Searching for leptoquarks with the ATLAS detector

Stergios Kazakos (IFAE, UAB)
on behalf of the ATLAS collaboration

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Introduction

★ **Leptoquarks (LQs)** are hypothetical particles with a fractional electric charge that couple simultaneously to a **lepton** and a **quark**.

★ LQs were originally predicted in GUT (e.g. SU(5) unification models), but also appear in other BSM scenarios (RPV SUSY, compositeness models).

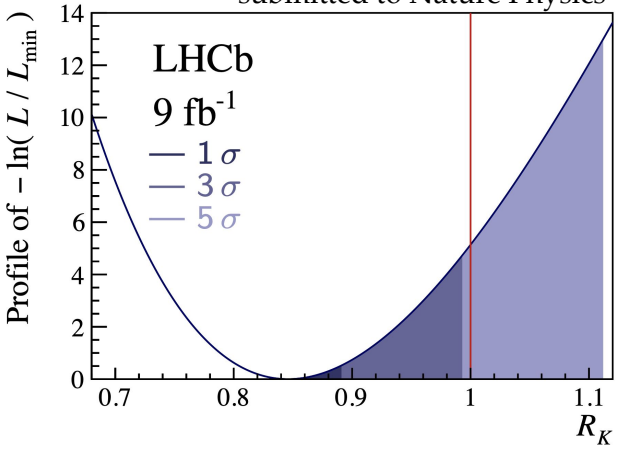
★ Most favoured candidate to explain the **B-physics anomalies** which point to potential Lepton Flavour Universality (LFU) violation.

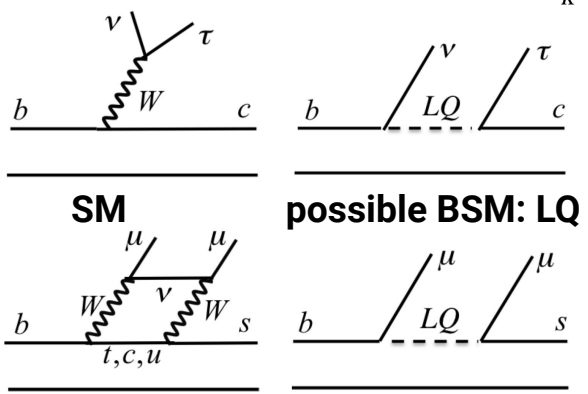
- The anomalies manifest both in **charged** and **neutral current processes**.
- The anomalies seem to persist in the latest LHCb measurement of **R(K) ratio**, with a deviation of **3.1σ** from the SM!

★ The simplest explanations of these anomalies involve either **a single vector LQ (U_1)**, or **two scalar leptoquarks** (a singlet - S_1, and a triplet - S_3):

- LQs will contribute with additional tree level diagrams!

[LHCb-PAPER_2021-004]
submitted to Nature Physics





Production and decay modes

★ Broad physics program of LQ searches with different final states:

- Based on the Buchmüller - Rückl - Wyler (BRW) model.

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- Targeting **up-** or **down-type LQs** ($\mathbf{LQ^u} \rightarrow Q = 2/3$, $\mathbf{LQ^d} \rightarrow Q = -1/3$).
- LQ decays in **1st**, **2nd** or **3rd** generation particles ($\mathbf{LQ_1}$, $\mathbf{LQ_2}$, $\mathbf{LQ_3}$).

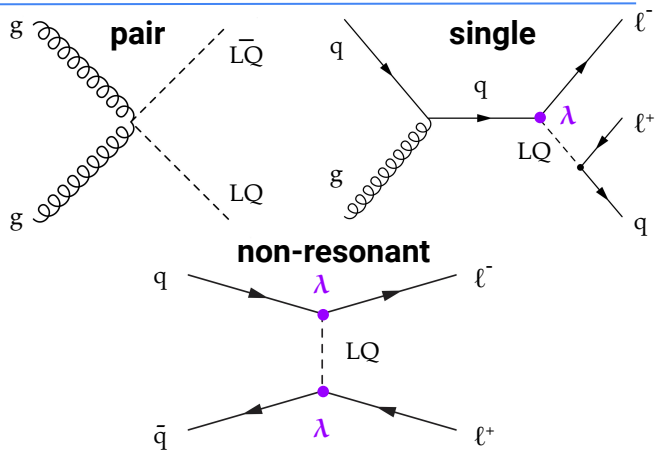
★ The main LQ production modes are:

1) **pair** production (cross-section (σ) dominated by QCD, mostly dependent on the mass (resonant))
2) **single** production ($\sigma \propto \lambda^2$)
3) **non-resonant** production ($\sigma \propto \lambda^4$)

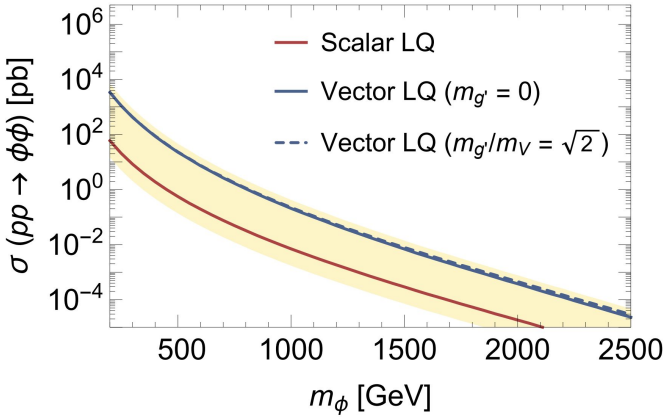
★ Current focus of this talk on **pair production** of **scalar LQs**:

- Targeting LQ decays into **flavour-diagonal** and **cross-generational** final states.
- Searches are ongoing also for the other production modes.
- Vector LQ models to follow later (higher cross-section).

λ: Yukawa coupling of LQ to quarks and leptons



JHEP 10 (2017) 097



Covered signatures

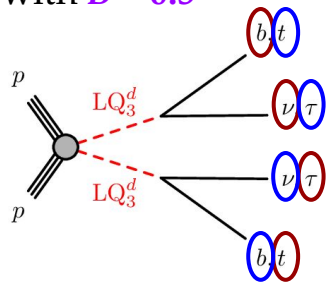
★ Public results of analyses targeting pair production of **scalar LQs** decaying to the following categories:

	u / d / s	c	b	t
e	Published in JHEP: *JHEP 10 (2020) 112*			Submitted to EPJC: *arXiv: 2010.02098*
μ				
τ				Submitted to JHEP: *arXiv: 2101.11582*
			Public CONF note: *ATLAS-CONF-2021-008*	
ν			Submitted to JHEP: *arXiv: 2101.12527*	Published in EPJC: *Eur. Phys. J. C 80 (2020) 737*

(* the entries in rows and columns denote the **quark** and **lepton** of the dominant decay mode)

re-interpretations from SUSY analyses

flavour-diagonal with $B = 0.5$



(* branching fraction B: relative coupling between LQ→qℓ and LQ→qν that controls the BR)

LQ_3 summary paper (36 fb^{-1}) published in JHEP: *JHEP 06 (2019) 144*

LQLQ → qeqe / qμqμ (q = u, d, s, c, b)

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★ First analysis on cross-generational LQ decays using dedicated **c-** and **b-jet identification algorithms**.
- An inclusive selection is used for u/d/s channels (pre-tag).

★ Region categorisation is based on m^{asym}:

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

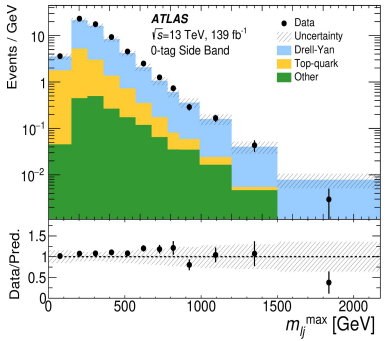
SB: $0.2 < m^{asym} < 0.4$

CR, SR: $m^{asym} < 0.2$

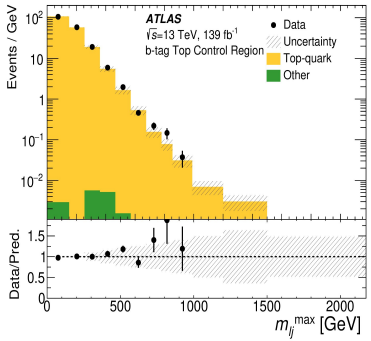
★ Average reconstructed LQ mass used as final discriminant:

$$m_{\ell j}^{\text{Av}} = (m_{\ell j}^{\max} + m_{\ell j}^{\min})/2$$

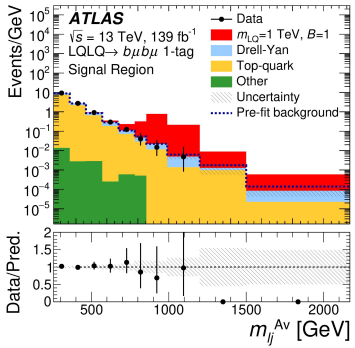
Side-Band region



Control region (Top CR)



Signal region



★ 2ℓOS, ≥ 2j selection

★ Main backgrounds from **Drell-Yan** and **$t\bar{t}$** processes:

- Their normalisations are left free floated in the fit as a single parameter.
- Other backgrounds estimated from MC.

★ Regions used in the fit:

qℓ channels: pre-tag **SR + SB + Top CR** (q = u/d/s)

cℓ channels: **SR + SB** in untagged, c-tag and b-tag categories are used together with the **Top CR** for c-tag and b-tag.

bℓ channels: **SR + SB** in 0-, 1-, and 2-tag categories are used together with the **Top CR** in 1- and 2-tag.

(Top CR: **eμ** selection, SB region: **ee** or **μμ** selection)

LQLQ → qeqe / qμqμ (q = u, d, s, c, b)

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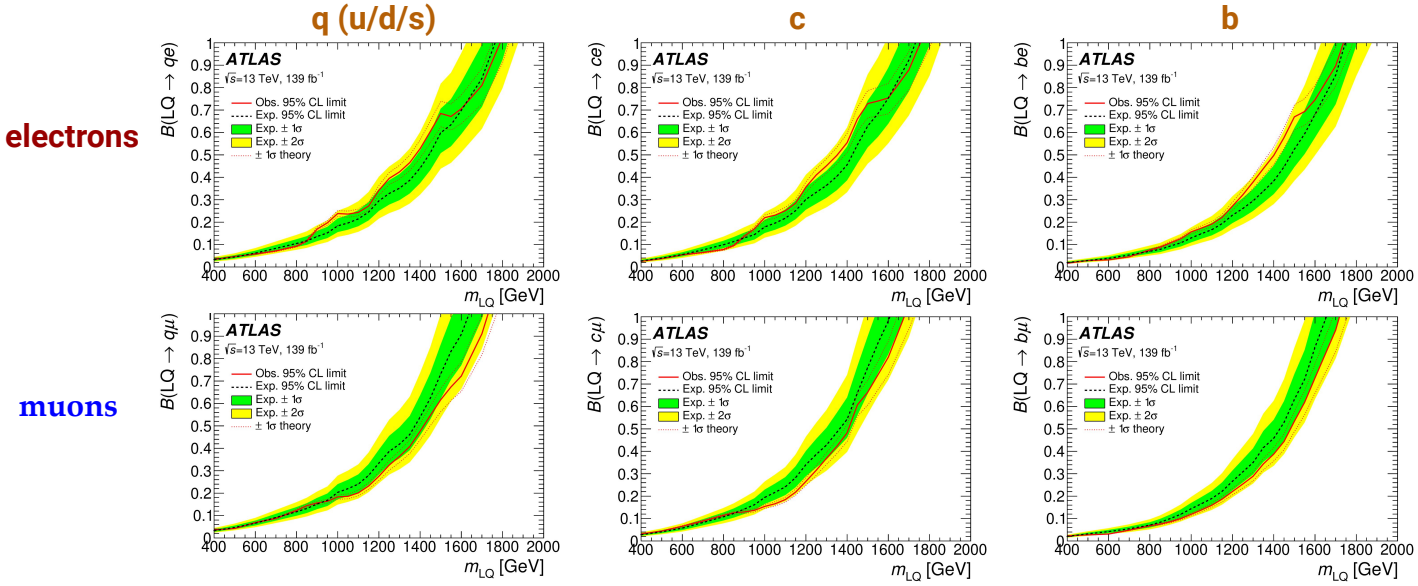
- ★ Search range from **0.4** to **2.0 TeV**.
- ★ No significant excess observed over the SM background in all of the six categories.
- ★ Exclusion limit is set as a function of mass and branching fraction (B):
  - $\mathbf{m_{LQ}}$**< 1.8 TeV** (**1.7 TeV**) excluded for electrons (muons) for $B = 1$, $\mathbf{m_{LQ}}$**< 0.8 TeV** excluded for $B = 0.1$
- ★ Improved sensitivity by about 300 – 400 GeV in LQ mass compared to previous scalar LQ searches.

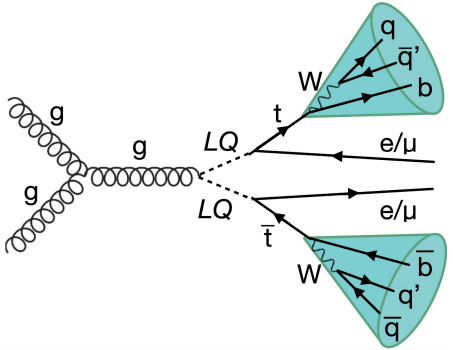


$LQ^dLQ^d \rightarrow$ tete / tμtμ (boosted)

arXiv: 2010.02098

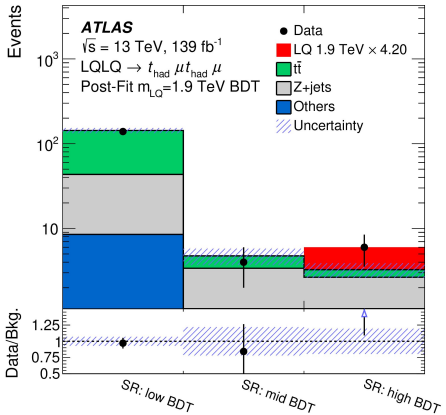
★ Targeting the **hadronic decay** channel in the **boosted regime**:

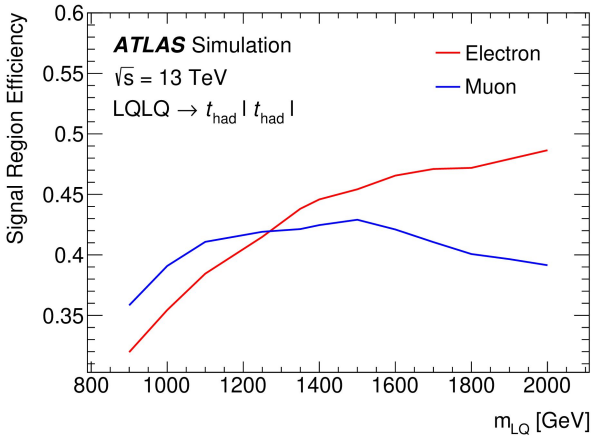
- 2ℓOS selection, requiring ≥ 2 large-R jets (R=1.0) to select the boosted tops



★ Signal over background classification using a gradient boosting BDT approach.

- Single classifier optimised for a range of LQ masses (mass-parameterised).
- Kinematic variables used as inputs calculated in the rest frame of intermediate particles (LQ, top, Z) using jigsaw reconstruction.
- Jet substructure variables used as inputs (μ channel only).





★ Two main background processes:

Z(→μμ, ee) + jets and **$t\bar{t}$** production

- Estimated from MC with normalisation constrained by dedicated control regions.

★ Background composition in signal regions:

$LQ^dLQ^d \rightarrow$ tete / tμtμ (boosted)

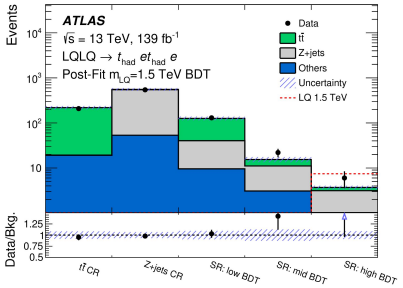
arXiv: 2010.02098

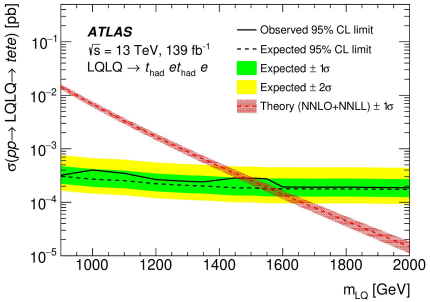
★ Simultaneous fit of **3 signal regions** (BDT score) + **2 control regions** (number of events).

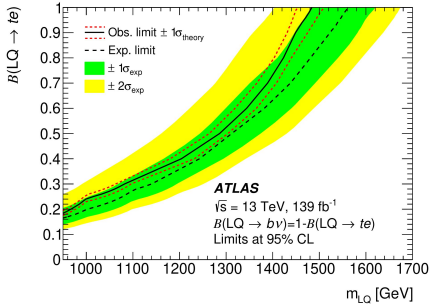
★ No significant excess observed over the SM background.

★ Exclusion limit is set as a function of mass and branching fraction (B):
- $\mathbf{m_{LQ}}$**< 1.48 TeV (1.47 TeV)** excluded for electrons (muons) for $\boldsymbol{B = 1}$

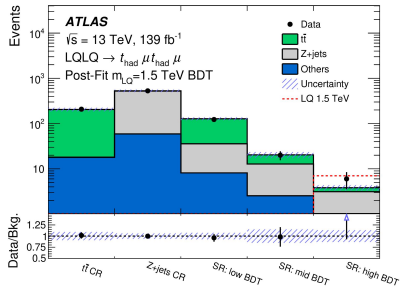
electrons

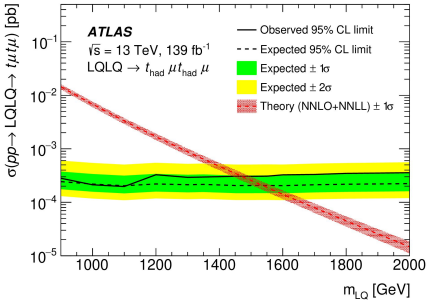


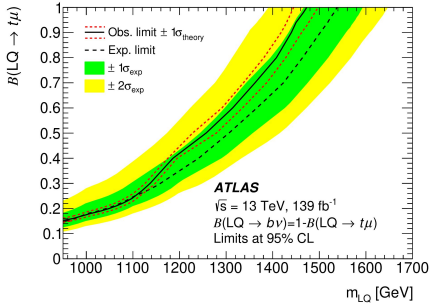




muons





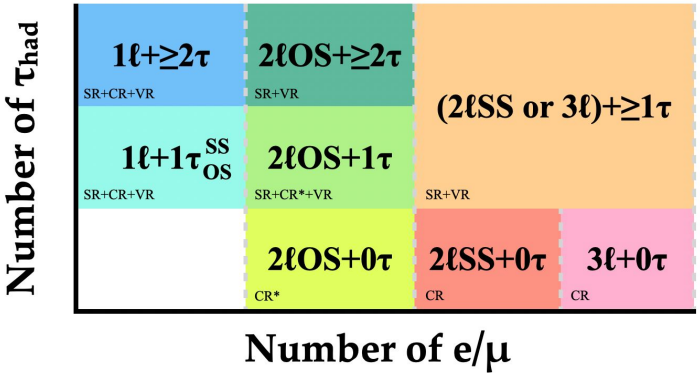


$LQ^dLQ^d \rightarrow t\tau t\tau$

arXiv: 2101.11582

★ First dedicated ATLAS analysis in this final state.

★ Channel categorisation is based on **number of light leptons (e/μ)** and **number of hadronic τs**.



★ **Major backgrounds (channel dependent):**
- $t\bar{t}$ (with fake non-prompt light leptons or fake τ_{had}), $t\bar{t}V$, $t\bar{t}H$, VV

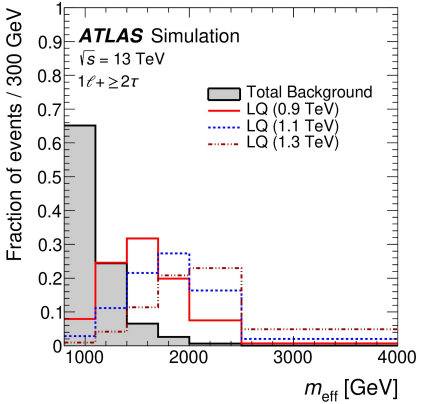
★ **6 validation (VR), 17 control (CR)** and **7 signal (SR)** regions are defined **orthogonal** to each other.
- Fitting $H_{T,\,lep}$ (= $\Sigma p_{T,\,lep}$) or **number of events** in CRs, m_{eff} in SRs.

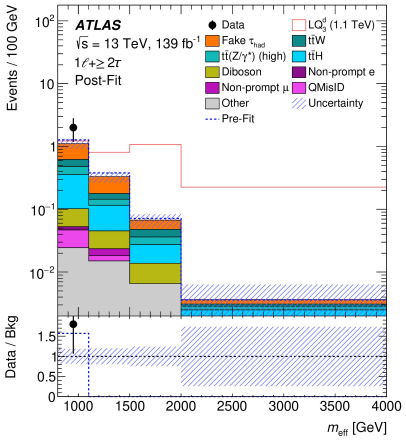
★ **DNN tau ID** for increased fake τ_{had} rejection at the same efficiency (ATL-PHYS-PUB-2019-033).

★ **Kinematic reweighting** (N_{jet} dependent) to correct for $t\bar{t}$ mismodelling at high m_{eff}.

Main discriminating variable

★ $m_{eff} = \sum_{(jet,\,e,\,\mu,\,\tau)} p_T + E_T^{miss}$

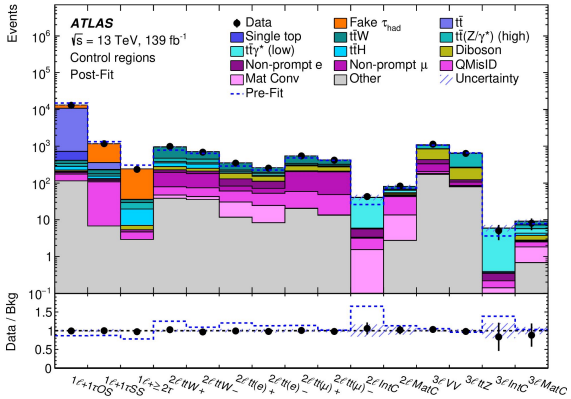


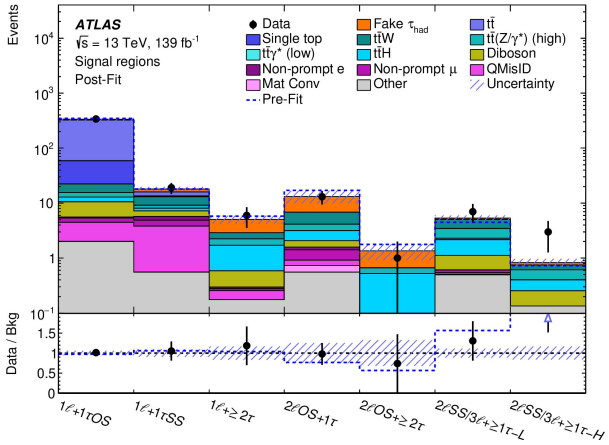


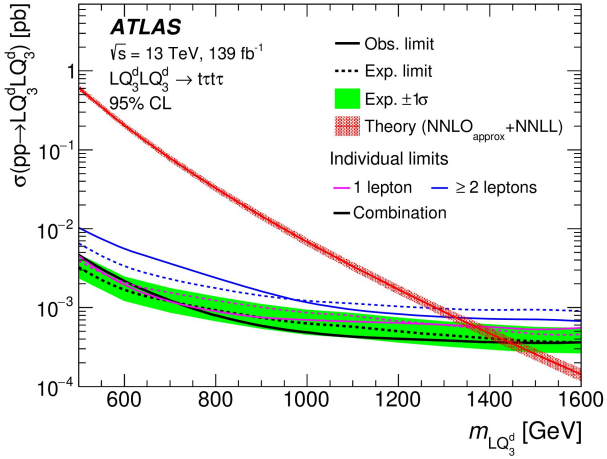
$LQ^dLQ^d \rightarrow t\tau t\tau$

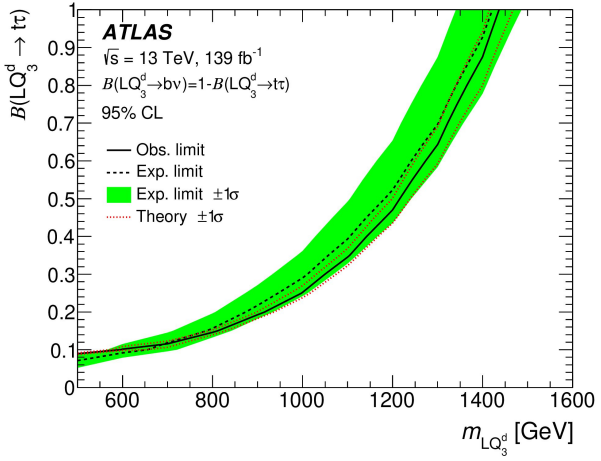
arXiv: 2101.11582

- **Search range** is from **0.5** to **1.6 TeV**.
- No significant excess observed over the SM background.
- Exclusion limit is set as a function of mass and branching fraction (B):
  - $\mathbf{m_{LQ} < 1.43\ TeV}$ (1.22 TeV) excluded for $\boldsymbol{B = 1}$ ($B = 0.5$)
- Most stringent limits so far on this LQ decay mode.









LQLQ → tνtν / bνbν / bττν / ttbν

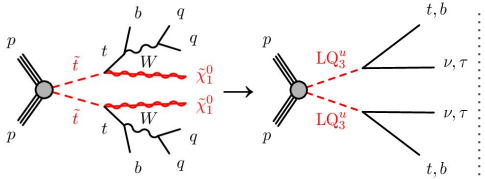
Eur. Phys. J. C 80 (2020) 737, arXiv: 2101.12527, ATLAS-CONF-2021-008

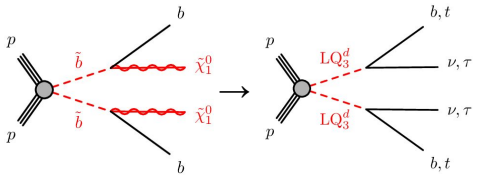
★ Various re-interpretations from SUSY analyses of **top** or **bottom squark** decays to neutralinos or gravitinos.

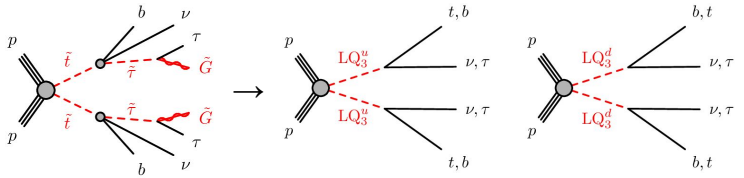
★ No significant excess observed over the SM expectation value.

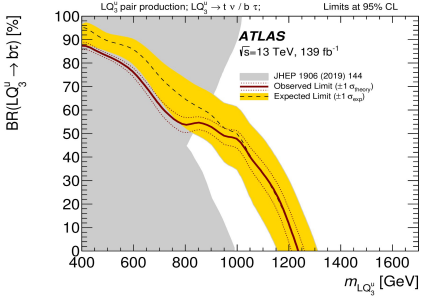
★ Exclusion limit is set as a function of mass and branching fraction (B):

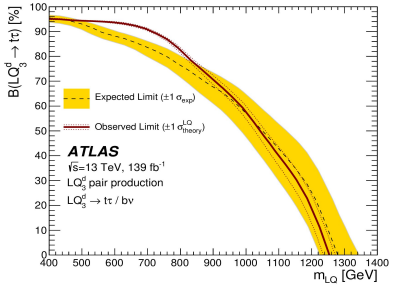
- Exclusion up to $\mathbf{m_{LQ} < 1.24\ TeV}$ for **tνtν** ($B = 0$).
- Exclusion up to $\mathbf{m_{LQ} < 1.26\ TeV}$ for **bνbν** ($B = 0$).
- Exclusion up to $\mathbf{m_{LQ} < 1.25\ TeV}$ for **bττν / ttbν** ($B = 0.5$).

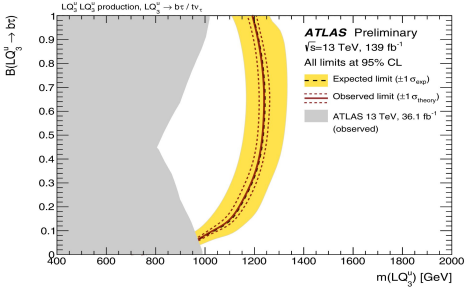


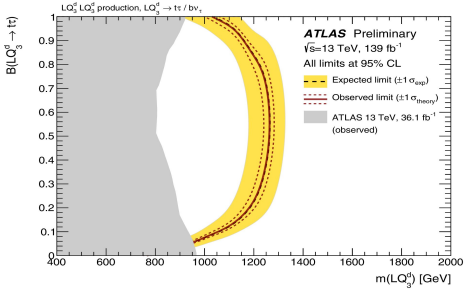












LQ combination

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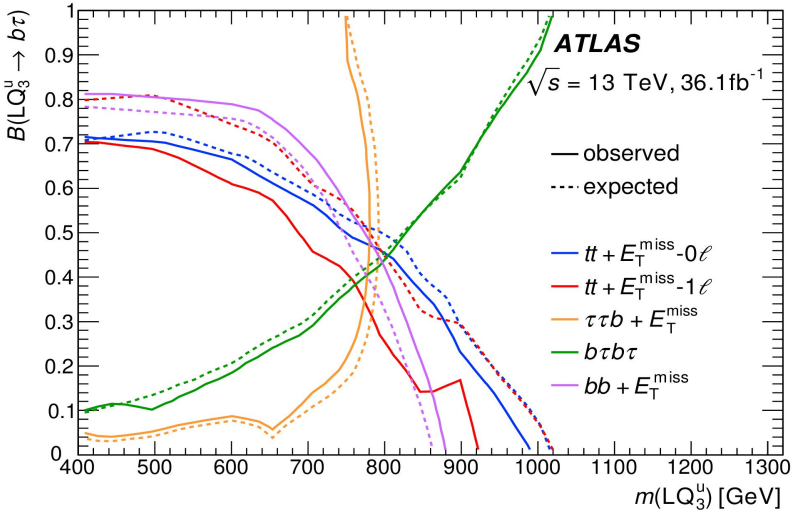
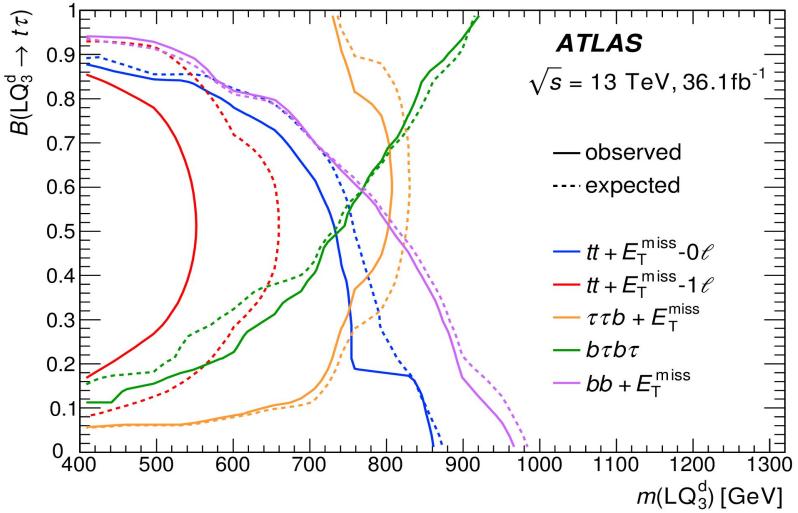
★ Already public summary plots from the LQ_3 combination for **36.1 fb^{-1}**:

- Results for up-type and down-type LQs.





★ In the searches presented today (with the full Run 2 dataset) the **mass exclusion** is **extended by ~250-500 GeV** compared to these partial Run 2 dataset results.

- Their combination is expected to further extend the reach!

Summary & outlook

★ Very exciting and promising results from LQ searches in ATLAS with full Run 2 dataset!

- Covering a wide range of phase space and final states.
- Exploring flavour-diagonal and cross-generational models.
- Significant improvement in sensitivity compared to previous searches.

★ No significant excess was observed over the SM expectation.

- Still the exclusion limits are pushed to even higher masses.
- Some of the most stringent limits available so far.

★ Most of these searches will also be interpreted in the context of **vector LQs**:
- Higher cross section → higher mass exclusion.

★ Already planning a **combination** of the LQ results for the full Run 2.

★ Many new analyses are on the way - stay tuned!

Thank you for your attention!

Backup

LQLQ → qeqe / qμqμ (q = u, d, s, c, b)

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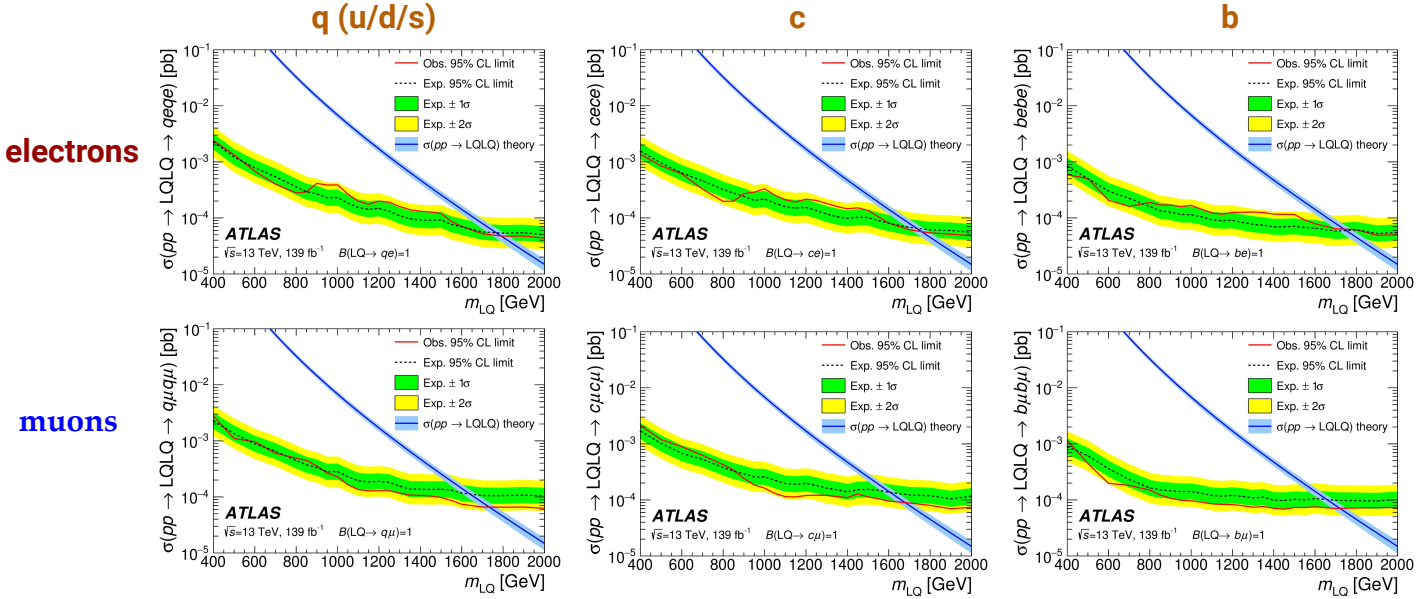
★ No significant excess observed over the SM background in all of the six categories.

★ Exclusion limit is set as a function of mass and branching fraction (B):
- $\mathbf{m_{LQ}}$**< 1.8 TeV (1.7 TeV)** excluded for electrons (muons) for $\boldsymbol{B = 1}$

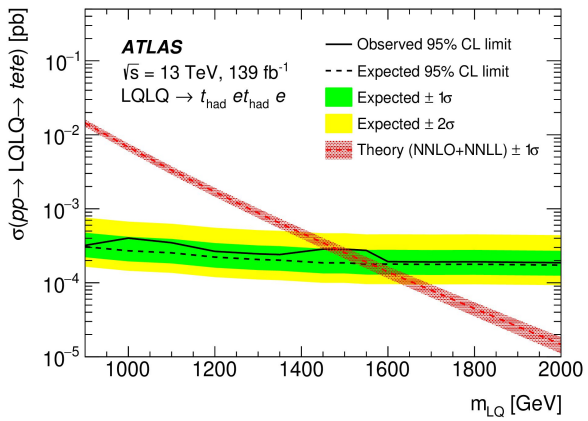
★ Improved sensitivity by about 300 – 400 GeV in LQ mass compared to previous scalar LQ searches depending on the lepton flavour.

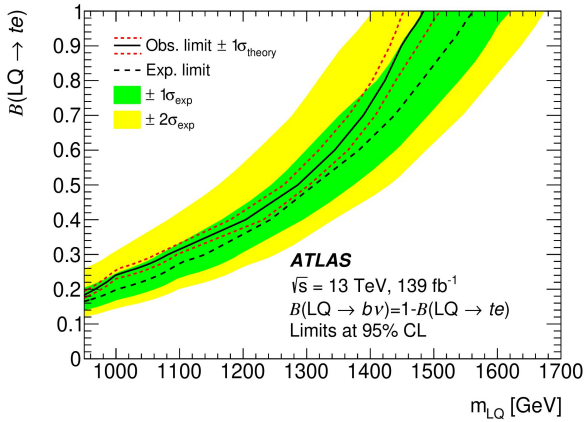


$LQ^dLQ^d \rightarrow tete$ / tμtμ (boosted)

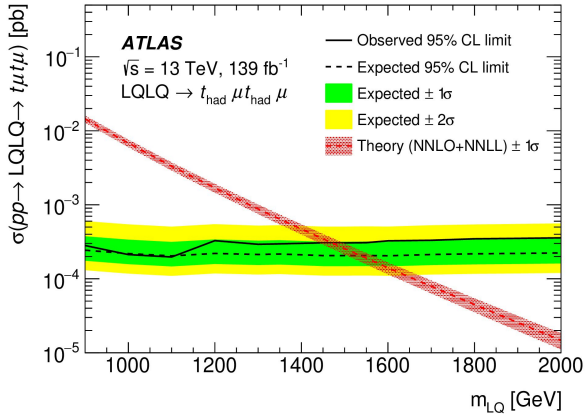
arXiv: 2010.02098

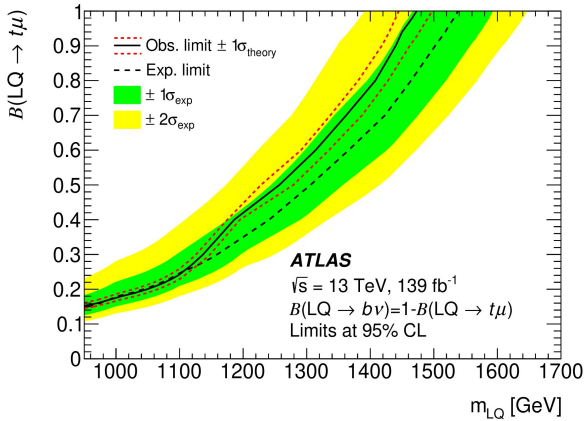
electrons





muons





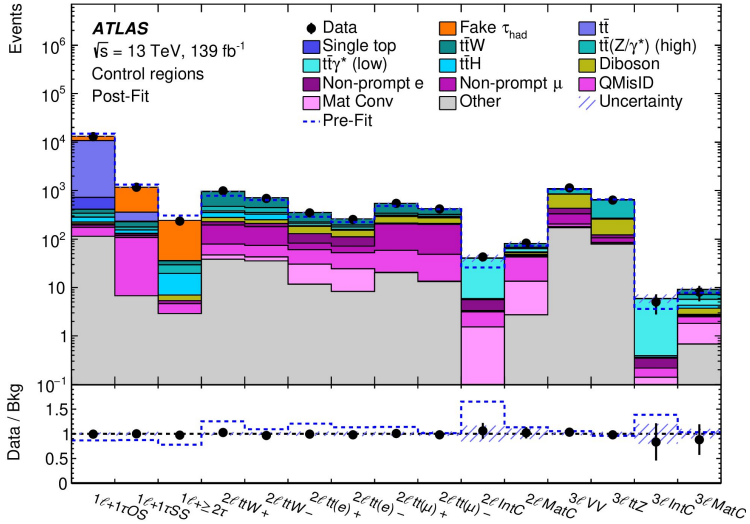
$LQ^dLQ^d \rightarrow t\tau t\tau$: Background estimation

arXiv: 2101.11582

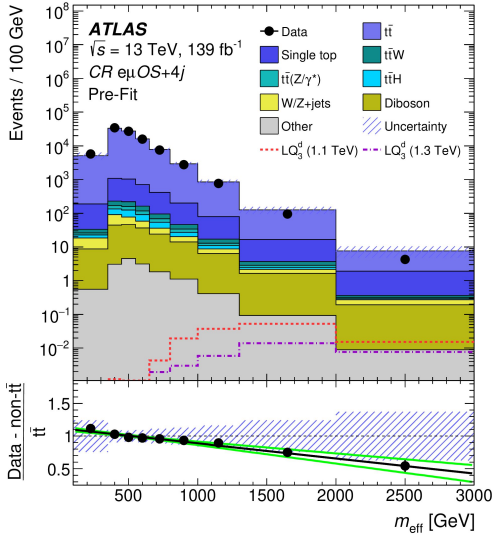
★ **Major backgrounds (channel dependent):** $t\bar{t}$ (with fake non-prompt light leptons or fake τ_{had}), $t\bar{t}V$, $t\bar{t}H$, VV

- Reducible background is split based on truth information: **fake τ_{had}**, **non-prompt leptons**, **conversions**
- **DNN tau ID** for increased fake tau rejection at the same efficiency (ATL-PHYS-PUB-2019-033)
- **Kinematic reweighting** (N_{jet} dependent) to correct for $t\bar{t}$ mismodelling at high m_{eff}.
- **Fake τ_{had}** estimation with MC and correction derived in a dedicated fake τ_{had} CR.
- **Background normalisation factors** acquired from a template fit using background "enriched" CRs.

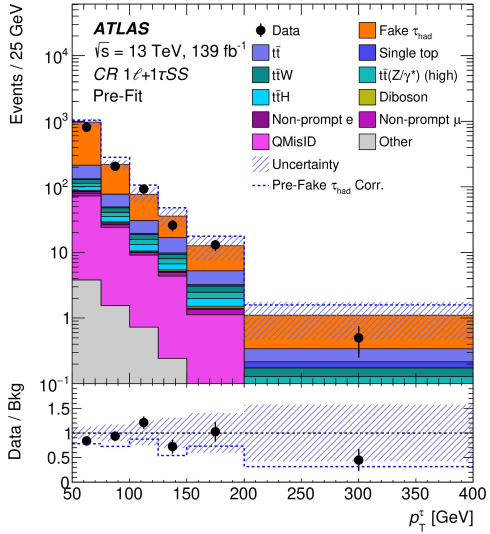
Analysis CRs (post-fit)



Kinematic Reweighting



Fake τ_{had} correction



$LQ^uLQ^u \rightarrow tvtv$

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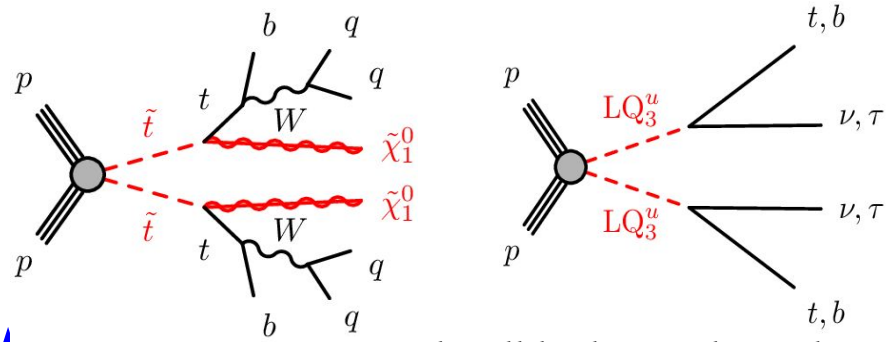
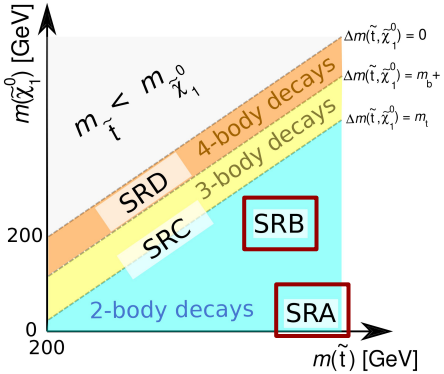
★ Re-interpretation of a SUSY analysis targeting heavy **top squark pair production** decaying into massless neutralinos.



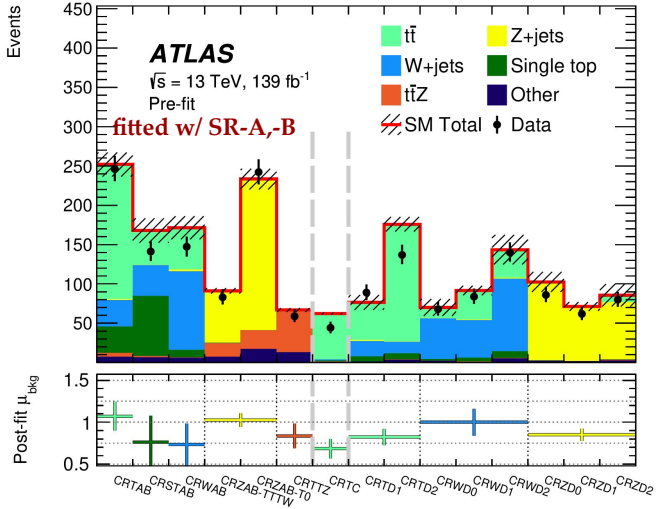
★ **$tt + E_T^{miss}$ final state** in the all-hadronic channel:
- E_T^{miss} trigger
- ≥ 4j, ≥ 2b, 0ℓ selection in the signal regions
- **2 large-R reclustered jets** for top candidates (R = 1.2)

★ Main backgrounds: **$t\bar{t}$**, **$t\bar{t}Z$**, **V+jets**, **single top**

★ Orthogonal signal regions categorised based on $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$:
- Sensitivity to LQ^u in the high Δm regions (**SRA**, **SRB**).



SRA & SRB fitted together with some of the CRs



$LQ^uLQ^u \rightarrow t\nu t\nu$

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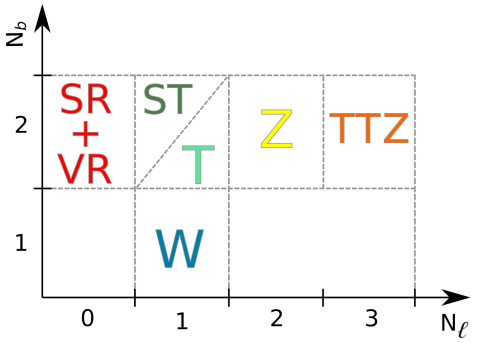
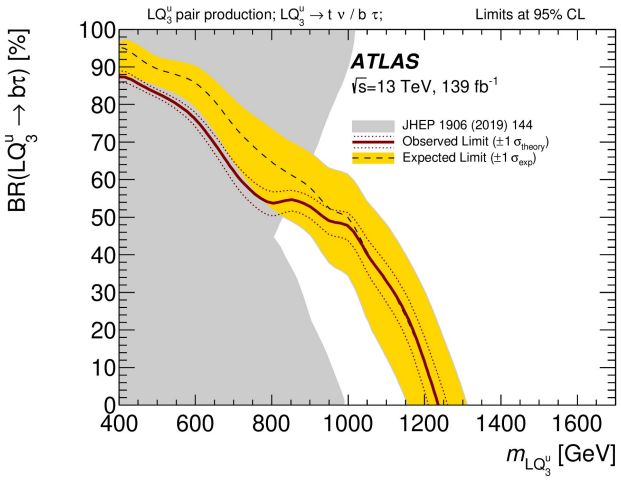
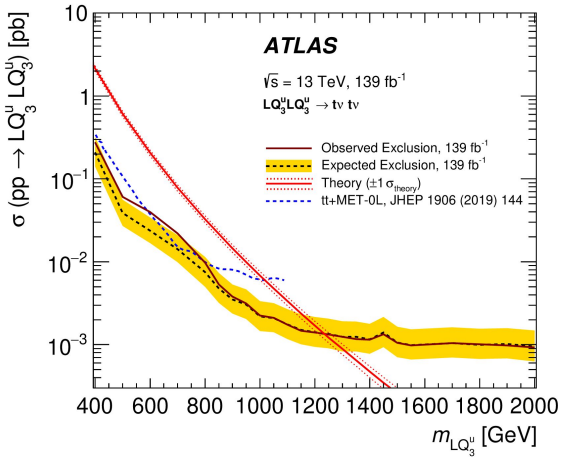
★ Simultaneous fit of the LQ signal strength in the **SRA** & **SRB** regions:
- Number of events is fitted after selections to maximise sensitivity.

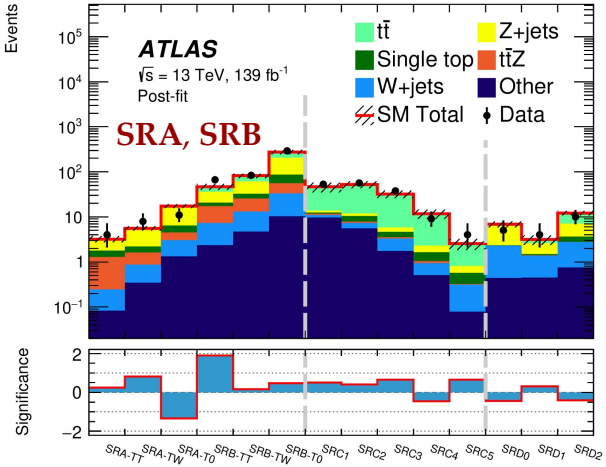
★ No significant excess observed over the SM expectation value.

★ Exclusion limit is set as a function of mass and branching fraction (B):
- $B = 0$ corresponds to **tνtν**, $B = 1$ corresponds to **bτbτ**.
- Exclusion of $\mathbf{m_{LQ} < 1.24\ TeV}$ for $B = 0$.





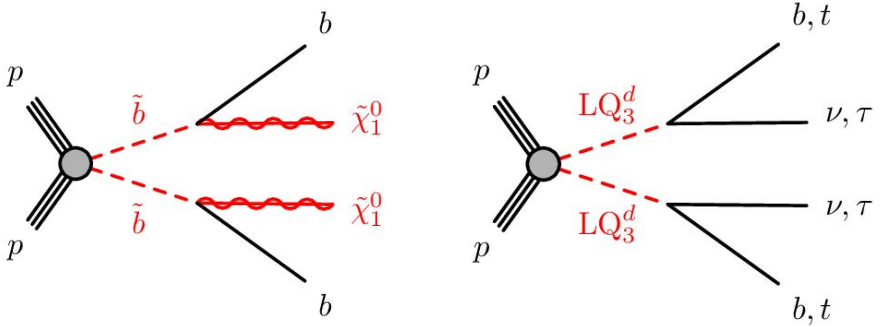




$LQ^dLQ^d \rightarrow b\nu b\nu$

arXiv: 2101.12527

★ Re-interpretation of a SUSY analysis targeting heavy **bottom squark pair production** decaying into stable neutralinos.

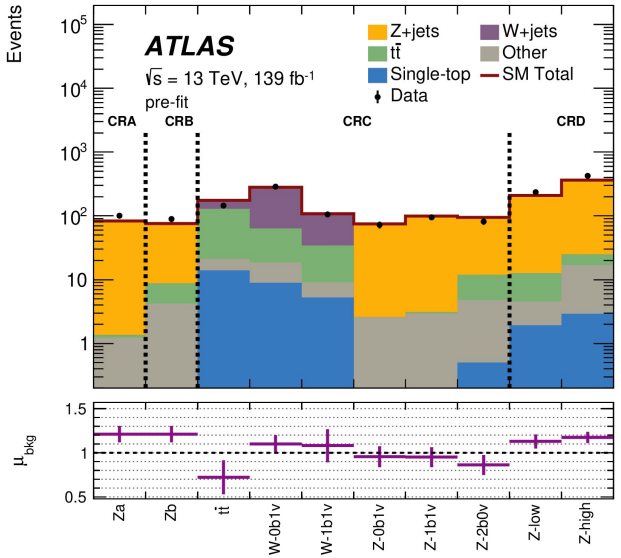


★ **b-jets + E_T^{miss} final state**:

- E_T^{miss} trigger
- 2-4j, 2b, 0ℓ selection in the signal regions of interest
- **DL1r b-tagging** @77% eff

★ Signal region **SRA** targeting large values of $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$, **SRB** targeting lower values of $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 200$ GeV:

- Sensitivity to LQ^d in both regions (**SRA**, **SRB**).



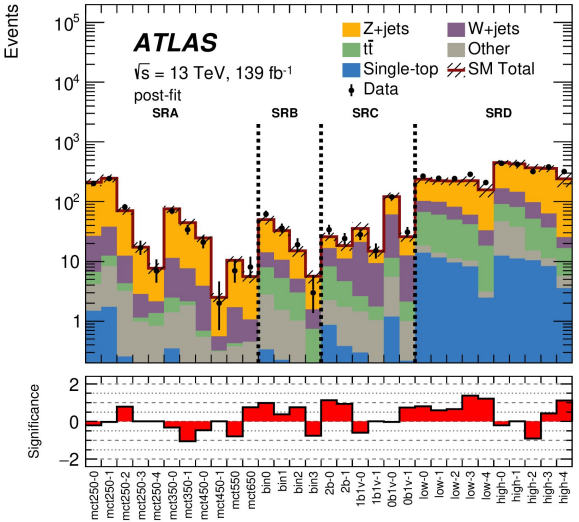
★ Main backgrounds: **V+jets**, **$t\bar{t}$**

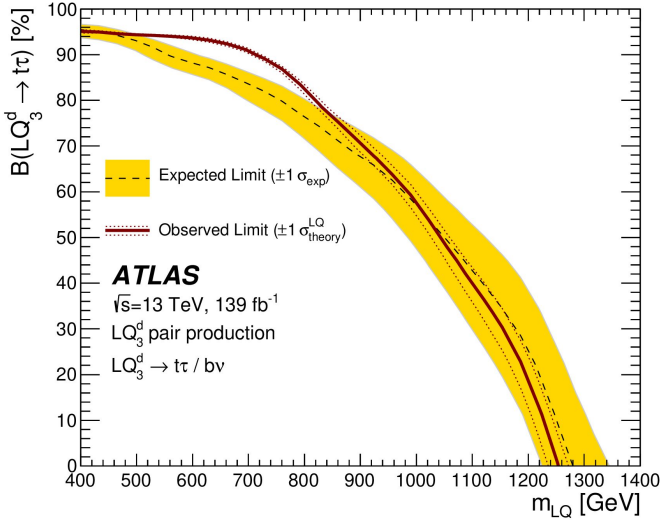
★ Control regions to constrain the normalisations of **$t\bar{t}$** and **V+jets**.

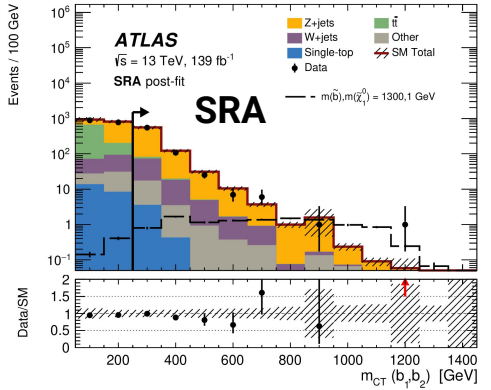
$LQ^dLQ^d \rightarrow b\nu b\nu$

arXiv: 2101.12527

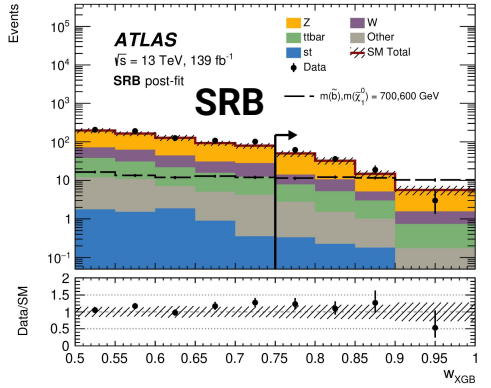
- Simultaneous fit of the LQ signal strength in the **SRA** & **SRB** regions.
- No significant excess observed over the SM expectation value.
- Exclusion limit is set as a function of mass and branching fraction (B):
  - $B = 0$ corresponds to **bνbν**, $B = 1$ corresponds to **ττττ**.
  - Exclusion of $\mathbf{m_{LQ} < 1.26\ TeV}$ for $B = 1$.







$$m^2_{CT}(v_1,\ v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$$

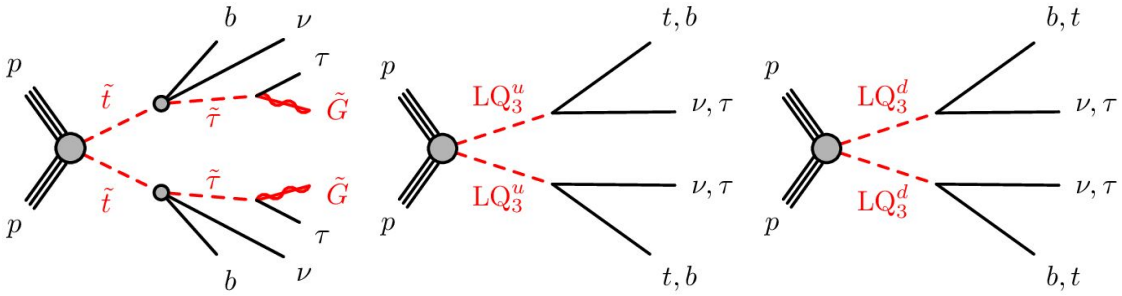


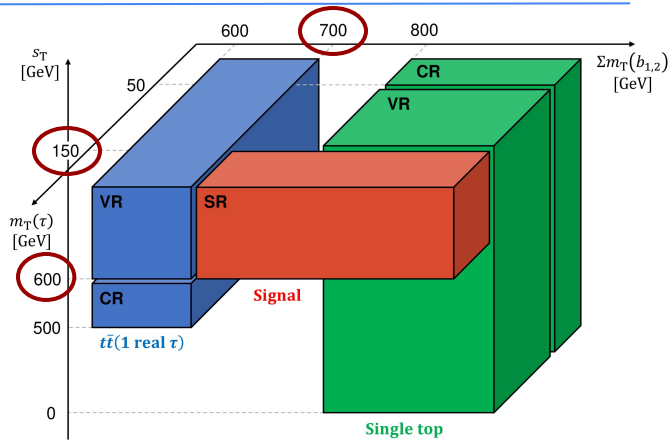
w_{XGB} (BDT)

$LQ^uLQ^u \rightarrow b\tau t\nu$ / $LQ^dLQ^d \rightarrow t\tau b\nu$

ATLAS-CONF-2021-008

★ Re-interpretation of a SUSY analysis targeting heavy **top squark pair production** decaying into gravitinos.





★ **b-jets + τ_{had} + E_T^{miss} final state**:
- **single-** and **di-tau channels**
- E_T^{miss} trigger (E_T^{miss} > 280 GeV for signal regions)
- Pre-selection: ≥ 2j, 0ℓ, ≥ 2b (≥ 1b) in single- (di-) tau channel

★ Region categorisation based on m_T **(τ)**, s_T* and **Σm_T(b$_{1,2}$)** variables.

★ Dominant backgrounds: **$t\bar{t}$**, **single-top**

★ Single-tau channel is used for the re-interpretation:
- Targeting cross-generational LQ decay modes.

$$^*s_T = p_T(\tau) + p_T(\text{jet}_1) + p_T(\text{jet}_2)$$

$LQ^uLQ^u \rightarrow b\tau t\nu$ / $LQ^dLQ^d \rightarrow t\tau b\nu$

ATLAS-CONF-2021-008

- Simultaneous fit of the LQ signal strength using **4 CRs** & the **single-tau multi-bin SR** (three bins in tau p_T).
- No significant excess observed over the SM expectation value.
- Exclusion limit is set as a function of mass and branching fraction (B):
  - Exclusion up to $\mathbf{m_{LQ} < 1.25\ TeV}$ for $\boldsymbol{B = 0.5}$ ($b\tau t\nu$ or $t\tau b\nu$).