F. Zwirner - University & INFN, Padova + IVSLA

SM Extensions with Gauged B-L

NO-VE, 17 April 2008

Mostly a critical review
after discussions with:
- L.Basso, M.Passera
- G.Villadoro

Plan

- Motivations
- Constraints on extra Z' bosons
- A minimal non-susy model
- A minimal susy model
- Kinetic mixing
- Conclusions and outlook

Neutrinos = a window on BSM physics

Sticking to the minimal SM degrees of freedom:

$$\Delta\mathcal{L} \sim \frac{(L\,H)^2}{2\,\Lambda} \rightarrow m_\nu \sim \frac{v^2}{\Lambda}$$ [Weinberg]

$$m_\nu \sim 10^{-1}\,eV \rightarrow \Lambda \sim 10^{14-15}\,GeV$$

Best guess for underlying degrees of freedom:

SM-singlet right-handed neutrinos (type-I see-saw)

What is then the underlying mass scale ?

With mass terms $m_D \sim y_N v$ and M_R, find:

$$\Lambda \sim \frac{M_R}{y_N^2} \qquad \begin{array}{c} M_R \sim 10^{14-15} GeV \\ y_N \sim 1 \end{array} \; ? \qquad \begin{array}{c} M_R \sim TeV \\ y_N \sim y_e \end{array} \; ?$$

[see Feruglio] [see Shaposhnikov]

Choose here $M_R \sim$ TeV and $y_N \sim y_e$

Hierarchy problem? Today's energy frontier!

Alone, no big impact at high-energy colliders:

$y_N \sim y_e$ ➔ SM & nu-R very weakly coupled

How to generate a more interesting coupling?

M_R = the scale of (B -) L breaking

Promote (B-L) to an extra U(1) gauge symmetry

A reason for right-handed neutrinos:

Y' = a Y + b (B-L) automatically anomaly-free

if fermions in SM families with nu-R

Weinberg, QFT-II, p.388: "a neutral vector boson somewhat heavier than the Z^0 and coupled to B-L seems like the most plausible addition to the SM"

Pragmatic motivation: “easy” LHC signal ?

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})

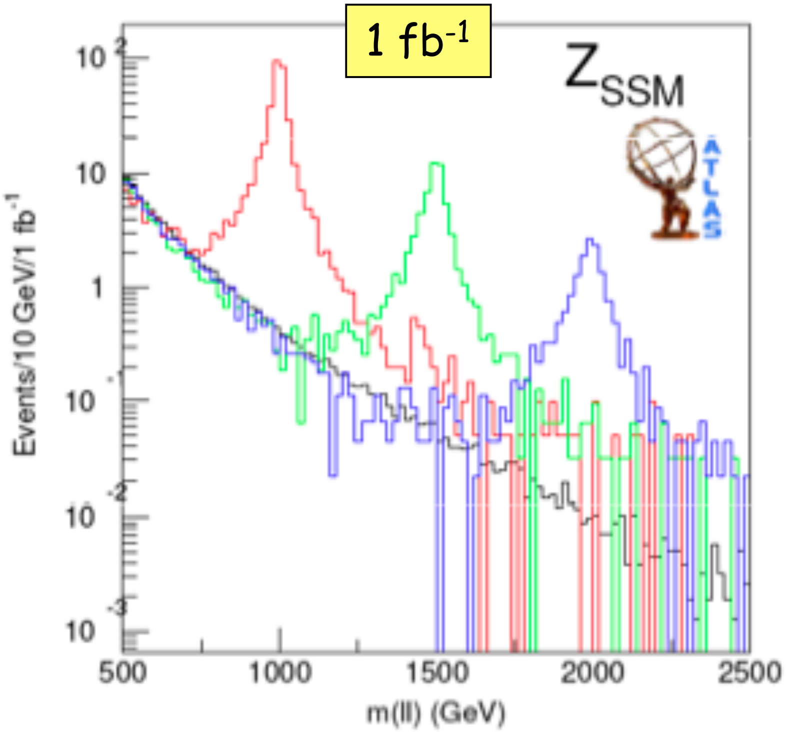
Mass	Expected events for 1 fb^{-1} (after all analysis cuts)	Integrated luminosity needed for discovery (corresponds to 10 observed evts)
1 TeV	~ 160	~ 70 pb^{-1}
1.5 TeV	~ 30	~ 300 pb^{-1}
2 TeV	~ 7	~ 1.5 fb^{-1}

- with 100 pb^{-1} large enough signal for discovery up to m > 1 TeV
- signal is (narrow) mass peak on top of small Drell Yan background
- ultimate calorimeter performance not needed

Ultimate ATLAS reach (300 fb^{-1}): ~ 5 TeV

[F. Gianotti, CERN-SPC, 17/9/07]

Similar reach for the CMS experiment



Further theoretical motivations

GUTs

Embeddable in SO(10) grand unification:

$SO(10) \rightarrow SU(3)_C x SU(2)_L x SU(2)_R x U(1)_{B-L}$

$\rightarrow SU(3)_C x SU(2)_L x U(1)_Y x U(1)_{Y'}$

e.g., with a Higgs in the adjoint 45 representation

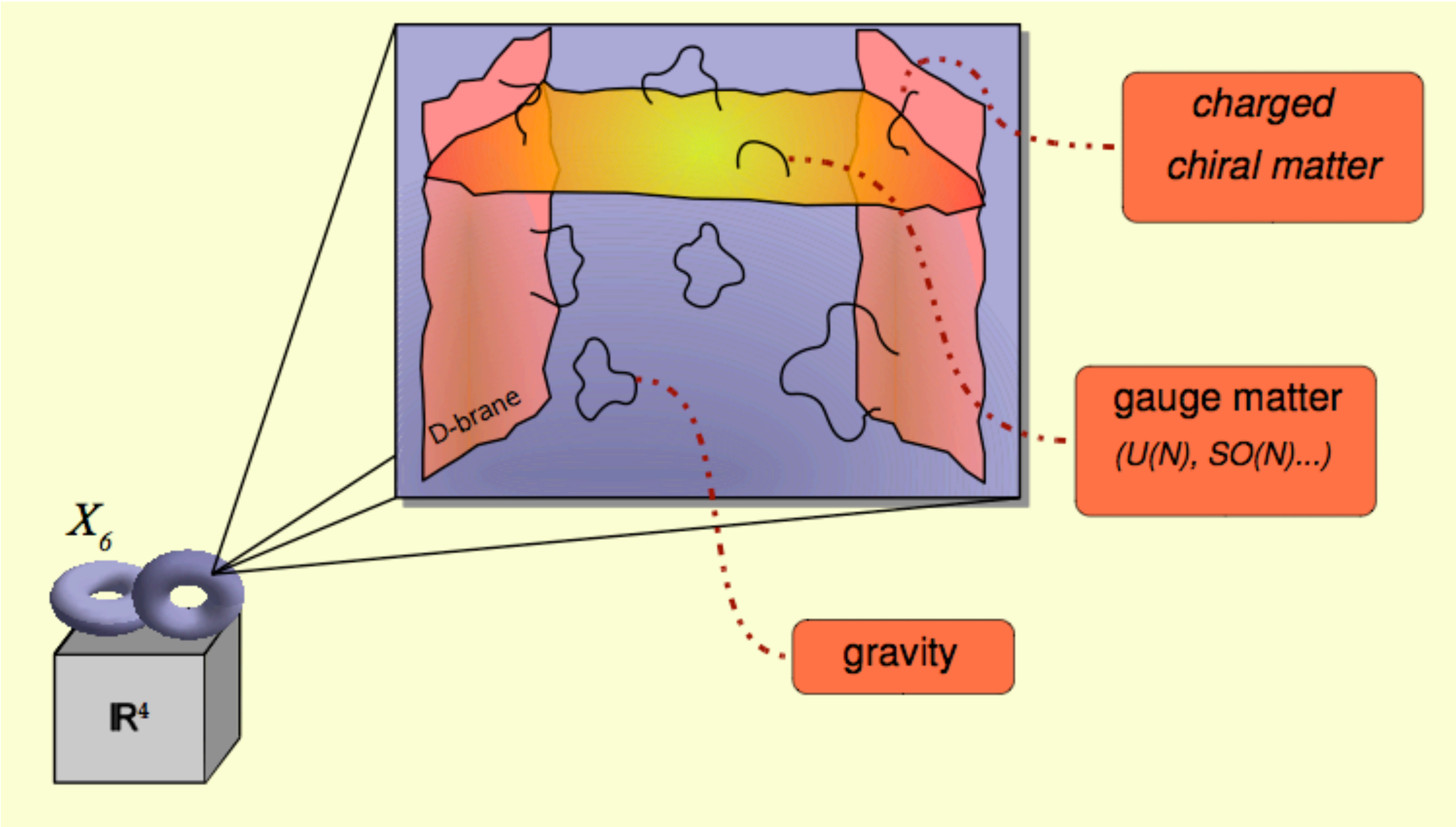
Type-II string models with D-branes

Gauge group for a stack of N parallel D-branes:

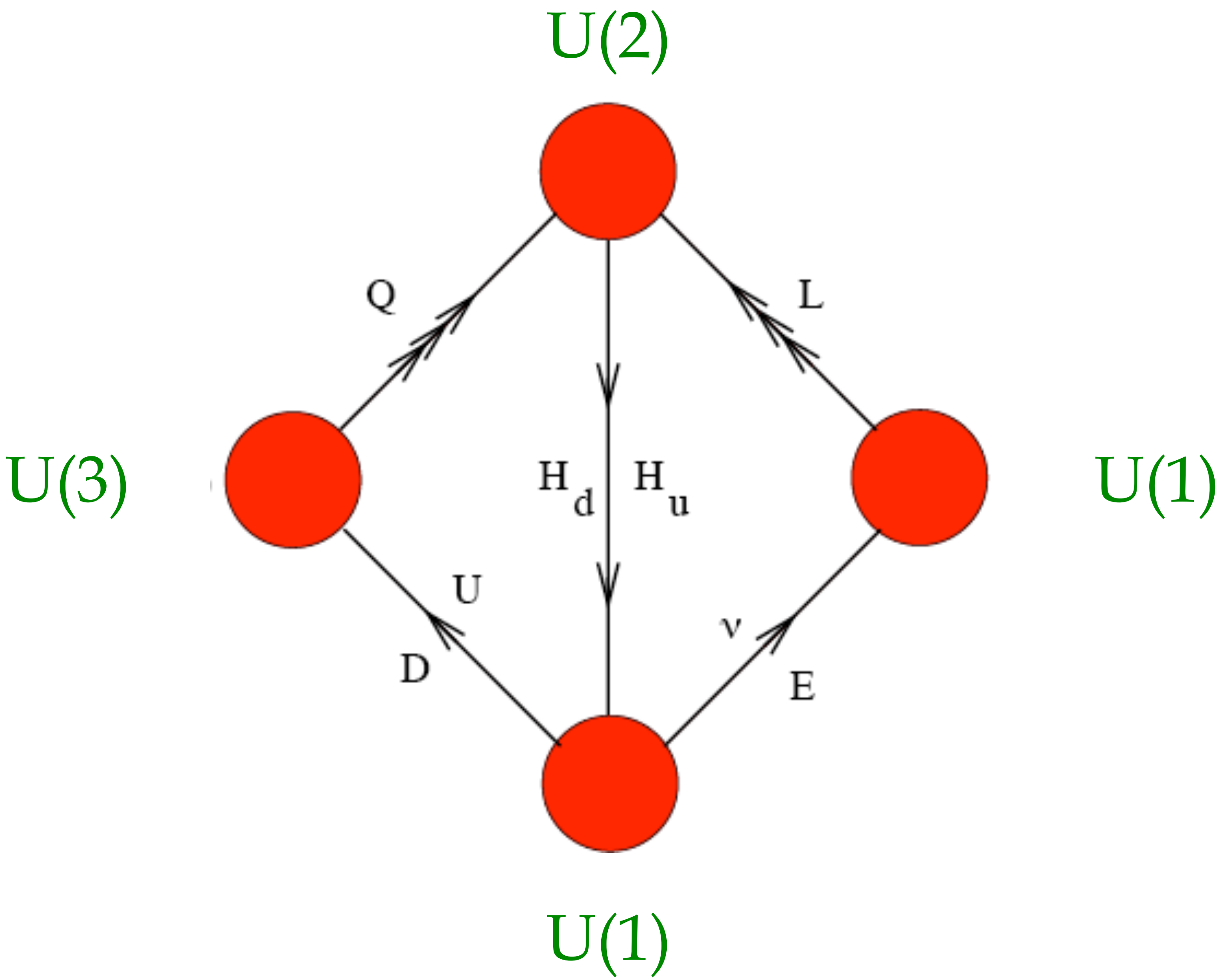
$U(N) \rightarrow SU(N) \, x \, U(1)$

Multiple U(1) factors frequent in realistic models often including a residual non-anomalous $U(1)_{B-L}$

A picture of the brane-world (IIA)



An example of SM-like "quiver"



LEP bounds on Z′

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} - \frac{1}{2} M^2_{Z'} Z'_\mu Z'^{\,\mu}$$

(diagonal kin. and mass term)

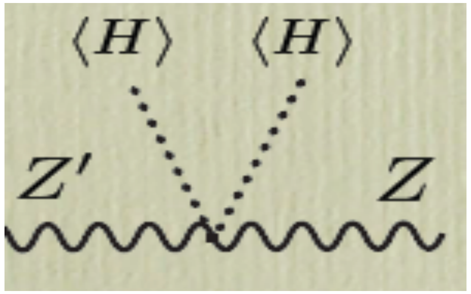
$$+ g_{Z'} Z'_\mu \sum_f \bar{f} z_f \gamma^\mu f + g_{Z'} (H^\dagger z_H Z'_\mu iD^\mu H + h.c.) + \dots$$

(couplings to SM fermions)

(Z-Z′ mixing after EWSB)

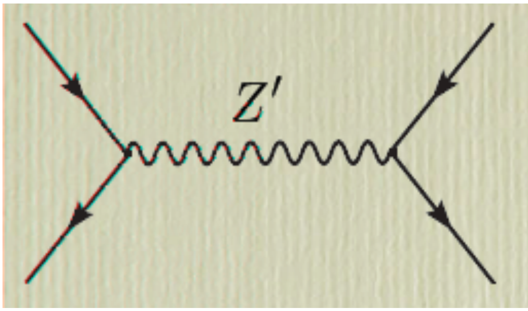
LEP-1 Z-pole data mostly constrain Z-Z′ mixing

$$|\theta| < \mathcal{O}(10^{-3})$$



$$\theta \sim \frac{g_{Z'}}{g_Z} \frac{M_Z^2}{M_{Z'}^2} z_H$$

LEP-2 (off-pole) data constrain 4-fermion effective operators



$$\sim \frac{g^2_{Z'}}{M^2_{Z'}} z_e z_f$$

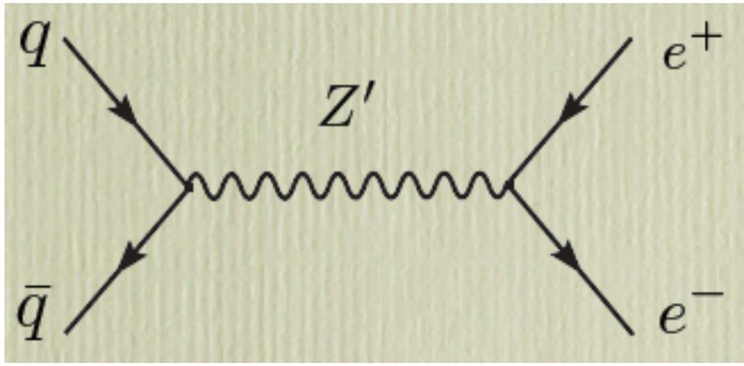
Tevatron bounds on Z′

More difficult to parametrize in a simple way!

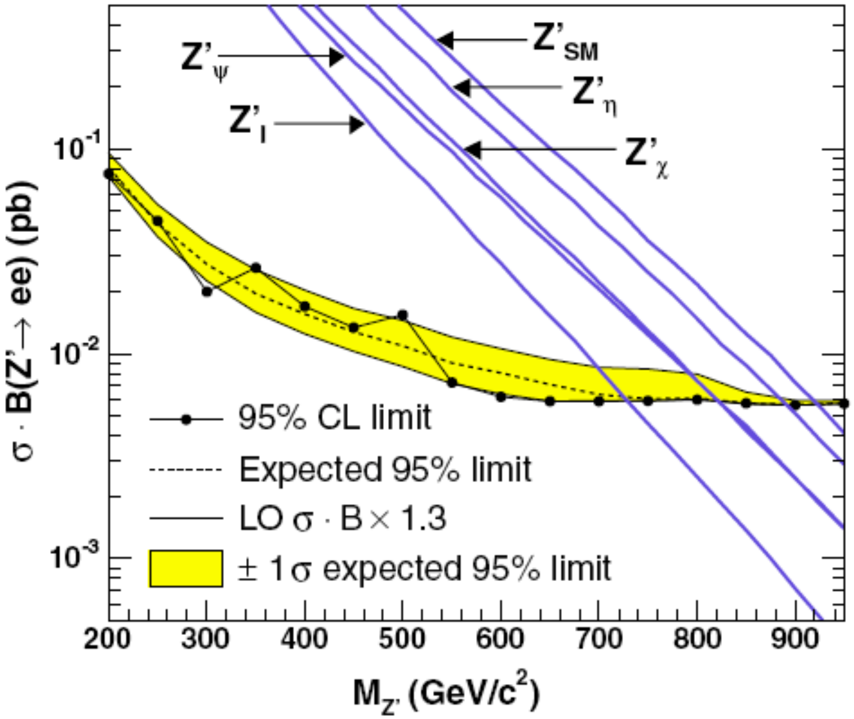
Typical bounds are on $\sigma(Z') \cdot BR(Z' \to l^+l^-)$

But (already at leading order):

$$\sigma(Z') = g_{Z'}^2\, f(z_q, z_u, z_d, s, M_{Z'}^2)$$



where f depends on the PDF



CDF Run II 1.3 fb^{-1}
PRL 99 (2007) 171802

Quantum numbers of the SM particles

	SU(3)	SU(2)	Y	$B-L$	T_{3R}	X
Q	3	2	1/6	1/3	0	−1
D^c	$\bar{3}$	1	1/3	−1/3	1/2	3
U^c	$\bar{3}$	1	−2/3	−1/3	−1/2	−1
L	1	2	−1/2	−1	0	3
E^c	1	1	1	1	1/2	−1
N^c	1	1	0	1	−1/2	−5
$H = H_2$	1	2	1/2	0	1/2	2
$\chi = \chi_2$	1	1	0	2	−1	−10
H_1	1	2	−1/2	0	−1/2	−2
χ_1	1	1	0	−2	1	10

$$Q = T_{3L} + Y \quad Y = T_{3R} + \frac{B-L}{2} \quad X = 4Y - 5(B-L) = 4T_{3R} - 3(B-L)$$

LEP1 bounds more easily evaded for Y'=B-L [z_H=0]

LEP2 bounds on $M_{Z'}$(TeV)/$g_{Z'}$: 6-7 for B-L, 15 for X

(most favourable case would be "leptophobic" Z')

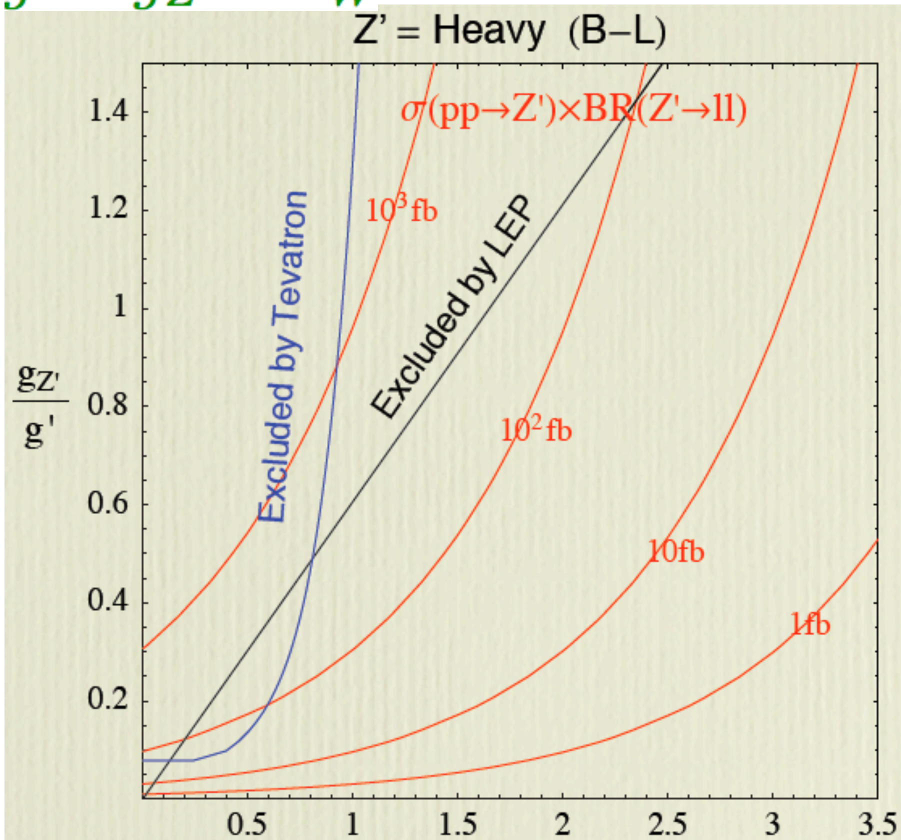
How much room left for the LHC ?

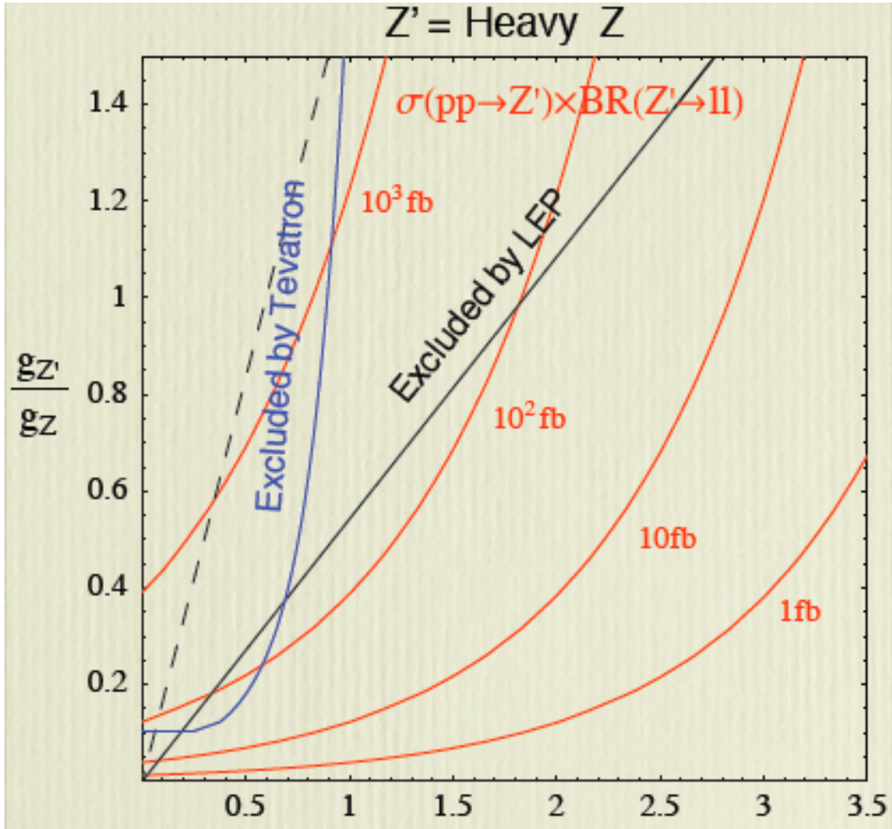
Normalization of $g_{Z'}$ and identity of Y′ model-dependent

Direct SO(10) breaking would give Y′~X and $g_{Z'}/g'$~0.2

Different possibilities within brane-world constructions

$g' = g_Z \sin\theta_W$





[Contino, talk at the Perugia LHC workshop, 30/1-2/2/08] $M_{Z'}(TeV)$

A minimal non-SUSY model

[Buchmuller-Greub-Minkowski 1991]

SM (with 3 right-neutrinos & Higgs doublet) + extra $U(1)_{Y'}$
+ complex SM-singlet Higgs x with B-L=-2 to generate M_R

$$\Delta\mathcal{L}_{Yuk} = y_R \nu_R \nu_R \chi + h.c.$$

$$V = m^2|H|^2 + \mu^2|\chi|^2 + \lambda_1|H|^4 + \lambda_2|\chi|^4 + \lambda_3|H|^2|\chi|^2$$

The gauged version of the singlet Majoron model
[Chikashige-Mohapatra-Peccei 1980]

Acceptable symmetry breaking for suitable parameter choices

Main phenomenological features:

[see, e.g., recent studies by Khalil et al, Basso et al]

- Z′ phenomenology as discussed before [with possible decays into right-handed neutrinos, no Z-Z′ tree-level mixing for canonical gauge kinetic terms & Y′=B-L, …]

- An extended Higgs spectrum: two neutral scalars h_1 & h_2 with complementary couplings to SM states controlled by their mixing angle. Typically, weakened signals at the LHC.

- The possibility of a purely radiative symmetry-breaking of the gauge symmetry via the Coleman-Weinberg mechanism (setting to zero the mass parameters in the scalar potential)

A minimal SUSY model

[Babu-Dutta-Mohapatra 2003, Khalil-Masiero 2007]

Enlarge the Higgs sector as required by supersymmetry:

$$H \to (H_1, H_2) \quad \chi \to (\chi_1, \chi_2)$$

Write general gauge-invariant renormalizable W :

$$W = W_{MSSM} + y_N L N^c H_2 + y_R N^c N^c \chi_1 + \mu' \chi_1 \chi_2$$

(automatically conserving baryon and lepton number)

After introducing soft SUSY breaking as usual:

- ➔Can realize radiative breaking of gauge symmetry
- ➔Link SU(2)xU(1), (B-L) and SUSY-breaking scales
- ➔Richer spectrum of neutralinos & neutral Higgses
- ➔An enlarged sneutrino sector within the TeV scale

Kinetic mixing

[Holdom 1986; DelAguila-Quiros-FZ 1987; …]

In the presence of (at least) two U(1) factors, can write

$$\mathcal{L}_{kin} = -\frac{1}{4}\,(g^{-2})_{mn}\,F^{m}_{\mu\nu}\,F^{n\,\mu\nu}$$

with $(g^{-2})_{mn}$ defining a matrix of coupling constants besides the two diagonal U(1) couplings, the third off-diagonal coupling g_x can be reabsorbed into $g_{Z'}$ Y′ but this is not stable against quantum corrections:

$$\frac{d(g^{-2})_{mn}}{dt} = -\frac{b_{mn}}{8\pi^2} \qquad b_{mn} = \frac{2}{3}\sum_f Q^f_m Q^f_n + \frac{1}{3}\sum_b Q^b_m Q^b_n$$

Only for orthogonal U(1) generators mixing postponed to 2-loop and threshold effects: almost true (excluding Higgs sector) for the (Y,X) or $(T_{3R}$,B-L) pairs in the table

SUSY kinetic mixing

In the supersymmetric case, gauge kinetic mixing
extends to gaugino masses and kinetic terms
also to the D-term part of the scalar potential

$$\mathcal{L}_{kin} = -\frac{1}{4}\int d^2\theta \; h_{mn} W^m W^n + h.c.$$

[old SUGRA literature; Dienes-Kolda-Russell 1997]

The MSSM RGE can be fully generalized [Villadoro, FZ]

Consequence: minimal models discussed above cannot be
extrapolated as such to very large scales (e.g. GUT scale)
kinetic mixing effects must be properly included, e.g.:

$$\theta \sim \frac{g_x}{g_Z}\frac{m_Z^2}{M_{Z'}^2}$$

Conclusions and outlook

- SM extensions with right-handed neutrinos and an extra U(1) gauging B-L [or Y'=aY+b(B-L)] are quite plausible
- LEP constraints are quite strong (often more than Tevatron) but leave still room for possible discoveries at the LHC
- Kinetic mixing effects cannot be neglected in general especially when extrapolating models to high scales
- Interesting to explore more systematically ranges of $g_{Z'}$ and Y' combinations allowed by brane-world models
- Can one build a natural (not fine-tuned) SUSY model of this kind, compatible with grand unification, precision tests and cosmological constraints (baryogenesis,…) ?

  If so, would be worth exploring in detail its predictions!