Search for color sextet scalars in early LHC experiments

Edmond L Berger
Argonne National Laboratory

In collaboration with:
Qing-Hong Cao, Chuan-Ren Chen, Gabe Shaughnessy
First years of the LHC decade will probe a new frontier of physics at the Terascale.

★ Focus here on **New Heavy Resonance**.

Production probes the large $x$ region where valence-quark dominance begins.

★ For early discovery at the LHC (7 TeV and 1 fb$^{-1}$ luminosity), it helps if the NP is:

- **Colored** - large production rate
- **Novel, easily detectable collider signature**
- **Small SM backgrounds**

**Colored**
Quark-quark initial states can produce sextet and anti-triplet resonances

\[ 3 \times 3 = 6 + \bar{3} \]

\[ 3 \times \bar{3} = 1 + 8 \]

Observation of sextet scalar (\( \phi \)) would imply changes in RGE unification equations.

\[ \phi_j^* K_{ab}^j q_a^T C^\dagger \lambda_R^{ab} P_R q_b + h.c. \]

Signature: same-sign charged lepton pair, b-jets, and large MET.

Top quark polarization is crucial.

We implement full spin correlations in our Monte Carlo simulation.

★ Large cross section

K is a Clebsch-Gordon factor.

Couplings (\( \lambda_R^{ab} \)) are not proportional to mass; bounds from Tevatron data.

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Electroweak quantum numbers

| $SU(2)_L$ | $U(1)_Y$ | $|Q| = |T_3 + Y|$ | Couplings |
|-----------|----------|---------------------|-----------|
| 1         | 1/3      | 1/3                 | QQ,       |
| 3         | 1/3      | 1/3, 2/3, 4/3       | Q         |
| 1         | 2/3      | 2/3                 | D         |


Jonathan M. Arnold, Maxim Pospelov, Michael Trott, Mark B. Wise
Constraints from the Tevatron

\[ \sigma_{tt+\bar{t}t} < 0.7 \text{ pb} \]

Distribution in \( M_{\ell\ell t_h} \)

\[ \ell^+ \quad \nu \quad t_\ell \quad t_h \quad j \quad j \quad j \]

Shaded region excluded
Signal and backgrounds

**Signal topology**

- Di-muons, better reconstruction than for electrons
- 2 b-jets and MET

**Prominent backgrounds (ALPGEN)**

- $t\bar{t} \rightarrow b\bar{b}W^+W^-$, $W^+ \rightarrow \ell^+\nu$, $W^- \rightarrow jj$, $b \rightarrow \ell^+$
- $W_1^+W_2^+jj$, $W^+ \rightarrow \ell^+\nu$
More positive di-muons

Same-sign top pairs contribute an asymmetry in charge multiplicity.

Strong dependence on sextet scalar mass owing to PDF dependence.

Same-sign charge ratio gives an independent check on scalar mass.
Acceptance cuts

- leptons:
  \[ p_{T,\ell} \geq 20 \text{ GeV} \quad |\eta_\ell| < 2.0 \]

- jets:
  \[ p_{T,j} \geq 50 \text{ GeV} \quad |\eta_j| < 2.5 \]

Separation:

\[ \Delta R_{\ell\ell,\ell_j,j_j} > 0.4 \]

Energy smearing

\[ \frac{\delta E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b \]

- leptons:
  \[ a = 10\%, \quad b = 0.7\% \]

- jets:
  \[ a = 50\%, \quad b = 3\% \]

Tagging rates / Mistag rates
The cuts to extract signal:

- Same sign di-muons
- Two jets with pT > 50 GeV

Shown are numbers of signal events:
- About 4.6 background events

CDF: $\sigma(tt+\bar{t}\bar{t})$
CDF: $m_{t\bar{t}} 95\%$ C.L.

Hadronization region ($\Gamma < 300$ MeV)
Q1: Are the muons and missing $X$ from $W$-boson decays?

Q2: Does each jet + lepton pair reconstruct a top quark?

Q3: What is the mass of the resonance?

Q4: What is top quark polarization?

Q5: Are the top quarks from a scalar decay?
MT2 is similar to transverse mass of W-boson, but works for the case of two missing particles in the final state.

\[(\mu_1^+, \mu_2^+, E_T) \leq m_W^2\]
Four unknowns and four on-shell conditions

\[ \begin{align*}
W_1 &= (p_{\mu_1} + p_{\nu_1})^2 \\
W_2 &= (p_{\mu_2} + p_{\nu_2})^2
\end{align*} \]

Quartic equation
Reconstructed event distribution

★ The mass of the heavy resonance can be determined:

Reconstructed \( p_{x}^{\nu 1} \)

★ Strong correlation between the true and reconstructed \( p_{x}^{\nu 1} \)
Can we determine the spin of the heavy resonance?

Not realistic for early LHC!

It requires \( \sim O(4000) \) events to verify the flat distribution.

Not easy!
Polarization correlates with angle between top quark spin and charged lepton momenta

\[ \frac{d\Gamma(t \rightarrow b\ell \nu)}{d\cos \theta} = \frac{1}{2} \left( 1 + \frac{N_+ - N_-}{N_+ + N_-} \cos \theta \right) \]

Polarization of the top quarks can be determined to be right-handed. If the top quarks are from a scalar decay, then

Right-handed top quark

\[ \frac{1}{2} (1 + \cos \theta) \]

are roughly 30 events required to distinguish from unpolarized case.

Charged lepton typically follows top quark spin.
A sextet scalar may be a long shot but offers good discovery potential due to its enhanced cross section relative to EW scale new physics; 30 events are sufficient. Naturally large same-sign dilepton rates allow background rejection.

**Search strategy**

\[ tt(\mu^+\mu^+) \quad \sigma_{\mu^+\mu^+} \gg \sigma_{\mu^-\mu^-} \quad \text{MT2} \]
Backup Slide
★ Rate for $\mathcal{L} =$

- Inelastic proton-proton reactions:
  - bottom quark pairs:
  - top quark pairs:
    - $W \rightarrow \ell \nu$
    - $Z \rightarrow \ell \ell$
  - Higgs boson (150 GeV)
  - Gluino, Squarks (1 TeV)

(1) LHC is a factor
QCD corrections for single color sextet scalar production are available

Han, Lewis, McElmurry

\[ \frac{d\sigma}{d\lambda} (\text{pb}) \]

\[ m_D \text{ (GeV)} \]
Among the top quark decay products, the charged lepton is maximally correlated with top quark spin.

\[
\frac{1}{\Gamma} \frac{d\Gamma(t \to b\ell\nu)}{d\cos \theta} = \frac{1}{2} \left( 1 + \frac{N_+ - N_-}{N_+ + N_-} \cos \theta \right)
\]

\(\theta\) is the angle, in the top quark rest frame, between the direction of the charged lepton and the spin of the top quark. In the helicity basis, top quark polarization is

(a) left-handed top \(\begin{pmatrix} 1 - \cos \theta \end{pmatrix}\) \hspace{1cm} (b) right-handed top

\[
\begin{array}{cccc}
\hline
\begin{array}{c}
\overset{\text{t}}{\bullet} \swarrow \searrow \nwarrow \nearrow \\
\end{array} & \begin{array}{c}
\overset{\text{b}}{\bullet} \swarrow \searrow \nwarrow \nearrow \\
\end{array} & \begin{array}{c}
\overset{\text{l}^+}{\bullet} \swarrow \searrow \nwarrow \nearrow \\
\end{array} & \begin{array}{c}
\overset{\text{W}^+}{\text{(left-hand)}} \swarrow \searrow \nwarrow \nearrow \\
\end{array} \\
\hline
\end{array}
\]