B-physics guided leptoquark searches

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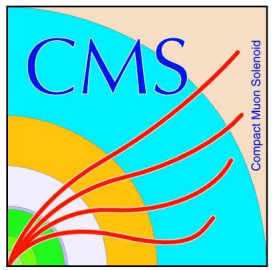
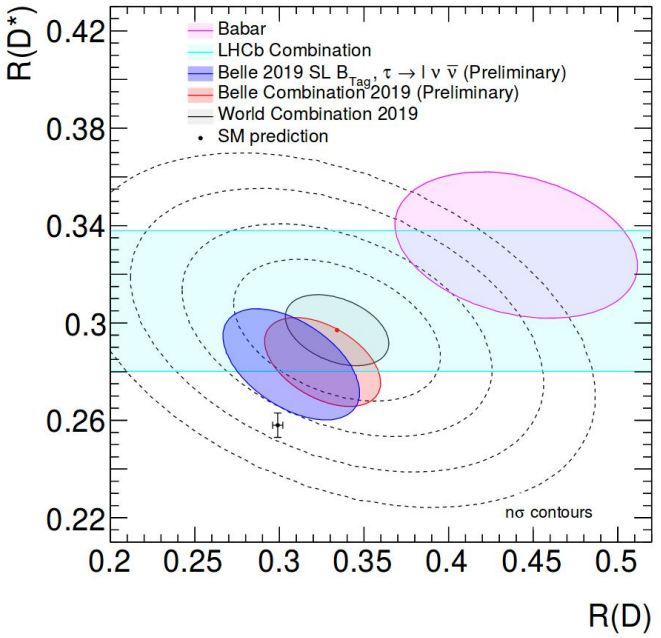
Standard Model at the LHC
April 2019



Motivation

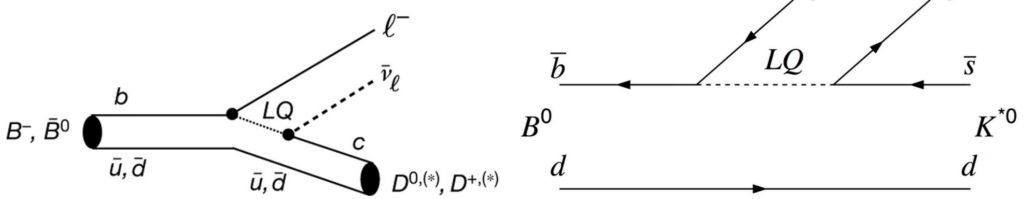
B-flavor measurements

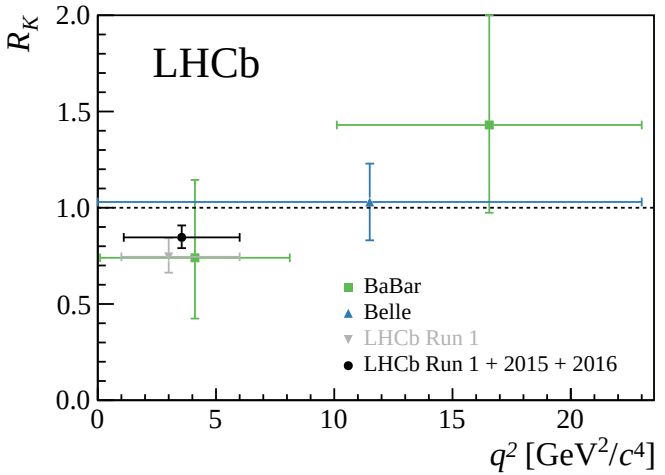
- Deviations from SM prediction in b-flavor observables
  - $R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)} \tau \bar{\nu})}{\Gamma(B \to D^{(*)} \ell \bar{\nu})}$ $(\sim 3.1\sigma)$
  - $R(K^{(*)}) = \frac{\Gamma(B \to K^{(*)} \mu\mu)}{\Gamma(B \to K^{(*)} ee)}$ $(\sim 2.5\sigma)$
  - $B^0 \to K^{*0}\mu\mu$ angular obs. $(\sim 3.4\sigma)$



Giacomo Caria, Moriond 2019 [arXiv:1904.08794]

- Leptoquarks possible solution
  - Strong couplings to 2nd/3rd generation $\Rightarrow$ weaker flavor constraints
  - Mass at TeV scale



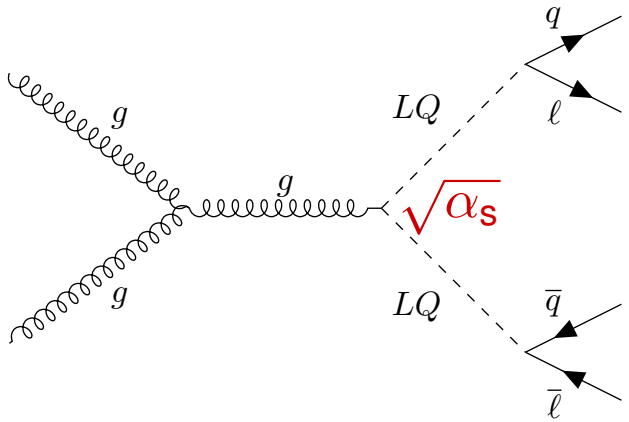


[arXiv:1903.09252]

Leptoquarks

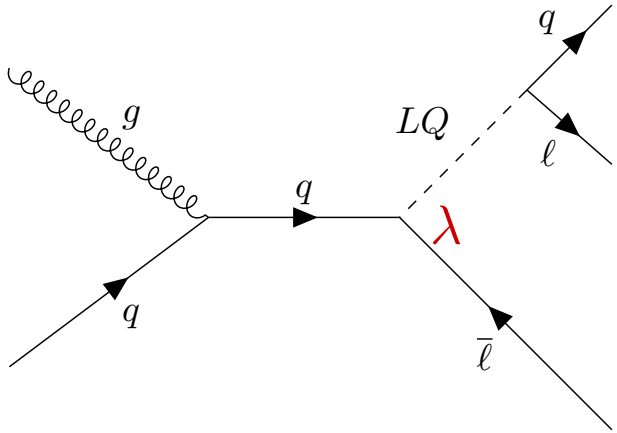
Properties

- New scalar (S=0) or vector (S=1) bosons
- Simultaneous coupling to quark and lepton
- Occur in various BSM models
  - GUTs, compositeness models, RPV SUSY, ...
- $\mathcal{B} = \mathrm{BR}(\mathrm{LQ} \to \mathrm{q}\ell) = 1 - \mathrm{BR}(\mathrm{LQ} \to \mathrm{q}\nu)$ free parameter



Production at the LHC

- Pair production via strong interaction
  - Depends only on M_{LQ}
- Single production via LQ radiation
  - Depends on M_{LQ} and LQ$\to$ qℓ coupling λ



Leptoquark couplings

	q	b	t
$\mathcal{B} = 0$ ν			
$\mathcal{B} = 1$ μ			
τ			

LQLQ $\rightarrow$ qℓqℓ / qℓqν

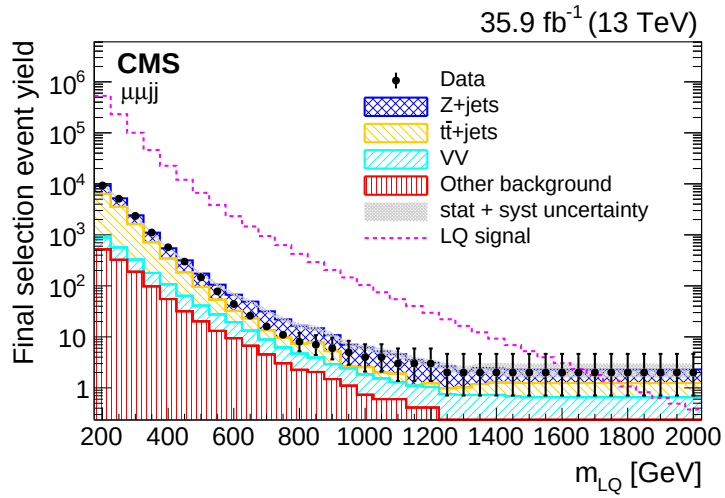
ATLAS: arXiv:1902.00377, subm. to EPJC
CMS e: Phys. Rev. D 99, 052002 (2019)
CMS μ: Phys. Rev. D 99, 032014 (2019)

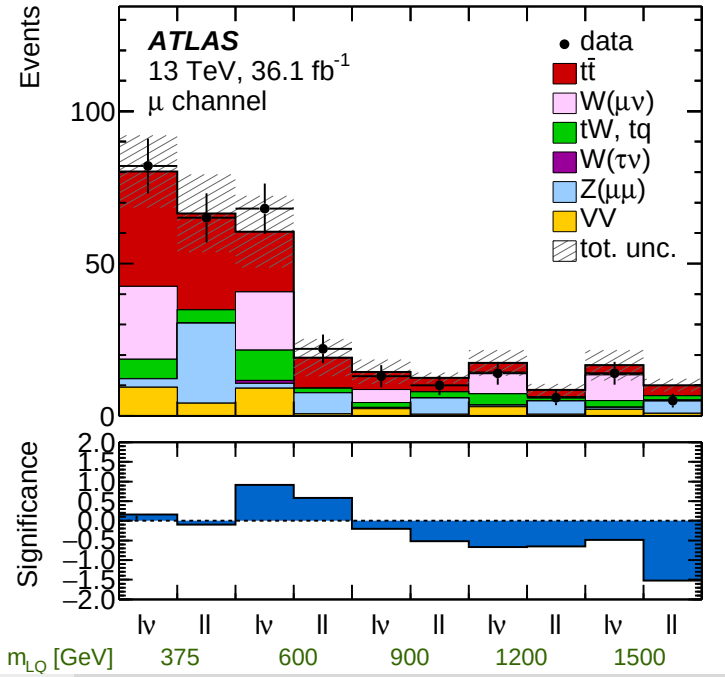
Strategy

- Final state: 2/1ℓ and 2 jets
- Similar strategy for $\ell = e, \mu$
- LQ candidates from jets, ℓ, $\not{E}_{\mathrm{T}}$
- Event selection optimized for each mass hypothesis
  - **CMS:** LQ mass, kinematics of jets, ℓ, $\not{E}_{\mathrm{T}}$
  - **ATLAS:** BDTs using similar variables

Background estimation

- Normalization of $\mathrm{t\bar{t}}$, V+jets obtained from data in control regions

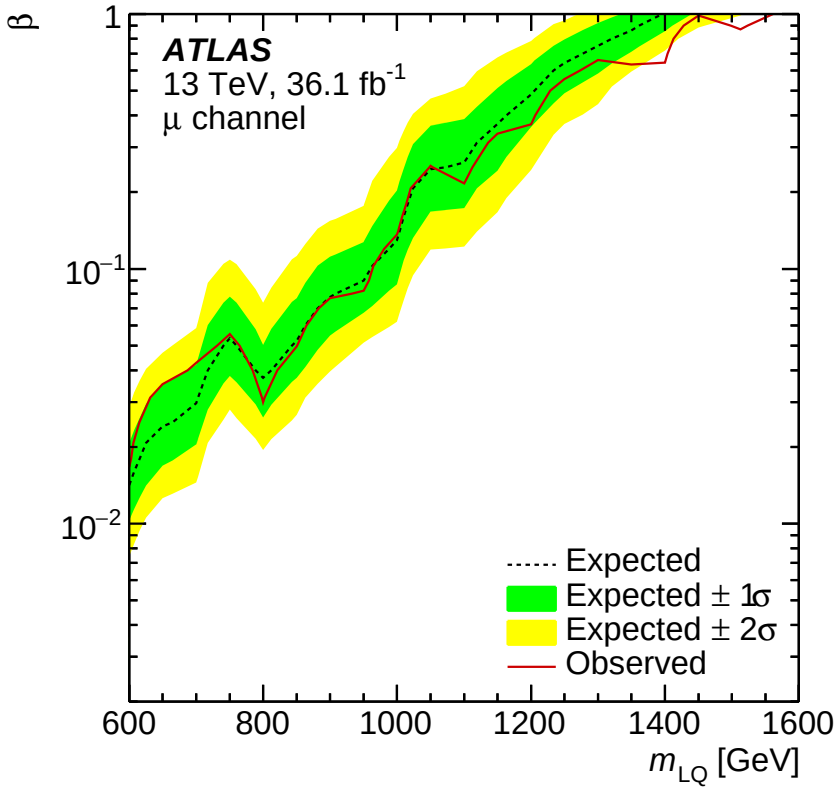


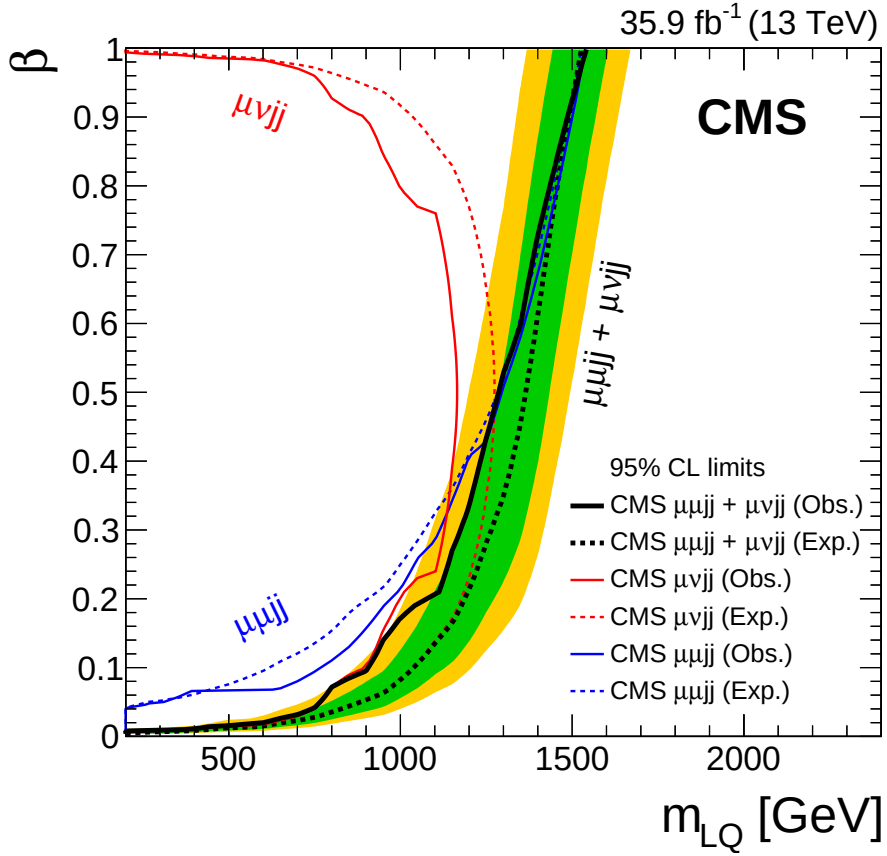


LQLQ $\rightarrow$ qℓqℓ / qℓqν

ATLAS: arXiv:1902.00377, subm. to EPJC
CMS *e*: Phys. Rev. D 99, 052002 (2019)
CMS μ: Phys. Rev. D 99, 032014 (2019)

- Limits set in M_{LQ} – $\mathcal{B}$ plane
- Combined limits from qℓqℓ and qℓqν channels
- **ATLAS:** LQ_1/LQ_2 exclusion: 1400/1560 GeV (1290/1230 GeV) for $\mathcal{B} = 1$ (0.5)
- **CMS:** LQ_1/LQ_2 exclusion: 1435/1530 GeV (1270/1285 GeV) for $\mathcal{B} = 1$ (0.5)





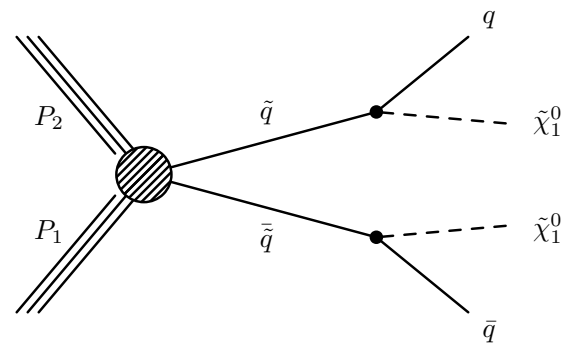
Leptoquark couplings

		q	b	t
$\mathcal{B} = 0$	ν	(✓)		
$\mathcal{B} = 1$	μ	✓		
	τ			

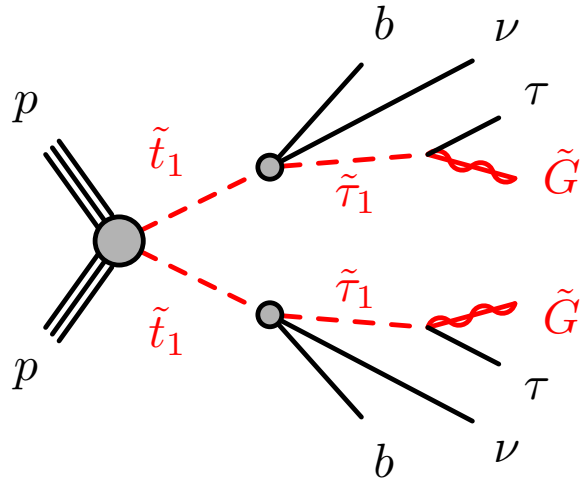
LQLQ $\rightarrow$ qνqν / bνbν / tνtν

ATLAS: arXiv:1902.08103, subm. to JHEP
CMS: Phys. Rev. D 98, 032005 (2018)

- SUSY searches for pair-produced squarks perfomed in LQ-like final state
- Re-interpretation in LQ models
- $\tilde{q} \rightarrow q\tilde{\chi}$ vs. scalar vs. vector LQ: signal acceptance compatible



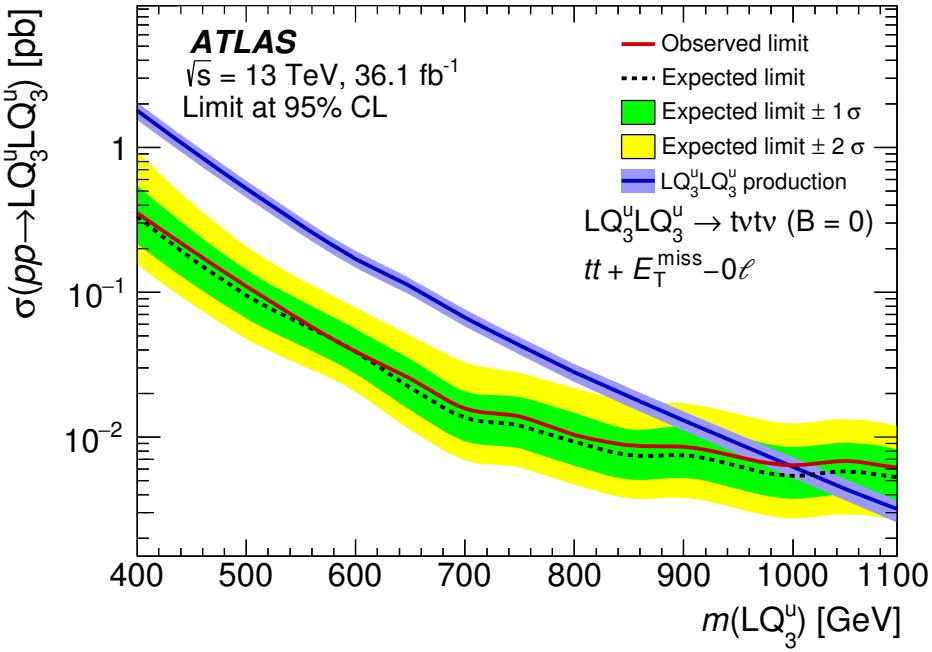
- $\tilde{q} \rightarrow q\tilde{\chi}$ corresponds to LQ$\rightarrow q\nu$ ($\mathcal{B} = 0$)
- $\tilde{t} \rightarrow b\nu\tau\tilde{G}$ sensitive to LQ for $\mathcal{B} = 0.5$

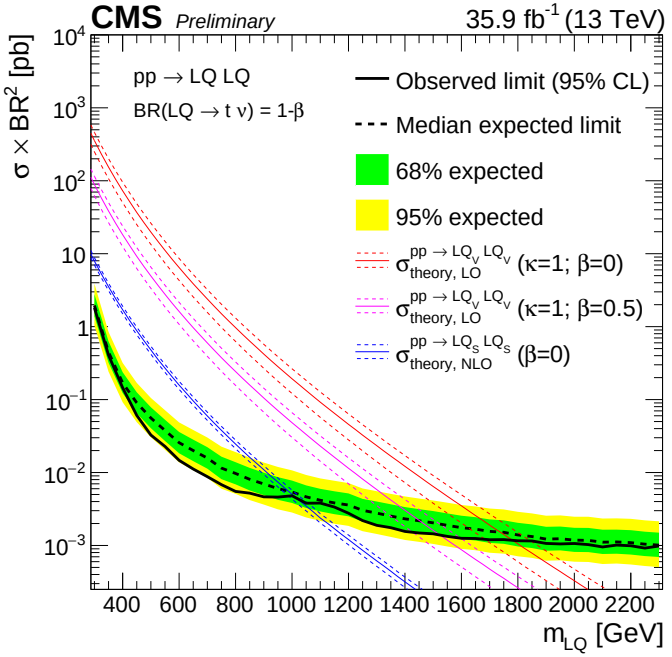


LQLQ $\rightarrow$ qνqν / bνbν / tνtν

ATLAS: arXiv:1902.08103, subm. to JHEP
CMS: Phys. Rev. D 98, 032005 (2018)

- Sensitivity to all quark flavors
- Assuming $\mathcal{B} = 0$:
  - **ATLAS:** LQs excluded up to 970 / 1000 GeV for b / t
  - **CMS:** LQs excluded up to 980 / 1100 / 1020 GeV for udsc / b / t
- For $\mathcal{B} = 0.5$:
  - **ATLAS:** Scalar LQLQ$\rightarrow$ tν bτ/bν tτ excluded up to 780 / 800 GeV
  - **CMS:** Vector LQLQ$\rightarrow$ tν bτ excluded up to 1530 GeV





Leptoquark couplings

	q	b	t
$\mathcal{B} = 0$ ν	✓	✓	✓
$\mathcal{B} = 1$ μ	✓		
τ			

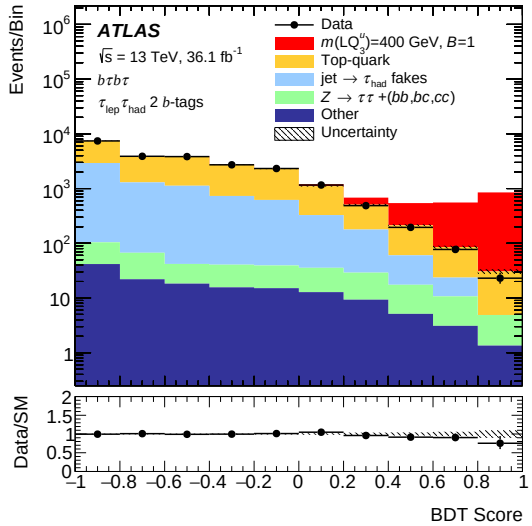
LQLQ $\rightarrow$ bτbτ

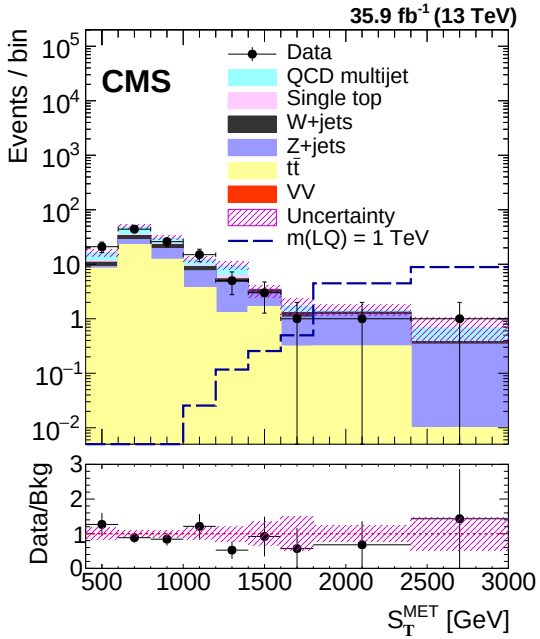
ATLAS: arXiv:1902.08103, subm. to JHEP
CMS: JHEP 03 (2019) 170

- Many final states based on τ decay modes
- Also sensitive to LQLQ $\rightarrow$ tτtτ
- **ATLAS:**
  - $\tau_h\tau_h$ and $\tau_h\tau_\ell$ final states
  - Categories in N_b
  - BDT output sensitive to LQ signal
- **CMS:**
  - $\tau_h\tau_h$ final state
  - Sensitive variable: scalar p_T sum

Background estimation

- Mis-ID τ_h contribution fully from data
- Normalization of $t\bar{t}$, Z+jets obtained from fit in control regions

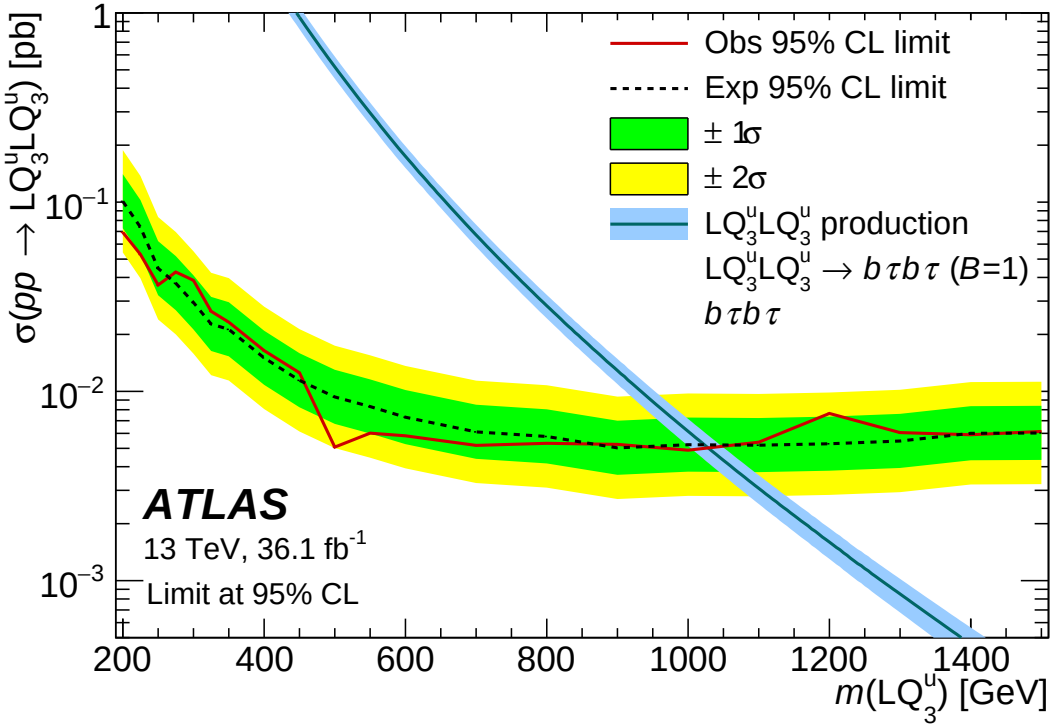


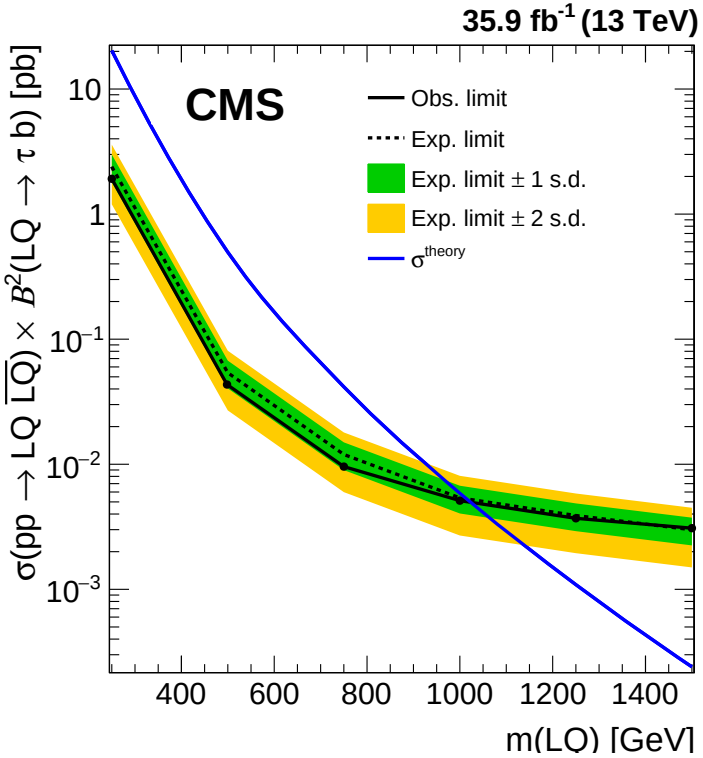


LQLQ $\rightarrow$ bτbτ

ATLAS: arXiv:1902.08103, subm. to JHEP
CMS: JHEP 03 (2019) 170

- Limits on LQLQ $\rightarrow$ bτbτ ($\mathcal{B} = 1$)
  - **ATLAS:** LQ excluded below $M_{\mathrm{LQ}} = 1030$ GeV
  - **CMS:** LQ excluded below $M_{\mathrm{LQ}} = 1020$ GeV





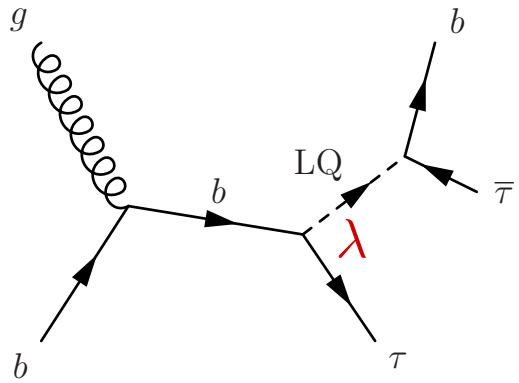
Leptoquark couplings

		q	b	t
$\mathcal{B} = 0$	ν	✓	✓	✓
$\mathcal{B} = 1$	μ	✓		
	τ		✓	

LQ $\rightarrow$ bτ

CMS: JHEP 07 (2018) 115

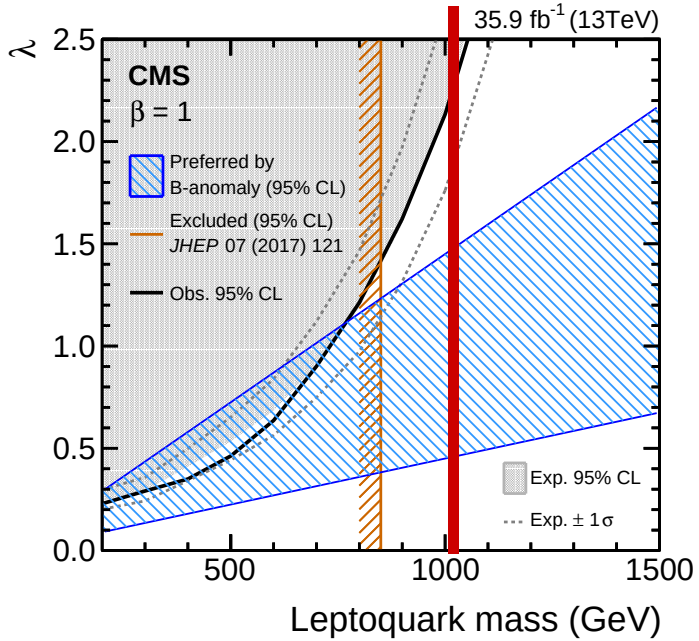
- **CMS** search for single LQ production in b$\tau\tau$ final state
- First search for single 3rd gen. LQ
- Combination of $\tau_h\tau_h$ and $\tau_h\tau_\ell$ channels
- Main backgrounds derived/constrained in data sidebands



Results

- Limits depend on M_{LQ} and λ
- Single LQ$\rightarrow$ bτ excluded up to $M_{LQ} = 740\,\text{GeV}$ $(\lambda = 1, \mathcal{B} = 1)$
- Stronger mass limits for high λ
- Pair-production limit at 1030 GeV

[ATLAS, arXiv:1902.08103]



Leptoquark couplings

		q	b	t
$\mathcal{B} = 0$	ν	✓	✓	✓
$\mathcal{B} = 1$	μ	✓		
	τ		✓	

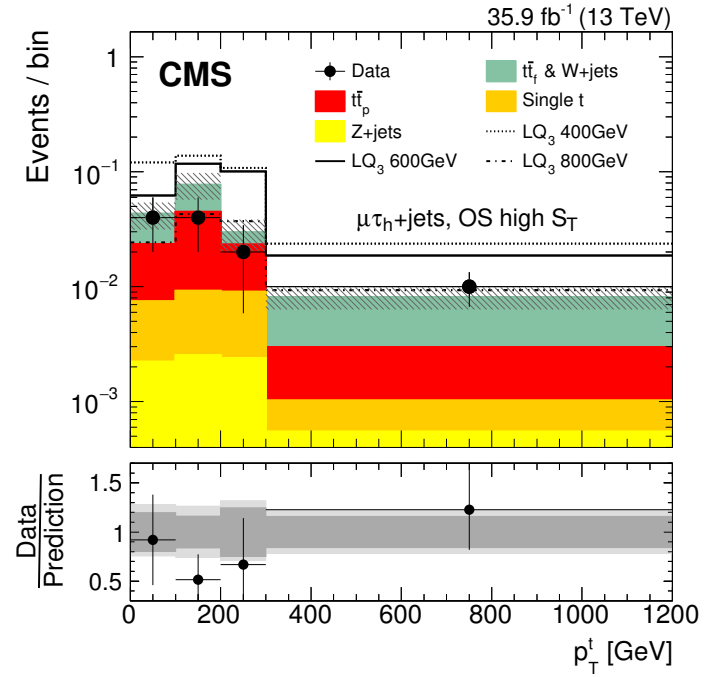
LQLQ $\rightarrow$ tτtτ

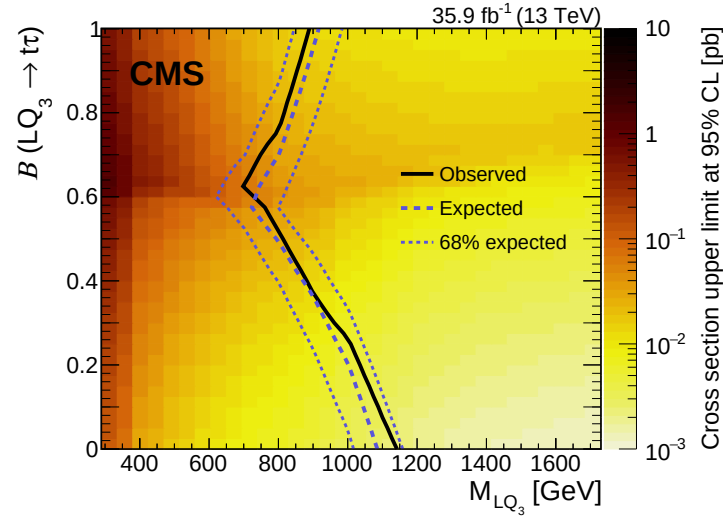
ATLAS: arXiv:1902.08103, subm. to JHEP
CMS: Eur. Phys. J. C 78 (2018) 707

- **CMS** search for pair-produced LQ $\rightarrow$ tτ
- Rich final state
  - Focus on 1ℓ + τ_h + jets
  - Multiple search regions enhance sensitivity
- Background from jets faking τ_h leptons estimated from data sidebands

Results

- **CMS:** LQs ($\mathcal{B} = 1$) excluded up to 900 GeV
- **ATLAS:** Reinterpretation of bτbτ search: $M_{LQ} < 930$ GeV





Leptoquark couplings

		q	b	t
$\mathcal{B} = 0$	ν	✓	✓	✓
$\mathcal{B} = 1$	μ	✓		
	τ		✓	✓

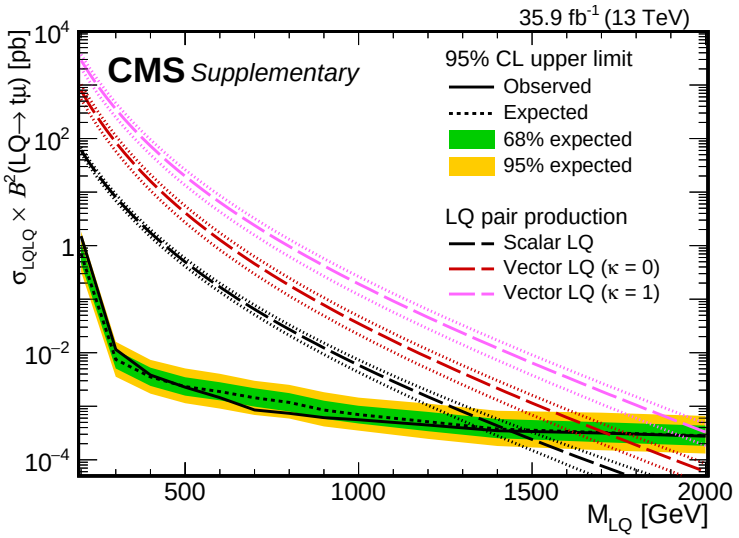
LQLQ $\rightarrow$ tμtμ

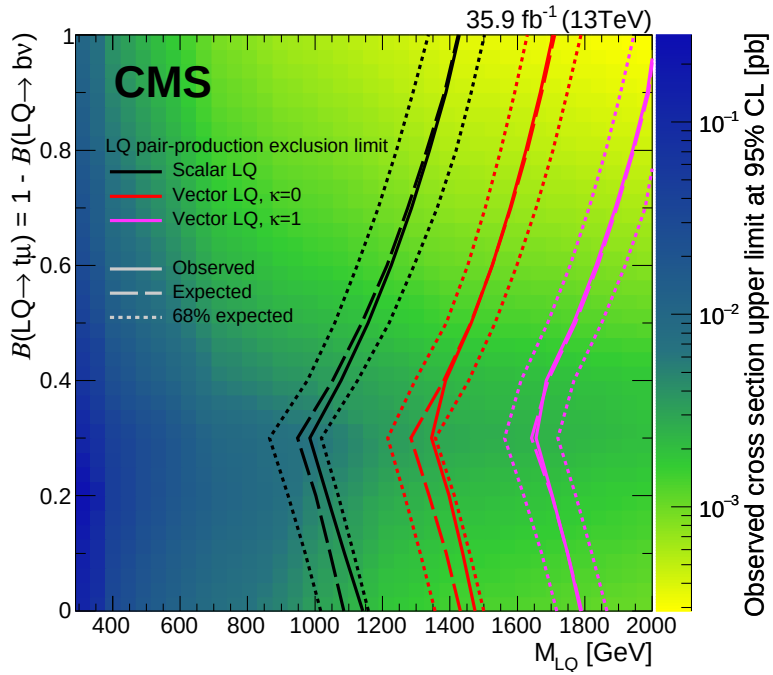
Phys. Rev. Lett. 121, 241802 (2018)

- **CMS:** First search for pair-produced LQ $\rightarrow$ tμ
- 2μ + jets final state grants high signal efficiency
- Dominant backgrounds derived from data

Results

- LQs ($\mathcal{B} = 1$) excluded up to 1420 GeV
- Combination with search for LQLQ$\rightarrow$ bνbν
- $M_{\mathrm{LQ}} < 980$ GeV excluded for all values of $\mathcal{B}$





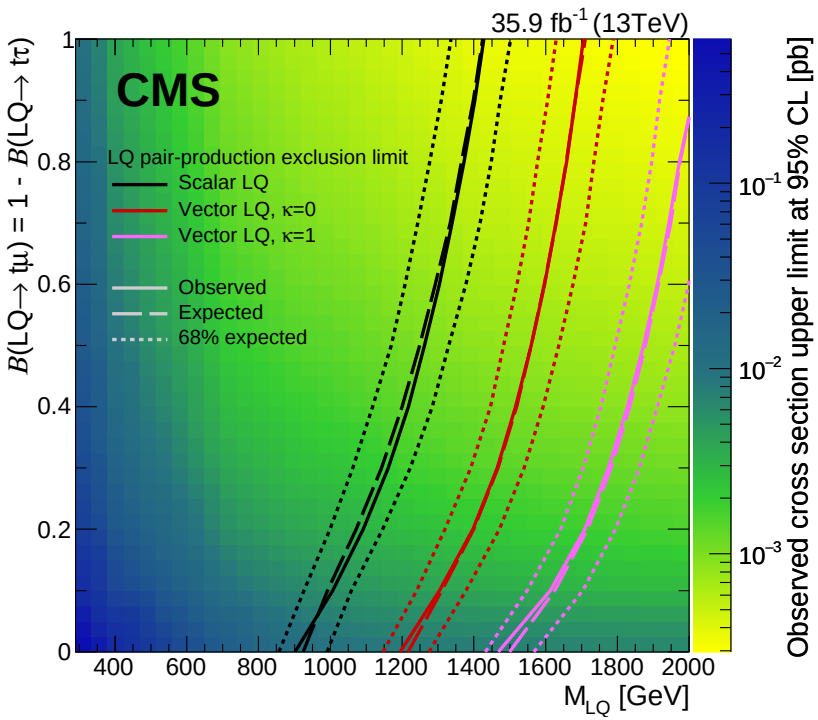
Leptoquark couplings

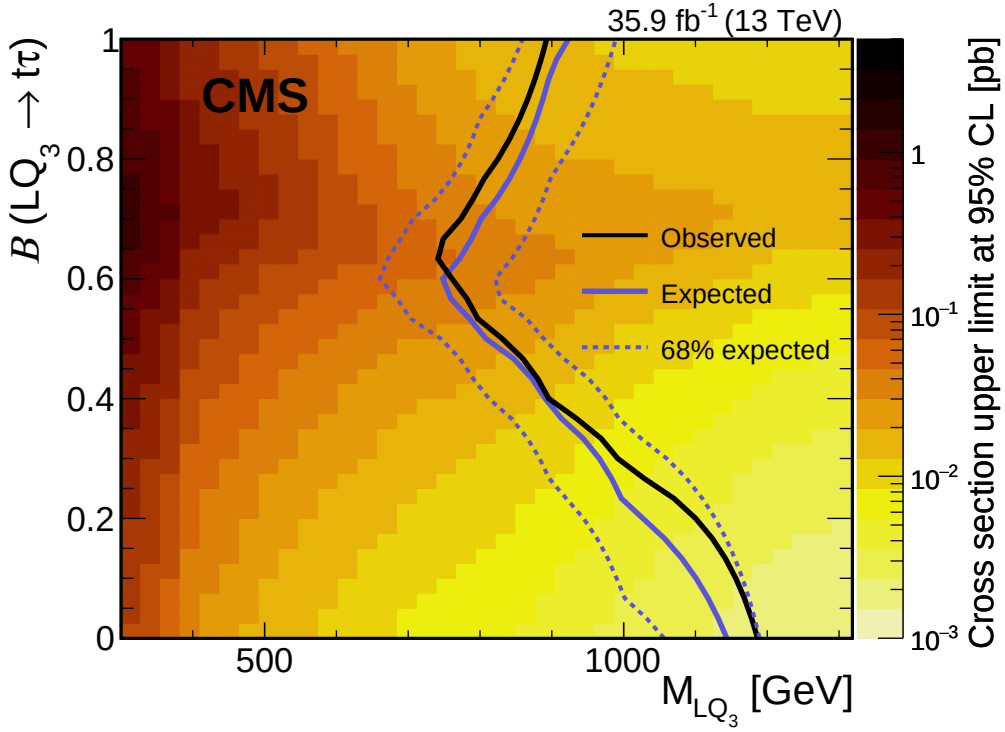
	q	b	t
$\mathcal{B} = 0$ ν	✓	✓	✓
$\mathcal{B} = 1$ μ	✓		✓
τ		✓	✓

The bigger picture – CMS

Phys. Rev. Lett. 121, 241802 (2018)
Eur. Phys. J. C 78 (2018) 707

- Full combination of LQLQ $\to$ tτtτ and LQLQ $\to$ tμtμ searches
  - Constrains cross-generational couplings ($\neq \mathcal{B}$)
- Overlay LQLQ $\to$ tτtτ and LQLQ $\to$ bνbν results
  - Limits as function of $\mathcal{B}$
- LQs excluded below 750 GeV for decays to tμ, tτ, bν





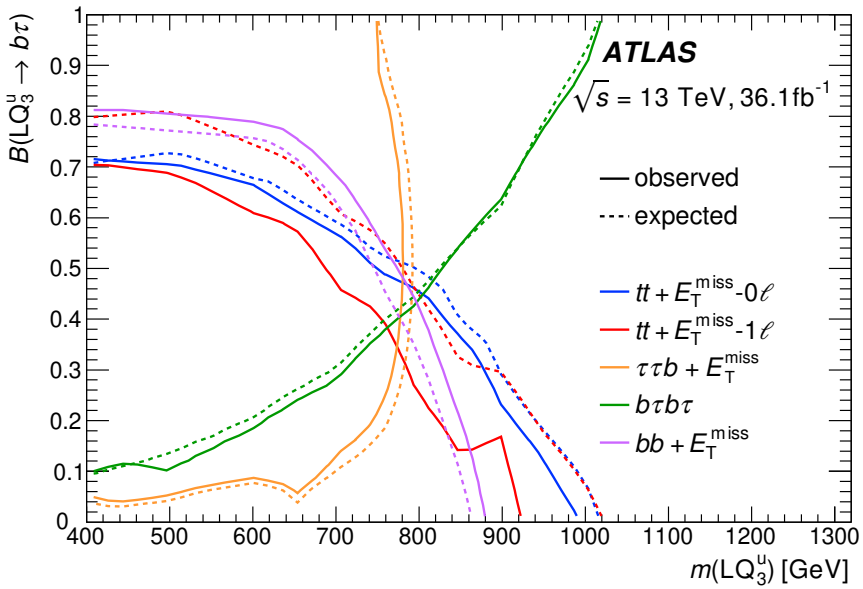
Leptoquark couplings

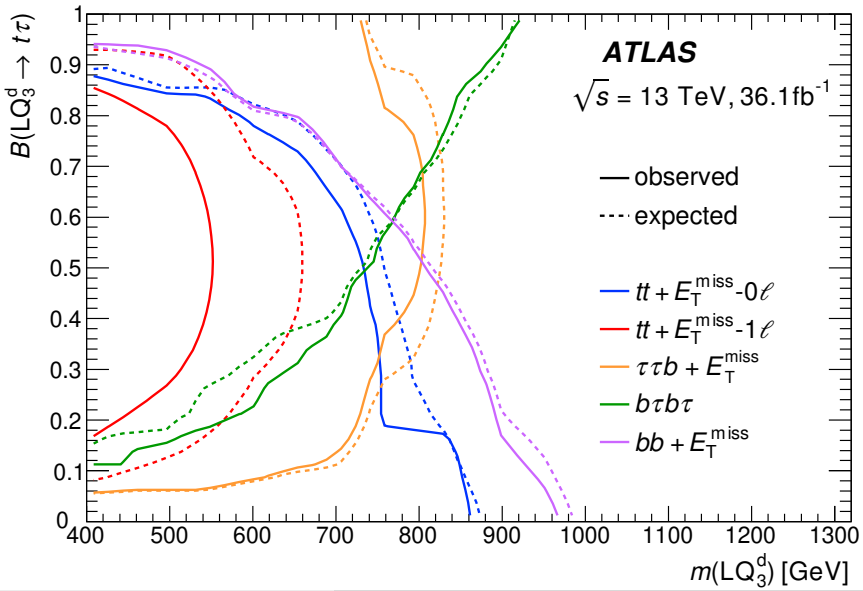
	q	b	t
$\mathcal{B} = 0$ ν	✓	✓	✓
$\mathcal{B} = 1$ μ	✓		✓
τ		✓	✓

The bigger picture – ATLAS

arXiv:1902.08103, subm. to JHEP

- Many searches sensitive to larger range of $\mathcal{B}$
- Overlay of individual limits on 3rd gen. LQs
- LQ_3^u and LQ_3^d excluded below $M_{LQ} = 800$ GeV for all $\mathcal{B}$
- Sensitivity up to TeV range





Leptoquark couplings

	q	b	t
$\mathcal{B} = 0$ ν	✓	✓	✓
$\mathcal{B} = 1$ μ	✓		✓
τ		✓	✓

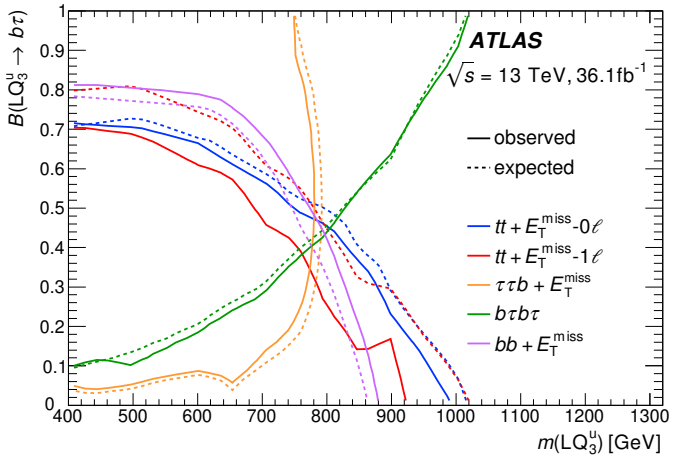
Leptoquark couplings

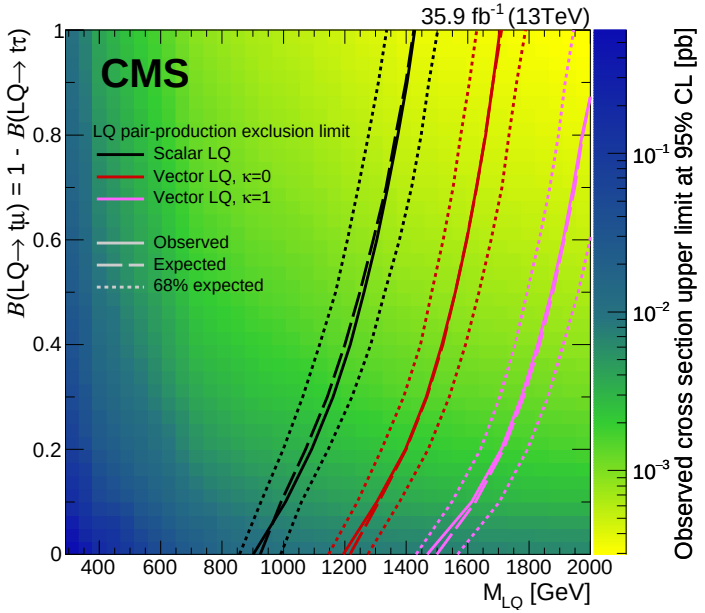
		q	b	t
$\mathcal{B} = 0$	ν	✓	✓	✓
$\mathcal{B} = 1$	μ	✓	(✓)	✓
	τ	(✓)	✓	✓

Conclusion

- LQs potential solution for b-anomalies
  - In particular: 3rd gen. couplings
- LHC experiments systematically study LQ parameter space in Run-2

	q	b	t
ν	✓	✓	✓
μ	✓	(✓)	✓
τ	(✓)	✓	✓





- No deviations from SM observed
- Exclusions up to TeV range

Outlook

CMS-PAS-FTR-18-028
CMS-PAS-FTR-18-008

- Many more years of LHC data-taking ahead
- Sensitivity reach estimated for up to 3000fb^{-1} at 14 TeV
- Expected mass exclusion limit substantially improved