(Some) *Z'* and *W'* models facing current LHC searches

Ennio Salvioni

CERN / University of Padua

mainly based on work in collaboration with C.Grojean, A.Strumia, R.Torre, G.Villadoro, F.Zwirner

thanks to R.Torre *for help,* ***and to*** J.Serra *for discussions*

March 27, 2012

Introduction

- Heavy spin-1 particles appear almost everywhere in New Physics models
- ***Very*** different motivations, properties, and signatures

  ➡ need to make strong choices
- Leave out colored states altogether
- I will cover some examples of

$Z' \longleftrightarrow$ spin-1, color-less, electrically neutral

$W' \longleftrightarrow$ spin-1, color-less, electric charge ± 1

- No signals so far in ~few fb^{-1} :
  - Present bounds on some classes of resonances
  - Discuss (briefly) other theoretically motivated cases for which bounds do not apply.

Plan

1. A “canonical” example: *Z’* in dileptons

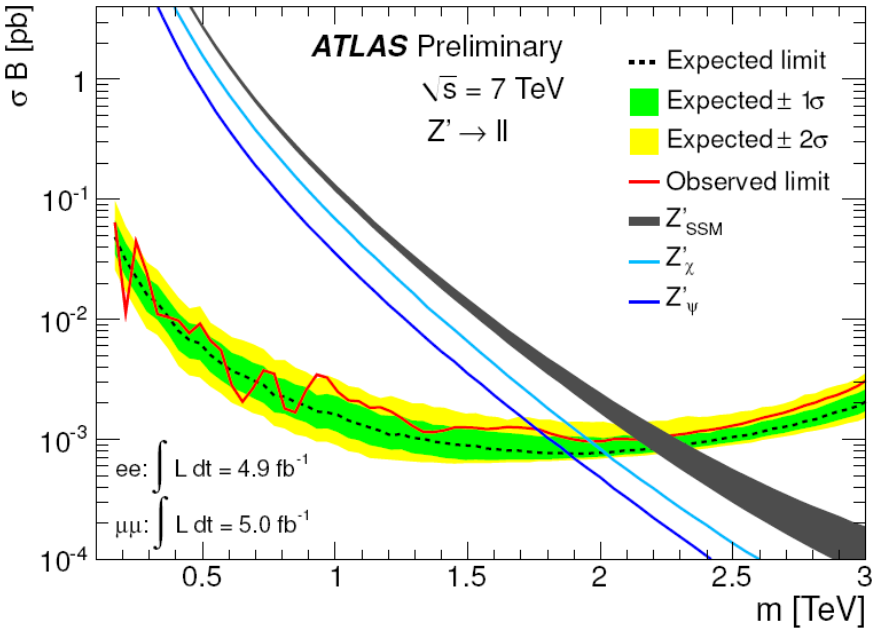
2. Strongly coupled resonances: what signals to expect?

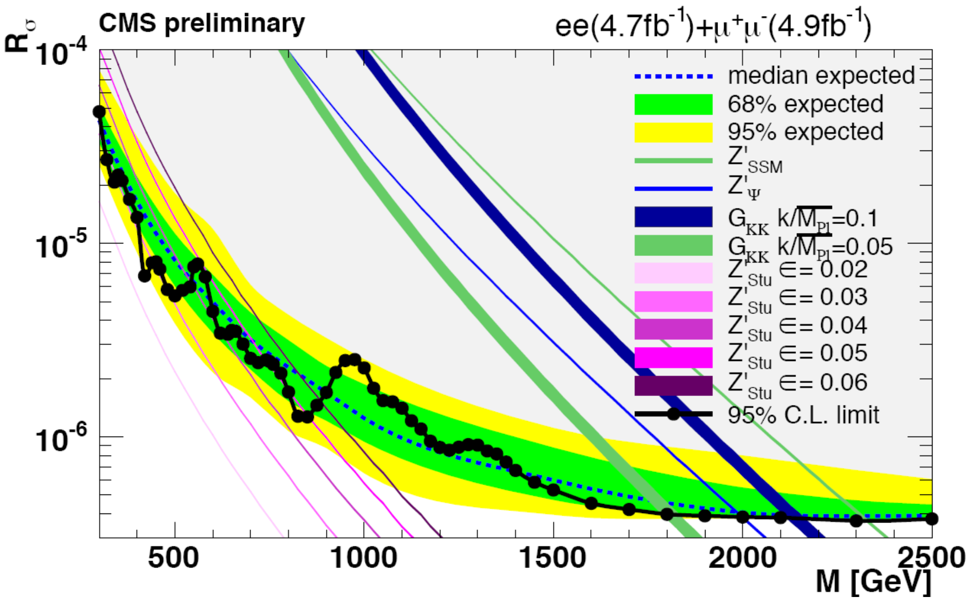
3. A “composite” *W’* at LHC 7-8: signals in dijets

1. *Z’* in dileptons

Z' in dileptons: where do we stand?

- **ATLAS** and **CMS** have collected ~ 5/fb each in 2011. No hint of a *Z'* has shown up ⟶ strong bounds on $\sigma(pp \to Z' \to ee\,,\mu\mu)$





ATLAS-CONF-2012-007 **CMS-EXO-11-019**

How do the LHC bounds compare to the strong LEP bounds,

and to Grand Unification constraints?

Minimal *Z'*: parameterization

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \longleftrightarrow Z'$$

- Appear e.g. in GUTs (including LR models), string models with D-branes, some Little Higgs theories…
- Theory is anomaly free with SM fermions + 3 RH neutrinos
- Coupling of *Z'* to fermions reads $(f = u_L, d_L, e_L, \ldots)$

$$\mathcal{L} = g_Z \sum_f Q_{Z'}(f) \overline{f} \gamma^\mu f \, Z'_\mu$$

Appelquist et al., hep-ph/0212073

ES, Villadoro, Zwirner 0909.1320

where

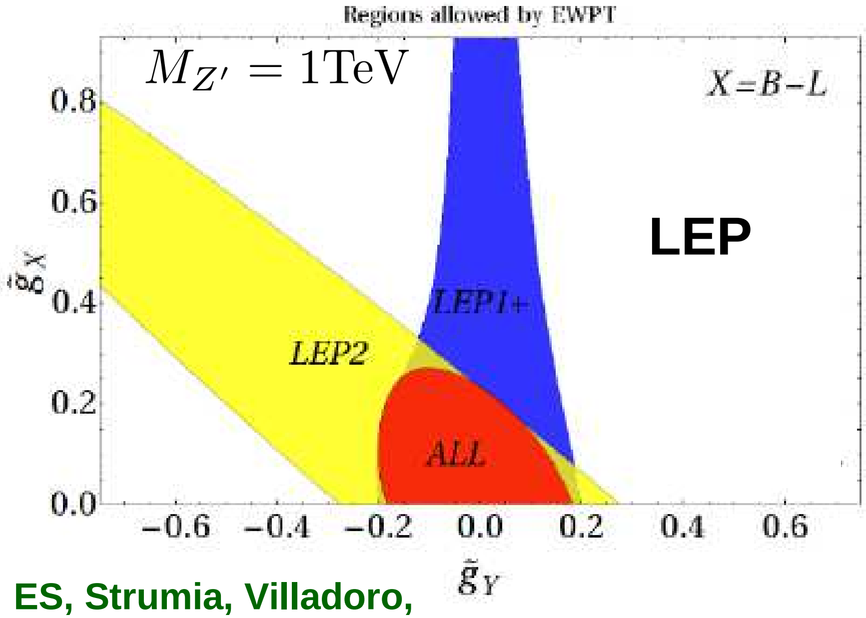
$$Q_{Z'} \simeq \tilde{g}_Y Y + \tilde{g}_{BL}(B-L)$$

mixing between *Y* and (*B* – *L*)

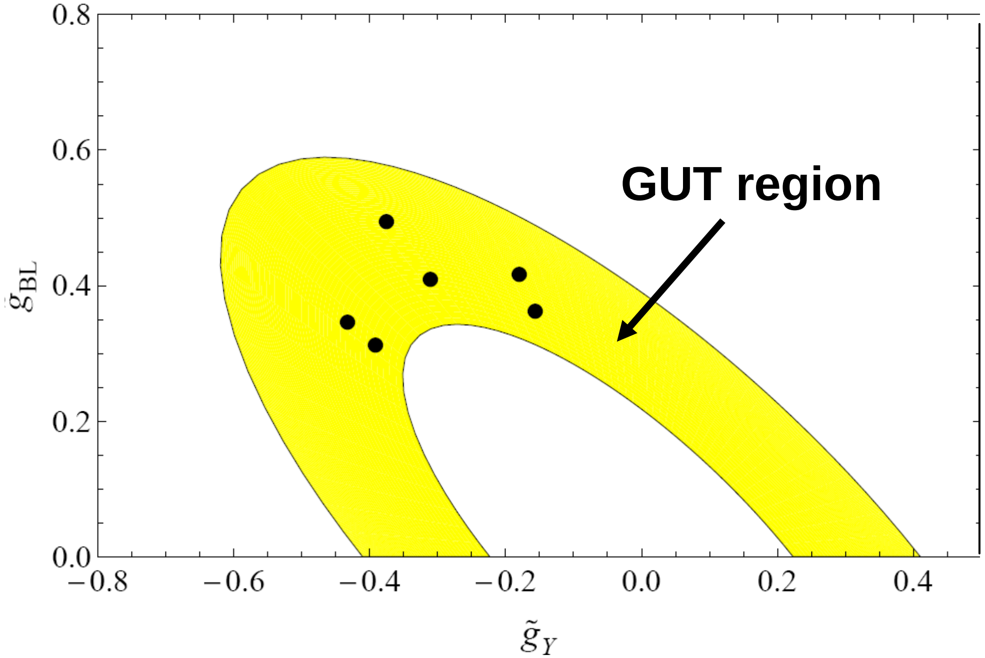
gauge coupling of (*B* – *L*)

- So **only 3 relevant parameters:** $M_{Z'}$, $\widetilde{g}_Y$, $\widetilde{g}_{BL}$

Minimal *Z'*: where do we stand?



ES, Strumia, Villadoro, Zwirner 0911.1450



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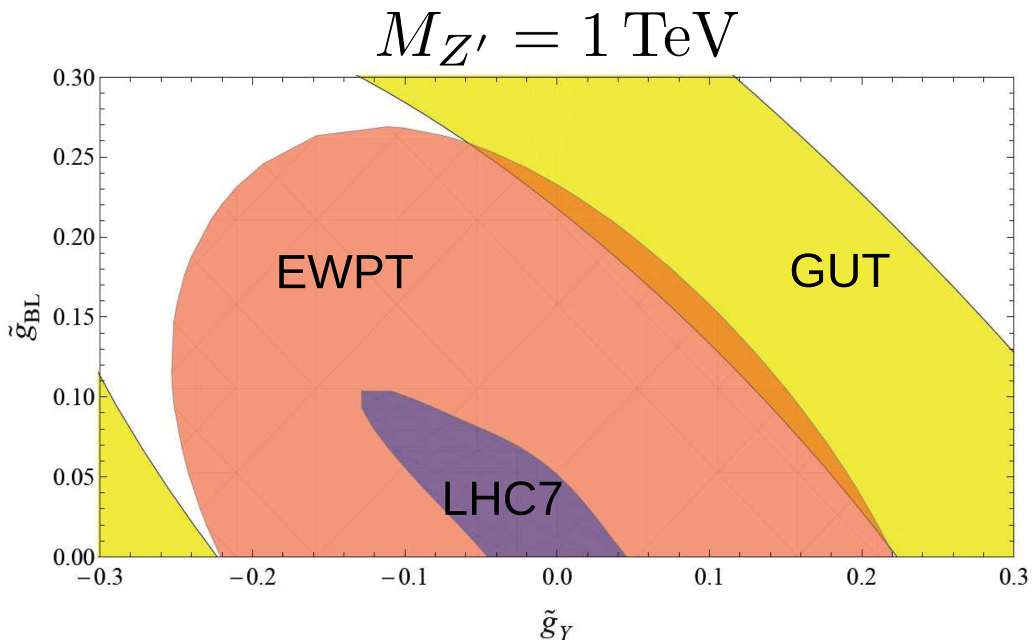
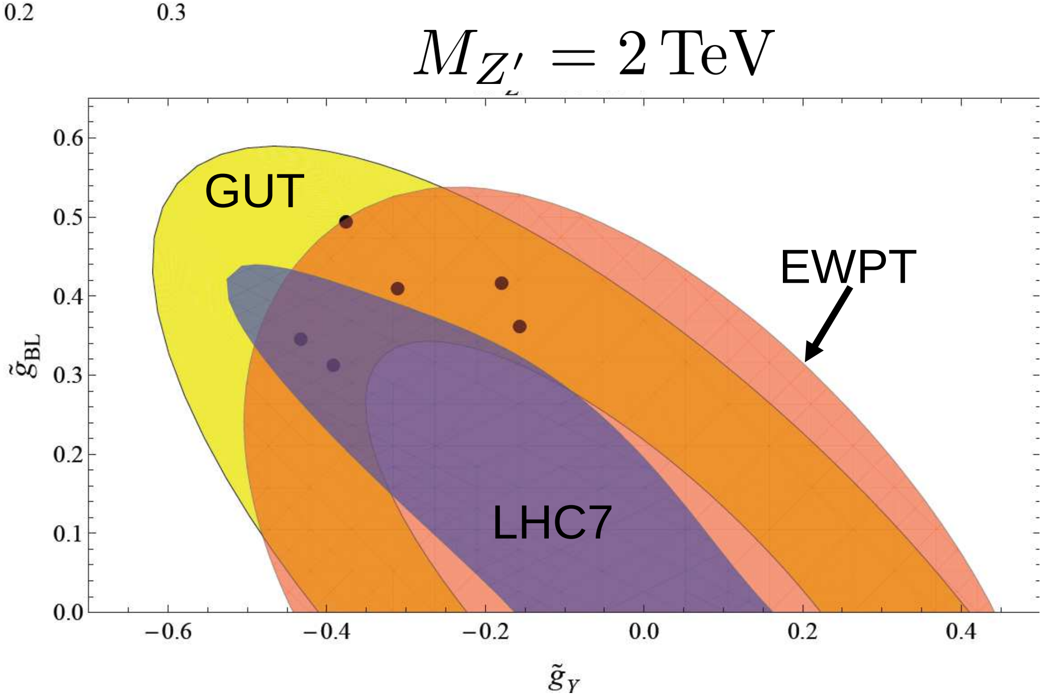
and to Grand Unification constraints?

Minimal *Z'*: where do we stand? (2)



- LHC has gone much beyond EWPT for $M_{Z'} \lesssim 2\,\mathrm{TeV}$



- The exploration of regions allowed by EW data ***and*** GUT - compatible (orange) has started

2. Strongly coupled resonances

Resonances: weak *vs* strong

- Minimal *Z'* are an example of resonance associated to a **weakly coupled** extension of the SM.
  They would give rise to experimentally "easy" signals, such as

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

- However, there is no compelling reason that requires such *Z'* to live at the TeV scale. **They could be much heavier**.

- Things are different in **strongly coupled** extensions of the SM, where a new strong interaction is responsible for breaking the EW symmetry.
  There, a ***natural*** EWSB implies that resonances of the new strong sector (including *Z'* s and *W'* s) **need to be around the TeV scale**.

- However, such resonances are more "elusive" at LHC: typical signals are "challenging" ones, such as

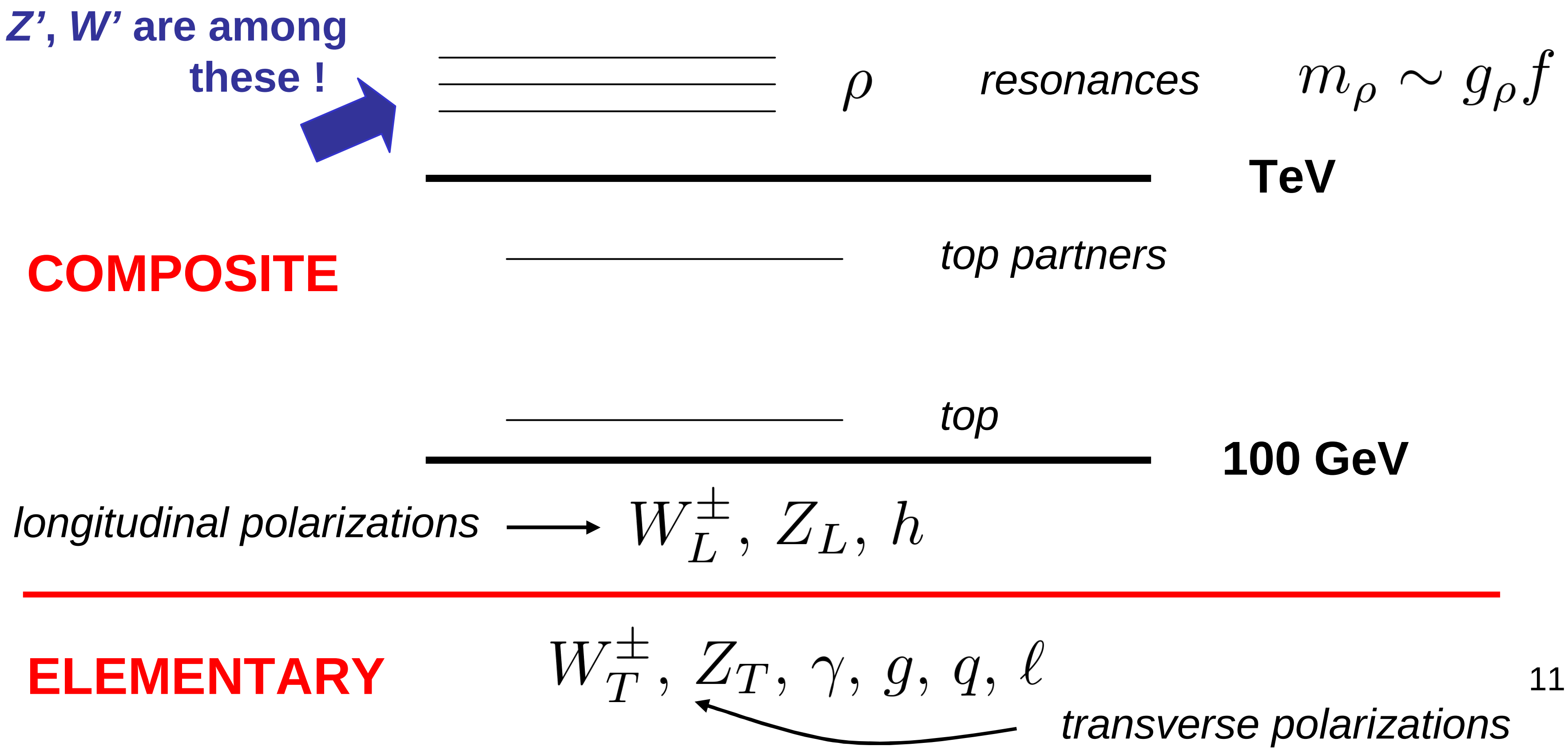
$$Z' \to W^+W^- \quad \text{or} \quad Z' \to Zh$$

Strongly coupled resonances

An appealing possibility:

see Azatov's talk (this morning) for more details

- A new strong interaction at TeV scale breaks EW symmetry, and the Higgs is a ***composite state*** of the new force.
  The Higgs is naturally lighter than ~ TeV because it is a pseudo-Goldstone boson *(like the pions in QCD)*.



Strongly coupled resonances (2)

- Given this picture, it is intuitively clear that composite $Z',\, W' \in \rho$ will have a **large coupling to the other composites**, including:

$$W_L^{\pm},\, Z_L,\, h,\, t$$

whereas couplings to elementary states (leptons, light quarks) are suppressed $\longrightarrow$ Drell–Yan production suppressed, and **typical signals** are

see e.g. Agashe et al., 0709.0007 and 0810.1497

$$Z' \to W^+W^-,\, Zh,\, t\bar{t} \qquad\qquad W' \to WZ,\, Wh,\, t\bar{b}$$

- Furthermore, EW precision data tell us that

$$\left(\hat{S} \sim \frac{m_W^2}{m_\rho^2} \lesssim 10^{-3}\right)$$

$$m_\rho \gtrsim 2\,\mathrm{TeV}$$

$\Longrightarrow$ **need to wait for LHC14**

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$\Rightarrow$ **need to wait for LHC14**

but: expect light ($m_{t'} \lesssim 1\,\mathrm{TeV}$) *fermionic* resonances

see ATLAS and CMS searches, later in this session

3. A “composite” *W*’ at LHC7-8

A "weakly constrained" resonance

- An example of "compositeness-inspired" resonance that could give signals at LHC7-8: an **isospin-singlet**

$$W' \in (\mathbf{1},\mathbf{1})_1$$ hypercharge

- Can write a gauge-invariant phenomenological Lagrangian for the *W'* only, without a companion *Z'* ➡ avoid the stronger bounds on *Z'* from EW data and colliders

- Because of gauge invariance, such resonance can be naturally "**leptophobic**" : dominant coupling $W'\,\overline{u}_R\,d_R$

- We will write a general Lagrangian (very weak assumptions)

Phenomenological Lagrangian

Grojean, ES, Torre, 1103.2761

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_V + \mathcal{L}_{V-SM}$$

$$\begin{aligned}\mathcal{L}_V &= D_\mu V_\nu^- D^\nu V^{+\mu} - D_\mu V_\nu^- D^\mu V^{+\nu} + M^2 V^{+\mu} V_\mu^- \\ &\quad - i g' c_B B^{\mu\nu} V_\mu^+ V_\nu^- ,\end{aligned}$$

$$\mathcal{L}_{V-SM} = V^{+\mu}\left(i g_H H^\dagger (D_\mu \tilde{H}) + \frac{g_q}{\sqrt{2}} (V_R)_{ij} \overline{u_R^i} \gamma_\mu d_R^j \right) + \text{h.c.}$$

no leptons here!

- Parameters: *W'* mass + couplings $g_q,\ g_H,\ c_B$
- RH quark mixing matrix $V_R = \mathbf{1}_3$ (very weak flavor bounds)

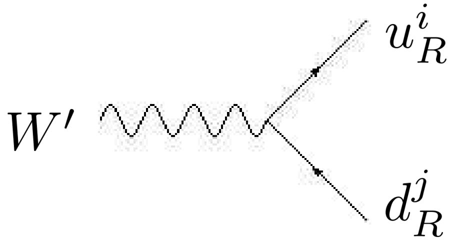
- g_H induces *W*-*W'* mixing ➡ mass eigenstates

$$\begin{pmatrix} W^+ \\ W'^+ \end{pmatrix} = \begin{pmatrix} c_{\hat\theta} & s_{\hat\theta} \\ -s_{\hat\theta} & c_{\hat\theta} \end{pmatrix} \begin{pmatrix} \hat{W}^+ \\ V^+ \end{pmatrix}$$

***W-W'* mixing angle** $\quad \hat\theta \sim -g_H g \left(\frac{v^2}{M^2}\right)$

Dijets

- Dominant coupling is to RH quarks:



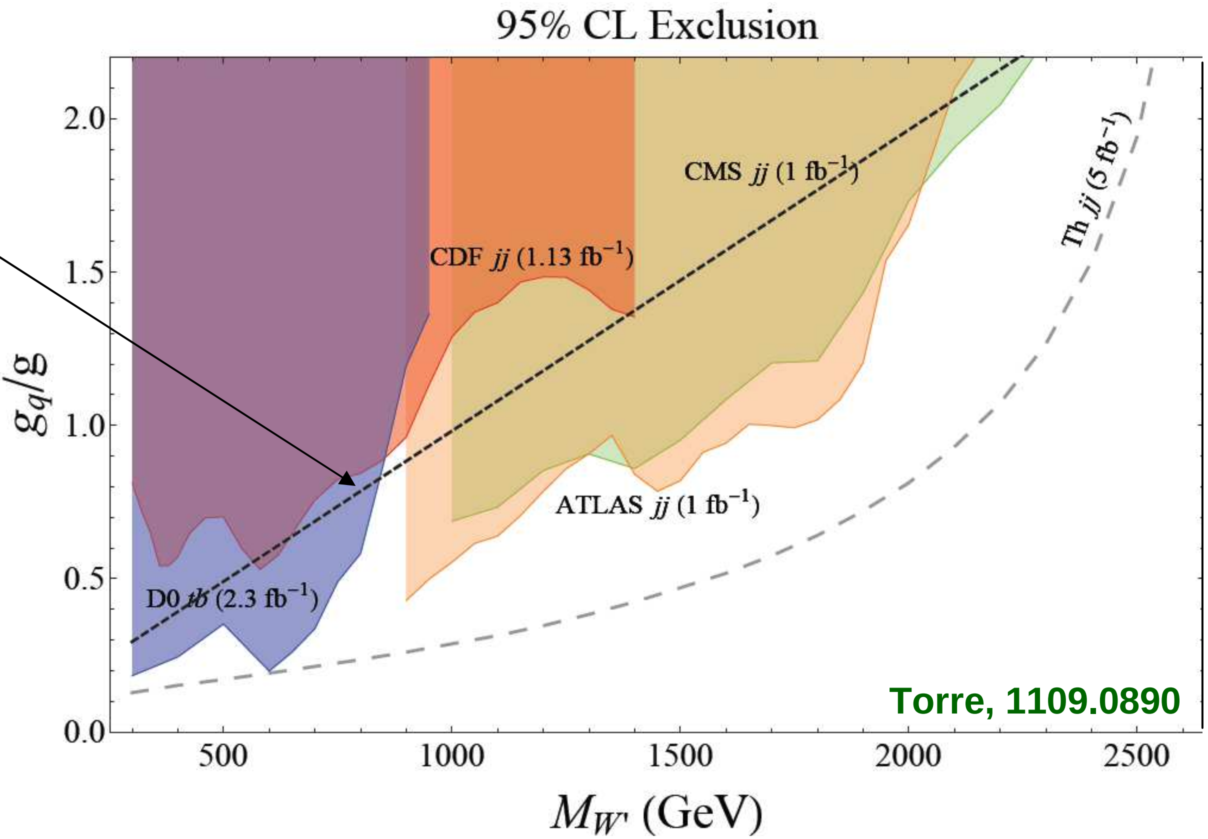
dijet signals

- Current status:

bound from dijet angular distributions (quark compositeness), CMS 2.2/fb

Domènech et al, 1201.6510

(searches for compositeness more important for strongly coupled resonances)



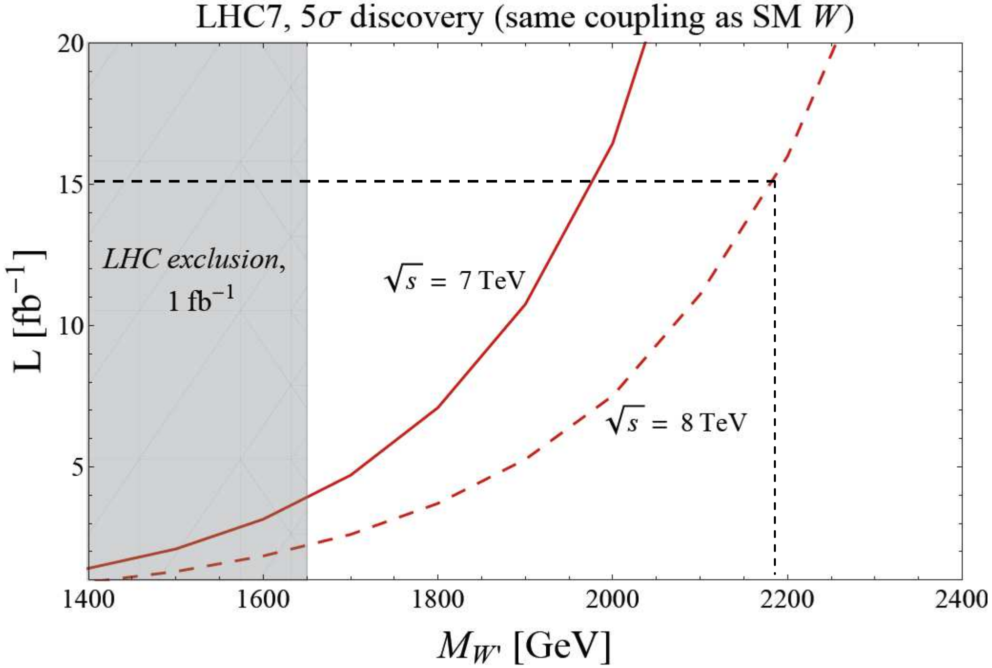
Torre, 1109.0890

- ATLAS & CMS searches for dijet resonances with 1/fb already placed strong bounds

ATLAS, 1108.6311
CMS, 1107.4771

Dijets (2)

- With 15/fb at 8 TeV, discovery possible up to $M_{W'} \sim 2.2\,\mathrm{TeV}$ for coupling $g_q = g \sim 0.65$
- However, exclusion from 5/fb at 7 TeV goes up to $\simeq 2\,\mathrm{TeV}$



- Phenomenology similar to a recent proposal to realize MFV in composite Higgs: this requires some chiralities of **light quarks to be largely composite**
  - ➡ sizable coupling of composite resonances to light quarks
  - ➡ **signals in dijets**
- RH quark compositeness less constrained than LH

Redi and Weiler, 1106.6357

Summary

- LHC7 data collected in 2011 already place strong bounds on some classes of *Z'* and *W'*.
  As an example, for **minimal *Z'*** exploration of GUT-compatible region has started.

- **Strongly coupled resonances** have suppressed production cross sections, and give rise to more challenging experimental signatures such as $Z' \to W^+W^-,\ Zh,\ t\bar{t}$
  EW data generically force $m_\rho \gtrsim 2\,\mathrm{TeV}$

  ➡ essentially an LHC14 business

- However, motivated constructions exist where coupling of composite resonances to light quarks is sizable. We discussed a ***W'*** as an example of this kind:

  ➡ signals in **dijets** could be seen even at LHC7-8.

Backup

Strongly coupled resonances at LHC14

- **Katz et al.** made a study of $Z' \to W^+W^-,\ Zh$ using jet substructure techniques: channels

$$Z' \to W^+W^- \to \ell\nu\, jj$$
$$Z' \to Zh \to \ell\ell\, bb$$
$$Z' \to Zh \to \nu\nu\, bb$$

1010.5253

- Model-independent discovery limits

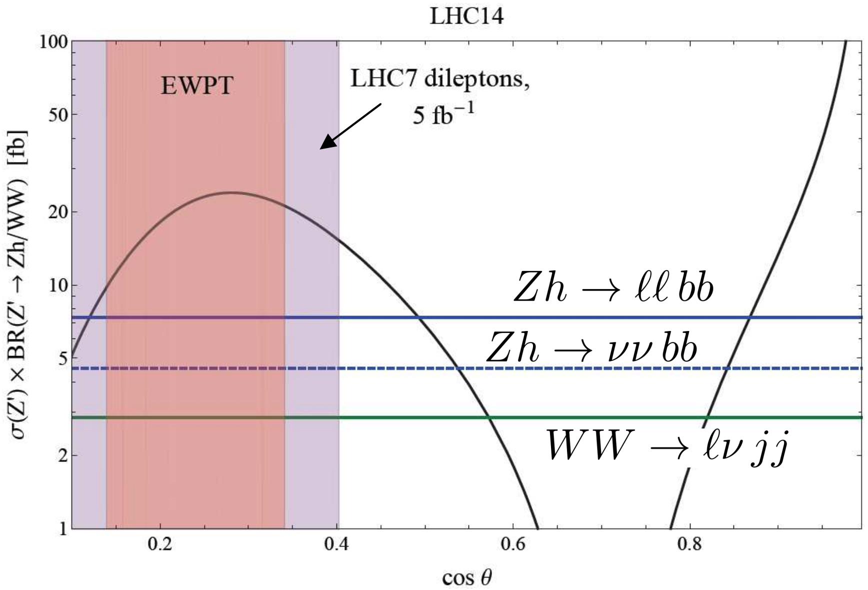
Luminosity	$m_{Z'} = 1$ TeV	$m_{Z'} = 2$ TeV	$m_{Z'} = 3$ TeV
$\mathcal{L} = 30$ fb^{-1}	58.3 fb	9.02 fb	2.70 fb
$\mathcal{L} = 100$ fb^{-1}	31.9 fb	4.94 fb	1.48 fb
$\mathcal{L} = 300$ fb^{-1}	18.4 fb	2.85 fb	0.85 fb
$S/B = 1$	501.5 fb	15.44 fb	1.36 fb

TABLE IV: $\sigma(Z') \times BR(Z' \to W^+W^-)$ *required for discovery or* $S/B = 1$ *in the* $(l\nu)(q\bar{q}')$ *mode.*

- Implications for specific models?

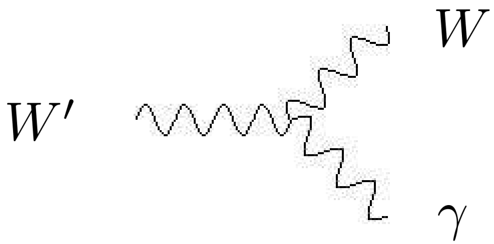
  example, *Littlest Higgs*

$$M_{Z'} = 2\,\mathrm{TeV}$$



Djouadi and ES, work in progress

The decay $W' \to W\gamma$



$\sim \hat{\theta}(c_B + 1)$

- $\hat{\theta}$ is *W-W'* mixing angle
- c_B appears in $\Delta\mathcal{L} = -ig' c_B B^{\mu\nu} V_\mu^+ V_\nu^-$

- Theoretically interesting because expected to be very small if *W'* is an elementary gauge boson (e.g., LR models…), but can be visible at LHC if *W'* is a **composite** $(c_B \neq -1)$

study of $W' \to W\gamma \to \ell\,\nu\,\gamma$ at LHC7 for $M_{W'} \sim 1\,\mathrm{TeV}$ (compatible with all pre-LHC bounds)

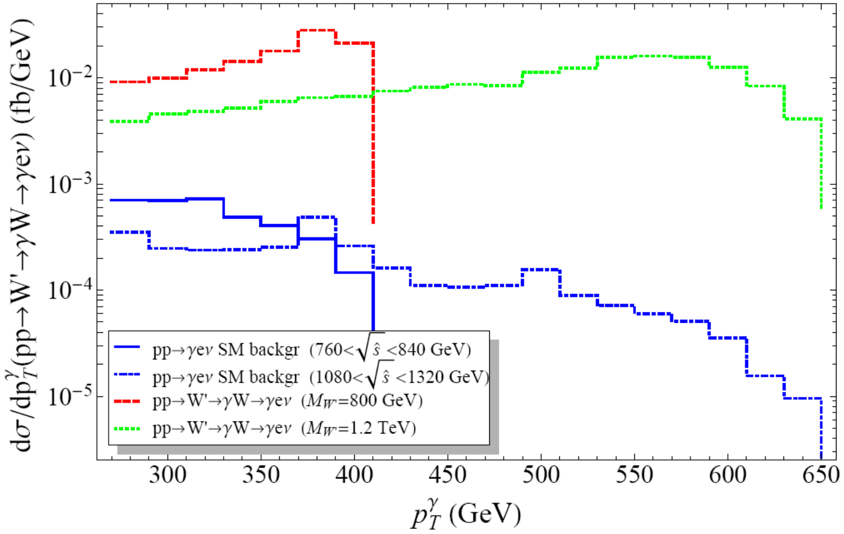
- Cuts:

$$p_T^\gamma > 250\,\mathrm{GeV},\ p_T^e > 50\,\mathrm{GeV},\ \not{E}_T > 50\,\mathrm{GeV},$$

$$|\eta_{e,\gamma}| < 2.5\,,\ |M(W\gamma) - M_{W'}| < 0.05\,M_{W'}$$

- Main background is irreducible $W\gamma$

photon p_T



Grojean, ES, Torre, 1103.2761

Iso-singlet *W'* : motivations

- *W'* $\leftrightarrow$ spin-1, color-singlet, unit electric charge state
- Require linear and renormalizable coupling to quarks: only 2 irreducible reprs. $(SU(3)_c,\, SU(2)_L)_Y$

Del Aguila, De Blas, Perez-Victoria, 1005.3998

iso-singlet $(\mathbf{1},\mathbf{1})_1$

Left-right models; Little Higgs with custodial symmetry

no associated neutral *Z'*

➡ can write phenomenological Lagrangian for *W'* only

➡ **constraints are weaker**

iso-triplet $(\mathbf{1},\mathbf{3})_0$

Some Little Higgs models; extra dimensions

W' and *Z'* are (almost) degenerate in mass

➡ strong bounds on *Z'* from EWPT and LHC/Tevatron also apply to *W'*

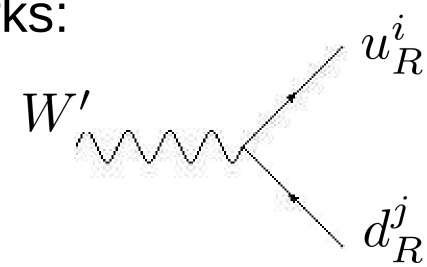
➡ needs to be heavy, or weakly coupled

➡ **we study an iso-singlet *W'***

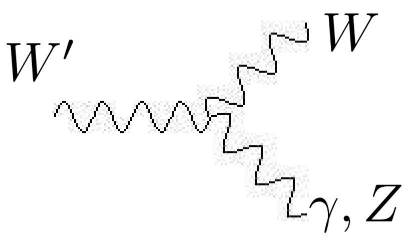
Couplings of *W'* to SM fields: summary

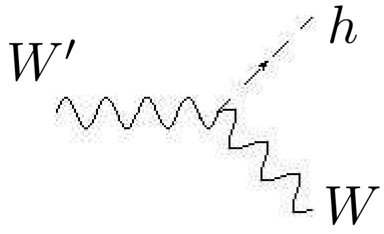
In mass eigenstate basis for both fermions and vectors, ***W' couples:***

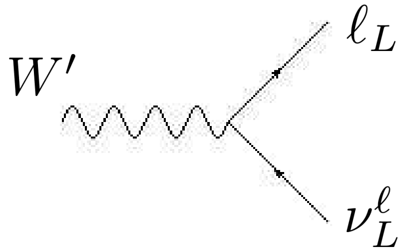
- dominantly to RH quarks:



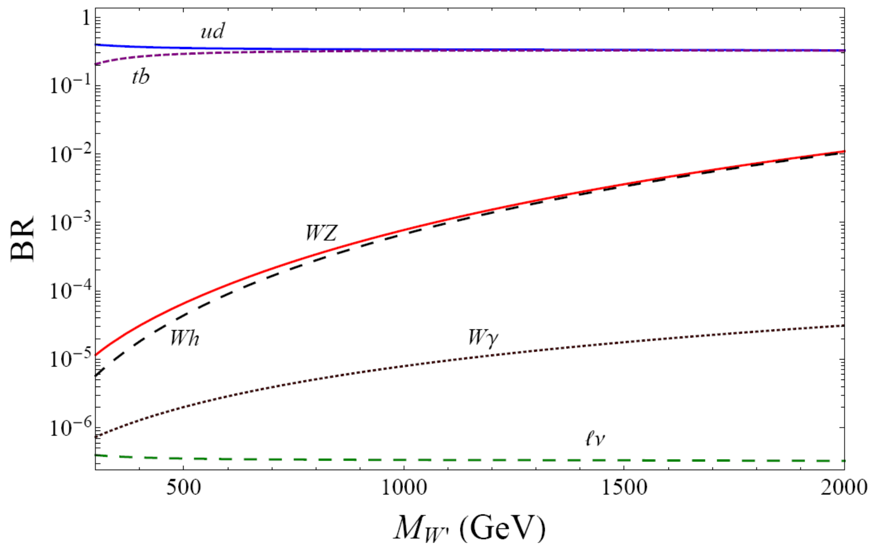
- to $W\gamma, WZ, Wh$, LH leptons, all proportional to $\hat{\theta}$:







$$\boxed{g_q = g,\ \hat{\theta} = 10^{-3},\ c_B = -3}$$



$W' \to W\gamma$ decay

$$\Gamma(W' \to W\gamma) = \frac{e^2}{96\pi}\underbrace{(c_B+1)^2\hat{\theta}^2}\frac{M_{W'}^2}{M_W^2}M_{W'}$$

$W' \to W\gamma$ is controlled by $|c_B+1|\hat{\theta}$

What are the bounds on these 2 parameters?

$W' \to W\gamma$ decay

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What are the bounds on these 2 parameters?

---

c_B **is not significantly constrained by current data.** $\left(\Delta\mathcal{L} = -ig' c_B B^{\mu\nu} V_\mu^+ V_\nu^-\right)$

From a theory point of view, **what to expect for** c_B **in extensions of the SM?**

General result: gyromagnetic ratio of any elementary particle of mass *M* (of any spin) coupled to photon must be $g = 2$ at tree level, if perturbative unitarity holds up to energies $E \gg M/e$. **Ferrara, Porrati, Telegdi, PRD 46 (1992)**

So if *W'* is an elementary gauge boson, expect $g_{W'} = 1 - c_B \approx 2 \to c_B \approx -1$

$W' \to W\gamma$ extremely suppressed, and likely out of the LHC reach.

But if *W'* is composite, $c_B \neq -1$ **can happen!** Only need to check that

cutoff is sufficiently larger than *W'* mass: from $BB \to VV$ scattering, find

$$\Lambda \geq 5M \qquad \text{for} \qquad |c_B| \leq 10\,.$$

Bounds on $\hat{\theta}$

- *W-W'* mixing ➡ contribution to *T*

$$\hat{T}_V = -\frac{\Delta^4}{M^2 m^2_{\hat{W}}} \qquad \left(m^2_{\hat{W}} = g^2 v^2/4\right)$$

Del Aguila, De Blas, Perez-Victoria, 1005.3998

Lower bound on m_h from LEP2 ➡ $\left|\frac{g_H}{M}\right| < 0.11\,\mathrm{TeV}^{-1}$

or equivalently

$$\boxed{\begin{array}{ll} |\hat{\theta}| < 1 \times 10^{-3}, & M_{W'} = 800\,\mathrm{GeV} \\ |\hat{\theta}| < 5 \times 10^{-4}, & M_{W'} = 2\,\mathrm{TeV} \end{array}}$$

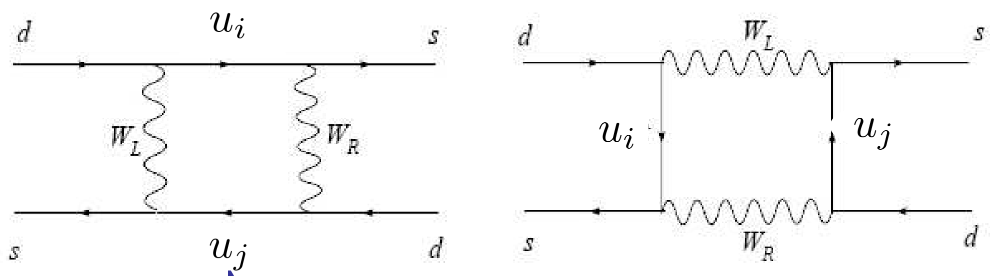
- $u \to d,s$ semileptonic transitions: e.g., $0^+ \to 0^+$ β decays, $\pi \to e\nu$, $K \to \pi l\nu$, etc. Find:

Buras, Gemmler, Isidori, 1007.1993; Langacker, Sankar, PRD 40 (1989)

$-1.6 \times 10^{-3} < g_q \hat{\theta} V_R^{ud} < 1.7 \times 10^{-3}$	small CP phases in V_R
$\sqrt{\sum_j \lvert V_R^{uj}\rvert^2} \times \lvert g_q \hat{\theta}\rvert < 10^{-2 \div -1}$	maximal CP phases

Indirect bounds on g_q

Main constraints come from $\Delta F = 2$ processes, in particular K_L-K_S mixing:



amplitude $\propto m_i m_j$ strongest limits are on *c* and *t* exchange,
i.e. on the combinations

$$|V_R^{cs,ts}||V_R^{cd,td}|$$

4 special forms are very weakly constrained:

$$\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix},\quad \begin{pmatrix}1&0&0\\0&0&1\\0&1&0\end{pmatrix},\quad \begin{pmatrix}0&1&0\\1&0&0\\0&0&1\end{pmatrix},\quad \begin{pmatrix}0&1&0\\0&0&1\\1&0&0\end{pmatrix}$$

We choose $|V_R| = \mathbf{1}_3$, for which the bound is **Langacker, Sankar, PRD 40 (1989)**

$$M_{W'} > (g_q/g)\,300\,\mathrm{GeV}$$

(90% CL, and avoiding extreme fine tuning).
This form also automatically satisfies constraints from $B^0_{d,s} - \overline{B}^0_{d,s}$ mixing.

Bounds on c_B from TGC

Assuming C and P conservation ($V_0 = \gamma, Z$)

$$\mathcal{L}_{\rm eff}^{WWV_0} = i g_{WWV_0} \Big[g_1^{V_0} V_0^{\mu} (W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) + k_{V_0} W^+_{\mu} W^-_{\nu} V_0^{\mu\nu} + \frac{\lambda_{V_0}}{m_W^2} V_0^{\mu\nu} W_{\nu}^{+\rho} W^-_{\rho\mu} \Big]$$

$SU(2)_L \times U(1)_Y$ gauge invariance ➡ 3 independent parameters:

$$g_1^Z - 1 = -\sin^2\hat{\theta}\,(1 + \tan^2\theta_w)$$

$$k_\gamma - 1 = -\sin^2\hat{\theta}\,(1 + c_B)$$

$$\lambda_\gamma = 0$$

Combine LEP2 measurement of TGC and bounds on $\hat{\theta}$ discussed previously

⬇

constrain c_B

However, $\hat{\theta}$ must be very small, so in practice c_B is **only constrained very weakly**. For example:

$$|\hat{\theta}| \sim 10^{-1} \quad \Rightarrow \quad -11 < c_B < 20$$

(very large compared to bounds!)

Gyromagnetic ratio of the *W'*

$$\mathcal{L}^{W'W'\gamma} = ie\left[A^{\mu}\left(W'^{-}_{\mu\nu}W'^{+\,\nu} - W'^{+}_{\mu\nu}W'^{-\,\nu}\right) + k'_{\gamma}W'^{+}_{\mu}W'^{-}_{\nu}F^{\mu\nu}\right]$$

$$k'_{\gamma} = 1 - \cos^2\hat{\theta}\,(1 + c_B)$$

Magnetic dipole moment of the *W'*: $\mu_{W'} = \frac{e}{2M_{W'}}\underbrace{(1 + k'_{\gamma})}_{g_{W'}}$

gyromagnetic ratio

So find

$$g_{W'} = 2 - \cos^2\hat{\theta}\,(1 + c_B)$$

If the *W'* is a fundamental gauge boson then $g_{W'} = 2$ at tree level

$$\Longrightarrow \quad c_B = -1$$