Direct Searches at the LHC in the context of B-anomalies
(ATLAS, CMS, LHCb)

Enrique Kajomovitz Ken
Technion, Israel Institute of Technology
Motivation

The recently measured B-anomalies may hint of Lepton Flavor Universality Violation in nature

- $R(K^{(*)})$ i.e. $b \rightarrow sll$ (neutral current): $\mu$ deficit vs. $e$
- $R(D^{(*)})$ i.e. $b \rightarrow c\ell\nu$ (charged current): $\tau$ enhanced

If true, these anomalies could be explained by the presence of new heavy particles with non-universal flavor couplings

- Candidates: leptoquarks, heavy vector bosons, . . .
This talk

- ATLAS, CMS and LHCb have rich programs in search resonant or non-resonant of phenomena from physics beyond the Standard Model
  - The talk covers direct searches for leptoquarks, heavy vector resonances, and long-lived lepton flavor violating decays
  - Due to the short time for the talk - I will only discuss recent results with very few details on the searches

- Interpretations of the results is as general/generic as possible: model-independent limits, or on specific simplified models (e.g. on allowed masses or coupling strengths)
Lepto-quark models and production mechanisms

- LQs are hypothetical particles which mediate quark-lepton transitions
  - Color-triplet bosons (spin 0 or 1) with a fractional electric charge \( (+\frac{2}{3} \text{ (up-type)}, -\frac{1}{3} \text{ (down type)}) \)
  - Parameters: \( m(LQ); \lambda \) - Yukawa coupling to the lepton-quark; \( B \) - relative coupling that control the branching fractions to \( LQ \rightarrow ql \) or \( LQ \rightarrow q\nu \)
  - Models with third generation LQs and cross-generational mixing are favored by the anomalies

- Production
  - Pair production: A the LHC typically dominates, strong interaction → it is largely independent of \( \lambda \)
  - Scalar / Vector: Can have large difference in cross section (x5-20 in Vector models)
  - Single production could be important for large \( \lambda \) or large mass where pair production may be inaccessible

- Searches - in general: look for events with high-pT pairs of jets and pairs of leptons (ll/\( lv \))
LQ-Pair production decaying to third generation quarks and leptons

- **Final state with $\geq 2$ b-jets and 1 $\tau_{\text{had}}$**
- **Scalar** (targets $B = 0.5$): Exclusion up to 1.25 TeV for scalar LQLQ - for both LQ$^u/d$
- **Vector**: Exclusion up to 1.5 / 1.8 TeV for vector LQLQ in minimal / Yang–Mills case

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**ATLAS material**

**Scalar**

**Vector (YM)**
Summaries - ATLAS third generation LQ searches

- Systematic coverage gives a strong mass reach over the whole range of branching fractions
LQ single + pair production to third generation quarks and leptons

- Simultaneous search for single + pair production
- Select events with final states $t\tau nb$ or $t\nu\tau$
- Interpretation for scalar and vector LQ
- Assume equal $\lambda$ for $t\tau$, $b\nu$, $t\nu$, $b\tau$ ($B=0.5$)

![Diagram of LQ production](image)

<table>
<thead>
<tr>
<th></th>
<th>LQ$_S$ (TeV)</th>
<th>LQ$_V$ $k = 0$ (TeV)</th>
<th>LQ$_V$ $k = 1$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\lambda$ = 1.5</td>
<td>0.95 (1.03)</td>
<td>1.29 (1.39)</td>
<td>1.65 (1.77)</td>
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<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
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<tr>
<td>Single</td>
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<tr>
<td></td>
<td>0.55 (0.56)</td>
<td>0.75 (0.81)</td>
<td>1.03 (1.12)</td>
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<tr>
<td></td>
<td>1.5</td>
<td>1.25 (1.35)</td>
<td>1.20 (1.29)</td>
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<tr>
<td></td>
<td>2.5</td>
<td>1.41 (1.53)</td>
<td>1.41 (1.53)</td>
</tr>
<tr>
<td>Pair+Single</td>
<td>0.98 (1.06)</td>
<td>1.02 (1.10)</td>
<td>1.34 (1.46)</td>
</tr>
</tbody>
</table>
LQ-Pair production with third generation quarks and first or second generation Leptons

- Final state with hadronically decaying top and a b-jet >=4 jets (1-b jet), MET, and exactly one lepton
- Specialized neural networks (S and V case) for Signal and background classification
- Targets: B = 0.5
- Vector and scalar interpretation

![Diagram](https://via.placeholder.com/150)
Summaries - ATLAS LQ with third generation quarks and lower generation leptons

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

March 2022

[ATLAS-CONF-2022-009]
Inclusive non-resonant multilepton search

- Inclusive search for non-resonant signals with multi-leptons
  - $\text{LQLQ} \rightarrow \text{tt} (l = e/\mu/\tau)$, only scalar LQ, $B = 1$
  - Model-independent SRs
  - SR in 7 channels: Leptons (1-3+) tops (0-2)
New heavy particles with flavor preferential couplings may be involved in the anomalies.

$W' \rightarrow tb$: Final state reconstructed from top-tagged large-R jet + b-jet.

ATLAS considers $W_R$ only.
Z’ with top-philic couplings

Final state with four tops:

- Z’ → 2 large-R jets
- 1 e/µ + >2 b-jets + 2 jets outside the large-R jets

ATLAS-CONF-2021-048
Heavy Boson Resonance Combination of searches

- Many different scenarios can be expressed within HVT
- This is powerful
  - Allows easily combining the results of different searches
  - Explore scenarios that we did not explicitly search for (from simple gauge group extensions, techni-color like theories, fermio-phobic scenarios, etc)
  - Statistical combination improves sensitivity; small real excesses add up, large independent fluctuations cancel out
Pair produced Vector Like Leptons in $3b + 2(\tau/\nu)$ final states

The 4321 model: UV-complete model that can explain the anomalies

- Search uses final states with 3 b jets and two third generation leptons
- Graph neural networks to learn kinematics in large jet multiplicity environment

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**CMS-PAS-B2G-21-004**
Long Lived Particles with flavor violating decays

Search for a long-lived particle decaying to $e\mu\nu$

- Three Production mechanisms are considered (direct, H, W)

Selection:

- Isolated opposite charge $e/\mu$
- High quality displaced vertex ($d_{sig} > 15$)
- BDT
- $M_{corr}$ (mass) from based on angle of $e\mu$ and $\nu$
- Simultaneous fit to $M_{corr}$ and $d_{e\mu}$
Summary

B-anomalies → motivation for a broad range of searches at LHC

- Main suspects LQs: ATLAS and CMS have a systematic program exploring a whole range of scenarios: Pair, and single production, third gen and mixed, scalar and vector
  - No BSM found → Limits up to ~2 TeV
- $W'/Z'$
  - ATLAS and CMS programs with boson, leptons, and quark decays (different productions modes as well)
    - Third gen specific searches
    - Combination of VV, VH, ll, lv searchees