

On behalf of the CMS
collaboration

A flavor for leptoquarks

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Including first-time shown update
of EXO-19-016 : 3rd-gen LQ result
ready for journal submission



University of
Zurich^{UZH}

July 18th, 2023
LP2023 Melbourne



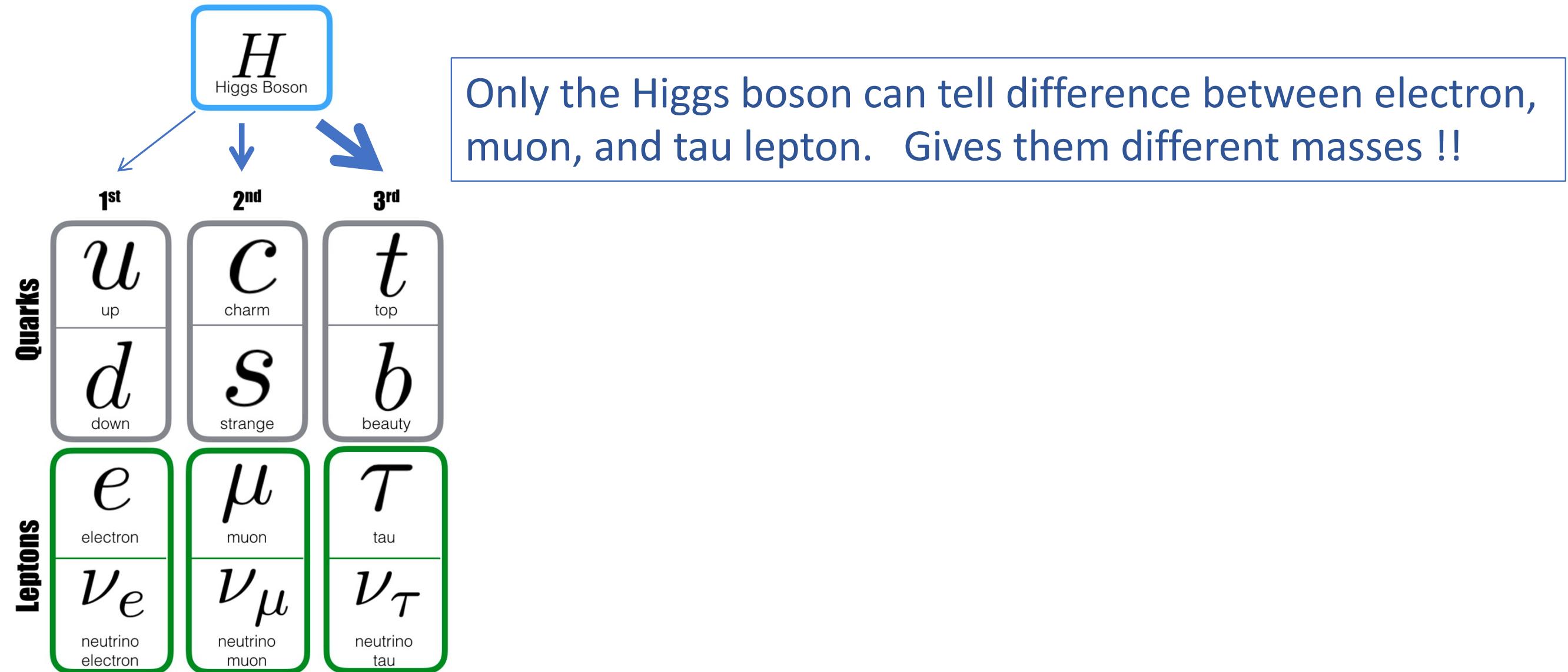
Theoretical puzzle : Similarity of quarks and leptons

	1 st	2 nd	3 rd
Quarks	u up	c charm	t top
	d down	s strange	b beauty
Leptons	e electron	μ muon	τ tau
	ν_e neutrino electron	ν_μ neutrino muon	ν_τ neutrino tau

Some underlying symmetry ?

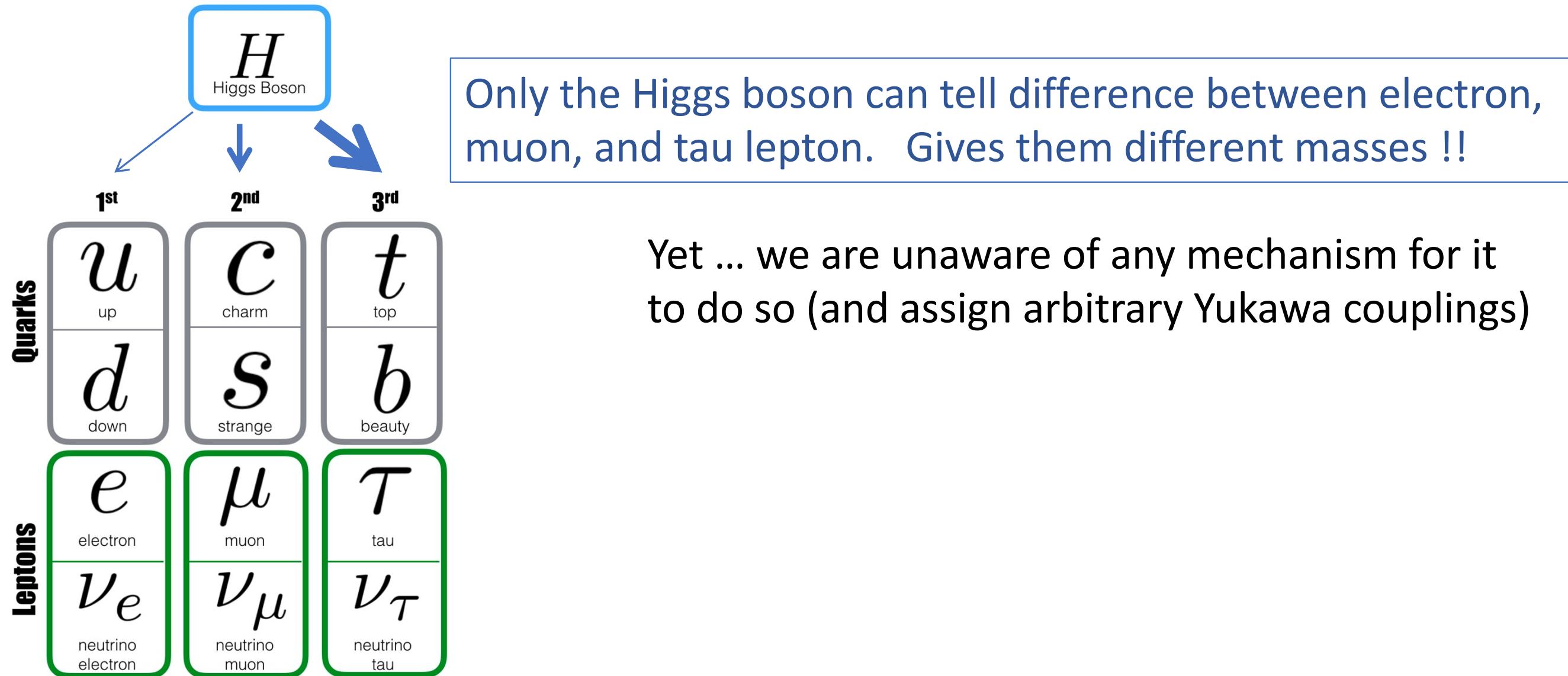
Theoretical Puzzle : flavor

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



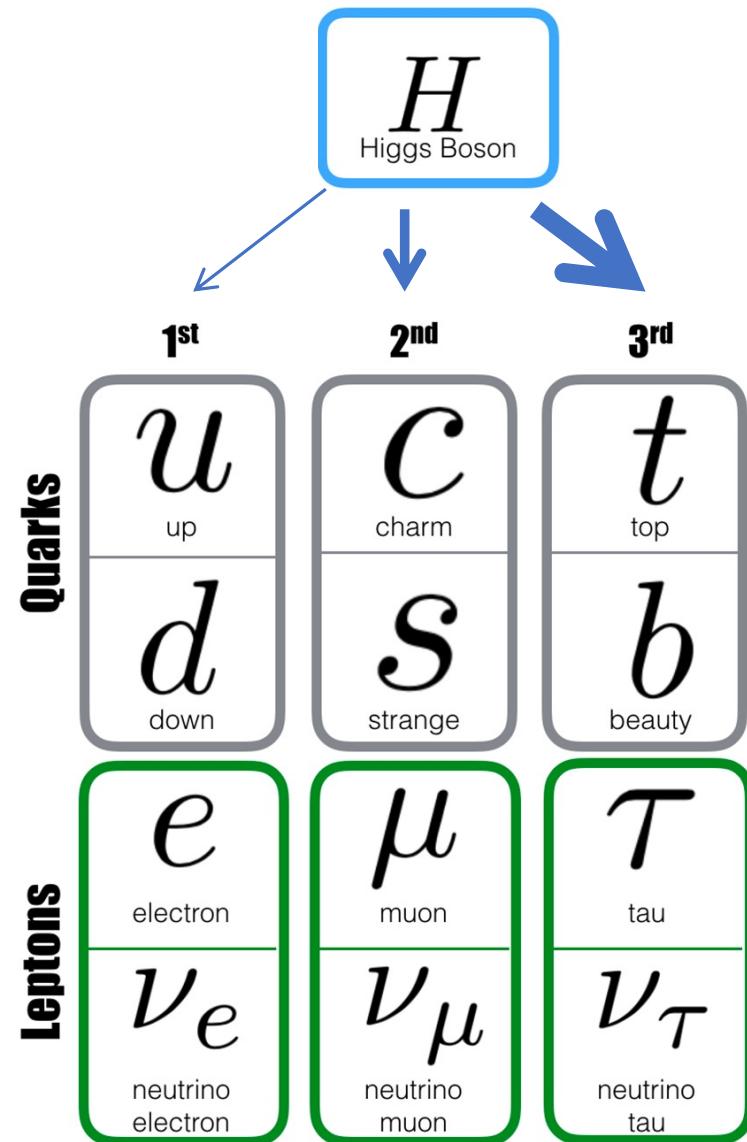
Theoretical Puzzle : flavor

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Theoretical Puzzle : flavor

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



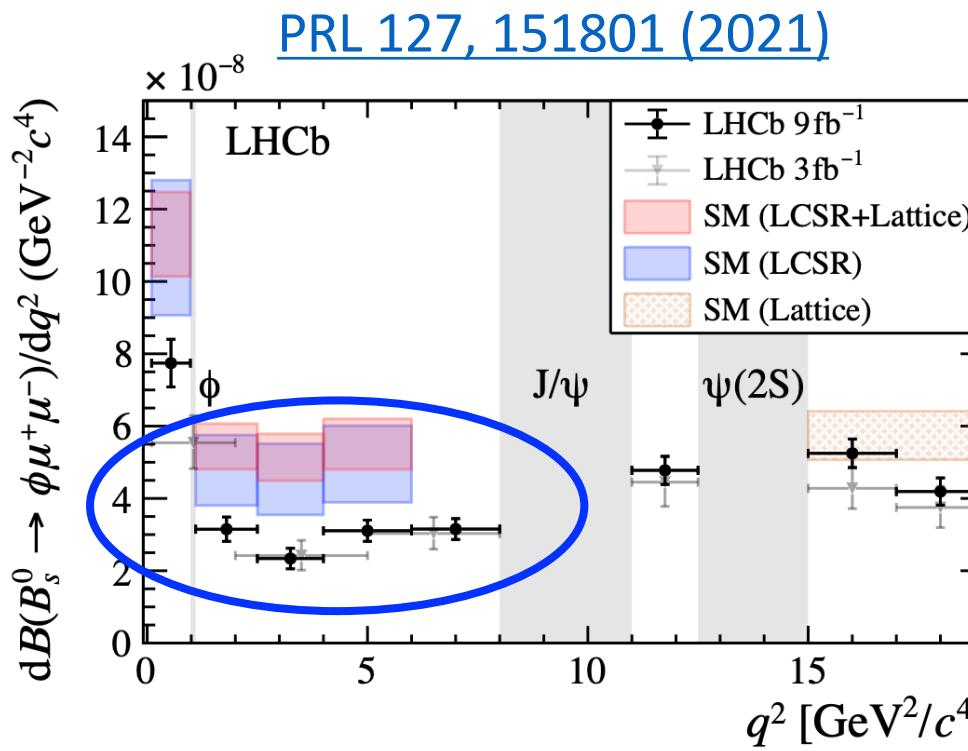
Only the Higgs boson can tell difference between electron, muon, and tau lepton. Gives them different masses !!

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

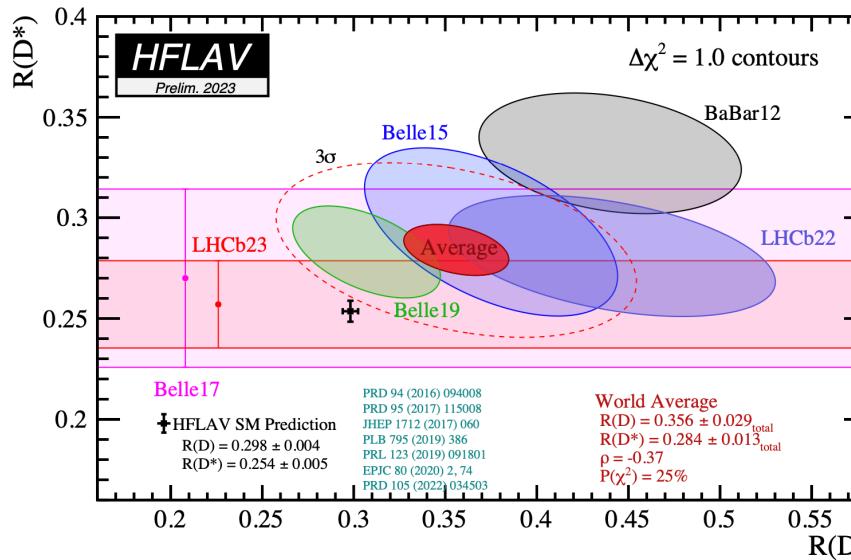
Precise measurements of Higgs couplings do not elucidate the **WHY** or **HOW**

New physics needed to tell the difference
 e vs. μ vs. τ
 u vs. c vs. t

Experimental puzzles : flavor anomalies in B decays

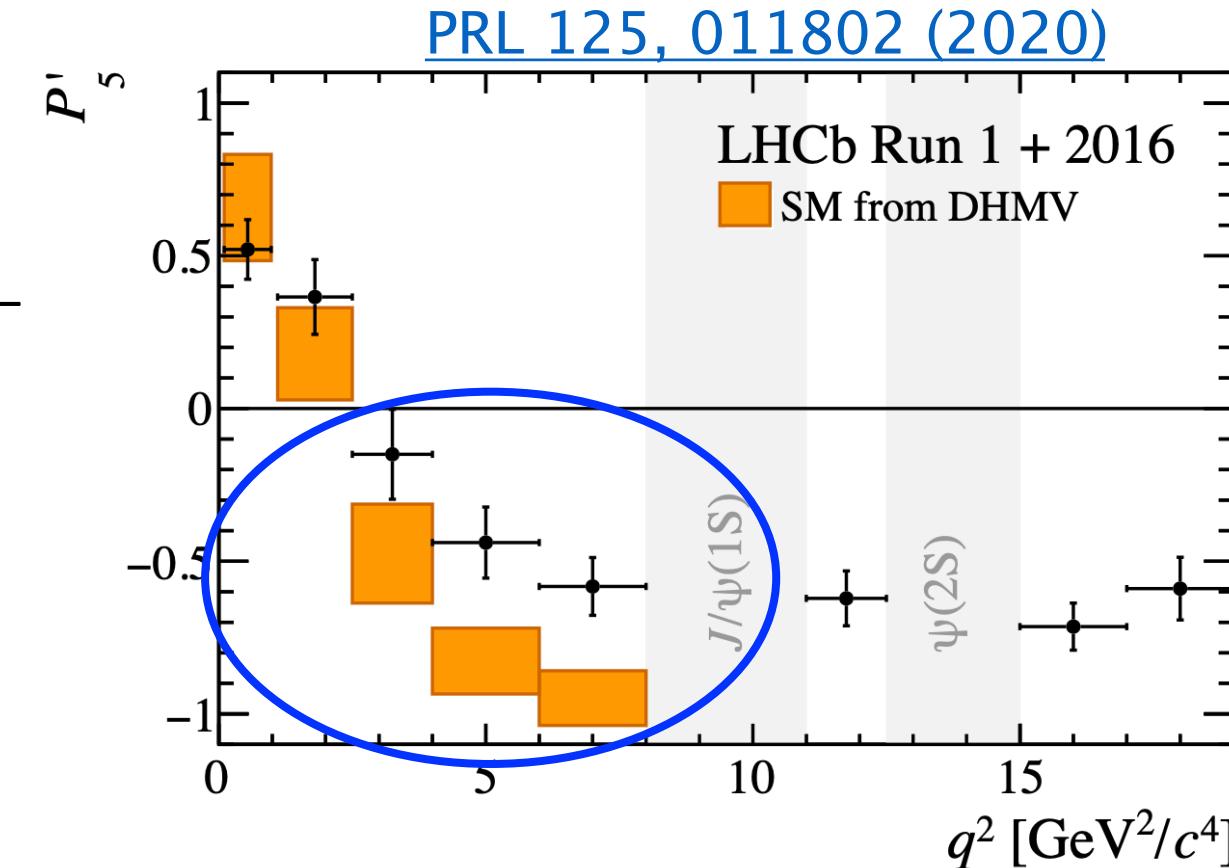


HFLAV (March 2023)



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

3.6σ



$B^0 \rightarrow K^0 \bar{\nu} \nu$
angular analysis

3.3σ

$R(D^*)$ & $R(D)$
(including latest
LHCb hadronic
tau result)

3.2σ

Other ratios between 3rd and 2nd generations :

2σ $R(J/\Psi)$: PRL 120, 121801 (2018) (LHCb)

1σ $R(\Lambda_c^+)$: PRL 120, 121801 (2018) (LHCb)

BSM explanations ?

New heavy mediators

Lepton flavor universality violation

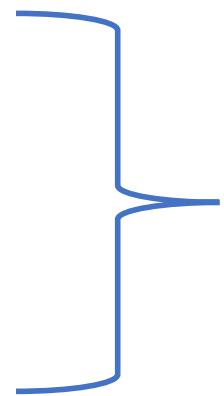
New left-handed currents

BSM explanations ?

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New left-handed currents



Leptoquarks !

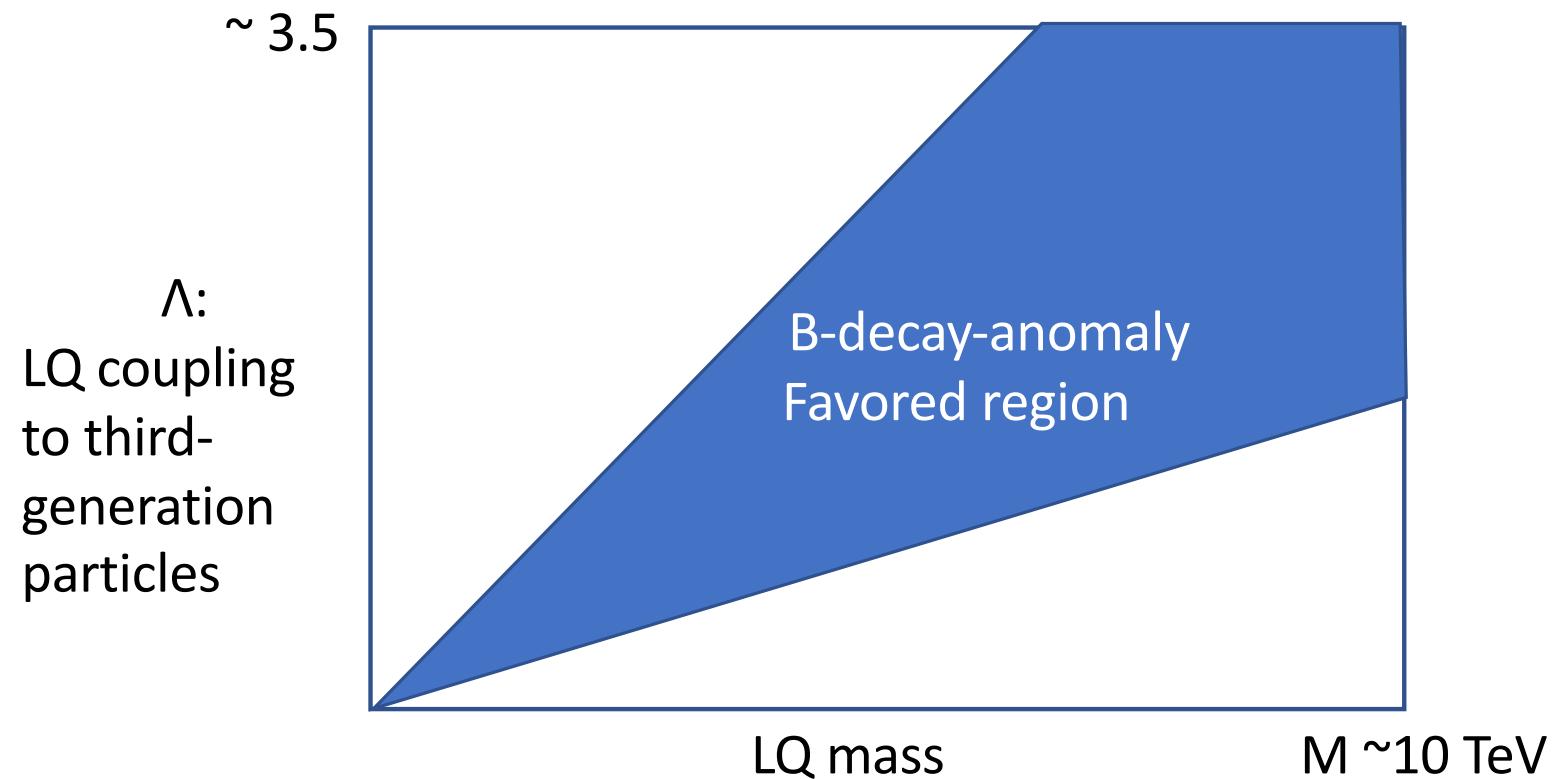
BSM explanations ?

New heavy mediators

Lepton flavor universality violation

New left-handed currents

Leptoquarks !



Leptoquarks

- Scalar or vector boson

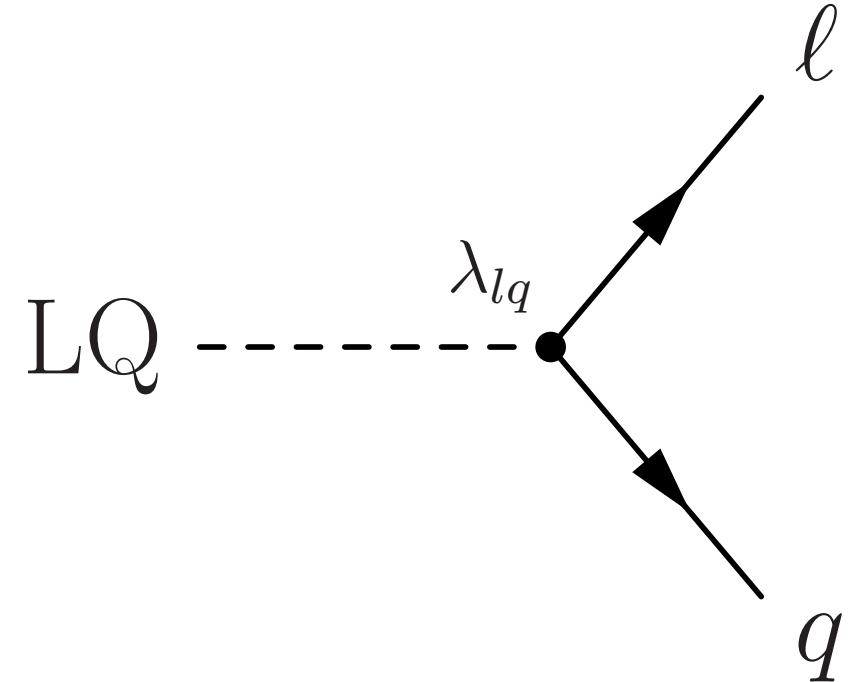
- Decay into ℓq

⇒ carry L, B, color

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

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

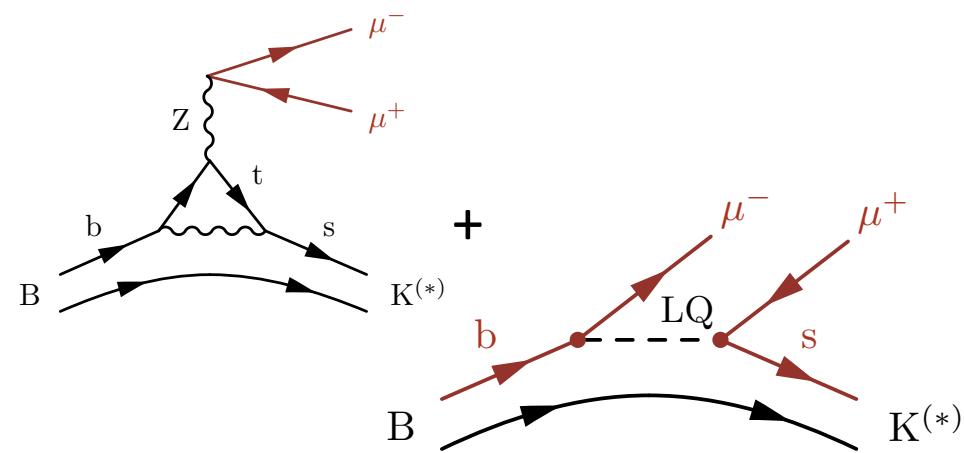
- Fractional charge



Flavor anomalies as explained by LQ

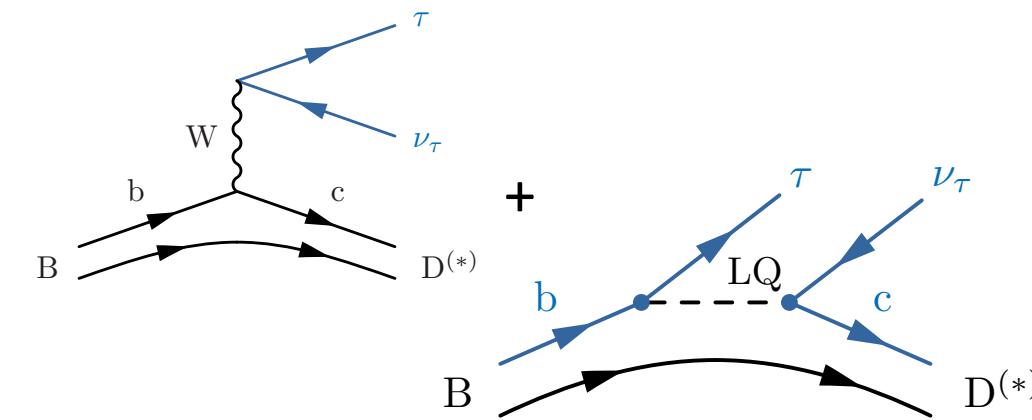
Measured

$$R_{K^{(*)}} = \frac{\Gamma(B \rightarrow K^{(*)} \mu\mu)}{\Gamma(B \rightarrow K^{(*)} ee)} < \boxed{\text{SM} \atop 1}$$



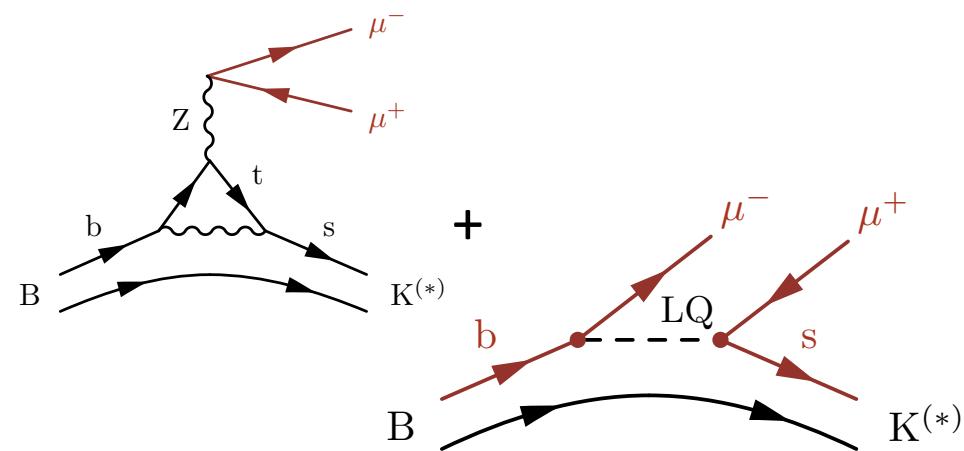
Measured

$$R_{D^{(*)}} = \frac{\Gamma(B \rightarrow D^{(*)} \tau \bar{\nu})}{\Gamma(B \rightarrow D^{(*)} \ell \bar{\nu})} > \boxed{\text{SM} \atop 0.25}$$

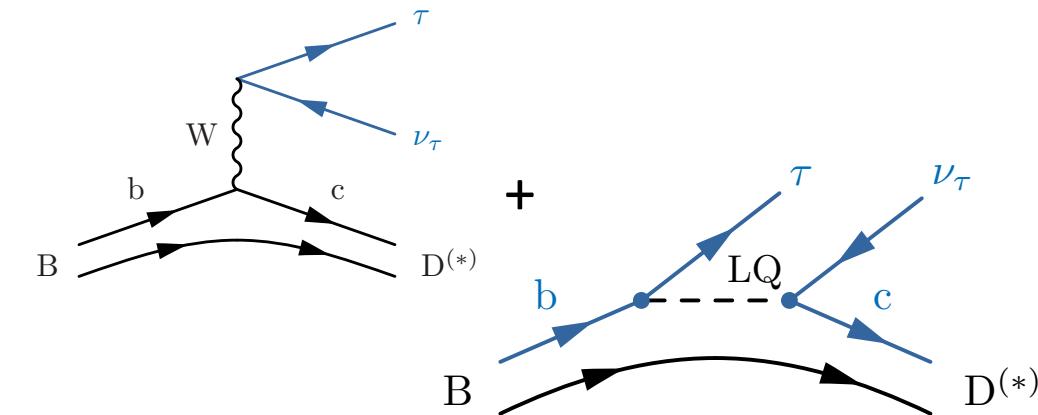


Flavor anomalies as explained by LQ

Measured
 $R_{K^{(*)}} = \frac{\Gamma(B \rightarrow K^{(*)} \mu\mu)}{\Gamma(B \rightarrow K^{(*)} ee)} < \boxed{\text{SM} 1}$



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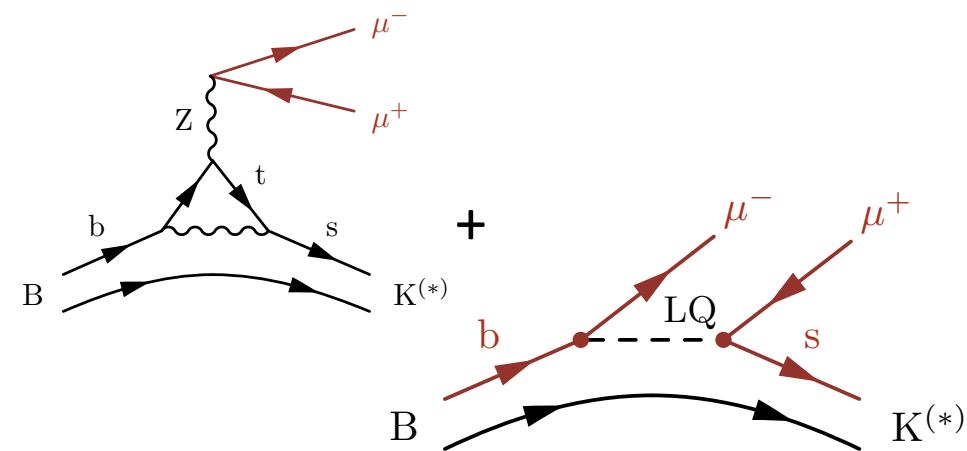
- Combined explanation of flavor and angular anomalies
- Vector LQ left-handed currents

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

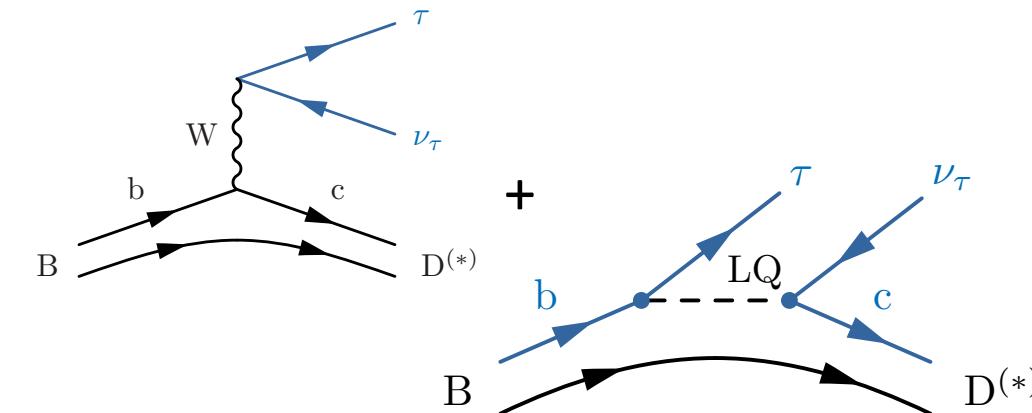
arXiv:1706.07808, arXiv:1903.11517

Flavor anomalies as explained by LQ

Measured
 $R_{K^{(*)}} = \frac{\Gamma(B \rightarrow K^{(*)} \mu\mu)}{\Gamma(B \rightarrow K^{(*)} ee)} < \boxed{1}$



Measured
 $R_{D^{(*)}} = \frac{\Gamma(B \rightarrow D^{(*)} \tau\bar{\nu})}{\Gamma(B \rightarrow D^{(*)} \ell\bar{\nu})} > \boxed{0.25}$



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

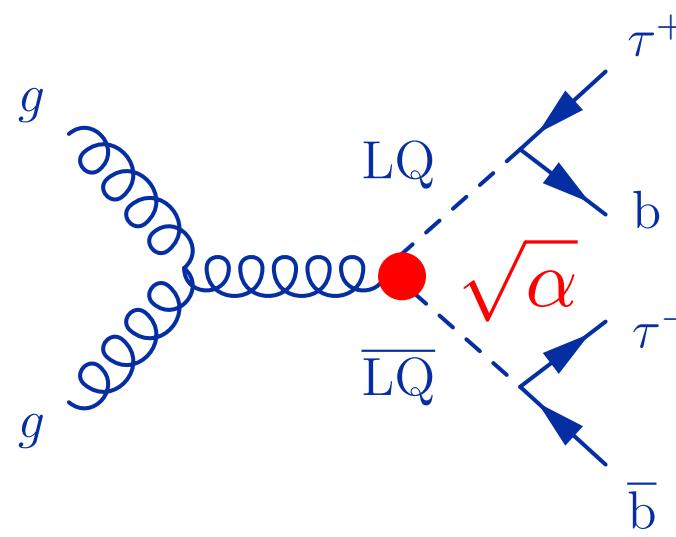
$$\Rightarrow V_{q\ell} \sim \begin{pmatrix} d/u' \\ s/c' \\ b/t' \end{pmatrix} \begin{pmatrix} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \\ 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{pmatrix} \quad \text{LQ} \approx \text{LQ}_3$$

arXiv:1706.07808, arXiv:1903.11517

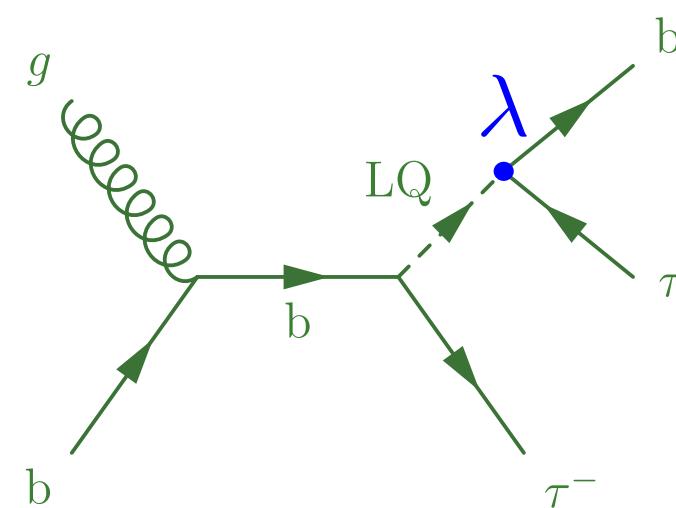
signs for destructive interference
with SM in $B \rightarrow K \mu\mu$ decay

Can we search for leptoquarks
directly ?

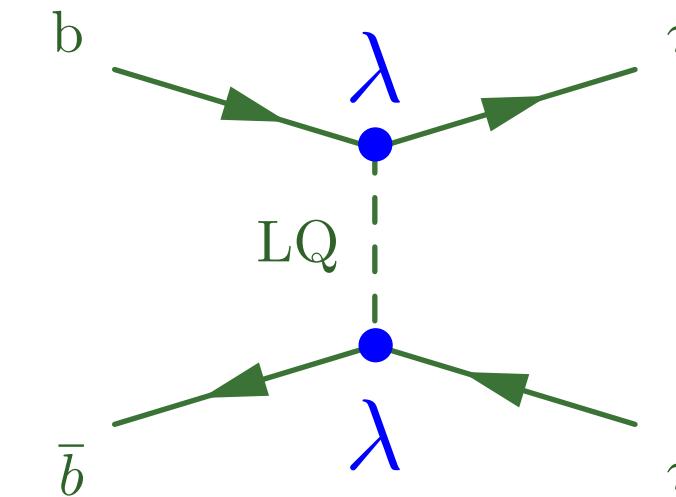
LQ pairs



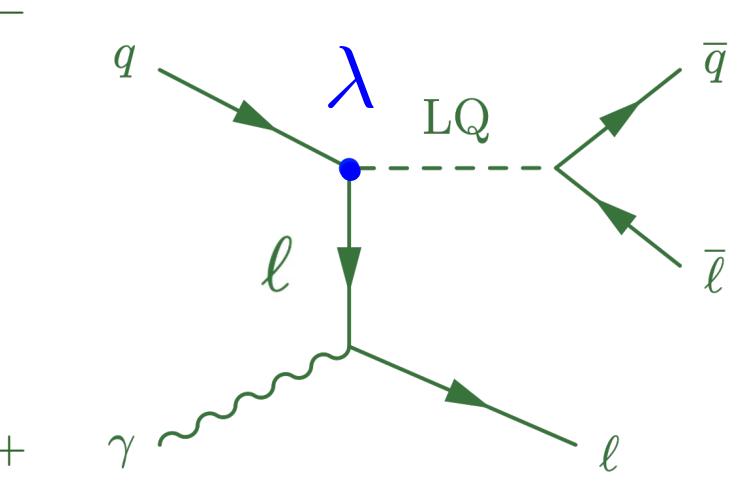
Single LQ



non-resonant LQ



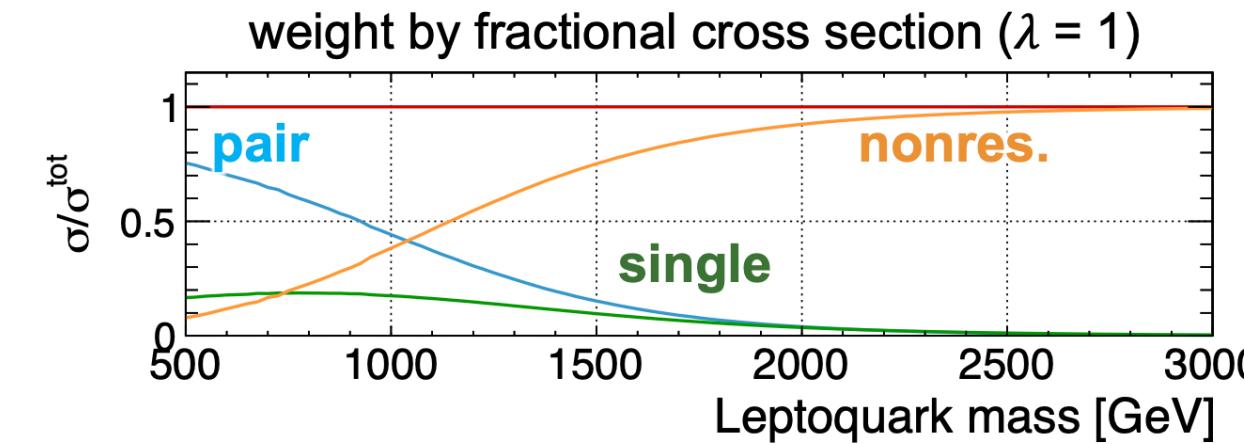
Lepton-quark



- Large QCD production
- Model independent
- Resonant

- $\sigma \propto \lambda^2$
- PDF suppression
- Wide-resonance at high λ
- $\sigma \propto \lambda^4$
- PDF suppression ^ 2
- No resonance

- $\sigma \propto \lambda^2$
- New lepton PDFs¹
- Resonance, no combinatorics

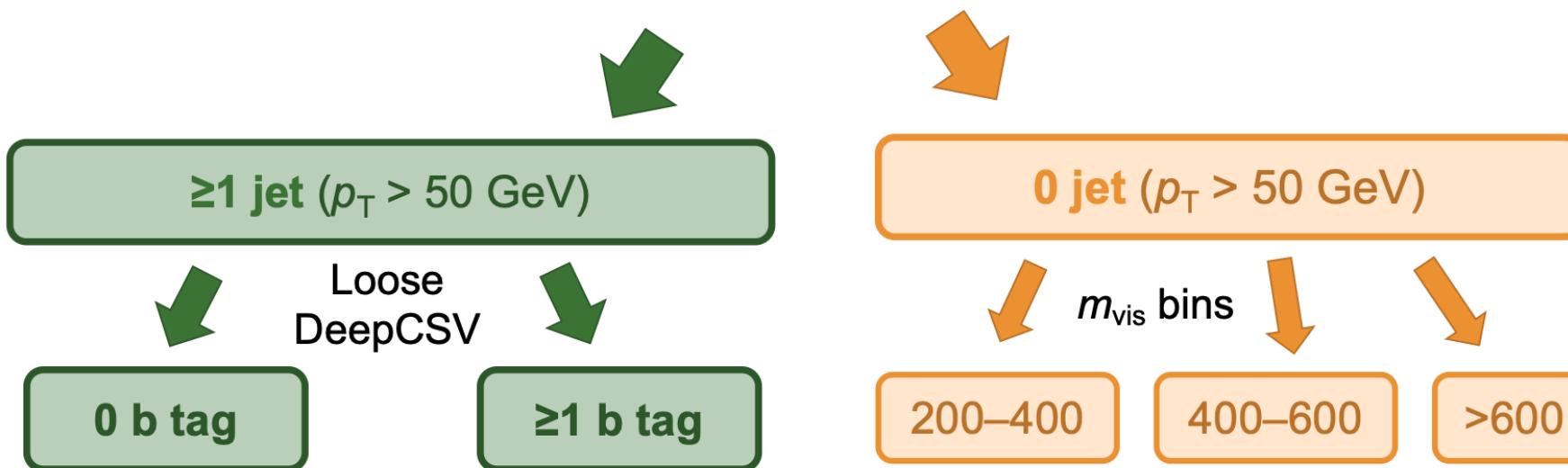


1: JHEP, [2005.06477](#)

CMS search for pair, single, non-resonant LQs

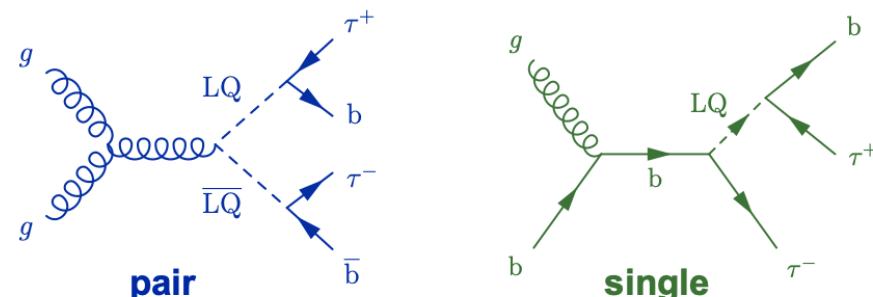
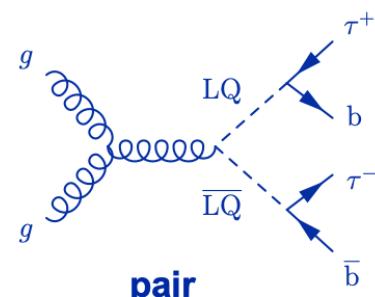
Summary of signal selections

$\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ and $e\mu$ pre-selections ($e/\mu/\tau_h p_T > 50 \text{ GeV}$)



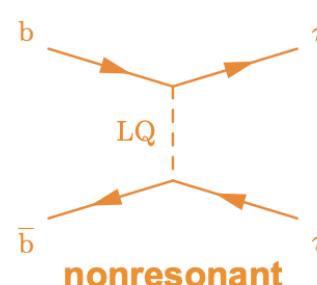
discriminating variable:

$$S_T^{\text{MET}} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^j + \text{MET}$$



discriminating variable:

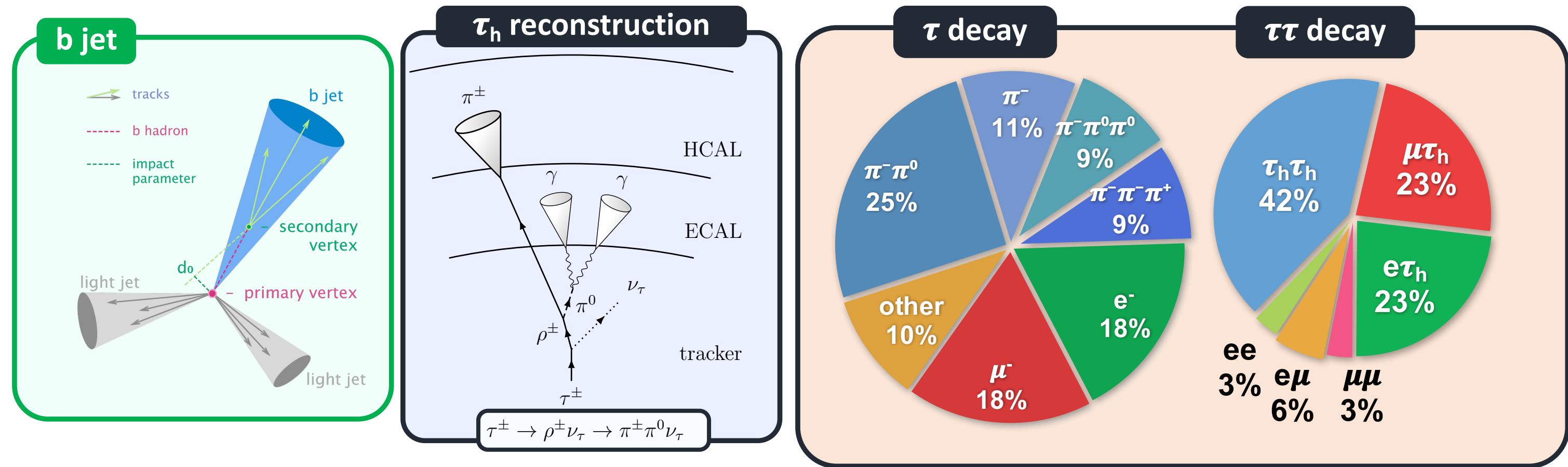
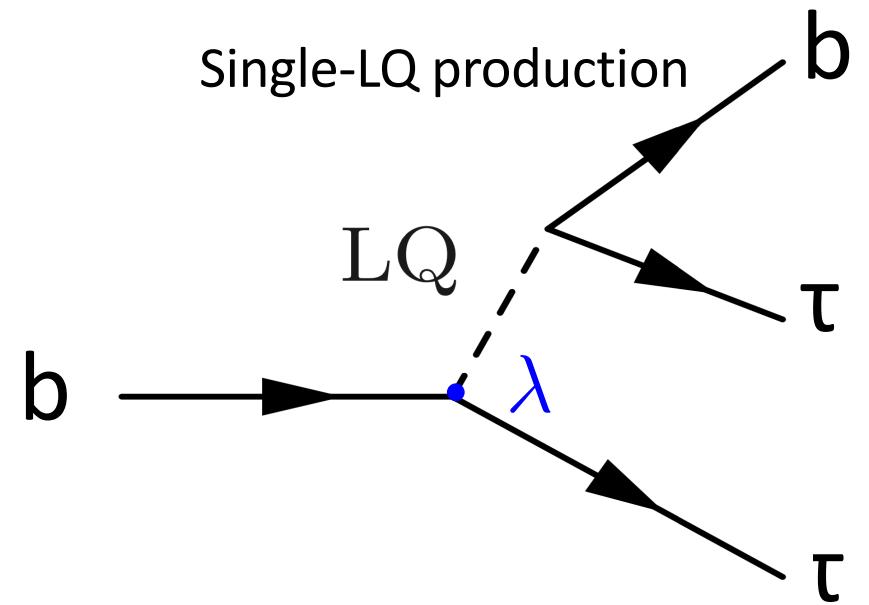
$$\chi = e^{\Delta\eta}$$



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

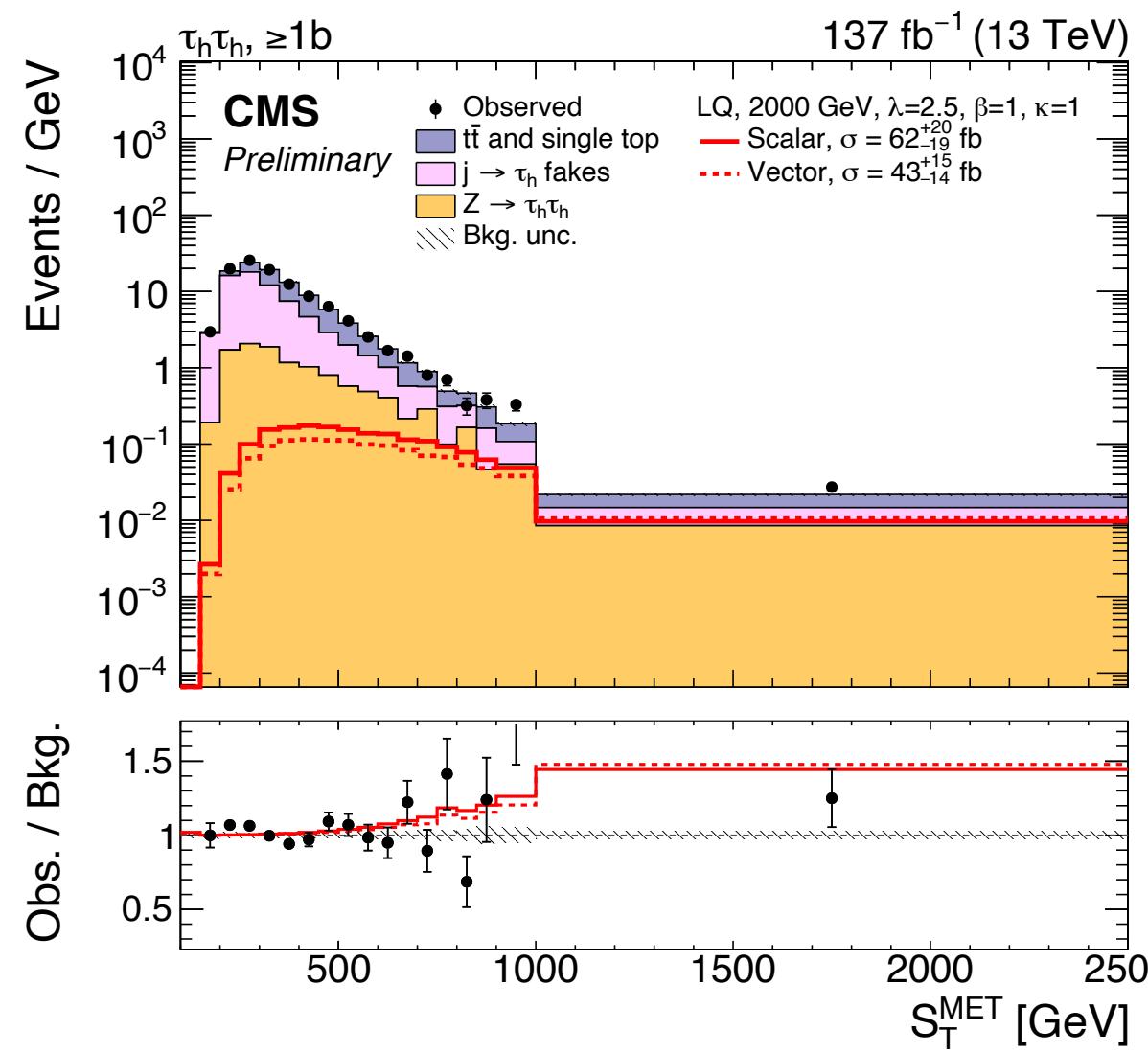
χ angular variable sensitive to changes in $\tau\tau$ angular distributions

Reconstruction of 3rd generation LQs

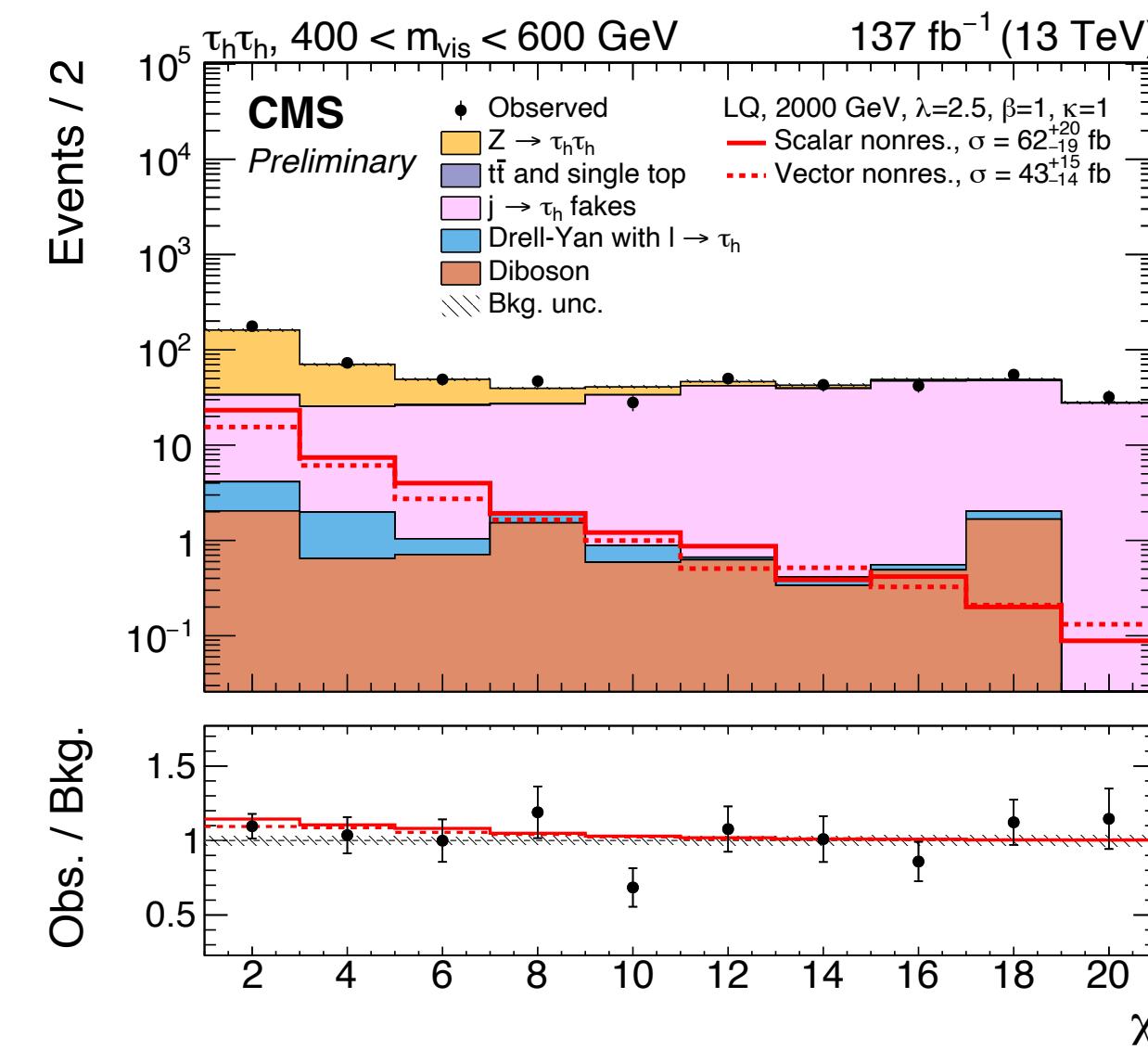


Comparison of observables :

STMET fit in **30 signal regions**
 (5 $\tau\tau$ modes * 3 years * two b-tag categories)

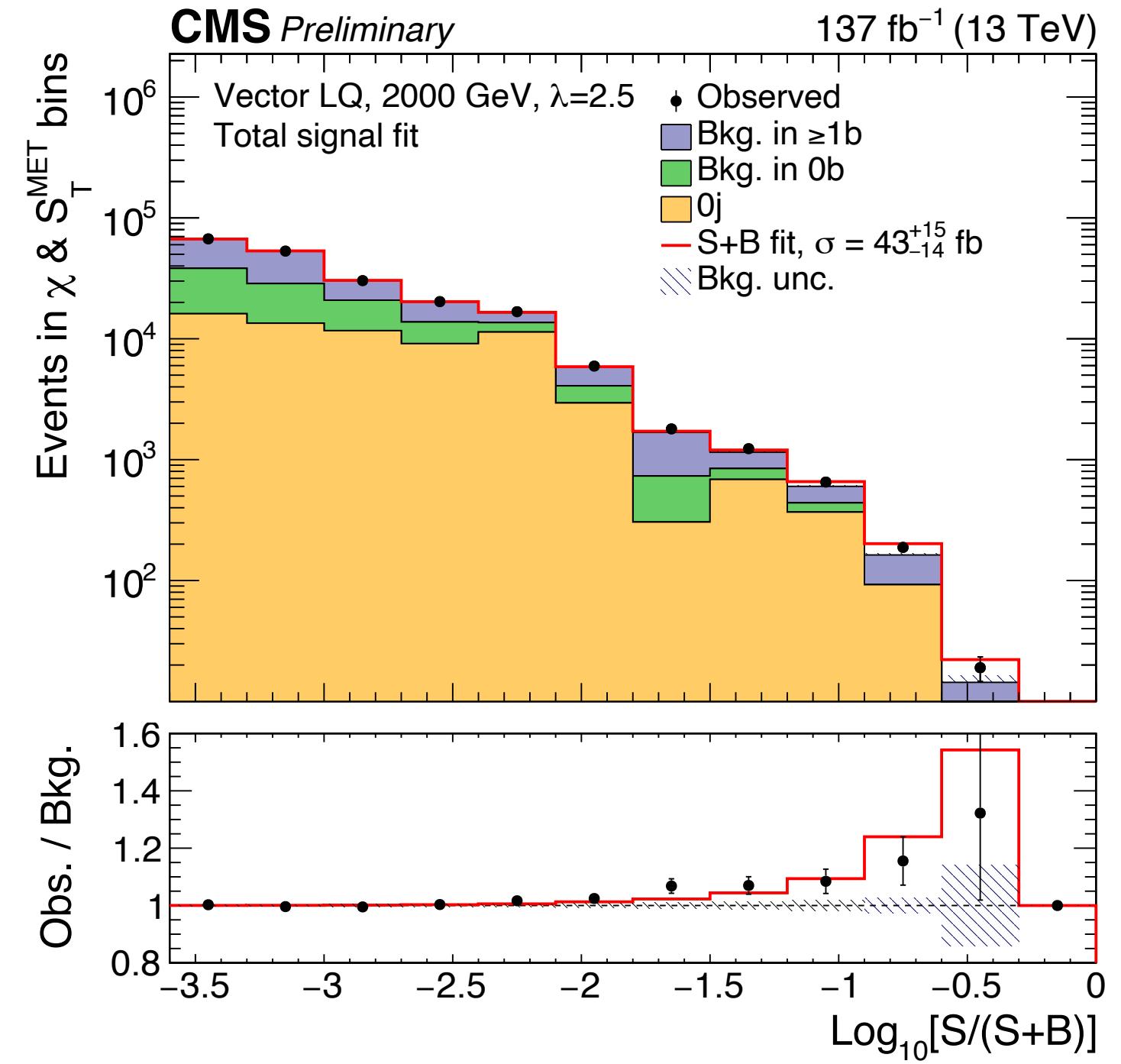


χ fit in **45 signal regions**
 (5 $\tau\tau$ modes * 3 years * 3 visible mass categ.)



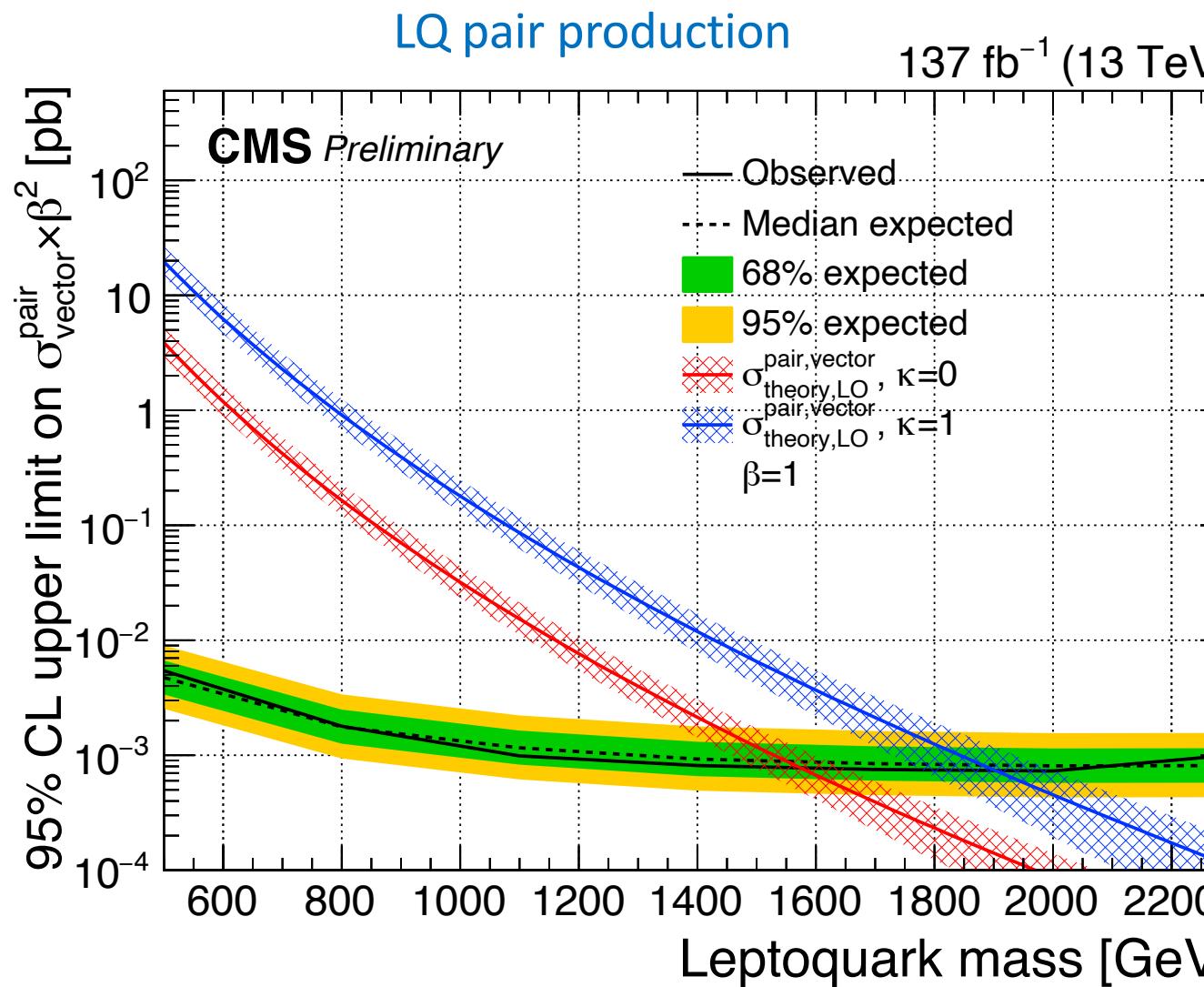
Digesting 75 signal regions

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

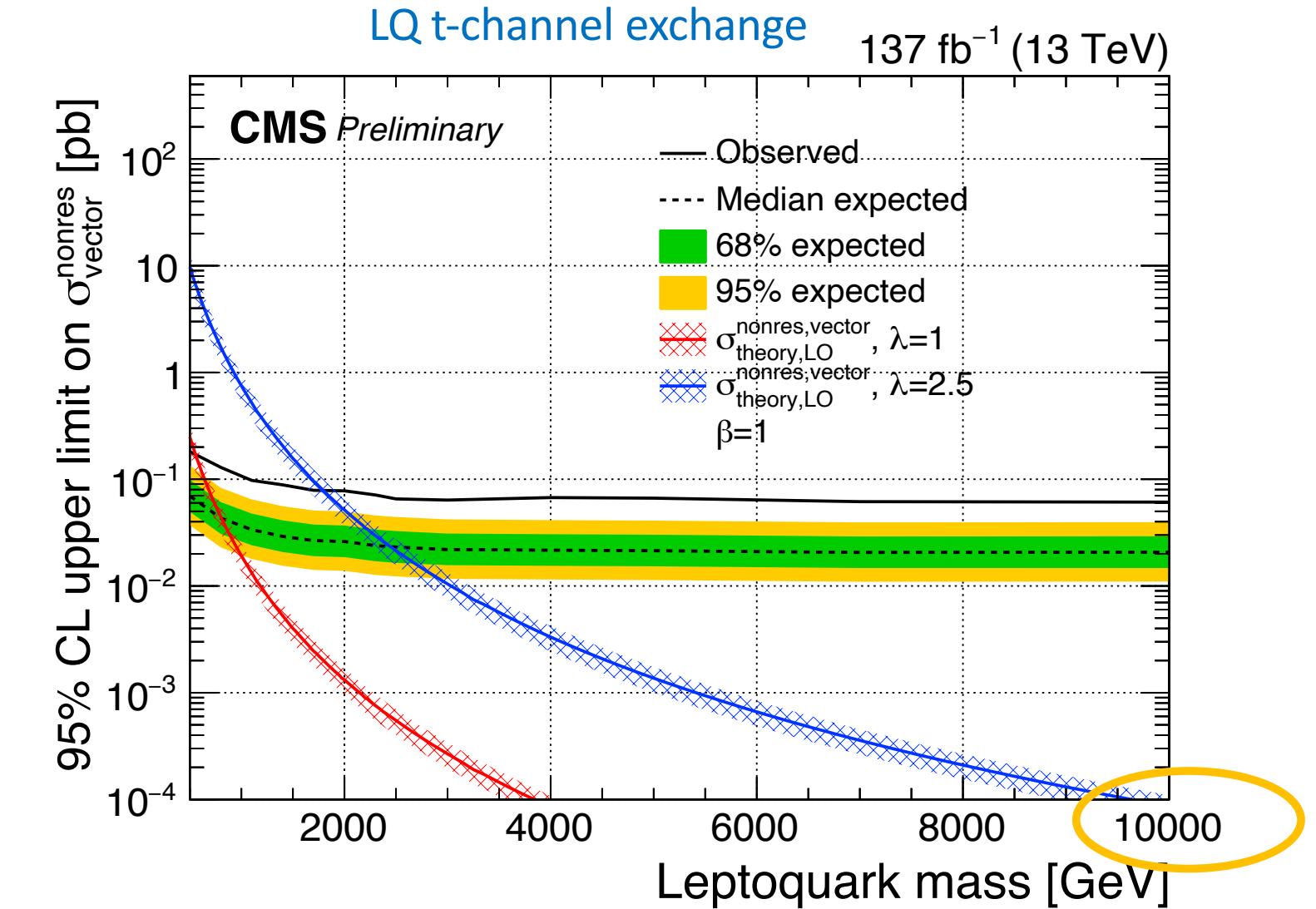


An excess is observed : $\sim 3.5 \sigma$

Excess :



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

Recent progress investigating excess before submitting for publication

- Fake tau model updated
- Some minor backgrounds added

Excess for benchmark $M_{LQ} = 2\text{TeV}$, $\Lambda=2.5$
 $\rightarrow 2.8\sigma$

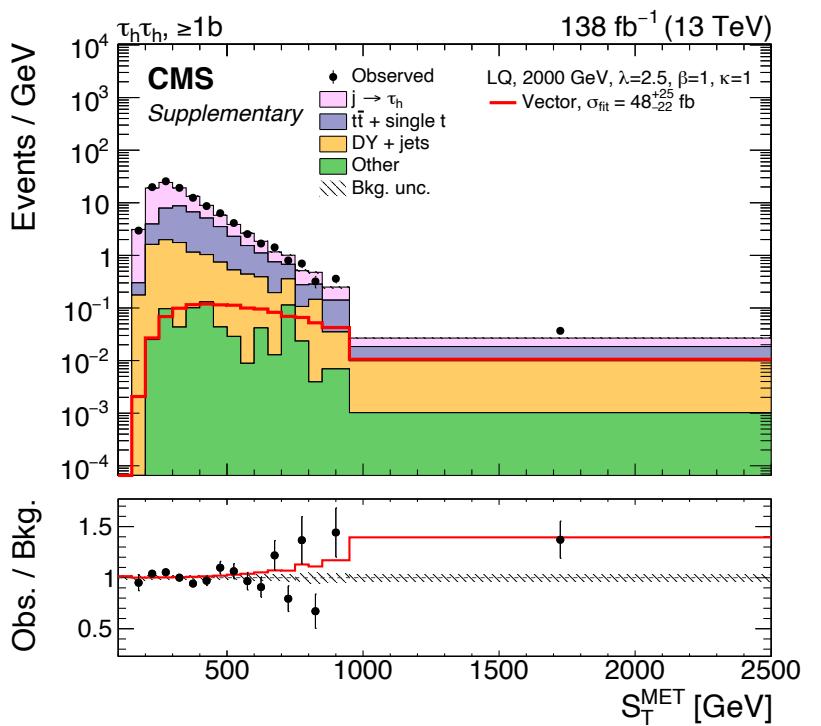
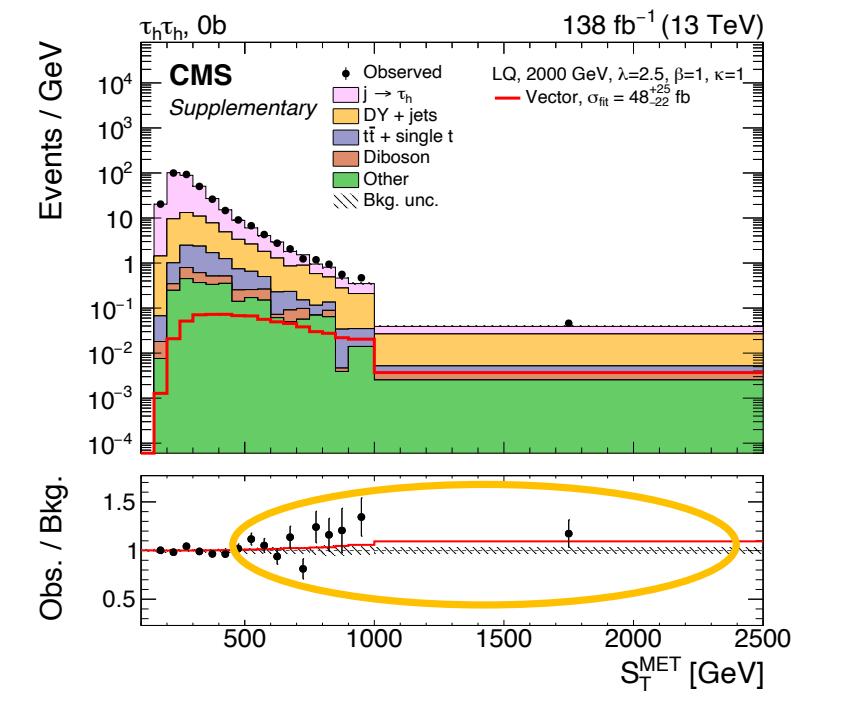
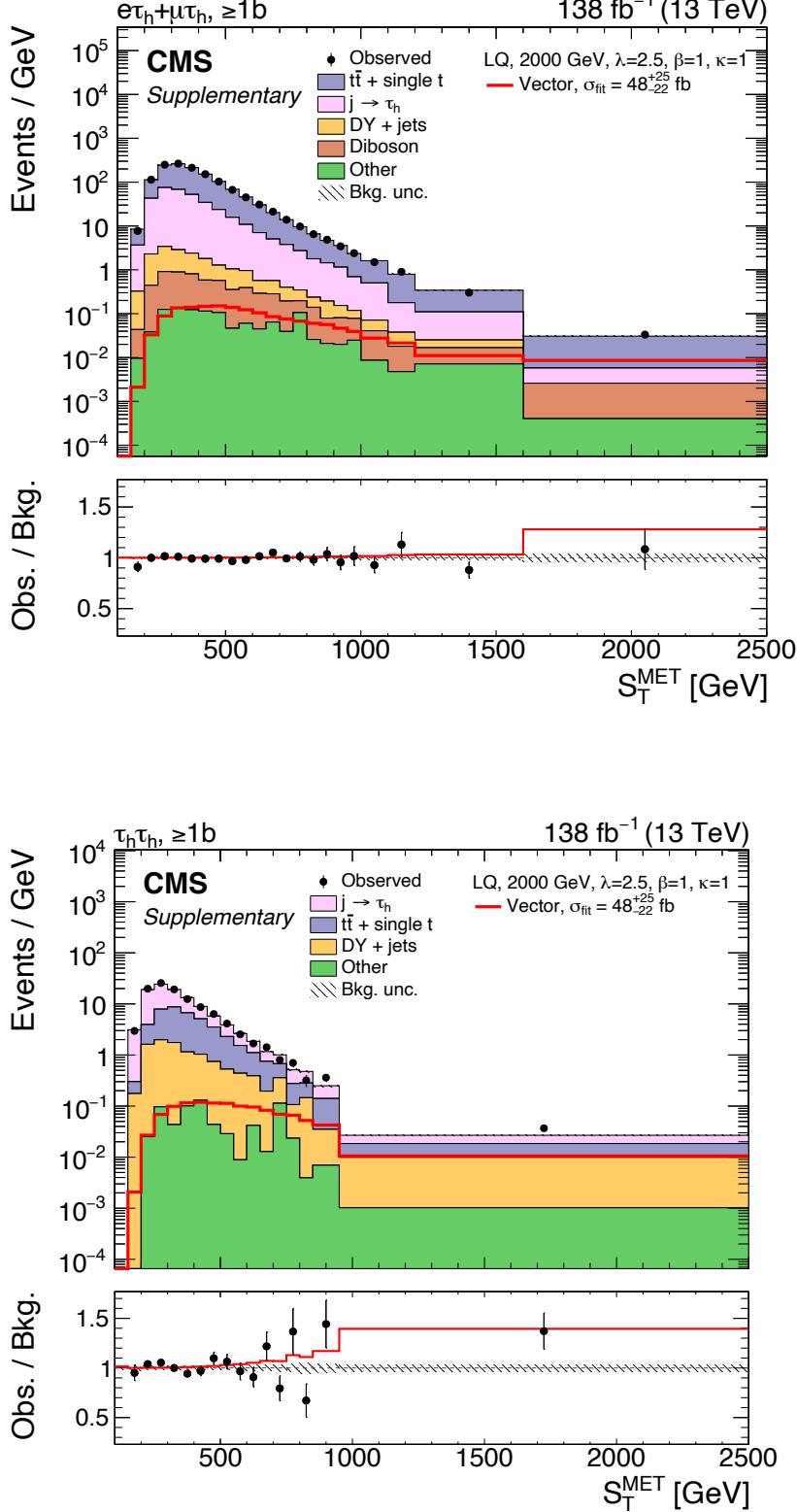
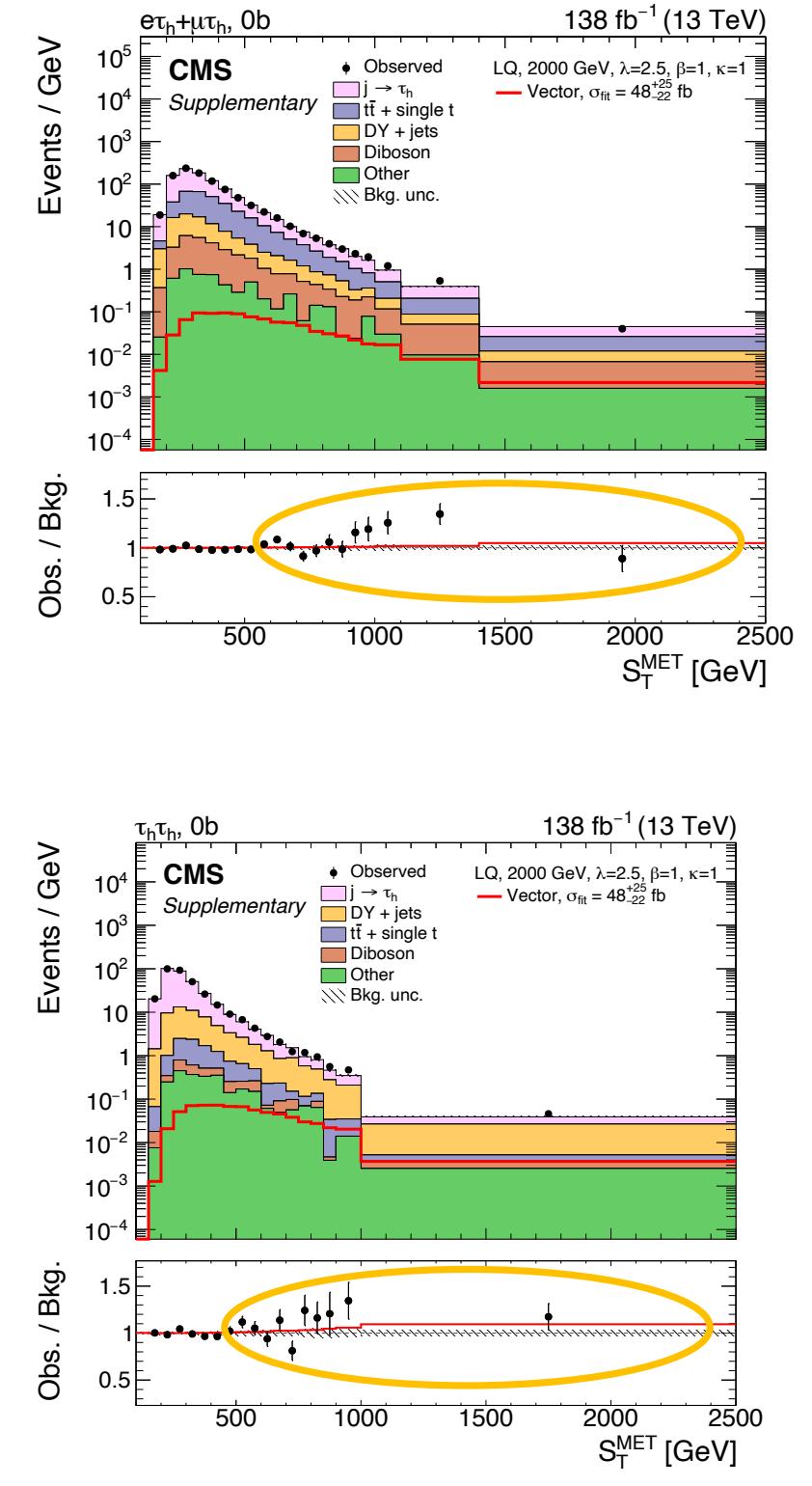
Excess is most prominent :

- non-resonant LQ production
 - Probes high mass
 - at high S_T^{MET} With 1 jet but 0 b-tags
 $\rightarrow 3.4 - 3.7\sigma$ excess in 0-b category

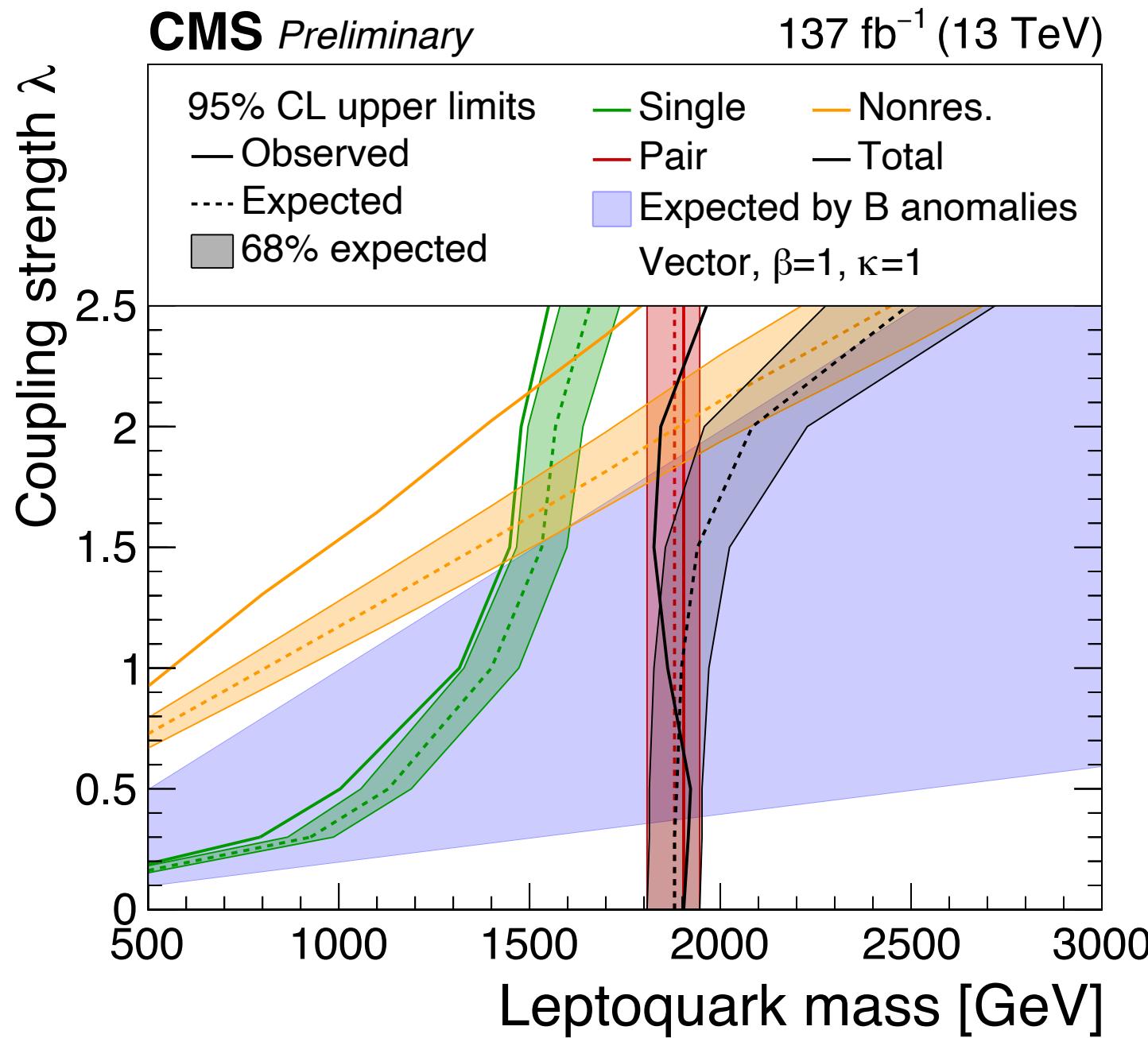
Not compatible with signal model of 100% $LQ \rightarrow b\tau$

Excess not excluded by ATLAS, such as non-resonant search [EXOT-2022-039](#), which requires b-tags in their analysis

First-time shown!



Could this be the LQ seen in B anomalies ?



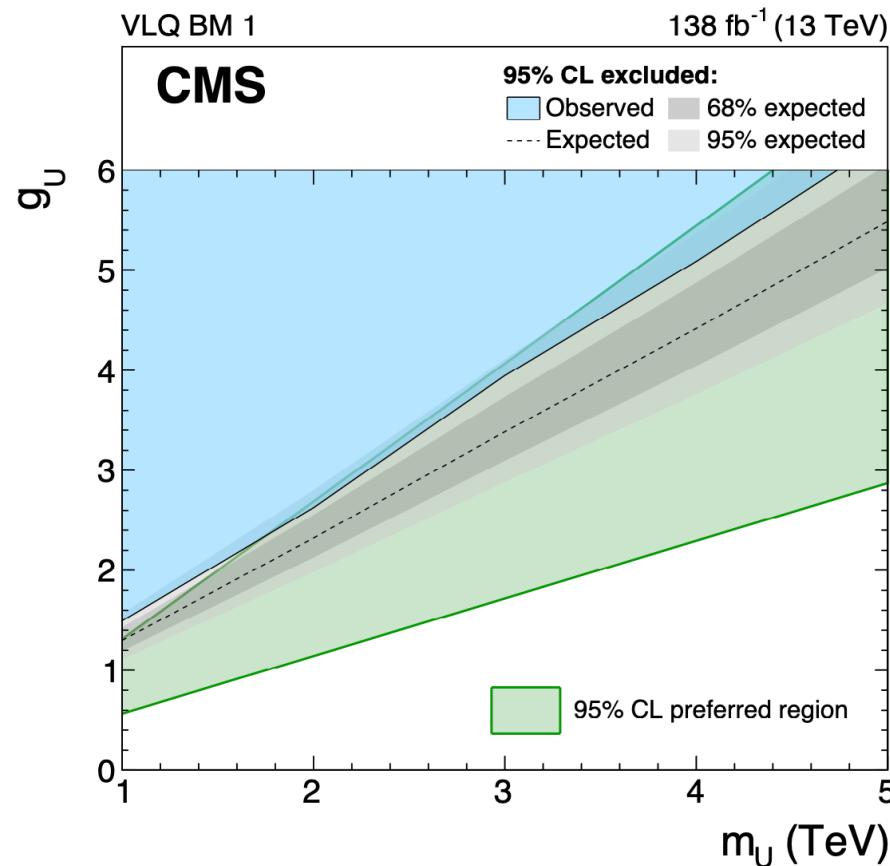
Expected limits just on the edge of the anomaly -favored region

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

However, excess is larger in $\tau + q$ than $\tau + b$

Cross-check ?

- Another CMS analysis (BSM Higgs search [JHEP, 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



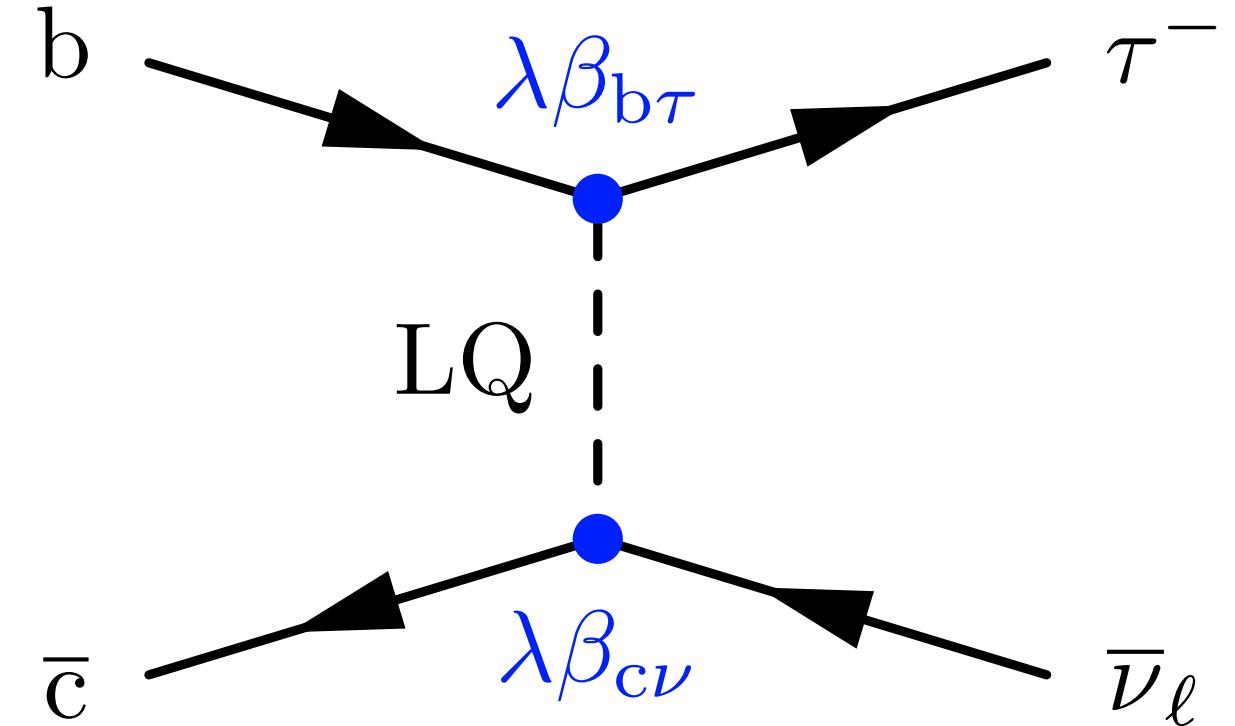
A 2-Sigma excess is observed across the mass region

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

If LQ with high-mass, high-coupling, where else might it be ?

Flavor structure

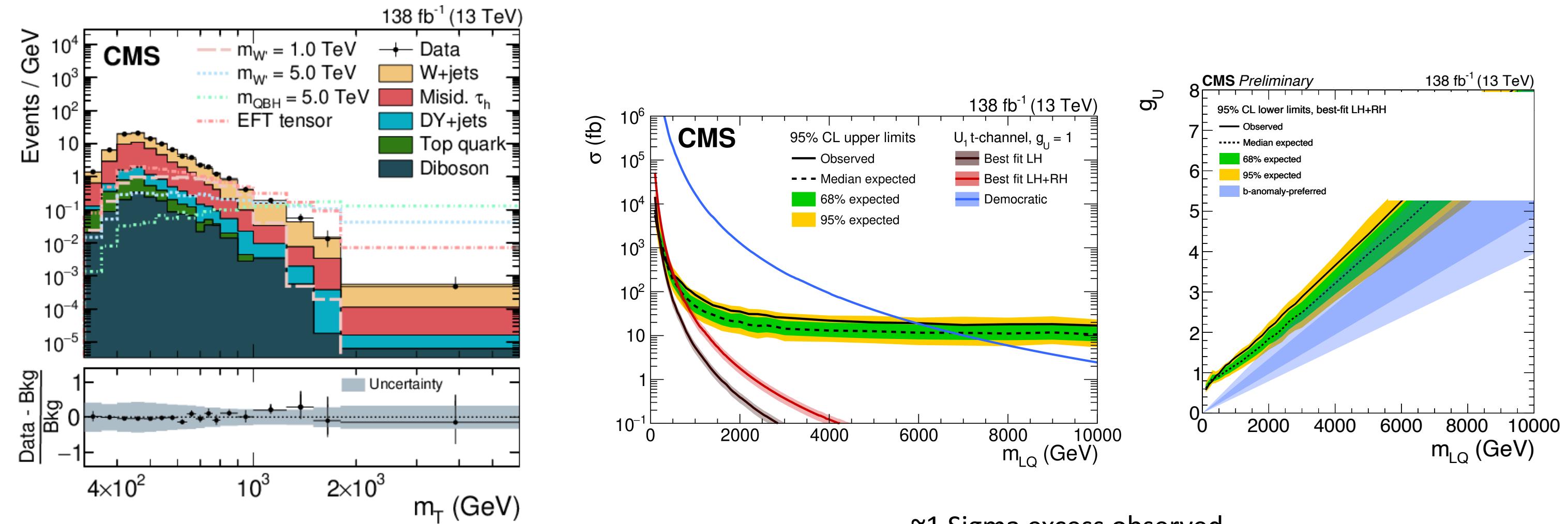
$$\Rightarrow V_{q\ell} \sim \begin{pmatrix} d/u' & s/c' & b/t' \end{pmatrix} \begin{pmatrix} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \\ 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{pmatrix}$$



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

Final state of $\tau + \nu$ is interesting for t-channel leptoquark exchange

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



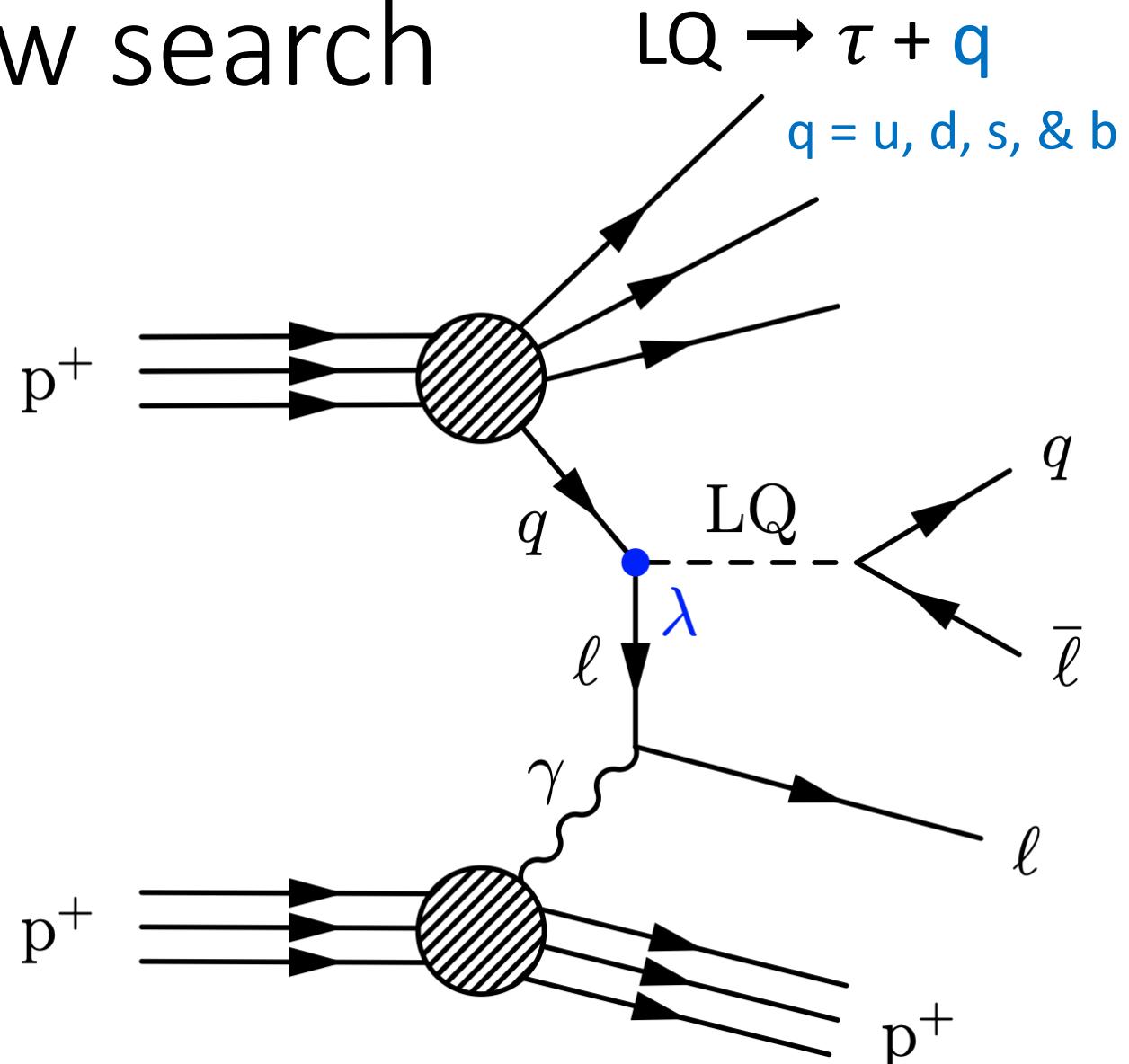
The coupling strengths excluded by searches in the tau+MET (CMS-EXO-21-009) and ditau (CMS-EXO-19-016) final state are compatible within approximately 5-25% for a vector LQ mass of 2 TeV and coupling benchmarks that could explain the b-anomalies.

New lepton PDFs open up new search possibilities

If EXO-19-016 excess is real, should also consider off-diagonal LQs:
... especially V_{23} & V_{32}

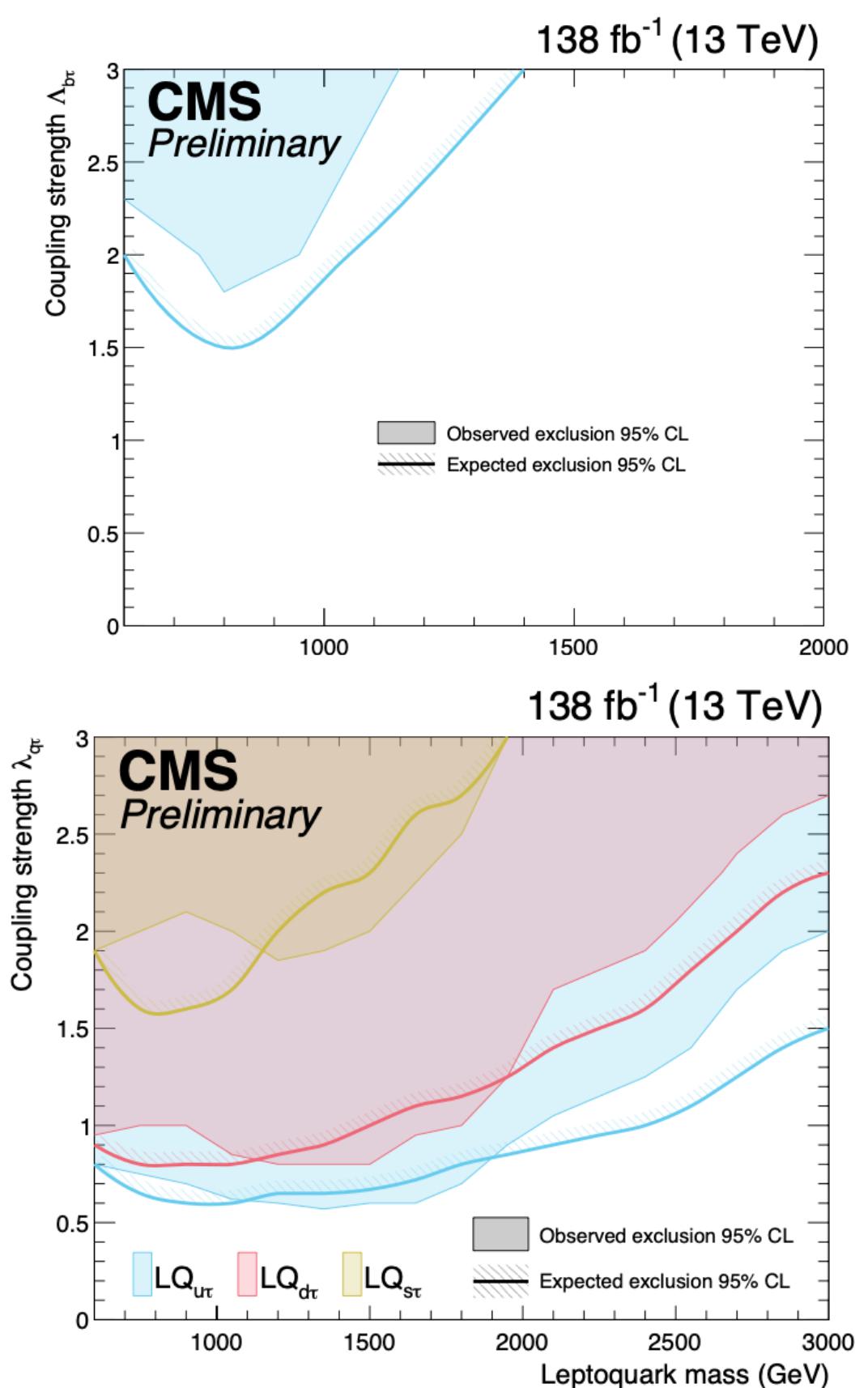
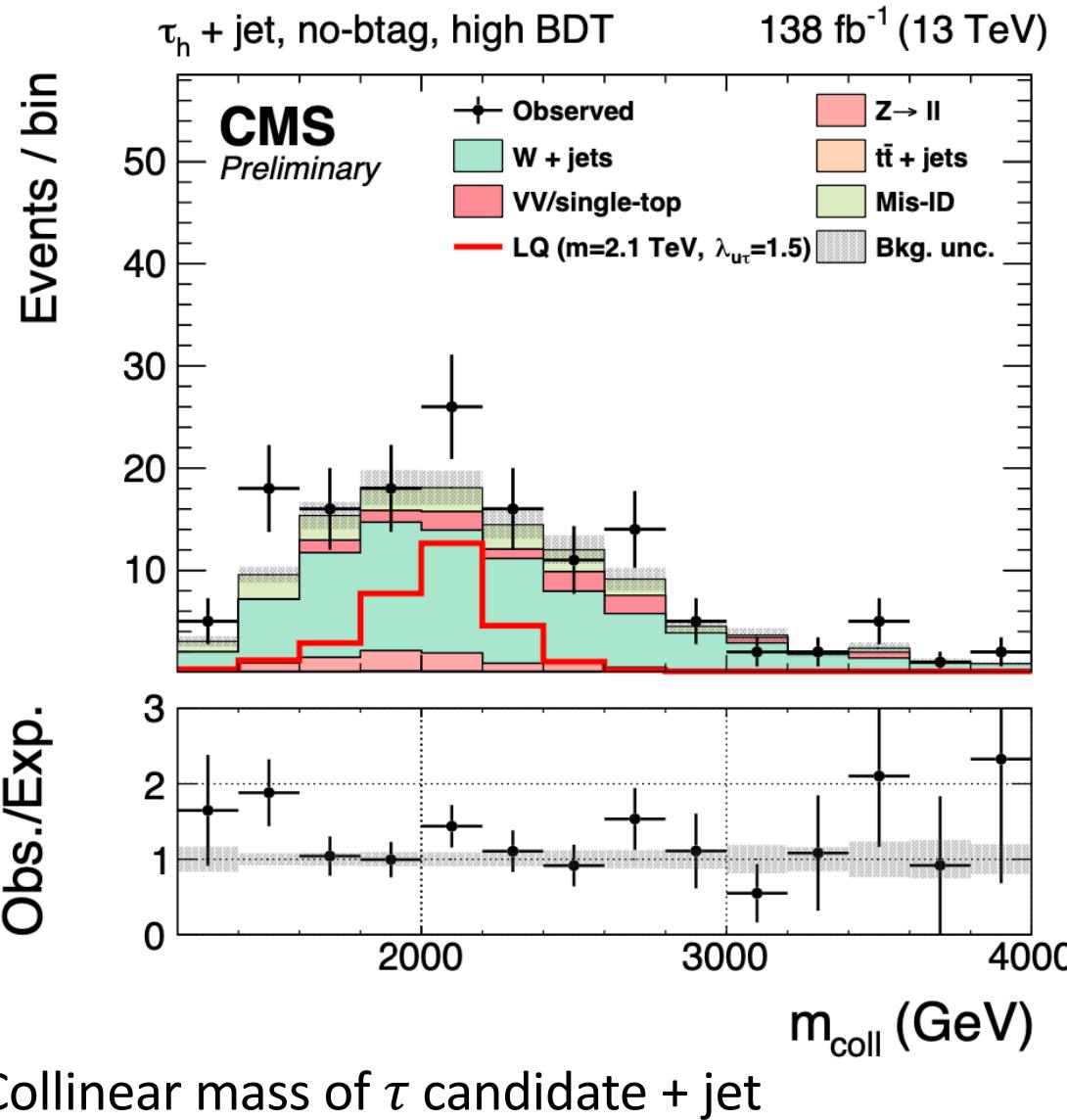
Flavor structure

$$\Rightarrow V_{q\ell} \sim \begin{pmatrix} d/u' & s/c' & b/t' \end{pmatrix} \begin{pmatrix} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \\ 0 & 0 & v_{u\tau} \\ 0 & 0 & v_{s\tau} \\ 0 & 0 & v_{b\tau} \end{pmatrix}$$



Results

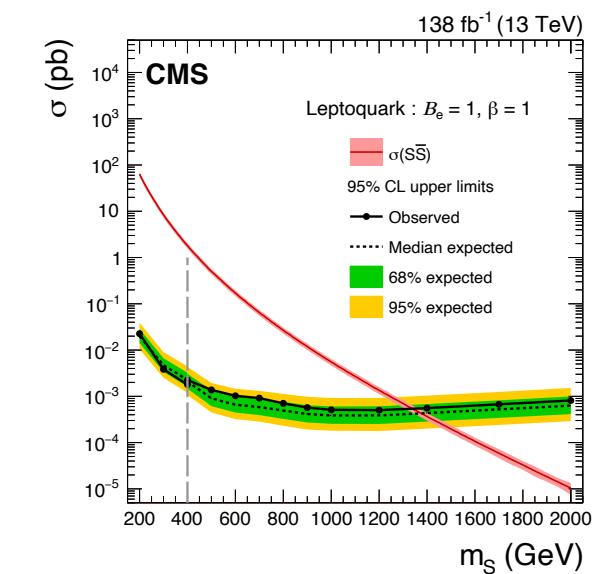
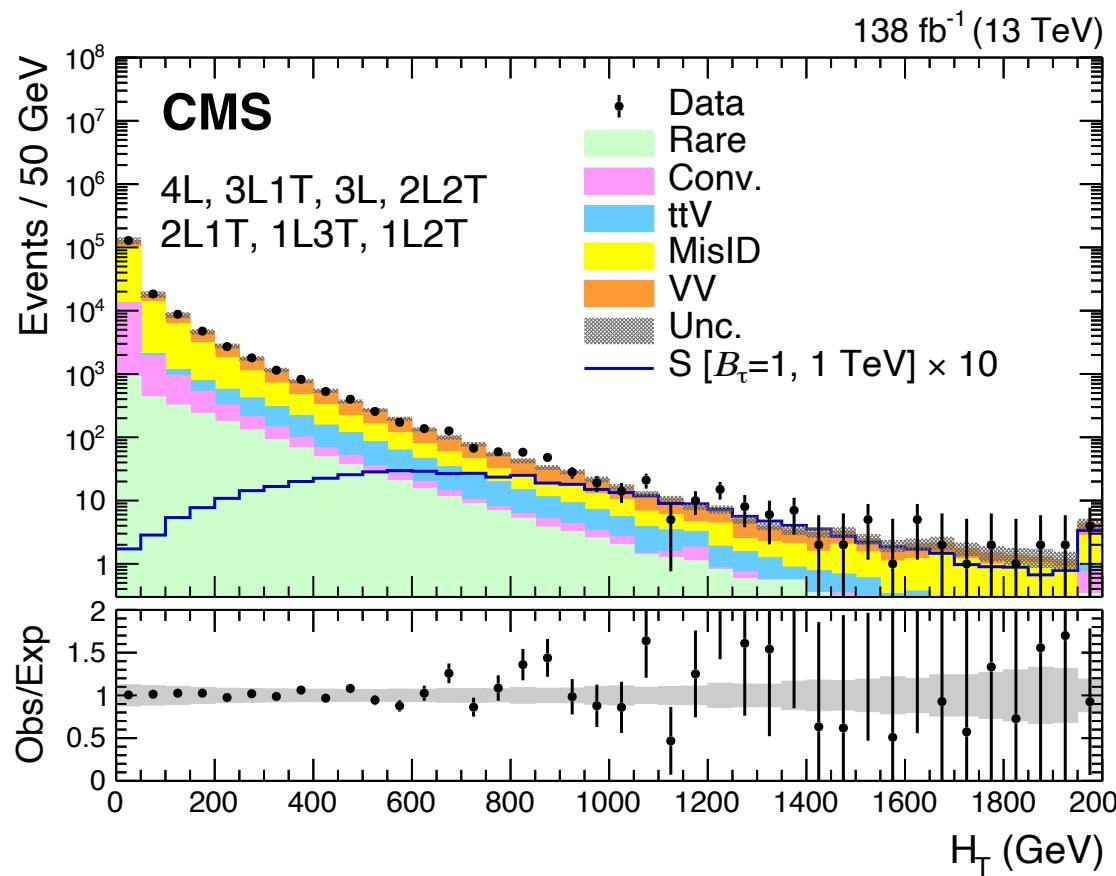
- Final states: $(\tau_e, \tau_\mu, \tau_h) + (\text{jet}, \text{b-jet})$



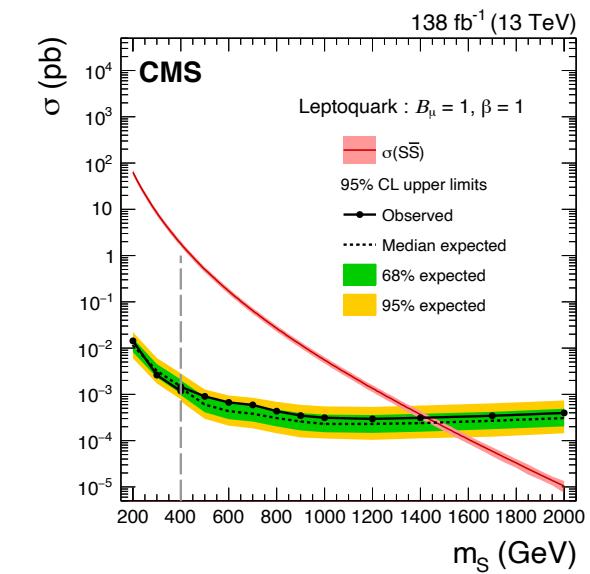
$LQ \rightarrow t + \ell$

$$\Rightarrow V_{q\ell} \sim \begin{pmatrix} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \\ d/u' & 0 & 0 \\ s/c' & 0 & 0 \\ b/t' & v_{te} & v_{t\mu} & v_{t\tau} \end{pmatrix}$$

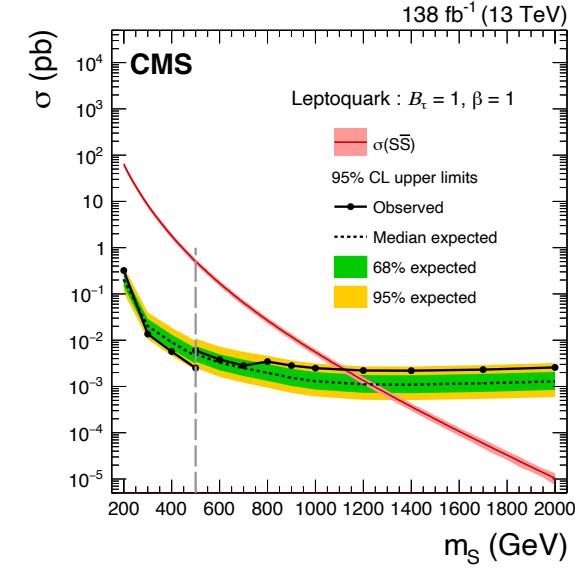
- Considers mixed generational couplings



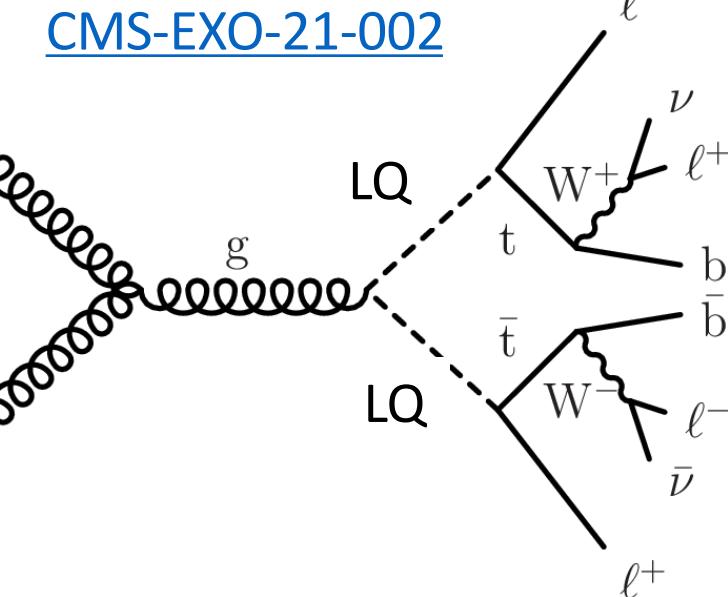
$LQ \rightarrow t + e$



$LQ \rightarrow t + \mu$



2σ excess



Summary: Leptoquark searches at CMS

- Third-generation leptoquarks offer explanation of flavor structure of SM, motivated by 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 2.8σ excess
 - Combined with other searches, favors high-mass (> 2 TeV) and high coupling
 - However, not necessarily 3rd generation LQ
 - $3.4 - 3.7\sigma$ excess in $\tau + \text{non-}b$ jet
 - Consider off-diagonal LQs
- Not covered : Many LQ searches in 1st/2nd generation on CMS physics pages

BACKUPS

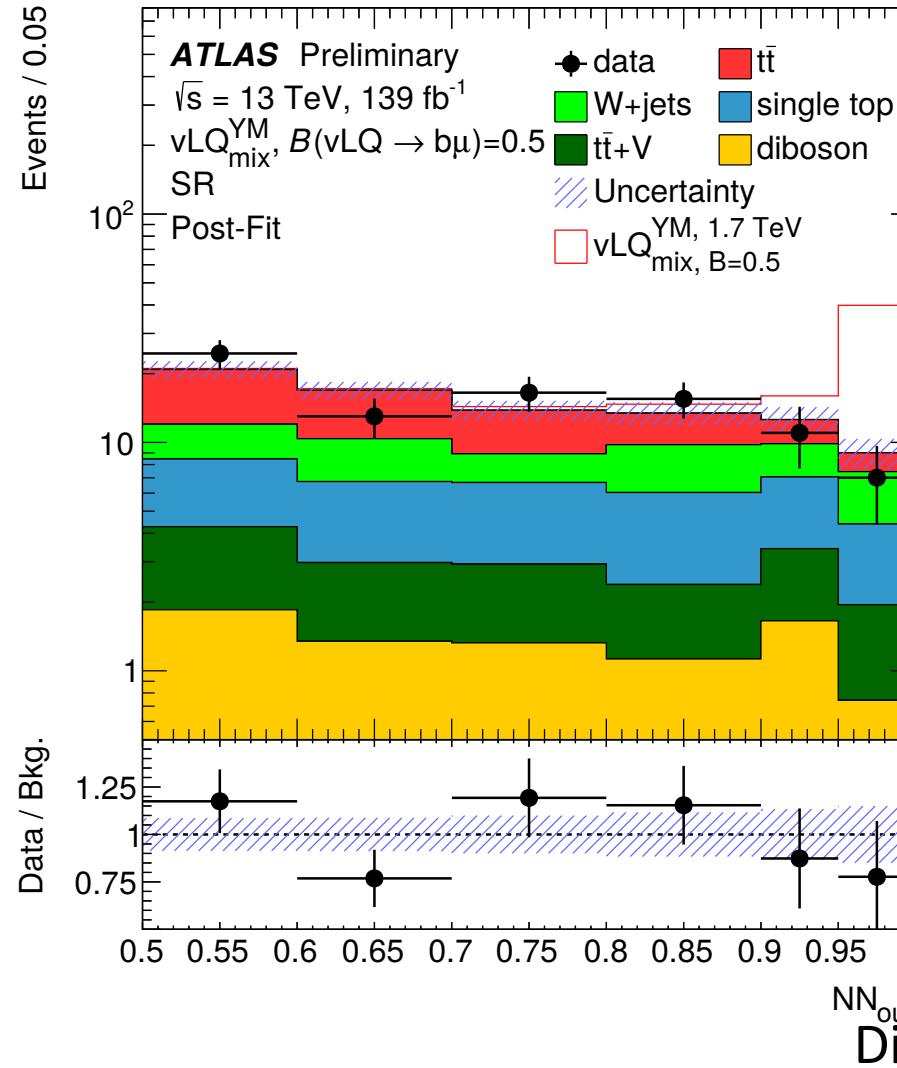
What about ATLAS ?

- ATLAS 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 ττb ([ATLAS-CONF-2022-037](#))
 - LQLQ with LQ → τb
 - Considers LQ with charge 4/3e
 - For the first time, single LQ production considered

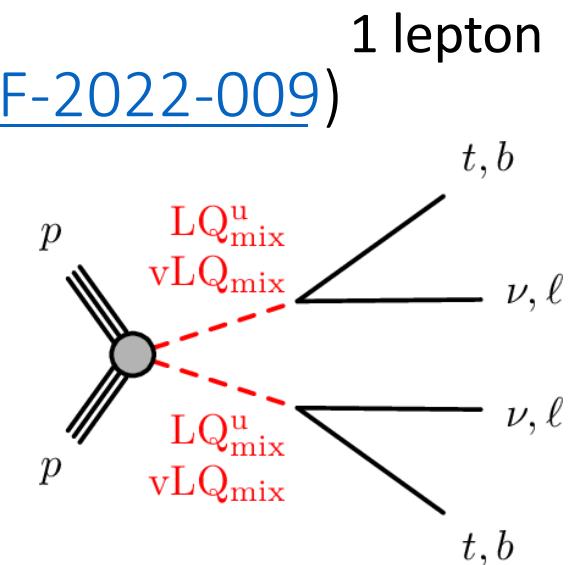
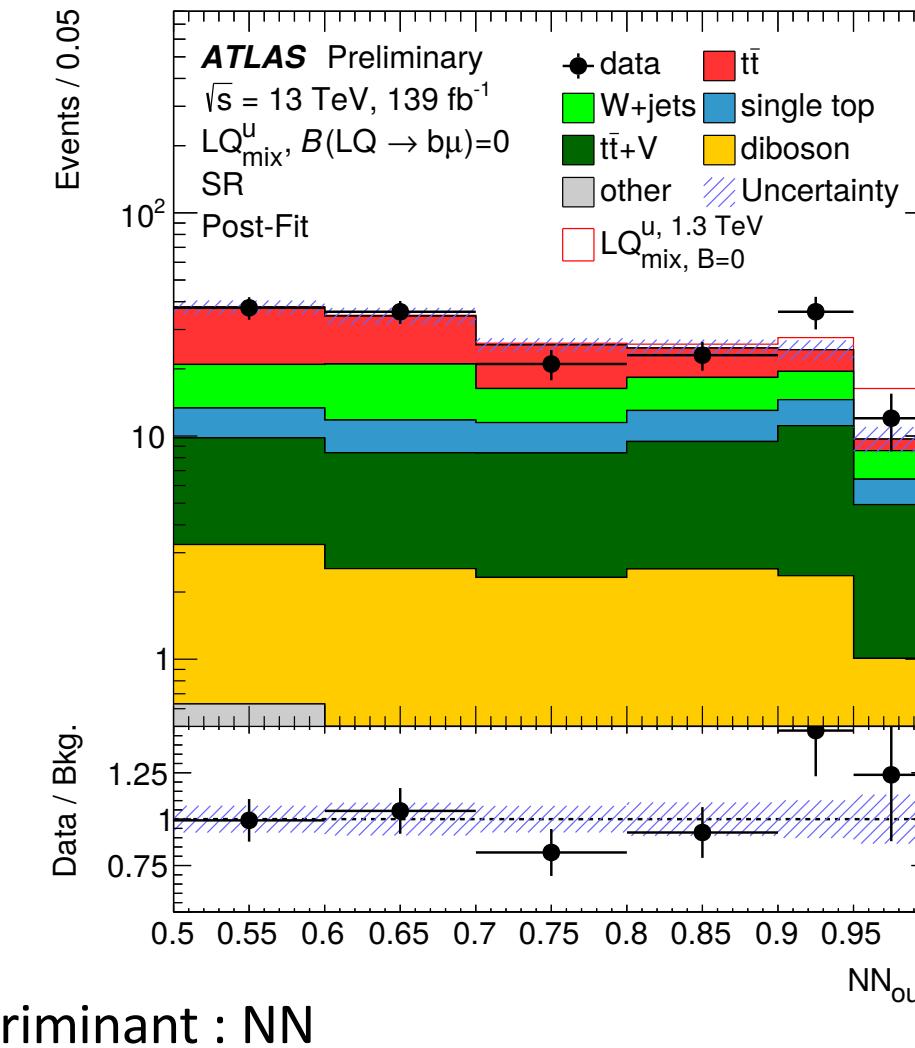
Searches for LQs with charge 2/3e and 1/3e ([ATLAS-CONF-2022-009](#))

$LQ \rightarrow t+\nu, t+e, t+\mu$ and $LQ \rightarrow b+\nu, b+e, b+\mu$

$b+\mu$



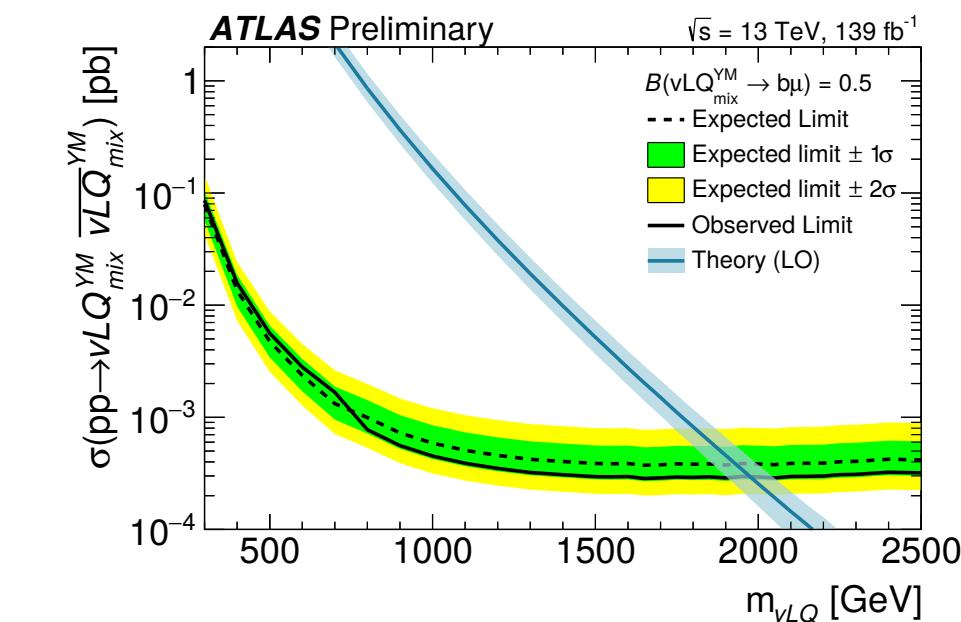
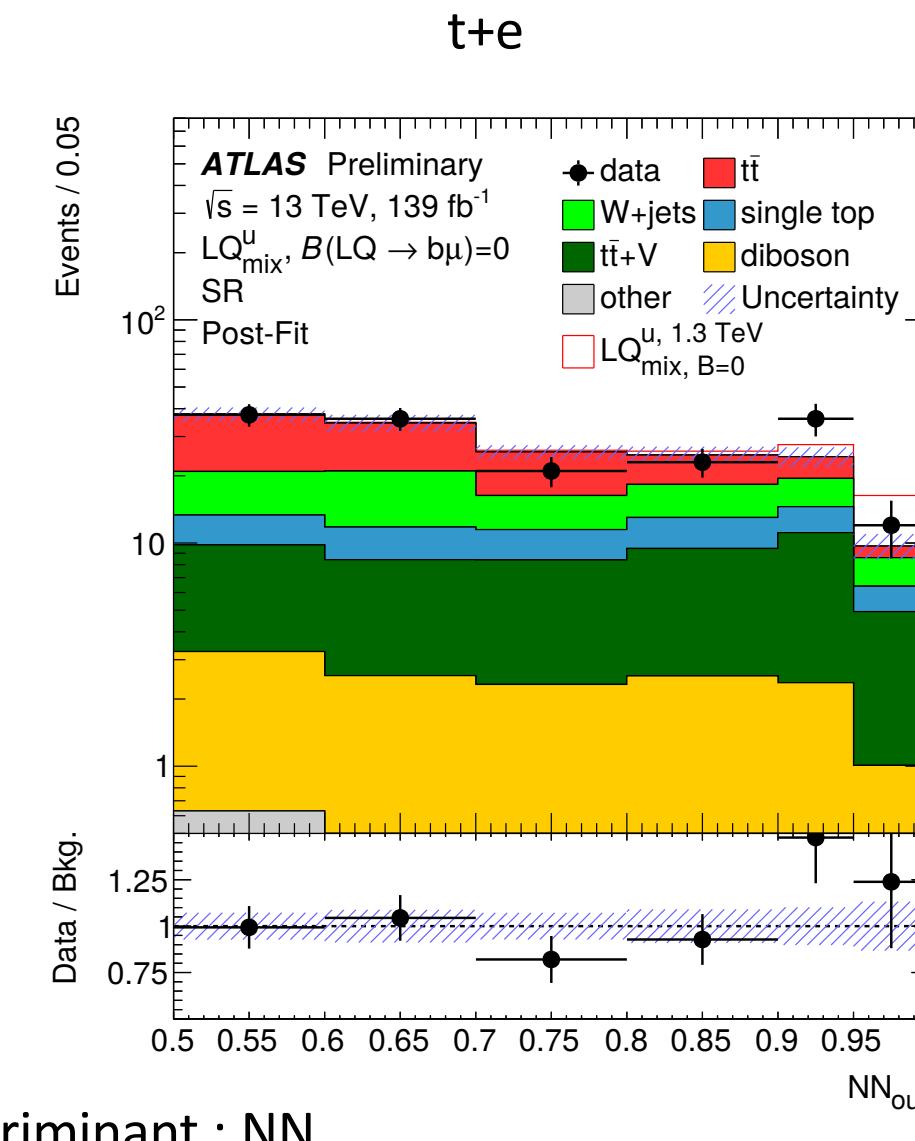
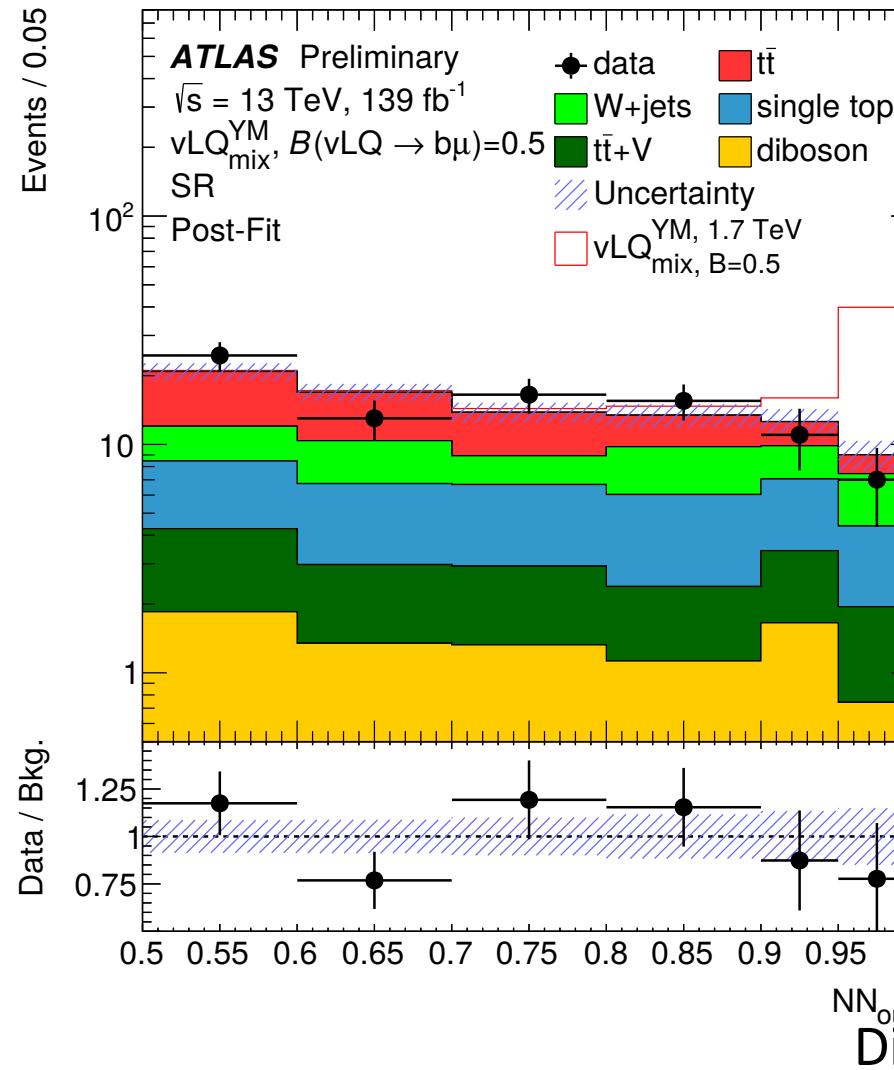
$t+e$



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

$LQ \rightarrow t+\nu, t+e, t+\mu$ and $LQ \rightarrow b+\nu, b+e, b+\mu$

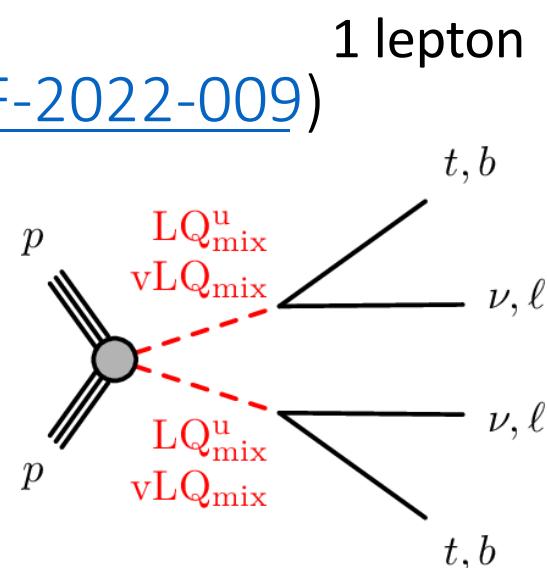
$b+\mu$



No excesses observed

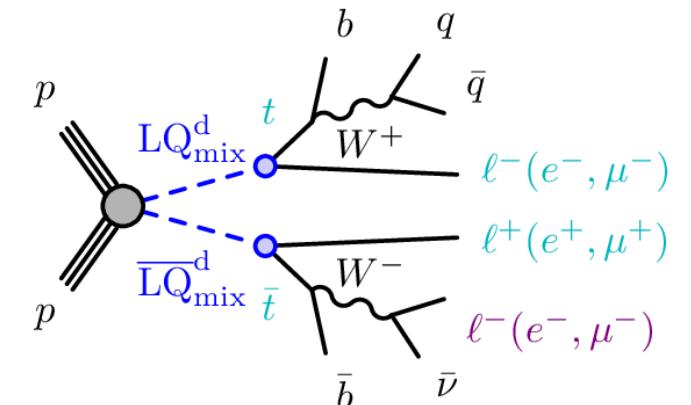
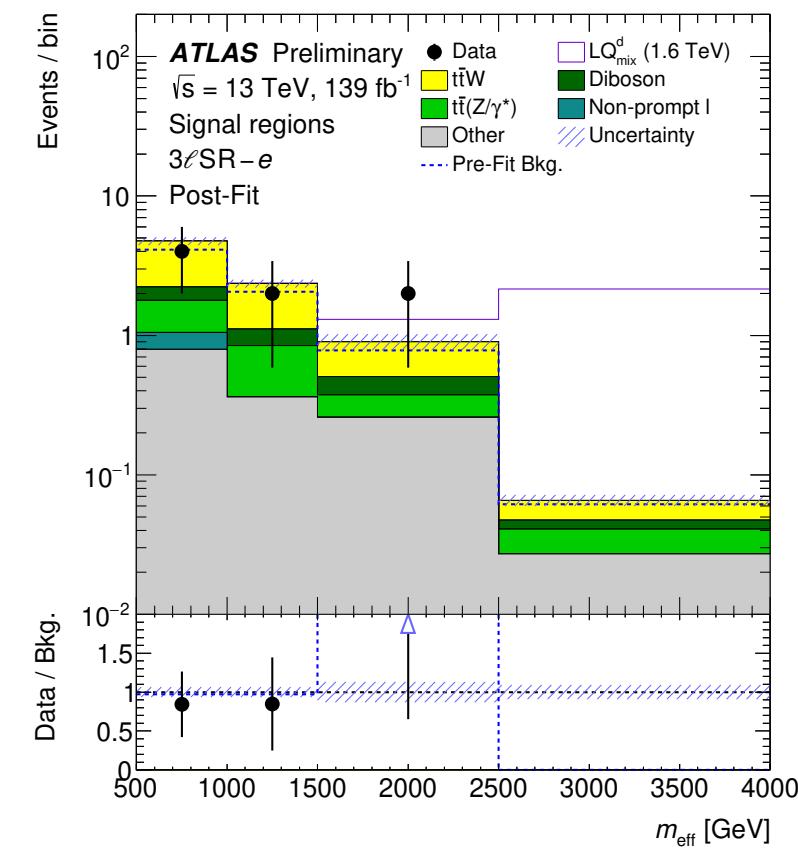
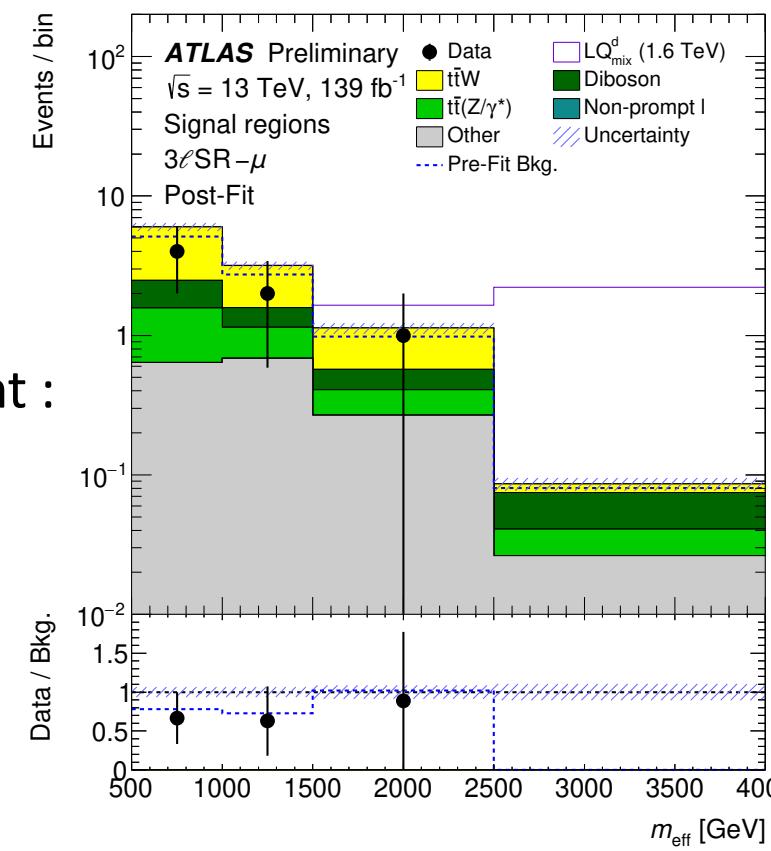
LQ limits on mass range 1.4 – 1.95 TeV

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



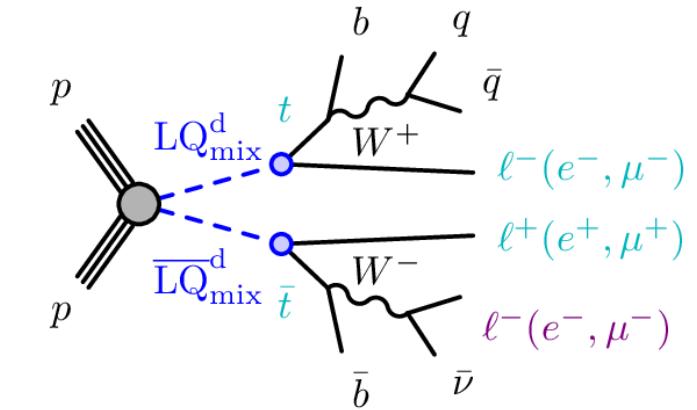
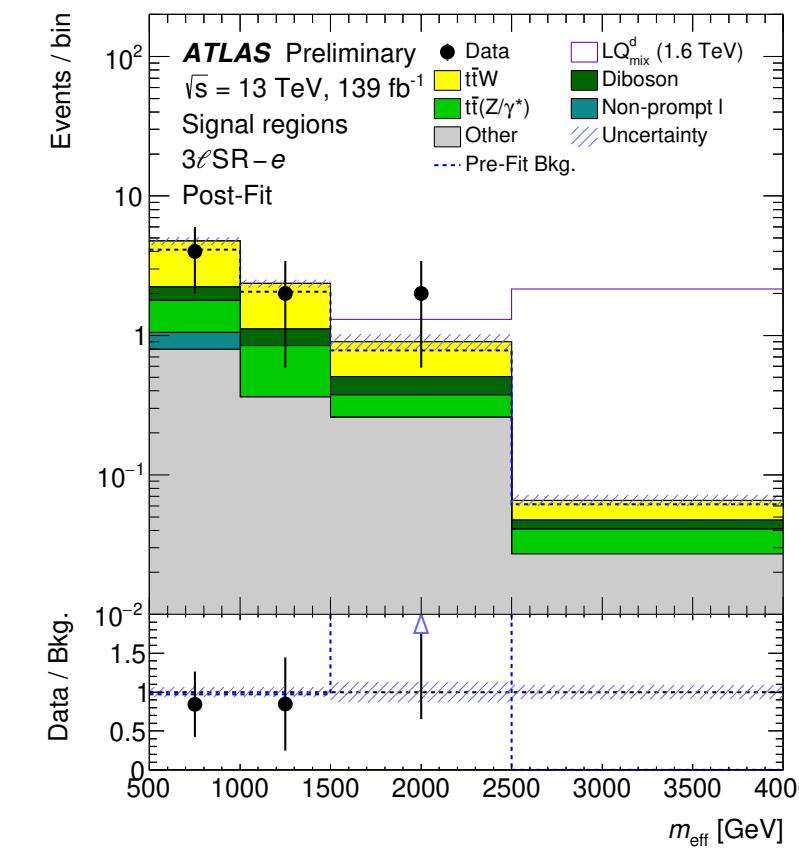
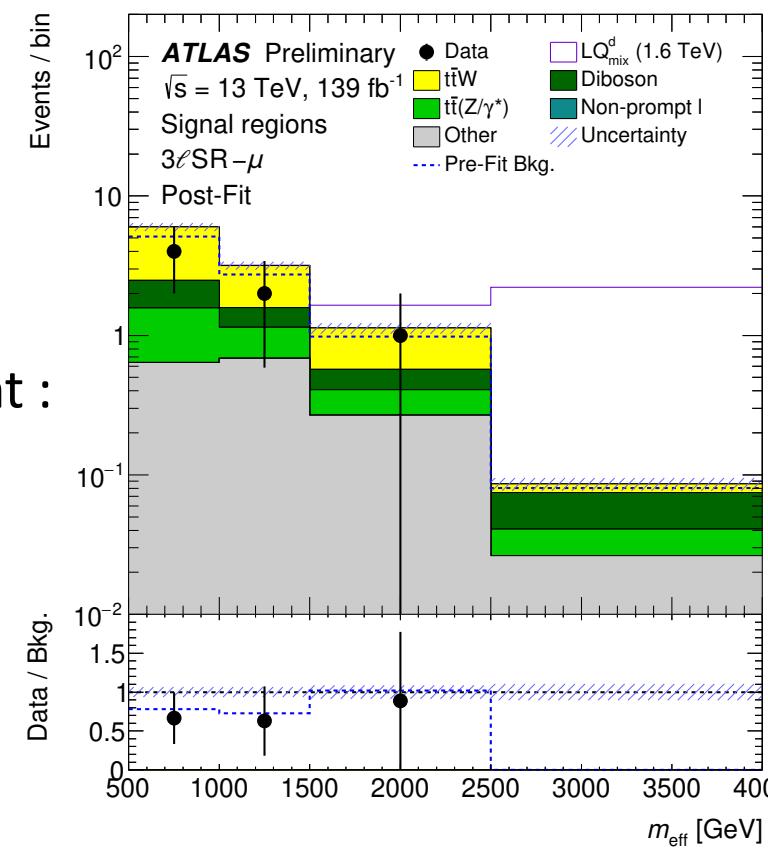
$LQLQ \rightarrow t\ell + t\ell$ (ATLAS-CONF-2022-052)

Discriminant :
 m_{eff}



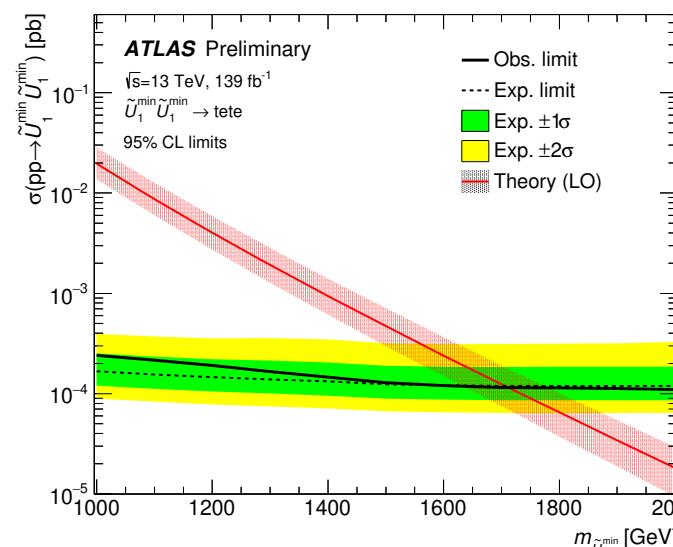
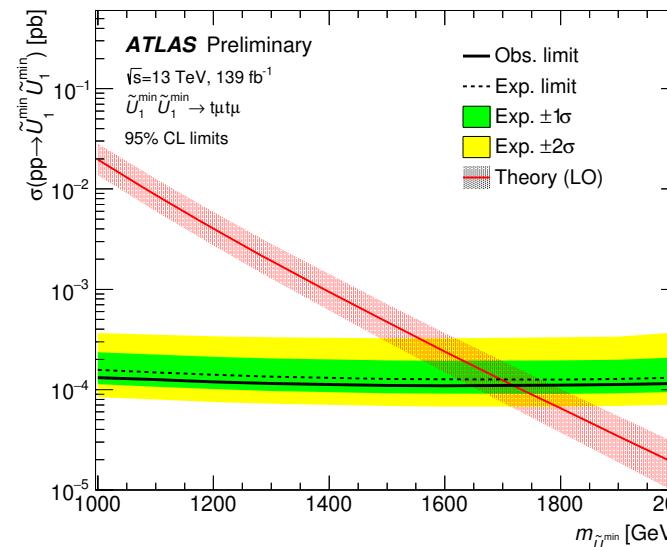
$LQLQ \rightarrow t\ell + t\ell$ (ATLAS-CONF-2022-052)

Discriminant :
 m_{eff}



No excess observed,
Limits on $M_{LQ} \sim 1.7 \text{ TeV}$

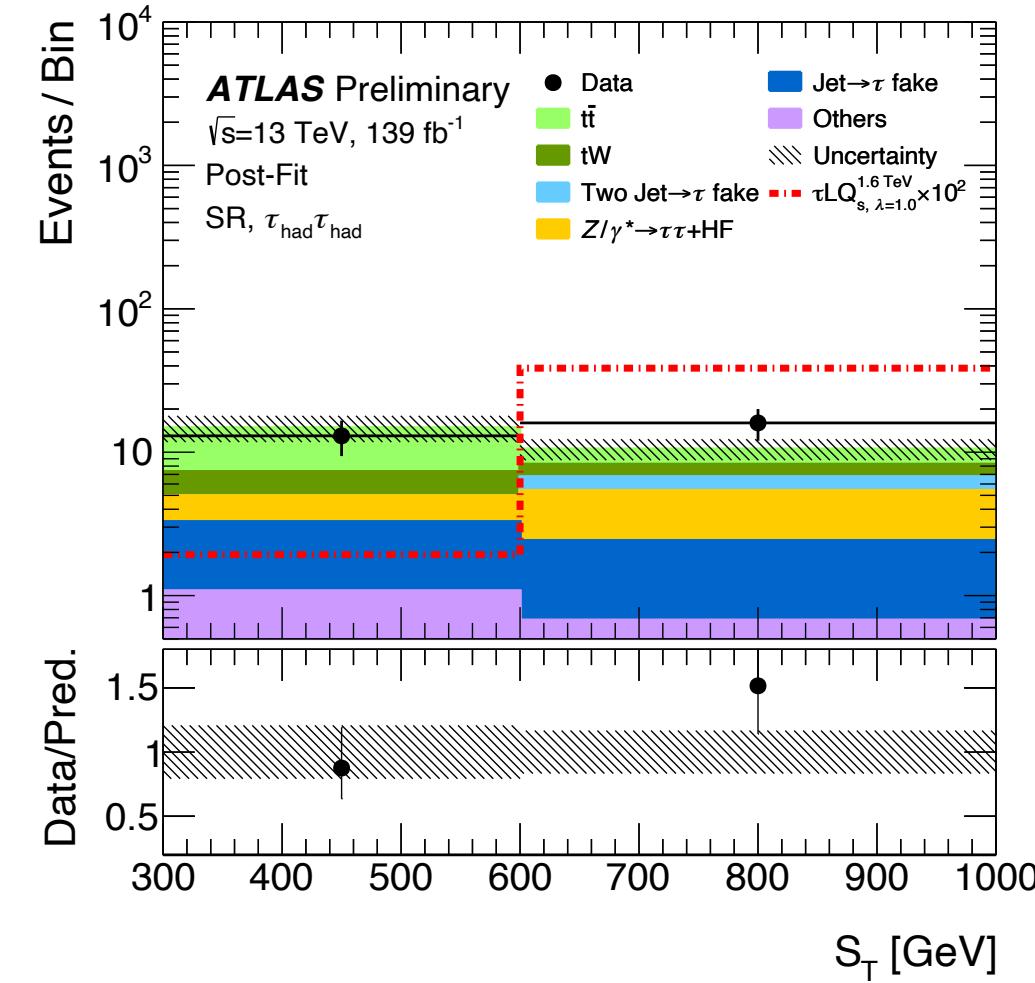
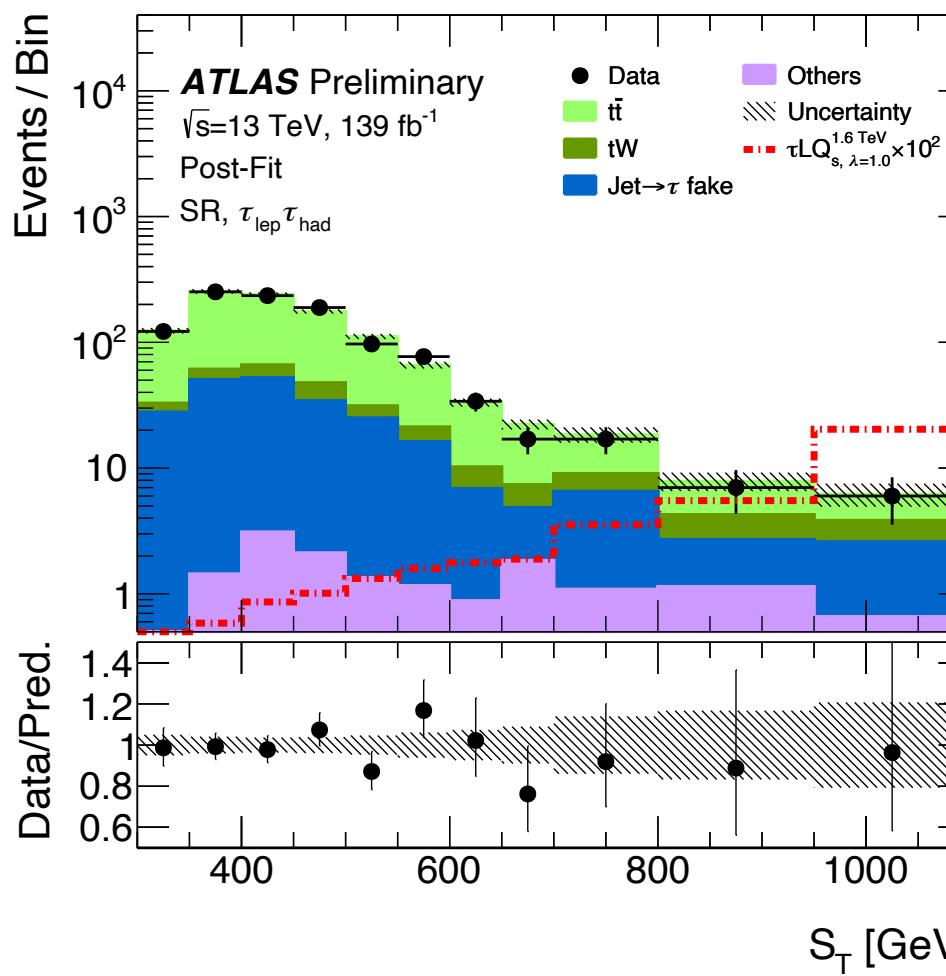
Limits



ATLAS LQ pair and single production

(ATLAS-CONF-2022-037)

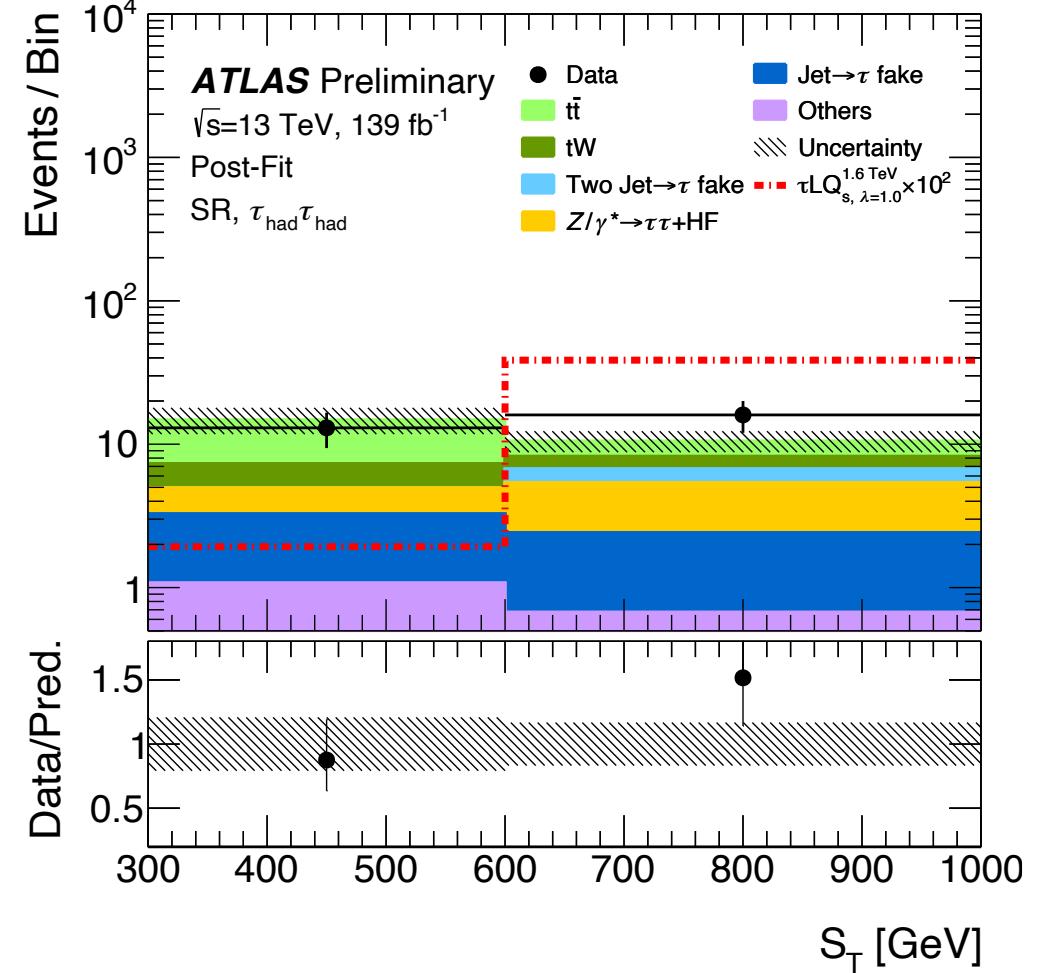
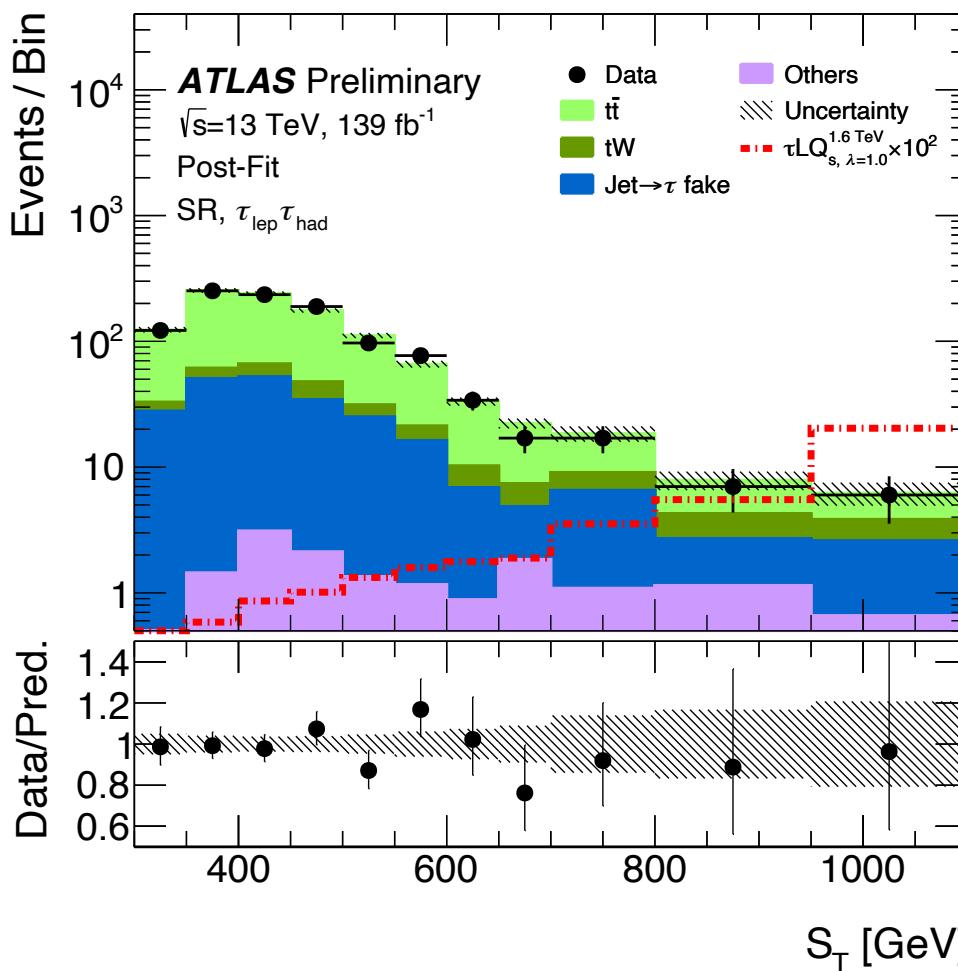
- New single-LQ search combined with LQ pair production
 - $b\tau\tau$ final state targets both
 - However, final state not sensitive to non-resonant production



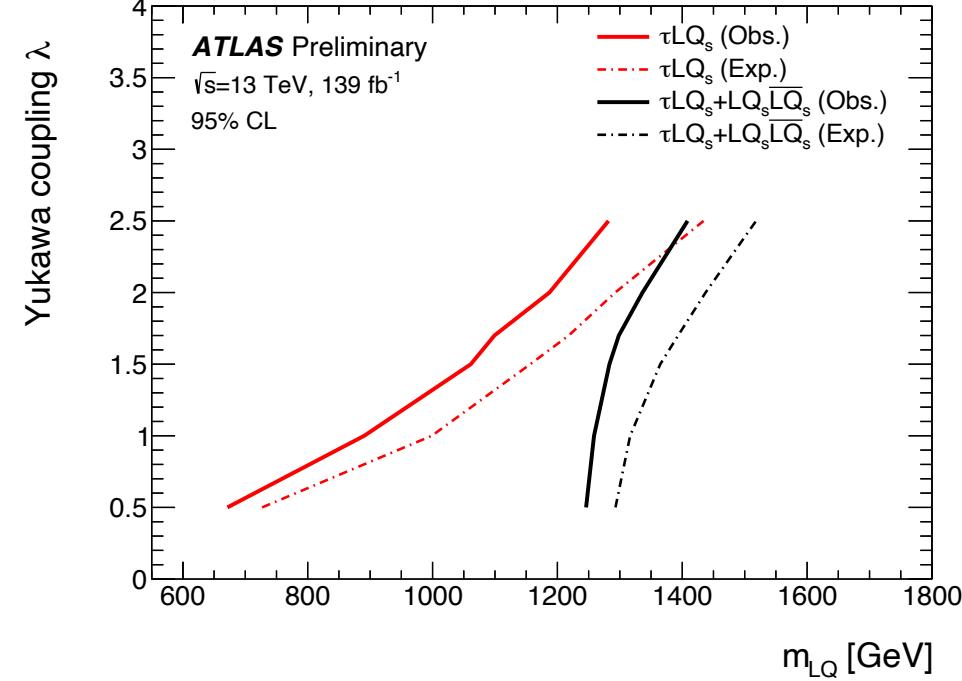
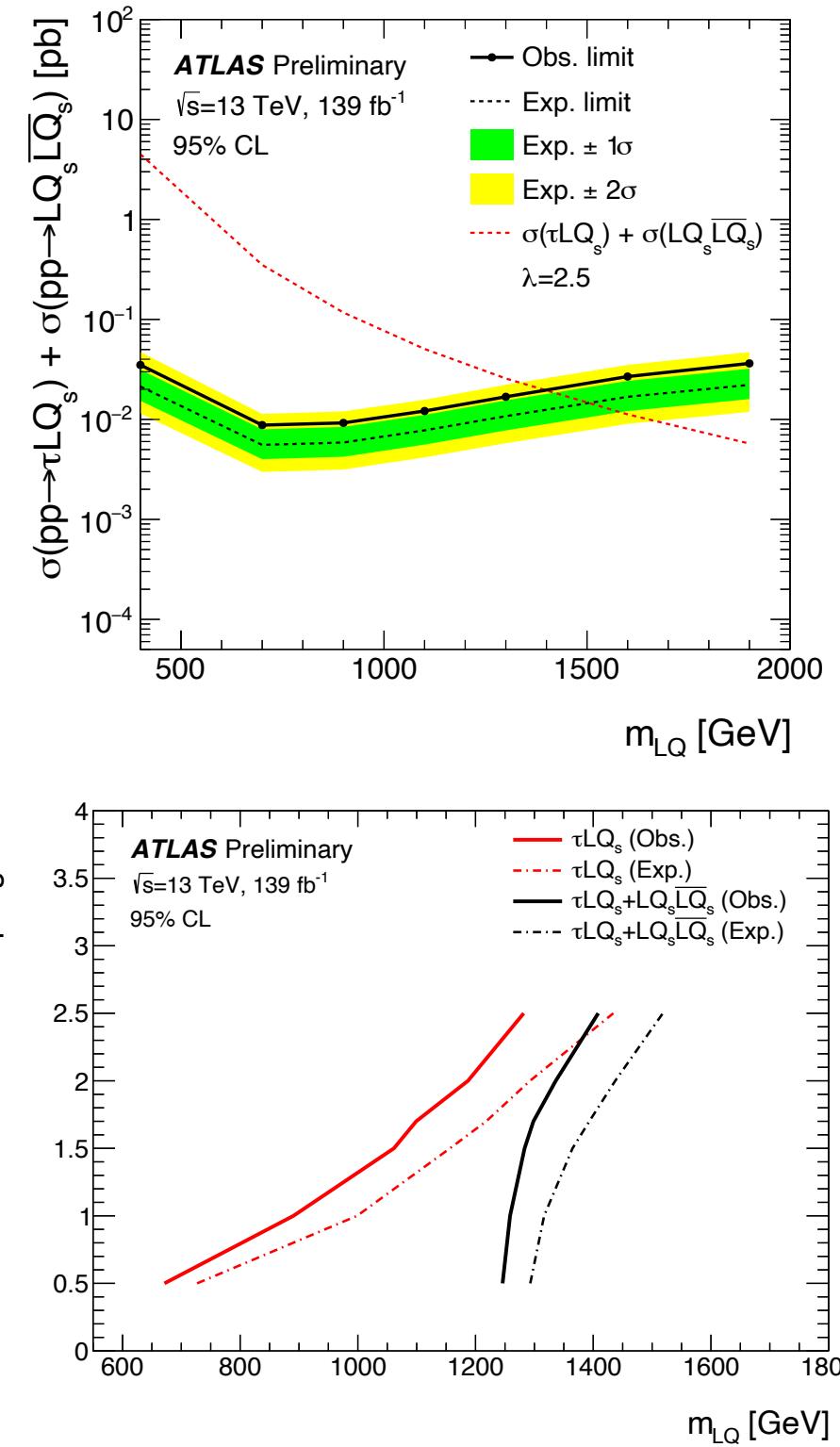
ATLAS LQ pair and single production

(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

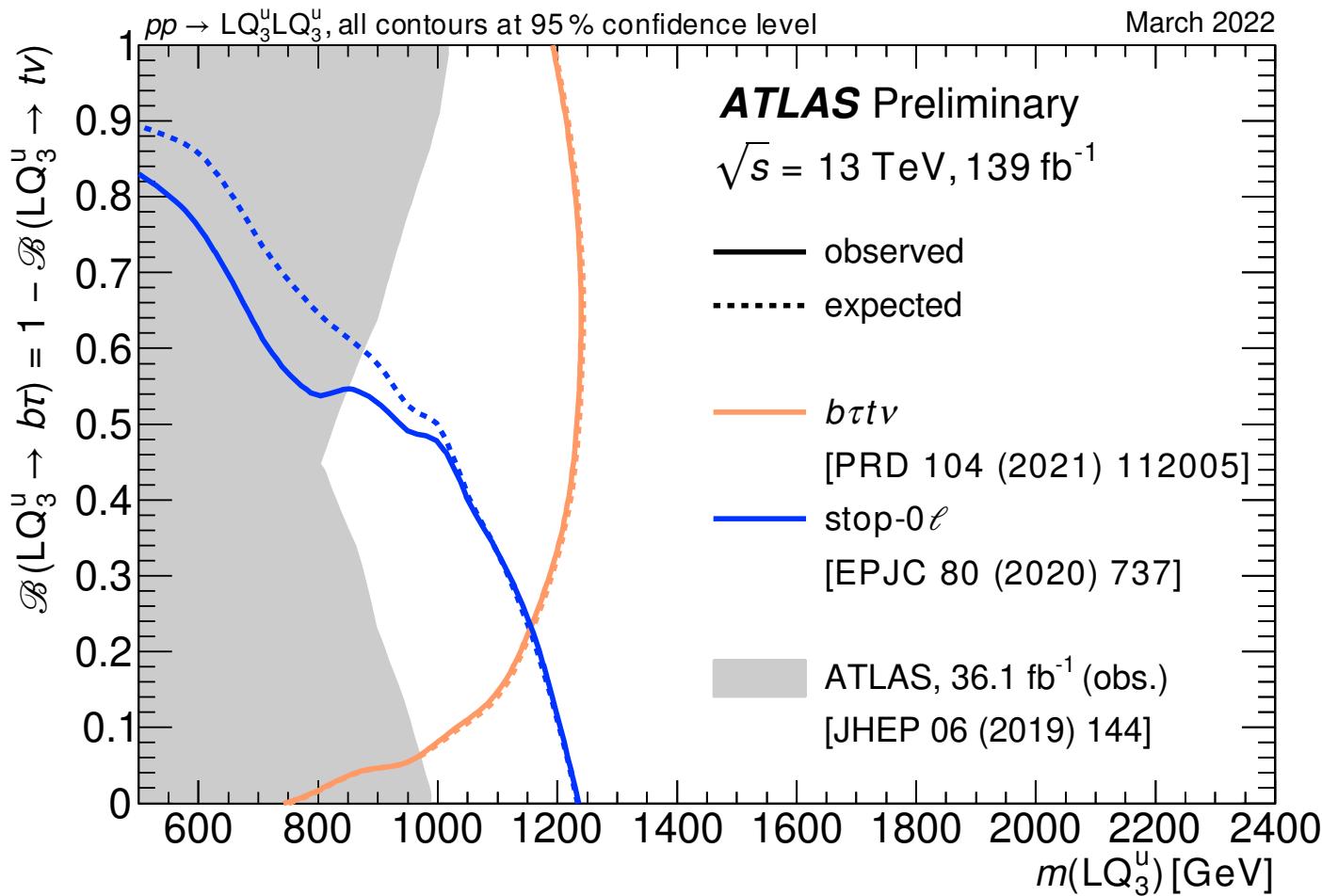


- No excess observed for $M_{\text{LQ}} < 2 \text{ TeV}$
- Mass constraints similar to CMS



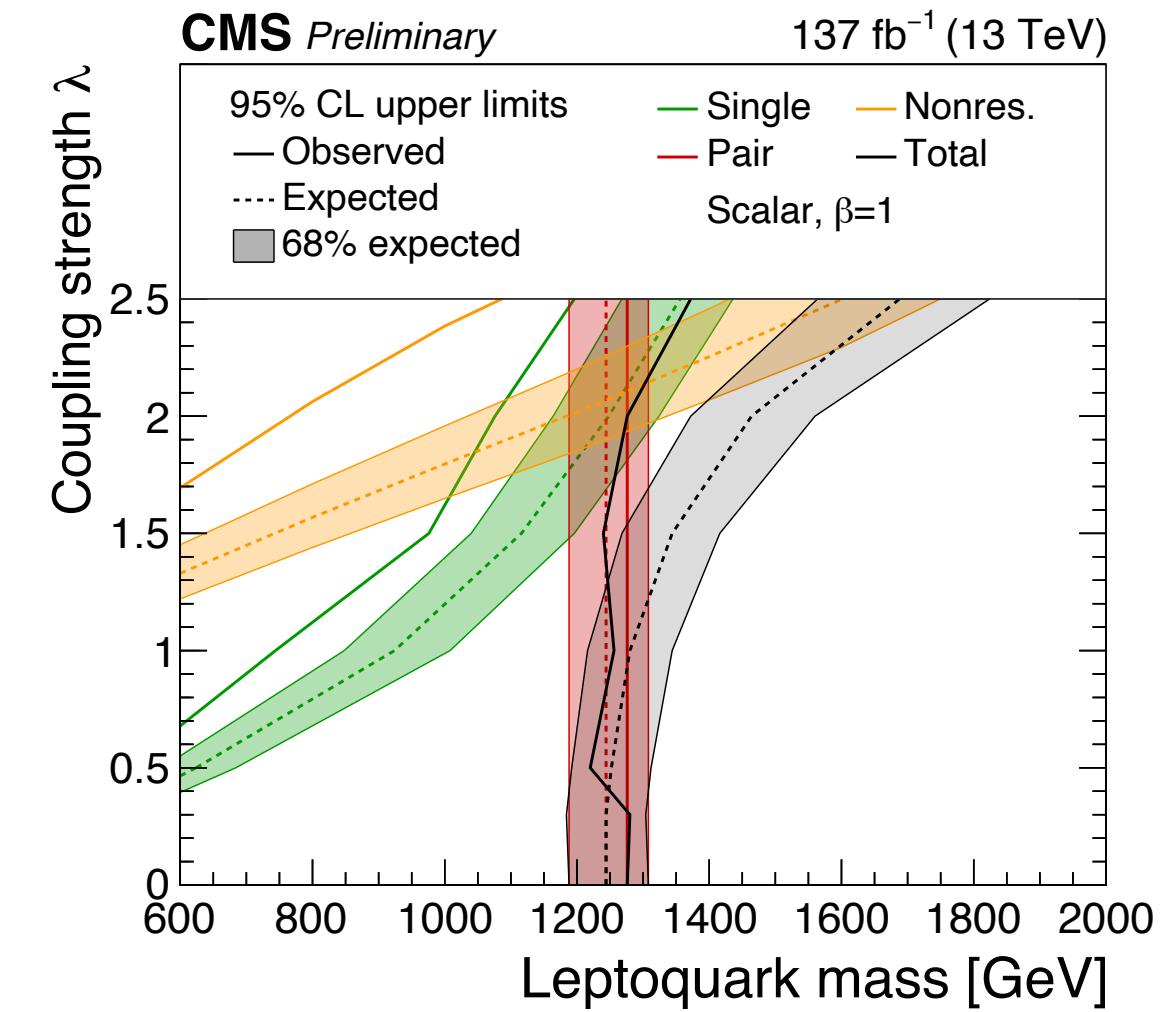
Some LQ summary plots (many more available)

[ATL-PHYS-PUB-2022-012](#)



As a function of BR to either $\tau\nu$ or $b\tau$

[CMS-PAS-EXO-19-016](#)



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