in the Φ_i are eaten by the Higgs mechanism when $SU(4)_w$ is broken.

  $\Longrightarrow$ Remaining 16 consist of two complex doublets h_u and h_d, three complex $SU(2)$ singlets σ_1, σ_2 and σ_3, and two real scalars η_u and η_d.

  (Kaplan and Schmaltz 2003)

Fermion Sector

- We choose the following set of fermion spectra which would be feasible enough to complete this little Higgs model (Kong 2003):

	$U(1)_Y$-states		
$(3_C, 4_L, \frac{1}{6})$	$\frac{1}{6}[Q]$	$\frac{2}{3}(T)$	$\frac{-1}{3}(B)$
$2\ (3_C, \bar{4}_L, \frac{1}{6})$	$2\ \frac{1}{6}[2\ Q]$	$2\ \frac{-1}{3}(D, S)$	$2\ \frac{2}{3}(U, C)$
$3\ (I_C, 4_L, \frac{-1}{2})$	$3\ \frac{-1}{2}[3\ L]$	$3\ \ 0(3\ N)$	$3\ \ \text{-}1(3\ E^-)$
$6\ (\bar{3}_C, 1_L, \frac{-2}{3})$	$6\ \frac{-2}{3}\ (\bar{u}, \bar{c}, \bar{t}, \bar{U}, \bar{C}, \bar{T})$		
$6\ (\bar{3}_C, 1_L, \frac{1}{3})$	$6\ \frac{1}{3}\ (\bar{d}, \bar{s}, \bar{b}, \bar{D}, \bar{S}, \bar{B})$		
$6\ (1_C, 1_L, 1)$	$3\ 1\ (e^+, \mu^+, \tau^+)$		$3\ \ 1(3\ E^+)$

$\Longrightarrow$ Anomaly cancellation is achieved when $N_f = N_c = 3 \Rightarrow$ one of the best features of this model.

- Electric charge generator: $Q = T_3 + Y$; $\quad Y = -\frac{1}{\sqrt{3}} T_8 + \sqrt{\frac{2}{3}} T_{15} + X I_4$

$X(\Phi_{1,2}) = -\frac{1}{2},\ X(\Phi_{3,4}) = \frac{1}{2};\ X(\psi_L^q) = \frac{1}{6},\ X(\psi_L^\ell) = -\frac{1}{2},\ X(\psi_R) = Q$