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Minimal Z' models and the early LHC

Indirect Searches for New Physics at the time of LHC
GGI, 23 March 2010

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

We entered the LHC era! But…

LHC parameters:

$\sqrt{S} = 14$ TeV

$L = 10^{34}$ cm^{-2} s^{-1}

answer to crucial questions
of fundamental physics

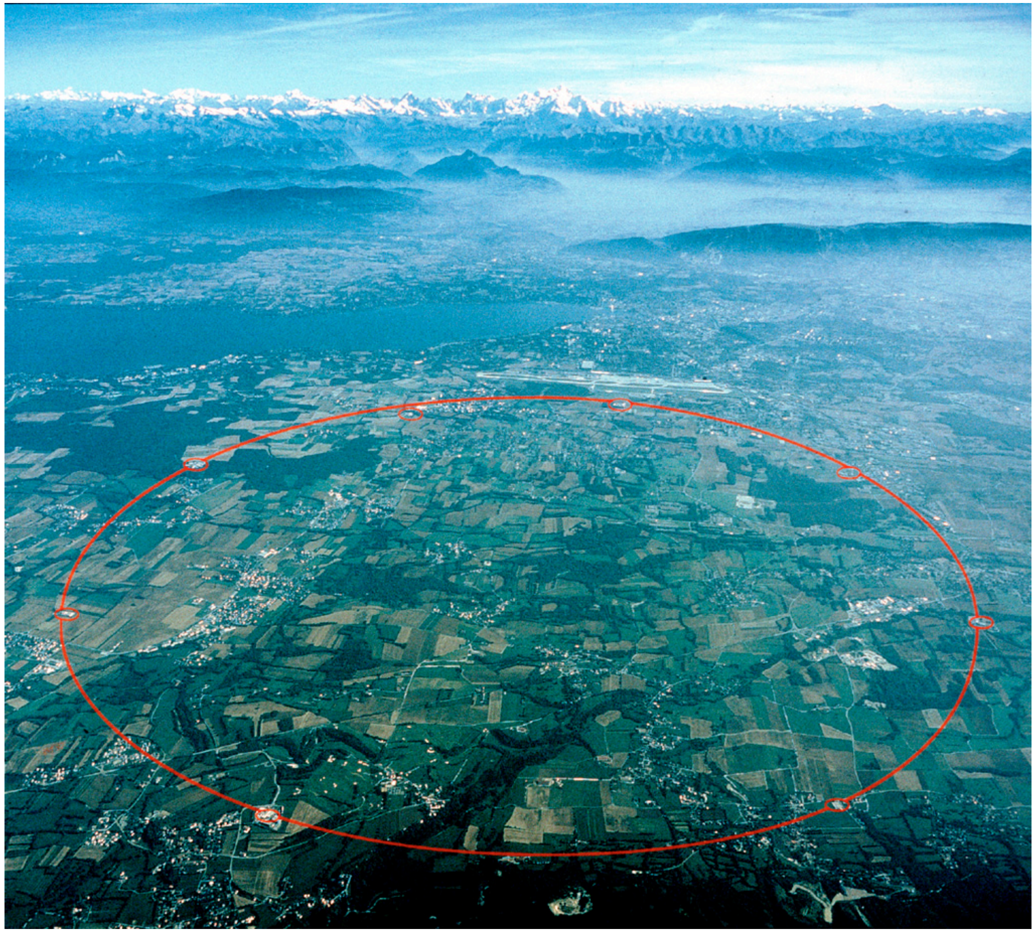
Near future prospects:

$\sqrt{S} = 7$ TeV in 2010-11

1-200 pb^{-1} in 2010?

up to 1 fb^{-1} by 2011?

then long break before safely
increasing the c.o.m. energy



Is there plausible new physics
-not already excluded by data
-accessible in O(1 year) time ?

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
(as sculpted on the stairs of my Department in Padua)

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

Plan:

- Z′ bosons at TeV scale: motivations
- A simple variety: minimal Z′ models
- Universal vs. non-universal models
- Simple theory of minimal models
- Direct vs. indirect bounds on Z′
- Prospects for the very early LHC

Theoretical motivations for extra U(1)s

GUTs based on r>4 gauge groups

SO(10) ➔ … ➔ $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$

E_6 ➔ … ➔ $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'} [\times U(1)_{Y''}]$

Type-II string models with D-branes

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

U(N) ➔ SU(N) x 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)

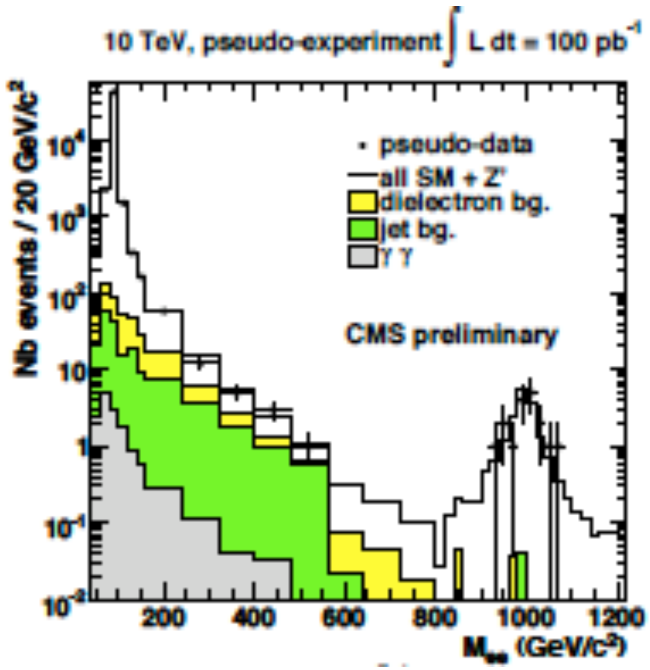
A down-to-earth motivation:

"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

- $G=SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$

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

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

Simple theory of minimal models

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

$$\mathcal{L} = -\frac{1}{4}\, h_{AB}\, F^A_{\mu\nu}\, F^{B\,\mu\nu} + \frac{1}{2}\, M^2_{AB}\, A^{A\mu}\, A^B_\mu + A^A_\mu\, J^\mu_A + \ldots$$

kinetic mixing mass mixing

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

$J_{Z'}{}^{o} = \Sigma_f \bar{f}\gamma^\mu Q_{Z'}{}^{o}(f) f$ $Q_{Z'}{}^{o} = (g_Y/g_Z)Y + (g_X/g_Z)X$

(Y: chiral; X: vectorial)

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

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

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 $\varphi_X \sim (0,X)$

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

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

$M_U \sim 10^{16}$ GeV

(SM or MSSM)

↓

favored range in

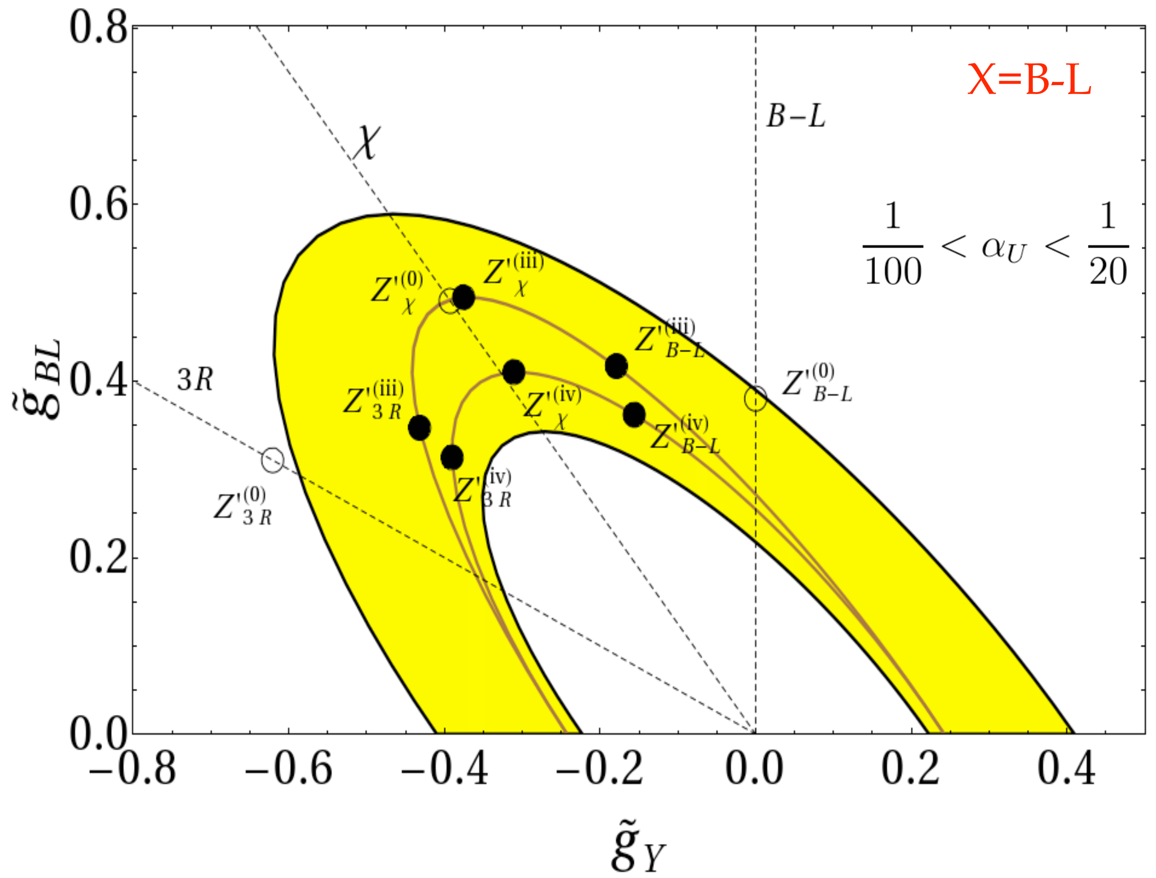
(g_Y, g_X) plane

Specific models

= special points

Kinetic mixing

induced by RGE!

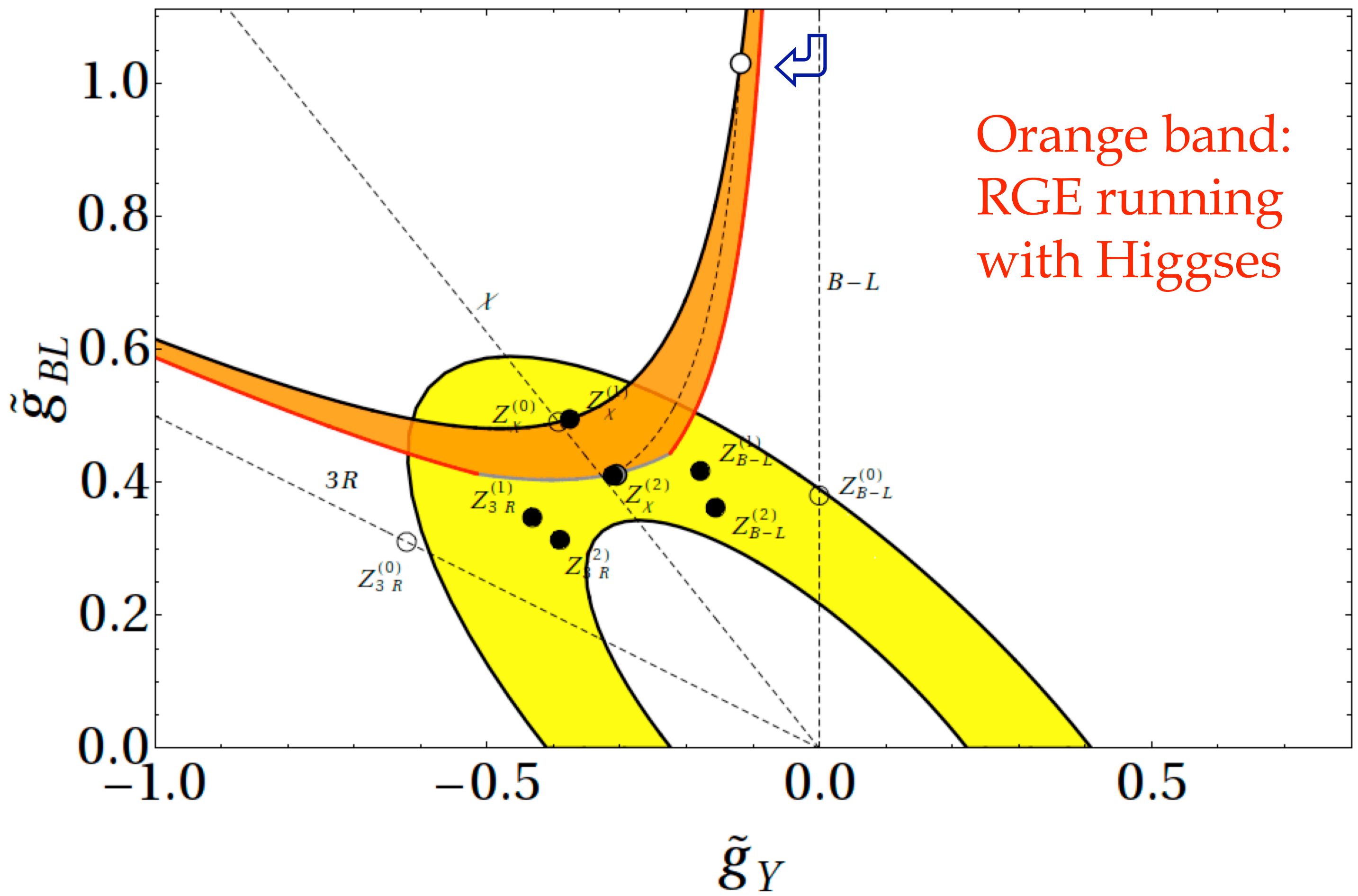


Minimal Z' models from D-branes

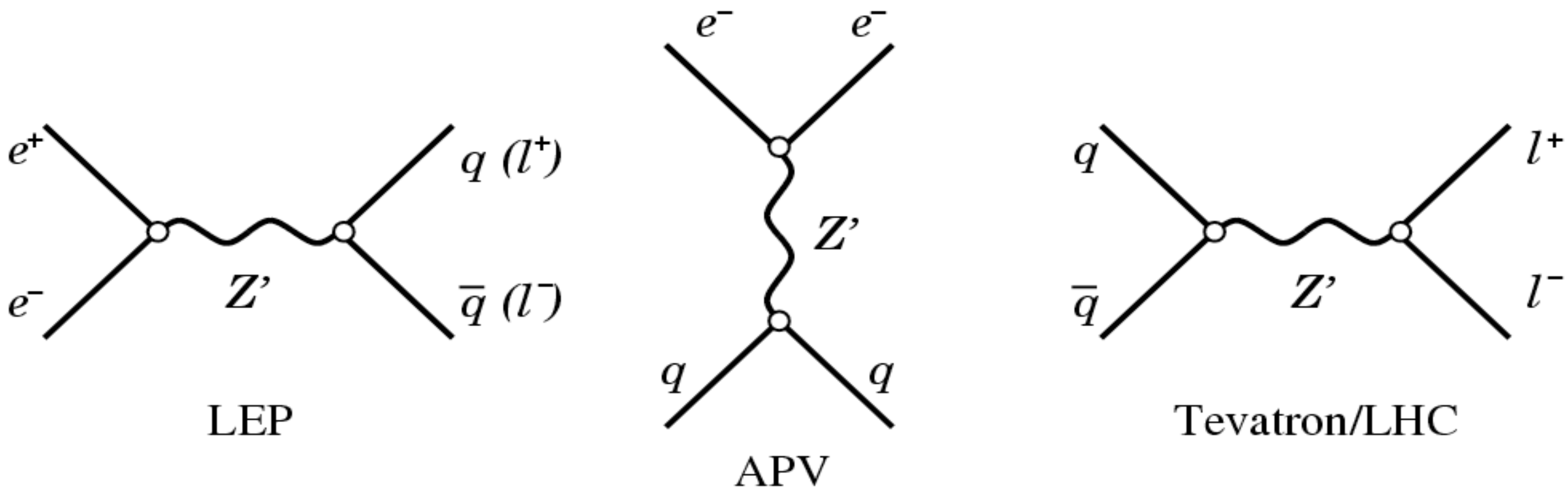
[see, e.g., Ghilencea-Ibanez-Irges-Quevedo, hep-ph/0205083]

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

Additional constraint if B and L wrap cycles of equal length



Direct vs. indirect bounds on Z′



the parameters involved are the same!

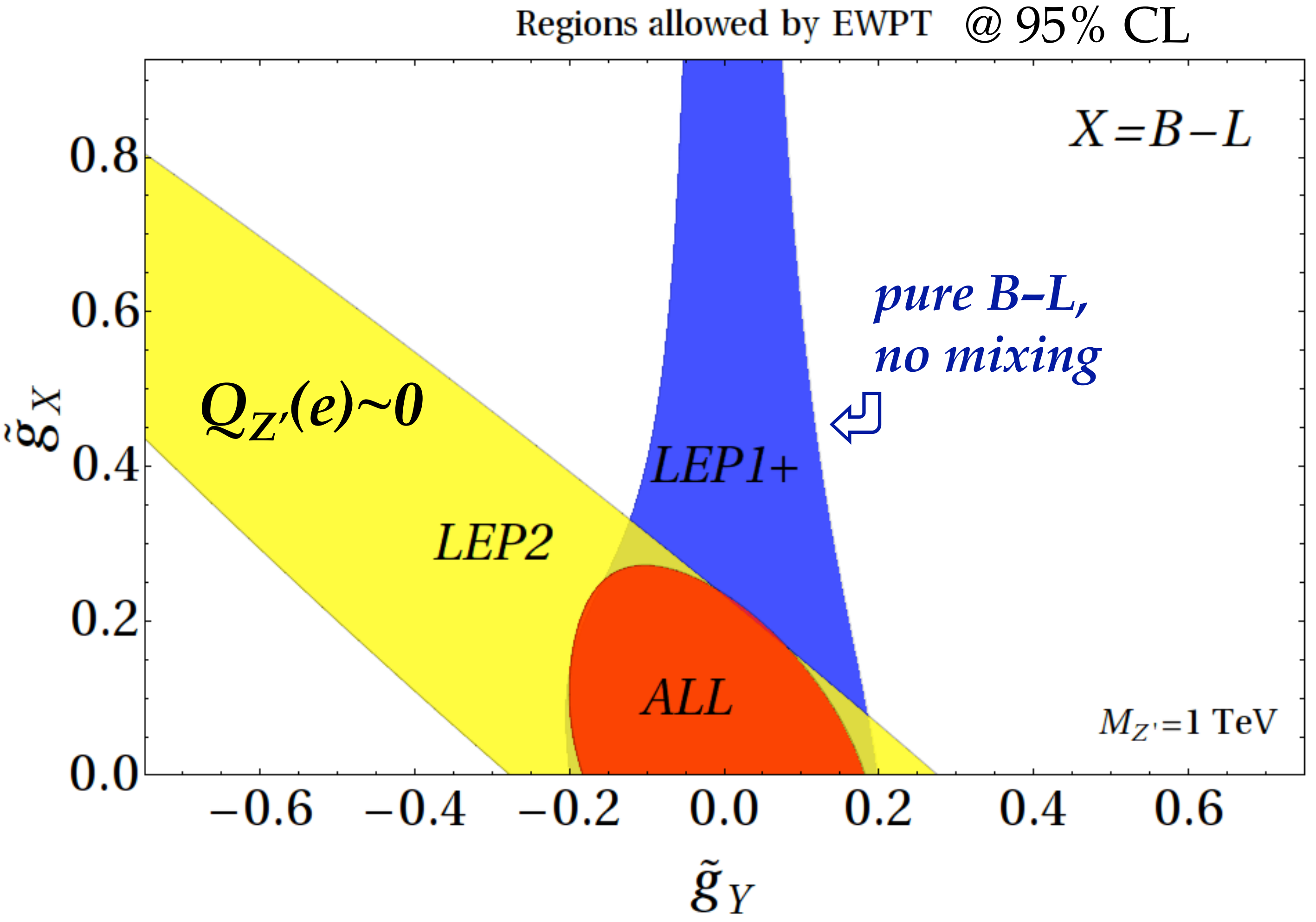
⇒

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



Constraints from EWPT: mass dependence

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

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

Universal (B-L): ➔

Non-universal:

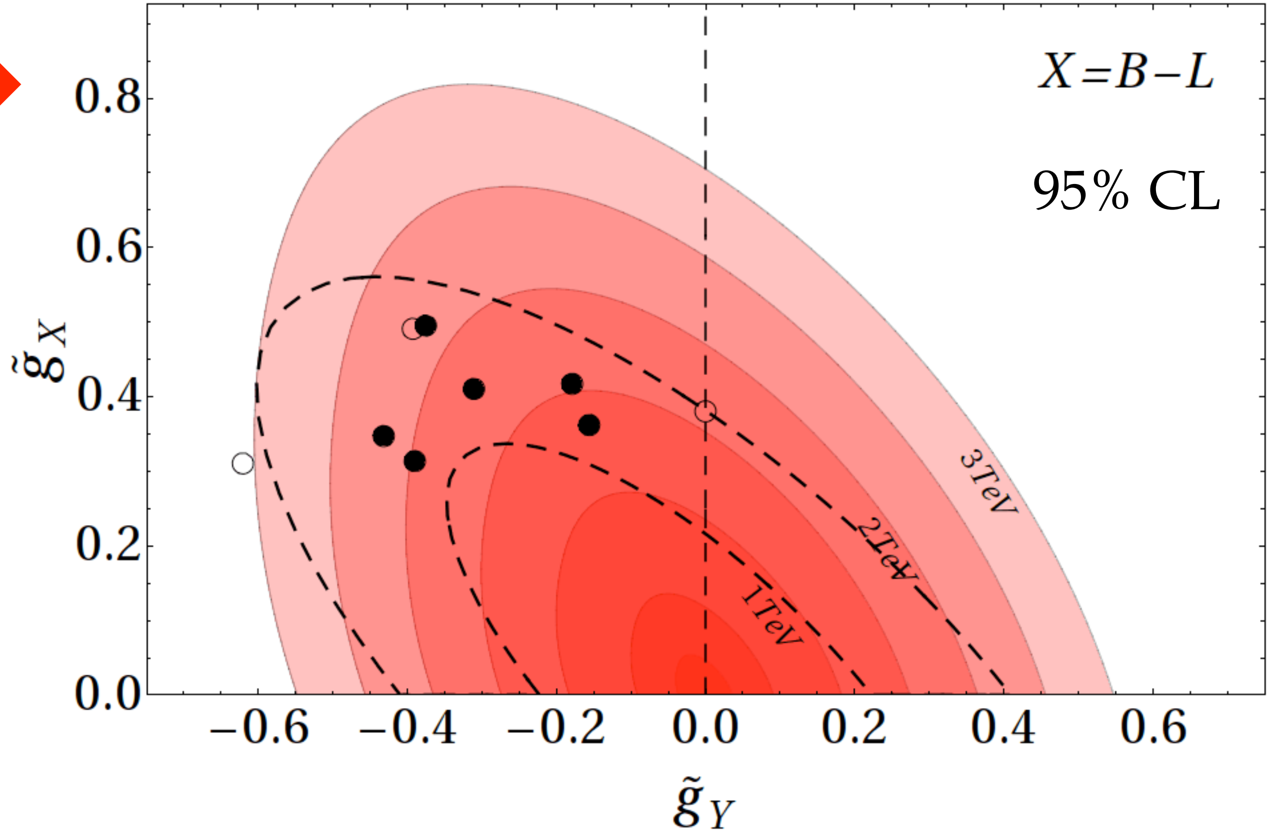
much weaker

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

$X = B - 3L_\mu$

$X = L_\mu - L_\tau$

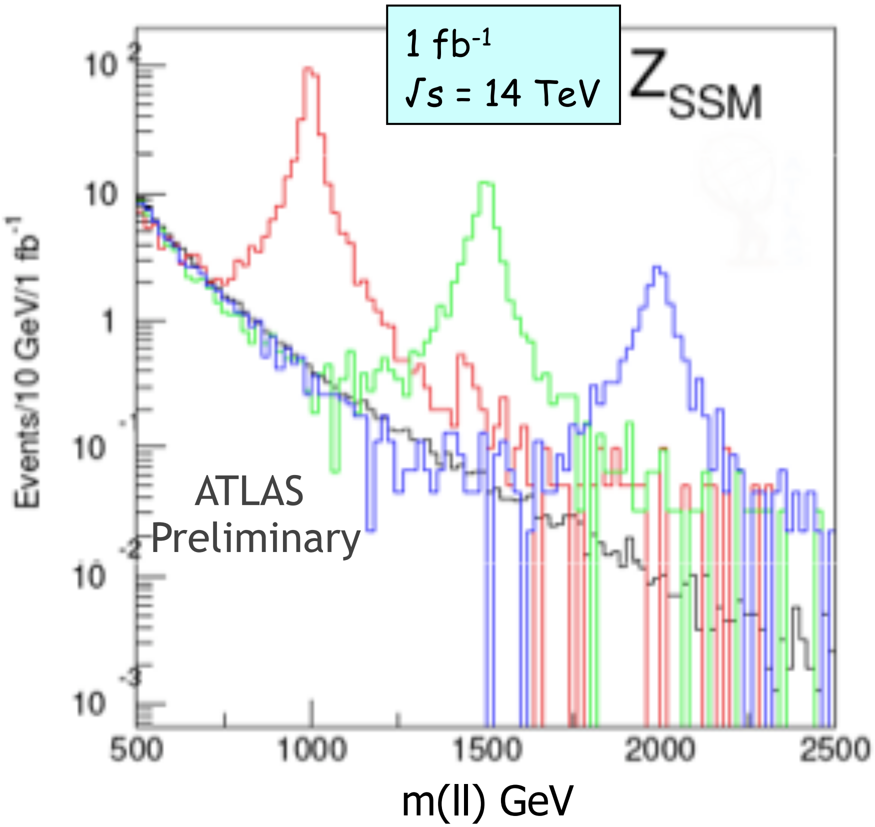
■ = allowed



One example of many….

[yesterday's talk on LHC, but many others I attended]

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



Z' (SSM): Tevatron limit ~ 1 TeV (95% C.L)	
50 pb^{-1}	: exclusion up to ~ 1 TeV (95% C.L.)
500 pb^{-1}	: discovery up to ~ 1.3 TeV exclusion up to ~ 1.5 TeV
1 fb^{-1}	: discovery up to ~ 1.5 TeV

Discovery reach above Tevatron limits
m ~ 1 TeV, perhaps in 2010 ?

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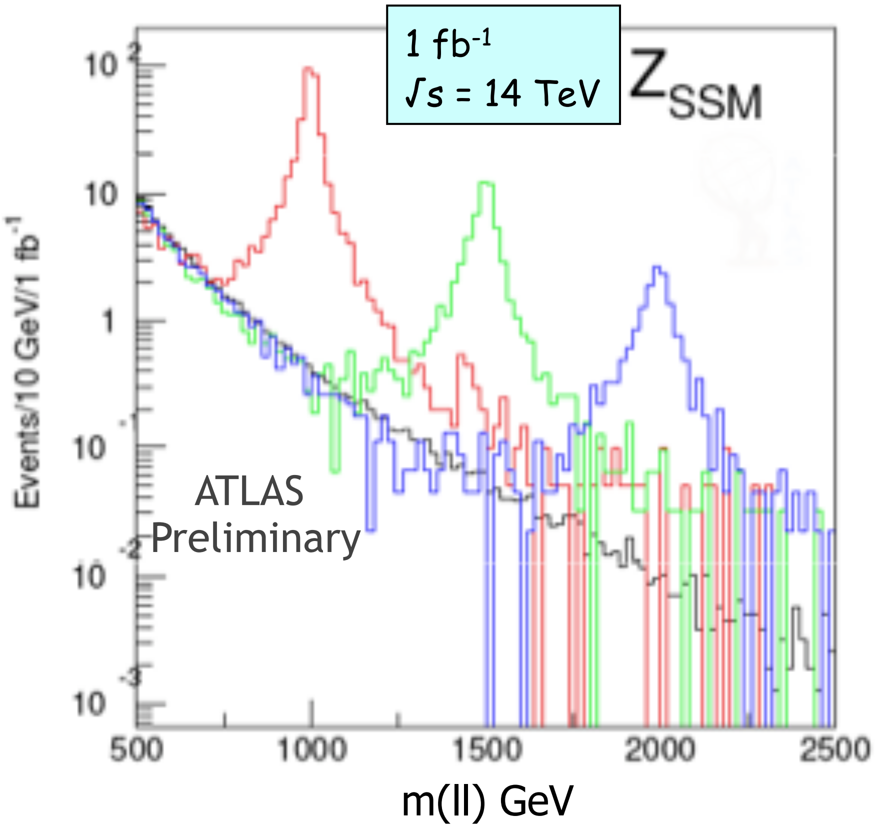

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Discovery reach above Tevatron limits m ~ 1 TeV, perhaps in 2010 ?

NO!

LEP2 [LEPEWWG 2006-01] ➔

$M(Z_{SSM}) > 1.787$ TeV (95% cl)

Now O(200 GeV) higher

Direct searches (Tevatron, LHC)

The experimentally relevant quantities are:

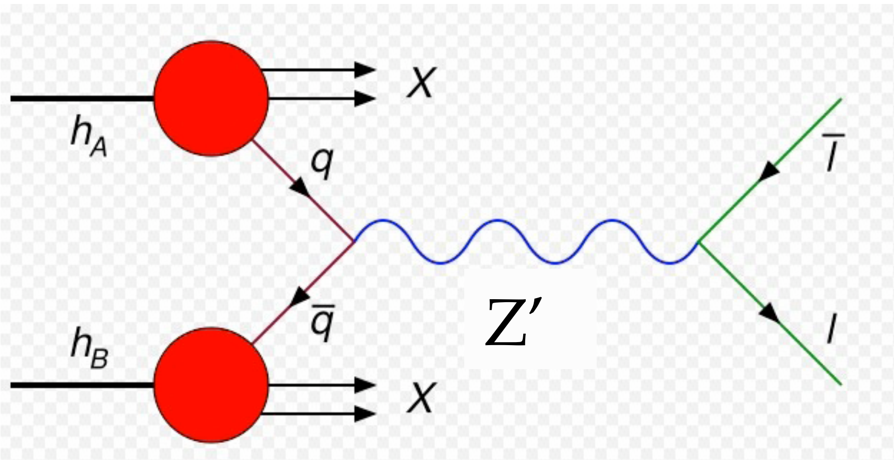
$$\sigma(p\bar{p} \to Z'X) \times \mathrm{BR}(Z' \to \ell^+\ell^-)$$

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

PDF(MSTW'08)@*NLO*

Z' → 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

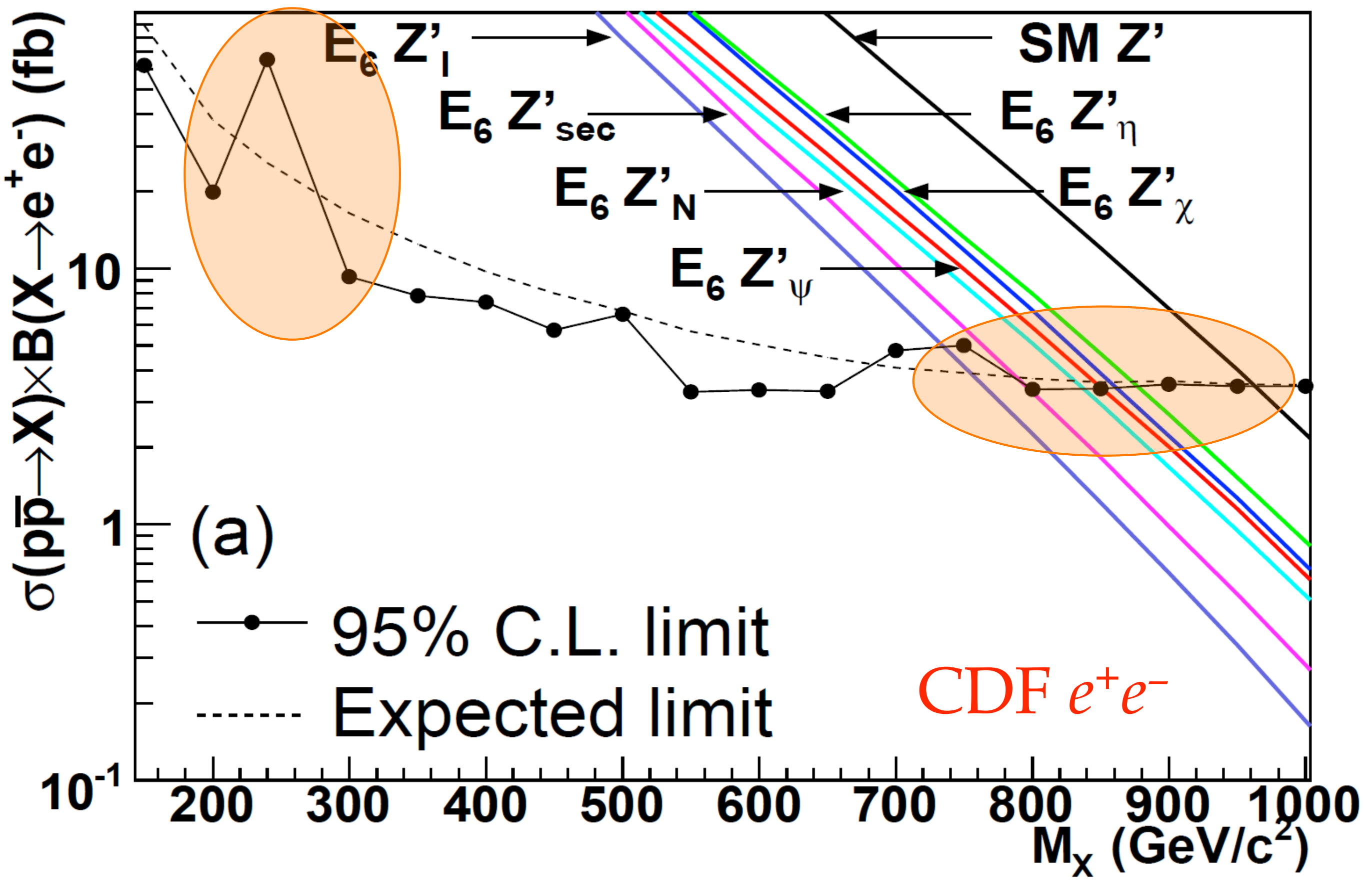


Backgrounds:
Drell-Yan (via γ^*,Z^*)
(very well understood)
+ reducible
(2 j , j+γ , W+j , ...)
Removed with mild p_T cut

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)



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%)

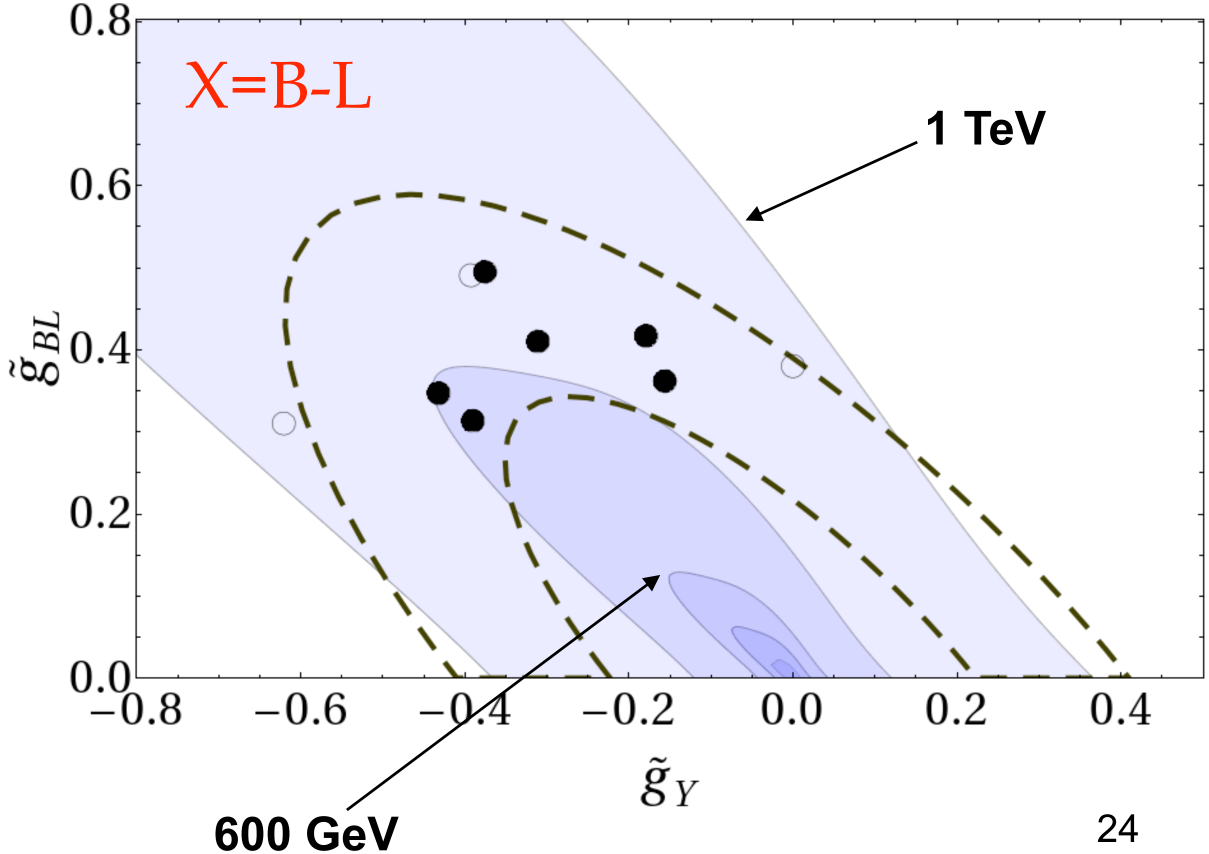
Tevatron direct searches: pheno

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

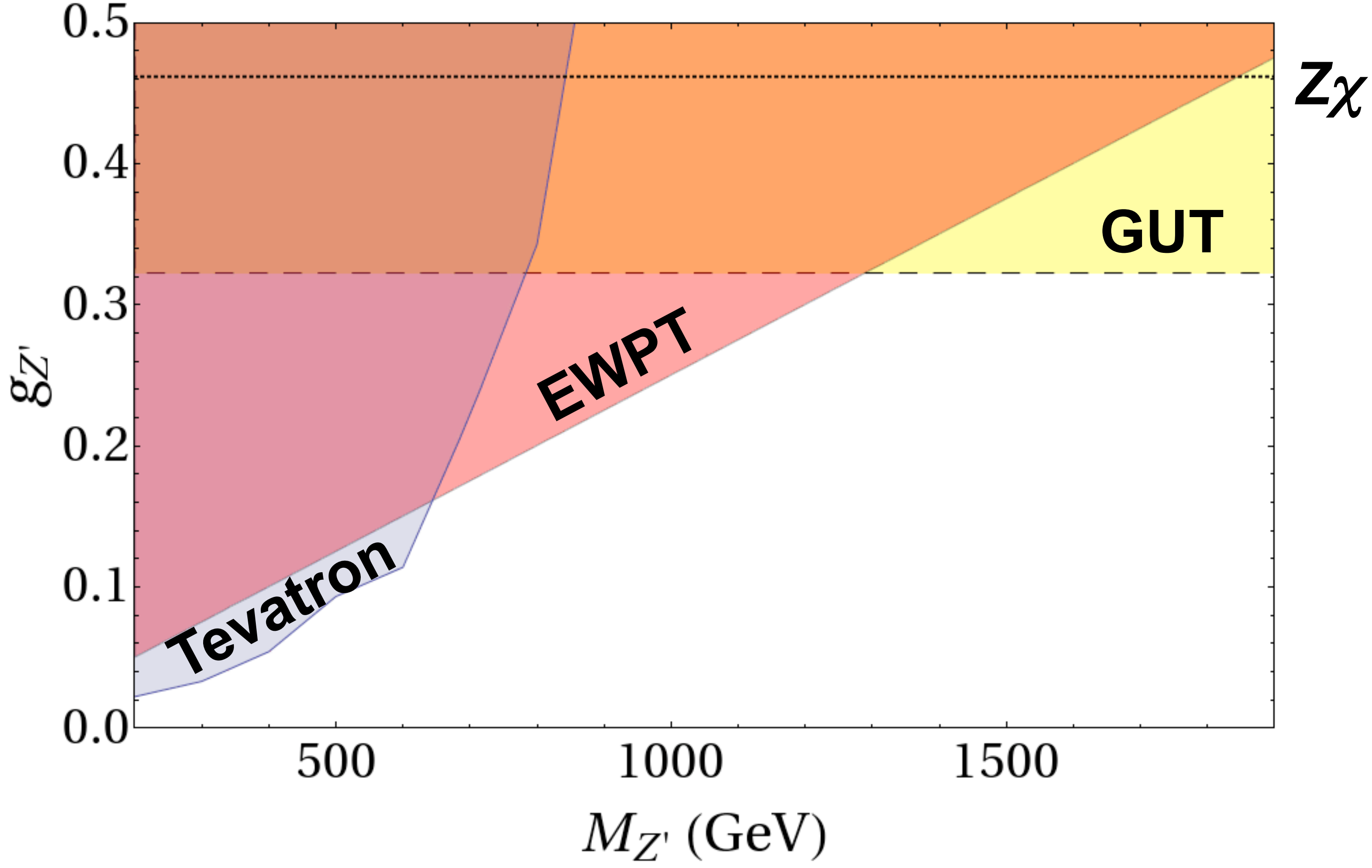
■ = allowed by Tevatron

Similar shape as EWPT

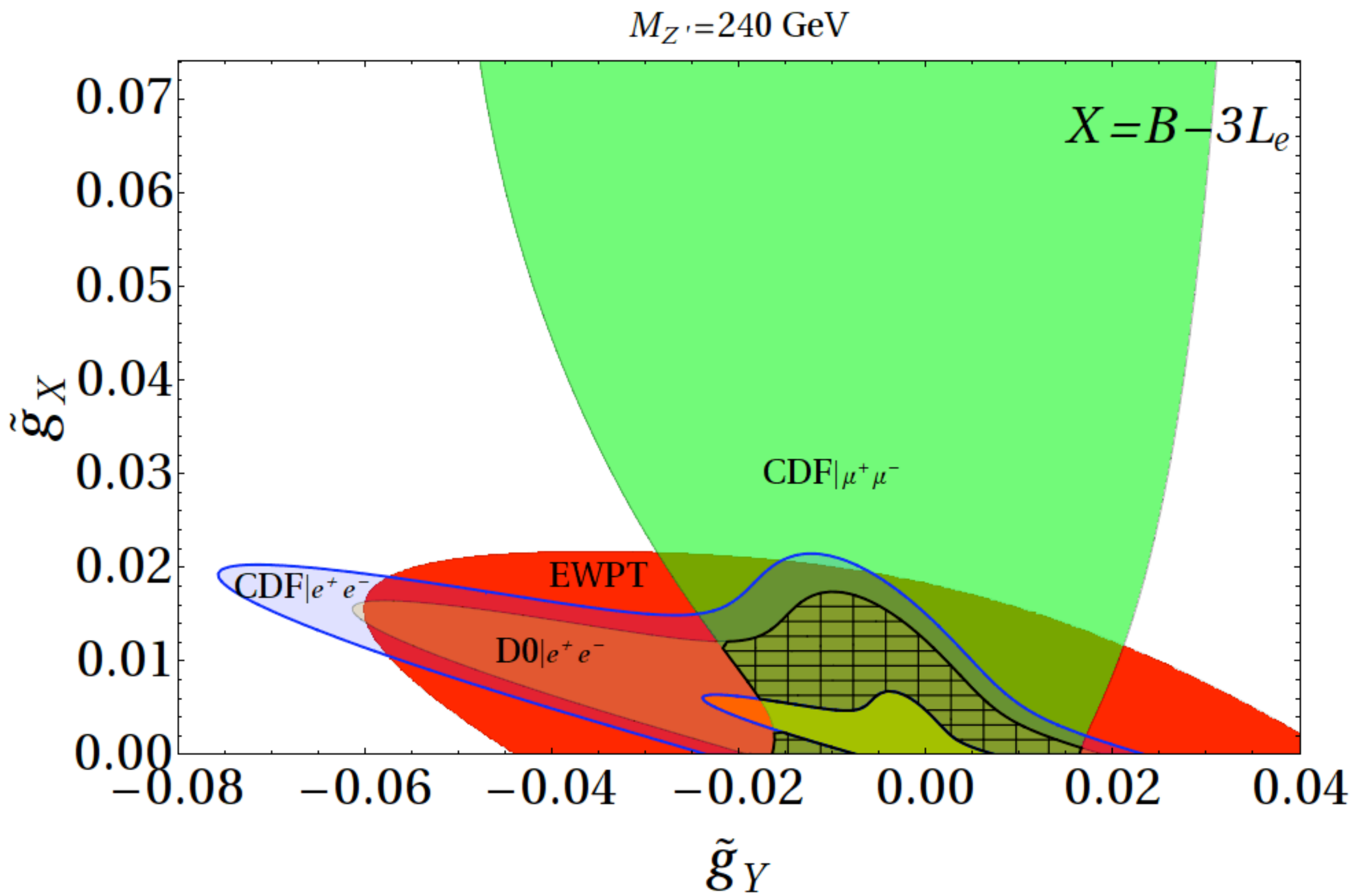
Allowed regions: > linear in $M_{Z'}$ (large-x PDF)



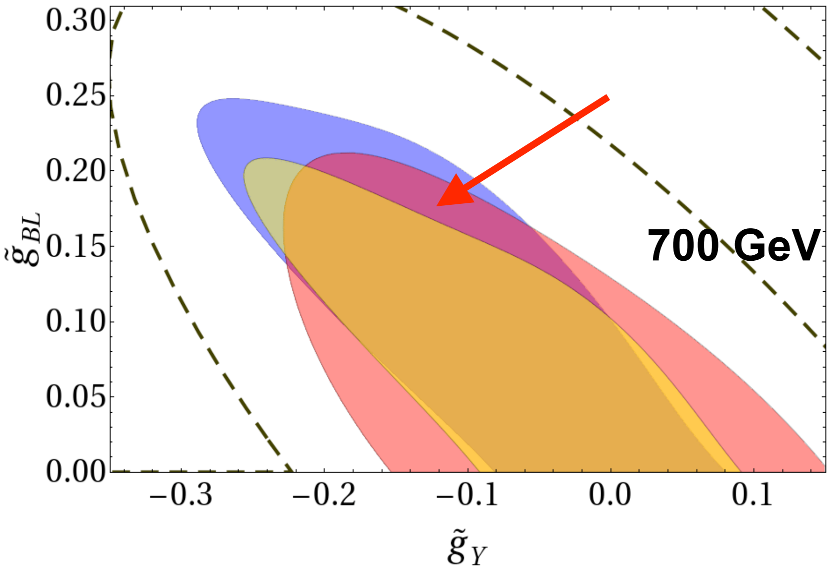
EWPT vs. Tevatron (Zχ example)



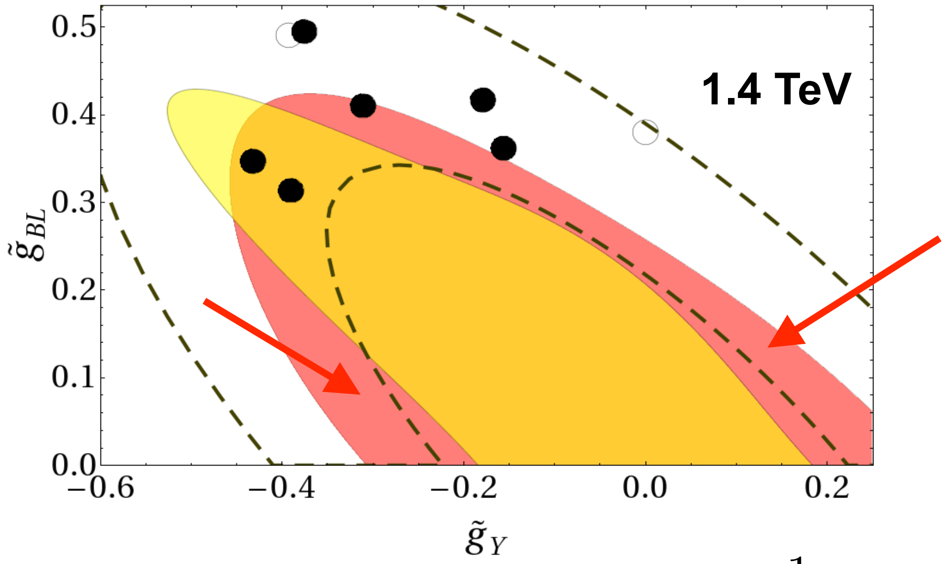
Electrophilic model and CDF dielectrons



Early LHC prospects (X=B-L)



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



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

= 95%CL allowed region by EWPT

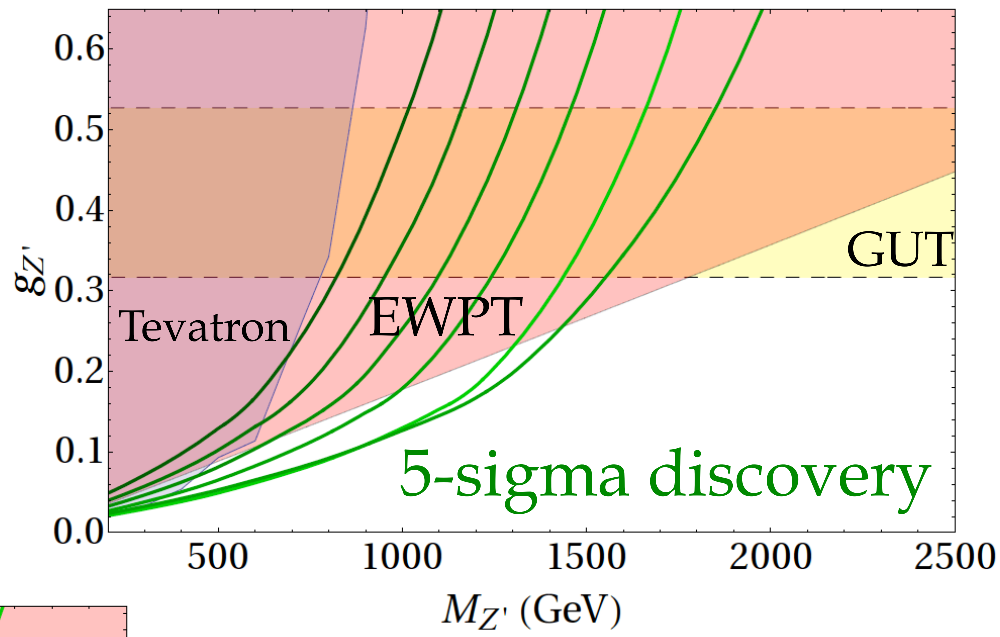
= 95%CL allowed region by Tevatron direct searches

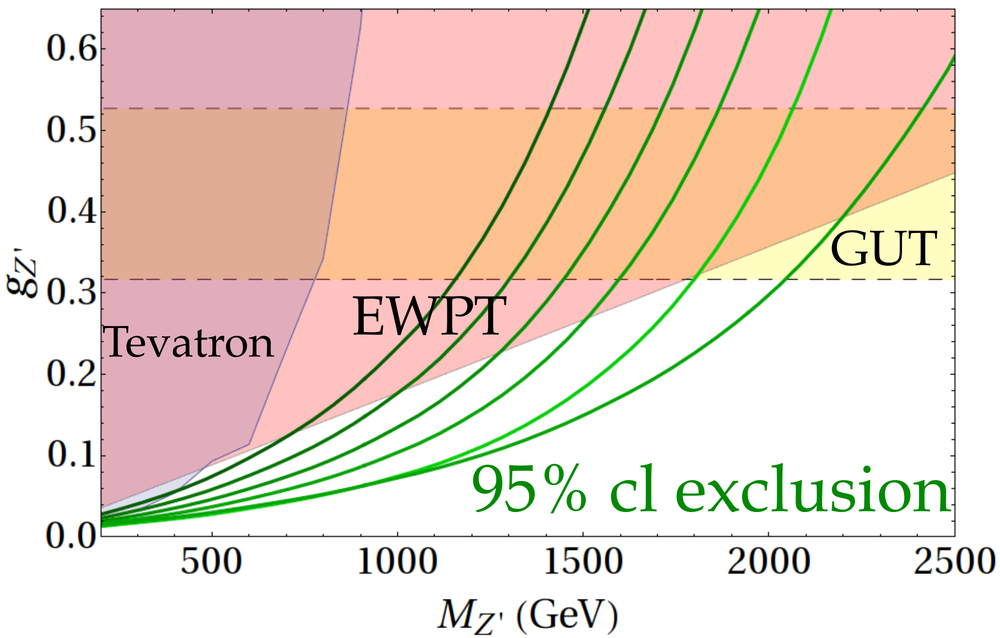
= region NOT accessibile to LHC (5σ discovery for given en. & lum.)

→ **POSSIBLE DISCOVERY**

Early LHC prospects (chi-model)

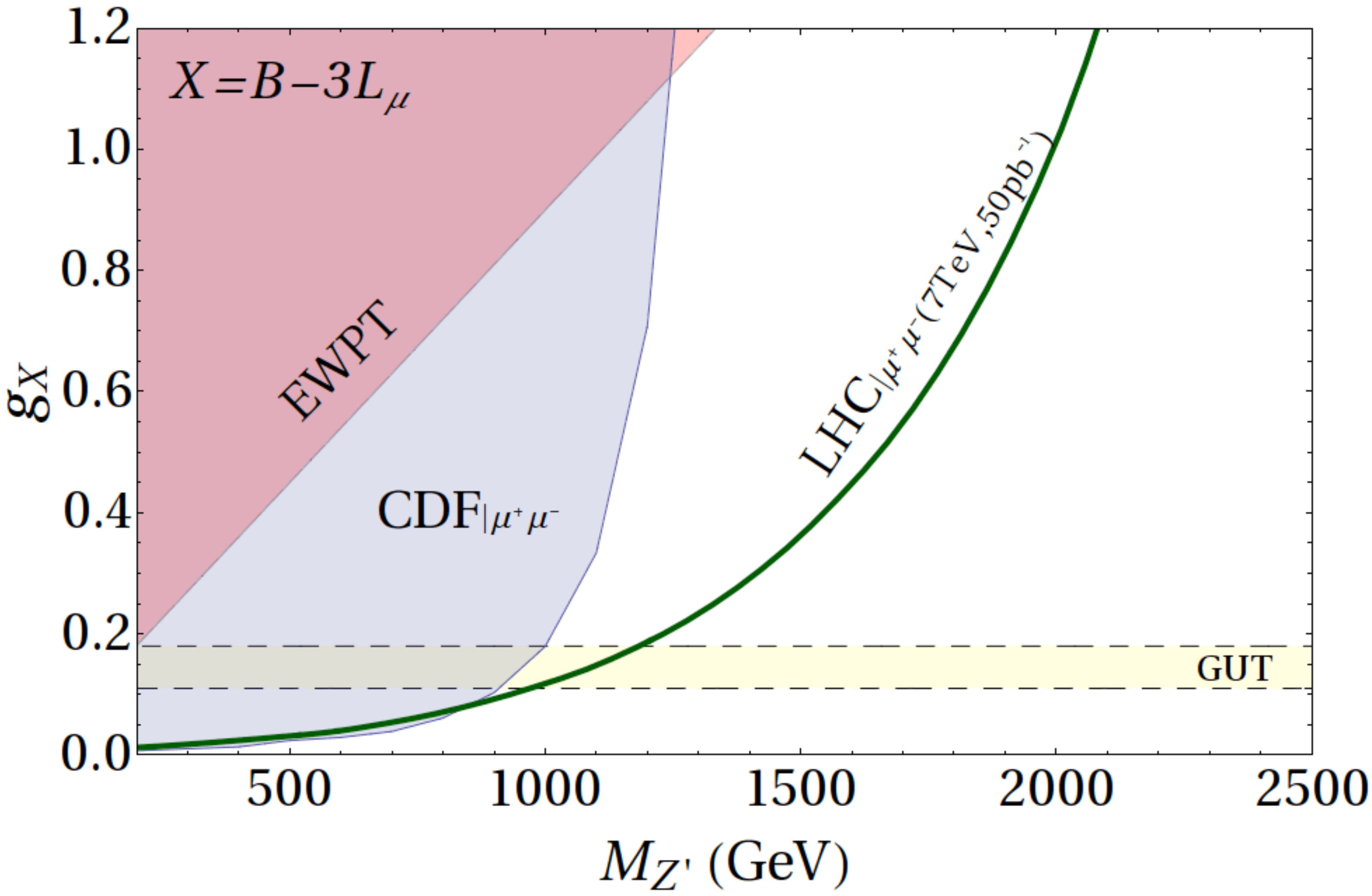
7 TeV
50,100,200,
400,1000 pb^{-1}
+
10 TeV 400 pb^{-1}





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

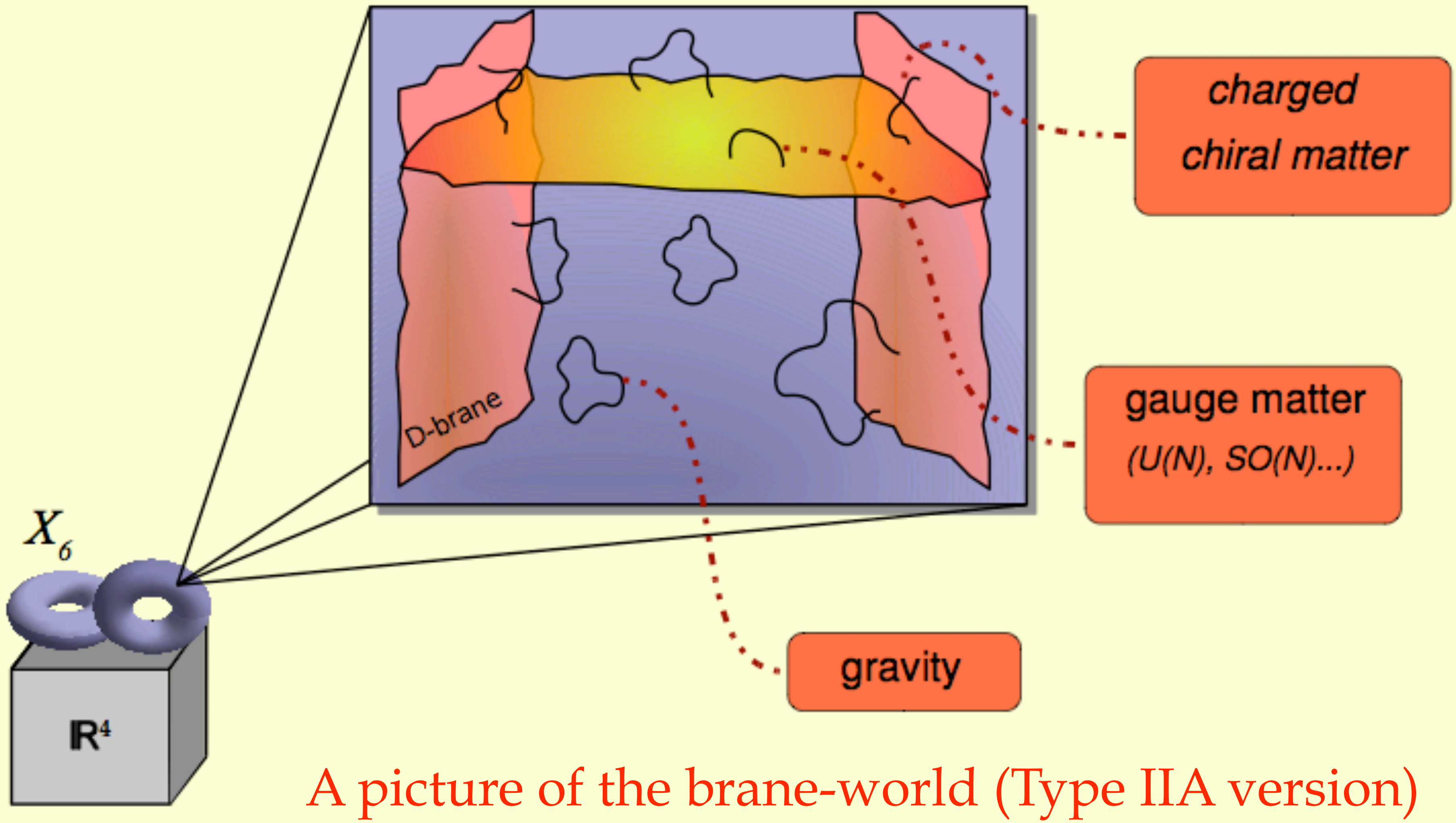
  -may explain the CDF di-electron excess if confirmed
- Z′ from D-branes quite stringently constrained

SPARE SLIDES

Prospects for 1^{st} year run at $\sqrt{S}$ = 7 TeV [M. Lamont]

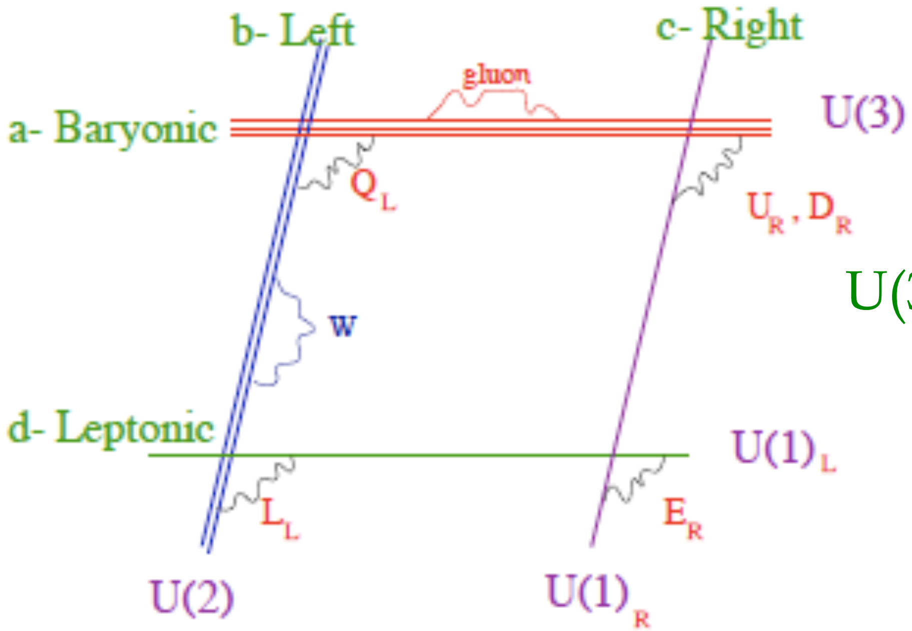
Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal	events/X
1	Beam commissioning							
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}		
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}		
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5	
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4	
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8	1.6
6	partial 50 ns – nominal crossing angle	144	7×10^{10}	2-3	3.1×10^{31}	~16 pb^{-1}	3.1	0.8
7		288	7×10^{10}	2-3	8.6×10^{31}	~32 pb^{-1}	6.2	
8		432	7×10^{10}	2-3	9.2×10^{31}	~48 pb^{-1}	9.4	
9		432	9×10^{10}	2-3	1.5×10^{32}	~80 pb^{-1}	12	
10		432	9×10^{10}	2-3	1.5×10^{32}	~80 pb^{-1}	12	
11		432	9×10^{10}	2-3	1.5×10^{32}	~80 pb^{-1}	12	

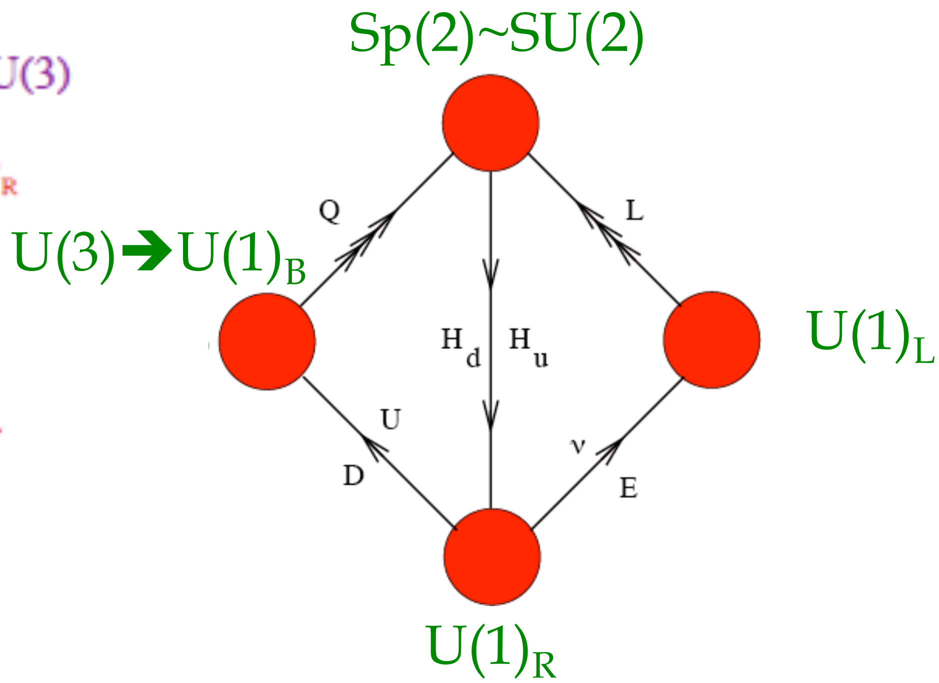
D-brane models with extra U(1)s



A picture of the brane-world (Type IIA version)

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	$+1$	$+1$
$Q_{Z'}$	$\frac{1}{6}\widetilde{g}_Y+\frac{1}{3}\widetilde{g}_{BL}$	$-\frac{2}{3}\widetilde{g}_Y-\frac{1}{3}\widetilde{g}_{BL}$	$\frac{1}{3}\widetilde{g}_Y-\frac{1}{3}\widetilde{g}_{BL}$	$-\frac{1}{2}\widetilde{g}_Y-\widetilde{g}_{BL}$	$\widetilde{g}_{BL}$	$\widetilde{g}_Y+\widetilde{g}_{BL}$

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

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

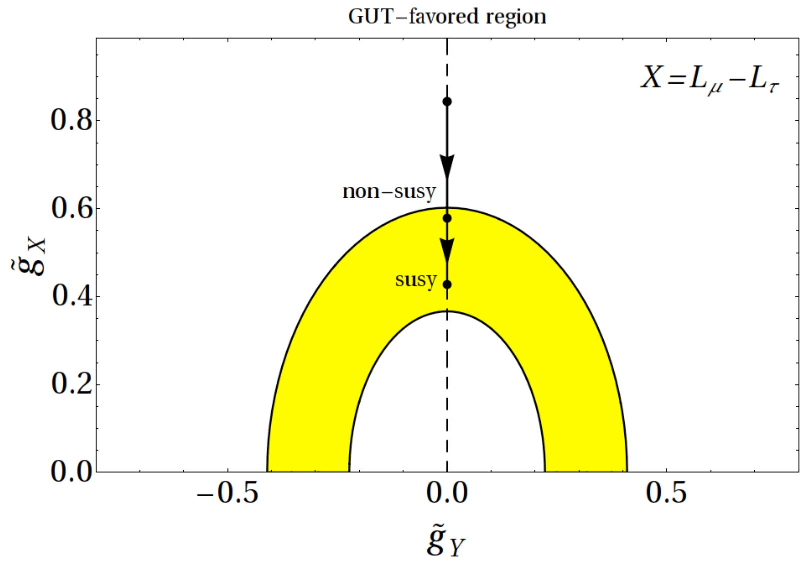
	T_{3L}	Y	$B-3L_b$	X	$Q_{Z'}$
$q_{La} \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}_a$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$+\frac{1}{6}$	$+\frac{1}{3}$	$+\frac{\beta}{3}$	$\frac{1}{6}\,\tilde{g}_Y + \frac{\beta}{3}\,\tilde{g}_X$
u_{Ra}	0	$+\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{\beta}{3}$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

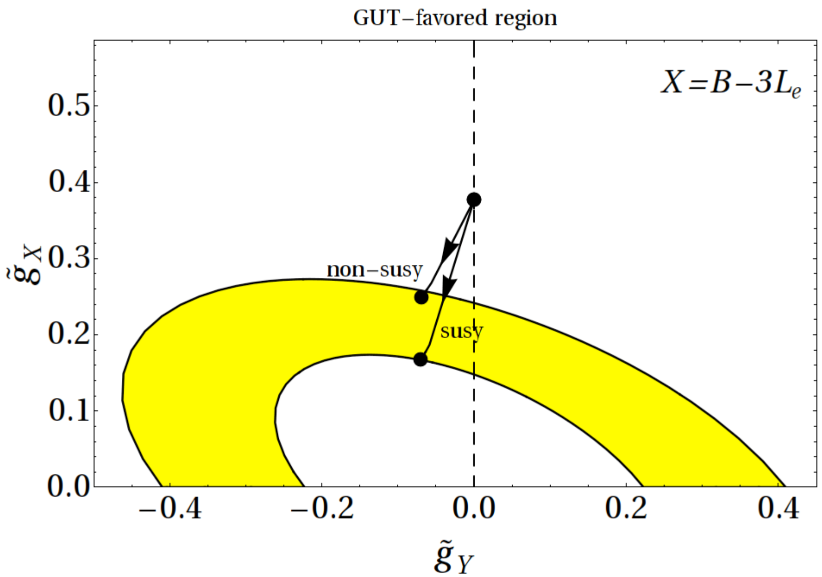
GUT-constraints on non-universal models

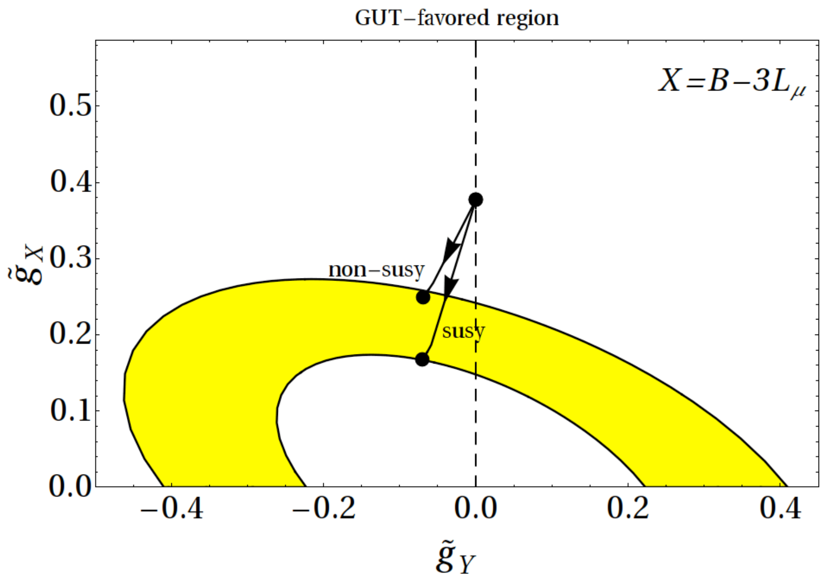
Plausible bound. conditions
@ M_U~10^{16} GeV
RGE running from M_U to M_Z
(SM or MSSM)

⬇

favored range in (g_Y , g_X) plane





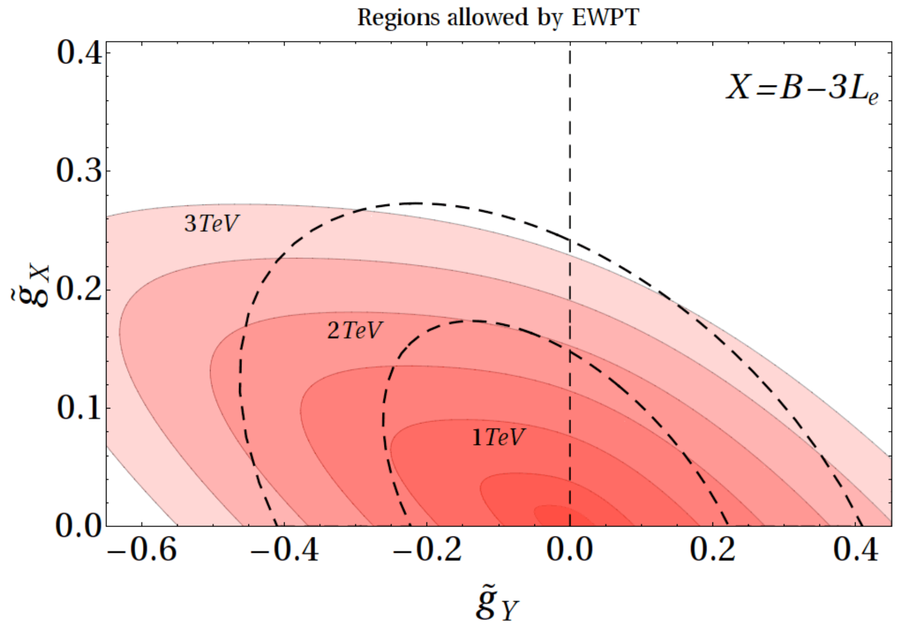


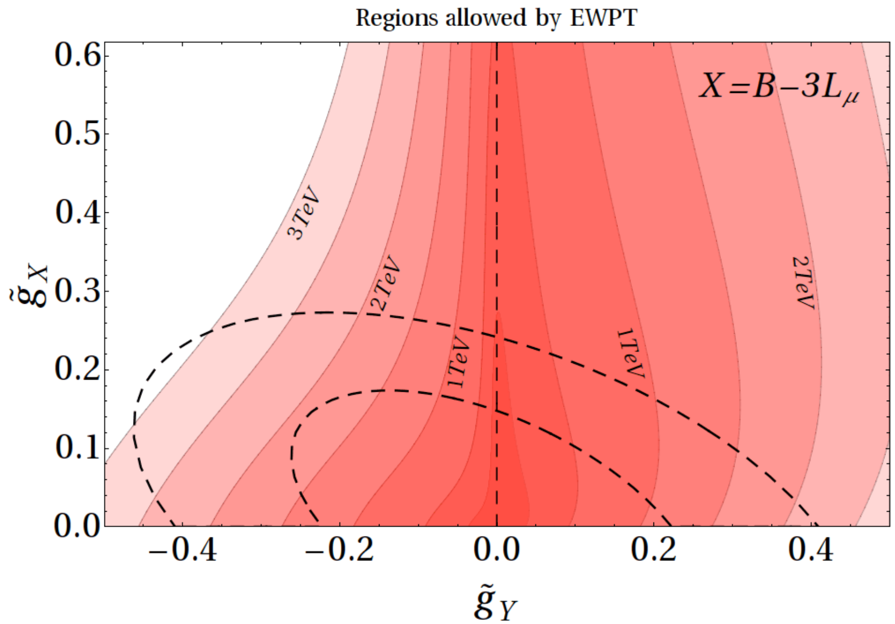
Bounds from EWPT: non-universal models

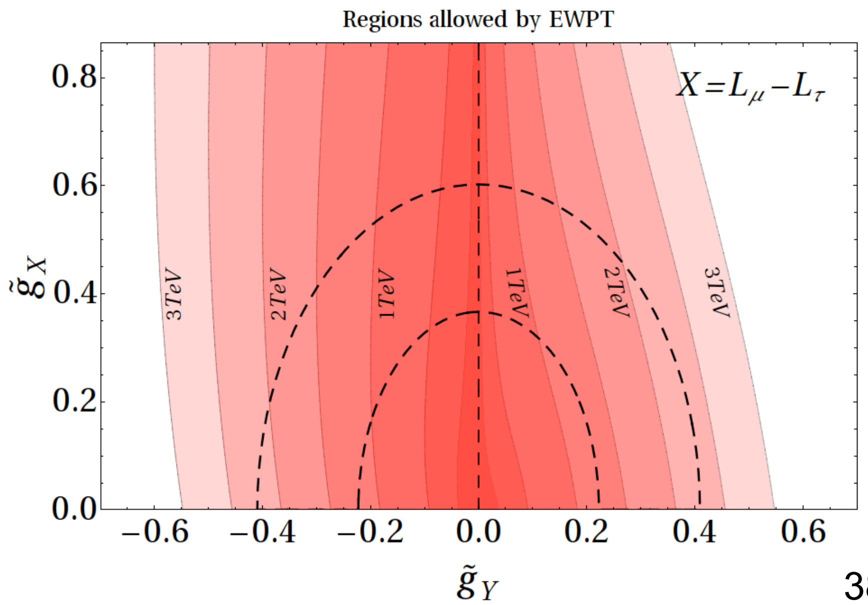
EWPT most sensitive
to electron couplings

$X=B\text{-}3L_e$ bounds
similar to $X=B\text{-}L$

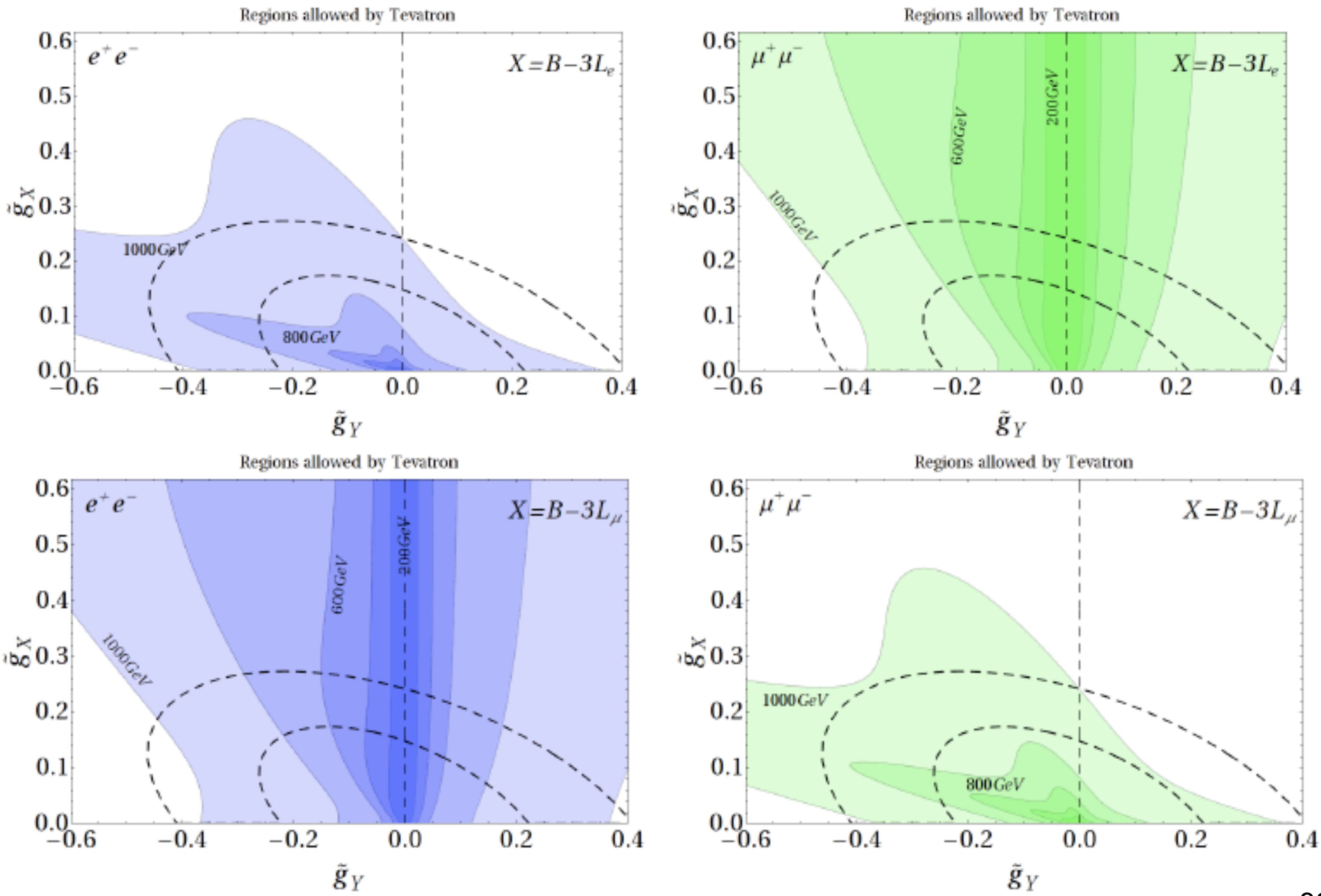
$X=B\text{-}3L_\mu$ and $X=L_\mu\text{-}L_\tau$
mostly via mixing effects







Tevatron direct searches: pheno
(non-universal models)



Typical acceptances at the LHC

X = B-L

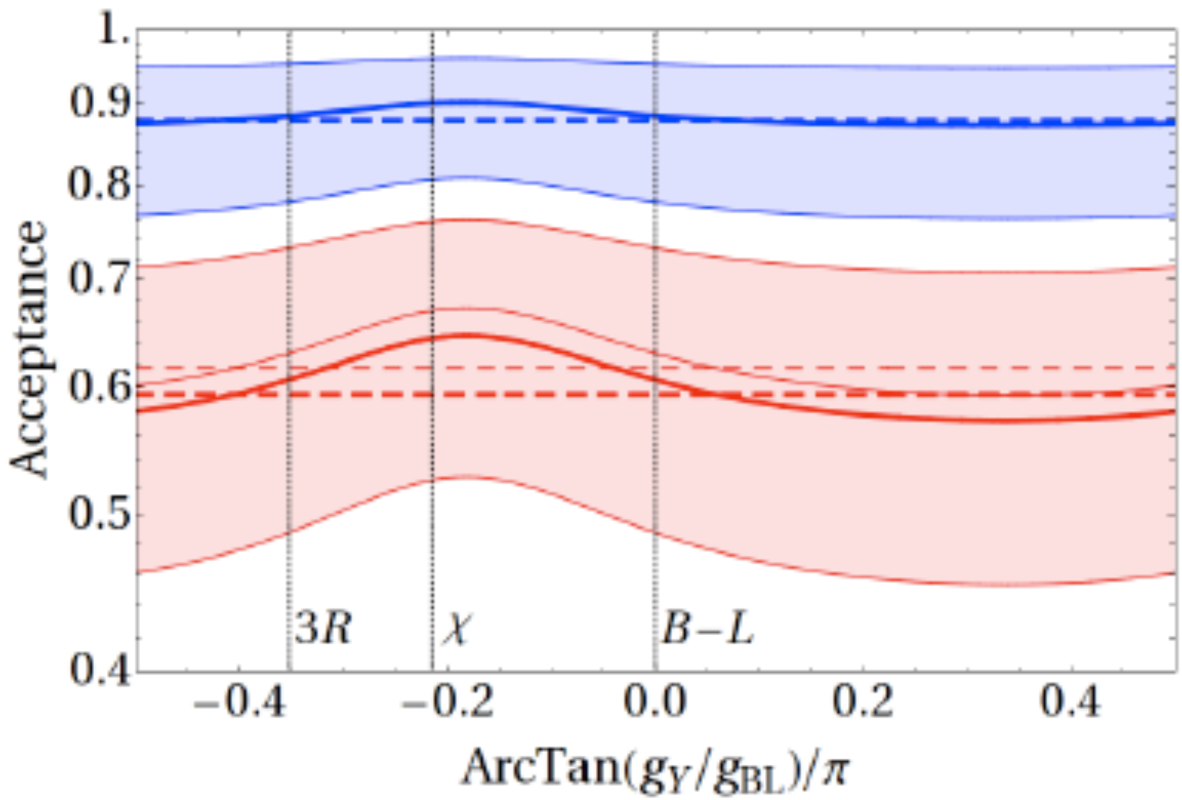


Figure 6: The geometrical acceptance for signal (solid lines) and SM-DY background (dashed lines), as a function of a parameter that scans over the minimal models, and for two representative values of $M_{\ell^+\ell^-}$: 200 GeV (red, lower) and 1 TeV (blue, upper). The different lines refer to the cut $|\eta| < 2.5$ 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 $|\eta| < 3.0$.

Universal χ model: EWPT vs. Tevatron vs. LHC

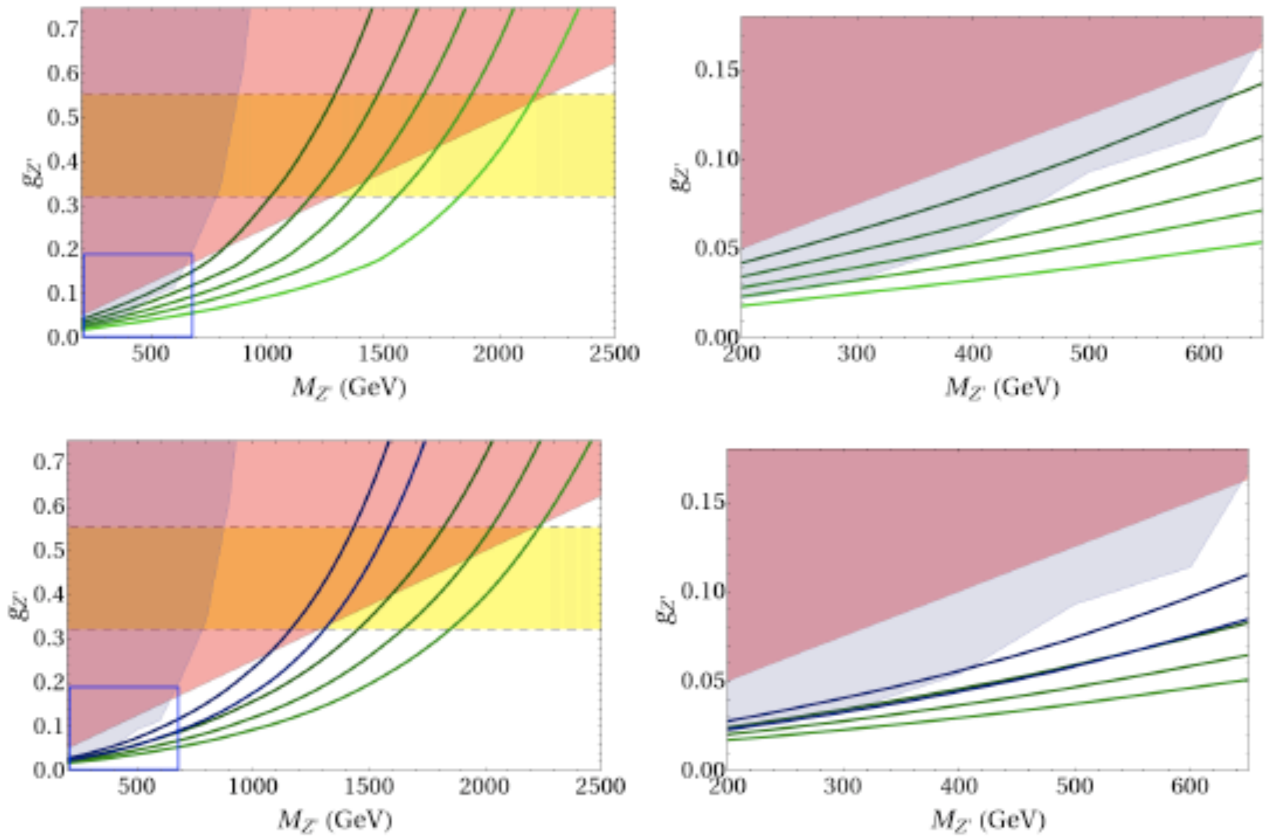


Figure 9: *First row.* The region of the $(M_{Z'}, g_{Z'})$ plane amenable to a '5σ' discovery at the LHC, for the Z_χ model, $\sqrt{s} = 10\,\text{TeV}$ and some representative values of the integrated luminosity; from left to right: 50, 100, 200, 400 and 1000 pb^{-1}. The red and blue region and the yellow band are the same as in Fig. 4. The second box is a zoom on the low-mass, low-coupling region. *Second row.* 95% CL exclusion contours from the LHC after 50 and 100 pb^{-1} at $\sqrt{s} = 7$ TeV (blue curves) and after 50, 100 and 200 pb^{-1} at $\sqrt{s} = 10$ TeV (green curves).

Early LHC prospects (non-universal models)