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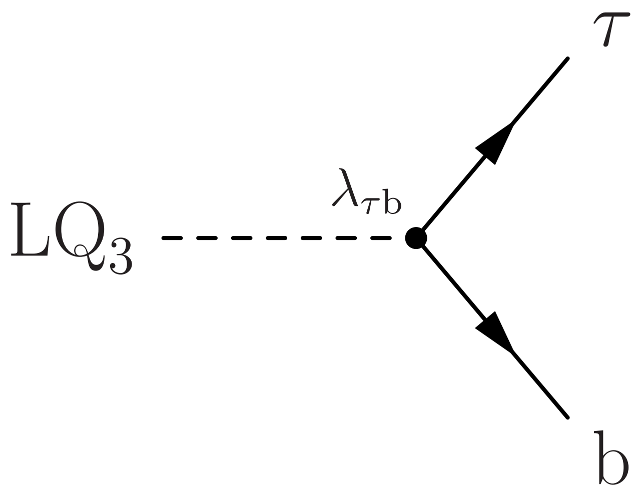

The search for third-generation leptoquarks

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Seminar in Theoretical Particle Physics, Zurich, 08/11/2022

MOTIVATION

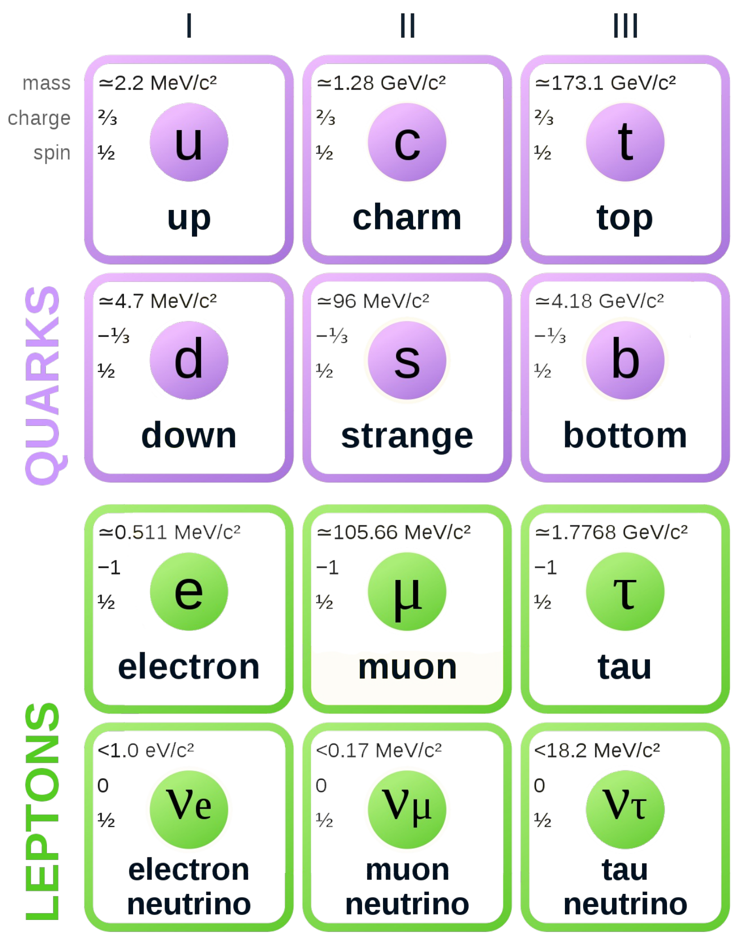
Standard Model's many symmetries…

Quantity	Symmetries	Electromagnetic	Weak	Strong	
Energy	Time translation	✔	✔	✔	*
Linear momentum	Spatial translation	✔	✔	✔	
Angular momentum	Rotations	✔	✔	✔	
Center-of-mass	Lorentz boosts	✔	✔	✔	
Charge, color, …	Gauge transformation	✔	✔	✔	
Isospin (uds)		✔	✗	✗	
B – L { Lepton number L		✔	✔	✔	
B – L { Baryon number B	accidental !	✔	✔	✔	
Lepton flavor		✔	✔	✔	
Quark flavor		✔	✗	✔	
Parity P		✔	✗	✔	
Charge conjugation C		✔	✗	✔	
Time reversal T		✔	✗	✔	
CP		✔	✗	✔	
CPT		✔	✔	✔	*

*** fundamental to Lorentz-invariant gauge field theories, like the SM**

Flavor universality in the SM

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

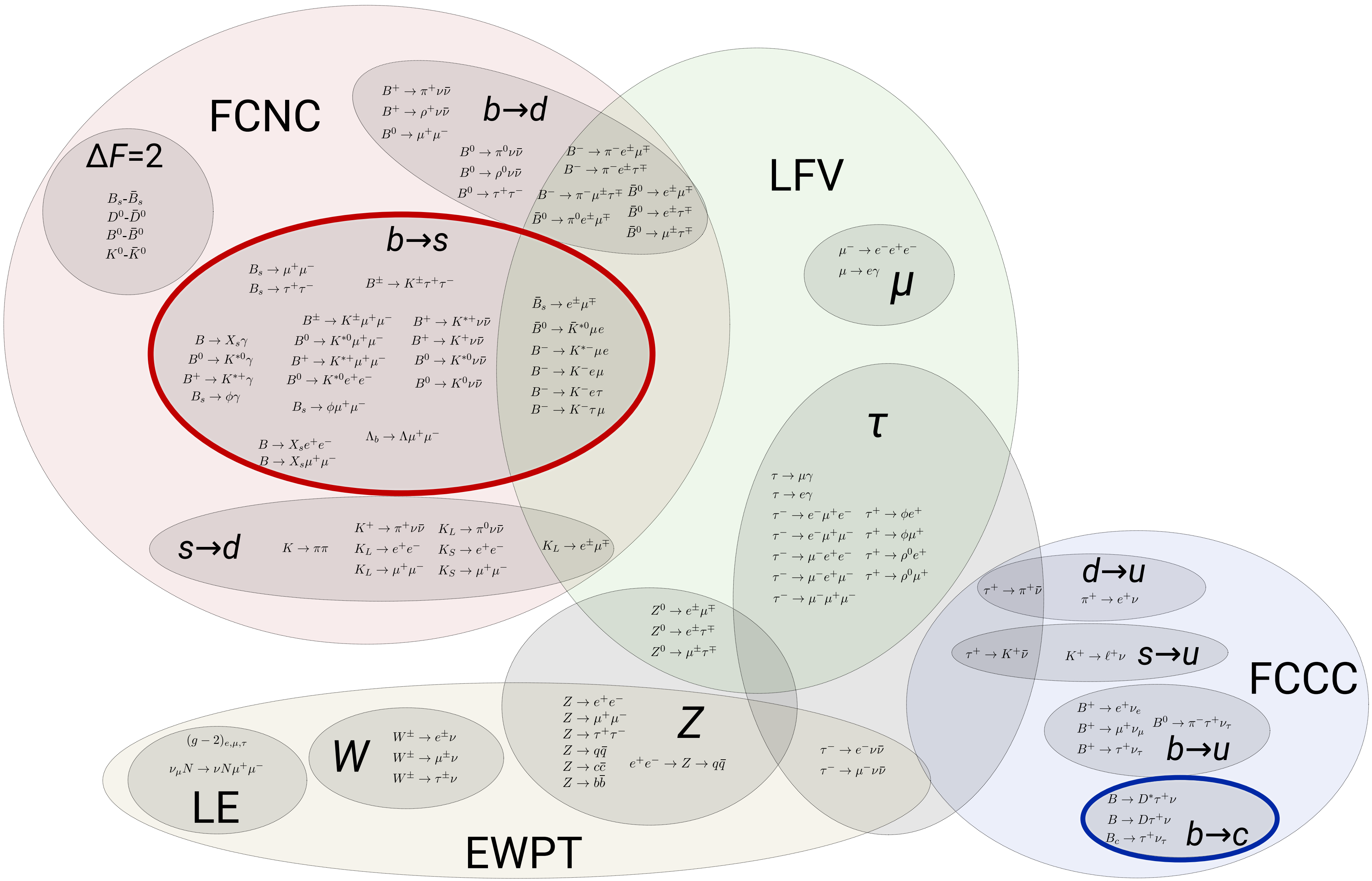


but by what mechanism ?

why three generations ?

⇒ hopefully new physics can explain

⇒ probe LFU in Nature !

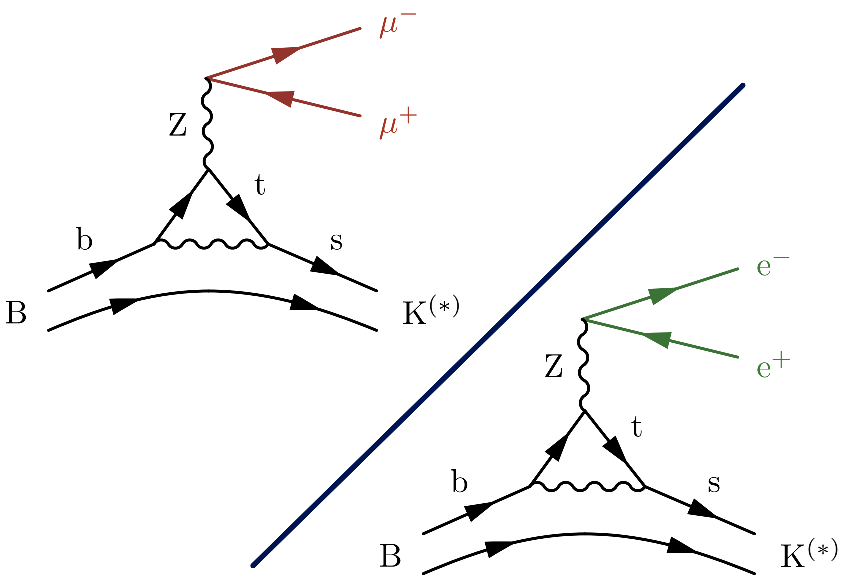


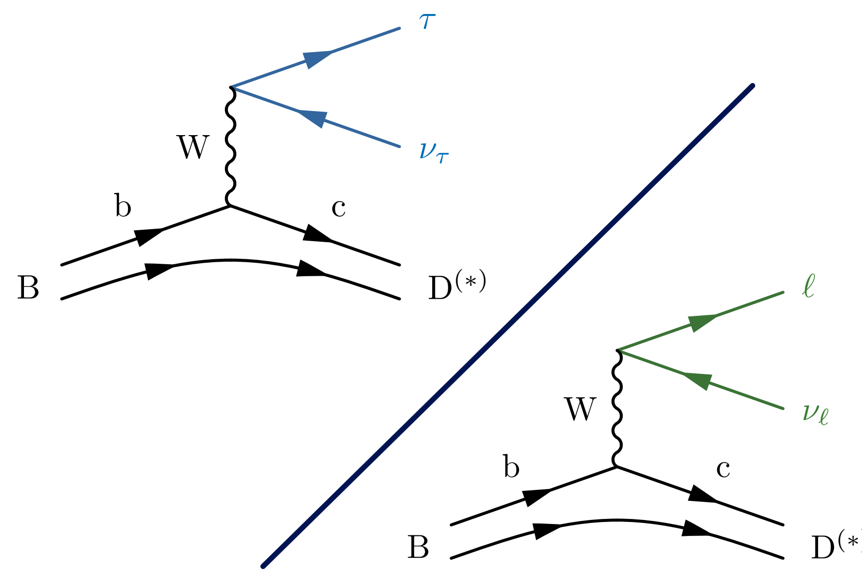
Straub [Moriond 2019], Aebischer et al. [arXiv:1810.07698]

Lepton flavor universality tests

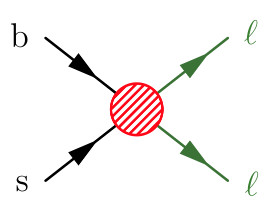
$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}ee\right)} \stackrel{\text{SM}}{=} 1$$

$$R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \stackrel{\text{SM}}{\sim} 0.25$$

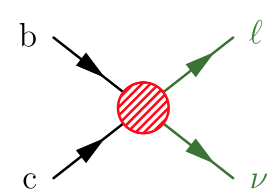




measure b → s**ℓℓ** transitions

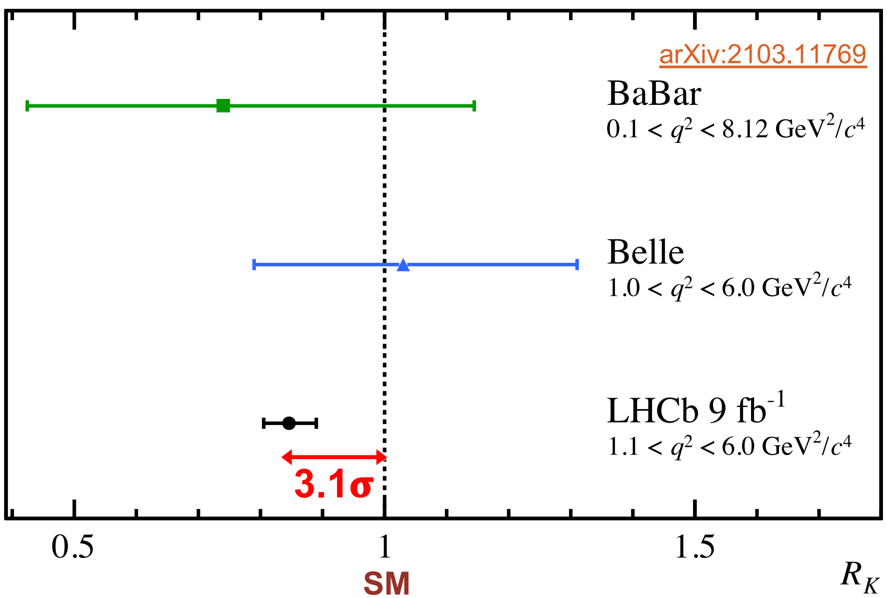


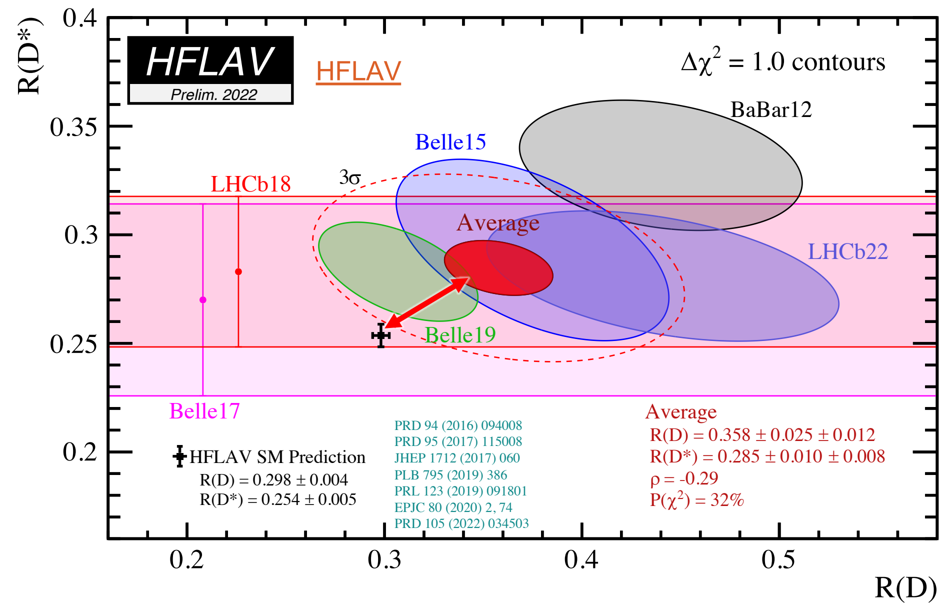
b → c**ℓν** transitions



B anomalies at Belle, BaBar, LHCb

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



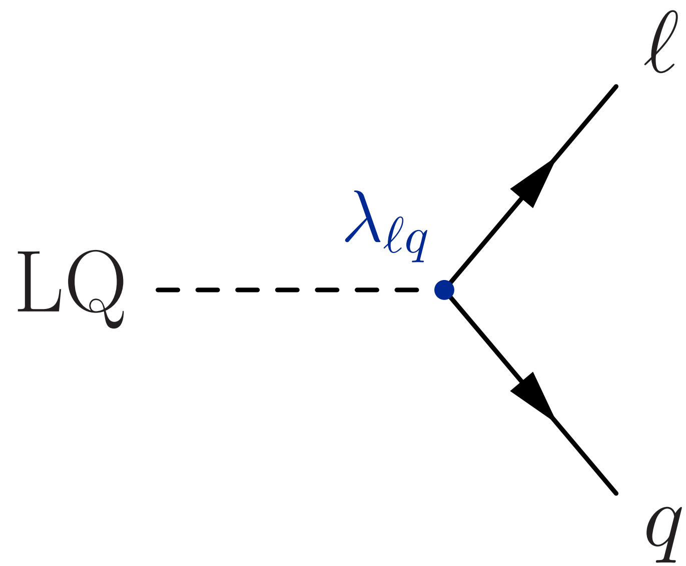


R(K$^{(*)}$) and angular observables combined ~ 4σ deviation

R(D$^{(*)}$) combined 3.2σ deviation

⇒ signs of new physics violating lepton flavor universality ?

Leptoquarks



- **scalar** or **vector boson**
- **decays into *ℓq***

  ⇒ carries L, B, color

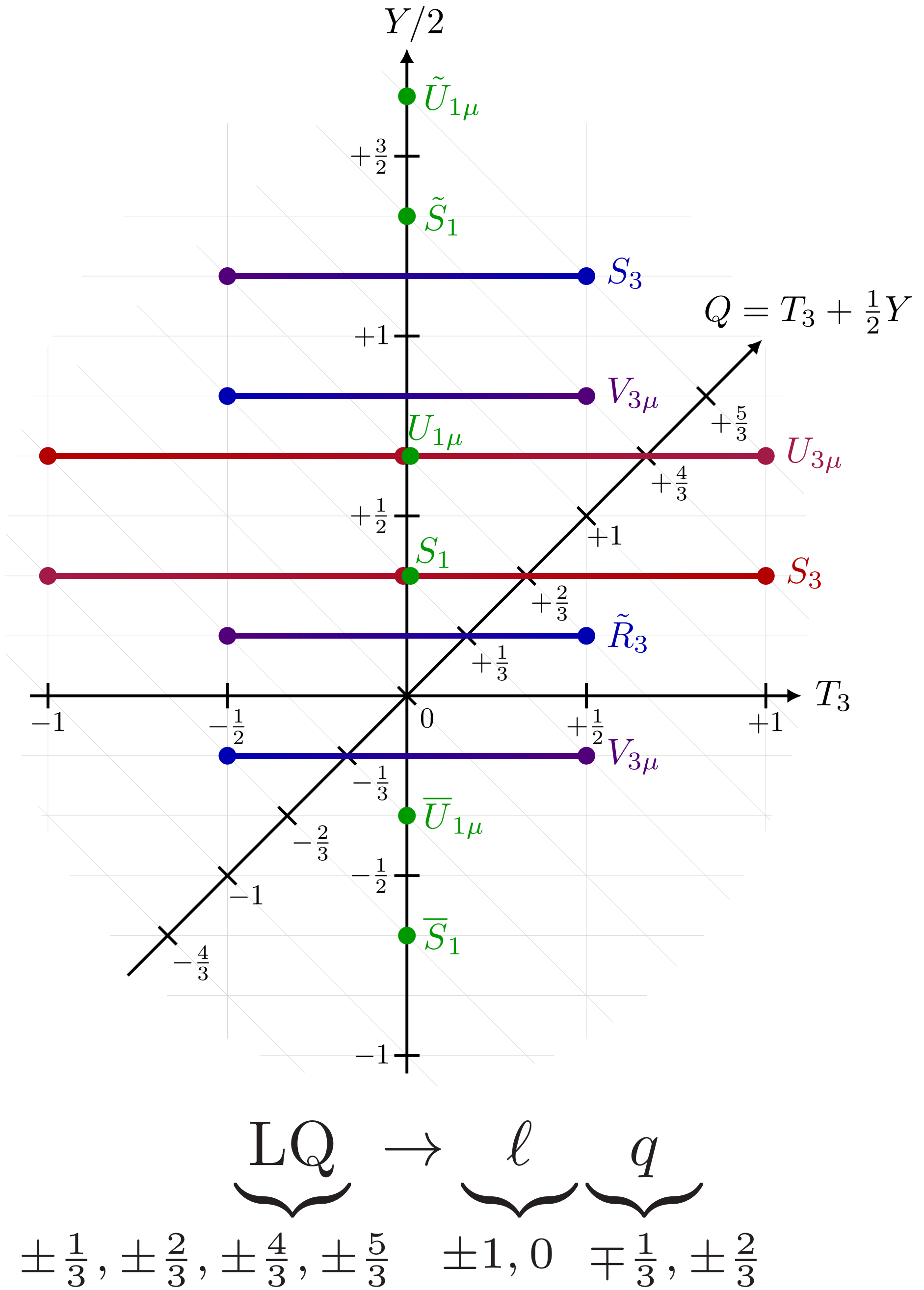
$$\underbrace{\mathrm{LQ}}_{\pm\frac{1}{3},\,\pm\frac{2}{3},\,\pm\frac{4}{3},\,\pm\frac{5}{3}} \rightarrow \underbrace{\ell}_{\pm 1,\,0}\ \underbrace{q}_{\mp\frac{1}{3},\,\pm\frac{2}{3}}$$

- **fractional charge**
- **coupling $\lambda_{\ell q}$**

$$J^\mu \equiv \lambda_{\ell q}\overline{Q}_q\gamma^\mu L_\ell$$

arXiv:1603.04993

Leptoquarks

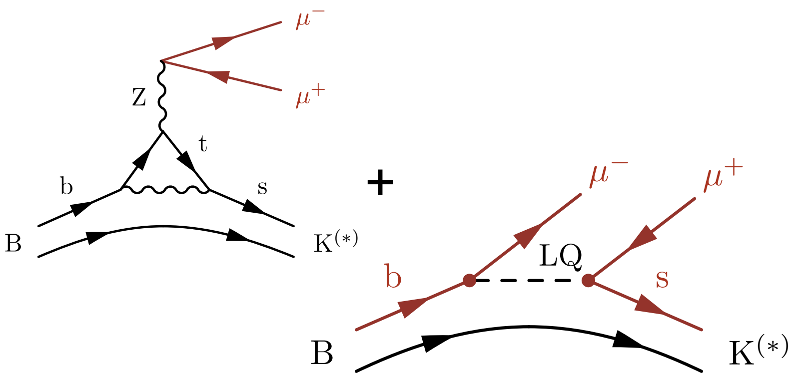


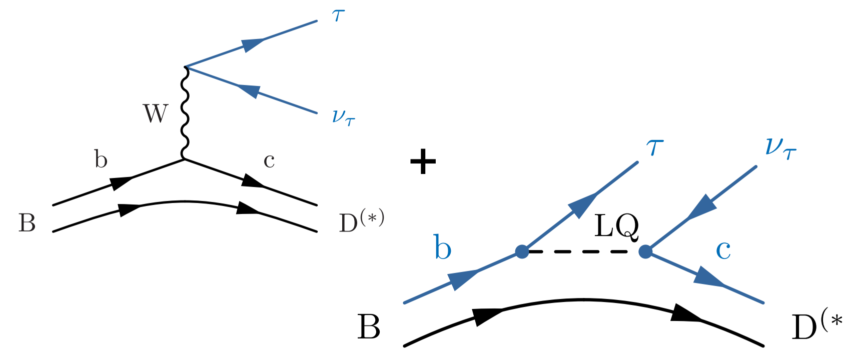
- **scalar** or **vector boson**
- **decays into *ℓq***
  ⇒ carries L, B, color
- **fractional charge**
- **coupling $\lambda_{\ell q}$**

arXiv:1603.04993

B anomalies according to LQs

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





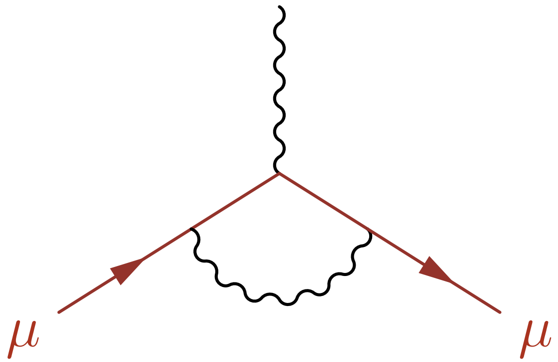
combined explanation with
vector leptoquark:

$$\Rightarrow \quad \lambda_{\ell q} \sim \begin{array}{c} \\ \mathrm{d}/\mathrm{u}' \\ \mathrm{s}/\mathrm{c}' \\ \mathrm{b}/\mathrm{t}' \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{e}/\nu_{\mathrm{e}} & \mu/\nu_{\mu} & \tau/\nu_{\tau} \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & +0.01 & 0.19 \\ 0 & -0.14 & 1 \end{pmatrix} \end{array} \quad \to \quad \mathrm{LQ} \approx \mathrm{LQ}_3$$

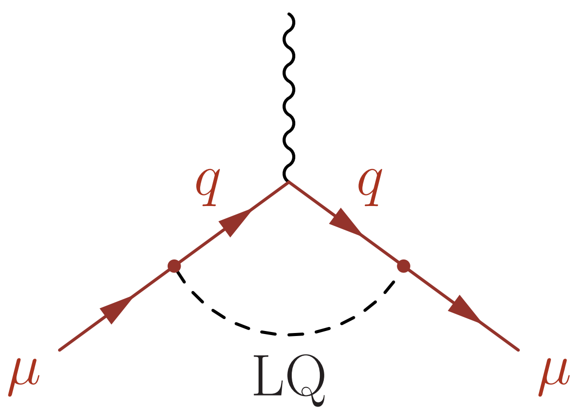
signs for destructive interference
with SM in B → K$\mu\mu$ decay

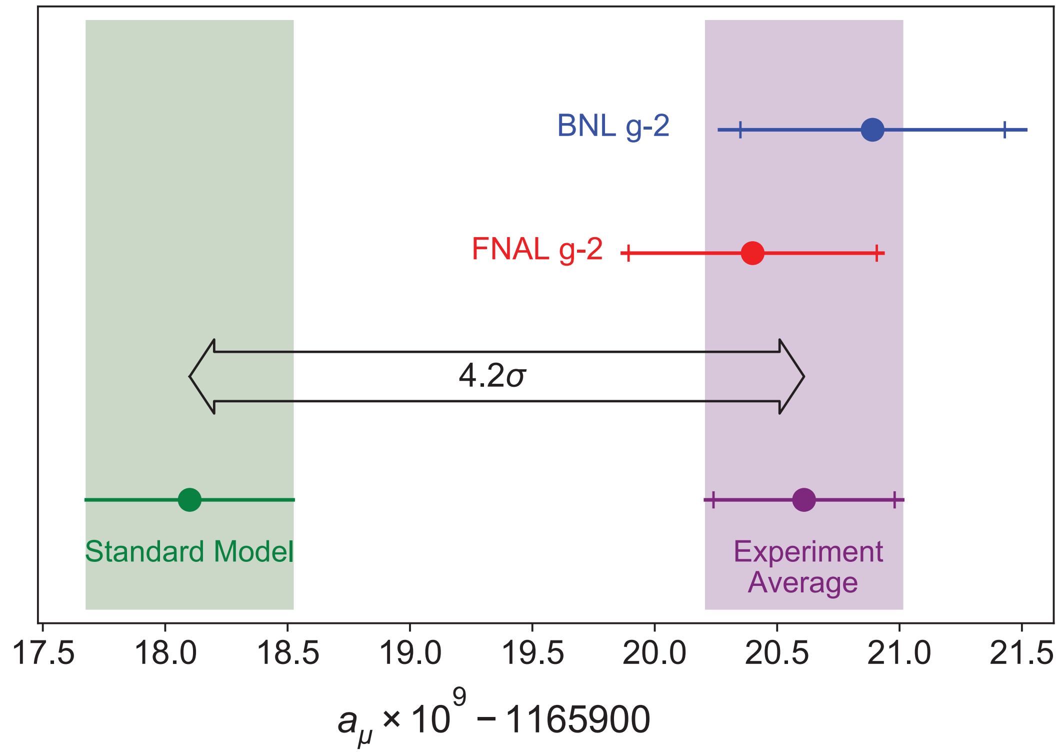
[Isidori group: arXiv:1706.07808, arXiv:1903.11517, arXiv:2103.16558]

Muon anomalous moment



+



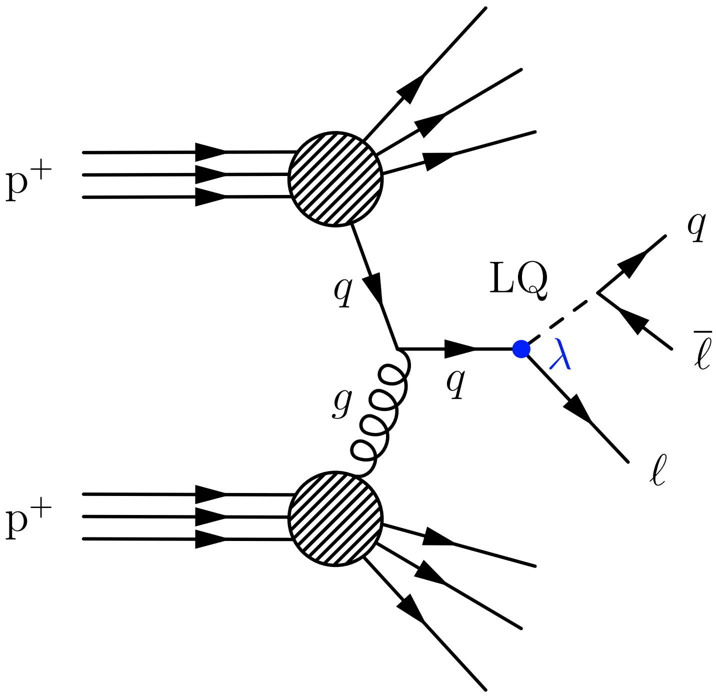


SM theory: 116 59<u>1 810</u> (43) × 10^{-11} (460 ppb)

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

BNL & FNAL combined 4.2σ deviation

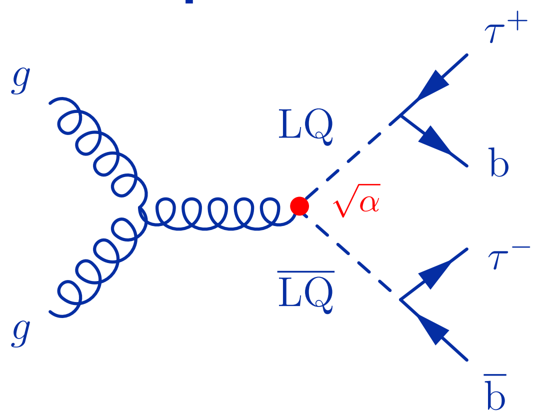
BNL: arXiv:hep-ex/0602035, FNAL: arXiv:2104.03281, theory WP: arXiv:2006.04822



LQ_3 SEARCHES AT CMS

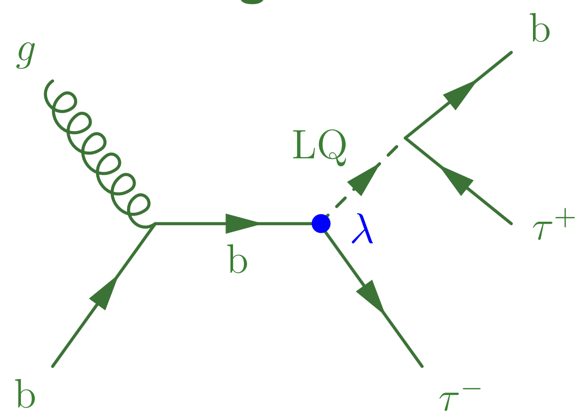
LQ production at CMS

pair



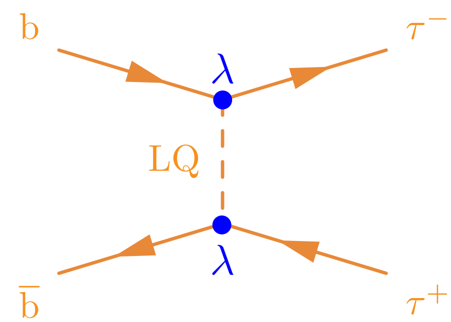
- ☺️ large,
- 🙂 model independent
- 🙂 resonant

single



- 🙂 $\sigma \propto \lambda^2$
- 🙁 b-PDF suppression
- 🙁 width $\propto \lambda^2$

nonresonant

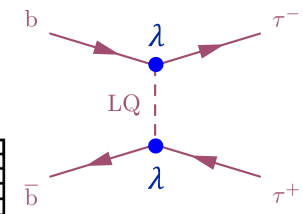


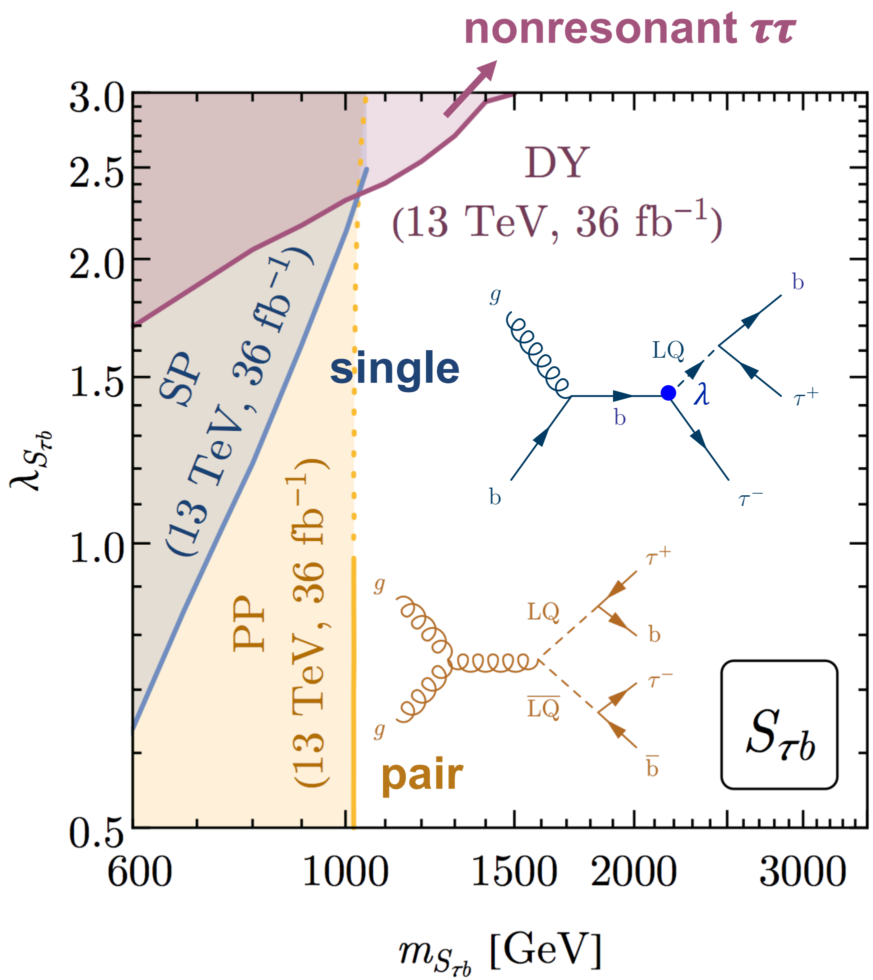
- 🙂 $\sigma \propto \lambda^4$
- 😱 (PDF suppression)^2
- 🙁 wide resonance

but kinematics largely independent of λ and mass

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 decay signatures at CMS

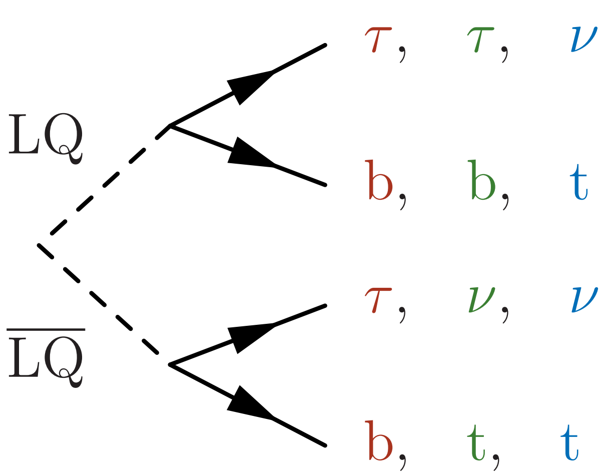
analyses often use a **parameter $\boldsymbol{\beta}$**:

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

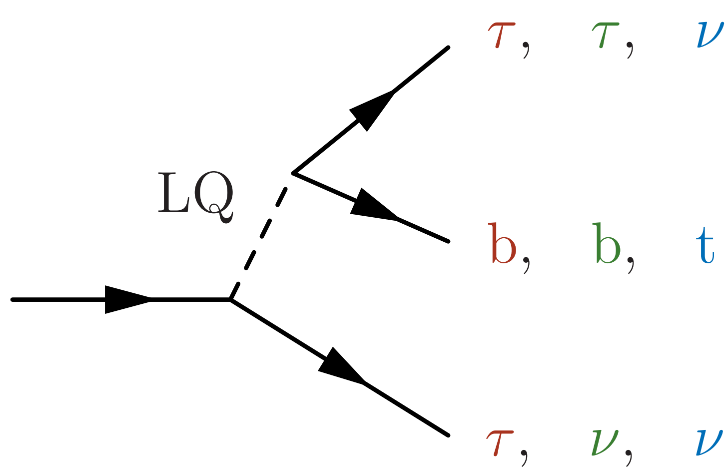
typical benchmarks β = 0, 0.5, 1

e.g. **purely third-generation $\mathbf{LQ_3}$**:

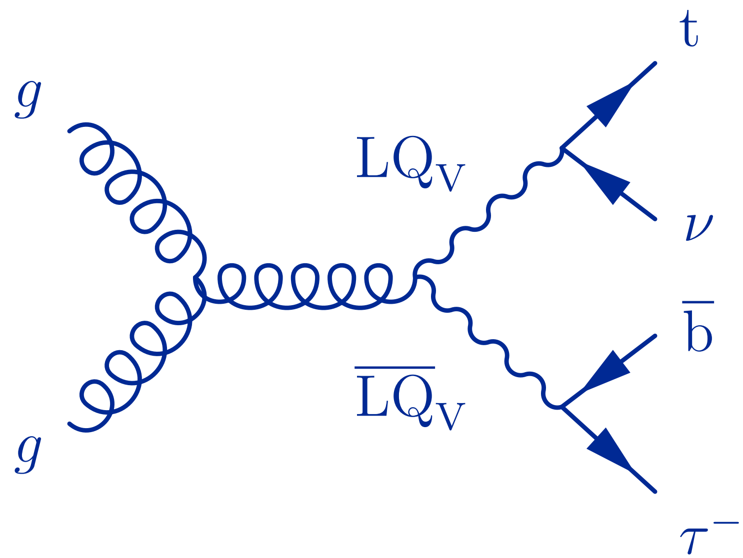
$$\mathcal{B}\left(\mathrm{LQ_3} \rightarrow \mathrm{b}\tau\right) = \beta$$
$$\mathcal{B}\left(\mathrm{LQ_3} \rightarrow \mathrm{t}\nu_\tau\right) = 1 - \beta$$



$\mathrm{bb}\tau\tau$, $\mathrm{bt}\tau\nu$, $\mathrm{tt}\nu\nu$



$\mathrm{b}\tau\tau$, $\mathrm{b}\tau\nu$, $\mathrm{t}\nu\nu$



$\mathbf{LQ_3 \to b\tau, t\nu}$

EXO-19-015 (β = 0.5)

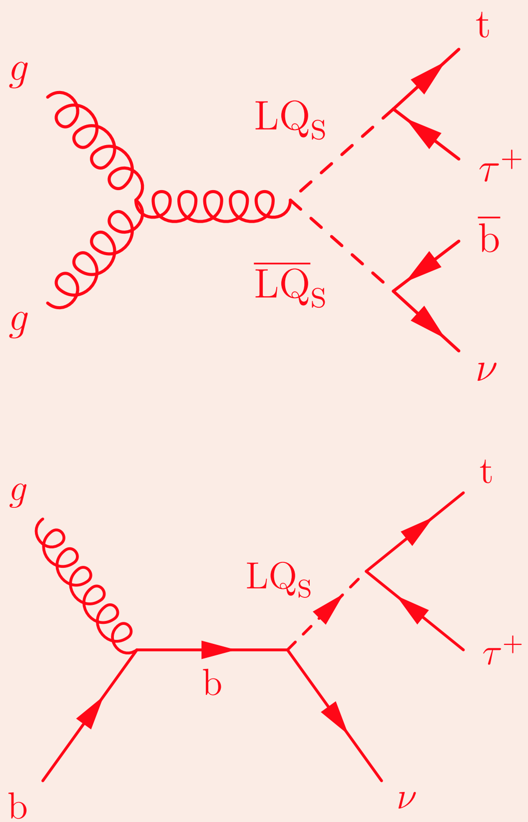
$LQ_3LQ_3 \rightarrow$ tνbτ / tτbν

arXiv:2012.04178
β = 0.5, 137 fb^{-1}

Scalar LQ_S

tτ 50%
bν 50%

arXiv:1706.07808



pair final state
tνbτ

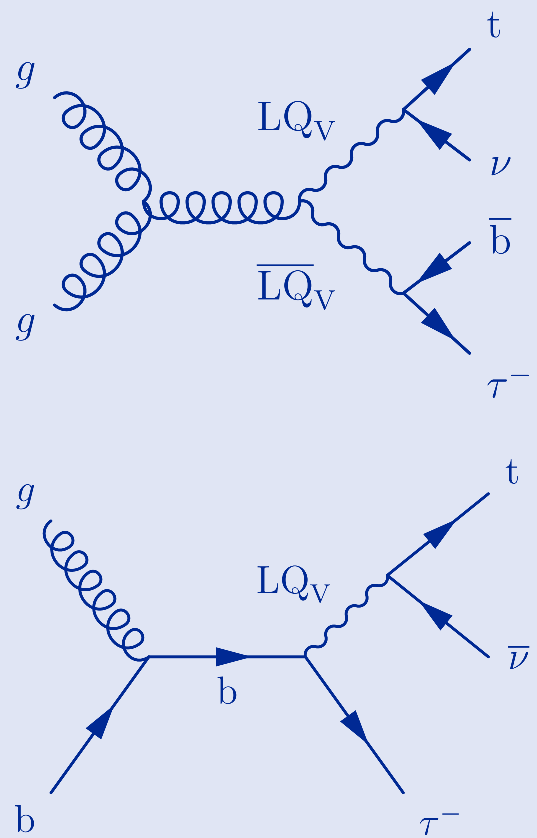
single final state
tν(b)τ

gluon splitting

Vector LQ_V

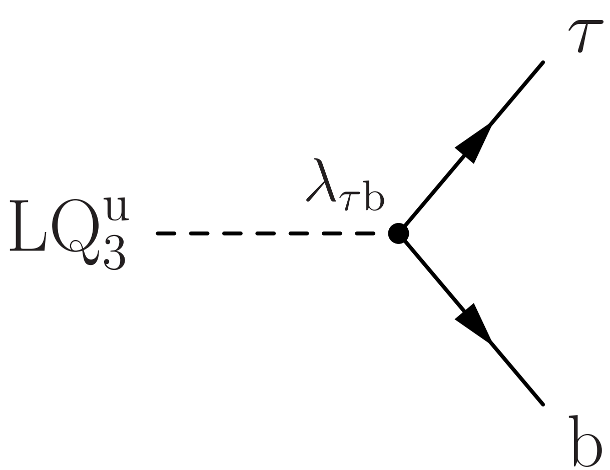
tν 50%
bτ 50%

arXiv:1808.02063

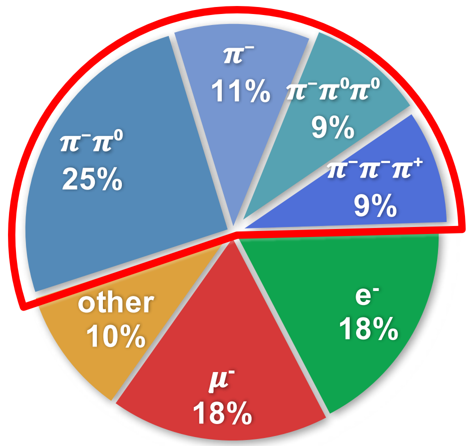


top PDF heavily suppressed

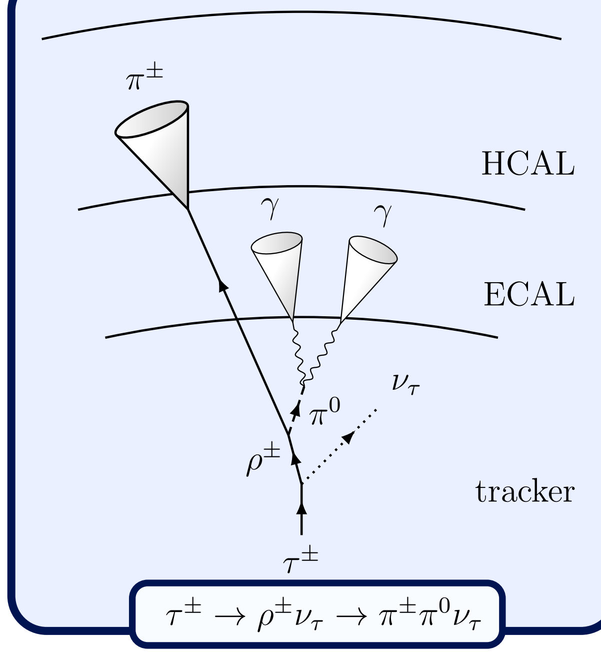
$LQ_3 \rightarrow b\tau$ reconstruction



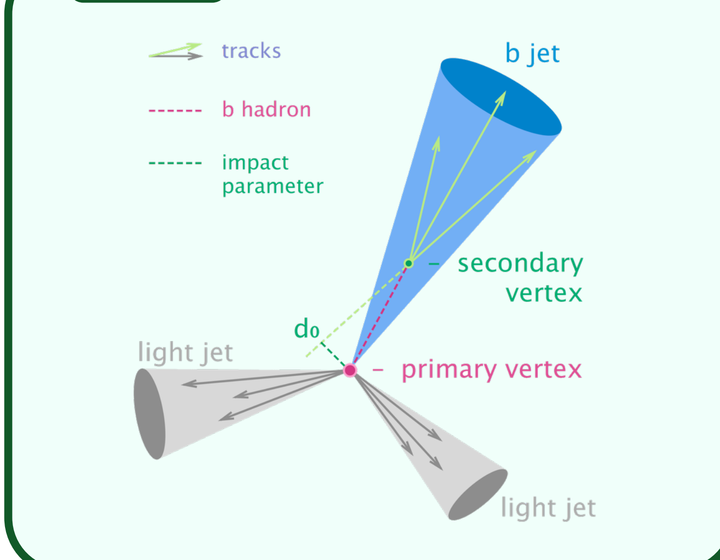
τ decay



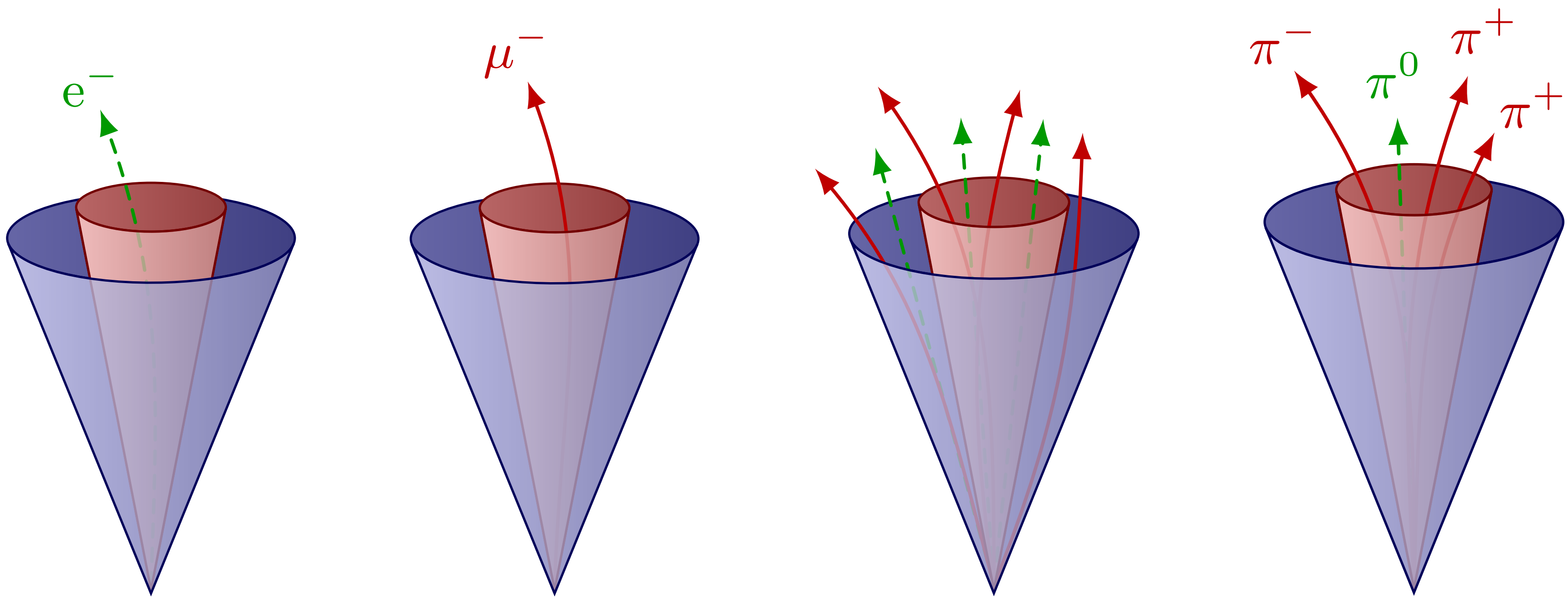
τ_h reconstruction



b jet



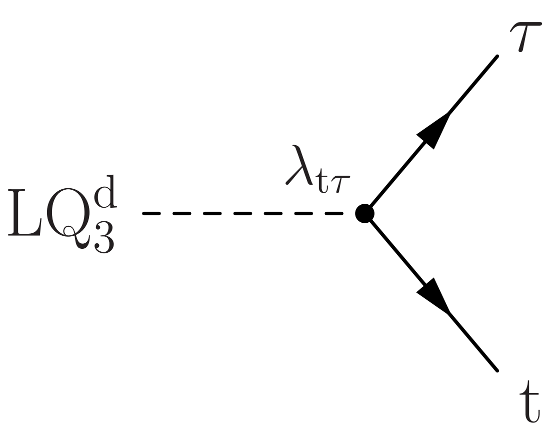
τ_h background

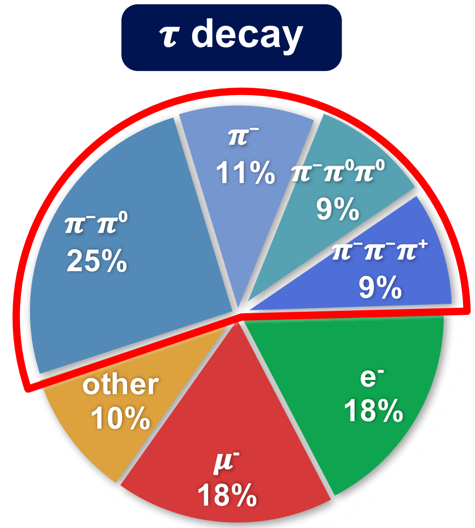


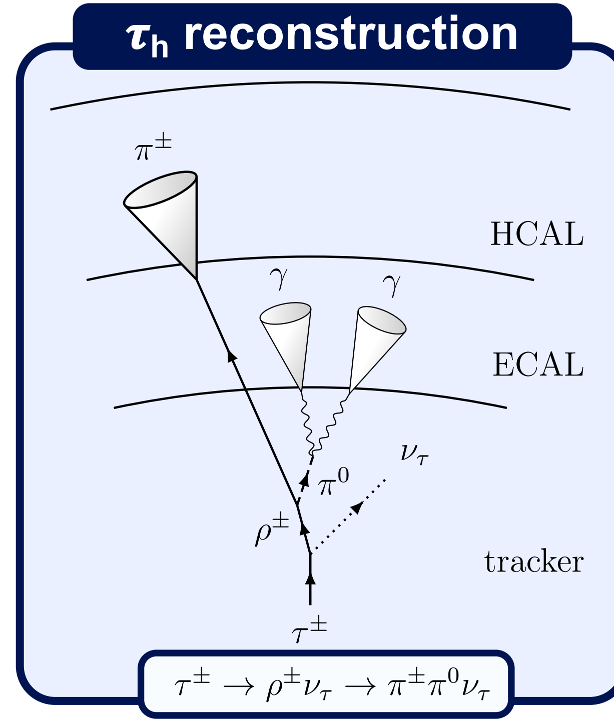
$e \rightarrow \tau_h$ fake $\mu \rightarrow \tau_h$ fake $j \rightarrow \tau_h$ fake real τ_h

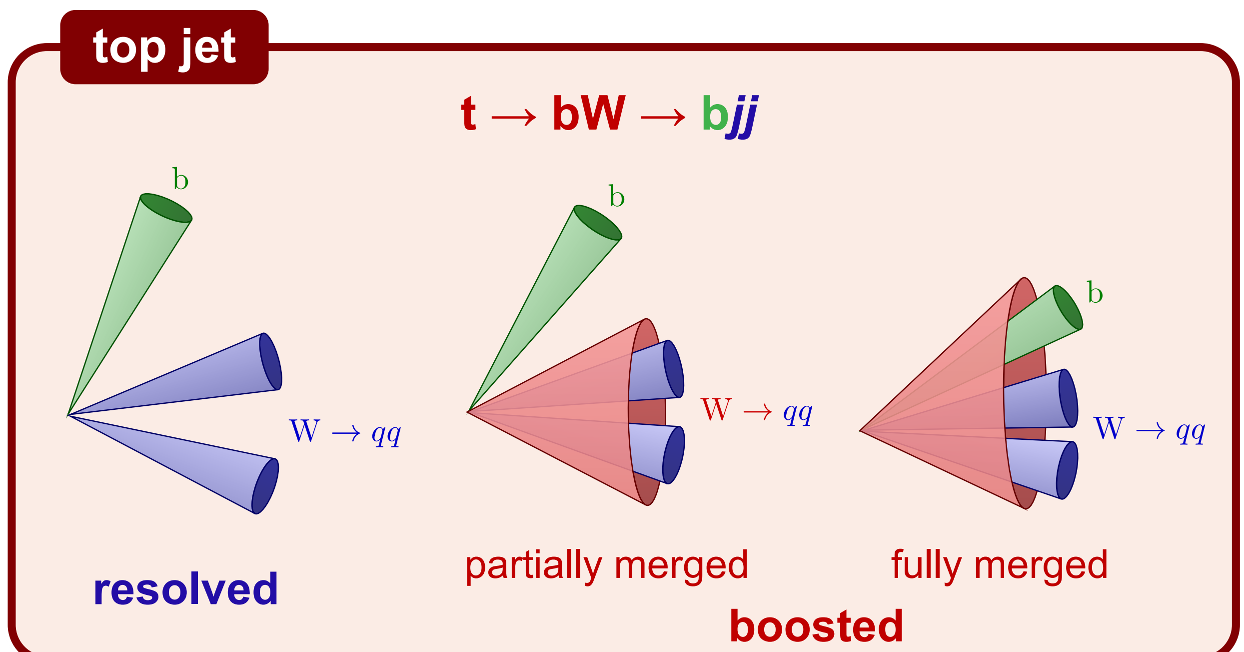
⇒ need for an efficient **identification algorithm**

$LQ_3 \to t\tau$ reconstruction









arXiv:2012.04178

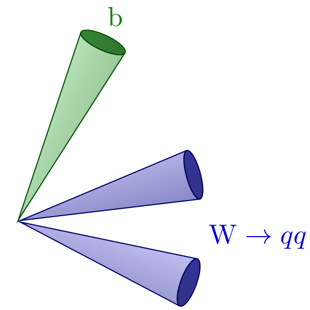
$\beta = 0.5$, 137 fb^{-1}

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

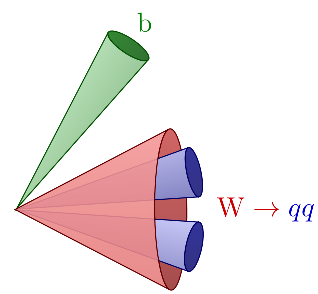
$$S_T = p_T^t + p_T^{\tau_h} + p_T^{miss}$$

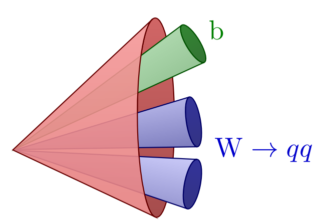
- single + pair is one signal



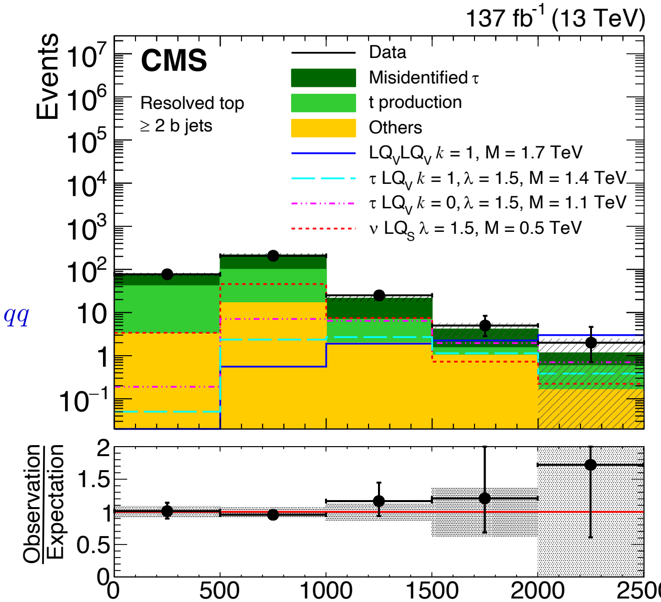
resolved top

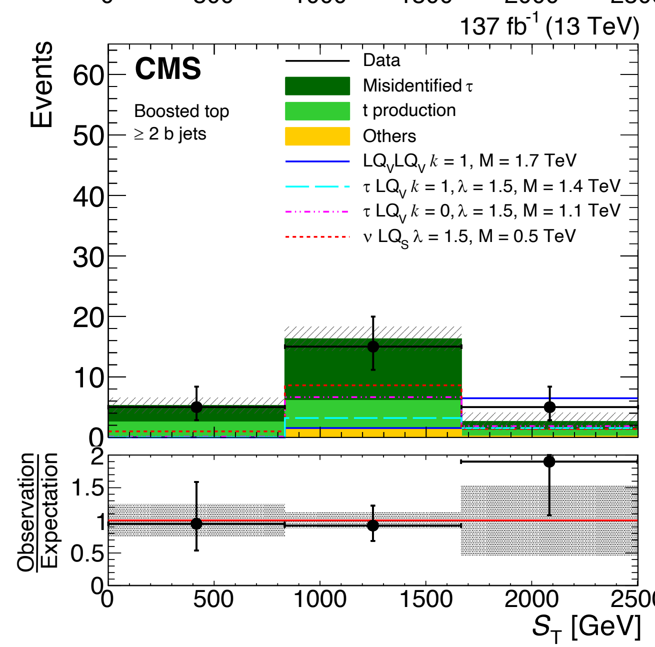
t → bW → bjj





boosted top



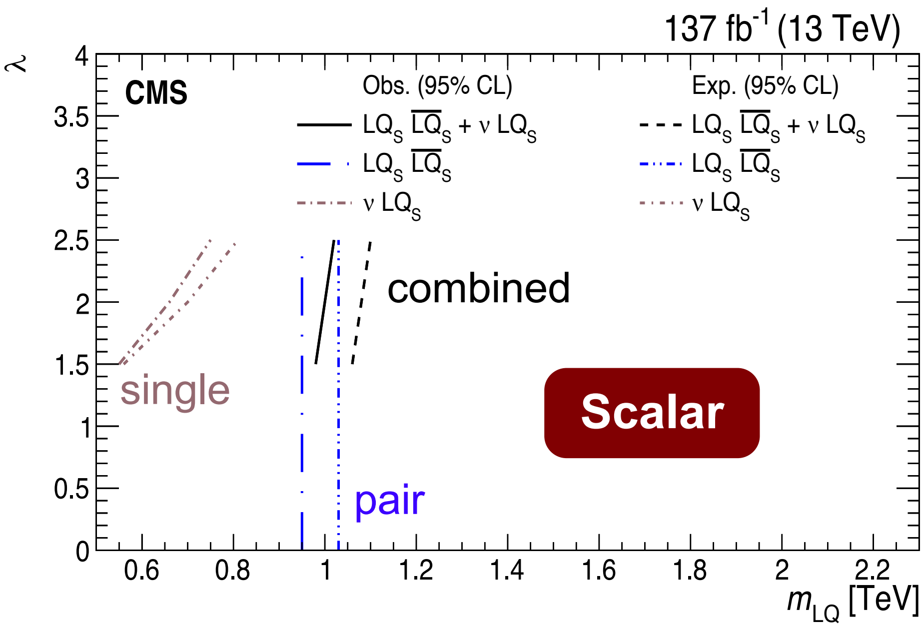


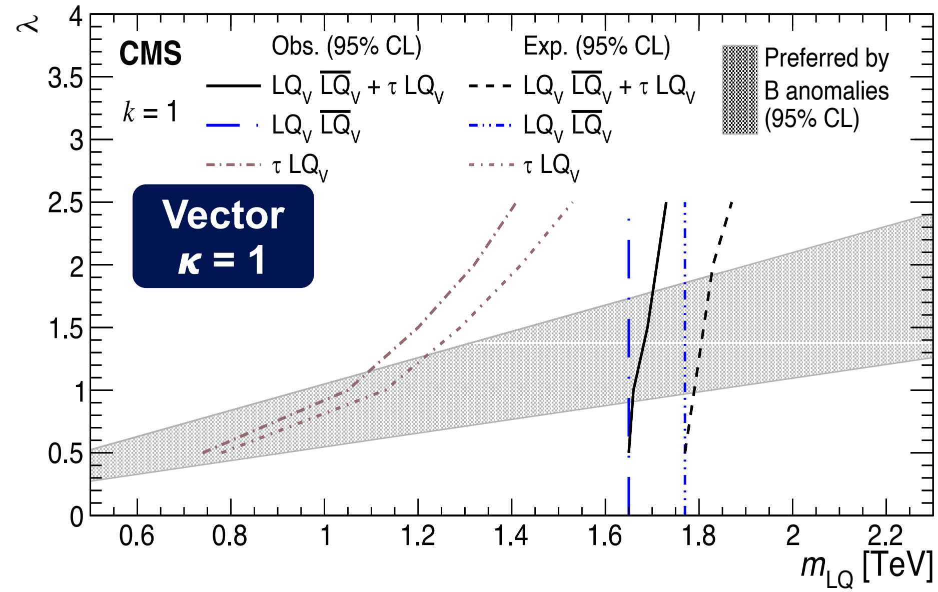
arXiv:2012.04178

β = 0.5, 137 fb^{-1}

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

no significant excess above the SM expectation observed

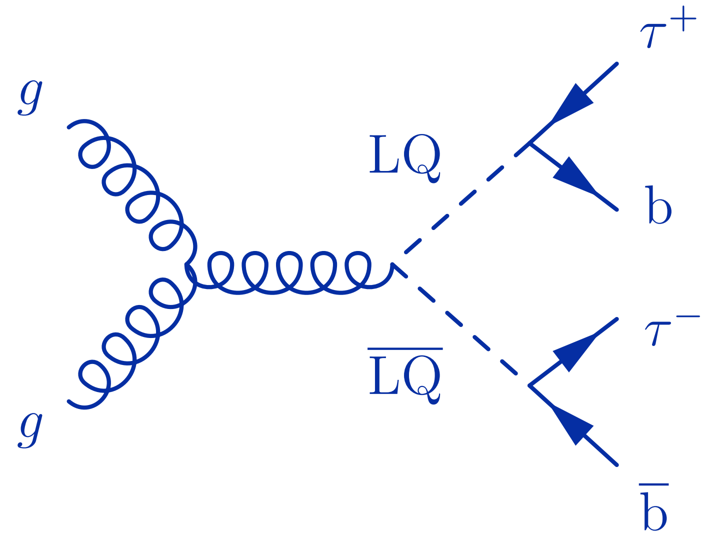




	LQ_S (TeV)	
Pair	0.95 (1.03)	
	$\lambda = 1.5$	2.5
Single	0.55 (0.56)	0.75 (0.81)
Pair+Single	0.98 (1.06)	1.02 (1.10)

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)



$\mathbf{LQ_3 \rightarrow b\tau}$

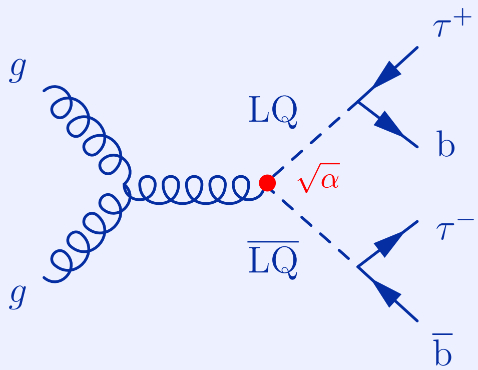
EXO-19-016, HIG-21-001, (β = 1)

LQ → bτ production at CMS

EXO-19-016

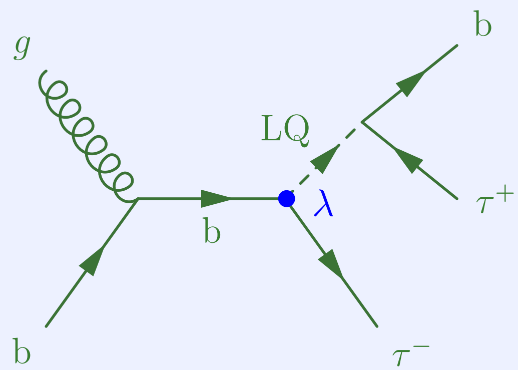
resonant

pair



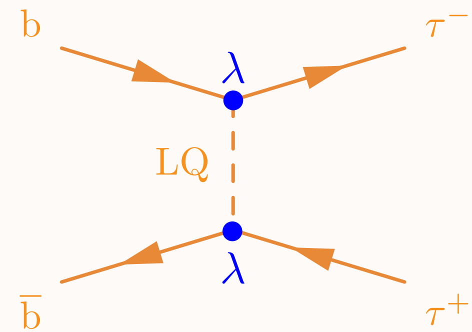
- large
- model independent

single

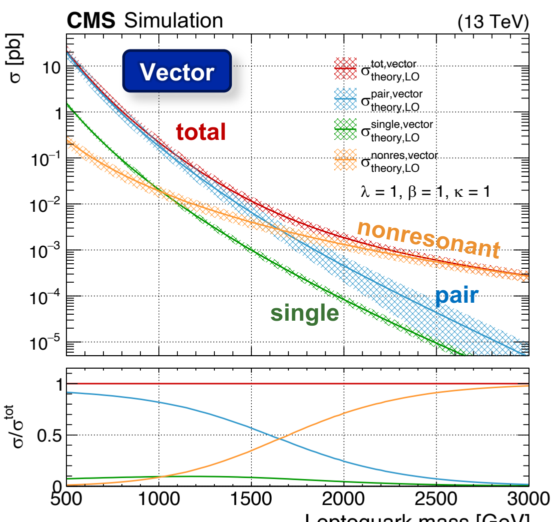


- $\sigma \propto \lambda^2$
- b-PDF suppression
  width $\propto \lambda^2$

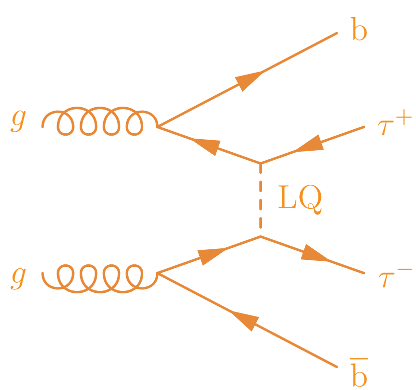
nonresonant

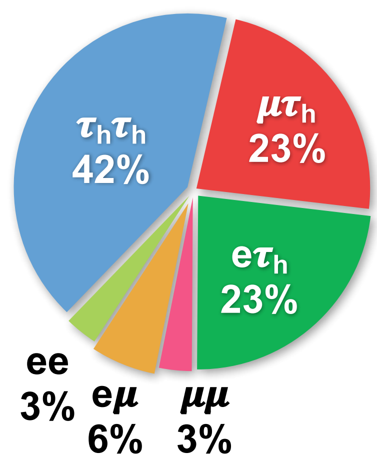


- $\sigma \propto \lambda^4$
- (PDF suppression)^2
- nonresonant

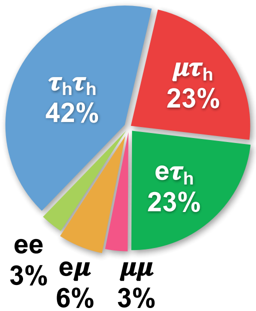


⇒ (b)(b)$\tau\tau$ signature





Summary of event categorization



$e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$ & $\mu\mu$ pre-selections, p_T > 50 GeV

≥1 jet (p_T > 50 GeV)

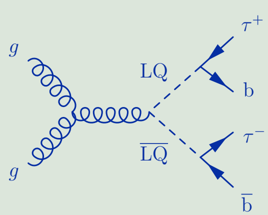
Loose DeepCSV
m_{vis} > 100 GeV

0 b tag

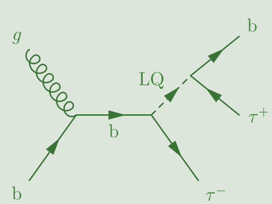
≥1 b tag

discriminating variable:

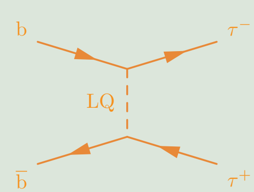
$$S_T^{MET} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{j} + MET$$



pair



single



nonresonant

0 jet (p_T > 50 GeV)

m_{vis} bins

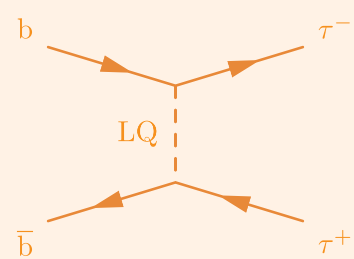
200–400

400–600

>600

discriminating variable:

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

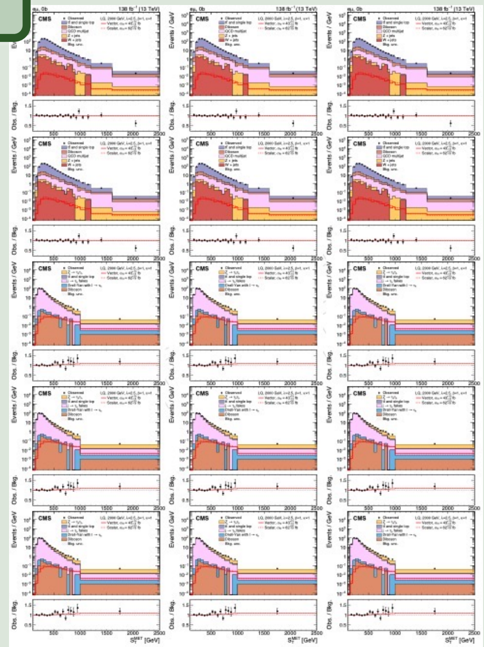


nonresonant

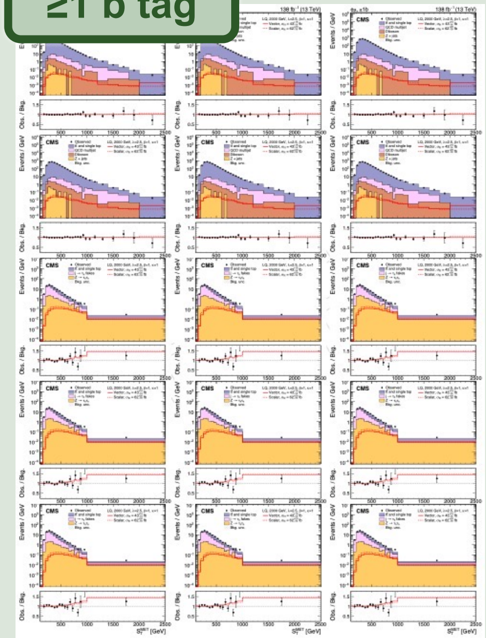
EXO-19-016

0 b tag

2016 **2017** **2018**



≥1 b tag



$\mu\mu$

$e\mu$

$e\tau_h$

$\mu\tau_h$

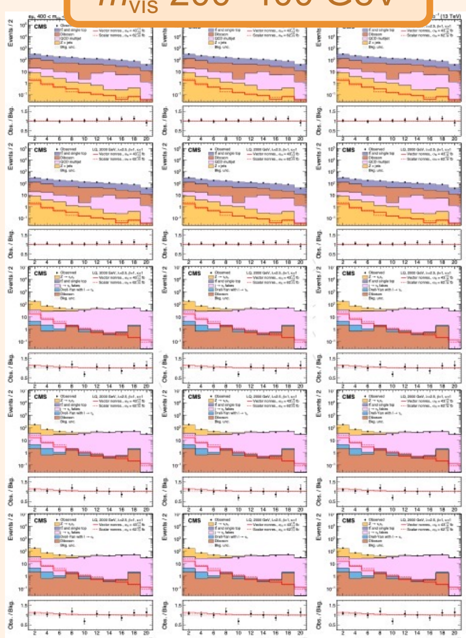
$\tau_h\tau_h$

S_T^{MET}

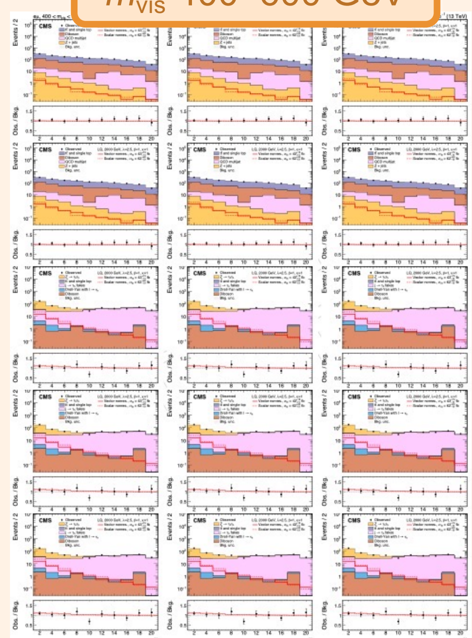
3 years × 5 channels × 5 categories

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

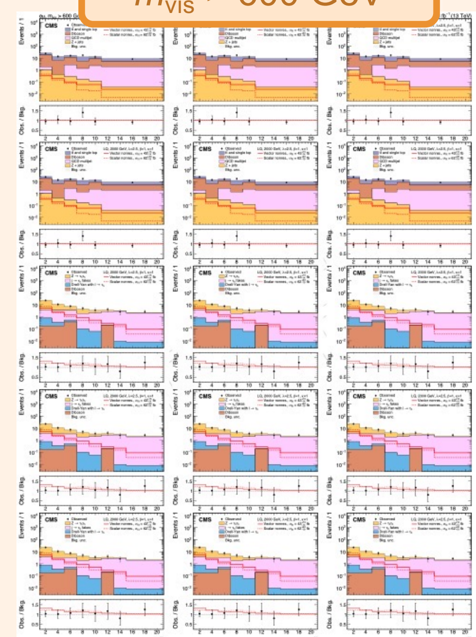
m_{vis} 200–400 GeV



m_{vis} 400–600 GeV



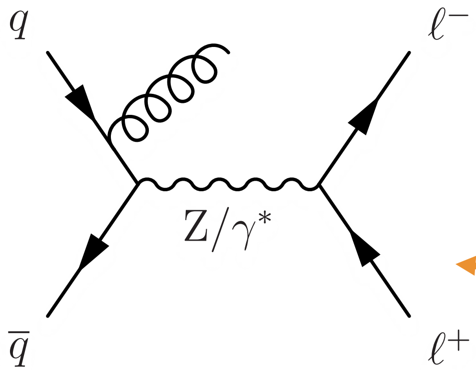
m_{vis} > 600 GeV



Main backgrounds

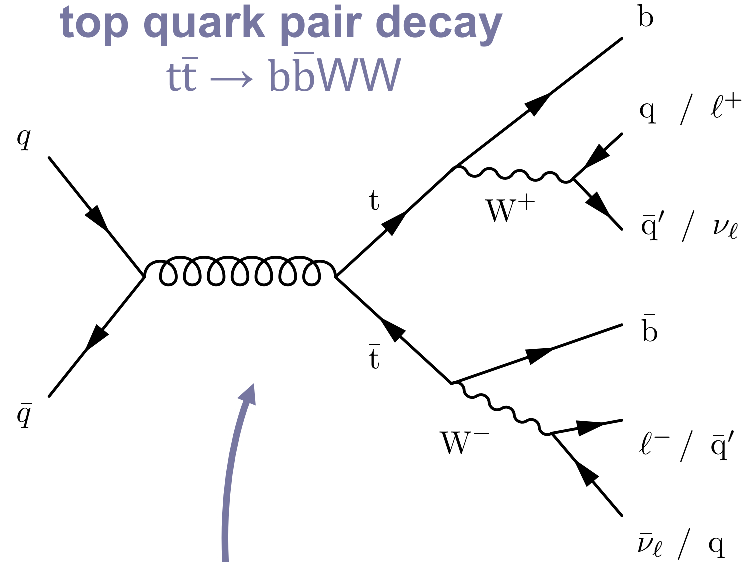
Drell-Yan + jets

$q\bar{q} \rightarrow j\,\ell^{-}\ell^{+}$



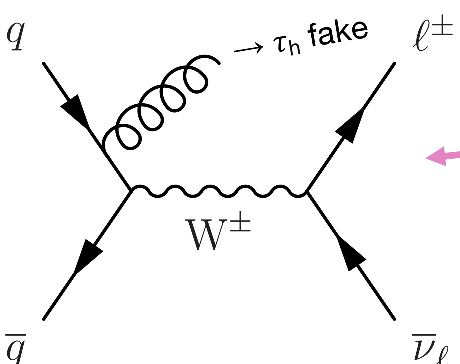
top quark pair decay

$t\bar{t} \rightarrow b\bar{b}WW$

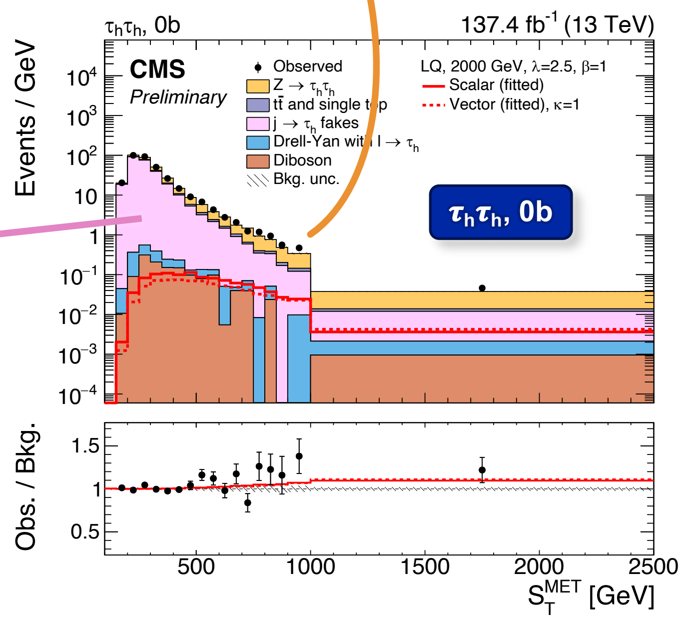


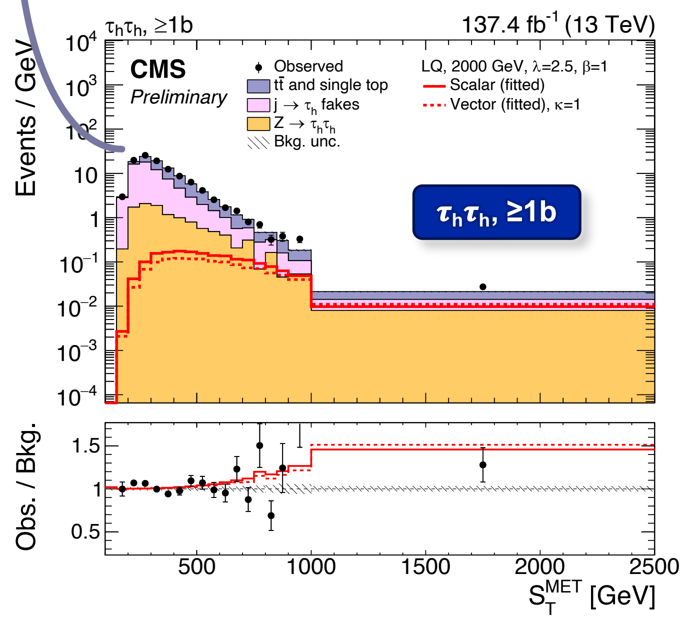
W + jets

$q\bar{q} \rightarrow j\,\ell^{-}\nu^{+}$



+ other

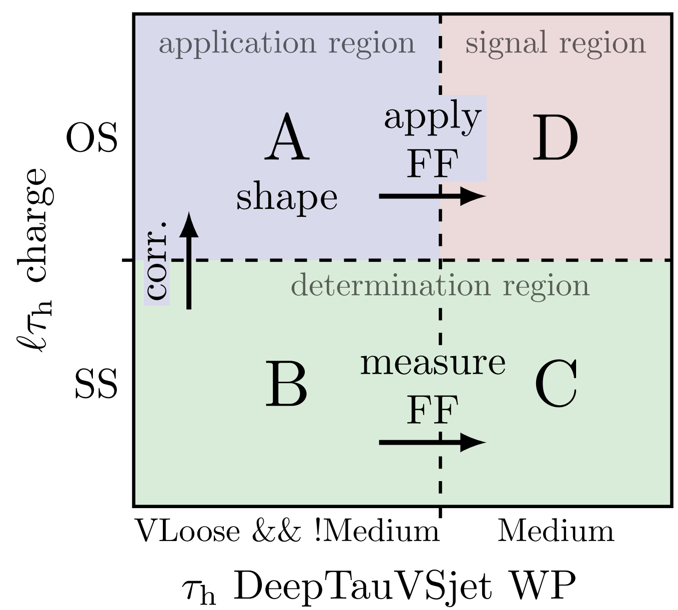




$j \to \tau_h$ fake background estimation

- background from jets misidentified as τ_h
- most dominantly from QCD and W + jets
- data-driven “fake factor” method estimates the fake rate and distribution shape from dedicated control regions
- similar to ABCD method, except
  1. **fake factors** (FFs) + **closure corrections** are measured as a function of several variables: p_T, ΔR, #jets, m_{vis}, …
  2. FFs are measured separately for **3 backgrounds** (QCD, W+jets, ttbar) to take into account the relative contribution of their flavor composition

$$N_D = N_A \underbrace{\frac{N_C}{N_B}}_{FF}$$



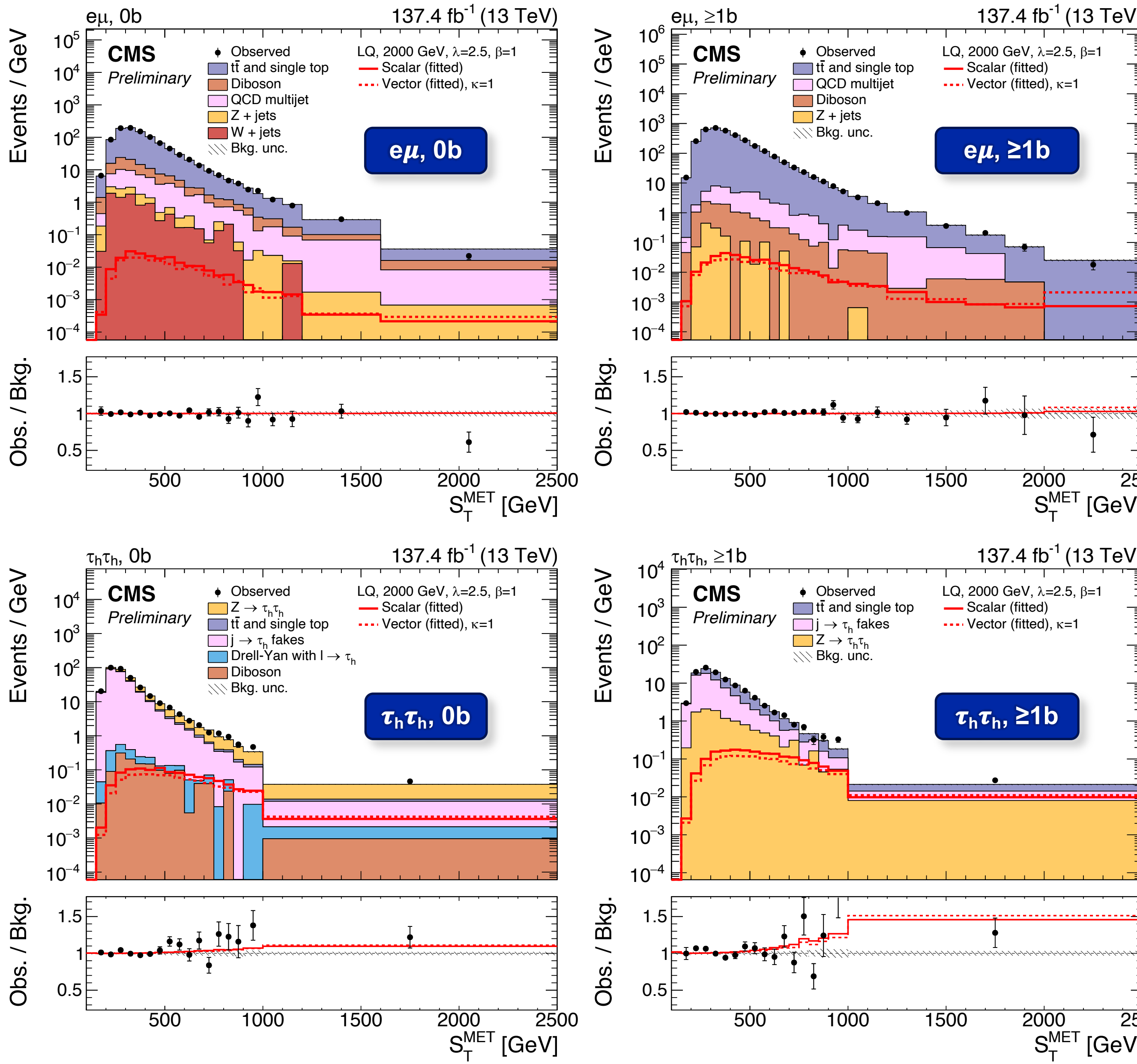
$$\mathrm{FF}(p_T^{\tau_h}, \ldots) = \frac{N(\texttt{Medium})_{DR}}{N(\texttt{VLoose \&\& !Medium})_{DR}}$$

[HIG-17-020, HIG-21-001]

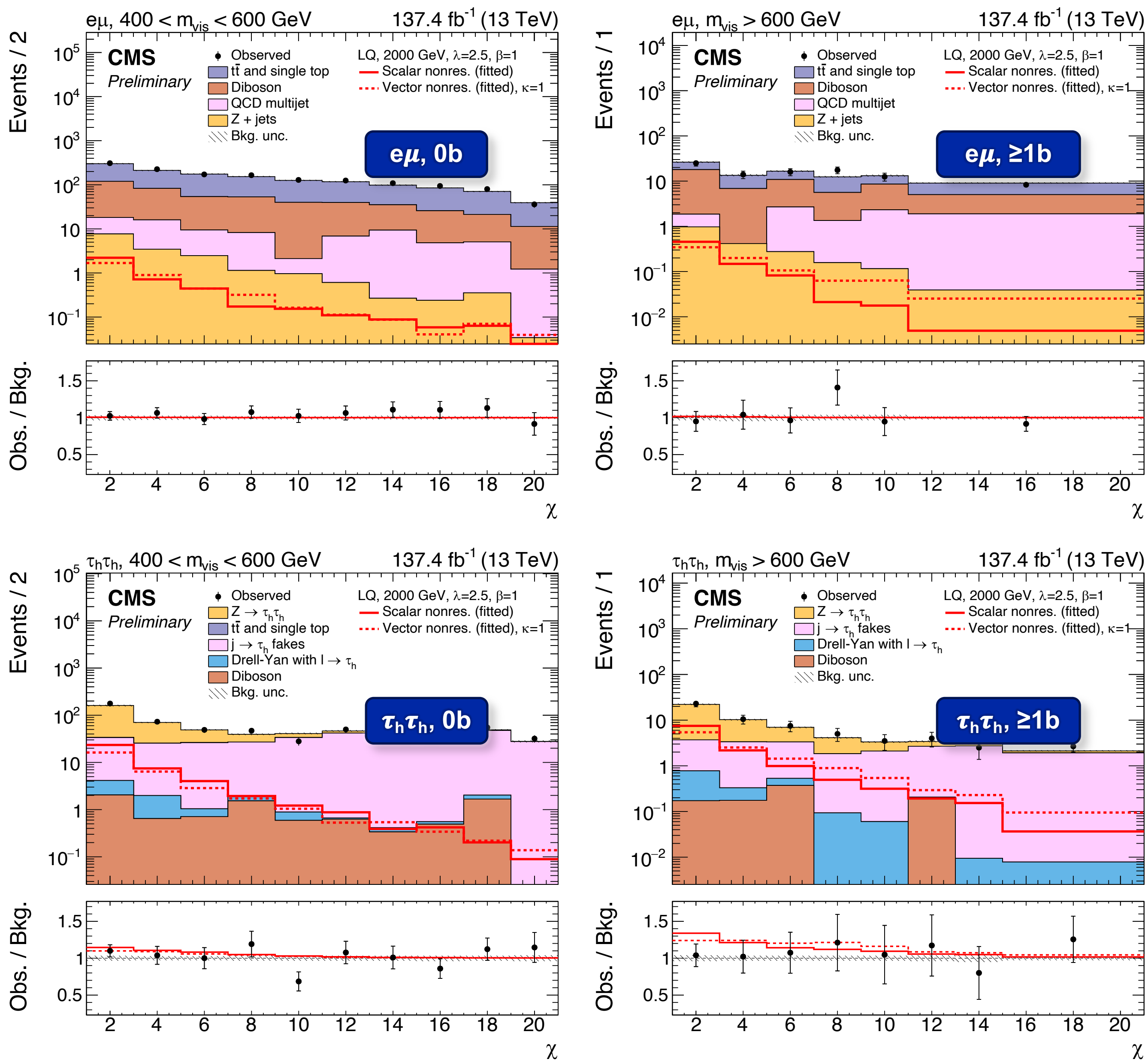
Postfit S_T^{MET} distributions in 0b & ≥1b

2000 GeV
λ = 2.5

for paper, add up distributions per year for full Run-2 plots

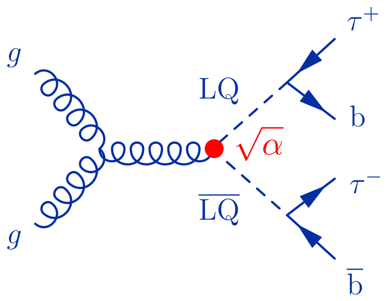


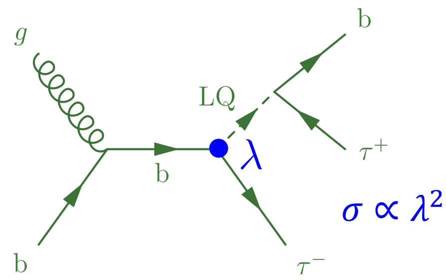
Postfit χ distributions in 0j

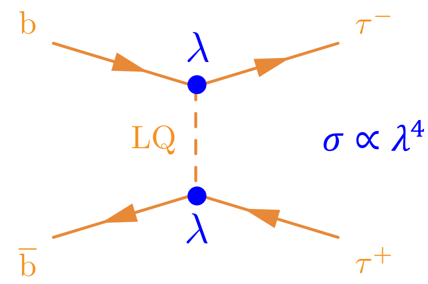


for paper, add up distributions per year for full Run-2 plots

Definition of signal strength



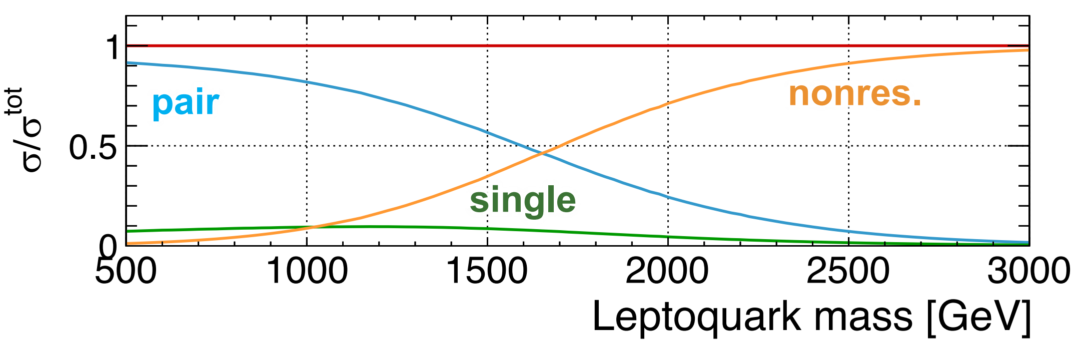




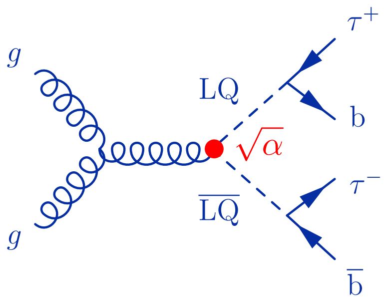
$$r(\text{total}) = r\left(\frac{\sigma_{\text{pair}}}{\sigma_{\text{tot}}}(\text{pair}) + \frac{\sigma_{\text{single}}}{\sigma_{\text{tot}}}(\text{single}) + \frac{\sigma_{\text{nonres}}}{\sigma_{\text{tot}}}(\text{nonres})\right)$$

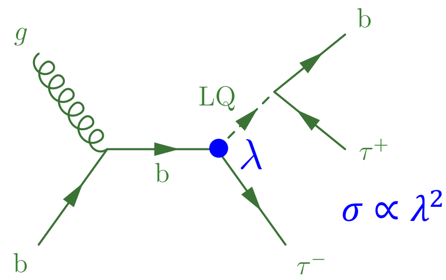
$$\approx r\left(\frac{\sigma_{\text{pair}}}{\sigma_{\text{tot}}}(\text{pair}) + \lambda^2\frac{\sigma^{\lambda=1}_{\text{single}}}{\sigma_{\text{tot}}}(\text{single}) + \lambda^4\frac{\sigma^{\lambda=1}_{\text{nonres}}}{\sigma_{\text{tot}}}(\text{nonres})\right)$$

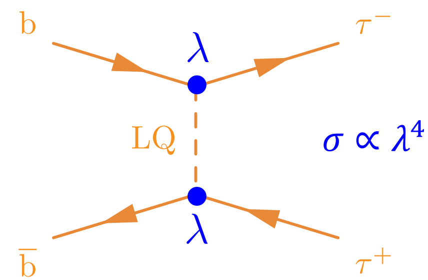
weight by fractional cross section (λ = 1)



Definition of signal strength





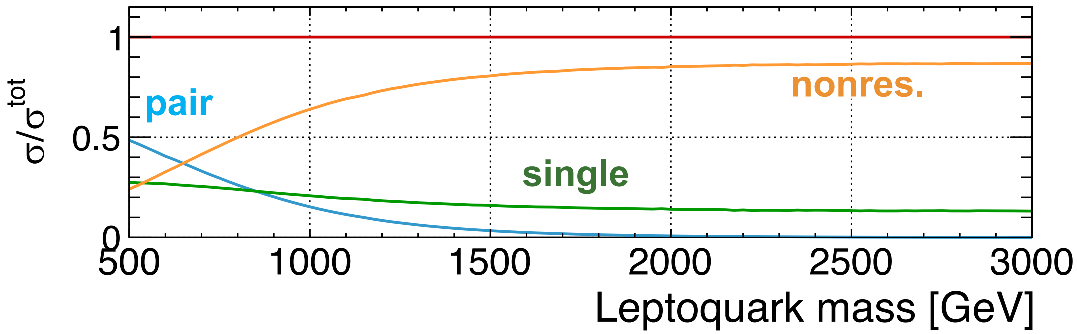


$$r(\text{total}) = r\left(\frac{\sigma_{\text{pair}}}{\sigma_{\text{tot}}}(\text{pair}) + \frac{\sigma_{\text{single}}}{\sigma_{\text{tot}}}(\text{single}) + \frac{\sigma_{\text{nonres}}}{\sigma_{\text{tot}}}(\text{nonres})\right)$$

$$\approx r\left(\frac{\sigma_{\text{pair}}}{\sigma_{\text{tot}}}(\text{pair}) + \lambda^2\frac{\sigma^{\lambda=1}_{\text{single}}}{\sigma_{\text{tot}}}(\text{single}) + \underbrace{\lambda^4\frac{\sigma^{\lambda=1}_{\text{nonres}}}{\sigma_{\text{tot}}}(\text{nonres})}\right)$$

low sensitivity, but dominant at high mass, high λ

weight by fractional cross section (λ = 2.5)

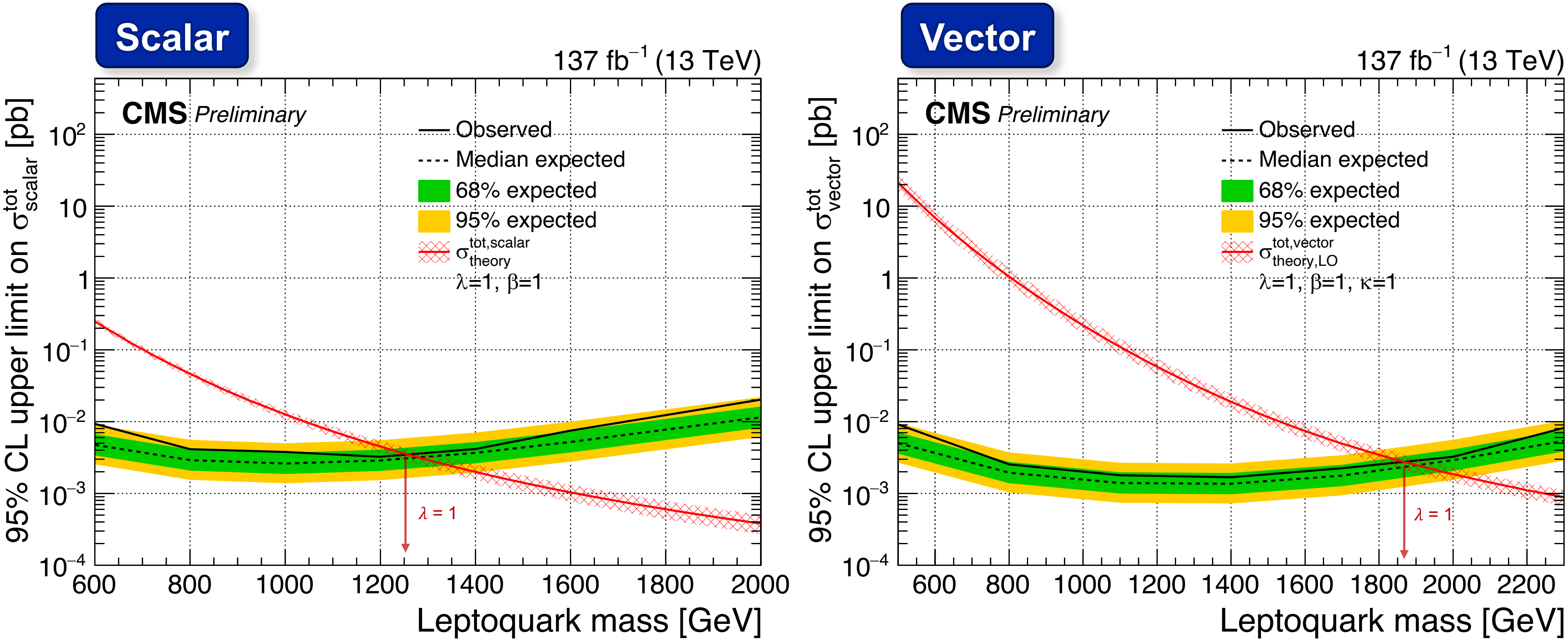


benchmarks

M = 1400 GeV, λ = 1 → sensitive to pair

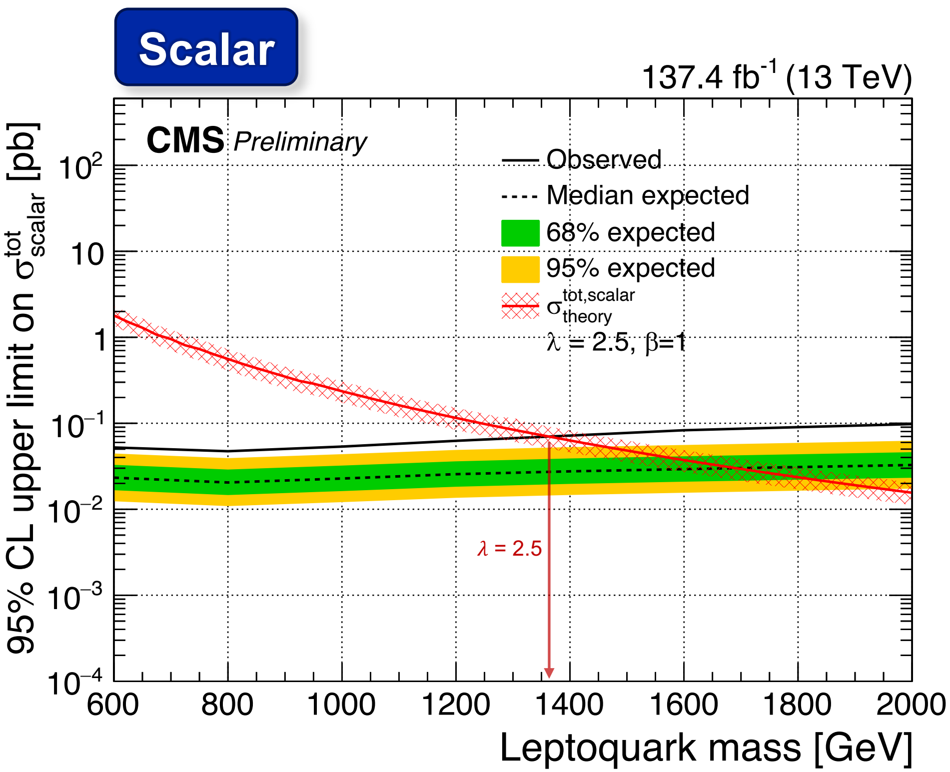
M = 2000 GeV, λ = 2.5 → sensitive to nonres.

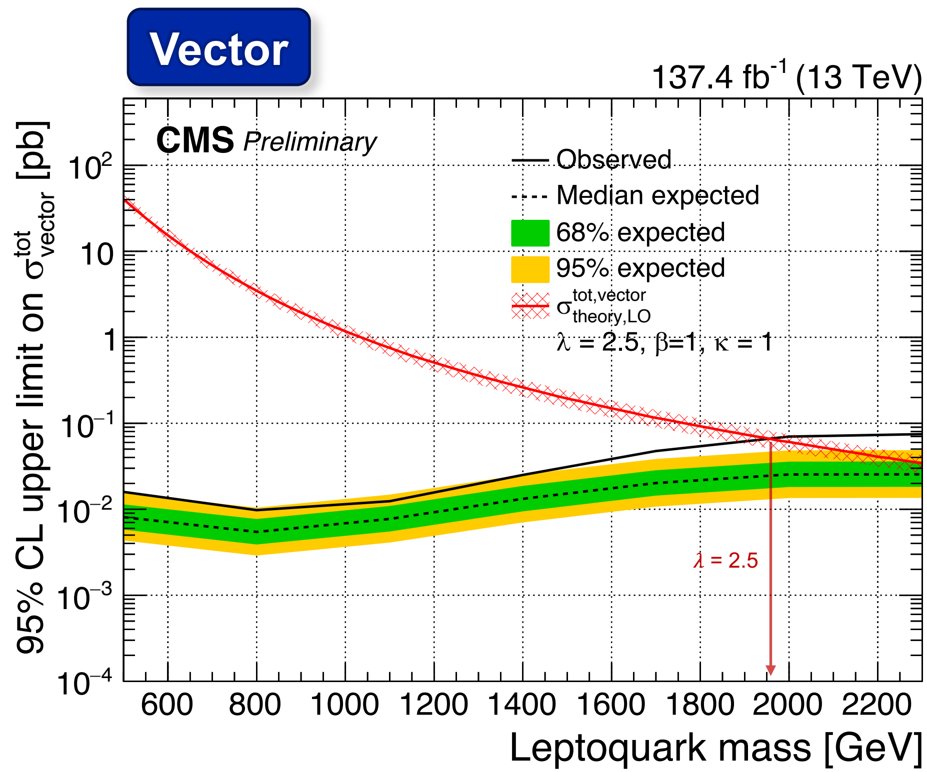
Combined upper limit, λ = 1



- no significant excess over the SM observed
- scalar (vector) LQ excluded up to **1.25** (**1.95**) TeV for λ = 2.5

Combined upper limit, λ = 2.5

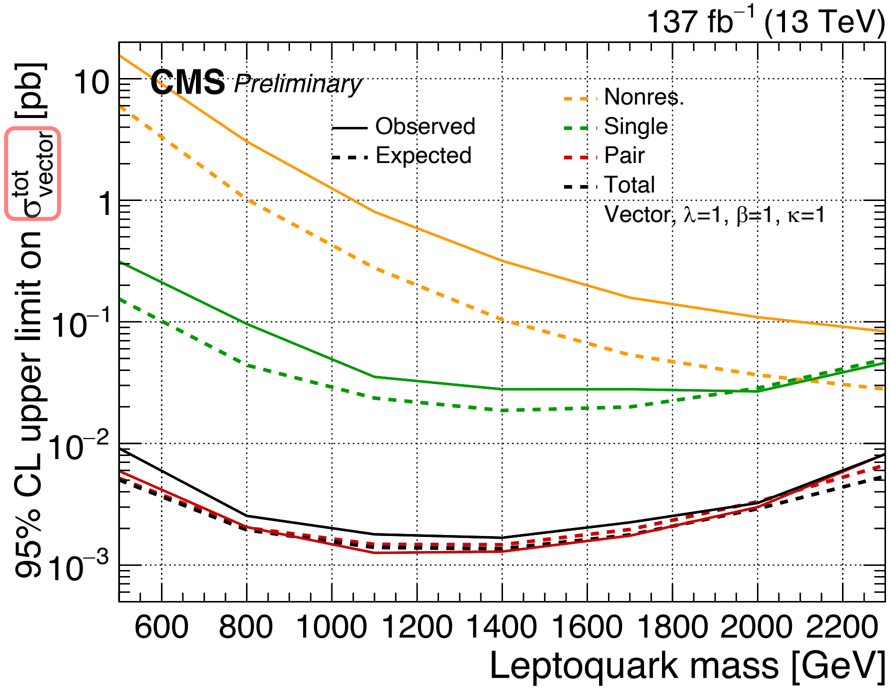


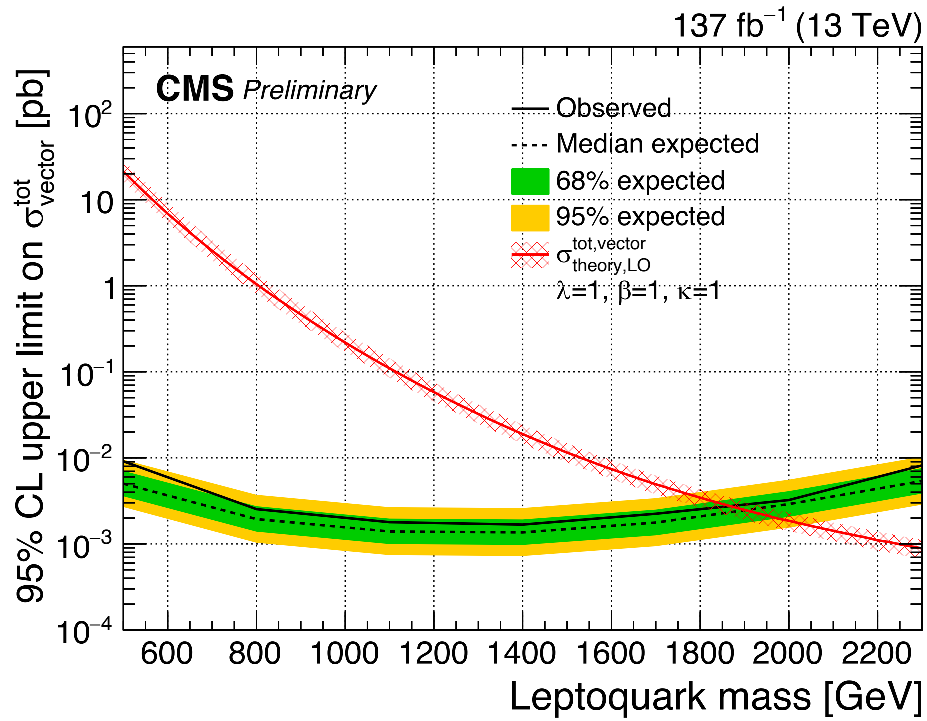


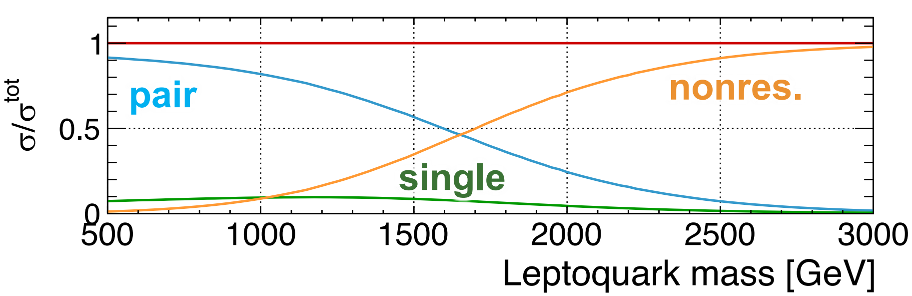
- ~3σ excess above M > 1800 TeV coming from nonresonant signal
- scalar (vector) LQ excluded up to **1.37** (**1.96**) TeV for λ = 2.5

Comparing production modes

pair production most sensitive at λ = 1, as expected

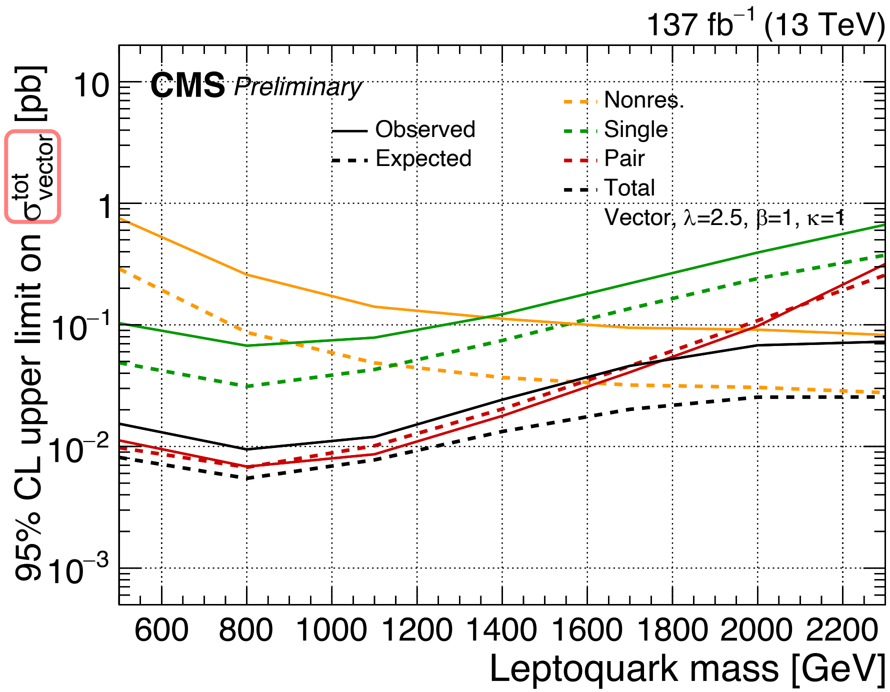


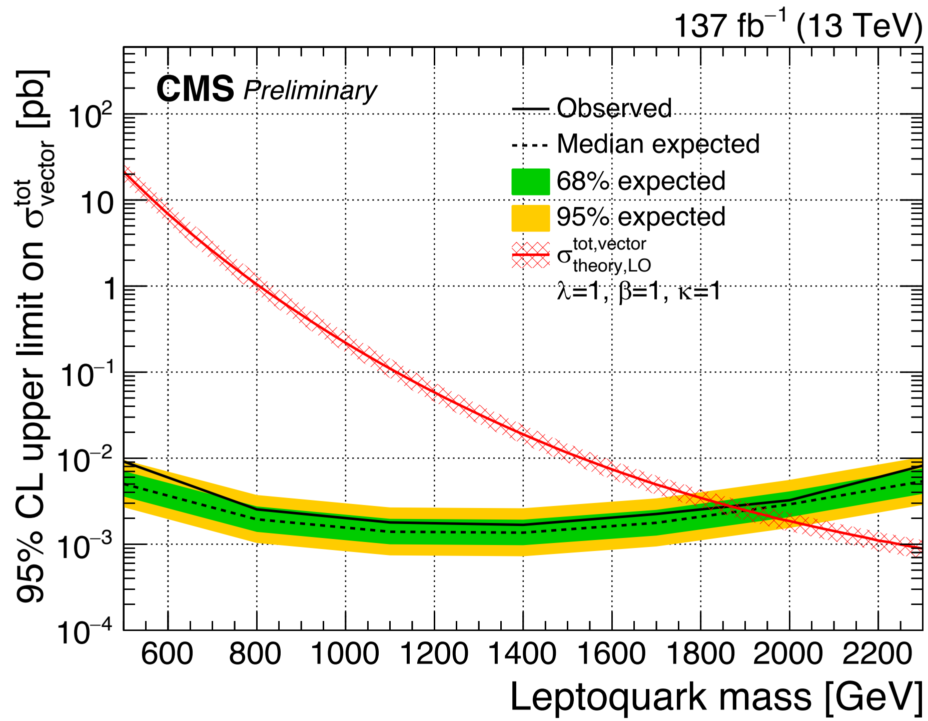


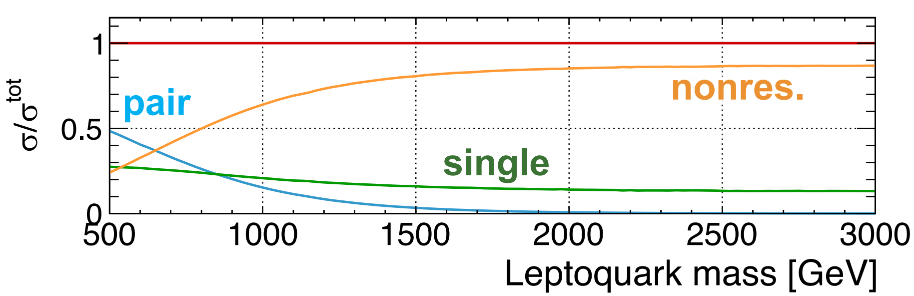


Comparing production modes

nonresonant production most sensitive at $\lambda = 2.5$, as expected

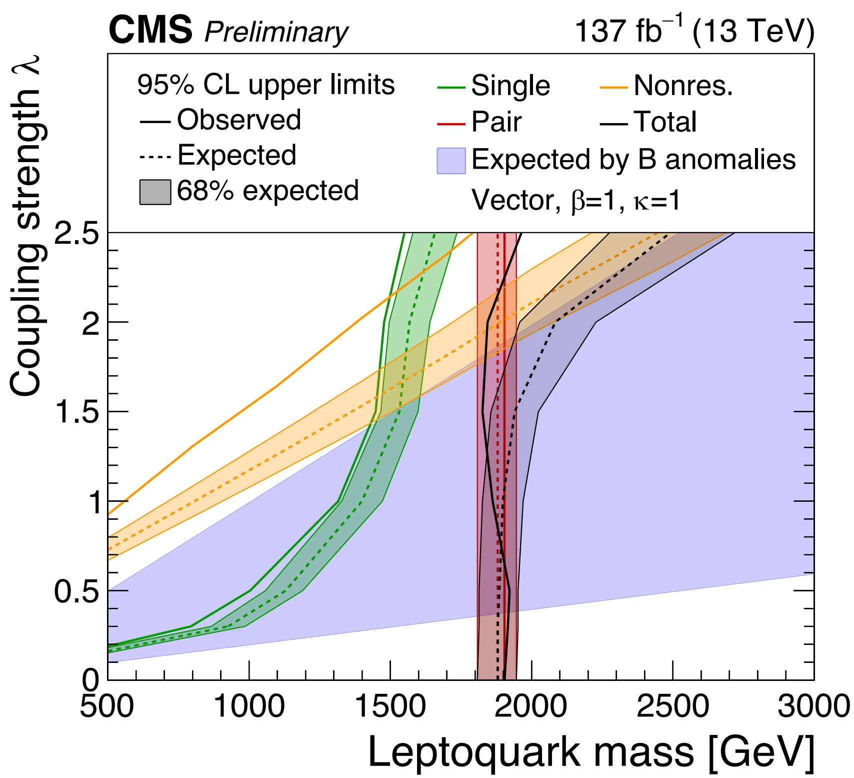






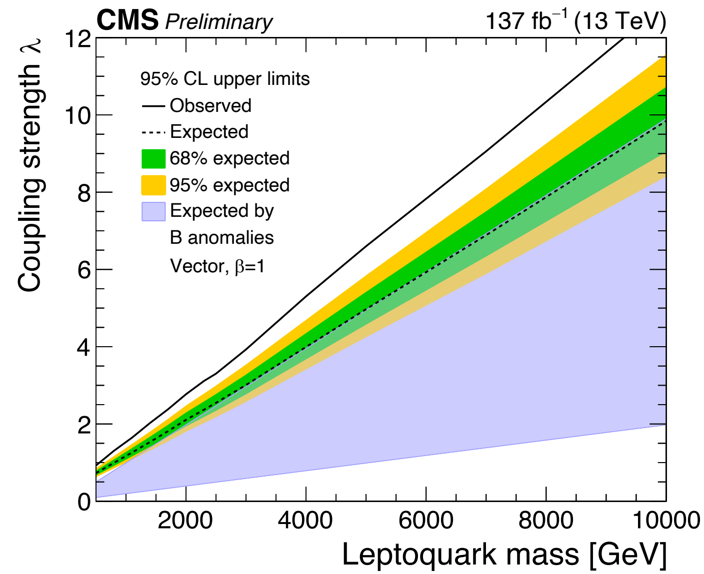
LQ → bτ exclusion limits of λ and mass

Resonant + nonresonant

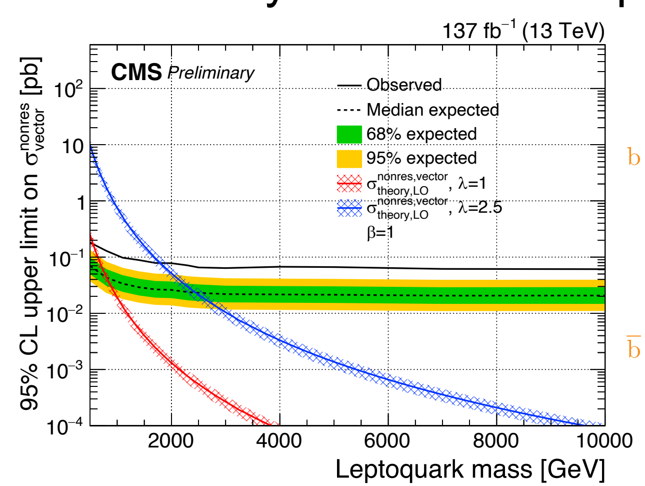


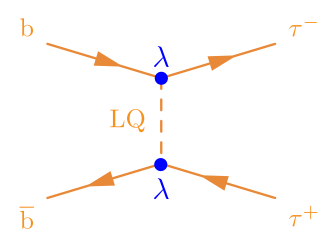
mass limit up to **~1.9 TeV**

Nonresonant only

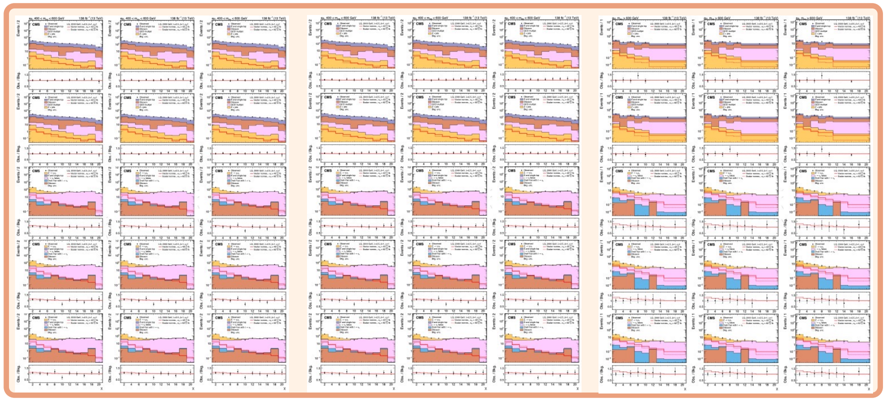


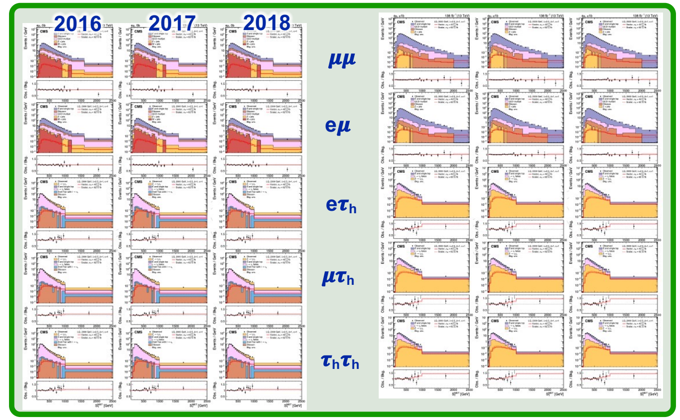
- ~3.5σ excess in nonresonant channel
- no sensitivity to mass or coupling:



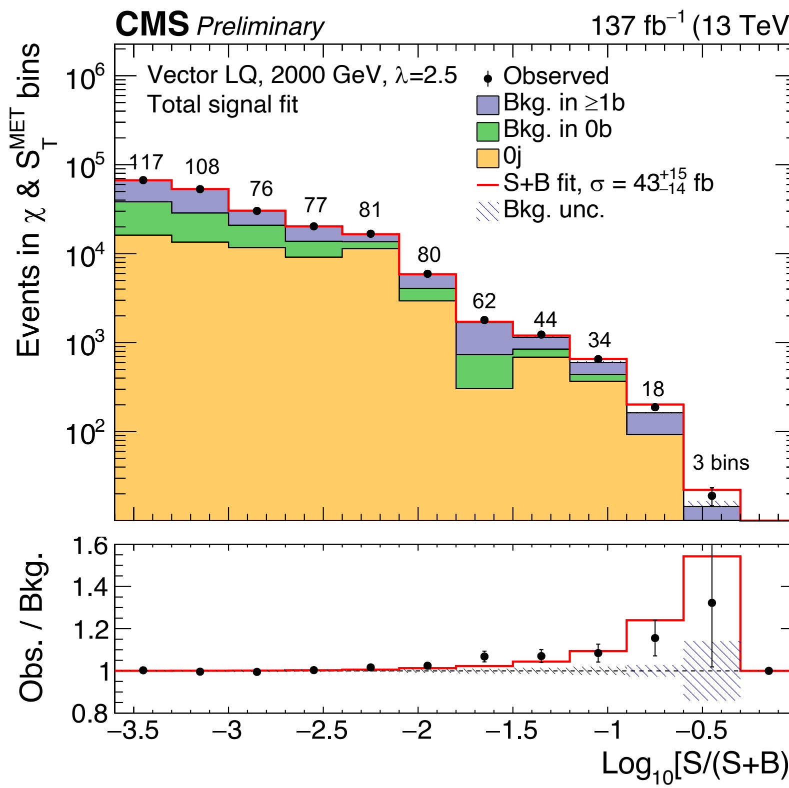


Reorder bins by S / (S+B)



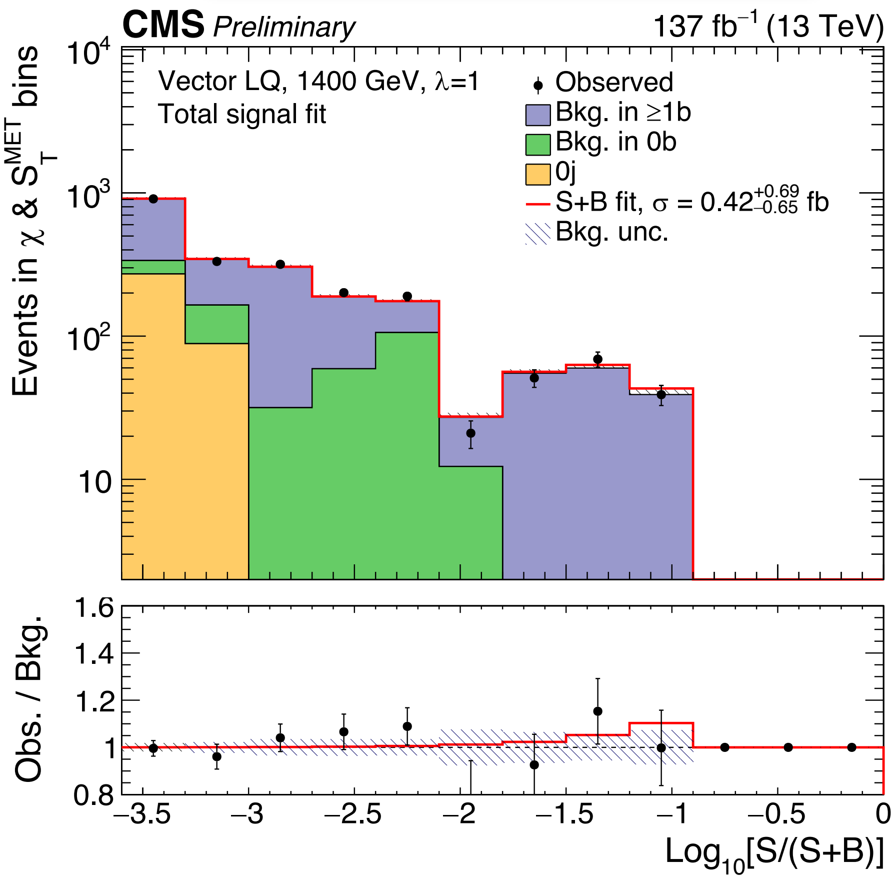


1. fit total signal (pair+single+nonres)
2. reorder and stack χ, S_T^{MET} bins by S/(S+B)
3. group backgrounds by category

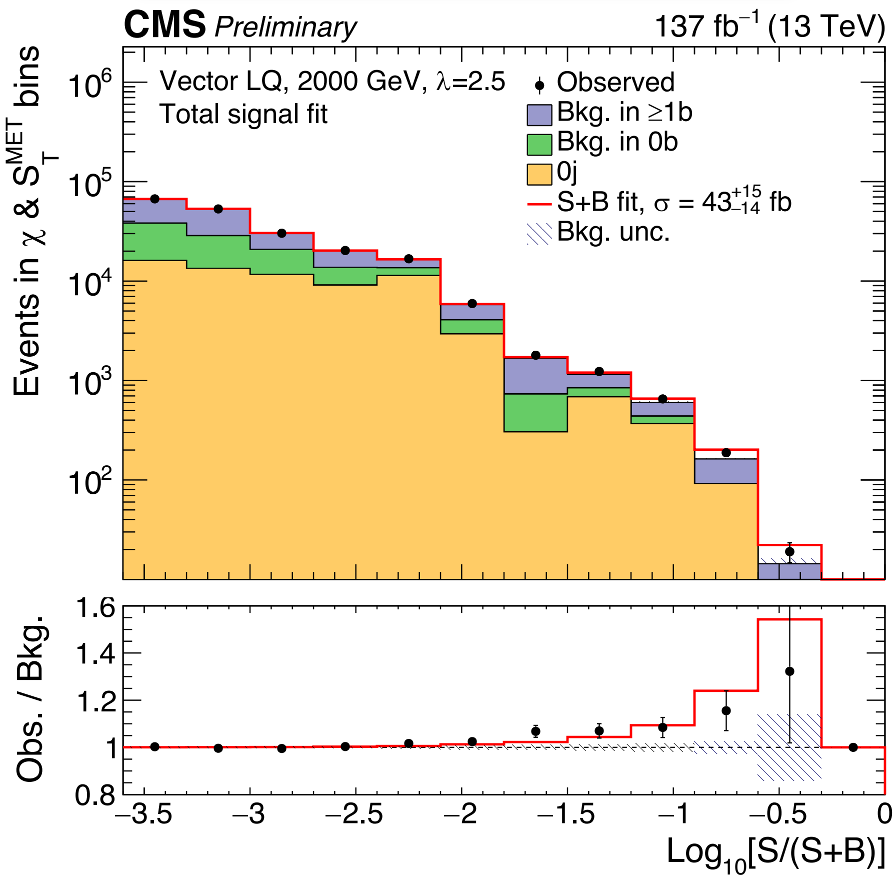


Reorder bins by S / (S+B)

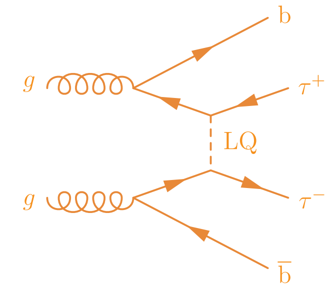
Vector, M = 1400 GeV, λ = 1



Vector, M = 2000 GeV, λ = 2.5



Comparison EXO-19-016 & HIG-21-001



	EXO-19-019	HIG-21-001
jet categories	"0j": veto jets p_T > 50 GeV "≥1j" with p_T > 50 GeV, m_{vis} > 100 GeV • "0b" = "0b≥1j" • "≥1b"	"No b tag" (no jet requirement) "B tag" with p_T > 20 GeV
observables	χ, S_T^{MET}	m_T^{tot}
Drell-Yan estimation	MC + Z p_T corrections from $\mu\mu$	Data-driven with "embedded" samples (from $\mu\mu$ events)
$j \rightarrow \tau_h$ estimation	Data-driven, "fake-factor" method	Data-driven, "fake-factor" method

EXO-19-016   HIG-21-001, arXiv:2208.02717

"best-fit" to B anomalies

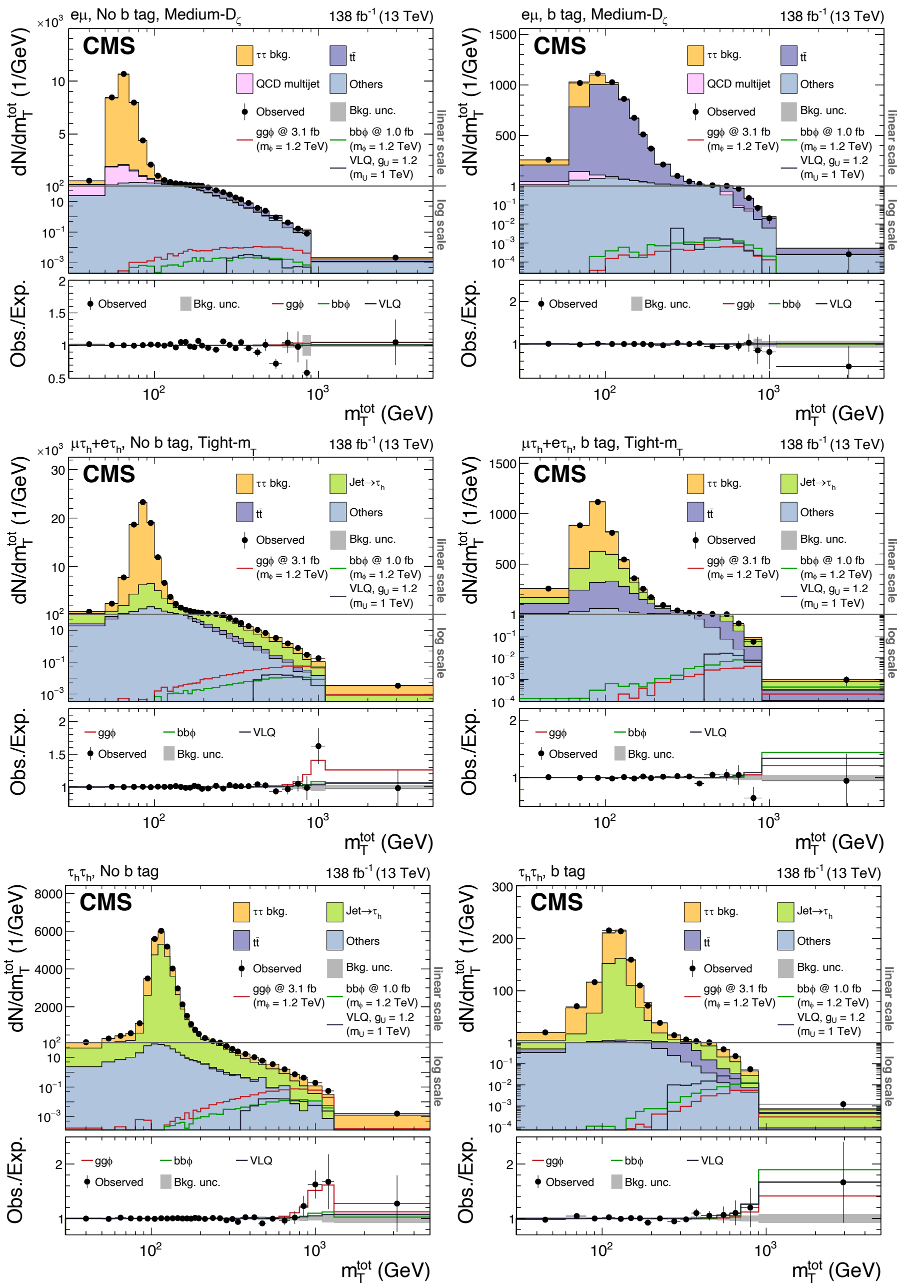
$$\lambda_{\ell q} = \lambda \cdot \begin{array}{c} \\ d/u' \\ s/c' \\ b/t' \end{array} \begin{array}{c} \begin{array}{ccc} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

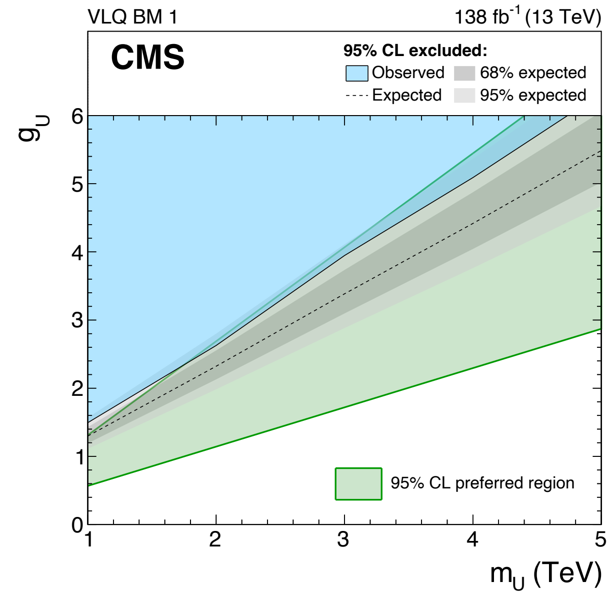
$$\lambda_{\ell q} = \frac{g_U}{\sqrt{2}} \cdot \begin{array}{c} \\ d/u' \\ s/c' \\ b/t' \end{array} \begin{array}{c} \begin{array}{ccc} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & +0.01 & 0.19 \\ 0 & -0.14 & 1 \end{pmatrix} \end{array}$$

arXiv:2103.16558

HIG-21-001: nonresonant $\tau\tau$ via vector LQ

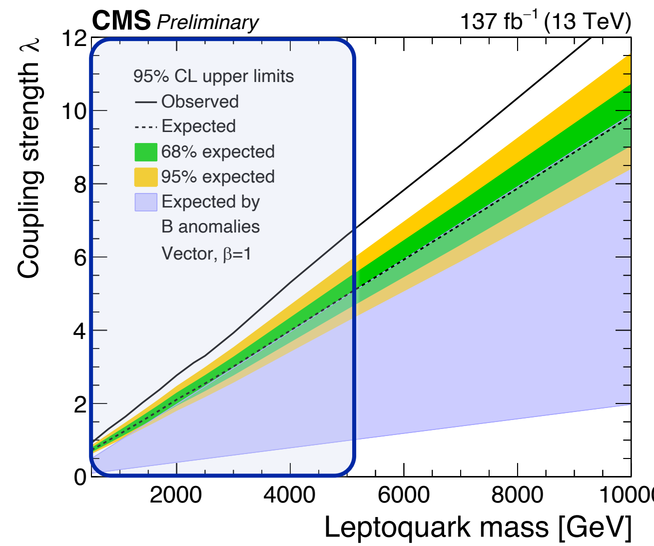
HIG-21-001
arXiv:2208.02717





$$\lambda = \frac{g_U}{\sqrt{2}}$$

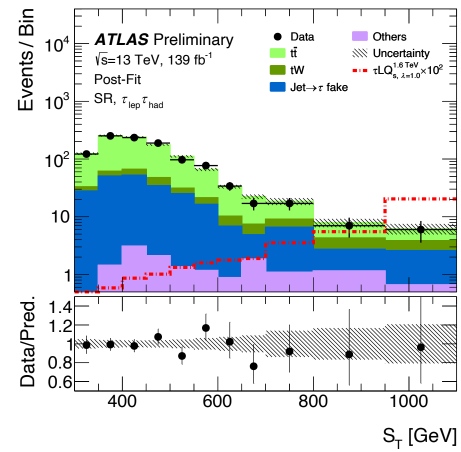
- similar LQ result to EXO-19-016
- ~2σ excess across mass spectrum

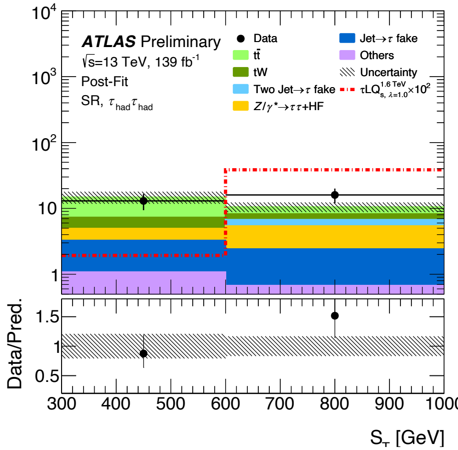


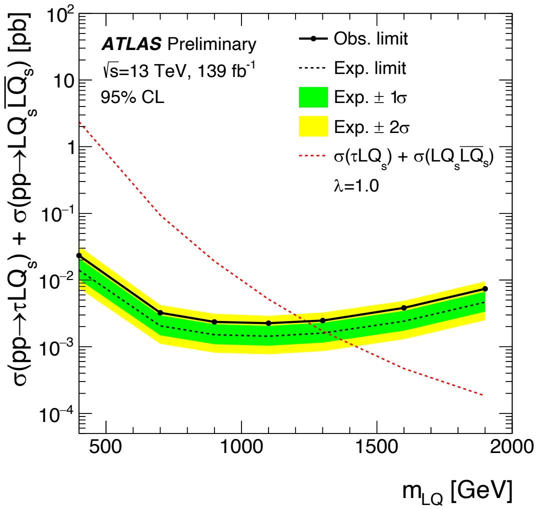
ATLAS: LQ → bτ pair + single

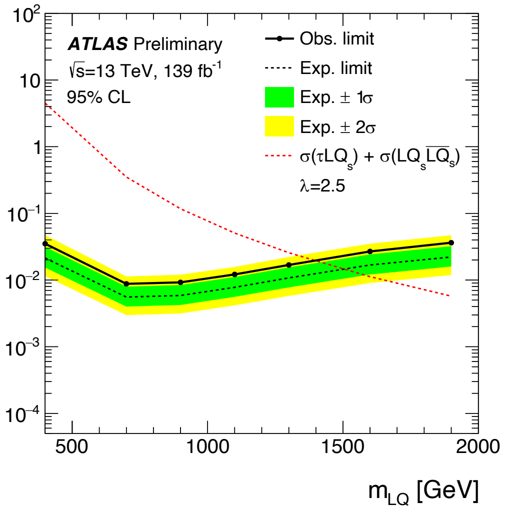
ATLAS-CONF-2022-009
ATLAS-CONF-2022-037

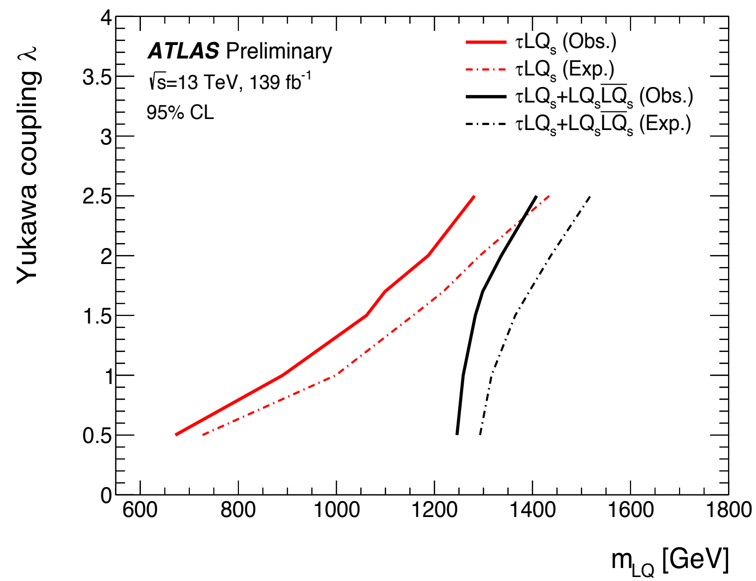
- new b$\tau\tau$ analysis with single + pair scalar LQ (no vector)
- no significant excess
- no nonresonant interpretation



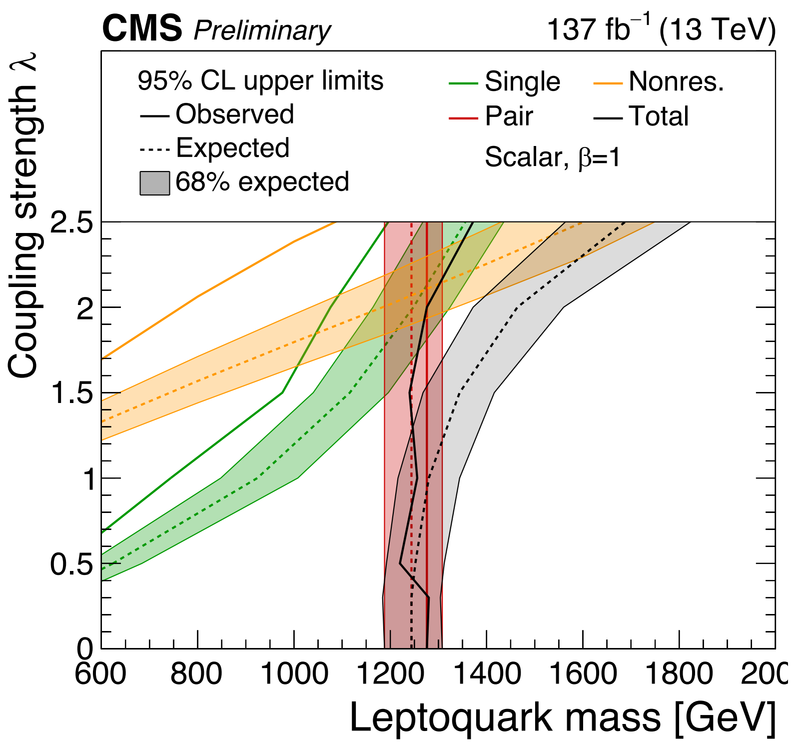


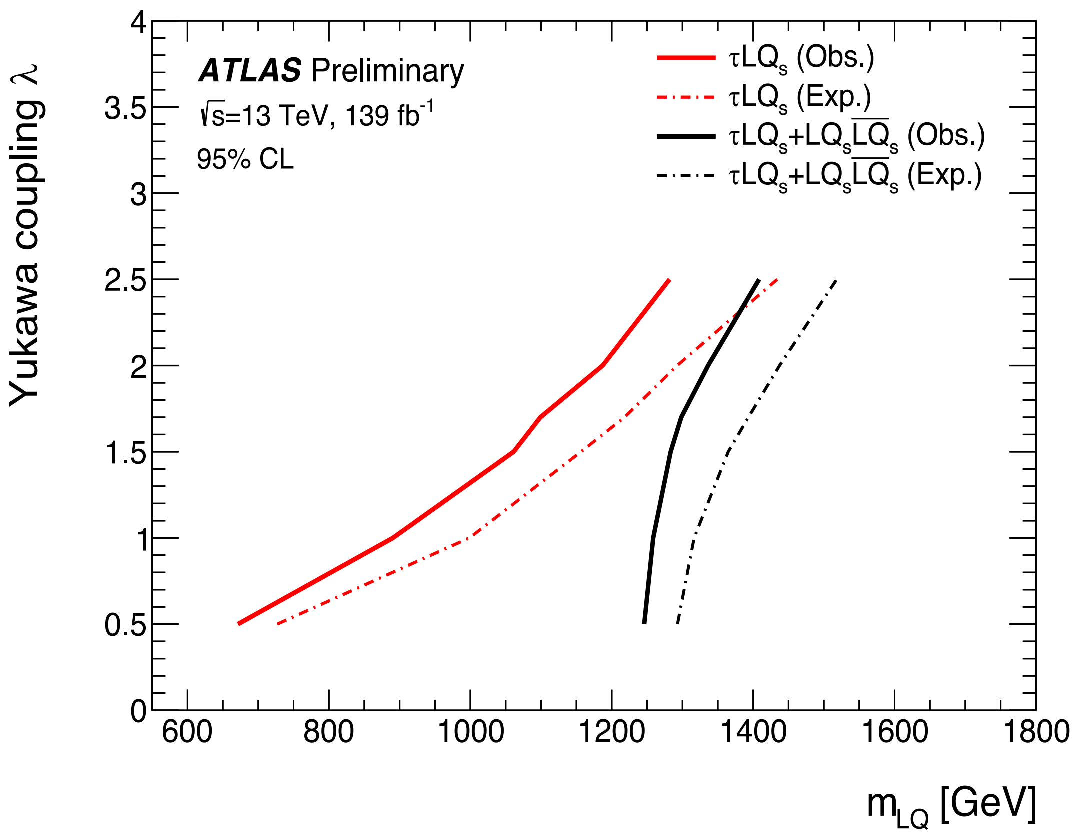




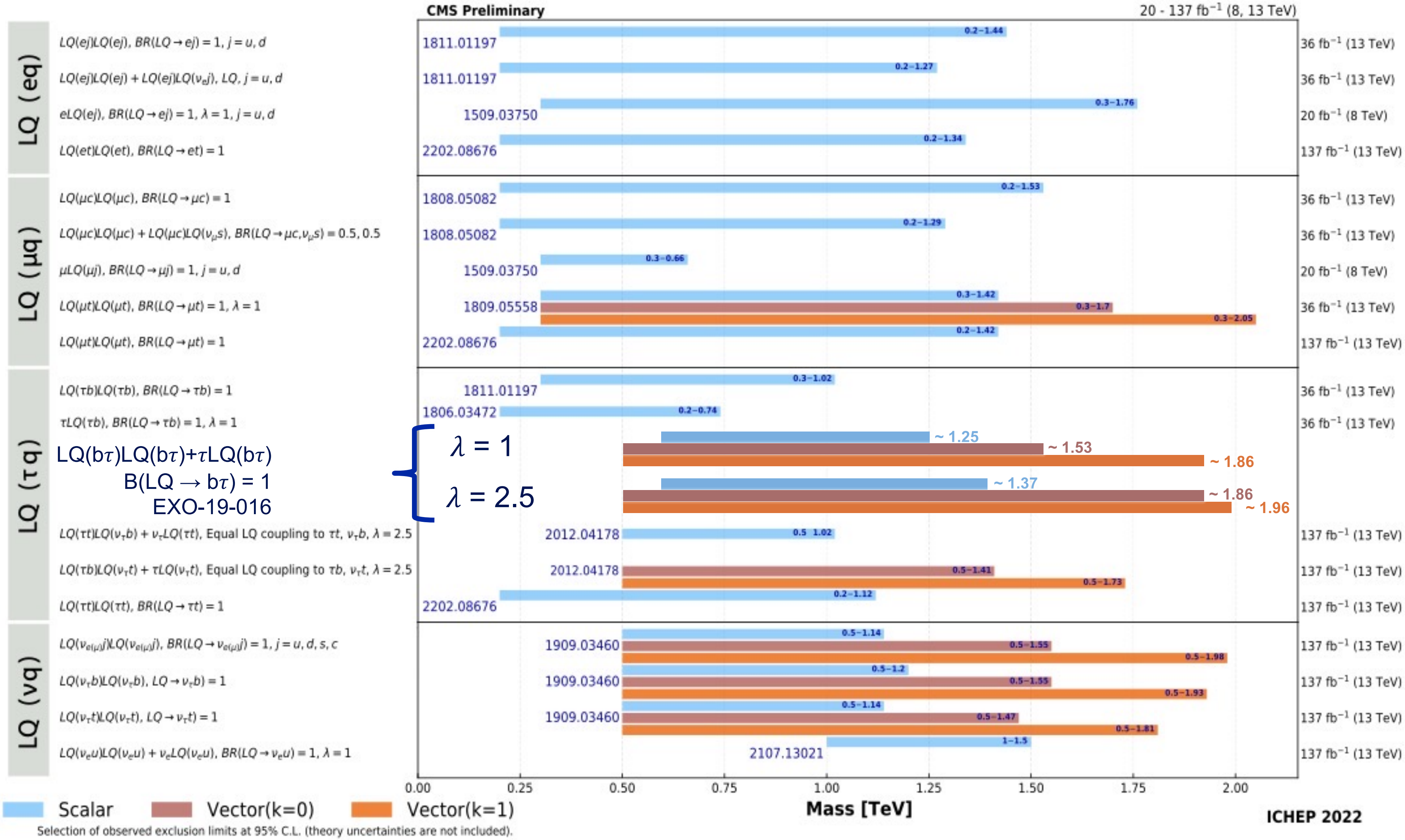


LQ → bτ exclusion limits of λ and mass

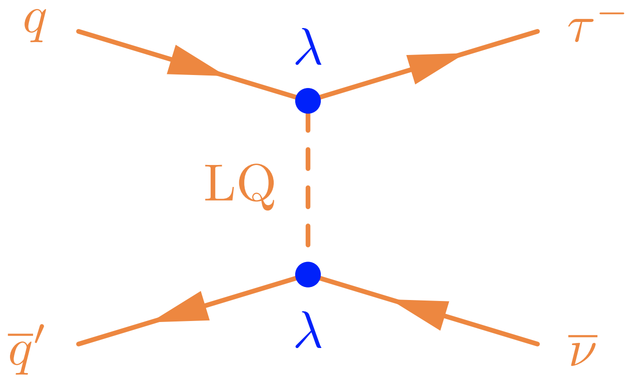




CMS LQ summary



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Leptoquark_summary_plot

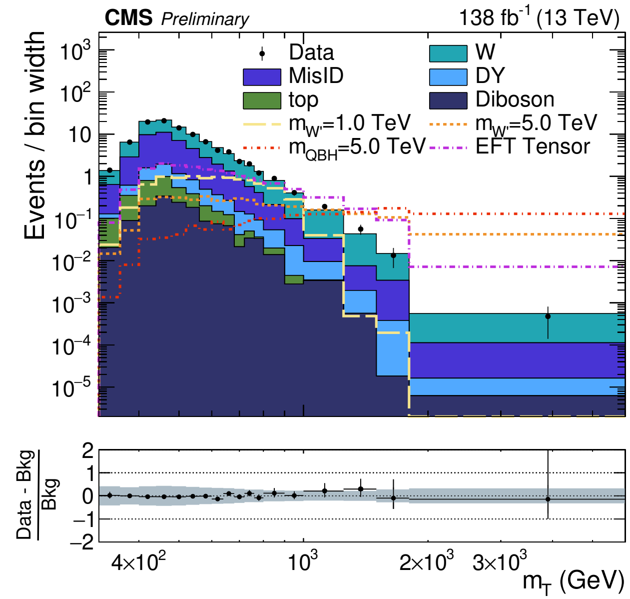


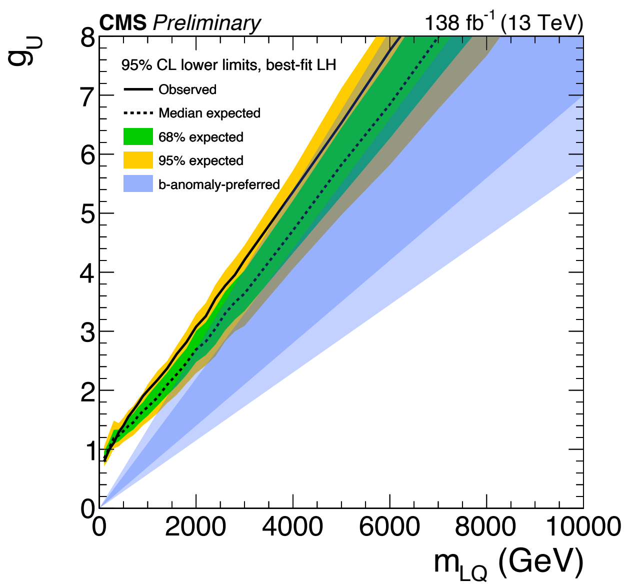
$LQ_3 \rightarrow b\nu$

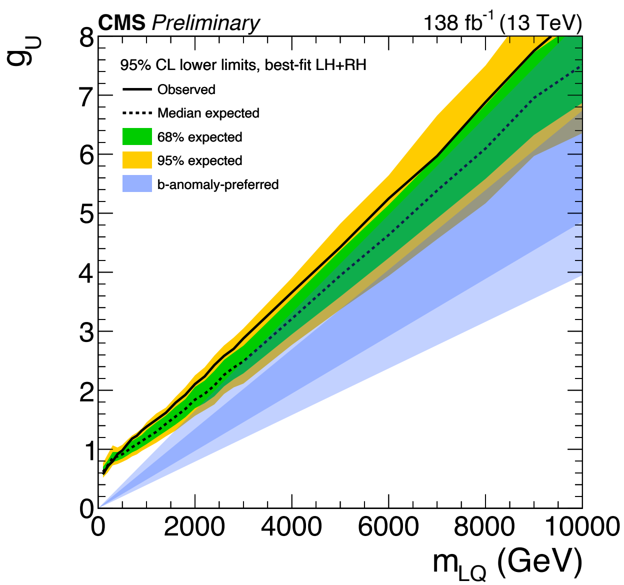
EXO-21-009

Nonres. LQ interpretation of EXO-21-009

- target τ+MET events
- fit m_T to target W' $\rightarrow \tau\nu$ & other signals
- easily reinterpretated with nonresonant $\tau\nu$ via LQ in *t* channel
- ~1σ across LQ mass, consistent with EXO-19-016 limit assuming LH couplings only
- first test of b $\rightarrow$ c$\tau\nu$ at TeV scale

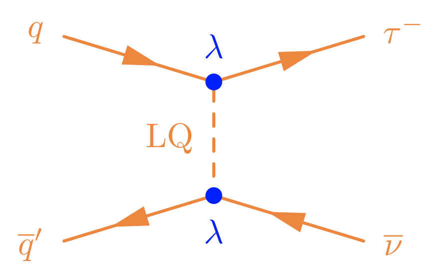






"best-fit" to B anomalies

$$\lambda_{\ell q} = \frac{g_U}{\sqrt{2}} \cdot \begin{array}{c} \\ \mathrm{d/u'} \\ \mathrm{s/c'} \\ \mathrm{b/t'} \end{array} \begin{array}{c} \begin{array}{ccc} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & +0.01 & 0.19 \\ 0 & -0.14 & 1 \end{pmatrix} \end{array}$$

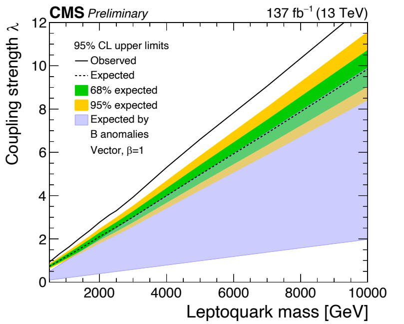


$$\lambda = \frac{g_U}{\sqrt{2}}$$

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
  - new results with 138 fb^{-1} probe in the 1.5–2 TeV region
- using signatures with τ or (b) jet may help tag NP that couples preferentially to higher generation fermions
- presented searches for nonresonant LQ production
  - (b)(b)$\tau\tau$ final state in different (b) jet categories
  - found nonresonant excess up to 3.4σ
  - cross checked between EXO-19-016 and HIG-21-001

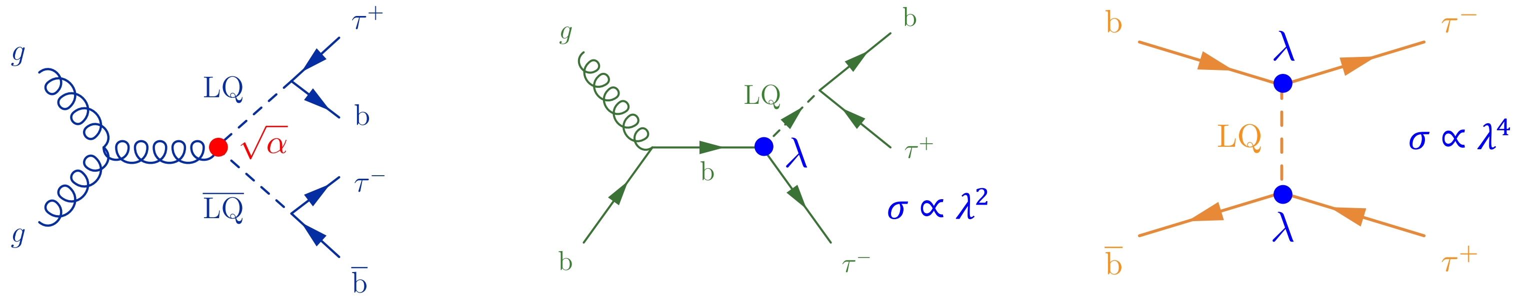


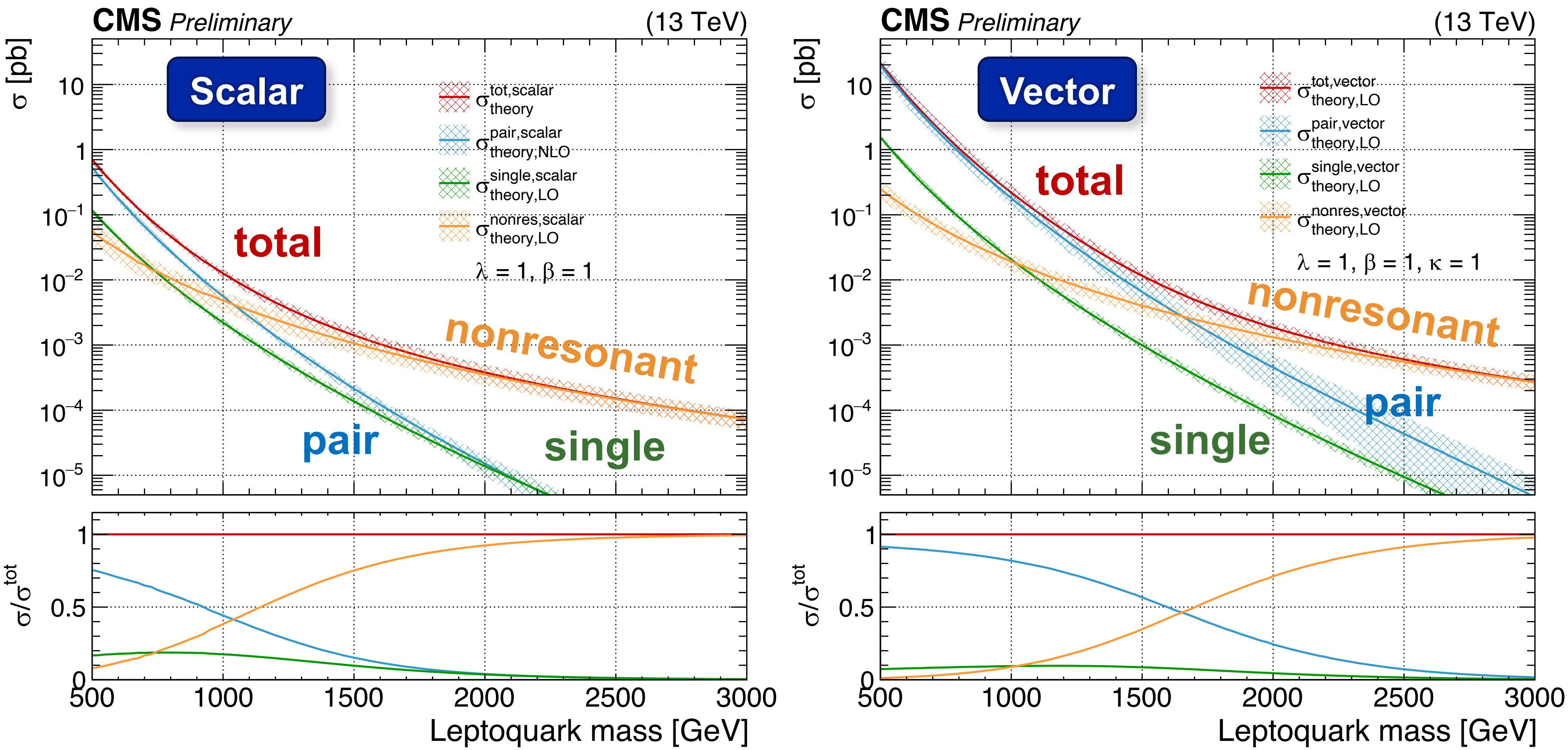
References

- Flavor Anomaly Workshop 2021
  https://indico.cern.ch/event/1055780/timetable/
- EXO-19-016 PAS
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-19-016/index.html
- EXO-21-009
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-21-009/index.html
- HIG-21-001
  http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-001/
- B2G-21-004
  http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-21-004/index.html
- CMS EXO results:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Leptoquark_summary_plot

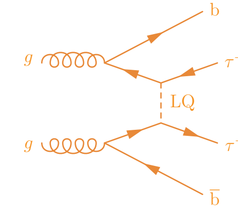
BACK UP

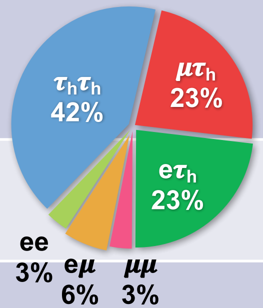
LQ cross sections @ 13 TeV





Comparison EXO-19-016 & HIG-21-001





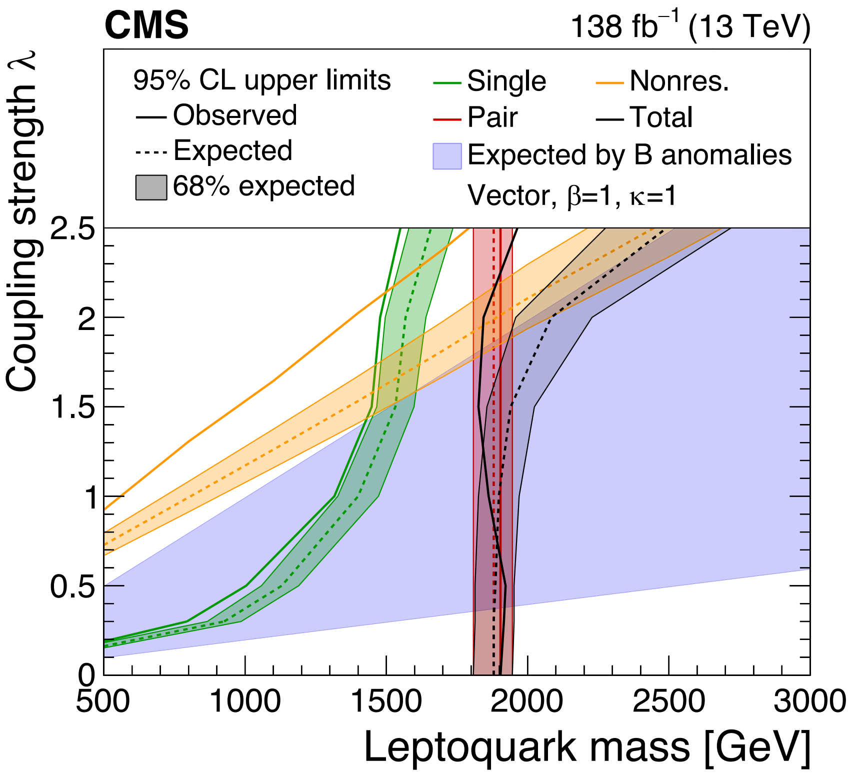
	EXO-19-019	HIG-21-001
signal models	scalar or vector LQ → bτ • single, pair LQ • nonres. $\tau\tau$	• MSSM $\varphi \rightarrow \tau\tau$ via gg → (b)(b)φ • vector LQ: nonres. $\tau\tau$
channels	eτ_h, $\mu\tau_h$, $\tau_h\tau_h$ + eμ, $\mu\mu$ p_T > 50 GeV	eτ_h, $\mu\tau_h$, $\tau_h\tau_h$ + eμ p_T > 15–40 GeV (trigger-dependent)
jet categories	"0j": veto jets p_T > 50 GeV • m_{vis} bins [200,400,600,∞[GeV "≥1j" with p_T > 50 GeV, m_{vis} > 100 GeV • "0b" = "0b≥1j" • "≥1b"	"No b tag" (no jet requirement) "B tag" with p_T > 20 GeV
observables	χ = exp($\Delta\eta$) in 0j S_T^{MET} in 0b and ≥1b	m_T^{tot}
Drell-Yan estimation	MC + Z p_T corrections from $\mu\mu$	Data-driven with "embedded" samples (from $\mu\mu$ events)
$j \rightarrow \tau_h$ estimation	Data-driven, "fake-factor" method	Data-driven, "fake-factor" method

EXO-19-016

HIG-21-001, arXiv:2208.02717

LQ → bτ exclusion limits of λ and mass

Resonant + nonresonant



Signal	m_{LQ} = 1400 GeV		m_{LQ} = 2000 GeV	
	σ_{fit} [fb]	z	σ_{fit} [fb]	z
Scalar				
Pair	$0.24^{+0.47}_{-0.45}$	0.5	$0.22^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.15^{+0.95}_{-0.92}$	1.3	$0.64^{+0.68}_{-0.65}$	1.0
Single, $\lambda = 2.5$	$9.1^{+5.6}_{-5.3}$	1.7	18^{+11}_{-11}	1.7
Nonres.	70^{+23}_{-22}	3.4	63^{+20}_{-19}	3.5
Total, $\lambda = 1$	$1.7^{+1.9}_{-1.8}$	0.9	$9.6^{+6.2}_{-5.9}$	1.7
Total, $\lambda = 2.5$	43^{+16}_{-15}	2.9	62^{+20}_{-19}	3.4
Vector, $\kappa = 0$				
Pair	$0.24^{+0.46}_{-0.44}$	0.0	$0.24^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.00^{+0.89}_{-0.85}$	1.2	$0.60^{+0.66}_{-0.63}$	1.0
Single, $\lambda = 2.5$	$9.1^{+6.5}_{-6.2}$	1.5	25^{+18}_{-17}	1.4
Nonres.	58^{+18}_{-17}	3.5	51^{+16}_{-15}	3.5
Total, $\lambda = 1$	$1.2^{+1.5}_{-1.4}$	0.8	$7.7^{+5.1}_{-4.8}$	1.7
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1
Vector, $\kappa = 1$				
Pair	$0.24^{+0.46}_{-0.44}$	0.0	$0.24^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.00^{+0.89}_{-0.85}$	1.2	$0.60^{+0.66}_{-0.63}$	1.0
Single, $\lambda = 2.5$	$9.1^{+6.5}_{-6.2}$	1.5	25^{+18}_{-17}	1.4
Nonres.	58^{+18}_{-17}	3.5	51^{+16}_{-15}	3.5
Total, $\lambda = 1$	$0.42^{+0.69}_{-0.66}$	0.6	$1.3^{+1.5}_{-1.4}$	0.5
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1

- ~3σ excess in nonresonant channel
- no sensitivity to mass or coupling

OTHER LQ ANALYSES

Third-generation LQ searches

$\beta = 0$

- **LQ → tν**
  scalar pair (2016, arXiv:1902.08103)
  scalar/vector pair (2016, SUS-19-005)
- **LQ → bν**
  scalar/vector pair (2016, SUS-19-005)

$\beta = 0.5$

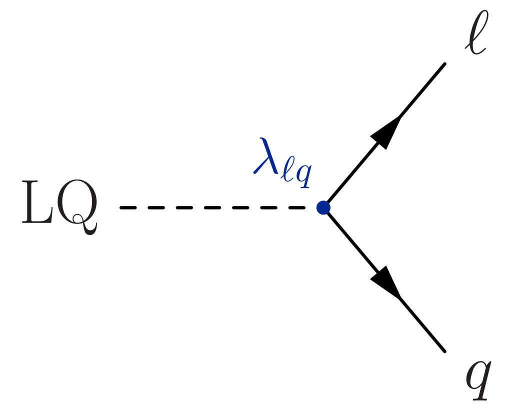
- **LQ → tτ, bν**
  scalar single+pair (Run 2, EXO-19-015)
  scalar pair (Run 2, ATLAS-CONF-2020-029)
- **LQ → tν, bτ**
  scalar pair (2016, arXiv:1902.08103)
  vector single+pair (Run 2, EXO-19-015)

$\beta = 1$

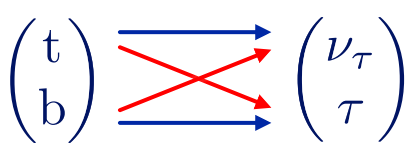
- **LQ → bτ**
  scalar pair (2016, EXO-17-016)
  scalar single (2016, EXO-17-029)
  scalar pair (2016, arXiv:1902.08103)
  scalar/vector pair (Run 2, arXiv:2108.07665)

  + scalar/vector pair+single+nonresonant (Run 2, EXO-19-016)
- **LQ → tτ**
  scalar pair (2016, B2G-16-028)
  scalar pair (Run 2, ATLAS-CONF-2020-029)

LQ_3 models & signatures



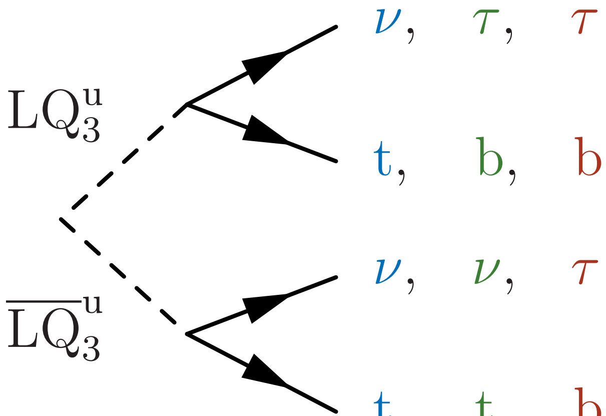
- scalar LQ_S (S = 0), vector LQ_V (S = 1)
- decays into ℓq
  - ⇒ carries L, B, color
  - ⇒ fractional charge
- coupling $\lambda_{\ell q}$
- simplified models restrict to up *or* down type:



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

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

- branching parameter β



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

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

typical benchmarks β = 0, 0.5, 1

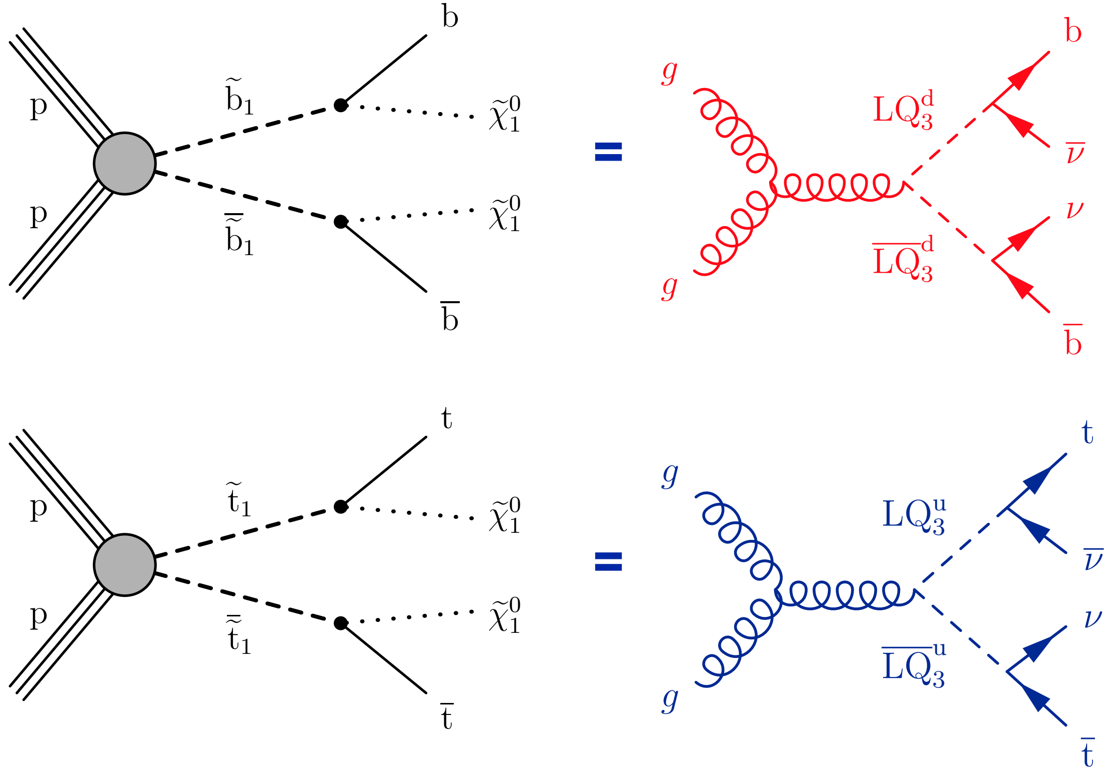
$$\mathrm{LQ}_3^{\mathrm{u}}\overline{\mathrm{LQ}}_3^{\mathrm{u}} \to \mathrm{t}\nu\mathrm{t}\nu, \mathrm{t}\nu\mathrm{b}\tau, \mathrm{b}\tau\mathrm{b}\tau$$

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

arXiv:1909.03460
β = 0, 137 fb^{-1}

$LQ_3LQ_3 \rightarrow b\nu b\nu$, $t\nu t\nu$

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



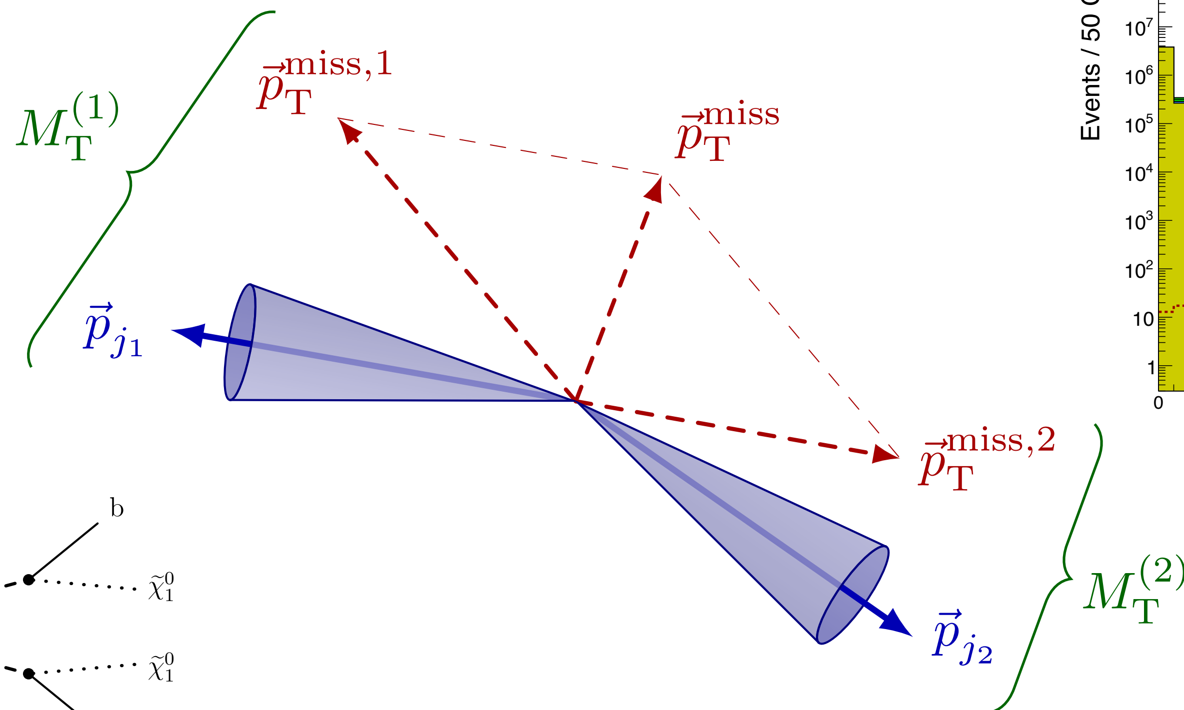
$$M_{T2} = \min_{\vec{p}_T^{\,miss,1} + \vec{p}_T^{\,miss,2} = \vec{p}_T^{\,miss}} \left[\max \left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

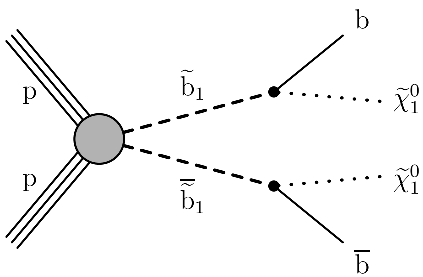
arXiv:1909.03460
β = 0, 137 fb^{-1}

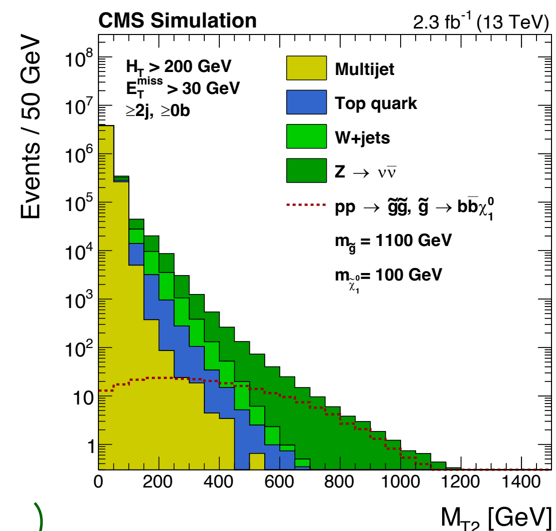
$LQ_3LQ_3 \rightarrow b\nu b\nu,\ t\nu t\nu$

- 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

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



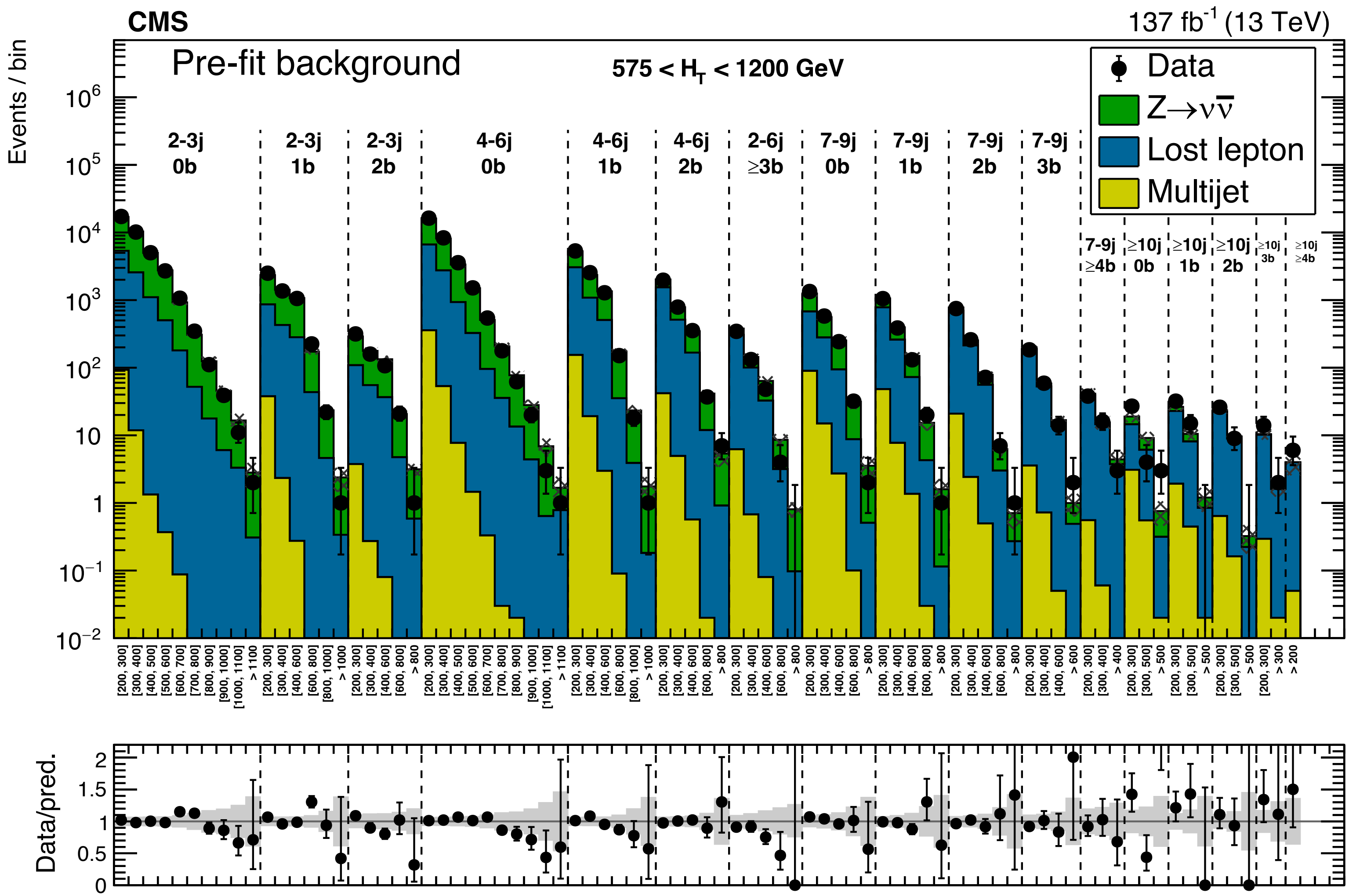




$\beta = 0$, 137 fb^{-1}

$LQ_3 LQ_3 \rightarrow b\nu b\nu$, $t\nu t\nu$ strategy

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



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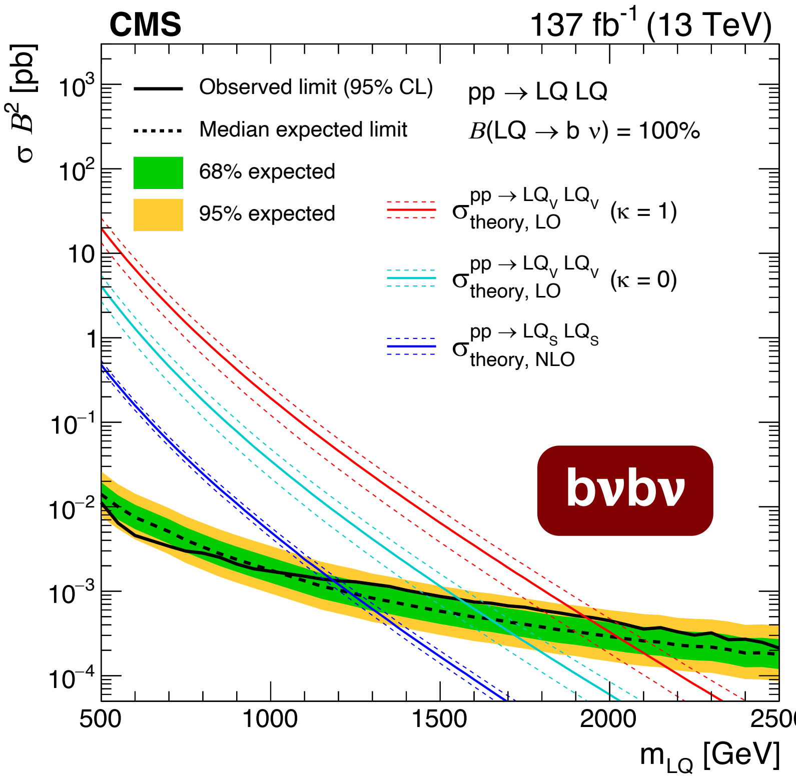
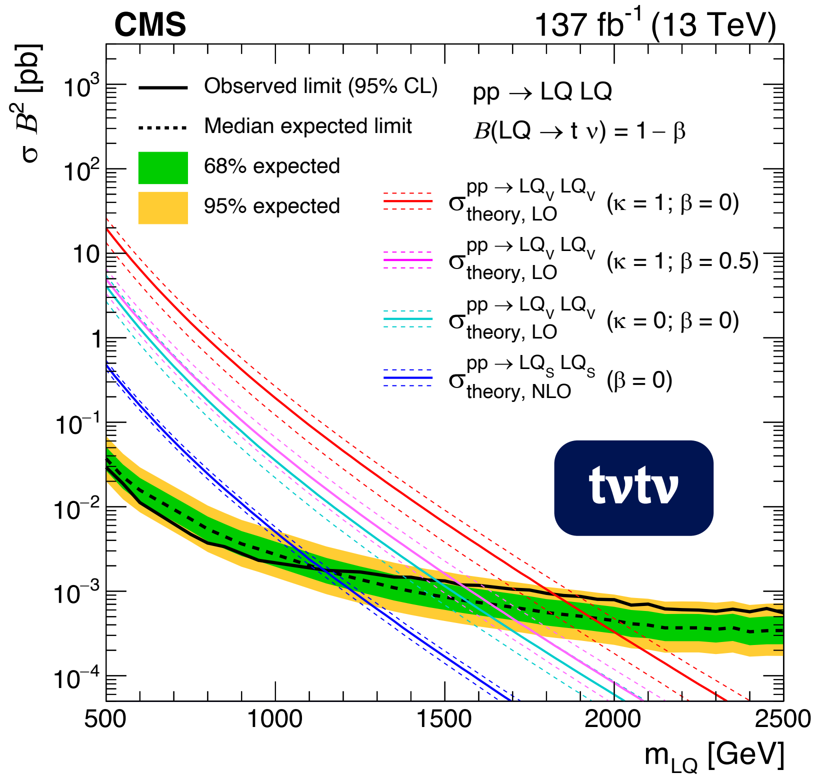
arXiv:1909.03460

β = 0, 137 fb^{-1}

LQ$_3$LQ$_3$ → bνbν, tνtν results





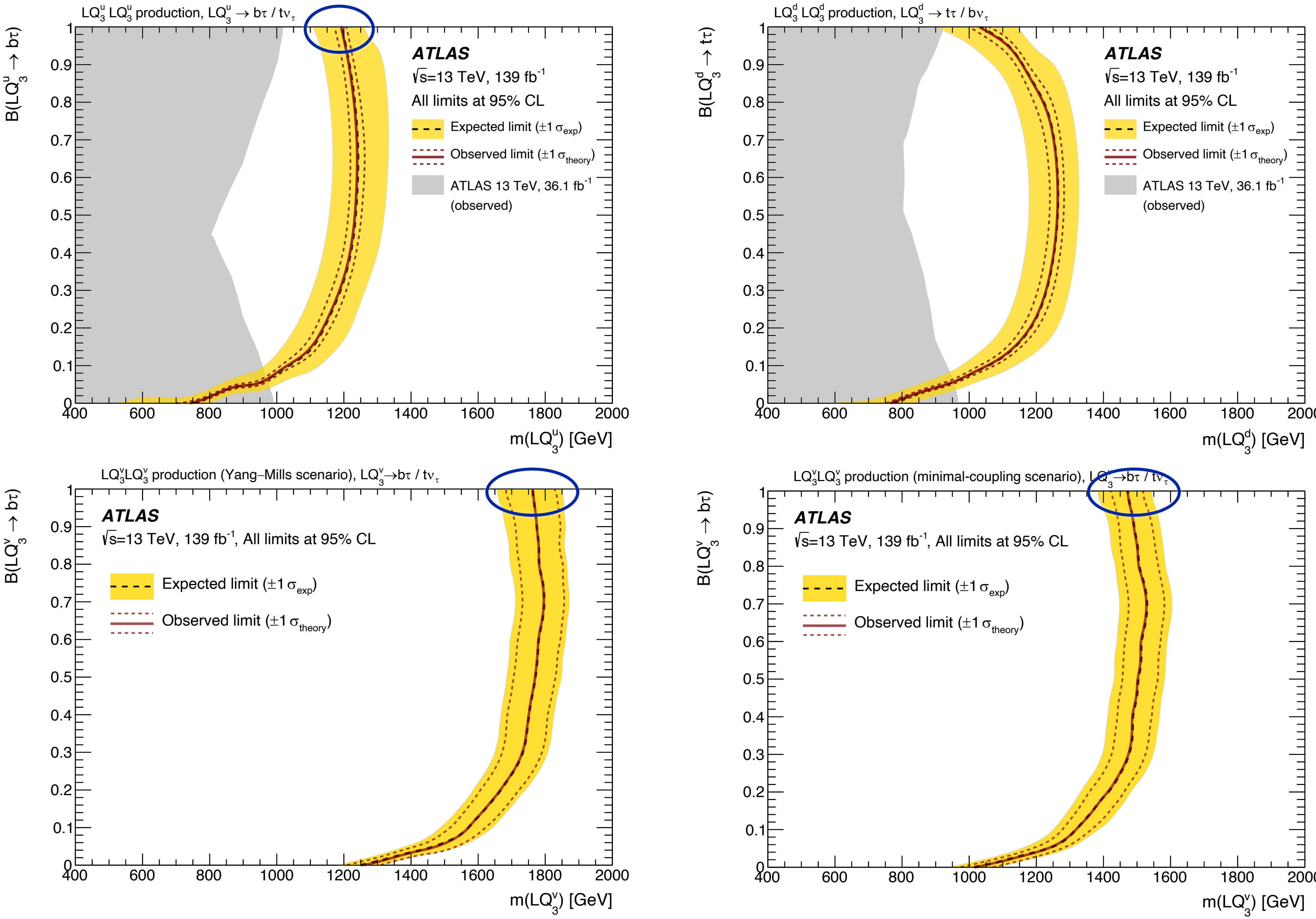
	LQ_S mass [GeV]	LQ_V, $\kappa = 1$ mass [GeV]	LQ_V, $\kappa = 0$ mass [GeV]
$LQ_i \to q\nu$ ($q = $ u, d, s, or c)	1140	1980	1560
$LQ_3^d \to b\nu$	1185	1925	1560
$LQ_3^u \to t\nu$	1140	1825	1475
$LQ_3^u \to$ { $t\nu$ ($\mathcal{B} = 50\%$); $b\tau$ ($\mathcal{B} = 50\%$) }	—	1550	1225

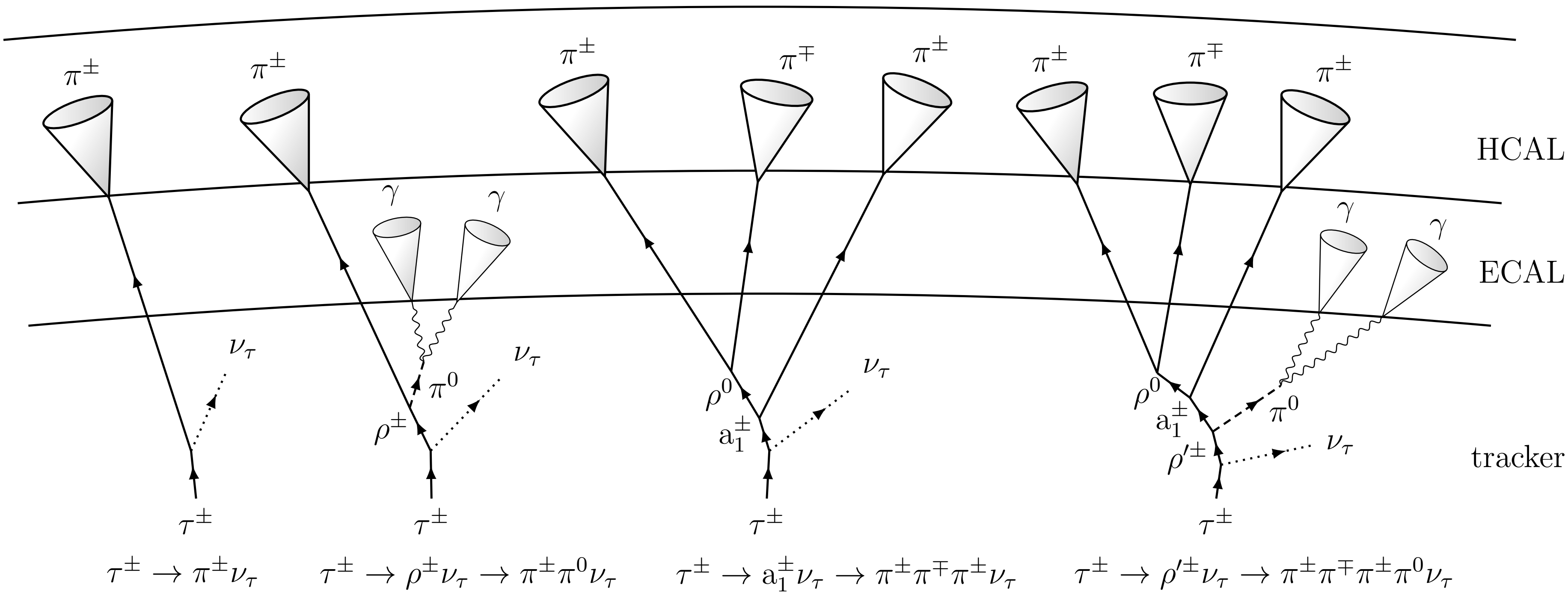
strongest constraints on scalar & vector production through pair production

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

ATLAS LQ → bτ

Run 2: arXiv:2108.07665





HADRONIC TAU RECONSTRUCTION & IDENTIFICATION

τ_h reconstruction

AK4 jet

- anti-k_T, R = 0.4
- seed for τ_h candidate

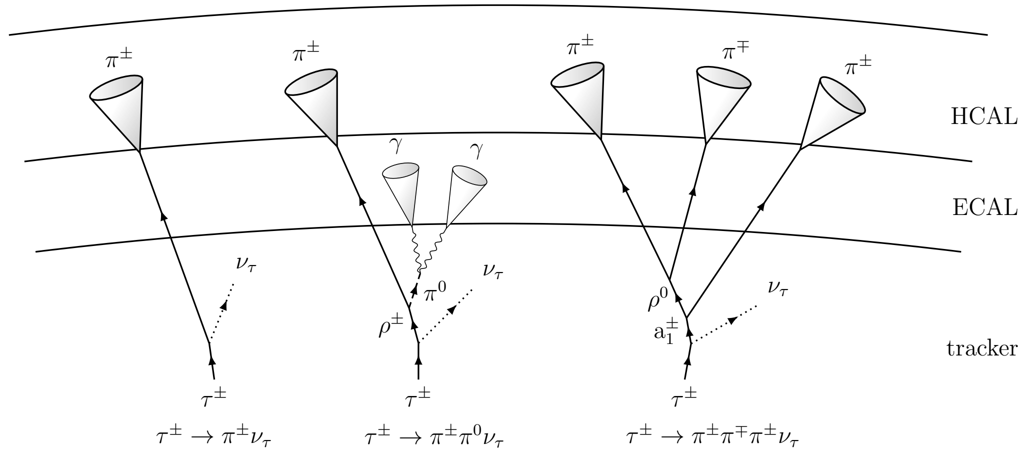
Decay mode reconstruction

- charged tracks ($\pi^{\pm}$)
- ECAL clusters (π^0)

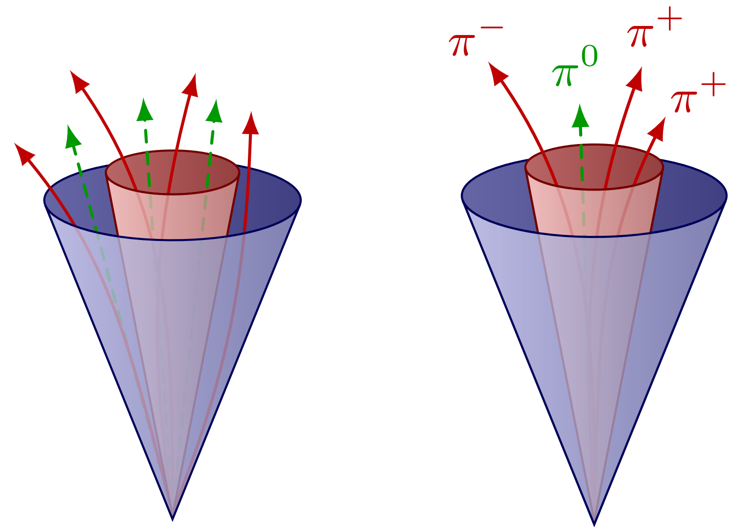
Identification

MVA to reject jets, e or μ

- lifetime
- isolation
- energy fractions

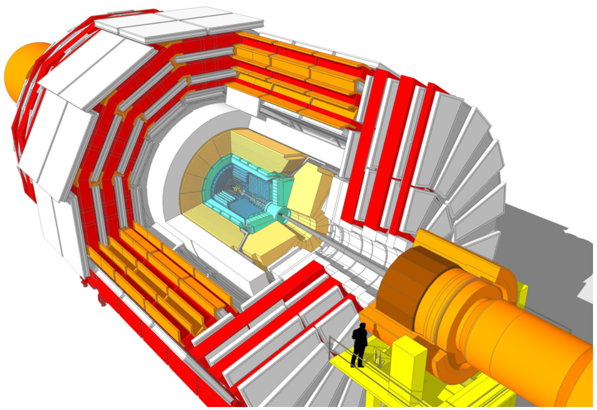


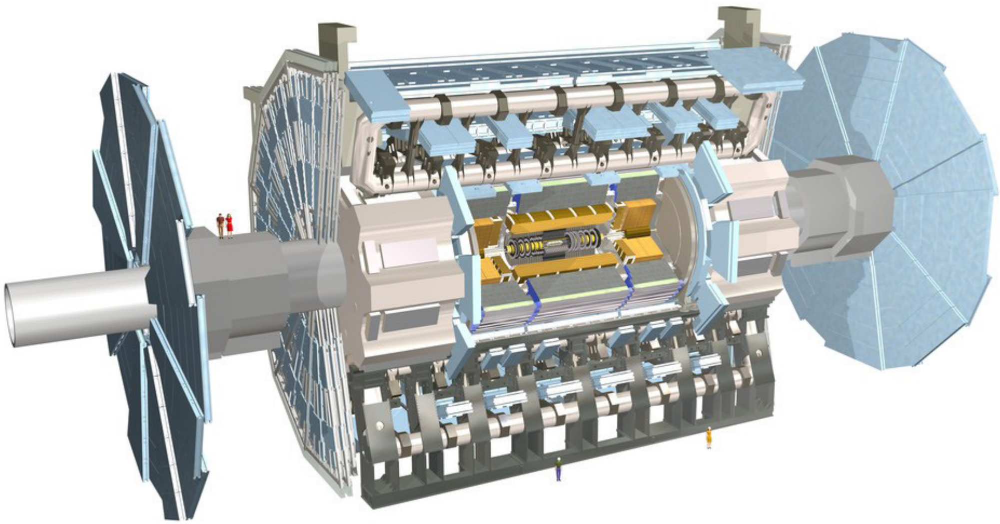
detector interactions of different decay modes



quark/gluon jet **τ_h jet**

Map to τ_h reconstruction & identification





HPS algorithm

→ BDT against jet
+ BDT against e
+ cut-based against μ

→ DNN "DeepTau" against jet/e/μ

"Baseline" algorithm

→ BDT against jet
+ overlap removal e/μ

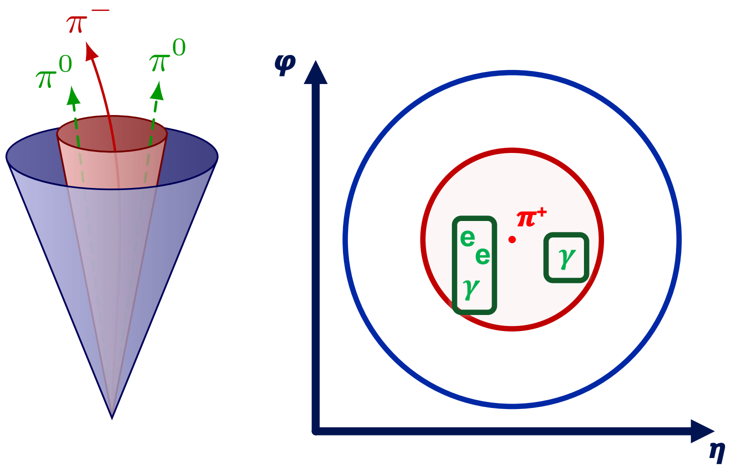
→ RNN against jet
+ BDT against e

Tau Particle Flow

CMS: τ_h reconstruction & identification

Hadron-plus-strips (HPS) algorithm

- seed: AK4 jet of particle flow (PF) hadrons, e/γ
- **signal cone** + **isolation cone**
- assign τ_h decay mode by counting
  - charged hadrons
  - ECAL clusters (e/γ merged into "strips")

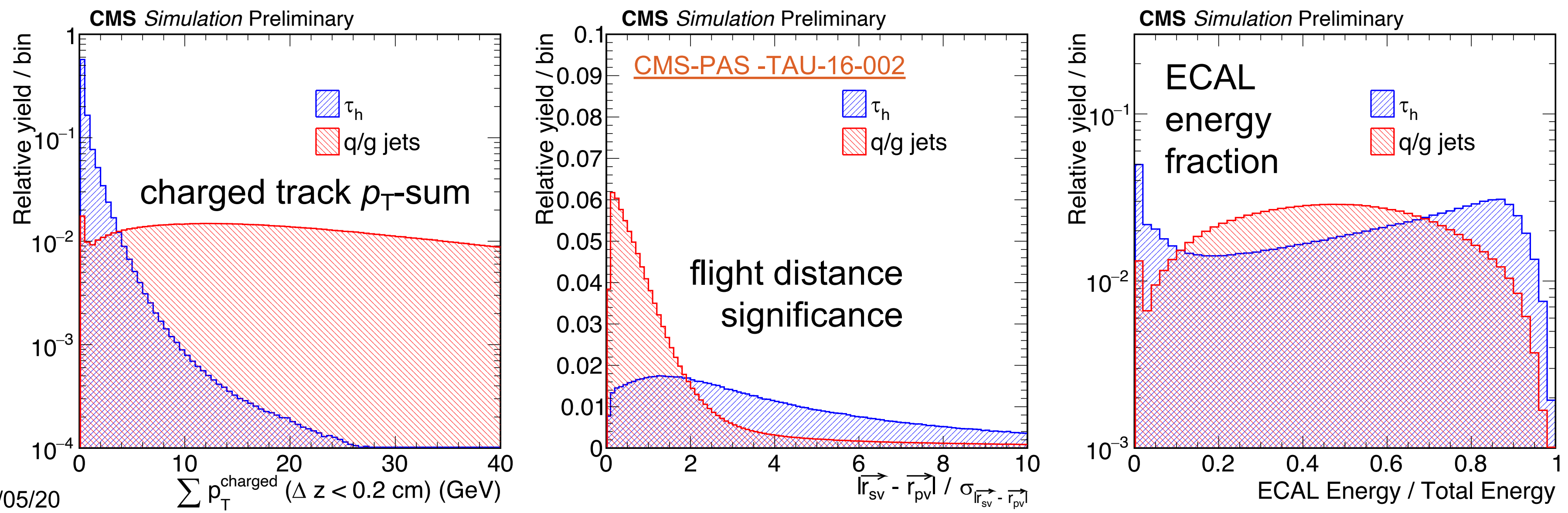


$p_T(h) > 0.5$ GeV
$p_T(e/\gamma) > 1.0$ GeV

$0.05 < \Delta R_{sig} < 0.2$
$\Delta R_{iso} = 0.4$

DeepTau algorithm

- convolutional deep neural network (DNN)
  - high level: τ lifetime, isolation, e/γ kinematics, …
  - PF hadron/μ/e/γ information in small $\eta\times\varphi$ cells of τ_h
- multiclassifier into τ_h, μ, e, or jet probabilities



CMS: τ_h reconstruction & identification

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- seed: AK4 jet of particle flow (PF) hadrons, e/γ
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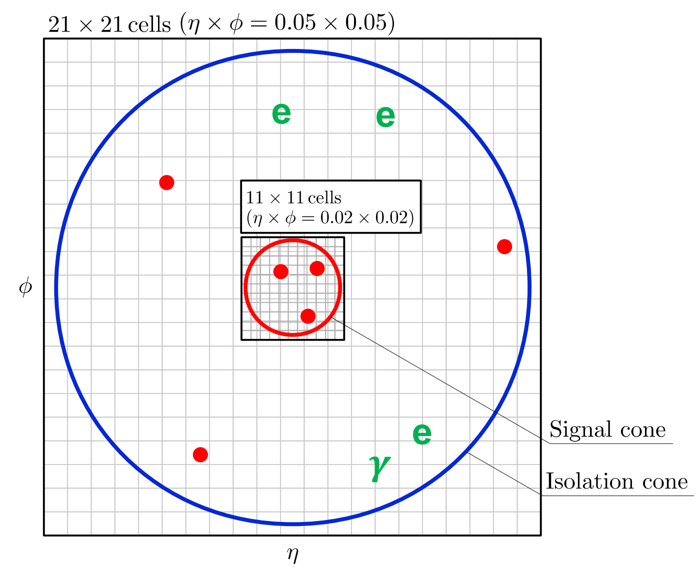

DeepTau algorithm

- convolutional deep neural network (DNN)
  - high level: τ lifetime, isolation, e/γ kinematics, …
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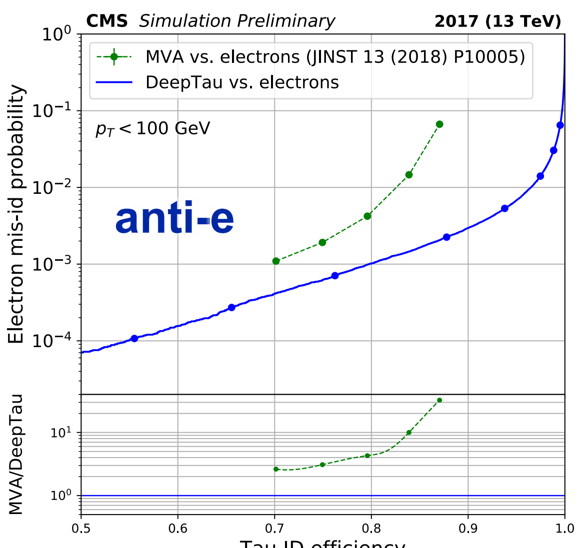
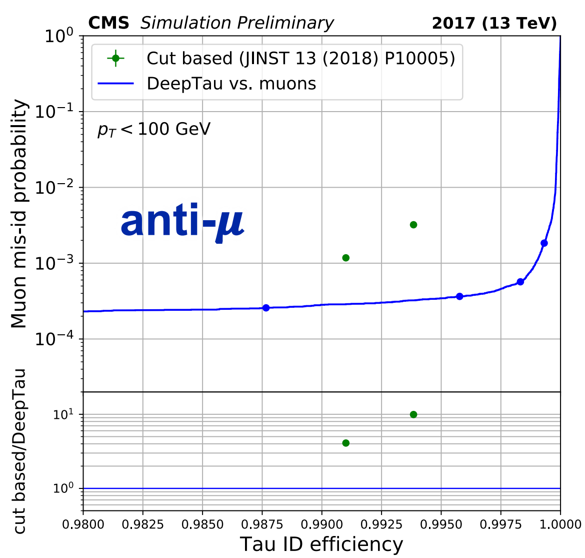
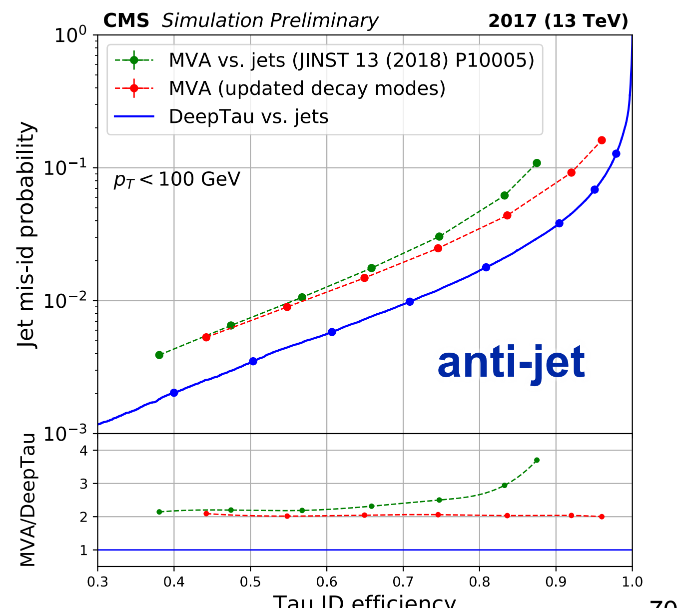
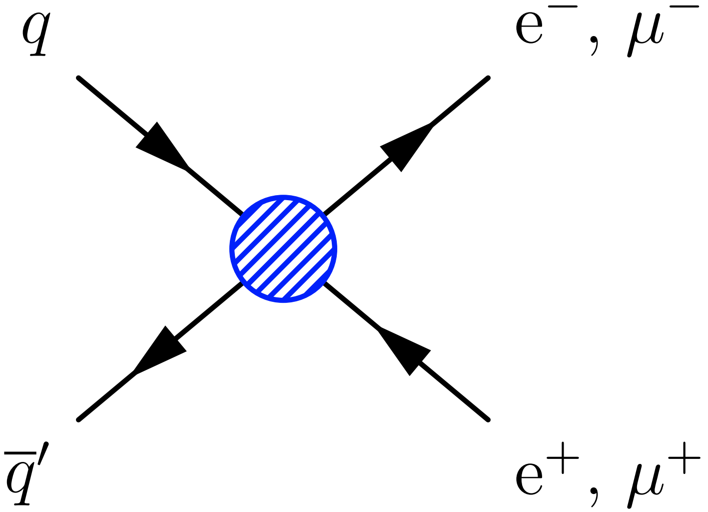






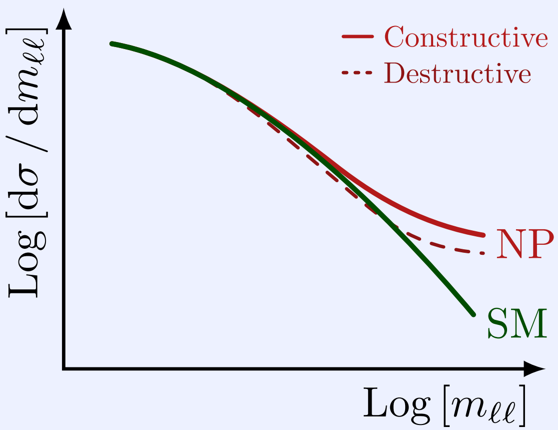


1ST & 2ND GENERATION

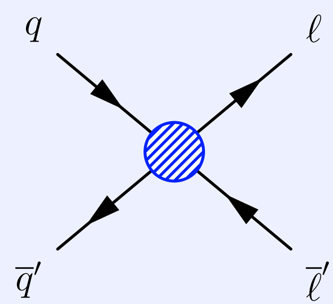
EXO-19-019, SMP-21-002

Introduction

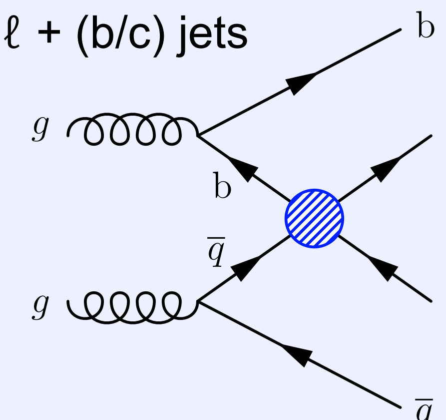
Many models predict deviations in **high-p_T dilepton tails**, and may violate **lepton-flavor universality** ee/$\mu\mu$/$\tau\tau$



$\ell\ell$ signature

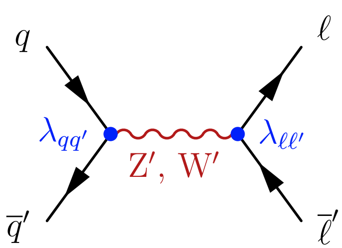


$\ell\ell$ + (b/c) jets

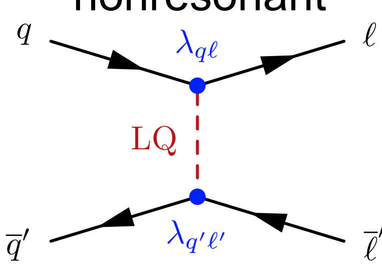


sensitive to b → s$\ell\ell$

resonant



nonresonant



⇒ four-fermion contact interation for $m \gtrsim 2$ TeV

higher-generation LQ-fermion are motivated by B anomalies:

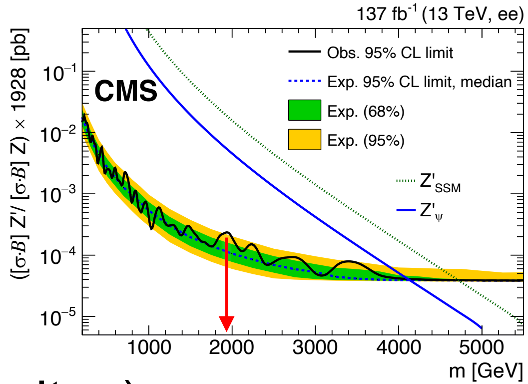
$$\lambda_{q\ell} \sim \begin{array}{c} \\ \mathrm{d/u'} \\ \mathrm{s/c'} \\ \mathrm{b/t'} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{e}/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & \mathcal{O}(0.01) & \mathcal{O}(0.1) \\ 0 & -\mathcal{O}(0.1) & 1 \end{pmatrix} \end{array}$$

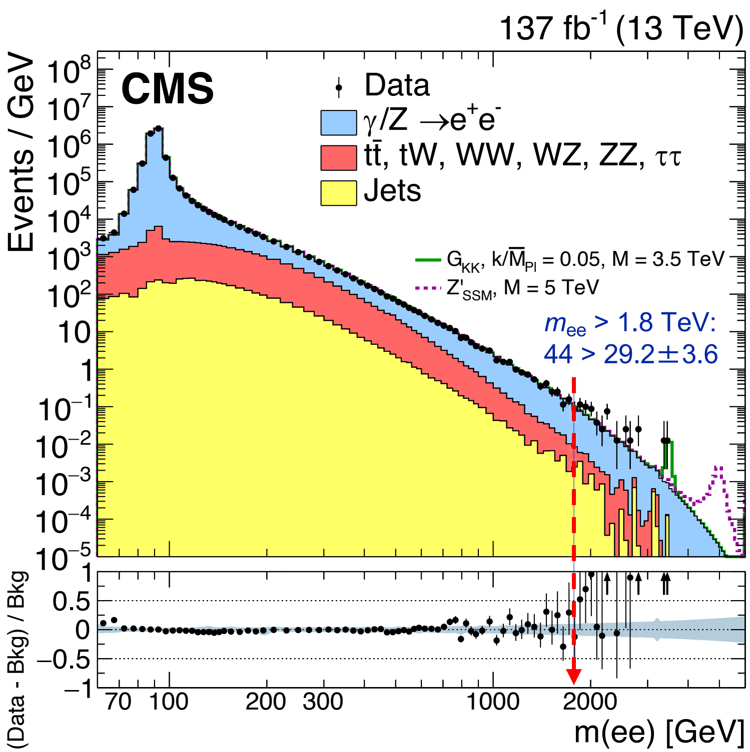
Flavor Anomaly Workshop 2021: https://indico.cern.ch/event/1055780/timetable/#b-425294-high-p_textt-searches
LQ models motivated by the B anomalies: arXiv:1706.07808, arXiv:1903.11517, arXiv:2103.16558

EXO-19-019, arXiv:2103.02708

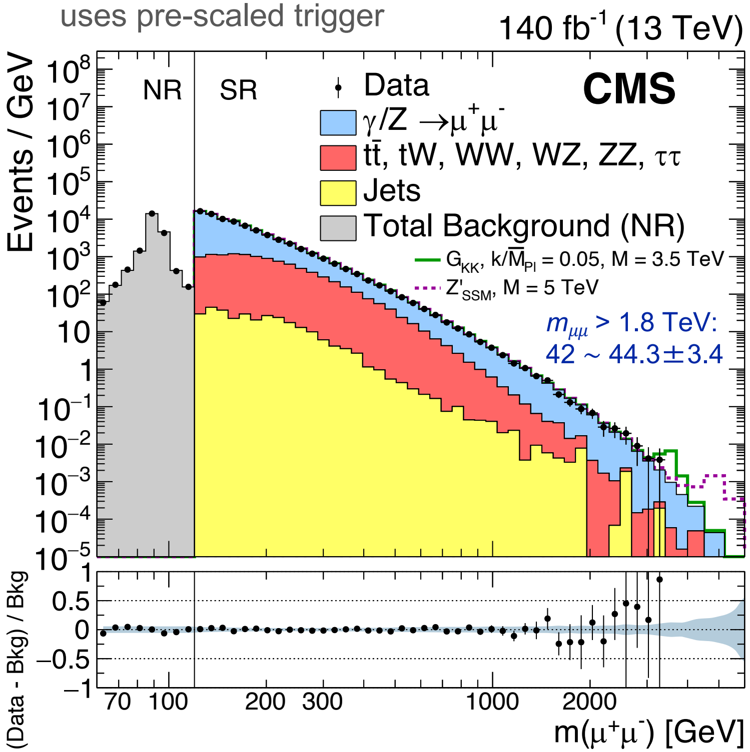
$\mu\mu$, ee searches

- select high-p_T e^+e^-, $\mu^+\mu^-$
- good data-MC agreement over whole range, except small excess for m_{ee} > 1.8 GeV
- resonant limits: spin-1 (Z', DM-mediator), spin-2 (graviton)
- nonresonant limits: four-fermion contact interaction, graviton



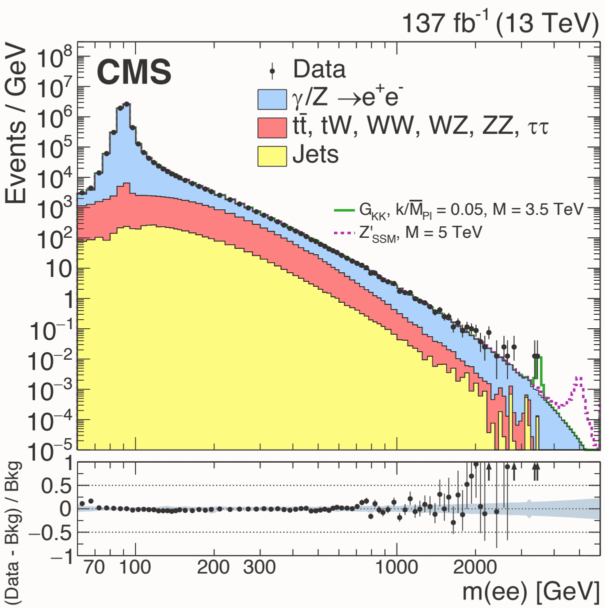


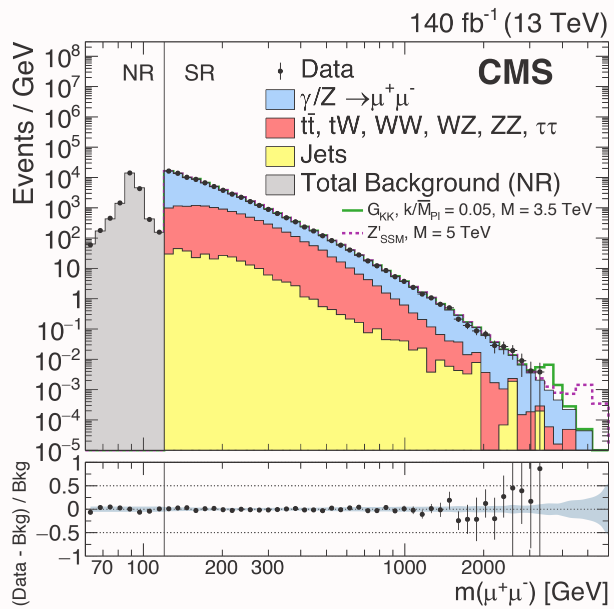
normalization region uses pre-scaled trigger

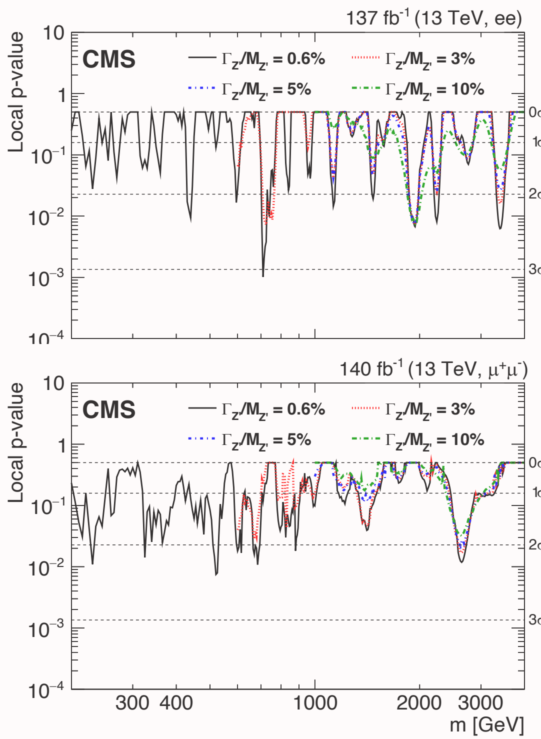


Resonant $\mu\mu$, ee searches

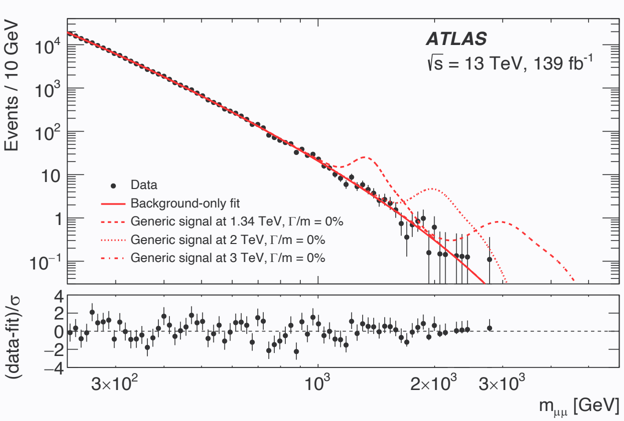
EXO-19-019, arXiv:2103.02708

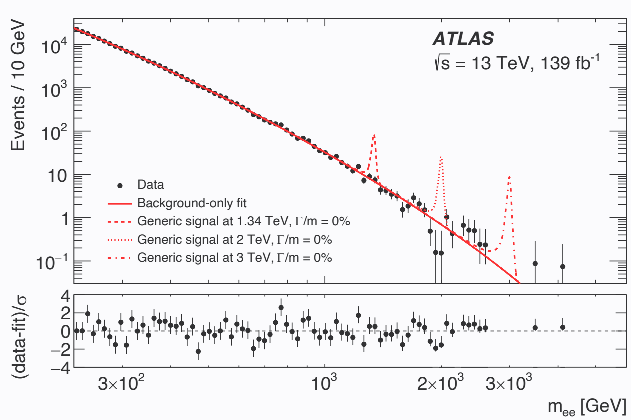


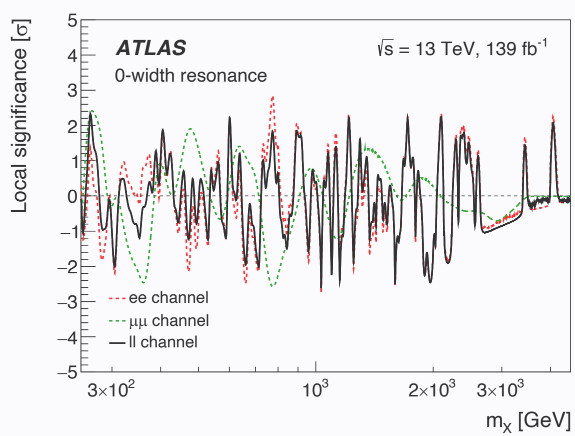




EXOT-2018-08, arXiv:1903.06248



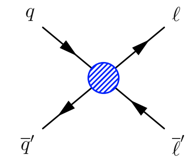




Nonresonant $\mu\mu$, ee searches

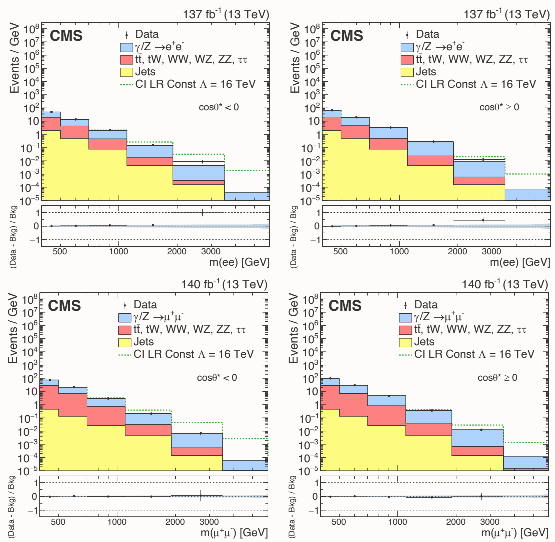
θ^*: scattering angle w.r.t. z axis in Collins-Soper frame

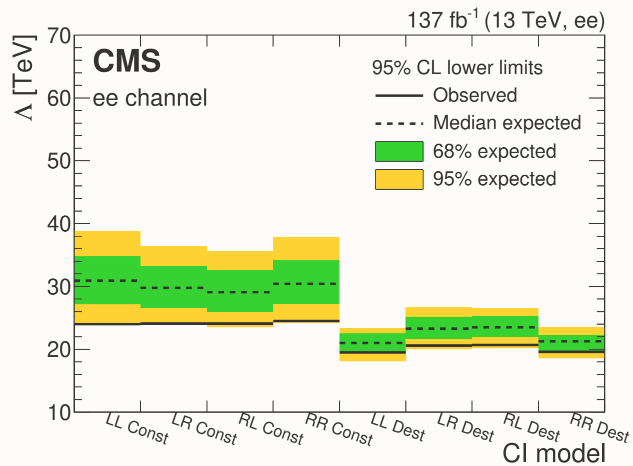
CI: (four-fermion) contact interaction

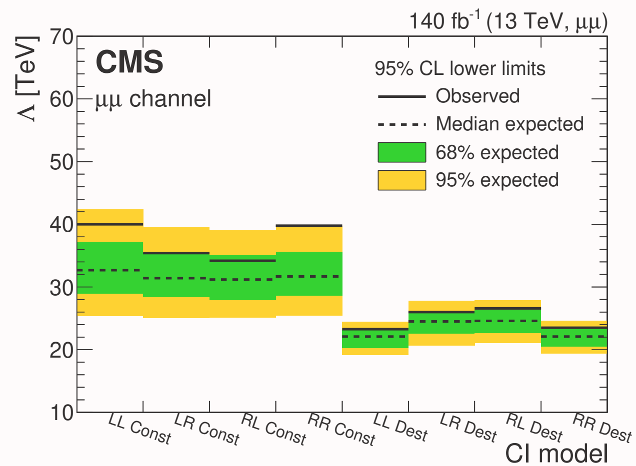


- seperate $m_{\ell\ell}$ into bins of $\cos\theta^* < 0$ and $\cos\theta^* \geq 0$
- fit LL, LR, RL, RR helicity currents separately
- set limit on CI energy scale Λ

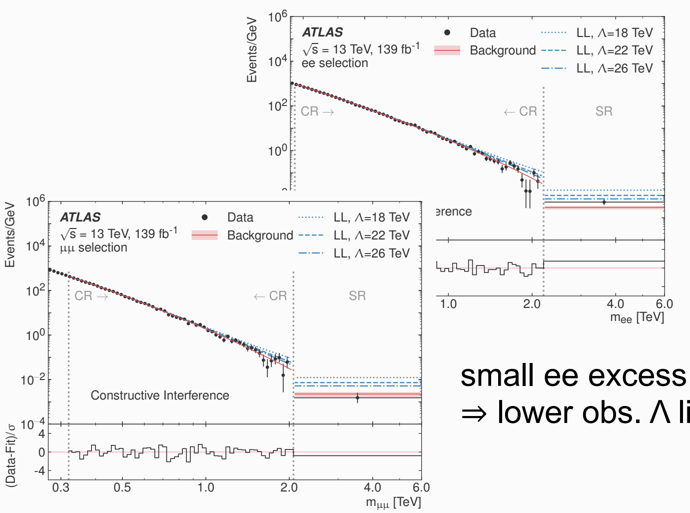
EXO-19-019, arXiv:2103.02708





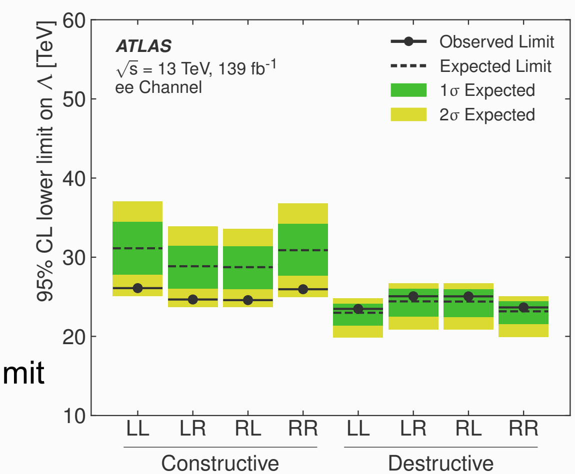


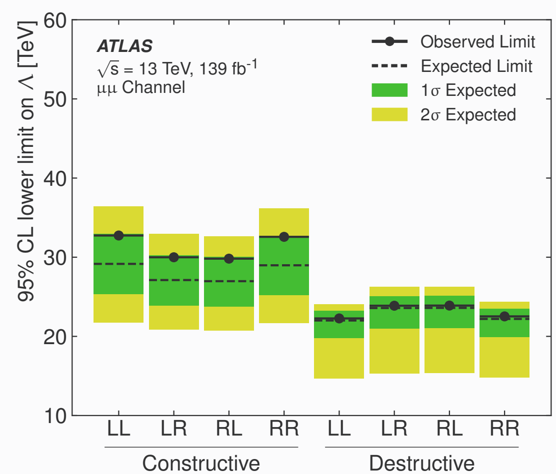
EXOT-2019-16, arXiv:2006.12946



small ee excess

⇒ lower obs. Λ limit

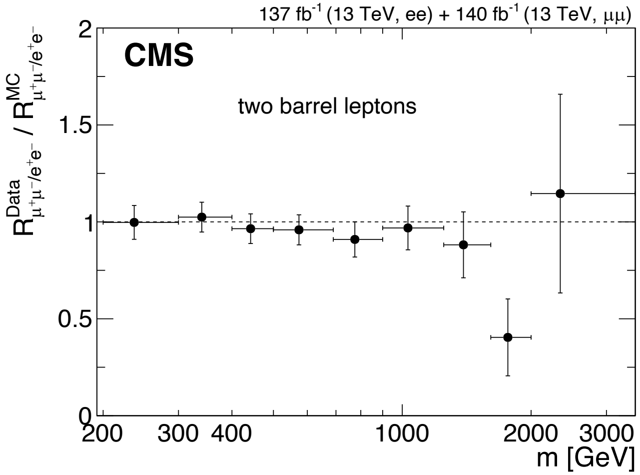


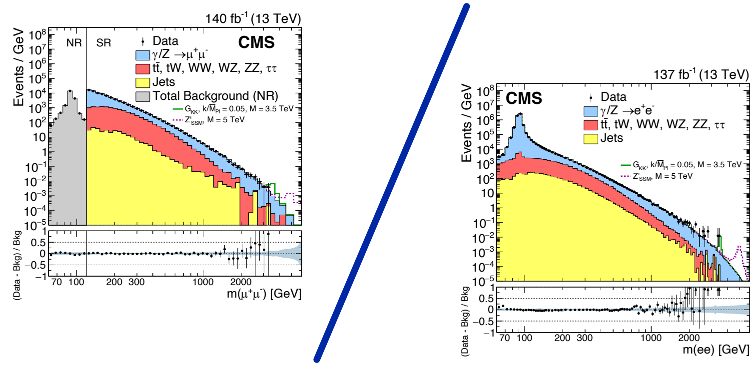


Ratio $\mu\mu$ / ee

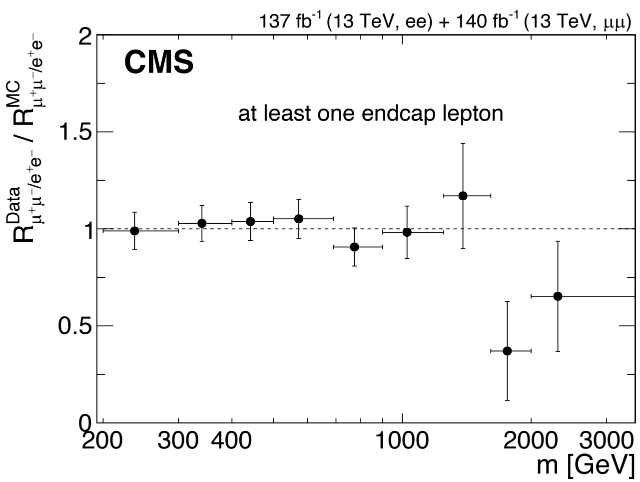
EXO-19-019, arXiv:2103.02708

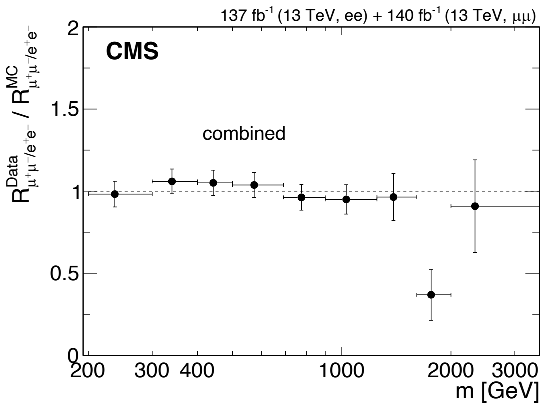
$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\mu^+\mu^-}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{e^+e^-}}$$

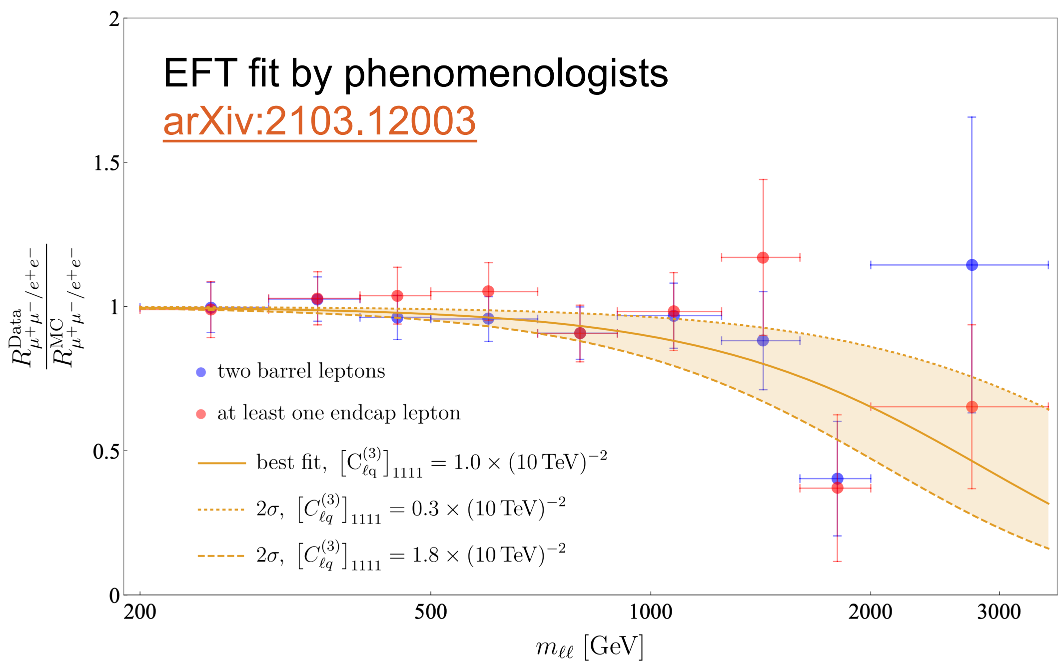




- differential ratio in two bins of η
- some deviation at high mass due to ee excess
- first-time test of LFU at TeV scale







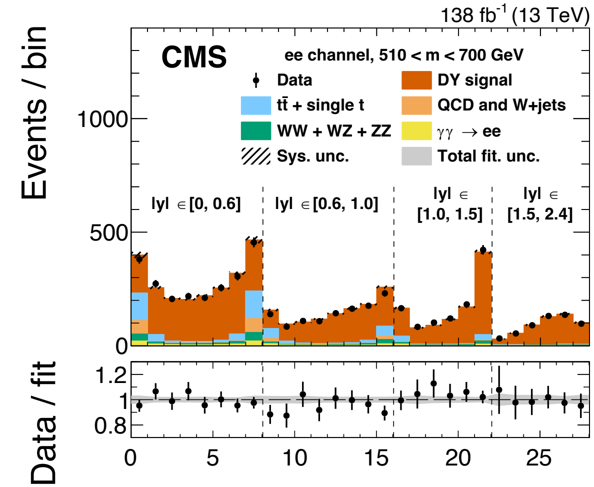
SMP-21-002, arXiv:2202.12327

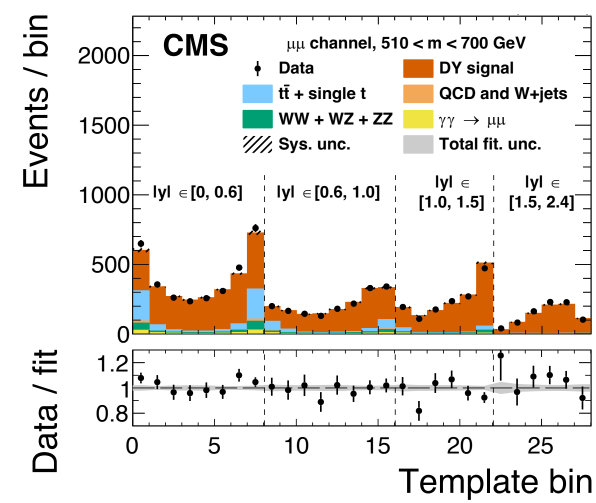
Forward-backward asymmetry

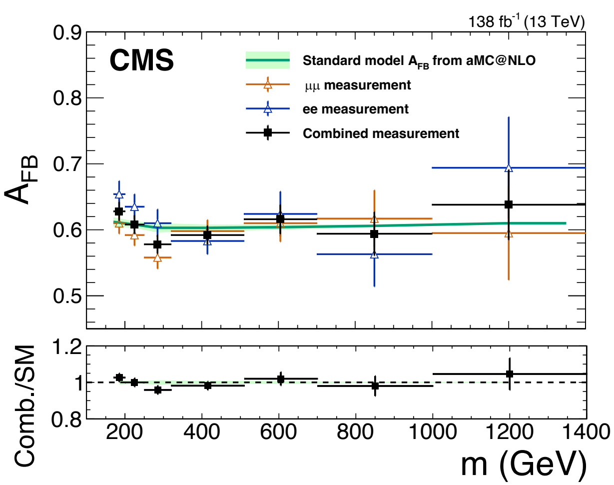
- select e^+e^-, $\mu^+\mu^-$
- $m_{\ell\ell} > 170$ GeV, low MET, veto b jets
- good data-MC agreement over whole range
- Z' can impact AFB through interference
  ⇒ set 4.4 TeV limit
- 2.4σ discrepancy between ee/$\mu\mu$ ($\Delta A_{FB} < 0$)

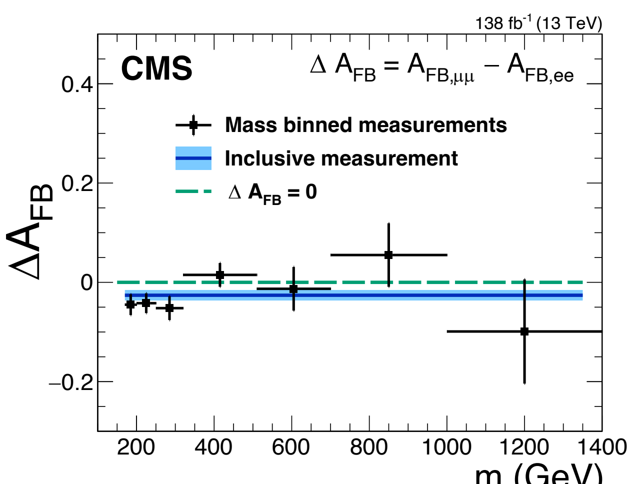
$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}} = 0.612 \pm 0.005({\rm stat}) \pm 0.007({\rm syst})$$

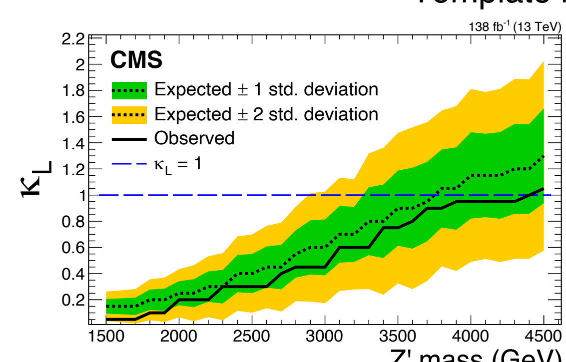
$$\Delta A_{\rm FB} = A_{\rm FB}^{\mu\mu} - A_{\rm FB}^{\rm ee} = -0.026 \pm 0.010({\rm stat}) \pm 0.004({\rm syst})$$







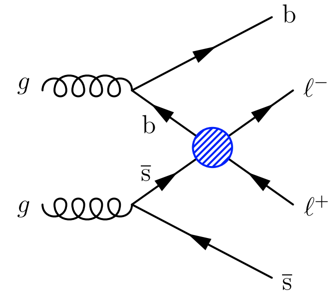


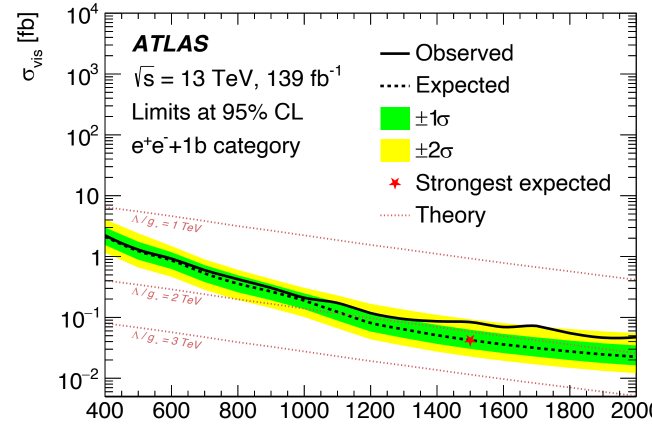


EXOT-2018-16, arXiv:2105.13847

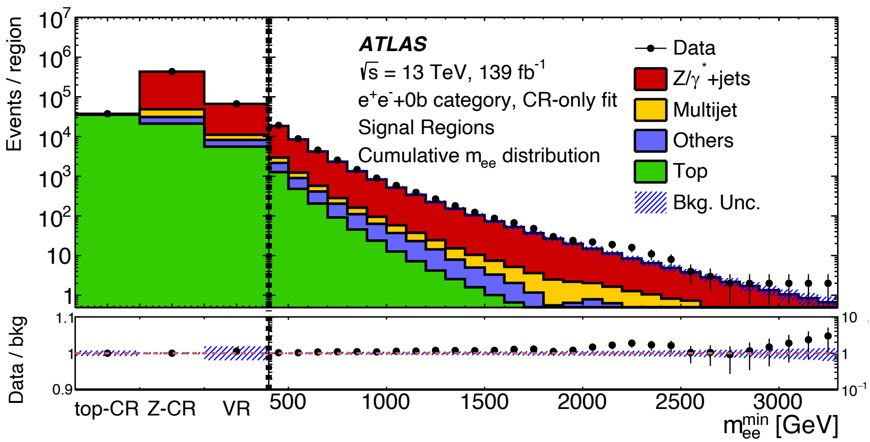
ATLAS: dilepton + 0/1 b jets

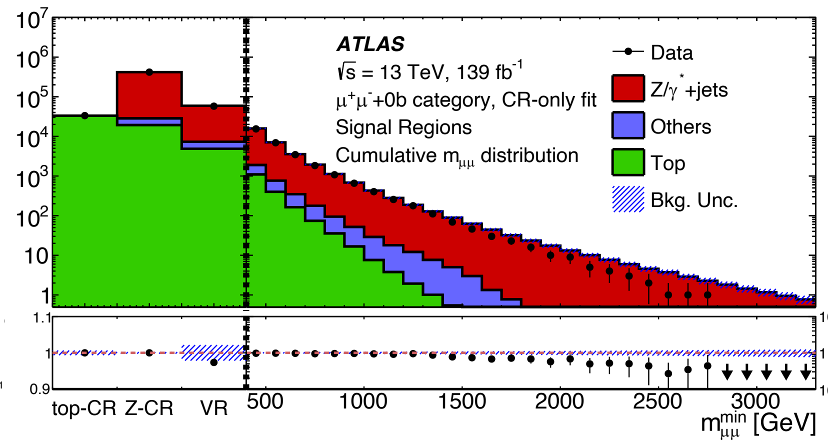
- select high-p_T e^+e^-, $\mu^+\mu^-$
- split into 0, ≥1 b jet category
- probes b → $s\ell\ell$ CI motivated by B anomalies

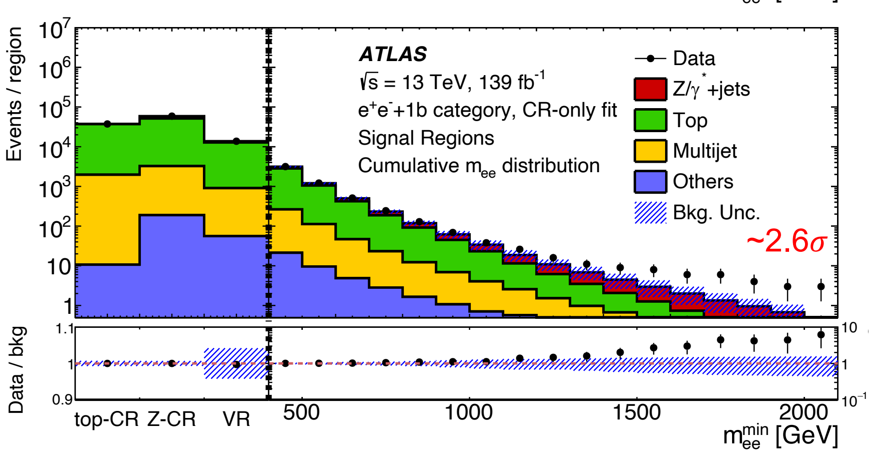


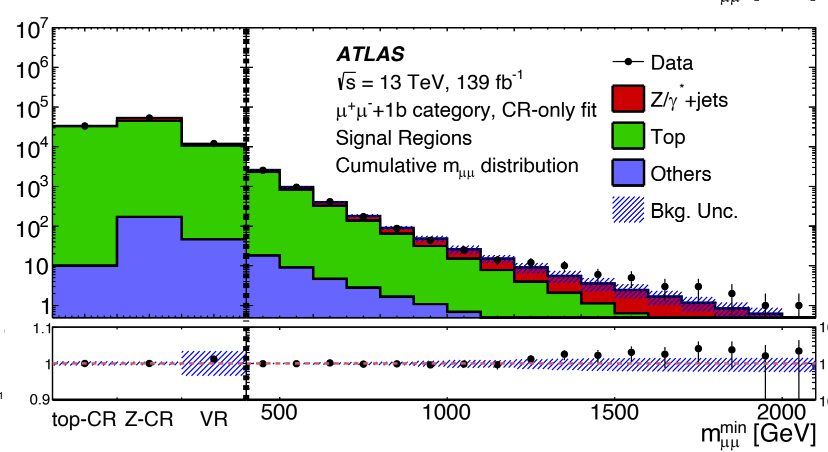


cfr. B anomalies favor $\Lambda/g_* \sim 30$ TeV









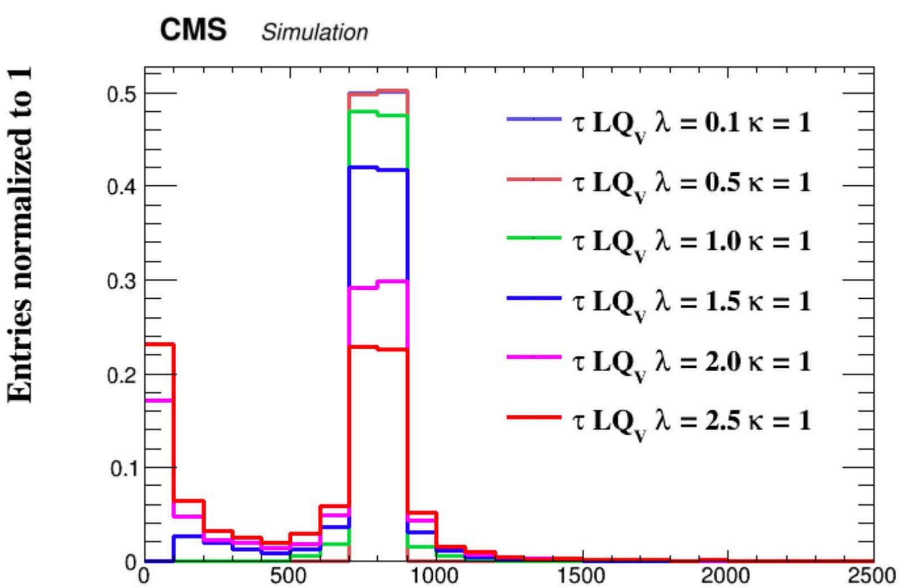
arXiv:2012.04178

β = 0.5, 137 fb^{-1}

Single production yield & efficiency

two competing effects when λ is increased:

- cross section $\sigma(\tau LQ) \sim \lambda^2$ 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

= $M(\tau\nu)$