Searches for Leptoquarks With the ATLAS Detector

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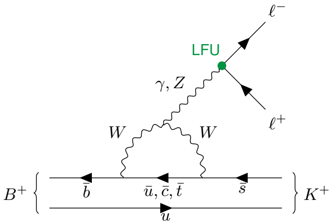
ATLAS EXPERIMENT

Lepton Flavor Universality in B-Meson Decays

- Standard Model: electroweak couplings of gauge bosons to leptons independent of flavor (lepton flavor universality)

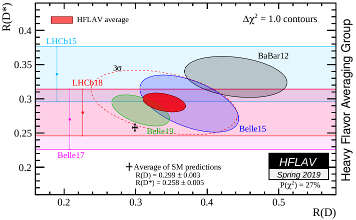


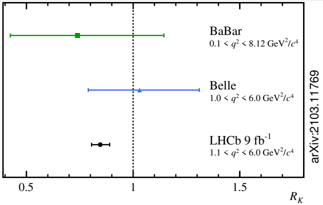
- LFU: could be violated if new particles couple differently to different lepton flavors

Lepton Flavor Universality in B-Meson Decays: “B anomalies”

- Tests of lepton flavor universality important part of physics program (not only) at B factories

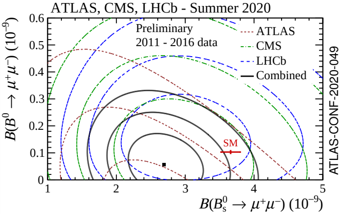
- Combination of measurements of $R(D)$ and $R(D^*)$
  - $R(D) = \mathcal{B}(B \to D\tau^- \nu)/\mathcal{B}(B \to D\ell^- \nu)$, $\ell = e/\mu$
  - independently measured at BaBar, Belle and LHCb
  - about 3σ away from SM
  - tree-level $\Rightarrow$ need large NP contribution





- LHCb measurement of $R(K) = 0.846^{+0.044}_{-0.041}$
  - $R(K) = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$
  - 3.1σ away from the SM prediction

- Consistent picture: deviations in related observables
  - e. g. ATLAS+CMS+LHCb: 2.1σ deviation in $\mathcal{B}(B^0_{(s)} \to \mu\mu)$
  - e. g. angular distributions
- Global EFT with NP fits much better than SM only ($> 5\sigma$)
- Still 3.9σ pull in $bs\ell\ell$ alone w/o look-elsewhere effect



Introducing: Leptoquarks

What Are Leptoquarks

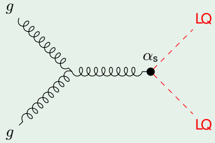
- Hypothetical particles with non-zero baryon and lepton number
- Carry color charge and fractional electric charge
- Decay into quark-lepton pair
- Can be a scalar or a vector particle
  - scalar LQ: simplest model
  - vector LQ: larger cross section, needs UV completion (model dependence)

Well Motivated

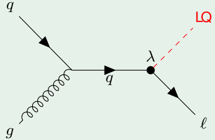
- Appear in many BSM scenarios, e. g. GUTs with larger gauge groups
- Relate quark and lepton sector
  - may provide explanation for similarities

Production Modes

- Pair production
  - via strong interaction, simplest model

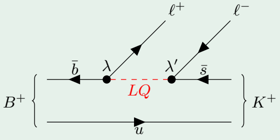


- Single production
  - dependent on coupling strength LQ–ℓ–q λ



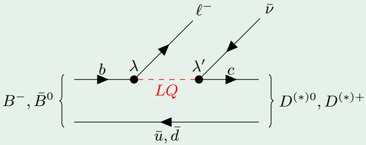
Leptoquarks to the Rescue

- LQs can explain observed deviations from lepton flavor universality in B-meson decays
  - need couplings to different lepton–quark combinations and different strength per flavor



$\rightarrow$ modifies $R(K)$

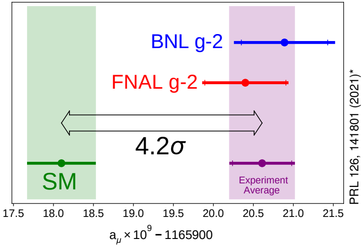
$R(K) = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$

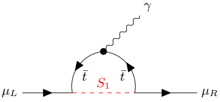


$\rightarrow$ modifies $R(D)$

$R(D) = \frac{\mathcal{B}(B \to D \tau^- \nu)}{\mathcal{B}(B \to D \ell^- \nu)}$

bonus: could also explain discrepancy in anomalous magnetic dipole moment of muon

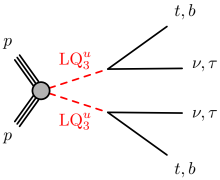




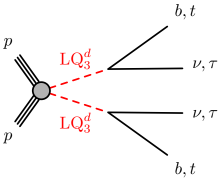
LQ Models in ATLAS

- 2 types: LQs with same electric charge either as up-type or down-type quarks
- Follow minimal Buchmüller–Rückl–Wyler model:
  LQs couple only to quarks and leptons of same generation ("1st- / 2nd- / 3rd-generation LQ")
- Model parameters: leptoquark mass and coupling parameter β
  - β determines branching fraction into charged leptons, e. g. for 3rd-generation leptoquarks:
    - $\beta = 0$: $\mathrm{LQ}_3^{\mathrm{u}} \to t\nu$
    - $\beta = 1$: $\mathrm{LQ}_3^{\mathrm{u}} \to b\tau$

up-type ($Q = \frac{2}{3}e$)



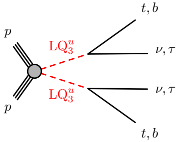
down-type ($Q = -\frac{1}{3}e$)

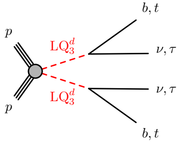


Searches in ATLAS

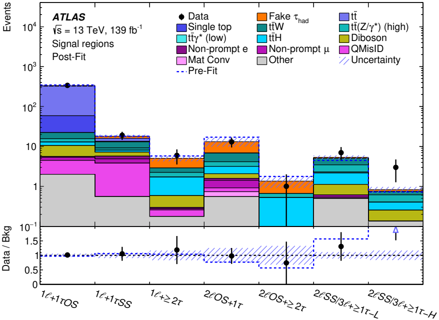
- Have both dedicated searches and reinterpretations

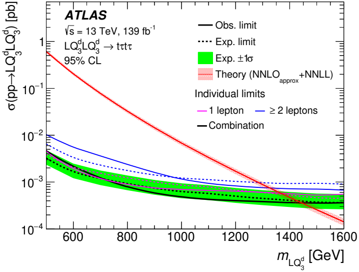
Searches for Pair Production of 3^{rd}-Generation Leptoquarks

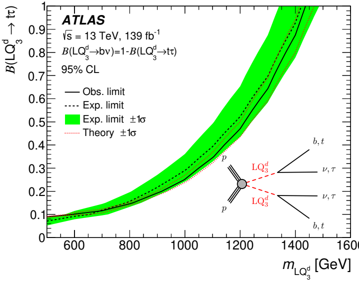




- Combines several final states:
  - $\geq 1\tau_{\text{had}}$ plus 1ℓ ($= e/\mu$) or 2ℓOS or 2ℓSS$/3\ell$
  - further split into 7 channels in total
- Strong exclusion limits despite complex final state thanks to 7 SRs and 15 CRs
- Exclusion:
  - for $\mathcal{B}(\text{LQ} \rightarrow \tau t) = 1$: up to 1.43 TeV
  - for $\mathcal{B}(\text{LQ} \rightarrow \tau t) = 0.5$: up to 1.22 TeV



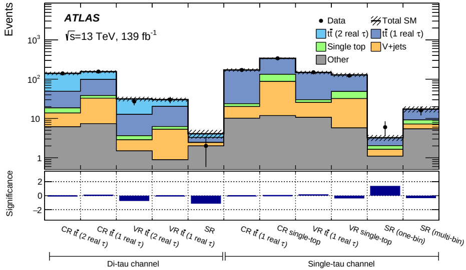


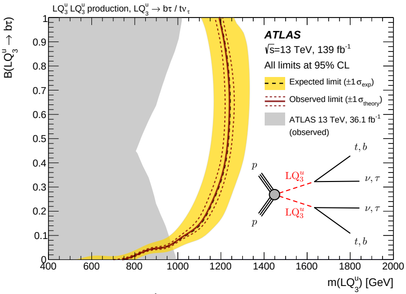


Search for LQLQ $\rightarrow b\tau b\nu$ (and $\tilde{t}\tilde{t}$ with $\tilde{t} \rightarrow b\nu\tilde{\tau}$, $\tilde{\tau} \rightarrow \tau\tilde{G}$)

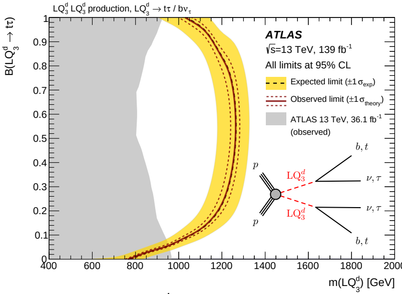
arXiv:2108.07665

- "Search for new phenomena in pp collisions in final states with tau leptons, b-jets, and missing transverse momentum with ATLAS"
- Selects events with ≥ 2 b-jets and 1 τ_{had}
  - also includes di-tau channel for SUSY search
- Exclusion up to 1.25 TeV for scalar LQLQ
  - for both LQ_3^u and LQ_3^d models
  - in broad range around $\beta \sim 0.5$



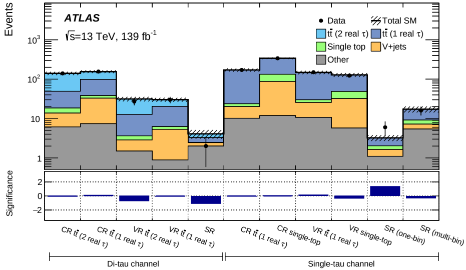


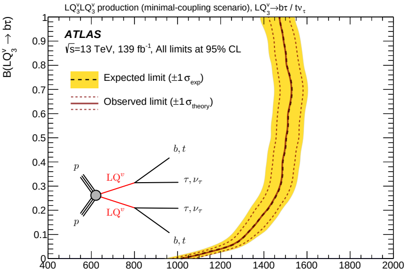
up-type 3rd-generation scalar LQ



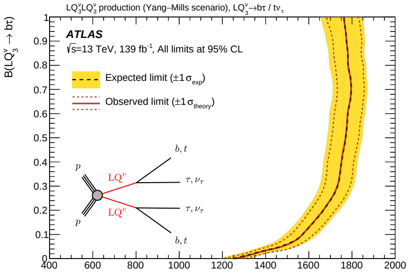
down-type 3rd-generation scalar LQ

- First ATLAS result with interpretation in vector-LQ scenarios
  - "most economical" solution for B anomalies
  - consider two scenarios, differ by LQ couplings
- No dedicated optimization: same selection as for scalar LQ
- Exclusion up to 1.5 / 1.8 TeV in minimal / Yang–Mills coupling case
  - difference due to larger cross section for YM





minimal-coupling scenario

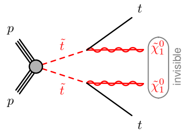


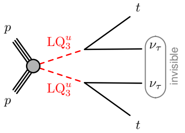
Yang–Mills scenario

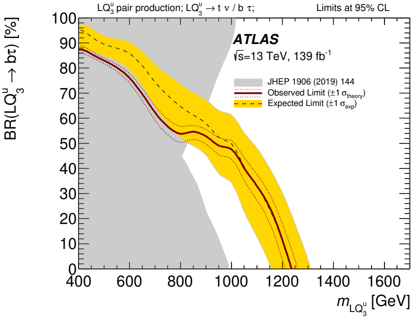
Reinterpretations of SUSY Searches

Up-type 3rd-generation leptoquarks

- Reinterpretation of search for $\tilde{t}\tilde{t}$ (with 0ℓ)
- Same final state for $\beta = 0$: $t\bar{t}$ + invisible







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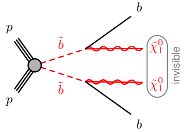
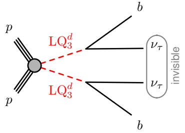
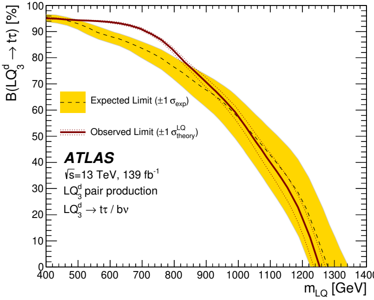
Down-type 3rd-generation leptoquarks

- Reinterpretation of search for $\widetilde{b}\widetilde{b}$ (with 0ℓ)
- Same final state for $\beta = 0$: $b\bar{b}$ + invisible







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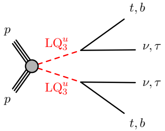
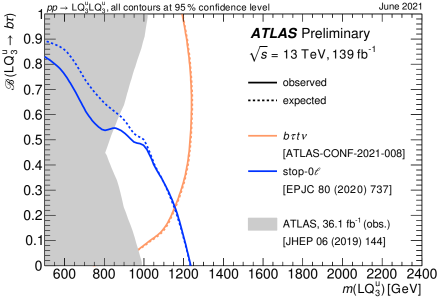
Summary of Pair-Production Searches

Up-type 3rd-generation leptoquarks

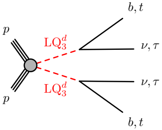
- 1 dedicated search ("$b\tau b\tau$" to be added)
- + reinterpretation of $\tilde{t}\tilde{t}$ (0ℓ) search

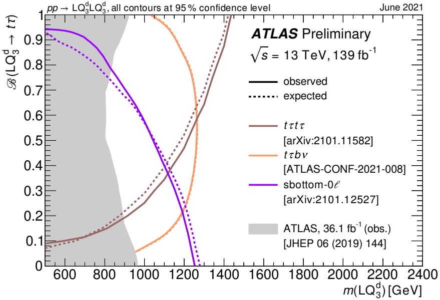




Down-type 3rd-generation leptoquarks

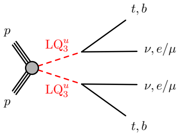
- 2 dedicated searches
- + reinterpretation of $\tilde{b}\tilde{b}$ (0ℓ) search

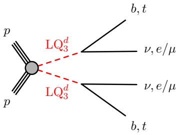




complementary coverage ⇒ strong mass reach over whole range of branching fractions

Searches for Pair Production of Leptoquarks With Mixed Decays

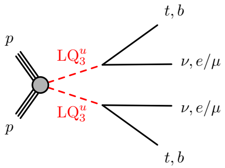




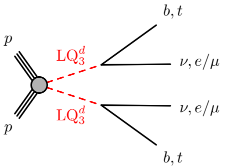
Search for Leptoquarks with Mixed Decays

- Mixed decays: searching for LQ pairs with cross-generational couplings
  - here: LQ $\rightarrow \ell q$ with $\ell \in \{e, \mu\}$ and q = any quark

up-type ($Q = \frac{2}{3}e$)



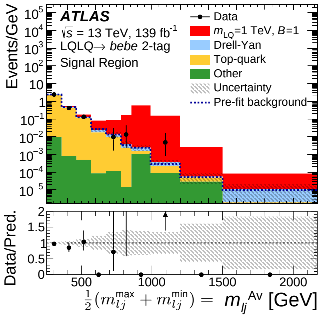
down-type ($Q = -\frac{1}{3}e$)

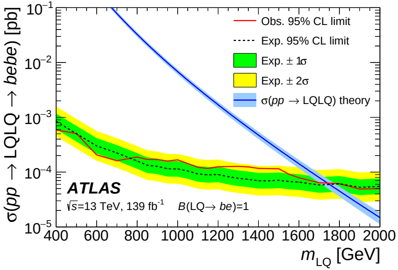


- 2 dedicated searches, targeting:
  1. $qq/cc/bb + ee/\mu\mu$
  2. (boosted) $tt + ee/\mu\mu$

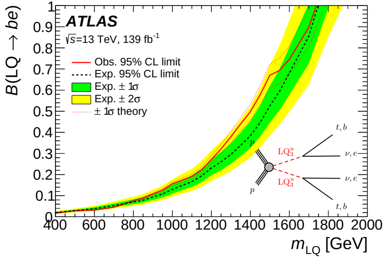
Strategy

- Select e^+e^- / $\mu^+\mu^-$ + ≥ 2 jets
- 7 event categories
  - based on number of b- and c-tagged jets
- LQ candidates = ℓ–j pairs closest in $m_{\ell j}$
  - compute average reconstructed LQ mass $m_{\ell j}^{\mathrm{Av}}$
- Normalization of / systematic uncertainties on dominant backgrounds: derived from CRs





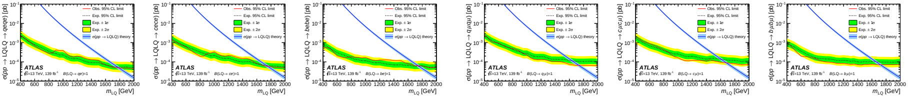
1-D limit on $\sigma(pp \to LQ^u_{mix} LQ^u_{mix} \to bebe)$ $(\beta = 1)$



2-D limits on $m(LQ)$ and $\mathcal{B}(LQ \to be)$

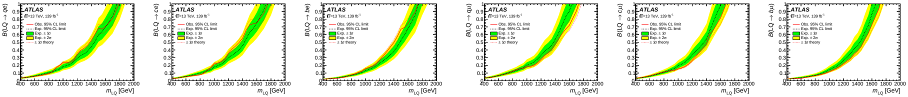
Search for Leptoquarks with Mixed Decays: $qq/cc/bb + ee/\mu\mu$ *JHEP 10 (2020) 112*

1-D limits on $\sigma(pp \rightarrow \text{LQLQ} \rightarrow q\ell q\ell)$



LQLQ $\rightarrow qeqe$ with $q = (u,d,s)/c/b$

LQLQ $\rightarrow q\mu q\mu$ with $q = (u,d,s)/c/b$

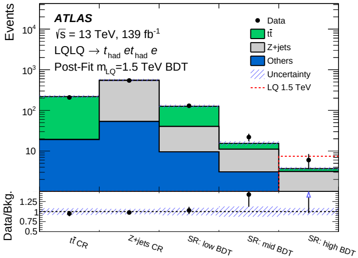


2-D limits on $m(\text{LQ})$ and $\mathcal{B}(\text{LQ} \rightarrow \ell^{\pm} q)$

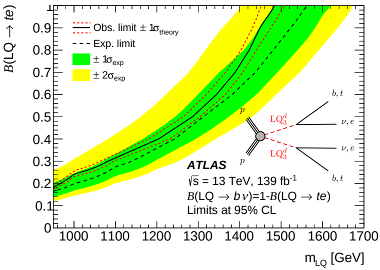
- Analysis considers 3 channels (inclusive, c-, b-quark) $\times$ lepton flavor (e, μ) = 6 scenerios
- Exclusion limits:
  - for $\mathcal{B}(\text{LQ} \rightarrow \ell^{\pm} q) = 1$: $m(\text{LQ}) > 1.8\,\text{TeV}$ (electron channel), $m(\text{LQ}) > 1.7\,\text{TeV}$ (muon channel)
  - for $\mathcal{B}(\text{LQ} \rightarrow \ell^{\pm} q) \geq 0.1$: $m(\text{LQ}) > 0.8\,\text{TeV}$ (electron and muon channel)
  - improving by up to 400 GeV upon earlier results
  - first limits on mixed decays using dedicated c- and b-jet identification algorithms

Strategy

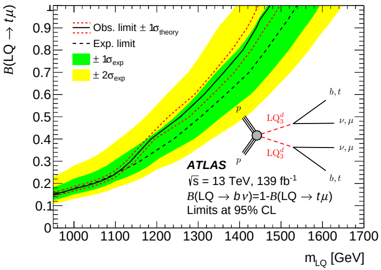
- Select e^+e^- / $\mu^+\mu^-$ + 2 large-R jets ($R = 1.0$)
- BDT based on 29 (32) kinematic observables
  - parameterized in theoretical LQ mass
- Using "recursive jigsaw technique"
  - to construct rest frames of intermediate particle states (resolves kinematic and combinatoric ambiguities)
  - rest frames serve as natural basis for BDT inputs



- 2 CRs to normalize $t\bar{t}/\ Z$ background
- 3 bins in SR based on BDT output score

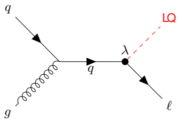


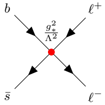
$LQ^d_{mix}LQ^d_{mix} \to tete\ (\beta = 1)$



$LQ^d_{mix}LQ^d_{mix} \to t\mu t\mu\ (\beta = 1)$

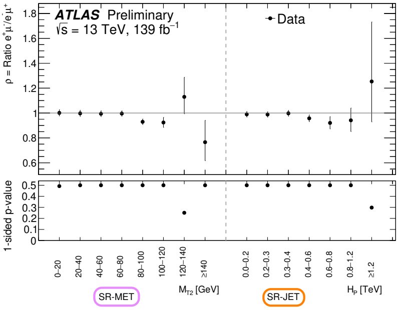
Related Searches: Single Production of Leptoquarks and Contact Interactions

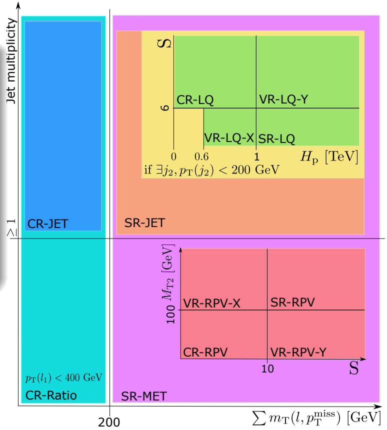




Measurement of Charge-Flavor Asymmetry

- First ATLAS measurement of $\rho = \frac{N(e^+\mu^-)}{N(e^-\mu^+)}$
  - expectation: $\rho_{\text{SM}} = 1$
- But: LHC collides p^+p^+, ⇒ bias $\rho_{\text{SM}}^{\text{ATLAS,LHC}} < 1$
  - mainly due to $W^+ \to \mu^+\nu$ + electron fake
  - estimated and subtracted using matrix method
- Completely data-driven measurement





inclusive selections to measure ratio ρ:

SR-MET and *SR-JET*

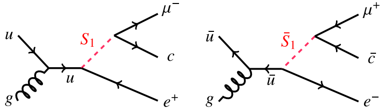
← no significant deviations above one found in any bin

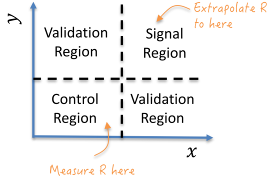
(globally: $\rho = 0.987^{+0.022}_{-0.021}$, 1.6σ)

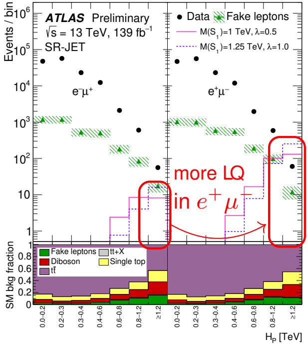
(more details: by C. Vergis)

Single-LQ Production

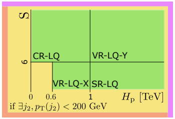
- Can also search for BSM processes with $\rho > 1$
- Here: production of scalar LQ S_1 $\quad \rho = \frac{N(e^+\mu^-)}{N(e^-\mu^+)}$
  - with couplings (only) to eu and μc



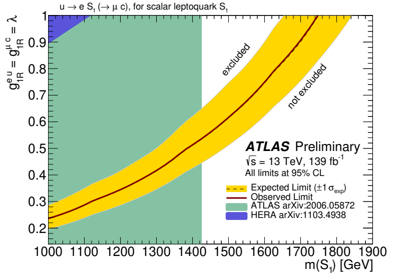




yields in SR-JET ($H_P = p_T(e) + p_T(\mu) + p_T(j_1)$)



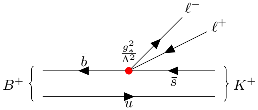
← subset of SR-JET used for LQ search



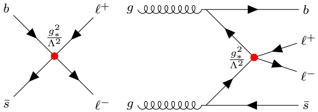
exclusion limit as fct. of $m(\text{LQ})$ *and* $\lambda_{eu} = \lambda_{\mu c}$

Search for $bs\ell\ell$ Contact Interaction

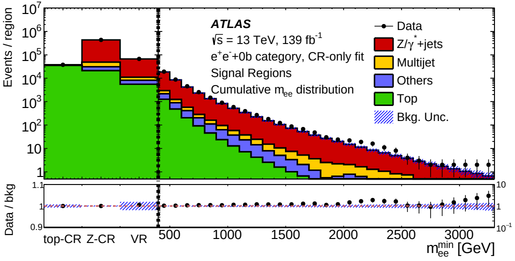
- Search inspired by B anomalies ($R(K)$)
- 4 categories: $e^+e^-/\mu^+\mu^-$ + $0/1$ b-jets
  - sequences of SRs based on $m_{\ell\ell}^{\text{min}}$
- Backgrounds: Z/γ+jets, $t\bar{t}/Wt/t\bar{t}V$, QCD
- Largest deviation in SRs: 1.5σ (globally, e^+e^-+1b)
  - model-independent limits on σ_{vis} and on CI
  - observed limits on Λ/g_* about 2 TeV
  - (CI parameters: scale Λ and coupling g_*)



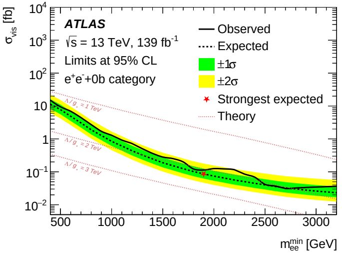
contribution of $bs\ell\ell$ CI to B anomalies



production of target final state in pp collisions



yields in CRs, VR, SRs ($\widehat{=}$ cumulative m_{ee}) and . . .



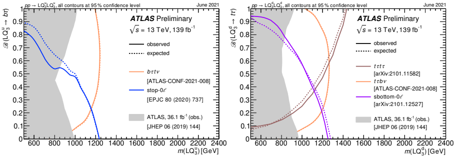
. . . limits on σ_{vis} in e^+e^- + b-veto channel

Conclusion

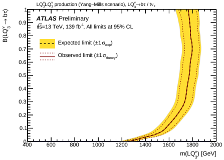
In Conclusion

Summary

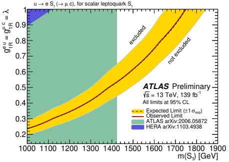
- ATLAS searches for leptoquarks cover a wide range of final states, no significant excess obs.
- Strong limits on pair production of scalar leptoquarks with flavor-diagonal and mixed decays
  - from combination of dedicated searches and reinterpretations of searches for supersymmetry
  - use simplified and consistent LQ model among all analyses
  - model parameters: LQ mass and branching fraction into charged leptons $\mathcal{B}(\text{LQ} \to q\ell^{\pm})$
- Recently started to also tackle more complex models:
  - first results on vector-leptoquark models (LQLQ $\to b\tau t\nu$) and on single production
  - search for $bs\ell\ell$ contact interaction



summary of 3rd-gen. LQLQ



vector LQ (YM)

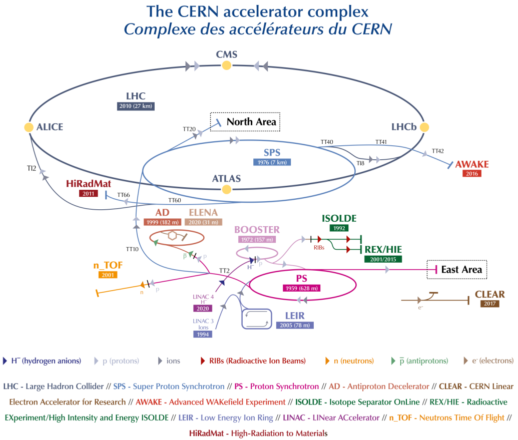


single LQ

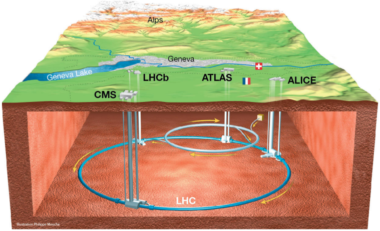
More to Cover

- Cross-gen. couplings: combinatorics in LQLQ decays $\Rightarrow$ many more decay modes to cover
- Single production: many channels uncovered, including those motivated by B anomalies
- Other production modes: LQ in t-channel; resonant production (Run 3?)

Extra Material



CERN-GRAPHICS-2019-002

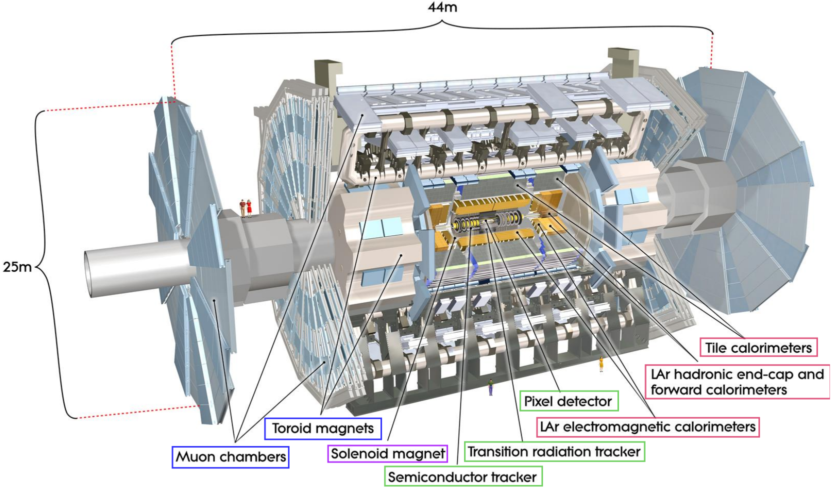


OPEN-PHO-ACCEL-2014-001

overall view of the LHC and the 4 big detectors: ALICE, ATLAS, CMS and LHCb

The LHC is the last ring (dark blue line) in a complex chain of particle accelerators. The smaller machines are used in a chain to help boost the particles to their final energies and provide beams to a whole set of smaller experiments.

The ATLAS Detector



- 44 m × 25 m × 25 m, 7000 tonnes
- Subdetectors = concentrical cylinders surrounding nominal IP
- Tracking detectors — solenoid magnet — calorimeters — muon spectrometer

Leptoquarks: Scalar vs Vector

Scalar LQ

- Single Yukawa-coupling parameter determines strength of coupling LQ–ℓq
- Production at LHC even mostly independent of this parameter

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
scalar leptoquarks	S_1	✗*	✓	✗*
scalar leptoquarks	R_2	✗*	✓	✗
scalar leptoquarks	$\widetilde{R}_2$	✗	✗	✗
scalar leptoquarks	S_3	✓	✗	✗
vector	U_1	✓	✓	✓
vector	U_3	✓	✗	✗

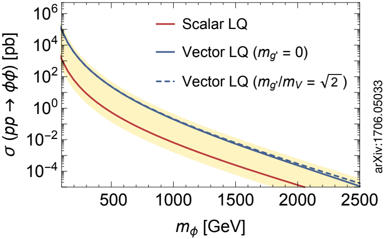
arXiv:1808.08179

(= can alleviate discrepancy, but not fully accommodate it)*

- The most "economic" models require (at least) 2 scalar LQs or 1 vector LQ to explain both B anomalies (plus potentially others)

Vector LQ

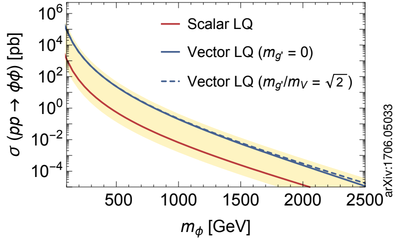
- Additional couplings (magnetic moment and electric quadrupole moment)
- Production cross sections typically much larger than for scalar LQ
- But kinematics similar

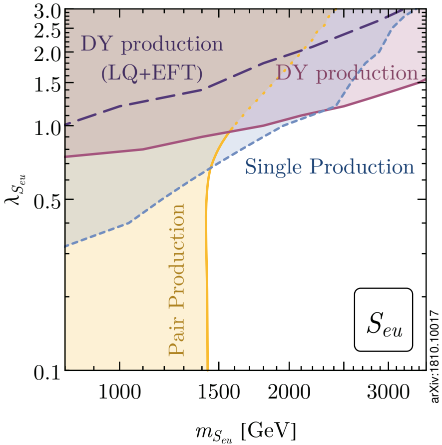


pair-production cross section

Pair Production at LHC

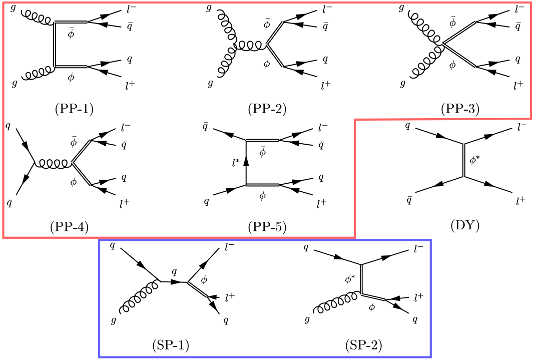
- Gluon-initiated production dominates for all (except very large) LQ masses



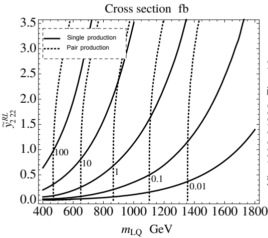


bounds on scalar minimal leptoquark from Run 2 pair production (yellow), projected Run 2 single production (blue), Run 2 DY-production (purple) at the LHC.

Leptoquarks: Single vs Pair Production II



arXiv:1810.10017, Fig. 1



arXiv:1603.04993, Fig. 19

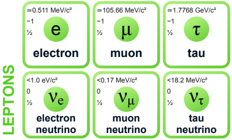
Cross sections for single and pair production of LQ at $\sqrt{s} = 8\,\text{TeV}$

Difference w.r.t. Pair Production

- Pair production largely independent of LQ-q-ℓ coupling λ (dominated by strong interaction)
- Single production important for large LQ-q-ℓ coupling (amplitude $\sim \lambda$) or large mass
  - need to consider dependence on λ as additional parameter
  - larger coupling $\lambda \Rightarrow$ larger width ($\Gamma_{S,V} \sim \lambda^2$, relevant when reconstruction $m(l,q)$)
  - at large coupling λ increased contribution of non-resonant production populates low-mass tails
- Amplitudes PP-1 to PP-4 $\sim g_s$, PP-5 and DY $\sim \lambda^2$, SP-X $\sim \lambda g_s$

Lepton Flavor Violation

- SM: number of leptons in each family conserved in interactions
- But: no fundamental principles forbid LFV processes
- Observation of neutrino oscillations:
  1. $\Rightarrow$ neutrinos have mass
  2. $\Rightarrow$ flavor not conserved in neutral lepton sector

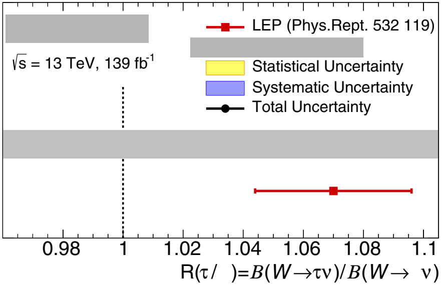


- No experimental evidence of LFV in charged sector
- Limits on LFV in production from LEP experiments:

$$\mathcal{B}(Z \to e\mu) < 1.7 \cdot 10^{-6}, \mathcal{B}(Z \to e\tau) < 9.8 \cdot 10^{-6}, \mathcal{B}(Z \to \mu\tau) < 12 \cdot 10^{-6}$$

- Lepton flavor universality:
  coupling of electroweak gauge bosons to leptons independent of lepton flavor in SM

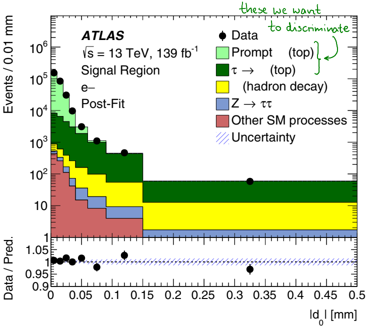
- LEP measurement: long-standing 2.7σ discrepancy from SM prediction (1.0)
  - $R(\tau/\mu) = \frac{\mathcal{B}(W\to\tau\nu_\tau)}{\mathcal{B}(W\to\mu\nu_\mu)} = 1.070 \pm 0.026$



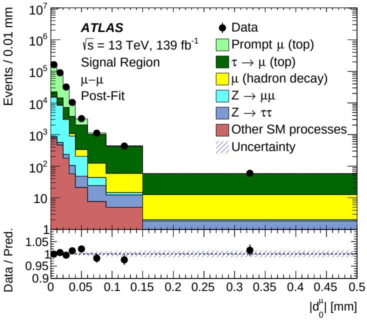
- LHC = "$t\bar{t}$ factory": 15 Hz production rate ⇒ search for violation of LFU in LHC dataset

Strategy

- Select pure sample of dileptonic $t\bar{t}$ events with 2 b-tags (plus $m_{\ell\ell}$ veto against Z / low-mass DY)
- Use *tag-and-probe* method in $e^{\pm}\mu^{\mp}$ or $\mu^{+}\mu^{-}$ events: e or μ as tag, (2nd) μ as probe
- Discriminate $W \to \mu\nu_{\mu}$ and $W \to \tau\nu_{\tau} \to \mu\nu_{\mu}\nu_{\tau}\nu_{\tau}$ based on
  - impact parameter $|d_0^{\mu}|$ (→ lifetime of tau lepton)
  - $p_{\mathrm{T}}(\mu)$ (→ energy shared with neutrino(s))
- Determine ratio $R(\tau/\mu)$ → many systematic uncertainties cancel



SR in $e\mu$, tag = e, probe = μ

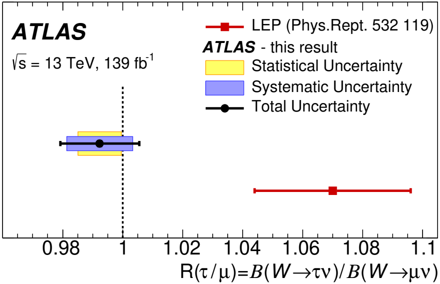


SR in $\mu\mu$, tag = μ, probe = μ

- Measured value from fit of 48 SR bins:

$$R(\tau/\mu) = \frac{\mathcal{B}(W\to\tau\nu_\tau)}{\mathcal{B}(W\to\mu\nu_\mu)} = 0.992 \pm 0.013$$

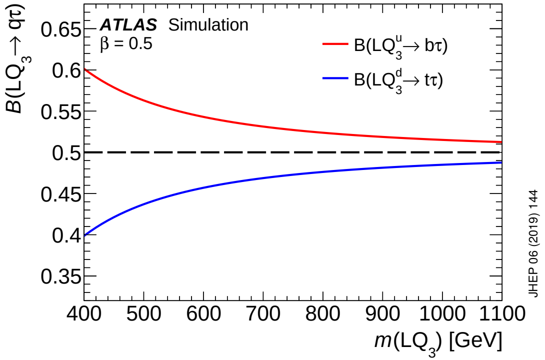
- Agrees well with SM ⇒ discrepancy seen by LEP not confirmed
- Most precise measurement of $R(\tau/\mu)$ to date



So all is well. . . or is it?

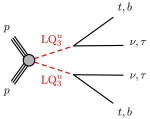
Branching Fraction and β Parameter

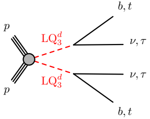
- For light decay products, branching fraction $B(\text{LQ} \to q\ell) \sim \beta$
  - coupling to charged lepton $= \sqrt{\beta}\lambda$
  - coupling to neutral lepton $= \sqrt{1-\beta}\lambda$
- Large mass of top quark leads to noticeable deviation (dependent on LQ mass)
  - decays to top quark suppressed w.r.t. decays including bottom quark instead



Our Models

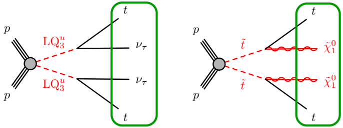
- Scalar up- and down-type LQ with electric charge $\frac{2}{3}e$ and $-\frac{1}{3}e$
- BR of decay to uncharged or charged lepton determined by parameter β
  - $\beta = 0$: $\mathrm{LQ}_3^{\mathrm{u}} \to \nu t$, $\mathrm{LQ}_3^{\mathrm{d}} \to \nu b$
  - $\beta = 1$: $\mathrm{LQ}_3^{\mathrm{u}} \to \tau b$, $\mathrm{LQ}_3^{\mathrm{d}} \to \tau t$
- No-mixing models assume LQ–ℓq couplings only within given generation



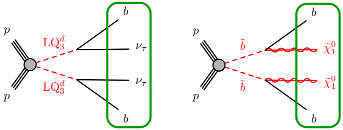


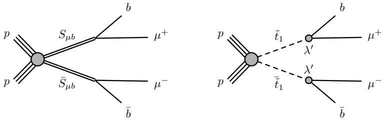
Why LQ & SUSY

- Colored squark / LQ: same pair production xsec
- Similar or even identical final states and kinematics
- $\Rightarrow$ Powerful reinterpretations of SUSY searches



same final state for massless neutralinos

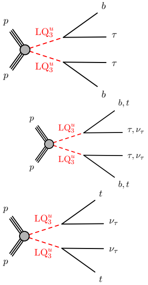


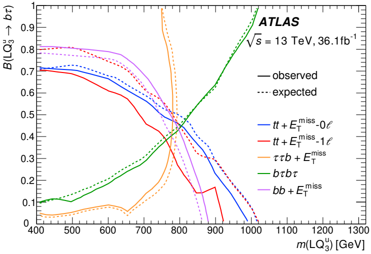


same final state as RPV stop decays

3^{rd}-gen. LQ paper

- Search for pair-produced LQ_3^u/LQ_3^d
- Reinterpretation of four third-generation SUSY analyses
- Plus reoptimized di-higgs analysis
- Results displayed as overlay (no combination)





1^{st}- + 2^{nd}-gen. LQ paper

- Considers LQ_1 and LQ_2
- Excludes LQ masses...
  - up to 1.5 TeV depending on β
  - for $\beta = 0.5$ up to 1.25 TeV
- Eur. Phys. J. C 79 (2019) 733