Phenomenology of the minimal $U(1)_{B-L}$ extension of the Standard Model

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LB, A. Belyaev, S. Moretti, C. Shepherd-Themistocleous: 0812.4313 [hep-ph] (to PRD)

LB, A. Belyaev, S. Moretti, G.M.Pruna: 0903.4777 [hep-ph] (to JHEP)

The model: triply-minimal extension

A $U(1)$ extension of the SM $\quad SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

New states:

- A scalar (χ, SM-singlet)
  $V = \cdots + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2$
- 3 RH neutrinos: $\nu_R \xrightarrow{\text{see-saw}} \nu_h$ ($\mathcal{O}(100)$ GeV)
  (anomaly cancellation)
  $\mathscr{L}_Y = \cdots - y^\nu \overline{l_L} \nu_R \widetilde{H} - y^M \overline{(\nu_R)^c} \nu_R \chi + \text{H.c.}$

In certain regions of the parameter space, they both can be *long-lived* particles (later)

Covariant derivative:

$$D_\mu \Psi_i = \partial_\mu \Psi_i + i \left[g_1 Y_i B_\mu + (Y_i \widetilde{g} + (B-L)_i g_1') B'_\mu \right] \Psi_i$$

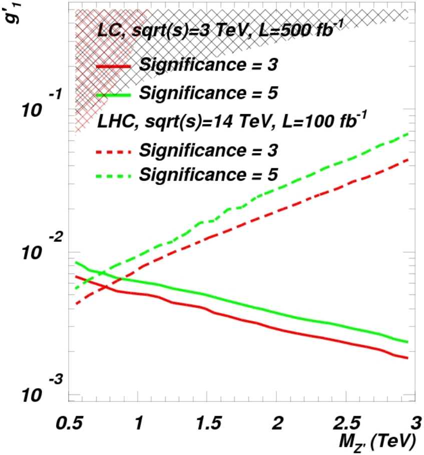
$\widetilde{g} = 0 \longrightarrow$ NO $Z - Z'$ mixing

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
q_L	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
l_L	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
H	1	2	$\frac{1}{2}$	0
χ	1	1	0	2

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$



(a)

← **Tevatron** and **LEP** bounds

← LHC: $L = 100\ \mathrm{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

and

← LC: $L = 500\ \mathrm{fb}^{-1}$, $\sqrt{s_{e^+e^-}} = 3$ TeV

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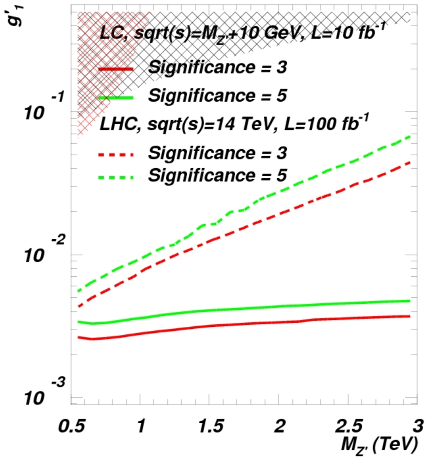


(b)

$\leftarrow$ **Tevatron** and **LEP** bounds

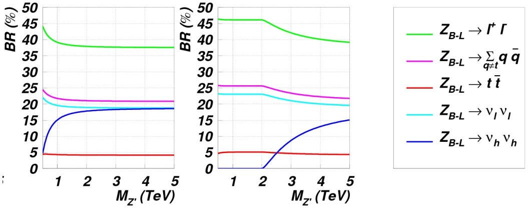
$\leftarrow$ LHC: $L = 100\ \mathrm{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

and

$\leftarrow$ LC: $L = 10\ \mathrm{fb}^{-1}$, $\sqrt{s_{e^+e^-}} = M_{Z'} + 10$ GeV

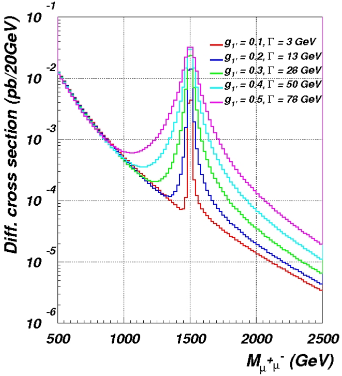
Z' phenomenology

$m_{\nu h} = 250$ GeV 1 TeV



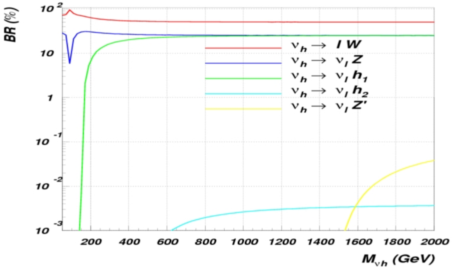
$$\sum_k BR\left(Z'_{B-L} \to l_k \overline{l_k}\right) \sim \frac{3}{4} \qquad \sum_k BR\left(Z'_{B-L} \to q_k \overline{q_k}\right) \sim \frac{1}{4}$$

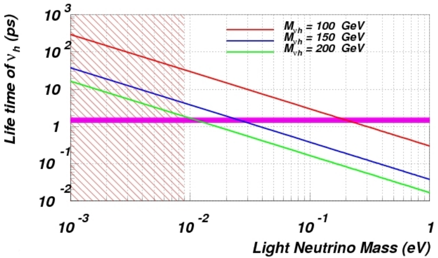
$p, p \to (\gamma, Z, Z') \to \mu^+\mu^-$



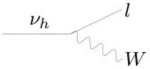
- Dominantly coupled to *leptons*
- $Z' \to \nu_h \nu_h$ up to $\sim 20\%$
- $g'_1 < 0.5$ from RGE analysis
- Γ up to hundreds of GeV

ν_h phenomenology





$$\tan 2\alpha_\nu = -2\sqrt{\frac{m_{\nu l}}{m_{\nu h}}}$$



$$= \frac{\sqrt{2}e}{4\sin\vartheta_W}\sin\alpha_\nu$$

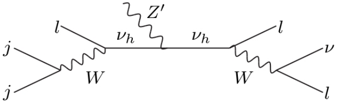
- $\Gamma = \Gamma(m_{\nu l}/m_{\nu h})$
- ν_h can be a long-lived particle
- DISPLACED VERTICES

χ can be decoupled from the SM: couples only to Z' and $\nu_{l,h}$: long-lived (under study)

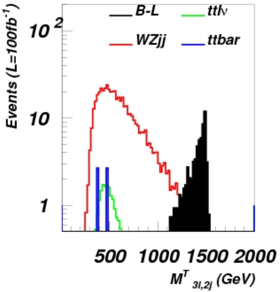
ν_h @ LHC: $BR(Z' \to 3l + 2j + \not{P}_T\ (1\nu), l = e, \mu)$ up to 2.5%

$$m_T^2 = \left(\sqrt{M_{vis}^2 + P_{T,vis}^2} + |\not{P}_T|\right)^2 - \left(\vec{P}_{T\,vis} + \vec{\not{P}}_T\right)^2$$

V. Barger *at all*, *Phys. Rev. D* **36** *(1987) 295*



$M_{Z'} = 1.5$ TeV, $g'_1 = 0.2$: $\sigma(pp \to Z') = 0.3$ pb
$M_{\nu_h} = 200$ GeV, $\mathscr{L} = 100$ fb^{-1}, bin $= 20$ GeV

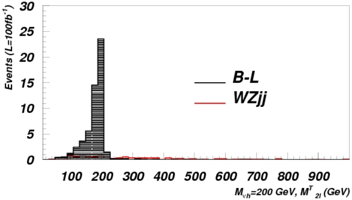


Backgrounds:

$WZjj$ associated production ($\sigma_{3l} = 246.7$ fb, $l = e, \mu, \tau$, w. cuts)

$t\bar{t}$ pair production ($\sigma_{2l} = 29.6$ pb, $l = e, \mu$) (3^{rd} lep. from b-quark)

$t\bar{t}l\nu$ associated production ($\sigma_{3l} = 8.6$ fb, $l = e, \mu, \tau$)



Cuts:

Kinematics, angular acceptance and isolation

W rec. from jets: $|M_{jj} - 80$ GeV$| < 20$ GeV

Z' rec.: $\left|M^T_{3l,2j} - 1500 \text{ GeV}\right| < 250$ GeV

Conclusions

- Simple SM extension at TeV scale, RH-neutrinos
- motivated by high-scale physics
- pure $B-L$ model, no $Z-Z'$ mixing
- exiting new phenomenology from heavy neutrinos
  - ▷ they bring the footprints of the $B-L$ model
  - ▷ clarity of the signal: M^T
- Analysis done with CalcHEP, implementation with LanHEP
- background: under control, model independent analysis

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displaced vertices and the measure of m_{ν_h} provide a
link to low-energy physics

FIRST (IND.) MEASURE OF m_{ν_l}

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displaced vertices and the measure of m_{ν_h} provide a link to low-energy physics

<u>FIRST</u> (IND.) MEASURE OF m_{ν_l}

- Nice interplay between Z', neutrinos and Higgs sector;
- (In progress) study of the Higgs sector:
  - ▷ width and branching, bounds (triviality, vacuum stability; unitarity)
  - ▷ reliability of using Z'_{B-L} as *source* of Higgs, through ν_h ($\nu_h \to \nu_l\ h_1$)

Backup slides

In Les Houches

unusual $Z'^{\star}_{B-L} \rightarrow Z'_{B-L} h_2 \rightarrow \nu_h \nu_h (20\%) \nu_h \nu_h (100\%) \rightarrow 8l(8j) + \not{P}_T$

▷ Problem: $\sigma(pp \rightarrow Z'_{B-L} h_2) = 0.1$ fb... :(

Underling events / parton shower in Pythia/Sherpa to validate W reconstruction's cut

Highly boosted W/Z:
$Z' \rightarrow \nu_h \nu_h$
where $\nu_h \rightarrow lW$ or νZ

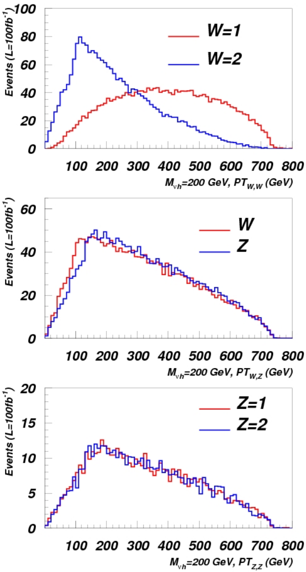


Figure: P_T distribution of Ws and Zs (P_T ordered just in the WW case) for $M_{Z'} = 1.5$ TeV, $g'_1 = 0.2$, $M_{\nu h} = 200$ GeV, distinguished by signature.

Z' experimental limit

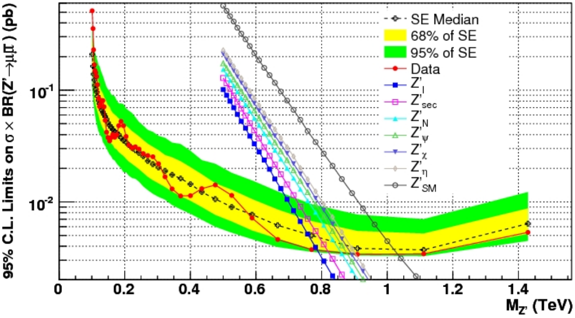
LEP bound:

G. Cacciapaglia *et all*, Phys. Rev. D **74** (2006) 033011

$$\frac{M_{Z'}}{g_1'} \geq 7\ \mathrm{TeV}$$

Tevatron (Translating Z'_{SM} bound):

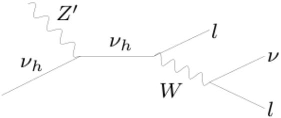
T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 091805 (2009)



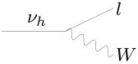
g_1'	$M_{Z'}$ (GeV)
0.065	600
0.075	680
0.090	740
0.1	800
0.2	960
0.5	1140

Heavy neutrino: example

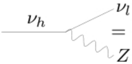
Consider only one generation:



- $\nu_{L,R} \rightarrow \nu_{l,h}$ $\qquad \tan 2\alpha_\nu = -2\sqrt{\frac{m_l}{M}}$



$= \frac{\sqrt{2}e}{4\sin\vartheta_W}\sin\alpha_\nu$



$= -\frac{e}{4\sin\vartheta_W\cos\vartheta_W}\sin 2\alpha_\nu$

- we can measure independently displaced vertex $V = V(m_l, M)$ and heavy neutrino mass $M = m_h$

hence, putting altogether, we get

INDIRECT MEASURE OF LIGHT NEUTRINO MASS m_l

Efficiencies

Set 1)

$$\begin{aligned} P_{T,l_1} &> 15 \text{ GeV}; \\ P_{T,j_{1,2}} &> 40 \text{ GeV}; \\ \left|\eta_{j_{1,2}}\right| &< 3; \\ \left|\eta_{l_{1,2,3}}\right| &< 2.5; \\ \Delta R_{lj} &> 0.5 \qquad \forall l = 1\ldots3, j = 1,2 \\ \Delta R_{l,l} &> 0.2; \\ \Delta R_{j,j} &> 0.5. \end{aligned}$$

W rec.)

$$|M_{jj} - 80 \text{ GeV}| < 20 \text{ GeV};$$

Z' rec.)

$$\left|M^T_{3l,2j} - 1500 \text{ GeV}\right| < 250 \text{ GeV};$$

Peak)

$$\begin{aligned} 0 < \; & M^T_{2l} < 250 \text{ GeV} \;\text{ or} \\ 400 \text{ GeV} < \; & M^T_{2l} < 550 \text{ GeV}; \end{aligned}$$

Cuts	Ev. Signal	Eff. %	Ev. $WZjj$	Eff. %	Ev. $t\bar{t}$	Eff. %	Ev. $t\bar{t}l\nu$	Eff. %	$S/\sqrt{B}$
$set1$	68.0	100	5875	100	99.6	100	89.1	100	0.87
$W rec.$	68.0	100	498.	8.5	5.38	5.4	19.3	21.8	2.97
$Z' rec.$	58.8	86.5	10.5	12.7	0	0.8	0.0667	2.2	18.0
$Peak$	56.0	94.1	4.48	67.6	0	56.4	0.0305	64.8	26.3

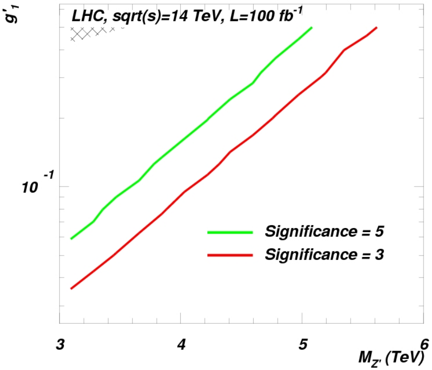
(Events for $\mathscr{L} = 100$ fb^{-1}, $\boldsymbol{M_{\nu_h} = 200}$ **GeV**)

Cuts	Ev. Signal	Eff. %	Ev. $WZjj$	Eff. %	Ev. $t\bar{t}$	Eff. %	Ev. $t\bar{t}l\nu$	Eff. %	$S/\sqrt{B}$
$set1$	73.6	100	5875.	100	99.7	100	89.1	100	0.95
$W rec.$	73.6	100	498.8	8.5	5.38	5.4	19.4	21.8	3.22
$Z' rec.$	68.8	93.4	10.58	12.7	0	0.8	0.0667	2.2	21.1
$Peak$	46.3	66.0	2.879	7.1	0	8.7	0.00952	10.1	27.6

(Events for $\mathscr{L} = 100$ fb^{-1}, $\boldsymbol{M_{\nu_h} = 500}$ **GeV**)

Z' Discovery potentials in di-muons

Significance contour levels plotted against g'_1 and $M_{Z'}$



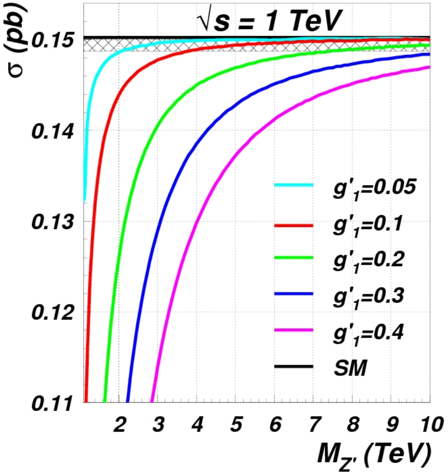
(c)

LHC: $L = 100\ \text{fb}^{-1}$ ($\sqrt{s_{pp}} = 14$ TeV)

$M_{Z'} \geq 3$ TeV

Z' Discovery potentials in di-muons

$\sigma(e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-)$ plotted against $M_{Z'}$, for $\sqrt{s_{e^+e^-}} = 1$ TeV ($M_{\mu\mu} > 200$ GeV)



(d)

$\leftarrow 1\%$ deviation from the SM hypothesis

g_1'	$M_{Z'}$ (TeV)	
	LHC 3σ observation	LC ($\sqrt{s} = 1$ TeV) 1% level
0.05	3.4	2.2
0.1	4.1	3.8
0.2	4.7	7.5

Table: maximum $M_{Z'}$ value accessible for selected g_1' values