A weakly constrained *W'* at the early LHC

Ennio Salvioni

CERN / **University of Padua**

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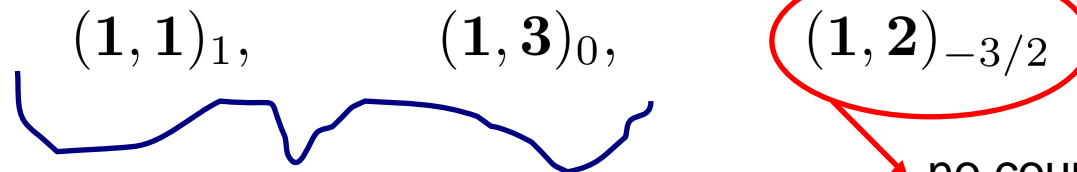## IST, Lisbon, June 1st, 2011

Introduction: effective approach

- W' ↔ spin-1, color-singlet, unit electric charge state
- Require linear and renormalizable coupling to SM fields:
  only 3 irreducible reprs. $(SU(3)_c, SU(2)_L)_Y$:   **Del Aguila, De Blas,**
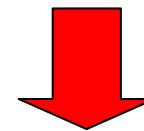 **Perez-Victoria, 1005.3998**

$$(\mathbf{1}, \mathbf{1})_1, \qquad (\mathbf{1}, \mathbf{3})_0, \qquad (\mathbf{1}, \mathbf{2})_{-3/2}$$

no coupling to quarks, only to leptons (invariance under $U(1)_Y$)

most commonly encountered in the literature, e.g.

- $(\mathbf{1},\mathbf{1})_1$: LR models, Little Higgs w/ custodial symmetry
- $(\mathbf{1},\mathbf{3})_0$: some Little Higgs models, extra dimensions

production at hadron colliders strongly suppressed

➡ **we discuss the $(\mathbf{1}, \mathbf{1})_1$ case**

(iso-singlet W')

Iso-singlet *W'* : motivations

- If the *W'* is part of an $SU(2)_L$ triplet, *W'* and *Z'* are degenerate in mass

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

  ➡ needs to be heavy, or weakly coupled

- For the $(\mathbf{1},\mathbf{1})_1$ instead, can write effective theory for *W'* only, without a *Z'* ➡ **constraints are weaker**

- If RH neutrinos are absent, or heavier than *W'*, then dominant decays are only hadronic: $W' \rightarrow jj, tb$
  a study of this 'pessimistic' scenario was missing
  (for recent studies of the case $M_N < M_{W'}$, see e.g.
  Schmaltz, Spethmann 1011.5918; Nemevsek *et al.*, 1103.1627)

  next talk

Effective Lagrangian

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

$$\mathcal{L}_V = D_\mu V_\nu^- D^\nu V^{+\mu} - D_\mu V_\nu^- D^\mu V^{+\nu} + \tilde{M}^2 V^{+\mu} V_\mu^-$$

$$+ \frac{g_4^2}{2} |H|^2 V^{+\mu} V_\mu^- - i g' c_B B^{\mu\nu} V_\mu^+ V_\nu^- ,$$

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

- no RH neutrinos ($\leftrightarrow$ heavier than *W'*); mass eigenst. basis for fermions

- parameters: *W'* mass + couplings g_q, g_H, c_B (g_4 irrelevant to us)

  + RH quark mixing matrix V_R , which does **not** need to be unitary

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

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

$$\Delta^2 = \frac{g_H g v^2}{2\sqrt{2}}$$

$$m_{\hat{W}}^2 = g^2 v^2 / 4$$

W-W' mixing angle $\quad \hat\theta \approx \dfrac{\Delta^2}{m_{\hat{W}}^2 - M^2}$

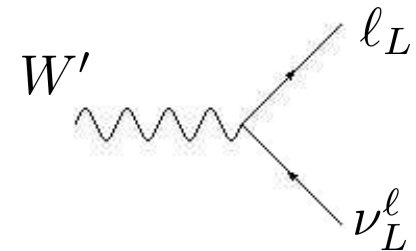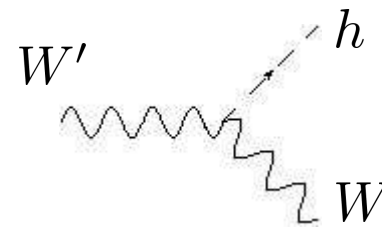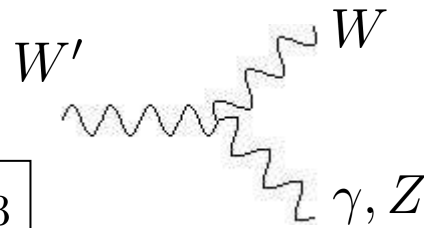$$M^2 = \tilde{M}^2 + g_4^2 v^2 / 4$$

Couplings of *W'* to SM fields: summary

In mass eigenstate basis for both fermions and vectors, **W' couples to:**
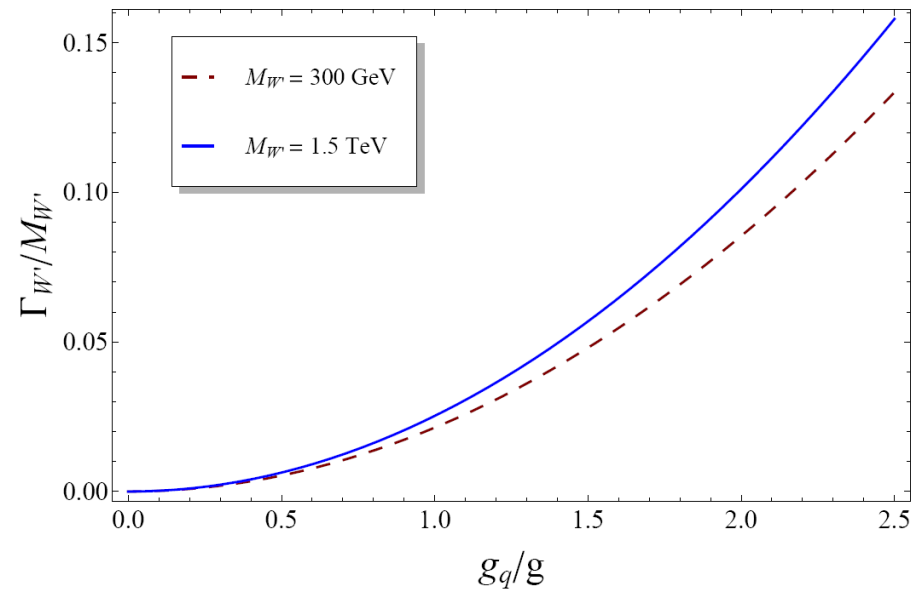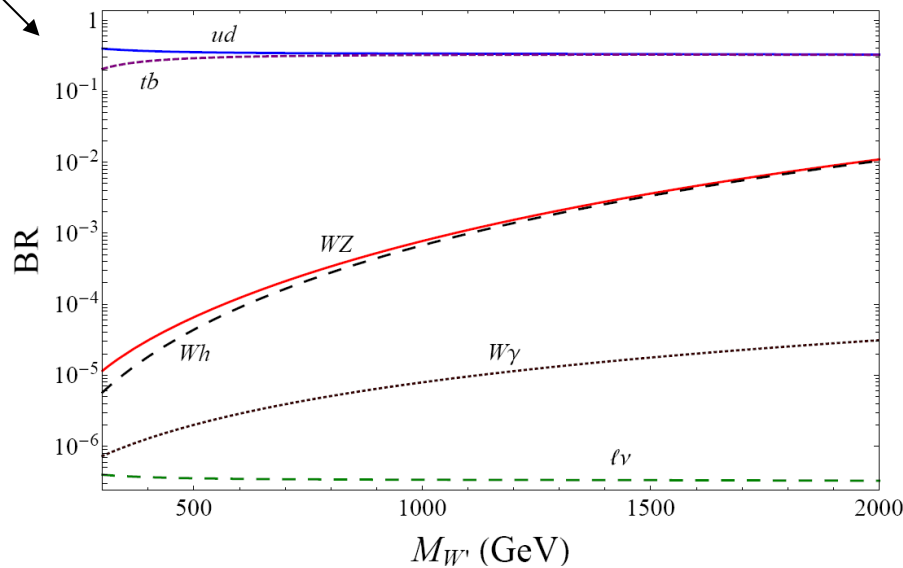
- RH quark currents (+ $O(\hat{\theta})$ coupling to LH quark currents):
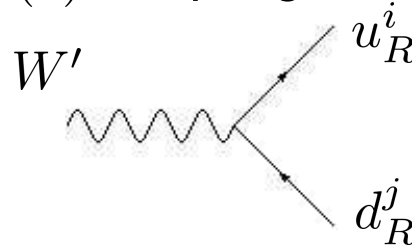
- *Wγ, WZ, Wh*, LH lepton currents, all proportional to $\hat{\theta}$:

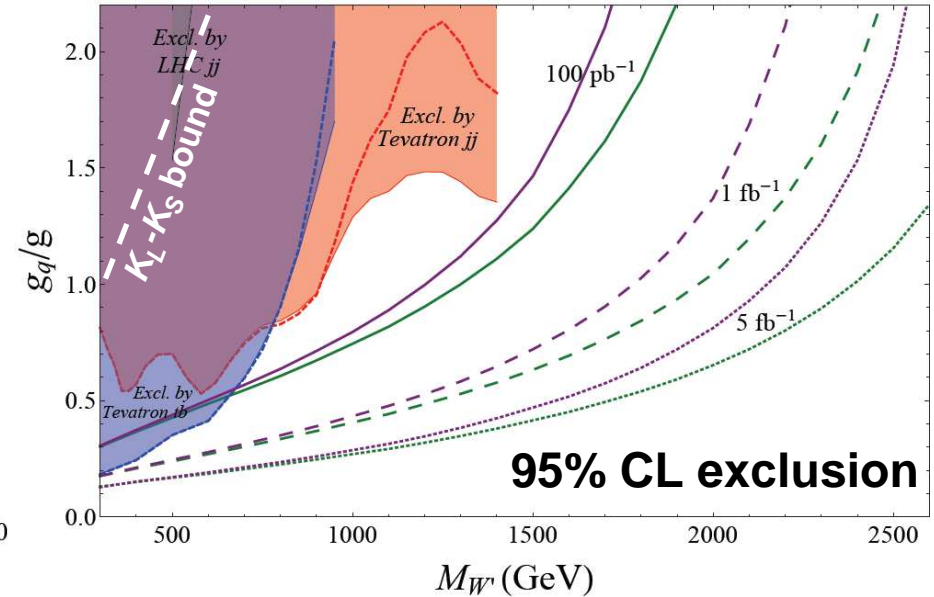$$g_q = g,\ \hat{\theta} = 10^{-3},\ c_B = -3$$
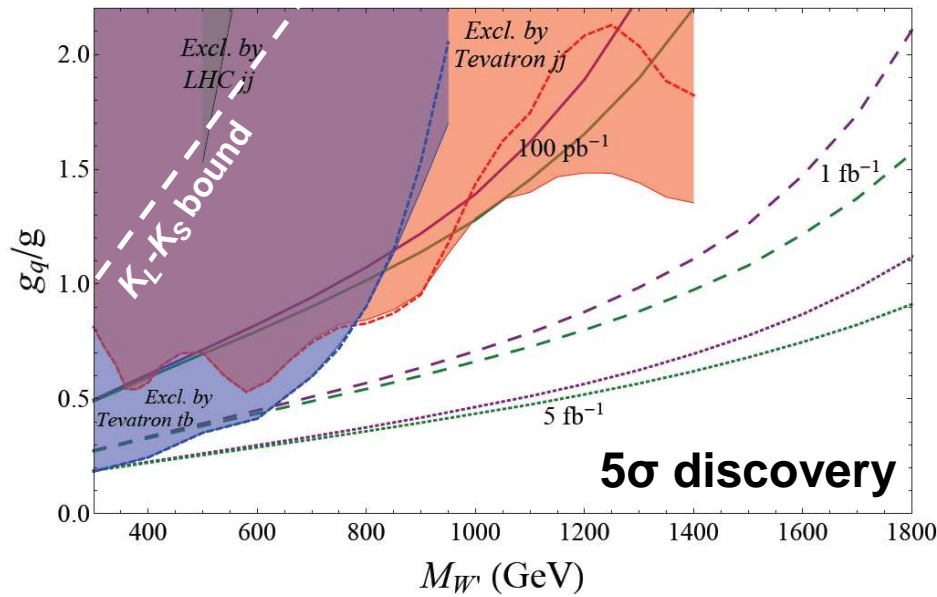
Bounds and early LHC pheno: outline

- **Dijet final state:** $W' \to jj$

- **Diboson final state:** $W' \to W\gamma$ **as a probe of the compositeness of the** W'

'Early LHC' $\Longleftrightarrow$ 7 – 8 TeV, L < 5 fb^{-1}

Early LHC reach: dijet

- Strongest indirect bound on g_q comes from K_L- K_S mixing. Bound depends heavily on assumed form for V_R ➡ choose $|V_R| = \mathbf{1}_3$, which gives the weakest constraint (also automatically satisfies bounds from $B^0_{d,s} - \overline{B}^0_{d,s}$).

- Tevatron bounds: in **red** from jj channel, in **blue** from tb

- Early LHC reach: discovery possible starting with around 100 pb⁻¹, sensitive first to $M_{W'}$ > 900 GeV. Exclusion: with 1 fb⁻¹, LHC does better than Tevatron for all masses $M_{W'}$ > 300 GeV.

For LHC searches in tb final state, see e.g. **Gopalakrishna et al., 1008.3508**

$W' \rightarrow W\gamma$ decay

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

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

What are the bounds on these 2 parameters?

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

What are the bounds on these 2 parameters?

c_B **is not significantly constrained by current data.**

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 $g \approx 2 \Rightarrow c_B \approx -1$

➡ $W' \to W\gamma$ 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

$$\Lambda \geq 5M \quad \text{for} \quad c_B \leq 10 \ .$$

So we can safely study the phenomenology of the W' for $c_B \leq 10$, without encountering problems with perturbative unitarity.

Bounds on $\hat{\theta}$

- *W-W' mixing* ➡ contribution to *T*

$$\hat{T}_V = -\frac{\Delta^4}{M^2 m_{\hat{W}}^2}$$

Lower bound on m_h from LEP2

➡ $\left|\frac{g_H}{M}\right| < 0.11\,\mathrm{TeV}^{-1}$

Del Aguila, De Blas, Perez-Victoria, 1005.3998

or equivalently

$$|\hat{\theta}| < 1 \times 10^{-3}, \qquad M_{W'} = 800\,\mathrm{GeV}$$
$$|\hat{\theta}| < 5 \times 10^{-4}, \qquad M_{W'} = 2\,\mathrm{TeV}$$
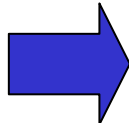
- $u \to d,s$ semileptonic transitions: e.g., $0^+ \to 0^+$ β decays, $\pi \to e\nu,\ K \to \pi l\nu$, etc. Find:

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

$$-1.6 \times 10^{-3} < g_q \hat{\theta} V_R^{ud} < 1.7 \times 10^{-3} \qquad \text{small CP phases in } V_R$$

$$\sqrt{\sum_j |V_R^{uj}|^2} \times |g_q \hat{\theta}| < 10^{-2 \div -1} \qquad \text{maximal CP phases}$$
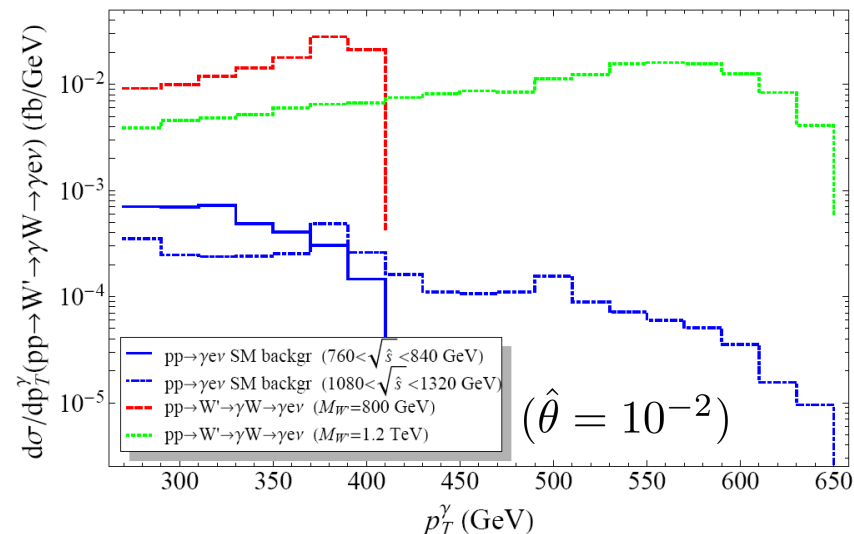
$W' \to W\gamma$: **early LHC analysis**

■ Benchmark point: $M_{W'} = 800\,\mathrm{GeV}$, $g_q = 0.84g$ (max. coupling allowed by Tevatron)

■ Select **leptonic *W* decay**. Cuts: $p_T^\gamma > 250\,\mathrm{GeV}$, $p_T^e > 50\,\mathrm{GeV}$, $\not{E}_T > 50\,\mathrm{GeV}$, $|\eta_{e,\gamma}| < 2.5$, $|M(W\gamma) - M_{W'}| < 0.05\,M_{W'}$

■ Background considered is irreducible $W\gamma$

- $W + j$ with jet misID as photon can be efficiently suppressed (however, also reduction of signal to ~ 80%, not included here) **ATLAS, 0901.0512**

- other instrumental backgrounds (such as $ee\not{E}_T$ with $e \to \gamma$, QCD faking $e + \not{E}_T$) are not included.

photon p_T ⟹
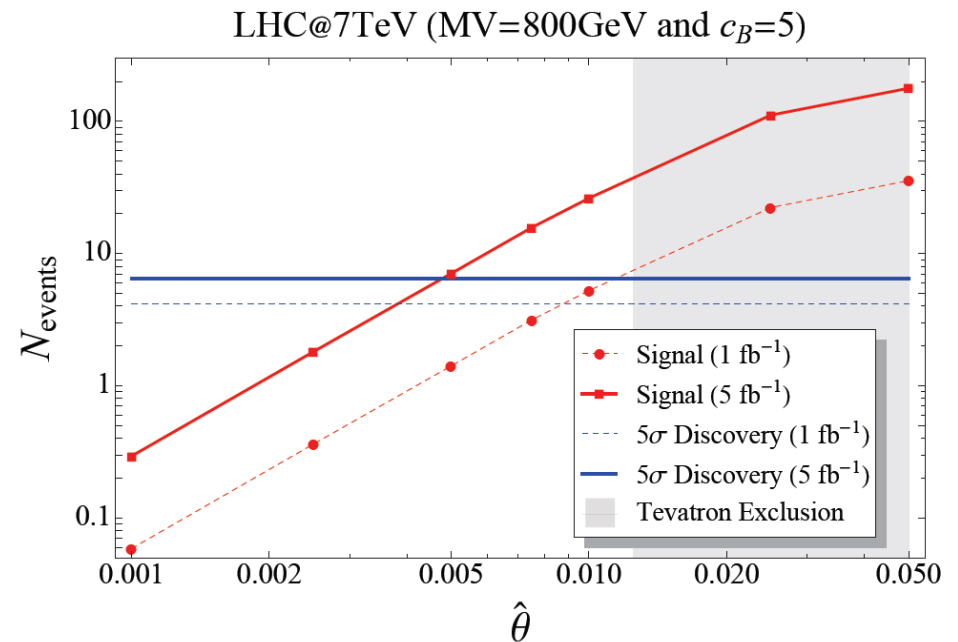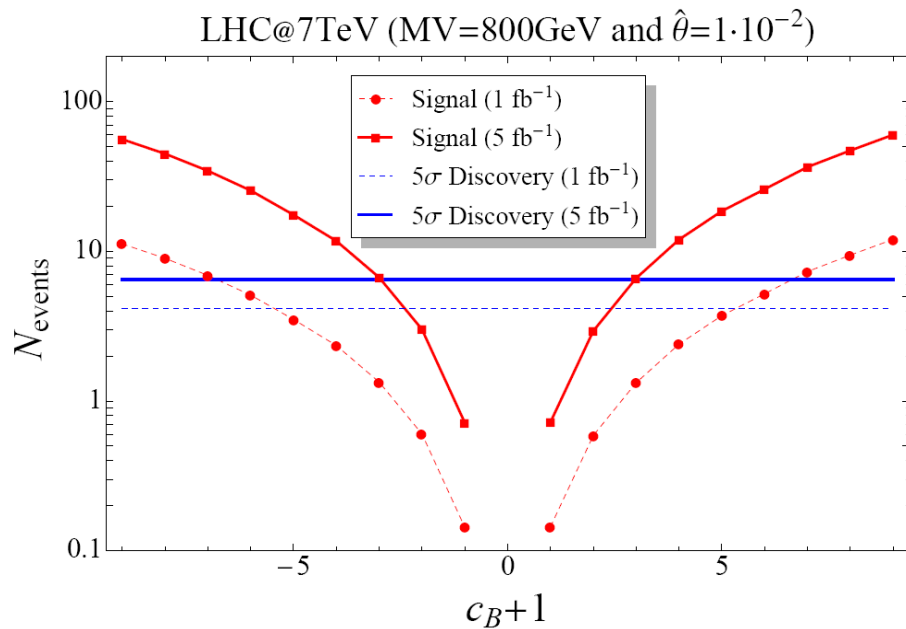
red = signal

solid blue = background

$(\hat{\theta} = 10^{-2})$

$W' \to W\gamma$: discovery prospects

LHC@7TeV (MV=800GeV and $\hat{\theta}=1\cdot 10^{-2}$)

LHC@7TeV (MV=800GeV and c_B=5)

- Shaded region is excluded by D0 *WZ* search   **D0, 1011.6278**

- Discovery possible for $|c_B + 1| > 2 \div 3$ and $\mathrm{few} \times 10^{-3} < \hat{\theta} < 10^{-2}$ **with 5 fb⁻¹ at 7 TeV**.

- Such values of the mixing angle are disfavored by *T*, but allowed by semi-leptonic transitions if CP phases in V_R are not negligible.

- **Observation of** $W' \to W\gamma$ **would be a hint of the compositeness of the** *W'*
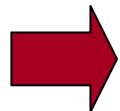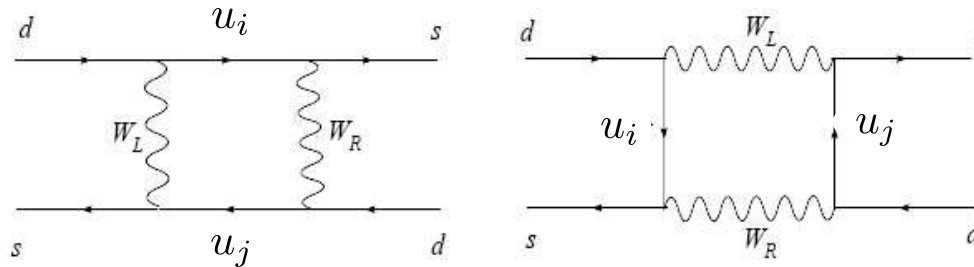
  ➡ **important to search for it at the 7 TeV – LHC !**

Backup

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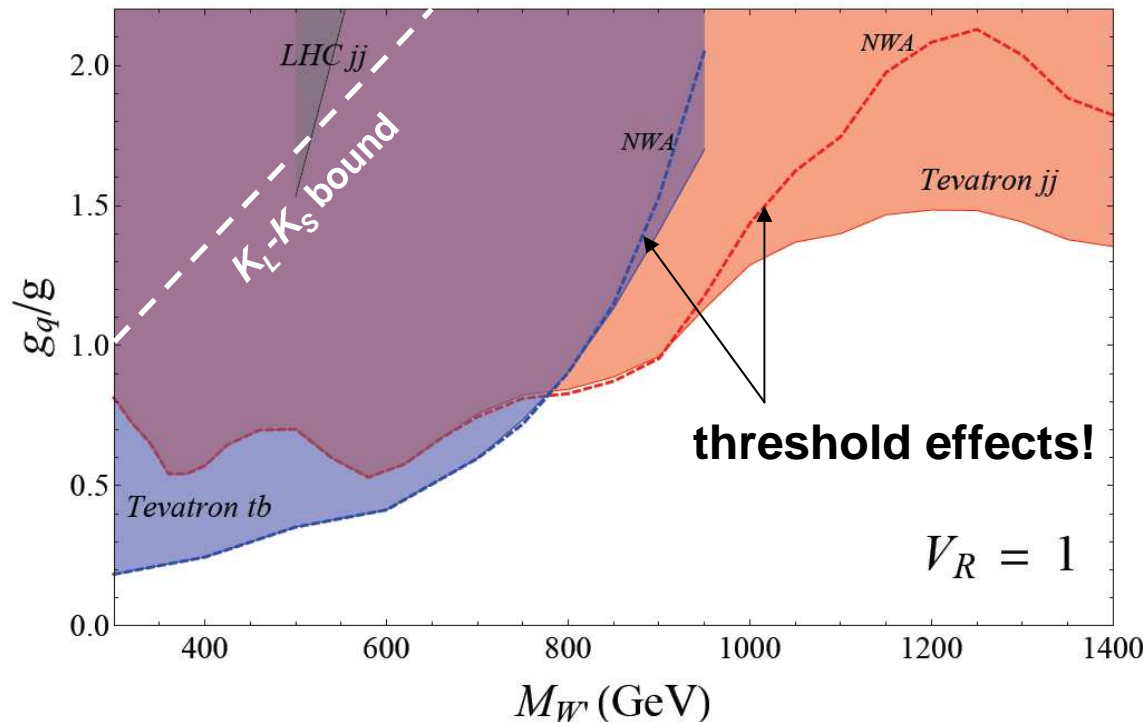
$$M_{W'} > (g_q/g)\, 300\,\text{GeV}$$

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

Bounds on g_q from Tevatron

Relevant channels: - jj CDF, 1.13 fb^{-1}

   - tb CDF, 1.9 fb^{-1} / D0, 2.3 fb^{-1}

assume $\hat{\theta} = 0$
(if mixing non-negligible,
bounds get only slightly
relaxed)

• For $M_{W'} > 800$ GeV, observe deviations from NWA: **threshold effect**, off-shell part of cross section is relevant when $M_{W'}^2/s$ is large.

• $\Gamma_{W'}$ has to be smaller than dijet mass resolution (~10% of mass at CDF)
➡   consider couplings $g_q \leq 2g$. For larger values, resonance width would be additional parameter.

Bounds on c_B from TGC

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

$$\mathcal{L}_{\text{eff}}^{WWV_0} = ig_{WWV_0} \left[g_1^{V_0} V_0^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + k_{V_0} W_\mu^+ W_\nu^- V_0^{\mu\nu} + \frac{\lambda_{V_0}}{m_W^2} V_0^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- \right]$$
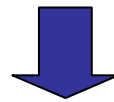
$SU(2)_L \times U(1)_Y$ gauge invariance ➡ 3 independent parameters:

$$g_1^Z - 1 = -\sin^2 \hat{\theta} \,(1 + \tan^2 \theta_w)$$
$$k_\gamma - 1 = -\sin^2 \hat{\theta} \,(1 + c_B)$$
$$\lambda_\gamma = 0$$

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:

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

(very large compared to bounds!)

Gyromagnetic ratio of the *W'*

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

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

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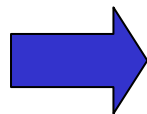
gyromagnetic ratio

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
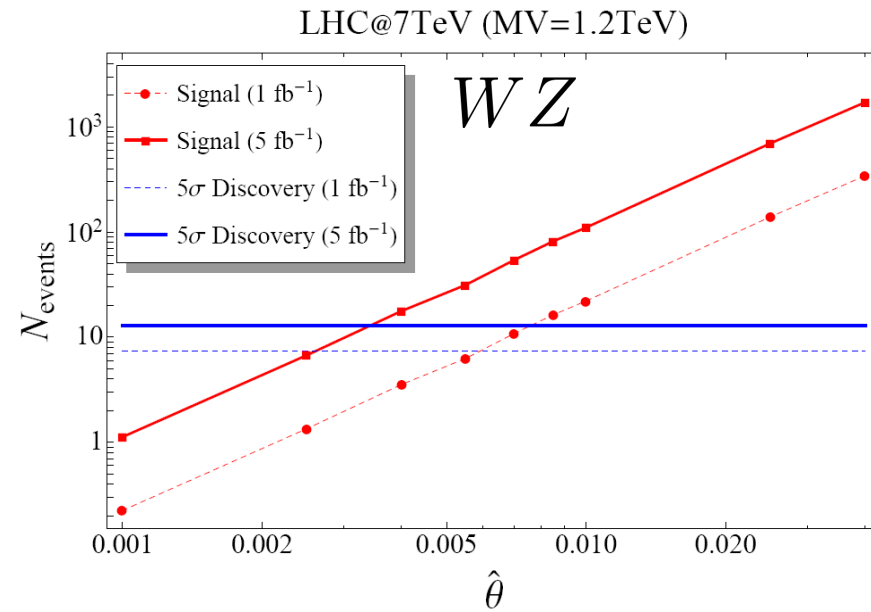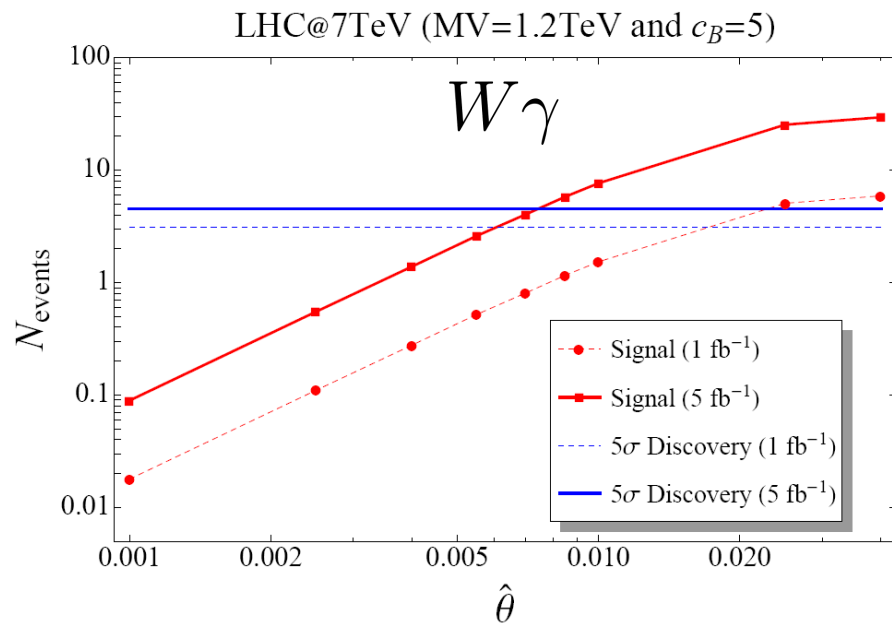
$$c_B = -1$$

$W' \to WZ$ at the early LHC

- Select leptonic *W* and hadronic *Z* ➡️ $e + \mathrm{MET} + jj$ final state, better than purely leptonic one for limited luminosity **Alves et al., 0907.2915**

- BR into *WZ* depends only on $\hat{\theta}$ ➡️ measuring rate of *WZ* would give an estimate of the mixing angle.

- As for *Wγ*, discovery at early LHC is possible for values of $\hat{\theta}$ disfavored by EWPT (*T* parameter), but allowed by $u \to d, s$ semileptonic processes, if CP phases in V_R are not negligible.
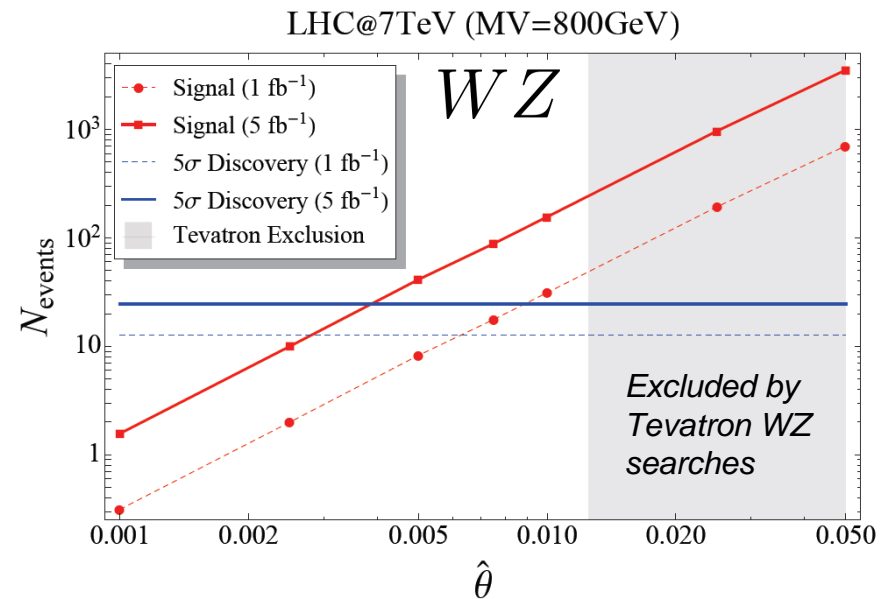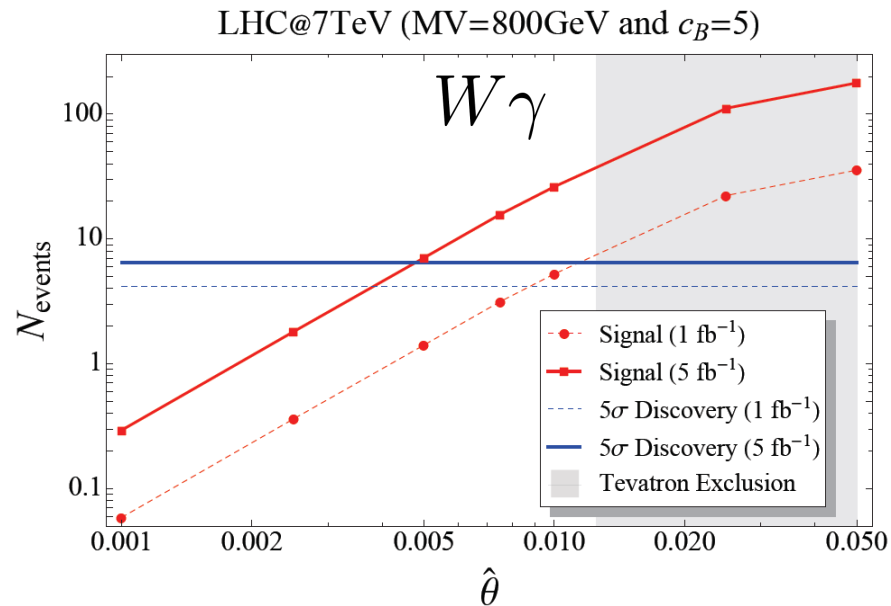
Comparison of $W\gamma$ and WZ

$$\boxed{M_{W'} = 1.2\,\text{TeV}}$$

$$(g_q = 1.48g)$$