UNIVERSITY OF Southampton

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From the Planck Scale to the Electroweak Scale

SO(10) at the LHC

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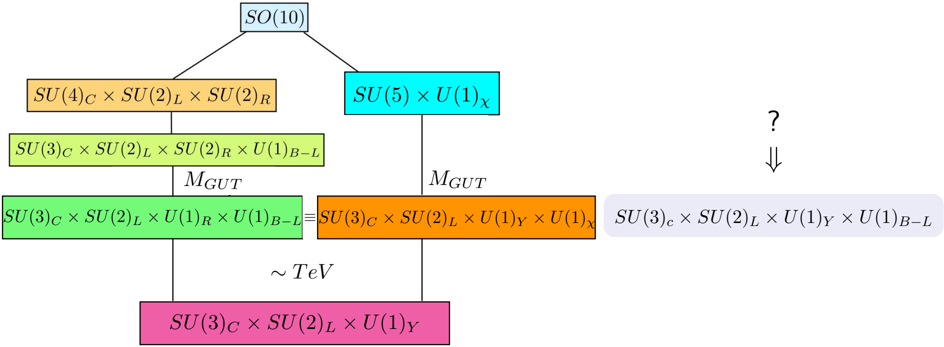
Introduction

- Several breaking patterns for $SO(10)$ to SM
- The gauge group $SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ may survive down to TeV scales, this is the "BLR" model
- More popular is $B-L$ model, $U(1)_Y \times U(1)_{B-L}$
- Both $B-L$ and BLR offer Z', which we may compare at the LHC



$U(1)_{B-L}$ 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 $B-L=0$
- Type-I see-saw explains light neutrino mass

BLR Review

- $SO(10) \rightarrow SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
- At TeV scale, $U(1)_R \times U(1)_{B-L} \rightarrow U(1)_Y$, broken by new Higgs $\chi_R^{1,2}$

Particle	T_{3L}	T_{3R}	T_{B-L}	$Y = T_{3R} + T_{B-L}$	$Q = T_{3L} + Y$
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: $H_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}_L$: ϕ_u^+	+1/2	+1/2	0	+1/2	+1
ϕ_u^0	-1/2	+1/2	0	+1/2	0
H: $H_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}_L$: ϕ_d^0	+1/2	-1/2	0	-1/2	0
ϕ_d^-	-1/2	-1/2	0	-1/2	-1

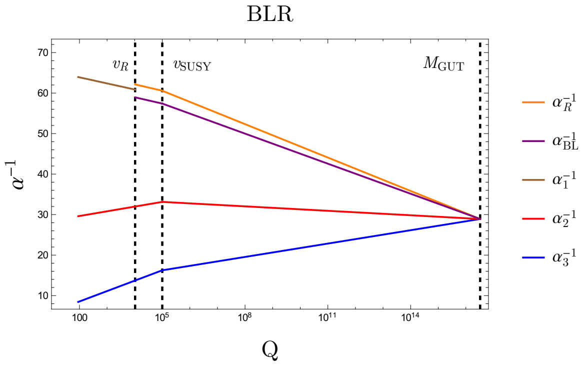
- Z' will interact with 2HDM, as it is charged under T_{3R}
- Light neutrino mass explained by linear see-saw mechanism, require additional SM singlets S, which do not affect phenomenology

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
  $= 1/102.4$ BLR Predicted*

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



*One-loop β functions, no threshold corrections, gauge-kinetic mixing included

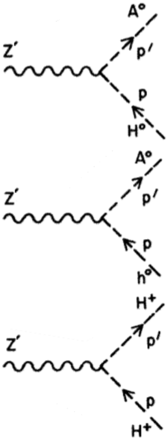
BLR at the LHC - Z' Higgs

- Z' coupling to 2HDM

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

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

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 $(g_{Z' S_1 S_2})(p + p')_\mu$

BLR at the LHC - Z' Fermions

- Z' coupling to fermions from $U(1)_R \times U(1)_{B-L} \to U(1)_Y$
- These two groups mix to produce SM hypercharge gauge boson and a massive Z'. The coupling of fermions to Z' is †

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

- May write this in terms of vector (L+R) and axial (L-R) couplings

$$-\mathcal{L}^{Z'} = Z'_\mu \bar{f} \gamma^\mu \frac{1}{2} (\bar{g}^f_V - \bar{g}^f_A \gamma^5) f$$

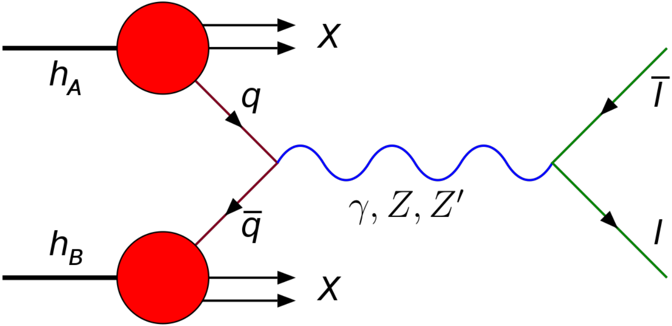
- Couplings determined using the `SARAH` program to calculate vertices

Model	Gauge Coupling	$\bar{g}^u_V$	$\bar{g}^u_A$	$\bar{g}^d_V$	$\bar{g}^d_A$	$\bar{g}^e_V$	$\bar{g}^e_A$	$\bar{g}^\nu_V$	$\bar{g}^\nu_A$
$B-L$	g_{BL}=0.592	0.197	0	0.197	0	-0.592	0	-0.296	-0.296
BLR	$g_R = 0.448$, $g_{BL} = 0.459$	-0.0103	-0.135	-0.279	0.135	0.300	0.135	0.217	0.217

† For this talk, we neglect gauge-kinetic mixing, but all numerical results take this into account

Drell-Yan

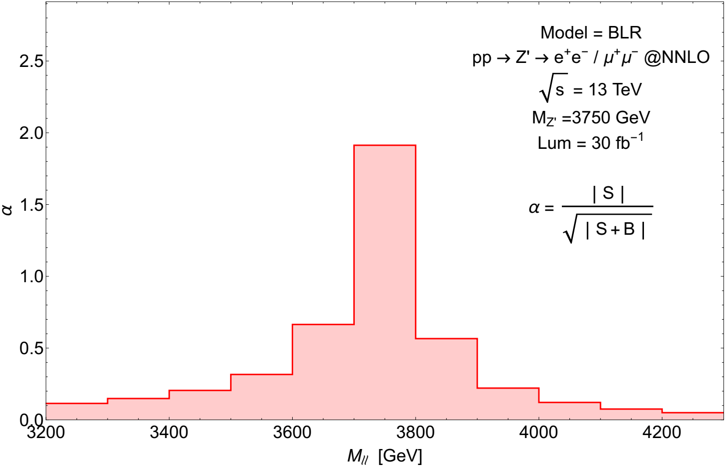
- The most promising channel to search for Z's at the LHC is Drell-Yan production, $pp \to \gamma, Z, Z' \to e^+e^-, \mu^+\mu^-$
- In this work, we include interference $[S = (pp \to \gamma, Z, Z' \to e^+e^-, \mu^+\mu^-) - (pp \to Z, \gamma \to e^+e^-, \mu^+\mu^-)]$ and finite width effects †



† Same code used as in 1504.01761

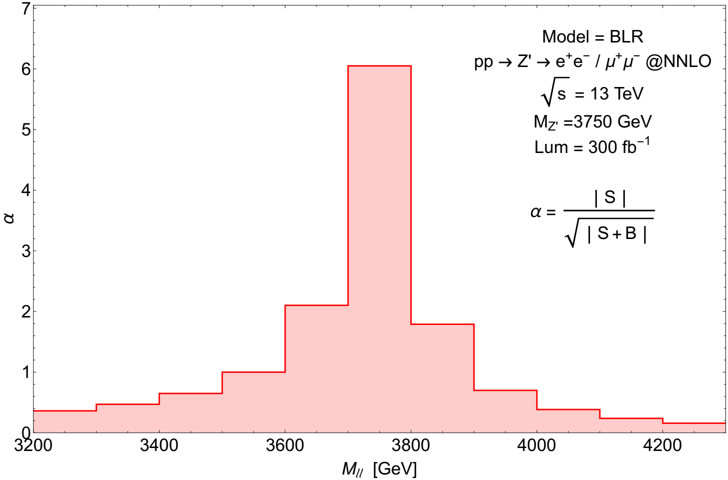
Drell-Yan Results - I

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



Drell-Yan Results - II

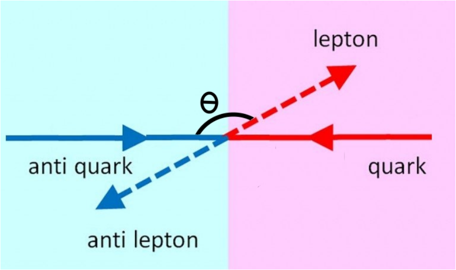
- By the end of Run 2, this Z' may be easily seen!



Drell-Yan & AFB

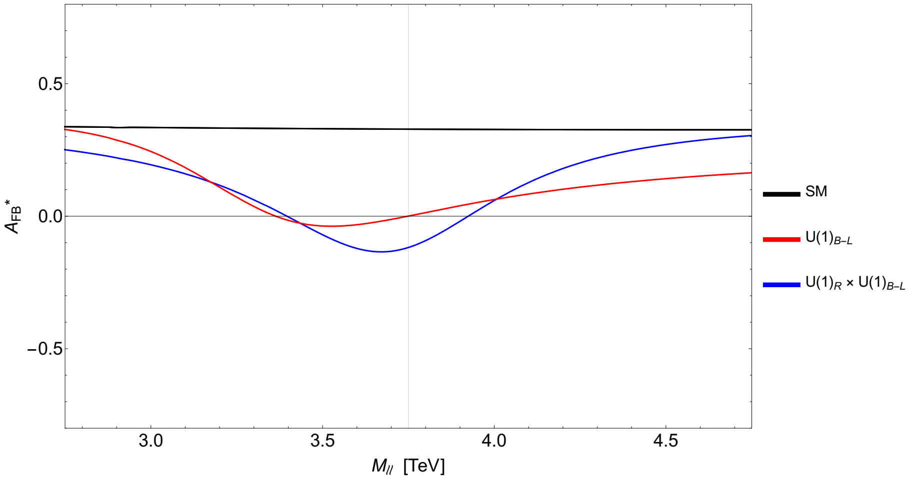
- If a Z' is discovered, one needs to differentiate to which model it belongs
- To characterise different models, one may measure the Forward-Backward Asymmetry, which varies depending on the specific vector and axial couplings

$$A_{FB} \equiv \frac{d\hat{\sigma}_F - d\hat{\sigma}_B}{d\hat{\sigma}_F + d\hat{\sigma}_B}, \quad d\hat{\sigma}_{F,B} = \int_{0,-1}^{1,0} \frac{d\hat{\sigma}}{d\cos\theta} d\cos\theta$$



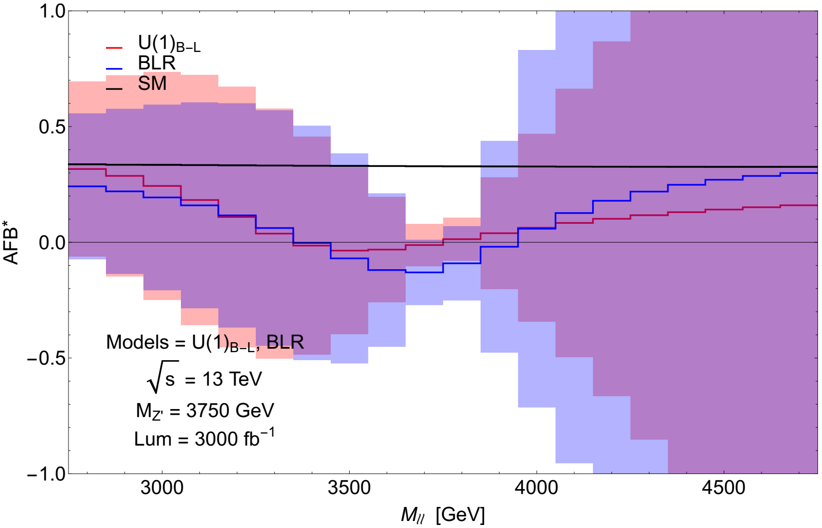
AFB Results

- The purely vector-like couplings for the $B - L$ model allows one to distinguish it from the BLR in the continuous case



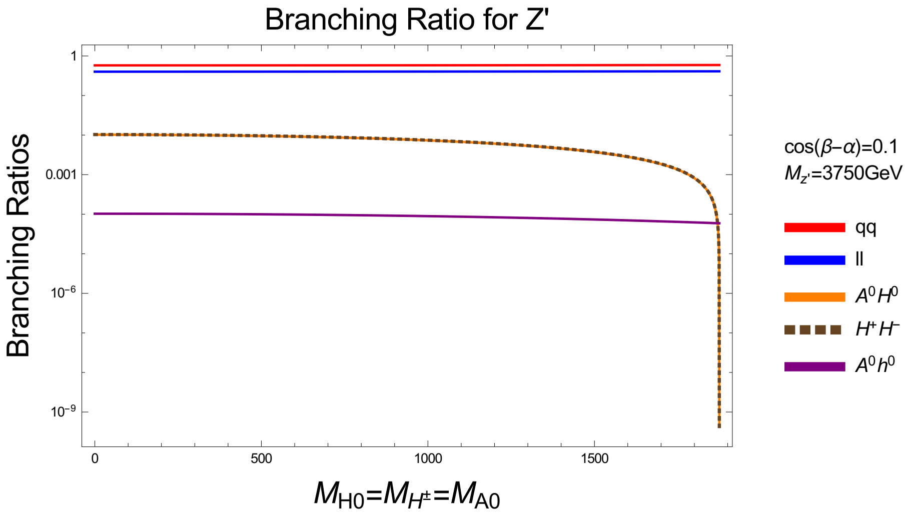
AFB Results

- At HL-LHC, including statistical errors, $\delta A_{FB} = \sqrt{1 - A_{FB}^2/N}$, one may be able to disentangle $B-L$ and BLR 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

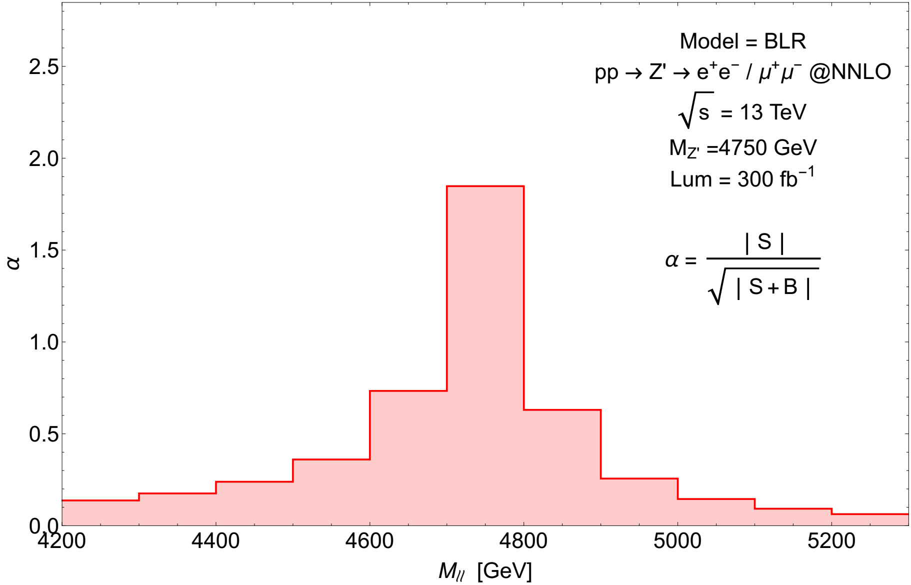
Backup Slides - β functions

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

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

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

Backup Slides - Mass Limits from Run 2



Backup Slides - LHC Cuts

- No rapidity cut on dilepton pair
- NNLO in QCD calculating using WZPROD and CTEQ for pdfs
- We include published acceptance $\times$ efficiency factors $(A \times \epsilon)$
- CMS analysis uses dedicated cut on invariant mass $|M_{\bar{l}l} - M_{Z'}| \leq 0.05 \times E_{LHC}$ to keep error in neglecting finite width and interference effects below 10%
- Including this effect we reproduce CMS limits within $1 - 2\%$

Backup Slides - Gauge-Kinetic Mixing

The kinetic sector for a gauge group $U(1)_1 \times U(1)_2$ will have a mixed term:

$$\mathcal{L}_{\rm kin} = -\frac{1}{4} F^{A_1}_{\mu\nu} F^{\mu\nu}_{A_1} - \frac{1}{4} F^{A_2}_{\mu\nu} F^{\mu\nu}_{A_2} - \frac{\kappa}{2} F^{A_1}_{\mu\nu} F^{\mu\nu}_{A_2}$$

$$\mathcal{L}_{\rm int} = \bar{\psi}_f \gamma_\mu Q^1_f g_1 A^\mu_1 \psi_f + \bar{\psi}_f \gamma_\mu Q^2_f g_2 A^\mu_2 \psi_f$$

The mixed kinetic term may be rotated away:

$$\mathcal{L}_{\rm kin} = -\frac{1}{4} F^{B_1}_{\mu\nu} F^{\mu\nu}_{B_1} - \frac{1}{4} F^{B_2}_{\mu\nu} F^{\mu\nu}_{B_2}$$

$$\mathcal{L}_{\rm int} = \bar{\psi}_f \gamma_\mu (g_{11} Q^1_f + g_{21} Q^2_f) B^\mu_1 \psi_f + \bar{\psi}_f \gamma_\mu (g_{12} Q^1_f + g_{22} Q^2_f) B^\mu_2 \psi_f$$