ATLAS & CMS Searches for LeptoQuarks

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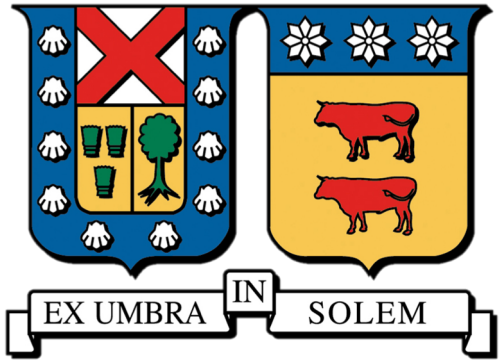
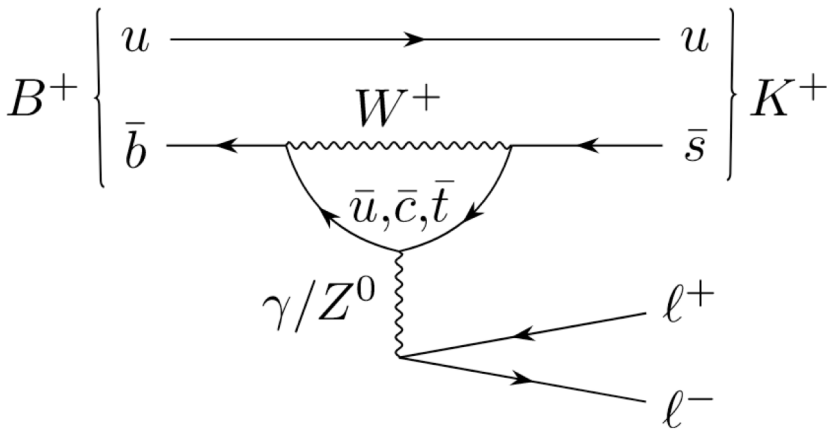
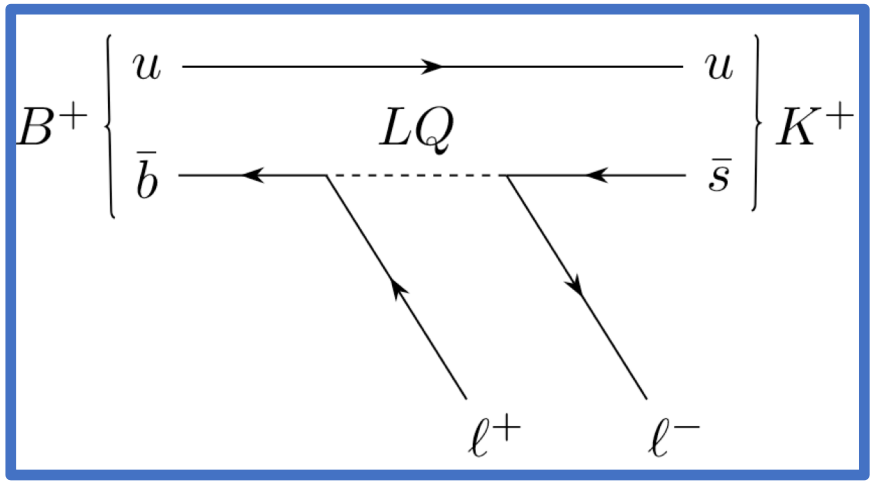
On behalf of the ATLAS and CMS collaborations







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)

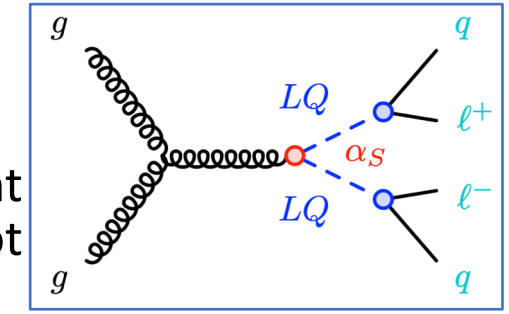
	u,d	c,s	t,b
e,ν	✅	✅	✅
μ,ν	✅	✅	✅
τ,ν	❌	❌	✅

Focus on scalar LQ in this talk

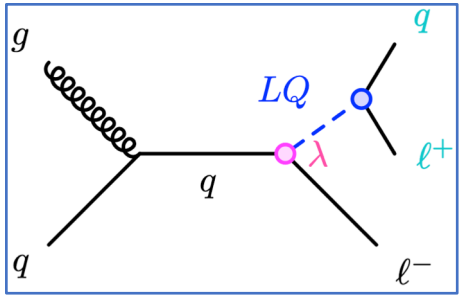
All LQ results can be found in the following links

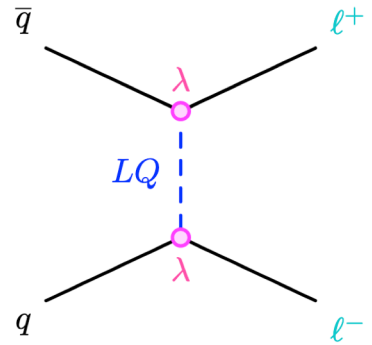
CMSPublicResults

ATLASPublicResults



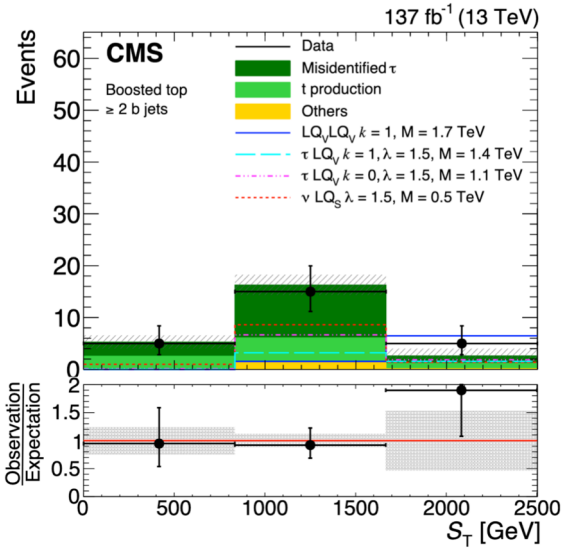
- At LHC pair-production is the dominant mechanism, non-resonant production not covered in this talk
- LQs are characterized by their Yukawa coupling to the lepton-quark $\boldsymbol{\lambda}$, or the relative couplings $\boldsymbol{\beta}$ that control the branching fraction to $\mathrm{LQ} \rightarrow \boldsymbol{ql}$ or $\mathrm{LQ} \rightarrow \boldsymbol{q\nu}$
- Search strategy is based on simplified signature-based searches with various $\boldsymbol{\beta}$ **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^{miss}).**

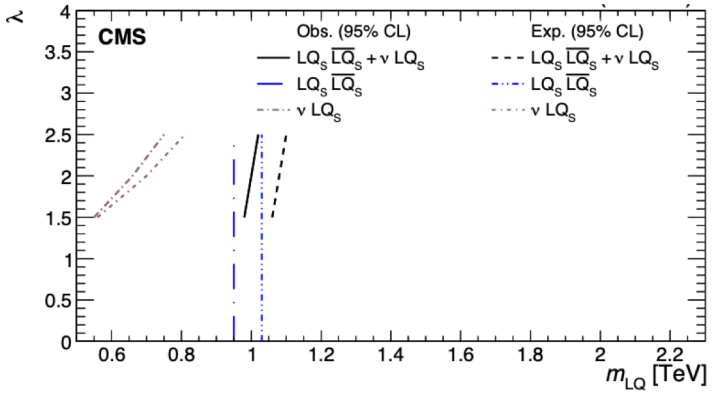


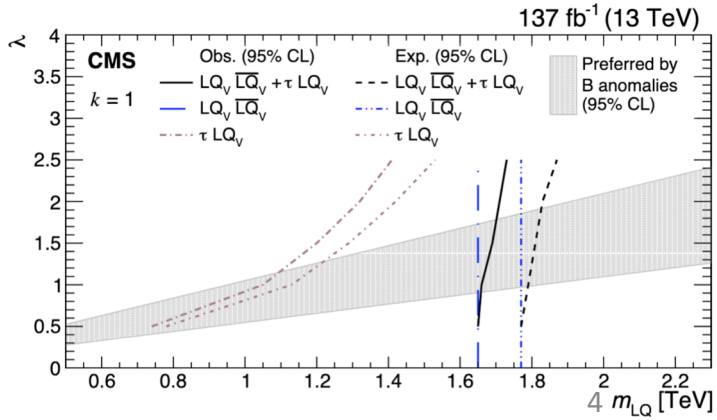


Search for single and pair produced 3rd generation LQs (CMS)

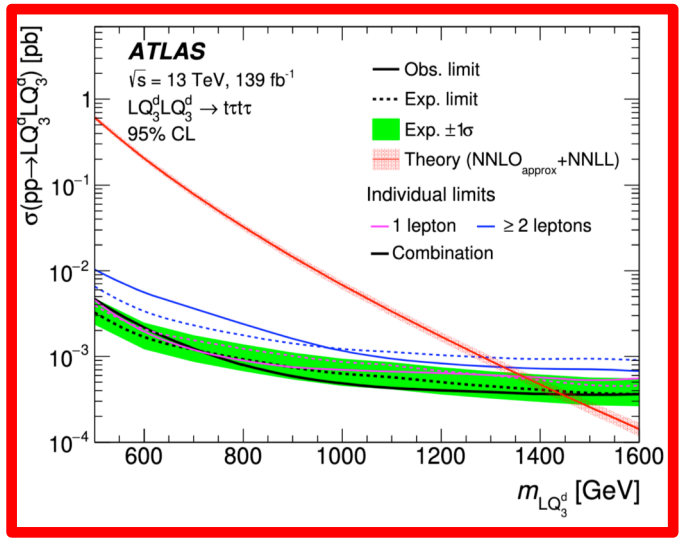
- Full Run 2 Single and Pair produced scalar or vector LQs searched simultaneously CMS-EXO-19-015 with the signatures ($\boldsymbol{t\tau\nu}$) & ($\boldsymbol{tb\tau\nu}$) respectively
- Search done as a function of the LQ mass and $\boldsymbol{\lambda}$ in a fully hadronic signature including boosted 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 ~1 TeV for $\lambda \in [1.5,2.5]$
- The VLQ search can exclude a large fraction of the parameter space preferred by LFU

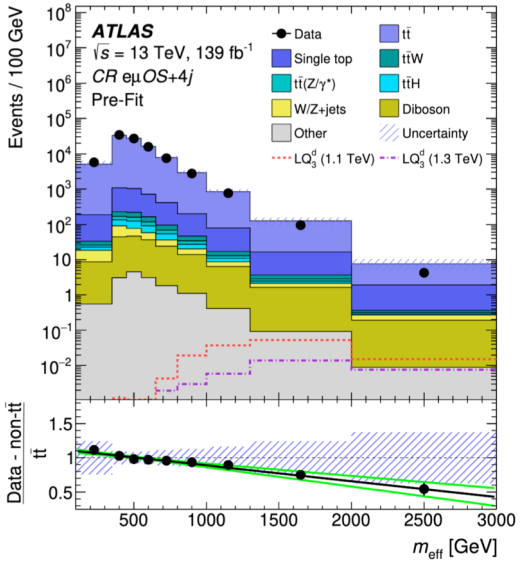




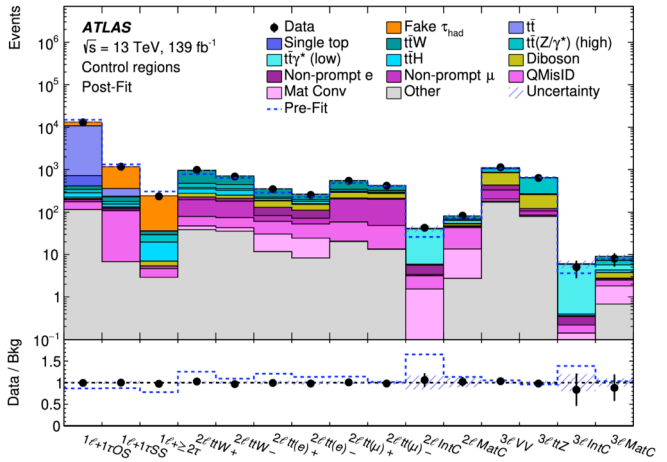


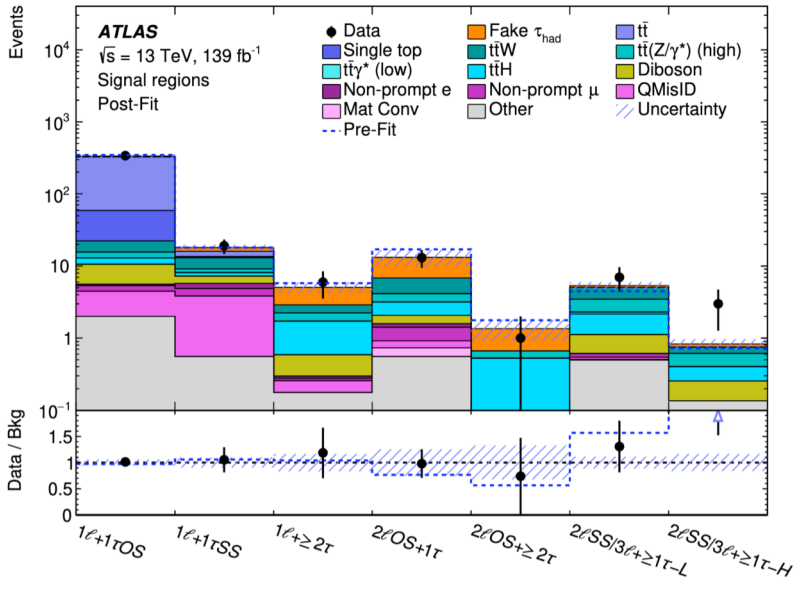
3rd generation scalar LQ searches (ATLAS)





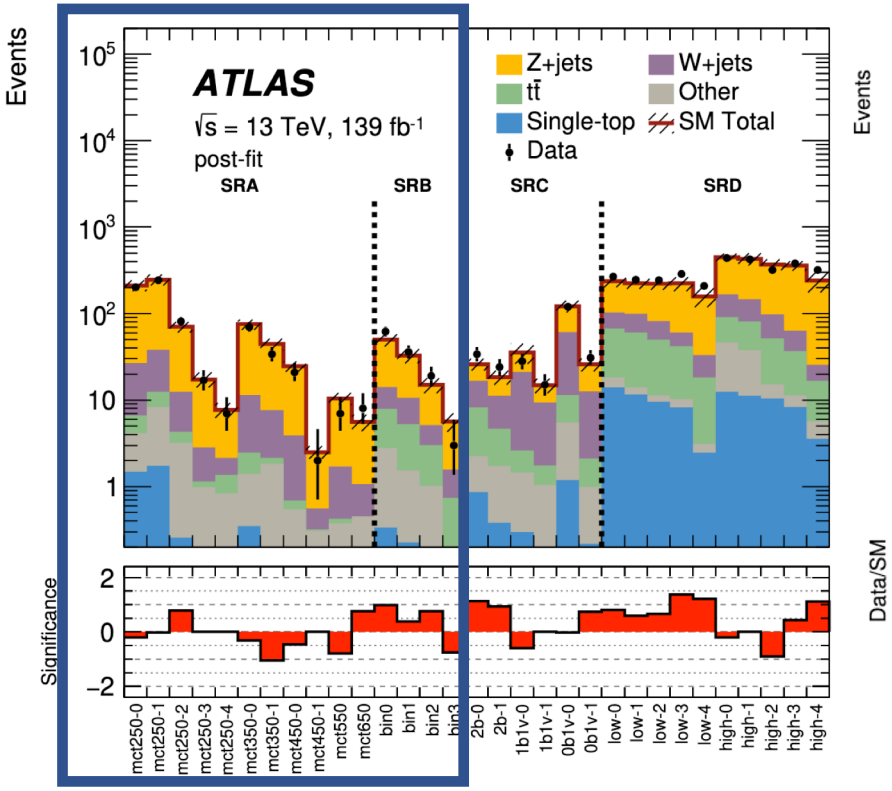
- Full Run 2 result arXiv:2101.11582v1 targeting down-type leptoquarks in the $t\tau$ decay channel
- 6 different final states corresponding to 7 SR are considered in the search, in addition 15 CR and 6 VR are used to estimate and validate the different backgrounds respectively
- Background sources vary 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

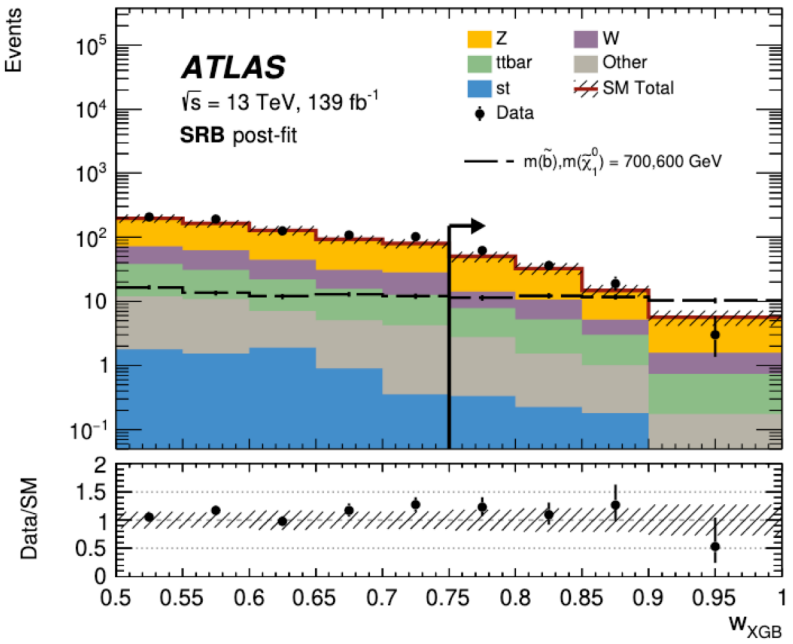


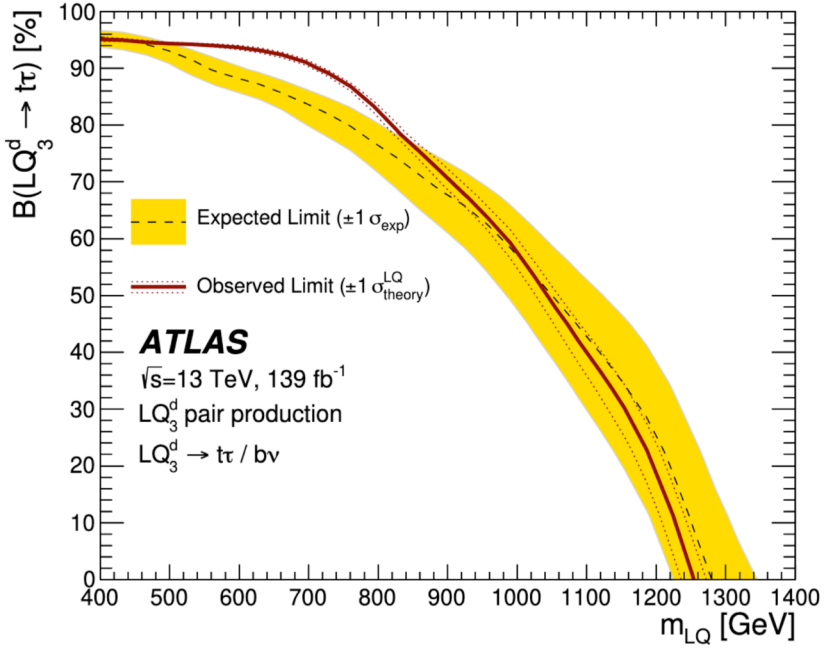


3rd generation scalar LQ searches (ATLAS)

- 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 $\boldsymbol{w_{xGB} > 0.85}$
- The main background come from ***Z+jets and W+jets*** production
- Limits on the LQ mass are set depending on $B(LQ_3^d \rightarrow t\tau)$ ranging from 400 GeV to 1.25 TeV

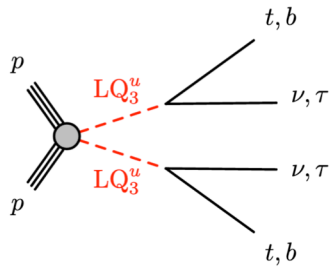


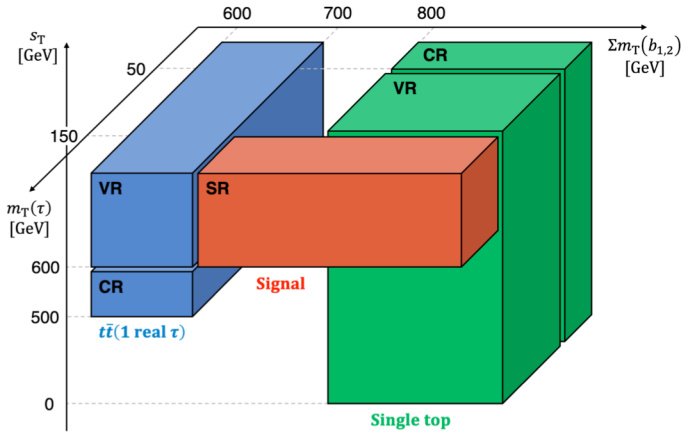


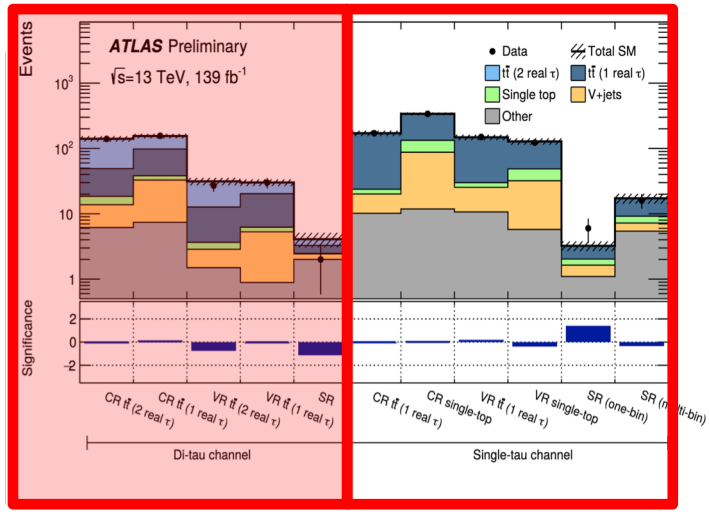


Limits are set on $B(LQ_3^d \rightarrow t\tau)$ as a function of m_{LQ}

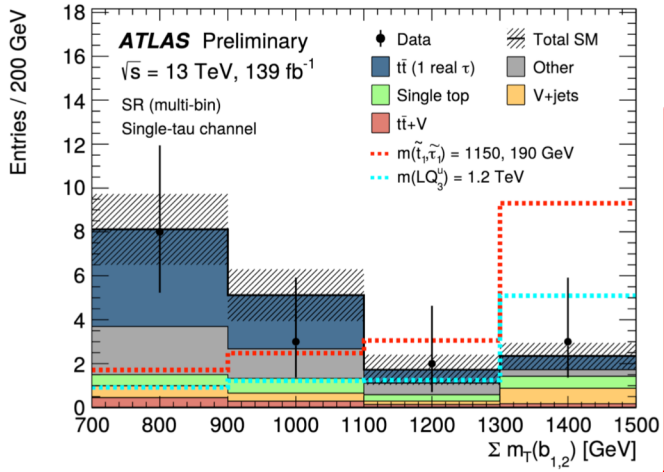
3rd generation scalar LQ searches (ATLAS)

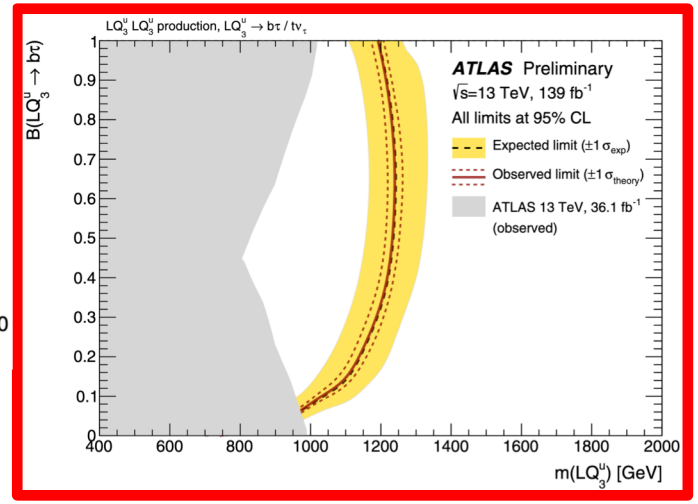






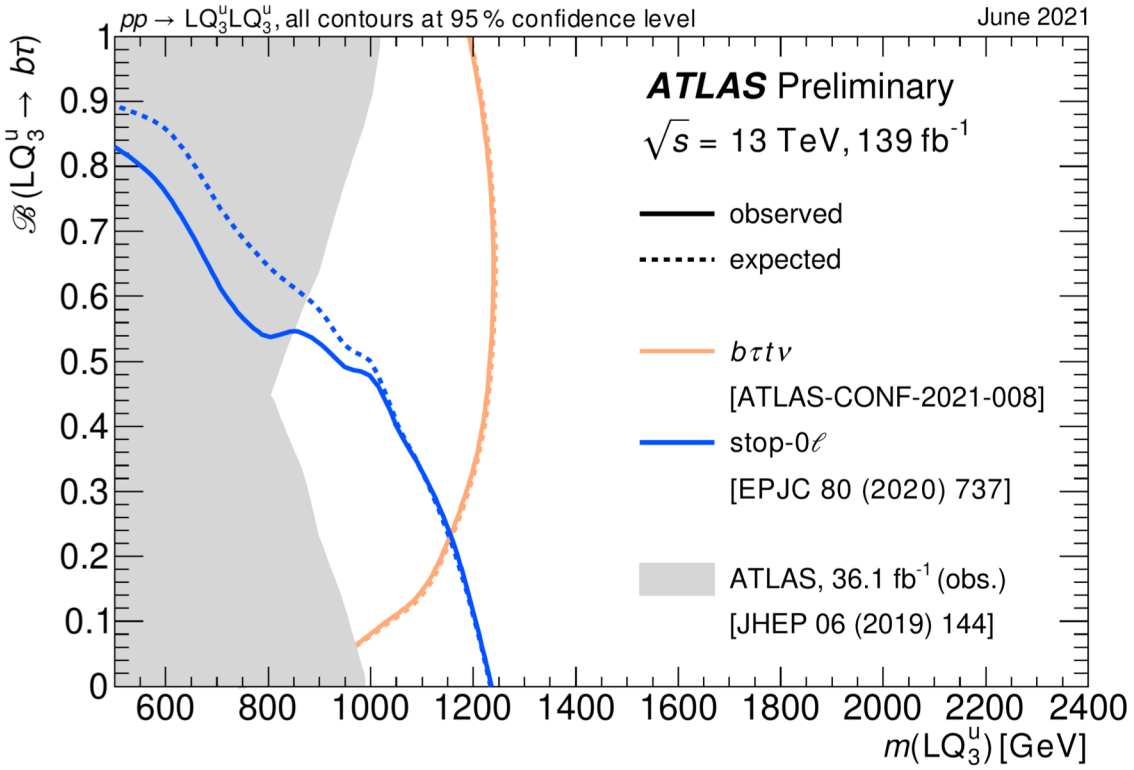
- Full Run 2 result [ATLAS-CONF-2021-008] targeting a **LQ benchmark** model and **top-squarks** comprising final states with b-jets, τ-leptons and missing momentum.
- Single tau signal region targeting LQ search in the $b\tau b\nu$ final state, with the tau decaying to hadrons only
- Limits are set on $\boldsymbol{B(LQ_3^d \rightarrow t\tau)}$ *and* $\boldsymbol{B(LQ_3^u \rightarrow b\tau)}$ as a function of m_{LQ}, with $\lambda = 0.3$
- Considerably extending the reach of previous ATLAS result [JHEP 06 (2019) 144]

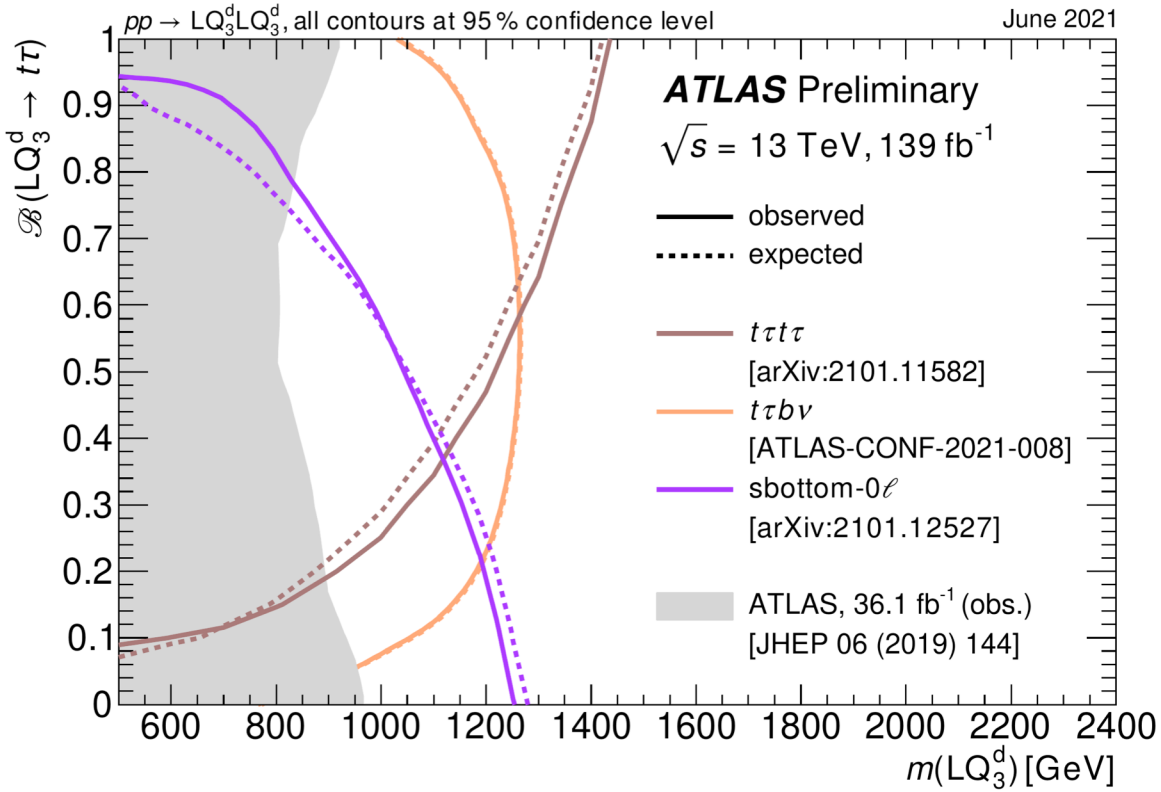




ATLAS Summary plots

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





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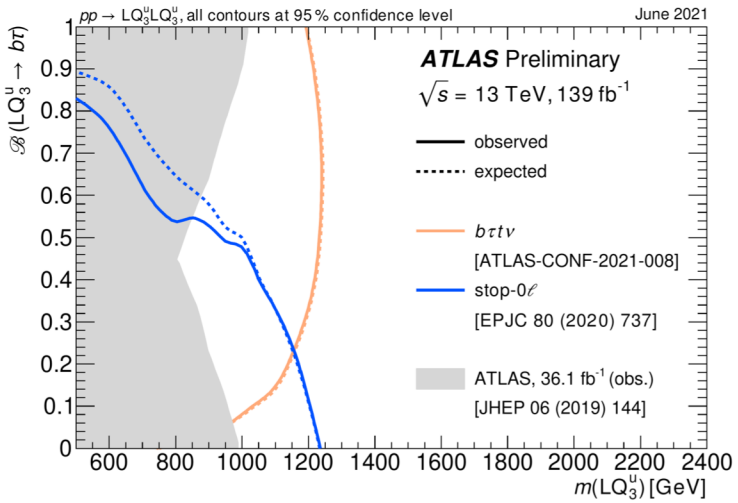

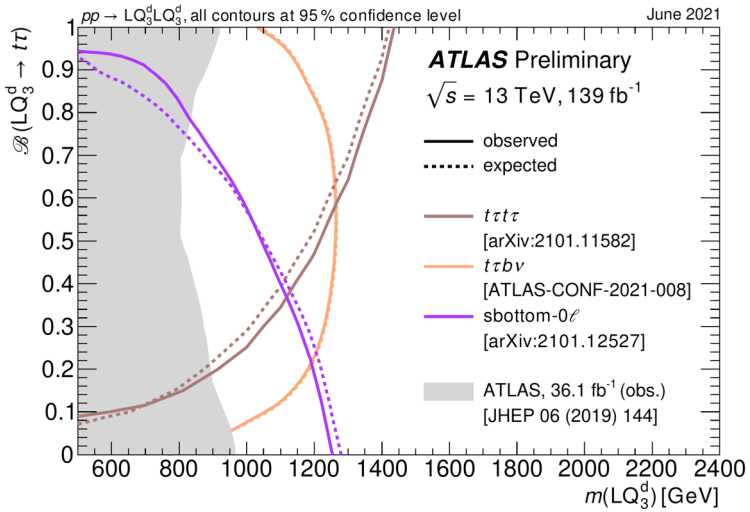

ATLAS/CMS comparison @ B=0.5

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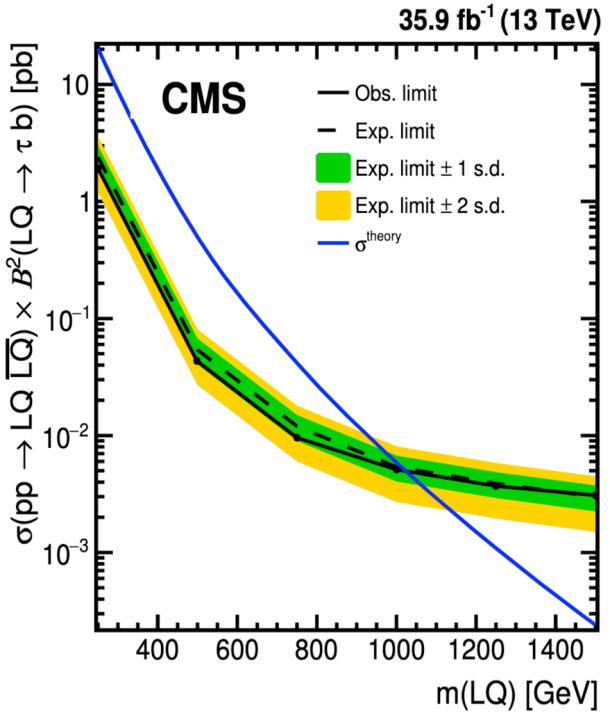
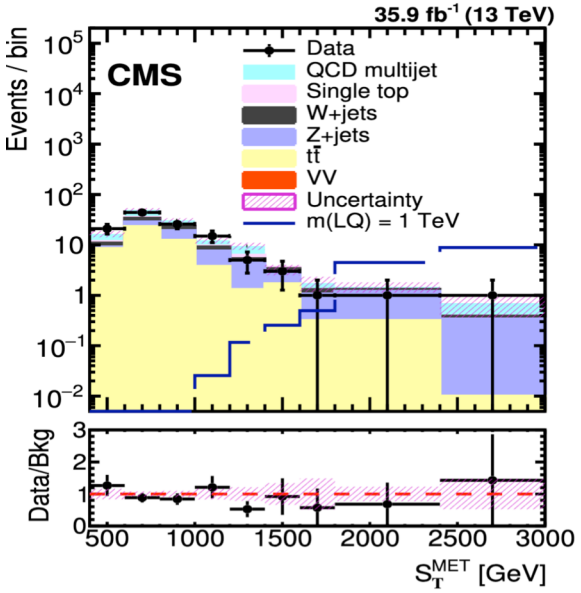
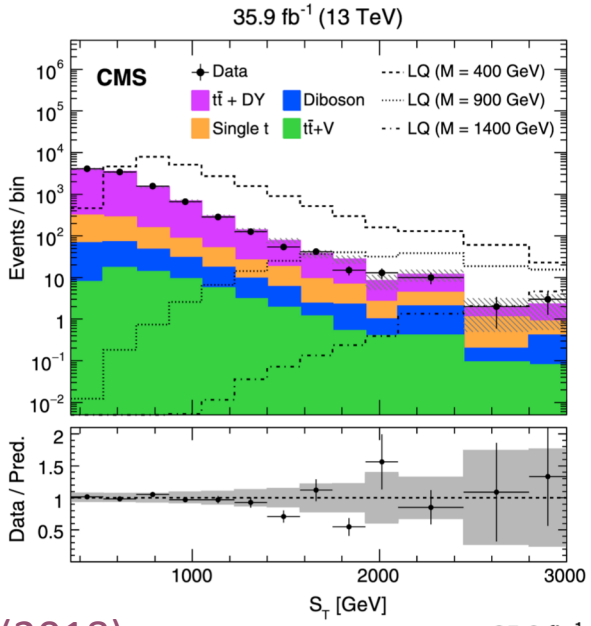
3rd generation scalar LQ searches (CMS)

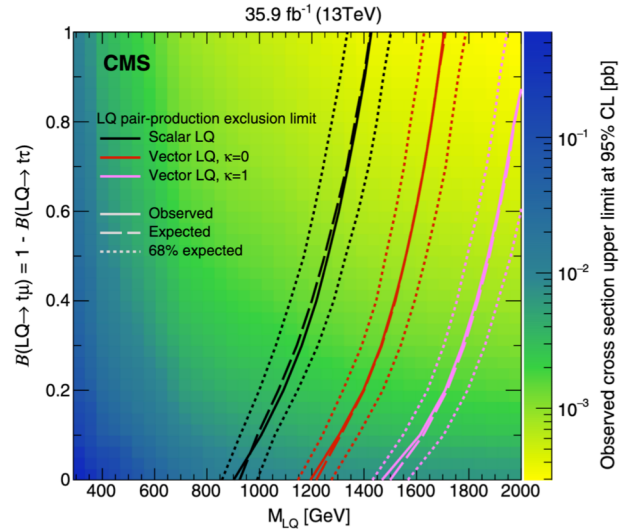
- Partial Run 2 results using 35.9 fb^{-1} of data JHEP03(2019)170
- The search was performed in the fully hadronic final state with **two *taus*** and two ***non-tagged jets***
- **b-jets** are used to obtain $t\bar{t}$**-enriched** CR for the estimation of the background rate in the SR and QCD contribution 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 τ'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



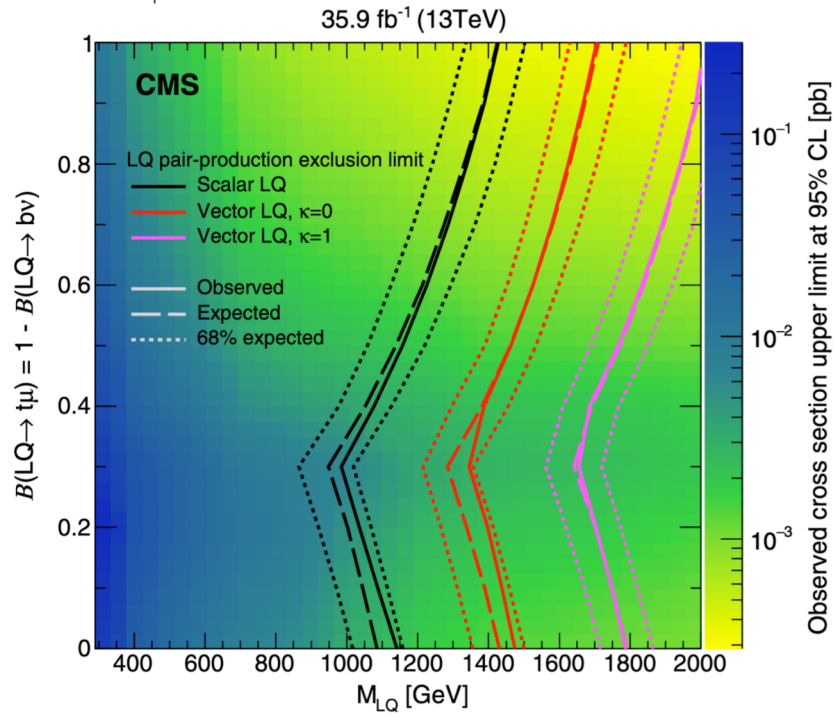


Search for LQ coupled to different generations (CMS)

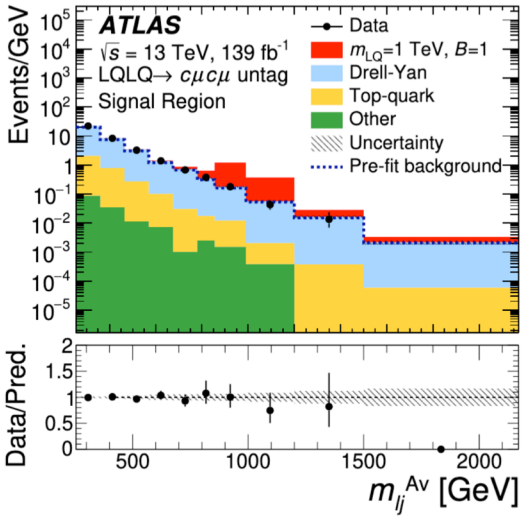


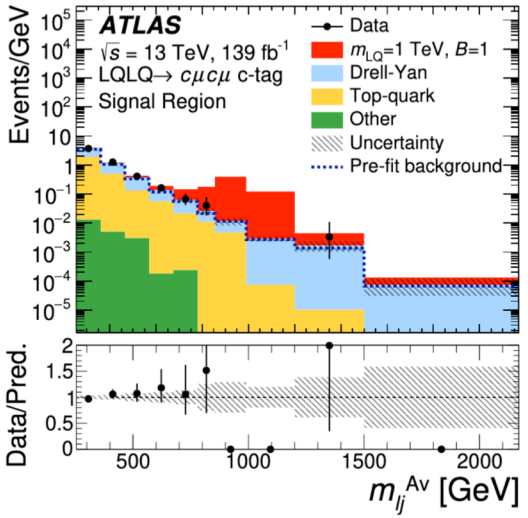


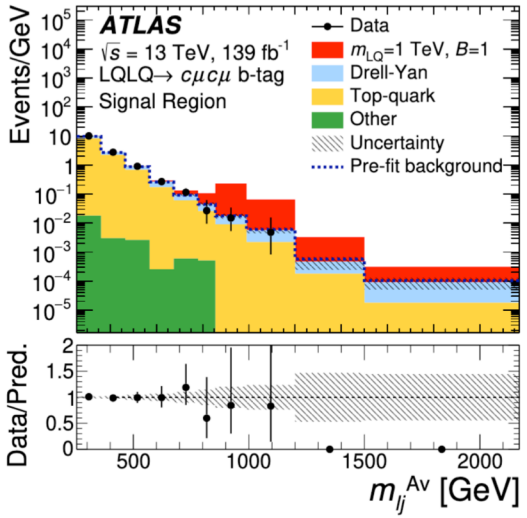
- Partial Run 2 result using 35.9 fb^{-1} of data Phys. Rev. Lett. 121 (2018) 241802
- This analysis combines events from two categories assuming a leptonically and a hadronically decaying top in **category A** and an inclusive **category B**, using m_{LQ}^{rec} and S_T as discriminant variables resp
- 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 $t\tau$** 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 $t\tau$ and $b\nu$



Search for LQ coupled to different generations (ATLAS)

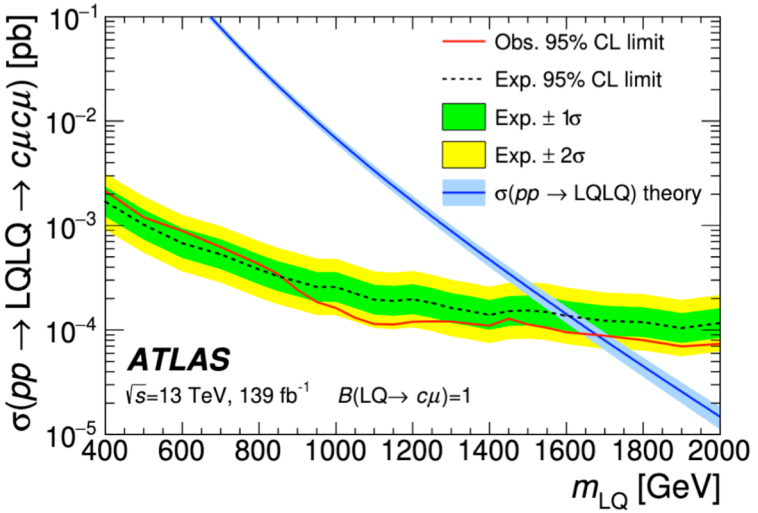


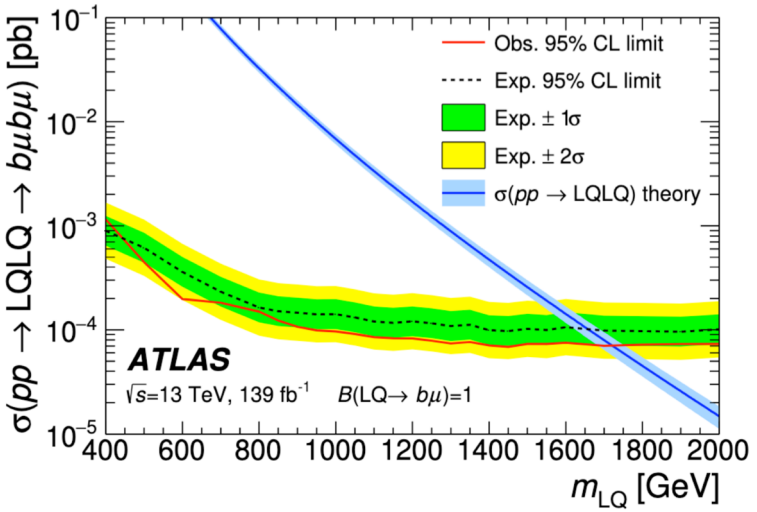




- In JHEP10(2020)112 searches for leptoquarks in final states of the form $lQlQ$ with $Q = c, b$ were performed for the first time
- This analysis considers LQs that can mix quarks from different generations with e, μ
- For these channels, the analysis use c or b-tagged jets, giving priority to b-tagging 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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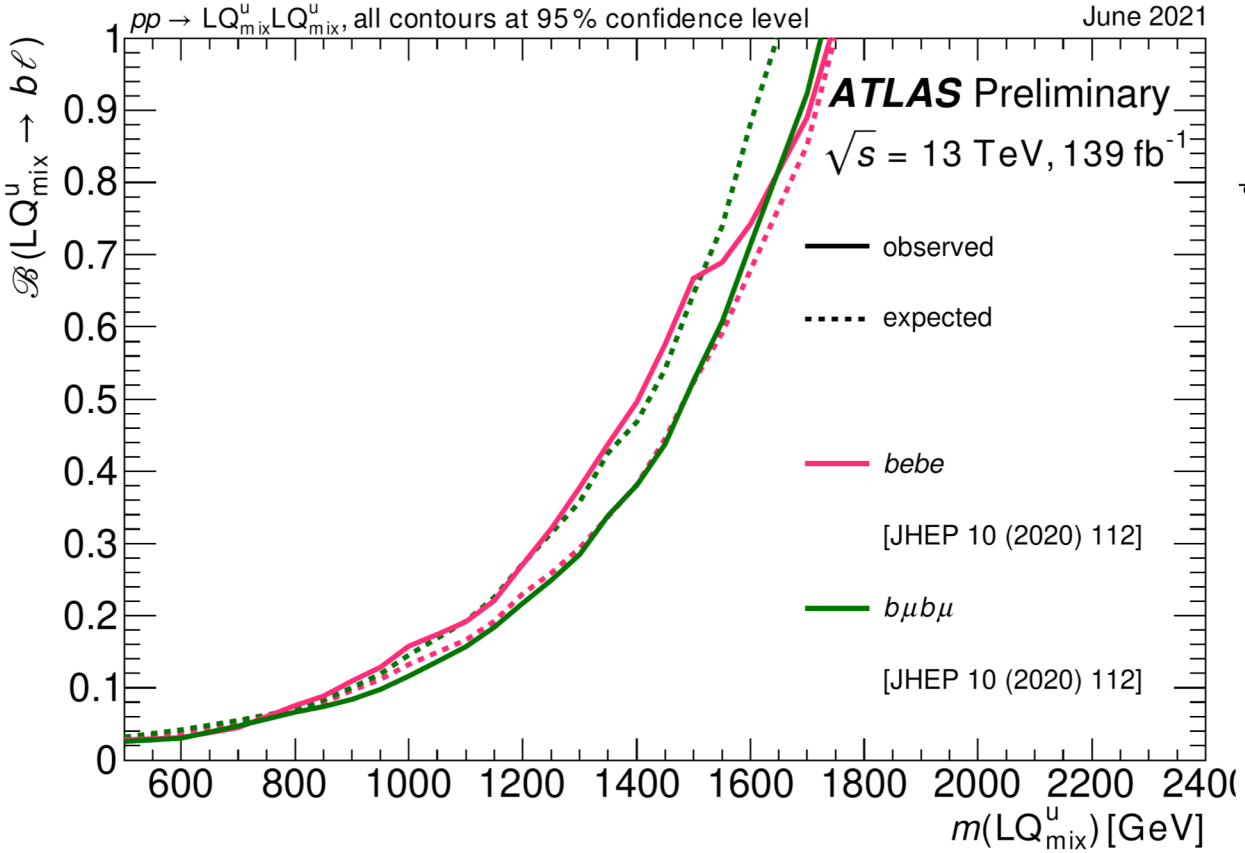
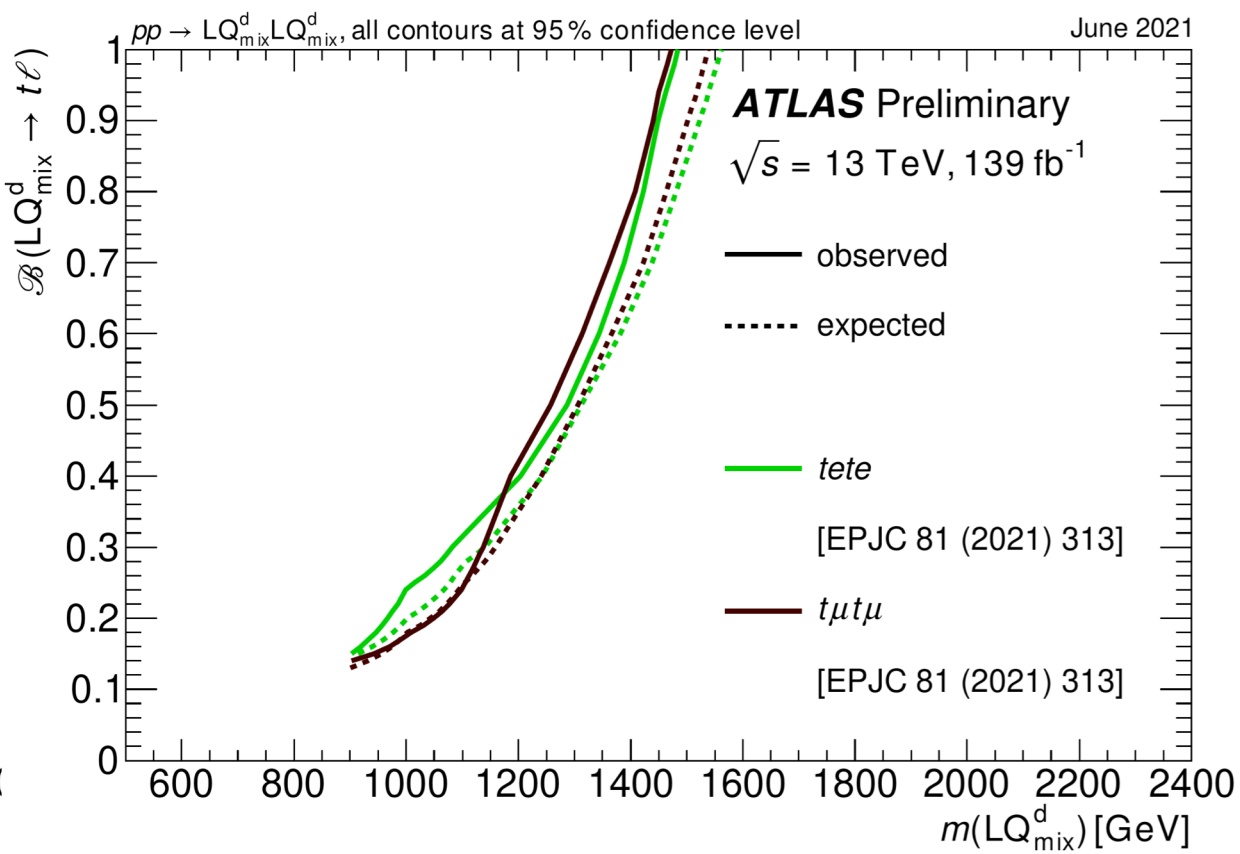
- This analysis considers LQs that can mix quarks from different generations with e, μ
- For these channels, the analysis use c or b-tagged jets, giving priority to b-tagging over c-tagging
- Three signal regions are used: b, c (tag) and untag (for c-jets) and 2,1 and 0-tags for b-jets.
- LQ masses above 1.6 TeV can be excluded in the absence of a significant deviation above the SM expectation

ATLAS Summary plots

- 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





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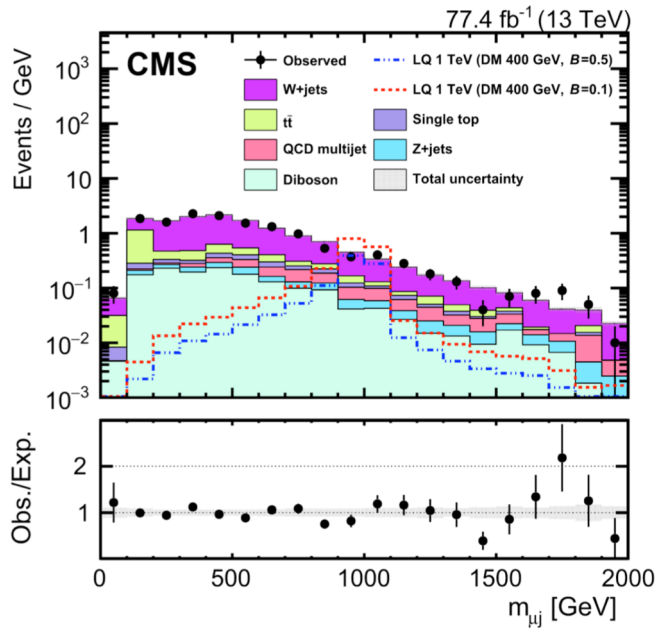
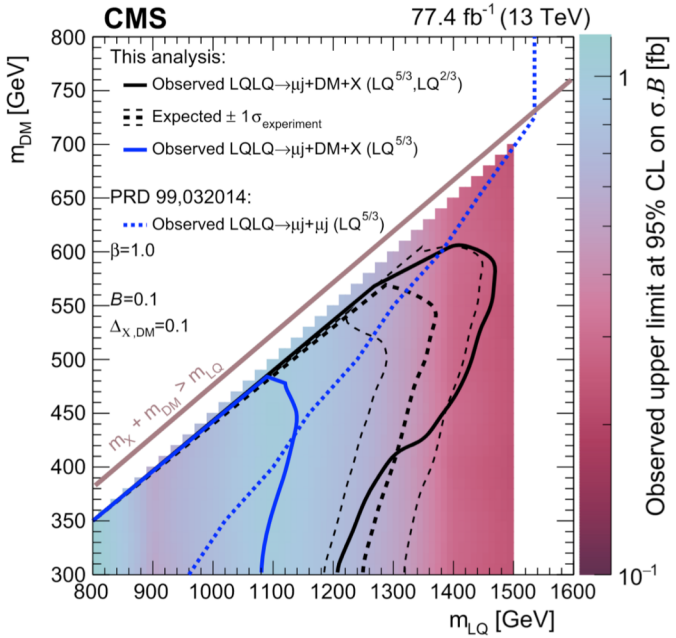
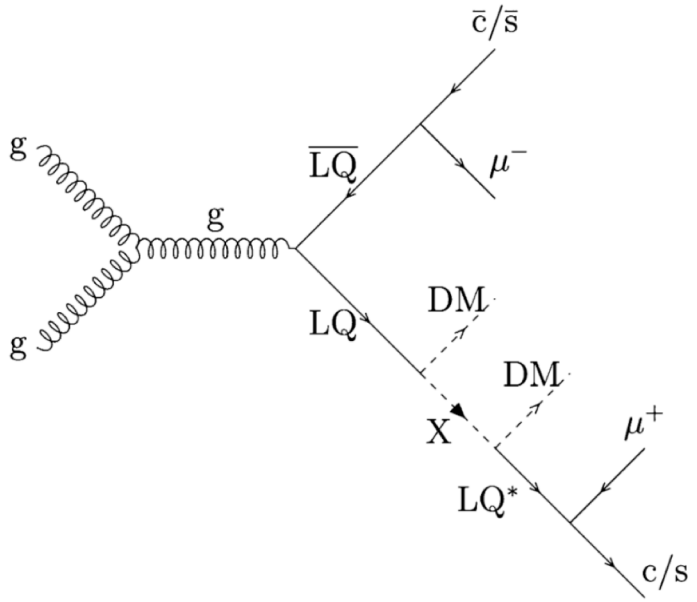




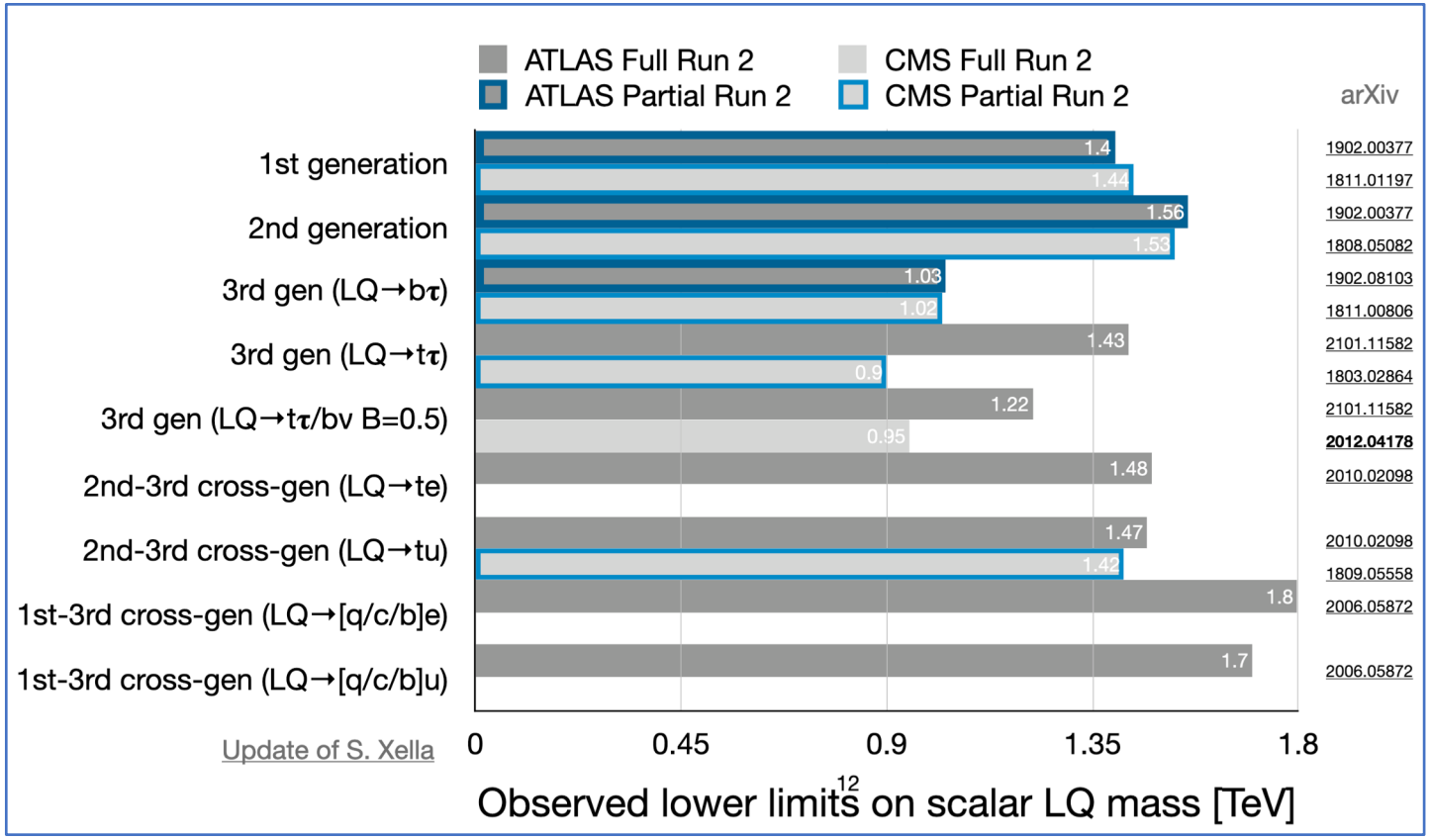


Search for LQ production and decay to **DM** (CMS)

- 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

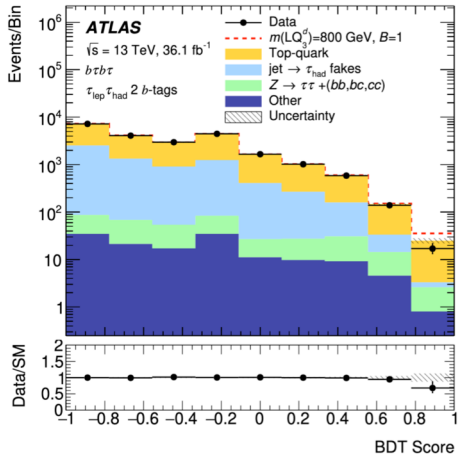
- Results for scalar leptoquark searches made by CMS & ATLAS using Run 2 data have been shown
- These searches target many different final states including cross generational ones mixing quark and leptons of different generations
- No significant excess over SM expectations have been found
- Strongest 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

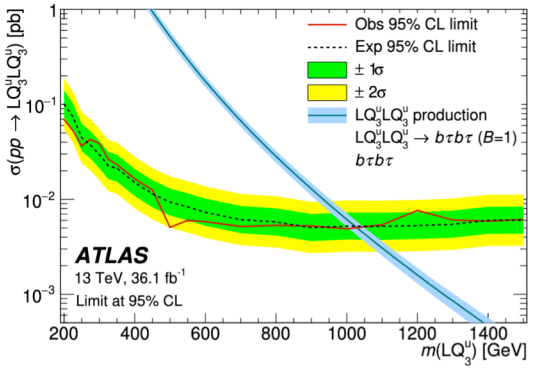


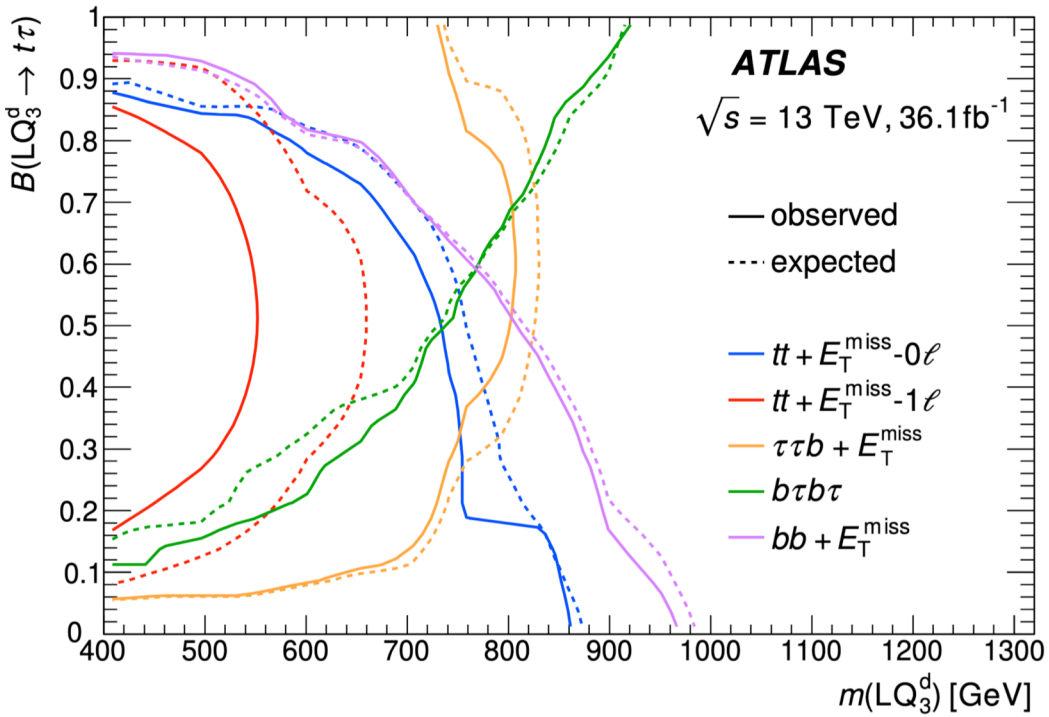
Backup

3rd generation scalar LQ searches

- Partial Run 2 result based on 36 fb^{-1} JHEP06(2019)144
- Dedicated $b\tau b\tau$ 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:* $\tau\tau b + E_T^{miss}$

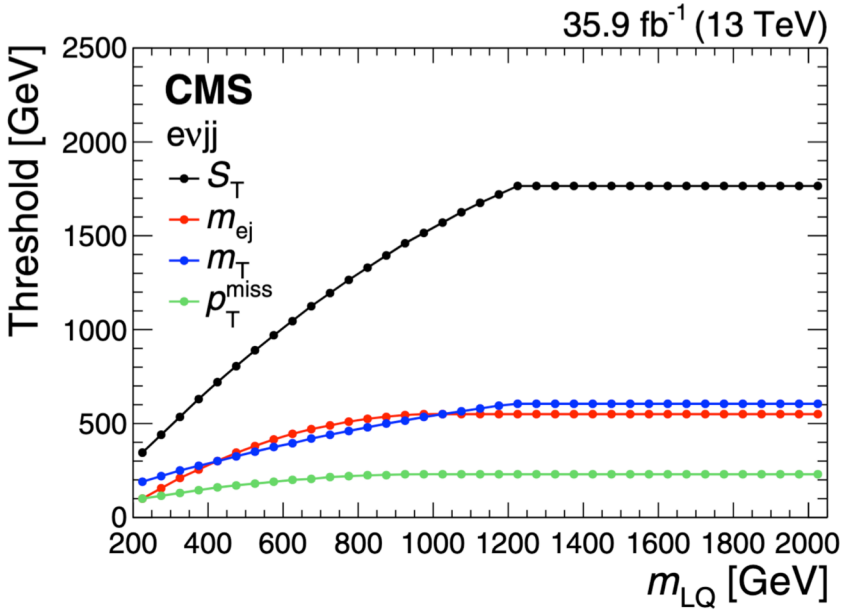


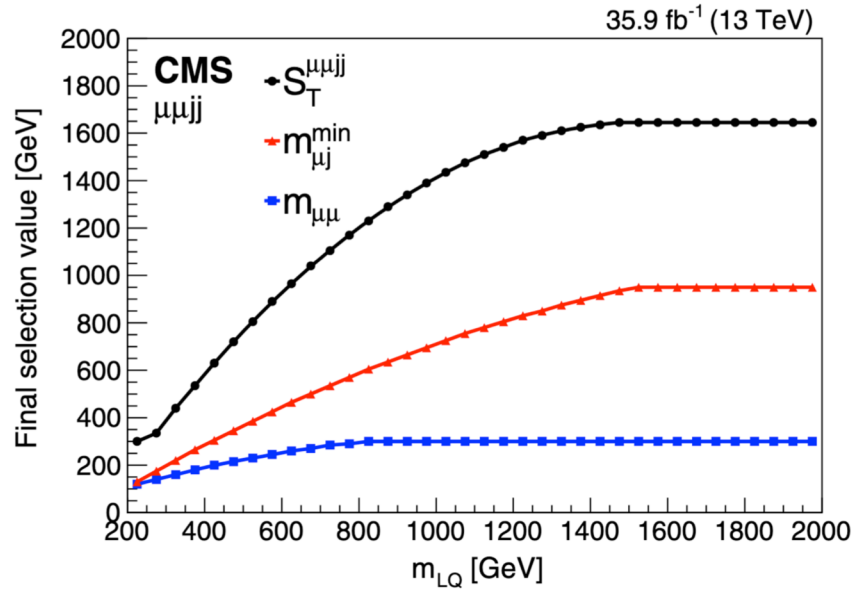




1st & 2nd generation scalar LQ searches (CMS)

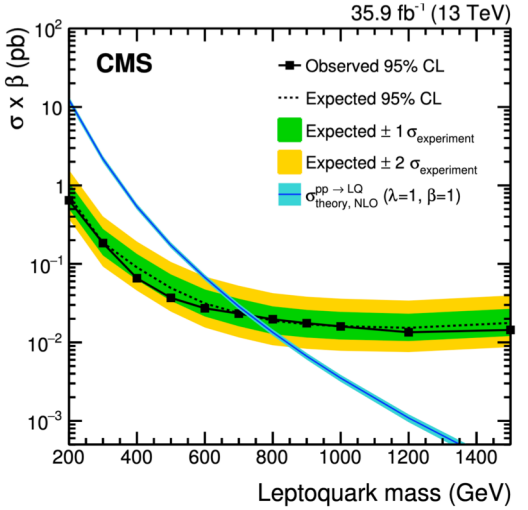
- Partial Run 2 results using 35.9 fb^{-1} of data
  - 1st generation paper PhysRevD 99, 052002 (2019)
  - 2nd generation paper PhysRevD 99, 032014 (2019)
- Very similar analysis strategies
- Both analyses include searches for up & down types leptoquarks, different variables are optimized as a function of the LQ mass in order to reach the largest sensitivity
- $m_{\mu j}^{min}$ 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

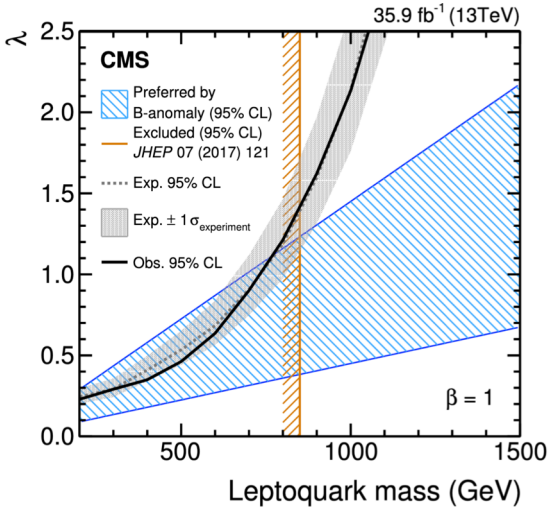


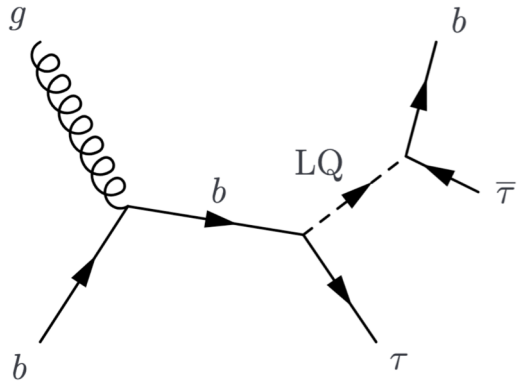


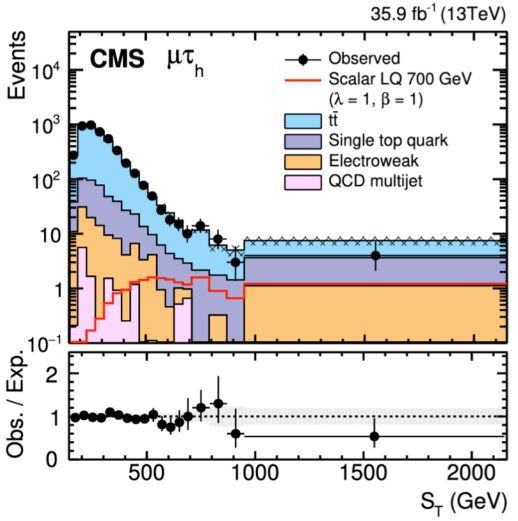
Search for single LQ production (CMS)

- Partial Run 2 result using 35.9 fb^{-1} of data JHEP07(2018)115
- Combines both semi-leptonic and fully hadronic two tau fina 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 missidentified $\tau_h l$ 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

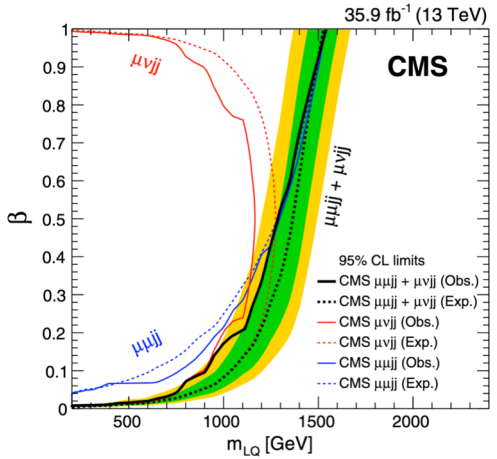


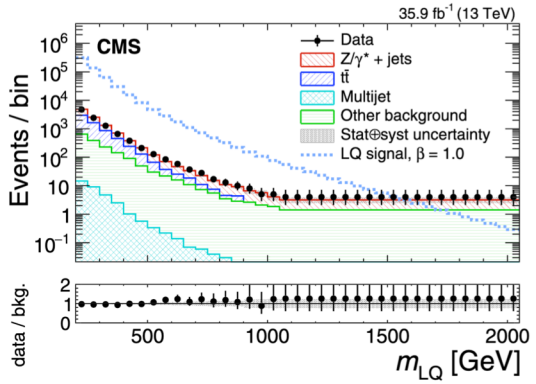






1st & 2nd generation scalar LQ searches (CMS)





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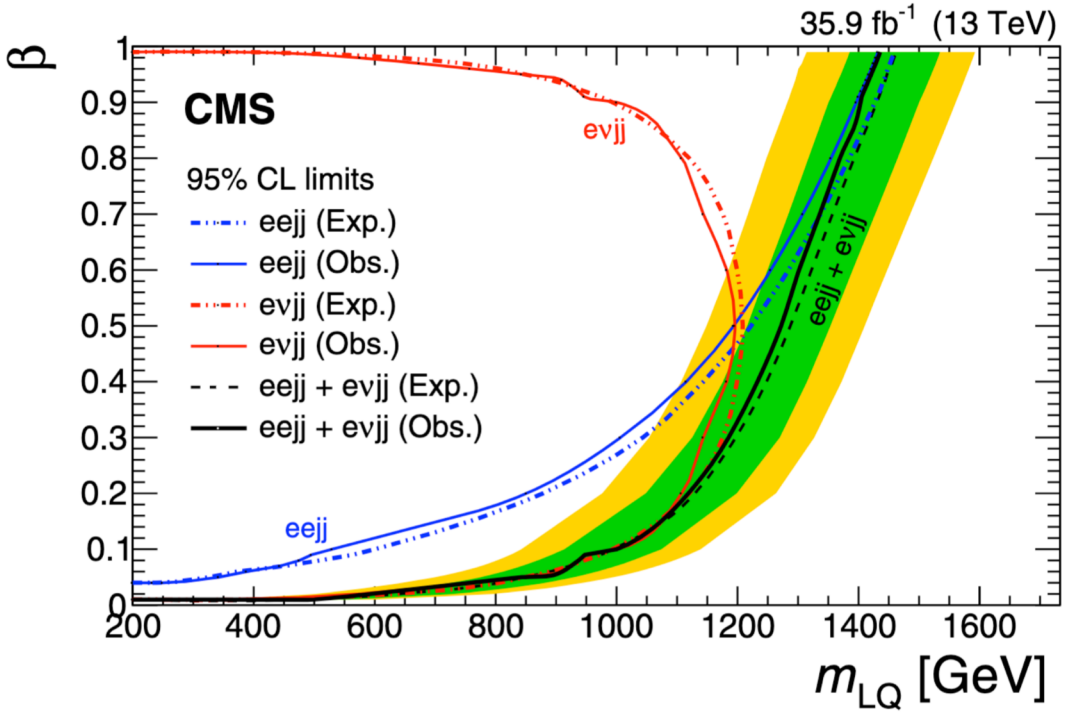
  - 2nd generation paper PhysRevD 99, 032014 (2019)
- Very similar analysis strategies
- Both analyses include searches for up & down types leptoquarks, different variables are optimized as a function of the LQ mass in order to reach the largest sensitivity
- $m_{\mu j}^{min}$ is obtained as the lower 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 β as a function of the leptoquark mass are obtained, ranging from 200 GeV to more than 1.5 TeV

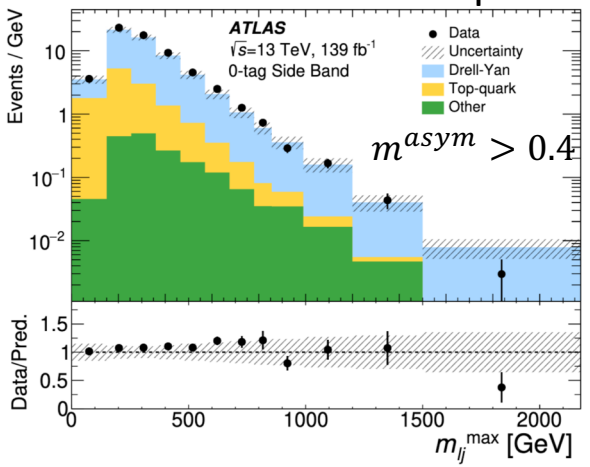


1st & 2nd generation scalar LQ searches (ATLAS)

Preselection
2 oppositely charged leptons (e, μ)
2 or more jets
$p_{\mathrm{T}}^{e} > 27$ GeV, $\lvert\eta_e\rvert < 2.47$; $p_{\mathrm{T}}^{\mu} > 27$ GeV, $\lvert\eta_\mu\rvert < 2.7$
$p_{\mathrm{T}}^{j} > 45$ GeV, $\lvert\eta_j\rvert < 2.5$
$p_{\mathrm{T}}^{\ell\ell} > 75$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5$ GeV$^{1/2}$
$m_{\ell\ell} > 130$ GeV

SB	SR	Top CR
ee or $\mu\mu$		$e\mu$
$0.2 < m^{\mathrm{asym}} < 0.4$	$m^{\mathrm{asym}} < 0.2$	

Pre-fit plot



- Full Run 2 analysis JHEP10(2020)112 supersede previous results with partial Run 2 data 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_{lj}, and m^{asym} is used to define the analysis regions

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

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