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Minimal Z' models and the early LHC

Planck 2010 – CERN - June 4, 2010

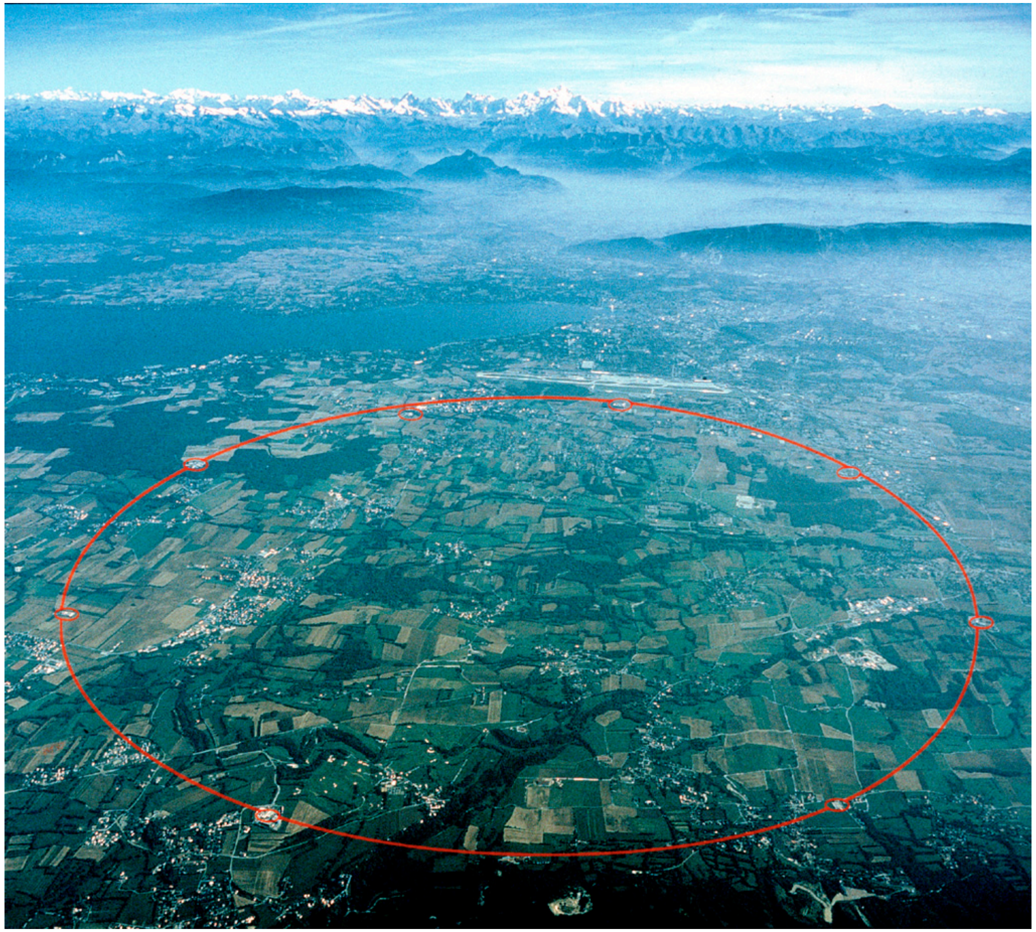
Original part of the talk based on:
E.Salvioni, G.Villadoro, F.Z.
arXiV:0909.1320 [JHEP11(2009)068] and unpublished
arXiV:0911.1450 [JHEP03(2010)010] (also with A.Strumia)

We are now in the LHC era, but…

"Design LHC"
answer crucial questions
on weak-scale physics

"Early LHC":
√S = 7 TeV
100 pb^{-1} in 2010?
up to 1 fb^{-1} by 2011?

Is there plausible new physics not already excluded by data accessible before Planck 2013 ?



A case study: new massive neutral gauge bosons (Z′)

A relatively modest task, however …

A relatively modest task, however …

Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

Galileo

I value more finding some truth, although on a light subject, than having long discussions about the greatest questions without achieving any truth.

Theoretical motivations for extra U(1)s

GUTs based on r>4 gauge groups

$SO(10) \rightarrow \ldots \rightarrow SU(3)_C x SU(2)_L x U(1)_Y x U(1)_{Y'}$

$E_6 \rightarrow \ldots \rightarrow SU(3)_C x SU(2)_L x U(1)_Y x U(1)_{Y'} [x U(1)_{Y''}]$

Type-II string models with D-branes

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

$U(N) \rightarrow SU(N) \times U(1)$

Multiple U(1) factors frequent in realistic models

Warning: TeV scale Z' possible, not required

Other theoretical contexts for TeV-scale Z′

- Higher-dimensional (ST or FT) models
- Strongly interacting Higgs sector (TeV)
- Little/Composite Higgs models (TeV)
- Higgsless models (TeV)

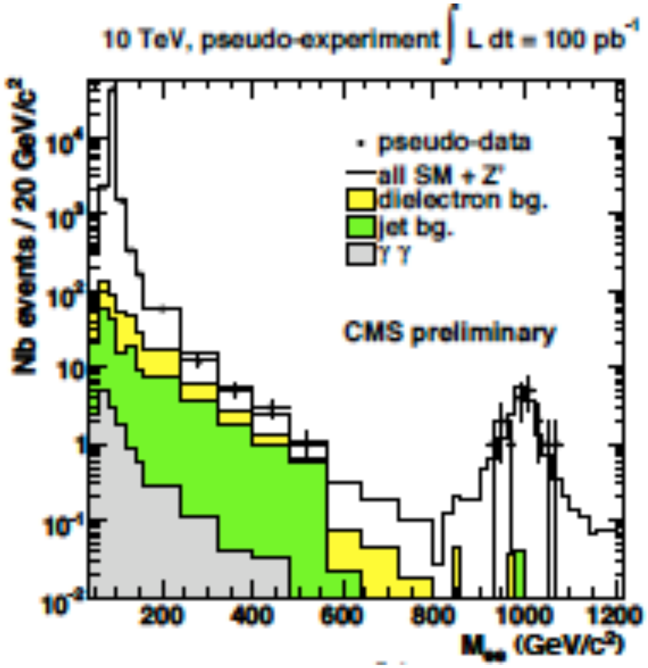
A down-to-earth motivation:

"Clean/Easy" signal

at hadron colliders

$Z' \rightarrow e^+ e^-, \mu^+ \mu^-$

one of the first searches



A simple variety: minimal Z′ models

[see, e.g., Appelquist-Dobrescu-Hopper, hep-ph/0212073]

Most economical renormalizable Z′ models

- $G=SU(3)_C xSU(2)_L xU(1)_Y xU(1)_{Y'}$

  No exotic vectors apart from a single Z′

- Only SM fermions & three RH neutrinos

  No exotic fermions charged under SM

- Automatic anomaly cancellation

  Allows to have very large cutoff scale Λ

  "Anomalous" U(1)s ➔ $\Lambda \sim 4\,\pi\, M_{Z'} /\ g$

Universal minimal Z′ models

Assume for now family-independent U(1) charges

With minimal SM fermions, only $U(1)_Y$ allowed

With RH neutrinos (best guess for d.o.f. behind neutrino masses and mixing), unique solution:

$$Y' = a\, Y + b\, X, \qquad (X = B-L)$$

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”

Non-universal minimal Z′ models

Anomalies cancel within each family ➔

possibility of family-dependent charges

(no flavour-dependence in quark sector viable):

$$X = \Sigma_{a=e,\mu,\tau} (\lambda_a/3)\, (B\text{-}3L_a)$$

Three benchmark models

- Electrophilic model: $X=B-3L_e$ $(\lambda_e=3,\ \lambda_\mu=\lambda_\tau=0)$
  Could 'explain' CDF dielectrons at M~240 GeV
- Muonphilic model: $X=B-3L_\mu$ $(\lambda_\mu=3,\ \lambda_e=\lambda_\tau=0)$
  Little constrained by EWPT ➔ LHC 'supermodel'
- Hadrophobic model: $X=L_\mu-L_\tau$ $(\lambda_e=0,\ \lambda_\mu=-\lambda_\tau=1)$
  May 'explain' positron excess in cosmic rays

[Ma; Davidson-Forte-Gambino-Rius-Strumia; He-Joshi-Lew-Volkas]

Simple theory of minimal models

General parameterization ($A,B = T_{3L}, Y, X$):

$$\mathcal{L} = -\frac{1}{4}\, \underset{\substack{\uparrow \\ \text{kinetic mixing}}}{h_{AB}}\, F^{A}_{\mu\nu}\, F^{B\,\mu\nu} + \frac{1}{2}\, \underset{\substack{\uparrow \\ \text{mass mixing}}}{M^2_{AB}}\, A^{A\mu}\, A^{B}_{\mu} + A^{A}_{\mu}\, J^{\mu}_{A} + \ldots$$

After suitable field redefinitions can write

(canonical kinetic terms, mass eigenstate basis):

$$L_{NC} = e\, A_\mu\, J_{em}{}^{\mu} + g_Z\, (Z_\mu\, J_Z{}^{\mu} + Z_\mu'\, J_{Z'}{}^{\mu})$$

where :

$J_Z = \cos\theta' J_z{}^o - \sin\theta' J_{Z'}{}^o \qquad J_{Z'} = \sin\theta' J_z{}^o + \cos\theta' J_{Z'}{}^o$

$J_Z{}^o$ = SM current coupled to SM Z^o

$$J_{Z'}{}^o = (g_Y/g_Z)\, J_Y + (g_X/g_Z)\, J_X$$

mass & kinetic mixing effects automatically included

Counting parameters:

SM (MSSM) Higgs field(s) do not carry any X charge

Assume additional Higgs fields singlets under $SU(2)_L$

After choosing X, 3 independent parameters:

$M_{Z'}$ g_Y g_X

$$J_{Z'}^{o} = \Sigma_f \bar{f}\gamma^{\mu} Q_{Z'}^{o}(f) f \qquad Q_{Z'}^{o} = (g_Y / g_Z)\underset{\substack{\uparrow \\ \text{chiral}}}{Y} + (g_X / g_Z)\underset{\substack{\uparrow \\ \text{vectorial}}}{X}$$

Kinetic + mass mixing
all encoded in g_Y

$$\tan\theta' = -\tilde{g}_Y \frac{M^2_{Z^0}}{M^2_{Z'} - M^2_{Z^0}}$$

$$\tilde{g}_Y = \frac{g_Y}{g_Z} \qquad \tilde{g}_X = \frac{g_X}{g_Z} \qquad M^2_{Z^0} = \frac{g_Z^2\, v^2}{4}$$

Lepton masses & mixing in non-universal models

Generated by renormalizable gauge-invariant interactions:

- No problem in reproducing charged lepton masses
- Neutrino masses generated by standard type-I see-saw

A GIM-like mechanism for leptonic FCNC

After diagonalizing charged lepton masses with U_L , U_R:

$$g_Z Z'_\mu \left(\overline{l_L} \gamma^\mu U_L^\dagger Q_{Z'} U_L l_L + \overline{e_R} \gamma^\mu U_R^\dagger Q_{Z'} U_R e_R + \overline{\nu_R} \gamma^\mu Q_{Z'} \nu_R \right)$$

But U_L , U_R do not mix sectors with different X charges:

- No tree-level FCNC involving charged leptons
- All leptonic FCNC suppressed by light ν masses

Theory constraints: RGE, GUTs

$$h_{AB} = \begin{pmatrix} \frac{1}{g'^2} & -\frac{g_Y}{g_{BL}}\frac{1}{g'^2} \\ -\frac{g_Y}{g_{BL}}\frac{1}{g'^2} & \frac{1}{g_{BL}^2} + \frac{g_Y^2}{g_{BL}^2}\frac{1}{g'^2} \end{pmatrix}$$

$$h_{AB}(M_U) = h_{AB}(M_Z) - \frac{b_{AB}}{(4\pi)^2}\log\left(\frac{M_U}{M_Z}\right)^2$$

$$b_{AB} = \frac{2}{3}\sum_f Q_f^A Q_f^B + \frac{1}{3}\sum_s Q_s^A Q_s^B$$

RGE running from

M_U~10^{16} GeV

(SM or MSSM)

↓

favored range in

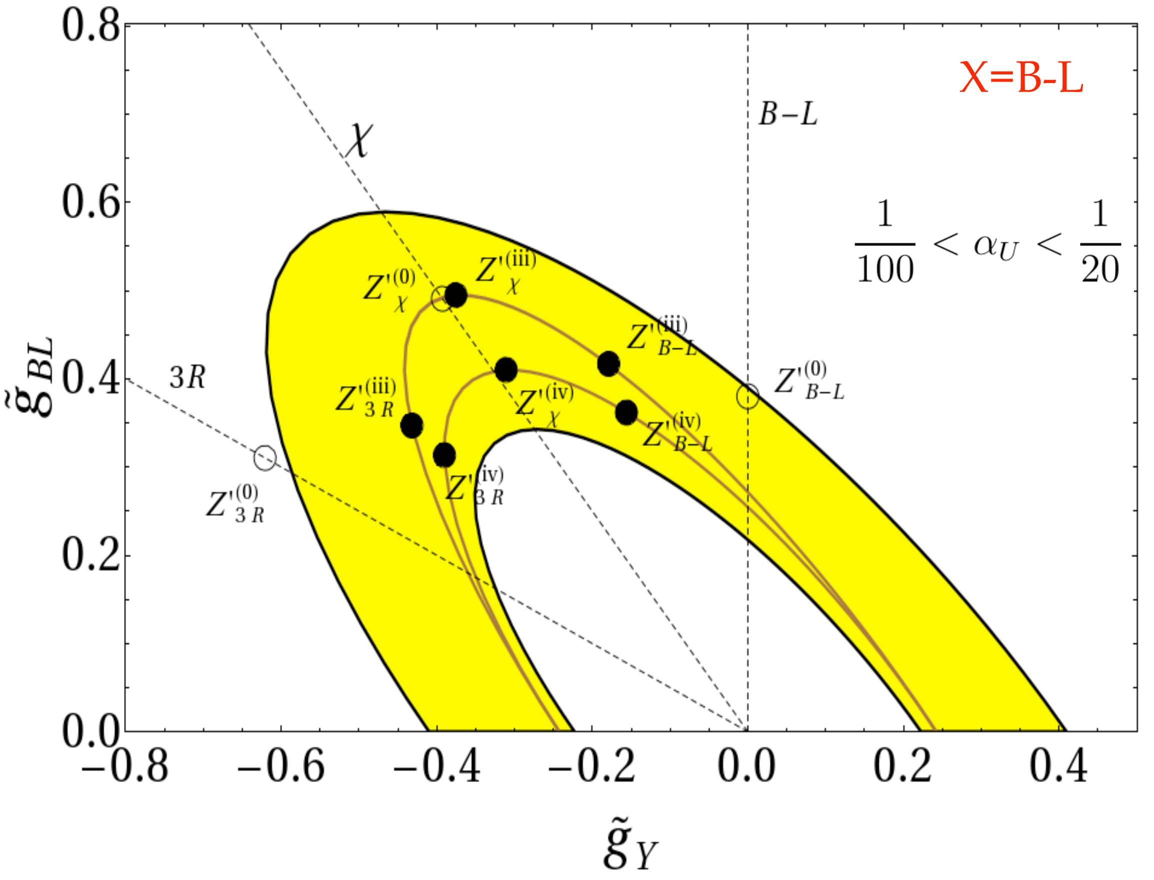
(g_Y , g_X) plane

Specific models

= special points

Kinetic mixing

induced by RGE!

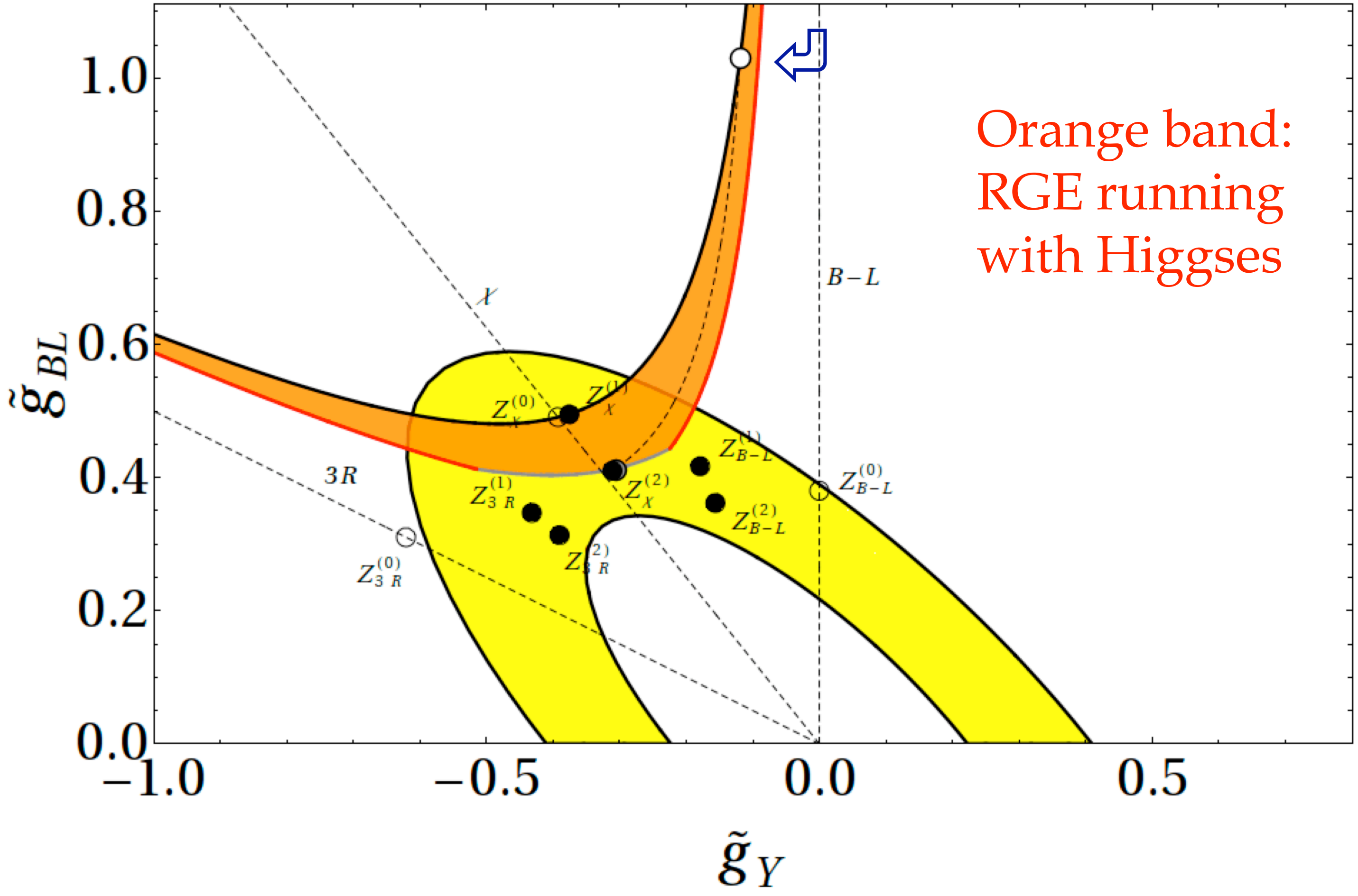


Minimal Z’ models from D-branes

[see, e.g., Ghilencea-Ibanez-Irges-Quevedo, hep-ph/0205083]

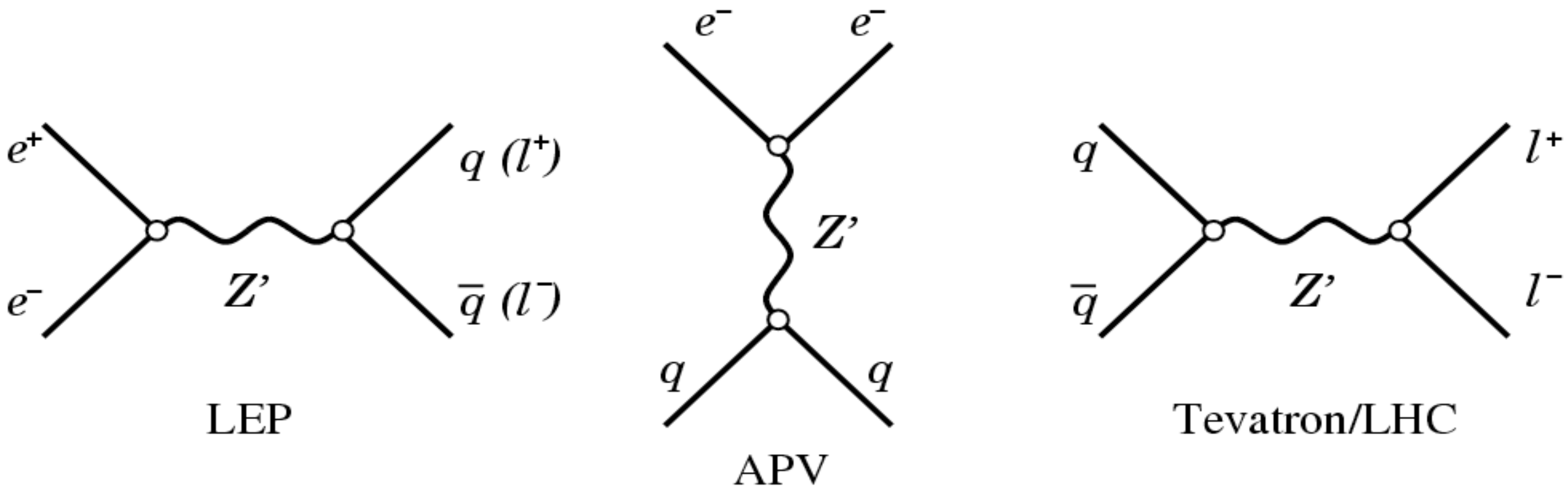
$$g_{BL} = -\frac{1}{2g_Y}(g_Y^2 + g'^2)$$

Additional constraint if B and L wrap cycles of equal length



Orange band:
RGE running
with Higgses

Direct vs. indirect bounds on Z′



the parameters involved are the same!

⇨

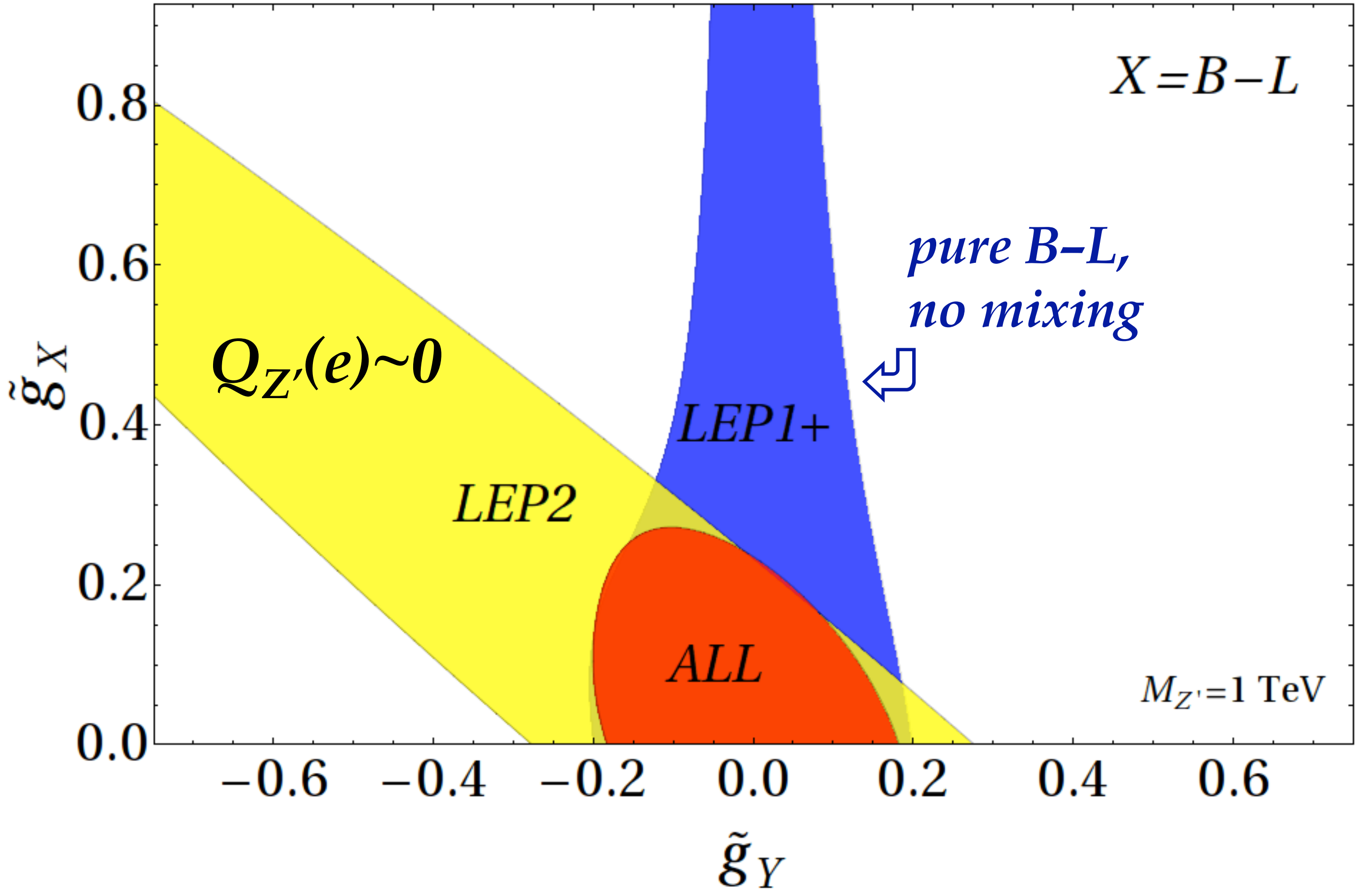
constraints from EWPT **cannot** be neglected when analysing the discovery potential of direct searches

Constraints from EWPT: LEP1+ vs. LEP2

LEP-1 (Z-pole) mostly constrains Z-Z′ mixing $|\theta| < \mathcal{O}(10^{-3})$

LEP-2 mostly constrains 4-fermion (≥2e) effective operators

Regions allowed by EWPT @ 95% CL



Constraints from EWPT: mass dependence

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{(J_{Z'^0})^{\mu}(J_{Z'^0})_{\mu}}{2\,M_{Z'}^2} \Rightarrow \text{ bounds on } \frac{g_{Z'}^2}{M_{Z'}^2}$$

	$Z'^{(0)}_{B-L}$	$Z'^{(\text{iii})}_{B-L}$	$Z'^{(\text{iv})}_{B-L}$	$Z'^{(0)}_{\chi}$	$Z'^{(\text{iii})}_{\chi}$	$Z'^{(\text{iv})}_{\chi}$	$Z'^{(0)}_{3R}$	$Z'^{(\text{iii})}_{3R}$	$Z'^{(\text{iv})}_{3R}$
$M_{Z'}$ (TeV)	1.80	1.77	1.53	2.61	2.54	2.11	3.64	2.61	2.36

Universal (B-L): →

Non-universal:

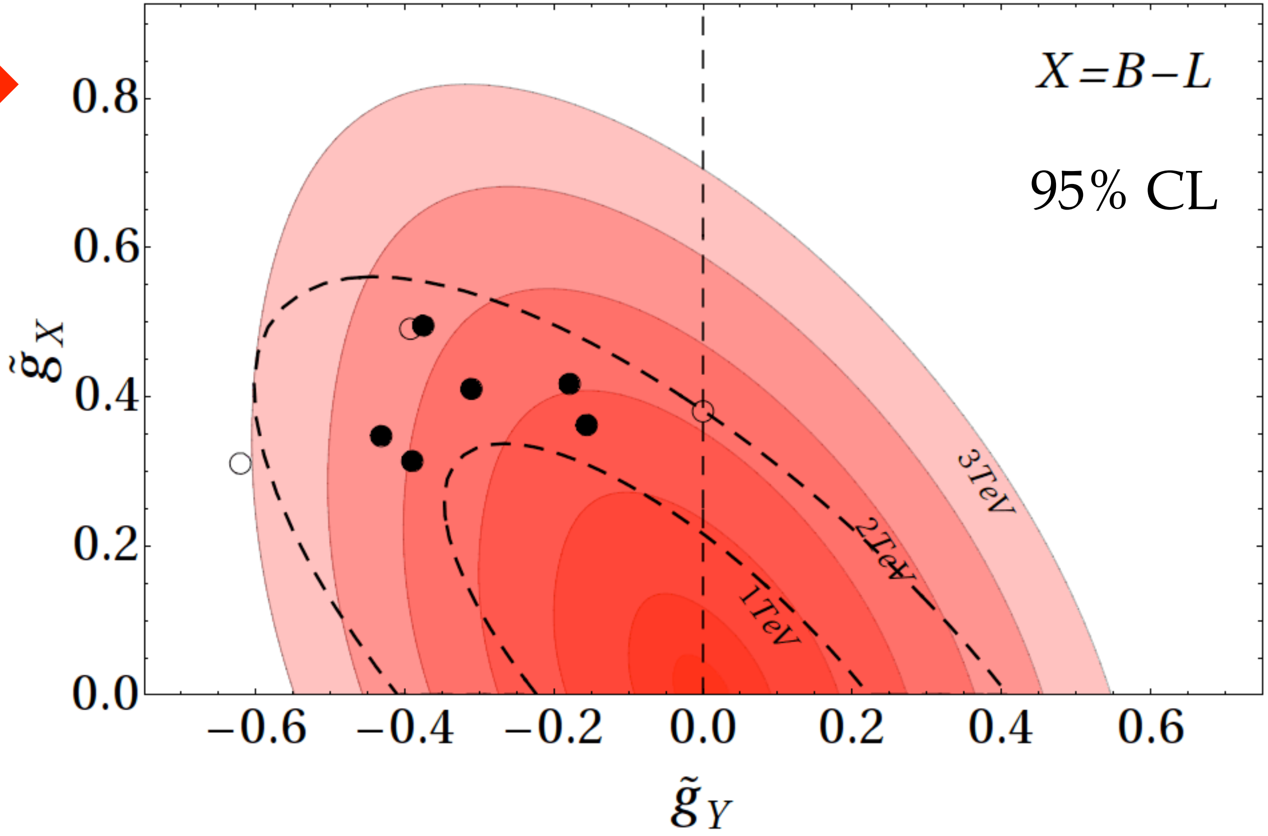
much weaker

for $\lambda_e \sim 0$, e.g.

$X = B - 3L_\mu$

$X = L_\mu - L_\tau$

🟥 = allowed



Direct searches (Tevatron, LHC)

The experimentally relevant quantities are:

$$\sigma(p\bar{p} \rightarrow Z'X) \times \mathrm{BR}(Z' \rightarrow \ell^+\ell^-)$$

$$\sigma(pp \rightarrow Z'X)$$

↑

PDF(MSTW'08)@*NLO*

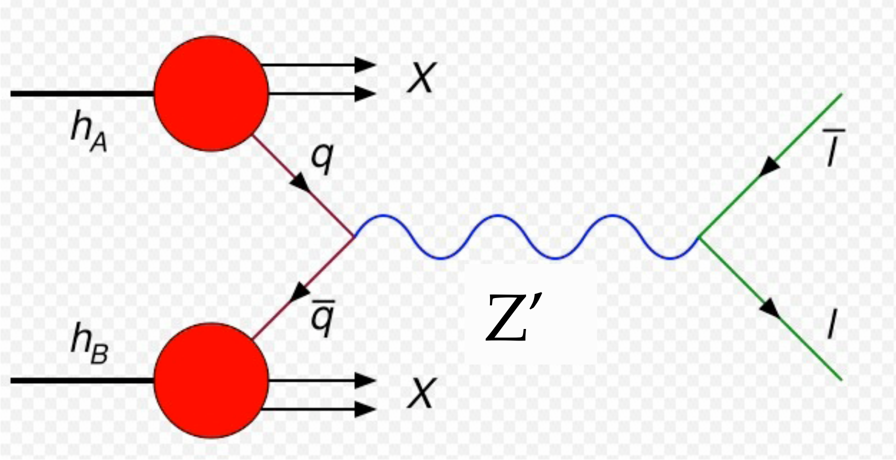
$Z' \rightarrow ff$, WW, Zh, ...

$\Gamma_{Z'}/M_{Z'} \sim 2\%$

(*for GUT-like* couplings)

some model dependence

as functions of $M_{Z'}$, assuming a sufficiently narrow width

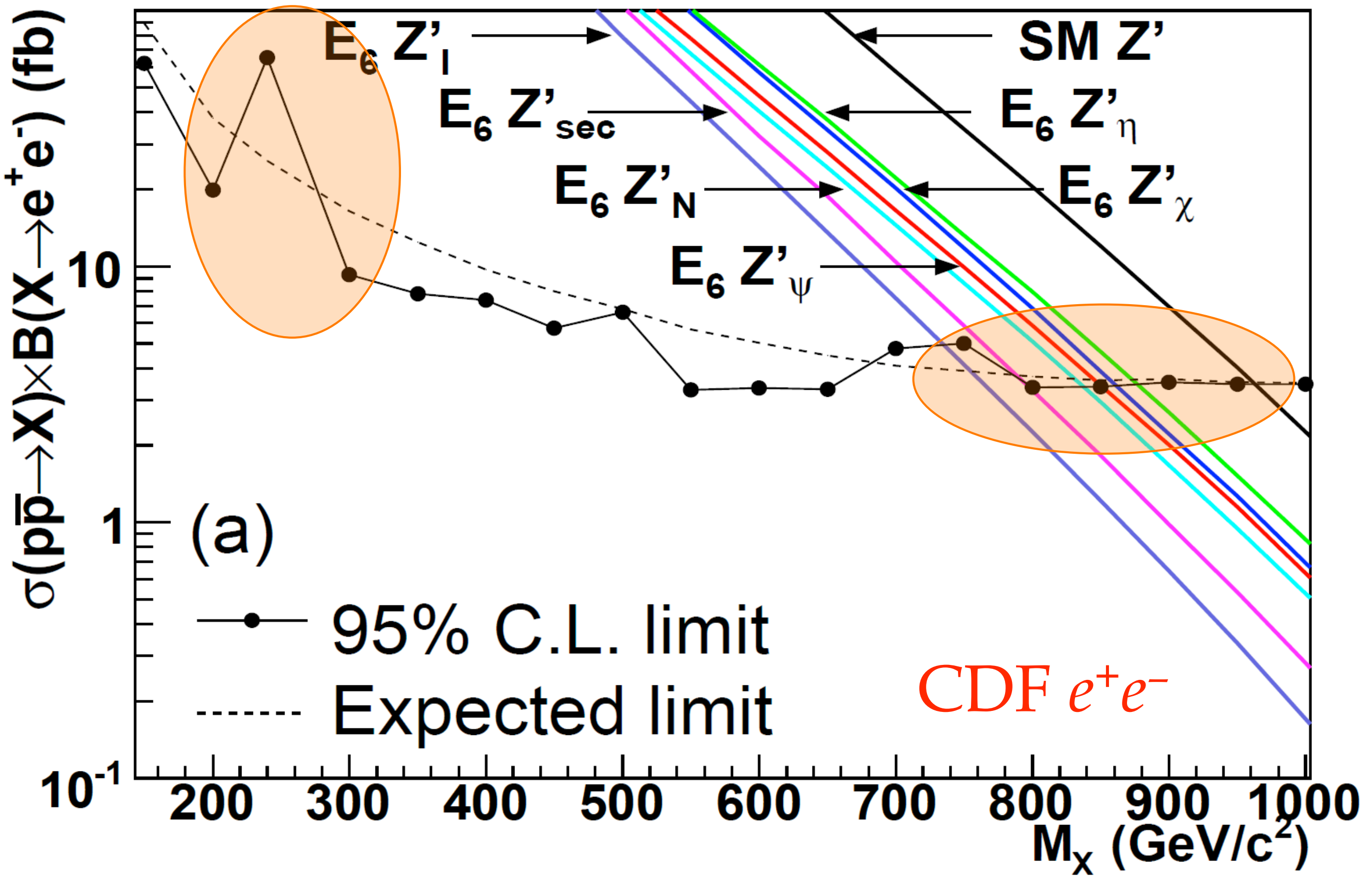


Backgrounds:
Drell-Yan (via γ^*,Z^*)
(very well understood)
+ reducible
(2 j , j+γ , W+j , ...)
Removed with mild p_T cut

Tevatron direct searches: data

[CDF, 0810.2059 (e) & 0811.0053 (μ); D0, 5923-CONF July 2009 (e)]

CDF excess in di-electrons at M~240 GeV
not seen in CDF $\mu^+\mu^-$ nor in D0 e^+e^- (~1σ)
2.5σ effect (>3σ in single bin)



CDF e^+e^-

Bounds on
"GUT" models
(minimal and
non-minimal)

CDF: e^+e^-
(2.5 fb^{-1},27-38%)
D0: e^+e^-
(3.6 fb^{-1},17-22%)
CDF: $\mu^+\mu^-$
(2.3 fb^{-1},13-40%)

Tevatron direct searches: update

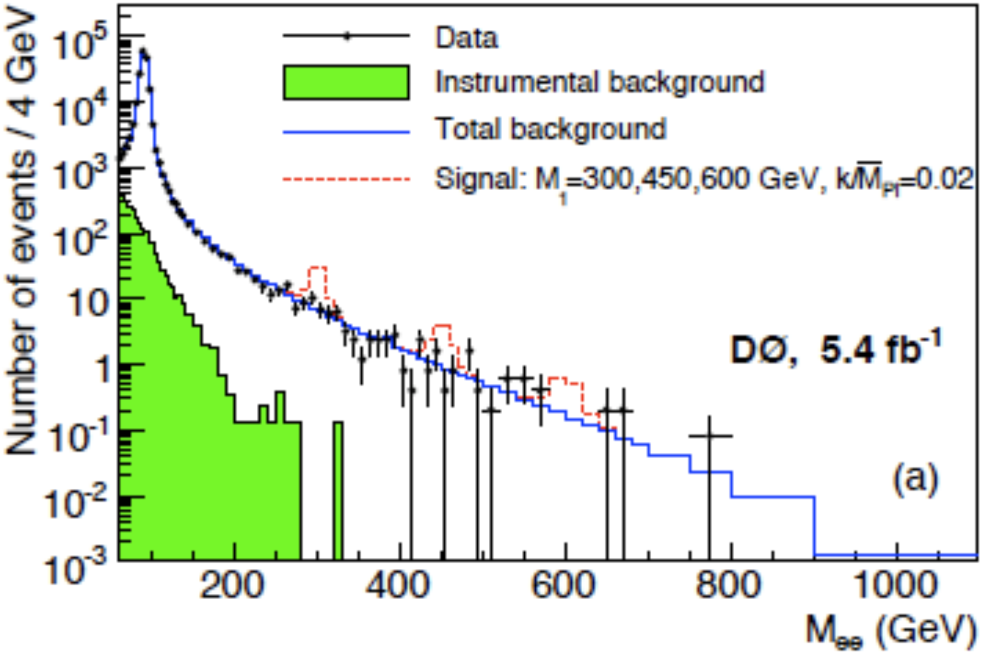
D0: e^+e^- *with 5.4 fb*$^{-1}$ *(combined with diphotons to put limits on RS gravs)*

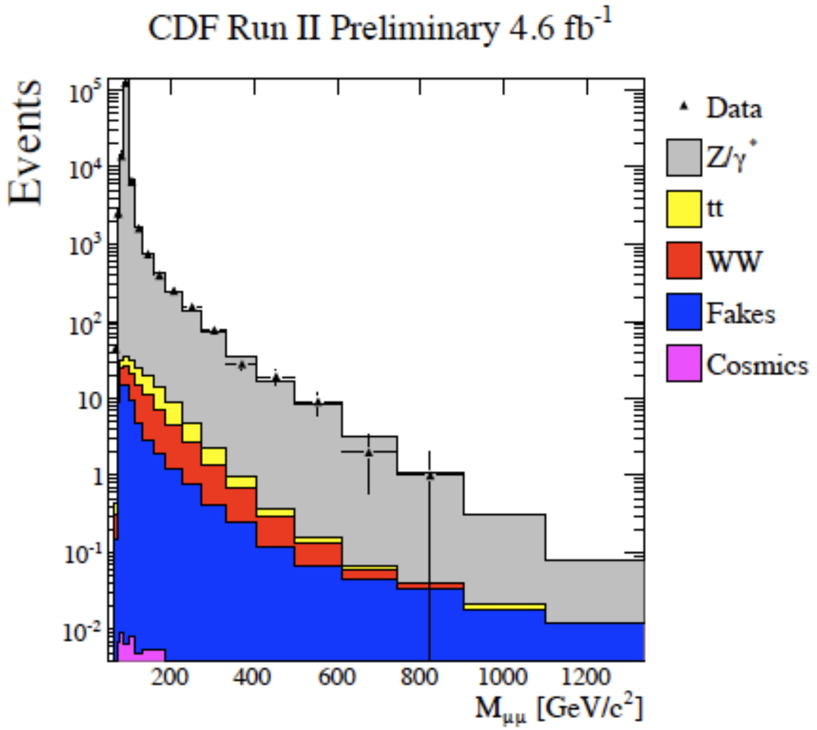
[arXiv:1004.1826 & talk by Qian]

Not yet analyzed for Z′ ➔ e^+e^-

CDF: $\mu^+\mu^-$ *with 4.6 fb*$^{-1}$
[talk by Whiteson]

Slight improvement of bounds for $M_{Z'}$>600 GeV





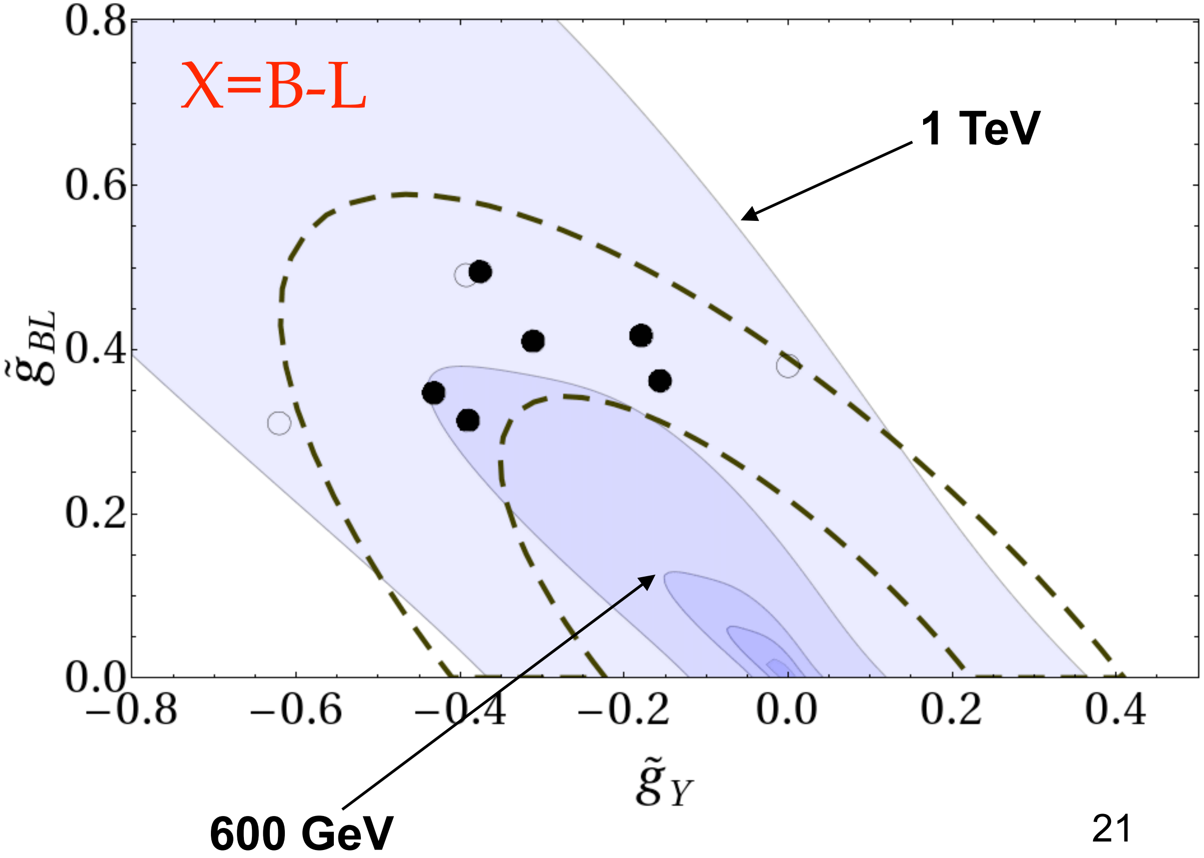
Tevatron direct searches: pheno

Easy to extract bounds on minimal Z′ models
(given X, relevant parameters are $M_{Z'}$, g_Y, g_X)

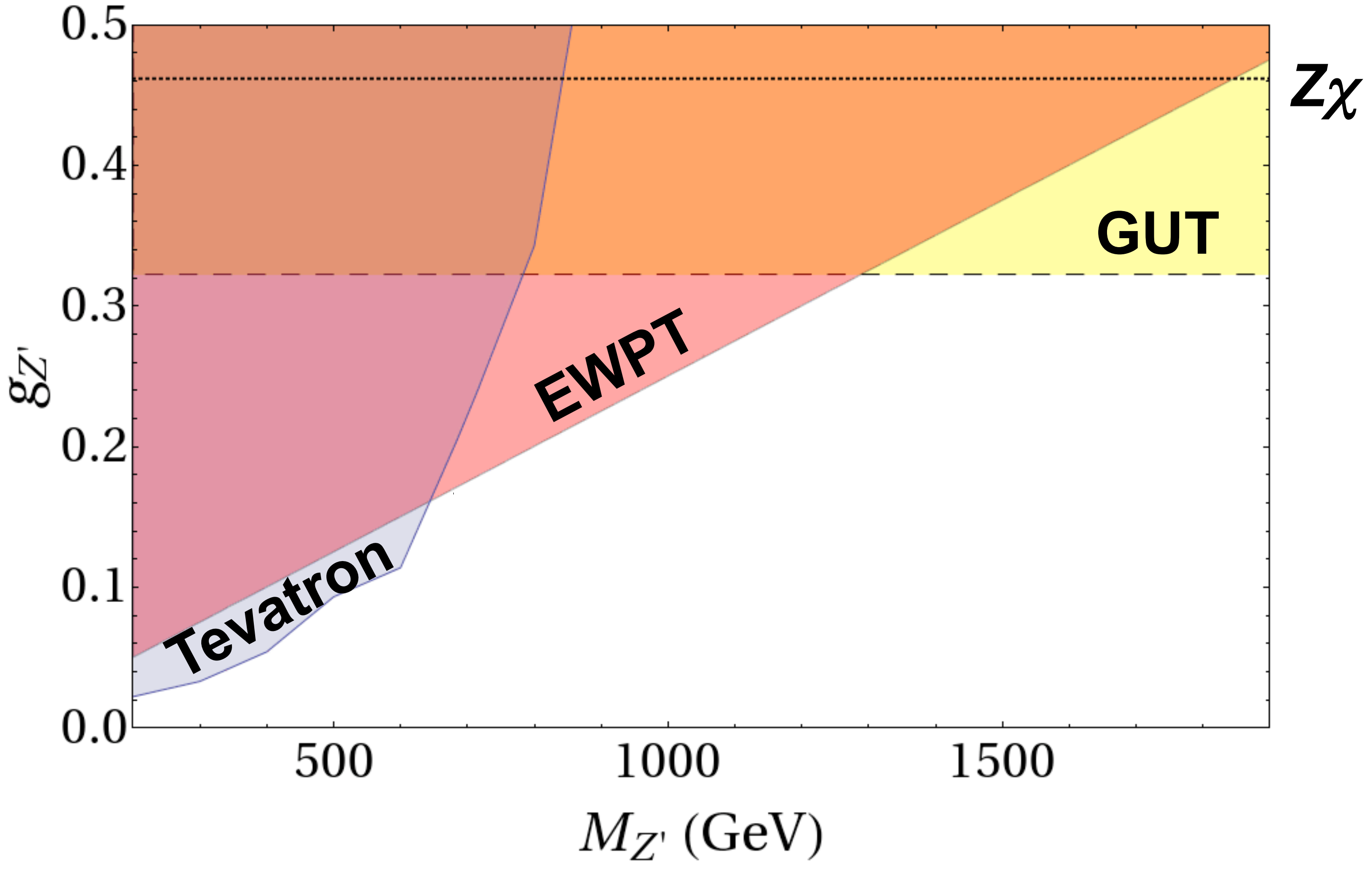
🟦 = allowed by Tevatron

Similar shape as EWPT

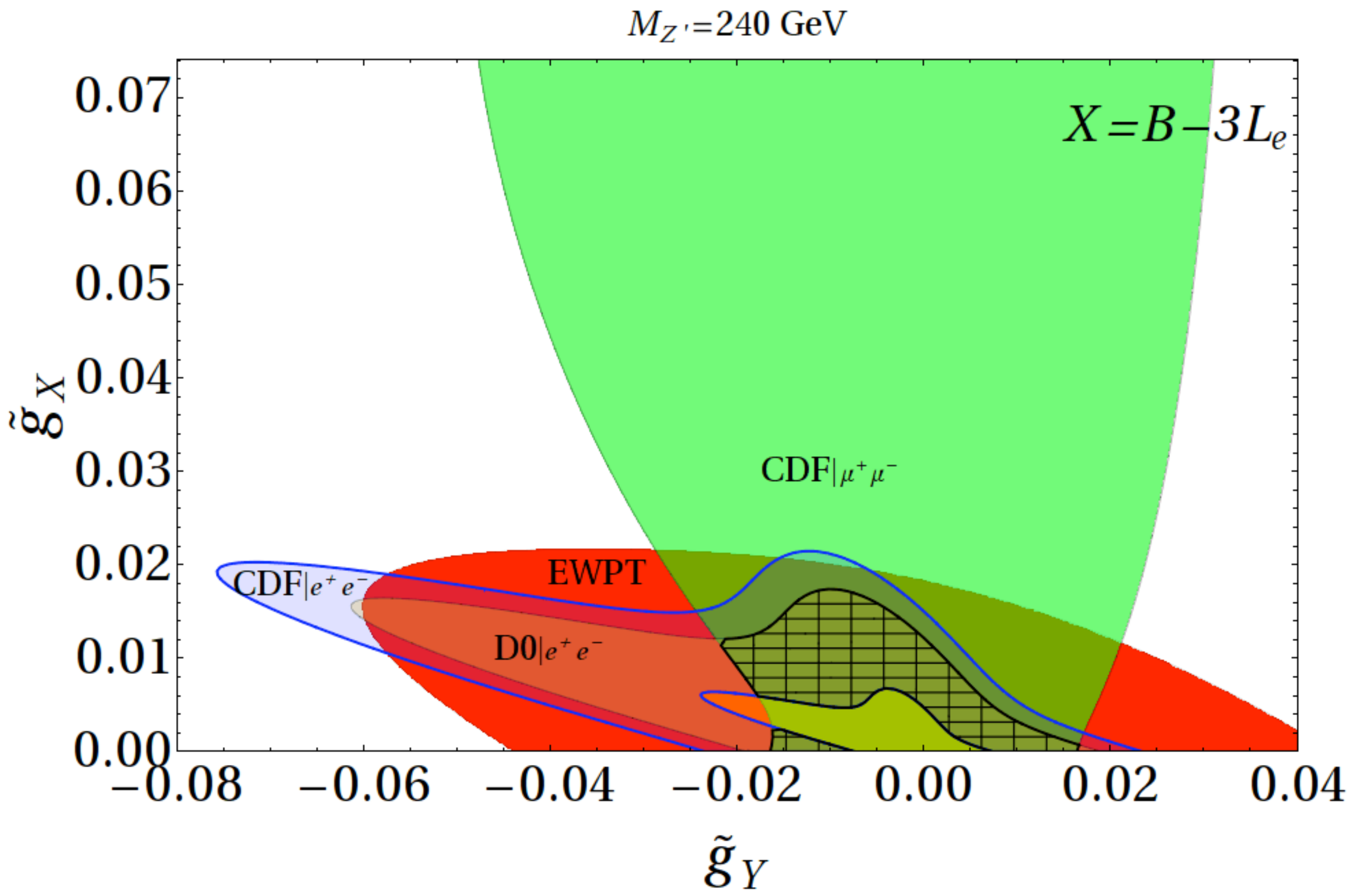
Allowed regions:
> linear in $M_{Z'}$
(large-x PDF)



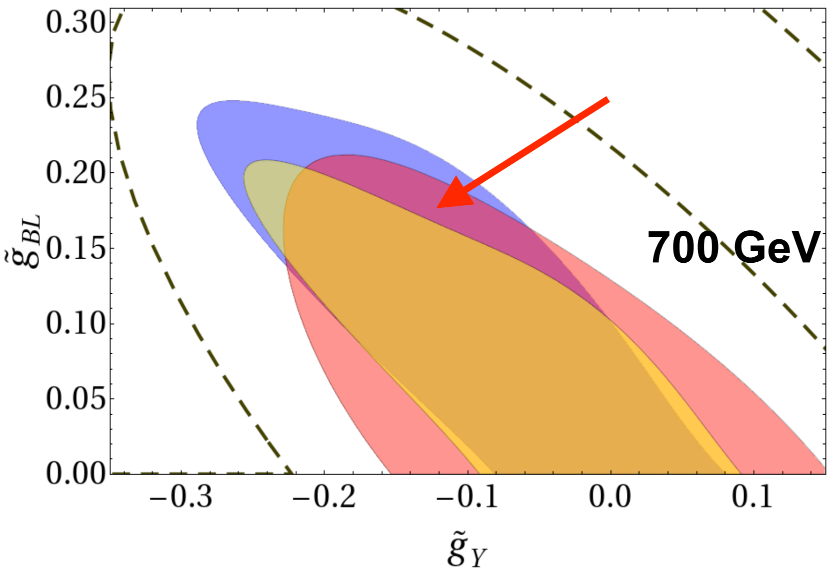
EWPT vs. Tevatron ($Z\chi$ example)



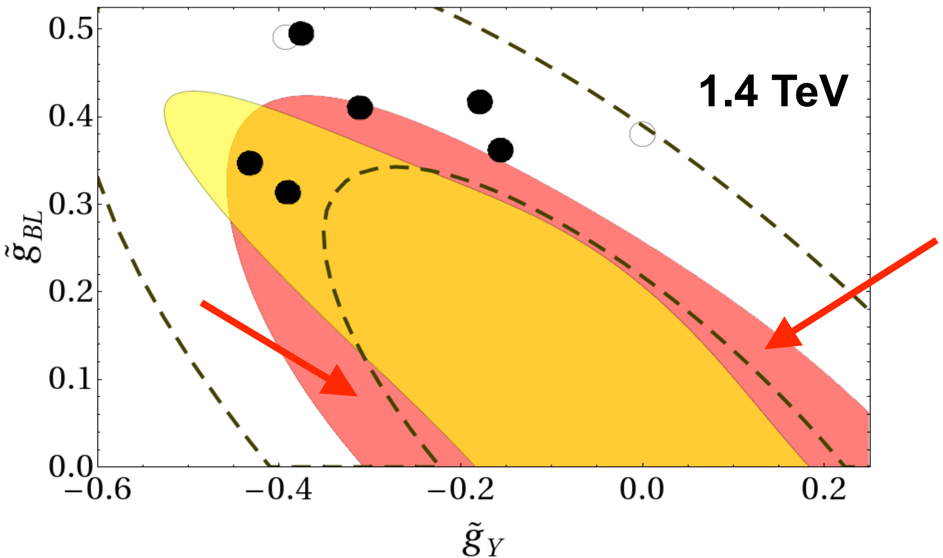
Electrophilic model and CDF dielectrons



Early LHC prospects (X=B-L)



7 TeV, $100\,\mathrm{pb}^{-1}$



10 TeV, $200\,\mathrm{pb}^{-1}$

🟥 = 95%CL allowed region by EWPT

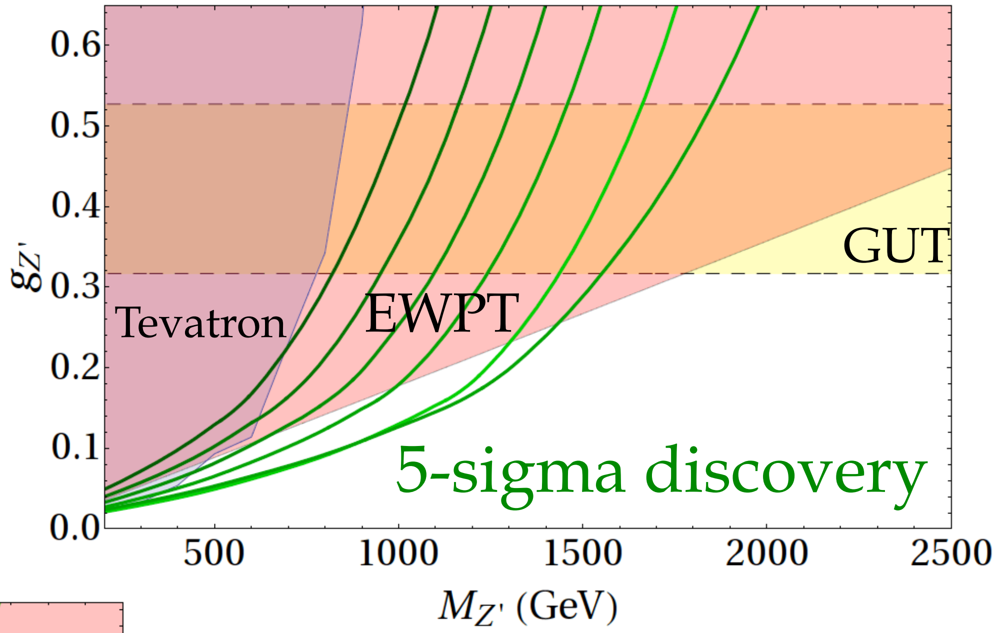
🟦 = 95%CL allowed region by Tevatron direct searches

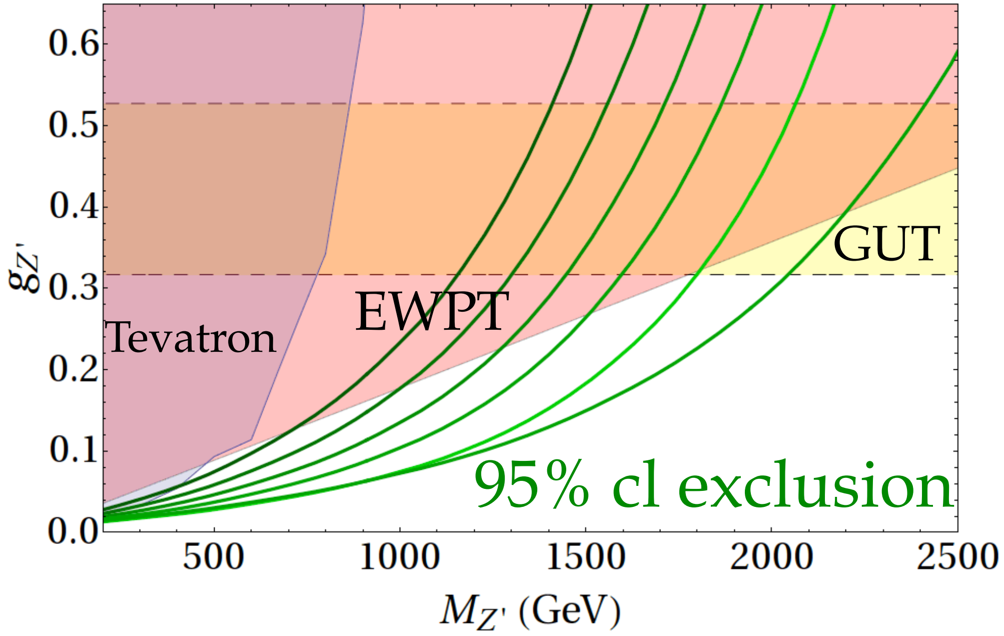
🟨 = region NOT accessibile to LHC (5σ discovery for given en. & lum.)

→ **POSSIBLE DISCOVERY**

Early LHC prospects (chi-model)

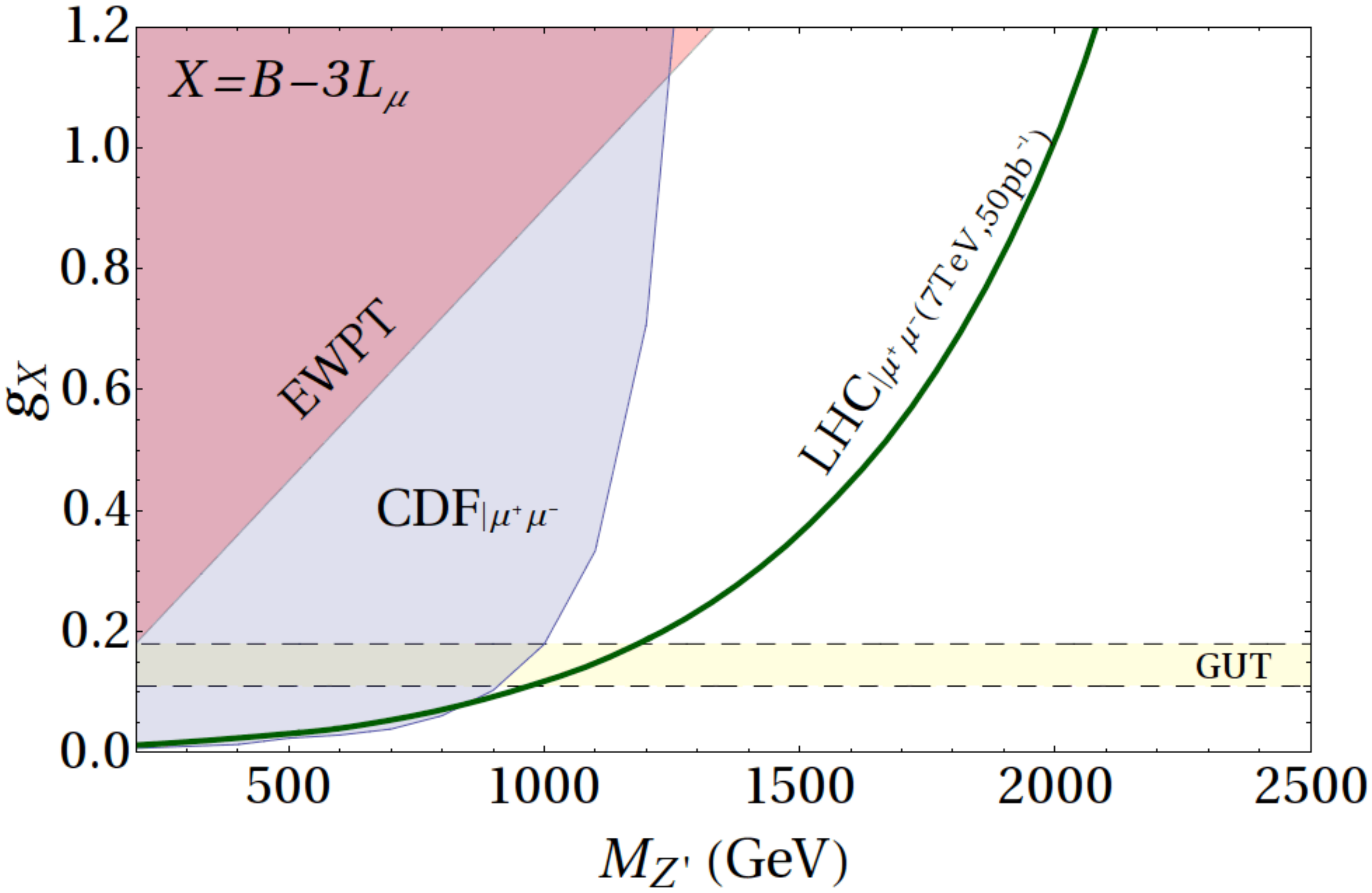
7 TeV
50,100,200,
400,1000 pb^{-1}
+
10 TeV 400 pb^{-1}





Early discoveries
possible only at
relatively low
masses & couplings
and in 2011…

Muonphilic model as LHC 'supermodel'



Conclusions

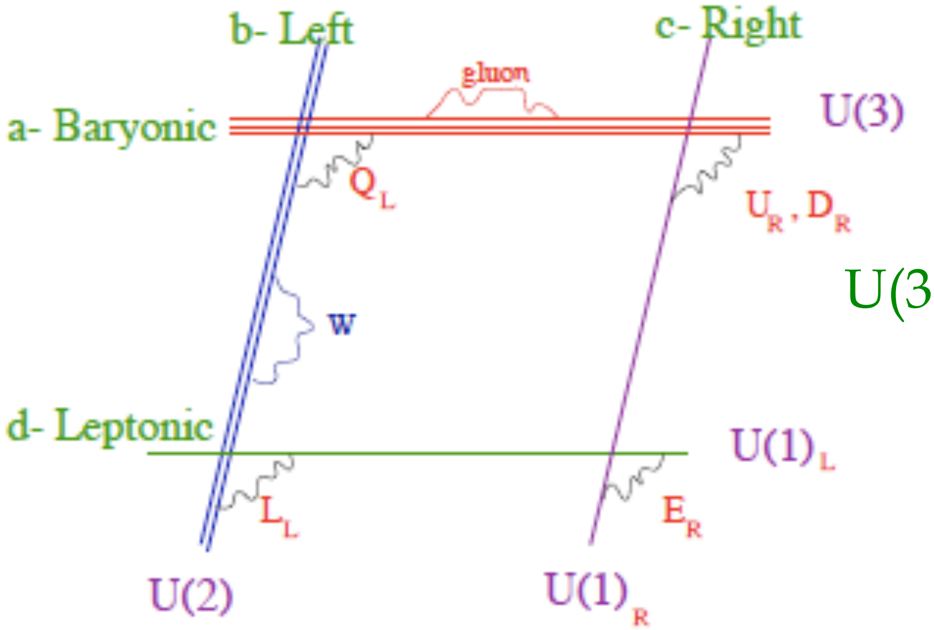
- Minimal Z′ good case study for very early LHC
- Variety of motivations suggests a more flexible parameterization than in GUTs
- Cannot ignore bounds from EWPT (with LEP2): stronger than Tevatron in GUT-favored region
- Cannot neglect kinetic mixing, RGE-generated
- Universal model may need some time to be explored by LHC, especially in the GUT-favored region
- Non-universal models with GIM-like mechanism:

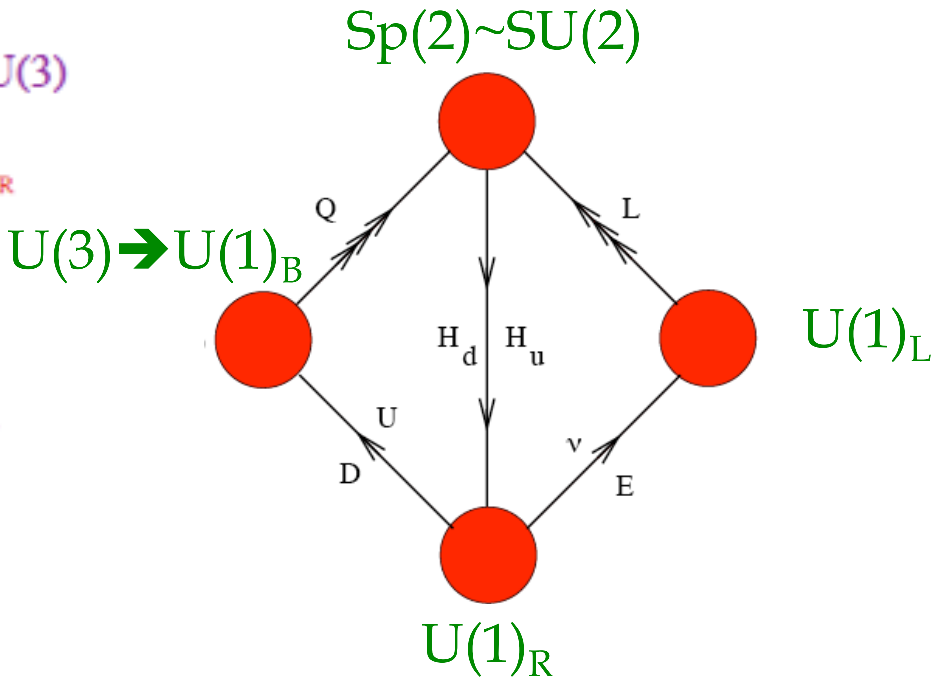
  -may have room for very early discovery at the LHC

  -may explain the CDF di-electron excess if confirmed
- Z′ from D-branes quite stringently constrained

BACK-UP SLIDES

Typical realistic constructions

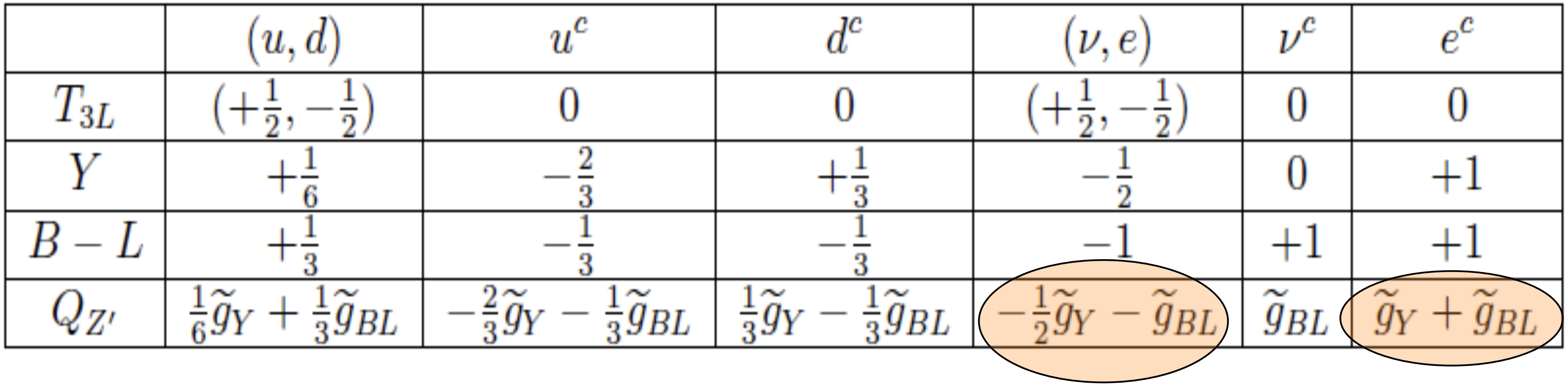




- Non-anomalous U(1)s associated with Y and B-L
- Anomalous U(1) factors get string-scale masses
- (B-L) may or may not stay light w.r.t. string scale

Neutral current couplings of the SM fermions

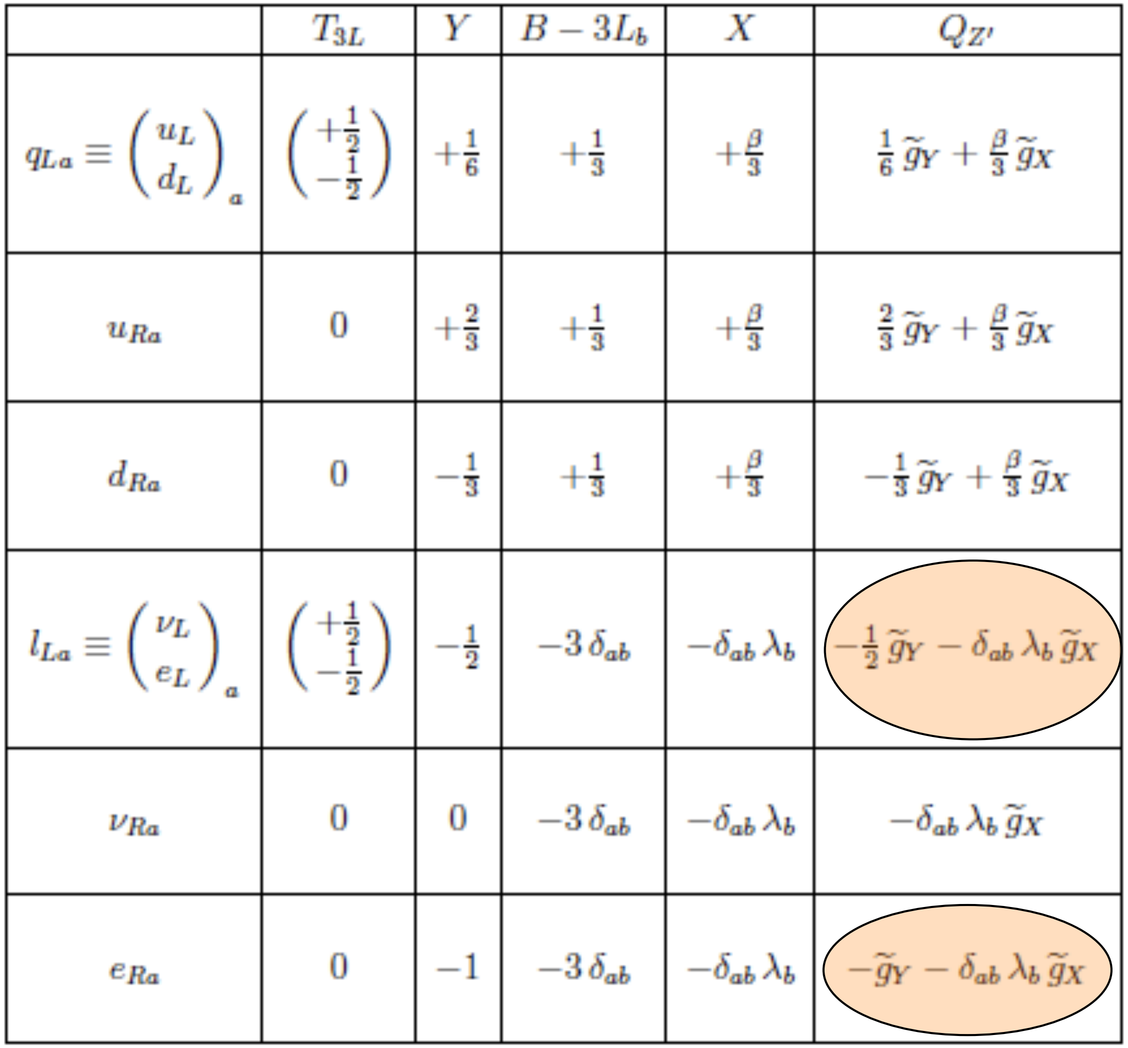
In the universal case X=B-L:



	(u,d)	u^c	d^c	(ν,e)	ν^c	e^c
T_{3L}	$(+\frac{1}{2},-\frac{1}{2})$	0	0	$(+\frac{1}{2},-\frac{1}{2})$	0	0
Y	$+\frac{1}{6}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{2}$	0	$+1$
$B-L$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	$+1$	$+1$
$Q_{Z'}$	$\frac{1}{6}\tilde{g}_Y+\frac{1}{3}\tilde{g}_{BL}$	$-\frac{2}{3}\tilde{g}_Y-\frac{1}{3}\tilde{g}_{BL}$	$\frac{1}{3}\tilde{g}_Y-\frac{1}{3}\tilde{g}_{BL}$	$-\frac{1}{2}\tilde{g}_Y-\tilde{g}_{BL}$	$\tilde{g}_{BL}$	$\tilde{g}_Y+\tilde{g}_{BL}$

Table 1: The charges of left-handed fermions controlling the electroweak neutral currents.

Neutral current couplings of the SM fermions $\beta = \sum_a \frac{\lambda_a}{3}$



	T_{3L}	Y	$B-3L_b$	X	$Q_{Z'}$
$q_{La} \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}_a$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$+\frac{1}{6}$	$+\frac{1}{3}$	$+\frac{\beta}{3}$	$\frac{1}{6}\,\tilde{g}_Y + \frac{\beta}{3}\,\tilde{g}_X$
u_{Ra}	0	$+\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{\beta}{3}$	$\frac{2}{3}\,\tilde{g}_Y + \frac{\beta}{3}\,\tilde{g}_X$
d_{Ra}	0	$-\frac{1}{3}$	$+\frac{1}{3}$	$+\frac{\beta}{3}$	$-\frac{1}{3}\,\tilde{g}_Y + \frac{\beta}{3}\,\tilde{g}_X$
$l_{La} \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_a$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$-3\,\delta_{ab}$	$-\delta_{ab}\,\lambda_b$	$-\frac{1}{2}\,\tilde{g}_Y - \delta_{ab}\,\lambda_b\,\tilde{g}_X$
ν_{Ra}	0	0	$-3\,\delta_{ab}$	$-\delta_{ab}\,\lambda_b$	$-\delta_{ab}\,\lambda_b\,\tilde{g}_X$
e_{Ra}	0	-1	$-3\,\delta_{ab}$	$-\delta_{ab}\,\lambda_b$	$-\tilde{g}_Y - \delta_{ab}\,\lambda_b\,\tilde{g}_X$

Lepton masses & mixing in non-universal models

Generated by renormalizable gauge-invariant interactions

Dirac: $$-\mathcal{L}^{(l)}_{\text{Yuk}} = \overline{e_R}\, Y^E\, l_L \widetilde{H} + \overline{\nu_R}\, Y^N\, l_L H + \text{h.c.}$$

Majorana: $$\mathcal{L}^{(\nu)}_M = \frac{1}{2}\,\overline{(\nu_R)}\, M_R(\varphi)\, \overline{\nu_R}^T + \text{h.c.}$$

Gauge invariance:

$$X(Y^E_{ab}) = X(Y^N_{ab}) = \lambda_b - \lambda_a \quad X[M_R(\varphi)_{ab}] = \lambda_a + \lambda_b$$

- No problem in reproducing charged lepton masses
- When X(M)=0 large bare Majorana masses allowed
- When X(M)≠0 need a suitable Higgs field φ_X~(0,X)

Light neutrino masses and mixing

Type-I see-saw: $m^{\nu} = (M^N)^T \cdot M_R^{-1} \cdot M^N \quad M^N = Y^N \langle H^0 \rangle$

$m^{\nu} = U^* \cdot \mathrm{diag}(m_1, m_2, m_3) \cdot U^{\dagger}$ can be reproduced

by a suitable $M_R = (M^N)^T \cdot (m^{\nu})^{-1} \cdot (M^N)$

A GIM-like mechanism for leptonic FCNC

After diagonalizing charged lepton masses with U_L , U_R:

$$g_Z Z'_{\mu} \left(\overline{l_L} \gamma^{\mu} U_L^{\dagger} Q_{Z'} U_L l_L + \overline{e_R} \gamma^{\mu} U_R^{\dagger} Q_{Z'} U_R e_R + \overline{\nu_R} \gamma^{\mu} Q_{Z'} \nu_R \right)$$

But U_L , U_R do not mix sectors with different X charges:

•No tree-level FCNC involving charged leptons

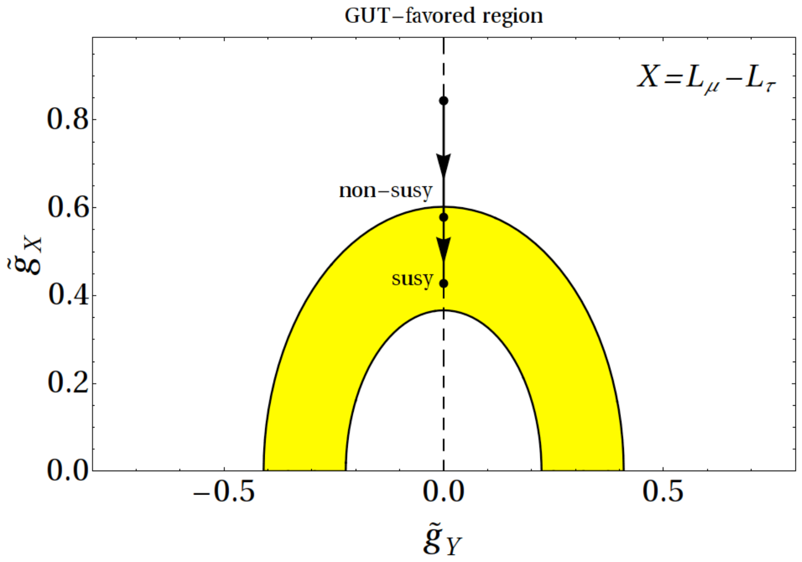
•All leptonic FCNC suppressed by light ν masses

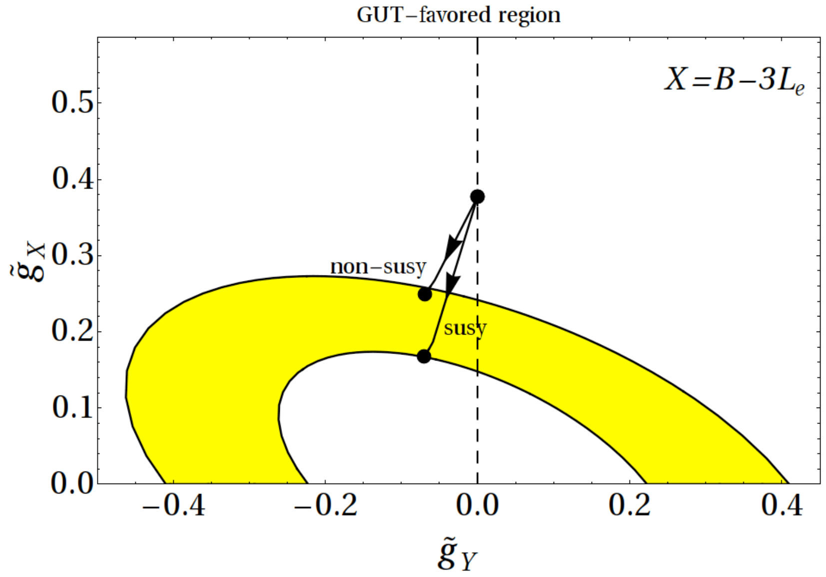
GUT-constraints on non-universal models

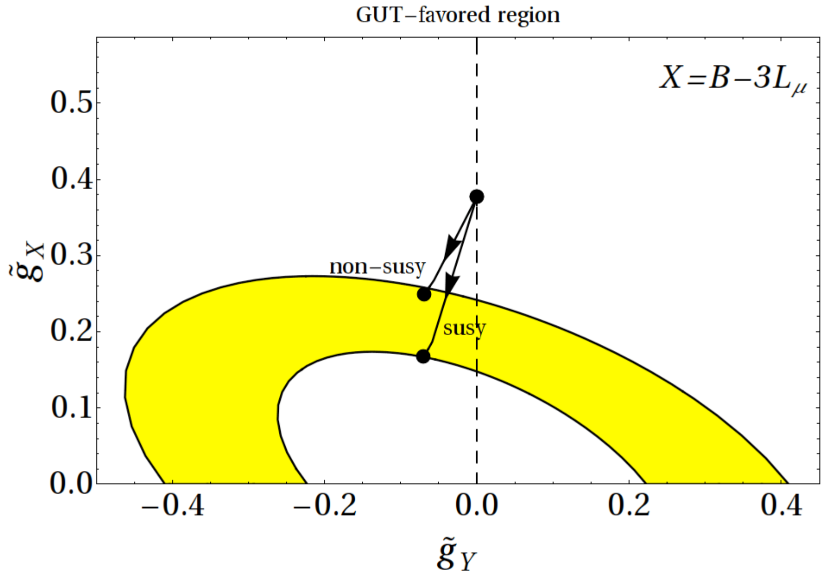
Plausible bound. conditions
@ M_U~10^{16} GeV
RGE running from M_U to M_Z
(SM or MSSM)

⬇

favored range in (g_Y , g_X) plane


GUT−favored region


GUT−favored region

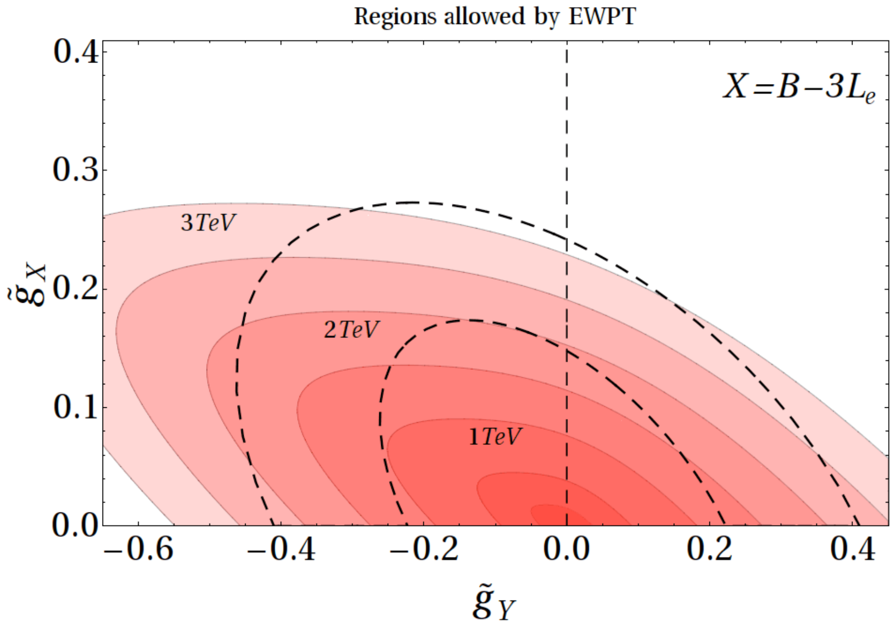

GUT−favored region

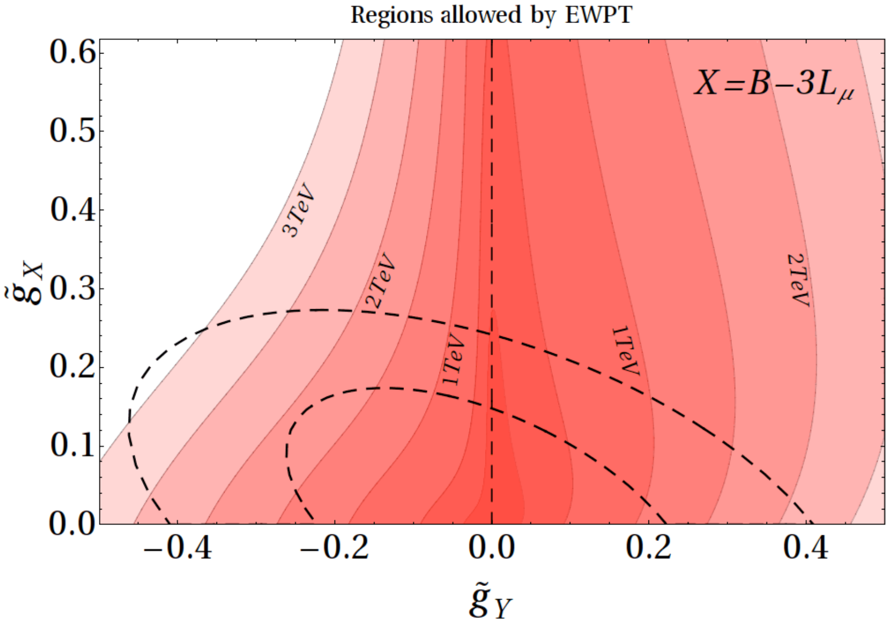
Bounds from EWPT: non-universal models

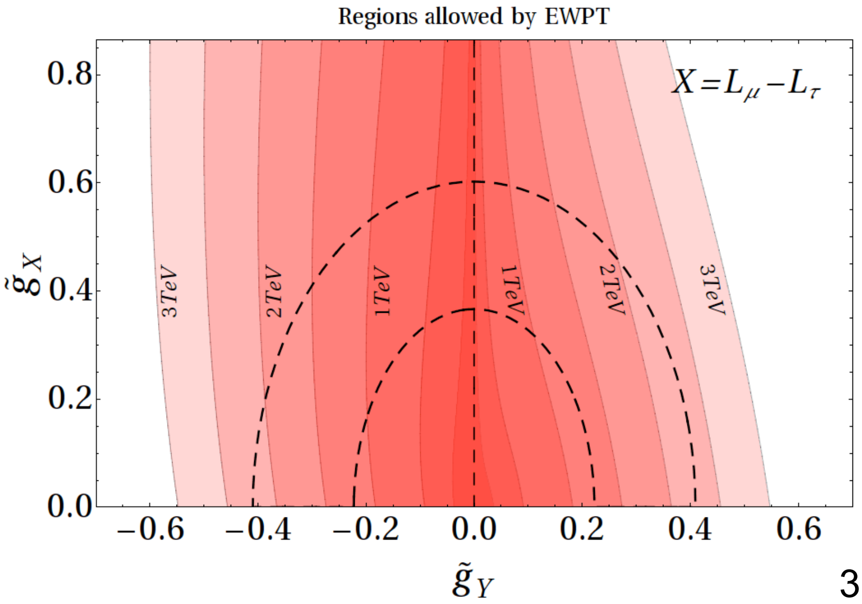
EWPT most sensitive
to electron couplings

X=B-3L$_e$ bounds
similar to X=B-L

X=B-3L$_\mu$ and X=L$_\mu$-L$_\tau$
mostly via mixing effects

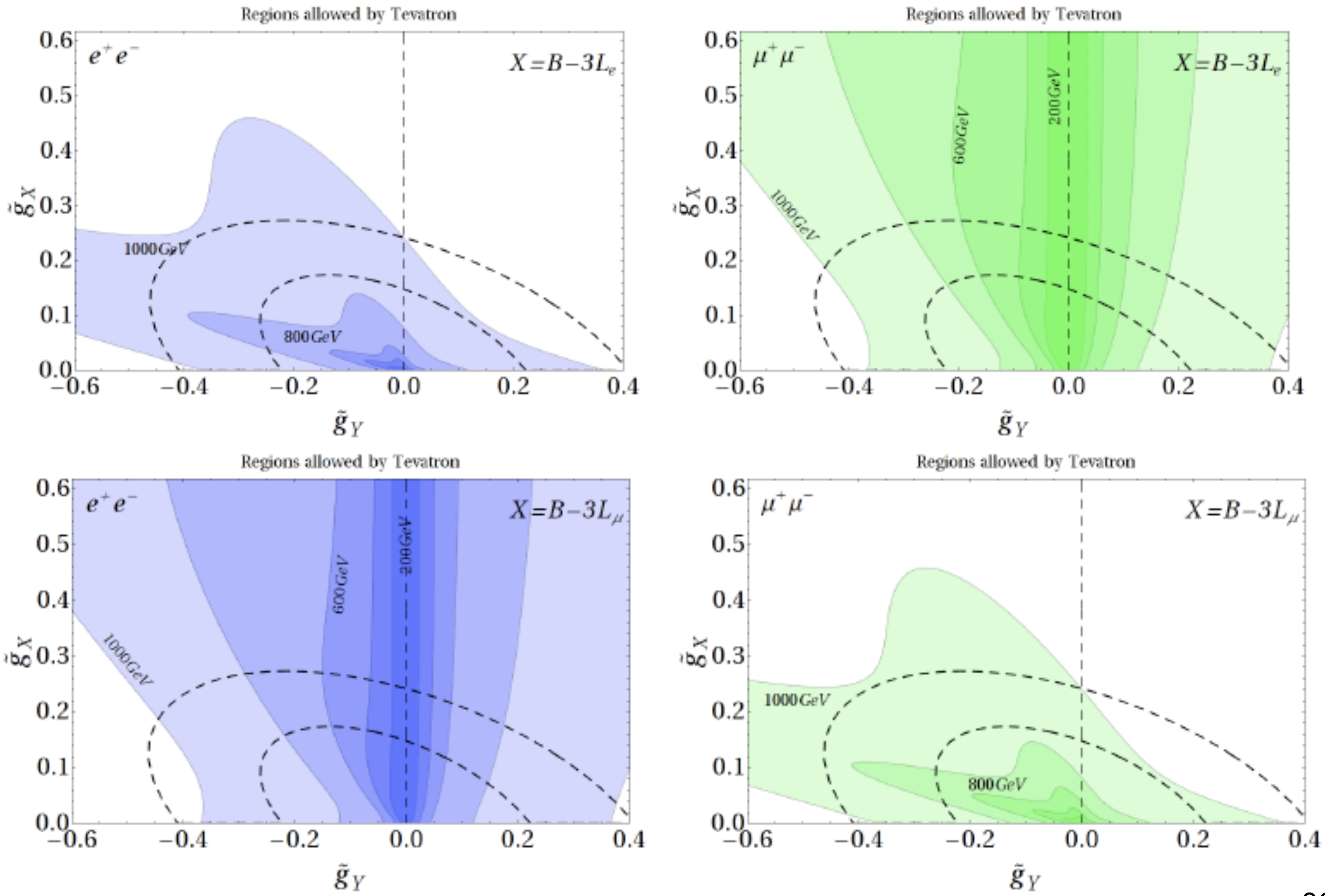




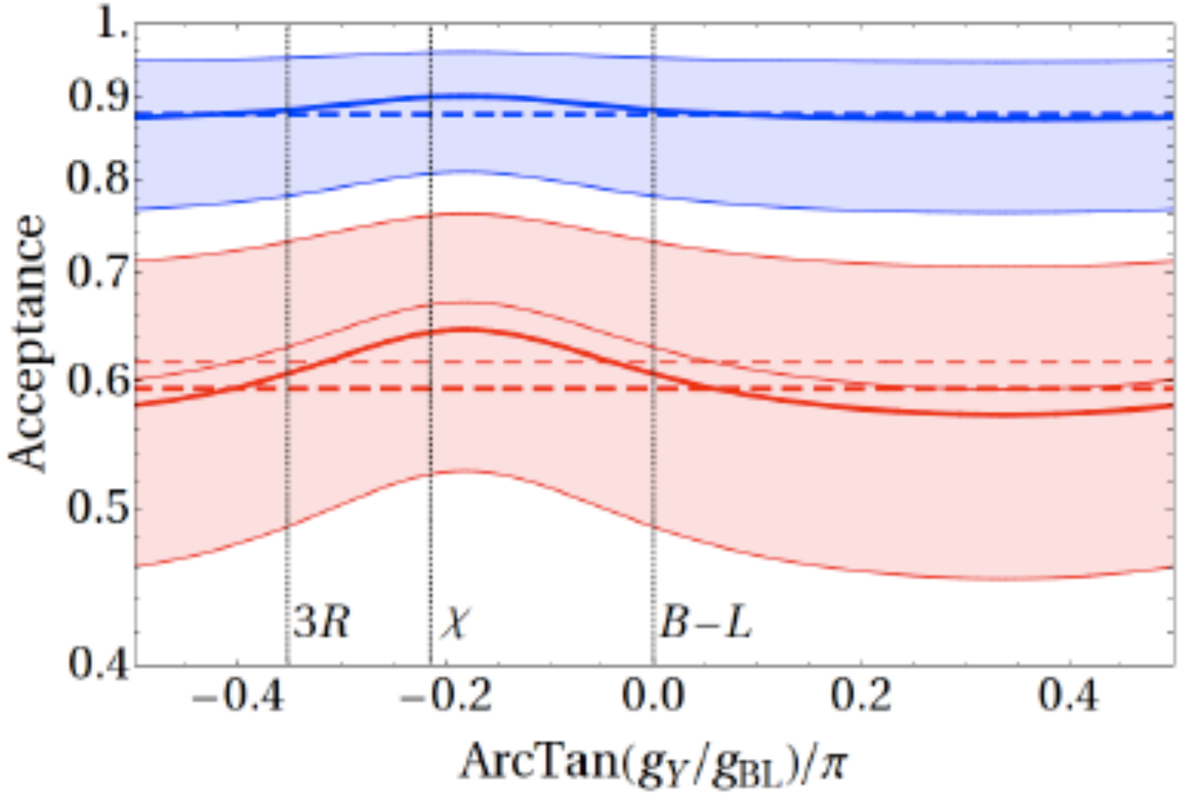


Tevatron direct searches: pheno

(non-universal models)



Typical acceptances at the LHC



X = B-L

Figure 6: The geometrical acceptance for signal (solid lines) and SM-DY background (dashed lines), as a function of a parameter that scans over the minimal models, and for two representative values of $M_{\ell^+\ell^-}$: 200 GeV (red, lower) and 1 TeV (blue, upper). The different lines refer to the cut $|\eta| < 2.5$ and $p_{T\ell} > 20$ GeV (thin) or $p_{T\ell} > 80$ GeV (thick). The colored bands show how much the acceptance varies by changing the rapidity-cut from $|\eta| < 2.1$ to $|\eta| < 3.0$.

Early LHC prospects (non-universal models)