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Searches for leptoquarks with the ATLAS detector

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ATLAS EXPERIMENT

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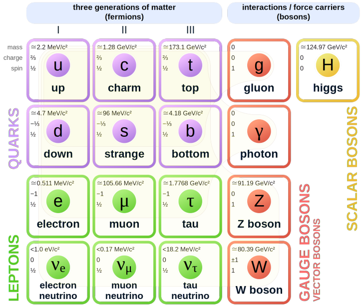
Ausbau von ATLAS am LHC: Physik mit dem ATLAS-Experiment
ErUM-FSP T02
ATLAS

Why leptoquarks ?

Standard Model of Elementary Particles



LQ models:

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

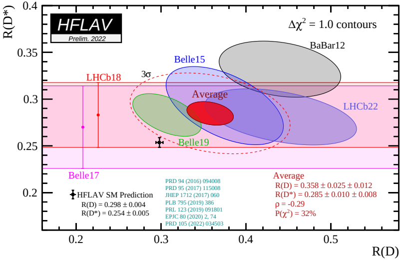
Angelescu, Becirevic, DAF, Sumensari [1808.08179]

- 3 gen. mirrored lepton $\leftrightarrow$ quark
- Charge: $q_{lep} \leftrightarrow n_{color} \times q_{quark}$
- leptoquarks (LQ) show up in many possible GUT scenarios.

- LQ have color+lepton number
- scalar and vector particles

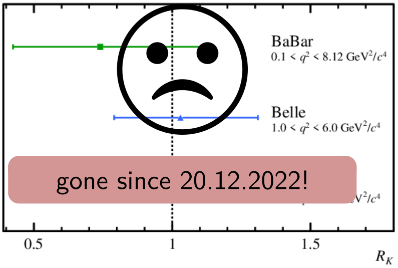
Observed anomalies

$R_{D^{(*)}}$ - 3σ discrepancy to SM



Heavy Flavor Averaging Group [1]

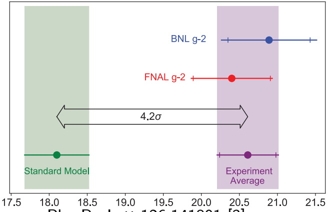
R_K - 3.1σ discrepancy to SM



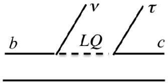
arXiv: 2103.11769 [2]

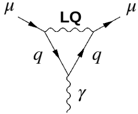
- $R_{D^{(*)}} = \dfrac{BR(\mathrm{B}\to\mathrm{D}^{(*)}\tau^-\nu_\tau)}{BR(\mathrm{B}\to\mathrm{D}^{(*)}\ell\nu)}$

μ magnetic Moment



PhysRevLett.126.141801 [3]





→ Results show significant deviation from SM prediction.
Contributions from LQs could explain this nicely!

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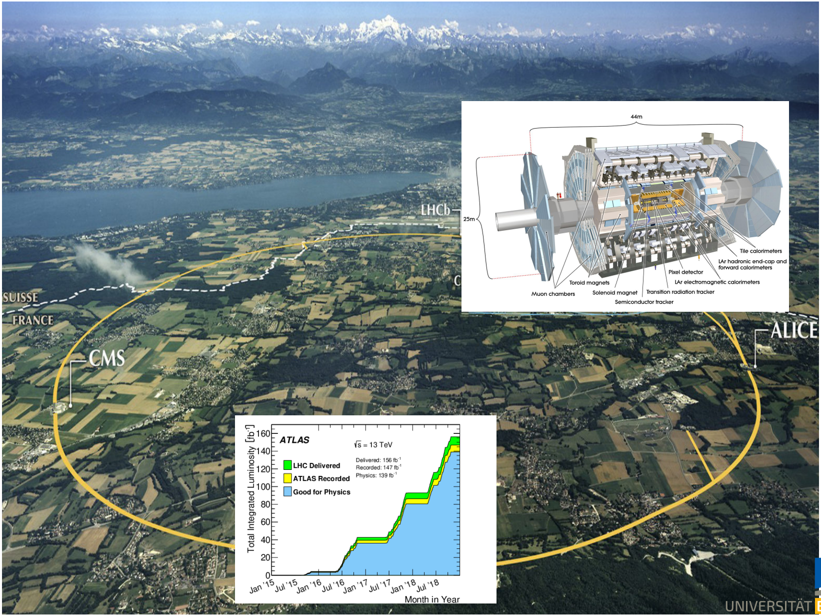
Search for LQ's at ATLAS



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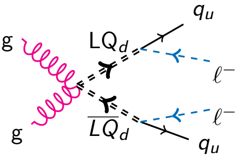
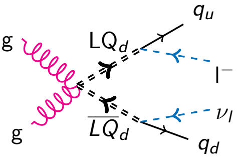
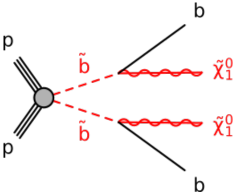
ATLAS search strategy



flavour-diagonal LQ



cross-generational



SUSY

- Investigation of pair produced (PP) leptoquarks via QCD
  $\Rightarrow$ almost model independent (compared to single production (SP) or non-resonant processes)
- Process analogous to other PP BSM particles (e.g. SUSY)
  $\Rightarrow$ Allows reinterpretation of existing analyses complementary to dedicated searches
- LQ_d: $|q| = \frac{1}{3}e$, LQ_u: $|q| = \frac{2}{3}e$
- $LQ^3_{u,d}$: couples excl. to 3rd gen.
- $LQ^{mix}_{u,d}$: couples to 3rd gen. q and 1/2 gen. lepton
- Exclusion contours : Leptoquarkmass (m(LQ)) against branching fraction to final state ($\mathcal{B}$)

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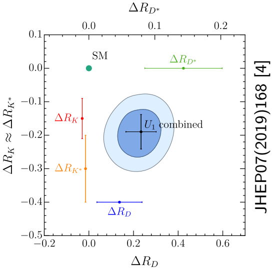
Vector LQ models $U_1/\tilde{U}_1$



- U_1 LQ was favoured explanation for anomaly in $R_{D^{(*)}}$ and $R_{K^{(*)}}$ – so far
- Only one particle solution to explain both anomalies
- still a valid scenario !

- U_1(q=2/3) and $\tilde{U}_1$ (q=5/3) explored by ATLAS
- Much larger x-section compared to kin. suppressed scalar LQs

$$\mathcal{L}_{U_1} \supset -ig_s\,(1-\kappa)\,U^{\dagger}_{1\mu}\,T^a\,U_{1\nu}\,G^{a\mu\nu}$$

For the vector LQ coupling to color can be suppressed (κ) $\Rightarrow$ 2 scenarios :

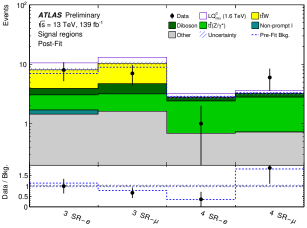
- Nominal coupling to color ($\kappa = 0$) Yang Mills (YM)
- Minimal coupling ($\kappa = 1$): coupling to gluon only via covariant derivative

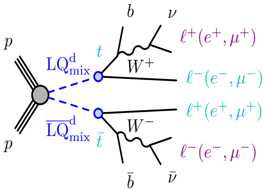
$LQ_d^{mix} LQ_d^{mix} \to t\ell\ t\ell$ (multilepton)

ATLAS-CONF-2022-052

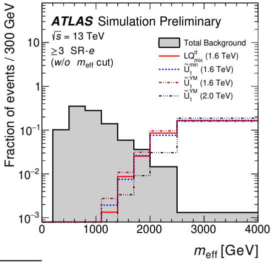
Strategy

- Select events with 2ℓ from LQ_d^{mix} + $1(2)\ell$ from t decay
- Require at least 2 jets, 1 btag. jet
- variables : M_{ll}^{min} and M_{eff} [1]
- Fit for $M_{ll}^{min} \geq 100$ GeV, $M_{eff} \geq 500$ GeV

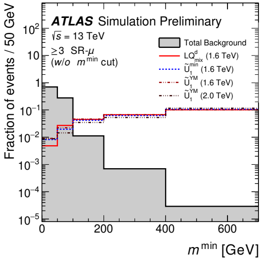




3ℓ SR ($eee/ee\mu$)



3ℓ SR ($\mu\mu\mu/\mu\mu e$)



[1] $M_{eff} = \Sigma p_T^{\ell} + \Sigma p_T^{jets}$

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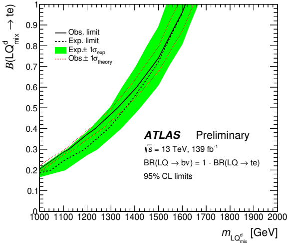
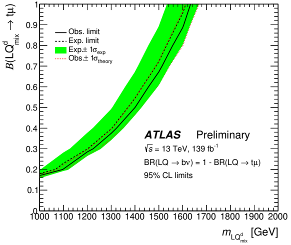
$LQ_d^{mix} LQ_d^{mix} \to t\ell\ t\ell$ (multilepton)

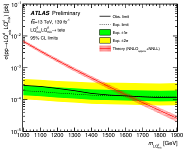
ATLAS-CONF-2022-052

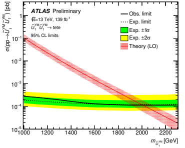
$LQ_d^{mix} LQ_d^{mix} \to tete$



$LQ_d^{mix} LQ_d^{mix} \to t\mu t\mu$







Observed limits at 95 % CL

- $m(LQ_d^{mix})$ [1] > 1.61 TeV/1.64 TeV for $te/t\mu$
- $m(\tilde{U}_1)$ [2] > 1.71 TeV/1.73 TeV for $te/t\mu$ (min.coupling)
- $m(\tilde{U}_1) > 2.0$ TeV for $te/t\mu$ (Yang Mills coupling)

[1] scalar down type LQ_d^{mix} $\mathcal{B}(LQ \to t\ell) = 1.0$
[2] vector down type LQ ($\tilde{U}_1$ model) $\mathcal{B}(LQ \to t\ell) = 1.0$

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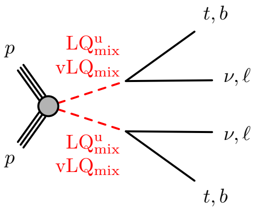
LQLQ → $t\nu b\ell$

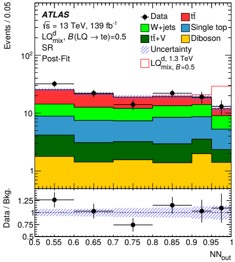
arXiv:2210.04517

Strategy

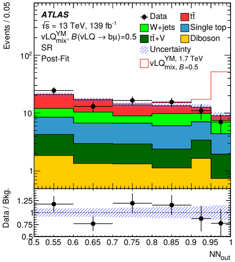
- Select $E_T^{miss} > 250$ GeV, 1ℓ and at least 4 jets
- Training region for neural network (NN): $n^b_{jets} > 1, m_T^{(\ell, E_T^{miss})} \geq 120$ GeV, am_{T2}[1] > 200 GeV
- Perform mle[1] fit over NN output (classifier below 0.5 as CR)



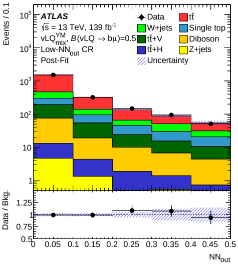
Training region ℓ=e



Training region $\ell=\mu$



low NN CR



1 2

[1] am_{T2} :asymmetric transverse mass [5, 6]
[2] Minimum likelihood estimator

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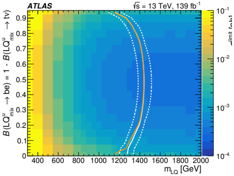
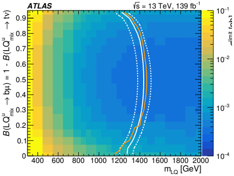
LQLQ $\rightarrow t\nu b\ell$

arXiv:2210.04517

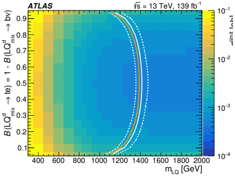
$LQ^u_{mix} \rightarrow be$



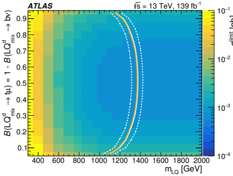
$LQ^u_{mix} \rightarrow b\mu$



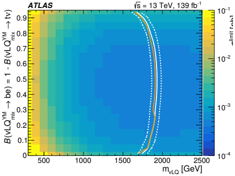
$LQ^d_{mix} \rightarrow te$



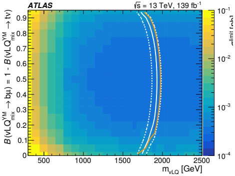
$LQ^d_{mix} \rightarrow t\mu$



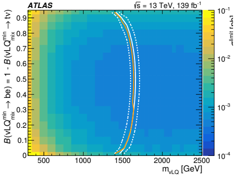
$vLQ_{mix} \rightarrow be(YM)$



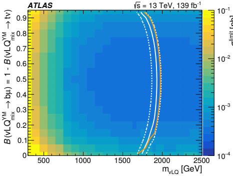
$vLQ_{mix} \rightarrow b\mu(YM)$



$vLQ_{mix} \rightarrow be\ (min)$



$vLQ_{mix} \rightarrow b\mu(min)$



8 scenarios

- scalar LQ^{mix}_u coupling to be/bμ
- scalar LQ^{mix}_d coupling to te/tμ
- vector $vLQ^{YM/min}$ (U_1) to be/bμ

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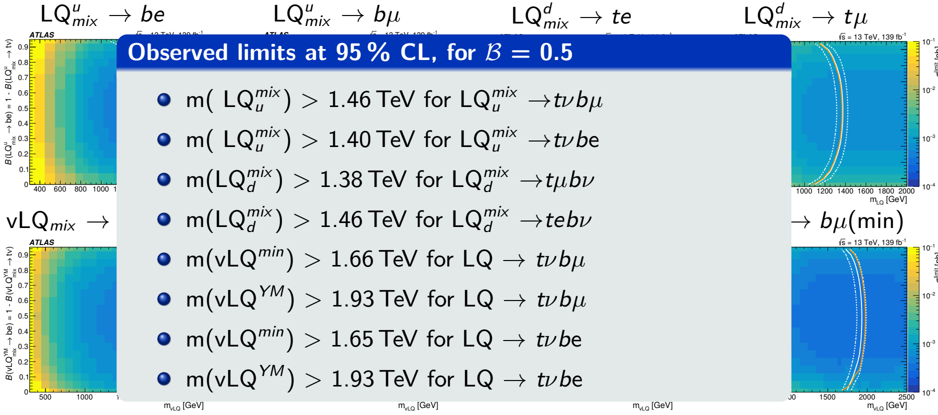
LQLQ $\to t\nu b\ell$

arXiv:2210.04517



Observed limits at 95 % CL, for $\mathcal{B} = 0.5$

- m(LQ^{mix}_u) > 1.46 TeV for $LQ^{mix}_u \to t\nu b\mu$
- m(LQ^{mix}_u) > 1.40 TeV for $LQ^{mix}_u \to t\nu be$
- m(LQ^{mix}_d) > 1.38 TeV for $LQ^{mix}_d \to t\mu b\nu$
- m(LQ^{mix}_d) > 1.46 TeV for $LQ^{mix}_d \to teb\nu$
- m(vLQ^{min}) > 1.66 TeV for LQ $\to t\nu b\mu$
- m(vLQ^{YM}) > 1.93 TeV for LQ $\to t\nu b\mu$
- m(vLQ^{min}) > 1.65 TeV for LQ $\to t\nu be$
- m(vLQ^{YM}) > 1.93 TeV for LQ $\to t\nu be$

8 scenarios

- scalar LQ^{mix}_u coupling to be/bμ
- scalar LQ^{mix}_d coupling to te/tμ
- vector $vLQ^{YM/min}$ (U_1) to be/bμ

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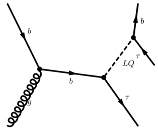
LQ single production : τ LQ $\to \tau b \tau$

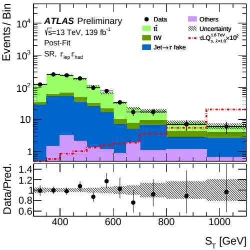
ATLAS-CONF-2022-037

Strategy

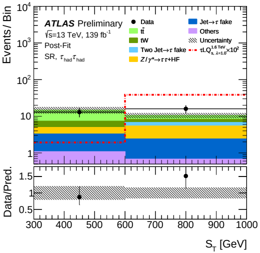
- First direct search for SP LQ at ATLAS
- exploit full-hadronic & semi-leptonic τ-decays (hh/lh)
- Select $m_{\tau\tau}^{vis} > 100$ GeV, S_T[1] >300 GeV, $p_T^{bjet} > 200$ GeV (optimized for resonant production)



$\tau^{lep}\tau^{had}$ SR



$\tau^{had}\tau^{had}$ SR



- Target $\tilde{S}_1$ model, q=4/3
- $\mathcal{L}_{\tilde{S}_1} \supset \lambda^{ij} \bar{d}_R^{Ci} \tilde{S}_1 e_R^j + \ldots$
- signal yield varies with Yukawa coupling λ

1 $S_T = p_T(\tau^1) + p_T(\tau^2) + p_T(bjet)$

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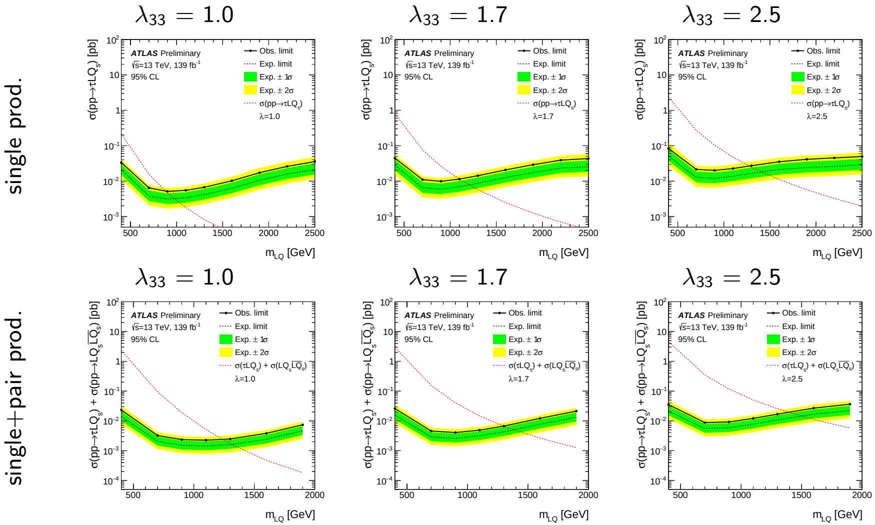
LQ single production : Yukawa coupling λ

ATLAS-CONF-2022-037



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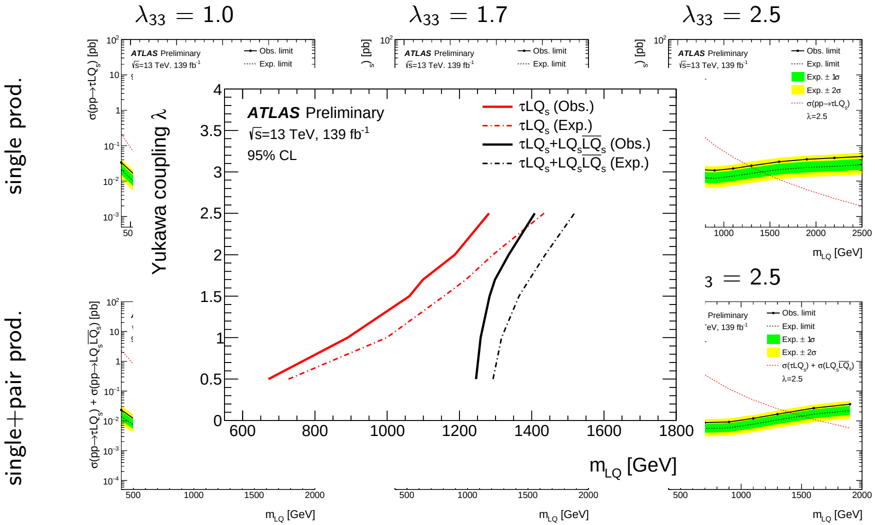
LQ single production : Yukawa coupling λ

ATLAS-CONF-2022-037

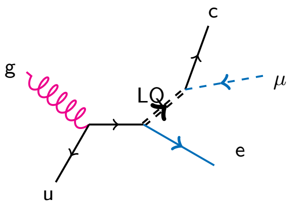


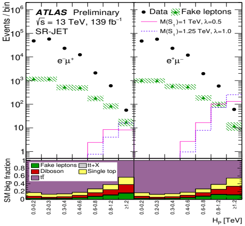
LQ single production

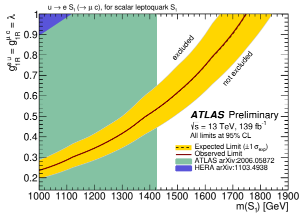
ATLAS-CONF-2021-045

Strategy

- Data driven analysis of $\rho = \frac{N(e^+\mu^-)}{N(e^-\mu^+)}$ e/μ asymmetry measurement
- Events with exactly 1 μ and 1 e (opposite charge)
- Main discriminating variable: $H_P = |\vec{p_T}^{e}| + |\vec{p_T}^{\mu}| + |\vec{p_T}^{jet_{lead}}|$
- MET significance < 6







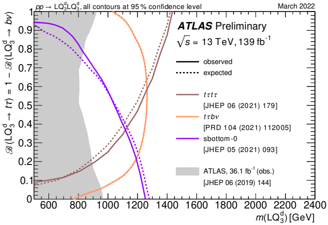
Observed limits at 95 % CL

- m(LQ) > 1.5 TeV for $\mathcal{B}(\text{LQ} \to \text{c}\ \mu) = \mathcal{B}(\text{LQ} \to \text{ue}) = 0.5$ with coupling strength $g_{eu} = g_{\mu c} > 0.6$

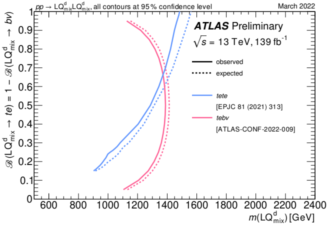
scalar LQ_{down} summary plots

ATL-PHYS-PUB-2022-012

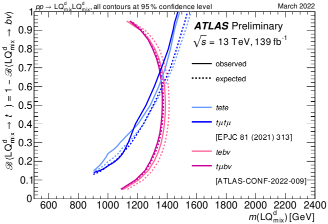
$LQ_d^3 \to t\,\tau$



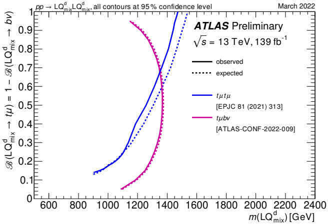
$LQ_d^{mix} \to te$



$LQ_d^{mix} \to t\ell$



$LQ_d^{mix} \to t\mu$



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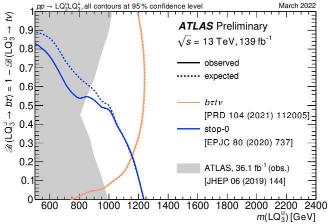
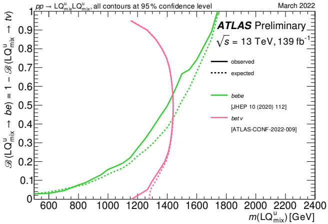
scalar LQ_{up} summary plots

ATL-PHYS-PUB-2022-012

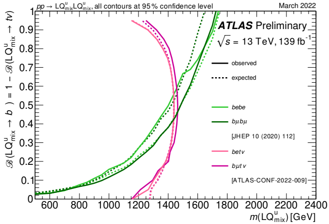
$LQ_u^3 \to b\,\tau$



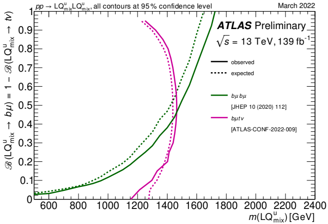
$LQ_u^{mix} \to be$



$LQ_u^{mix} \to b\ell$



$LQ_u^{mix} \to b\mu$



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Summary

- ATLAS published wide range of searches for LQs using $140\,\text{fb}^{-1}$ recorded during Run 2 at LHC
- Some full Run 2 results are still in progress
- Improvements in flavor tagging and τ-reconstruction will used in future analysis
- LHC Run 3 has started last year and HL LHC will follow: ATLAS is looking forward to significantly more data to be analyzed ($\approx$ 20 times more data expected)

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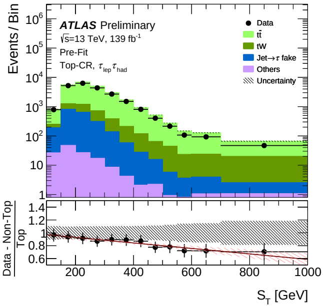
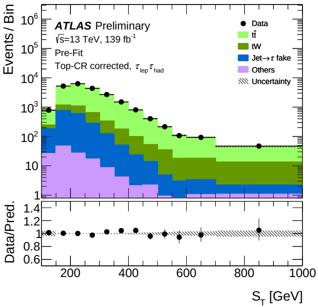
τ LQ $\rightarrow \tau b \tau$: top reweighting

- top MC generally badly modeled at high S_T
- correction determined in CR

without correction

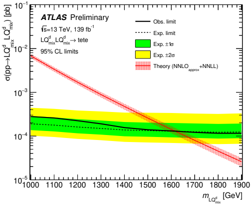


with correction applied

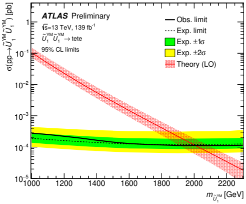


LQLQ $\rightarrow t\ell\ t\ell$ (multilepton)

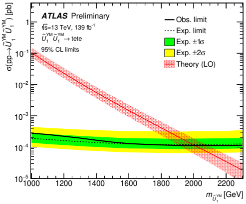
LQ $\rightarrow te$



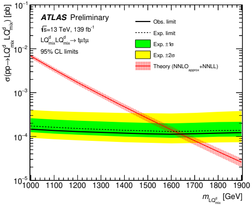
$\tilde{U}_1^{YM} \rightarrow te$



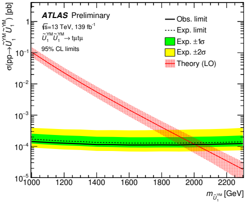
$\tilde{U}_1^{min} \rightarrow te$



LQ $\rightarrow t\mu$



$\tilde{U}_1^{YM} \rightarrow t\mu$



$\tilde{U}_1^{min} \rightarrow t\mu$