A weakly constrained $W'$
at the early LHC

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based on C.Grojean, ES, R.Torre, arXiv: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 reps. $(SU(3)_c, SU(2)_L)_Y$

\[
\begin{align*}
\text{iso-singlet} & \quad (1, 1)_1 \\
\text{Left-right models; Little Higgs with custodial symmetry}
\end{align*}
\]

\[
\begin{align*}
\text{iso-triplet} & \quad (1, 3)_0 \\
\text{Some Little Higgs models; extra dimensions}
\end{align*}
\]

- no associated neutral $Z'$
- can write effective theory for $W'$ only
- constraints are weaker

- $W'$ and $Z'$ are (almost) degenerate in mass
- strong bounds from EWPT on $Z'$ also apply to $W'$
- needs to be heavy, or weakly coupled

we study an iso-singlet $W'$
Effective Lagrangian

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{V} + \mathcal{L}_{V-SM} \]

\[ \mathcal{L}_{V} = D_{\mu} V_{\nu}^{\mu} D^{\nu} V^{+\mu} - D_{\mu} V_{\nu}^{\mu} D^{\nu} V^{+\nu} + \tilde{M}^{2} V^{+\mu} V_{\mu}^{-} \]

\[ + \frac{g_{4}^{2}}{2} |H|^{2} V^{+\mu} V_{\mu}^{-} - ig' c_{B} B^{\mu\nu} V_{\mu}^{+} V_{\nu}^{-} , \]

\[ \mathcal{L}_{V-SM} = V^{+\mu} \left( ig_{H} H^{\dagger} (D_{\mu} \tilde{H}) + \frac{g_{q}}{\sqrt{2}} (V_{R})_{ij} \bar{u}_{R}^{i} \gamma_{\mu} d_{R}^{j} \right) + \text{h.c.} \]

- no RH neutrinos (↔ heavier than \( W' \)); mass eigenst. basis for fermions
- parameters: \( W' \) mass + couplings \( g_{q}, g_{H} \leftrightarrow \hat{\theta}, c_{B} \) (\( g_{4} \) irrelevant to us)
- RH quark mixing matrix \( V_{R} \), which does not need to be unitary
- \( g_{H} \) induces \( W-W' \) mixing \[ \Delta^{2} = \frac{g_{H} g_{V}^{2}}{2\sqrt{2}} \]
  \[ m_{W}^{2} = g^{2} v^{2} / 4 \]
  \[ M^{2} = \tilde{M}^{2} + g_{4}^{2} v^{2} / 4 \]

mixed states \[ \begin{pmatrix} W^{+} \\ W'^{+} \end{pmatrix} = \begin{pmatrix} c_{\hat{\theta}} & s_{\hat{\theta}} \\ -s_{\hat{\theta}} & c_{\hat{\theta}} \end{pmatrix} \begin{pmatrix} \hat{W}^{+} \\ V^{+} \end{pmatrix} \]

mixing angle \[ \hat{\theta} \approx \frac{\Delta^{2}}{m_{W}^{2} - M^{2}} \]
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):
  \[
  W' \quad u_R^i \quad V_R^{ij} \quad d_R^j \\
  \]
  we take $|V_R| = 1_3$
  weakest constraints

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

\[
W' \quad \gamma \nabla \quad W' \quad W \nabla \quad W' \quad h \nabla \quad W' \quad \ell_L \\
\]

$g_q = g$, $\hat{\theta} = 10^{-3}$, $c_B = -3$
$W' \rightarrow W\gamma$ decay

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

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

What are the bounds on these 2 parameters?
$W' \to W \gamma$ decay

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

$W' \to W \gamma$ 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 unitarity violation problems.
Bounds on $\hat{\theta}$

- $W-W'$ mixing contribution to $T$

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

Lower bound on $m_h$ from LEP2

or equivalently

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

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

$$-1.6 \times 10^{-3} < g_q \hat{\theta} V_{R}^{ud} < 1.7 \times 10^{-3}$$

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

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Del Aguila, De Blas, Perez-Victoria, 1005.3998
$W' \rightarrow W\gamma$: early LHC analysis

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

- Cuts: $p_T^\gamma > 250 \text{ GeV}$, $p_T^e > 50 \text{ GeV}$, $E_T > 50 \text{ GeV}$, $|\eta_{e,\gamma}| < 2.5$, $|M(W\gamma) - M_{W'}| < 0.05 M_{W'}$

- Background considered is irreducible $W\gamma$
  
  - $W + j$ with jet misID as photon can be efficiently suppressed (however, also reduction of signal to $\sim 80\%$, not included here)  \textbf{ATLAS, 0901.0512}
  
  - other instrumental backgrounds (such as $eeE_T$ with $e \rightarrow \gamma$, QCD faking $e + E_T$) are not included.

\begin{itemize}
  \item **photon** $p_T$
  
  \begin{itemize}
    \item **red** = signal
    \item **solid blue** = background
  \end{itemize}
\end{itemize}
$W' \rightarrow W\gamma$ : discovery prospects

- Shaded region is excluded by D0 WZ search \[ \text{D0, 1011.6278} \]
- Discovery possible for $|c_B + 1| > 2\div 3$ and 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** $W' \rightarrow W\gamma$ **would be a hint of the compositeness of the** $W'$ **important to search for it at the 7 TeV – LHC !**
Backup
Bounds on $c_B$ from TGC

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

\[ \mathcal{L}_{\text{eff}}^{WWV_0} = i g_{WWV_0} \left[ g_1 V_0^\mu (W^\mu W_+ - W_+ W^-) + k V_0 W_+ W^\mu W_0^\mu + \frac{\lambda V_0}{m_W^2} W_+ W_+ W_+ W^- \right] \]

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

\[
\begin{align*}
g_1^Z - 1 &= -\sin^2 \hat{\theta} (1 + \tan^2 \theta_w) \\
k_{\gamma} - 1 &= -\sin^2 \hat{\theta} (1 + c_B) \\
\lambda_{\gamma} &= 0
\end{align*}
\]

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 \( W' \)

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

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

Magnetic dipole moment of the \( W' \):

\[
\mu_{W'} = \frac{e}{2 M_{W'}} \left( 1 + k'_{\gamma} \right)
\]

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

\[c_B = -1\]
Indirect bounds on $g_q$

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

\[
\begin{align*}
\begin{array}{c}
\text{d} & \quad u_i & \quad \bar{w}_i & \quad \bar{w}_j & \quad s \\
\text{s} & \quad u_j & \quad \bar{w}_R & \quad \bar{w}_R & \quad d
\end{array}
\end{align*}
\]

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:

\[
\begin{align*}
& \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}
\end{align*}
\]

We choose $|V_R| = 1_3$, for which the bound is \[M_W > (g_q/g) \times 300 \text{ GeV}\] (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]

- 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.

assume $\hat{\theta} = 0$

(if mixing non-negligible, bounds get only slightly relaxed)
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 $m_{jj} > (1 - \epsilon/2) M_{W'}$ [ $\epsilon = 8\% (M_{W'} = 500 \text{ GeV}) \div 5\% (M_{W'} = 2.5 \text{ TeV})$ is dijet mass resolution] get discovery and exclusion limits

- Discovery needs at least few hundreds pb$^{-1}$; sensible first to $M_{W'} > 900 \text{ GeV}$.

- Exclusion: with 1 fb$^{-1}$, LHC does better than Tevatron for all masses $M_{W'} > 300 \text{ GeV}$.

We do not discuss the $tb$ final state here; see e.g. Gopalakrishna et al., 1008.3508
$W' \rightarrow WZ$ at early LHC

- Select leptonic $W$ and hadronic $Z$ 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 $W\gamma$, discovery at early LHC is possible for values of $\hat{\theta}$ disfavored by EWPT ($T$ parameter), but allowed by semileptonic processes, if CP phases in $V_R$ are not small.
Comparison of \( W\gamma \) and \( WZ \)

\[ M_{W'} = 1.2 \text{ TeV} \]

\((g_q = 1.48g)\)