On behalf of the CMS & ATLAS collaborations

A flavor for leptoquarks

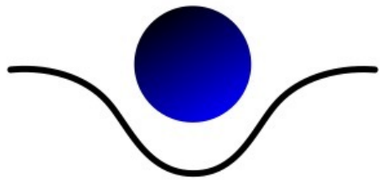
Ben Kilminster (on CMS)

University of Zürich

Lots of new, exciting results presented at ICHEP 2022 !!

University of Zurich[UZH]

Aug. 29th, 2022
BLV2022 Brussels



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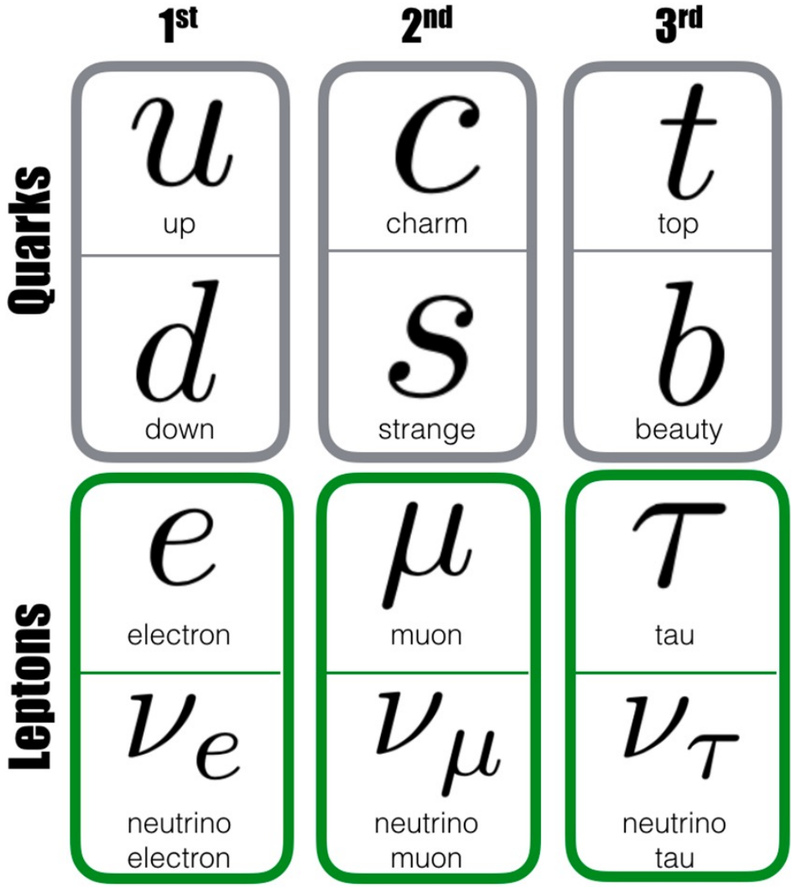
Theoretical puzzle : Similarity of quarks and leptons



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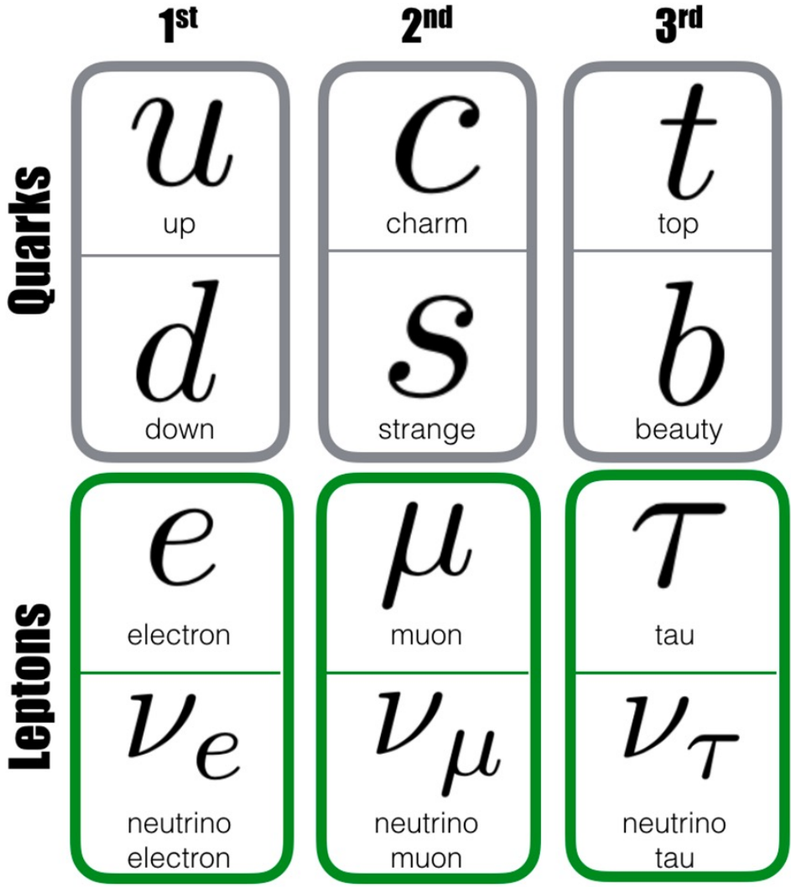
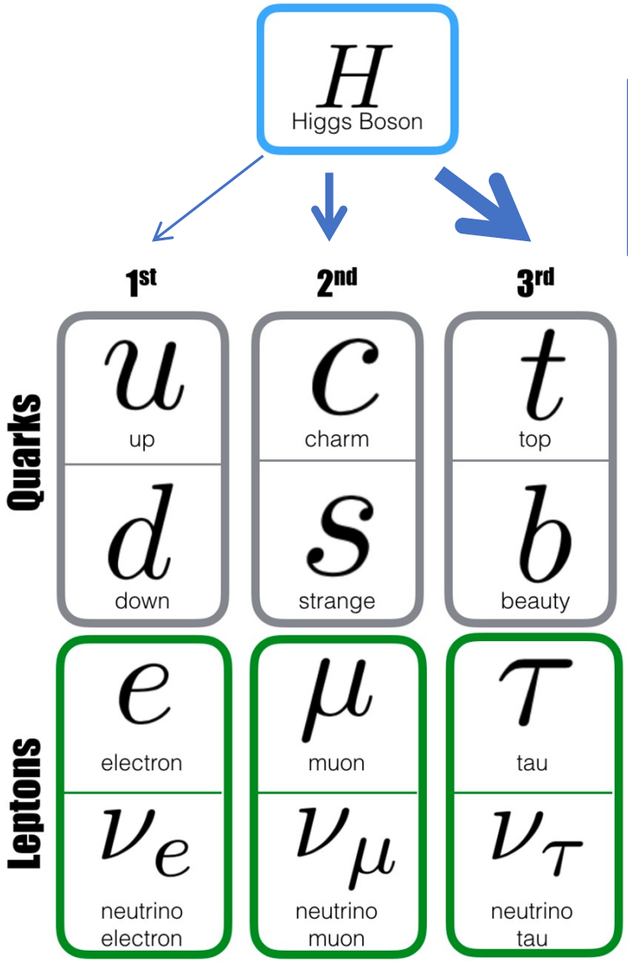


Some underlying symmetry ?

Theoretical Puzzle : flavor

- WHY three generations of identical particles
- HOW do they get different masses ?



Only the Higgs boson can tell difference between electron, muon, and tau lepton. Gives them different masses !!

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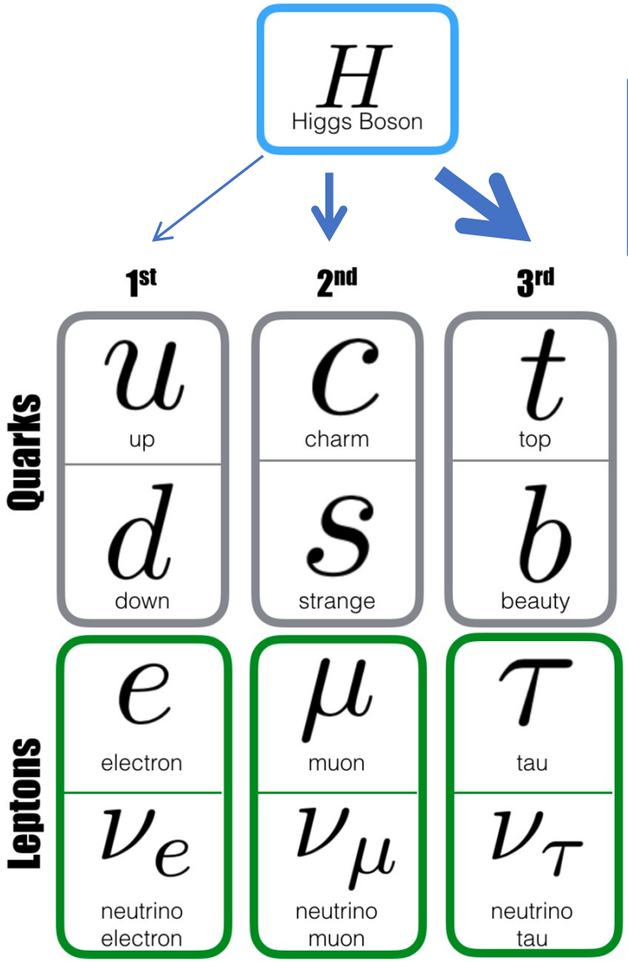

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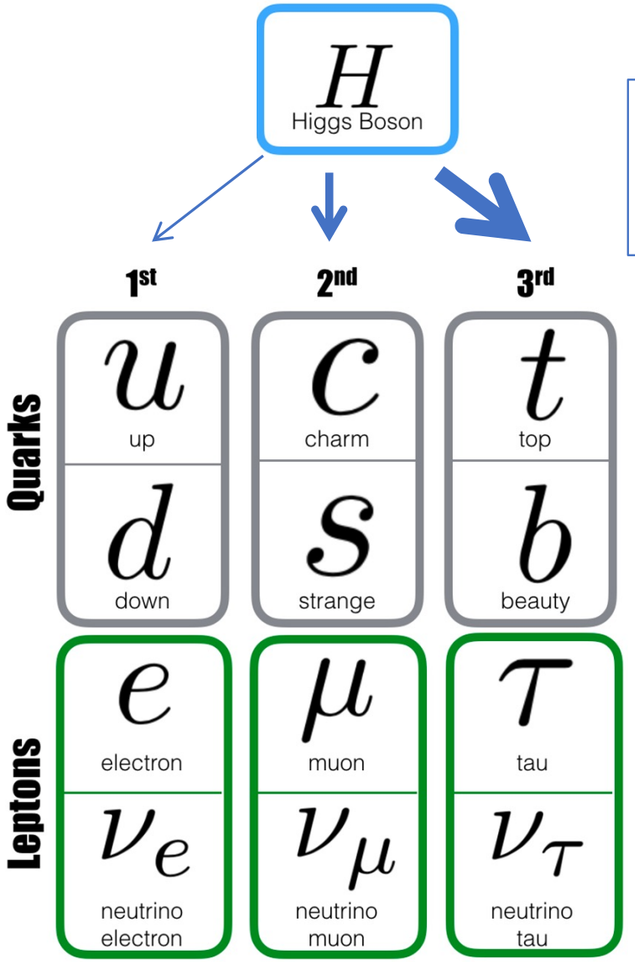


Only the Higgs boson can tell difference between electron, muon, and tau lepton. Gives them different masses !!

Yet … we are unaware of any mechanism for it to do so (and assign arbitrary Yukawa couplings)

Precise measurements of Higgs couplings do not elucidate the WHY or HOW

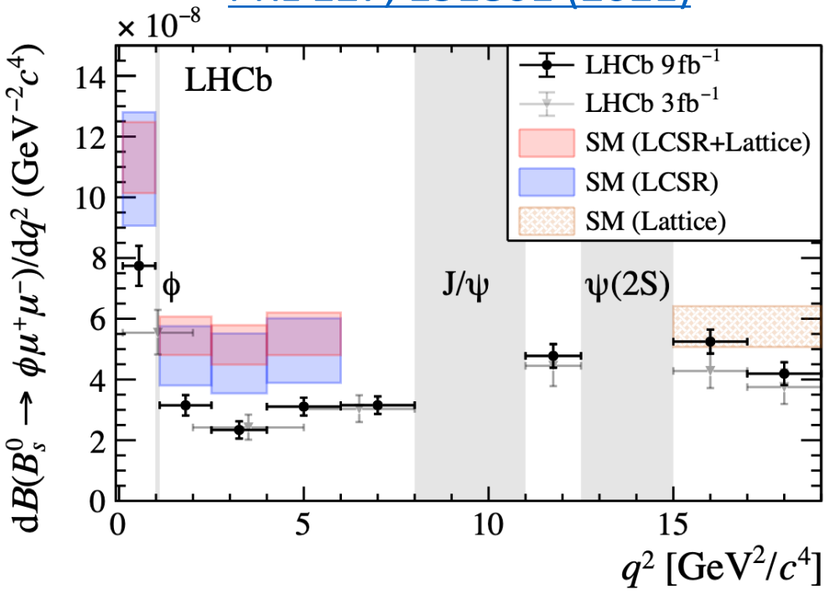
New physics needed to tell the difference

e vs. μ vs. τ

u vs. c vs. t

Experimental puzzles : flavor anomalies in B decays

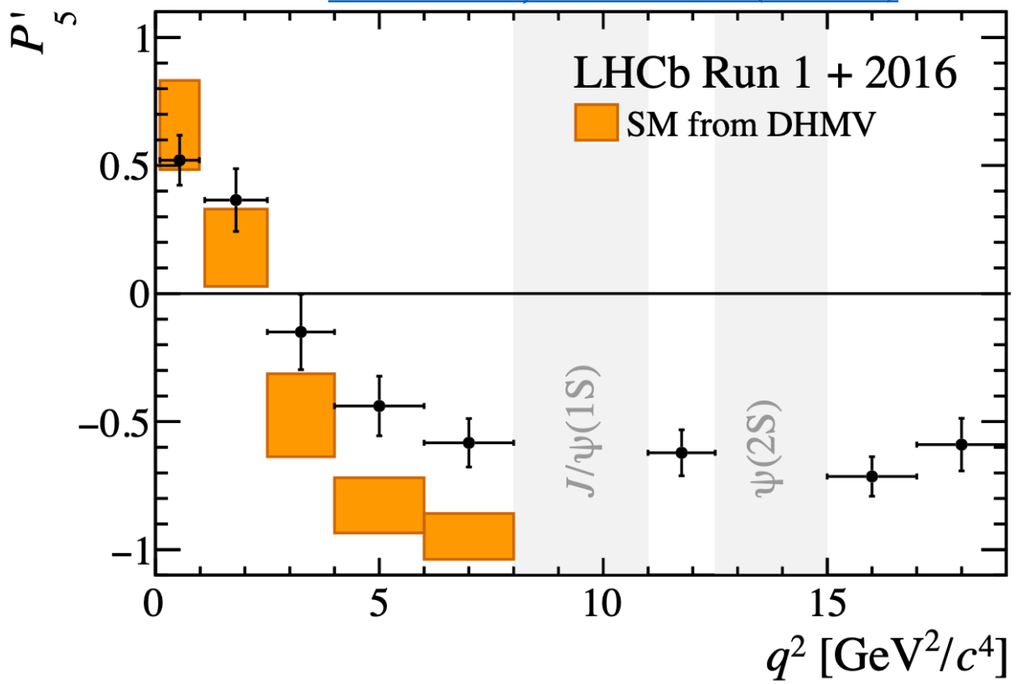
PRL 127, 151801 (2021)



$B_s^0 \rightarrow \phi\mu^+\mu^-$ Angular analysis

3.6 σ

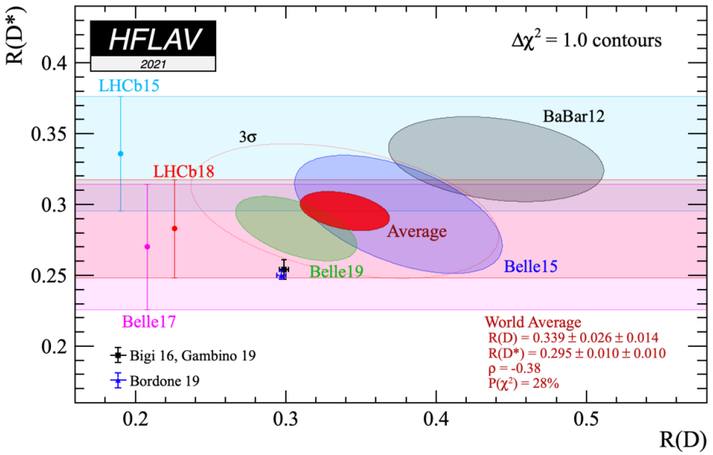
PRL 125, 011802 (2020)



$B^0 \rightarrow K^{0*}\mu\mu$ angular analysis

3.3 σ

HFLAV



R(D*) & R(D)
arXiv:2103.11769

3.1 σ

Other measurements :

3.1 σ R(K) : arXiv:2103.11769 (LHCb)

2.4 σ R(K*) : JHEP 08 (2017) 055 (LHCb)

2 σ R(J/Ψ) : PRL 120, 121801 (2018) (LHCb)

BSM explanations ?

New heavy mediators

Lepton flavor universality violation

New left-handed currents

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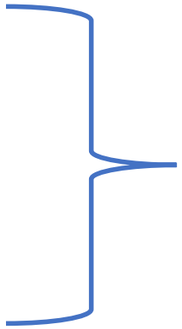

Leptoquarks !

BSM explanations ?

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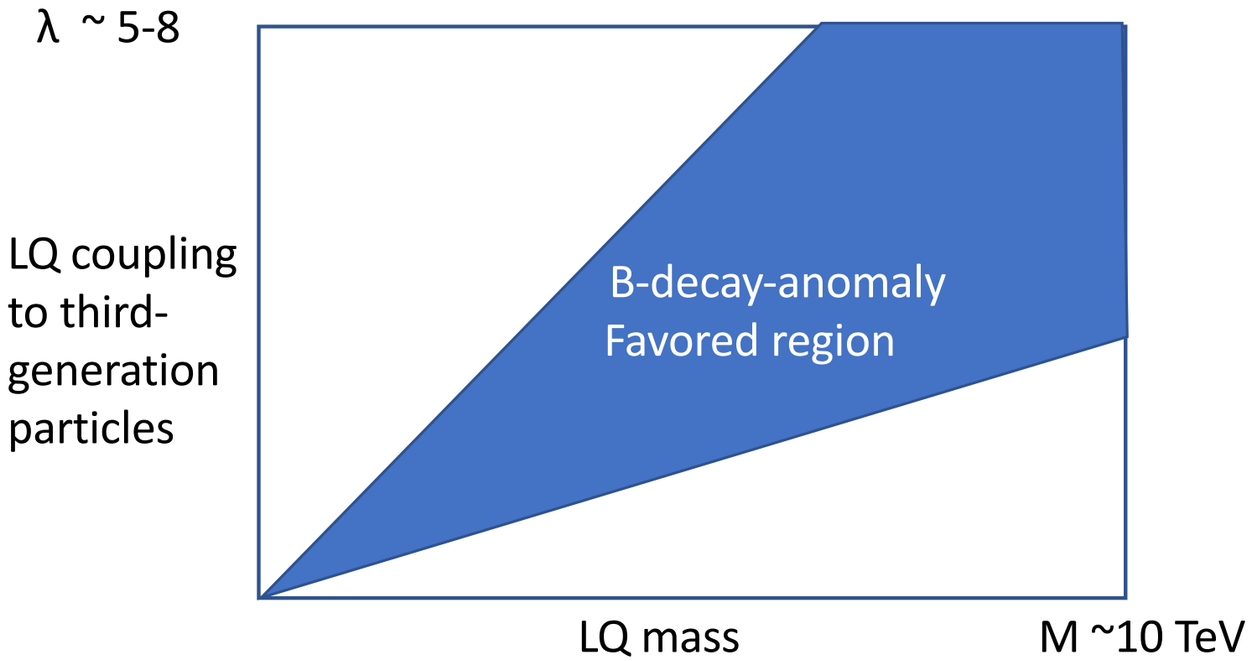
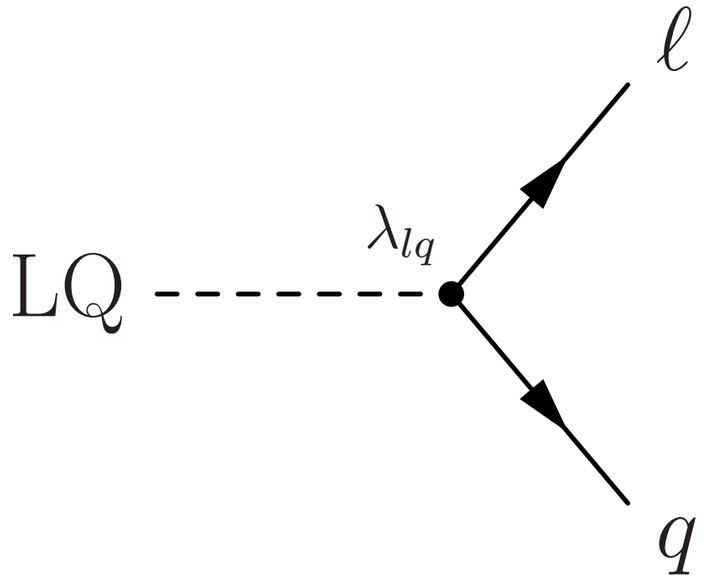
Leptoquarks !



Leptoquarks

- **Scalar** or **vector boson**



- **Decay into ℓq**

  $\Rightarrow$ carry L, B, color

- **Coupling LQ-ℓ-q : $\lambda_{\ell q}$**

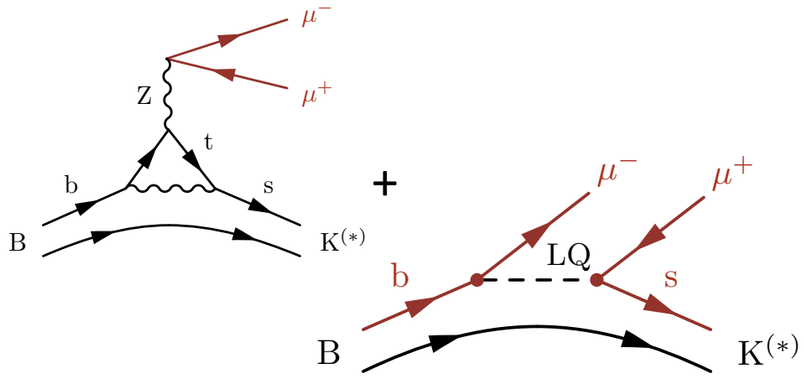
$$\underbrace{\mathrm{LQ}}_{\pm\frac{1}{3},\pm\frac{2}{3},\pm\frac{4}{3},\pm\frac{5}{3}} \rightarrow \underbrace{\ell}_{\pm 1,0} \underbrace{q}_{\mp\frac{1}{3},\pm\frac{2}{3}}$$

- **Fractional charge**

Flavor anomalies as explained by LQ

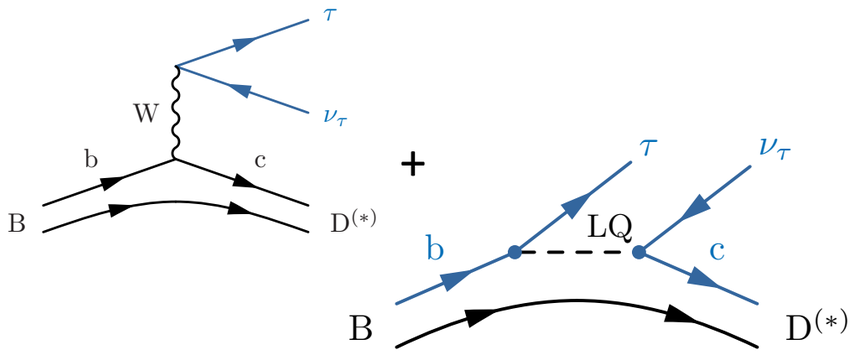
Measured

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}\mathrm{ee}\right)} < \boxed{\begin{matrix}\text{SM}\\ 1\end{matrix}}$$



Measured

$$R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} > \boxed{\begin{matrix}\text{SM}\\ 0.25\end{matrix}}$$



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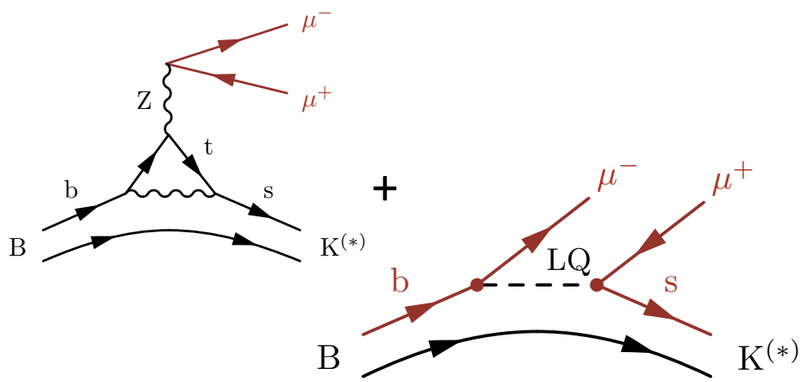

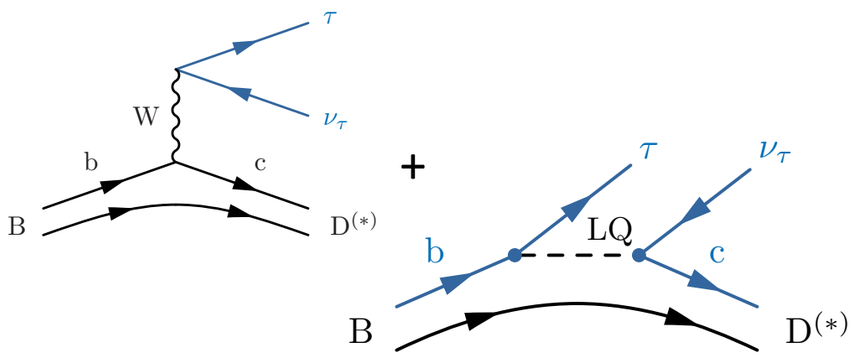

- Combined explanation of flavor and angular anomalies
- Vector LQ left-handed currents

Flavor structure

$$\Rightarrow \quad V_{q\ell} \sim \begin{matrix}\\ \mathrm{d}/\mathrm{u}' \\ \mathrm{s}/\mathrm{c}' \\ \mathrm{b}/\mathrm{t}'\end{matrix} \begin{matrix}\begin{matrix}\mathrm{e}/\nu_\mathrm{e} & \mu/\nu_\mu & \tau/\nu_\tau\end{matrix}\\ \begin{pmatrix} 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{pmatrix}\end{matrix}$$

arXiv:1706.07808, arXiv:1903.11517

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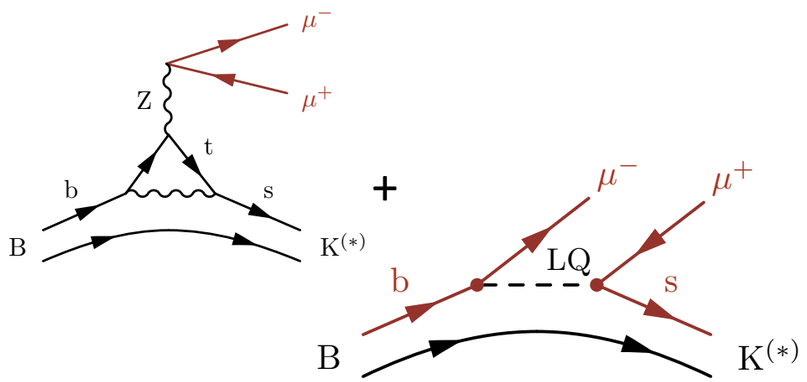

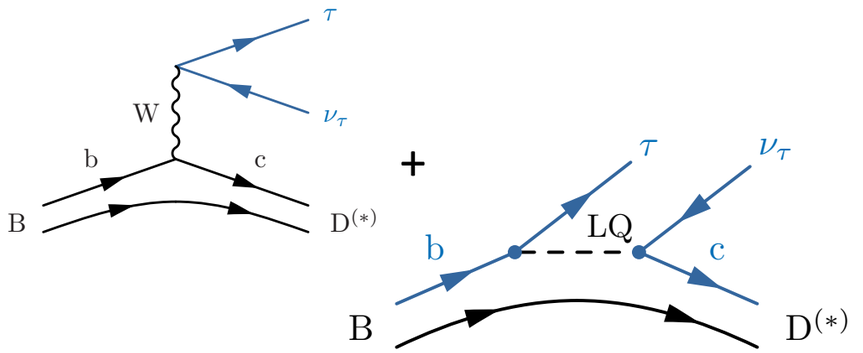

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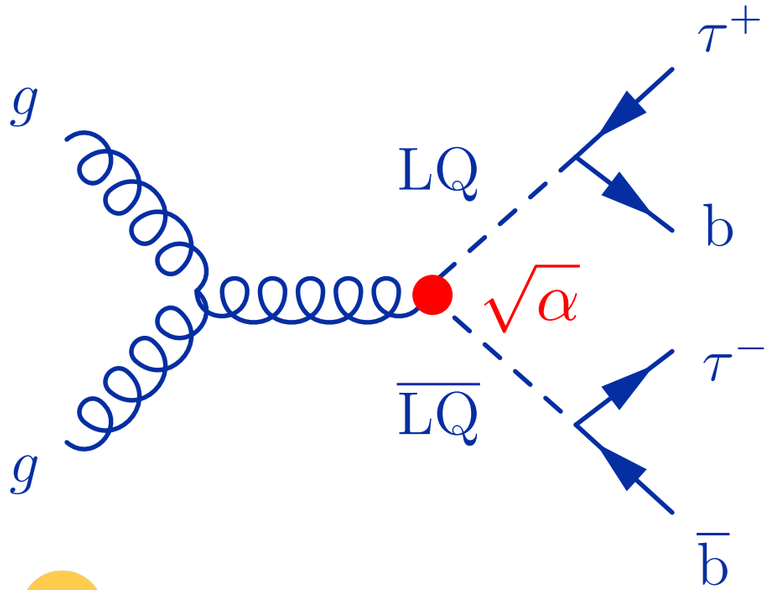
$$\mathrm{LQ} \approx \mathrm{LQ}_3$$

arXiv:1706.07808, arXiv:1903.11517

signs for destructive interference with SM in B → K$\mu\mu$ decay

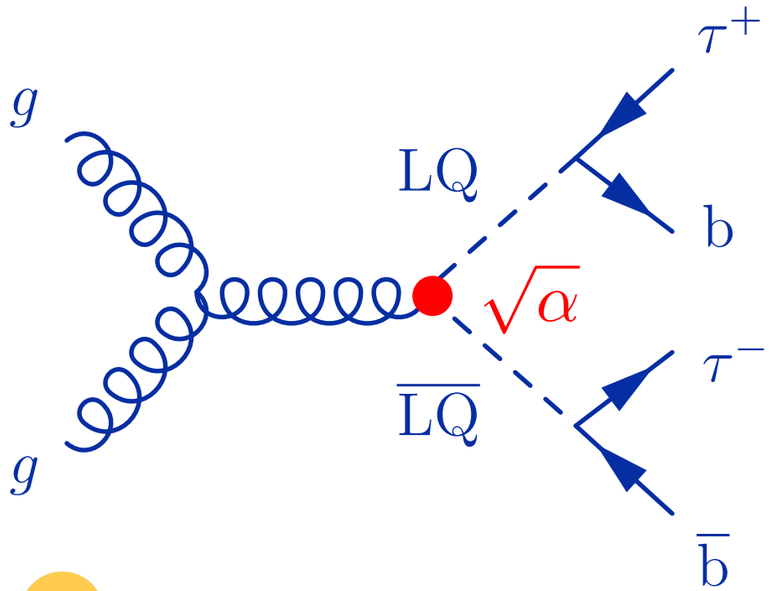
Can we search for leptoquarks directly ?

LQ pairs



- Large QCD production
- Model independent
- Resonant

LQ pairs



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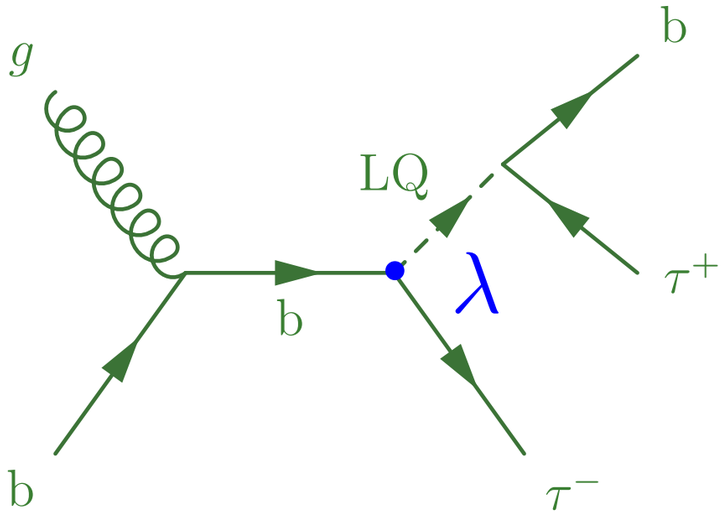
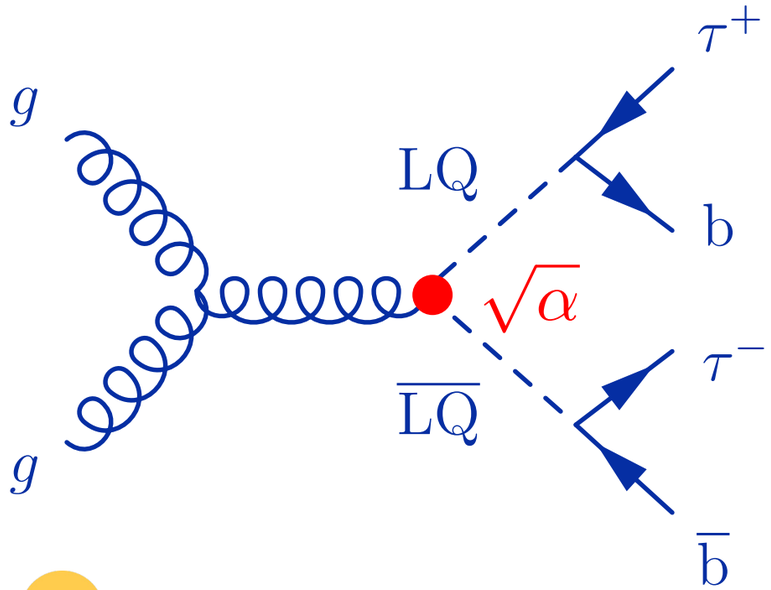
Single LQ



- $\sigma \propto \lambda^2$
- PDF suppression
- Wide-resonance at high λ

LQ pairs



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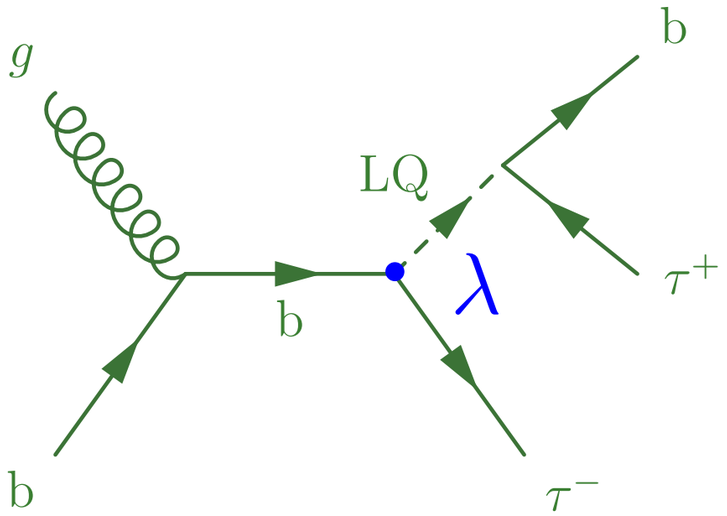

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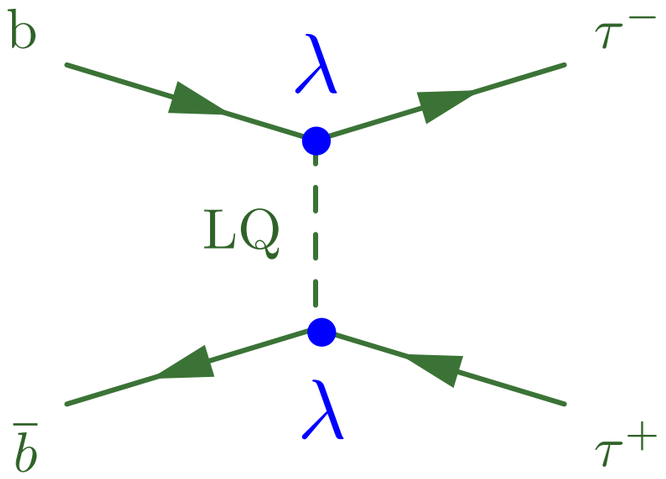
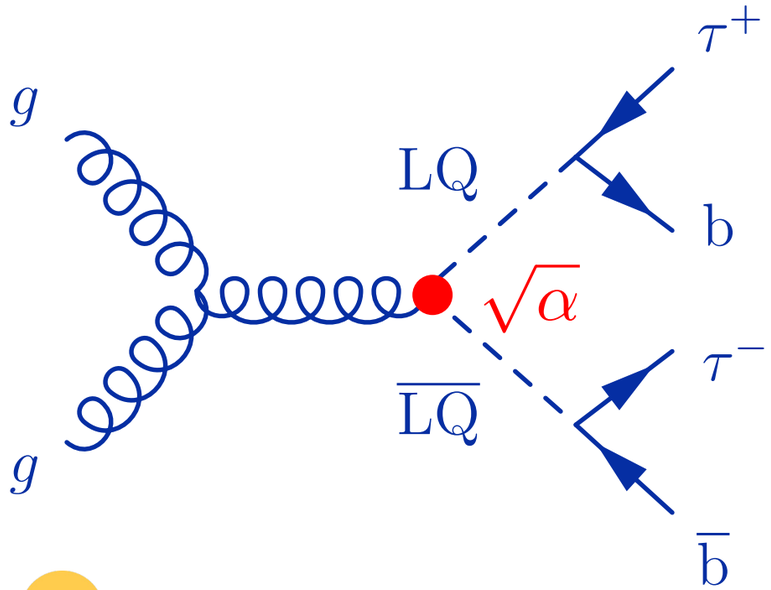
non-resonant LQ



- $\sigma \propto \lambda^4$
- PDF suppression ^ 2
- No resonance

LQ pairs



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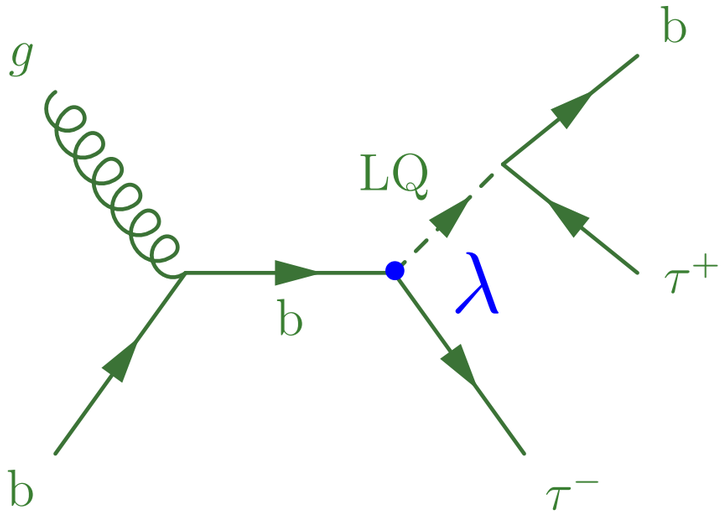

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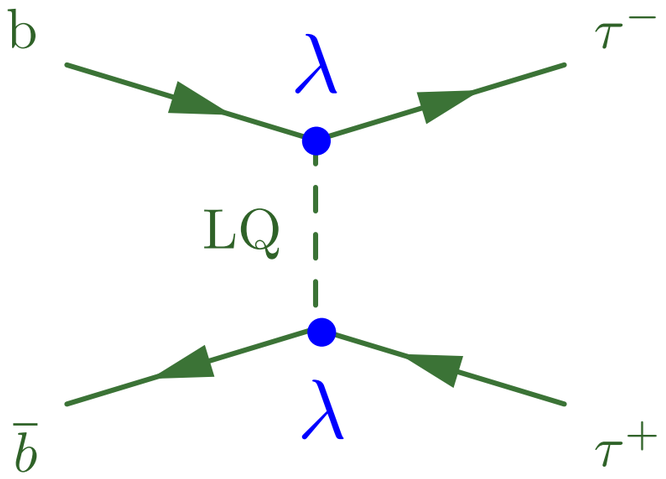

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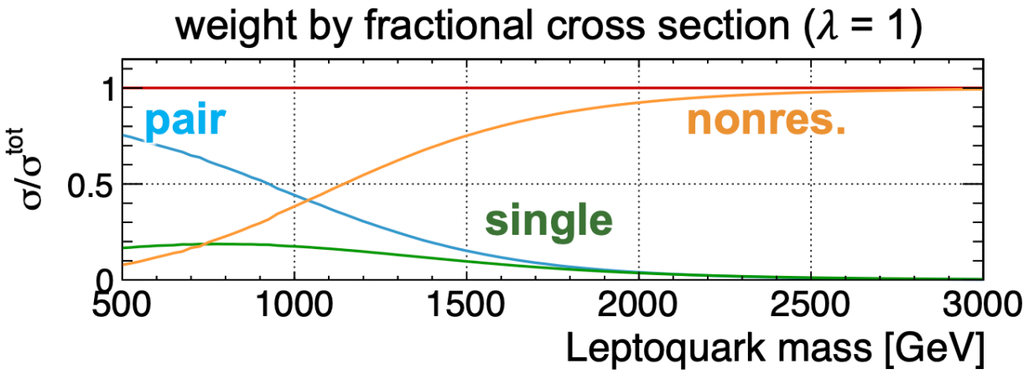
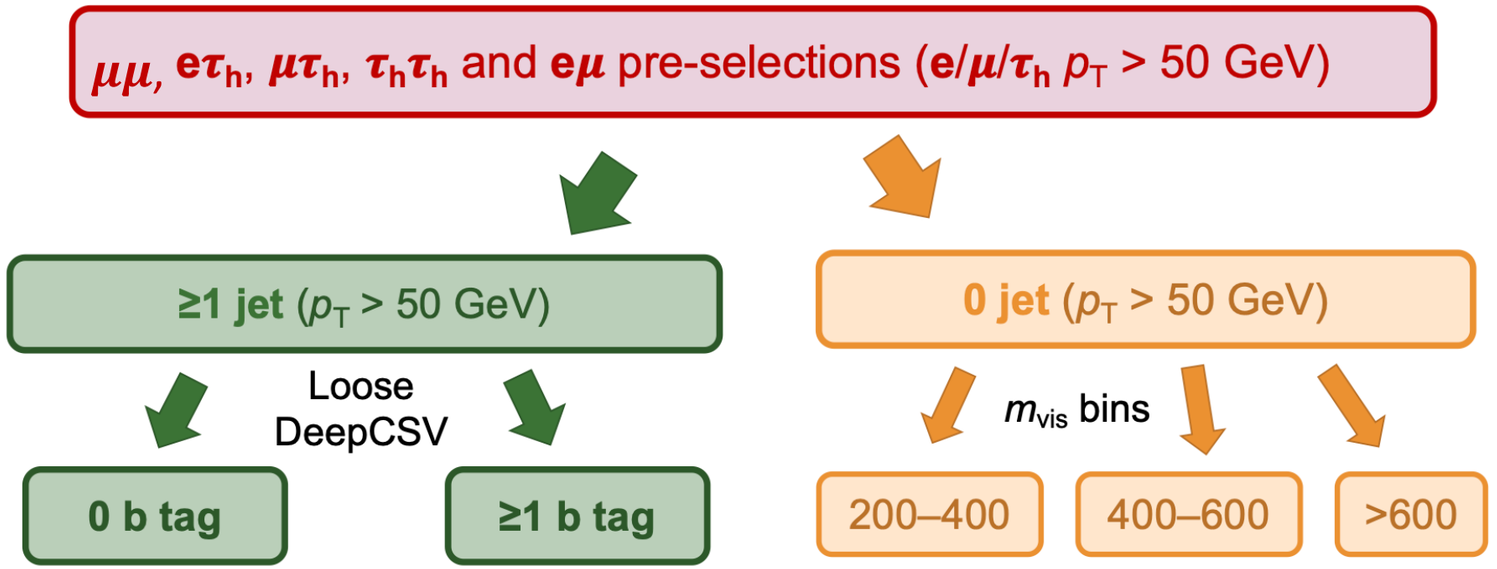


New @ ICHEP : CMS-EXO-19-016
CMS search for pair, single, non-resonant LQs

Summary of signal selections

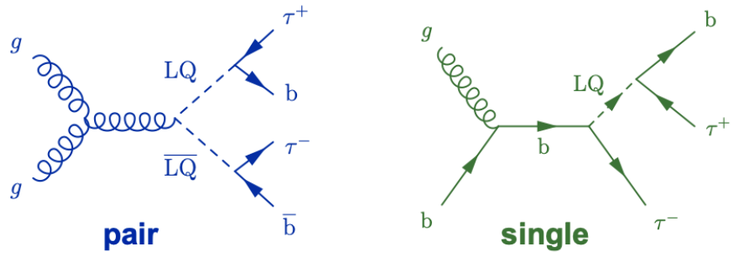


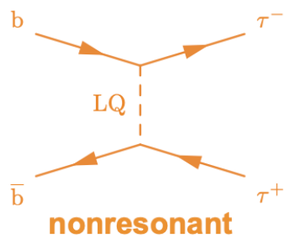
discriminating variable:

$$S_{\mathrm{T}}^{\mathrm{MET}} = p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{j} + \mathrm{MET}$$

discriminating variable:

$$\chi = e^{\Delta\eta}$$

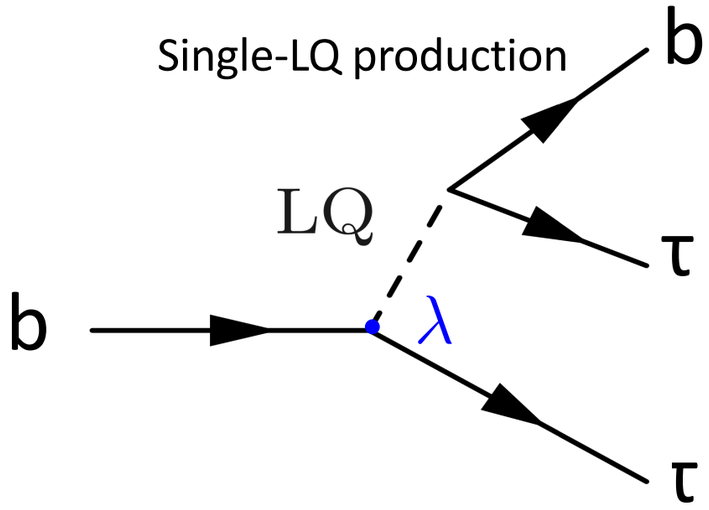


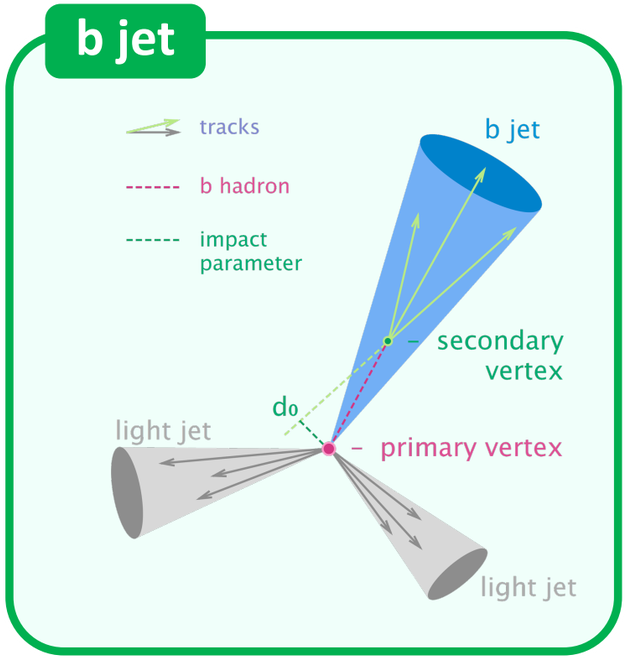


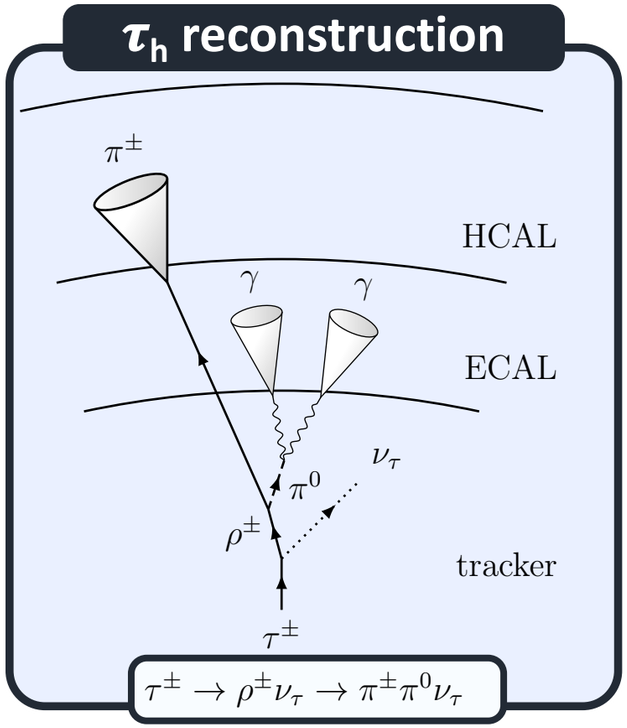
S_T^{MET} sensitive to LQ signal with high P_T objects

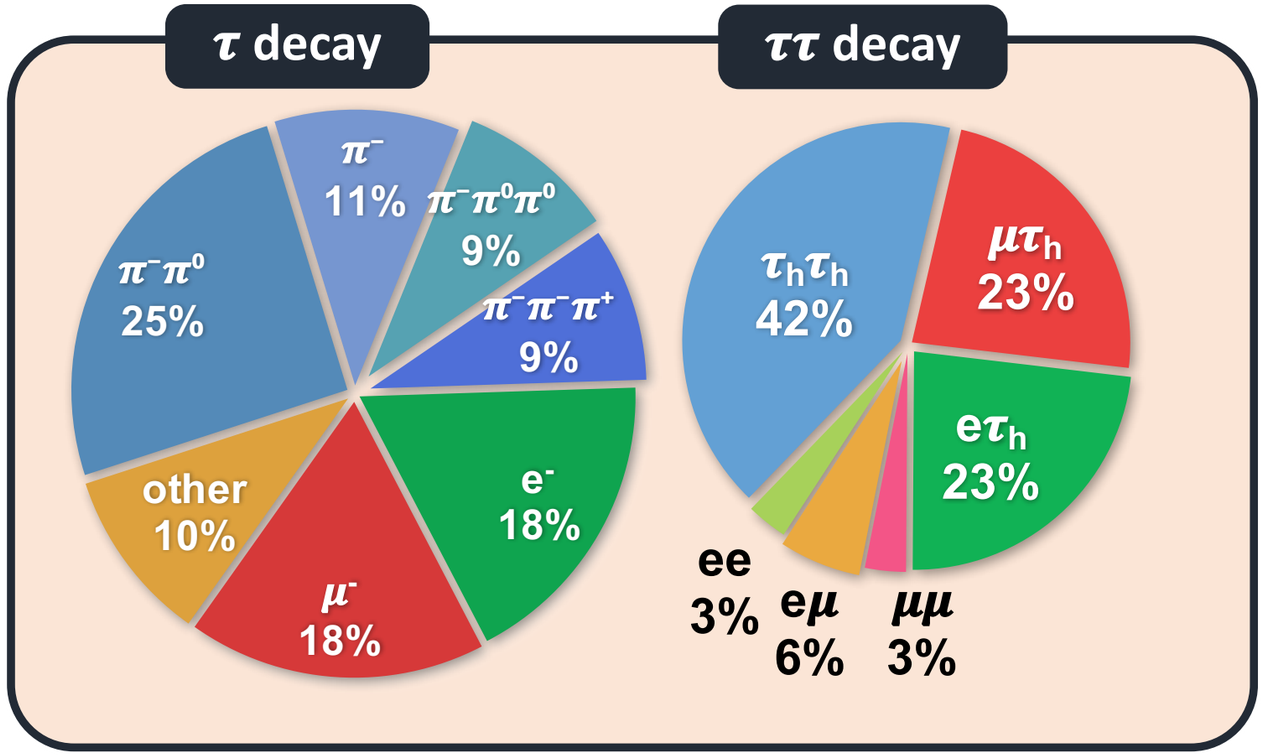
χ angular variable sensitive to changes in ττ angular distributions

Reconstruction of 3rd generation LQs



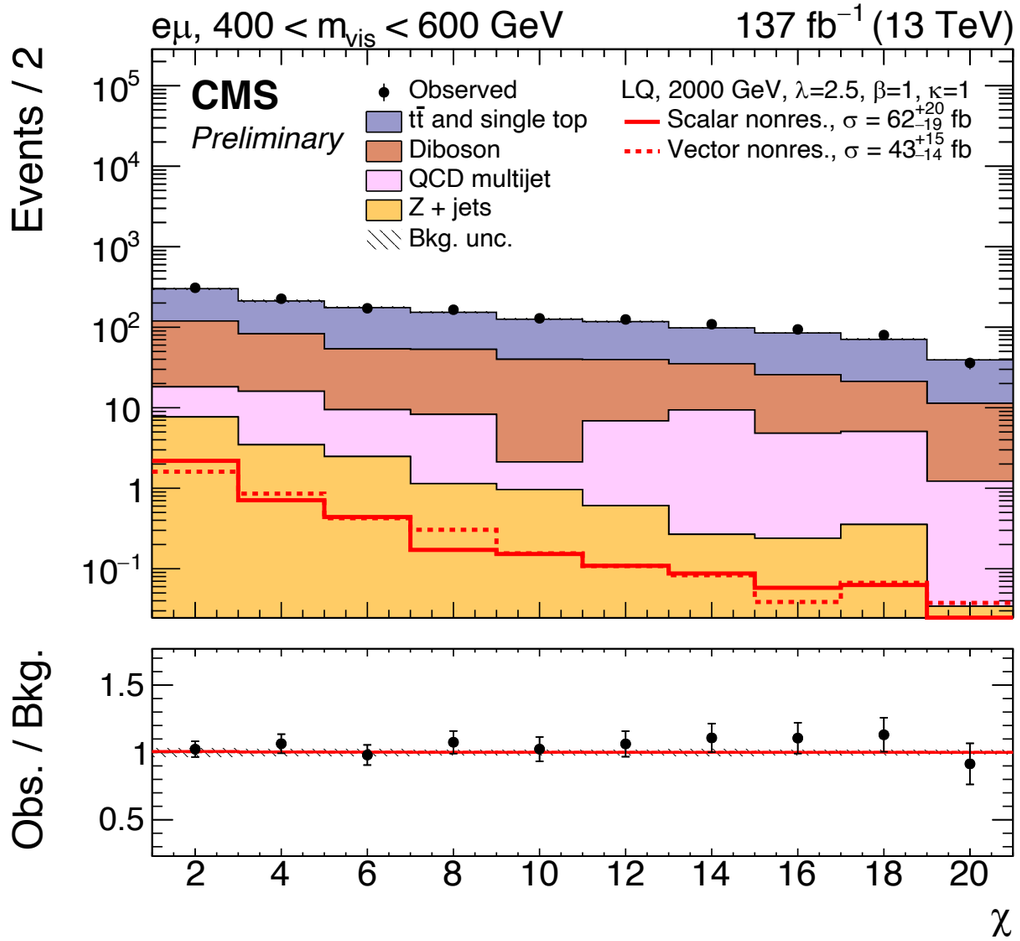


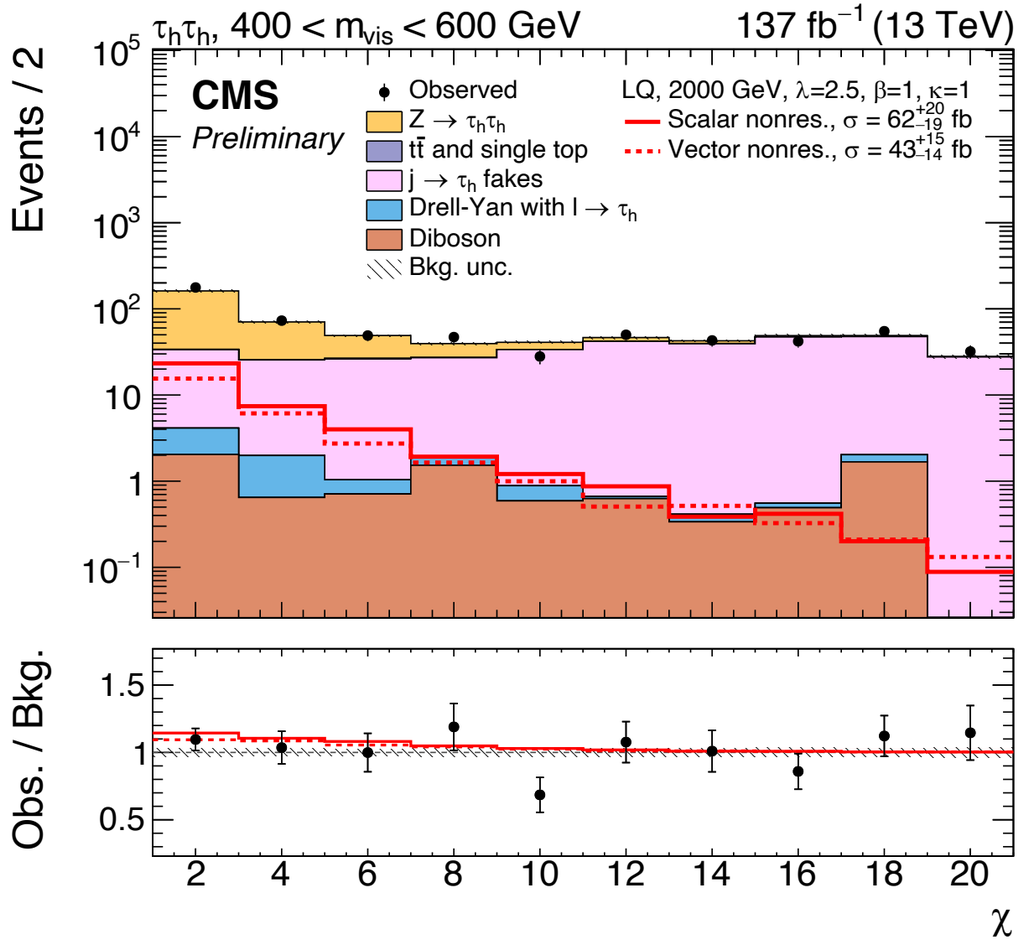




Comparison of observables :
χ fit in 45 signal regions (5 ττ modes * 3 years * 3 visible mass categ.)

CMS-EXO-19-016

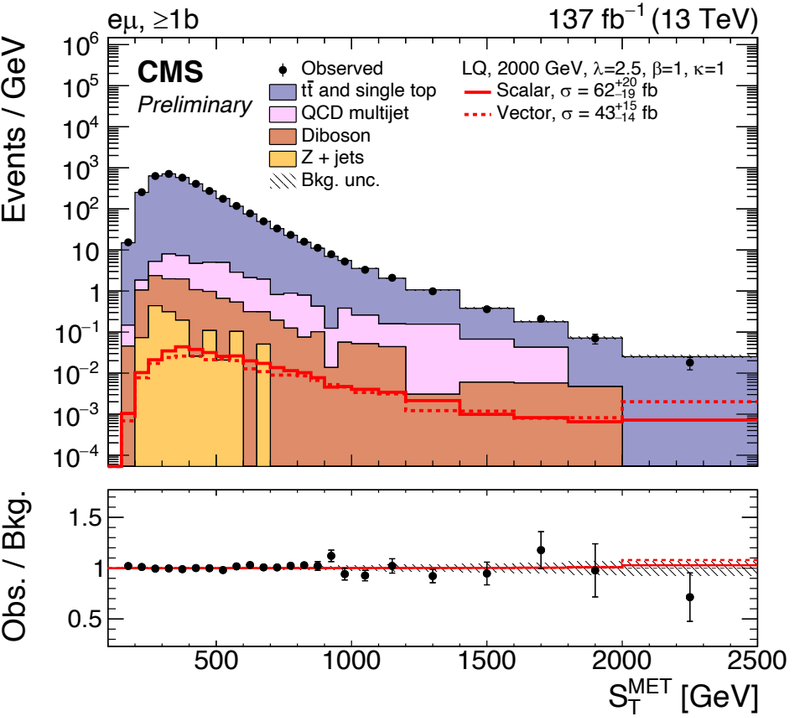


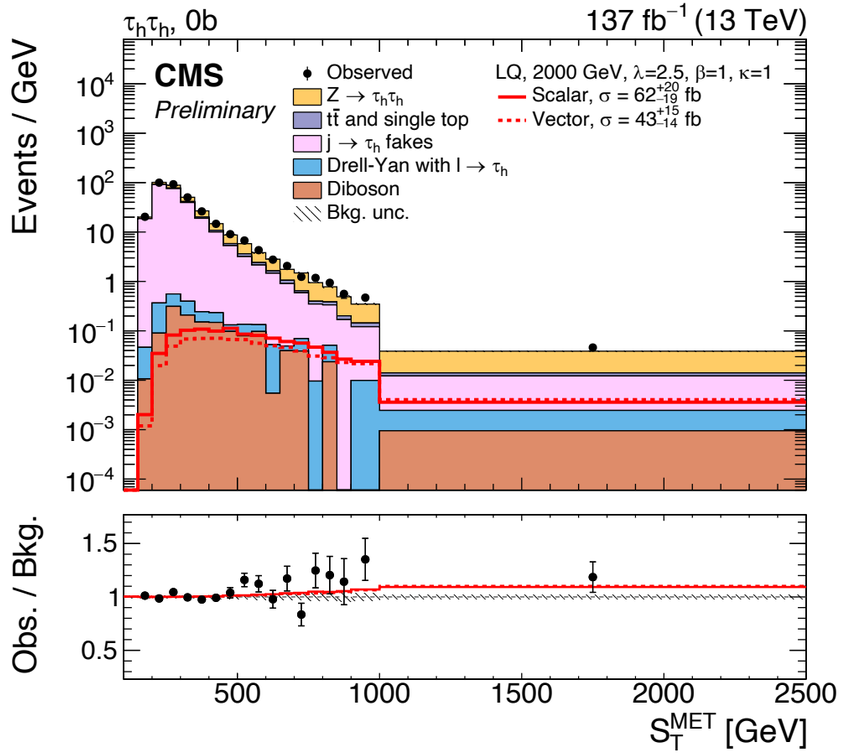


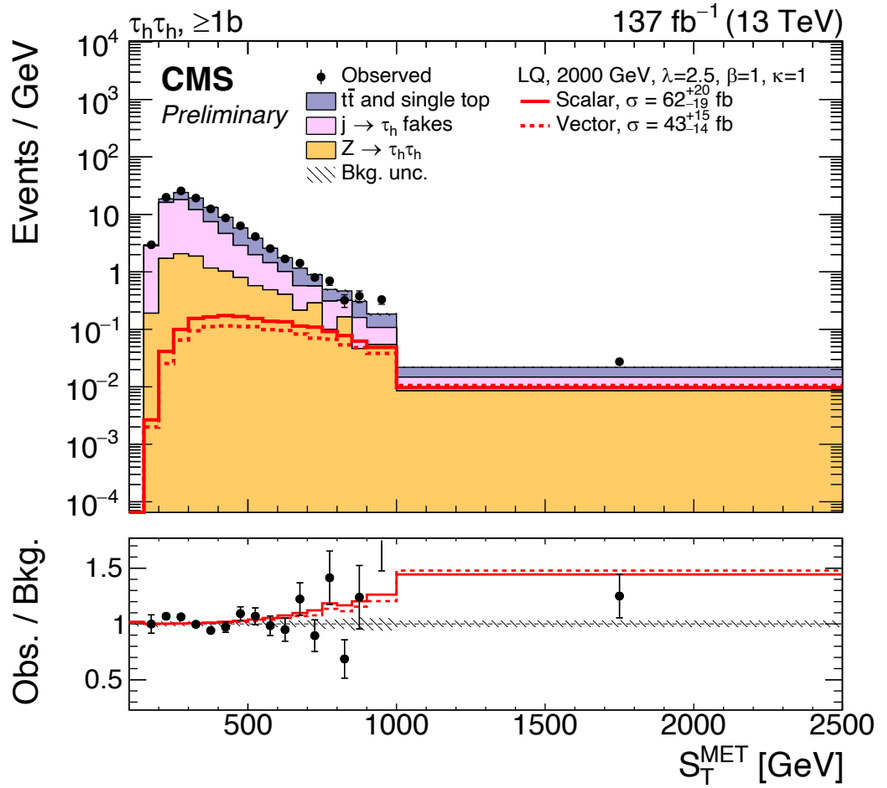
CMS-EXO-19-016

Comparison of observables : STMET fit in 30 signal regions (5 ττ modes * 3 years * two b-tag categories)

3 examples showing different background compositions :





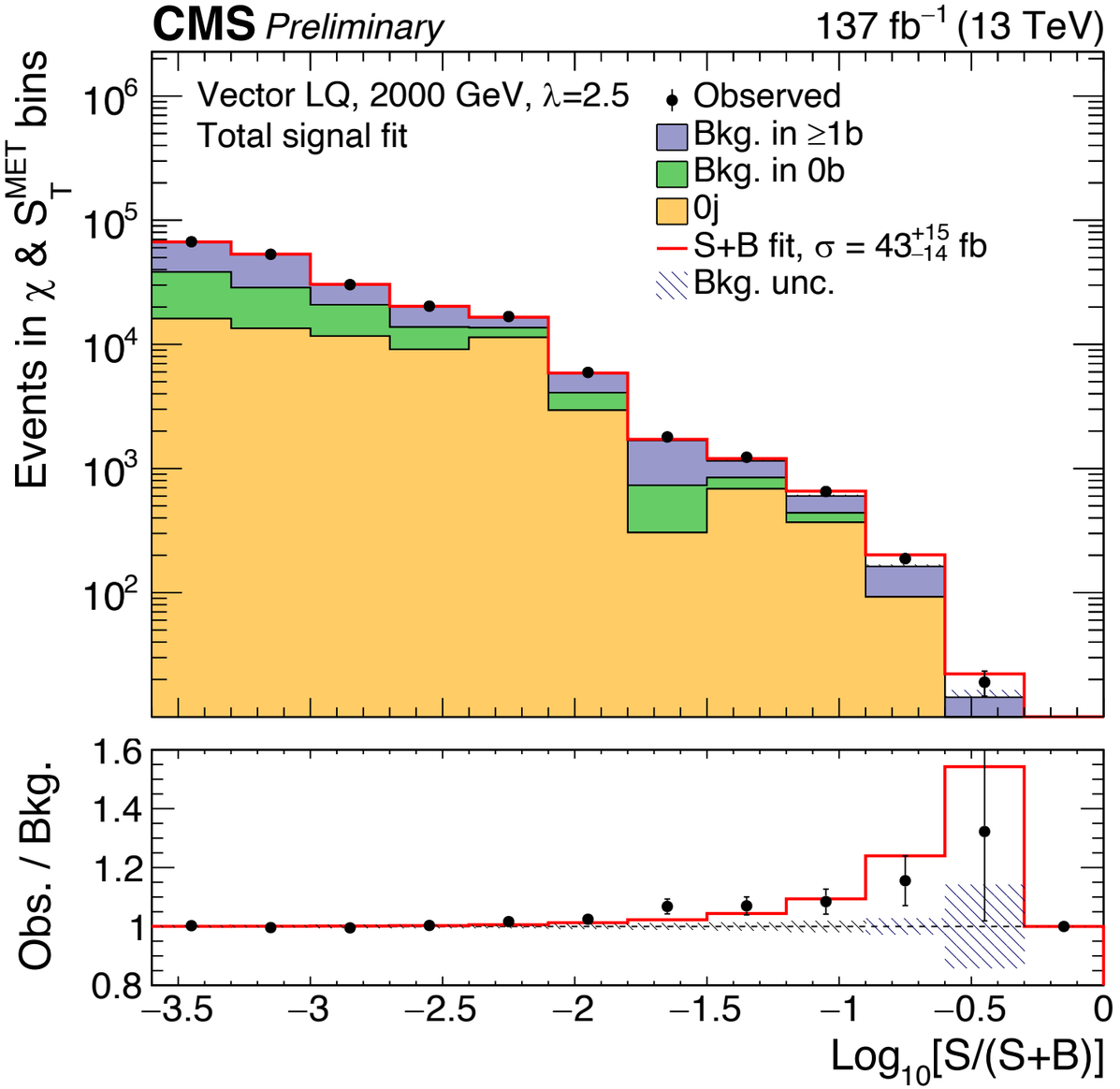


Some disagreements in the tails

CMS-EXO-19-016

Digesting 75 signal regions

Here, we order bins from all 75 signal regions by increasing signal significance, and show best fit of S+B

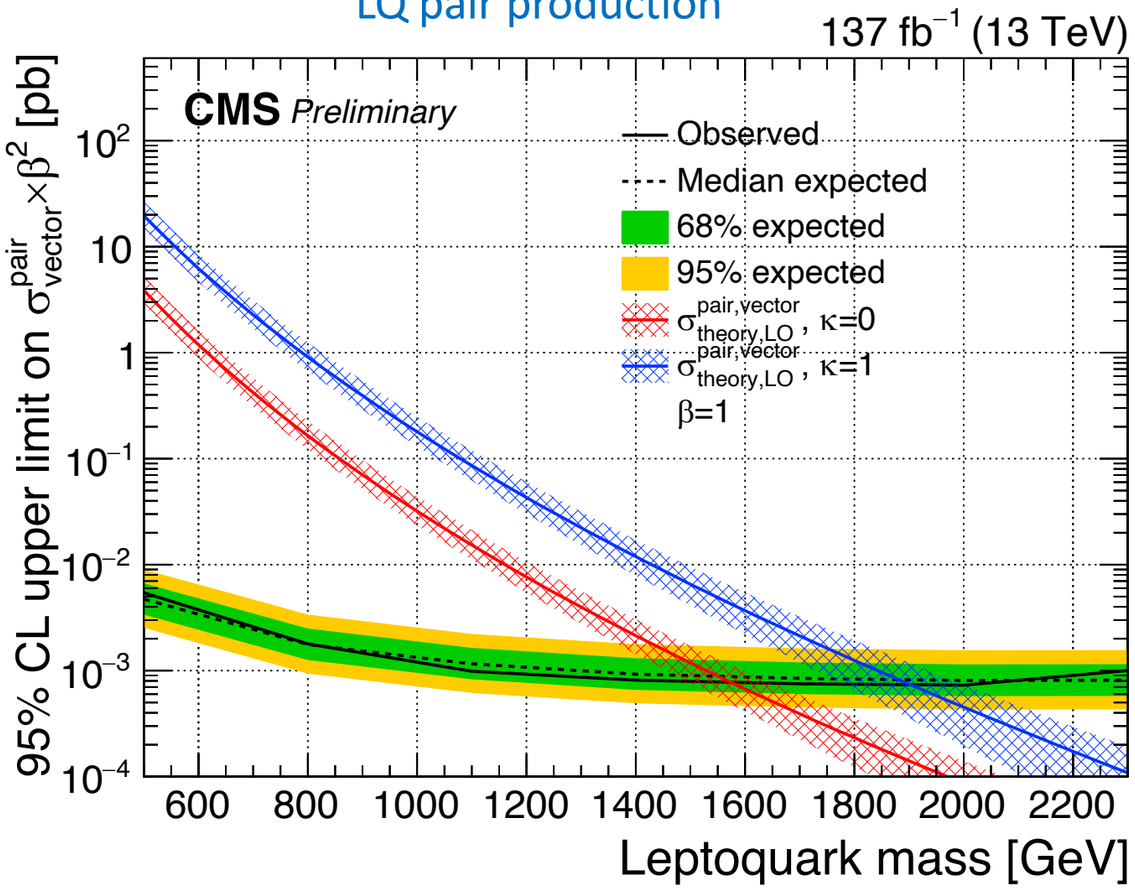


An excess is observed : ~ 3.5 σ

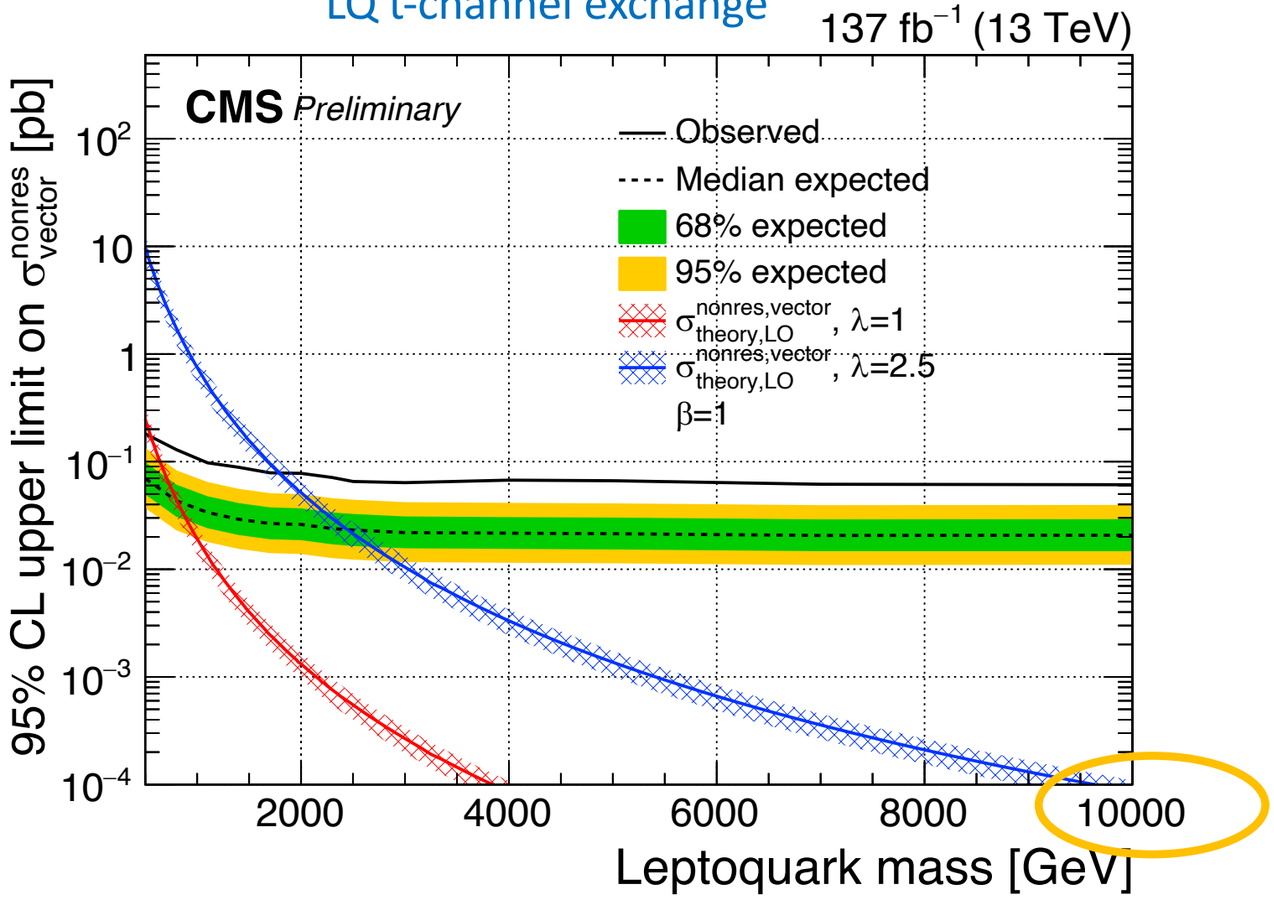
Excess :

CMS-EXO-19-016

LQ pair production



LQ t-channel exchange

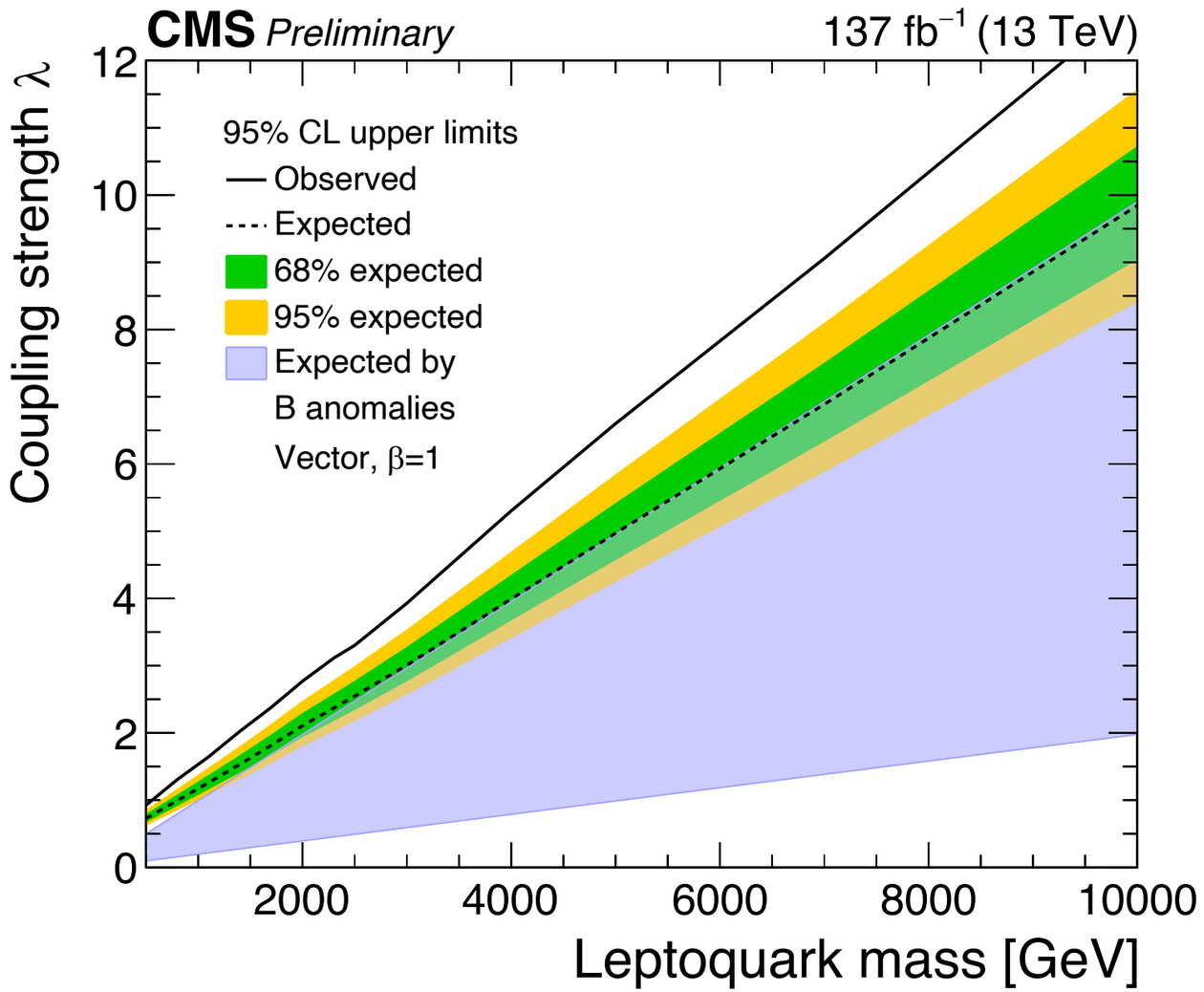


Pair-produced leptoquarks excluded below 1.6 – 1.9 TeV

Non-resonant t-channel LQ exchange shows mass-independent excess, extending to high masses

Possible signal is more consistent with a LQ with high-mass & high-coupling

Could this be the LQ seen in B anomalies ?

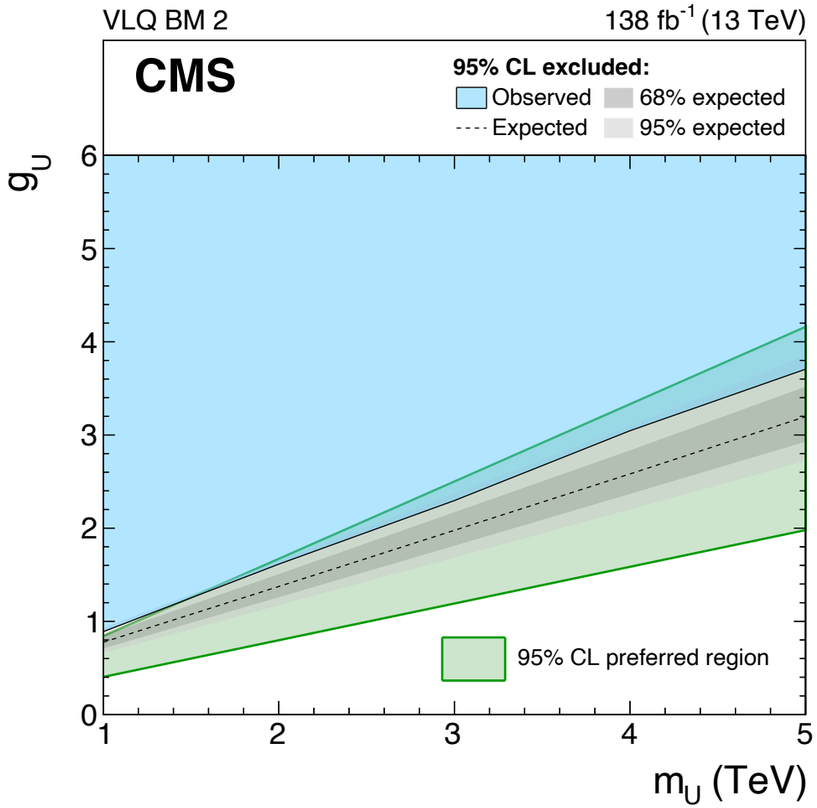


Expected limits just on the edge of the anomaly - favored region,

Since LQ pair production excludes masses < 2 TeV, the excess points to high mass & coupling

Cross-check ?

- Another CMS analysis (BSM Higgs search CMS-HIG-21-001) has also considered t-channel LQ exchange
  - Considers $\tau\tau$ with and without >=1 b-tag
  - Different event selection, optimization, & discriminating variables
  - Considers interference with SM processes



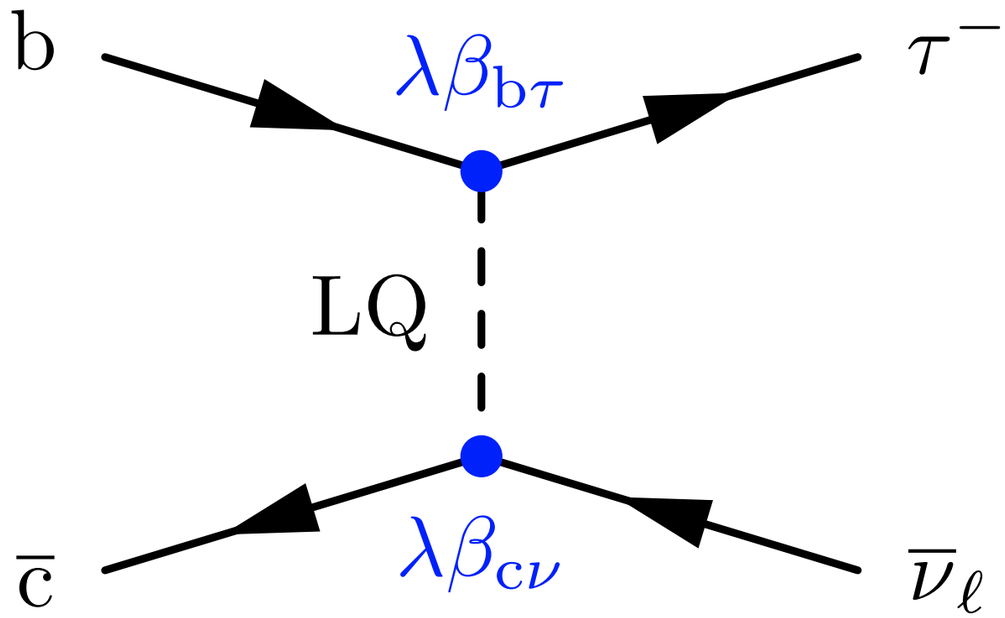
A 2-Sigma excess is observed across the mass region

- Additional cross-checks show consistency with CMS-EXO-19-016
- Interference found to be less than 10% at masses above 2 TeV

If this signal is real, where else might it be ?

Flavor structure

$$\Rightarrow \quad V_{q\ell} \sim \begin{array}{c} \\ \mathrm{d}/\mathrm{u}' \\ \mathrm{s}/\mathrm{c}' \\ \mathrm{b}/\mathrm{t}' \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{e}/\nu_\mathrm{e} & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{pmatrix} \end{array}$$

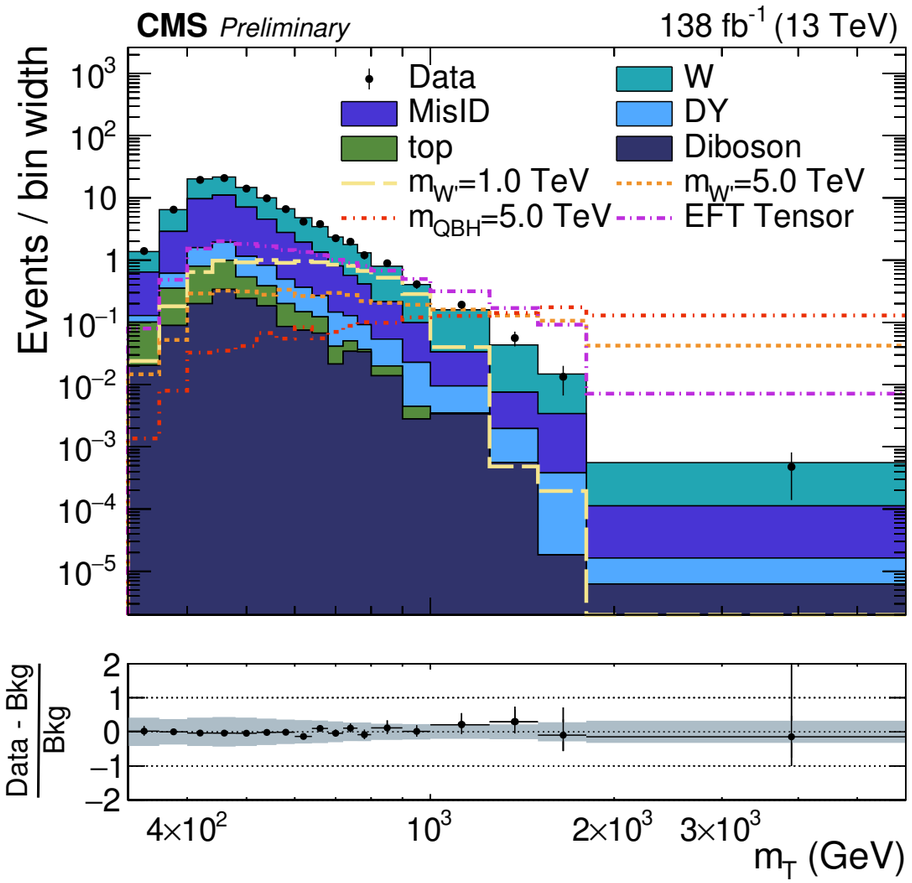


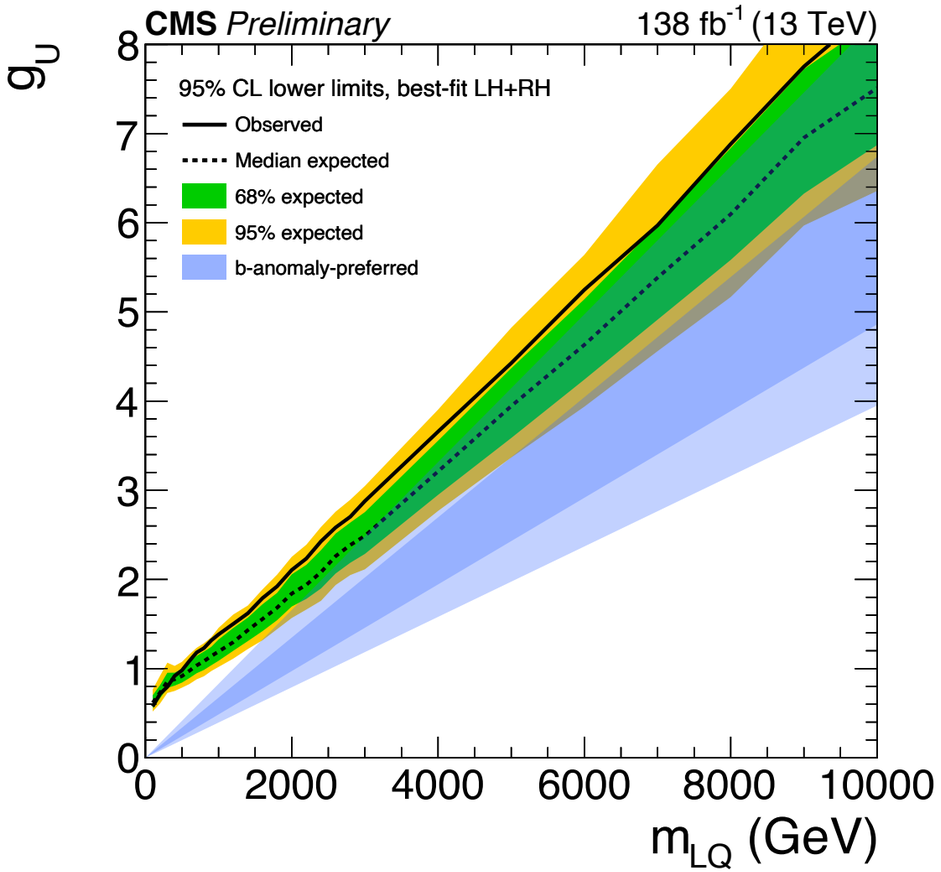
LQ-c-ν coupling is off-diagonal : 10% size of LQ-b-τ

Final state of τ + ν is interesting for t-channel leptoquark exchange

CMS-EXO-21-009

Search for t-channel LQ exchange in $\tau + \nu$

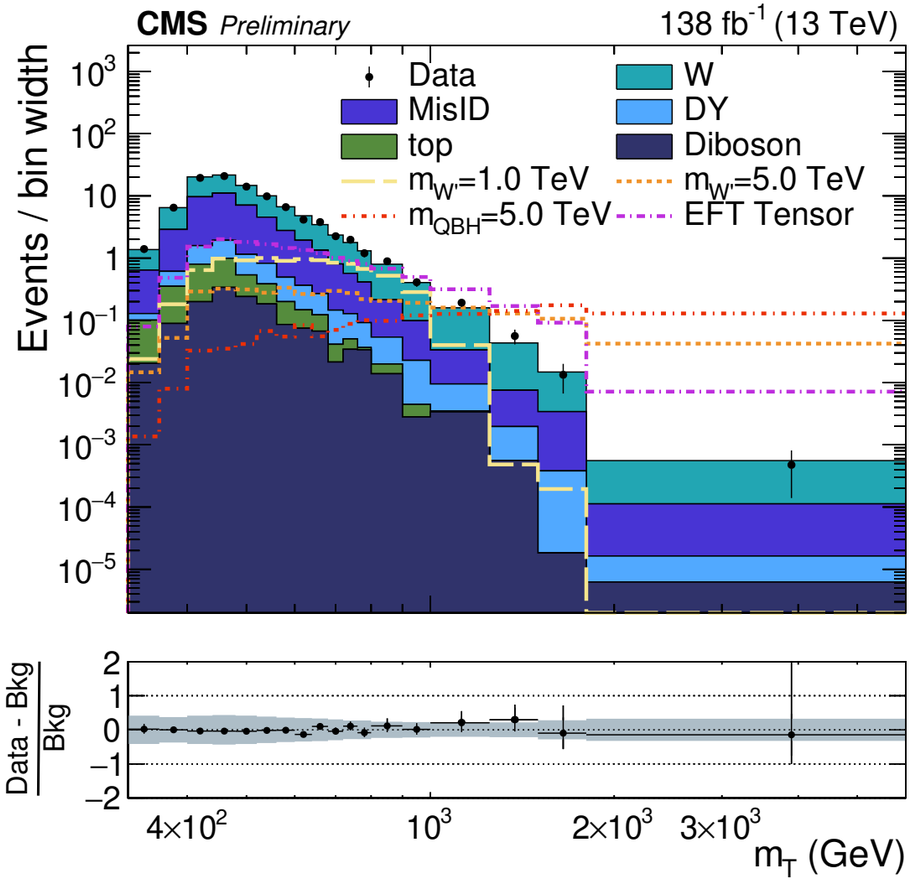


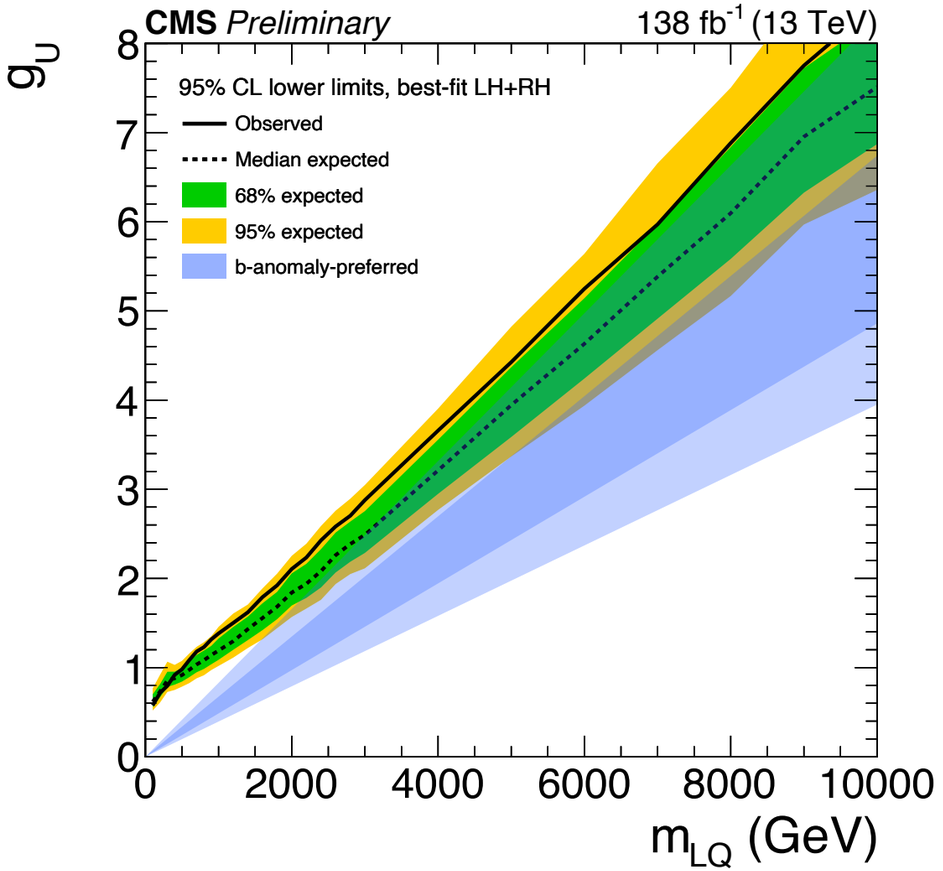


~1 Sigma excess observed

CMS-EXO-21-009

Search for t-channel LQ exchange in $\tau + \nu$





~1 Sigma excess observed

The coupling strengths excluded by searches in the tau+MET (CMS-EXO-21-009) and ditau (CMS-EXO-19-016) final state are compatible within approximately 5-25% for a vector LQ mass of 2 TeV and coupling benchmarks that could explain the b-anomalies.

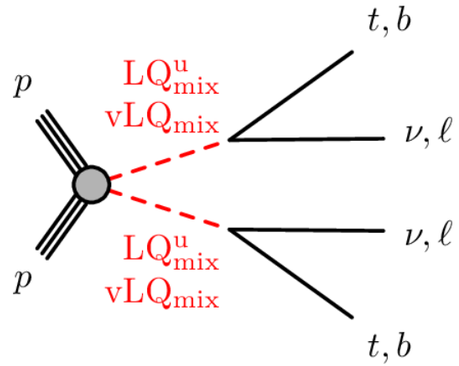
What about ATLAS ?

- ATLAS has 3 new (ICHEP 2022) LQ results :
  - Search for scalar/vector LQs ➞ to 3rd gen. quarks + 1st/2nd gen. leptons (ATLAS-CONF-2022-009)
    - LQ (pairs) ➞ (t,b) + (e,μ,ν) with exactly 1e or 1μ in the final state
    - Considers up-type LQ (charge = 2/3e) and down-type LQ (charge = 1/3e)
  - Search for scalar/vector LQLQ ➞ tℓ + tℓ with ℓ = e,μ (ATLAS-CONF-2022-052)
    - LQ pairs ➞ te + te OR tμ + tμ
    - Considers down-type LQ (charge = 1/3e)
    - 3 or 4 leptons in final state
  - Search for scalar LQs in $\tau\tau$b (ATLAS-CONF-2022-037)
    - LQLQ with LQ ➞ τb
    - Considers LQ with charge 4/3e
    - For the first time, single LQ production considered

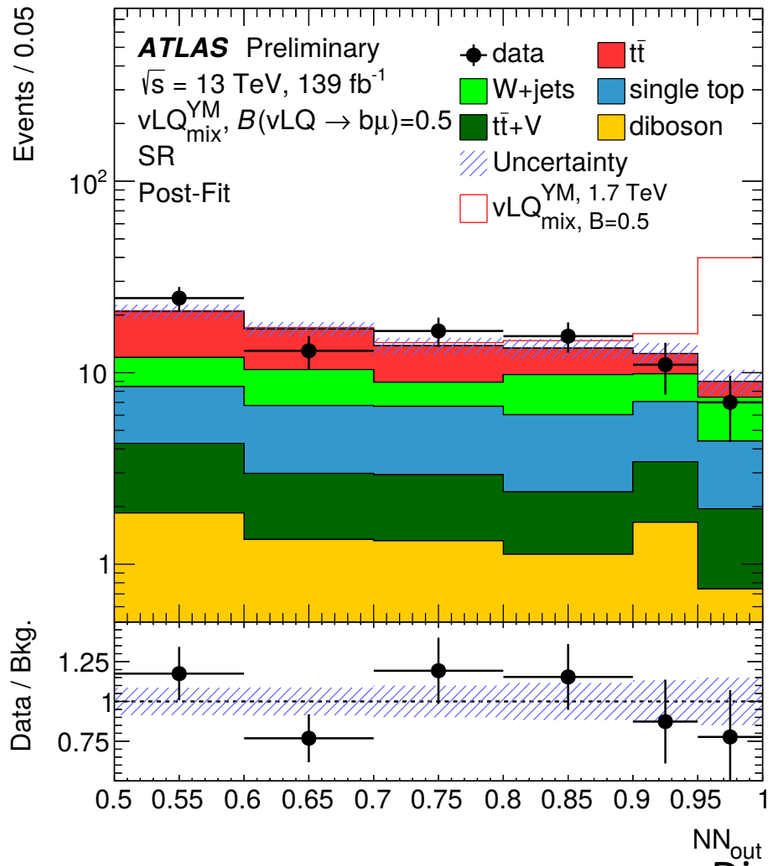
Searches for LQs with charge 2/3e and 1/3e (ATLAS-CONF-2022-009)

1 lepton

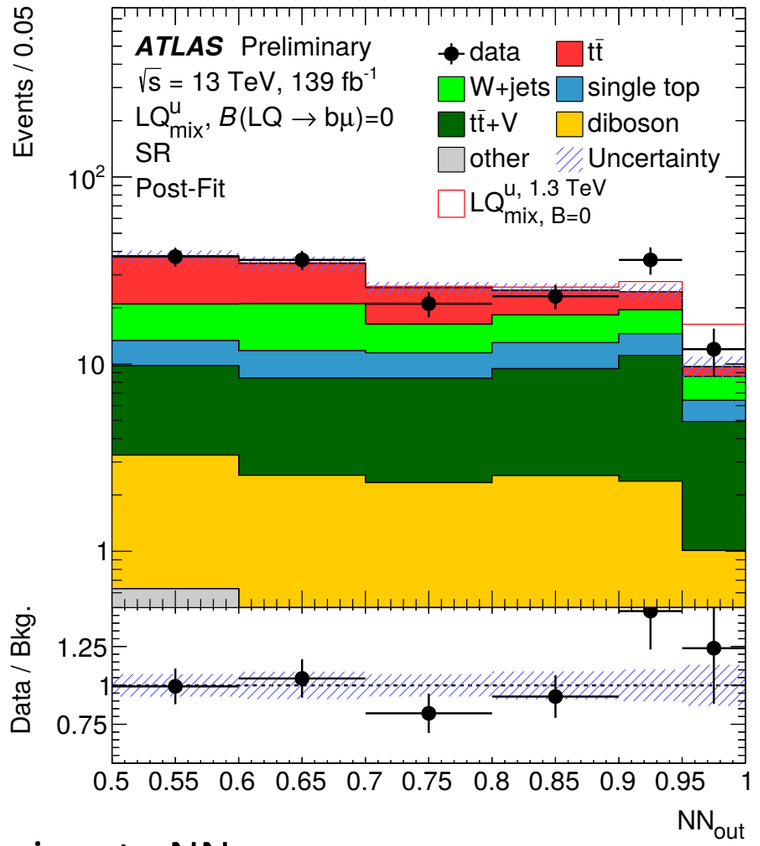
LQ → t+ν, t+e, t+μ and LQ → b+ν, b+e, b+μ



b+μ



t+e

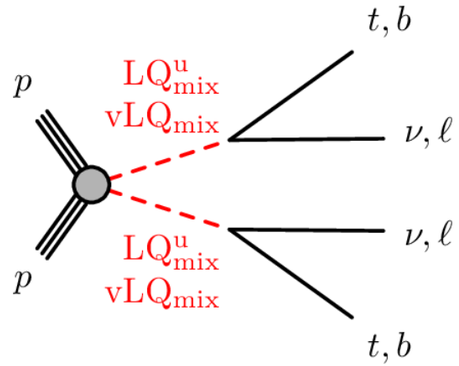


Discriminant : NN

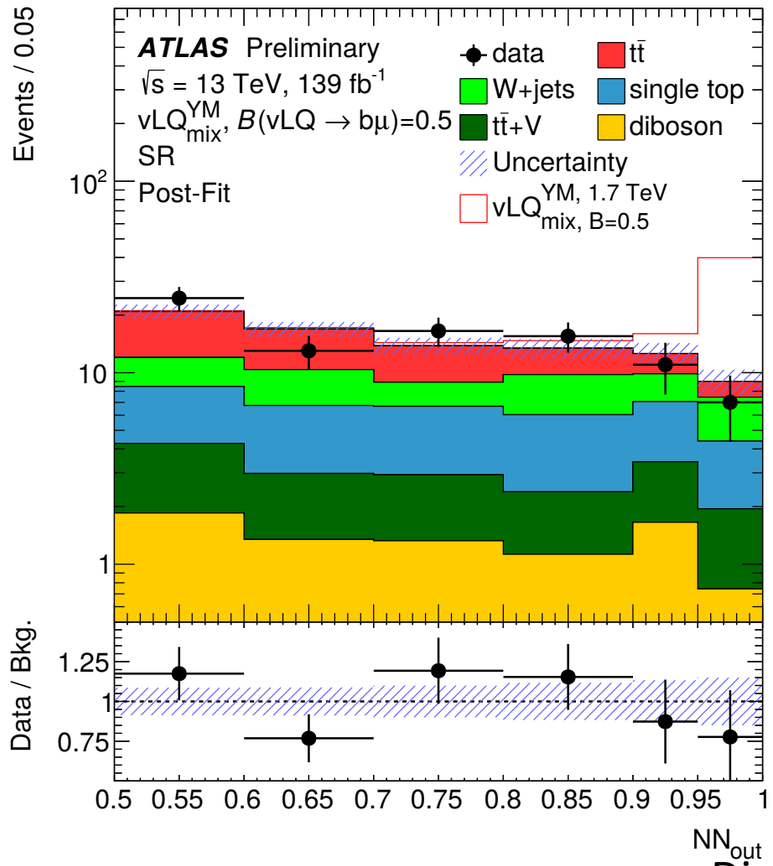
Searches for LQs with charge 2/3e and 1/3e (ATLAS-CONF-2022-009)

1 lepton

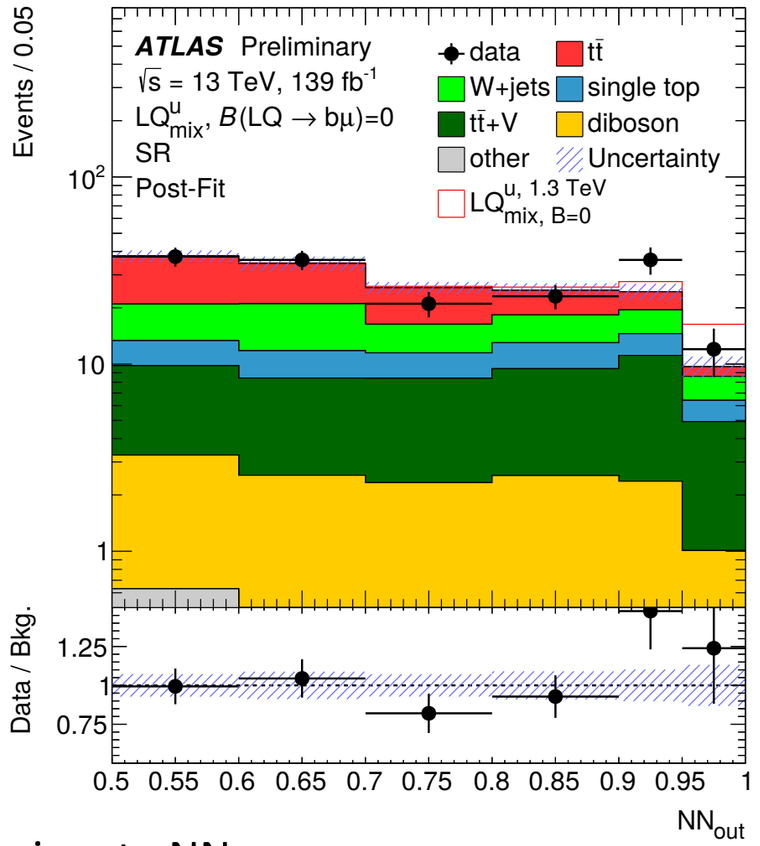
LQ → t+ν, t+e, t+μ and LQ → b+ν, b+e, b+μ



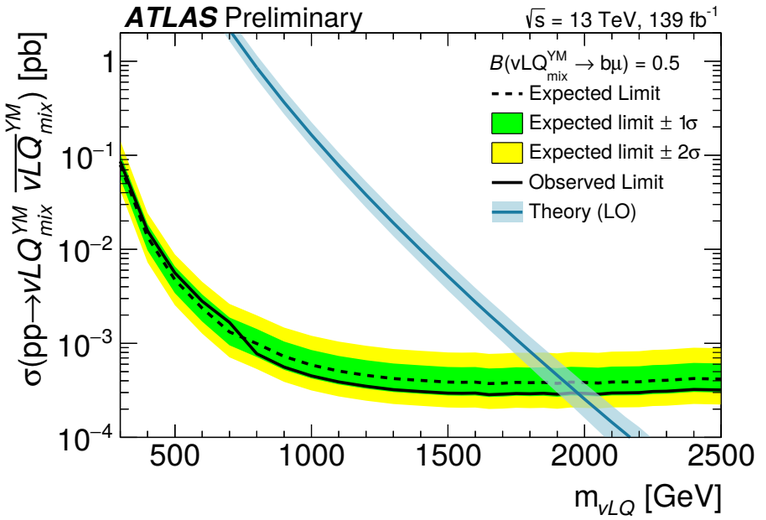
b+μ



t+e



Discriminant : NN



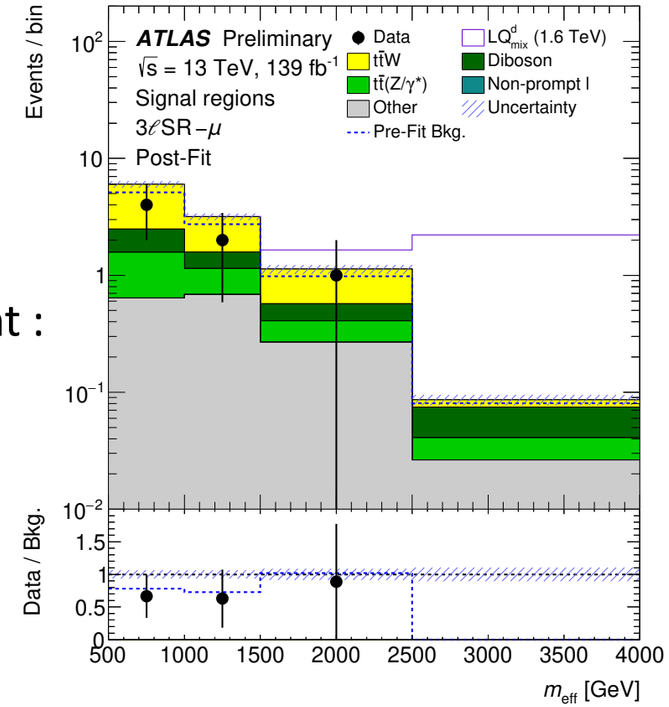
No excesses observed

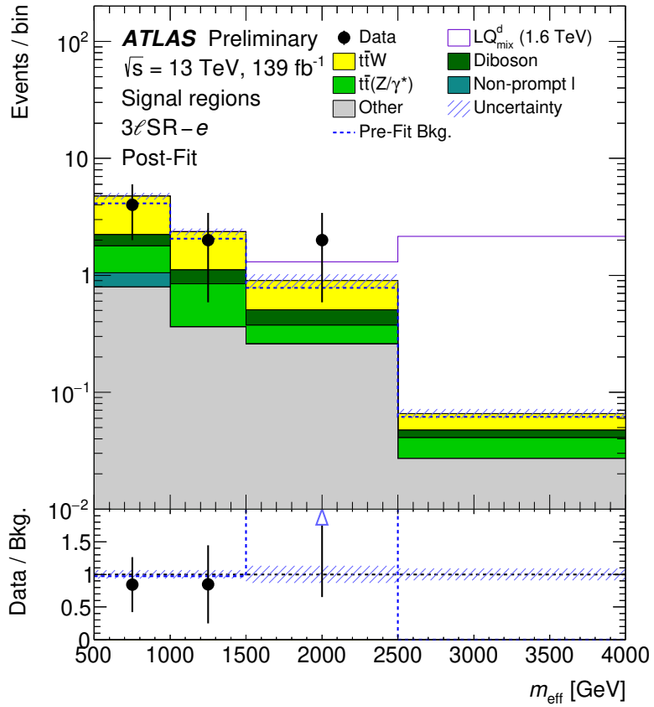
LQ limits on mass range 1.4 – 1.95 TeV

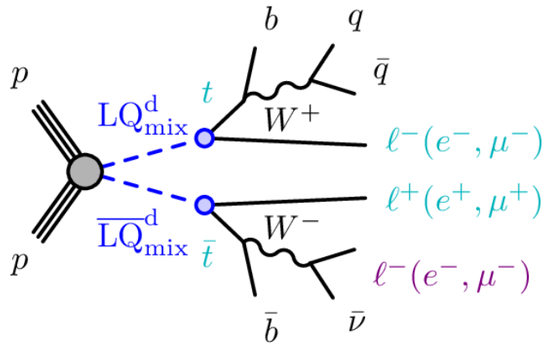
Strongest limits : vector LQs with Yang Mills couplings > vector LQs with minimal couplings > Scalar LQs

LQLQ → tℓ + tℓ (ATLAS-CONF-2022-052)

Discriminant : m_{eff}

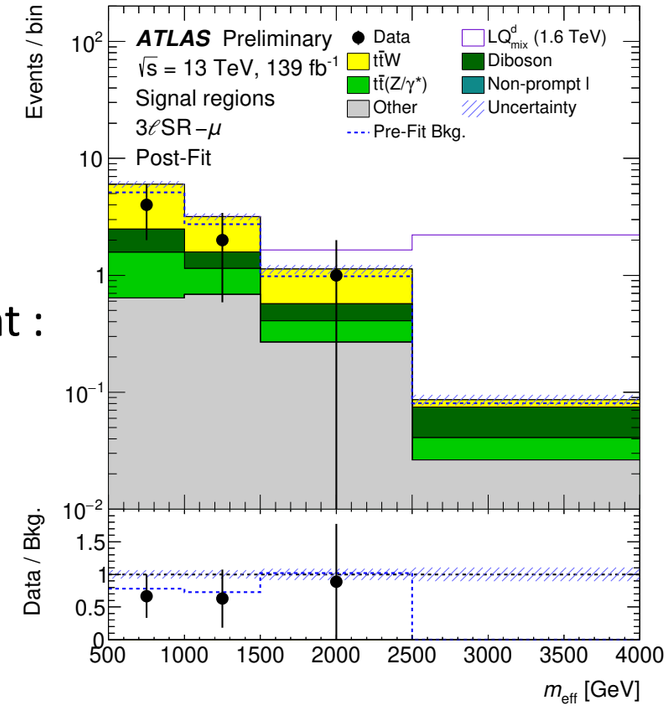


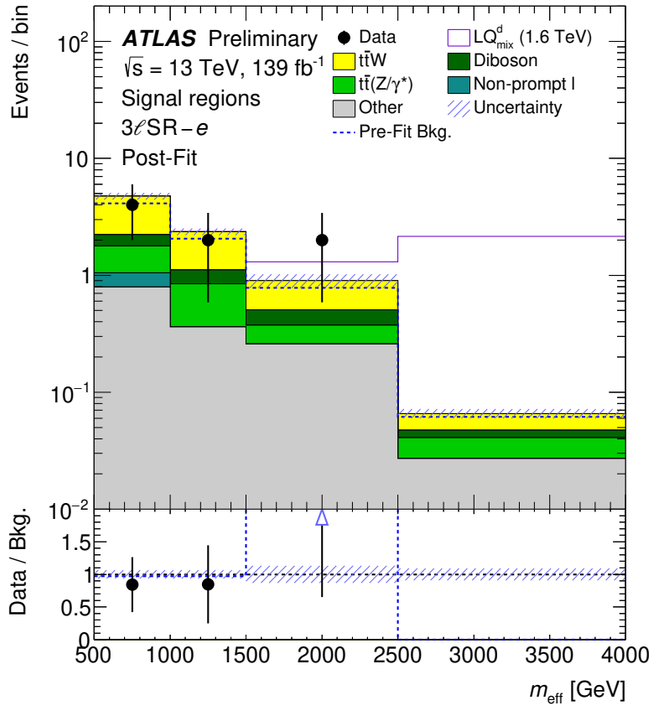


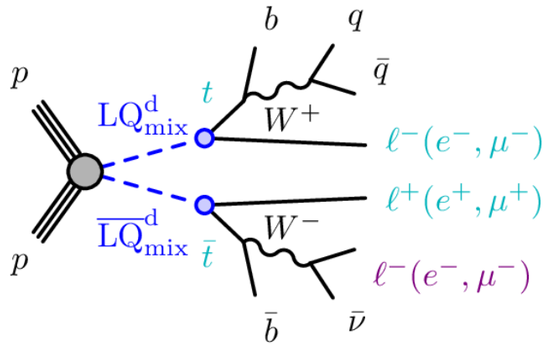


LQLQ → tℓ + tℓ (ATLAS-CONF-2022-052)

Discriminant : m_{eff}

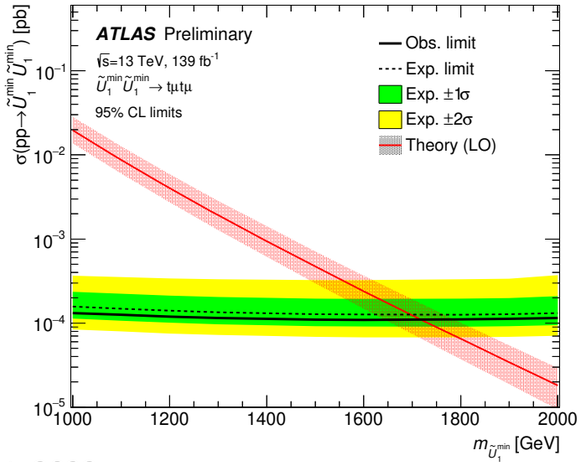


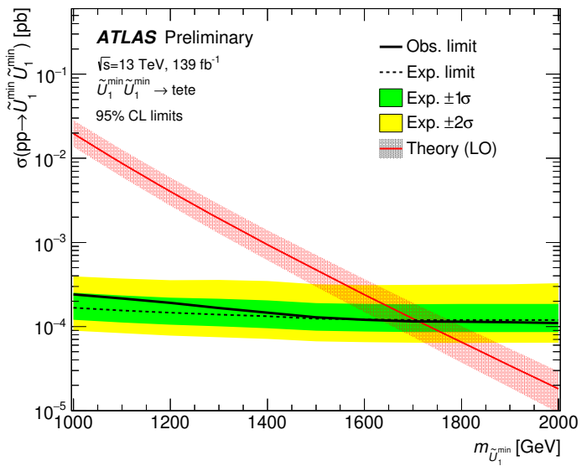




No excess observed,
Limits on M_{LQ} ~ 1.7 TeV

Limits

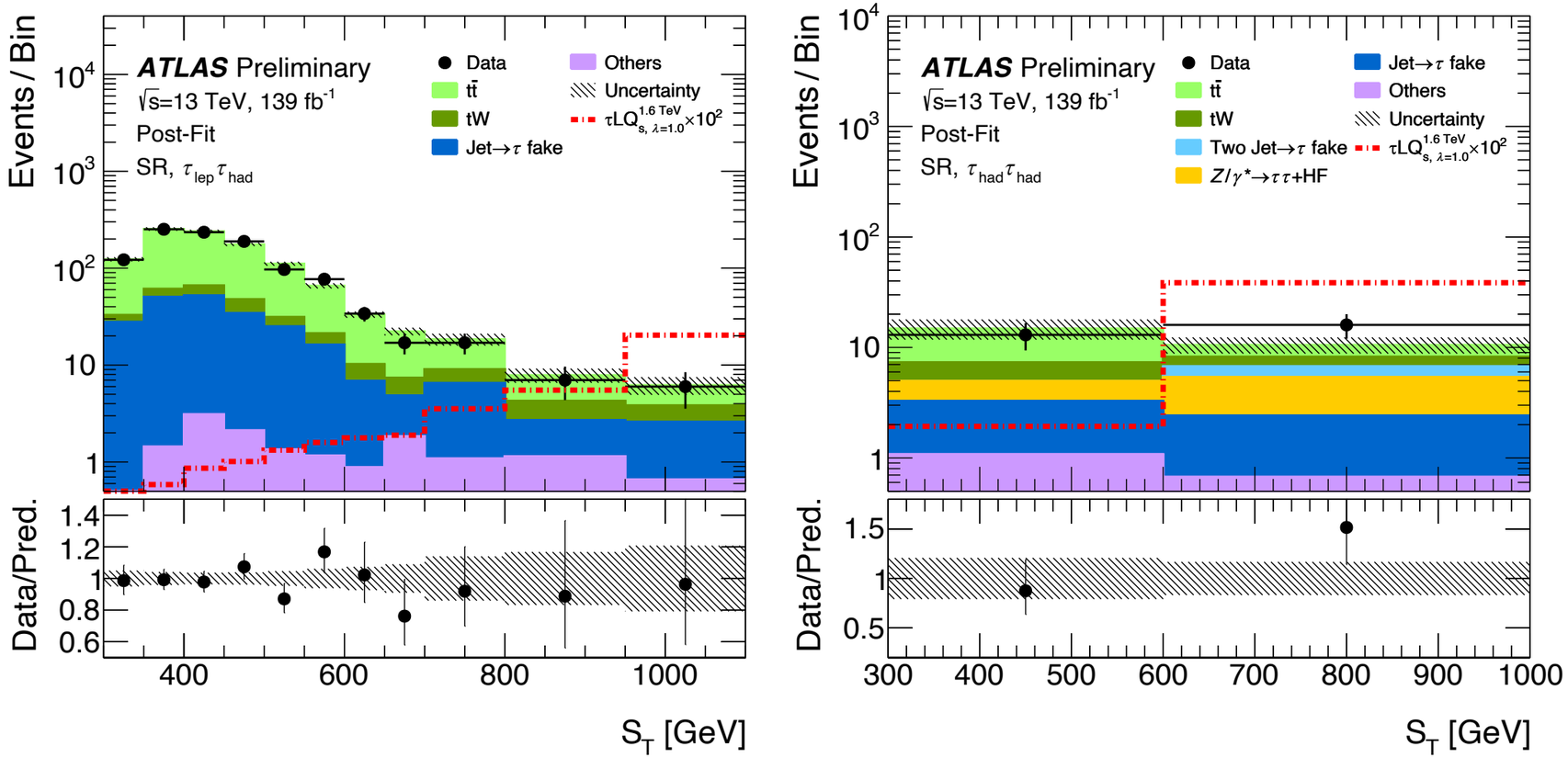




ATLAS LQ pair and single production

(ATLAS-CONF-2022-037)

- New single-LQ search combined with LQ pair production
  - b$\tau\tau$ final state targets both
  - However, final state not sensitive to non-resonant production



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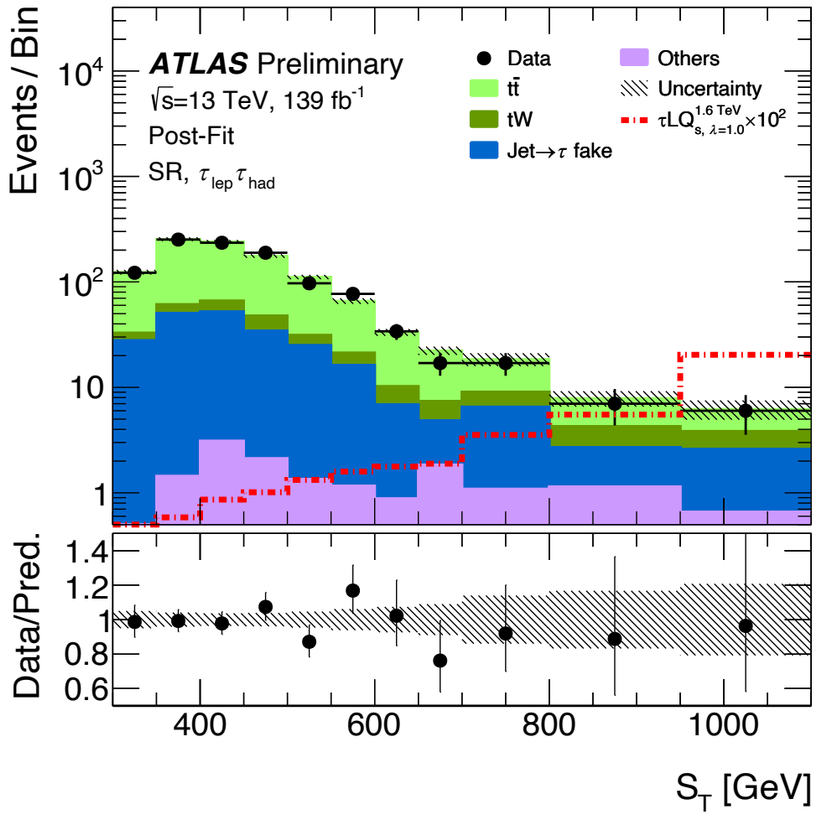
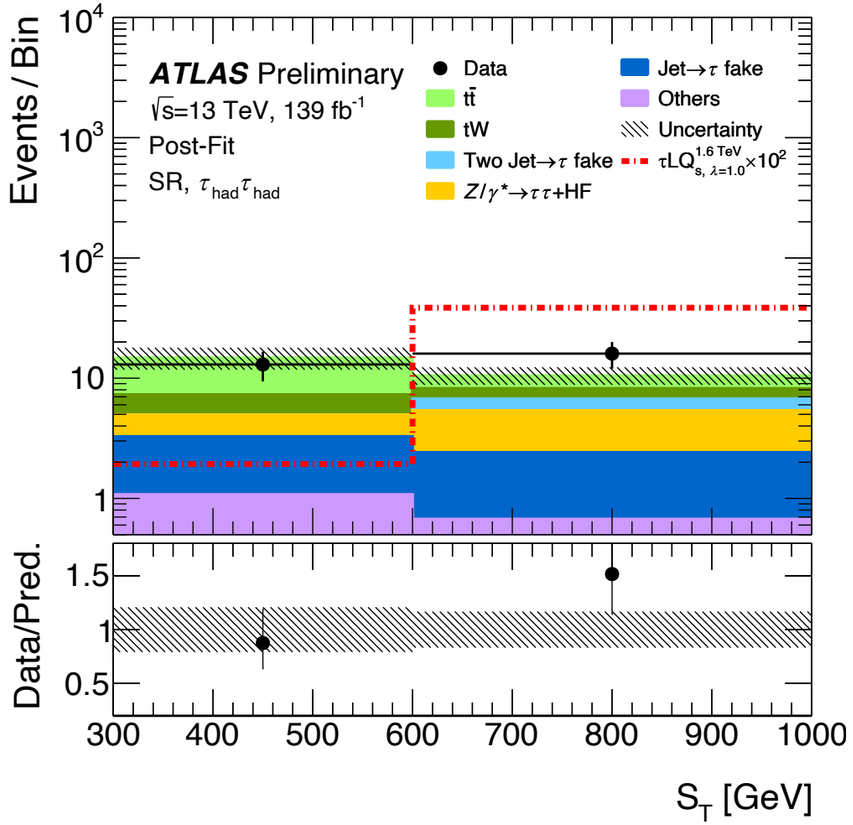
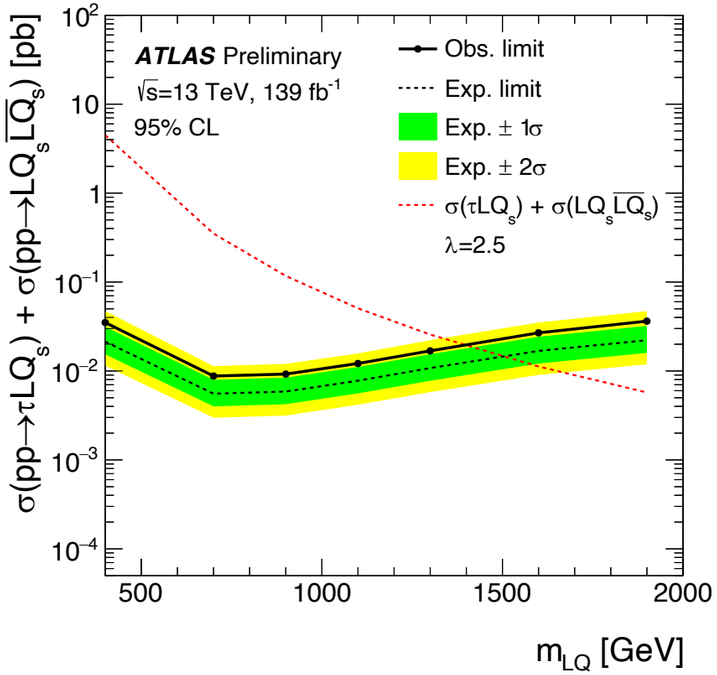
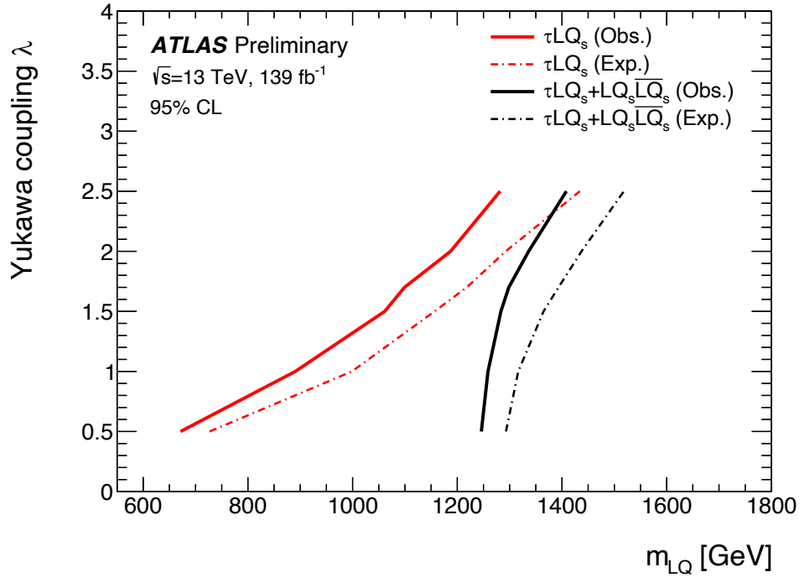




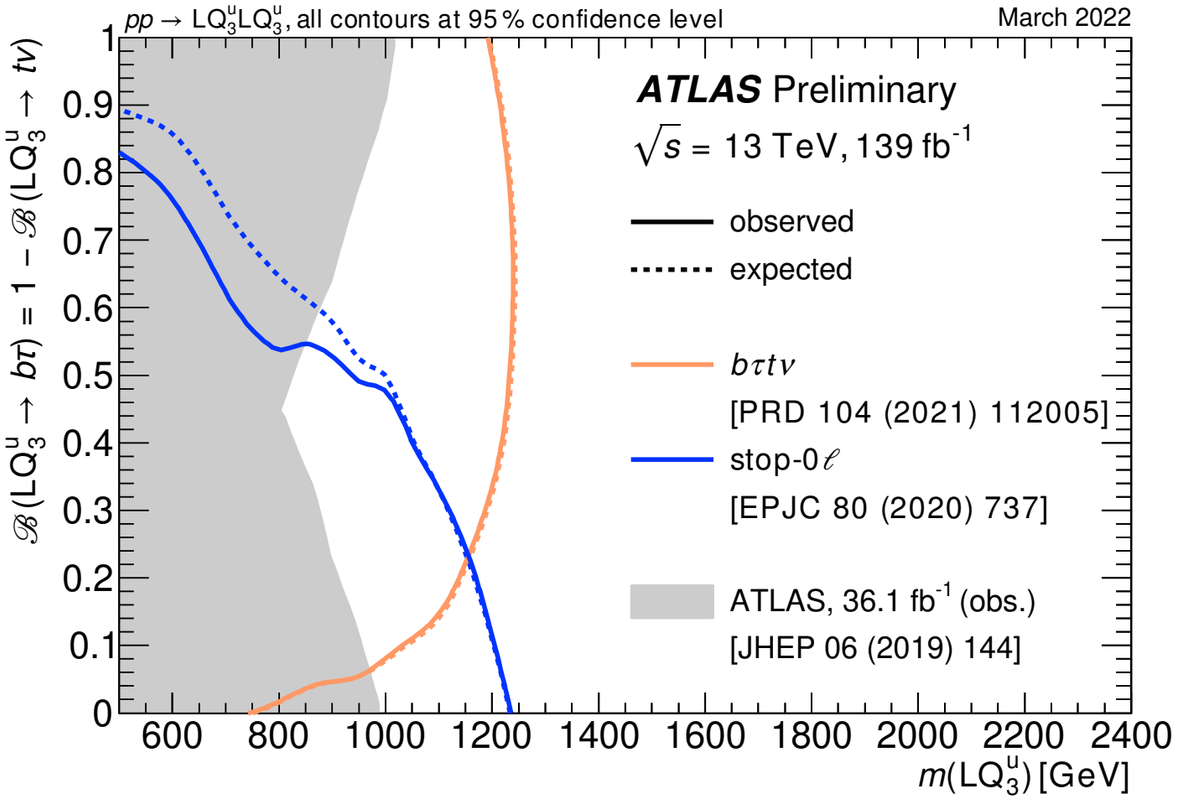




- No excess observed for M_{LQ} 2 TeV
- Mass constraints similar to CMS

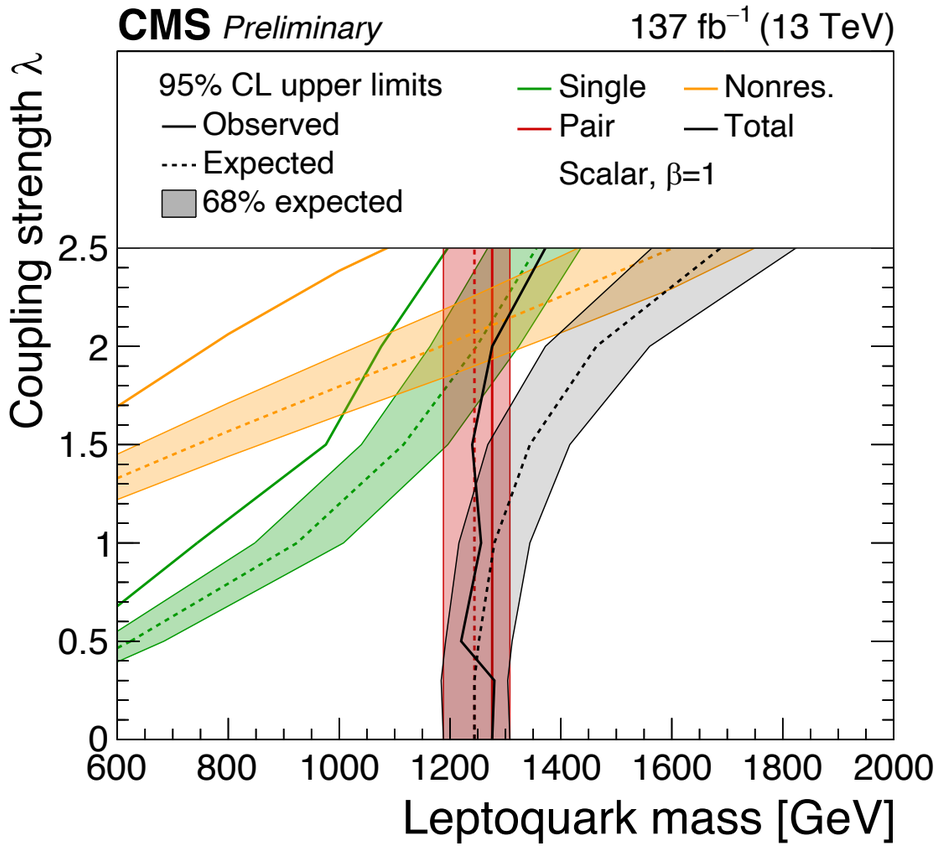
Some LQ summary plots (many more available)

ATL-PHYS-PUB-2022-012



As a function of BR to either tν or bτ

CMS-PAS-EXO-19-016



Coupling vs. mass
combining single + pair + nonresonant LQ production

Summary: Leptoquark searches at CMS & ATLAS

- Third-generation leptoquarks offer explanation of flavor structure of SM and could be responsible for B anomalies
- 3G LQ pair production sets coupling-independent mass constraints below M_{LQ} of ~2 TeV
- Non-resonant, t-channel LQ exchange allows possibility to probe high masses & high couplings favored by B anomalies
  - CMS sees an intriguing 3.5σ excess
  - Combined with other searches, favors high-mass (> 2 TeV) and high coupling
- Not covered : Many LQ searches in 1st/2nd generation on CMS and ATLAS physics pages

CMS-EXO-19-016