Z'_{B-L} discovery potential at the LHC for $\sqrt{s} = 7$ TeV

Lorenzo Basso (UoS and RAL)

In collaboration with: S. Moretti, A. Belyaev, G.M. Pruna, C.H. Shepherd-Themistocleous

LB, A. Belyaev, S. Moretti, C.H. Shepherd-Themistocleous: Phys. Rev. D **80**, 055030 (2009) [hep-ph:0812.4313]

LB, A. Belyaev, S. Moretti, G.M. Pruna: JHEP **0910**, 006 (2009) [hep-ph:0903.4777]

LB, A. Belyaev, S. Moretti, G.M. Pruna, C.H. Shepherd-Themistocleous: hep-ph:1002.3586

Outline

1) The $B-L$ model
   - Motivations
   - Particle content

2) Phenomenology (at the LHC)
   - Z' properties: decays and width
   - Analysis details
   - LHC @ $\sqrt{s}=7$ TeV
   - Tevatron comparison
   - Exclusions

3) Appendix: Heavy neutrino phenomenology (at the LHC)
   - Decays and width
   - Tri-lepton signature

4) Conclusions

A triply minimal extension

- **Motivations**
  - ▷ ν_R naturally included
  - ▷ $U(1)_{B-L}$ (accidental) global symmetry in the SM
  - ▷ interesting phenomenology
  - ▷ part of a bigger picture (GUT, baryogenesis)
- **Gauge sector**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- **Fermion sector**

One extra fermion per generation: ν_R

(Required by anomaly cancellation)

- **Scalar sector**

One extra SM-singlet scalar: χ

($U(1)_{B-L}$ symmetry breaking)

The model: triply-minimal extension

A $U(1)$ extension of the SM

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

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

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

Interactions and spectrum

Covariant derivative (in a suitable basis):

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

$Z - Z'$ mixing:

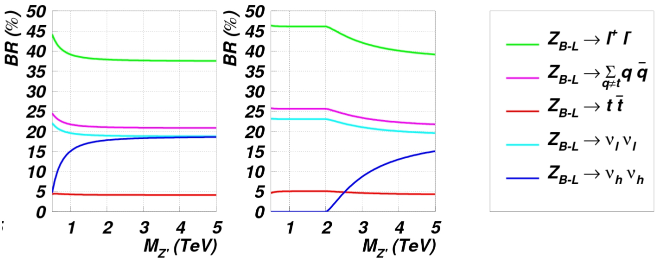
$$\begin{pmatrix} B^\mu \\ {W_3}^\mu \\ B'^\mu \end{pmatrix} = \left(\begin{array}{cc|c} \cos\vartheta_w & -\sin\vartheta_w \cos\vartheta' & \sin\vartheta_w \sin\vartheta' \\ \sin\vartheta_w & \cos\vartheta_w \cos\vartheta' & -\cos\vartheta_w \sin\vartheta' \\ \hline 0 & \sin\vartheta' & \cos\vartheta' \end{array}\right) \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu_{B-L} \end{pmatrix}$$

$$\boxed{\widetilde{g} = 0 \longrightarrow \vartheta' = 0}$$

No (tree level) $Z - Z'$ mixing in the pure $B - L$ model

Z' phenomenology

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



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

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

- 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

Depending on $m_{\nu h}$ and $M_{Z'}$:

$$\begin{aligned} Z' \to l^+ l^- \quad &\simeq \quad 12.5\% \div 15.5\% \\ Z' \to q\bar{q} \quad &\simeq \quad 4\% \div 5\% \end{aligned}$$

In this work: $m_{\nu h} = 200$ GeV

Aim of our work

The $B-L$ symmetry breaking takes place at the TeV scale. Its rich phenomenology (Z', Higgs(es) and heavy neutrinos signatures) can be observed at TeV machines.

We focus our analysis on the Z'-sector at the LHC at its current stage, $\sqrt{s}=7$ TeV.
We consider the $pp(\overline{p}) \to l^+l^-$ ($l=e,\mu$) channel as a representative process to study new signatures of the Z'_{B-L} vector boson.

The $B-L$ model is not a usual benchmark for data analyses nor colliders reach studies $\longrightarrow$ *systematic parton level analysis, with k-factors*.
(no ISR, photon conversions, fakes, muon reconstuctions,...)

Differences wrt the other more common Z' models:

- no axial coupling: $(B-L)^R=(B-L)^L$ hence $g^A_{Z'}=\dfrac{g^R_{Z'}-g^L_{Z'}}{2}=0$,
- free value of the coupling g'_1,
- new coupled matter (ν_h) $\to$ not-fixed BRs.

Analysis details

Analysis with CalcHEP, model implemented via LanHEP.

We have assumed standard acceptance cuts at LHC and Tevatron (the same for electrons and muons):

$$\begin{aligned} \text{LHC}: \quad & p_T > 10\ \text{GeV}, \quad & |\eta| < 2.5, \\ \text{Tevatron}: \quad & p_T > 18\ \text{GeV}, \quad & |\eta| < 1, \end{aligned}$$

and a cut on the invariant mass (early vs improved scenario):

$$\begin{aligned} e^{\pm}\ \text{@ LHC:}\ \frac{|M_{ee} - M_{Z'}|}{\text{GeV}} &< \text{max}\left(\frac{\Gamma_{Z'}}{2}, \begin{pmatrix} 0.02 \\ 0.005 \end{pmatrix} \frac{M_{Z'}}{\text{GeV}} \right), \\ \mu^{\pm}\ \text{@ LHC:}\ \frac{|M_{\mu\mu} - M_{Z'}|}{\text{GeV}} &< \text{max}\left(\frac{\Gamma_{Z'}}{2}, \begin{pmatrix} 0.08 \\ 0.04 \end{pmatrix} \frac{M_{Z'}}{\text{GeV}} \right), \end{aligned}$$

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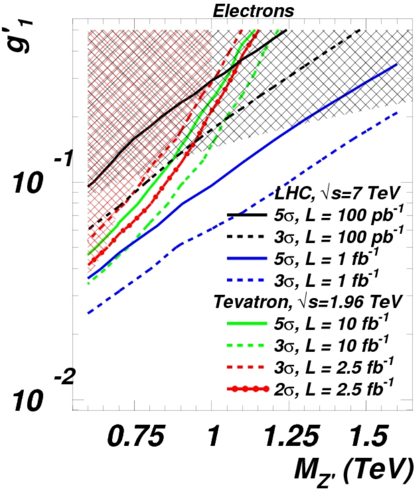
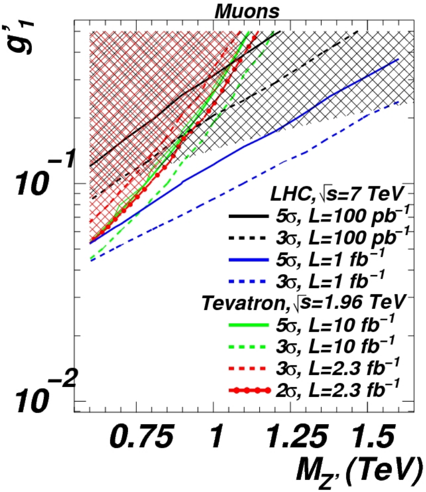
e^\pm \text{ @ Tevatron: } \frac{|M_{ee}-M_{Z'}|}{\text{GeV}} &< \max\left(\frac{\Gamma_{Z'}}{2}, \left(0.135\sqrt{\frac{M_{Z'}}{\text{GeV}}} + 0.02\frac{M_{Z'}}{\text{GeV}}\right)\right), \\
\mu^\pm \text{ @ Tevatron: } \frac{|M_{\mu\mu}-M_{Z'}|}{\text{GeV}} &< \max\left(\frac{\Gamma_{Z'}}{2}, 0.0005\left(\frac{M_{Z'}}{2\,\text{GeV}}\right)^2\right).
\end{aligned}$$

Z' Discovery potentials for $\sqrt{s} = 7$ TeV

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

Electrons ↓ **Tevatron** and **LEP** bounds↓ Muons

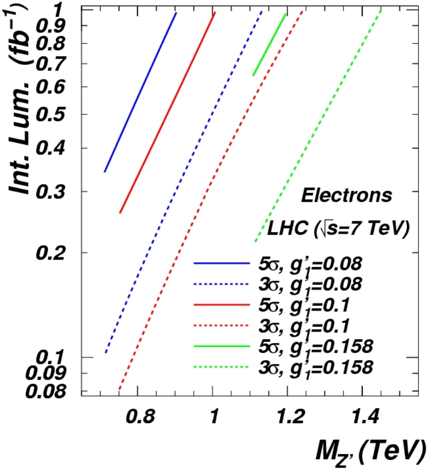




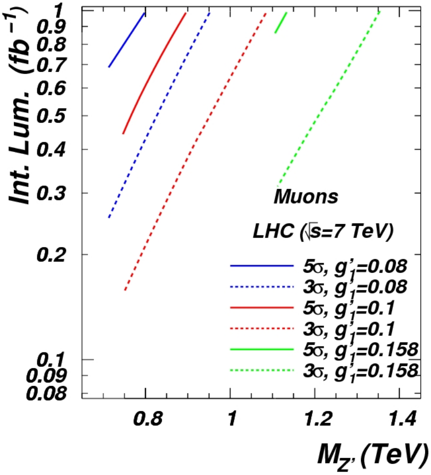
Z' Discovery potentials for $\sqrt{s} = 7$ TeV

Luminosity vs $M_{Z'}$ (for fixed values of g'_1) at the LHC

Electrons



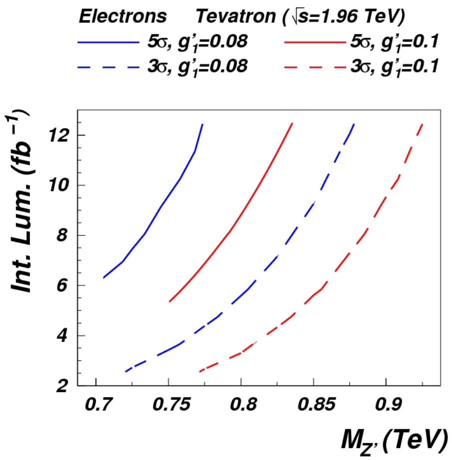
Muons



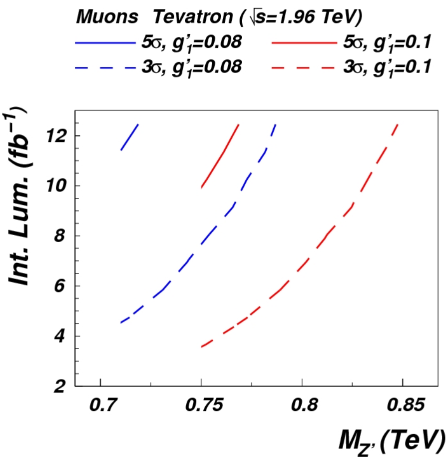
Z' Discovery potentials at the Tevatron

Luminosity vs $M_{Z'}$ (for fixed values of g'_1)

Electrons

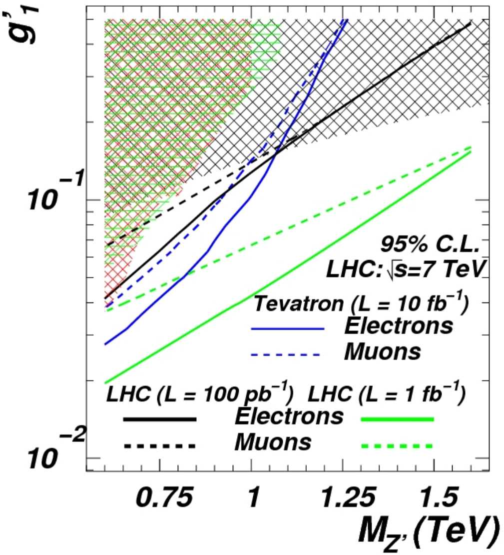


Muons



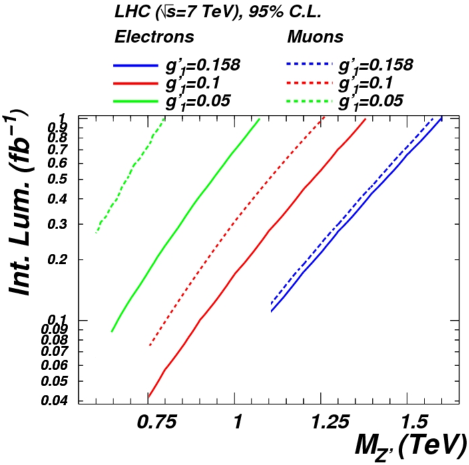
Z' exclusions @ 7 TeV

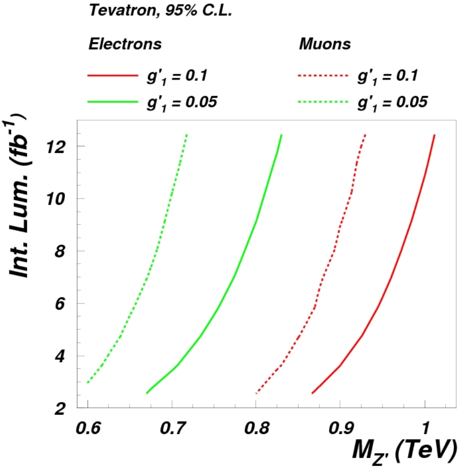
Significance contour levels plotted against g'_1 and $M_{Z'}$



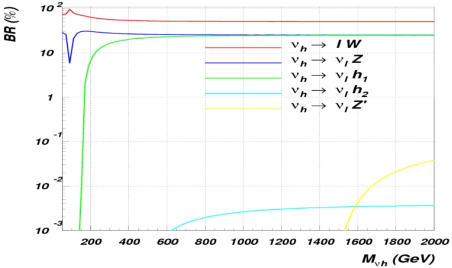
Z' exclusions @ 7 TeV (II)

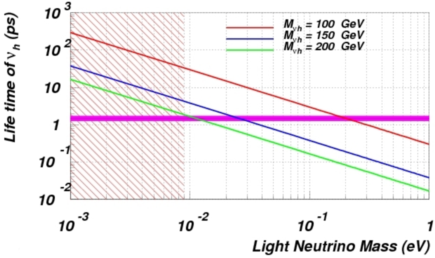
Luminosity vs $M_{Z'}$ (for fixed values of g'_1)



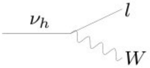


Appendix: ν_h phenomenology





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



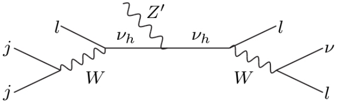
$$= \frac{\sqrt{2}e}{4\sin\vartheta_W}\sin\alpha_\nu$$

- $\Gamma = \Gamma(m_{\nu l}/m_{\nu h})$
- ν_h can be a long-lived particle
- DISPLACED VERTICES (e.g., from a high energetic and isolated lepton)

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 *et al*, *Phys. Rev. D* **36** *(1987) 295*



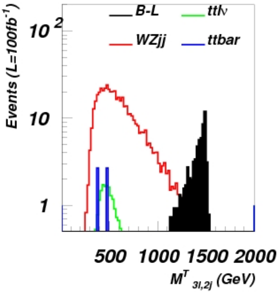
$M_{Z'} = 1.5$ TeV, $g'_1 = 0.2$: $\sigma(pp \to Z') = 0.3$ pb
$M_{\nu_h} = 200$ GeV, $\mathscr{L} = 100$ fb^{-1}, bin $= 20$ GeV

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, $l = e, \mu, \tau$)

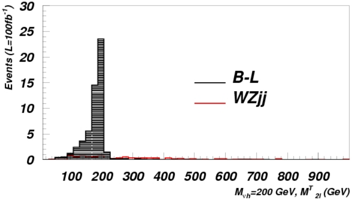


Cuts:

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

- $\surd$ Simple SM extension at TeV scale, RH-neutrinos
- $\surd$ motivated by high-scale physics (GUT, baryogenesis)
- $\surd$ pure $B-L$ model, no $Z-Z'$ mixing, only vectorial coupling

- Discovery power limited by existing experimental constraints
  good prospects at LHC $@ \sqrt{s}=7$ TeV
- Better sensitivity to electrons (also, width measure possible)

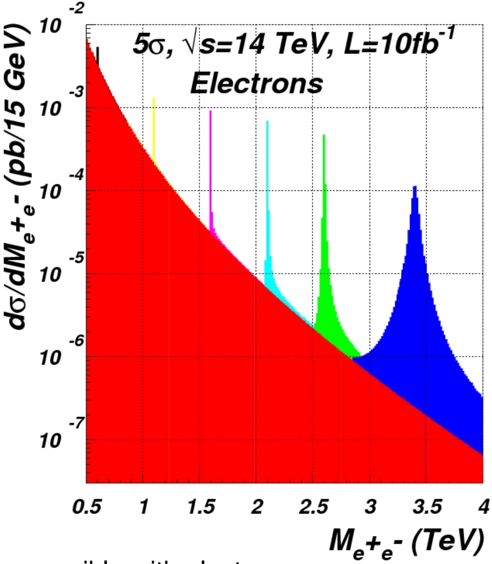
Tevatron$@10$ fb^{-1} stil competitive with LHC$@7$ TeV:

- LHC requires 1 fb^{-1} for same sensitivity to small couplings
- but it is not limited by kinematics: 5σ observation at LHC$@7$ TeV up to $M_{Z'}=1.25(1.20)$ TeV with electrons(muons)
- Otherwise, 95% C.L. exclusions

What's next: look for $\boldsymbol{\nu_h}$

Backup slides

Line shape



Z' width measure possible with electrons

Validation

Comparison of our simulation (CalcHEP) wrt $D\varnothing$ analysis of expected backgrounds [1] at 3.6 fb^{-1} of integrated luminosity. From Table II in *http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/NP/N66/*.

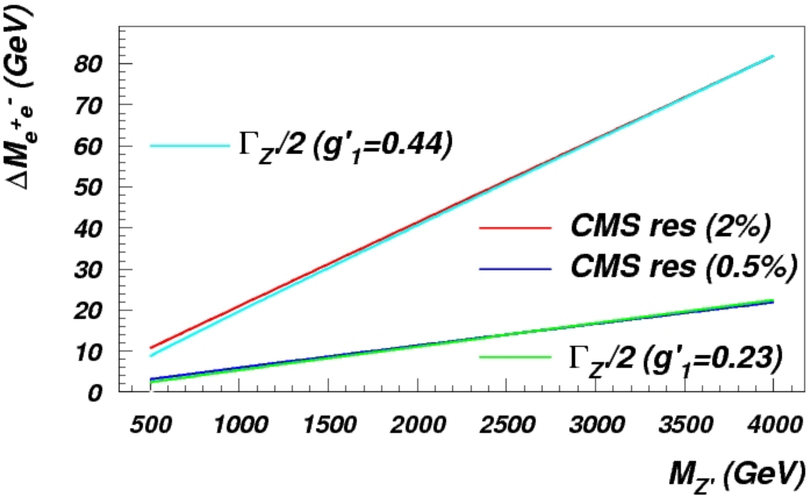
The compatibility is, as usual, defined as:

$$\frac{Ev - Ev_{D\varnothing}}{\sigma_{D\varnothing}} .$$

		$D\varnothing$ analysis		Our simulation	
$M_{Z'}$ (GeV)	Mass Window Lower Limit (GeV)	Expected Bkg Events	Signal Acceptance	Expected Bkg Events	Compatibility Level
400	353	22.4 ± 0.7	0.172	23.2	1.1
500	445	7.92 ± 0.22	0.188	8.23	1.4
600	536	2.93 ± 0.07	0.199	3.00	1.0
700	626	1.052 ± 0.025	0.207	1.110	2.3
750	673	0.631 ± 0.016	0.209	0.653	1.4
800	718	0.384 ± 0.010	0.211	0.391	0.7
850	762	0.222 ± 0.006	0.212	0.235	2.2
900	810	0.134 ± 0.004	0.216	0.135	0.4
950	858	0.0701 ± 0.0023	0.214	0.0750	2.1
1000	902	0.0410 ± 0.0015	0.216	0.0440	2.0

[1] The $D\varnothing$ simulation is modelled using the PYTHIA Monte Carlo event generator, with CTEQ6L1 PDFs, and then processed through the standard $D\varnothing$ detector simulation based on GEANT3.

CMS resolution vs Z' width

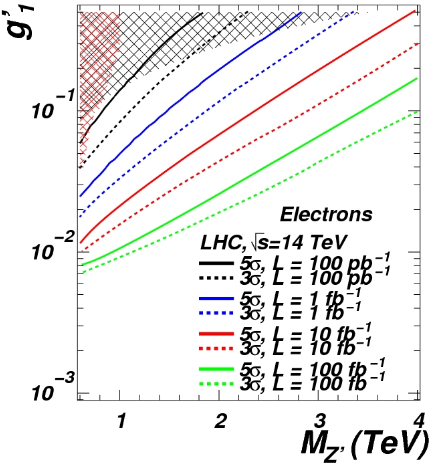


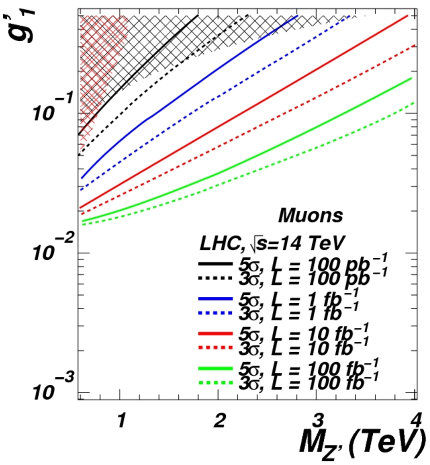
Peak dominated by experimental resolution if $g'_1 \lesssim 0.4(0.2)$

Z' Discovery potentials for $\sqrt{s} = 14$ TeV

Significance contour levels plotted against g_1' and $M_{Z'}$, improved resolutions.

Electrons ↓ **Tevatron** and **LEP** bounds↓ Muons

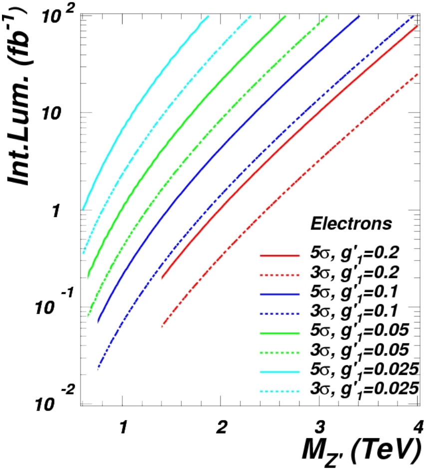




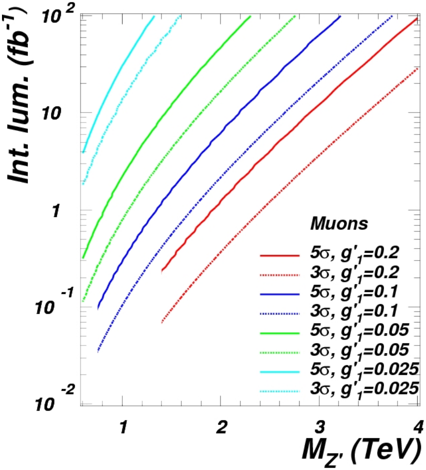
Z' Discovery potentials for $\sqrt{s} = 14$ TeV

Luminosity vs $M_{Z'}$ (for fixed values of g'_1)

Electrons

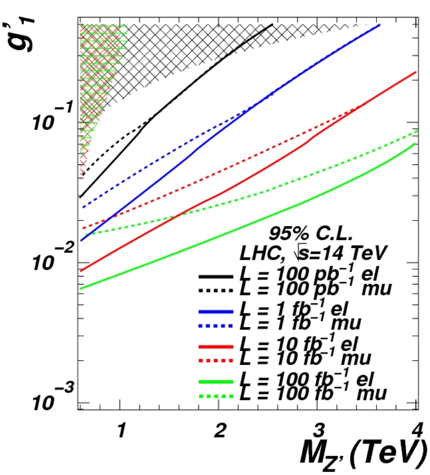


Muons

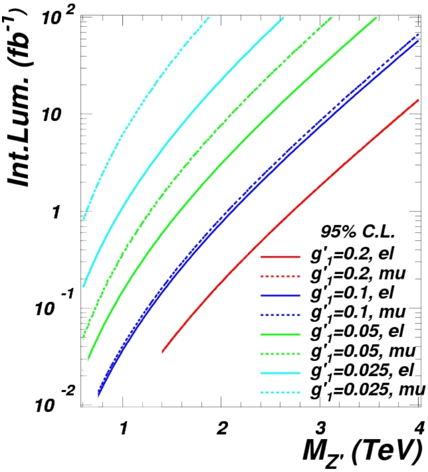


Z' exclusions @14 TeV

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



Luminosity vs $M_{Z'}$ (for fixed values of g'_1)



Z' experimental limit

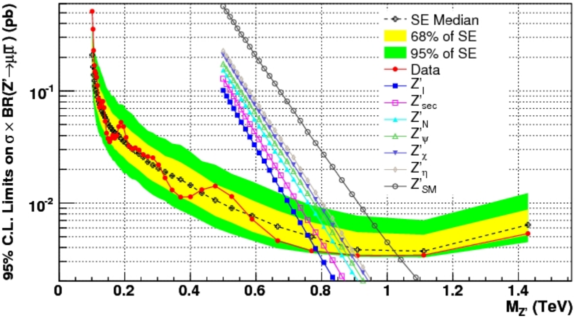
LEP bound:

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

$$\frac{M_{Z'}}{g'_1} \geq 7 \text{ TeV}$$

Tevatron (comparing our prediction to experimental data):

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

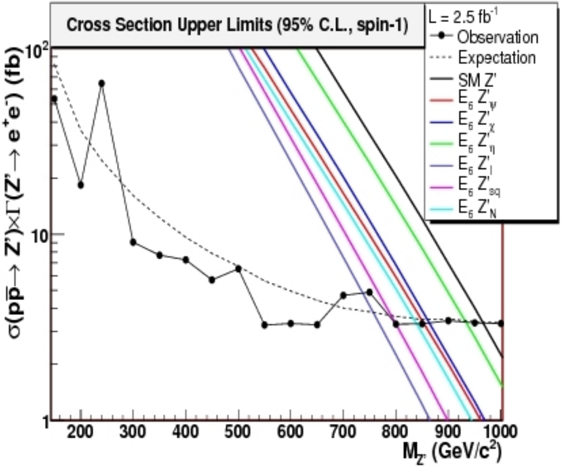


$p\bar{p} \to \mu^+\mu^-$	
g'_1	$M_{Z'}$ (GeV)
0.06	600
0.1	750
0.123	800
0.2	900
0.3	1000
0.5	1195

Z' experimental limit: continue

Tevatron (comparing our prediction to experimental data):

Electrons T. Aaltonen *et al.* [CDF], Phys. Rev. Lett. **102**, 031801 (2009):



$p\bar{p} \to e^+e^-$	
g'_1	$M_{Z'}$ (GeV)
0.042	600
0.086	700
0.115	800
0.19	900
0.3	1000