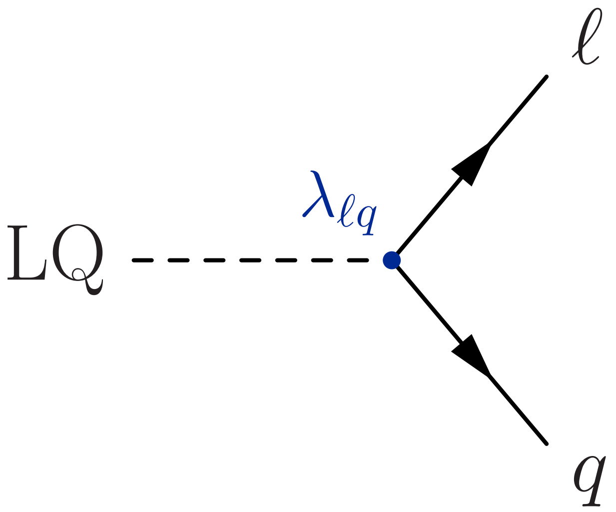
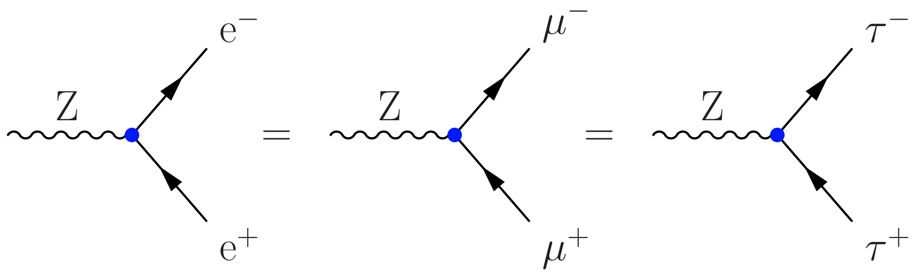


Leptoquark searches at ATLAS & CMS

Izaak Neutelings (CERN) on behalf of the ATLAS & CMS Collaborations
izaak.neutelings@cern.ch

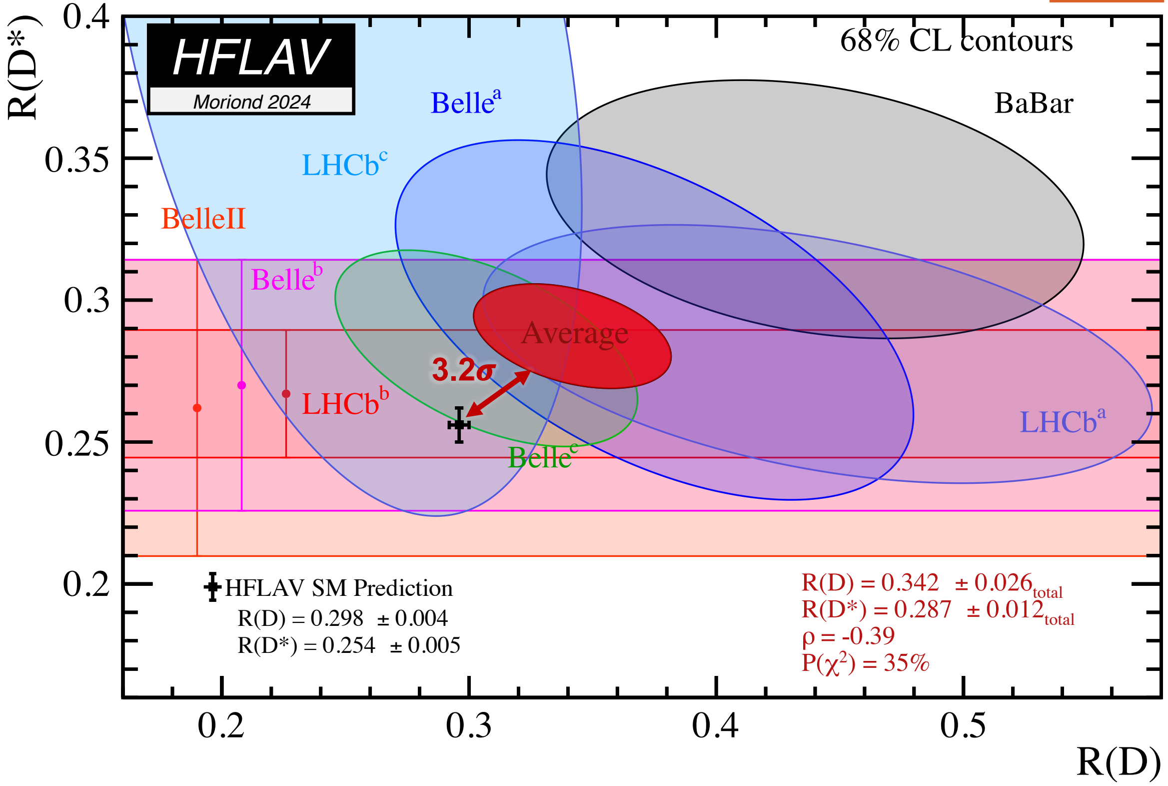
Moriond EW 2025, 26/03/2025

Introduction

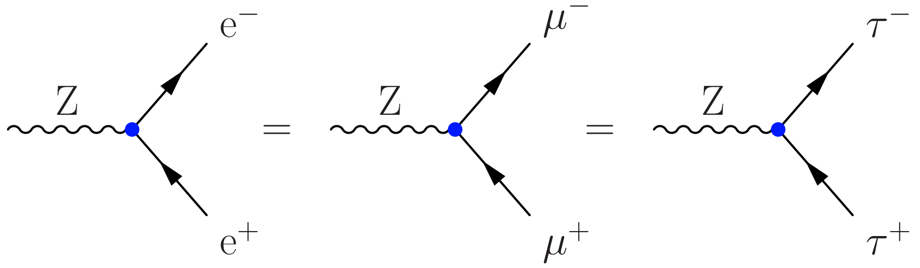


- the SM has **lepton flavor universality** (LFU)
- it appear as an "accidental" symmetry
  ⇒ LFU violation would be a clear sign of new physics (NP)
- experimental evidence of LFU violation ?
  – B anomalies: $R(D^{(*)})$, P'_5, $B \to K^{(*)}\nu\nu$, ...
  – muon $g-2$ arXiv:2308.06230

HFLAV



Introduction



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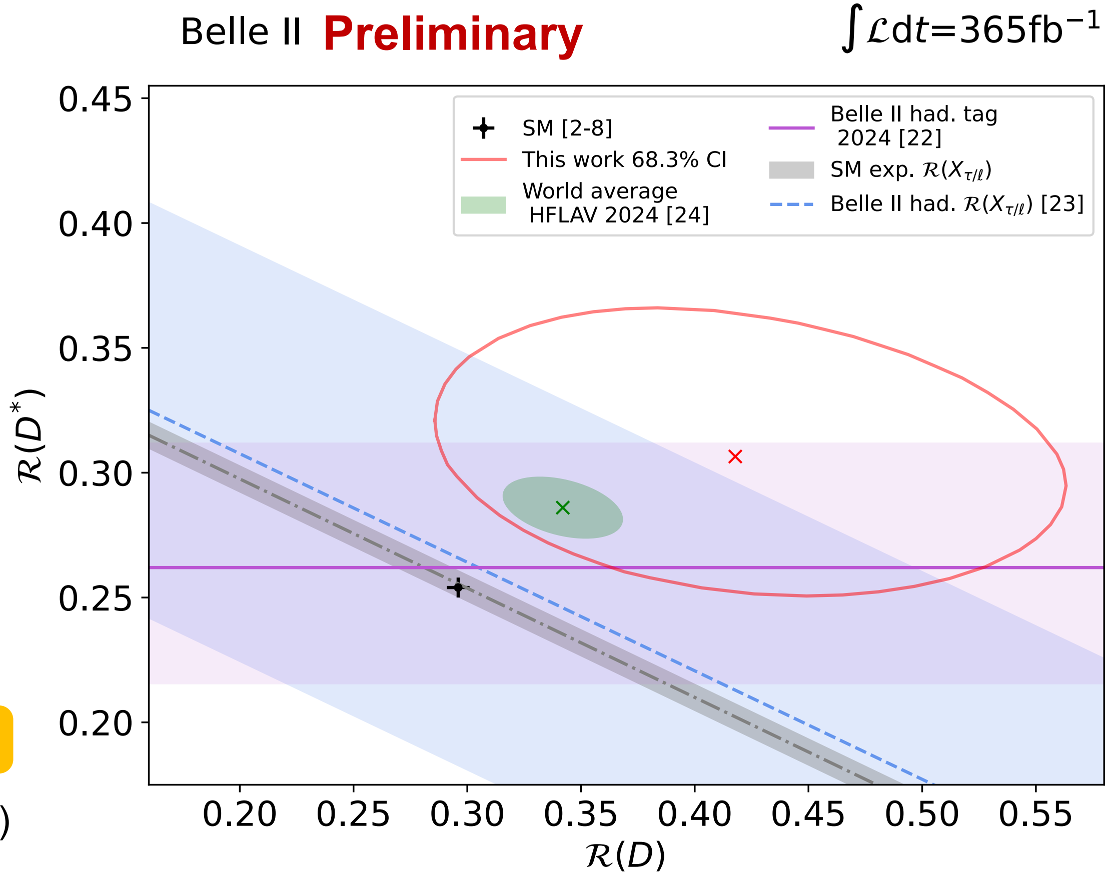


see T. Martinov's talk

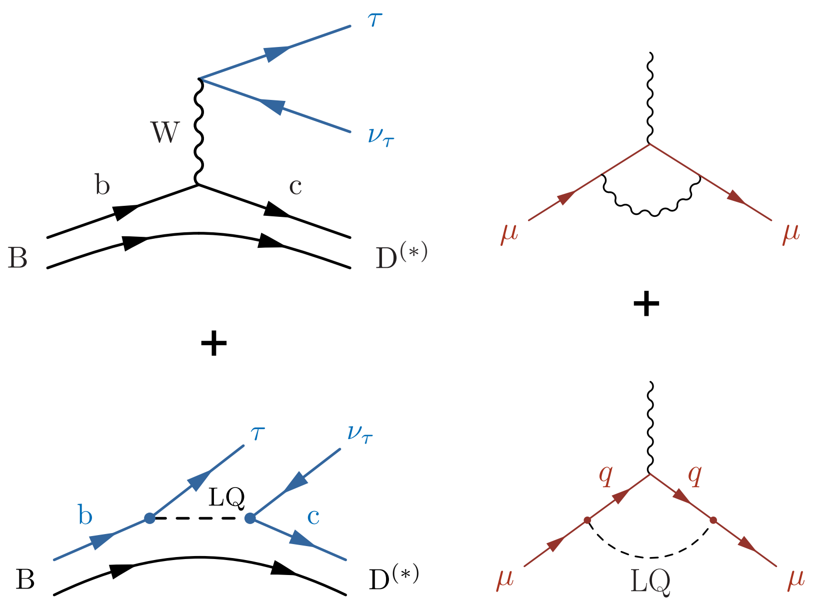
(by courtesy of Belle Collaboration)

Introduction

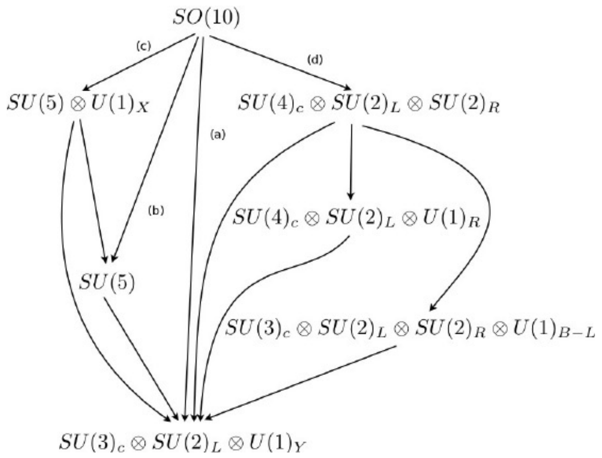
- the SM has **lepton flavor universality** (LFU)
- it appear as an “accidental” symmetry

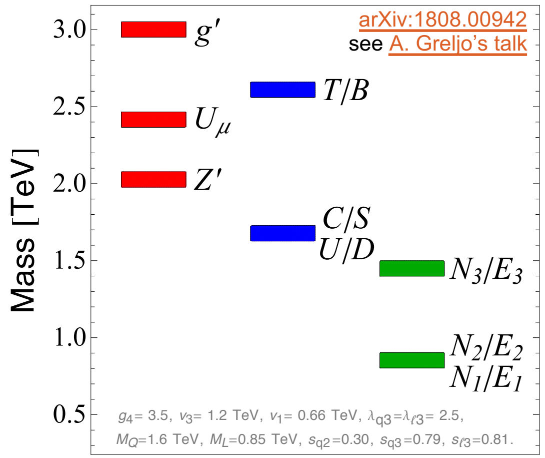
  ⇒ LFU violation would be a clear sign of new physics (NP)
- experimental evidence of LFU violation ?
  - B anomalies: $R(D^{(*)})$, P'_5, $B \to K^{(*)}\nu\nu$, ...
  - muon $g-2$ arXiv:2308.06230

  ⇒ can be explained by **leptoquarks** (LQs)



- LQs naturally arise from many NP models:
  - GUTs like Pati-Salam, 4321 model, ...
  - SUSY with R-parity violation
  - compositeness
  - technicolor



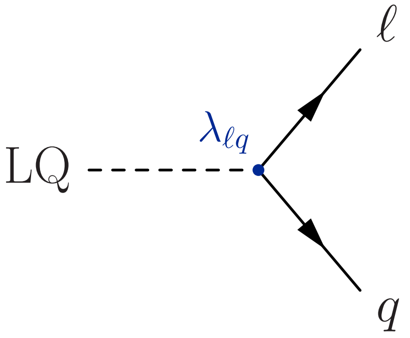


LQ models

- **scalar** or **vector boson**
- **couples to a quark & lepton**

  ⇒ carries L, B, color, EM charge

$$\underbrace{\mathrm{LQ}}_{\pm\frac{1}{3},\,\pm\frac{2}{3},\,\pm\frac{4}{3},\,\pm\frac{5}{3}} \;\to\; \underbrace{\ell}_{\pm1,\,0}\;\underbrace{q}_{\mp\frac{1}{3},\,\pm\frac{2}{3}}$$



LQ models in LHC searches

- **scalar** or **vector boson**
- **couples to a quark & lepton**

  ⇒ carries L, B, color, EM charge
- typical model parameters in LHC searches:

  1. ***m_{LQ}*** ~0.2–10 TeV

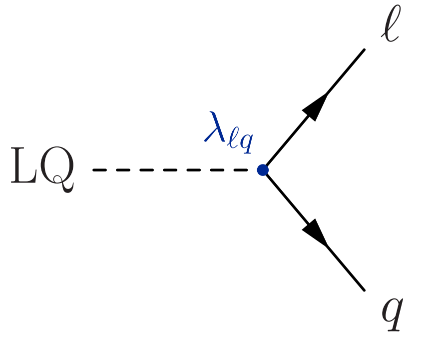
  2. **coupling strength $\boldsymbol{\lambda_{\ell q}}$** to fermions

  3. **branching fraction $\boldsymbol{\beta}$** to charged leptons:

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

  4. **“non-minimal” coupling $\boldsymbol{\kappa}$** to gluons (vector LQ)

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



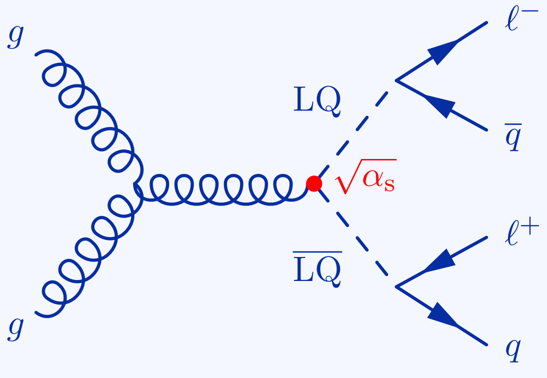
typical benchmarks:
- β = 1 (*no* neutrinos)
- β = 0.5 (mix)
- β = 0 (*only* neutrinos)

typical benchmarks:
- κ = 0 (minimal coupling)
- κ = 1 (Yang–Mills)

overview of LQ models: arXiv:1603.04993; diagram

LQ production at the LHC

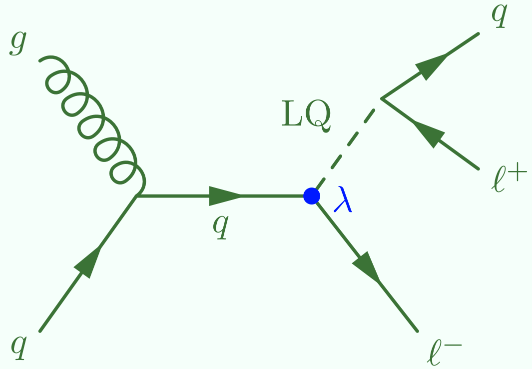
Pair production



- 😊 large
- 🙂 model independent
- 🙂 resonant

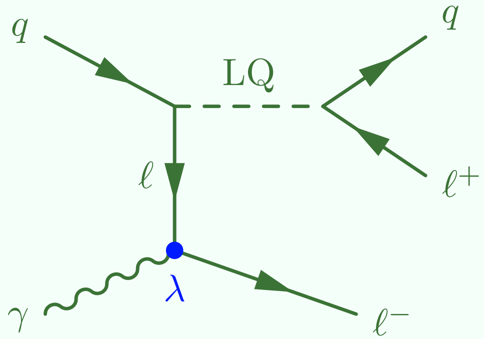
Single production

gluon-induced



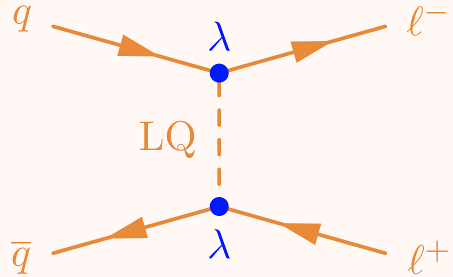
- 🙂 $\sigma \propto \lambda^2$
- 🙁 width $\propto \lambda^2$

lepton-induced



- 🙂 $\sigma \propto \lambda^2$
- 🙂 large cross section
- 🙁 suppressed γ PDF
- 🙁 forward lepton

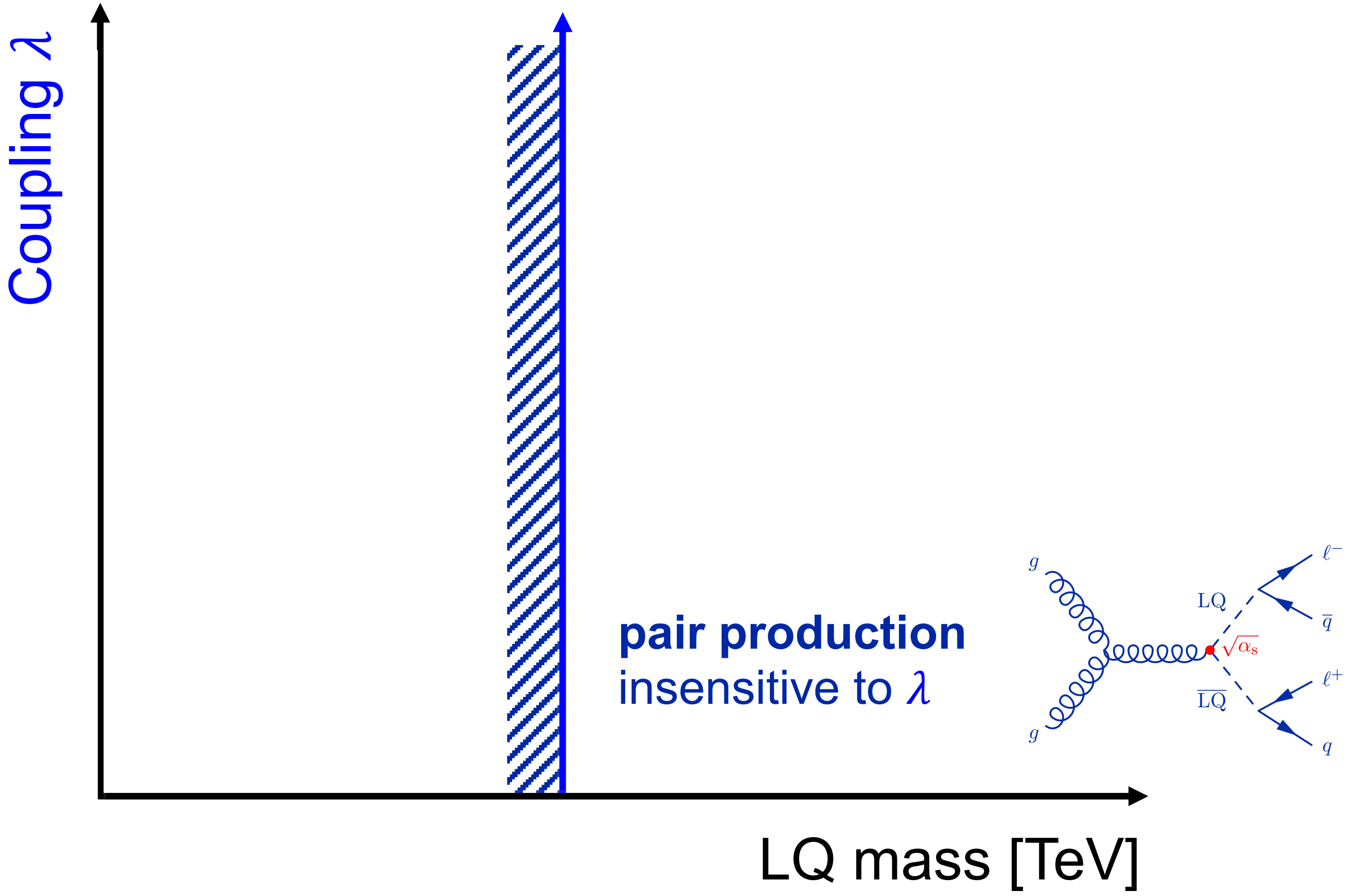
Nonresonant production



- 🙂 $\sigma \propto \lambda^4$
- 😰 wide resonance
- 🙂 kinematics largely independent of (m,λ)

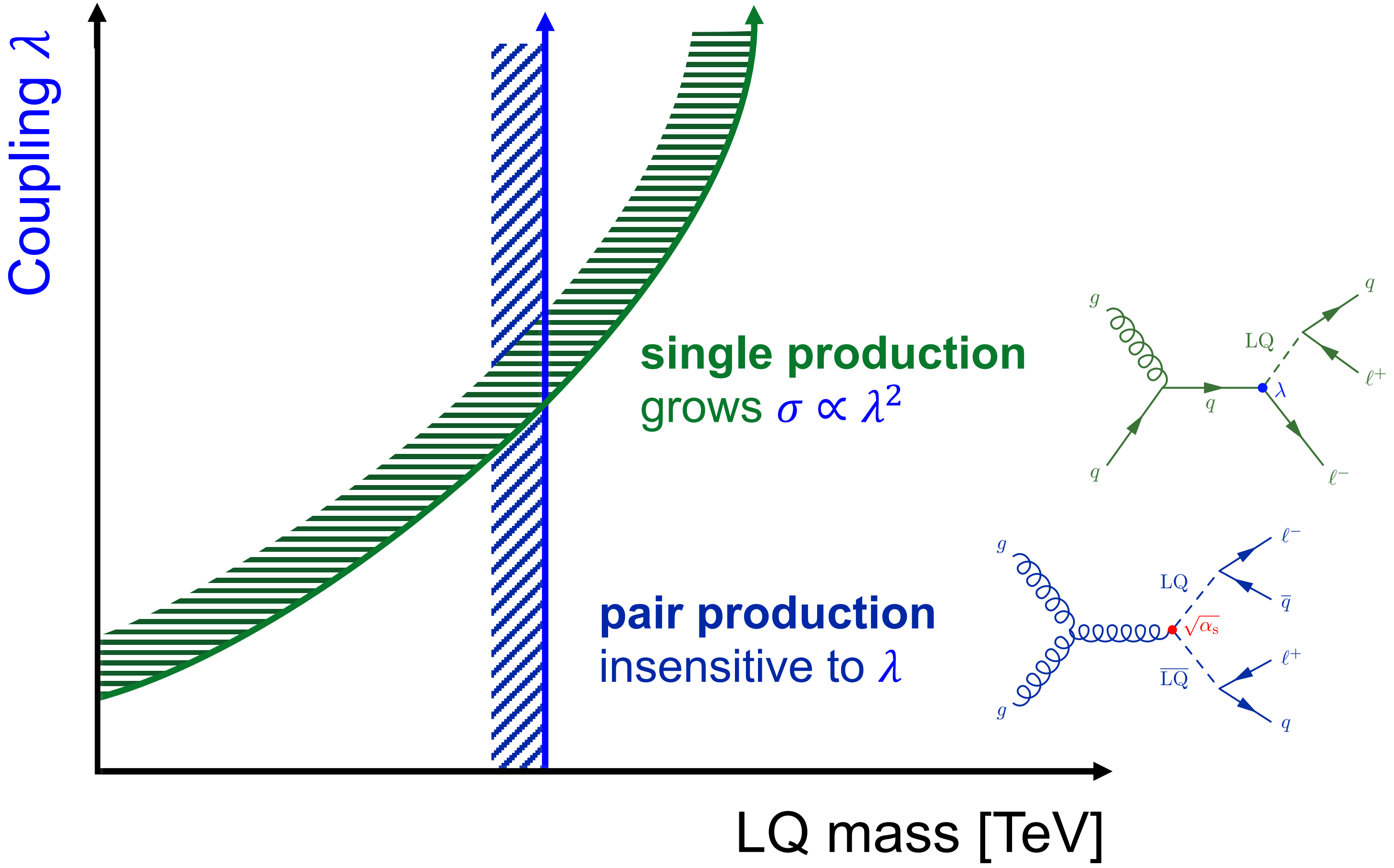
similar **final states**: two high-p_T & nonresonant leptons

Complementarity of LQ signals



pheno papers: arXiv:1609.07138, arXiv:1810.10017

Complementarity of LQ signals



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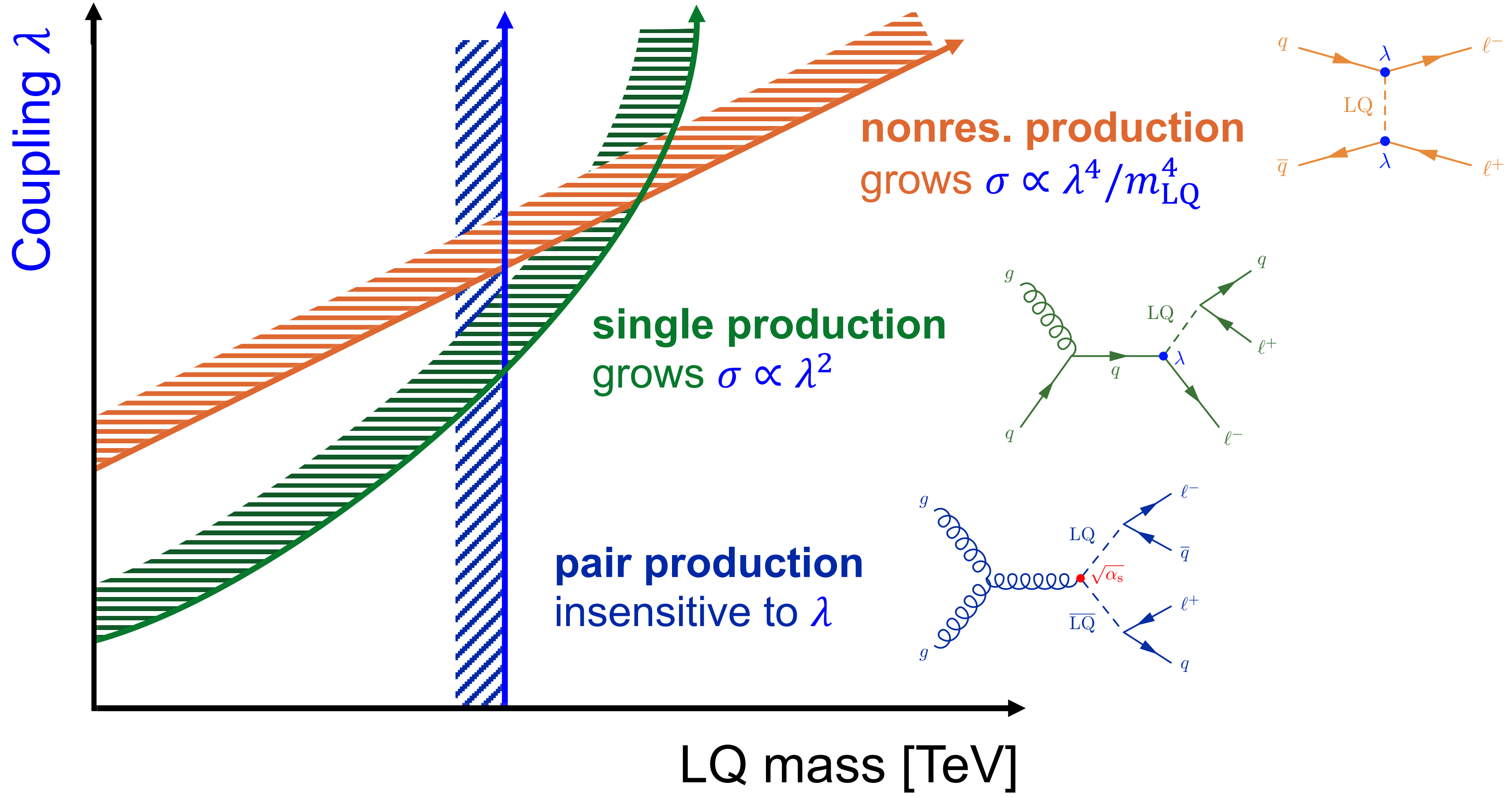
Complementarity of LQ signals

single & **nonresonant** signals have often been overlooked,
but they open a large phase space at large couplings (λ)



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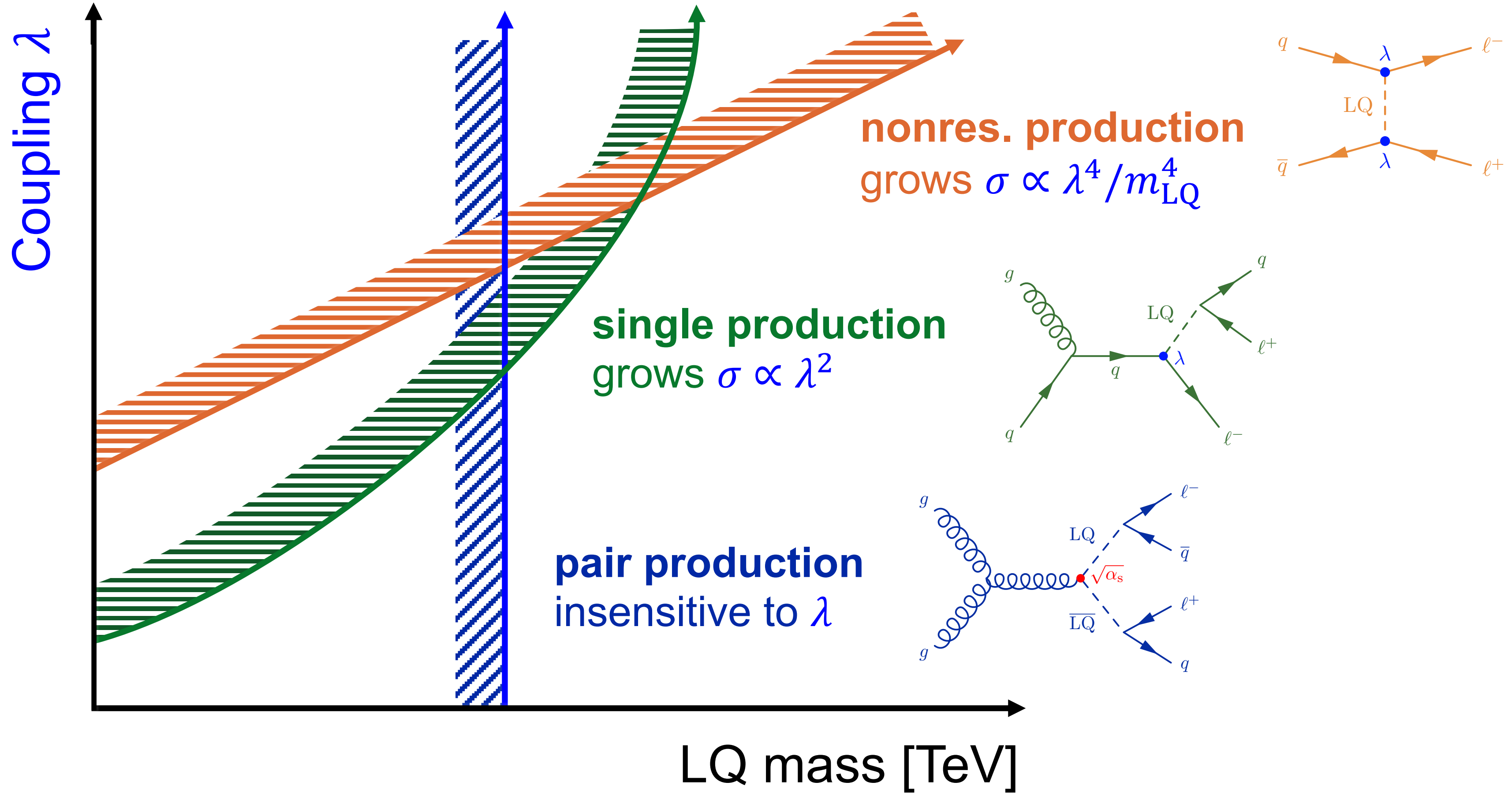
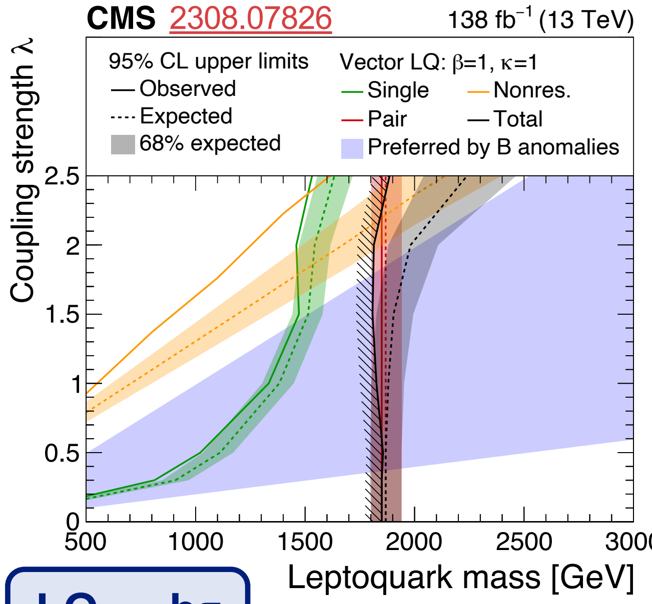
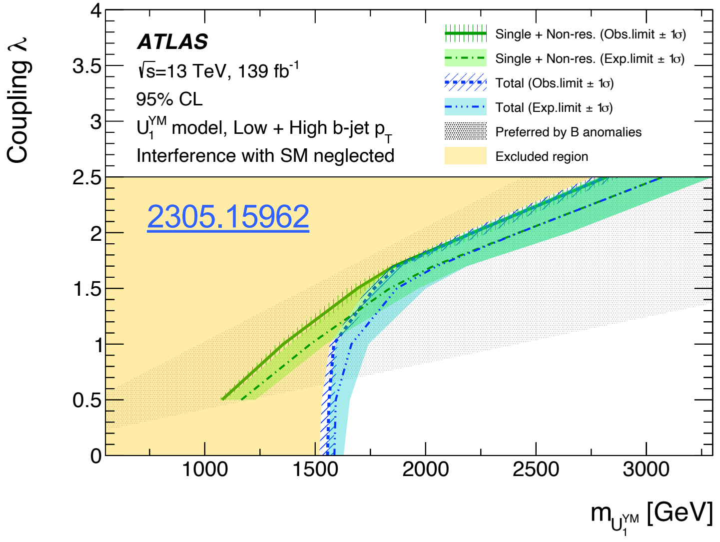




LQ → bτ



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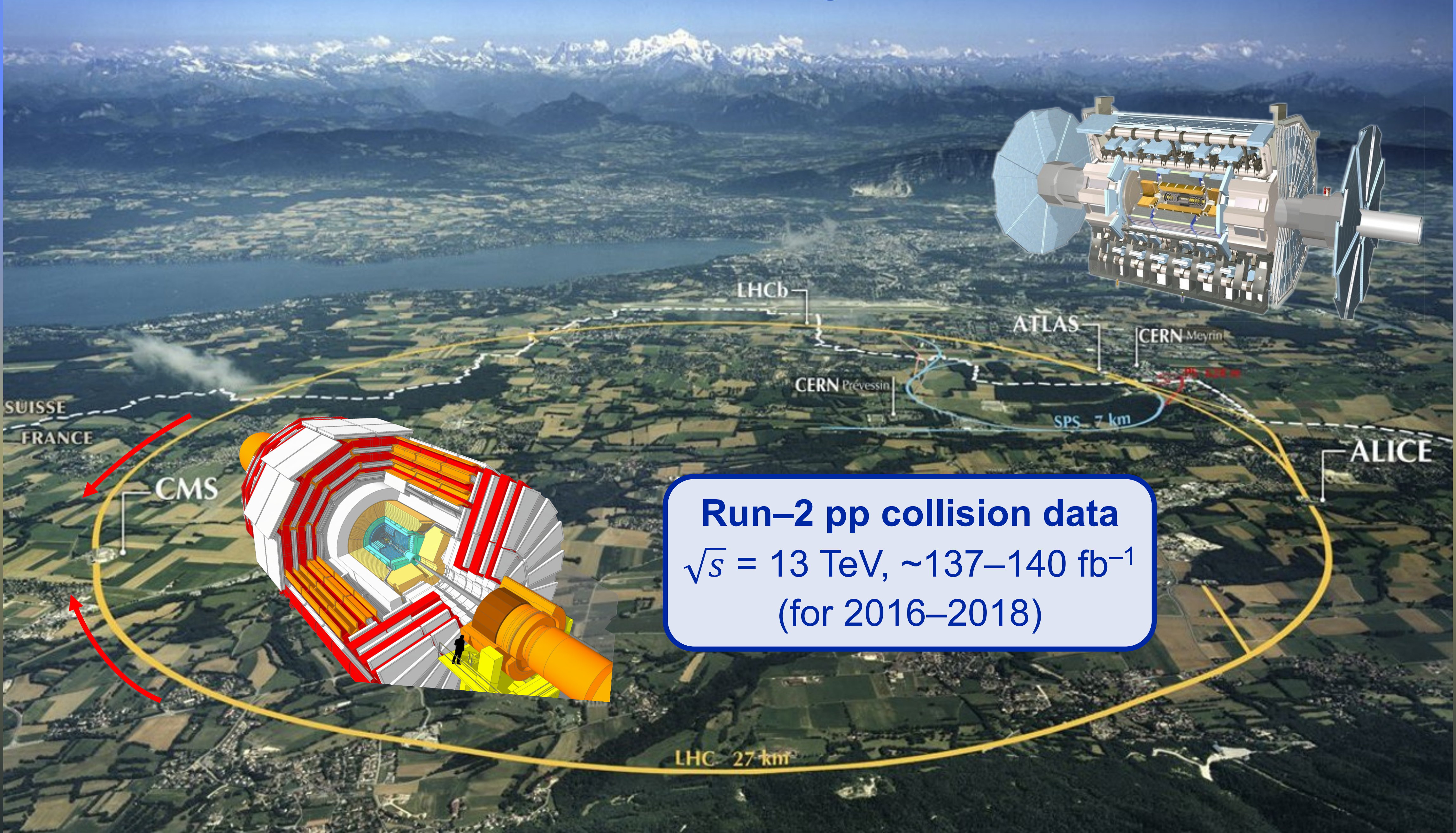
The ATLAS & CMS detectors @ LHC, CERN



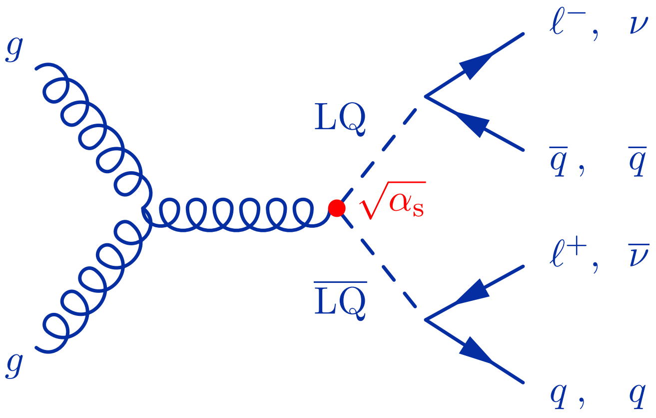
Run–2 pp collision data

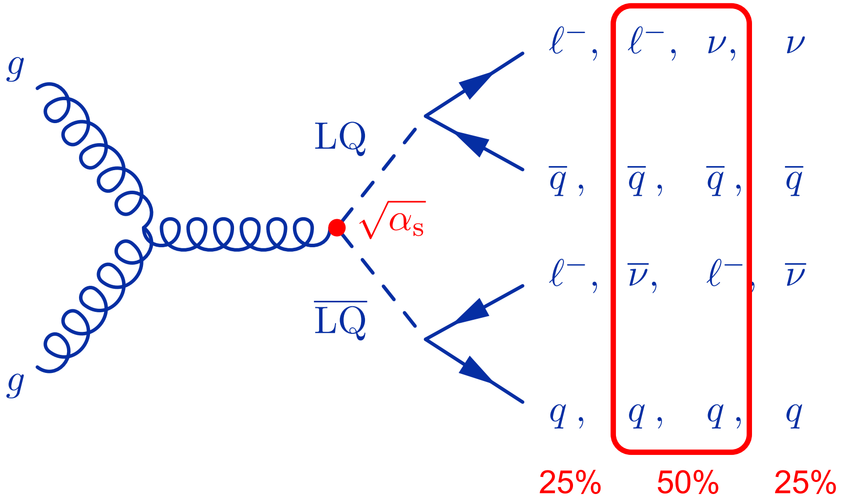
$\sqrt{s}$ = 13 TeV, ~137–140 fb^{-1}

(for 2016–2018)

Final states covered in Run-2 data: Pair production

137–140 fb^{-1}





β = 1, 0

		jj	cc	bb	tt
β = 0	νν	CMS 1909.03460	NEW ! ATL 2410.17824 CMS 1909.03460	ATL 2101.12527 CMS 1909.03460	ATL 2004.14060 CMS 1909.03460
β = 1	ee		ATL 2006.05872	ATL 2006.05872	ATL 2010.02098 ATL 2306.17642 CMS 2202.08676
	μμ			ATL 2006.05872 CMS 2402.08668	
	ττ	ATL 2303.09444		ATL 2108.07665 ATL 2303.01294 CMS 2308.07826	ATL 2101.11582 CMS 2202.08676

β = 0.5

		jj	cs	tb
β = 0.5	eν			ATL 2210.04517
	μν			
	τν			ATL 2108.07665 CMS 2012.04178

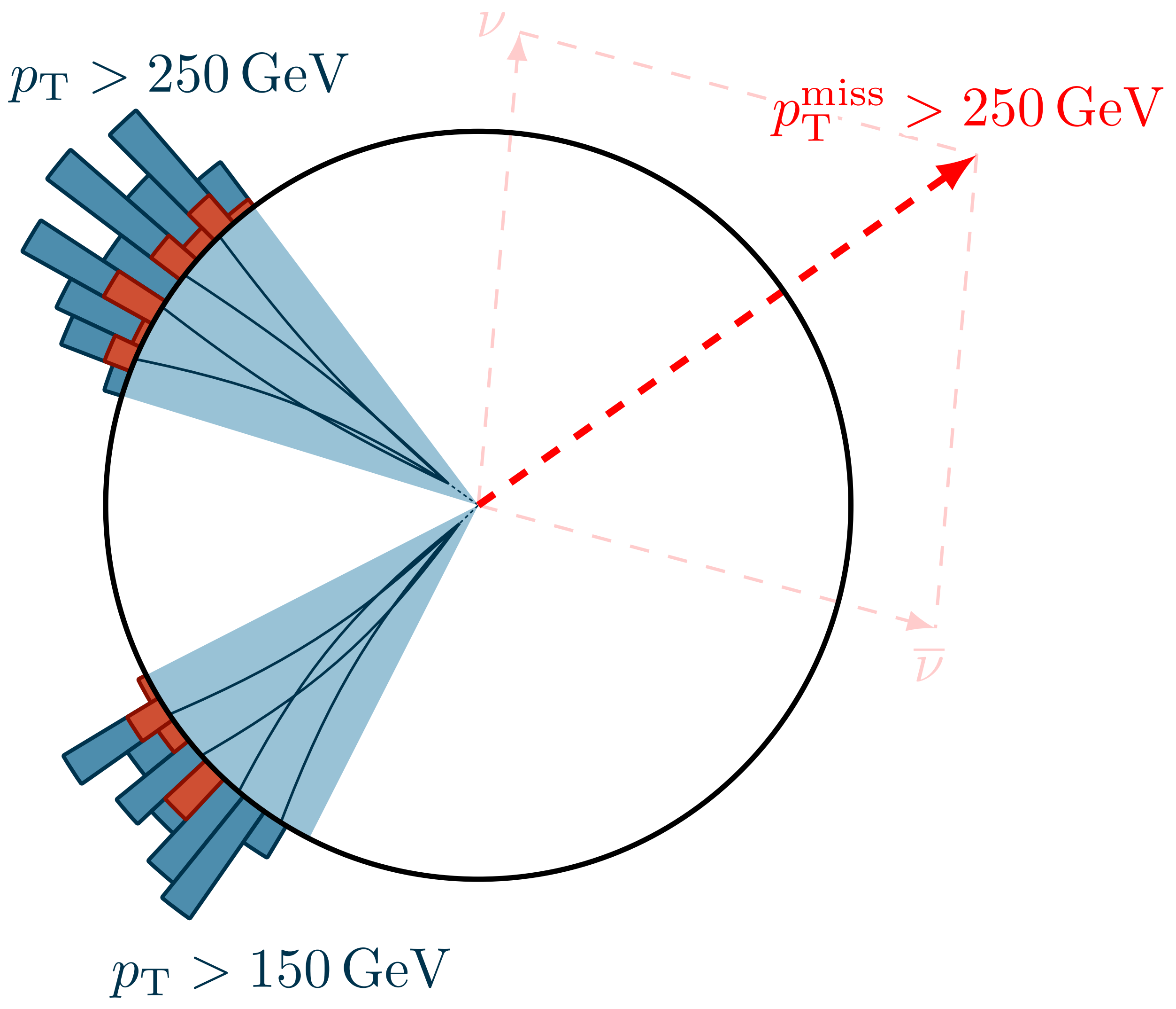
↳ covers $\tau\tau \to \mu\mu$, eμ, eτ_{had}, $\mu\tau_{\mathrm{had}}$, $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channels

Pair production: LQ LQ → cνcν

ATLAS 2410.17824
Submitted to JHEP

NEW !

- search for pair production of t/c squarks or LQs
- select signal events
  - e, μ, τ, b-jet veto
  - E_T^{miss} > 250 GeV
  - ≥ 2 c-tagged jets
  - m_{cc} > 200 GeV



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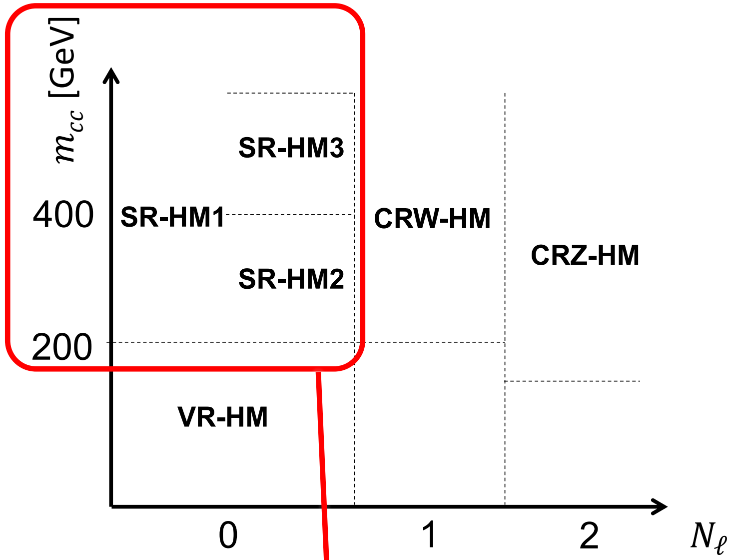
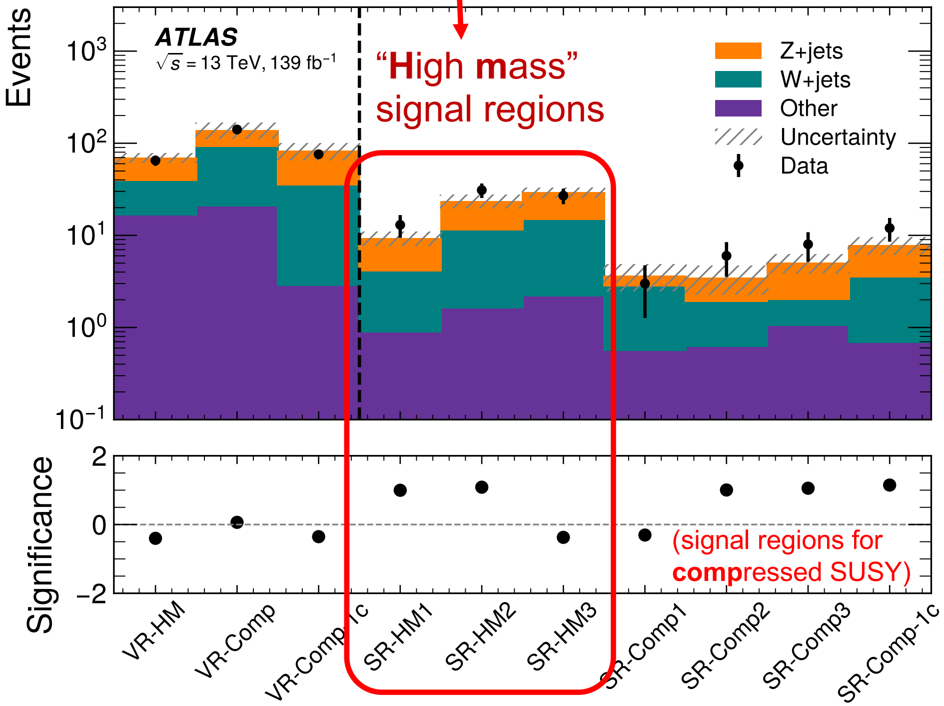
- select signal events
  - e, μ, τ, b-jet veto
  - **$E_{\mathrm{T}}^{\mathrm{miss}}$ > 250 GeV**
  - **≥ 2 c-tagged jets**
  - m_{cc} > 200 GeV
- split into three signal regions with cuts on **m_{cc}** and **E_T^{miss} significance** (= $E_{\mathrm{T}}^{\mathrm{miss}}/\sigma[E_{\mathrm{T}}^{\mathrm{miss}}]$)
- control backgrounds in events with
  - 1 leptons for W + jets
  - 2 leptons for Z + jets
- extract signal from cut-and-count





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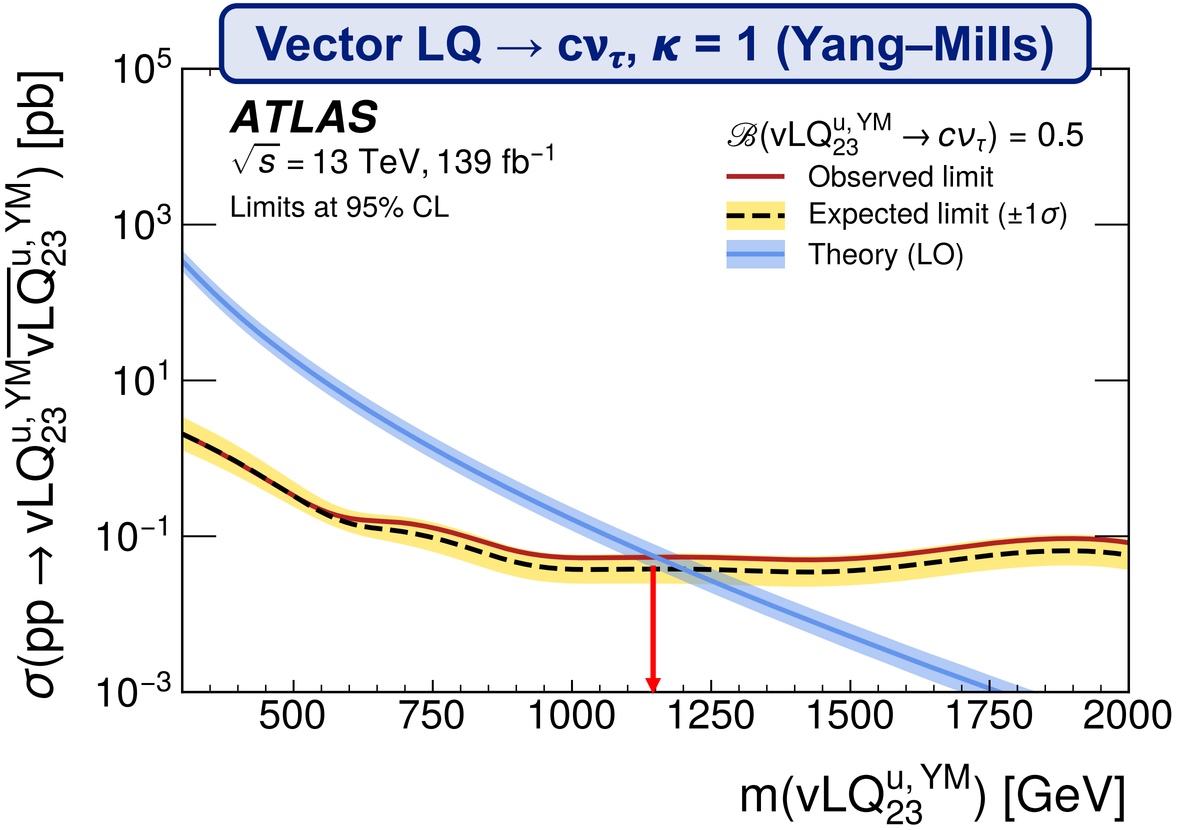
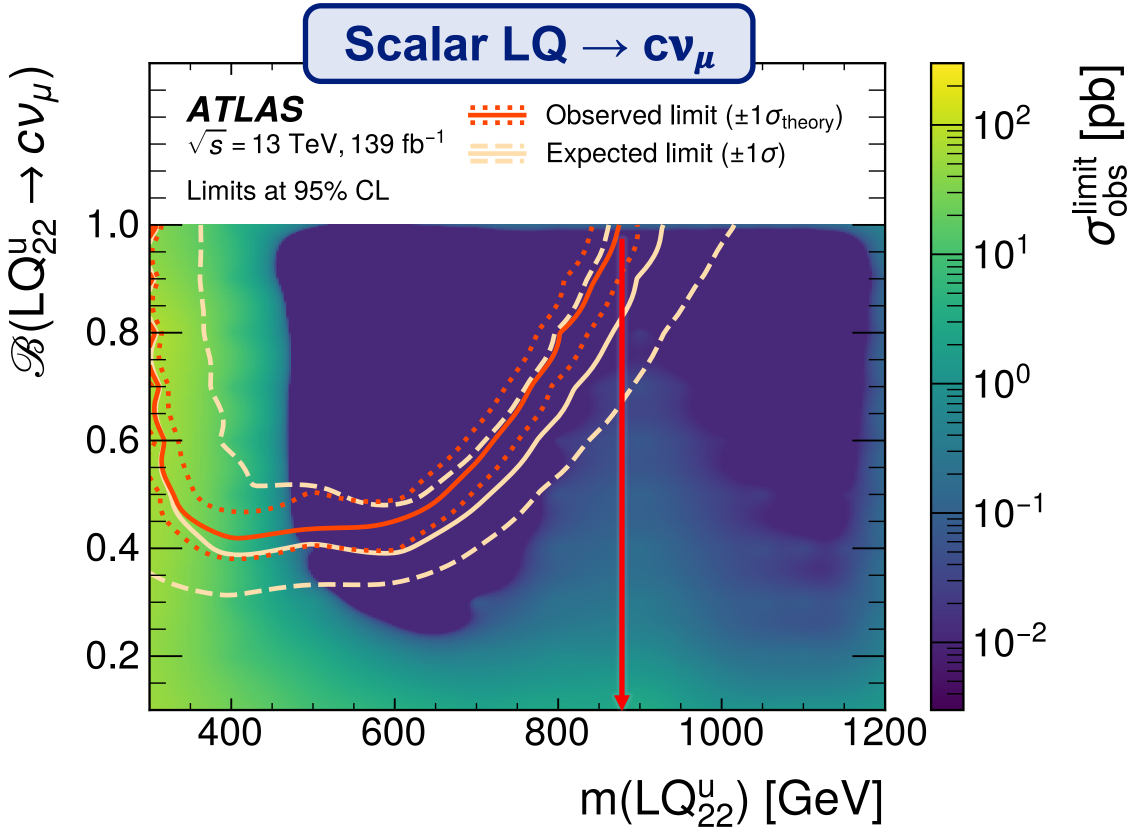
Pair production: LQ LQ → cνcν

- set upper limits on σ(LQ LQ → $c\nu_\tau c\nu_\tau$)
- set upper limits on B(LQ → $c\nu_{e/\mu}$)
- masses up to 900 (1150) GeV are excluded for a scalar (vector) LQ





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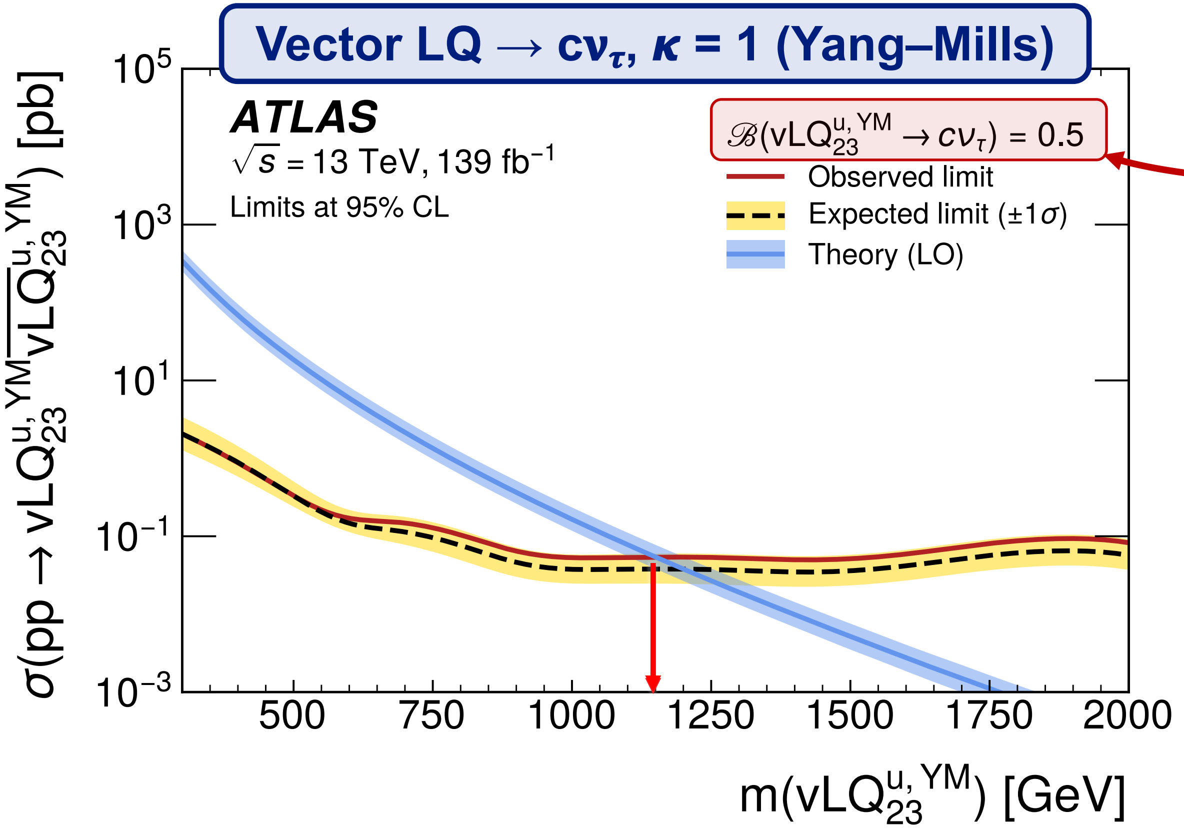

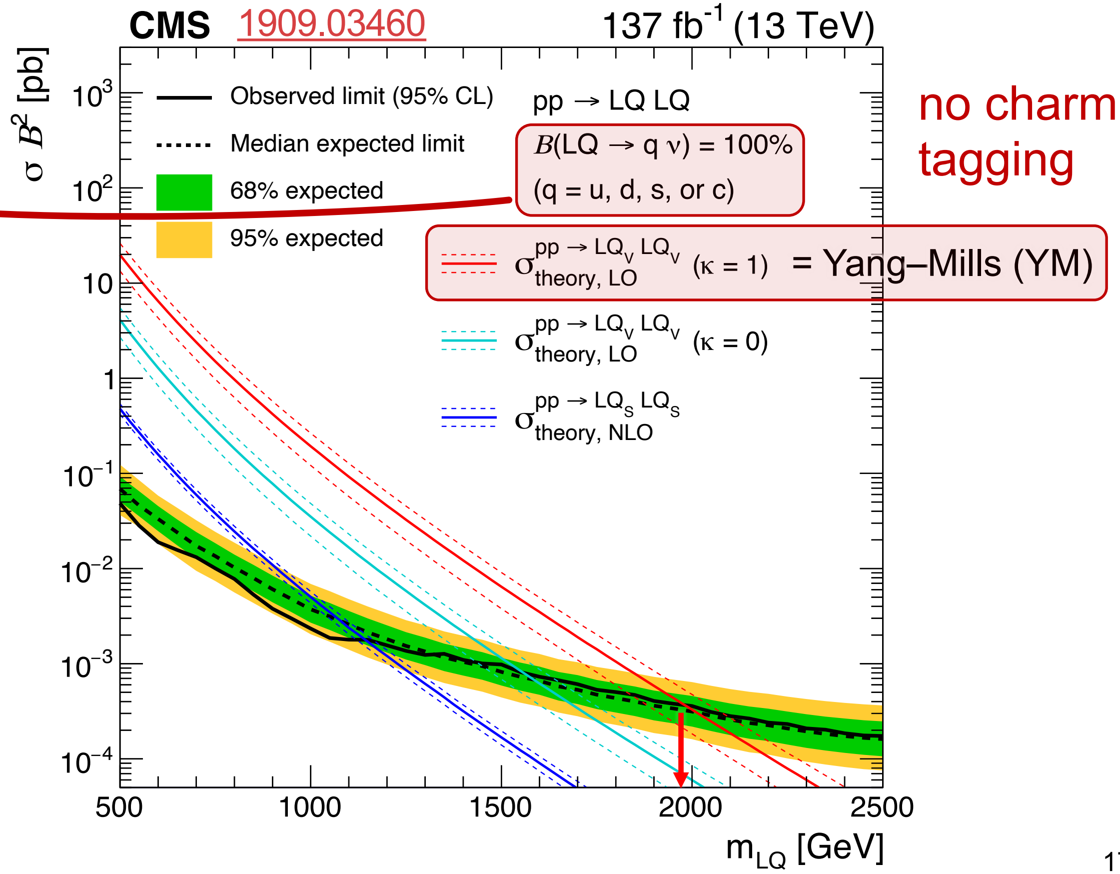

no charm tagging

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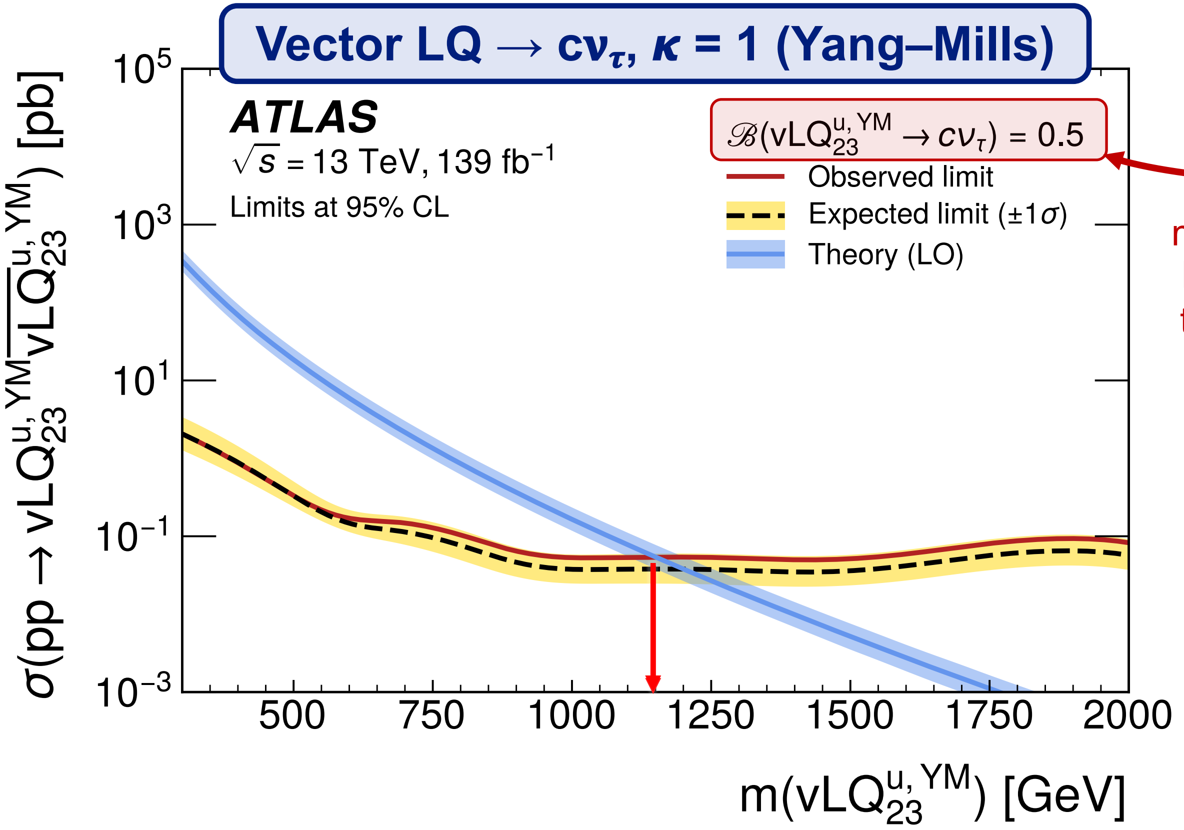
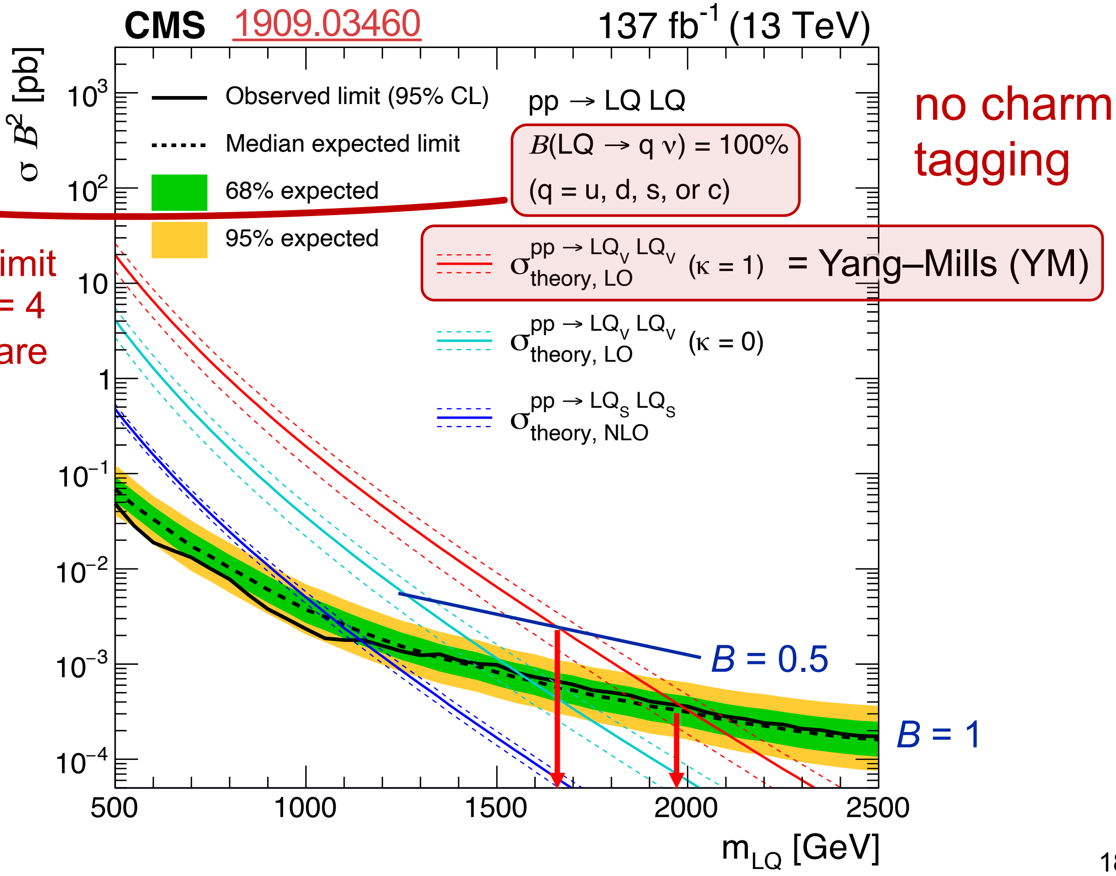


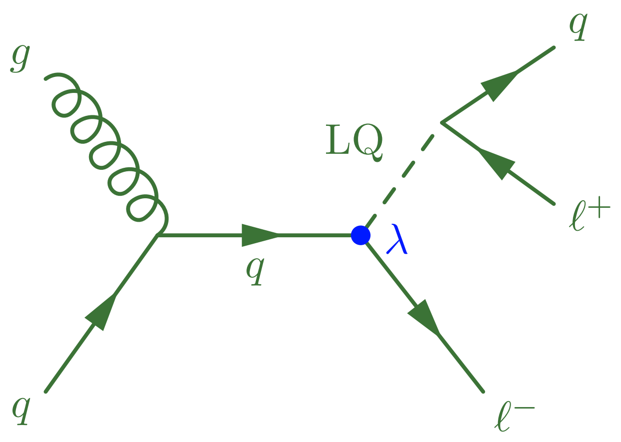
multiply limit by $1/B^2$ = 4 to compare



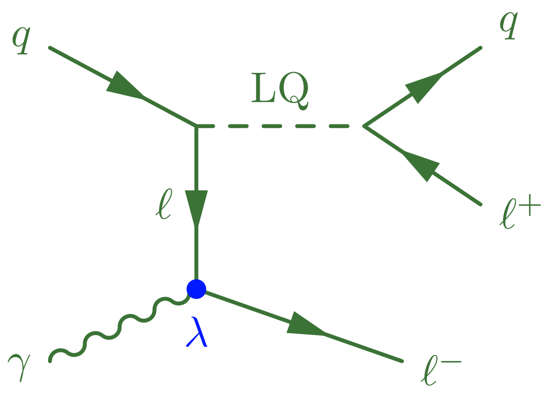
no charm tagging

Final states covered in Run-2 data: Single production

gluon-induced production



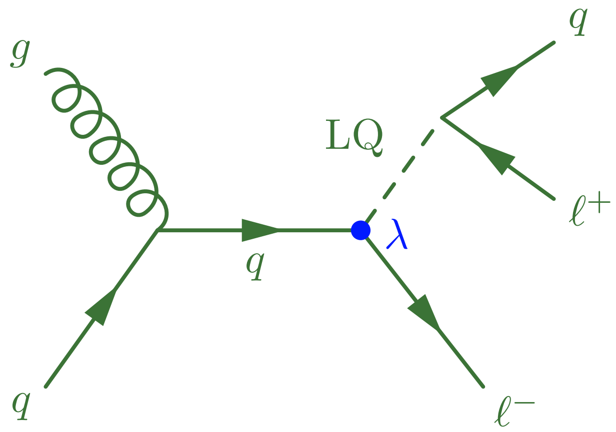
lepton-induced production



	j	c	b(b)(b)	t
ν(ν)	CMS 2107.13021			
e(e)				
eμ	ATL 2112.08090			
μ(μ)				
τ(ν)				CMS 2012.04178
τ(μq)				ATL 2403.06742 CMS-PAS-TOP-22-011
τ(τ)	CMS 2308.06143		ATL 2305.15962 CMS 2308.07826 CMS 2308.06143	

Final states covered in Run-2 data: Single production

gluon-induced production



	j	c	b(b)(b)	t
ν(ν)	CMS 2107.13021			
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eμ	ATL 2112.08090			
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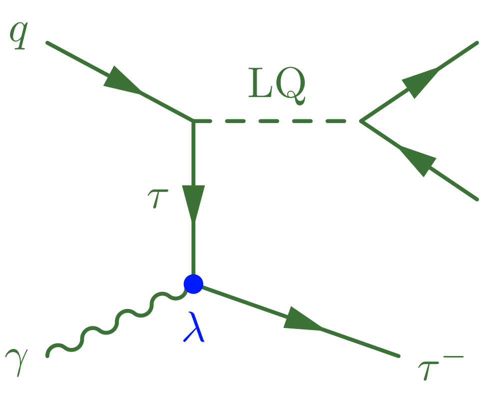
τ(ν)				CMS 2012.04178
τ(μq)				ATL 2403.06742 CMS-PAS-TOP-22-011
τ(τ)	CMS 2308.06143		ATL 2305.15962 CMS 2308.07826 CMS 2308.06143	

first and only lepton-induced result

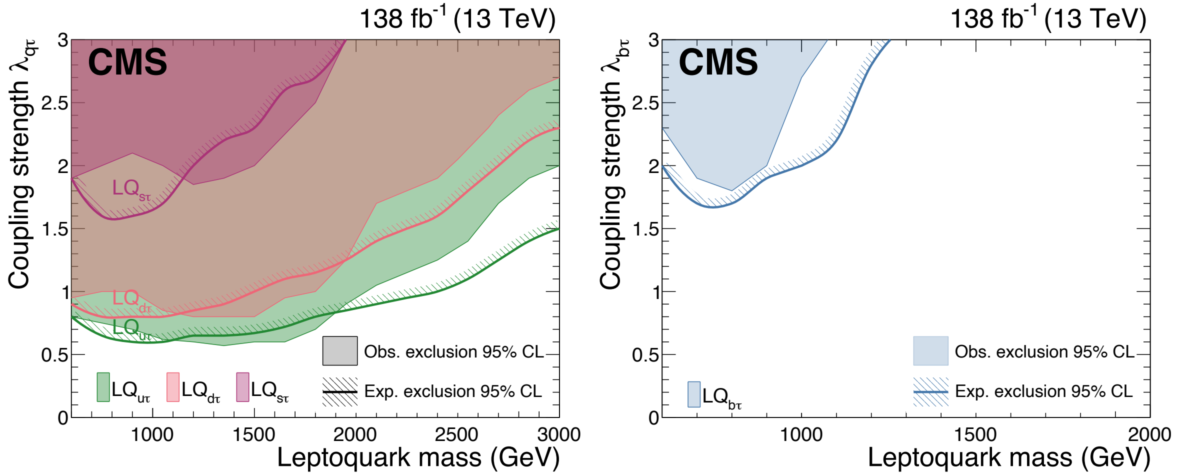
lepton-induced production



covers j = u, d, s, or b

covers $\tau \rightarrow$ e, μ, τ_{had} channels

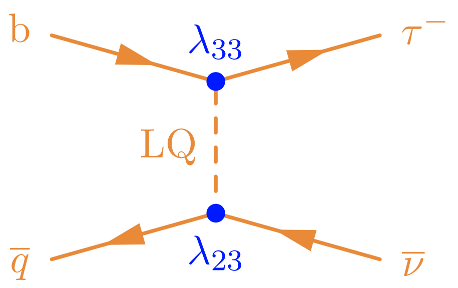
falls out of acceptance

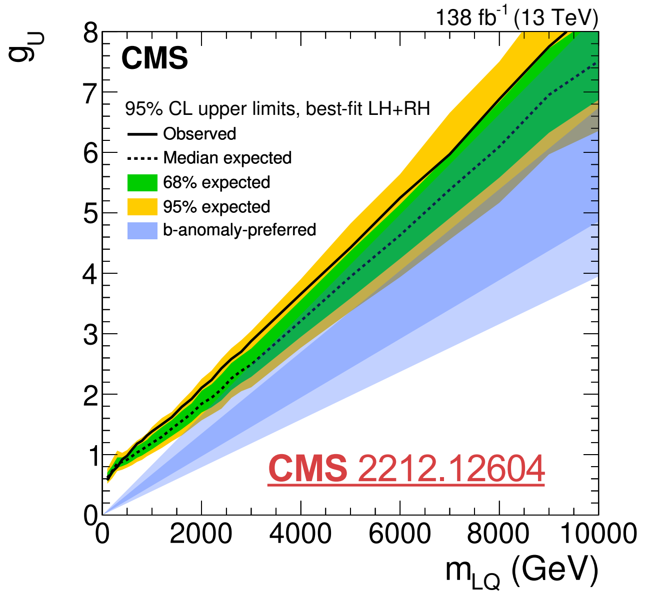


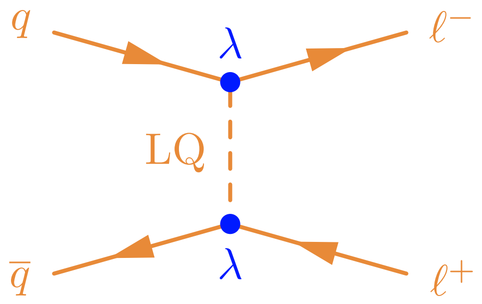
Final states covered in Run-2 data: Nonres. production

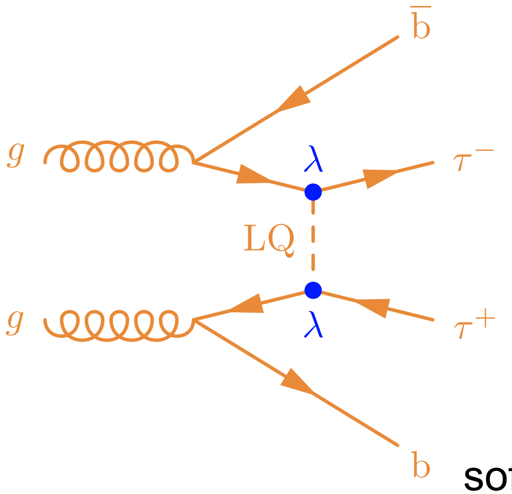
	e	μ	τ(b)(b)
ν			CMS 2212.12604
e	CMS 2503.20023 (NEW !)		
μ		CMS 2503.20023 (NEW !)	ATL 2403.06742 CMS-PAS-TOP-22-011
τ			ATL 2305.15962 ATL 2503.19836 (NEW !) CMS 2308.07826 CMS 2208.02717

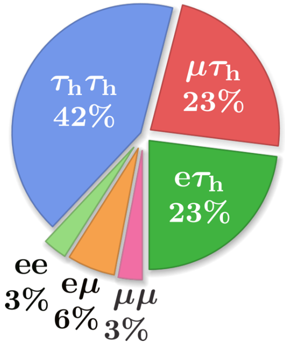
↳ cover $\tau\tau \rightarrow e\tau_{had}, \mu\tau_{had}, \tau_{had}\tau_{had}$ channels



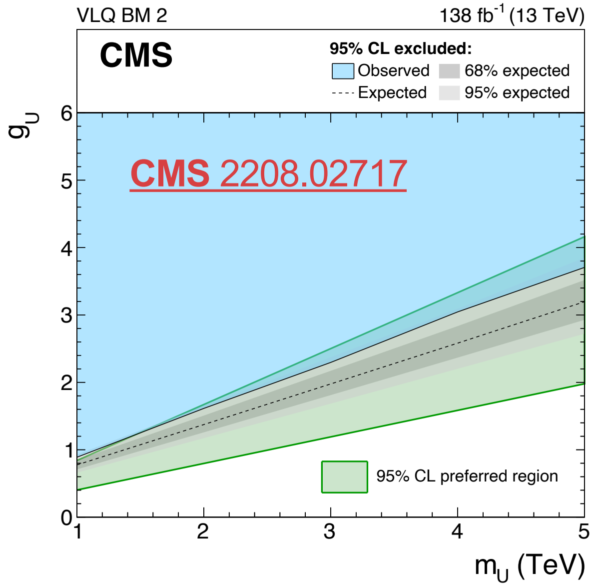








softer & more forward



Nonresonant *t*-channel: qq → ee, *μμ*

CMS 2503.20023
submitted to JHEP

NEW !

- nonresonant LQ signal would interfere with Drell–Yan (DY)
- angular distributions ($|y_{\ell\ell}|$, $\cos\theta^*$) are sensitive to the nonres. LQ signal at extreme dilepton masses ($m_{\ell\ell}$)
- construct parametrized templates by reweighting DY simulation (NLO MadGraph) with **analytic functions**:

pheno paper:
arXiv:1610.03795

previous A_{FB} measurement:
arXiv:2202.12327

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}c_*} \propto \left[\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}c_*}\right]_{\mathrm{DY}} + g_{\mathrm{LQ}}^2 N_{\mathrm{int}}(m_{\ell\ell}) \left(\frac{(1+c_*)^2}{1-c_*+\frac{2m_{\mathrm{LQ}}^2}{m_{\ell\ell}^2}}\right) + g_{\mathrm{LQ}}^4 N_{\mathrm{pure}}(m_{\ell\ell}) \left(\frac{1+c_*}{1-c_*+\frac{2m_{\mathrm{LQ}}^2}{m_{\ell\ell}^2}}\right)^2$$

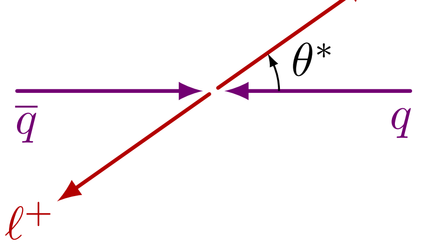
SM Drell–Yan ($\gamma^*/Z \to \ell\ell$)

interference term (destructive for LQ → dℓ)

"pure" nonres. ℓℓ contribution from LQ

Collins-Soper frame (COM frame):

$c_* = \cos\theta^*$



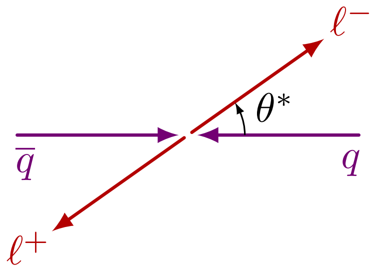
⇒ theory parameters A_0 and A_4 for DY cross section, plus LQ-fermion coupling g_{LQ}^2

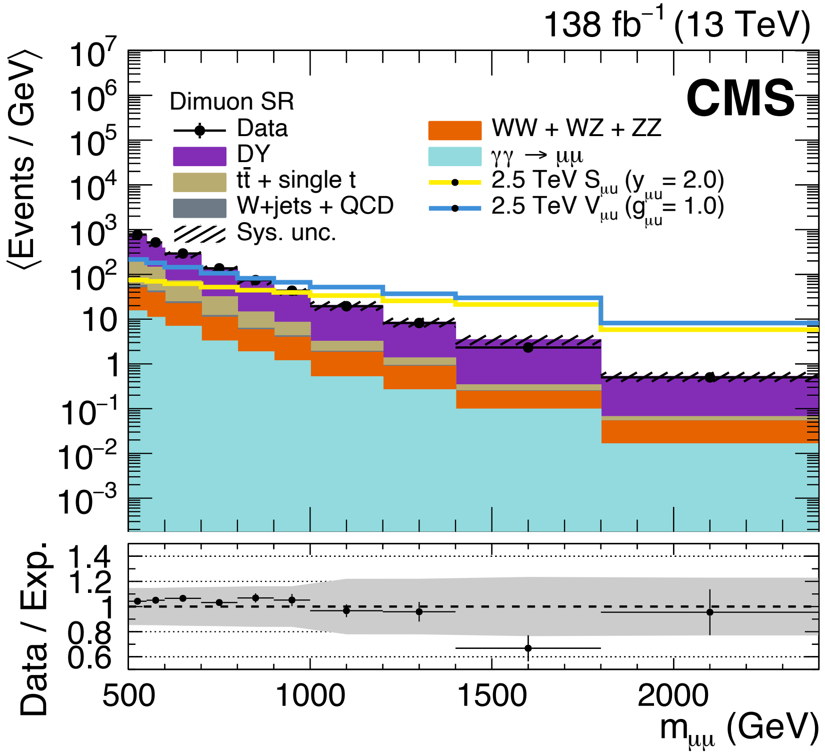
Nonresonant *t*-channel: qq → ee, $\mu\mu$

CMS 2503.20023
submitted to JHEP

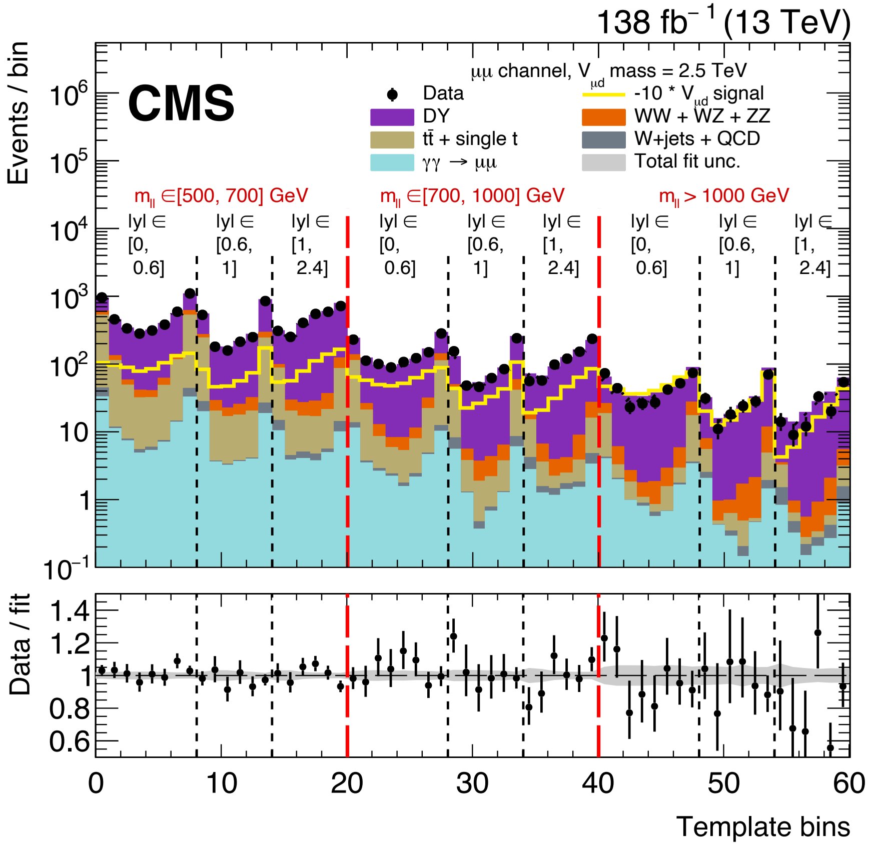
NEW !

- select **dielectron** or **dimuon** events with $m_{\ell\ell}$ > 500 GeV
- validate ttbar & diboson background in **eμ** control region
- bin signal region in reconstructed $m_{\ell\ell}$, rapidity $|y_{\ell\ell}|$, cos θ^*
- fit the DY parameters (A_0, A_4) and LQ-fermion coupling g^2_{LQ}





bin in $|y_{\ell\ell}|$
and cos θ^*

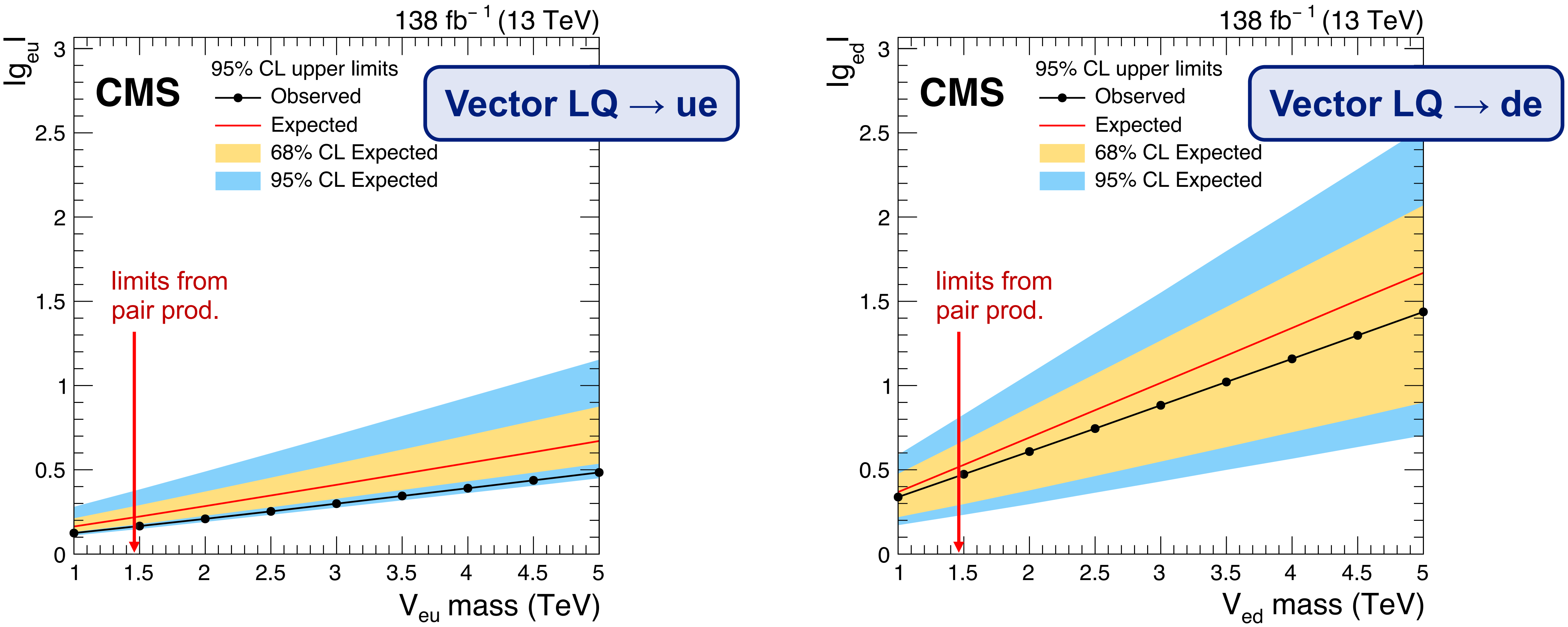


Nonresonant *t*-channel: qq → ee, *μμ*

CMS 2503.20023
submitted to JHEP

NEW !

- set *stringent* limits on coupling & mass for 8 LQ models coupling to e
- sensitivity up to **5 TeV** for large couplings (g > 1.5) !

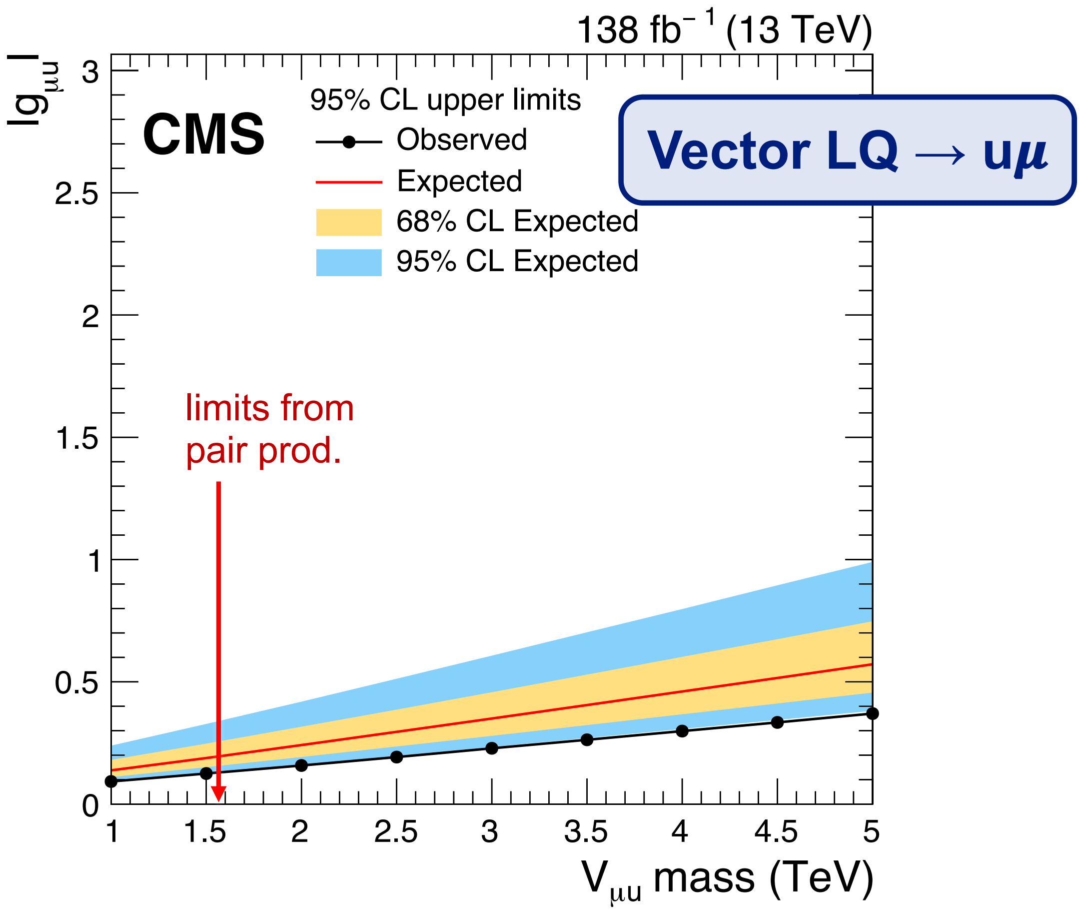


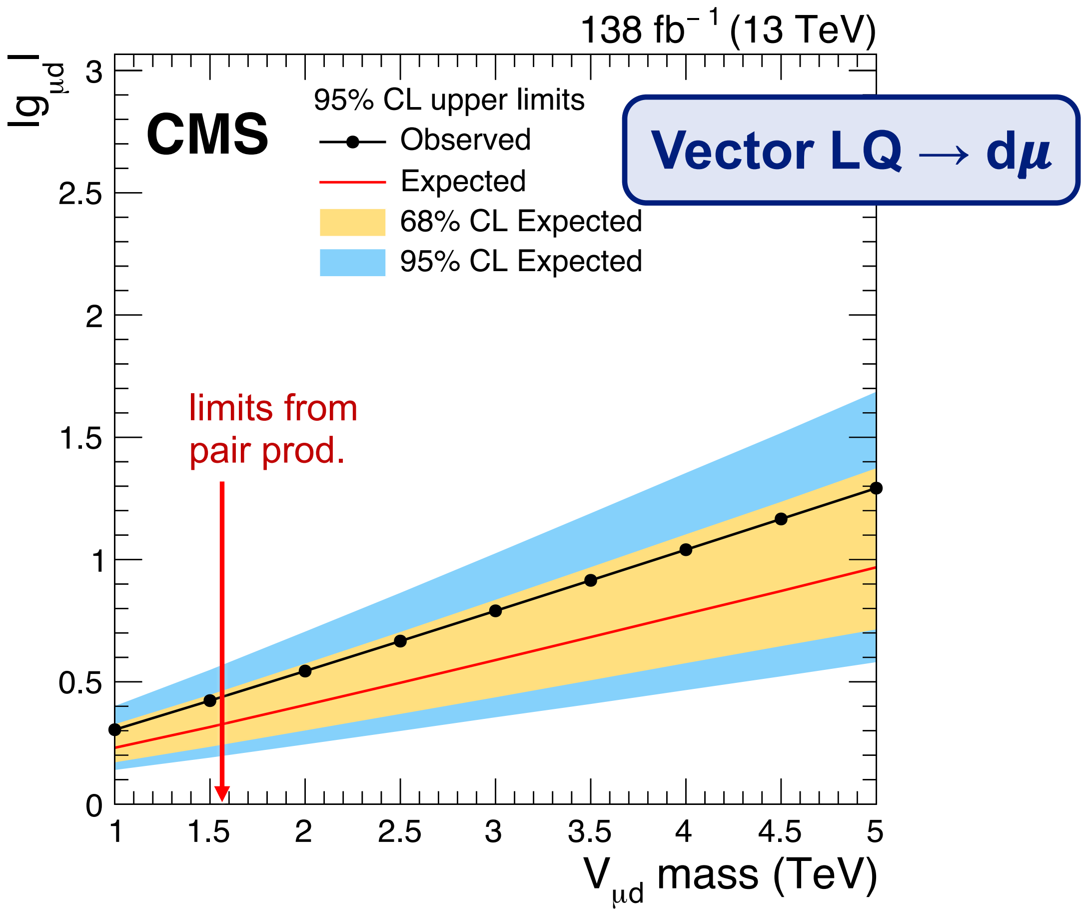
Nonresonant *t*-channel: qq → ee, $\mu\mu$

CMS 2503.20023
submitted to JHEP

NEW !

- set *stringent* limits on coupling & mass for 8 LQ models coupling to e or μ
- sensitivity up to **5 TeV** for large couplings (g > 1.5) !



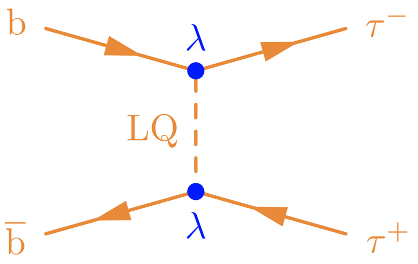


Nonresonant *t*-channel: bb → ττ

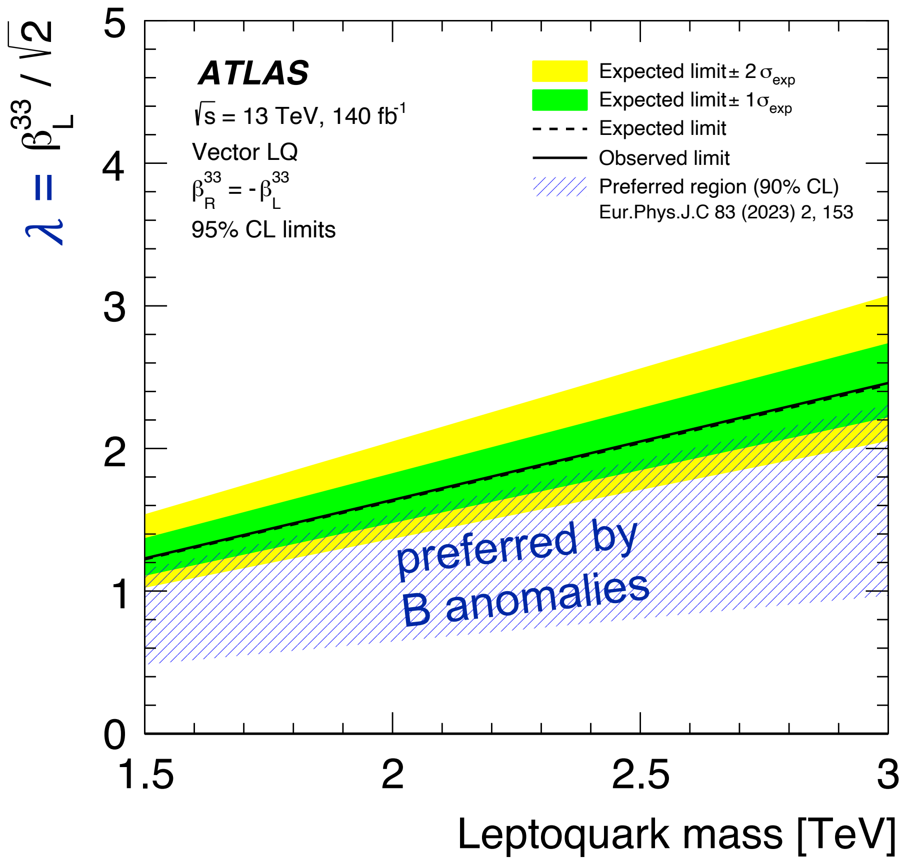
ATL 2503.19836

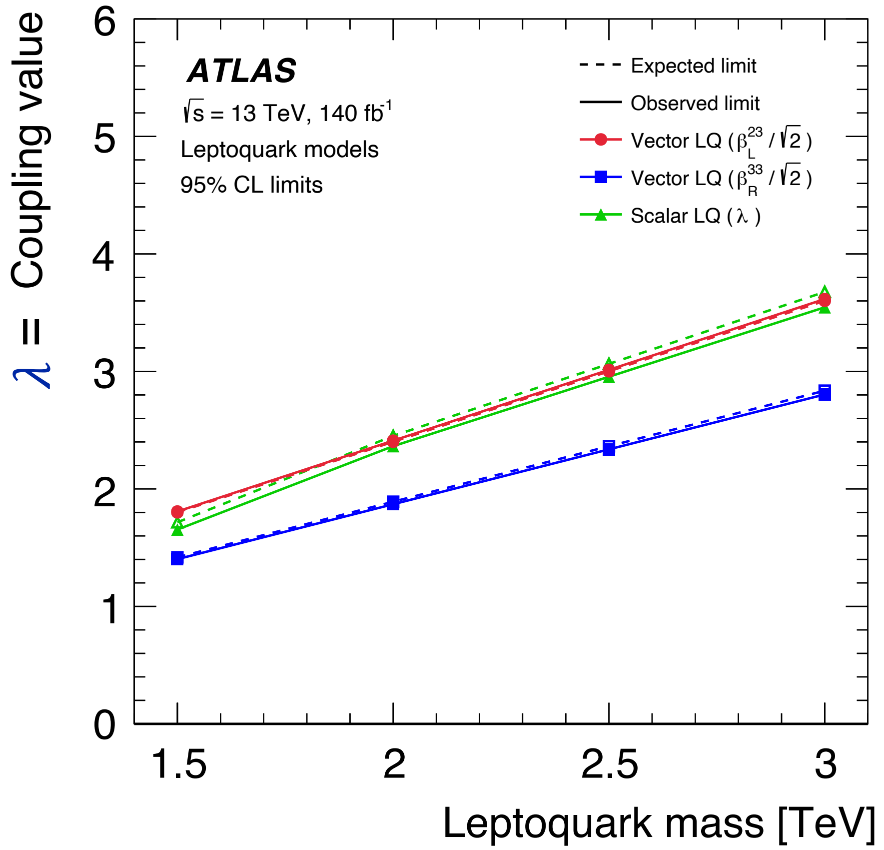
NEW !

see talk by C. Pollard



- measurement of Z (→ $\tau_{had}\tau_{had}$) + b jet cross section at high mass
- includes interference
- set limits on coupling λ vs. m_{LQ}:





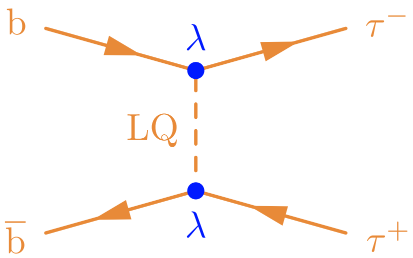
Nonresonant t-channel: bb $\rightarrow \tau\tau$

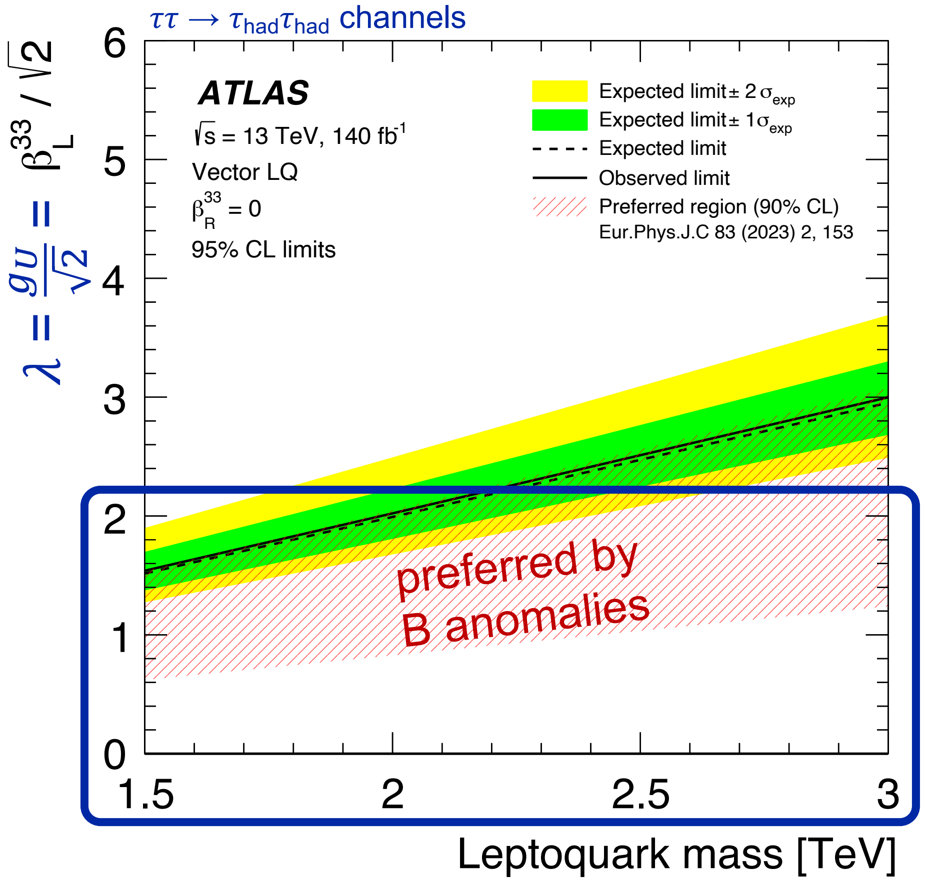
ATL 2503.19836

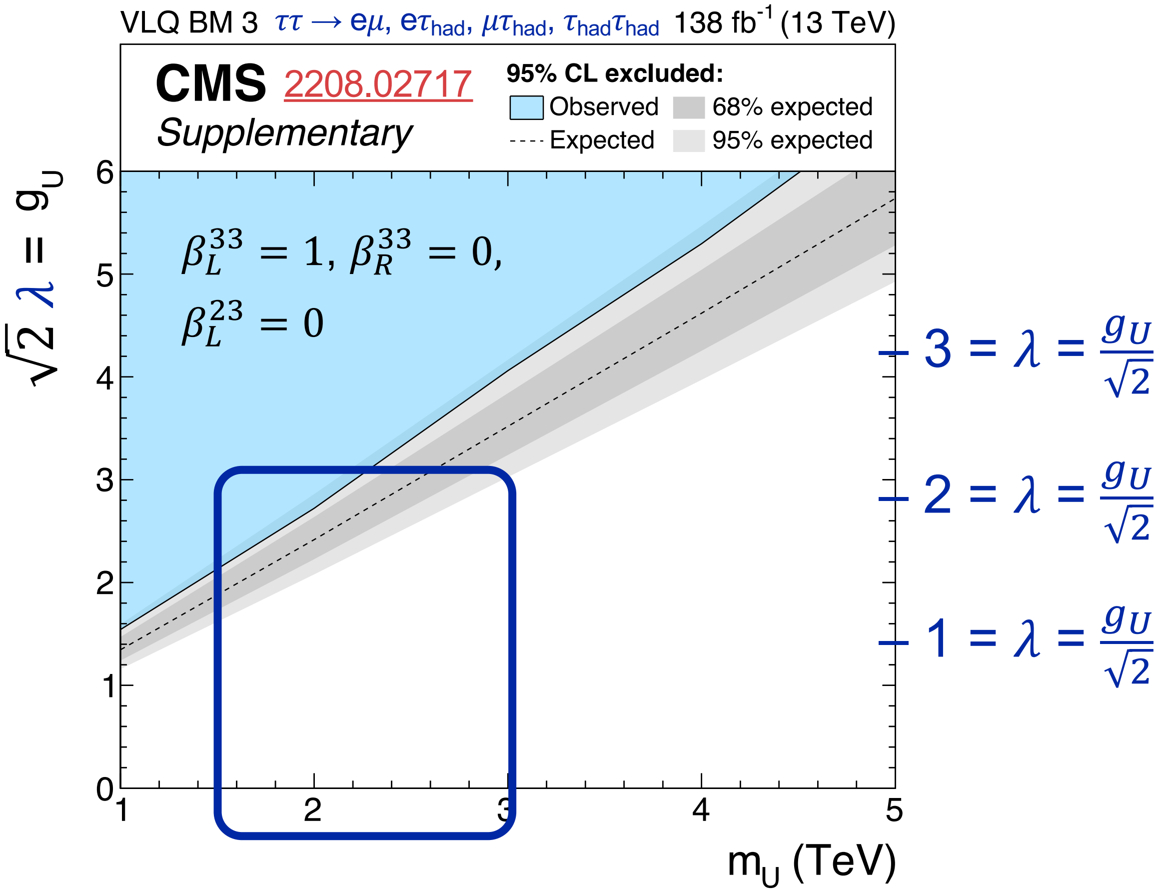
NEW !

see talk by C. Pollard

- measurement of Z ($\rightarrow \tau_{had}\tau_{had}$) + b jet cross section at high mass
- includes interference
- set limits on coupling λ vs. m_{LQ}:

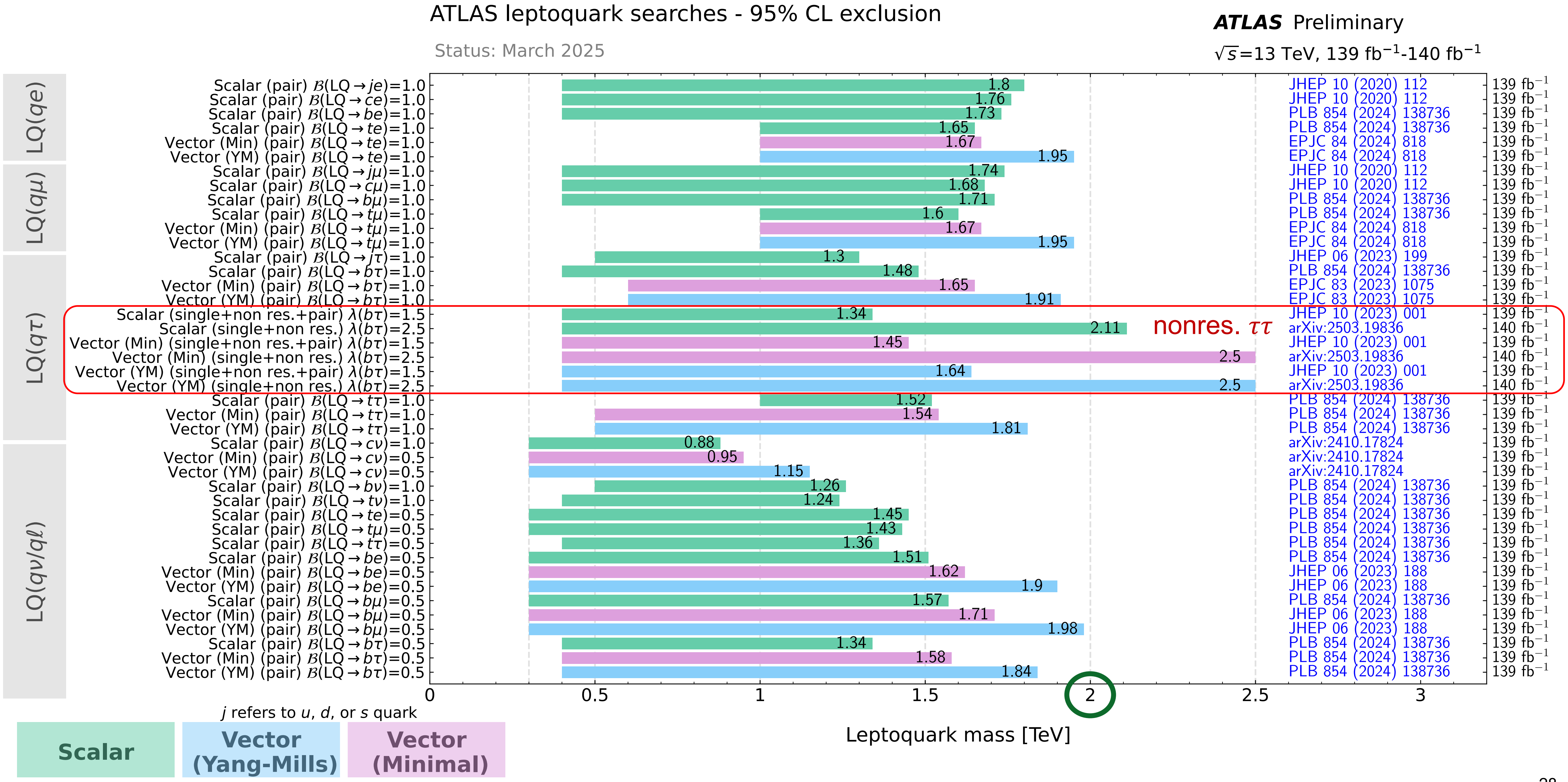






ATLAS summary of mass exclusions

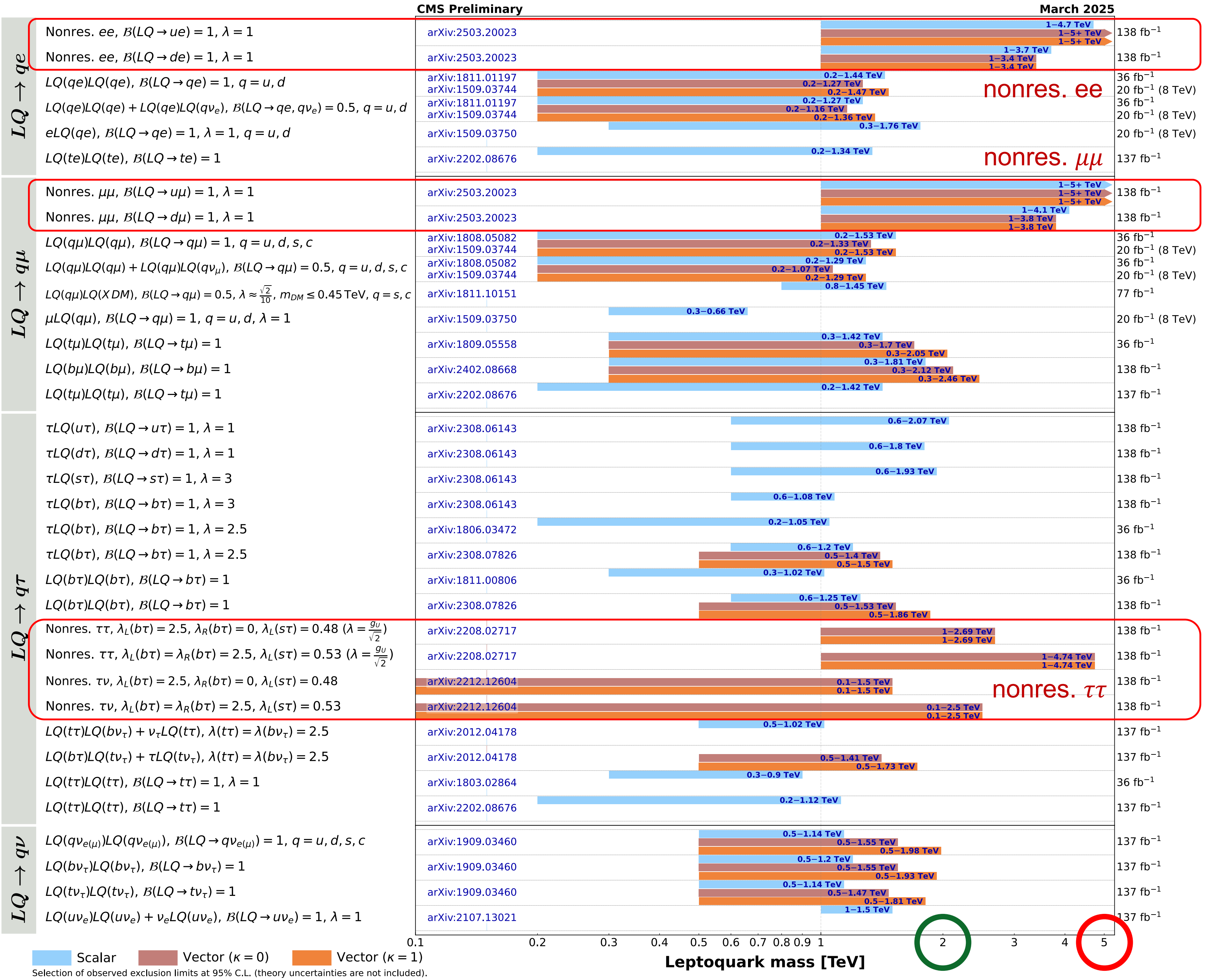
source



CMS summary of mass limits

in Run 2, ATLAS & CMS could exclude LQs **up to 2 TeV** for λ ~ 1 with pair production

thanks to nonres. signals, we can reach **above 5 TeV** for λ > 1.5



source

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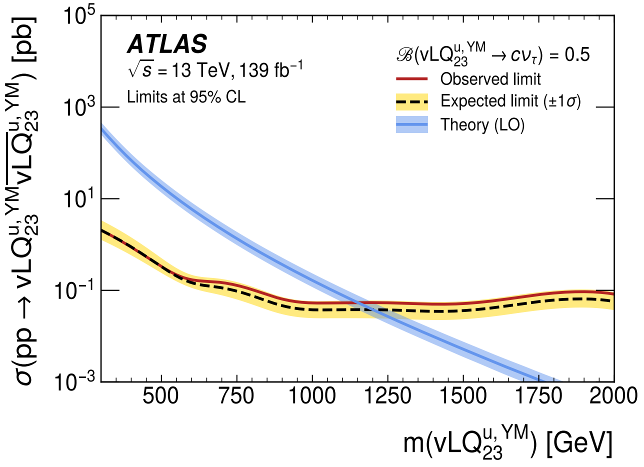
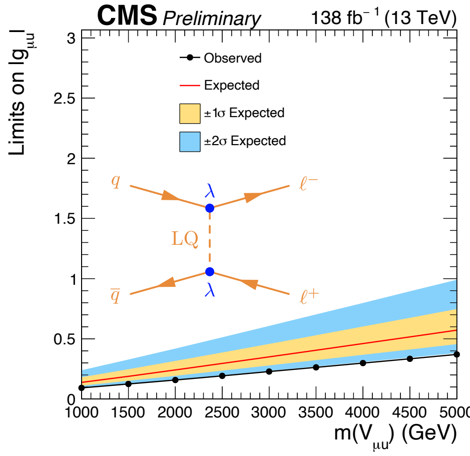
SUMMARY

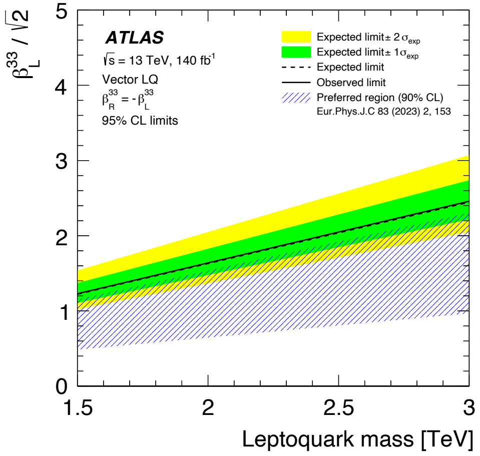
Summary

- ATLAS & CMS have explored many final states in Run 2
  - scalar/vector, up/down-type models, ...
  - single, pair, and nonresonant signatures
- searches for pair production can reach **~ 2 TeV**
- recent searches for nonresonant LQ signals open a large phase space at large mass and couplings λ, **beyond 5 TeV**
- still many opportunities for ℓ + (c) jets final states
- the new [LHC BSM Working Group]() will help to coordinate choices of benchmarks and methods between ATLAS & CMS to facilitate comparisons and combinations

Thank you for your attention !







Final states covered with Run-2 data

Pair production β = 1, 0

		jj	cc	bb	tt
β = 0	$\nu\nu$	CMS 1909.03460	NEW ! ATL 2410.17824 CMS 1909.03460	ATL 2101.12527 CMS 1909.03460	ATL 2004.14060 CMS 1909.03460
β = 1	ee		ATL 2006.05872 (ee, $\mu\mu$)	ATL 2006.05872	ATL 2010.02098 ATL 2306.17642 CMS 2202.08676 (ee, $\mu\mu$)
	$\mu\mu$			ATL 2006.05872 CMS 2402.08668	
	$\tau\tau$	ATL 2303.09444 (jj, cc)		ATL 2108.07665 ATL 2303.01294 CMS 2308.07826	ATL 2101.11582 CMS 2202.08676

Pair production β = 0.5

		jj	cs	tb
β = 0.5	eν			ATL 2210.04517 (eν, $\mu\nu$)
	$\mu\nu$			
	$\tau\nu$			ATL 2108.07665 CMS 2012.04178

a lot of ground covered, but still many final states with (c) jets unexplored in Run 2 !

Single production

	j	c	b(b)(b)	t
$\nu(\nu)$	CMS 2107.13021			
e(e)				
eμ	ATL 2112.08090 (j, c)			
$\mu(\mu)$				
$\tau(\nu)$				CMS 2012.04178
$\tau(\mu$q)				ATL 2403.06742 CMS-PAS-TOP-22-011
$\tau(\tau)$	CMS 2308.06143		ATL 2305.15962 CMS 2308.07826 CMS 2308.06143	

Nonres. production

	e	μ	τ(b)(b)
ν			CMS 2212.12604
e	CMS 2503.20023	NEW !	
μ		CMS 2503.20023	ATL 2403.06742 CMS-PAS-TOP-22-011
τ			ATL 2305.15962 ATL 2503.19836 NEW ! CMS 2308.07826 CMS 2208.02717

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 (Arne Reimers, ICHEP 2024)
  https://indi.to/xXR8H
- LQ searches at ATLAS (Krisztian Peters, ICHEP 2024)
  https://indi.to/bb249

Diagrams with LaTeX source code:

- TikZ.net
- Feyn.net

BACK UP

BACK UP: PHENOMENOLOGY

The 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	✔	✔	✔
EM charge, color	Gauge transformation	✔	✔	✔
B – L {	Lepton number L	✔	✔	✔
	Baryon number B	✔	✔	✔
	Lepton flavor	✔	✔	✔
	Quark flavor	✔	✗	✔
	Isospin (uds)	✗	✗	✔
	Chirality (LH, RH)	✗	✗	✔
	Parity P	✔	✗	✔
	Charge conjugation C	✔	✗	✔
	Time reversal T	✔	✗	✔
	CP	✔	✗	✔
	CPT	✔	✔	✔

* fundamental to relativistic gauge field theories

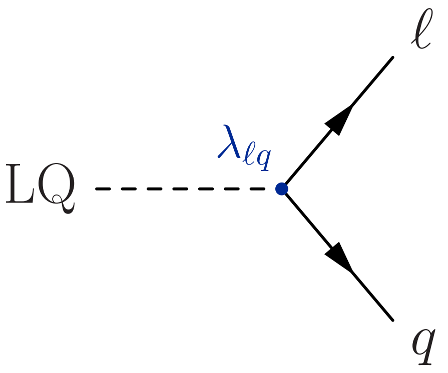
respected by SM gauge interactions but not fundamental !
⇒ "accidental" symmetry ?

caveats:

- flavor symmetries are *broken* by mass differences (Higgs-fermion couplings in Yukawa sector)
- other symmetries are *broken*
  - *explicitly* by nonzero (quark) masses
  - *anomalously* by quantum effects or regularization
  - *spontaneously* by the Higgs or QCD vacuum

Leptoquark models

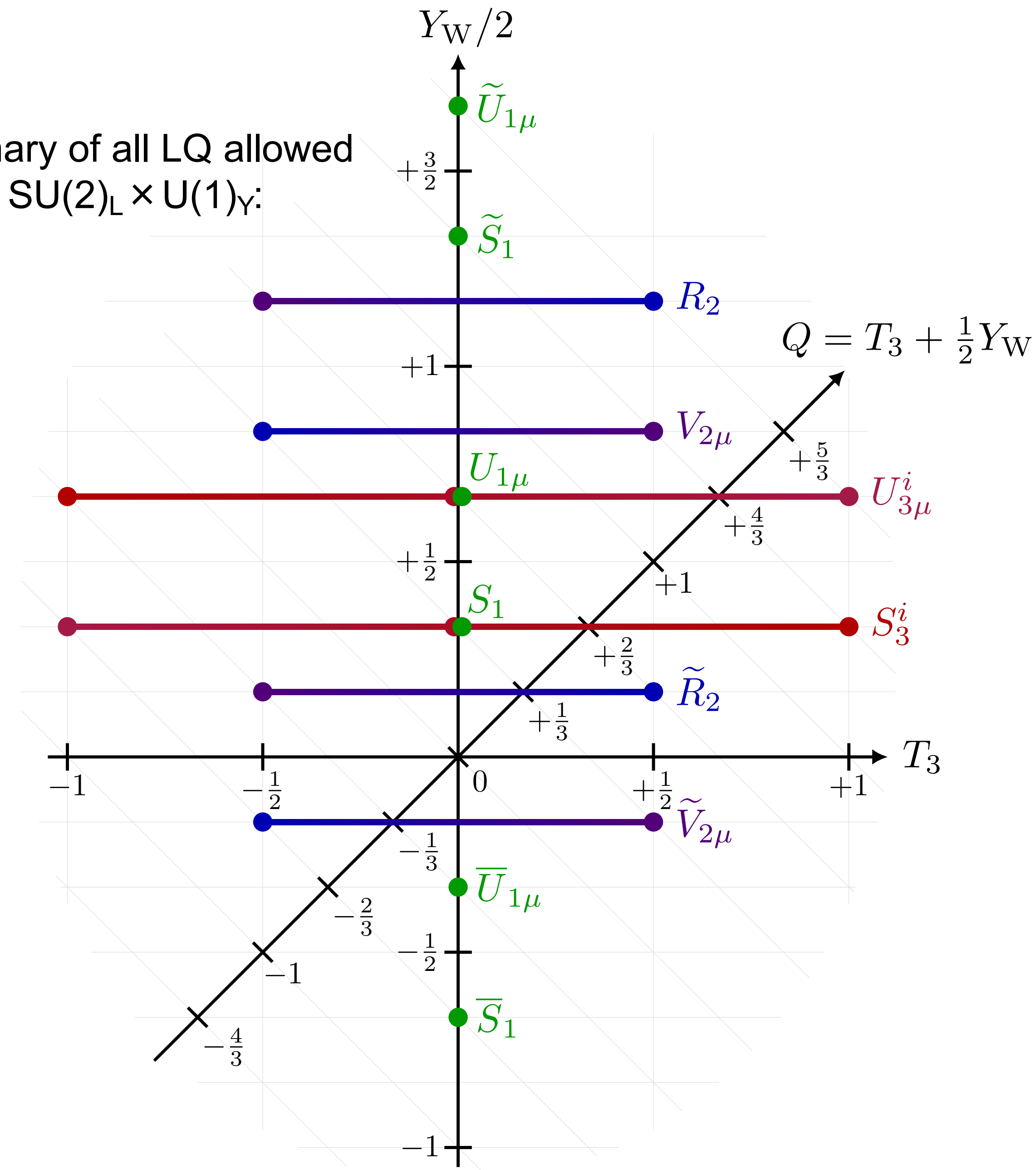
- **scalar** or **vector boson**
- **couples to fermions ($\lambda_{\ell q}$)**



⇒ carries L, B, color, EM charge

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

summary of all LQ allowed under $SU(2)_L \times U(1)_Y$:



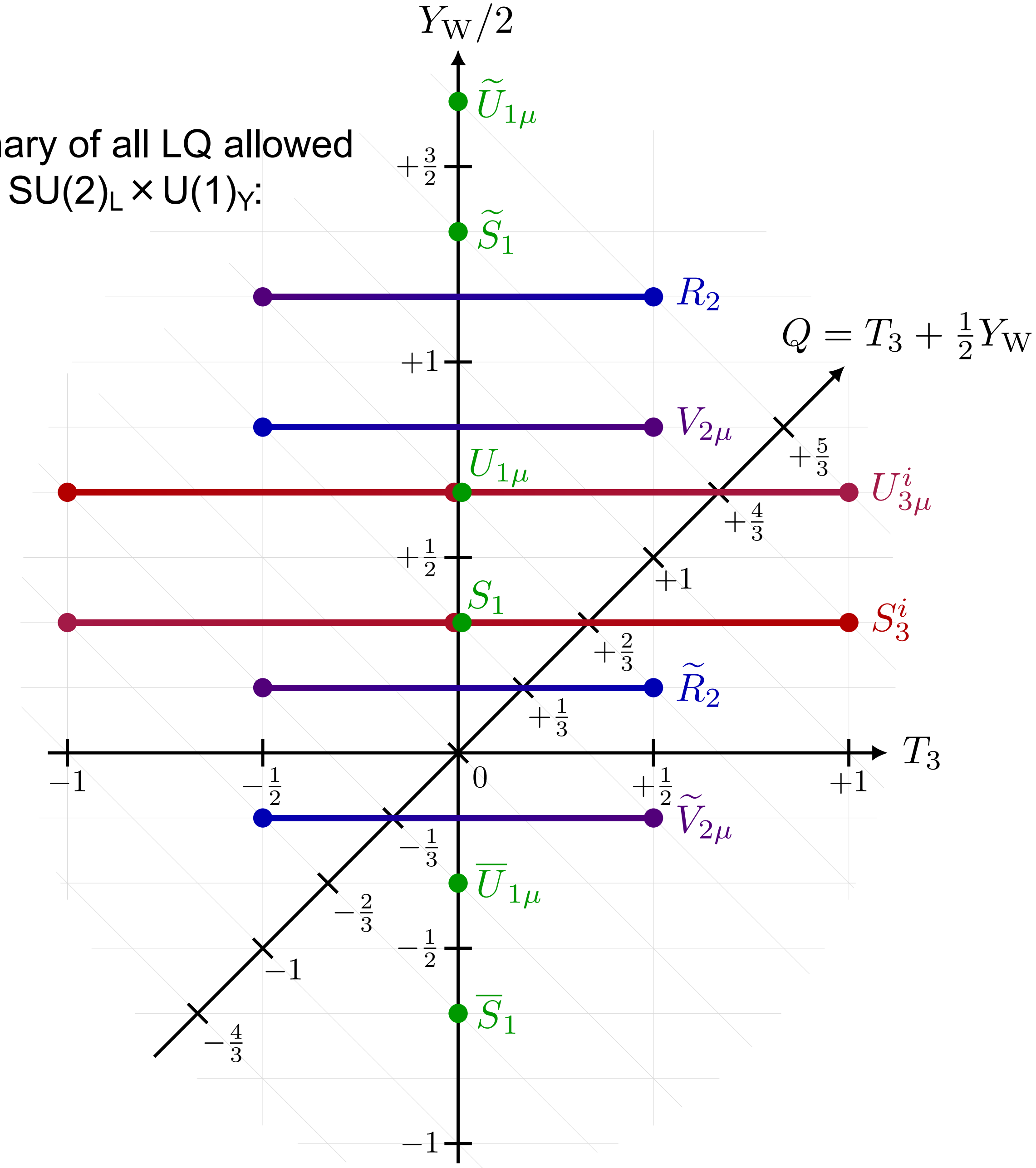
overview of LQ models: arXiv:1603.04993; diagram

Leptoquark models

summary of all LQ allowed under $SU(2)_L \times U(1)_Y$:

Table 3.1: Summary of all possible LQ fields with their representation under $SU(3)_C \times SU(2)_L$, along with hypercharge Y, fermion number $F = 3B + L$, charge $Q = T_3 + Y/2$, and the fermion current(s) they couple to (hermitian conjugate omitted). Bold numbers indicate the dimension of the representation under the respective gauge group. Charge conjugation is indicated by $\psi^C = C\overline{\psi}^T$ with $C = i\gamma^2\gamma^0$. Adapted from Refs. [112] and [181].

LQ field	$SU(3)_C$	$SU(2)_L$	$Y/2$	$F = 3B + L$	$Q = T_3 + Y/2$	Fermion current
Scalar						
$\overline{S}_1$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	-2	$\mp\frac{2}{3}$	$\overline{u}_R^C \nu_R$, $\overline{d}_R^C d_R$
S_1	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	-2	$\pm\frac{1}{3}$	$\overline{Q}_L^C \varepsilon L_L$, $\overline{u}_R^C e_R$, $\overline{d}_R^C \nu_R$, $\overline{Q}_L^C \varepsilon Q_L$, $\overline{u}_R^C d_R$
$\widetilde{S}_1$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$4/3$	-2	$\pm\frac{4}{3}$	$\overline{d}_R^C e_R$, $\overline{u}_R^C u_R$
$\widetilde{R}_2$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0	$\mp\frac{1}{3}, \pm\frac{2}{3}$	$\overline{d}_R \varepsilon L_L$, $\overline{Q}_L \nu_R$
R_2	$\mathbf{3}$	$\mathbf{2}$	$7/6$	0	$\pm\frac{2}{3}, \pm\frac{5}{3}$	$\overline{u}_R \varepsilon L_L$, $\overline{e}_R Q_L$
S_3^i	$\overline{\mathbf{3}}$	$\mathbf{3}$	$1/3$	-2	$\pm\frac{1}{3}, \mp\frac{2}{3}, \pm\frac{4}{3}$	$\overline{Q}_L^C \varepsilon T_i L_L$, $\overline{Q}_L^C \varepsilon T_i Q_L$
Vector						
$\overline{U}_{1\mu}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	0	$\mp\frac{1}{3}$	$\overline{d}_R \gamma^\mu \nu_R$
$U_{1\mu}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	0	$\pm\frac{2}{3}$	$\overline{Q}_L \gamma^\mu L_L$, $\overline{d}_R \gamma^\mu e_R$, $\overline{u}_R \gamma^\mu \nu_R$
$\widetilde{U}_{1\mu}$	$\mathbf{3}$	$\mathbf{1}$	$5/3$	0	$\pm\frac{5}{3}$	$\overline{u}_R \gamma^\mu e_R$
$\widetilde{V}_{2\mu}$	$\overline{\mathbf{3}}$	$\mathbf{2}$	$-1/6$	-2	$\pm\frac{1}{3}, \mp\frac{2}{3}$	$\overline{u}_R^C \gamma^\mu L_L$, $\overline{Q}_L^C \gamma^\mu \nu_R$, $\overline{d}_R^C \gamma^\mu Q_L$
$V_{2\mu}$	$\overline{\mathbf{3}}$	$\mathbf{2}$	$5/6$	-2	$\pm\frac{1}{3}, \pm\frac{4}{3}$	$\overline{d}_R^C \gamma^\mu \varepsilon L_L$, $\overline{Q}_L^C \varepsilon \gamma^\mu e_R$, $\overline{Q}_L^C \gamma^\mu u_R$
$U_{3\mu}^i$	$\mathbf{3}$	$\mathbf{3}$	$2/3$	0	$\mp\frac{1}{3}, \pm\frac{2}{3}, \pm\frac{5}{3}$	$\overline{Q}_L \gamma^\mu T_i L_L$



LQ decay signatures at the LHC

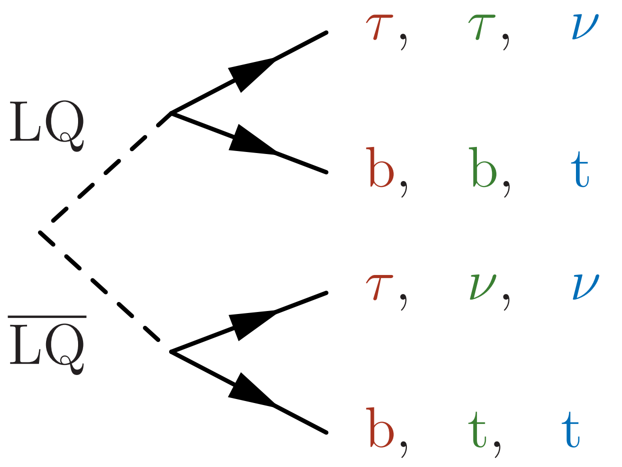
analyses often use a **parameter *β***:

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

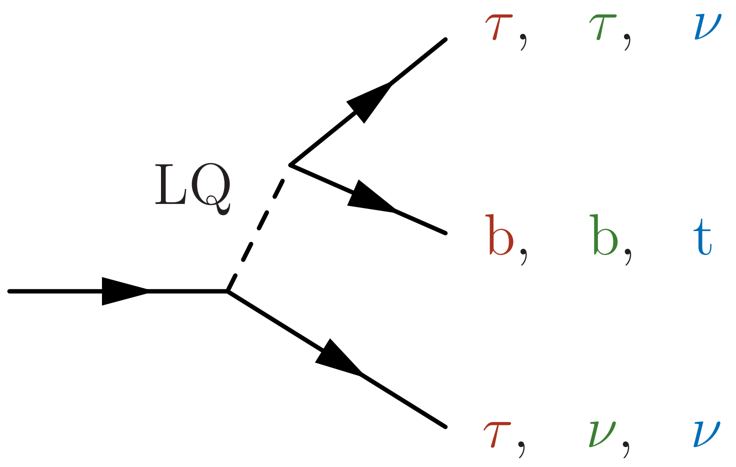
typical benchmarks β = 0, 0.5, 1

e.g. **purely "third-generation" LQ → bτ, tν**:

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



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



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

BACK UP: PAIR PRODUCTION

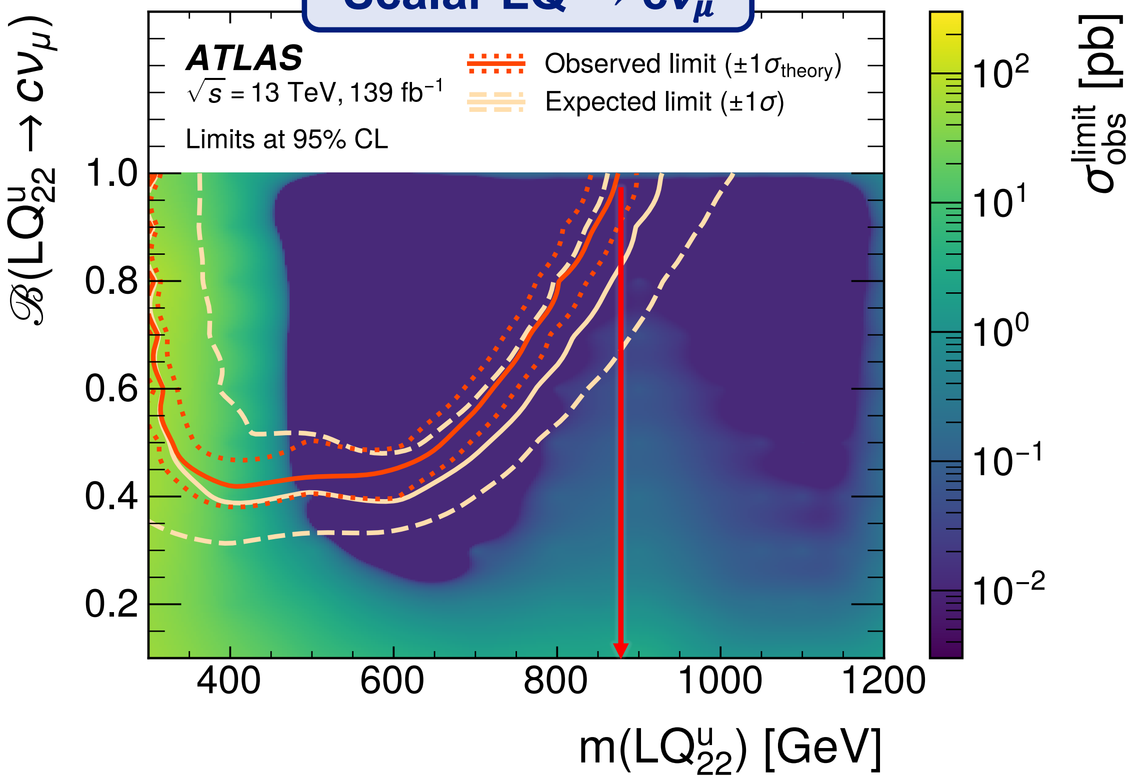
Pair production: LQ LQ → cνcν

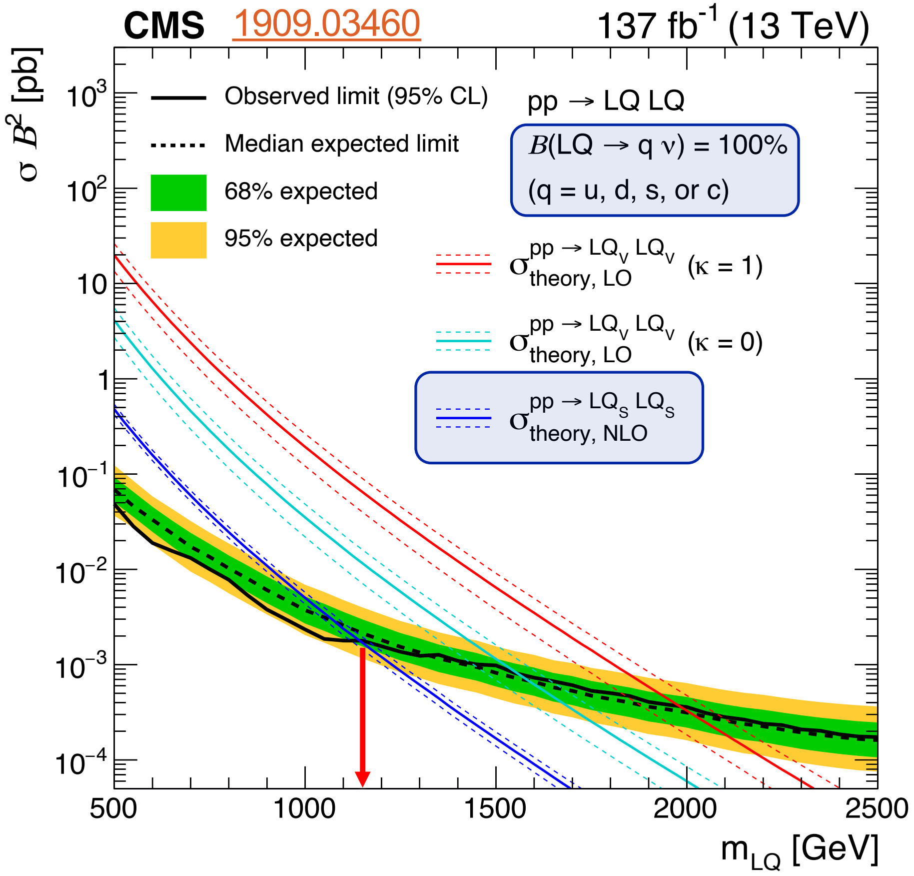
ATLAS 2410.17824
Submitted to JHEP

NEW !

- set upper limits on σ(LQ LQ → $c\nu_\tau c\nu_\tau$)
- set upper limits on B(LQ → $c\nu_{e/\mu}$)
- masses up to 900 (1150) GeV are excluded for a scalar (vector) LQ

Scalar LQ → $c\nu_\mu$





no charm tagging

[ATLAS 2401.11928](#)

ATLAS combination of pair production

also see review paper:
[ATLAS 2403.09292](#)

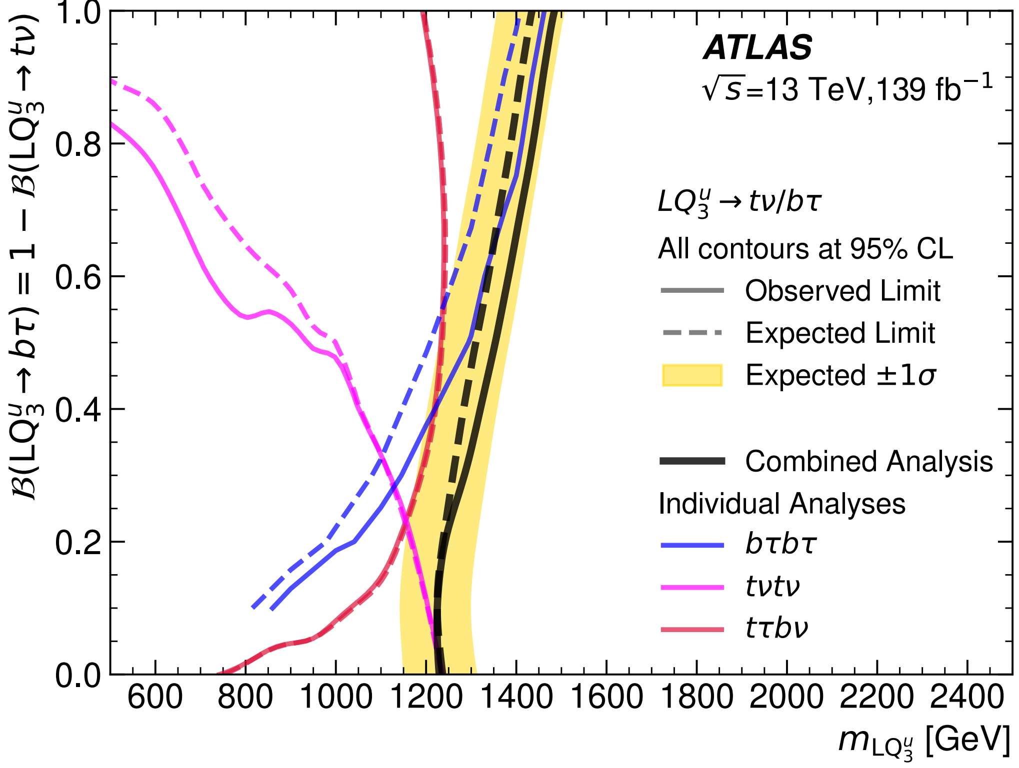
- combine 9 independent searches for pair production
- orthogonality from lepton requirements with negligible overlap
- improved mass exclusion thanks to complementarity

$\beta = 1$
$b\tau b\tau$

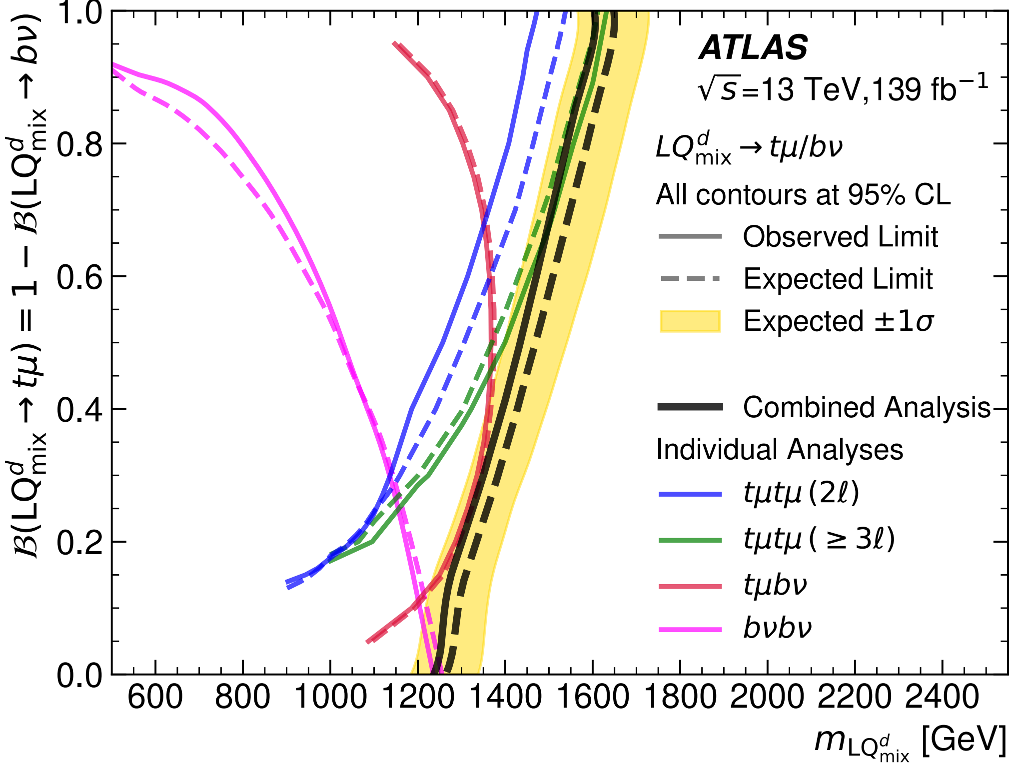
$\beta = 0.5$
$t\nu b\tau$

$\beta = 0$
$t\nu t\nu$

Scalar LQ → tν or bτ



Scalar LQ → tμ or bν



BACK UP: NONRES. PRODUCTION

Nonresonant t-channel: qq → ee, $\mu\mu$

CMS 2503.20023
submitted to JHEP

NEW !

7 Template construction

To model the dilepton differential distributions, parameter-independent templates are constructed for each piece of the differential cross section of LQ production shown in Eqs. (4) and (5). For the SM DY component, the differential cross section is reparametrized as follows:

$$\left[\frac{d\sigma}{dc_*}(m^2_{\ell\ell})\right]_{\text{DY}} \propto \frac{3}{4(2+\alpha)}\left\{(1+c_*^2) + \frac{(2+\alpha)}{2}\,A_4\,c_* + \alpha(1-c_*^2)\right\}, \tag{6}$$

where $\alpha = \frac{2A_0}{2-A_0}$. The first two terms are symmetric and antisymmetric in c_*, respectively, and the third term is proportional to α. The LQ exchange comprises two terms with coefficients y^4_{LQ} or g^4_{LQ} for the pure exchange of the LQ and, y^2_{LQ} or g^2_{LQ} for the interference with Z/γ^*. The templates for these five pieces of the cross section are denoted as f_s (symmetric), f_a (antisymmetric), and f_α (corresponding to the third term) for the three DY templates and $f_{\text{LQ(pure)}}$ and $f_{\text{LQ(int)}}$ for the pure and interference LQ terms, respectively.

In Ref. [35], the f_s , f_a , and f_α templates are constructed by binning events in c_R and reconstructed $|y|$. These templates are constructed for various mass regions, and the fit is performed for each mass region separately. In this paper, the two-dimensional templates are extended to three dimensions by additionally binning in the reconstructed $m_{\ell\ell}$. The templates are constructed by reweighting simulated DY events as analytical functions of generator-level quantities to match the differential distributions of the three pieces of the DY cross section. To reduce statistical fluctuations in the simulator, each event is used twice, once with $+c_*$ and once with $-c_*$, with a weight of 0.5 to keep the normalization unchanged. The reweighting functions for the DY templates, f_s , f_a , and f_α respectively, are:

$$w_s(|c_*|) = \frac{1+c_*^2}{1+c_*^2+\alpha(1-c_*^2)};\ \text{and} \tag{7}$$

$$w_a(c_*) = \frac{c_*}{1+c_*^2+\alpha(1-c_*^2)}; \tag{8}$$

$$w_\alpha(|c_*|) = \frac{1-c_*^2}{1+c_*^2+\alpha(1-c_*^2)}. \tag{9}$$

The denominator of the DY reweighting functions is determined for each event from distributions of simulated SM DY events that are binned in $\cos\theta^*$ and generator-level $|y|$. The α values in the denominator are determined by fitting the generator-level distributions of the simulated events. Finally, to avoid negative values in the antisymmetric template, f_a, a linear combination of f_s and f_a is used in the fit, defined by $f_\pm = \frac{f_s \pm f_a}{2}$.

For the templates corresponding to the two LQ terms, $f_{\text{LQ(pure)}}$ and $f_{\text{LQ(int)}}$, events are reweighted as functions of both c_* and $m_{\ell\ell}$. The reweighting functions are given by:

$$w^{S,V}_{\text{LQ(pure)}}(c_*, m_{\ell\ell}) = \left(N^{S,V}_{\text{pure}}(m_{\ell\ell}) \frac{(1 \mp c_*)^2}{\left(1 - c_* + \frac{2m^2_{\text{LQ}}}{m^2_{\ell\ell}}\right)^2} \right) \frac{1}{N_{\text{SM}}(m_{\ell\ell})(1+c_*^2)}; \tag{10}$$

$$w^{S,V}_{\text{LQ(int)}}(c_*, m_{\ell\ell}) = \left(N^{S,V}_{\text{int}}(m_{\ell\ell}) \frac{(1 \mp c_*)^2}{\left(1 - c_* + \frac{2m^2_{\text{LQ}}}{m^2_{\ell\ell}}\right)} \right) \frac{1}{N_{\text{SM}}(m_{\ell\ell})(1+c_*^2)}, \tag{11}$$

where S and V denote the scalar or vector case. The prefactors, $N^{S,V}_{\text{pure/int}}(m_{\ell\ell})$, depend on the vector and axial-vector couplings of the quarks and leptons to the Z boson, as well as the quark charges. Thus, templates for an LQ coupling to a lepton and quark of specific flavors have different shapes compared to an LQ coupling to a different lepton and quark. The $N_{\text{SM}}(m_{\ell\ell})$ prefactor represents the coefficient of the symmetric term $(1+c_*^2)$ in the SM DY angular distribution. The denominators of the LQ reweighting functions are different from those of the SM DY functions, calculated from the analytical form of the LO SM DY cross section for each event. This is because the LQ modifies the $m_{\ell\ell}$ distribution, which must be taken into account in the reweighting.

The reweighting procedure described above has several benefits. The effects of misassigning the direction of the incident quark in the c_* computation, called the "dilution" effect, are accounted for correctly. Additionally, no dedicated MC samples need to be produced for the LQ process or its interference. The distribution of LQ events can be obtained by reweighting SM DY MC events using the analytical functional form of the LQ differential cross section.

The reweighting procedure was further validated by fitting LQ and DY templates at the generator level to simulated LQ signals using MADGRAPH5_aMC@NLO using the SLQRULES package [69]. Signals were generated at various mass points from 1–5 TeV. The fitted results agreed with the expected coupling values up to a maximum of 30% at $m_{\text{LQ}} = 1$ TeV, decreasing with m_{LQ}. The discrepancy is attributable in part to the fact that the reweighting procedure does not account for NLO effects in the LQ exchange. We account for this in our fits by applying a 30% systematic uncertainty in the normalization of the LQ templates.

The total template for the scalar LQ case, binned in reconstructed $m_{\ell\ell}$, y, and c_R, is given by:

$$f_{\text{data}} = \sum_j f^j_{\text{bkg}} + N(\alpha)\left(\alpha\, f_\alpha + \left(1 + \frac{3A_4}{8N}\right) f_+ + \left(1 - \frac{3A_4}{8N}\right) f_-\right) + y^4_{\text{LQ}} f_{\text{LQ(pure)}} + y^2_{\text{LQ}} f_{\text{LQ(int)}}, \tag{12}$$

where f^j_{bkg} are templates for the non-DY backgrounds and $N(\alpha) = \frac{3}{4(2+\alpha)}$. The same template is used for the vector LQ case using the corresponding reweighting functions, and replacing y_{LQ} with g_{LQ}. The coefficients A_4, α, and either y^2_{LQ} or g^2_{LQ} are extracted in the fits to data.

Events are divided into bins based on $m_{\ell\ell}$, $|y|$, and c_R. For $m_{\ell\ell}$, three bins are used with bin edges at 500, 700, and 1000 GeV, with the fourth bin containing all events with $m_{\ell\ell} > 1000$ GeV. Three bins are defined for $|y|$, with edges at 0, 0.6, 1, and 2.4. The binning in c_R depends on the rapidity. Within the first rapidity bin, events are divided into eight bins in c_R of width 0.25. For the other two rapidity bins, events are divided into six bins in c_R, with edges of -1, -0.5, -0.25, 0, 0.25, 0.5, and 1. Bin edges were chosen after ensuring that there were sufficient simulated events in each bin, and fit uncertainties were minimized without losing precision.

Additional templates are created for the other background processes, with one template each for the MisID background, photon-induced dilepton production, DY $\tau\tau$ production, the combined top quark backgrounds ($t\bar{t}$, tW), and the combined diboson backgrounds (WW, ZZ, WZ). The top quark and MisID templates are symmetrized in c_R to reduce statistical fluctuations. The diboson, photon-induced dilepton, and DY $\tau\tau$ backgrounds are not symmetrized because of their significant inherent asymmetry.

analysis methods based on previous A_{FB} measurement arXiv:2202.12327

Nonresonant t-channel: qq → ee, $\mu\mu$

CMS 2503.20023
submitted to JHEP

NEW !

Table 1: Properties of the R_2, $\widetilde{R}_2$, and U_3 LQs from Ref. [18]. This paper describes a search for R_2 LQs with RL couplings and charge 5/3, $\widetilde{R}_2$ LQs with RL couplings and charge 2/3, and U_3 LQs with charges 2/3 and 5/3.

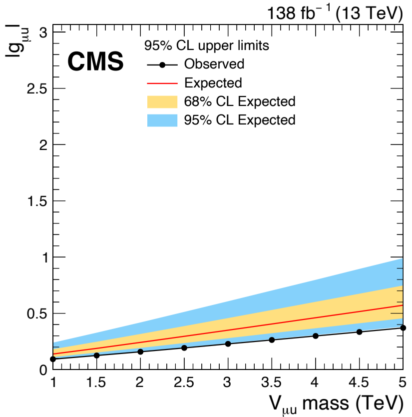
LQ family	$(SU(3), SU(2), U(1))$	Spin	Charge
R_2	(3, 2, 7/6)	0	5/3, 2/3
$\widetilde{R}_2$	(3, 2, 1/6)	0	2/3, -1/3
U_3	(3, 3, 2/3)	1	5/3, 2/3, -1/3

The LQ-quark-lepton interactions are defined by the following terms in the Lagrangian:

$$\mathcal{L} \supset y_{\ell u}\overline{u}_R \ell_L R^{5/3} + y_{\ell d}\overline{d}_R \ell_L \widetilde{R}^{2/3} + g_{\ell u}\overline{u}_L \gamma^\mu \ell_L U_\mu^{5/3} + g_{\ell d}\overline{d}_L \gamma^\mu \ell_L U_\mu^{2/3} + \text{h.c.}, \quad (1)$$

where $y_{\ell u}$ ($y_{\ell d}$) are the couplings of the charge 5/3 (2/3) R_2 ($\widetilde{R}_2$) scalar LQs to fermions and $g_{\ell u}$ ($g_{\ell d}$) are the couplings of the charge 5/3 (2/3) vector U_3 LQs to fermions. The terms describing

In general, for equal coupling values, the cross sections for vector LQ production are larger than for scalar LQ production, hence the limits on $|g_{LQ}|$ are generally stronger than those on $|y_{LQ}|$. The limits on up-type couplings are stronger than the limits on down-type couplings because of the larger up quark content of the proton. In the V_{ed} and $V_{\mu d}$ cases, the interference process is negative, and the likelihood functions for these models are thus quite asymmetric and nonquadratic. This leads to smaller cross sections and weaker expected and observed limits than the other cases. The uncertainties in the expected limits are also accordingly larger than in the other cases. Further, the observed limit on $|g_{ed}|$ is more stringent than the expected limit, despite the positive best fit value for the V_{ed} mass of 2.5 TeV, as shown in Table 4. This stems from the asymmetric nuisance impacts arising from the nonquadraticity in the likelihood, as discussed in Section 8.



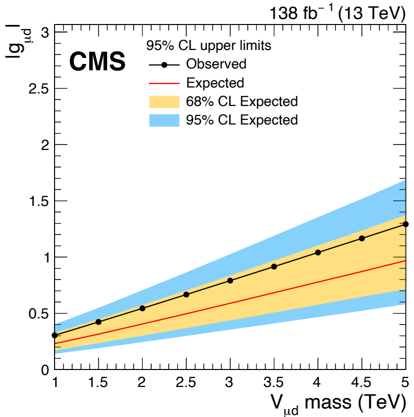


Table 3: Best fit values of A_0, A_4, and y^2_{LQ} for scalar LQ models. The Feldman–Cousins confidence interval for y^2_{LQ} is shown at 68% CL. Results are shown for a candidate m_{LQ} of 2.5 TeV.

Model	A_0	A_4	y^2_{LQ}	Lower bound on y^2_{LQ}	Upper bound on y^2_{LQ}
$S_{\mu u}$	0.02 ± 0.06	1.59 ± 0.07	$-0.13^{+0.14}_{-0.15}$ (stat)$^{+0.06}_{-0.11}$ (syst)	0	0.082
$S_{\mu d}$	0.02 ± 0.06	1.60 ± 0.07	$-0.11^{+0.18}_{-0.20}$ (stat)$^{+0.09}_{-0.13}$ (syst)	0	0.119
S_{eu}	0.07 ± 0.07	1.61 ± 0.08	$-0.10^{+0.15}_{-0.17}$ (stat)$^{+0.07}_{-0.11}$ (syst)	0	0.093
S_{ed}	0.07 ± 0.07	1.62 ± 0.08	$-0.09^{+0.20}_{-0.23}$ (stat)$^{+0.11}_{-0.13}$ (syst)	0	0.138

Table 4: Best fit values of A_0, A_4, and g^2_{LQ} for vector LQ models. The Feldman–Cousins confidence interval for g^2_{LQ} is shown at 68% CL. Results are shown for a candidate m_{LQ} of 2.5 TeV.

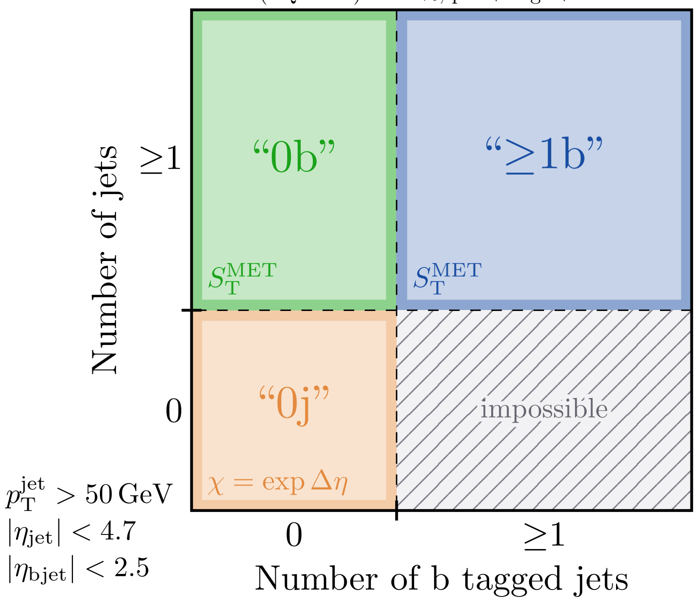
Model	A_0	A_4	g^2_{LQ}	Lower bound on g^2_{LQ}	Upper bound on g^2_{LQ}
$V_{\mu u}$	0.01 ± 0.05	1.63 ± 0.06	$-0.10^{+0.02}_{-0.02}$ (stat)$^{+0.04}_{-0.08}$ (syst)	0	0.029
$V_{\mu d}$	0.01 ± 0.05	1.61 ± 0.06	$0.14^{+0.05}_{-0.05}$ (stat)$^{+0.14}_{-0.07}$ (syst)	0.036	0.328
V_{eu}	0.05 ± 0.07	1.66 ± 0.08	$-0.09^{+0.03}_{-0.03}$ (stat)$^{+0.04}_{-0.08}$ (syst)	0	0.026
V_{ed}	0.06 ± 0.07	1.64 ± 0.08	$0.13^{+0.06}_{-0.06}$ (stat)$^{+0.17}_{-0.09}$ (syst)	0.038	0.352

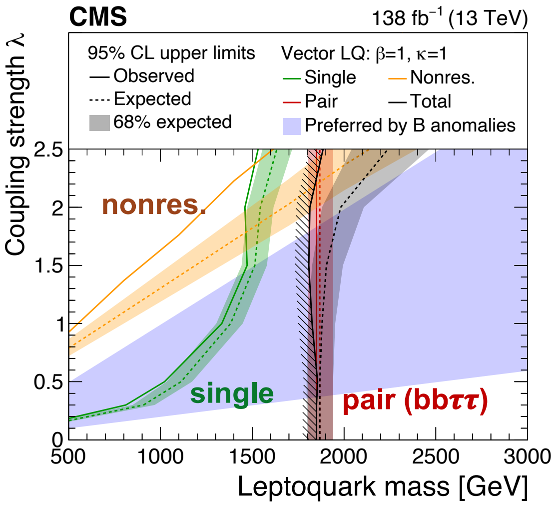
Nonresonant $\tau\tau$: jet selections

2308.07826

CMS, EXO-19-016

$\mathcal{B}(\mathrm{LQ} \to \mathrm{b}\tau) = 100\%$, pair+single+nonres.

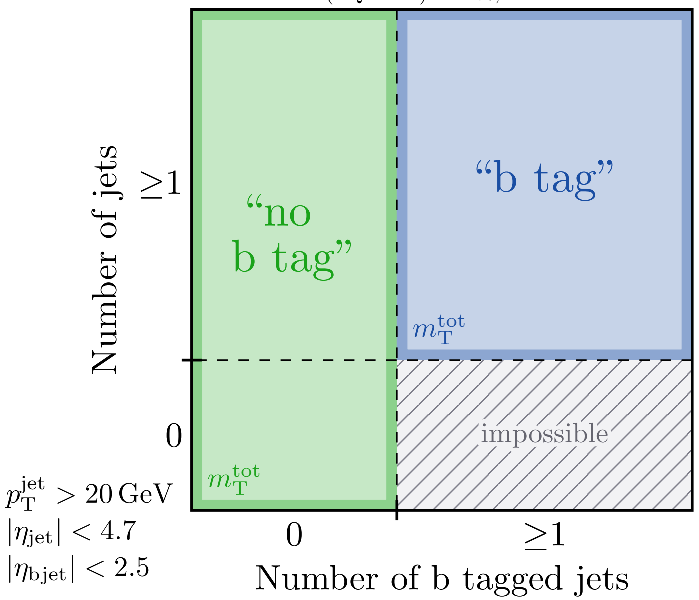


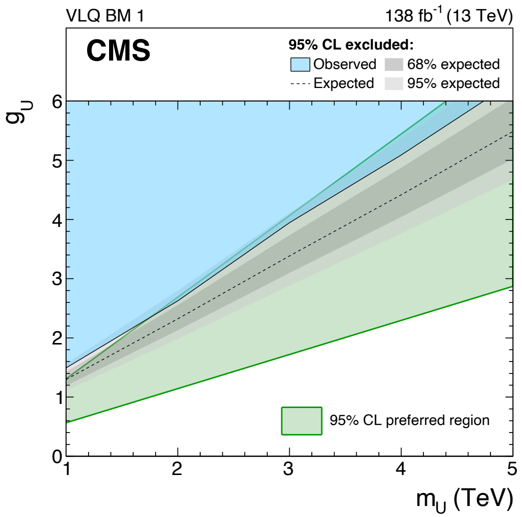


2208.02717

CMS, HIG-21-001

$\mathcal{B}(\mathrm{LQ} \to \mathrm{b}\tau) \sim 50\%$, nonres.

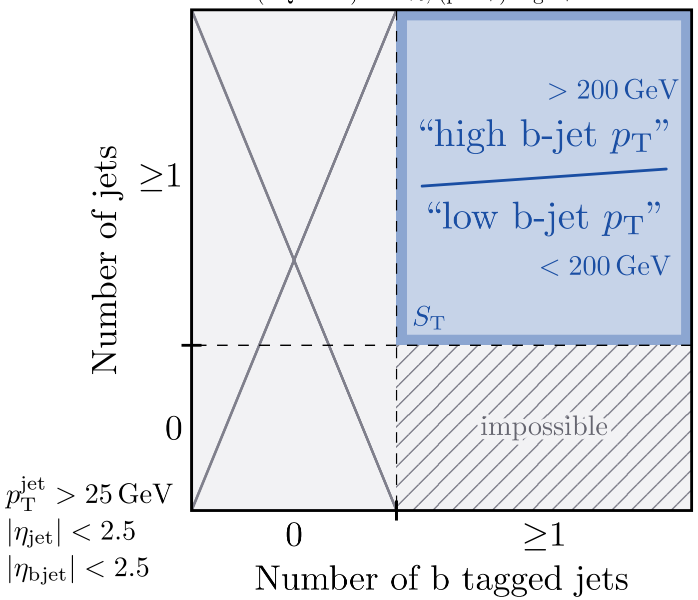


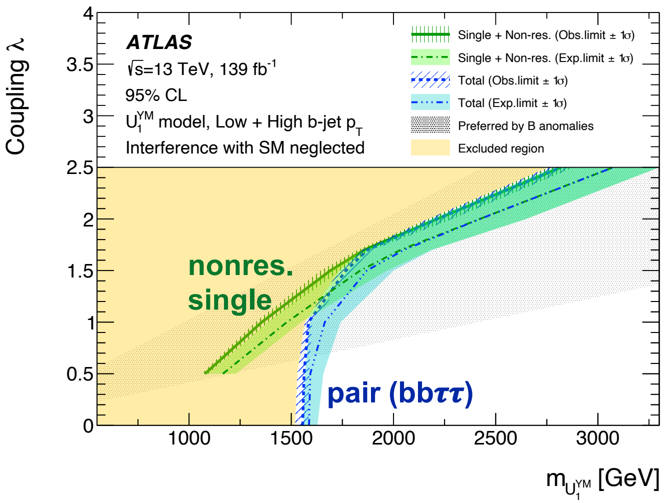


2305.15962

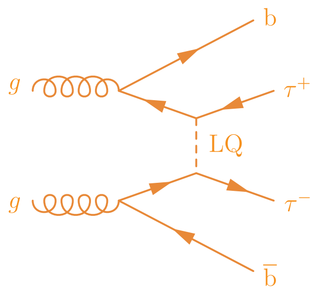
ATLAS, EXOT-2022-039

$\mathcal{B}(\mathrm{LQ} \to \mathrm{b}\tau) \sim 50\%$, (pair+)single+nonres.





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



	EXO-19-019, arXiv:2308.07826	HIG-21-001, arXiv:2208.02717
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)
$j \to \tau_h$ estimation	Data-driven, "fake-factor" method	Data-driven, "fake-factor" method

"best-fit" to B anomalies

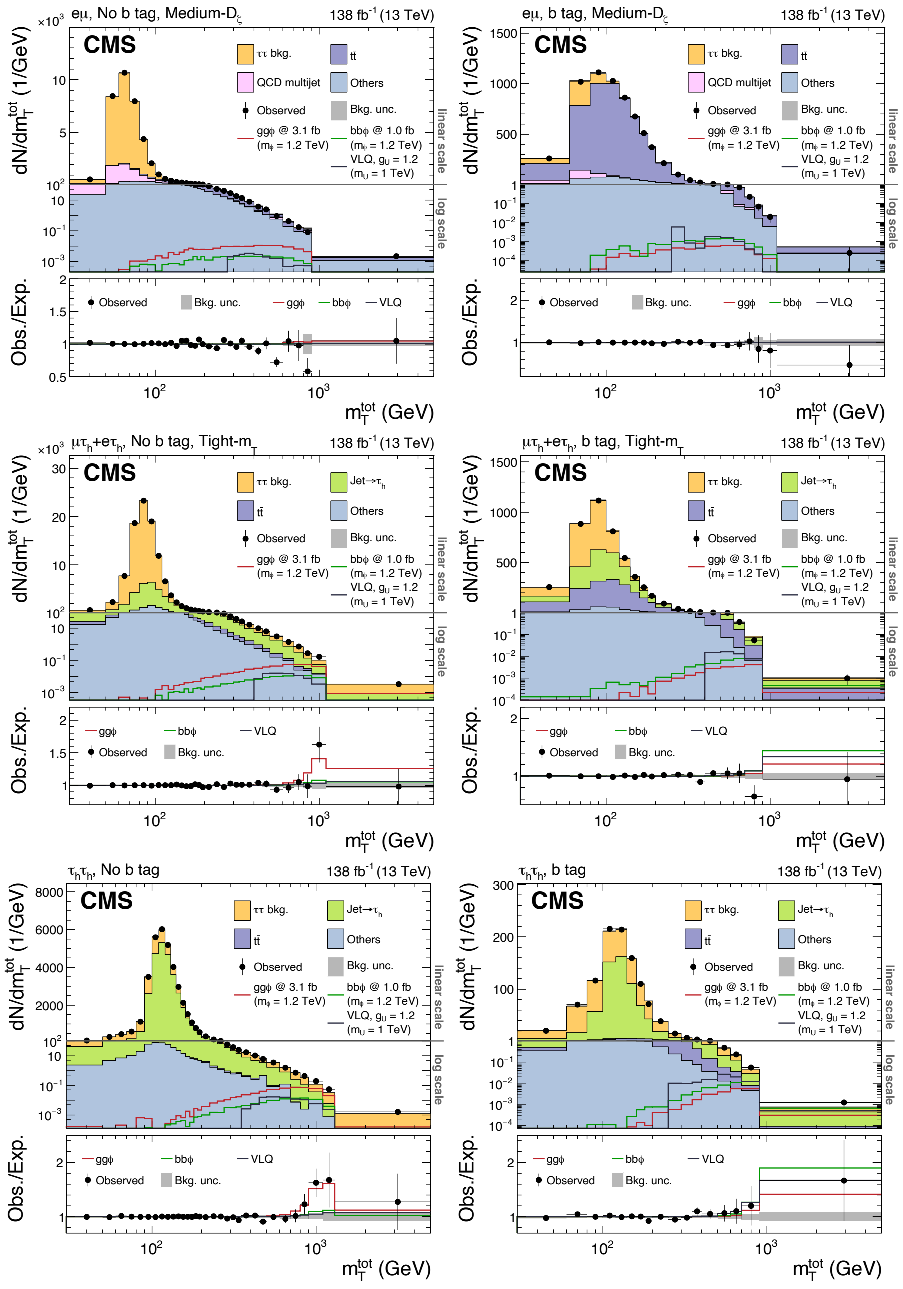
arXiv:2103.16558

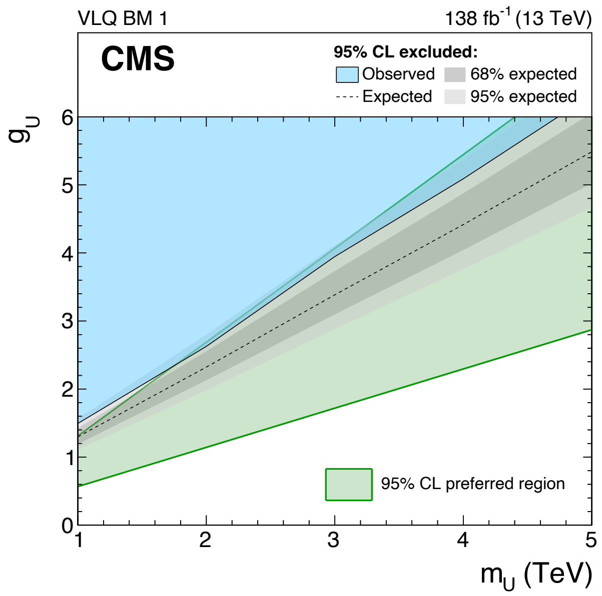
$$\lambda_{\ell q} = \lambda \cdot \begin{array}{c} \\ d/u' \\ s/c' \\ b/t' \end{array} \begin{array}{c} \begin{array}{ccc} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

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

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

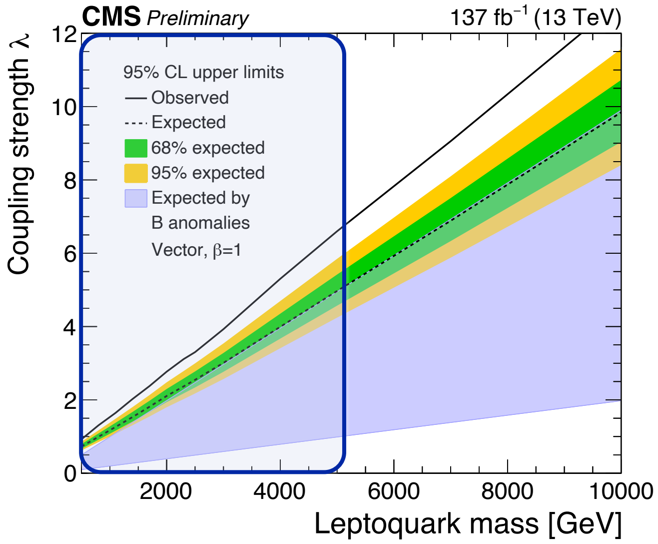
HIG-21-001
arXiv:2208.02717





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

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



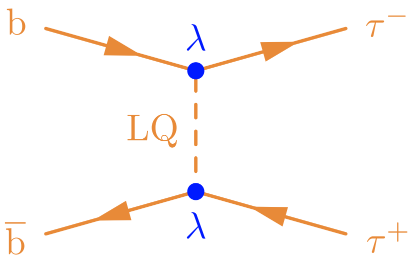
Nonresonant *t*-channel: bb → ττ

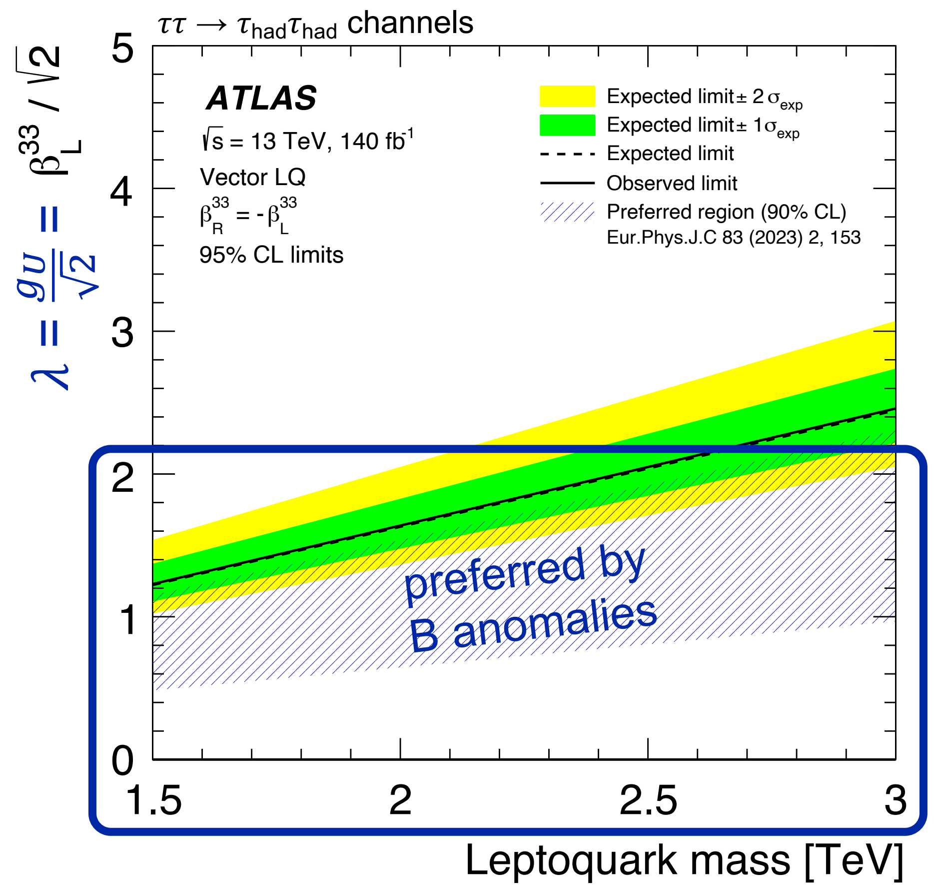
ATL 2503.19836

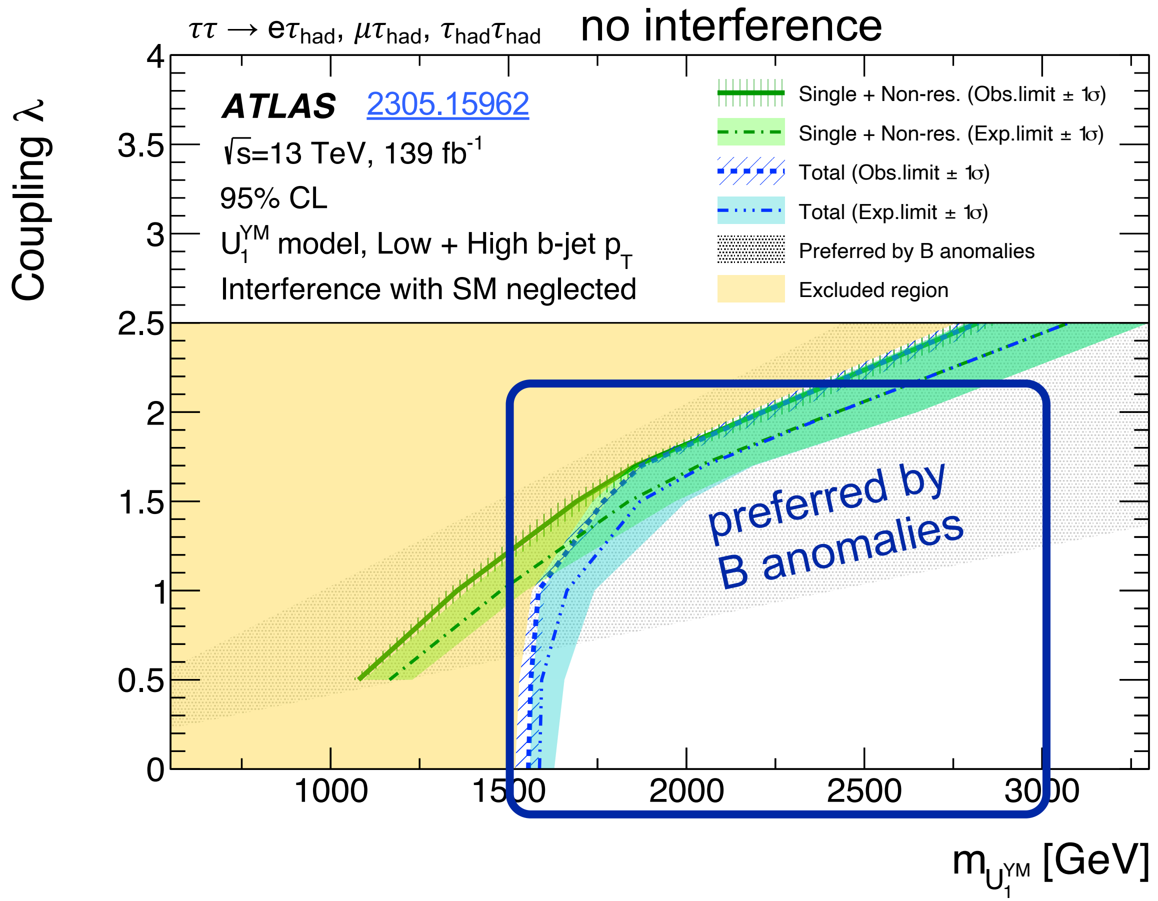
NEW !

see talk by C. Pollard

- measurement of Z (→ $\tau_{had}\tau_{had}$) + b jet cross section at high mass
- includes interference
- set limits on coupling λ vs. m_{LQ}:







Nonresonant *t*-channel: bb → $\tau\tau$

ATL 2503.19836 NEW !

see talk by C. Pollard

- measurement of Z (→ $\tau_{had}\tau_{had}$) + b jet cross section at high mass
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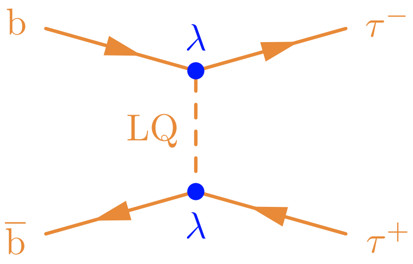

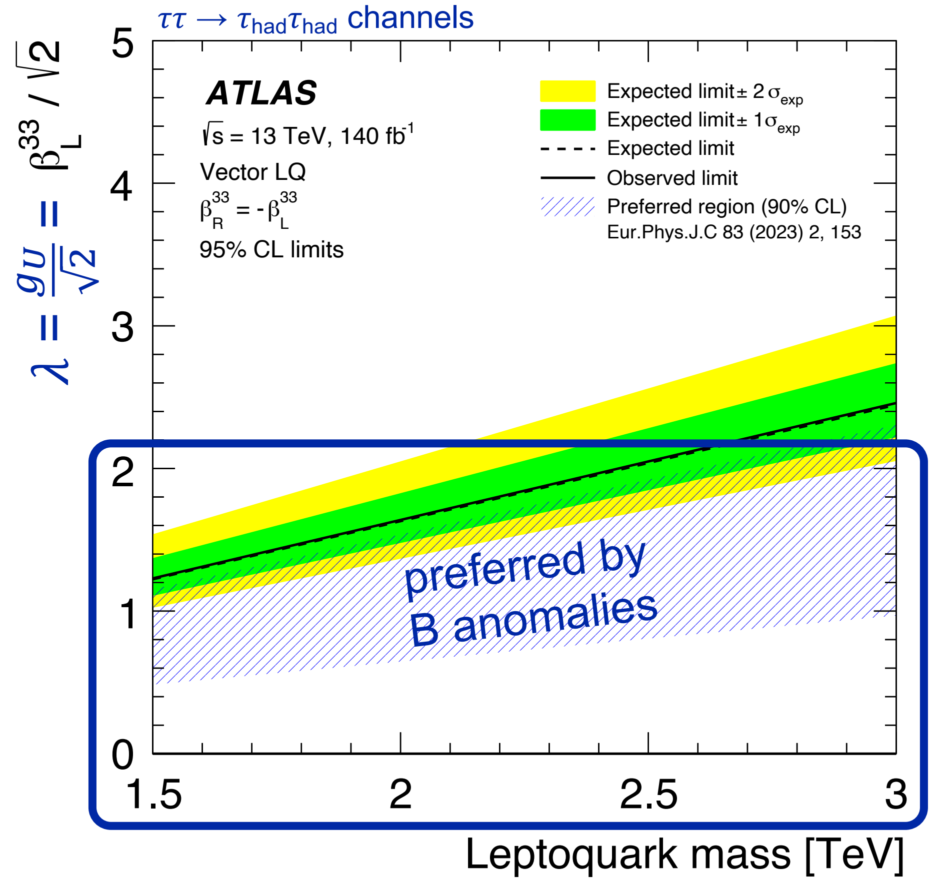

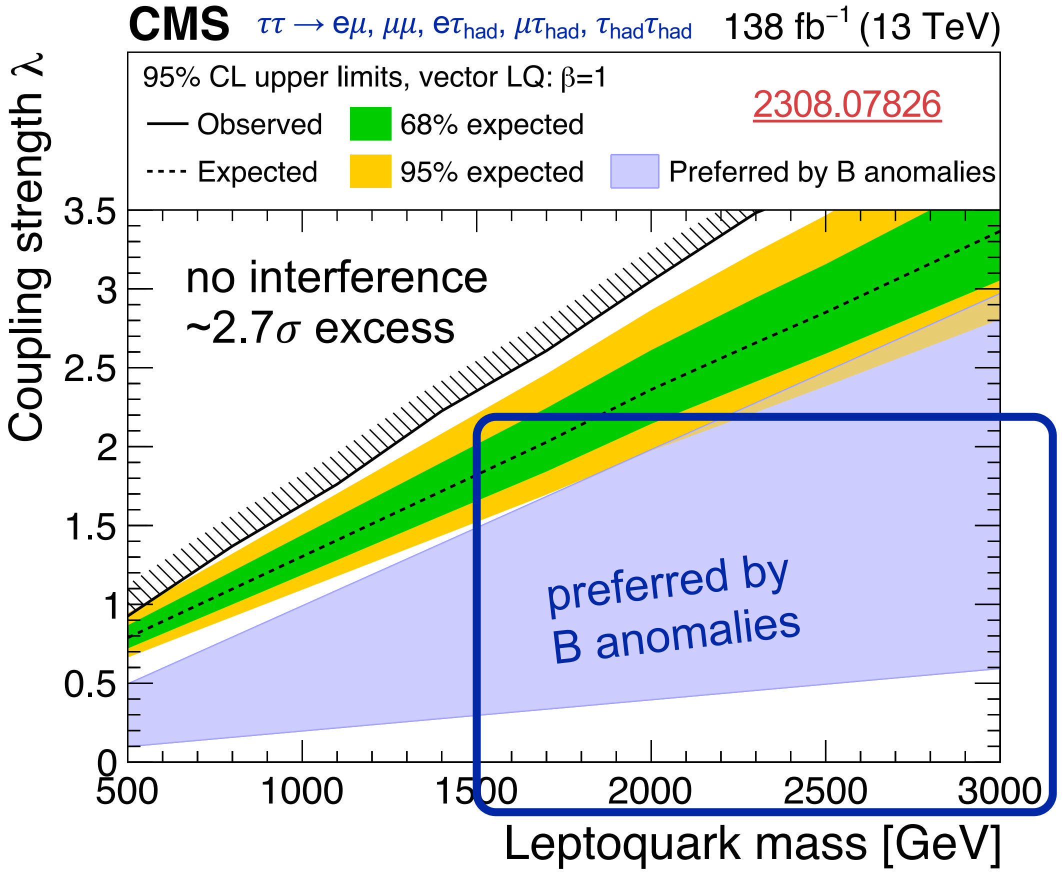

Nonresonant *t*-channel: bb → ττ

ATL 2503.19836 NEW !

see talk by C. Pollard

- measurement of Z (→ $\tau_{had}\tau_{had}$) + b jet cross section at high mass
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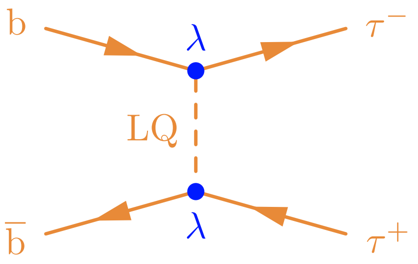
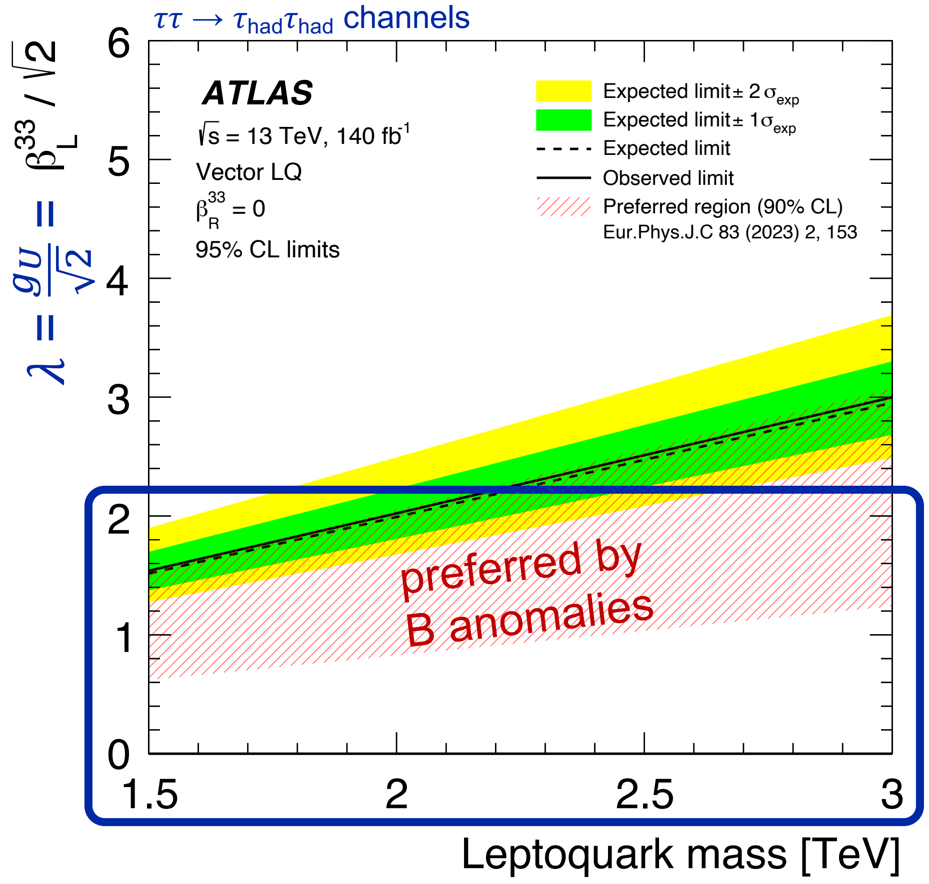
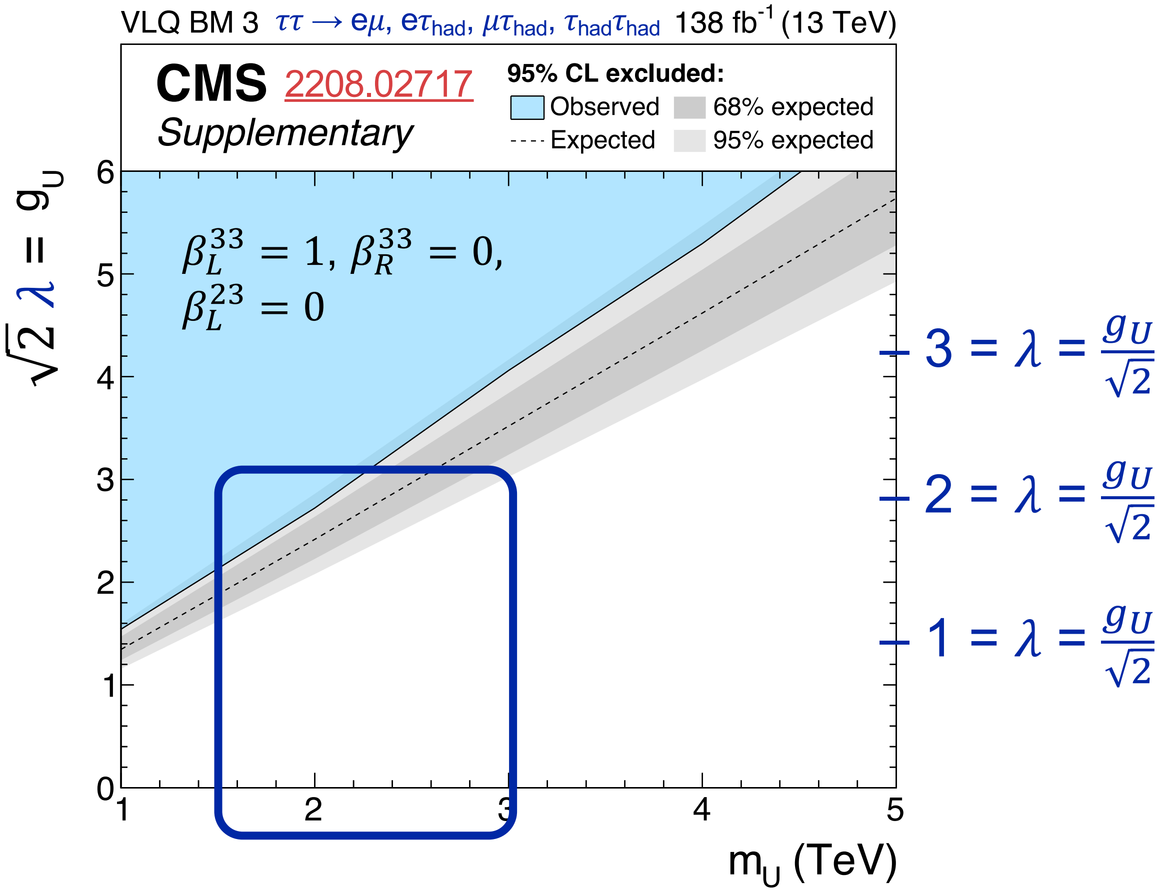




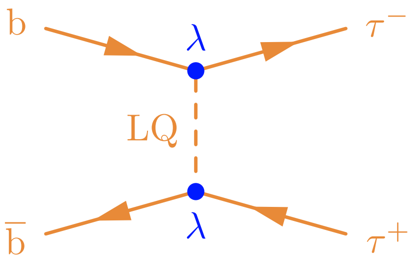


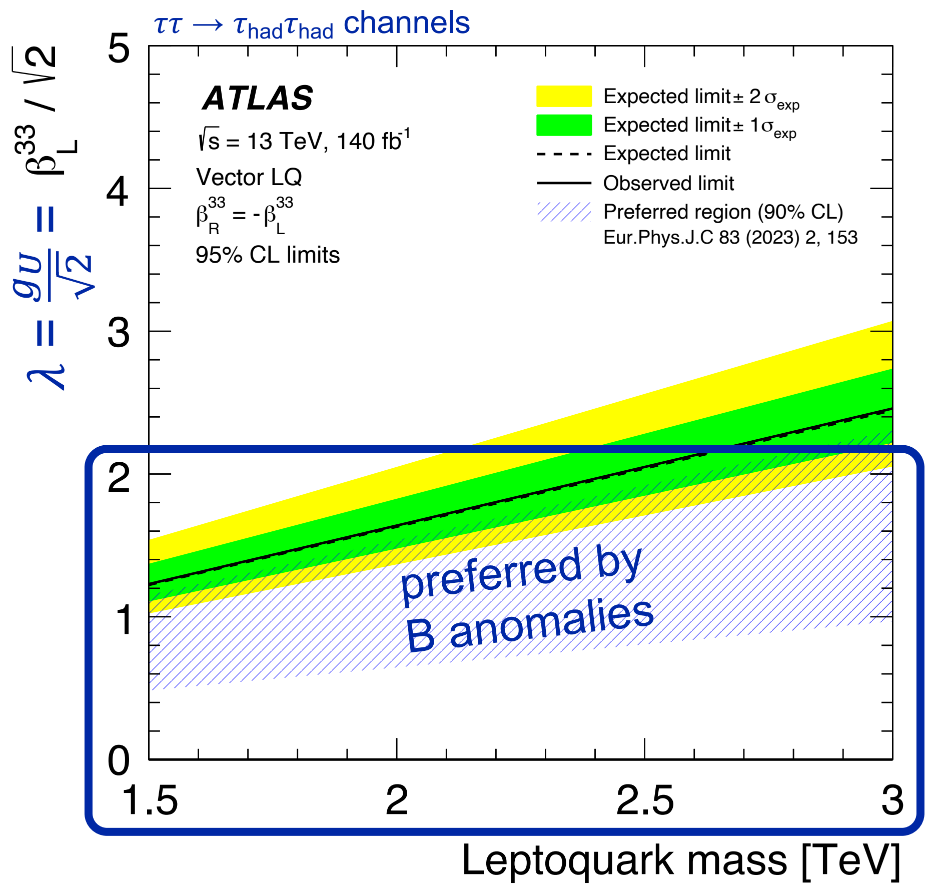
Nonresonant *t*-channel: bb → $\tau\tau$

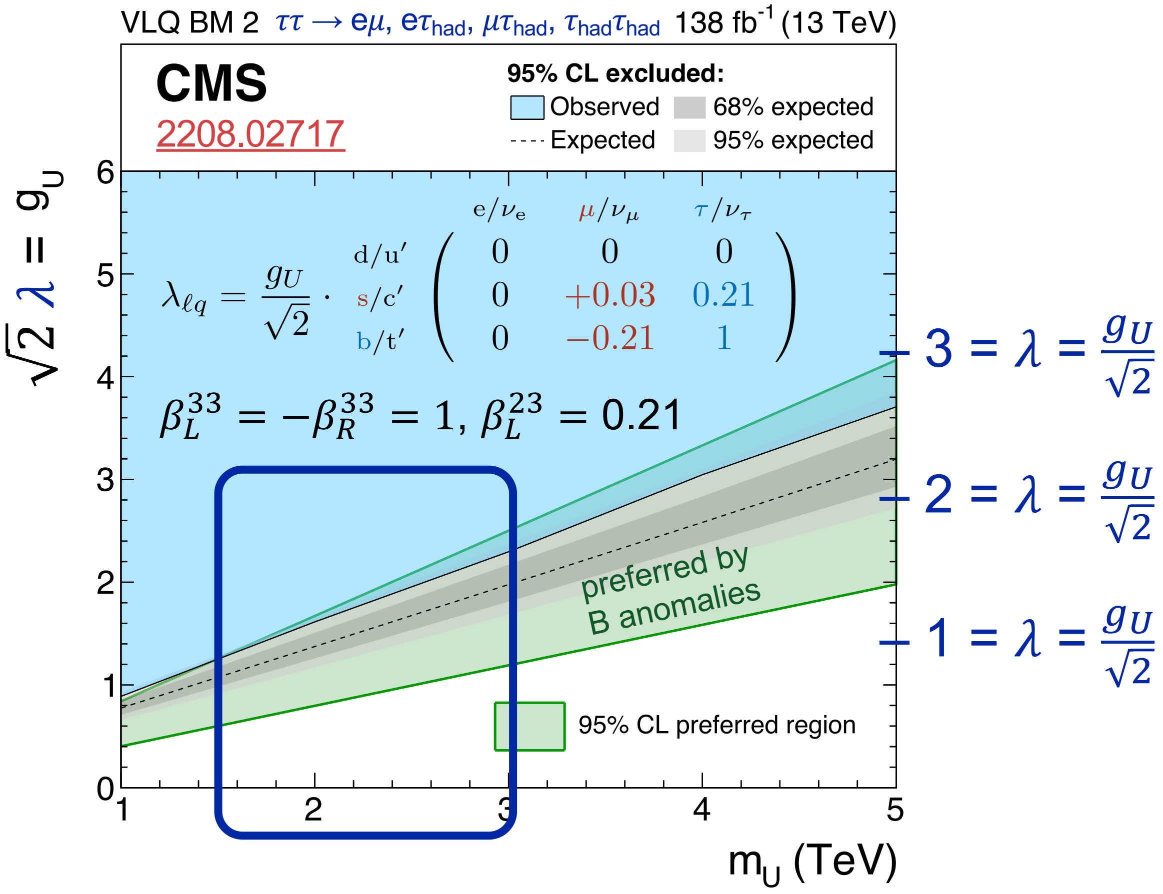
[ATL 2503.19836](#) **NEW !**

see [talk by C. Pollard](#)

- measurement of Z ($\rightarrow \tau_{had}\tau_{had}$) + b jet cross section at high mass
- includes interference
- set limits on coupling λ vs. m_{LQ}:

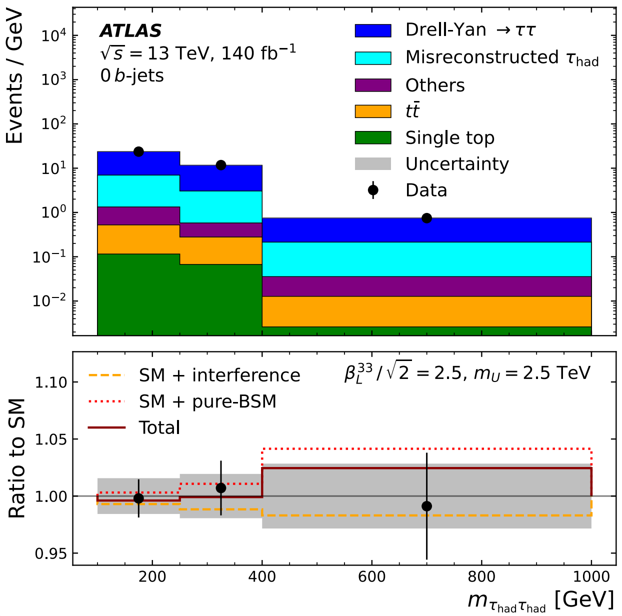


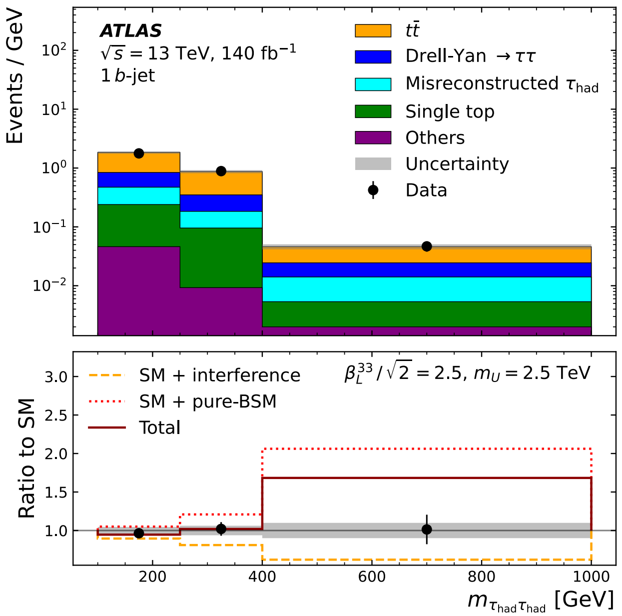


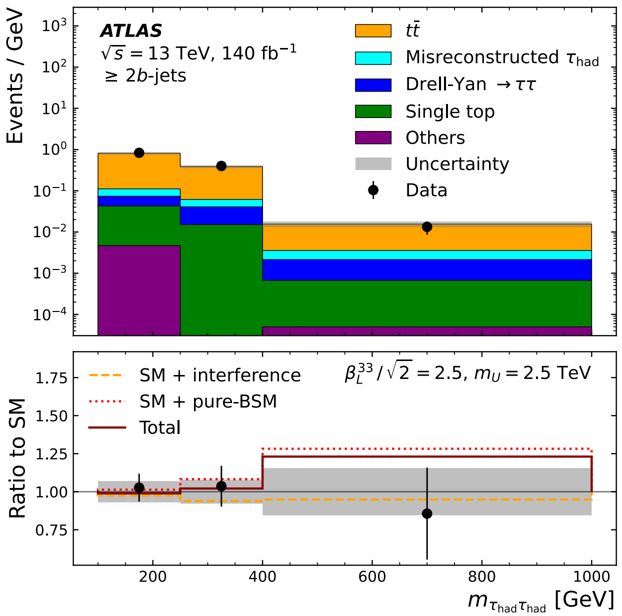


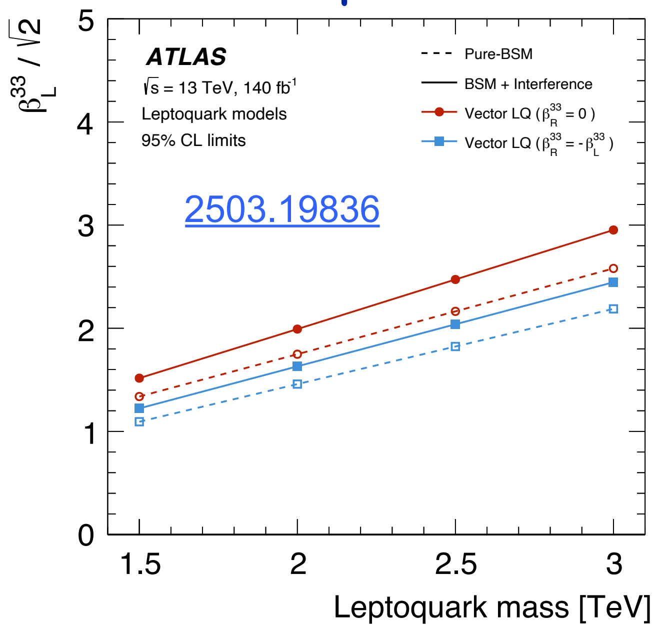
Nonresonant $\tau\tau$: interference with SM Drell–Yan

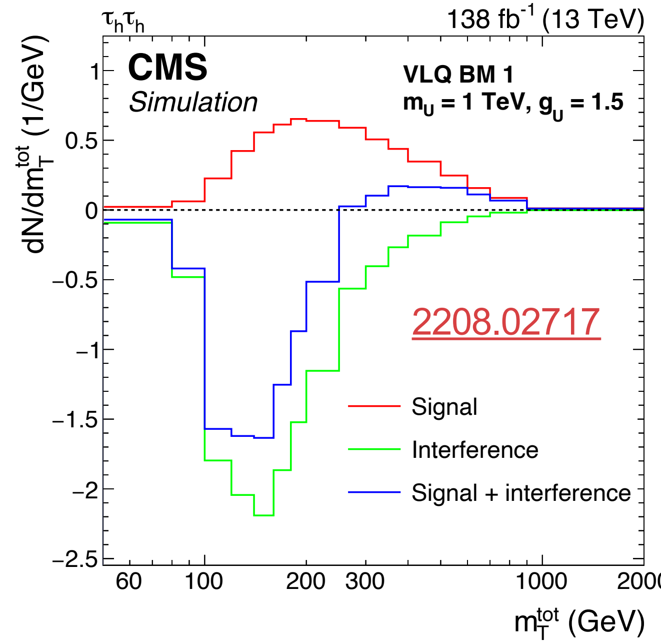
2503.19836





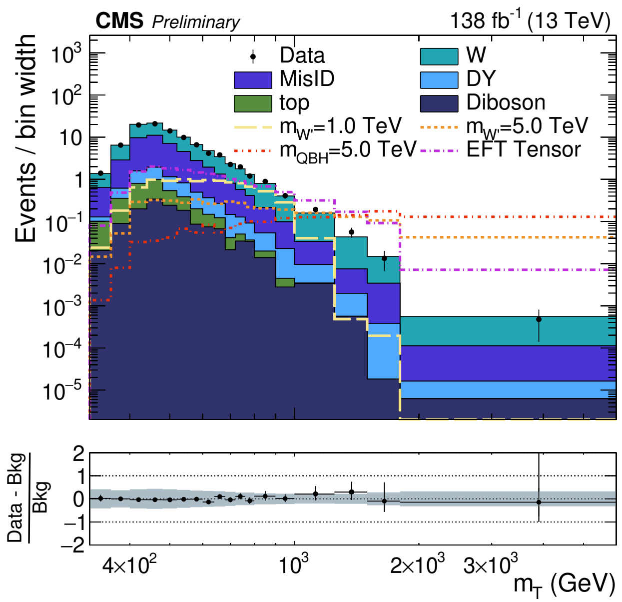


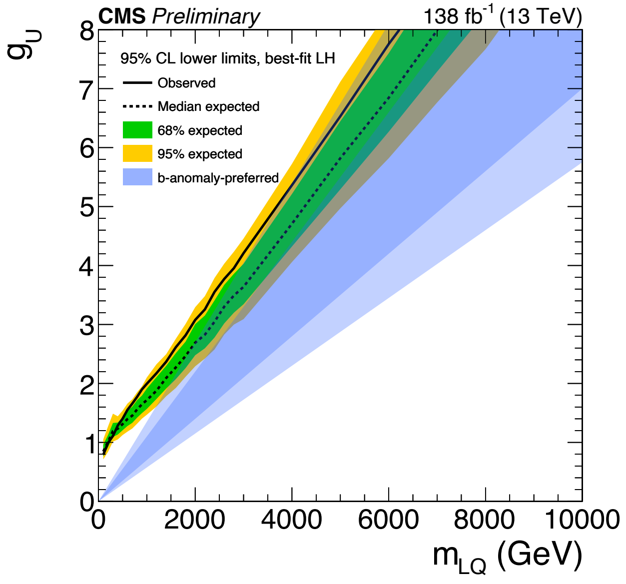


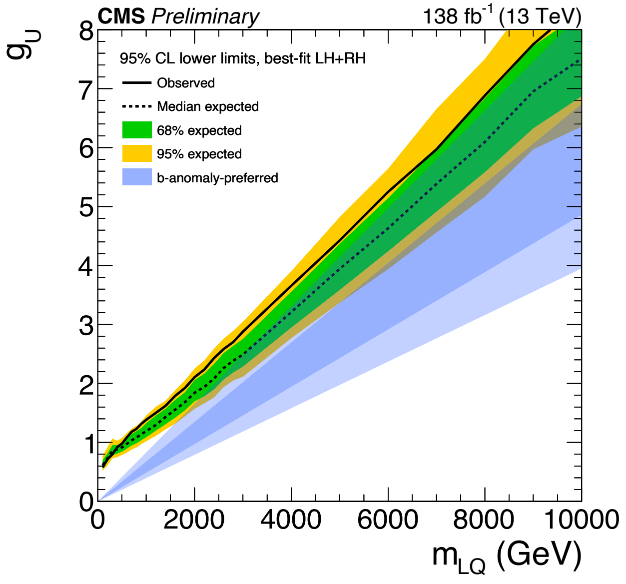


Nonres. LQ interpretation of EXO-21-009

- 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

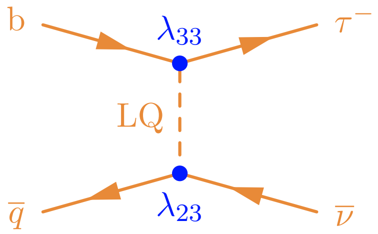






"best-fit" to B anomalies

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



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