Searches for leptoquarks in CMS

EPS-HEP2019 - 10-17 July 2019 - Ghent

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(Some) general ideas Beyond the Standard Model and the Leptoquark

Can $SU(3) \times SU(2) \times U(1)$ originate from a larger symmetry group? → Grand Unified Theory

Can fermions be made of more fundamental objects? → Compositeness

Can a symmetry exist between fermions and bosons? → Supersymmetry

Quarks and leptons unified in a fermionic multiplet with lepton-quark interaction mediated by new gauge bosons

Bound states of fundamental constituents may decay to a quark and a lepton

Possible decay of sparticles to a quark and a lepton (see e.g. R-parity violation scenario)

These theories foresee new bosons that carry both lepton and baryon number: the "Leptoquarks" (LQ)
**LQ @ CMS and link with the B-physics anomalies**

- LQ searches already well-motivated and carried out within CMS
- Recent enhanced interested due to a series of anomalies in the B-physics sector

**Standard Model process**

Quark level transition $b \rightarrow s \ell \ell$

$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}e^+e^-)}$

$R_K, R_{K^*}$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis:

$B^0 \rightarrow \phi\mu^+\mu^-$

$\sim 4 \sigma$ from combined results  [arxiv:1903.09578]

Quark level transition $b \rightarrow c\ell\nu$

$R_{D^{(*)}}^{\tau/\ell} = \frac{\Gamma(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \rightarrow D^{(*)}\ell\bar{\nu})}$

$R_D, R_{D^*}$ combined $\sim 3 \sigma$ deviation

HFAG


- In the context of B-phys anomalies:
  - Couplings to 2nd, 3rd lepton generations favoured
  - Upper limit on new physics scale: 9 (80) TeV for $b\rightarrow c\ell\nu$ ($b\rightarrow s\ell\ell$) transition ([arXiv:1706.01868])
  - Anomalies clarified by beginning of Phase 2 ([arXiv:1709.10308])
Properties of the LQ

Interaction through the coupling $\lambda$

- Fractional electric charge: $\pm 5/3, \pm 4/3, \pm 2/3, \pm 1/3 \, e$

- **Scalar or Vector**
  
  $\sigma$ depends only from mass for scalar LQ
  
  $\rightarrow$ scalar LQ traditionally considered in searches

  \[ \Gamma_S = \frac{|\lambda|^2}{16\pi} m_{\text{LQ}} \]  
  
  Narrow resonances
  
  \( (\Gamma/M \lesssim 10\%, \lambda \lesssim 2.5) \)

  Vector LQ is gaining interest to explain $B$-meson anomalies
LQ production and decay

Pair LQ prod.  

\[ \text{BR}(LQ \rightarrow \ell q) = \beta \quad \beta \text{ unknown} \]

Single LQ prod.

Today

\[
\begin{align*}
qq\nu\nu & \\
jj\nu\nu & \\
bv\nu & \\
tt\nu &
\end{align*}
\]

\[
\begin{align*}
qq\ell\ell & \\
tt\mu\mu & \\
tt\tau\tau & \\
bv\tau\tau & \text{(and } b\tau\tau) \\
jj\ell\ell &
\end{align*}
\]

\[
\begin{align*}
qq\ell\nu & \\
jj\ell\nu &
\end{align*}
\]
LQLQ in the $qq\nu\nu$ (10.1103/PhysRevD.98.032005)

$E_T$+jets signatures typical of SUSY searches

**Event selection**

- jet: $p_T > 30$ GeV, $|\eta| < 2.4$
- $E_T > 250$ GeV for $HT < 1$ TeV, else $E_T > 30$ GeV
- $\Delta\phi(E_T,j_{1,2,3,4}) > 0.3$
- veto on leptons

- $HT = \sum pT_{T_j}$
- MT2 is a generalization of MT for decay chain with 2 unobserved particles

$$M_{T2}(m_X) = \min_{pT_{T_{j1}},pT_{T_{j2}},p_{T_{T}}} \left[ \max\left(M_T^{(1)},M_T^{(2)}\right) \right]$$

Main backgrounds:

- $Z + jets$ background from $Z \rightarrow \ell\ell$ events
- "Lost leptons" background ($W + jets$, $t\bar{t}$) from events with 1 lep (e or $\mu$)
Results of LQLQ in the qqvv final state

Vector LQ
Scalar LQ

LQLQ → vvjj
LQLQ → vvbb

<table>
<thead>
<tr>
<th></th>
<th>Scalar LQ</th>
<th>Vector LQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQLQ → vvjj</td>
<td>980</td>
<td>1790</td>
</tr>
<tr>
<td>LQLQ → vvbb</td>
<td>1100</td>
<td>1810</td>
</tr>
<tr>
<td>LQLQ → vvtt</td>
<td>1020</td>
<td>1780 (β = 0)</td>
</tr>
</tbody>
</table>

Preferred scenario for B-phys. anom.

LQLQ in the $t\bar{t}\mu\mu$ final state  

Event selection

- $2\mu$+jets
- $N_\ell \geq 3$
- $N_\ell = 2$
- $M_{LQ}$
- $p_T \geq 30$ GeV

Muons, Electrons, Jets

- $|\eta| \leq 2.4$

Background estimation

- $2e$+jets
- $N_{\mu} = 0$

Higgs, Diboson, Single $t$

CMS

35.9 fb$^{-1}$ (13 TeV)
Results of LQLQ in the $tt\mu\mu$ final state in combination with $tt\tau\tau$ (10.1140/epjc/s10052-018-6143-z) and $bb\nu\nu$ (10.1103/PhysRevD.98.032005) searches.
LQLQ in $b\bar{b}\tau\tau$ (10.1007/JHEP03(2019)170) and $\tau LQ$ in $b\tau$ (10.1007/JHEP07(2018)115) final states

- $Z, W + \text{jets}, t\bar{t}$ From simulation, after normalization to data $Z, W, t\bar{t}$ enriched control regions
- **Multijet** data-driven
Results of LQLQ in bb\tau and \tau LQ in b\tau final states

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{CMS results for the production cross-section of LQLQ in bb\tau and \tau LQ in b\tau final states. The plot shows the cross-section as a function of the LQ mass.}
\end{figure}

**Pre**selection

- ≥ 2 ℓ, pT>53 GeV  |η| < 2.4
- ≥ 2 j, pT>50 GeV  |η| < 2.4
- E_T > 55 GeV (in ℓνjj)

A search region is defined for each mass point (cut and count)

**Event variables**

- M_µµ > 50 GeV
- S_T = \( \sum pT \ell_1 + \ell_2 + j_1 + j_2 > 300 \text{ GeV} \)
- M_{µj}^{min} smallest of M_{µj} pairs minimizing LQ-LQ mass diff

Similar selection for µνjj

Drell-Yan from simulation normalized to Z-peak

tt data-driven estimation

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**Figure**: CMS plots showing the distribution of events as a function of the minimum mass (m_{ej}^{min}) and the minimum mass (m_{µj}^{min}) with different mass points and uncertainties.
Results of LQLQ in $jj\ell\ell$ final states

$BR(LQ \rightarrow \ell q) = \beta$

$BR(LQ \rightarrow \nu q) = 1 - \beta$
Summary and conclusions

- Searches for LQ are well-motivated → CMS has a vast physics program to look for them
- Recent results in B-meson sector (to be confirmed) indicate signs of potential Lepton Flavor Universality violation:
  - new LQ-like particles with O(1) TeV mass
  - higher generations of fermions favored
- While (eagerly) awaiting new results from LHCb and Bell II we are carrying out new measurements to test all the possible scenarios
Backup slides
Analysis strategy

Event selection

- jet: $p_T > 30$ GeV, $|\eta| < 2.4$
- $E_T > 250$ GeV for $HT < 1$ TeV, else $E_T > 30$ GeV
- $\Delta \phi (E_T, j_1, 2, 3, 4) > 0.3$
- veto on leptons

- $HT = \sum p_T j_i$
- MT2 is a generalization of MT for decay chain with 2 unobserved particles

$$M_{T2}(m_X) = \min_{p_T^{(1)}, p_T^{(2)}} \max \left( M_T^{(1)}, M_T^{(2)} \right)$$

Event categorization in $N_j$, $N_b$, HT and MT2 (or jet pT for evt with 1 jet)
LQLQ → ττtt

Category $\ell \tau_h$

- OS $\ell \tau_h + \text{jets}$
- SS $\ell \tau_h + \text{jets}$

Category $\ell \tau_h \tau_h$

<table>
<thead>
<tr>
<th>Jet selection</th>
<th>$\geq 4$ jets</th>
<th>$\geq 3$ jets</th>
<th>$\geq 3$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\text{miss}}$ selection</td>
<td>$p_T^{\text{miss}} &gt; 100$ GeV</td>
<td>$p_T^{\text{miss}} &gt; 50$ GeV</td>
<td>$p_T^{\text{miss}} &gt; 50$ GeV</td>
</tr>
<tr>
<td>$\tau_h$ selection</td>
<td>$p_T &gt; 100$ GeV</td>
<td>—</td>
<td>$p_T^{\tau_1} &gt; 65$ GeV, $p_T^{\tau_2} &gt; 35$ GeV</td>
</tr>
<tr>
<td>$b$ tagging</td>
<td>$\geq 1$ $b$ tag</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$S_T$ selection</td>
<td>—</td>
<td>—</td>
<td>$S_T &gt; 350$ GeV</td>
</tr>
</tbody>
</table>
### Signal extraction

<table>
<thead>
<tr>
<th>Category $\ell \tau_h$</th>
<th>$\ell \tau_h + \text{jets}$</th>
<th>$\ell \tau_h + \text{jets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS $\ell \tau_h + \text{jets}$</td>
<td>$p_T^1$ in two $S_T$ bins (&lt;$\geq$1.2 TeV)</td>
<td>number of events (sensitive to mLQ&lt;$0.4$ TeV)</td>
</tr>
<tr>
<td>SS $\ell \tau_h + \text{jets}$</td>
<td>jet triplet combination with the best top mass</td>
<td></td>
</tr>
</tbody>
</table>

#### Diagrams

- **CMS**
  - Data
  - $t\bar{t}$ & W+jets
  - $Z$+jets
  - Single $t$
  - LQ, 600 GeV
  - LQ, 800 GeV

**Note:**
- $t\bar{t}$ & W+jets misidentified as $\tau_{\text{had}}$
- Estimated as control region in data.

**Legend:**
- $\tau_{\text{high}}$
- $S_T$

**Events/bin**
- $35.9$ fb$^{-1}$ (13 TeV)

**Data/Prediction**
- $p_T^1$ [GeV]
Define a control region (CR) inverting $\tau$ isolation cut

- Subtract non-contribution
- Reweight shape and normalization using MC information

$t\bar{t}$ and $W + jets$ background estimation
Results

Vary $\beta$ from 0 to 1 to set limit on $\beta$ vs. $m_{LQ}$

Lower limit on $m_{LQ} = 900$ GeV

This exclusion comes from sbottom search arXiv:1705.04650 (assuming LQ can decay either $\tau\tau$ or $\nu\bar{b}$)