A weakly constrained W’ at the early LHC

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based on **C.Grojean, ES, R.Torre**, arXiv:**1103.2761**

Introduction: effective approach

- *W'* $\leftrightarrow$ 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

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

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

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

(iso-singlet *W'*)

$(\mathbf{1},\mathbf{2})_{-3/2}$: no coupling to quarks, only to leptons (invariance under $U(1)_Y$)

production at hadron colliders strongly suppressed

Iso-singlet *W'* : motivations

- If the *W'* is part of an $SU(2)_L$ triplet, *W'* and *Z'* are degenerate in mass (except for terms $\propto v$)
  ➡ strong bounds on *Z'* from EWPT also apply to *W'*
  ➡ needs to be heavy, or weakly coupled

- For the (**1**,**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: $W' \to jj, tb$
  a study of this 'pessimistic' scenario was missing
  (for recent studies of the case $m_{\nu_R} < M_{W'}$, see e.g.
  Schmaltz, Spethmann 1011.5918; Nemevsek *et al.*, 1103.1627)

Effective Lagrangian

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

$$\begin{aligned}\mathcal{L}_V &= D_\mu V_\nu^- D^\nu V^{+\mu} - D_\mu V_\nu^- D^\mu V^{+\nu} + \tilde{M}^2 V^{+\mu} V_\mu^- \\ &+ \frac{g_4^2}{2}|H|^2 V^{+\mu} V_\mu^- - \; i g' c_B B^{\mu\nu} V_\mu^+ V_\nu^- \,, \\ \mathcal{L}_{V-SM} &= V^{+\mu}\left(i g_H H^\dagger (D_\mu \tilde{H}) + \frac{g_q}{\sqrt{2}} (V_R)_{ij} \overline{u_R^i} \gamma_\mu d_R^j \right) + \text{h.c.}\end{aligned}$$

- no RH neutrinos (↔ 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

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

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

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

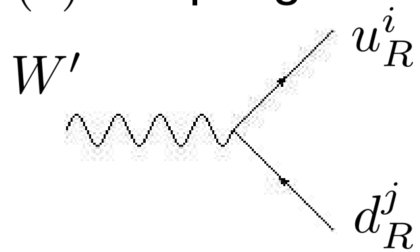
$$m_{\hat W}^2 = g^2 v^2/4$$

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

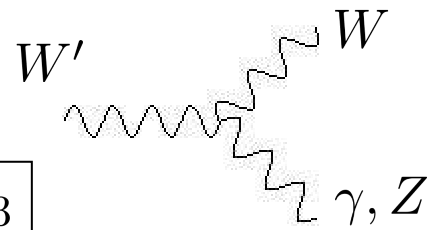
Couplings of W' to SM fields: summary

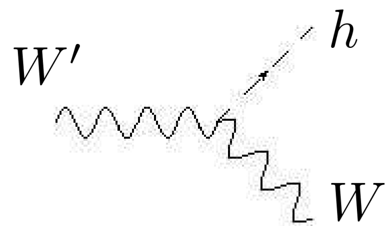
In mass eigenstate basis for both fermions and vectors, *W'* couples to:

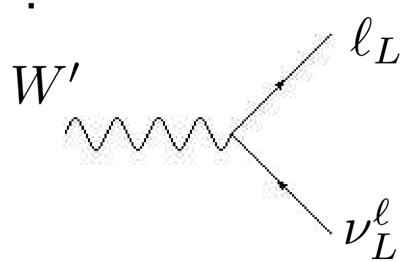
- RH quark currents (+ $O(\hat{\theta})$ coupling to LH quark currents):



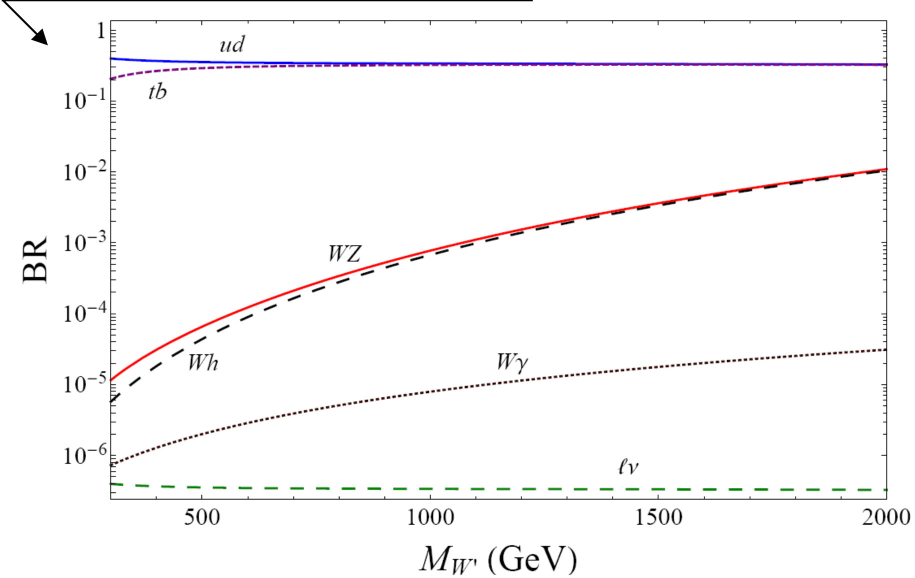
- *Wγ*, *WZ*, *Wh*, LH lepton currents, all proportional to $\hat{\theta}$:

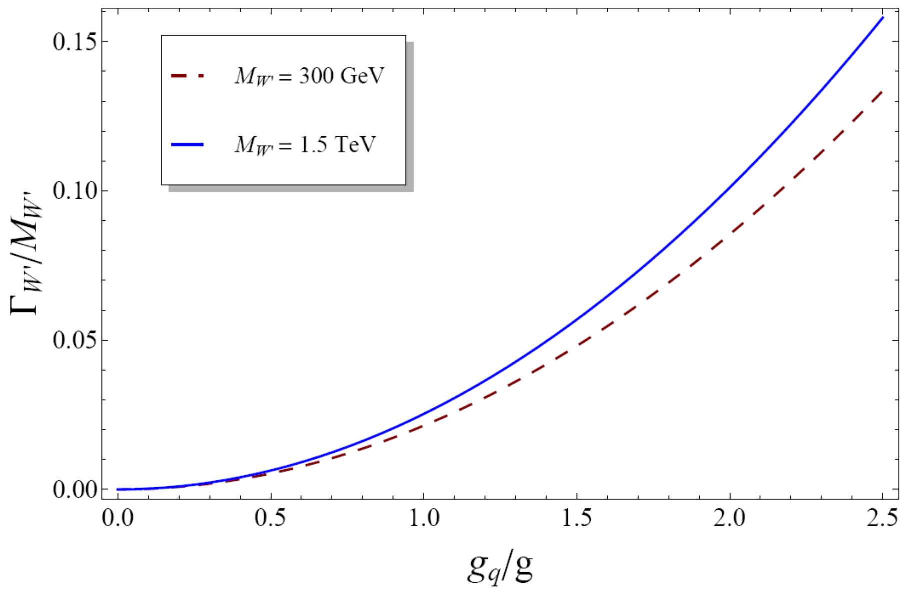






$g_q = g$, $\hat{\theta} = 10^{-3}$, $c_B = -3$





Outline

- **Constraints on *W'* mass and couplings:**
  - Bounds on the *W*-*W'* mixing angle $\hat{\theta}$
  - Indirect bounds on coupling to quarks g_q
  - Tevatron bounds on g_q

- **Early** (7 - 8 TeV, *L* < 5 fb^{-1}) **LHC reach:**
  - Dijet final state: $W' \to jj$
  - Diboson final states: $W' \to W\gamma$ as a probe of the compositeness of the *W'*, and $W' \to WZ$

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

$$|\hat{\theta}| < 4 \times 10^{-3}, \qquad M_{W'} = 300\,\mathrm{GeV}$$
$$|\hat{\theta}| < 5 \times 10^{-4}, \qquad M_{W'} = 2\,\mathrm{TeV}$$

- *u* → *d,s* semileptonic transitions: e.g., $0^+ \to 0^+$ *β* decays, *π* → *eν*, *K* → *πlν*, etc. Find:

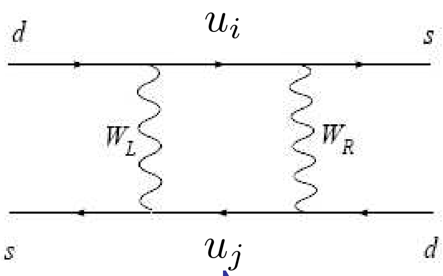
Buras, Gemmler, Isidori, 1007.1993; Langacker, Sankar, PRD 40 (1989)

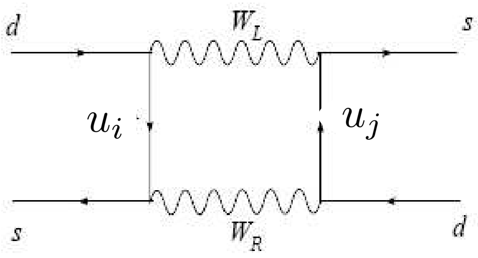
$$-1.6 \times 10^{-3} < g_q \hat{\theta} V_R^{ud} < 1.7 \times 10^{-3}$$ small CP phases in V_R

$$\sqrt{\sum_j |V_R^{uj}|^2} \times |g_q \hat{\theta}| < 10^{-2 \div -1}$$ maximal CP phases

Indirect bounds on g_q

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





amplitude $\propto m_i m_j$ $\Rightarrow$ 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)**

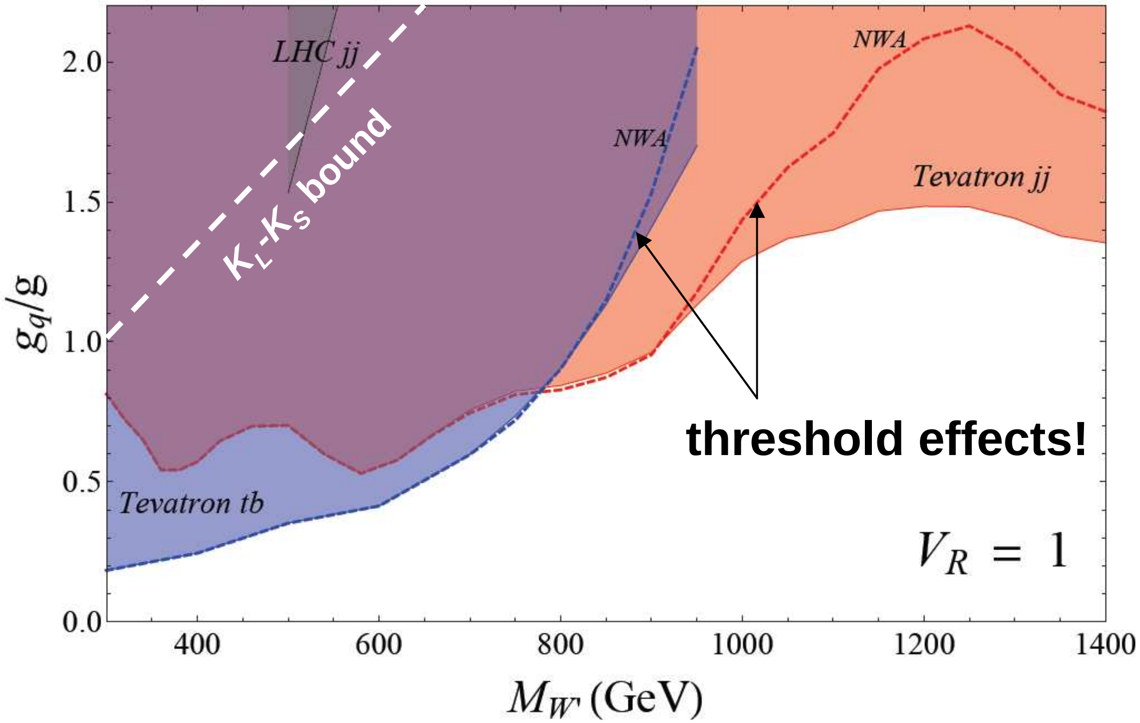
$$M_{W'} > (g_q/g)\,300\,\mathrm{GeV}$$

(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 g_q from Tevatron

Relevant channels: - *jj* CDF, 1.13 fb^{-1} **CDF, 0812.4036**

- *tb* CDF, 1.9 fb^{-1} / D0, 2.3 fb^{-1} **CDF, 0902.3276** **D0, 1101.0806**



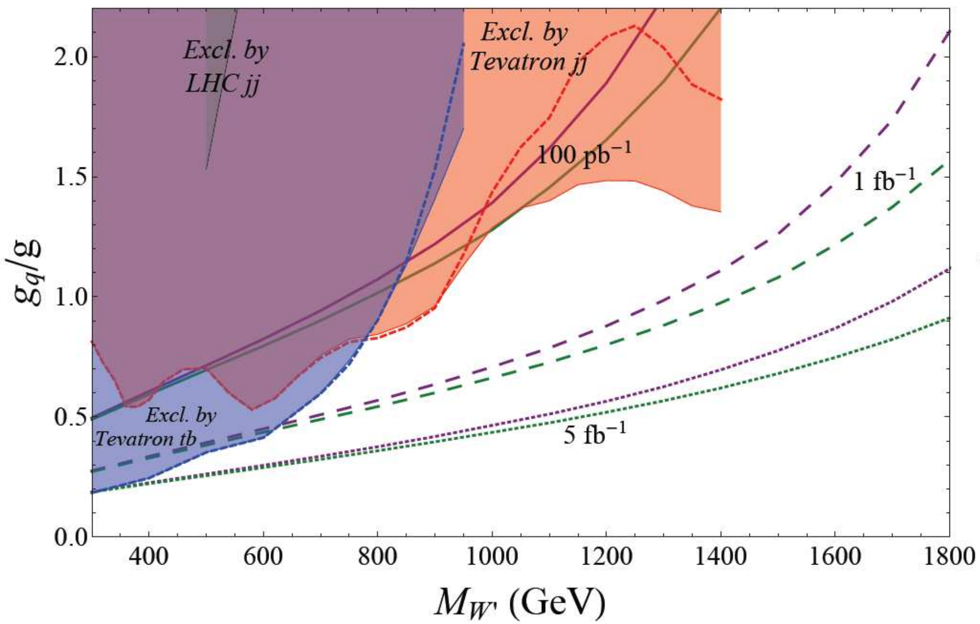
assume $\hat{\theta} = 0$
(if mixing non-negligible, bounds get only slightly relaxed)

- 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.

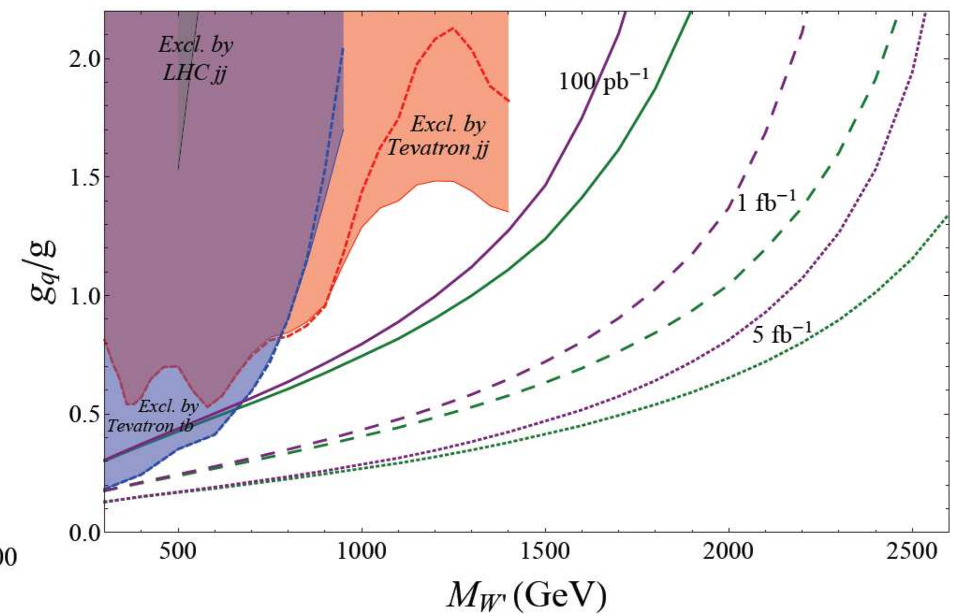
- $\Gamma_{W'}$ has to be smaller than dijet mass resolution (~10% of mass at CDF)
➡ consider couplings $g_q \leq 2g$. For larger values, resonance width would be additional parameter.

Early LHC reach: dijet

5σ discovery



95% CL exclusion



- Simple cuts: $|\eta| < 2.5,\ |\Delta\eta| < 1.3$; compare integrals of signal and background over $m_{jj} > (1-\epsilon/2)M_{W'}$ [$\epsilon = 8\%(M_{W'} = 500\,\mathrm{GeV}) \div 5\%(M_{W'} = 2.5\,\mathrm{TeV})$ is dijet mass resolution] ➡ get discovery and exclusion limits **CMS, 1010.0203**
- Discovery needs at least few hundreds pb^{-1}; sensible first to $M_{W'} > 900$ GeV .
- Exclusion: with 1 fb^{-1}, LHC does better than Tevatron for all masses $M_{W'} > 300$ GeV .

We do not discuss the tb final state here; see e.g. **Gopalakrishna et al., 1008.3508**

Diboson final states: $W\gamma,\, WZ$

$$\Gamma(W' \to WZ) = \frac{g^2\cos^2\theta_w}{192\pi}(1+\tan^2\theta_w)^2\hat{\theta}^2\frac{M_{W'}^2}{M_W^2}\frac{M_{W'}^2}{M_Z^2}M_{W'}$$
$$\Gamma(W' \to W\gamma) = \frac{e^2}{96\pi}(c_B+1)^2\hat{\theta}^2\frac{M_{W'}^2}{M_W^2}M_{W'}$$

While *W'* → *WZ* only depends on the *W-W'* mixing angle, *W'* → *Wγ* is controlled by $|c_B+1|\hat{\theta}$. c_B has essentially no current experimental constraint.

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'* → *Wγ* 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

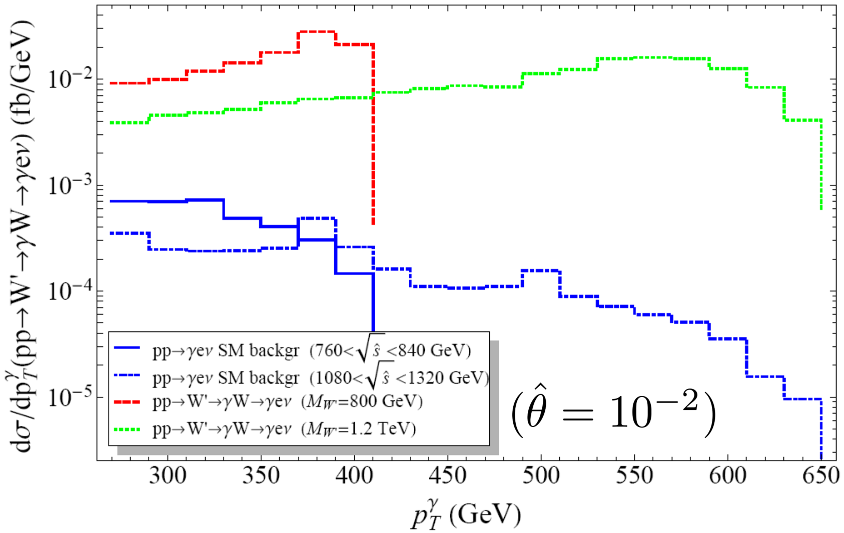
$$\Lambda \geq 5M \quad \text{for} \quad c_B \leq 10\,.$$

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

$W' \to W\gamma$: early LHC analysis

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

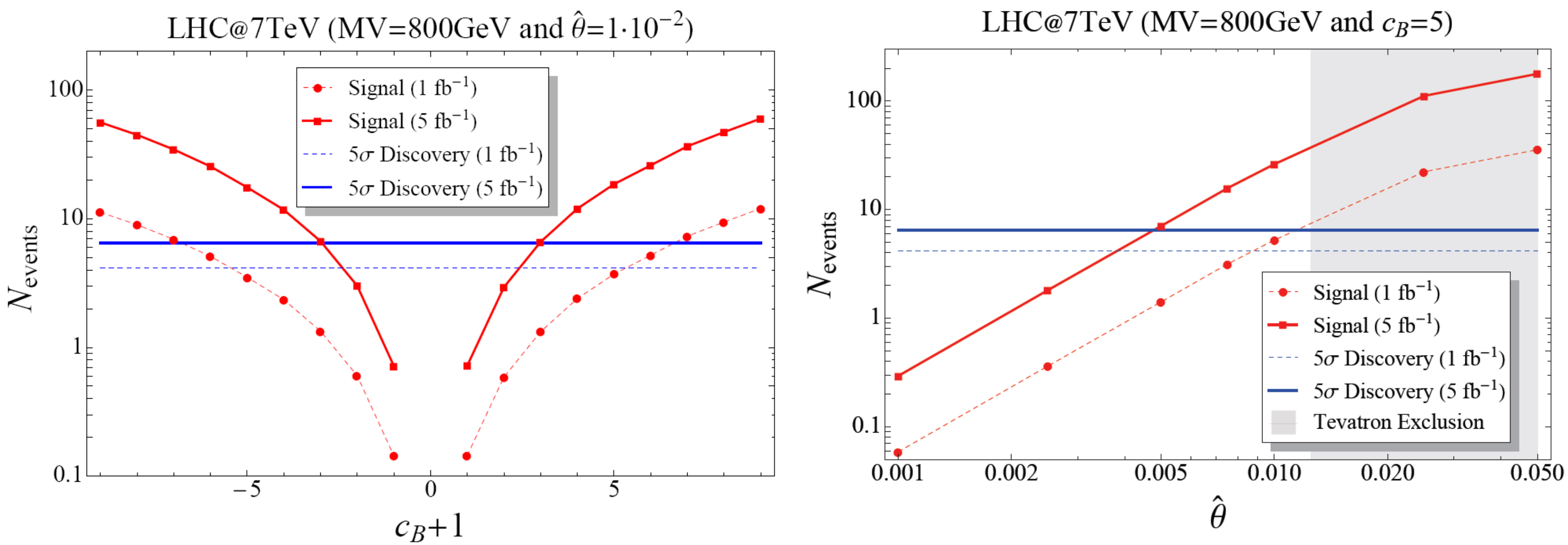
photon p$_T$



red = signal

solid blue = background

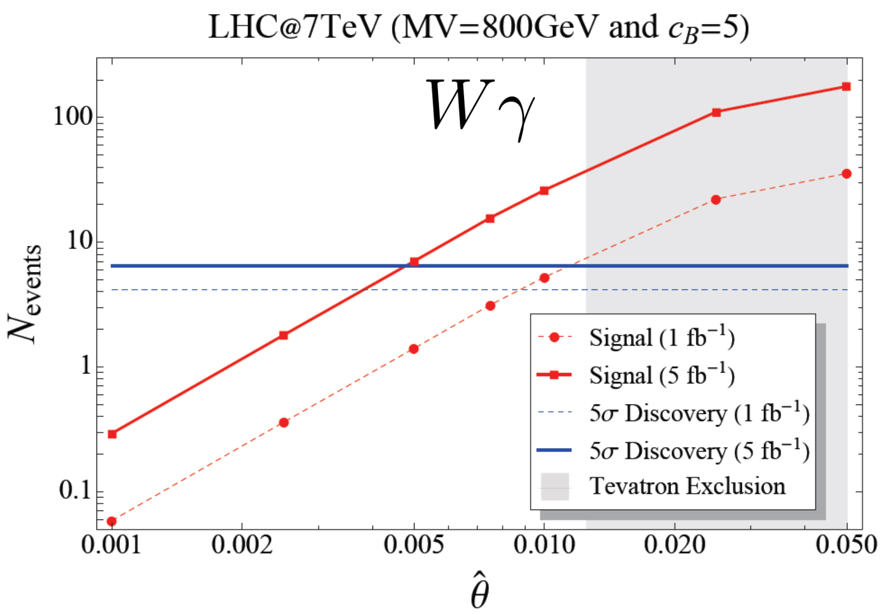
$W' \to W\gamma$: discovery prospects

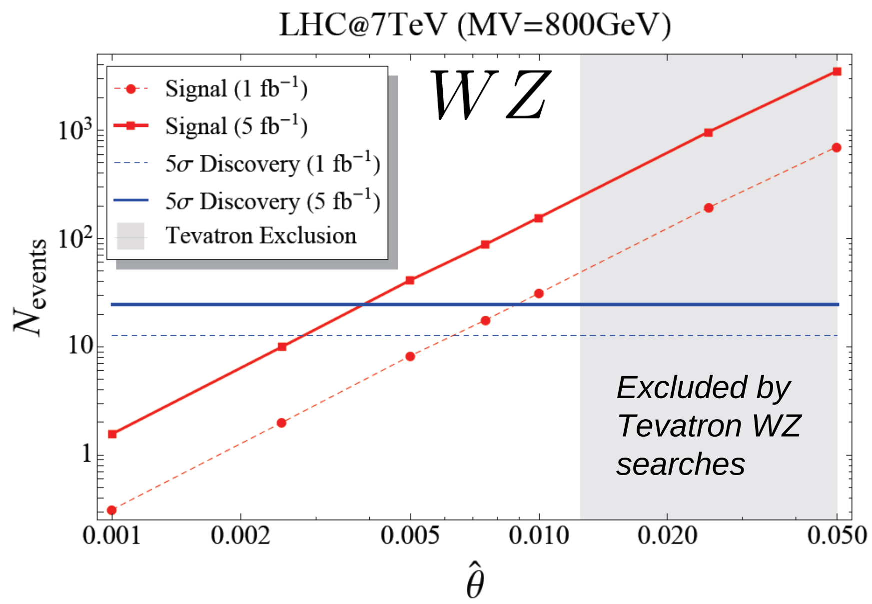


- Shaded region is excluded by D0 *WZ* search **D0, 1011.6278**
- Discovery possible for $|c_B + 1| > 2 \div 3$ and $\text{few} \times 10^{-3} < \hat{\theta} < 10^{-2}$ with 5 fb^{-1} at 7 TeV.
- Such values of the mixing angle are disfavored by *T*, but allowed by semi-leptonic transitions if CP phases in V_R are not small.
- **Observation of *W'* → *Wγ* would be a hint of the compositeness of the *W'*.**

$W' \to WZ$ at 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 small.





Summary and conclusions

- We applied an effective approach to study a *W'* transforming as an iso-singlet under the SM, for which constraints are weaker than for the iso-triplet case.

- We discussed the current bounds on the parameters describing the heavy vector: the *W*-*W'* mixing angle must be small, while **a sizable coupling to quarks $g_q \sim g$ is allowed even for** $M_{W'}$ < 1 TeV.

- An early LHC discovery of the *W'* in the dijet channel is possible with at least few hundreds pb^{-1} at 7 TeV.

- We also presented the early LHC reach in the diboson channels $W' \to W\gamma, WZ$, and showed how **observation of $W' \to W\gamma$ would point to a composite** *W'*, since this decay is strongly suppressed if the resonance is a gauge boson.

Backup

Bounds on c_B from TGC

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

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

$SU(2)_L \times U(1)_Y$ 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

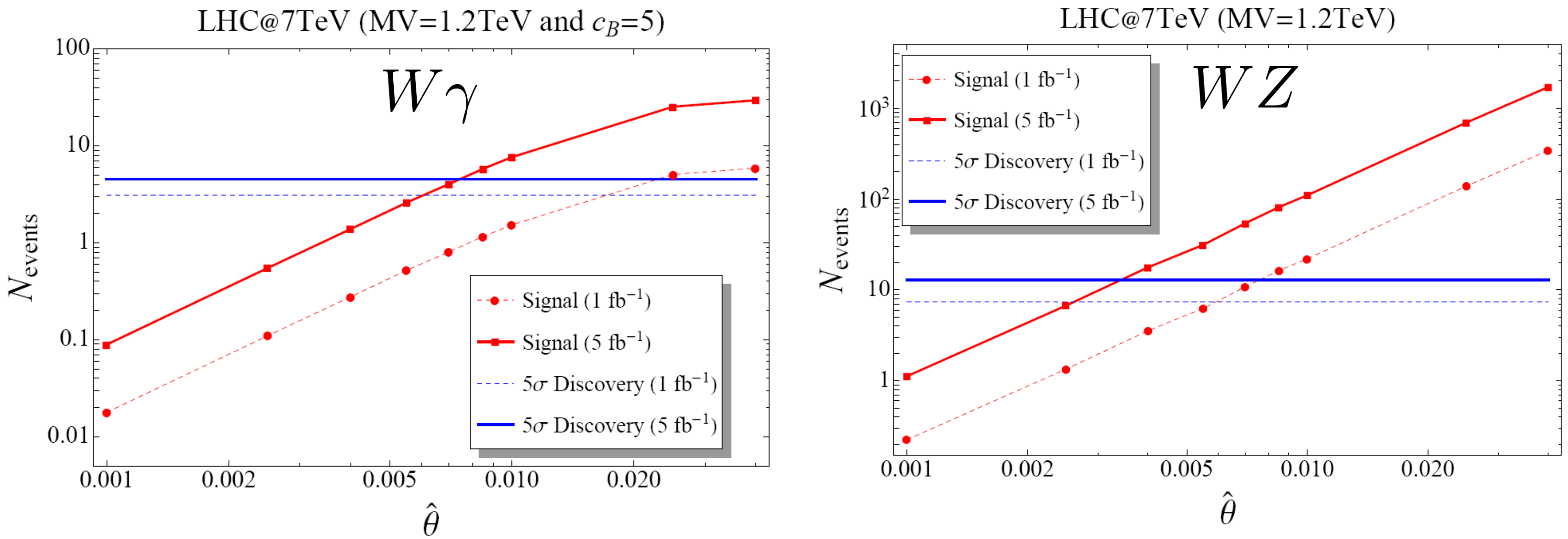
However, $\hat\theta$ must be very small, so in practice c_B is **only constrained very weakly**. For example:

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

(very large compared to bounds!)

Comparison of $W\gamma$ and WZ /2

$$M_{W'} = 1.2\,\mathrm{TeV}$$



$$(g_q = 1.48g)$$

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

$$\Rightarrow \quad c_B = -1$$