On behalf of the
CMS collaboration

A flavor for leptoquarks

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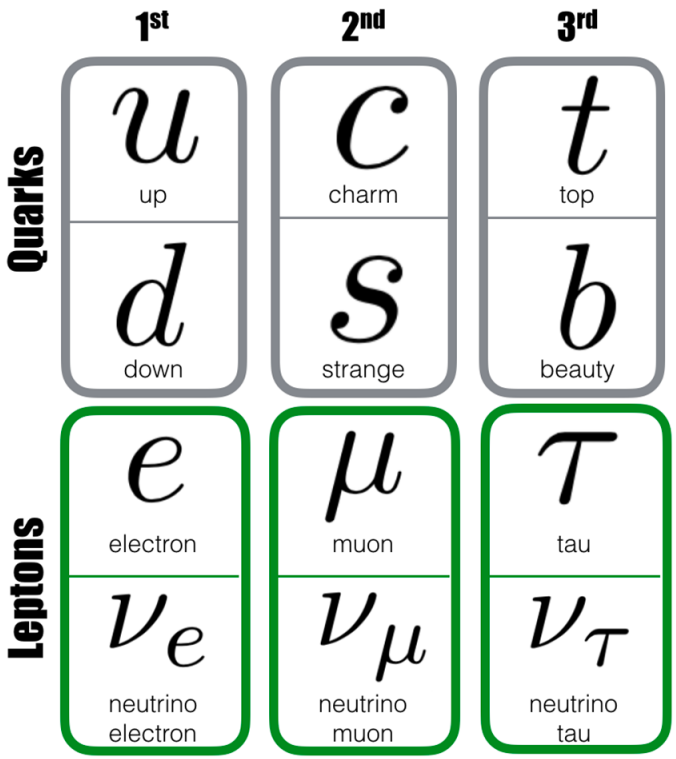
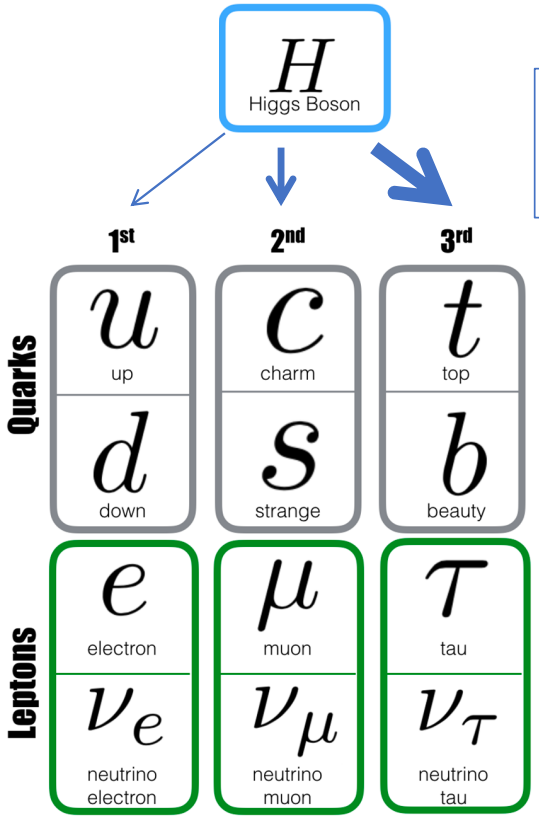
Theoretical puzzle : Similarity of quarks and leptons



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 !!

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

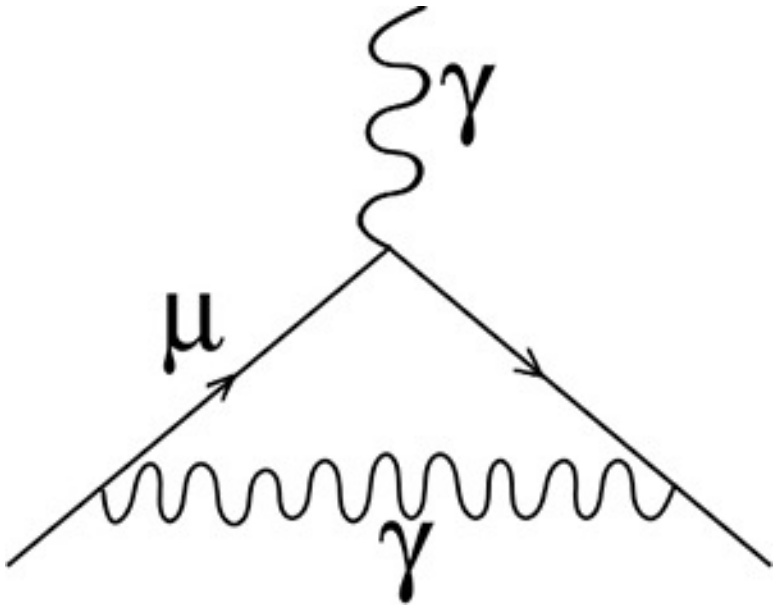
New physics needed to tell the difference

e vs. μ vs. τ

u vs. c vs. t

Puzzle : $(g\text{-}2)_\mu$

- Long-standing discrepancy of anomalous magnetic moment of muon



4.2 σ discrepancy

New theory June 2020, Phys. Rept. 887 (2020) 1-166

New experiment April 2021 PRL 126, 141801 (2021)

$a_\mu \equiv (g-2)\mu/2$

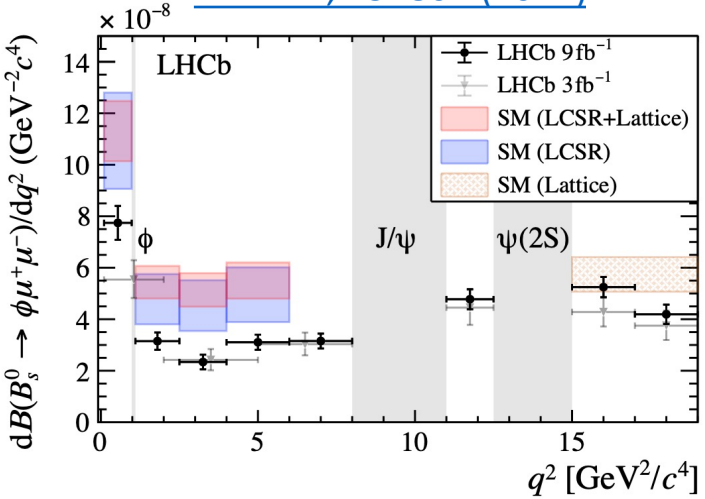
Theory : $116\ 59\ 1810(43) \times 10^{-12}$

Experiment : $116\ 59\ 2061(41) \times 10^{-12}$

4.2 σ discrepancy

Experimental puzzles : flavor anomalies in B decays

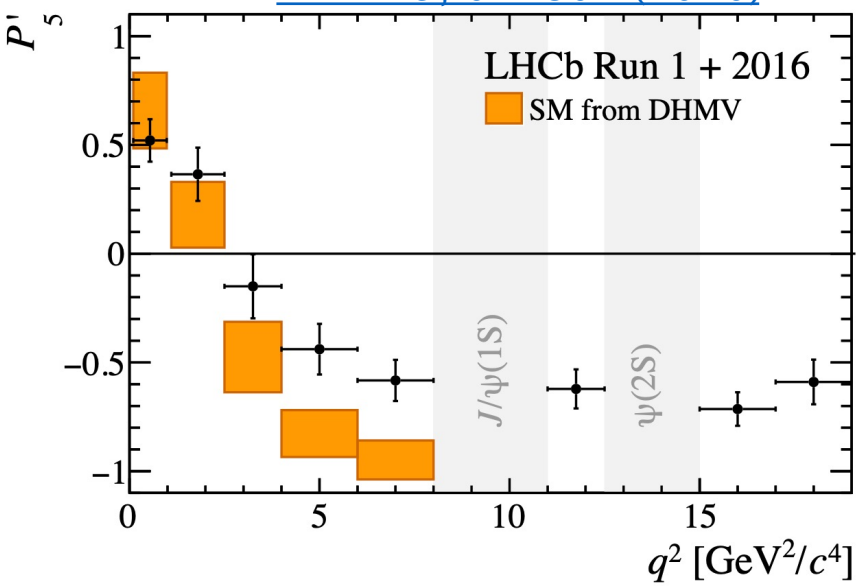
PRL 127, 151801 (2021)



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

3.6 σ

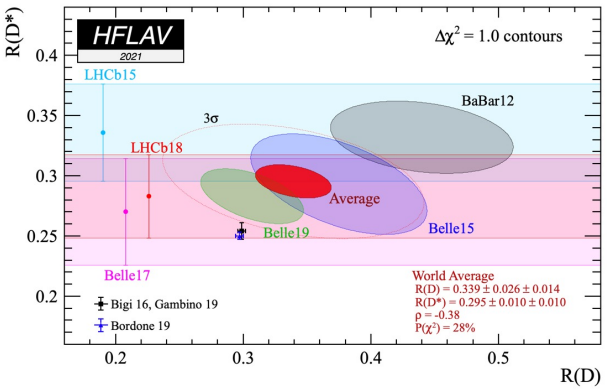
PRL 125, 011802 (2020)



$B^0 \to K^{0*}\mu\mu$ 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

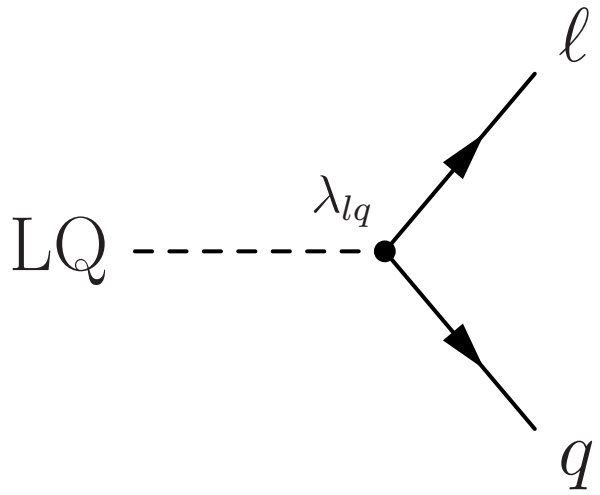
Lepton flavor universality violation

New left-handed currents

Leptoquarks !

Leptoquarks

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



- **Decay into ℓq**

  $\Rightarrow$ carry L, B, color

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

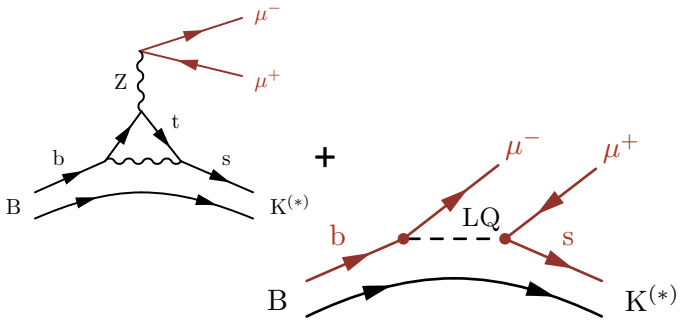
$$\underbrace{\mathrm{LQ}}_{\pm\frac{1}{3},\pm\frac{2}{3},\pm\frac{4}{3},\pm\frac{5}{3}} \rightarrow \underbrace{\ell}_{\pm 1,0} \underbrace{q}_{\mp\frac{1}{3},\pm\frac{2}{3}}$$

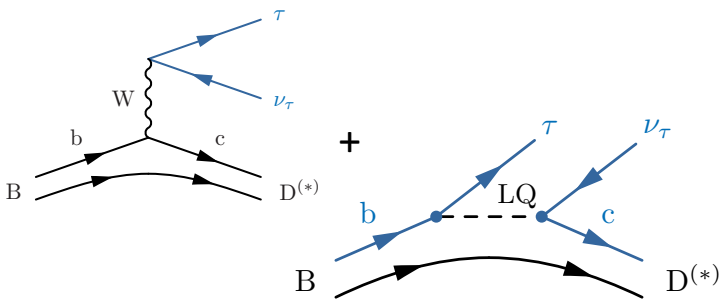
- **Fractional charge**

Flavor anomalies as explained by LQ

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

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





arXiv:1706.07808, arXiv:1903.11517

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

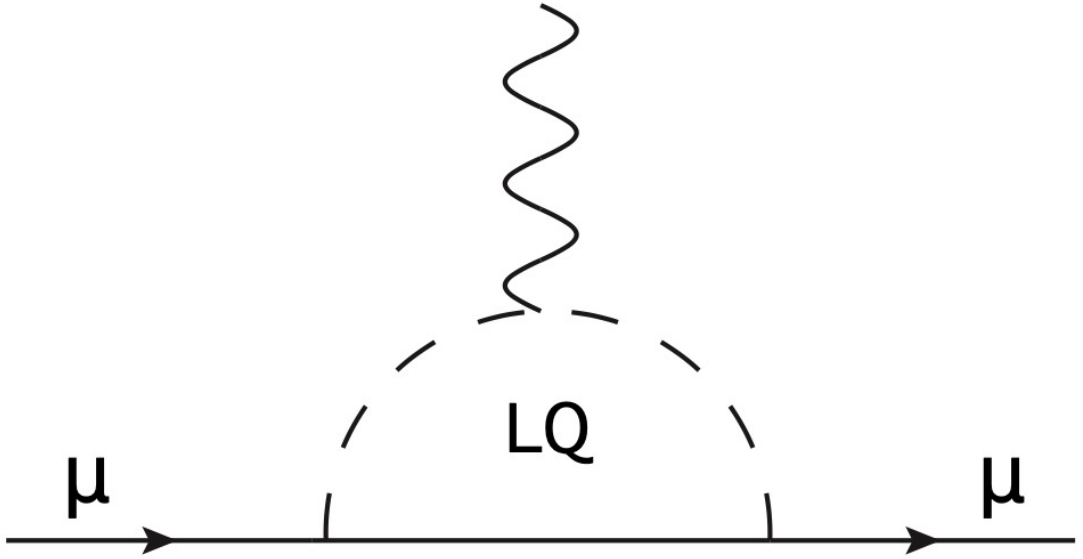
Flavor structure

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

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

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

Leptoquarks in $(g\text{-}2)_\mu$

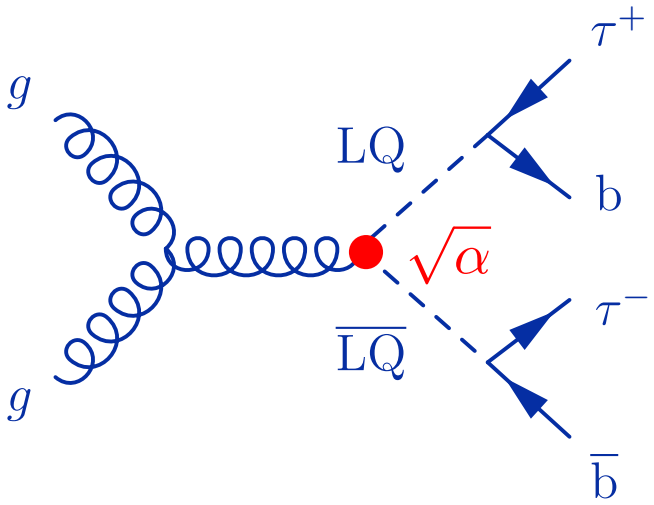


(For example : 2104.02982, 2105.08670, 2108.10055, 2110.03707, 2104.11229, 2104.03341, 2008.02643)

Can we search for leptoquarks directly ?

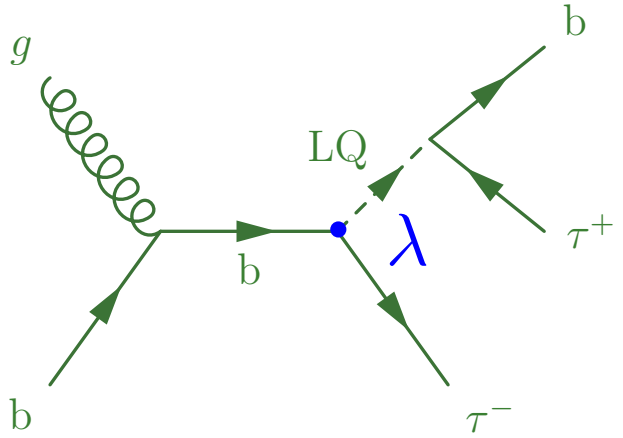
LQ production at the LHC (example for 3rd Gen)

pair



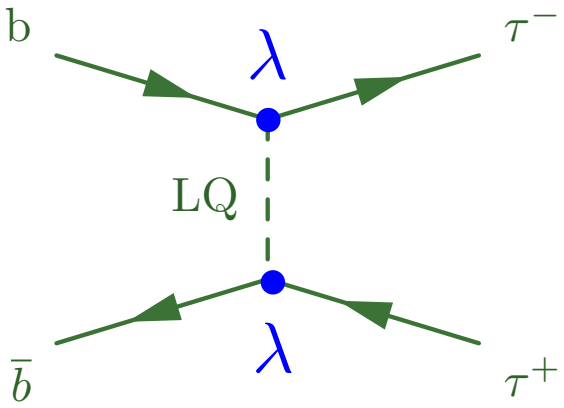
- Large QCD production
- Model independent
- Resonant

single



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

non-resonant



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

Leptoquark searches at CMS

Single LQ		
1st	2nd	3rd
ej + e	μj + μ	τb + τ tν+τ/tτ+ν

With full Run 2 data
137 fb^{-1}

LQ pairs			
	1st	2nd	3rd
ℓq + ℓq	ee + jj	μμ + jj	ττ + bb ττ + tt
		μμ + tt	
ℓq + νq	eν + jj	μν + jj	τν + bb τν + tt tτ+bν/tν+bτ
νq + νq	νν + jj		νν + bb νν + tt

Phys. Rev. D 99, 052002 (2019)

1st Generation LQs
LQLQ pair → eq + eq, eq + vj

Selection :

electron trigger

(1) 2 high-Pt electrons with MET (missing transverse energy)

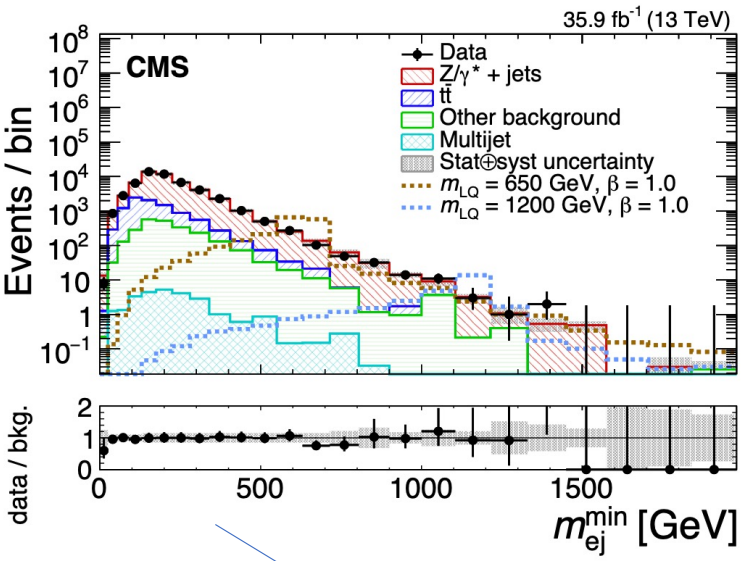
2 high-Pt (>50 GeV) jets

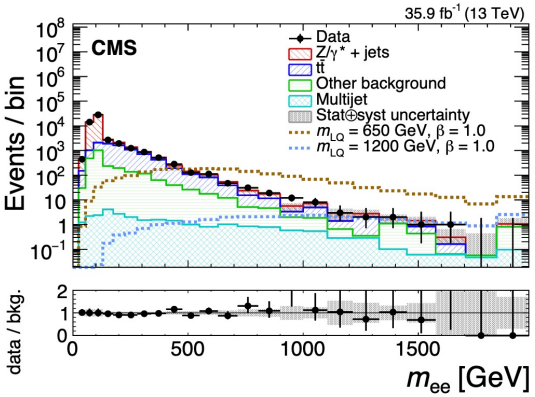
No jet-flavor requirements

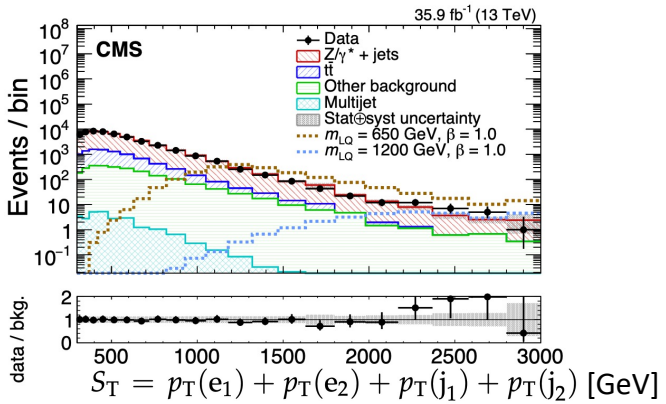
Construct LQ candidates which minimize | $M(LQ_1) - M(LQ_2)$ |

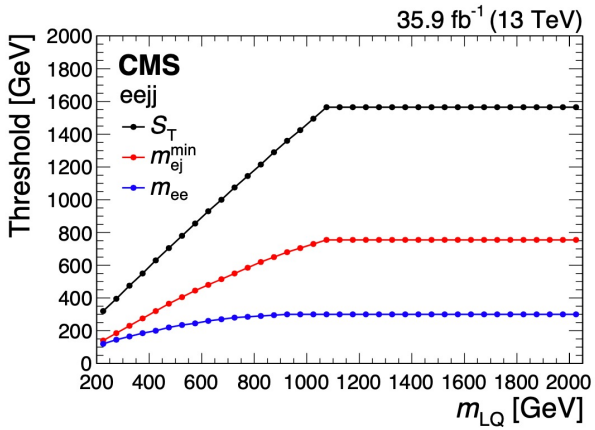
The eejj final state : 3 distributions used in counting experiment

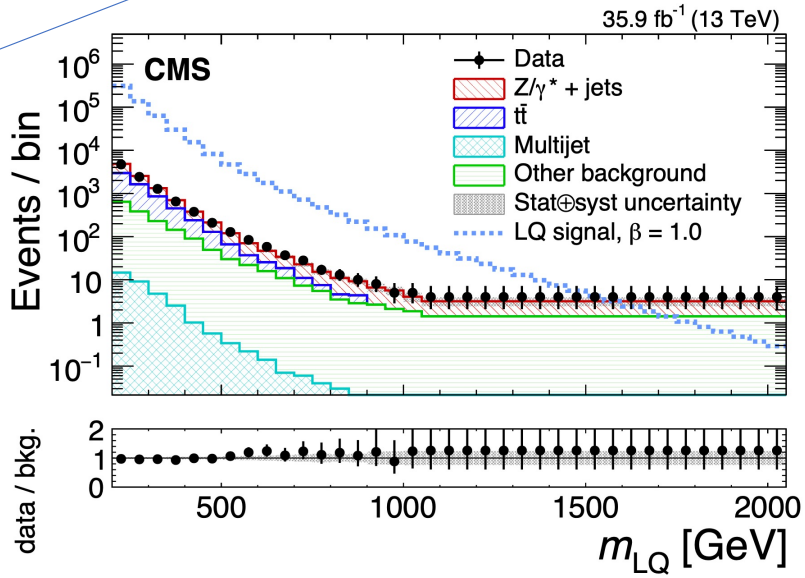
Phys. Rev. D 99, 052002 (2019)











Cuts optimized for LQ mass

Counting experiment (correlated bins)

Phys. Rev. D 99, 052002 (2019)

1st Generation LQs : LQLQ → eq + eq, eq + vq

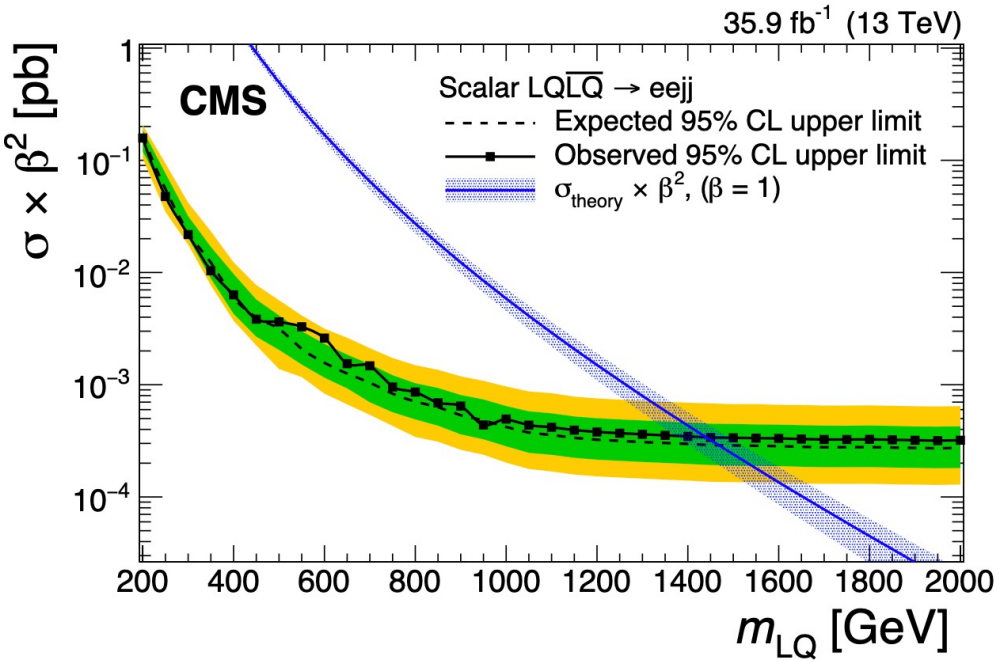
β defines branching fractions of LQ

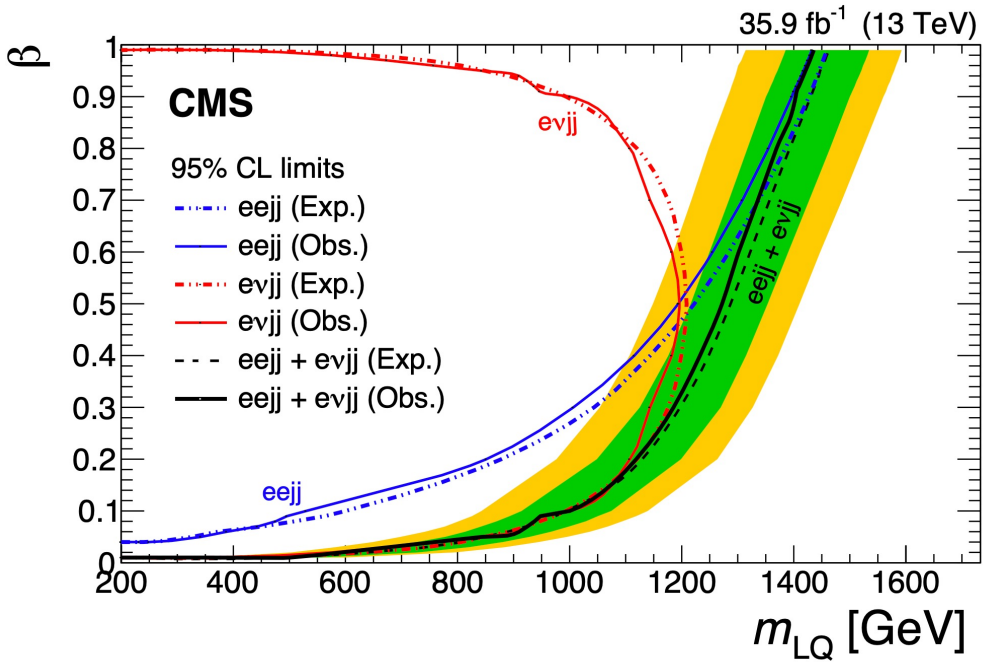
β=1 LQ → eq only

β=0 LQ → vq only

β=0.5 LQ → eq and LQ → vq (same)

eejj+evjj: Combo improves ~ β=0.5

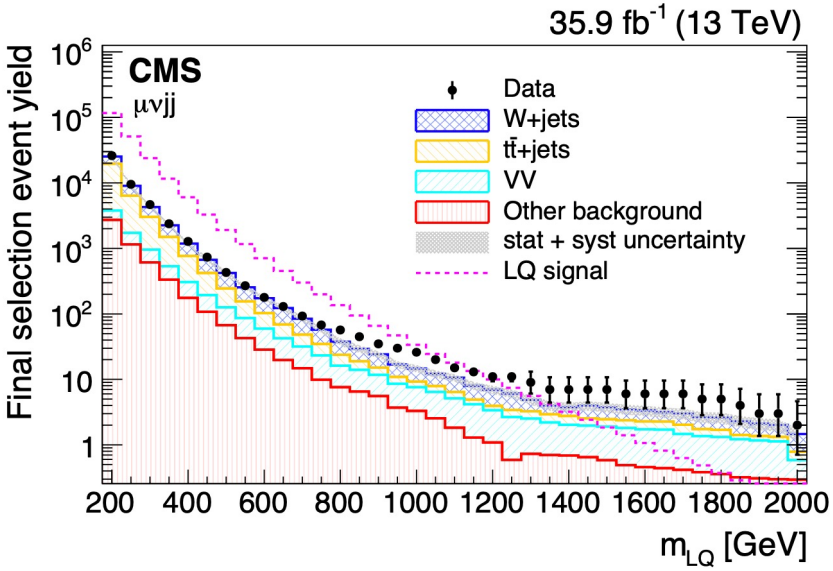




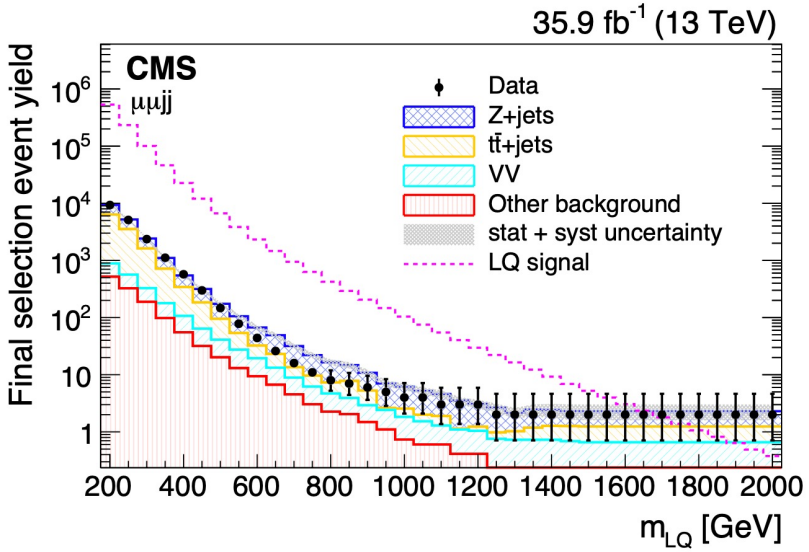
2nd Generation LQs

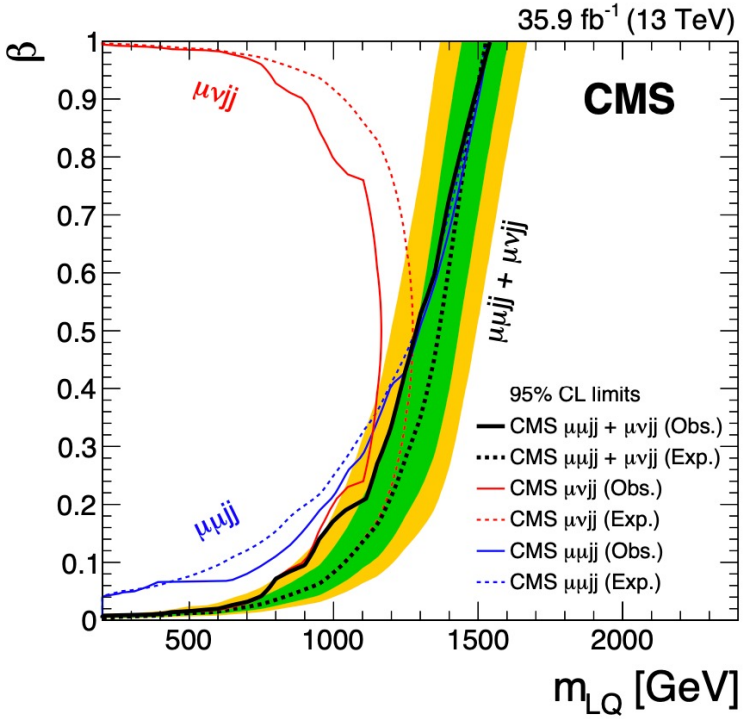
(same strategy as 1st gen LQ)

μν+jj



μμ+jj





Phys. Rev. D 99, 032014 (2019)

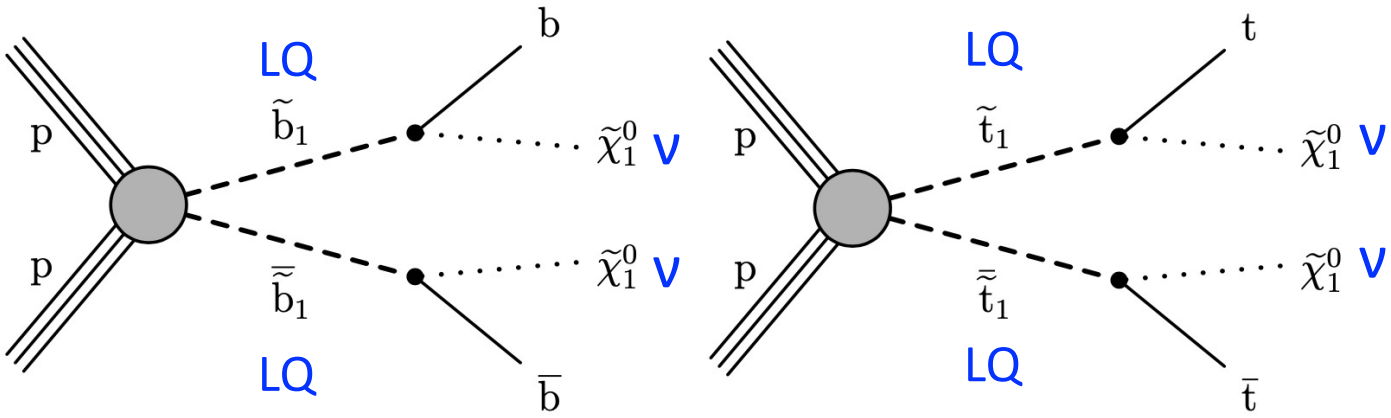
Eur. Phys. J. C 80 (2020) 3

3rd Generation LQs: LQ ➞ bν + bν, tν + tν

With 137 fb^{-1}

Interpretation of top & bottom squark searches with 137 fb^{-1}

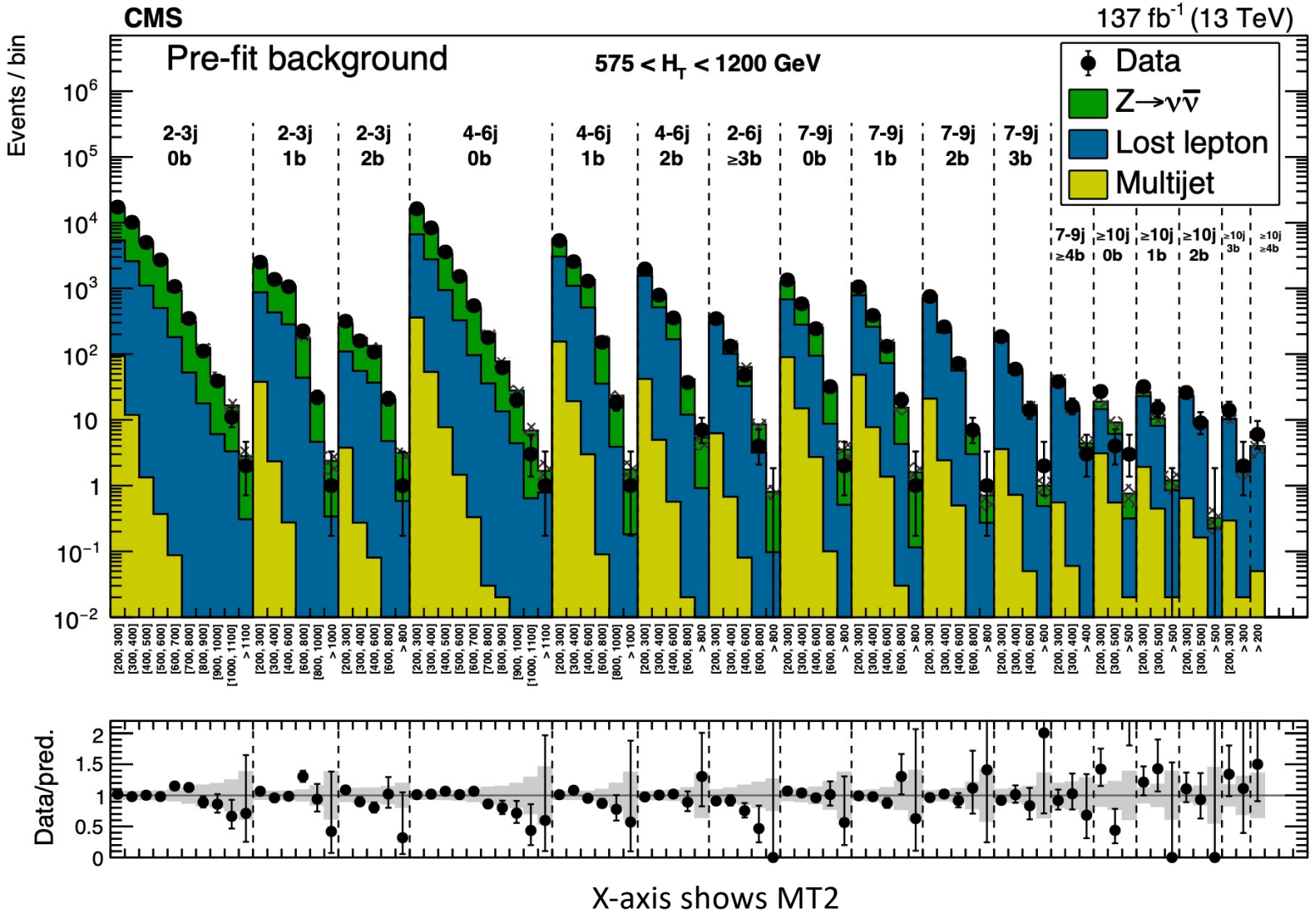
Considering 25% of LQLQ decays
(Not considering τ decays)



Considering events with jets + significant missing transverse energy

$$M_{T2} = \min_{\vec{p}_T^{\,miss\,X(1)} + \vec{p}_T^{\,miss\,X(2)} = \vec{p}_T^{\,miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

Eur. Phys. J. C 80 (2020) 3



X-axis shows MT2

Fit of MT2 in bins of :

jets

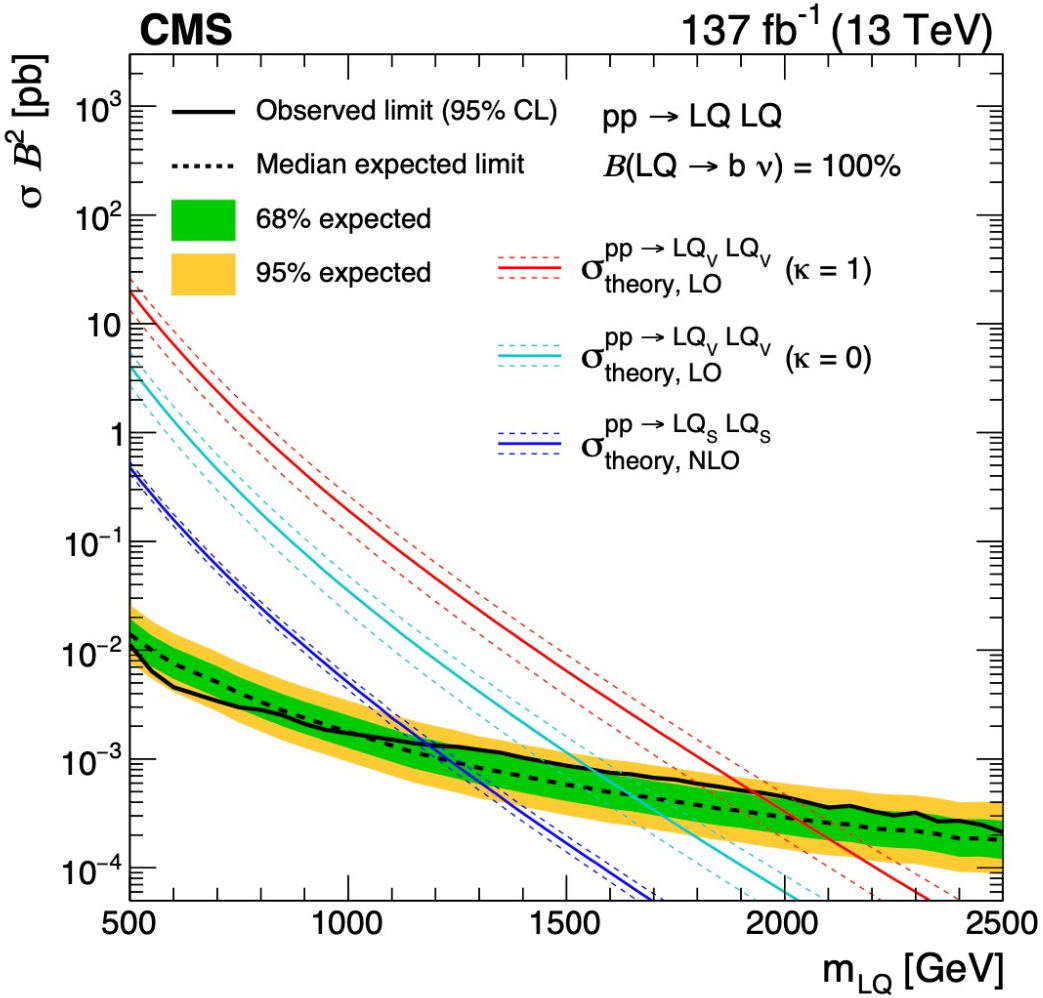
B-tags

H_T range

Charged lepton, τ_{had} veto

Eur. Phys. J. C 80 (2020) 3

With 137 fb^{-1}

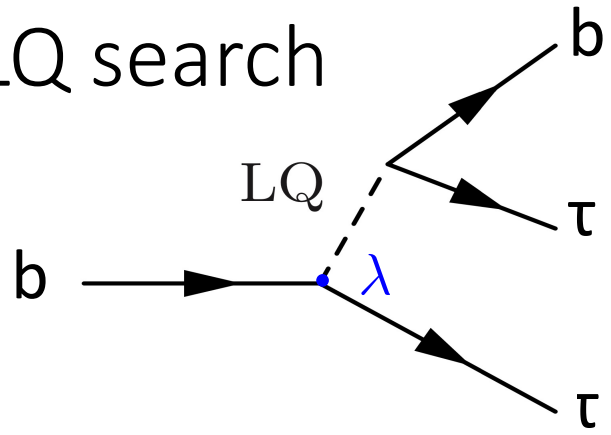


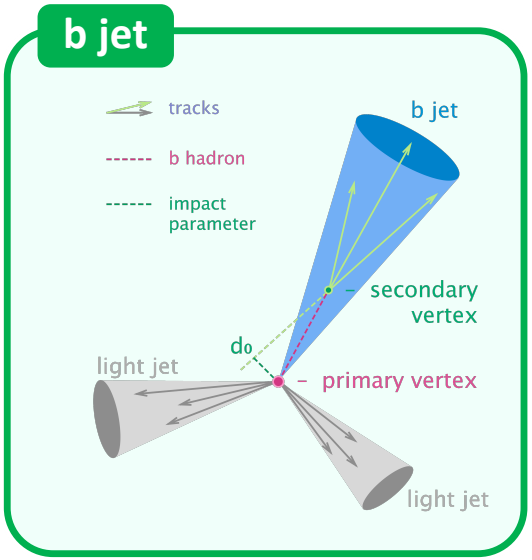
Provides strongest constraints on scalar and vector leptoquarks through pair production

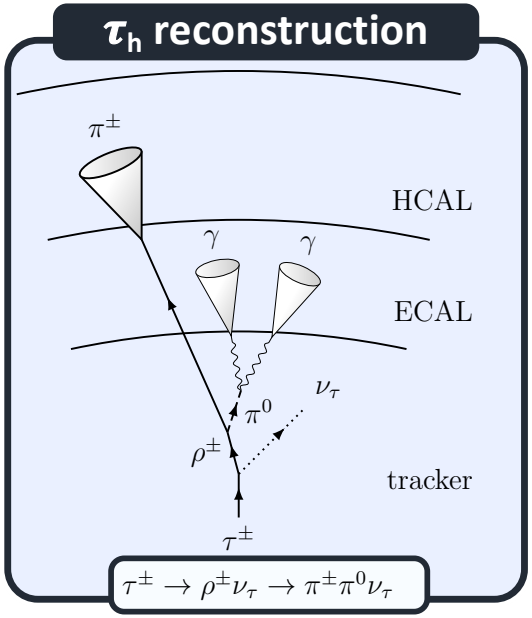
- For 1st, 2nd, 3rd generation leptoquarks

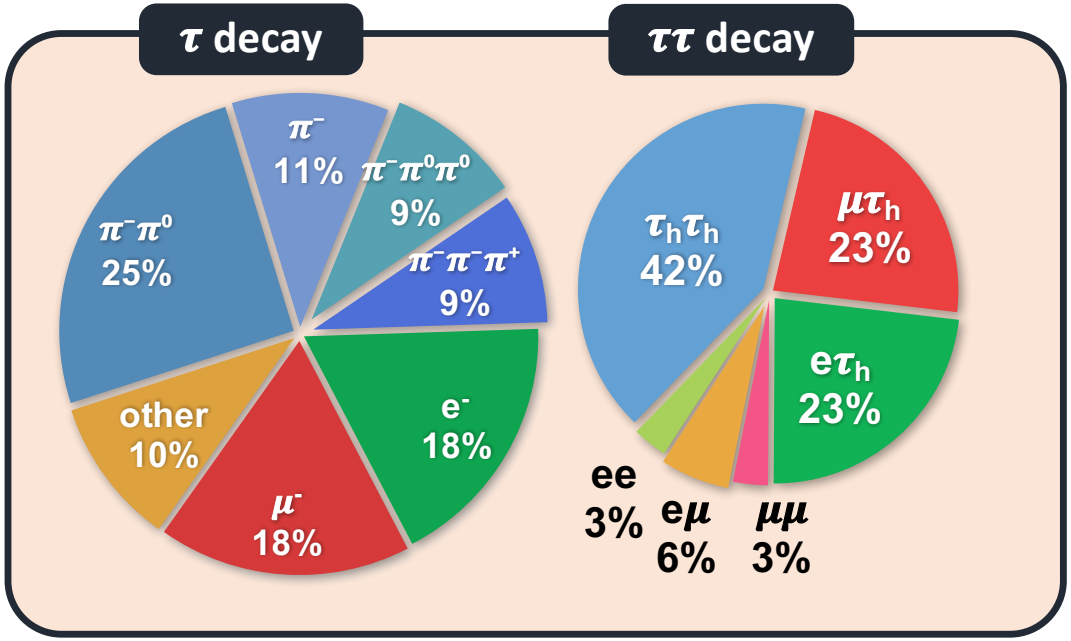
	LQ_S mass [GeV]	LQ_V, $\kappa = 1$ mass [GeV]	LQ_V, $\kappa = 0$ mass [GeV]
$LQ \to q\nu$ ($q = u, d, s$, or c)	1140	1980	1560
$LQ \to b\nu$	1185	1925	1560
$LQ \to t\nu$	1140	1825	1475
$LQ \to \begin{cases} t\nu & (\mathcal{B} = 50\%) \\ b\tau & (\mathcal{B} = 50\%) \end{cases}$	—	1550	1225

3rd generation single LQ search





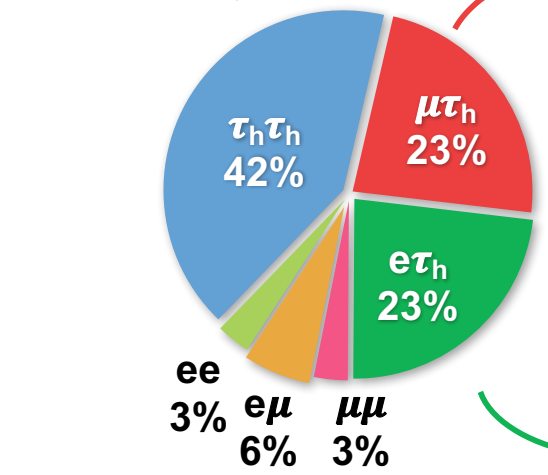




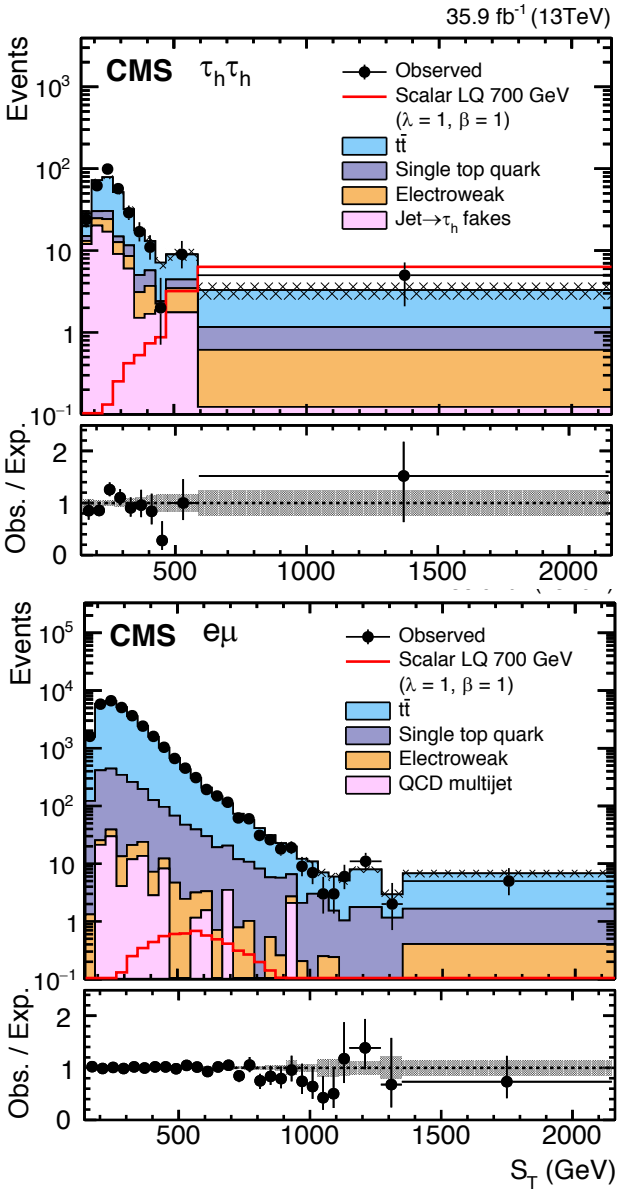
JHEP 07 (2018) 115

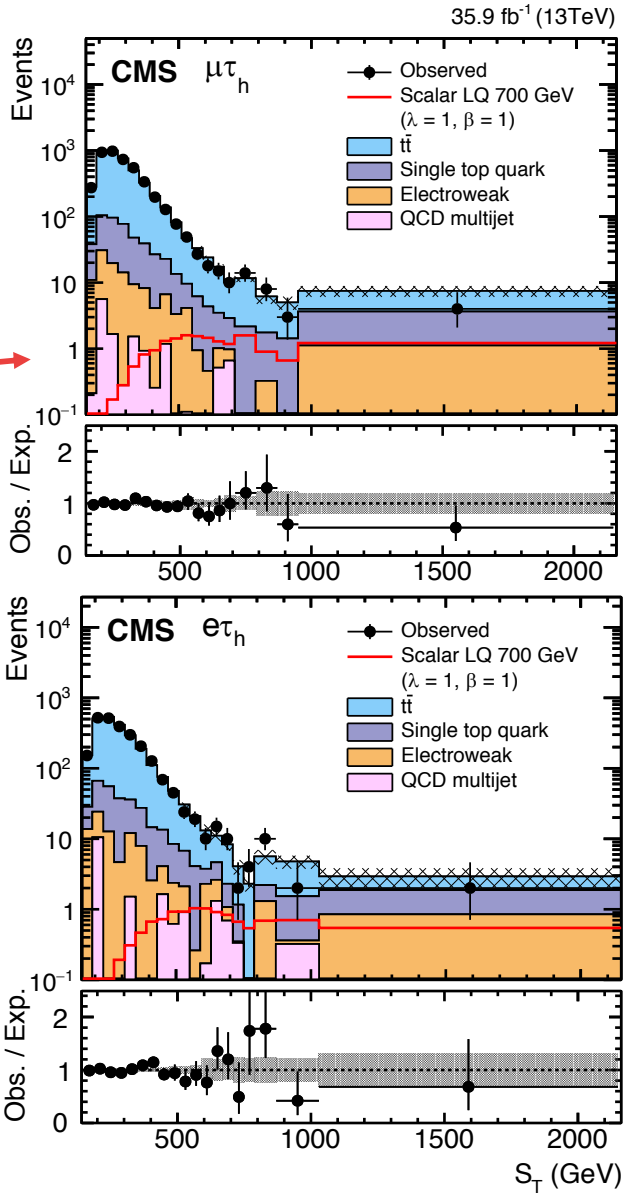
$S_T = \tau_1\, p_T + \tau_2\, p_T + j1\, p_T + MET$

require 1 b jet
+ $\tau\tau$ final states:

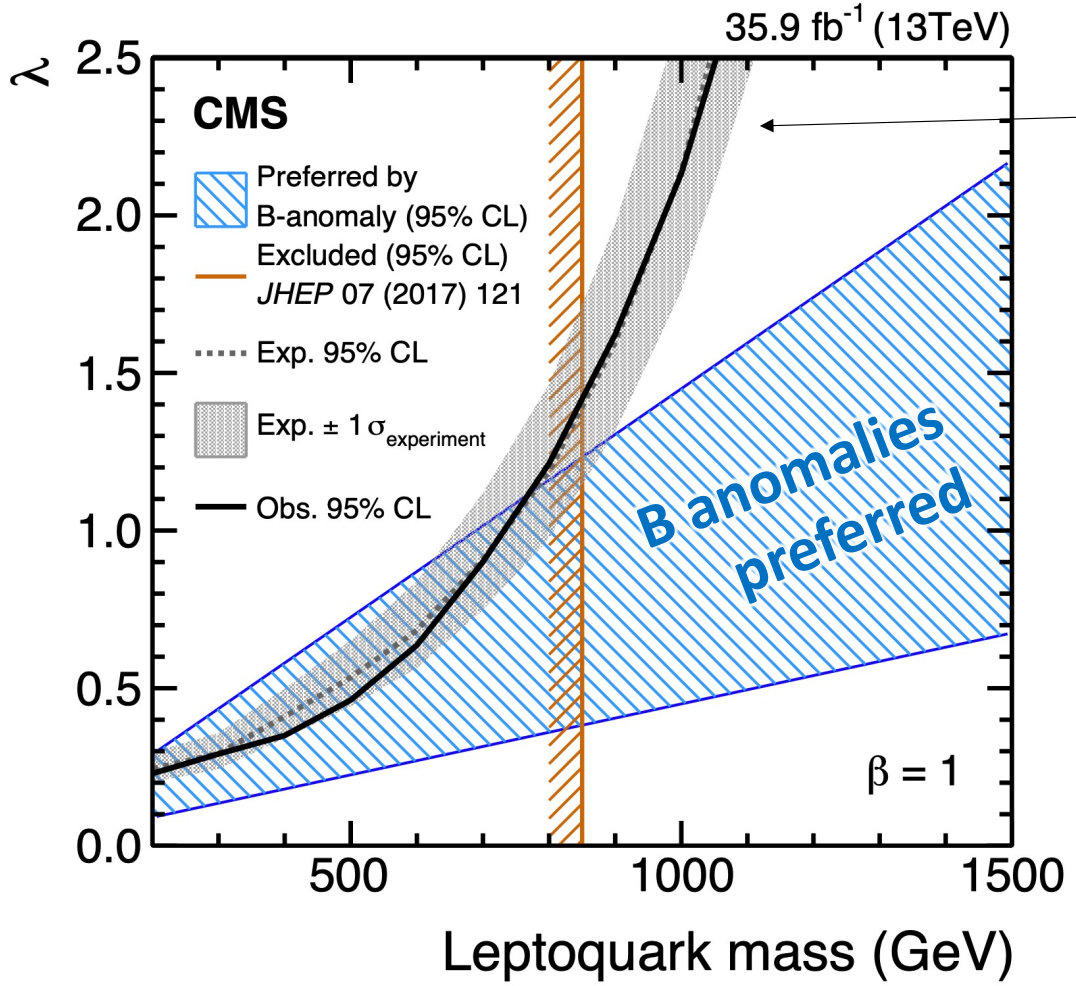


$e\mu$ control region to constrain uncertainties





Upper limits on Single 3rd generation LQ production → bτ



σ(single) ~ λ^2

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JHEP 07 (2017) 121

Democratic decays to 3rd generation LQs

PLB 819 (2021) 136446

With 137 fb^{-1}

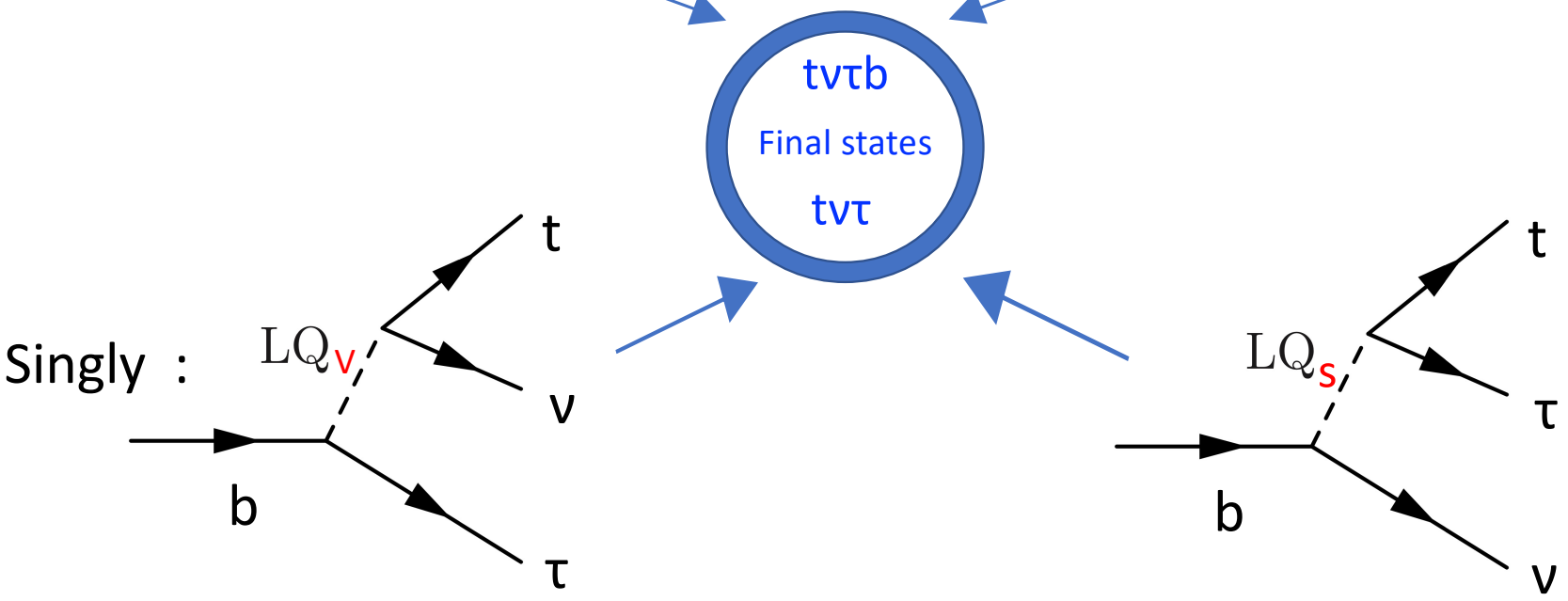
LQ_V → tν 50%, τb 50%

(From theory : 1706.07808)

LQ_S → tτ 50%, bν 50%

(From theory : 1808.02063)

In Pairs : $LQ_V\,LQ_V$ $LQ_S\,LQ_S$



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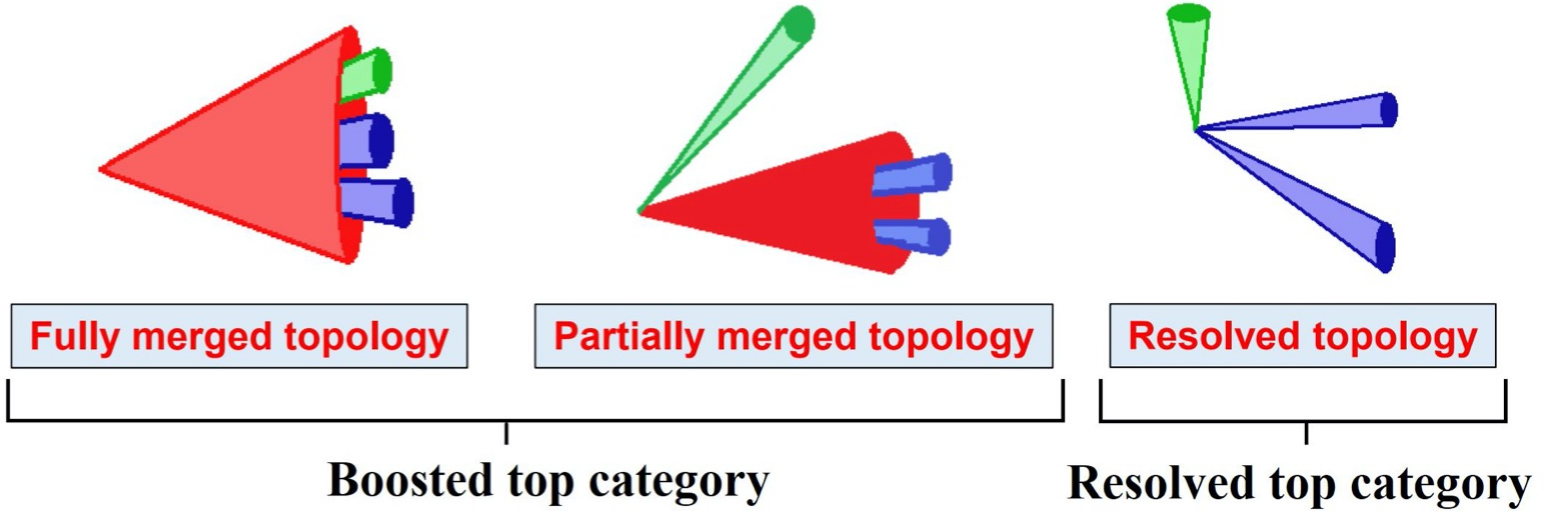
Final state tντ(b) – all-hadronic final state

Top reconstruction

- **Three reconstruction algorithms** to have good sensitivity in all mass range
  - ✓ **Fully merged topology**: top candidate is a top-jet
  - ✓ **Partially merged topology**: top candidate given by one W-jet and one ak4 jet
  - ✓ **Resolved topology**: top candidate given by three ak4 jets



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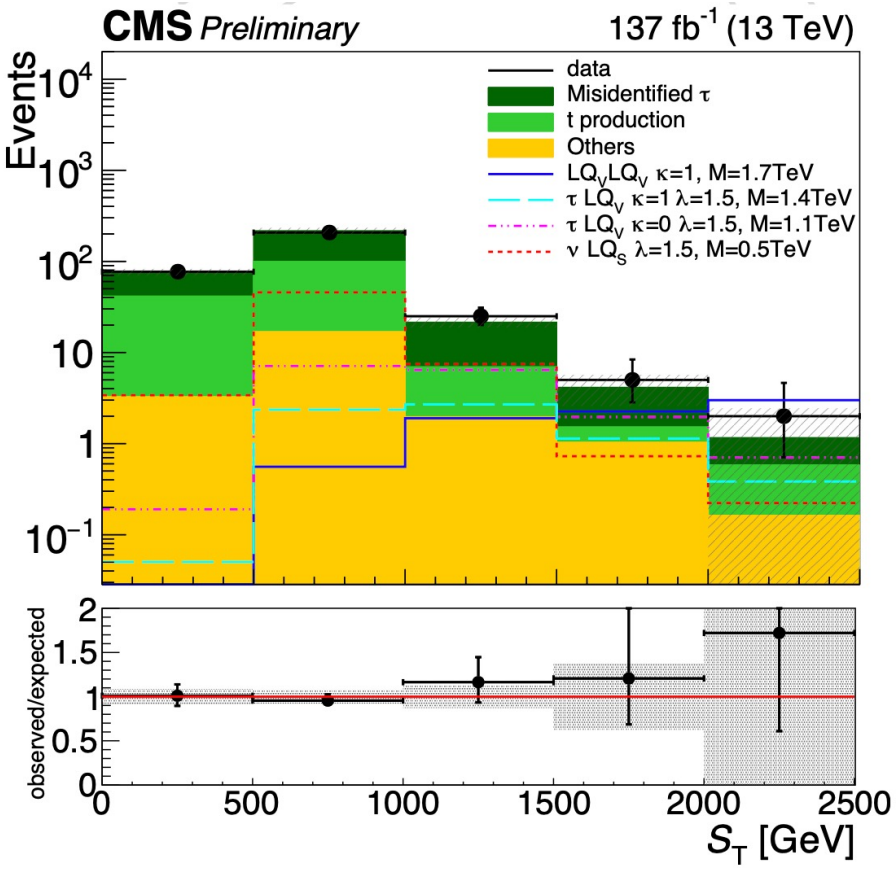
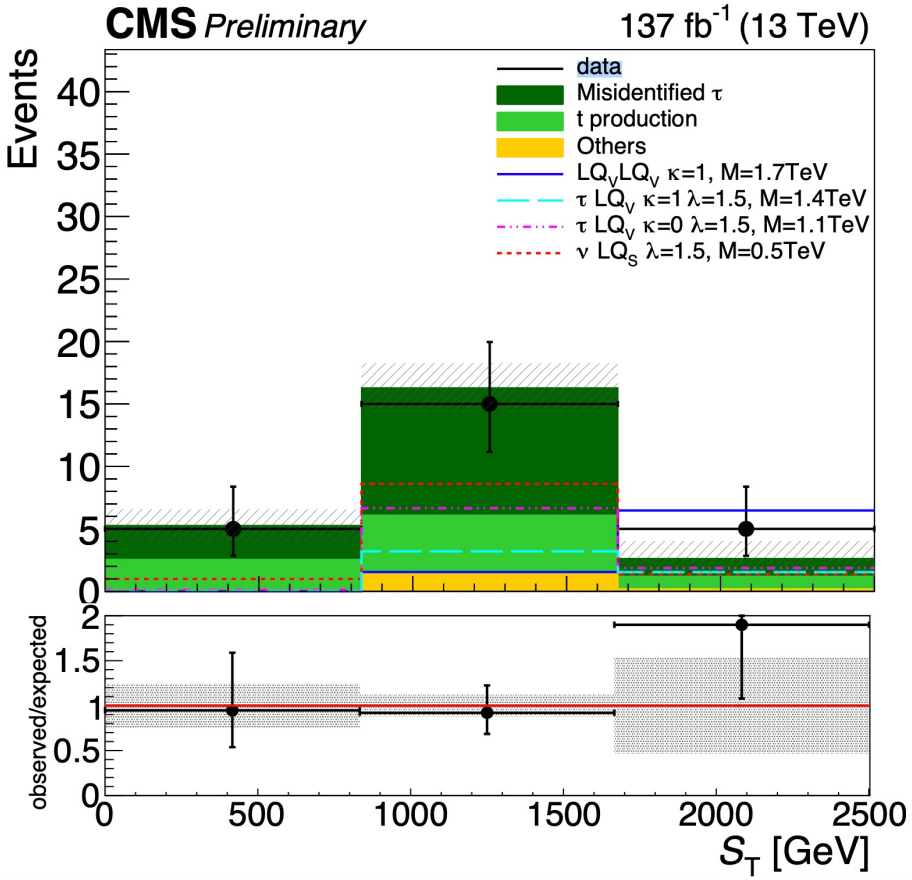


Resolved top, 2 b-jets



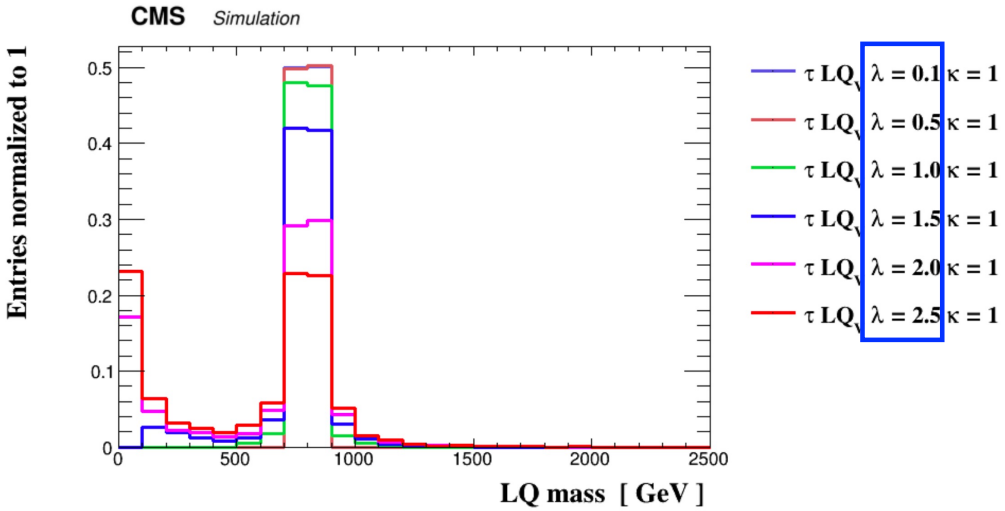
Boosted top, 2 b-jets

PLB 819 (2021) 136446

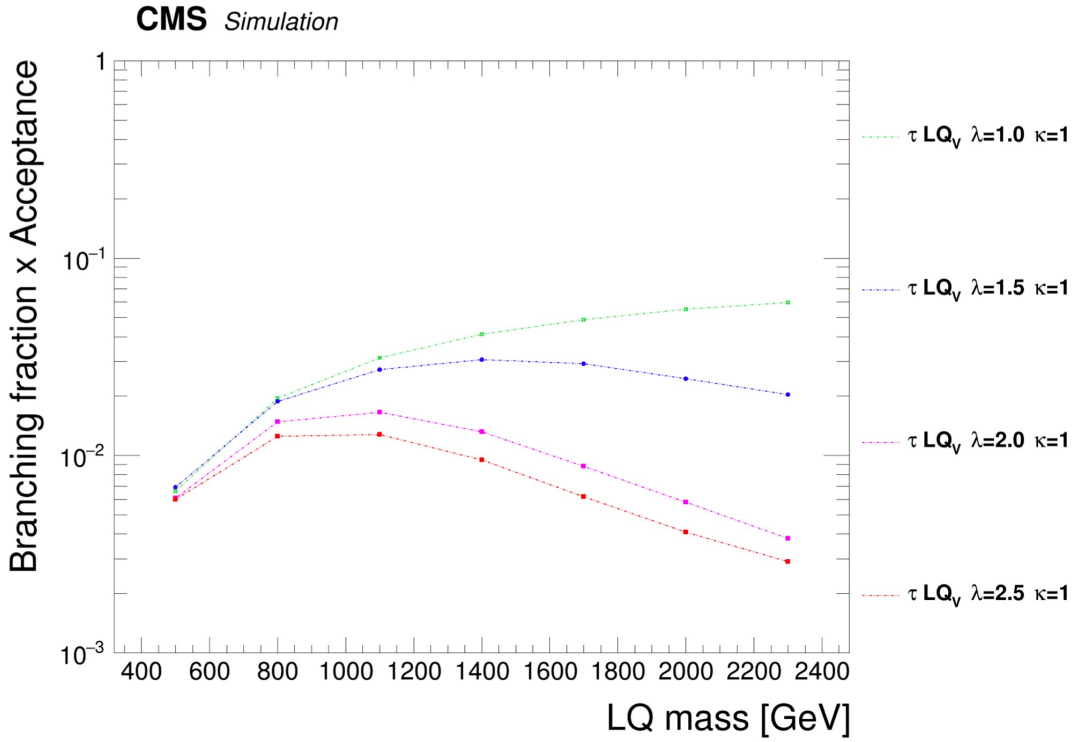
Signal efficiency for singly produced leptoquarks

- Cross-section scales with LQ-l-q coupling λ^2, but kinematics also affected
- At high λ, efficiency of selection decreases with mass due to low-mass off-shell events

Shape comparison for different λ



Single-LQ_V production, k=1



ttν(b) search

PLB 819 (2021) 136446

With 137 fb^{-1}

Combo

LQ pair

Single LQ

Preferred by B-anomalies (95% CL)

Obs. (95% CL) $LQ_V \overline{LQ}_V + \tau LQ_V$

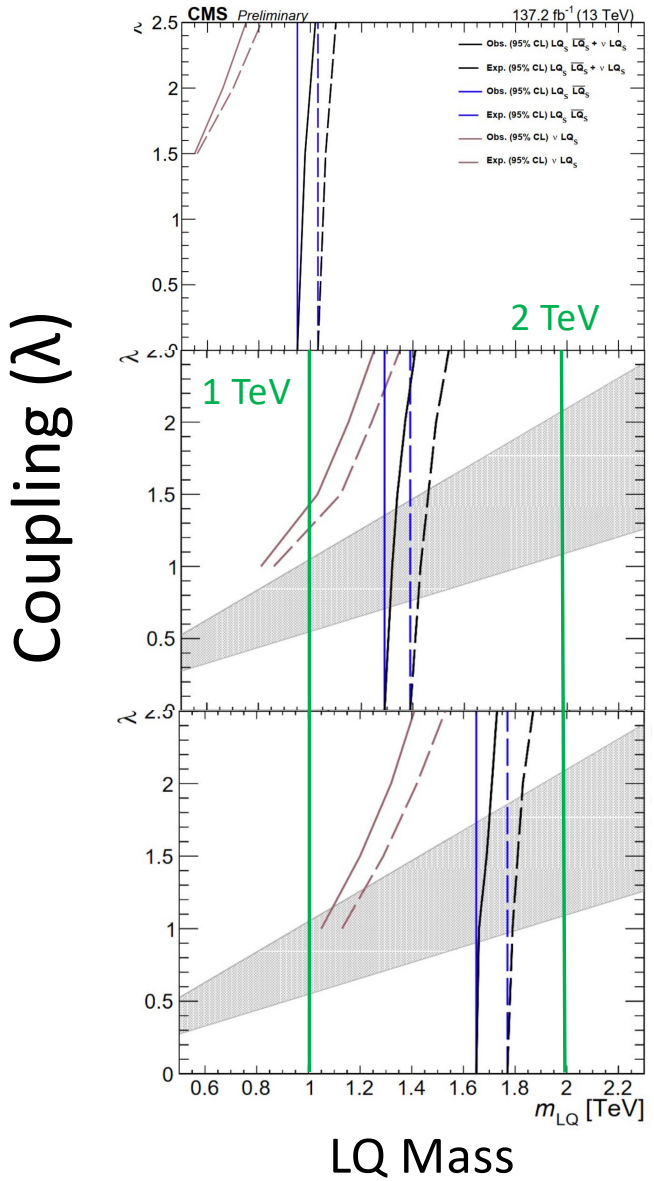
Exp. (95% CL) $LQ_V \overline{LQ}_V + \tau LQ_V$

Obs. (95% CL) $LQ_V \overline{LQ}_V$

Exp. (95% CL) $LQ_V \overline{LQ}_V$

Obs. (95% CL) τLQ_V

Exp. (95% CL) τLQ_V



Coupling (λ)

LQ Mass

Scalar

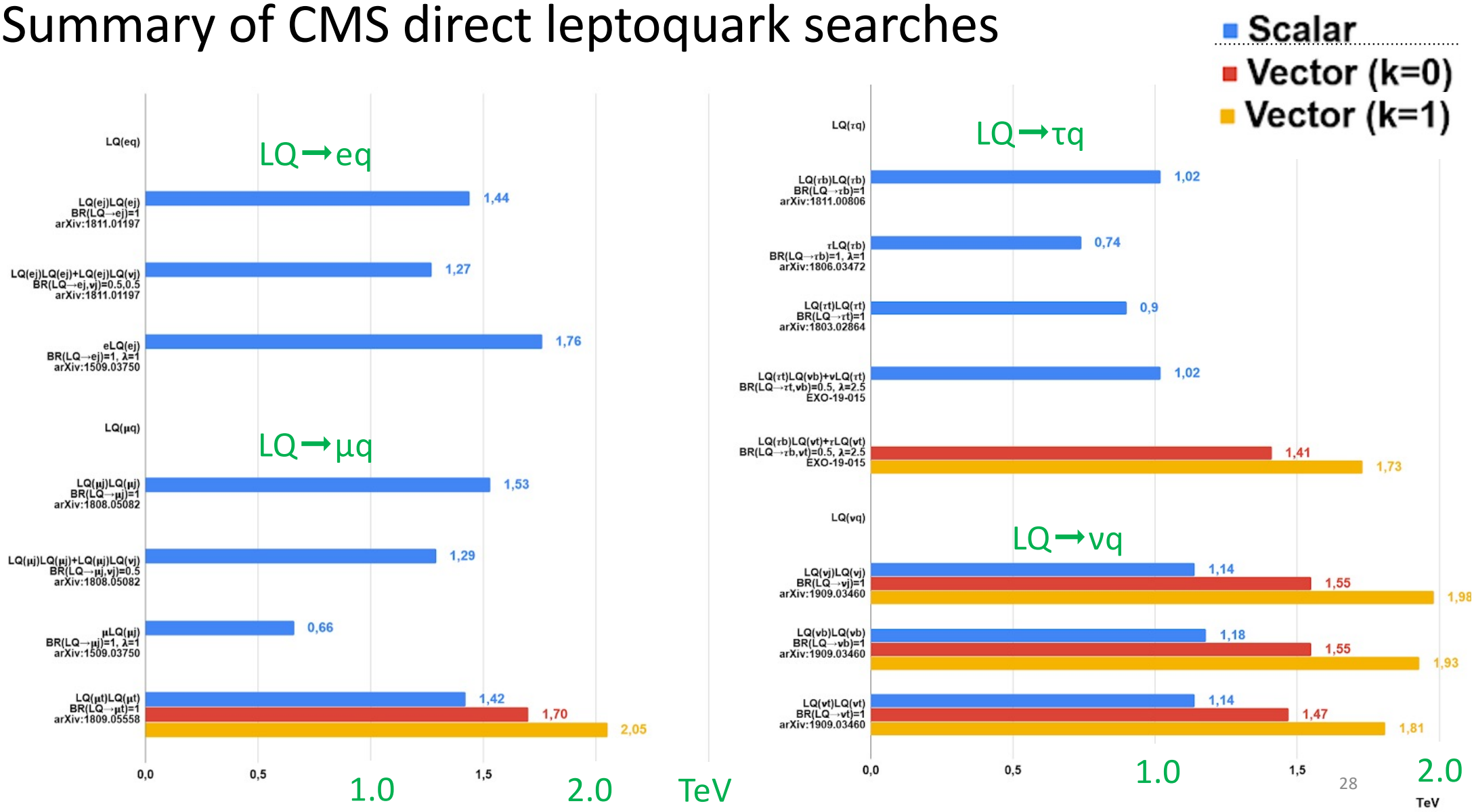
Vector, k = 0

Minimal coupling

Vector, k = 1

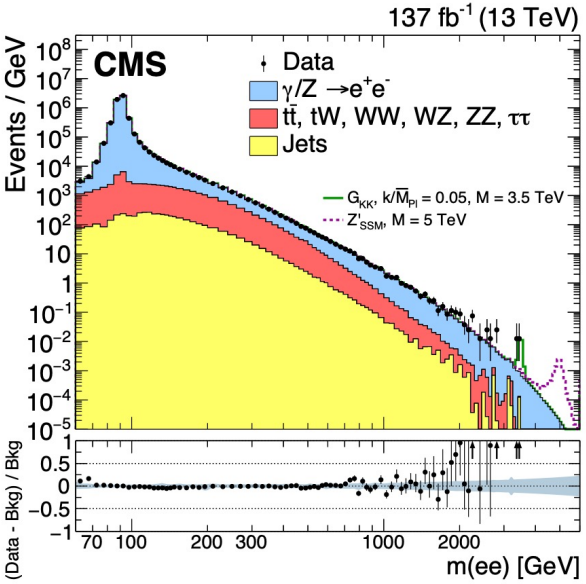
Yang-Mills coupling

Summary of CMS direct leptoquark searches

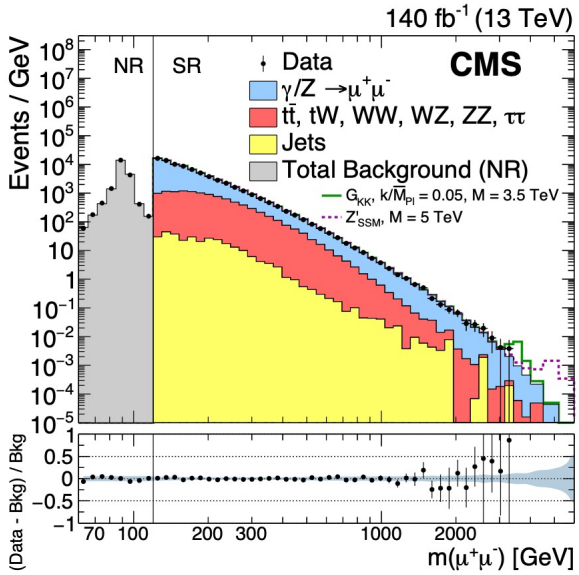


Search for Z’ mediators with LFUV

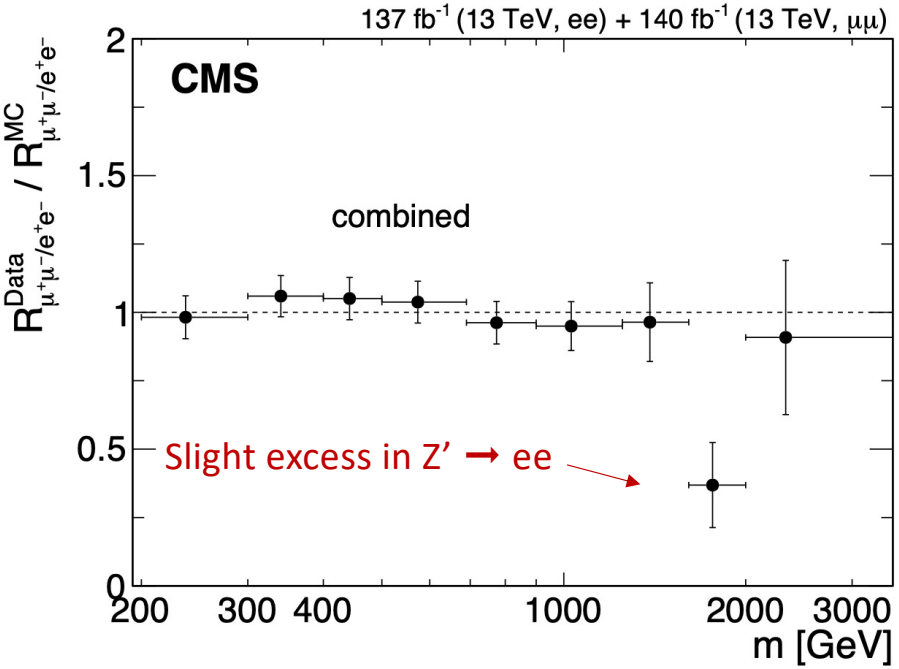
Z’ ➞ ee



Z’ ➞ μμ



Ratio of Z’ ➞ μμ / Z’ ➞ ee probes different couplings to ee and μμ



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Summary of CMS searches for leptoquarks

- Leptoquarks are motivated theoretically and experimentally
- CMS has directly searched for all 3 generations of leptoquarks
  - Several analyses updated to 137 fb^{-1}
- For 3rd-generation searches
  - Dedicated searches for leading models explaining flavor anomalies
    - Scalar & vector leptoquarks
    - LQ$\rightarrow t\nu$, $b\nu$, $t\tau$, $b\tau$
    - Pair production and single production
  - Probing up to LQ masses of ~ 1.5 – 2 TeV region
- Several new results with full Run-2 dataset in the works, stay tuned !

BACKUPS

Acknowledgements

- Izaak Neutelings (at UZH) produced the nice latex Feynman diagrams & figures

Yang-Mills couplings with leptoquarks

- Z.Phys. C76 (1997) 137-153: arXiv:hep-ph/9610408, "Leptoquark Pair Production in Hadronic Interactions"

τ_h reconstruction