SO(10) at the LHC

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RISE - Warsaw 2017

December 4, 2017

Introductions

- There are two main breaking patterns for $SO(10)$ leading to the SM gauge group:
  - $SO(10) \to SU(5) \times U(1)_\chi$ (The $SU(5)$ embedding, which breaks to the SM at GUT scale and the $U(1)_\chi$ breaks at TeV scale)
  - $$\begin{array}{ccc} SO(10) \to SU(4)_{PS} & \times SU(2)_L \times & SU(2)_R \\ \Downarrow & & \Downarrow \\ U(1)_{B-L} \times SU(3)_c & & U(1)_R \end{array}$$ (Pati-Salam, which leads to the left-right symmetric model gauge group)
- This leads to the "BLR" model, $SO(10) \to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
- More popular is the "B-L" model, but this has unknown GUT origins $?? \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Each of these three models offers a Z', and in this work we compare the properties of all three, with a focus on the BLR

Outline

1. $U(1)_{B-L}$ Review
2. $U(1)_R \times U(1)_{B-L}$ Review
   - Z' Couplings to Fermions / Scalars
   - RGEs
3. $U(1)_\chi$ Review
4. Results
   - Vector & Axial Couplings
   - Drell-Yan & AFB
   - Higgs Results
5. Conclusions

In collaboration with Steve King, Stefano Moretti [arXiv: 1712.xxxxx]

$U(1)_{B-L}$ Review

- Gauge group, $G_{BL} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Cannot be embedded into any known GUT theory
- Particle content: MSSM and in addition,

Chiral Superfield		Spin 0	Spin 1/2	G_{B-L}
RH Sneutrinos / Neutrinos (x3)	$\hat{\nu}$	$\tilde{\nu}_R^*$	$\bar{\nu_R}$	(**1**, **1**, 0, $\frac{1}{2}$)
Bileptons/Bileptinos	$\hat{\eta}$	η	$\tilde{\eta}$	(**1**, **1**, 0, -1)
	$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	(**1**, **1**, 0, 1)

Vector Superfields	Spin 1/2	Spin 1	G_{B-L}
BLino / B' boson	$\tilde{B}'^0$	B'^0	(**1** **1**, 0, 0)

- However, Z' will not interact with the 2HDM sector, as the Higgs have $B - L = 0$

BLR Review: Particle content

- Below the GUT scale $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
- At the Z' mass scale (TeV), $U(1)_R \times U(1)_{B-L} \to U(1)_Y$, where the hypercharge generator is $Y = T_{3R} + T_{B-L}$
- To break the symmetry, two Higgs superfields $\chi_{1,2}$ gain VEVs in scalar component with non-zero T_{3R} and T_{B-L}
- If $\chi_{1,2}$ arise from $SU(2)_R$ doublet, $T_{3R} = \pm 1/2$, hence, $T_{B-L} = \pm 1/2$. Opposite charges required for anomaly cancellation / holomorphicity in SUSY
- Light neutrino mass explained by linear see-saw mechanism, require additional SM singlets S, which do not affect phenomenology

BLR: Particle Content

Particle	T_{3L}	T_{3R}	T_{B-L}	$Y = T_{3R} + T_{B-L}$	$Q = T_{3L} + Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	+1/2 -1/2	0 0	+1/6 +1/6	+1/6 +1/6	+2/3 -1/3
u_R	0	+1/2	+1/6	+2/3	+2/3
d_R	0	-1/2	+1/6	-1/3	-1/3
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	+1/2 -1/2	0 0	-1/2 -1/2	-1/2 -1/2	0 -1
e_R	0	-1/2	-1/2	-1	-1
ν_R	0	+1/2	-1/2	0	0
χ_R^1	0	-1/2	+1/2	0	0
χ_R^2	0	+1/2	-1/2	0	0
S	0	0	0	0	0
H: $H_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}_L$	+1/2 -1/2	+1/2 +1/2	0 0	+1/2 +1/2	+1 0
H: $H_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}_L$	+1/2 -1/2	-1/2 -1/2	0 0	-1/2 -1/2	0 -1

BLR at the LHC - Z' Fermions

- Z' coupling to fermions from $U(1)_R \times U(1)_{B-L} \to U(1)_Y$:

$$-\mathcal{L}_{\rm BLR} = \bar{f}\gamma^\mu \left(g_R T_{3R} W^3_{\mu R} + g_{BL} T_{B-L} B^{BL}_\mu\right) f$$

- These two groups mix to produce SM hypercharge gauge boson and a massive Z':

$$\begin{pmatrix} B^{BL}_\mu \\ W^3_{\mu R} \end{pmatrix} = \begin{pmatrix} \cos\theta_{BL} & -\sin\theta_{BL} \\ \sin\theta_{BL} & \cos\theta_{BL} \end{pmatrix} \begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix}$$

$$\to g_R \sin\theta_{BL} = g_{BL}\cos\theta_{BL} = g_Y$$

- The coupling of fermions to Z' is

$$\boxed{-\mathcal{L}^{Z'}_{\rm BLR} = Z'_\mu \bar{f}\gamma^\mu g_Y \left(\cot\theta_{BL} T_{3R} - \tan\theta_{BL} T_{B-L}\right) f}$$

- Where all parameters defined by RGEs, and the SM hypercharge is obtained from the $U(1)_R$ and $U(1)_{B-L}$ couplings:

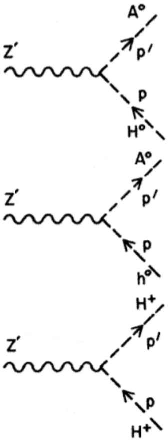
BLR at the LHC - Z' Higgs

- Z' coupling to Higgs (standard 2HDM calculation)

$$\mathcal{L}_{Z',\text{scalars}} = (D_\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (D_\mu \tilde{\Phi}_2)^\dagger (D_\mu \tilde{\Phi}_2)$$

$$D_\mu = \partial_\mu - i \frac{g_Y}{s_{BL} c_{BL}} (T_{3R} - s^2_{BL} \frac{Y}{2})$$

Vertex	$g_{Z' S_1 S_2}$
$Z' H^0 A^0$	$\frac{-g_R \cos\theta_{B-L} \sin(\beta - \alpha)}{2}$
$Z' h^0 A^0$	$\frac{g_R \cos\theta_{B-L} \cos(\beta - \alpha)}{2}$
$Z' H^+ H^-$	-i $\frac{g_R \cos\theta_{B-L}}{2}$

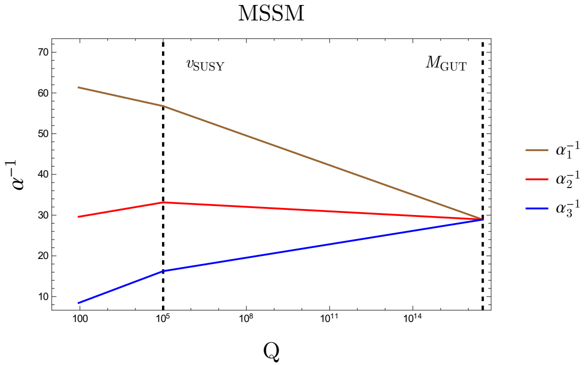


- The Feynman rule for the vertex is given by $(g_{Z' S_1 S_2})(p + p')_\mu$

Renormalisation Group Equations - MSSM

- Strong and weak (α_3, α_2) run up from experimental values. Hypercharge (α_1) run down from here.
- $\alpha_Y(M_Z) = 1/98.4$ Experimentally measured
  $= 1/102.3$ MSSM Predicted [1]

β-function coefficient	$Q < v_{SUSY}$	$Q > v_{SUSY}$
b_1	41/10	33/5
b_2	-19/6	+1
b_3	-7	-3



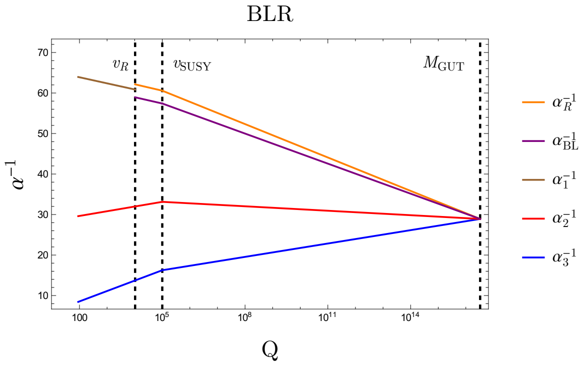
[1] One-loop β functions, no threshold corrections

Renormalisation Group Equations - BLR

- Multiple scales: BLR breaking and separated SUSY scale
- $\alpha_1^{-1} = \frac{3}{5}\alpha_R^{-1} + \frac{2}{5}\alpha_{BL}^{-1}$
- $\alpha_Y(M_Z) = 1/98.4$ Experimentally measured
  $= 1/106.6$ BLR Predicted[2]

β-function coefficient	$Q < v_{SUSY}$	$Q > v_{SUSY}$
b_2	-19/6	$+1$
b_3	-7	-3
	$Q < v_R$	
b_1	41/10	

β-function coefficient	$v_R < Q < v_{SUSY}$	$Q > v_{SUSY}$
b_R	13/3	15/2
b_{BL}	17/4	27/4



[2] One-loop β functions, no threshold corrections, gauge-kinetic mixing included

$U(1)_\chi$ Review

- Same particle content as the BLR but slightly different couplings for Z' to fermions, $-\mathcal{L}_\chi^{Z'} = Z'_\mu \bar{f} \gamma^\mu g_\chi T_\chi f$
- Generator may be written in terms of $B - L$ and R as it is orthogonal to hypercharge $Y = T_{3R} + T_{BL}$

$$T_\chi = \sqrt{\frac{3}{5}} \left(\sqrt{\frac{2}{3}} T_{3R} - \sqrt{\frac{3}{2}} T_{B-L} \right)$$

- At high scale, this matches the BLR coupling

$$Q_{BLR} = \cot\theta_{BL} T_{3R} - \tan\theta_{BL} T_{B-L}$$

- Because the GUT-normalised coupling ratio is $\tan\theta_{BL} = g_{BL}/g_R = \sqrt{3/2}$
- These couplings run, so at low scale so the models are not identical

Z' LHC measurement

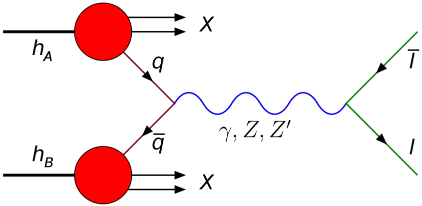
- Now we have coupling strength, we may write vector and axial couplings
- $-\mathcal{L}^{Z'} = Z'_\mu \bar{f}\gamma^\mu \frac{1}{2}(\bar{g}_V^f - \bar{g}_A^f \gamma^5) f$
- $\bar{g}_{V,A}^f(\mathrm{BLR}) = g_Y \left[(\cot\theta_{BL}) g_{V,A}^f(R) - (\tan\theta_{BL}) g_{V,A}^f(BL) \right]$

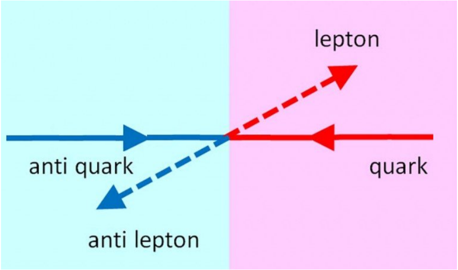
Model	Gauge Coupling	$\bar{g}_V^u$	$\bar{g}_A^u$	$\bar{g}_V^d$	$\bar{g}_A^d$	$\bar{g}_V^e$	$\bar{g}_A^e$	$\bar{g}_V^\nu$	$\bar{g}_A^\nu$
$B-L$	g_{BL}=0.592	0.197	0	0.197	0	-0.592	0	-0.296	-0.296
BLR	See above Eq	-0.0187	-0.129	-0.276	0.129	0.314	0.129	0.221	0.221
χ	g_χ=0.462	0	-0.146	-0.292	0.146	0.292	0.146	0.219	0.219

Figure: Numerical values of the vector and axial couplings for the $U(1)_{B-L}$, $U(1)_{B-L} \times U(1)_R$ and $U(1)_\chi$ models. Note that we have decoupled the right-handed neutrinos in calculating g_V^ν and g_A^ν.

Drell-Yan & AFB

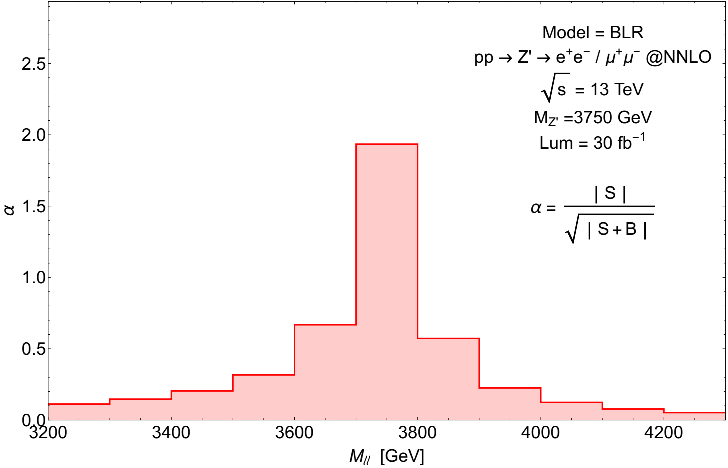
- The most promising channel to search for Z's at the LHC is Drell-Yan production, $pp \to \gamma, Z, Z' \to e^+e^-, \mu^+\mu^-$
- To characterise different models, one may measure the Forward-Backward Asymmetry, which varies depending on the specific vector and axial couplings





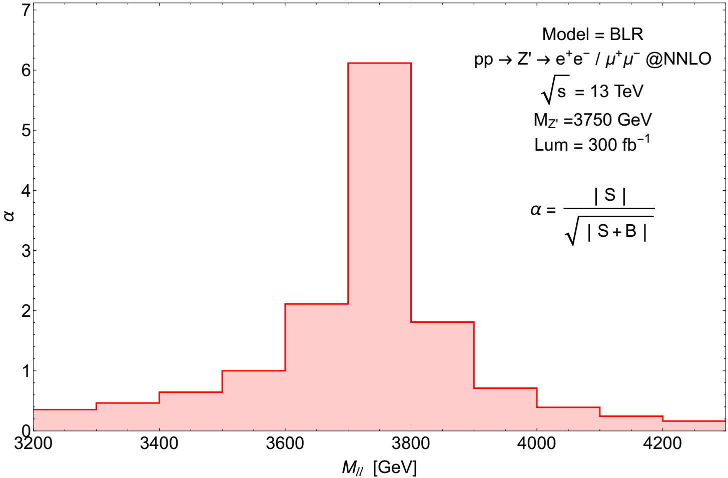
Drell-Yan Results - I

- Set Z' mass using 2σ significance $\rightarrow M_{Z'} = 3750$GeV (current limit)



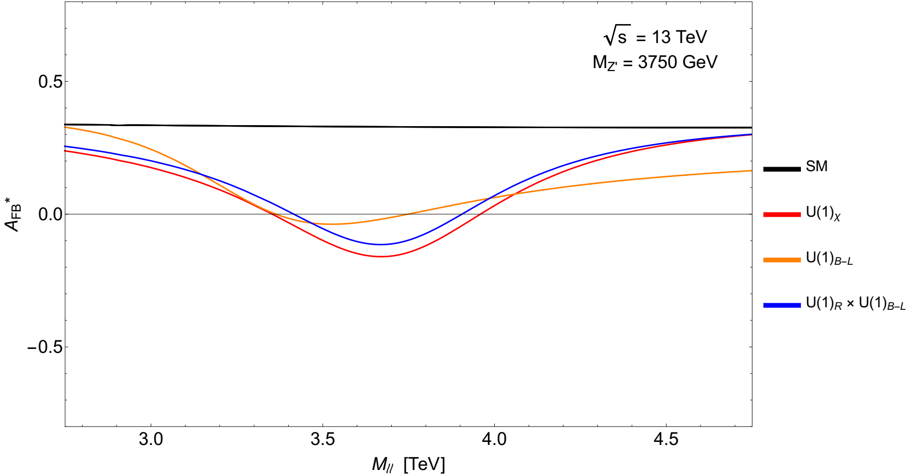
Drell-Yan Results - II

- By the end of Run 2, this Z' may be easily seen!



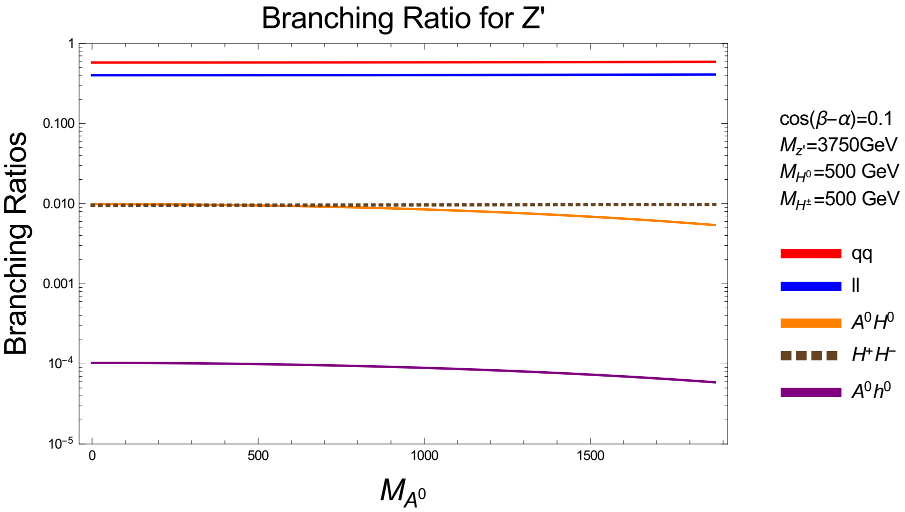
AFB Results

- The purely vector-like couplings for the $B - L$ model allows one to distinguish it from the BLR or χ models



Higgs Results

- Exotic Z' decays in the BLR to Higgses may not only differentiate models, but also, the Z' acts as a portal to the 2HDM!



Conclusions

- The BLR is a well motivated model, with motivations from GUT theories
- Low scale phenomenology of Z' is an interesting way to probe different high-scale models
- Identifying which model a Z' belongs to may become an important task in the near future, as candidates undetectable now offer clear signals in the next runs of the LHC

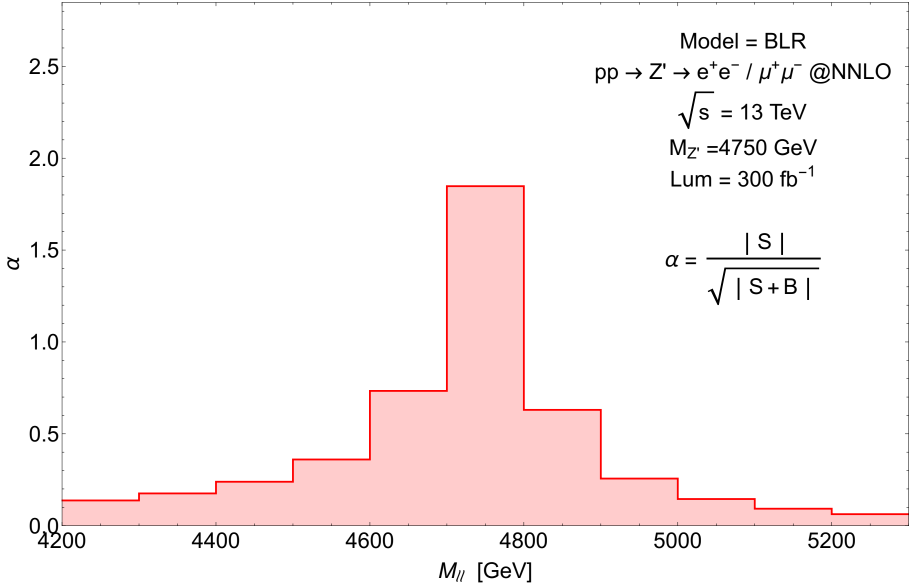
Backup Slides - β functions

$$\frac{dg_R}{dt} = \frac{1}{(4\pi)^2}\frac{15g_R^3}{2}, \tag{1}$$

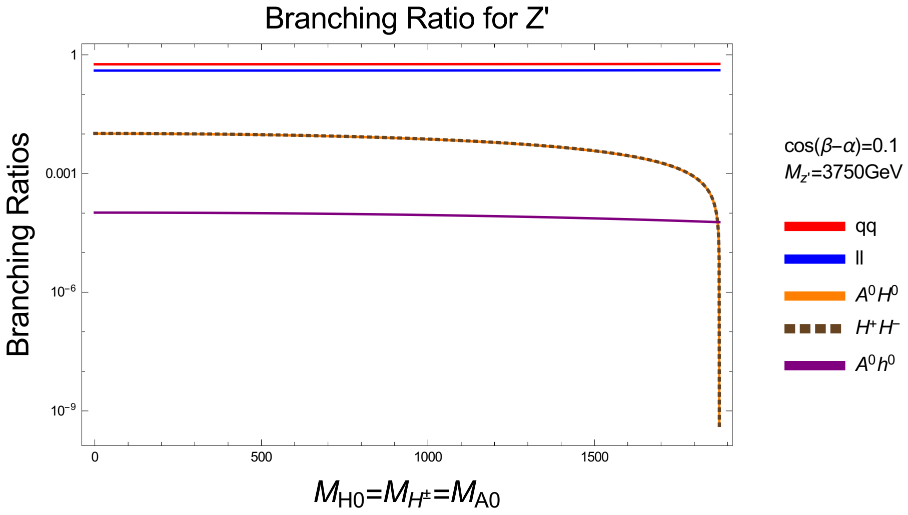
$$\frac{d\tilde{g}}{dt} = \frac{1}{(4\pi)^2}\left[\left(\frac{27}{4}g_{BL}^2 - \sqrt{\frac{3}{2}}g_{BL}\tilde{g} + \frac{15}{2}\tilde{g}^2\right)\tilde{g} + \left(-\sqrt{\frac{3}{2}}g_{BL} + 15\tilde{g}\right)g_R^2\right] \tag{2}$$

$$\frac{dg_{BL}}{dt} = \frac{1}{(4\pi)^2}\left(\frac{27}{4}g_{BL}^2 - \sqrt{\frac{3}{2}}g_{BL}\tilde{g} + \frac{15}{2}\tilde{g}^2\right)g_{BL}. \tag{3}$$

Backup Slides - Mass Limits from Run 2



Backup Slides - Other Branching Ratio Plot



Backup Slides - BLR Z' Coupling

$$-\mathcal{L}_{\text{BLR}}^{Z'} = Z'_\mu \bar{f} \gamma^\mu \left(g_R \cos\theta_{BL} T_{3R} - g_{BL} \sin\theta_{BL} T_{B-L} \right) f$$