Minimal Z'
and the early LHC

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Cargese 2010 - Physics at TeV colliders: from Tevatron to LHC

Cargese, July 24, 2010

ES, G.Villadoro, F.Zwirner 0909.1320 [JHEP],
ES, A.Strumia, G.Villadoro, F.Zwirner 0911.1450 [JHEP]

A new gauge boson: motivations

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \longleftrightarrow Z'$$

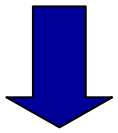
Theoretical

- Grand Unified Theories (e.g. $SO(10)$ or E_6)
- Alternative models for EWSB (Little Higgs, Higgsless models, strong EWSB…)
- String models with D-branes

Experimental

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

very ‘clean’ signals at LHC



one of the first searches performed

Minimal Z': theory

SM fields + 3 ν_R + **non-anomalous** $U(1)_X$ (only renormalizable int.)

In mass eigenstate basis, with canonical kinetic terms:

$$\mathcal{L}_{NC} = eJ_{em}A + g_Z(Z\,J_Z + Z'\,J_{Z'})$$

where:

$$J_Z = \cos\theta' J_{Z^0} - \sin\theta' J_{Z'^0}$$
$$J_{Z'} = \sin\theta' J_{Z^0} + \cos\theta' J_{Z'^0}$$

$J_{Z^0} =$ current coupled to the Z *in the SM*

kinetic mixing

$$J_{Z'^0} = \frac{g_Y}{g_Z} J_Y + \frac{g_X}{g_Z} J_X$$

Appelquist et al., hep-ph/0212073

Z-Z' mixing angle:

$$\tan\theta' = -\frac{g_Y}{g_Z}\frac{M_{Z^0}^2}{M_{Z'}^2 - M_{Z^0}^2} \qquad M_{Z^0} = \frac{gv}{2}$$

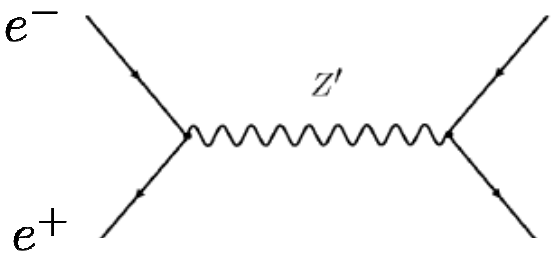
Given *X*, **only 3 parameters** describe the *Z'* pheno:

$$M_{Z'}, \qquad g_Y, \qquad g_X$$

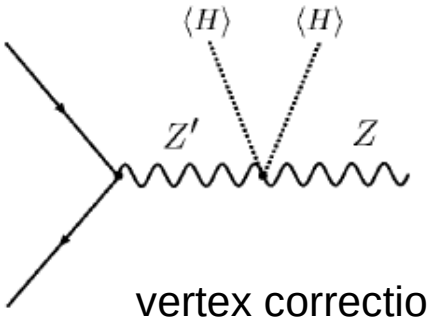
Phenomenology

Electroweak precision tests (mainly LEP):

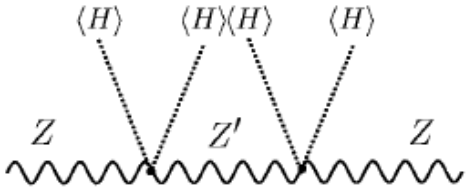
(see Contino, 0804.3195)



contact interaction



vertex correction

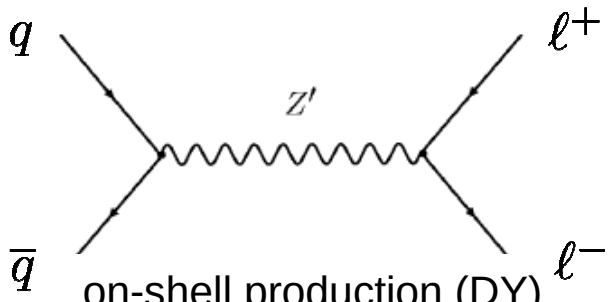


correction to Z mass

All of these are $\propto \frac{g^2_{Z'}}{M^2_{Z'}}$! ⇒ bounds are **linear** in coupling *vs* mass

$$(g_{Z'} = \sqrt{g_Y^2 + g_X^2})$$

Hadron colliders (Tevatron and LHC):



on-shell production (DY)

Limits grow **more than linearly** with $M_{Z'}$, due to PDF suppression at large *x*

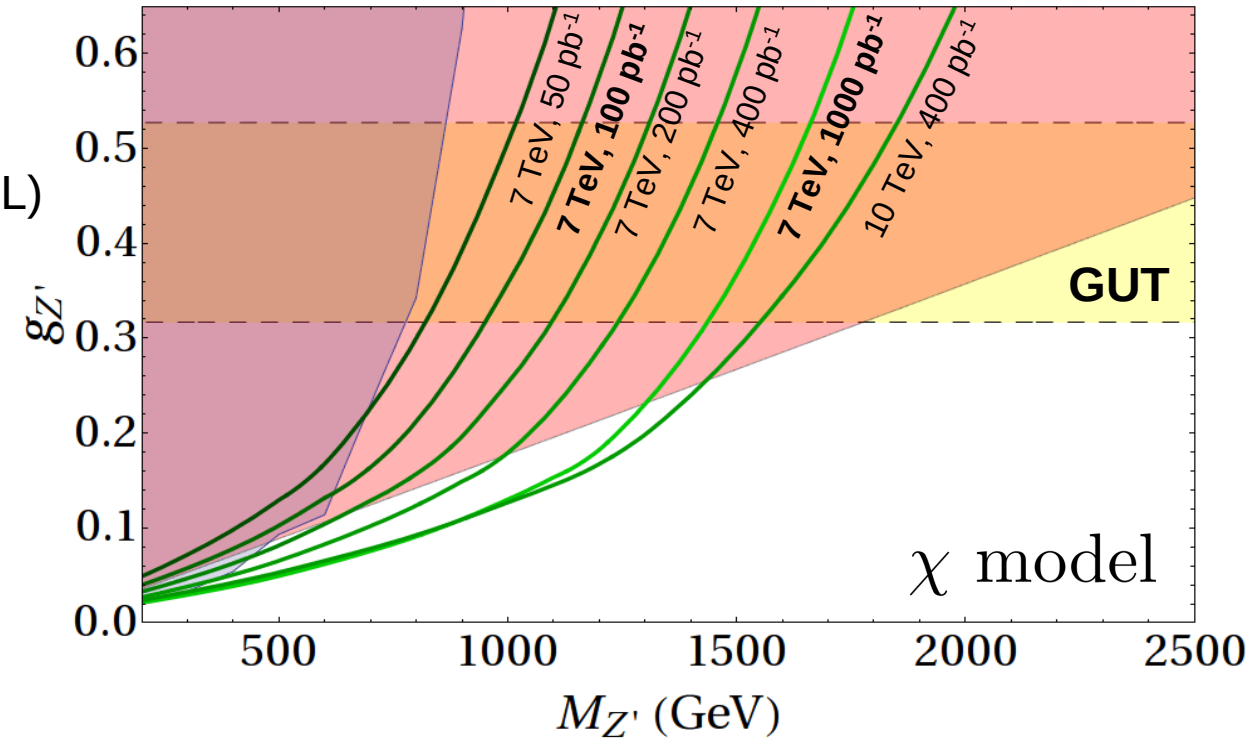
Present bounds and early LHC reach

If **flavor-universal** ➡ unique anomaly-free choice: ***X = (B-L)***

RED = excluded by EW precision tests (95%CL)

BLUE = excluded by Tevatron (95%CL)

GREEN = LHC discovery reach (5σ)



➢ at 7 TeV and L~ 100 pb^{-1} (2010), no discovery is possible

➢ at 7 TeV and L~1 fb^{-1} (2011), slightly better, **<u>but</u>** GUT region not accessible yet (needs, e.g., 10 TeV and *O*(1) fb^{-1})

Non-universal Z'

Cancellation of anomalies allows family-dependent charges:

$$X = \sum_{a=e,\mu,\tau} \frac{\lambda_a}{3}(B - 3L_a)$$

- GIM-like mechanism at work ➡ no tree-level FCNC in the charged lepton sector!
- Realistic masses & mixing for light neutrinos can be obtained via a suitable choice of Majorana mass matrix

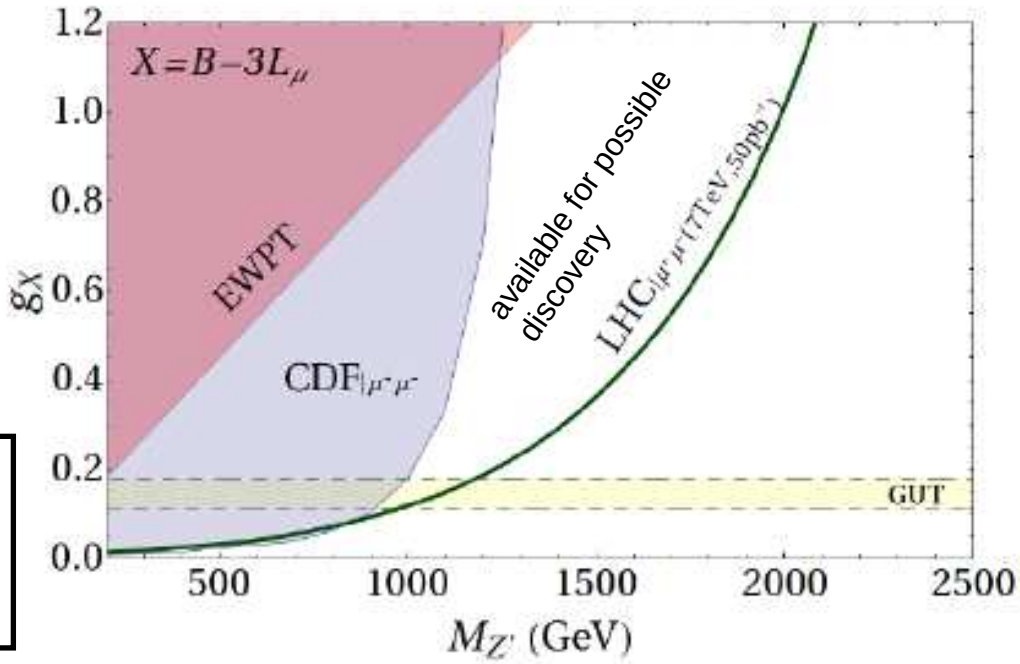
Example: $X = B - 3L_\mu$

muonphilic Z'

- weakly constrained by EWPT
- Tevatron reach limited to $M_{Z'} \leq 1$ TeV

➡ **accessible at LHC with only 50 pb^{-1} at 7 TeV !**

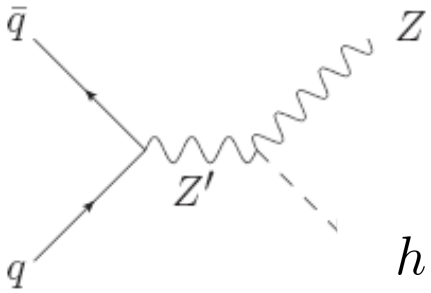
"Pure" B-3L$_\mu$: no Z-Z' mixing



Backup

Current work

Z-Z' mixing ➡ $Z' \to Z\,h$ decay ➡ look for it at the LHC



$$\Gamma(Z' \to Z\,h) \approx \frac{g_Y^2}{192\pi} M_{Z'}$$

$$(M_{Z'} >> m_h,\, M_Z)$$

$$Br(Z' \to Z\,h) \approx few\,\%$$

- Low-mass Higgs: $h \to b\,\bar{b}$ (?)
- Higher-mass Higgs: $h \to W\,W$

For $M_{Z'} < 1.5\,TeV$, signal/background is promising

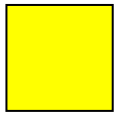
GUT-favored region of parameters

approximate unification at

$$M_U \approx 10^{16}\ \mathrm{GeV}$$

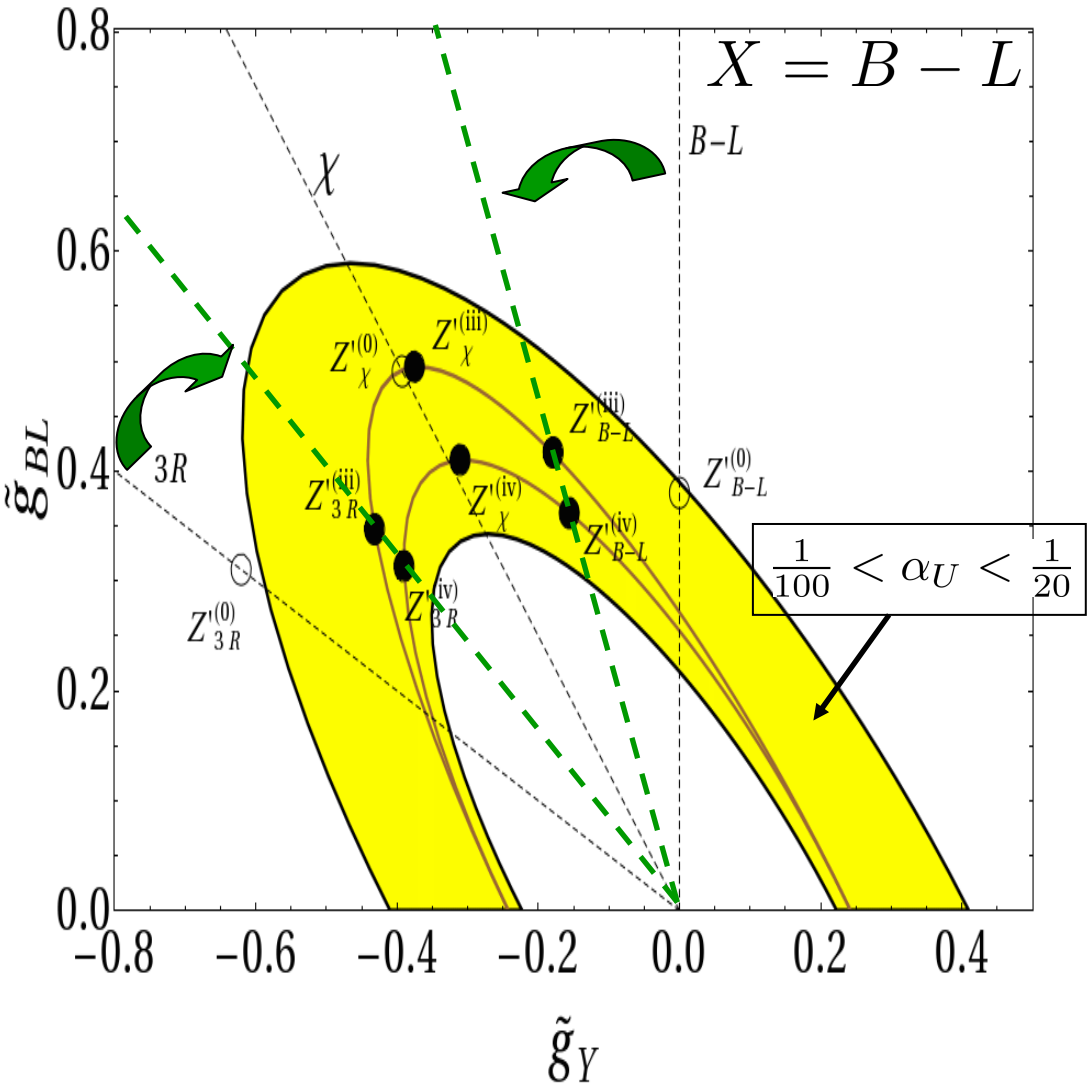
RGE running

$$M_U \to M_Z$$

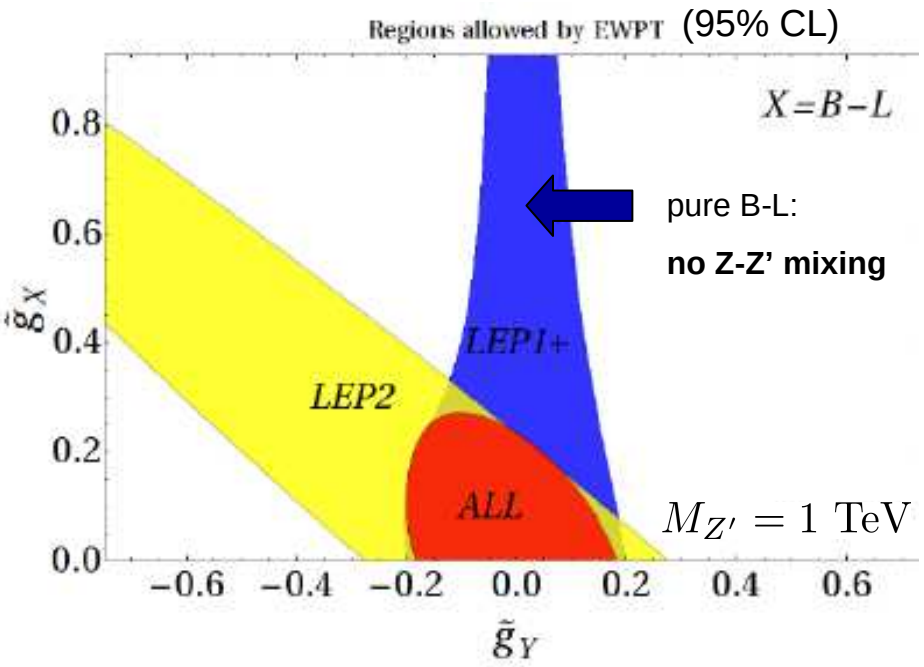


= preferred region of eff.couplings $(\widetilde{g}_Y, \widetilde{g}_{BL})$

- **points & lines** = specific models
- **kinetic mixing effects sizable !**

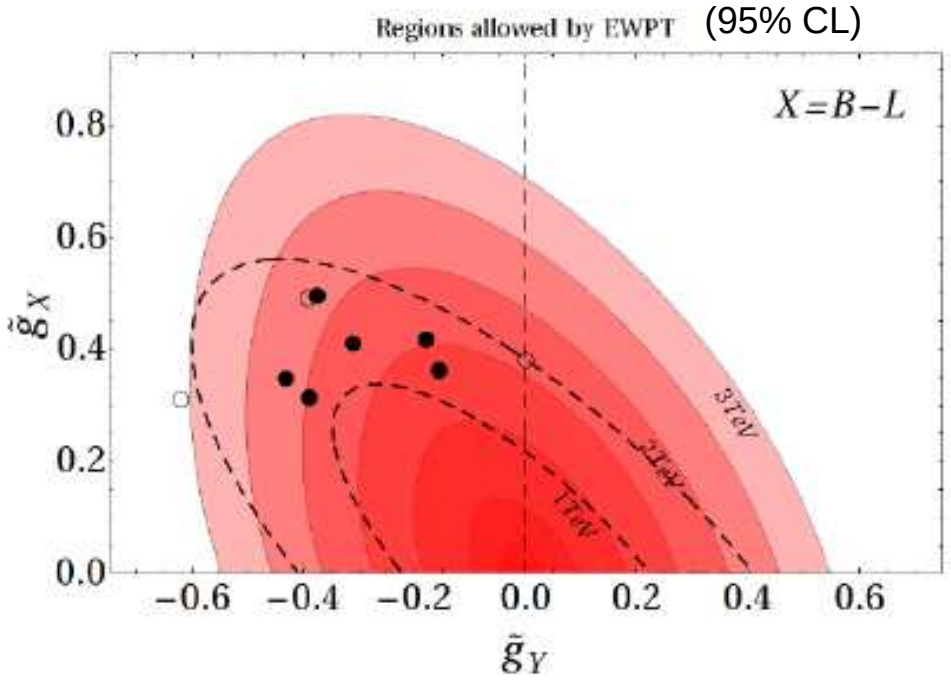


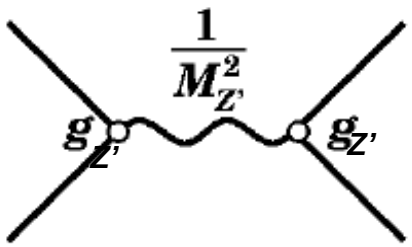
Bounds from Electroweak Precision Tests



pure B-L:

no Z-Z' mixing





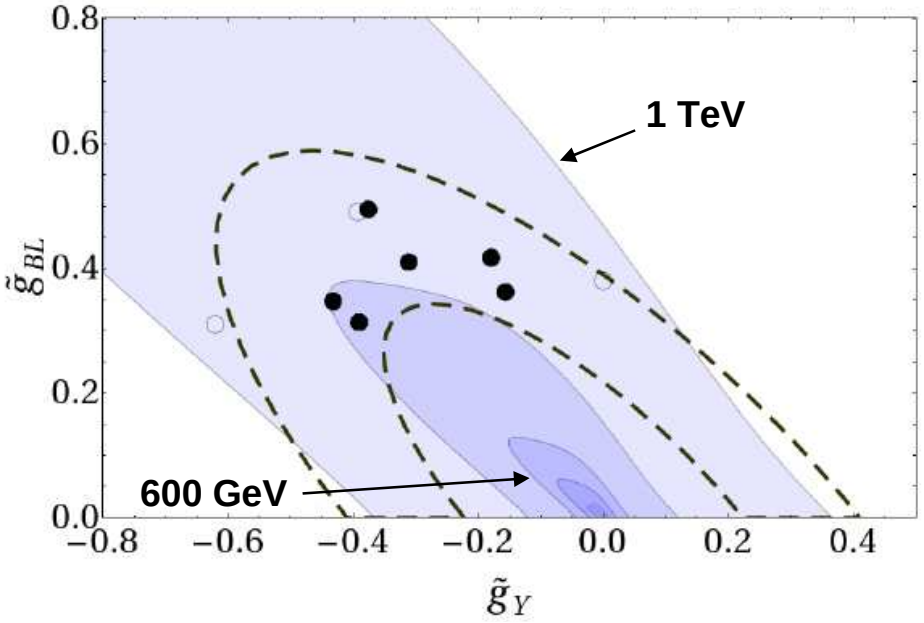
bounds on $\dfrac{g_{Z'}^2}{M_{Z'}^2}$

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

Bounds from direct searches at Tevatron

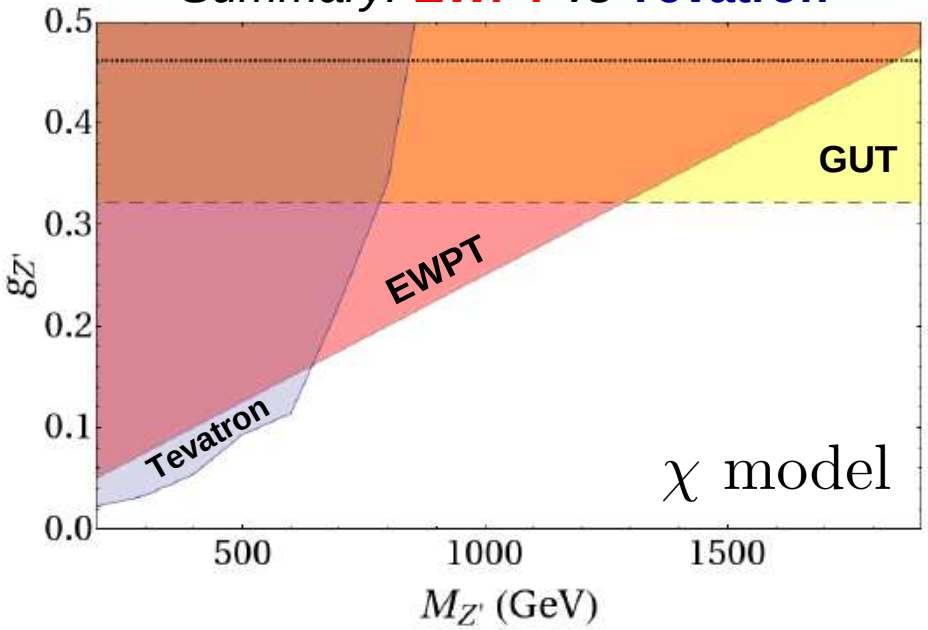
CDF/D0 dielectrons & dimuons, $2.3 - 3.6\ \mathrm{fb}^{-1}$: bounds on $\sigma(\bar{p}p \to Z')Br(Z' \to l^+l^-)$ $(l = e,\ \mu)$

PDF @ NLO



allowed regions (95% CL)
grow **faster** than linearly with $M_{Z'}$
due to PDF suppression at large *x*

Summary: **EWPT** *vs* **Tevatron**



Tevatron leading for $M_{Z'} < 700\ \mathrm{GeV}$,
EWPT stronger in the high mass range

(see also Contino, 0804.3195)

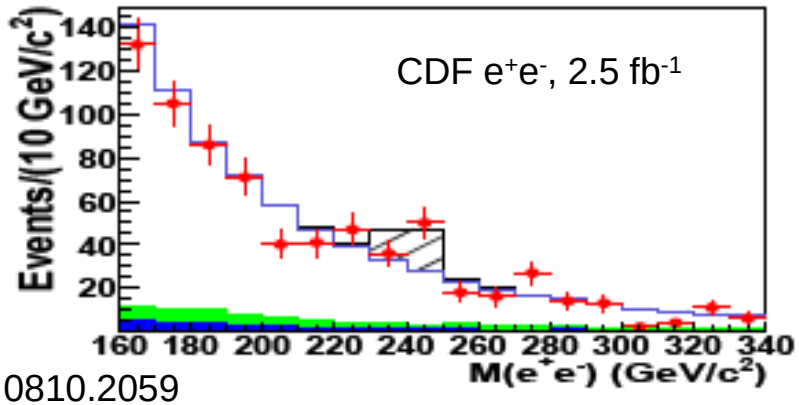
Non-universal Z'

Cancellation of anomalies allows family-dependent charges:

$$X = \sum_{a=e,\mu,\tau} \frac{\lambda_a}{3}(B - 3L_a)$$

- GIM-like mechanism at work ➡ no tree-level FCNC in the charged lepton sector!
- Realistic masses & mixing for light neutrinos can be obtained via a suitable choice of Majorana mass matrix

Example 2: $X = B - 3L_e$



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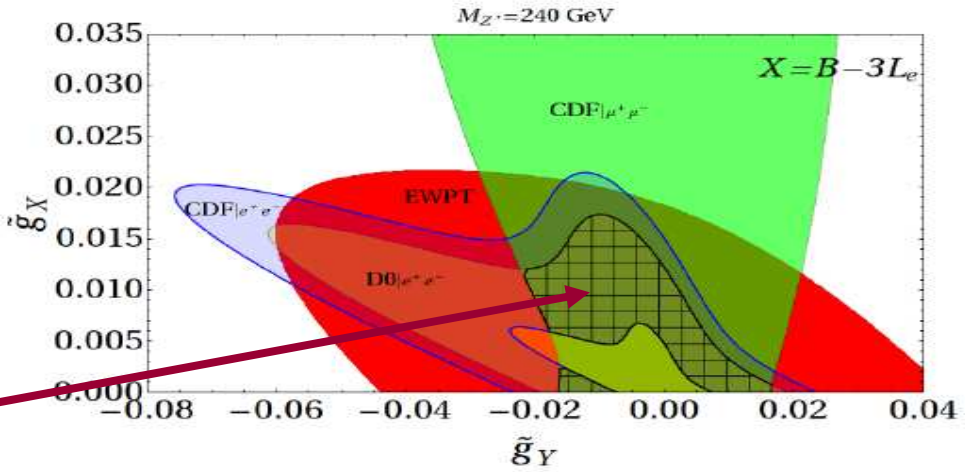
can explain 2.5σ 'excess' observed by CDF at 240 GeV in the dielectron channel, but not confirmed by dimuons



Region allowed by ALL data

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 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 :

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

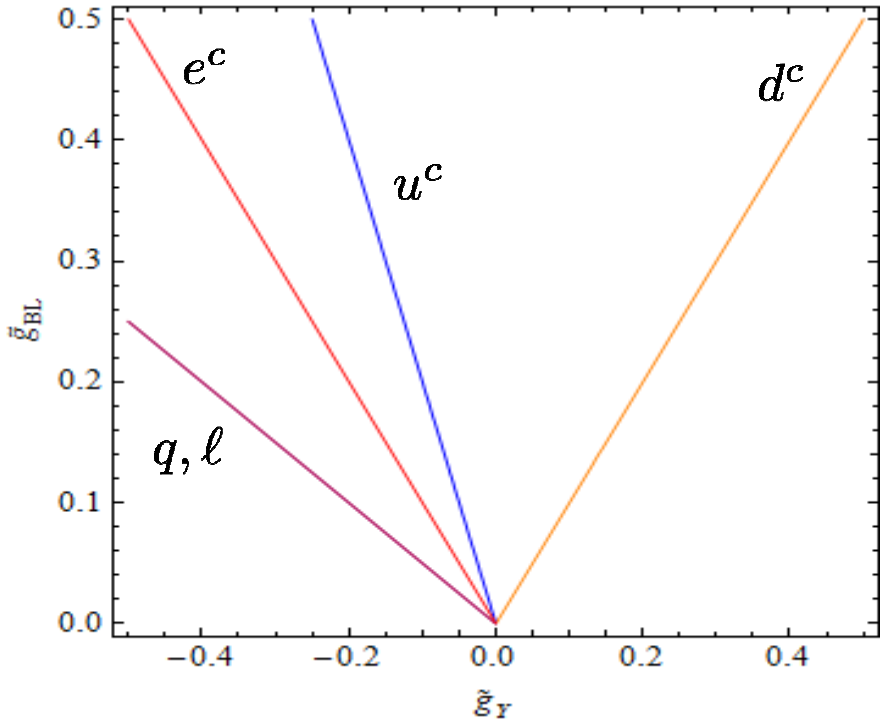
But U_L , U_R do not mix sectors with different X charges:

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

Z' charges

$$X = B - L$$

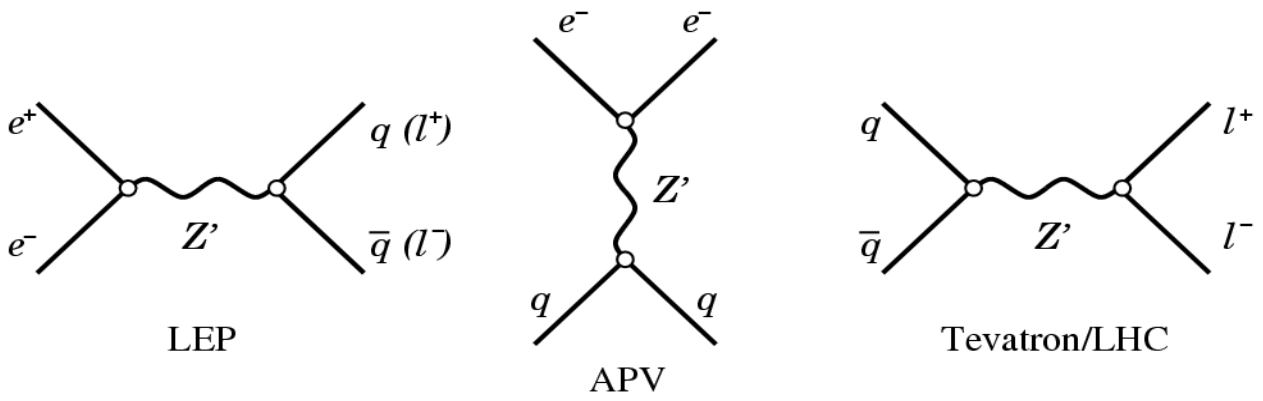
	$q = (u, d)$	u^c	d^c	$\ell = (\nu, e)$	ν^c	e^c
T_{3L}	$(+\frac{1}{2}, -\frac{1}{2})$	0	0	$(+\frac{1}{2}, -\frac{1}{2})$	0	0
Y	$+\frac{1}{6}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{2}$	0	$+1$
$B-L$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	$+1$	$+1$
$Q_{Z'}$	$\frac{1}{6}\widetilde{g}_Y + \frac{1}{3}\widetilde{g}_{BL}$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



Matter fields least coupled to the *Z'* for

$$\widetilde{g}_Y \approx -\widetilde{g}_{BL}$$

Direct vs indirect bounds

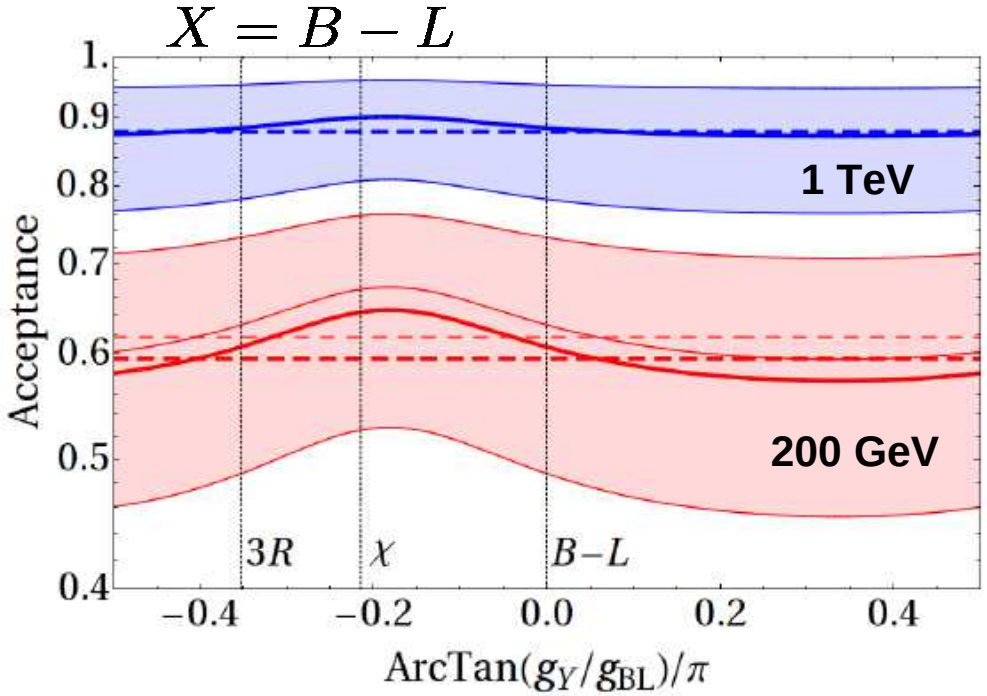


…the parameters involved are the same!

bounds from **EWPT** **cannot be neglected** when assessing the discovery potential of direct searches

Early LHC

- LHC in 2010/2011: CoM energy 7 TeV, luminosity $\leq 1\,\mathrm{fb}^{-1}$
- main background : SM Drell-Yan



- **NLO calculation** (MSTW08 PDFs)
- acceptance similar for signal and background
- model-dependence < 10 %

➡ assumed acceptance depending **only on invariant mass** of dilepton pair

signal

background

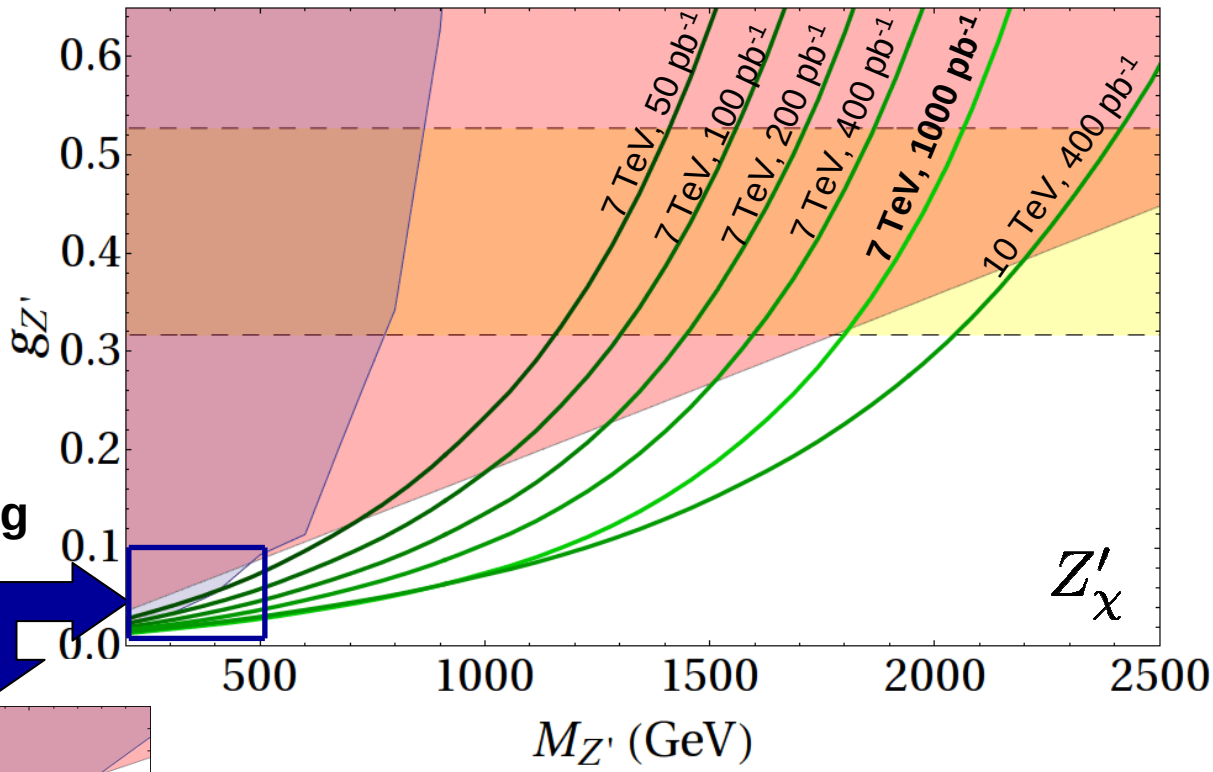
$p_{T\ell} > 20\ (\mathbf{80})$ GeV

- $\Gamma_{Z'}/M_{Z'} \leq 2\%$, not far from initial experimental resolution

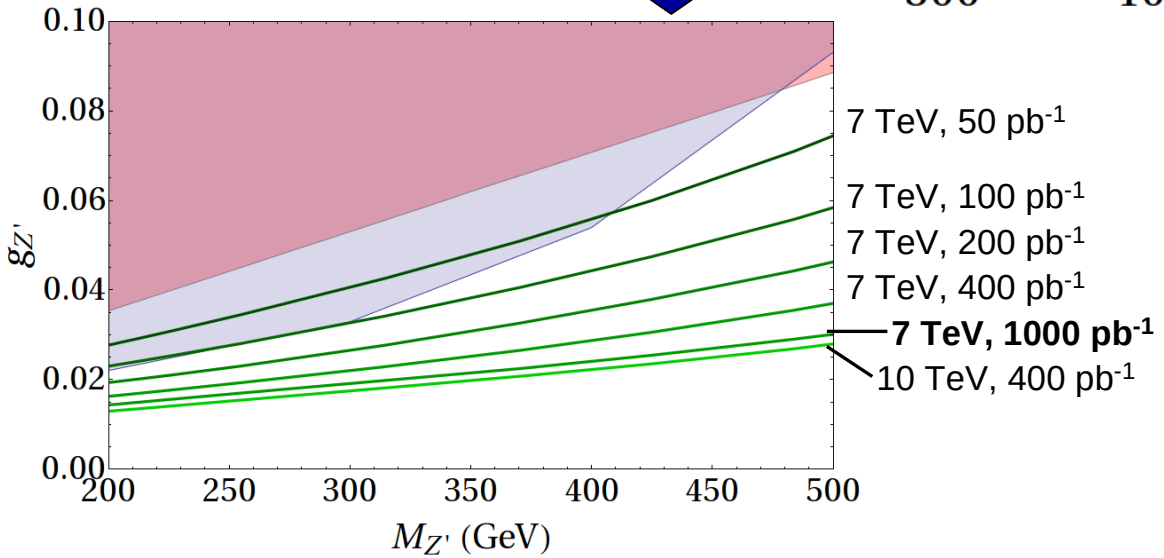
Compare signal & background in $\pm 1.5\%$ interval (simplifying assumption) around lepton inv. mass ➡ '5σ' discovery limits

Early LHC: exclusion (95% CL)

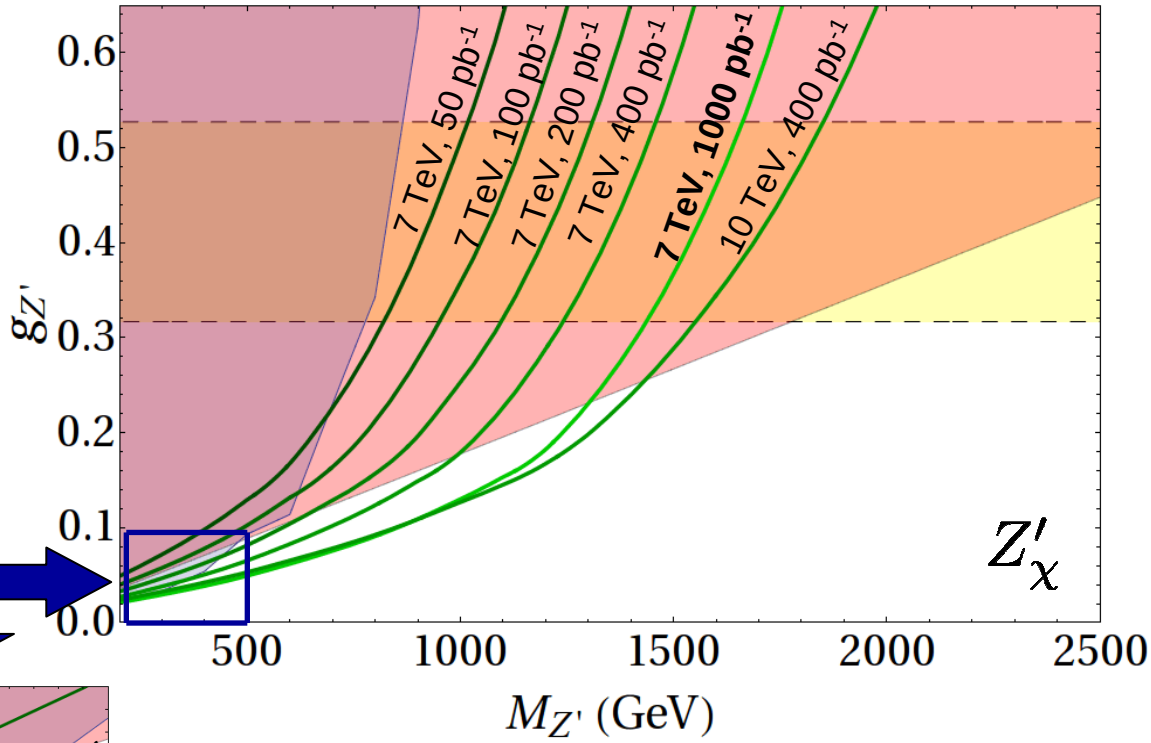
If no excess is observed, **strong bounds** already in first runs (better than EWPT and Tevatron up to 1.5 TeV with 400 pb^{-1} @ 7 TeV);
but GUT region out of reach at 7 TeV and 1 fb^{-1}



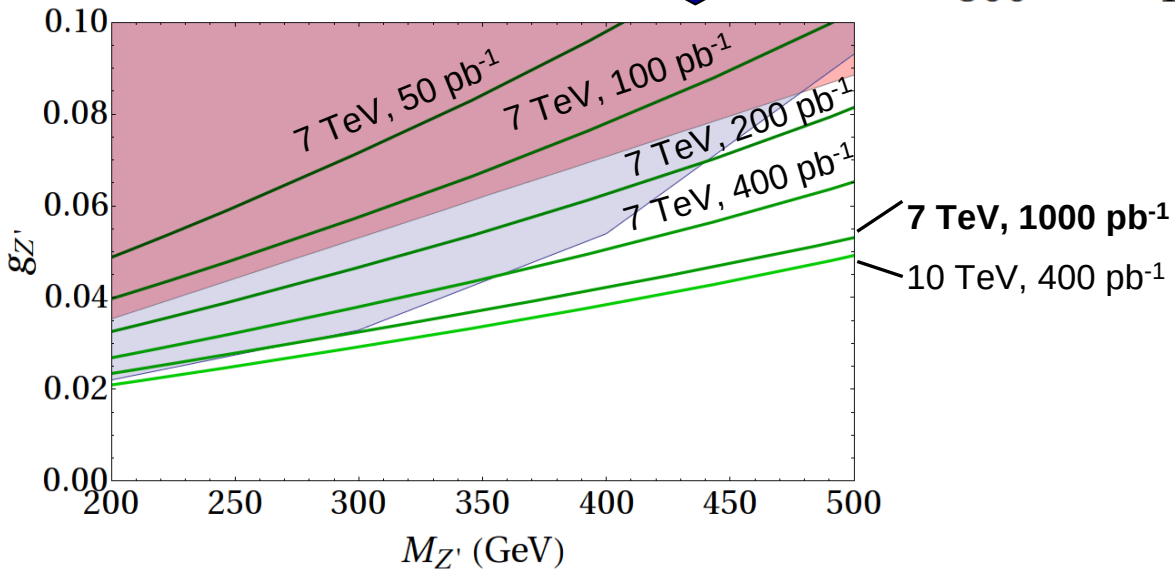
Low mass & small coupling region



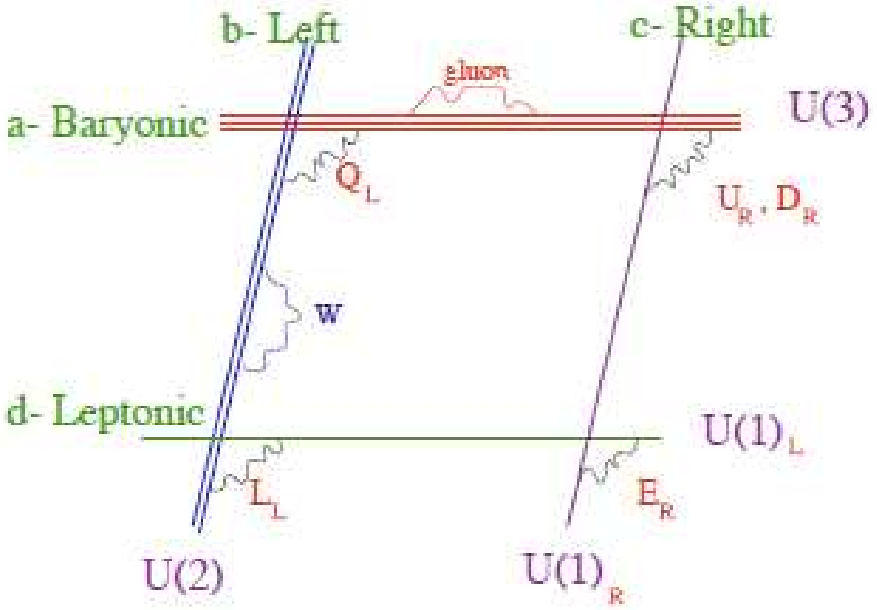
Early LHC: discovery



Low mass & small coupling region



Z' from D-brane models



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

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

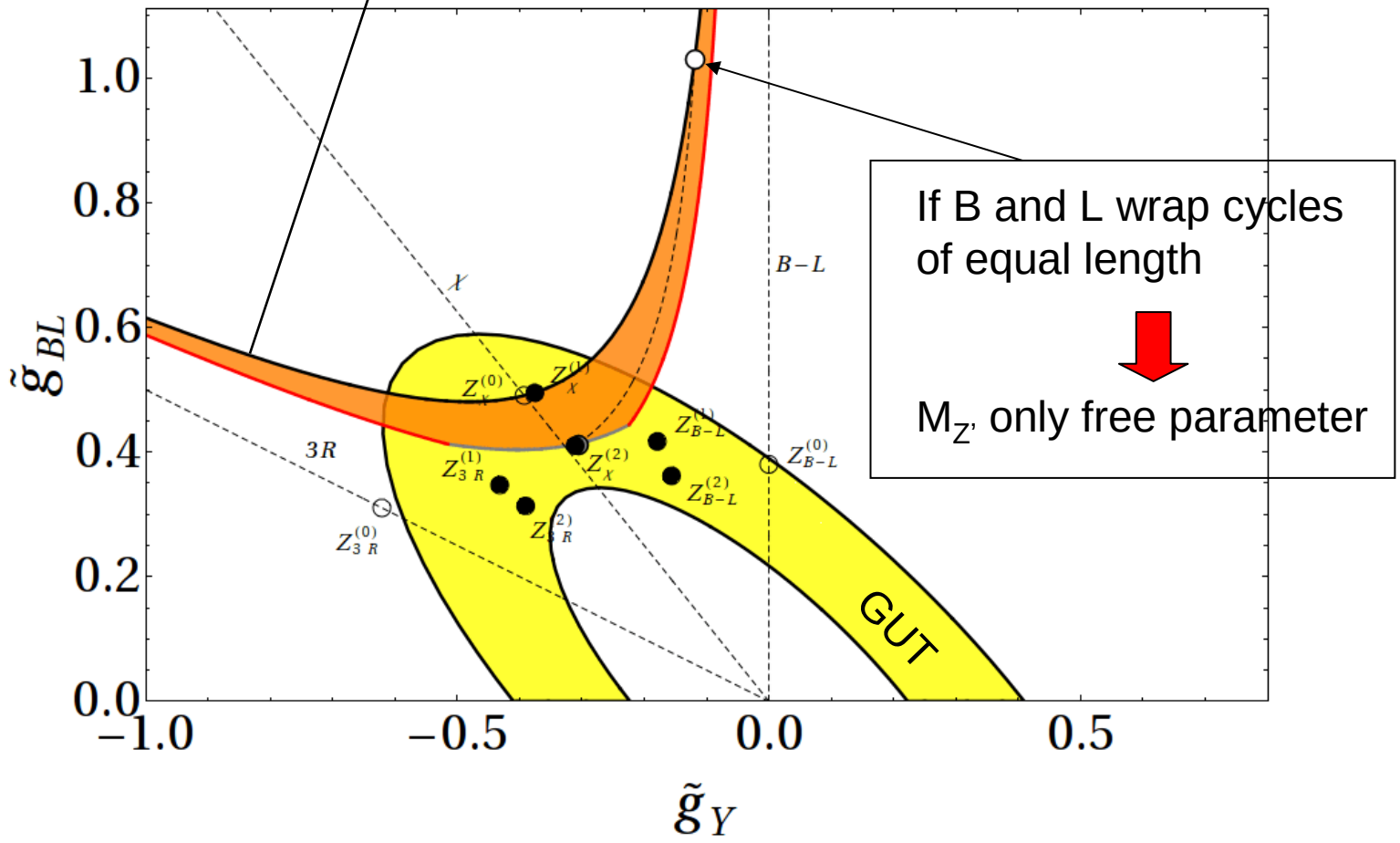
see, e.g., Ghilencea et al, hep-ph/0205083

- several U(1) factors naturally arise
- anomalous U(1)s get string-scale mass
- Y and (possibly) B-L remain light compared to string scale

Z' from D-branes

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

additional constraint ➡ **only 2 indep. parameters!**



If B and L wrap cycles of equal length

➡

$M_{Z'}$ only free parameter

Orange band = RGE running from M_{string} to the weak scale