Properties of the minimal $U(1)_{B-L}$ extension of the SM

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Outline

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

2) Gauge sector: Z' boson
- Decays and width
- Discovery potential for the LHC @ $\sqrt{s}=7$ TeV (Tevatron comparison)

3) Fermion sector: Heavy neutrinos
- Decays and width
- Tri-lepton signature

4) Scalar Sector: two Higgs bosons
- Theoretical bounds
- Prod. cross sections and BRs
- Selected signatures

5) 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:

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

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

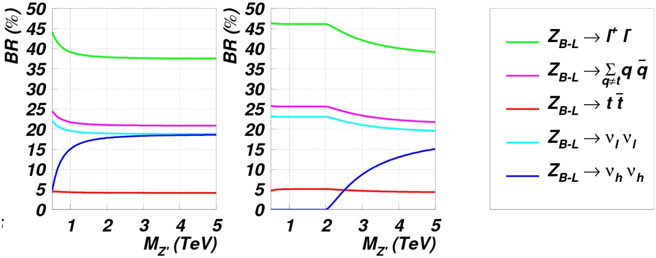
No $Z - Z'$ mixing in the pure $B - L$ model

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) $\rightarrow$ not-fixed BRs.

Z' phenomenology

$m_{\nu h} = 250$ GeV $\qquad$ 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 $M_{Z'}$:

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

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

Analysis details

[arXiv:1002.3586]

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,...)

Analysis with CalcHEP, model implemented via LanHEP.

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

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

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

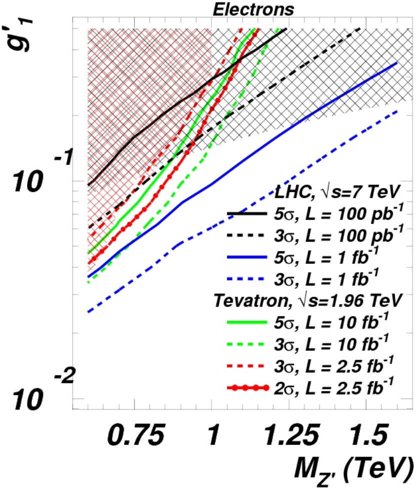
$$e^\pm \text{ @ LHC: } \frac{|M_{ee}-M_{Z'}|}{\text{GeV}} < \max\left(\frac{\Gamma_{Z'}}{2}, \begin{pmatrix} 0.02 \\ 0.005 \end{pmatrix} \frac{M_{Z'}}{\text{GeV}}\right),$$

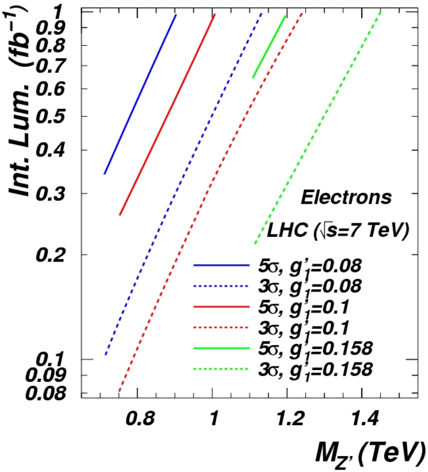
$$e^\pm \text{ @ Tevatron: } \frac{|M_{ee}-M_{Z'}|}{\text{GeV}} < \max\left(\frac{\Gamma_{Z'}}{2}, \left(0.135\sqrt{\frac{M_{Z'}}{\text{GeV}}} + 0.02\frac{M_{Z'}}{\text{GeV}}\right)\right).$$

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

Significance contour levels and required luminosity for electrons
(Similar plots for muons in the final state)

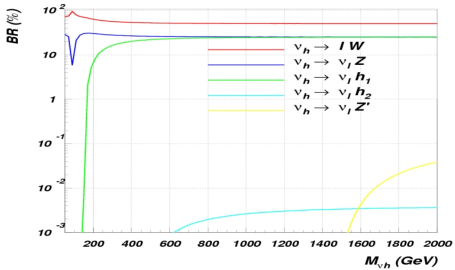
g_1' vs. $M_{Z'}$ ↓ **Tevatron** and **LEP** bounds↓ Fixed g_1'

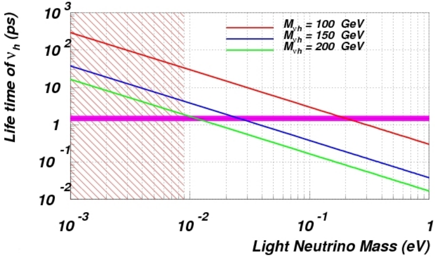




ν_h phenomenology

[Phys. Rev. D **80** 055030 (2009)]





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

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

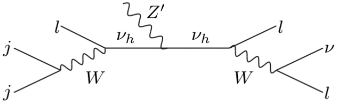
- $\Gamma = \Gamma(m_{\nu l}/m_{\nu h})$
- ν_h can be a long-lived particle
  - DISPLACED VERTICES (e.g., from a high energetic and isolated lepton)

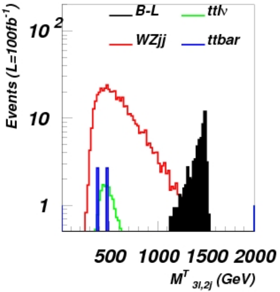
Notice: $\nu_h \to \nu_l h_1$ (more later)

ν_h @ LHC: $BR(Z' \to 3\ell + 2j + \not{P}_T\ (1\nu),\ \ell = e, \mu)$ 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** *295 (1987)*





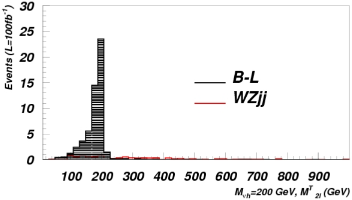
$M_{Z'} = 1.5$ TeV, $g_1' = 0.2$: $\sigma(pp \to Z') = 0.3$ pb
$M_{\nu_h} = 200$ GeV, $\mathscr{L} = 100$ fb^{-1}, bin $= 20$ GeV

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

The scalar sector

Scalar Lagrangian

$$\mathscr{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger D_\mu \chi - V(H,\chi)$$

$$V(H,\chi) = m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2$$

$V(H,\chi)$ is bounded from below if

$$\lambda_1,\ \lambda_2 > 0$$

$$4\lambda_1\lambda_2 - \lambda_3^2 > 0$$

$$\boldsymbol{SU(2) \times U(1) \times U(1) \longrightarrow U(1)_{e.m.}} \qquad H \equiv \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix} \quad \chi \equiv \frac{h' + x}{\sqrt{2}}$$

Scalar spectrum:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ h' \end{pmatrix}$$

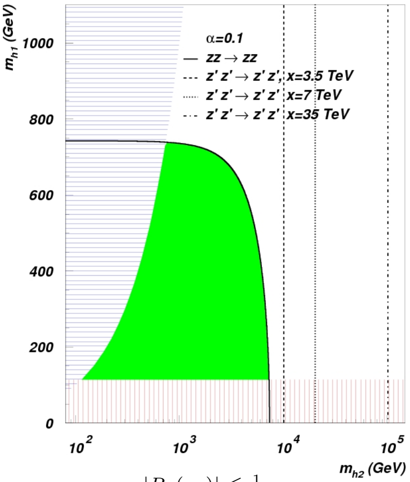
Properties:

- $m_{h_1}^2 \leq m_{h_2}^2$ and $\alpha \in \left[0, \frac{\pi}{2}\right]$,
- $\lambda_3 \neq 0$, so $h_2 \rightarrow h_1 h_1$ is possible ($\lambda_3 = 0$ for $\alpha = 0, \pi/2$ or for $m_{h_1} = m_{h_2}$),
- $h_1(h_2)$ couples to SM[new] fields prop. to $\cos\alpha(\sin\alpha)$ [and vice-versa].

Scalar sector: theoretical Bounds for $\alpha = 0.1$

Unitarity

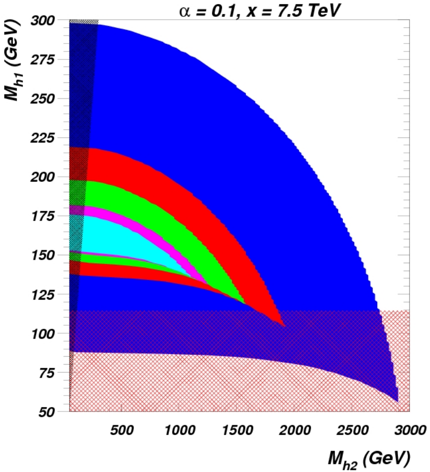
[Phys. Rev. D **81** 095018 (2010)]



$|Re(a_0)| \leq \frac{1}{2}$

Triviality + Vacuum Stability

[Phys. Rev. D **82** 055018 (2010)]



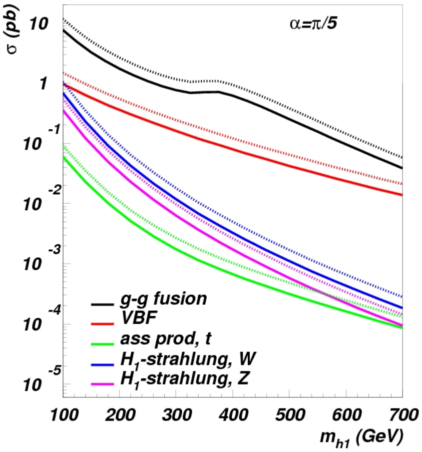
$\lambda_i(Q) \leq 1$ and $4\lambda_1(Q)\lambda_2(Q) - \lambda_3^2(Q) > 0$

$\forall Q < Q'$

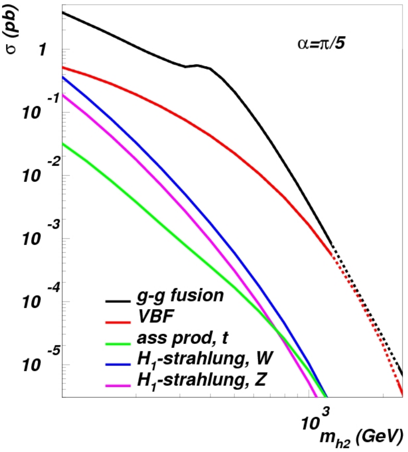
Scalar sector: phenomenology

[arXiv:1011.2612]

h_1: Prod. Cross Sections ($\alpha = \frac{\pi}{5}$)



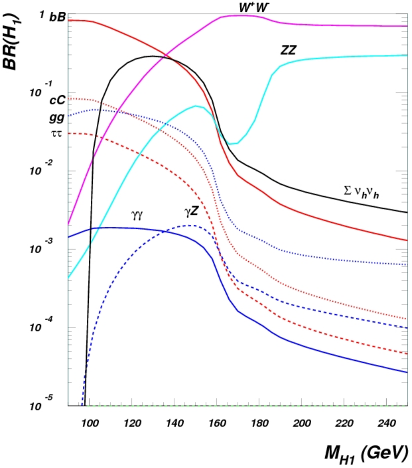
h_2: Prod. Cross Sections ($\alpha = \frac{\pi}{5}$)



LHC @ $\sqrt{s} = 7$ TeV

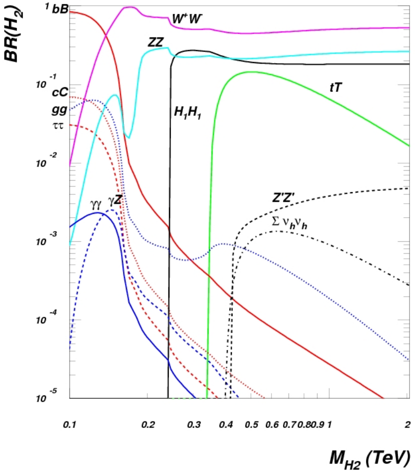
Scalar sector: BRs

h_1 BRs ($\alpha = \frac{2\pi}{5}$)



$m_{\nu_h} = 50$ GeV

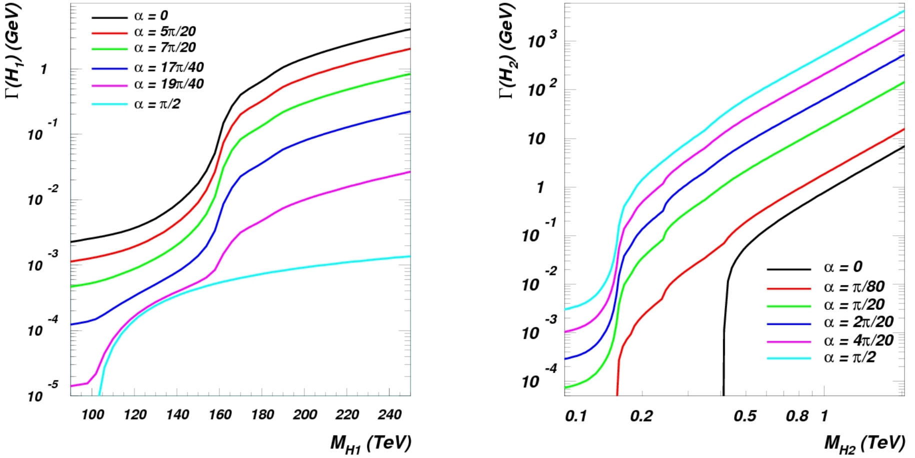
h_2 BRs ($\alpha = \frac{3\pi}{20}$)



$M_{Z'} = 210$ GeV, $m_{h_1} = 120$ GeV
$m_{\nu_h} = 200$ GeV

Scalar sector: total widths

$\Gamma(h_1)$ $\Gamma(h_2)$

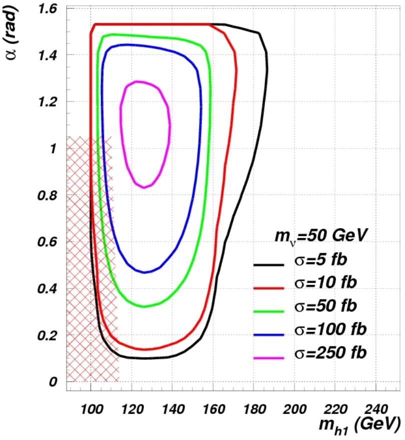


$m_{\nu_h} = 50$ GeV $M_{Z'} = 210$ GeV, $m_{h_1} = 120$ GeV

For instance, $\frac{\Gamma(h_2)}{M_{h_2}} < 10\%$ when $M_{h_2} = 1$ TeV for $\alpha = \frac{\pi}{10}$ (blue line)

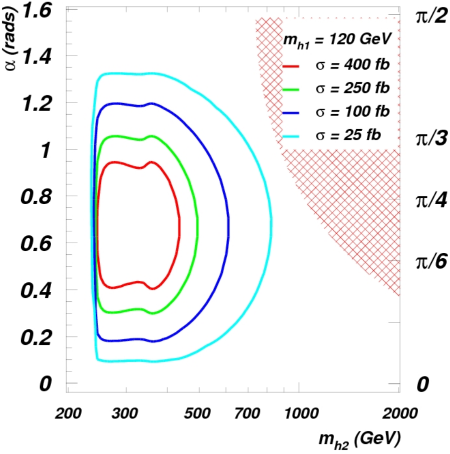
Scalar sector: selected final states

$\sigma(gg \to h_1 \to \nu_h \nu_h)$ for $\sqrt{s} = 7$ TeV



$m_{\nu_h} = 50$ GeV

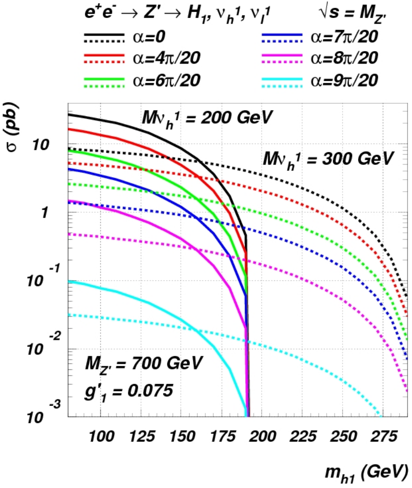
$\sigma(gg \to h_2 \to h_1 h_1)$ for $\sqrt{s} = 14$ TeV

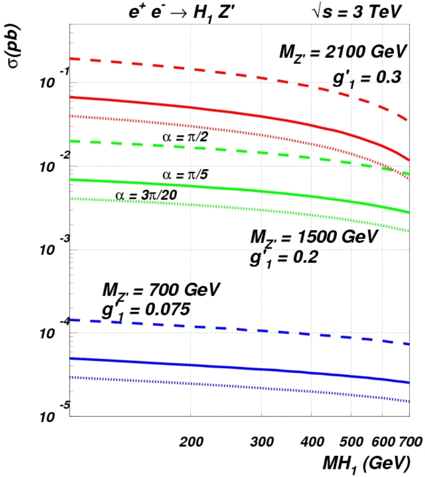


$m_{h_1} = 120$ GeV

Scalar sector: Higgs @ LC (In progress)

Two new channels for producing h_1 via Z'





Strengths: Z' dominantly coupled to leptons and tunable LC CM energy

Conclusions

$\surd$ Simple SM extension at TeV scale, RH-neutrinos

$\surd$ motivated by high-scale physics

$\surd$ pure $B-L$ model, no $Z-Z'$ mixing, only vectorial coupling

- Z' discovery power limited by existing experimental constraints
- Interesting new signatures in the gauge and scalar sectors
- Striking signatures (multi leptons, displaced vertices, ...)

Novel and *observable* tri-lepton signature from $h_1 \to \nu_h \nu_h$ ($\sqrt{s}=7$ TeV) for M_h in the 115-160 GeV range

Good prospects at the LHC, both at $\sqrt{s}=7$ and 14 TeV

Scope to probe the model at future LCs

Backup slides

Z' experimental limit

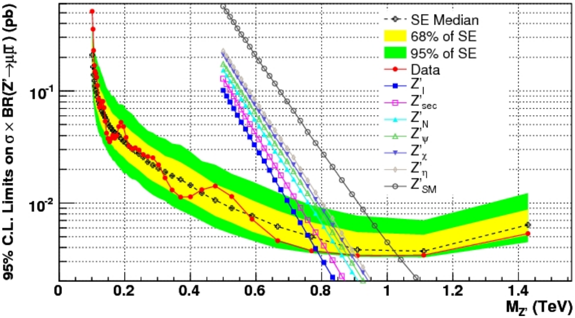
LEP bound:

G. Cacciapaglia *et all*, 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):

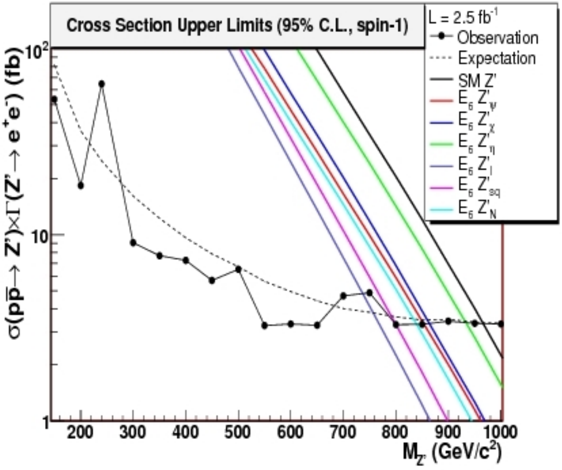


$p\bar{p} \to \mu^+\mu^-$	
g'_1	$M_{Z'}$ (GeV)
0.06	600
0.1	750
0.123	800
0.2	900
0.3	1000
0.5	1195

Z' experimental limit: continue

Tevatron (comparing our prediction to experimental data):

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

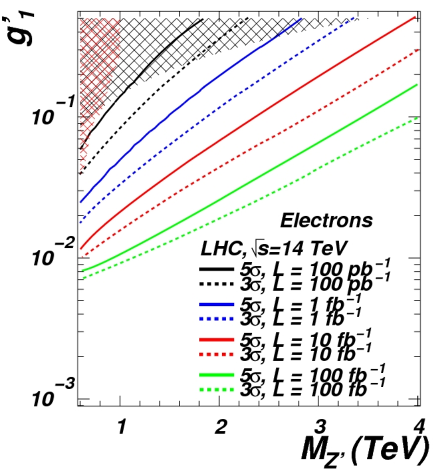


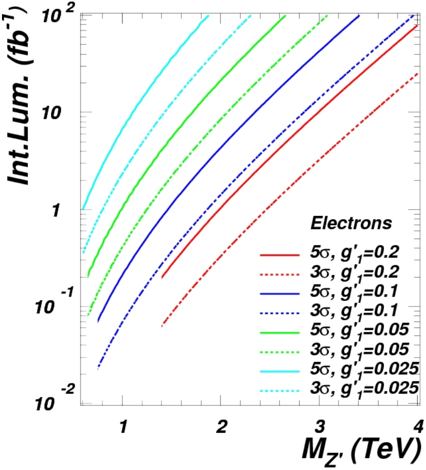
$p\overline{p} \to e^+e^-$	
g_1'	$M_{Z'}$ (GeV)
0.042	600
0.086	700
0.115	800
0.19	900
0.3	1000

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

Significance contour levels and required luminosity for electrons
(Similar plots for muons in the final state)

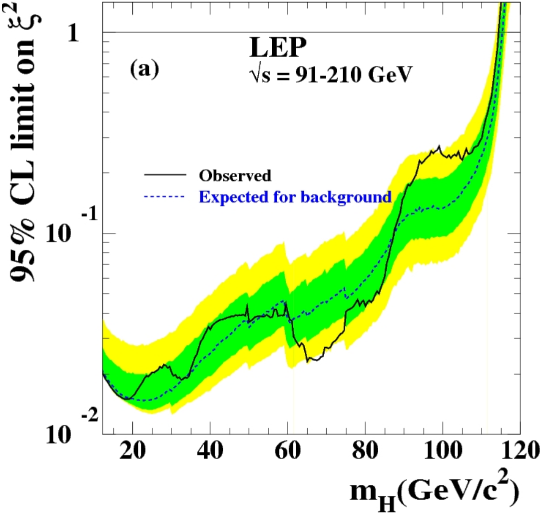
g_1' vs. $M_{Z'}$ ↓ **Tevatron** and **LEP** bounds↓ Fixed g_1'





Higgs experimental limit:

R. Barate *et al.* [LEP Working Group for Higgs boson searches], Phys. Lett. B **565** (2003) 61:



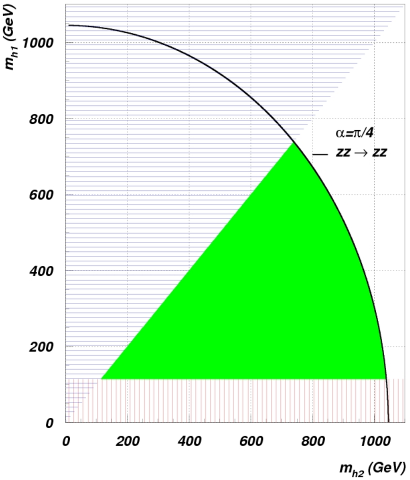
$$\xi \equiv \cos\alpha$$

$$\alpha = 0.1 \rightarrow (\cos\alpha)^2 = 0.99$$
$$\alpha = \frac{\pi}{3} \rightarrow (\cos\alpha)^2 = 0.25$$

Scalar sector

Theoretical Bounds for $\alpha = \frac{\pi}{4}$

Unitarity



Triviality + Vacuum Stability