ATLAS & CMS Searches for LeptoQuarks

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Introduction

- LQs are hypothetical particles which mediates quark-lepton transitions, occurring naturally in models of unification and in models of quark-lepton substructure.
- These are color-triplet bosons (spin 0 or 1) with a fractional electric charge (+2/3, -1/3 for Up or Down types).
- They have received considerable interest since could explain the LFU anomalies in B meson decays mediated by charged or neutral currents, observed by Babar, Belle & LHCb.
- Models with third generation LQs and cross-generational mixing are favored by the anomaly.
Searches for LQs at the LHC

Combinations covered by ATLAS & CMS Searches (not all covered here)

At LHC pair-production is the dominant mechanism, non-resonant production not covered in this talk

LQs are characterized by their Yukawa coupling to the lepton-quark $\lambda$, or the relative couplings $\beta$ that control the branching fraction to $\text{LQ} \to q\ell$ or $\text{LQ} \to q\nu$

Search strategy is based on simplified signature-based searches with various $\beta$ scenarios including diagonal and cross-generational couplings

A typical LQ search look for events with high $p_T$ objects in the final state including a pair of jets and a pair of leptons or a charged lepton and a neutrino ($p_T^{\text{miss}}$).

Focus on scalar LQ in this talk

All LQ results can be found in the following links

CMSPublicResults  ATLASPublicResults
Search for single and pair produced 3\textsuperscript{rd} generation LQs (CMS)

- Full Run 2 Single and Pair produced scalar or vector LQs searched simultaneously [CMS-EXO-19-015](https://cds.cern.ch/record/2683958) with the signatures ($t\tau\nu$) & ($t\bar{b}\tau\nu$) respectively

- Search done as a function of the LQ mass and $\lambda$ in a fully hadronic signature including boosted top topologies

- Discriminating variable $S_T$ corresponding to the scalar $p_T$ sum of the top candidate, taus and the $p_T^{miss}$ in the final state

- Main background comes from misidentified tau leptons, and is estimated entirely using data driven methods

- The best limits are found for scalar LQ masses combining single and pair production of $\sim 1$ TeV for $\lambda \in [1.5, 2.5]$

- The VLQ search can exclude a large fraction of the parameter space preferred by LFU
3rd generation scalar LQ searches (ATLAS)

- Full Run 2 result \textit{arXiv:2101.11582v1} targeting down-type leptoquarks in the $t\tau$ decay channel

- 6 different final states corresponding to 7 SR are considered in the search, in addition 15 CR and 6 VR are used to estimate and validate the different backgrounds respectively

- Background sources vary significantly depending on the signature considered but main contributions come in general from $t\bar{t} + X$

- Missmodelings in the $t\bar{t}$ background are corrected using data driven estimates

- Strong limits are set on the mass of the LQ exclusively decaying into $t\tau$ of $\sim 1.43$ TeV
3rd generation scalar LQ searches (ATLAS)

- Full Run 2 analysis described in arXiv:2101.12527v1 interprets the search for pair-produced $b$-squarks decaying into $bb + E_T^{miss}$ in terms of LQs.
- Signal regions A & B requiring $E_T^{miss} > 250$ GeV are combined for the LQ analysis.
- In SR B a BDT discriminant is trained using different kinematic variables, requiring $w_{xGb} > 0.85$.
- The main background come from $Z+jets$ and $W+jets$ production.
- Limits on the LQ mass are set depending on $B(LQ_3^d \rightarrow tt)$ ranging from 400 GeV to 1.25 TeV.

Limits are set on $B(LQ_3^d \rightarrow tt)$ as a function of $m_{LQ}$.
3rd generation scalar LQ searches (ATLAS)

- Full Run 2 result ATLAS-CONF-2021-008 targeting a LQ benchmark model and top-squarks comprising final states with b-jets, \(\tau\)-leptons and missing momentum.
- Single tau signal region targeting LQ search in the \(b\tau bv\) final state, with the tau decaying to hadrons only.
- Limits are set on \(B(LQ^d_3 \to t\tau)\) and \(B(LQ^u_3 \to b\tau)\) as a function of \(m_{LQ}\), with \(\lambda = 0.3\).
- Considerably extending the reach of previous ATLAS result JHEP 06 (2019) 144.
Full Run 2 Limits on the branching ratio of a third generation leptoquark are shown as a function of its mass. For up (left) and down-type (right).

New analyses greatly improve the exclusion limits of those using the partial Run 2 dataset.

$b\tau\nu$ analysis ATLAS-CONF-2021-008 sensitive to both leptoquark types.
ATLAS Summary plots

- Full Run 2 Limits on the branching ratio of a third generation leptoquark are shown as a function of its mass. For up (left) and down-type (right).
- New analyses greatly improve the exclusion limits of those using the partial Run 2 dataset.
- $btbv$ analysis ATLAS-CONF-2021-008 sensitive to both leptoquark types.

ATLAS/CMS comparison @ B=0.5
3rd generation scalar LQ searches (CMS)

- Partial Run 2 results using 35.9 fb⁻¹ of data JHEP03(2019)170
- The search was performed in the fully hadronic final state with two taus and two non-tagged jets
- b-jets are used to obtain tt̅-enriched CR for the estimation of the background rate in the SR and QCD contribution is estimated with the ABCD method
- A variable $S_T^{MET}$ equal to the scalar sum of the $p_T$’s of the two hardest jets, the $\tau$’s and the missing $p_T$ is used as a discriminating variable
- Two similar searches were performed previously with smaller datasets JHEP03(2017)077 & JHEP07(2017)121
Search for LQ coupled to different generations (CMS)

- Partial Run 2 result using 35.9 fb\(^{-1}\) of data [Phys. Rev. Lett. 121 (2018) 241802]

- This analysis combines events from two categories assuming a leptonically and a hadronically decaying top in category A and an inclusive category B, using \(m^{\text{rec}}_{LQ}\) and \(S_T\) as discriminant variables resp.

- Leptoquarks decaying exclusively into \(t\mu\) are searched for and excluded up to masses of 1420 GeV

- This result is combined with previous results on LQs decaying into \(tt\) [Eur. Phys. J. C78, 707 (2018)] and \(b\nu\) [Phys. Rev. D98, 032005 (2018)]

- In the absence of a deviation from the SM expectations limits are set in two different scenarios where the LQ can decay also to \(tt\) and \(b\nu\)
Search for LQ coupled to different generations (ATLAS)

- In JHEP10(2020)112 searches for leptoquarks in final states of the form $lQLQ$ with $Q = c, b$ were performed for the first time.
- This analysis considers LQs that can mix quarks from different generations with $e, \mu$.
- For these channels, the analysis use $c$ or $b$-tagged jets, giving priority to $b$-tagging over $c$-tagging.
- Three signal regions are used: $b$, $c$ (tag) and untag (for $c$-jets) and 2,1 and 0-tags for $b$-jets.
Search for LQ coupled to different generations (ATLAS)

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- Three signal regions are used: $b$, $c$ (tag) and untag (for c-jets) and 2,1 and 0-tags for b-jets.
- LQ masses above 1.6 TeV can be excluded in the absence of a significant deviation above the SM expectation.
• Full Run 2 Limits on the branching ratio of mixed-generation leptoquarks are shown as a function of its mass. For up (left) and down-type (right)
• Limits ranging from ~ 500 GeV to 1.6 TeV depending on the BR.
• Down type LQ searches not described in this talk
Search for LQ production and decay to DM (CMS)

• Partial Run 2 result using 77.4 fb\(^{-1}\) of data [Phys. Let. B 795(2019) 76-99]
• In this particular scenario, proposed in “The coannihilation codex” the LQ couples to a fermionic dark matter particle
• Which subsequently decays into low energy SM particles through an offshell LQ
• The LQ is of the second generation, the muon is used as a proxy to get peak on the invariant mass of \(\mu + j\)
Summary

• Results for scalar leptoquark searches made by CMS & ATLAS using Run 2 data have been shown.
• These searches target many different final states including cross generational ones mixing quark and leptons of different generations.
• No significant excess over SM expectations have been found.
• Strongest limits to date have been obtained on leptoquark masses, couplings and branching ratios.
• Pushing the frontiers of the parameter space of BSM models where new physics could be hiding.
Backup
3rd generation scalar LQ searches

- Partial Run 2 result based on 36 fb$^{-1}$ [JHEP06(2019)144]
- Dedicated $btbt$ BDT combined $\tau_h \tau_l + \tau_h \tau_h$ based analysis sensitive to both down and up-type leptoquarks
- Other searched channels come from reinterpreted SUSY searches:
  - Bottom-squark pair production: $bb + E_T^{miss}$
  - Top-squark pair production: $tt + E_T^{miss}$ with 0 or 1 $l$
  - Top-squark decaying through $s$-taus: $\tau\tau b + E_T^{miss}$
1st & 2nd generation scalar LQ searches (CMS)

- Partial Run 2 results using 35.9 fb⁻¹ of data
- Very similar analysis strategies
- Both analyses include searches for up & down types leptoquarks, different variables are optimized as a function of the LQ mass in order to reach the largest sensitivity
- \( m_{\mu j}^{\text{min}} \) is obtained as the lower of the two mass combination values that minimizes the mass of the leptoquark
- Main backgrounds comes from Z+jets and \( t\bar{t} \) events and are estimated from MC and data respectively
Search for single LQ production (CMS)

- Partial Run 2 result using 35.9 fb⁻¹ of data JHEP07(2018)115
- Combines both semi-leptonic and fully hadronic two tau final states
- The main background is $t\bar{t}$, estimated from data and MC for $l\tau_h$ & $\tau_h\tau_h$ respectively
- The discriminating variable $S_T$ is defined as the scalar sum of the $p_T$ of all particles in the final state
- Largest systematic uncertainties comes from sub-dominant background normalizations and misidentified $\tau_h$ rate
- Exclusion limit result is presented as a function of the coupling to the lepton-quark and the mass of the leptoquark and compared with the favored region from the anomaly observed in B-decays by LHCb
1st & 2nd generation scalar LQ searches (CMS)

- Partial Run 2 results using 35.9 fb⁻¹ of data
- Very similar analysis strategies
- Both analyses include searches for up & down types leptoquarks, different variables are optimized as a function of the LQ mass in order to reach the largest sensitivity
- \( m_{LL}^{min} \) is obtained as the lower of the two mass combination values that minimizes the mass of the leptoquark
- Main backgrounds comes from \( Z + \) jets and \( t\bar{t} \) events and are estimated from MC and data respectively
- Combined limits on \( \beta \) as a function of the leptoquark mass are obtained, ranging from 200 GeV to more than 1.5 TeV
1\textsuperscript{st} & 2\textsuperscript{nd} generation scalar LQ searches (ATLAS)

- Full Run 2 analysis \textcite{JHEP10(2020)112} supersedes previous results with partial Run 2 data \textcite{Eur.Phys.J.C 79 (2019) 733} improving them by 300-400 GeV depending on the lepton flavor.

- LQ candidates are found by reconstructing their inv. mass $m_{ij}$, and $m^{\text{asym}}$ is used to define the analysis regions

$$m^{\text{asym}} = \frac{m_{ij}^{\text{max}} - m_{ij}^{\text{min}}}{m_{ij}^{\text{max}} + m_{ij}^{\text{min}}} < 0.4$$

- Dominant backgrounds arise from $DY + jets$ and $t\bar{t}$ production and are calculated from simulation, although some shape systematics are obtained from data.