Universität Zürich[UZH]

Physik-Institut

Third-generation leptoquark searches in CMS

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INTRODUCTION

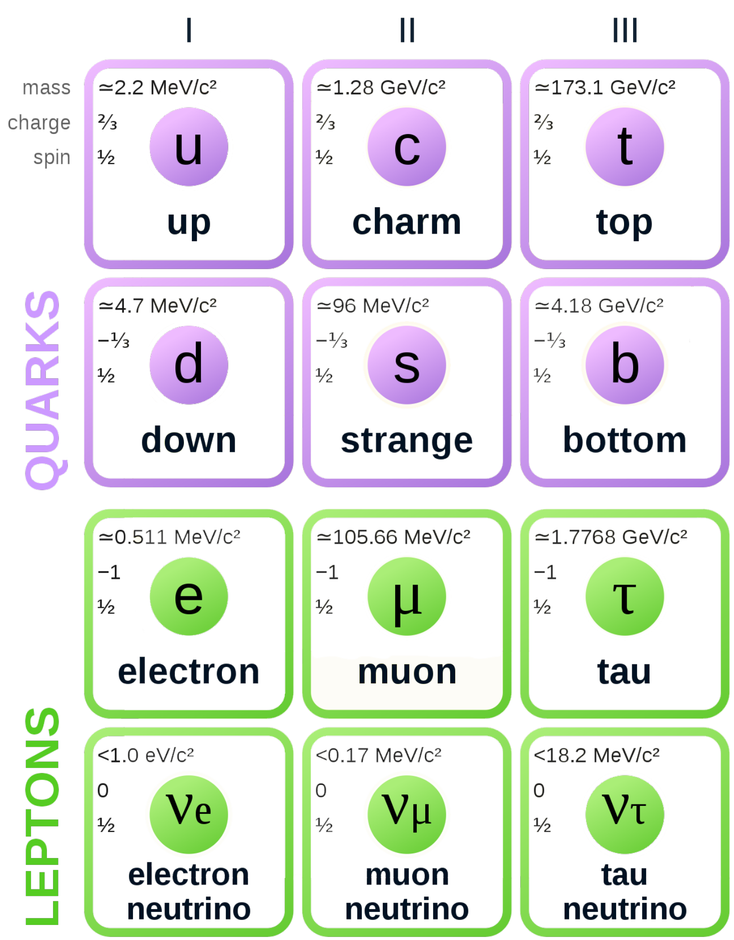
Standard Model's many symmetries…

Quantity	Symmetries	Electromagnetic	Weak	Strong
Energy	Time translation	✔	✔	✔
Linear momentum	Spatial translation	✔	✔	✔
Angular momentum	Rotations	✔	✔	✔
Center-of-mass	Lorentz boosts	✔	✔	✔
Charge, color, …	Gauge transformation	✔	✔	✔
Lepton number L		✔	✔	✔
Baryon number B		✔	✔	✔
Isospin		✔	✗	✗
Lepton flavor **not fundamental !**		✔	✔	✔
Quark flavor		✔	✗	✔
Parity P		✔	✗	✔
Charge conjugation C		✔	✗	✔
Time reversal T		✔	✗	✔
CP		✔	✗	✔
CPT		✔	✔	✔

* fundamental to relativistic gauge field theories, like the SM

Flavor universality in the SM

- SM gauge couplings cannot differentiate leptons
- only the Higgs can via Yukawa coupling



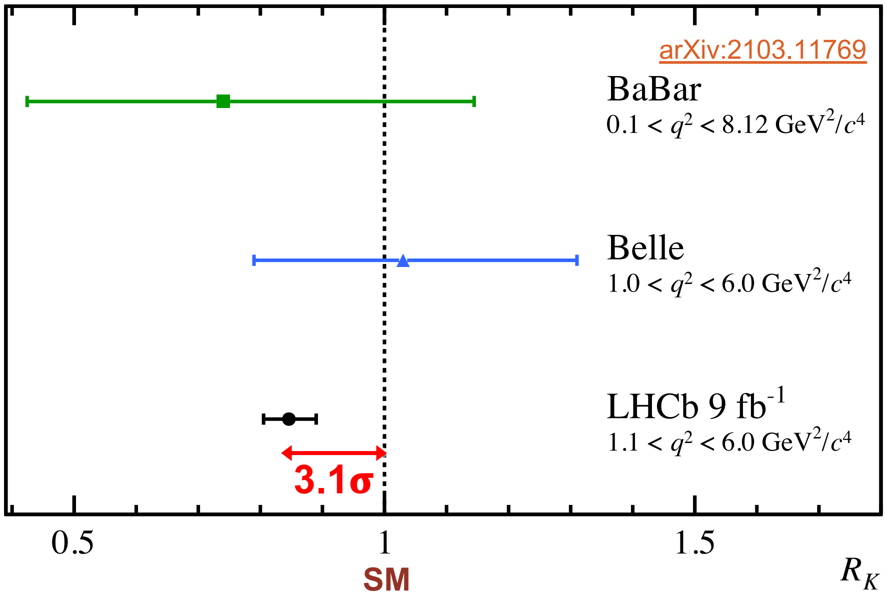
but by what mechanism ?

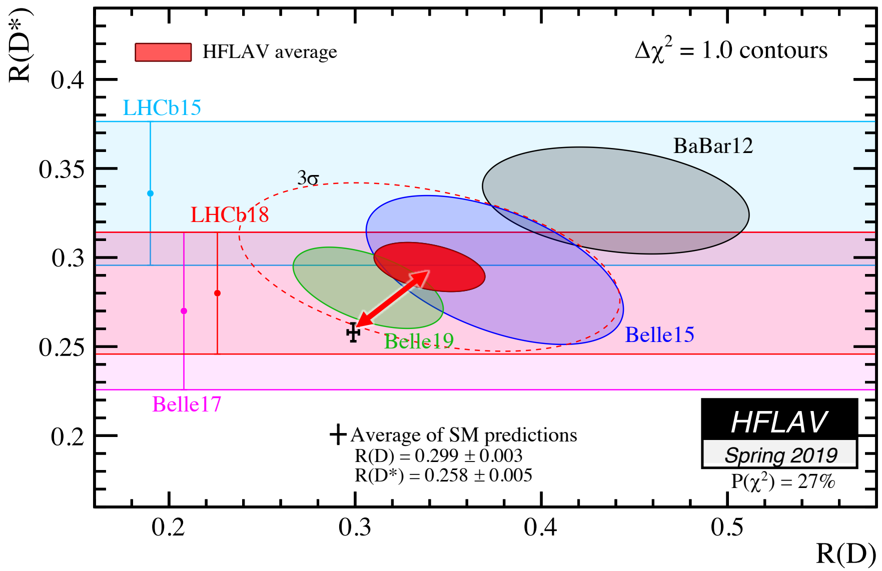
why three generations ?

⇒ hopefully new physics can explain

B anomalies at Belle, BaBar, LHCb

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}ee\right)} \overset{\text{SM}}{<} 1 \qquad R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\text{SM}}{>} 0.25$$



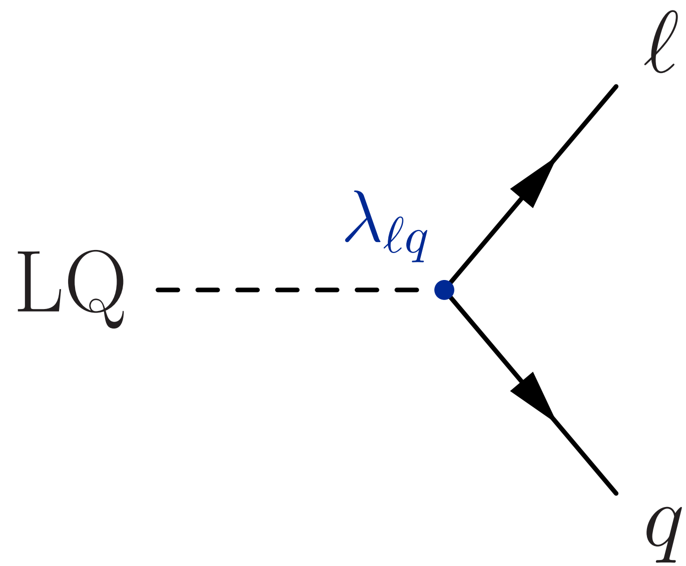


R(K$^{(*)}$) and angular observables combined ~ 4σ deviation

R(D$^{(*)}$) combined 3.1σ deviation

⇒ signs of new physics violating lepton flavor universality?

Leptoquarks

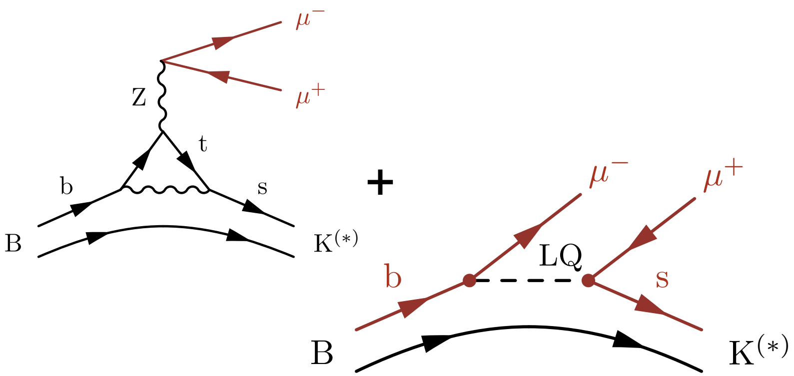


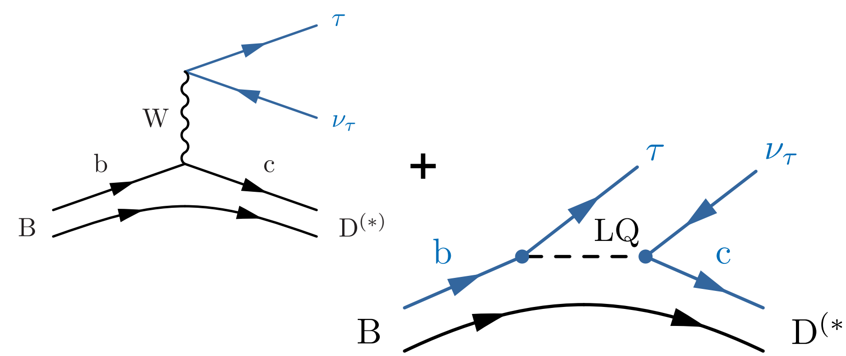
- **scalar** or **vector boson**
- **decays into *ℓq***
  ⇒ carries L, B, color
- **fractional charge**
- **coupling $\lambda_{\ell q}$**

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

B anomalies according to LQs

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}\mathrm{ee}\right)} \overset{\textbf{SM}}{\boxed{< 1}} \qquad R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\textbf{SM}}{>} 0.25$$





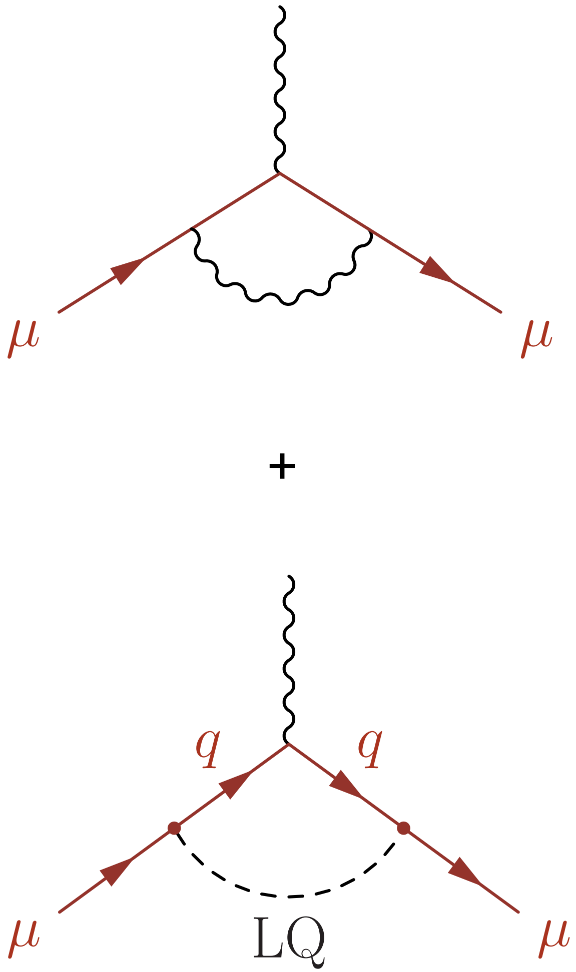
combined explanation with vector leptoquark:

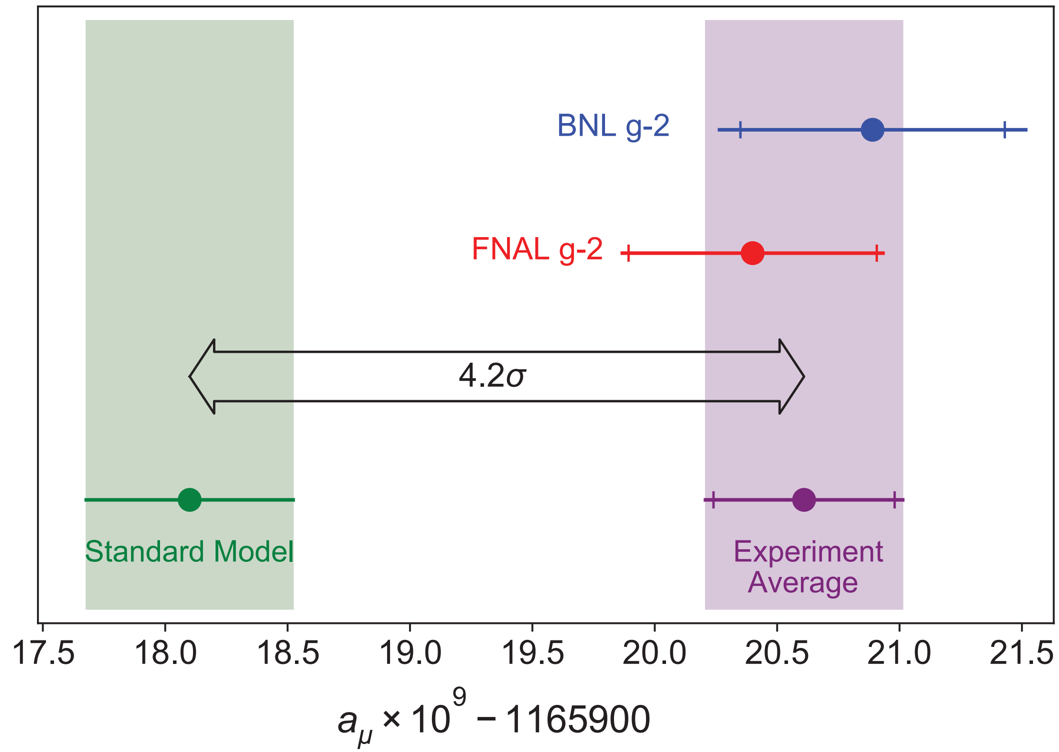
$$\Rightarrow \quad \lambda_{\ell q} \sim \begin{array}{c} \\ \mathrm{d}/\mathrm{u}' \\ \mathrm{s}/\mathrm{c}' \\ \mathrm{b}/\mathrm{t}' \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{e}/\nu_{\mathrm{e}} & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \left(\begin{array}{ccc} 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{array}\right) \end{array} \qquad \mathrm{LQ} \approx \mathrm{LQ}_3$$

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

[Isidori group: arXiv:1706.07808, arXiv:1903.11517]

Muon anomalous moment





SM theory: 116 591 810 (43) × 10^{-11} (460 ppb)

Experiment: 116 592 061 (41) × 10–11 (350 ppb)

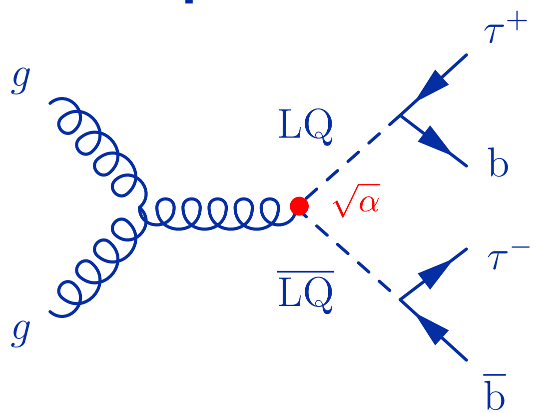
BNL & FNAL combined 4.2σ deviation

BNL: arXiv:hep-ex/0602035, FNAL: arXiv:2104.03281, theory WP: arXiv:2006.04822

LQ_3 SEARCHES AT CMS

LQ production at CMS

pair

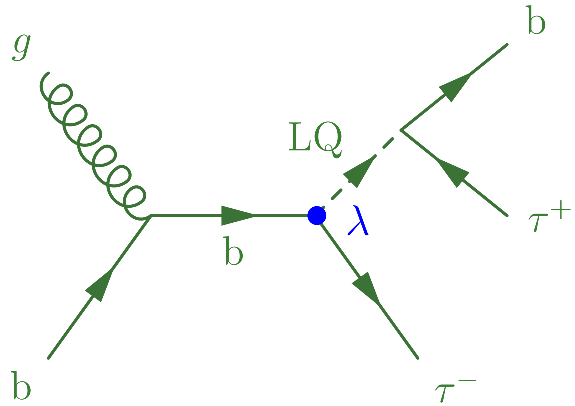


☺️ large,

🙂 model independent

🙂 resonant

single

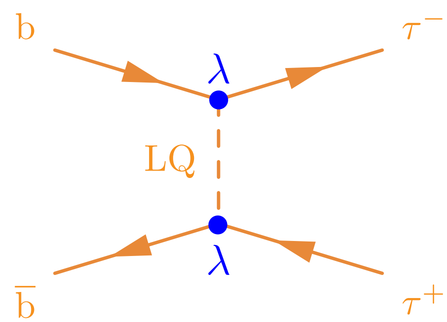


🙂 $\sigma \propto \lambda^2$

🙁 b-PDF suppression

🙁 width $\propto \lambda^2$

nonresonant

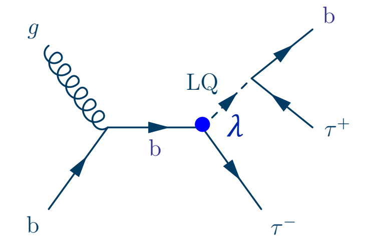


🙂 $\sigma \propto \lambda^4$

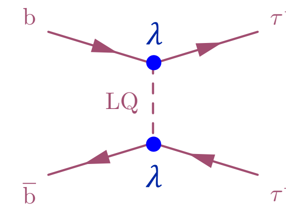
😱 PDF suppression ^ 2

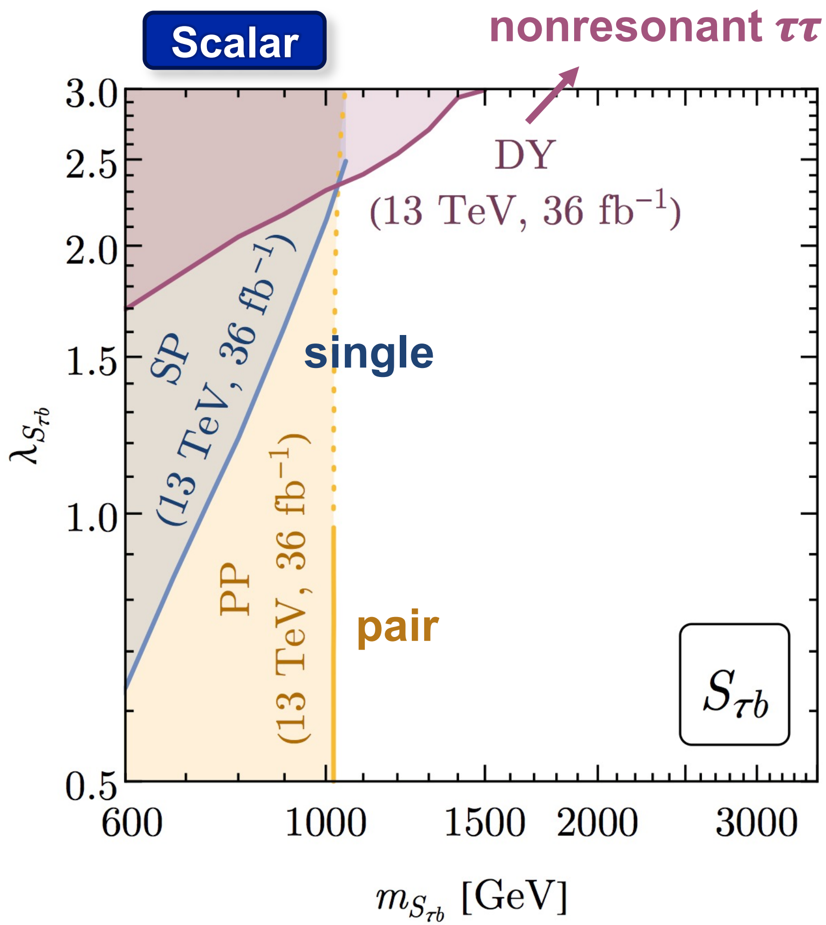
🙁 wide resonance

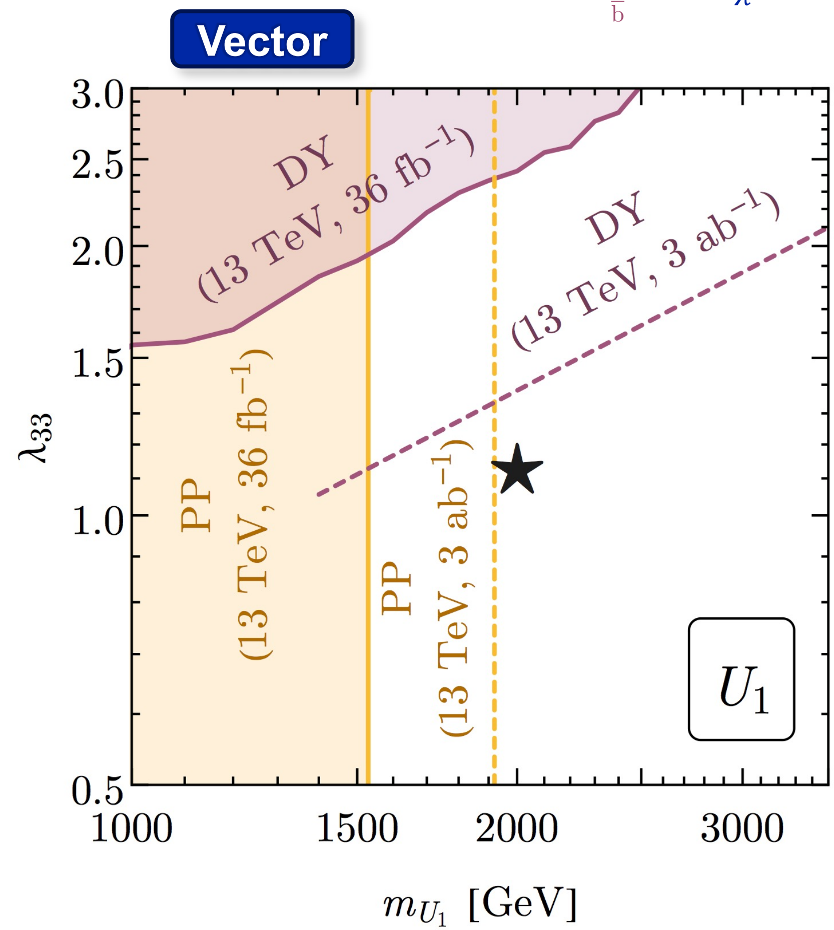
Exclusion in λ vs. mass space



use the fact that single production has $\boldsymbol{\sigma \sim \lambda^2}$,
and nonresonant $\tau\tau$ production $\boldsymbol{\sigma \sim \lambda^4}$
to exclude higher masses & couplings λ



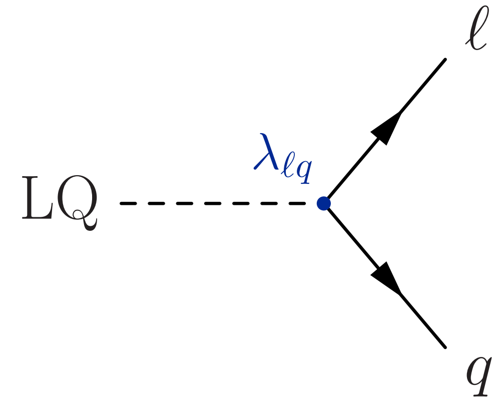




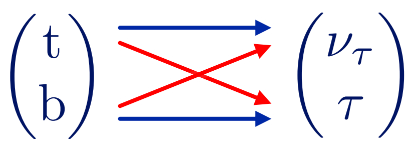
pheno papers: arXiv:1609.07138, arXiv:1810.10017

LQ_3 models & signatures

- scalar LQ_S (S = 0), vector LQ_V (S = 1)
- decays into ℓq
  - ⇒ carries L, B, color
  - ⇒ fractional charge
- coupling $\lambda_{\ell q}$



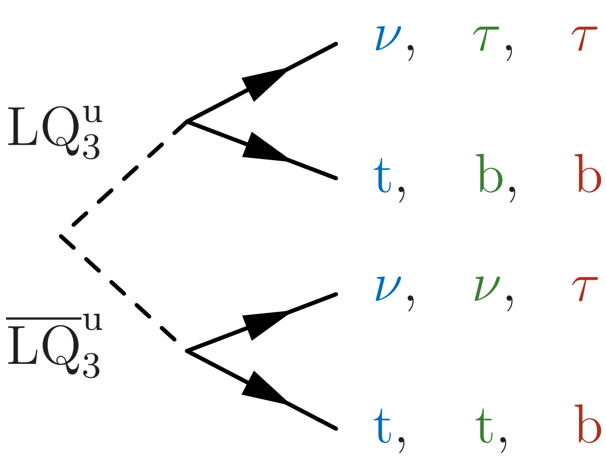
- simplified models restrict to up *or* down type:



$$\mathrm{LQ}_3^{\mathrm{u}} \rightarrow \mathrm{t}\nu,\ \mathrm{b}\tau, \quad Q = +\tfrac{2}{3}$$

$$\mathrm{LQ}_3^{\mathrm{d}} \rightarrow \mathrm{t}\tau,\ \mathrm{b}\nu, \quad Q = -\tfrac{1}{3}$$

- branching parameter β



$$\mathcal{B}\left(\mathrm{LQ} \rightarrow q\ell^{\pm}\right) = \beta$$

$$\mathcal{B}\left(\mathrm{LQ} \rightarrow q'\nu\right) = 1 - \beta$$

typical benchmarks β = 0, 0.5, 1

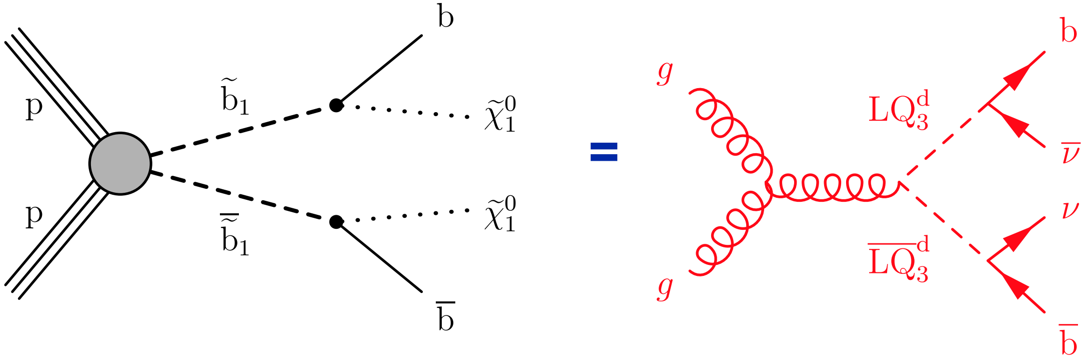
$$\mathrm{LQ}_3^{\mathrm{u}}\overline{\mathrm{LQ}}_3^{\mathrm{u}} \rightarrow \mathrm{t}\nu\mathrm{t}\nu, \mathrm{t}\nu\mathrm{b}\tau, \mathrm{b}\tau\mathrm{b}\tau$$

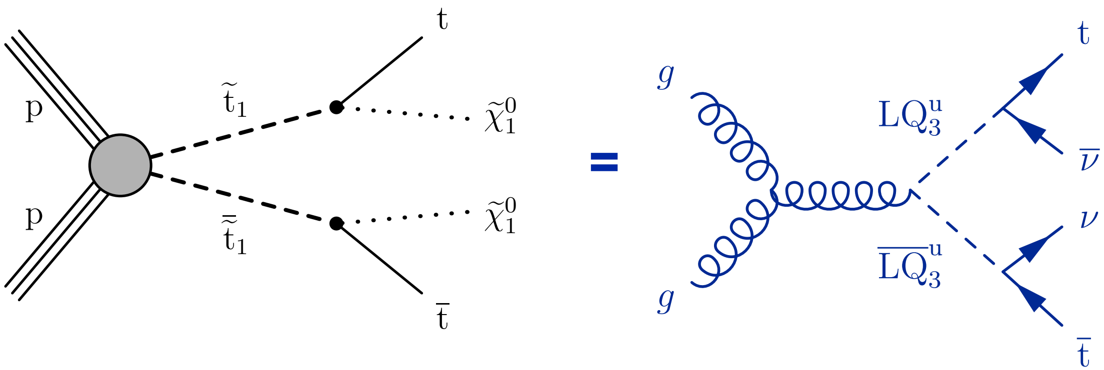
$$\mathrm{LQ}_3^{\mathrm{d}}\overline{\mathrm{LQ}}_3^{\mathrm{d}} \rightarrow \mathrm{t}\tau\mathrm{t}\tau, \mathrm{t}\tau\mathrm{b}\nu, \mathrm{b}\nu\mathrm{b}\nu$$

$LQ_3LQ_3 \to b\nu b\nu,\ t\nu t\nu$

arXiv:1909.03460
β = 0, 137 fb^{-1}

reinterpret stop & sbottom searches with ≥2 jets + MET:



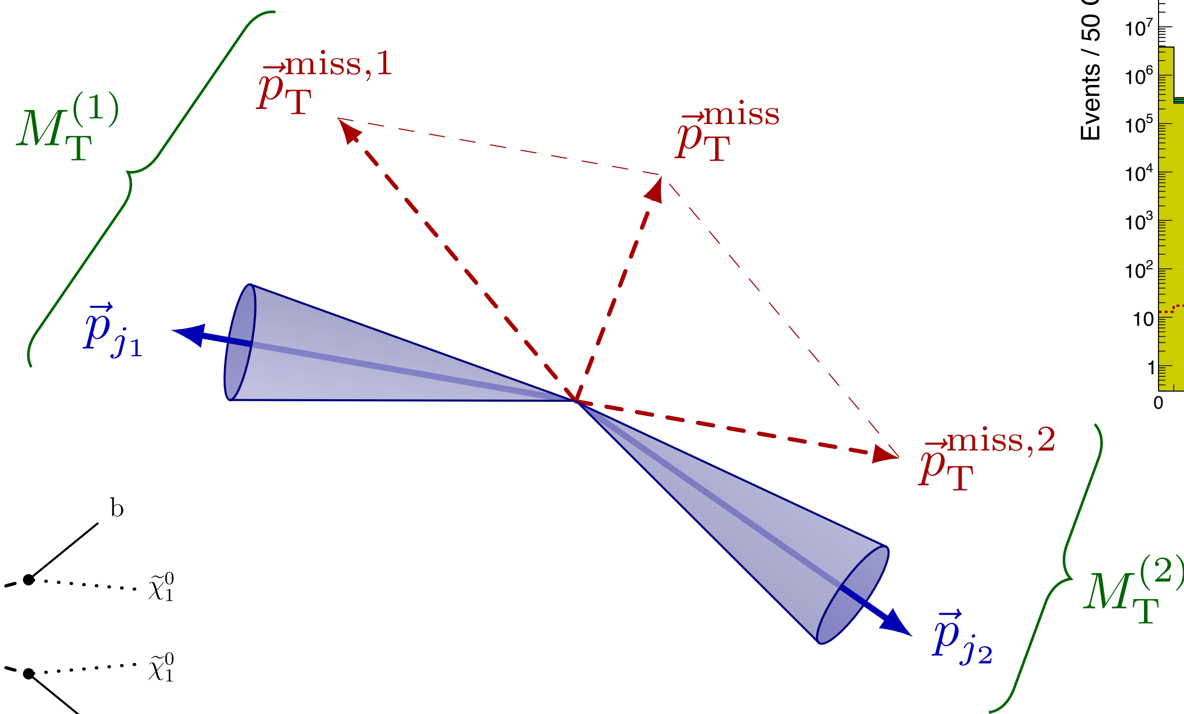


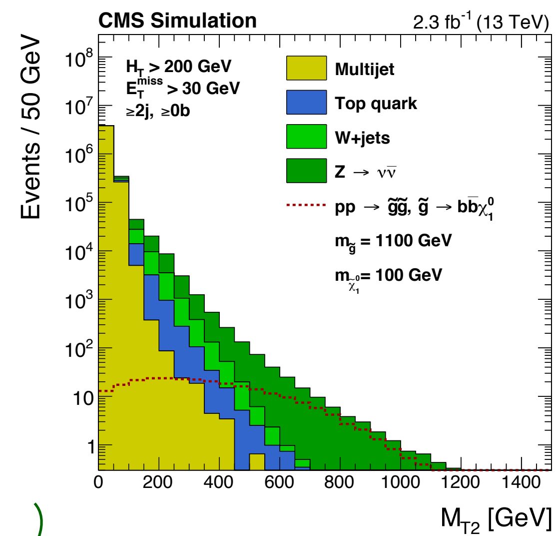
$$M_{T2} = \min_{\vec{p}_T^{\,\mathrm{miss},1} + \vec{p}_T^{\,\mathrm{miss},2} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

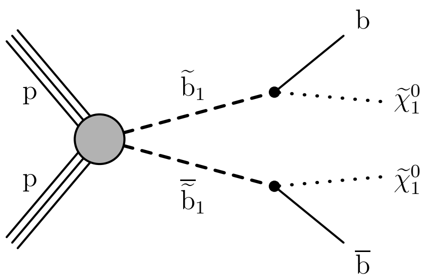
$LQ_3LQ_3 \to b\nu b\nu,\ t\nu t\nu$

- select events with **≥2 jets**, large p_T^{miss}, H_T > 250 GeV
- cluster visible objects into 2 large pseudo-jets
- decompose p_T^{miss} to minimize

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





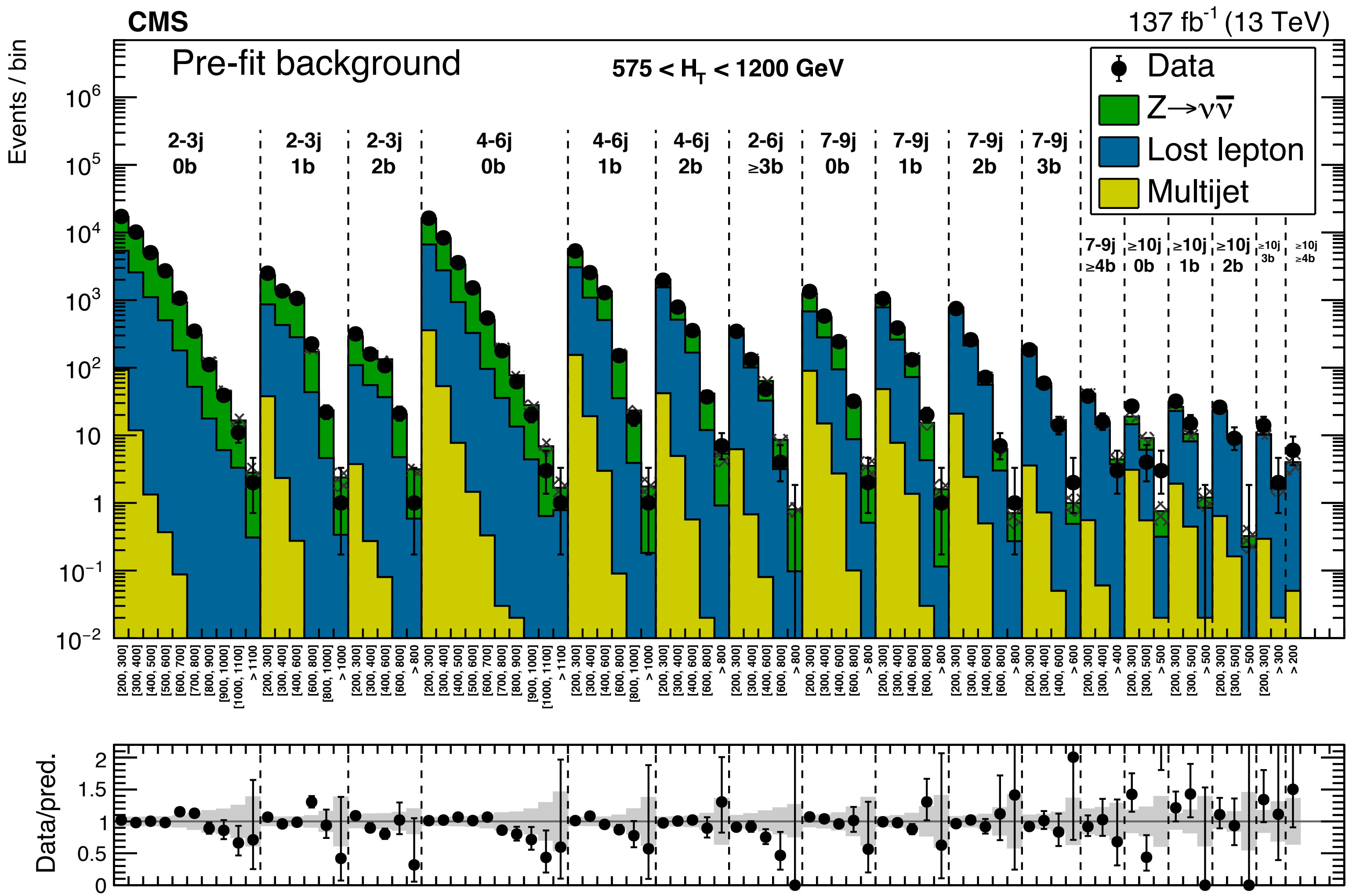


arXiv:1909.03460

β = 0, 137 fb^{-1}

LQ$_3$LQ$_3$ → bνbν, tνtν strategy

- select 2 jets, veto charged lepton, τ_h
- fit M_{T2} in many bins of #jets, b tags, H_T

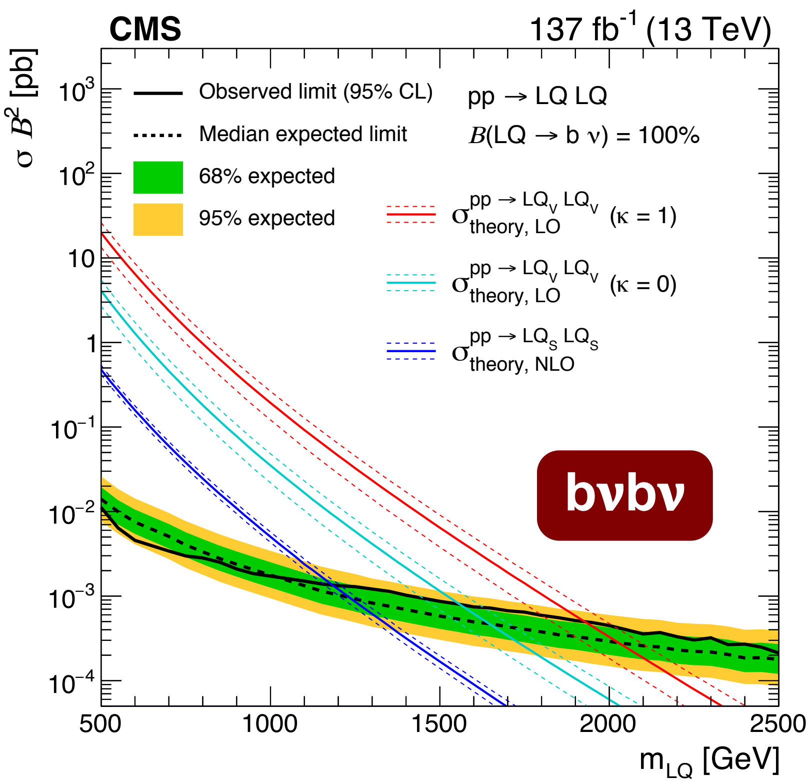


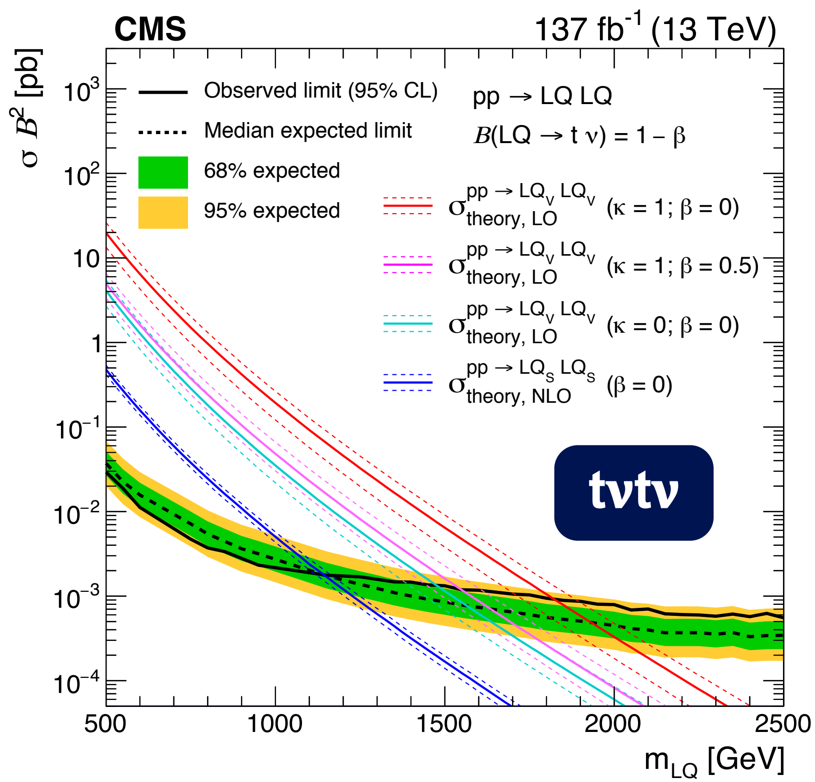
$$M_{T2} = \min_{\vec{p}_T^{\text{miss},1} + \vec{p}_T^{\text{miss},2} = \vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

M_{T2} [GeV]

β = 0, 137 fb^{-1}

LQ$_3$LQ$_3$ → bνbν, tνtν results



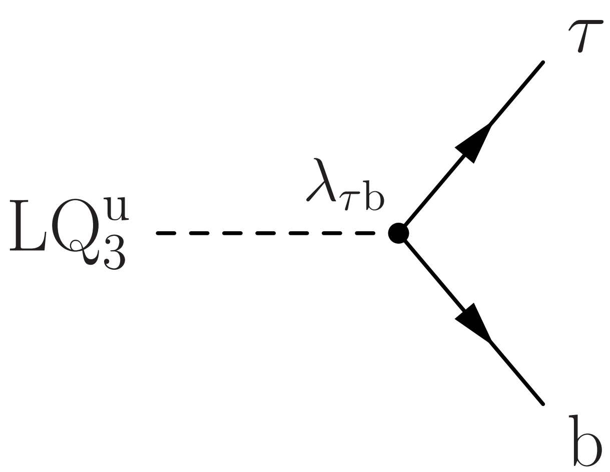


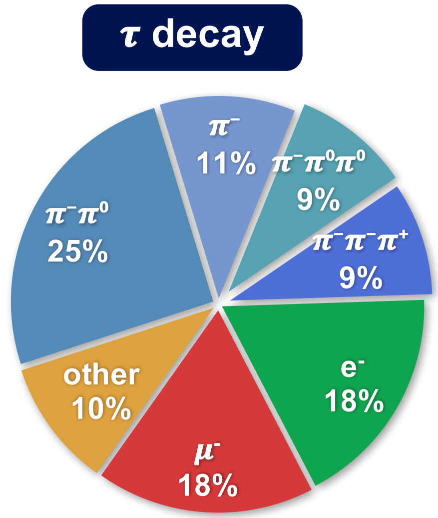
	$\mathrm{LQ_S}$ mass [GeV]	$\mathrm{LQ_V},\ \kappa = 1$ mass [GeV]	$\mathrm{LQ_V},\ \kappa = 0$ mass [GeV]
$\mathrm{LQ}_i \to q\nu$ ($q = \mathrm{u, d, s,}$ or c)	1140	1980	1560
$\mathrm{LQ_3^d} \to \mathrm{b}\nu$	1185	1925	1560
$\mathrm{LQ_3^u} \to \mathrm{t}\nu$	1140	1825	1475
$\mathrm{LQ_3^u} \to \begin{cases} \mathrm{t}\nu & (\mathcal{B} = 50\%) \\ \mathrm{b}\tau & (\mathcal{B} = 50\%) \end{cases}$	—	1550	1225

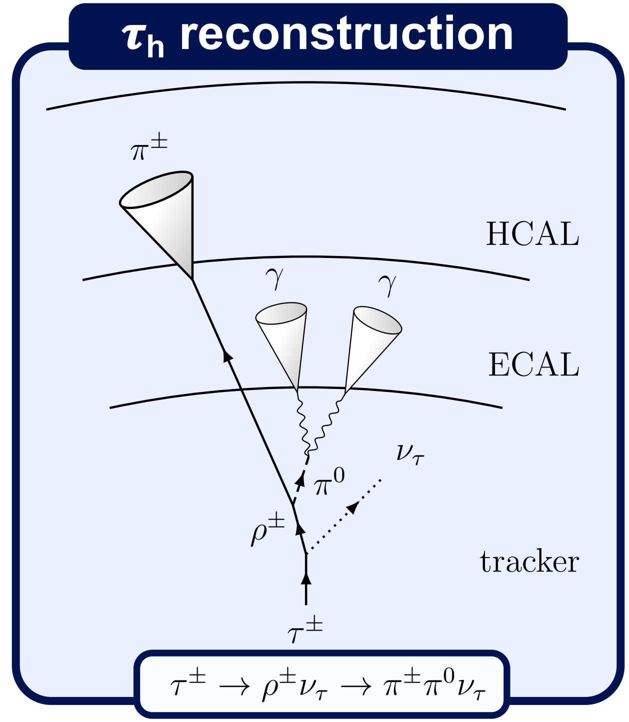
strongest constraints on scalar & vector production through pair production

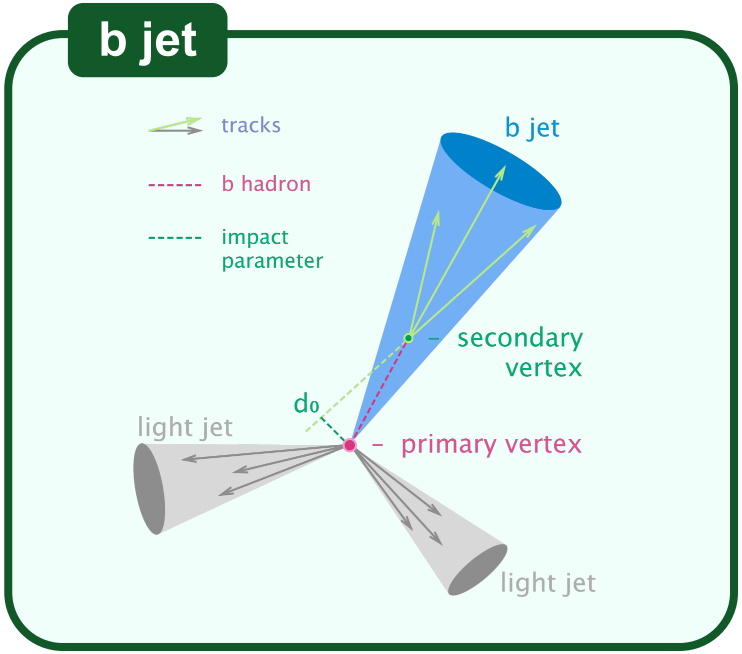
non-minimal coupling κ = 1 (Yang-Mills), 0 (minimal)

$LQ_3 \rightarrow b\tau$ reconstruction





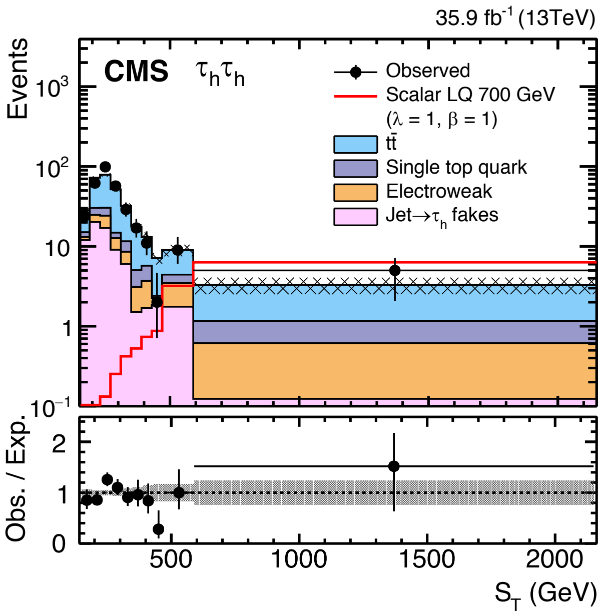




$LQ_3 \rightarrow b\tau$ single production

arXiv1806.03472

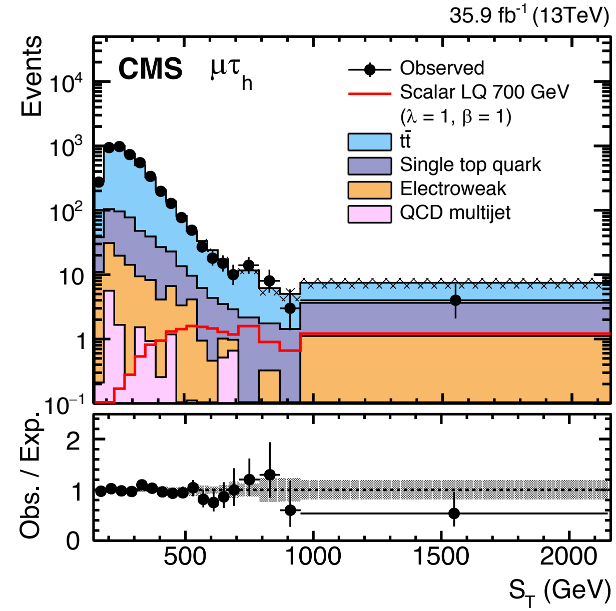
scalar, β = 1, 35.9 fb^{-1}

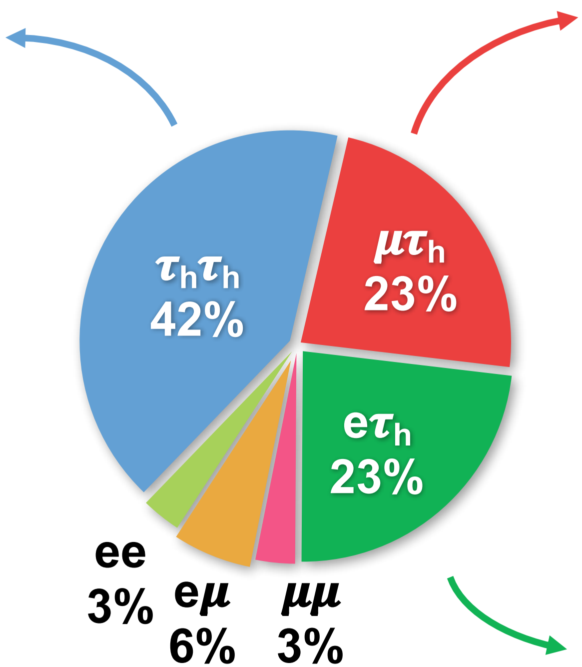


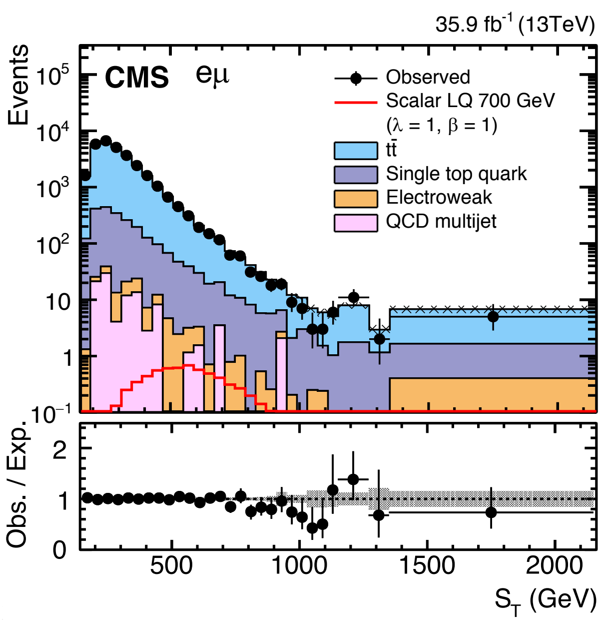
require 1 b jet + $\tau\tau$

fit "scalar sum p_T"

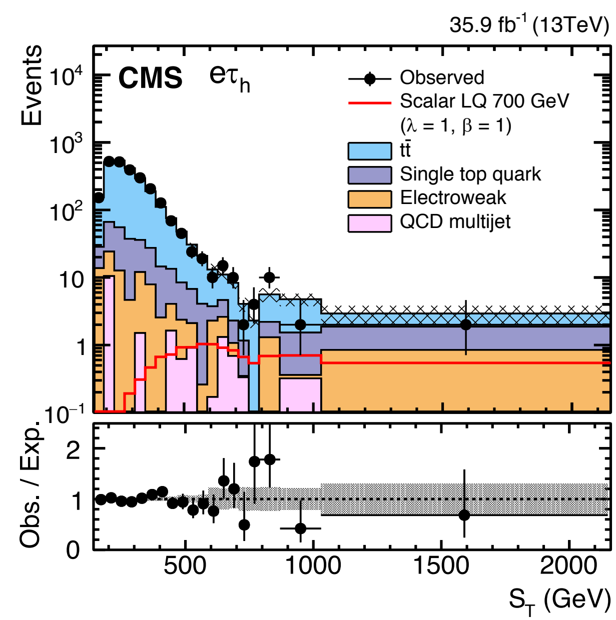
$$S_T = p_T^{\tau^1_{vis}} + p_T^{\tau^2_{vis}} + p_T^{j}$$



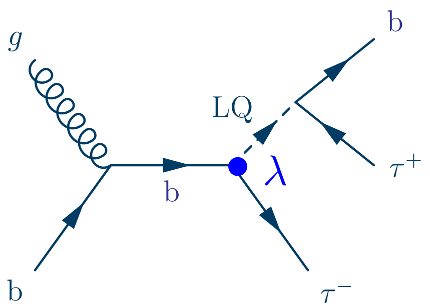




$e\mu$ control region to constrain uncertainties

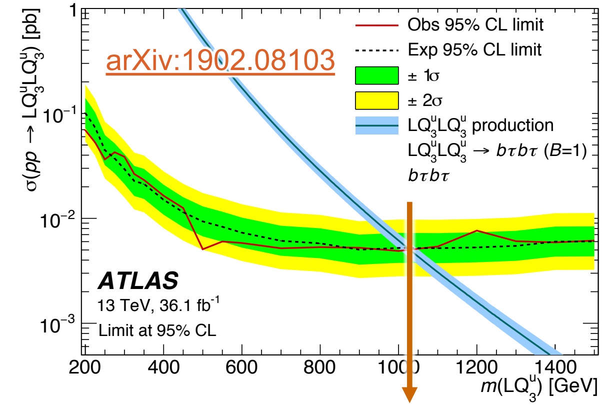


$LQ_3 \rightarrow b\tau$ upper limits



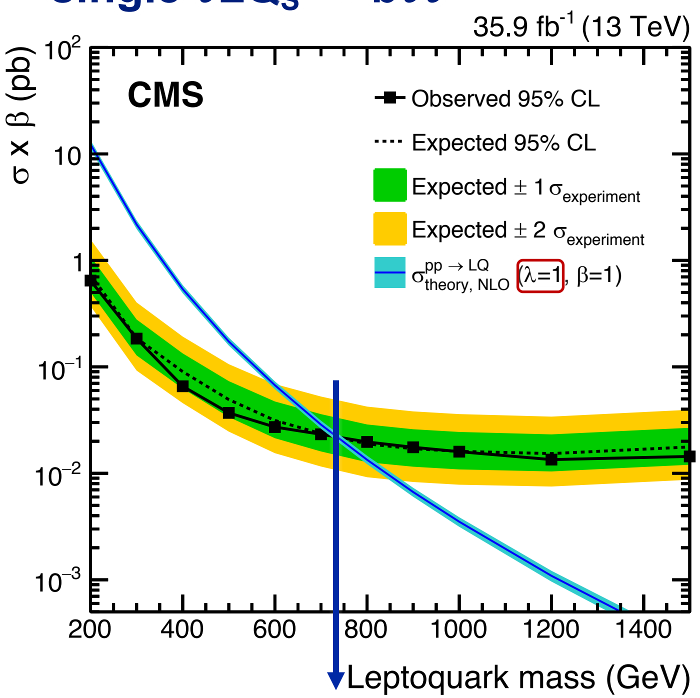
single production becomes more important at high couplings: $\sigma(\tau LQ) \sim \lambda^2$

pair $LQ_S LQ_S \rightarrow bb\tau\tau$



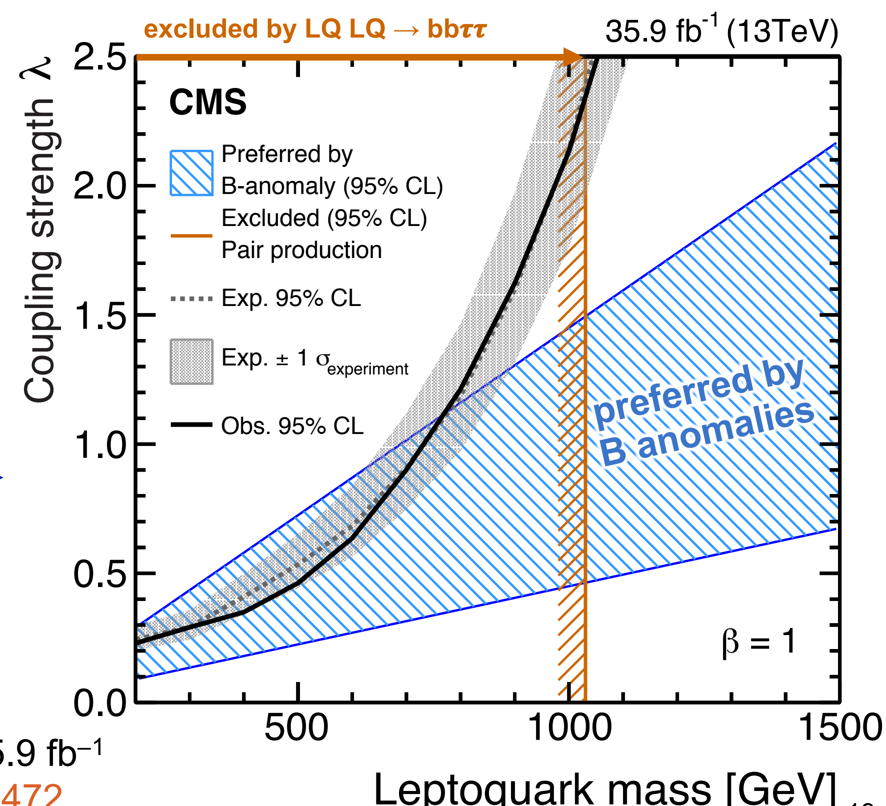
lower limit **m_{LQ} ~ 1030 GeV**

single $\tau LQ_S \rightarrow b\tau\tau$



m_{LQ} > 744 GeV

$\sigma(\tau LQ) \sim \lambda^2$



scalar, β = 1, 35.9 fb^{-1}
arXiv1806.03472

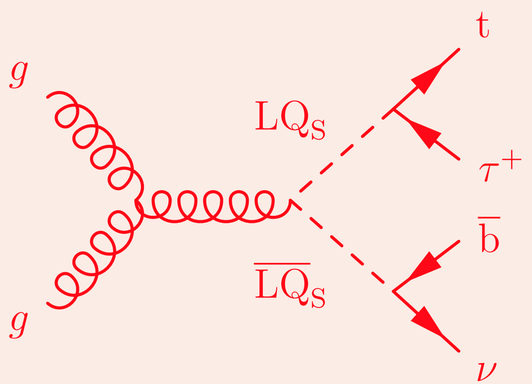
arXiv:2012.04178
$\beta = 0.5$, 137 fb^{-1}

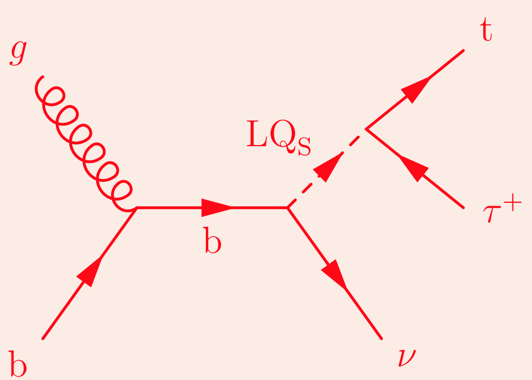
$LQ_3 LQ_3 \rightarrow t\nu b\tau$ / $t\tau b\nu$

Scalar LQ_S

$t\tau$ 50%
$b\nu$ 50%

arXiv:1706.07808





pair final state
$t\nu b\tau$

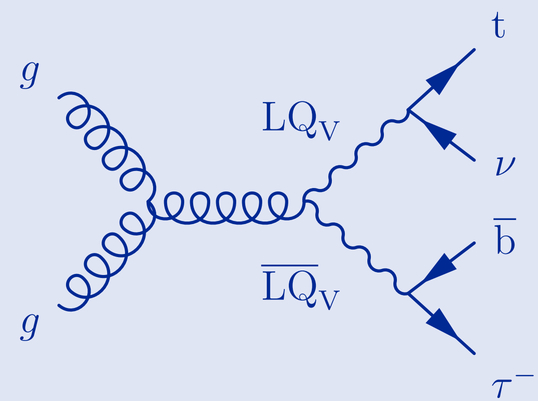
single final state
$t\nu(b)\tau$

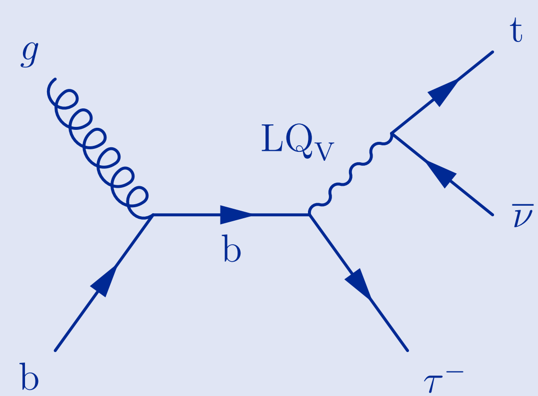
gluon splitting

Vector LQ_V

$t\nu$ 50%
$b\tau$ 50%

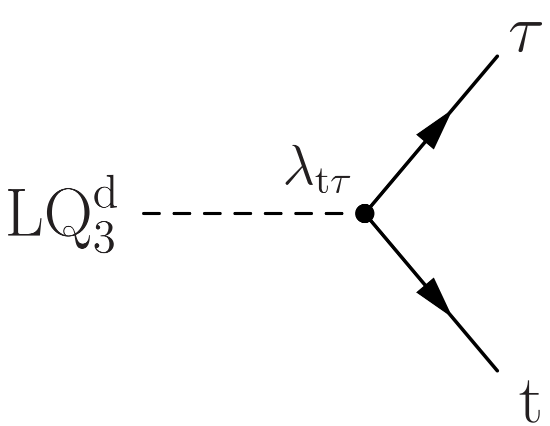
arXiv:1808.02063

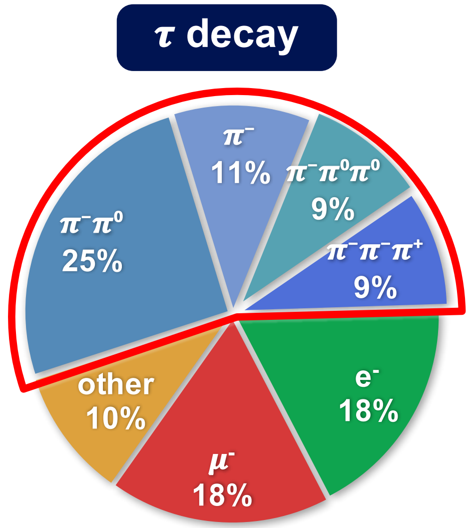


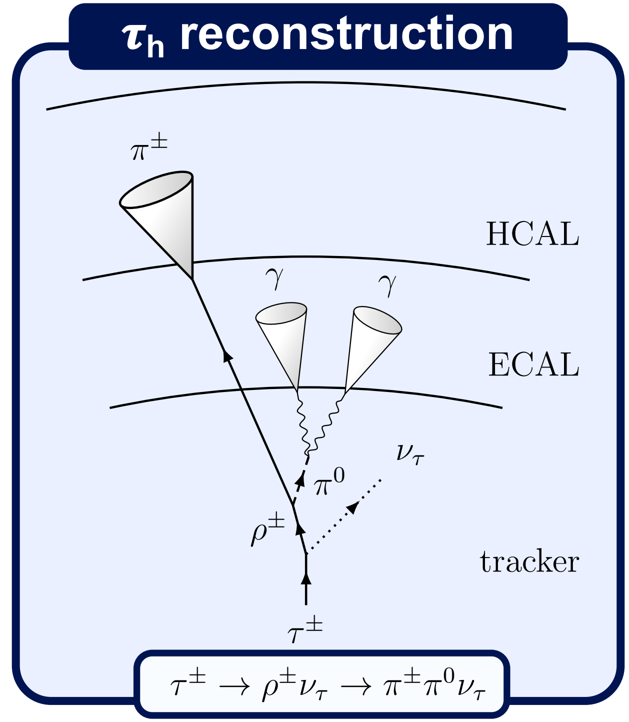


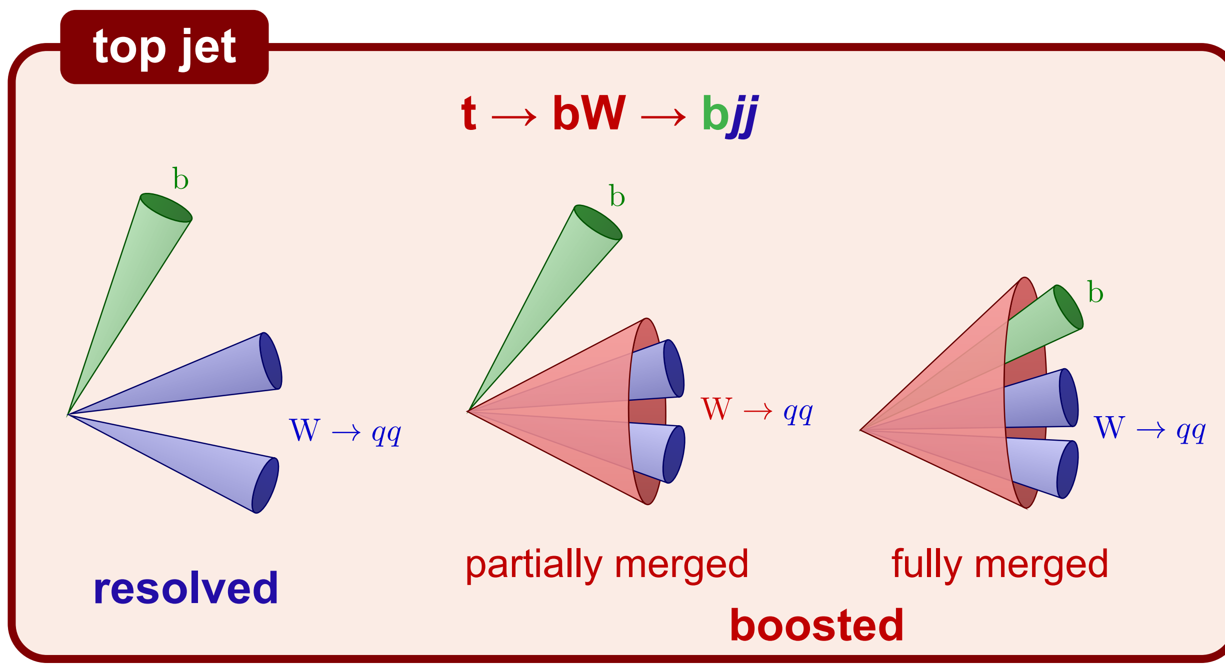
top PDF heavily suppressed

$LQ_3 \to t\tau$ reconstruction









arXiv:2012.04178

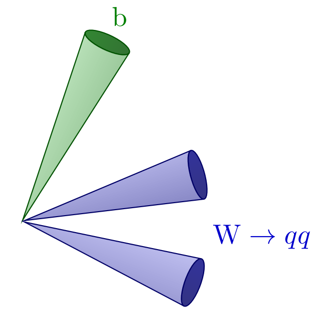
β = 0.5, 137 fb^{-1}

$LQ_3LQ_3 \rightarrow t\nu b\tau$ / $t\tau b\nu$ strategy

- reconstruct τ lepton in fully hadronic final state
- reconstruct top in fully hadronic final state:
  1. **resolved**: 3 AK4 jets
  2. **boosted**, partially merged
  3. **boosted**, fully merged
- four categories:
  – two b jet categories: 1b, ≥2b
  – resolved or boosted top
- fit scalar sum p_T

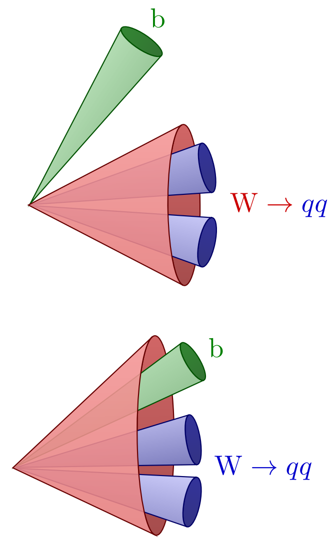
$$S_T = p_T^t + p_T^{\tau_h} + p_T^{\text{miss}}$$

- single + pair is one signal

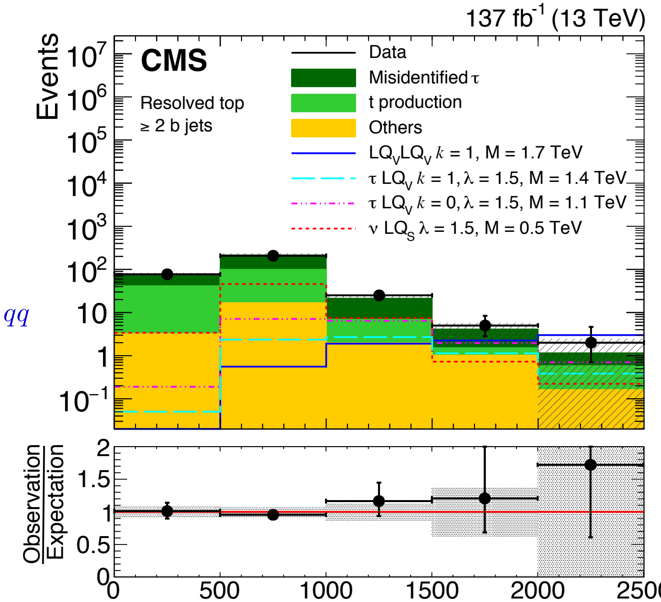


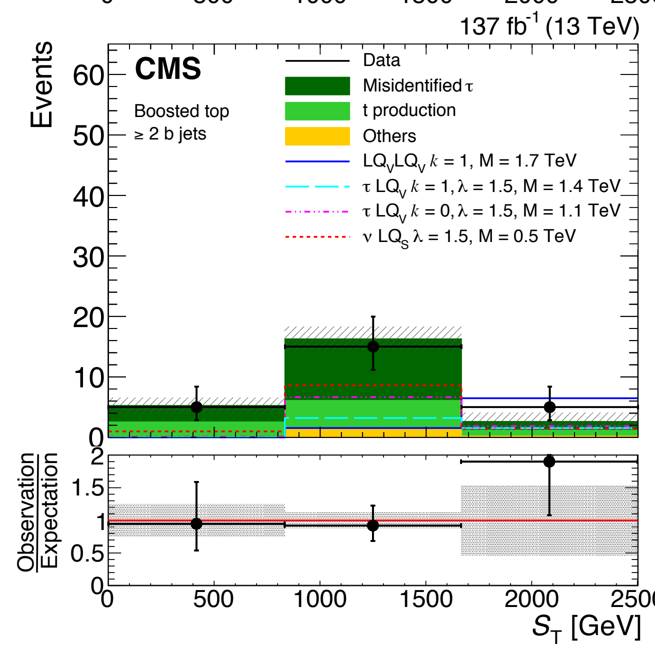
resolved top

t → bW → bjj



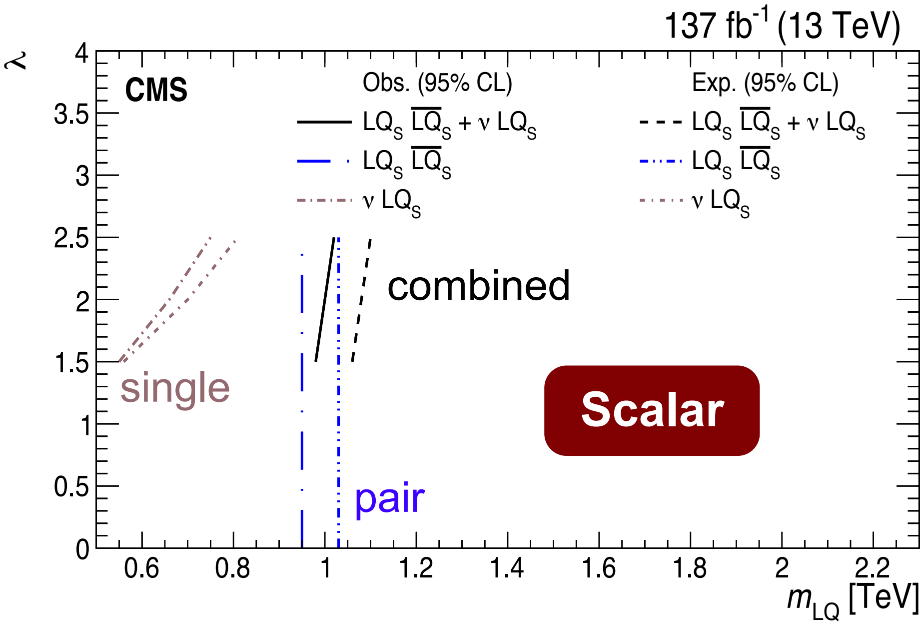
boosted top

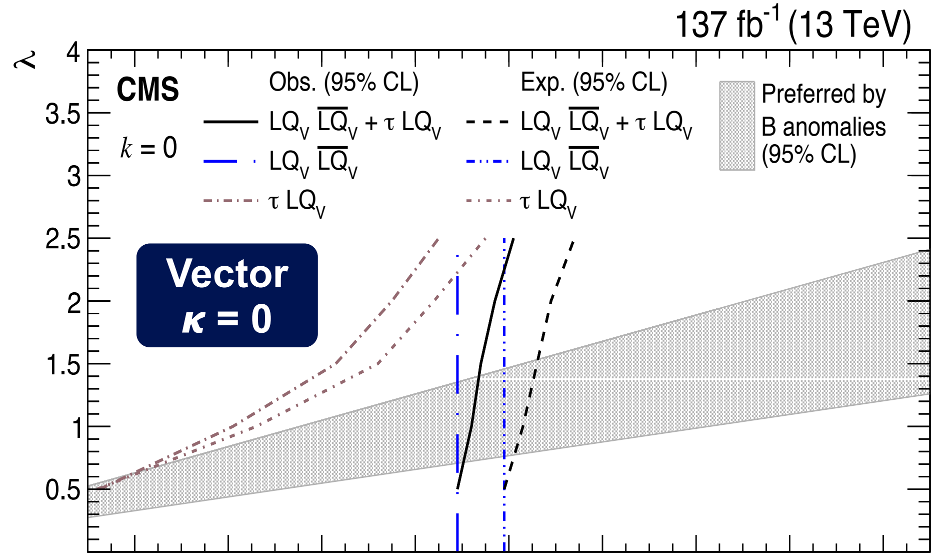


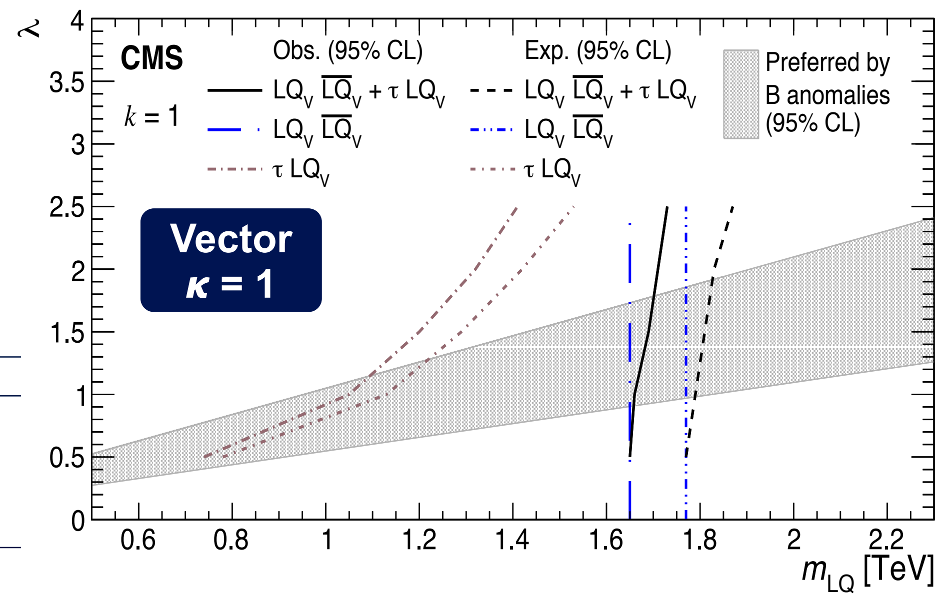


$LQ_3LQ_3 \rightarrow t\nu b\tau$ / $t\tau b\nu$ results

arXiv:2012.04178
β = 0.5, 137 fb^{-1}







	LQ_S (TeV)	
Pair	0.95 (1.03)	
	$\lambda = 1.5$	2.5
Single	0.55 (0.56)	0.75 (0.81)
Pair+Single	0.98 (1.06)	1.02 (1.10)

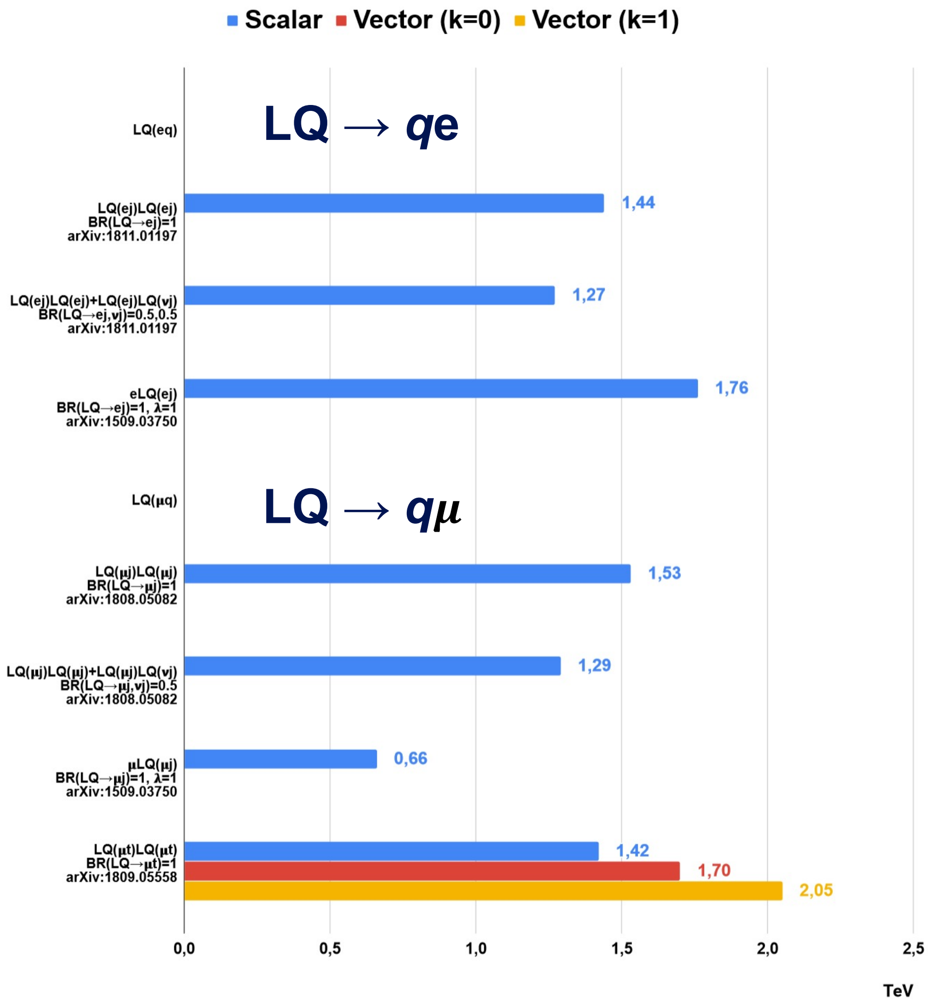
Obs. (Exp.)

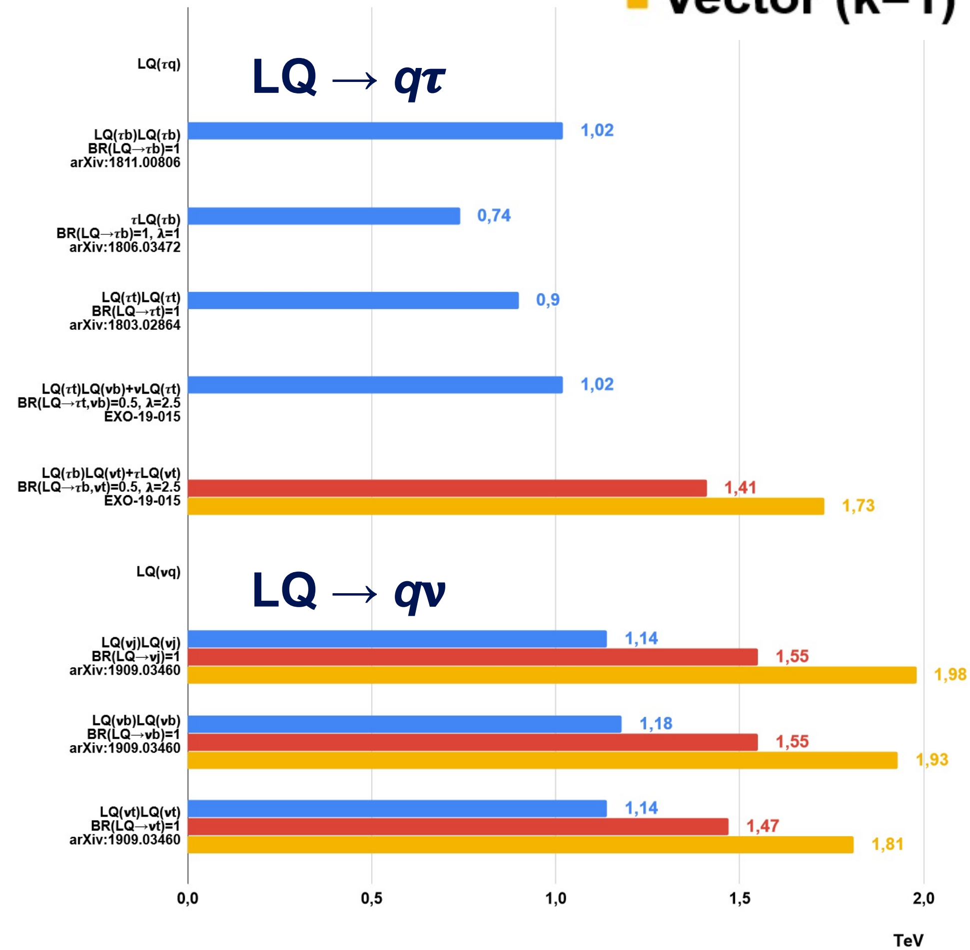
	LQ_V, $k=0$ (TeV)		LQ_V, $k=1$ (TeV)	
Pair	1.29 (1.39)		1.65 (1.77)	
	$\lambda = 1.5$	2.5	1.5	2.5
Single	1.03 (1.12)	1.25 (1.35)	1.20 (1.29)	1.41 (1.53)
Pair+Single	1.34 (1.46)	1.41 (1.54)	1.69 (1.81)	1.73 (1.87)

(Thanks to F. Romeo)

CMS LQ summary

Scalar
Vector (k=0)
Vector (k=1)





(Thanks to F. Romeo)

CMS LQ_3 summary

SUMMARY

Summary

- third-generation LQs are well motivated by theory and recent experimental results, like the B anomalies
- CMS has performed searches for several scenarios and resonant signatures
  - scalar, vector
  - single, pair production
  - LQ $\rightarrow$ tν, bτ, or tτ, bν
  - new results with 137 fb^{-1} probe in the 1.5–2 TeV region
- looking forward to new Run-2 results
  - vector LQ $\rightarrow$ bτ (β = 1)
  - including nonresonant $\tau\tau$ production (LQ *t*-channel)

References

- *The Leptoquark Hunter's Guide: Pair Production*
  https://arxiv.org/abs/1706.05033
- *The Leptoquark Hunter's Guide: Large Coupling* (single + *t*-channel)
  https://arxiv.org/abs/1810.10017
- *B-physics anomalies: a guide to combined explanations*
  https://arxiv.org/abs/1706.07808
- *Revisiting the vector leptoquark explanation of the B-physics anomalies*
  https://arxiv.org/abs/1903.11517
- *Leptoquark toolbox for precision collider studies*
  https://arxiv.org/abs/1801.07641
- LQ searches at CMS (Ben Kilminster, ICHEP 2020)
  https://indico.cern.ch/event/868940/

SUMMARY

LQ decay signatures at CMS

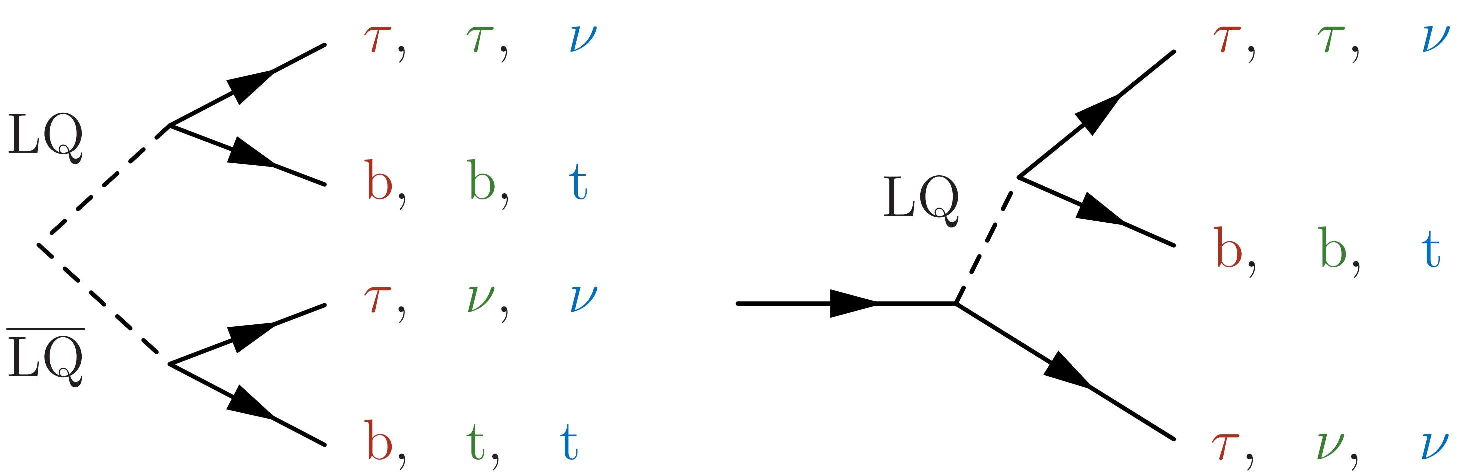
analyses often use a **parameter β**:

$$\mathcal{B}\left(\mathrm{LQ} \to q\ell\right) = \beta$$
$$\mathcal{B}\left(\mathrm{LQ} \to q'\nu\right) = 1 - \beta$$

typical benchmarks β = 0, 0.5, 1

e.g. **purely third-generation LQ$_3$**:

$$\mathcal{B}\left(\mathrm{LQ}_3 \to \mathrm{b}\tau\right) = \beta$$
$$\mathcal{B}\left(\mathrm{LQ}_3 \to \mathrm{t}\nu_\tau\right) = 1 - \beta$$



$\mathrm{bb}\tau\tau$, $\mathrm{bt}\tau\nu$, $\mathrm{tt}\nu\nu$ $\qquad$ $\mathrm{b}\tau\tau$, $\mathrm{b}\tau\nu$, $\mathrm{t}\nu\nu$

Third-generation LQ searches

LQ $\rightarrow$ bτ coupling strength λ
non-minimal coupling κ (vector)
$\beta = B(\mathrm{LQ} \rightarrow q\ell) = 1 - B(\mathrm{LQ} \rightarrow q\nu)$

***β* = 0**

- **LQ → t*ν***
  scalar pair (2016, arXiv:1902.08103)
  scalar/vector pair (2016, SUS-19-005)
- **LQ → b*ν***
  scalar/vector pair (2016, SUS-19-005)

***β* = 0.5**

- **LQ → t*τ*, b*ν***
  scalar single+pair (Run 2, EXO-19-015)
  scalar pair (Run 2, ATLAS-CONF-2020-029)
- **LQ → t*ν*, b*τ***
  scalar pair (2016, arXiv:1902.08103)
  vector single+pair (Run 2, EXO-19-015)

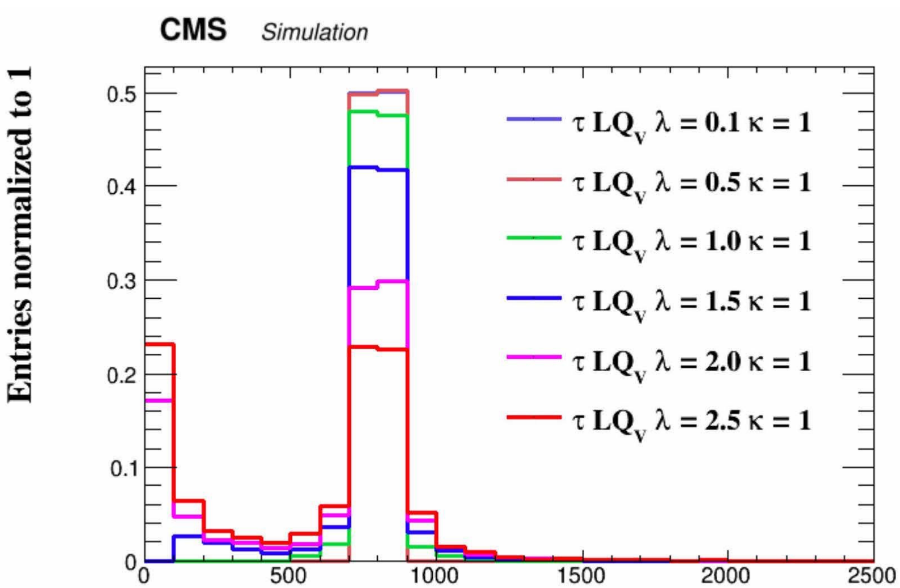
***β* = 1**

- **LQ → b*τ***
  scalar pair (2016, EXO-17-016)
  scalar single (2016, EXO-17-029)
  scalar pair (2016, arXiv:1902.08103)
- **LQ → t*τ***
  scalar pair (2016, B2G-16-028)
  scalar pair (Run 2, ATLAS-CONF-2020-029)

Single production yield & efficiency

two competing effects when λ is increased:

- cross section $\sigma(\tau\mathrm{LQ}) \sim \lambda^2$ at Breit-Wigner peak
- width increases, degrading efficiency
- pole at low mass of highly off-shell events increases yield, but degrades efficiency



low-mass pole (highly off-shell)

Breit-Wigner LQ mass peak

= $M(\mathrm{t}\nu)$