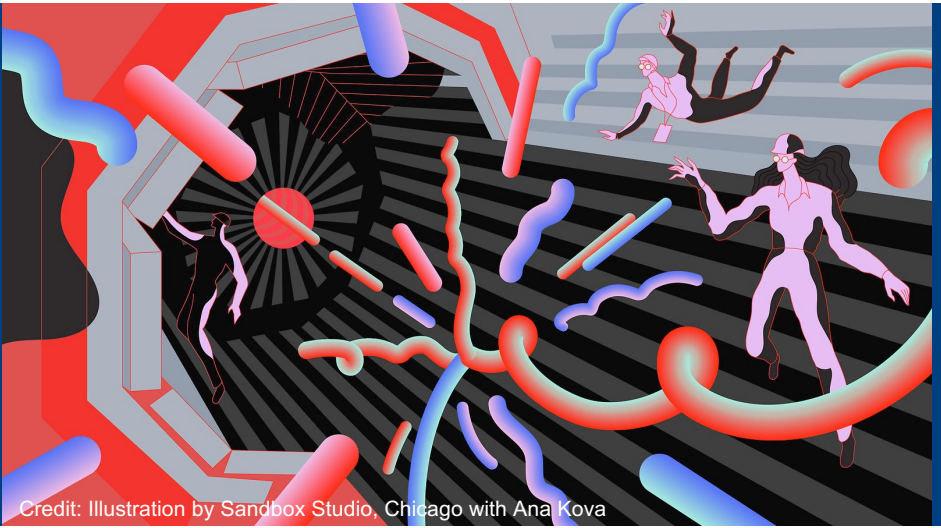
57th Rencontres de Moriond 2023: Electroweak Interactions & Unified Theories, 18-25 March 2023



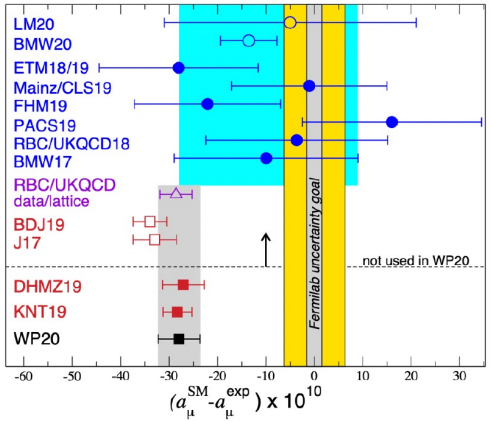
Leptoquarks and flavour anomaly searches

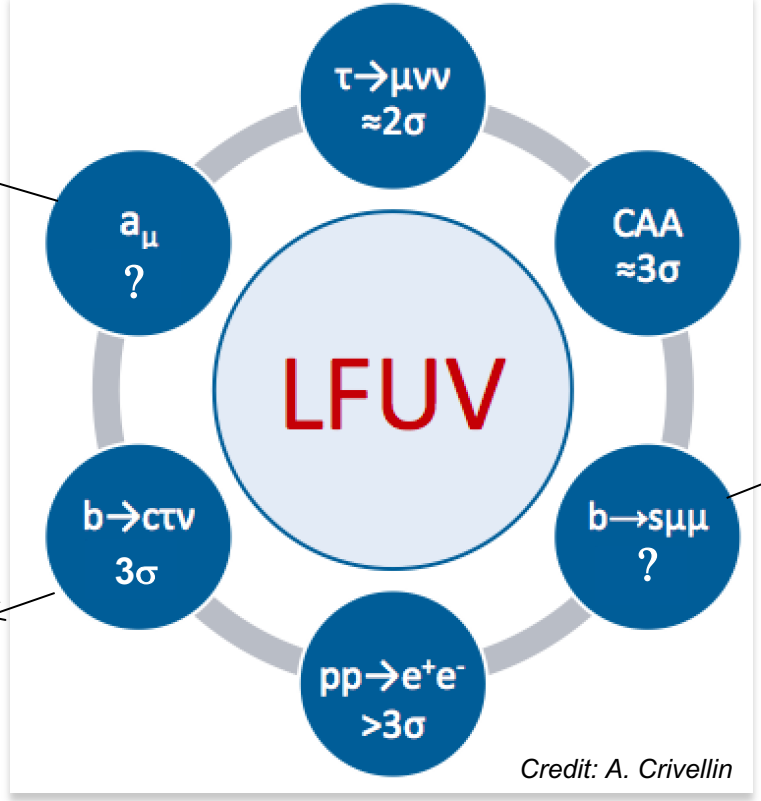
Aurelio Juste (ICREA/IFAE)

On behalf of the ATLAS and CMS Collaborations

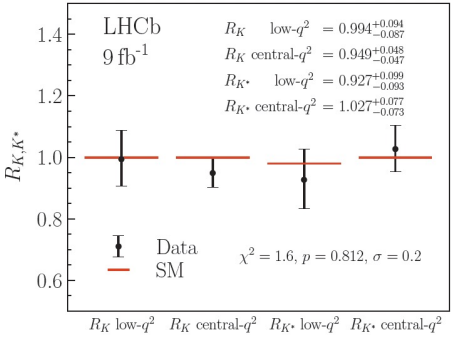
Flavour anomalies

arXiv:2106.06723



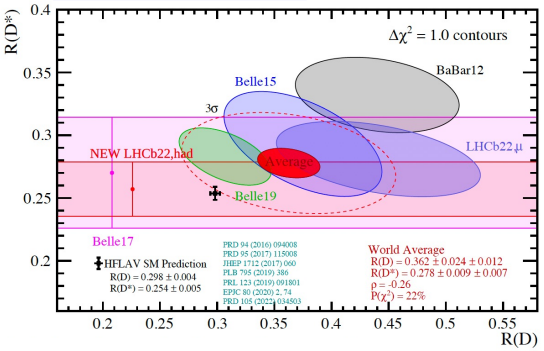


arXiv:2212.091

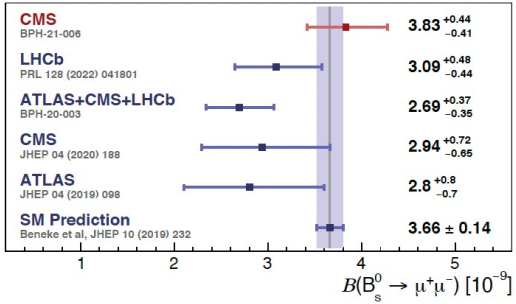


No longer evidence of μ/e universality violation

Updated at La Thuile 2023



D. Kovalskyi, ICHEP 2022



Flavour anomalies

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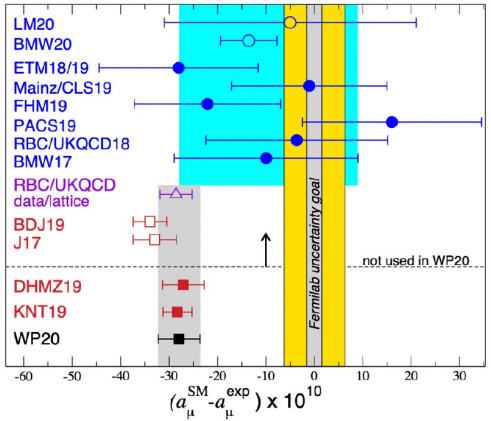
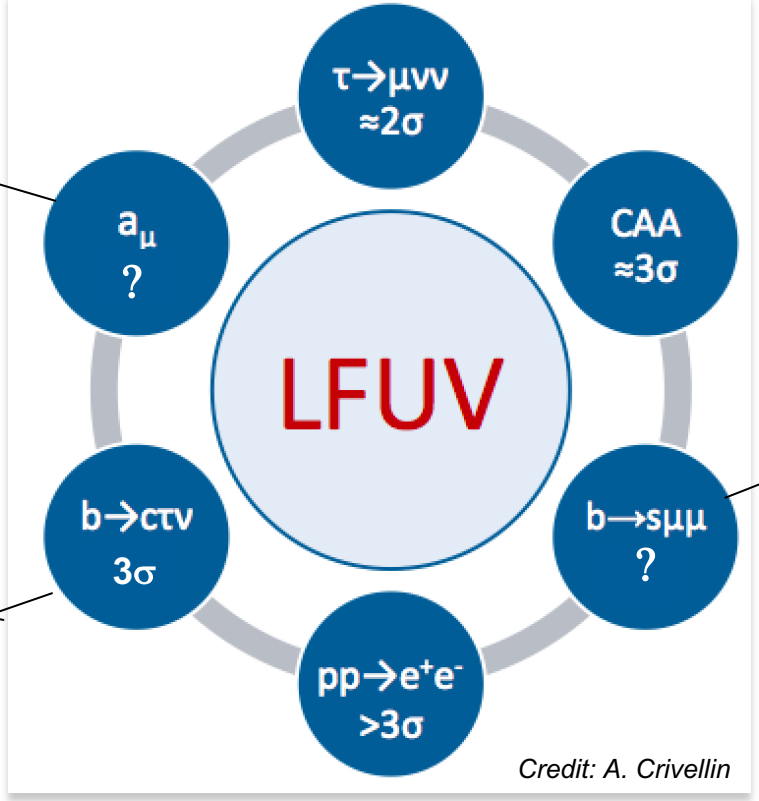
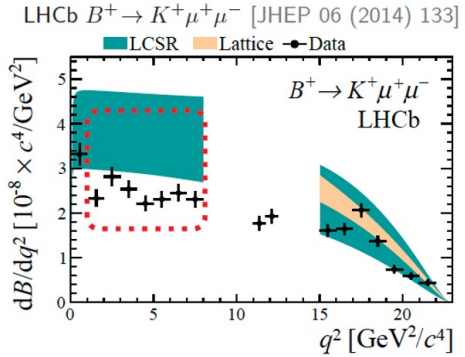
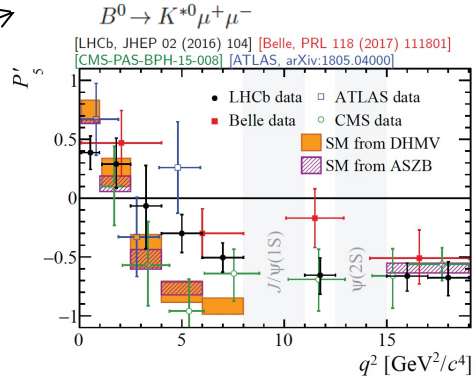




However, the other b→sμμ anomalies are still there!





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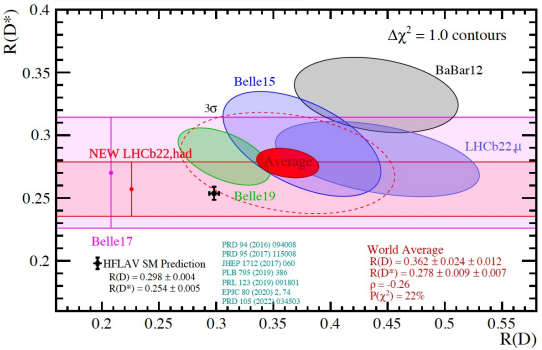
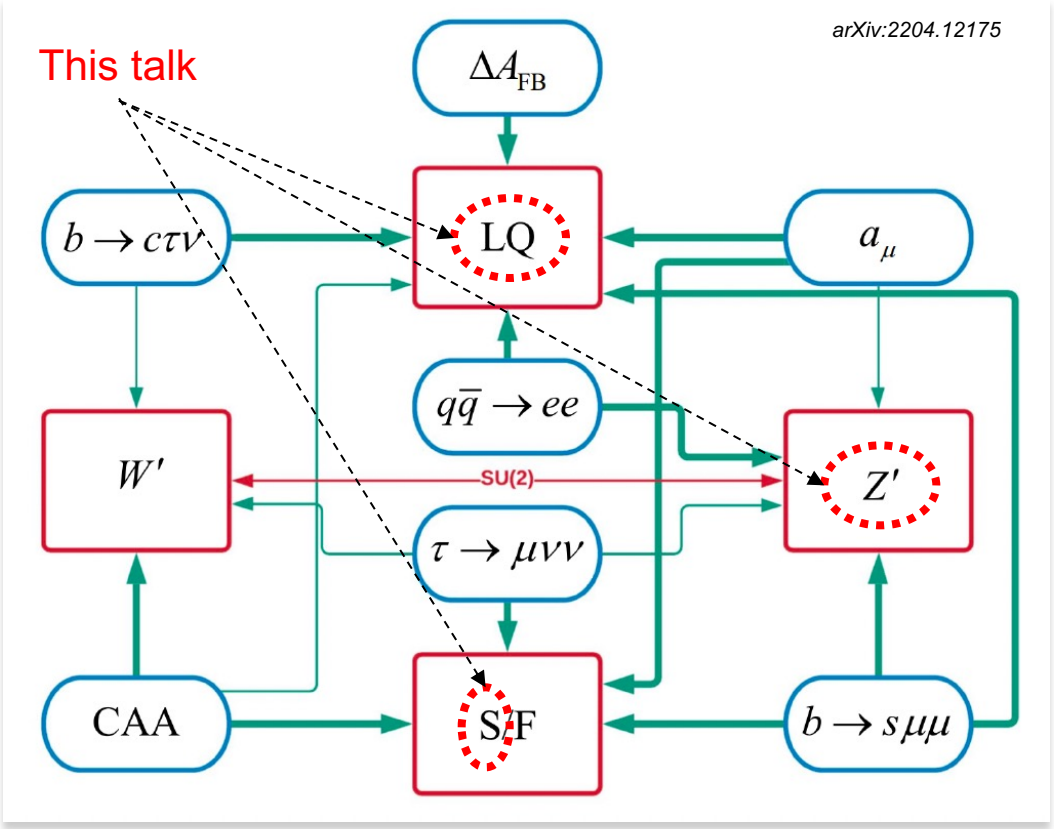


Possible new physics explanations

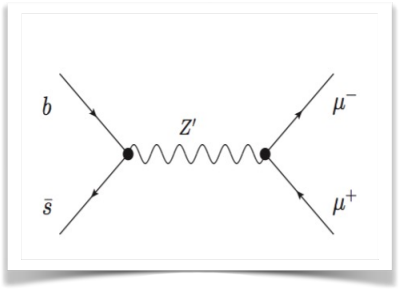
- Hundreds of phenomenological papers over the last years proposing explanations.
- Successful explanations need to satisfy many constraints.
- Today will discuss recent searches (since Moriond 2022) by ATLAS and CMS in the context of non-SUSY explanations of these anomalies.

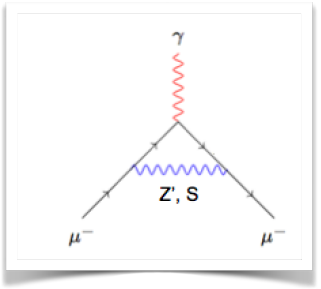


For recent results on searches for new heavy fermions, see **Haifa Rejeb's talk today**

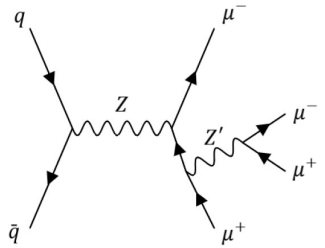
Leptophilic vectors/scalars: Overview

- Flavoured light vectors and (pseudo-)scalars appear in many SM extensions that explain b→sμμ (for masses >10 GeV) and a_μ.

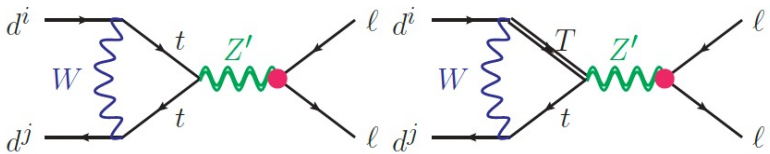


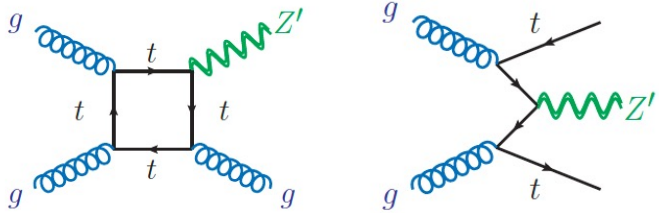


- E.g. a Z' associated with the spontaneously broken $U(1)_{L\mu-L\tau}$ symmetry only interacts with the 2nd and 3rd generation of leptons at tree level
  ➔ Challenging at a hadron collider.
  - For $M_{Z'/S}$>5 GeV can perform searches at the LHC.
  - For lighter Z'/S can use fixed target experiments (very light scalars can be long-lived!).



- Flavor-violating couplings to quarks can also be generated without new sources of flavor violation via loops.
  ➔ Searches for Z' in associated production particularly interesting!





arXiv:1704.06005

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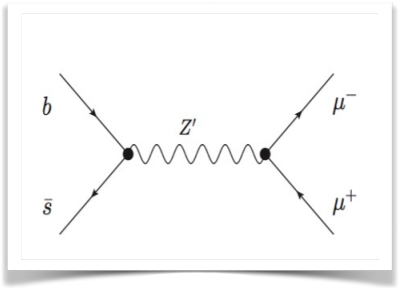
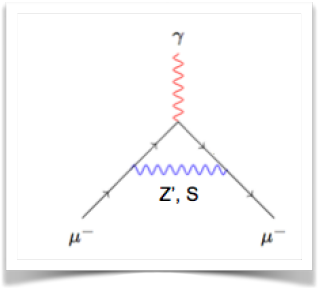
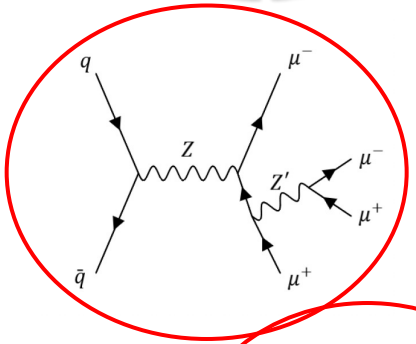
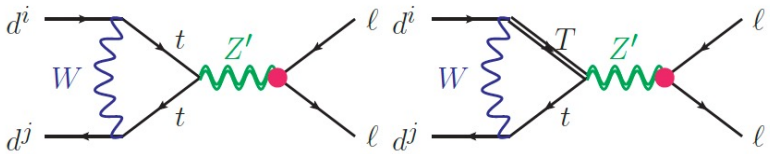
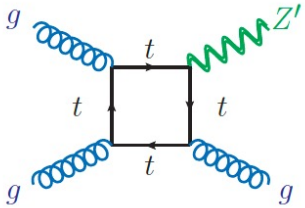
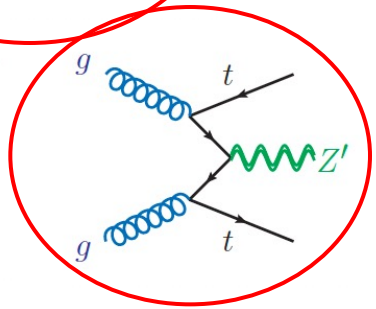








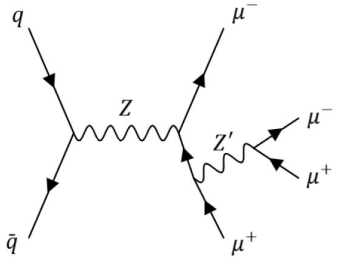


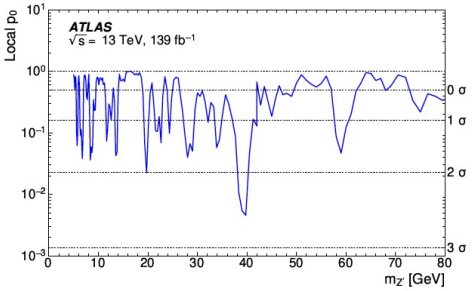


arXiv:1704.06005

Z'μμ→4μ

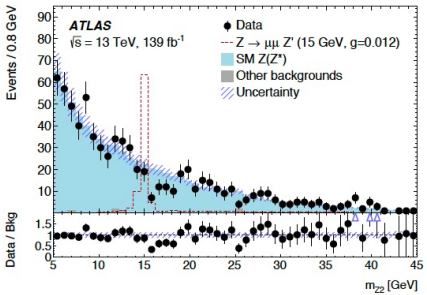
- Search for Z' in $L_\mu - L_\tau$ model.
- Event preselection:
  - ≥4μ w/ p_T>20/15/8/3 GeV.
  - min($m_{\mu\mu}$)>4 GeV, min$\Delta R_{(\mu\mu)}$>0.2
  - 80<$m_{4\mu}$<180 GeV (excl 110-130 GeV)
- Main background: Z(Z*/γ*)→4μ
- Dimuon mass pairing:
  - Z1: $\mu^+\mu^-$ pair with smallest $|m_{Z1}-m_Z|$
  - Z2: remaining $\mu^+\mu^-$ pair with largest m_{Z2}
- Further signal-to-background discrimination via cut on a DNN trained using muon and Z1, Z2 kinematics.
- Final discriminating variable: m_{Z1} or m_{Z2} after DNN cut.

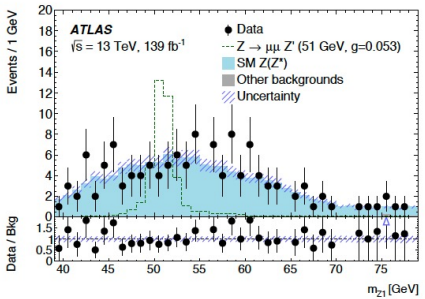


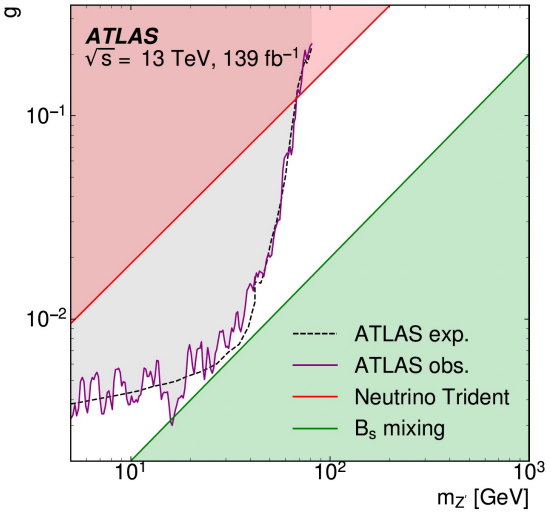


No significant excess observed

HDBS-2018-57



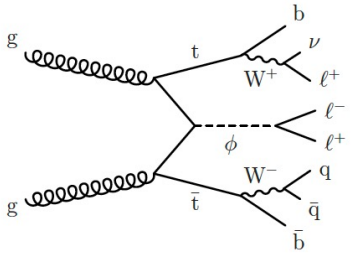


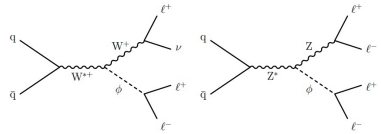


Equivalent CMS analysis:
CMS-EXO-18-008

ttϕ(→ee,μμ,ττ)

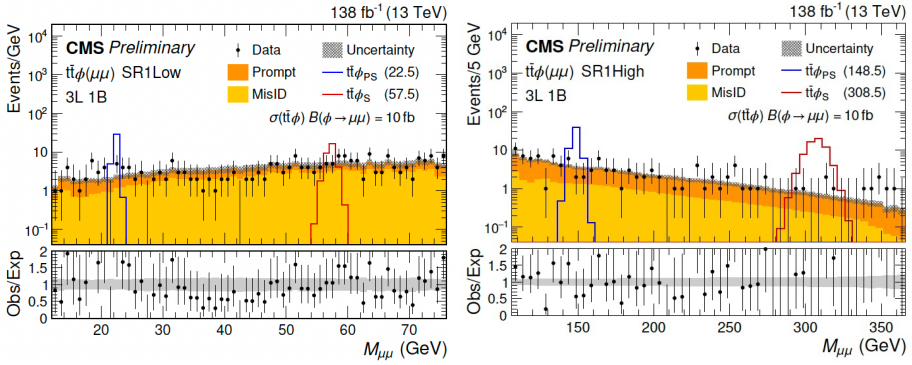
- Search for ttϕ(→ee,μμ,ττ), with ϕ=scalar or pseudoscalar.
- Broad multilepton search considering 3l and 4l multiplicities (including e, μ and τ_{had}).
- Complex event selection and categorization.
- Main background: tZ*/γ*, non-prompt/fake leptons
- A total of 19 signal regions considering different lepton flavor combinations and targeting low/high mass hypotheses.
- Final discriminating variable: dilepton mass.



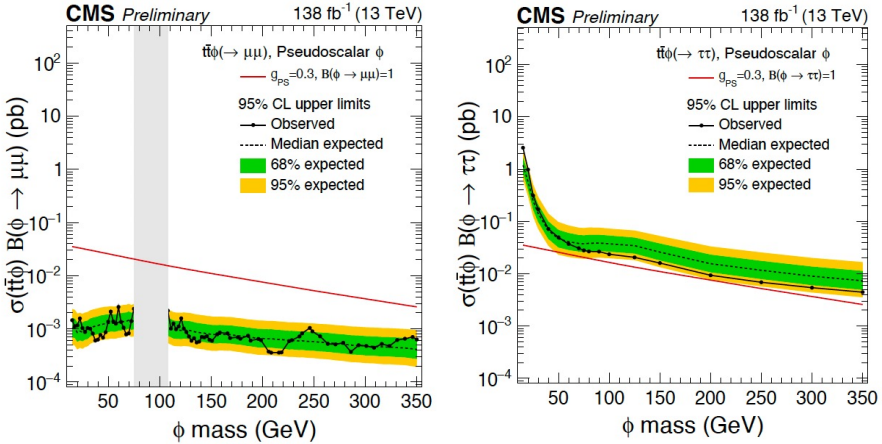


Also interesting results on searches for Vϕ(→ee,μμ,ττ)! Not discussed here.

[CMS-PAS-EXO-21-018]



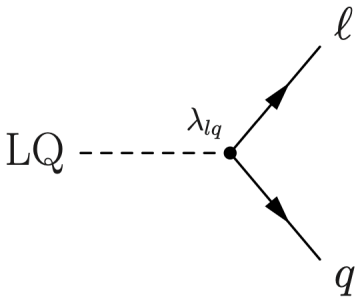
No significant excess observed



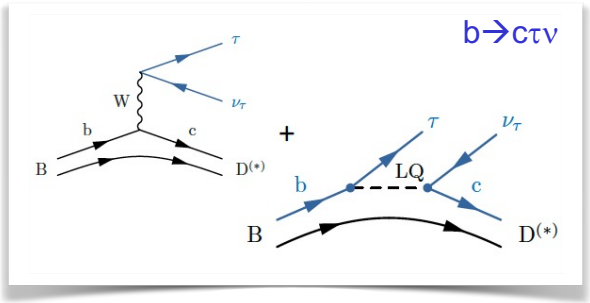
Experimental limits should also closely apply to ttZ'

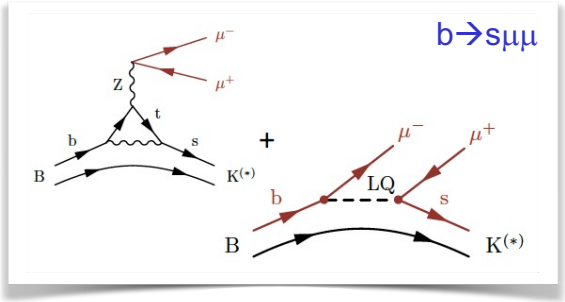
Leptoquarks: Overview

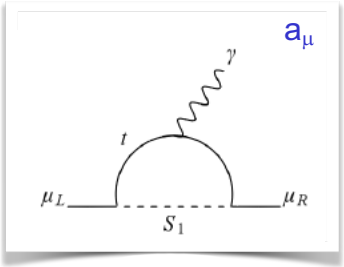
- Leptoquarks (LQ) appear in BSM extensions trying to address the SM flavor (and other) puzzles, e.g. GUT SU(5), Pati-Salam SU(4), RPV SUSY, composite Higgs models.
  - Scalars (*S*, *R*) or vectors (*U*)
  - Have fractional charge and carry color, B and L quantum numbers
  - Mediate interactions between quarks and leptons



- Can provide an explanation for different flavor anomalies:







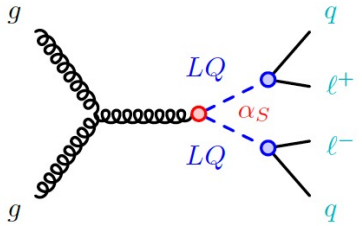
LQ type	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$(g-2)_\ell$ at 1L
S_1	✗*	✓	✓
$\tilde{S}_1$	(✗)	(✗)	✗
$\vec{S}_3$	✓	✗	✗
R_2	✗*	✓	✓
$\tilde{R}_2$	✗	✗	✗
U_1	✓	✓	✗
$\tilde{U}_1$	✓	✗	(✗)
$\vec{U}_3$	✓	✗	(✗)

Most favoured?

arXiv:1808.00943
arXiv:2002.12544

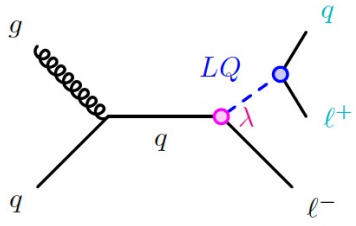
Leptoquarks: Production and decay

Pair production



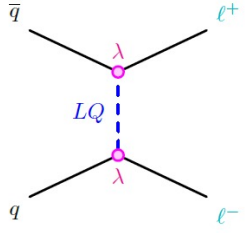
QCD production (universal mode)
σ only depends on m_{LQ}
Sensitivity to low m_{LQ}

Single production

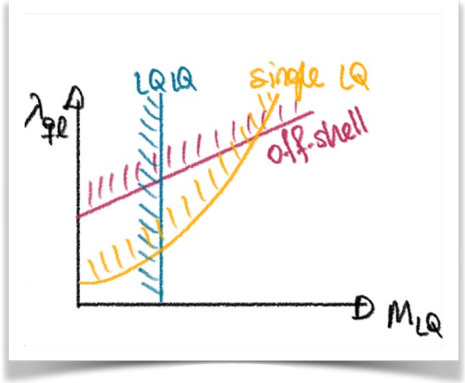


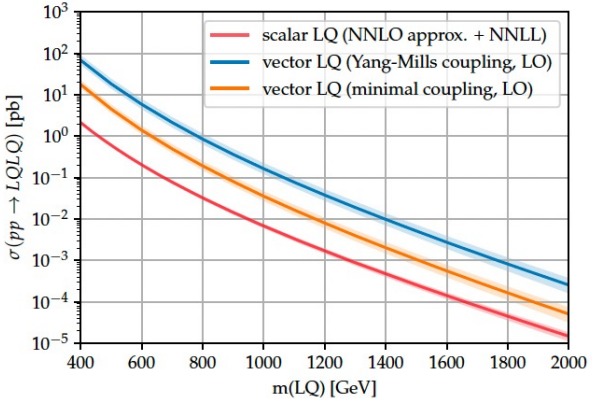
Depends on q PDF
$\sigma \sim \lambda^2$
Sensitivity to higher m_{LQ}
if λ sufficiently large

Off-shell production



(Depends on q PDF)^2
$\sigma \sim \lambda^4$
Sensitivity to very high m_{LQ}
if λ sufficiently large





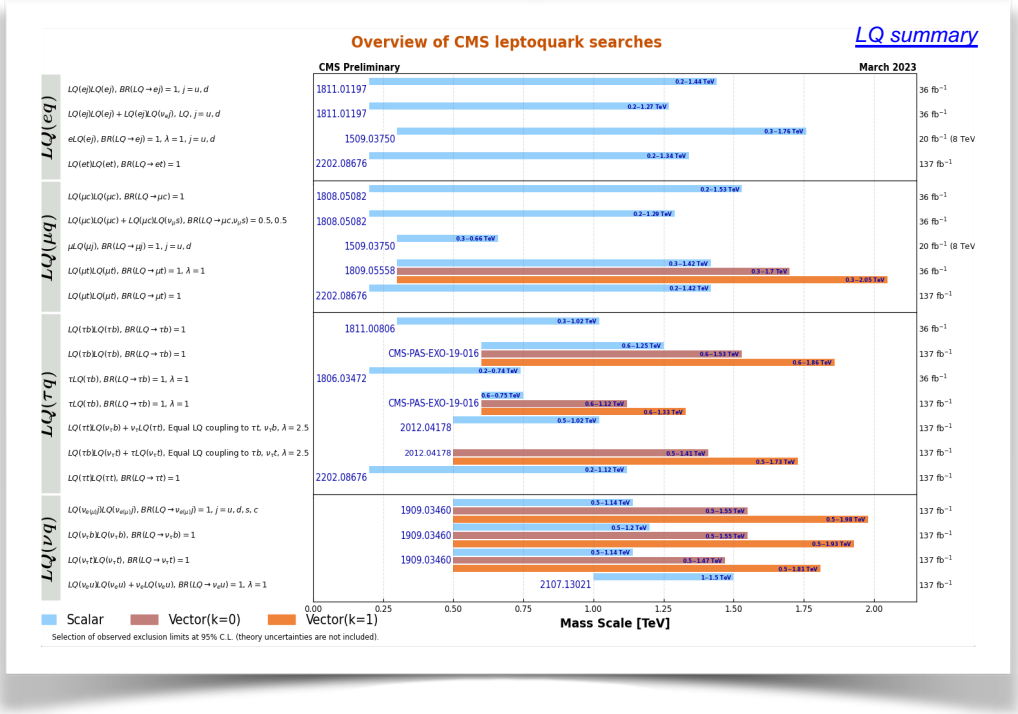
- Explanations of the flavor anomalies put the focus on particular couplings:

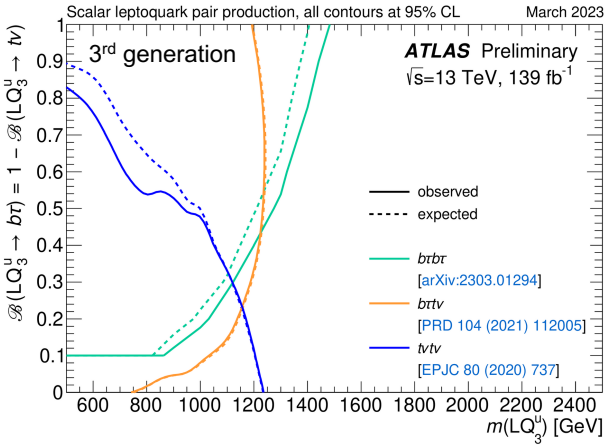
E.g. for the U_1 LQ: $\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \approx \begin{pmatrix} 0 & 0 & +0.04 \\ 0 & +0.02 & +0.2 \\ 0 & -0.2 & 1 \end{pmatrix}$ ← LQ≈LQ_3

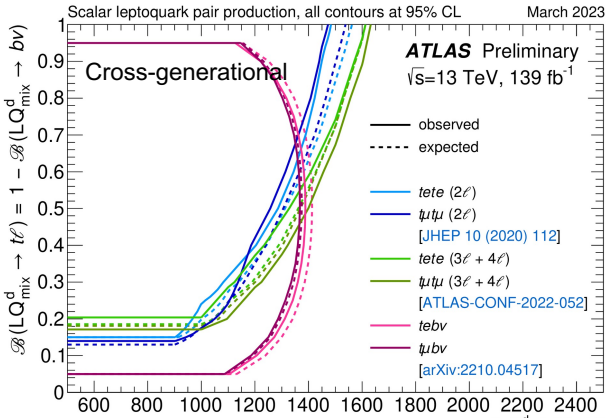
arXiv:2103.16558

- However, other coupling textures are possible and there may be other LQs that do not affect flavor anomalies ➔ Need a broad program!

Leptoquarks: State of the art





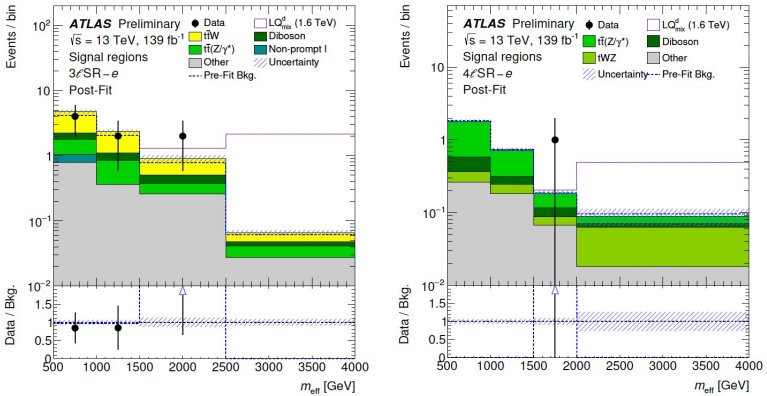


- Broad program of searches for pair-production (including combinations!).
- Growing program of single LQ searches.
- Increasing focus on non-resonant production to reach highest masses.

ATL-PHYS-PUB-2023-006

LQ-t-l (l=e,μ): Pair production

- Event preselection:
  - 3 or 4 light leptons (e or μ), ≥2 jets, ≥1 b-jets
- Main backgrounds: ttW, ttZ/γ*, diboson
- Event categorization:
  - Signal regions: (3l, 4l) separately for tete tμtμ, $\min(m_{ll})$>100 GeV.
  - Control regions for main bkgs and validation regions ($\min(m_{ll})$<100 GeV).
- Final discriminating variable:
  - Effective mass: $m_{eff} = \sum_{l,jets} p_T + p_T^{miss}$



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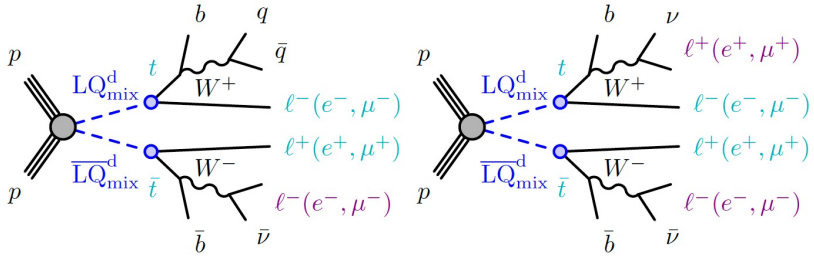
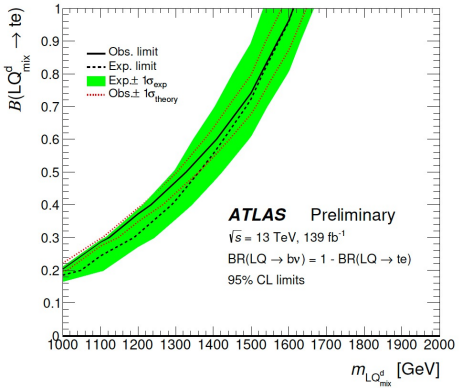
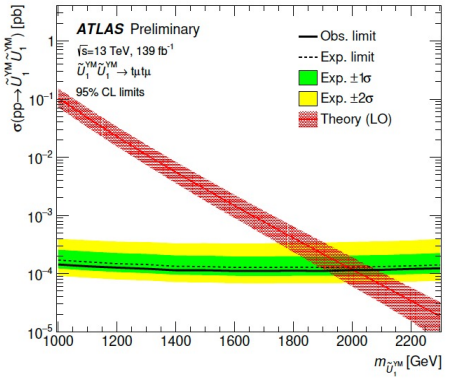


[ATLAS-CONF-2022-052]





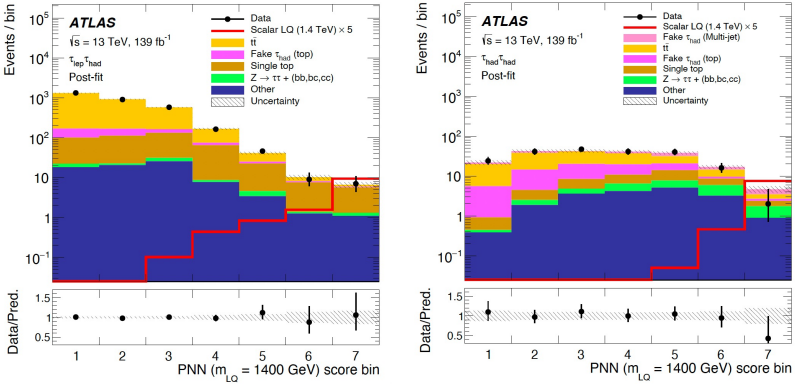
For both LQLQ→tete & LQLQ→tμtμ

Obs. limits @95% CL (for BR=1):
- Scalar LQ: m_{LQ}>1.6 TeV
- Vector LQ (min. coupl.): m_{LQ}>1.7 TeV
- Vector LQ (YM coupl.): m_{LQ}>2.0 TeV

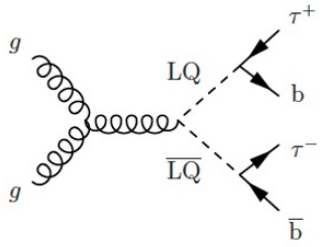
Equivalent CMS analysis (see also backup): [CMS-EXO-21-002]

LQ-b-τ: Pair production

- Event preselection:
  - $\tau_{had}\tau_{had}$, $\tau_l\tau_{had}$ (l=e,μ) channels
  - ≥2 jets, ≥1 b-jets
  - Single τ_{had} triggers and single-lepton triggers
- Additional requirements:
  - $S_T = \sum_{\tau,j1,j2} p_T + p_T^{miss}$ > 600 GeV
  - p_T^{miss}>100 GeV
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Final discriminating variable: Neural Network

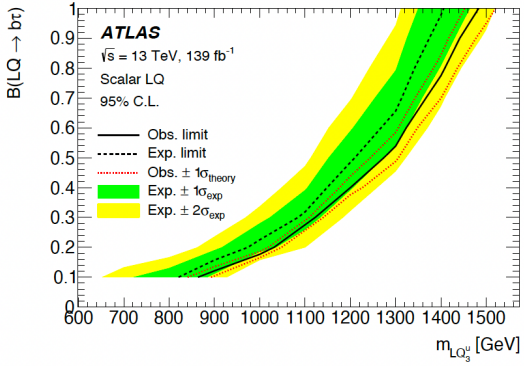


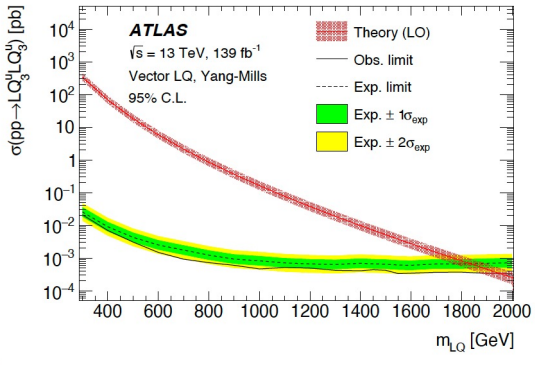
No significant excess observed



For a recent search on excited taus (and LQLQ→τqτq interpretation) see **Aaron Paul O'Neill's talk on Friday**

EXOT-2021-015





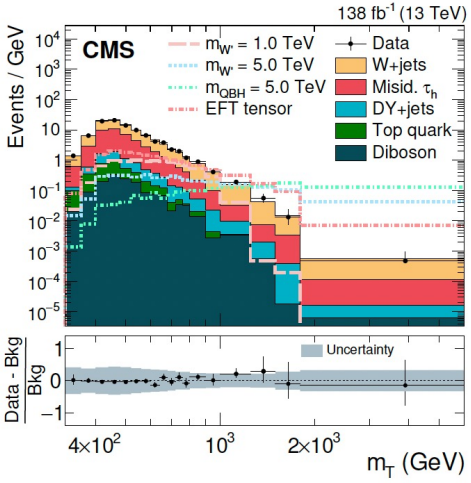
Obs. limits @95% CL (assuming BR=1):
Scalar LQ: m_{LQ}>1.49 TeV
Vector LQ (min. coupl.): m_{LQ}>1.69 TeV
Vector LQ (YM coupl.): m_{LQ}>1.96 TeV

LQ-b-τ and LQ-c-ν: Non-resonant production

- Event preselection:
  - 1 τ_{had} candidate, p_T>130/190 GeV
  - p_T^{miss}>200 GeV
  - Single τ_{had} trigger and p_T^{miss} trigger
- Main backgrounds: W+jets, Fake τ_{had}
- Final discriminating variable:
  - Transverse mass: $m_T(\tau_{had}, p_T^{miss})$

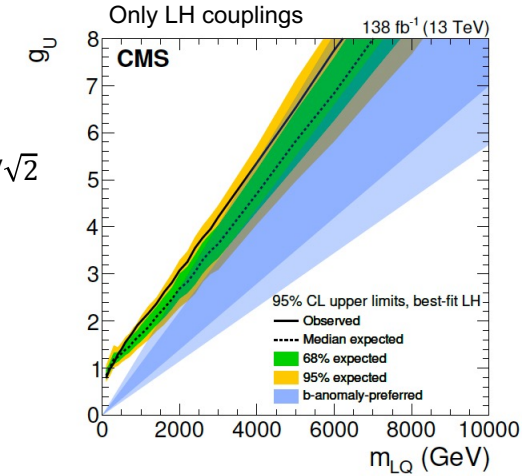
Neglecting interference w/ SM bkg

CMS-EXO-21-009

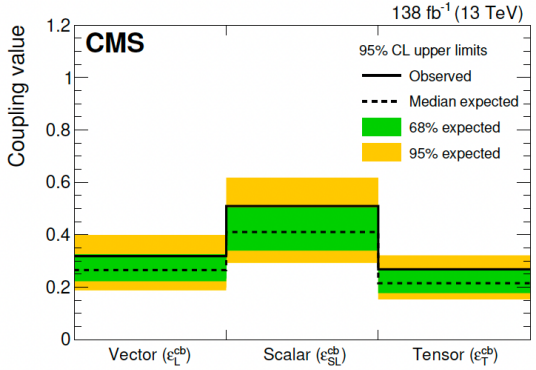


No significant excess observed

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



Starting to probe B-anomaly-preferred region

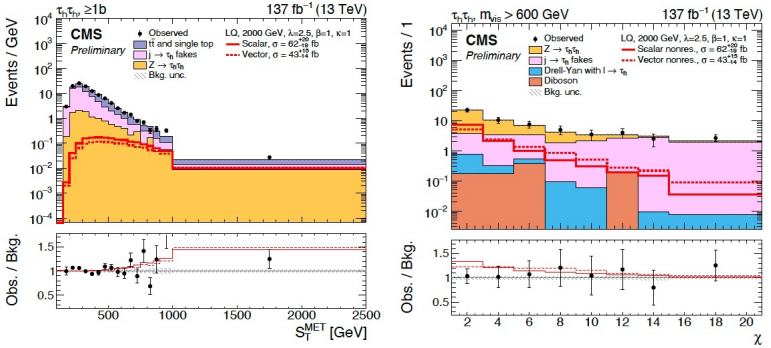


First limits on bcτν CIs

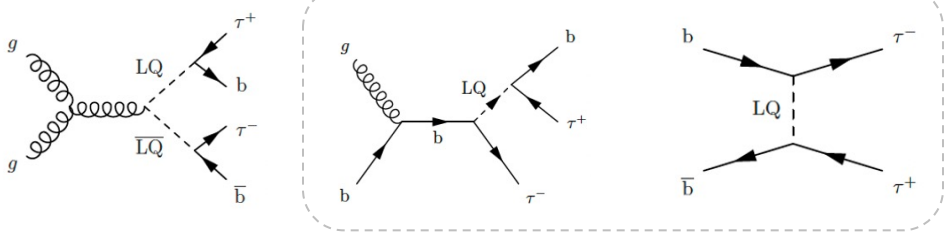
$$\mathcal{L}_{\text{eff}} \supset -\frac{2V_{ib}}{v^2}\Big[\left(1+\epsilon_L^{ib}\right)\bar{\tau}\gamma_\mu P_L\nu_\tau\cdot\bar{u}_i\gamma^\mu P_L b + \epsilon_R^{ib}\bar{\tau}\gamma_\mu P_L\nu_\tau\cdot\bar{u}_i\gamma^\mu P_R b + \epsilon_T^{ib}\,\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau\cdot\bar{u}_i\sigma^{\mu\nu}P_L b + \epsilon_{S_L}^{ib}\,\bar{\tau}P_L\nu_\tau\cdot\bar{u}_i P_L b + \epsilon_{S_R}^{ib}\,\bar{\tau}P_L\nu_\tau\cdot\bar{u}_i P_R b\Big] + \text{h.c.}$$

LQ-b-τ: All production modes

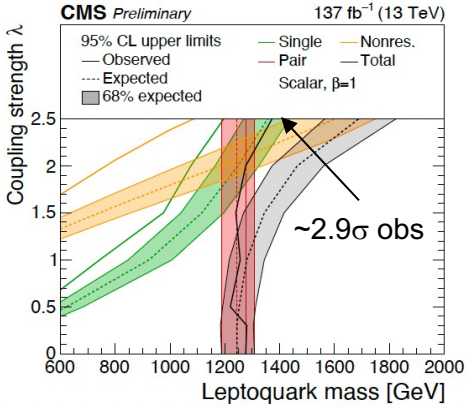
- Event preselection:
  - $\tau_{had}\tau_{had}$, $e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\mu\mu$ channels
  - Di-τ_{had} triggers and single-lepton triggers
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Event categorization:
  - Resonant: ≥1 jets (p_T>50 GeV), split in 2 categories: 0 and ≥1 b-jets (p_T>50 GeV)
  - Non-resonant: =0 jets (p_T>50 GeV), low boost & $\Delta\eta$, split in 3 m_{vis} categories
- Final discriminating variable:
  - Resonant: $S_T^{MET} = \sum_{\tau,j1} p_T + p_T^{miss}$
  - Non-resonant: $\chi = \exp(|y_{\tau 1} - y_{\tau 2}|)$

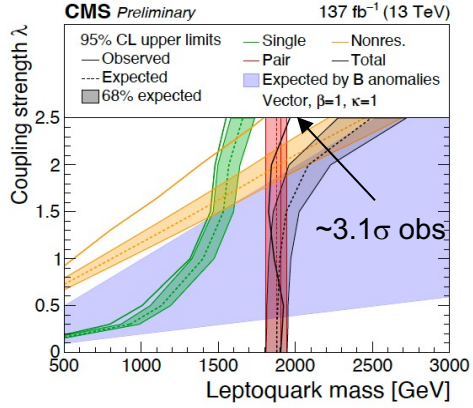


Neglecting interference w/ SM bkg



CMS-PAS-EXO-19-016



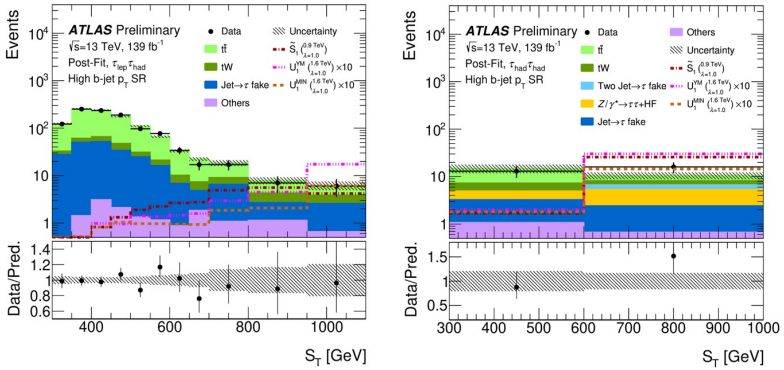


Caveat: the U_1 LQ has BR=0.5

Obs. limits @95% CL:
Scalar LQ (BR=1): m_{LQ}>1.37 TeV for λ=2.5
Vector LQ (YM coupl., BR=1): m_{LQ}>1.96 TeV for λ=2.5

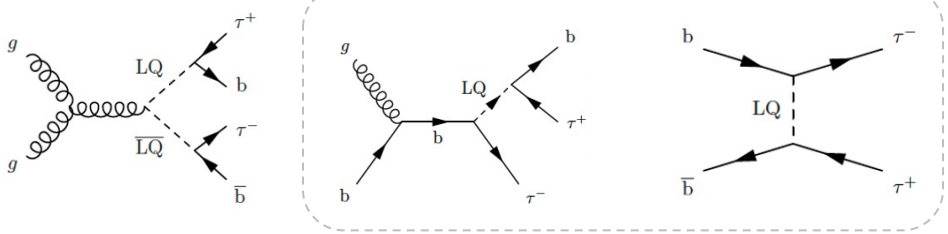
LQ-b-τ: All production modes

- Event preselection:
  - $\tau_{had}\tau_{had}$, $\tau_l\tau_{had}$ (l=e,μ) channels
  - ≥1 jets, ≥1 b-jets (p_T>25 GeV)
  - Single τ_{had} triggers and single-lepton triggers
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Event categorization:
  - High b-jet p_T: ≥1 b-jets (p_T>200 GeV)
  - Low b-jet p_T: ≥1 b-jets (25<p_T<200 GeV)
- Final discriminating variable: $S_T = \sum_{\tau,b1} p_T + p_T^{miss}$

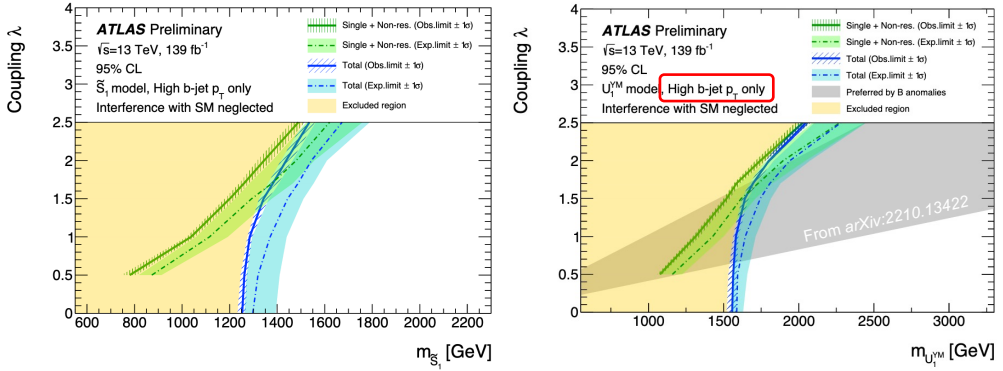


No significant excess observed

Neglecting interference w/ SM bkg



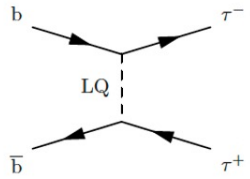
EXOT-2022-39



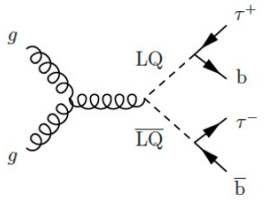
Obs. limits @95% CL:
Scalar LQ (BR=1): m_{LQ}>1.53 TeV for λ=2.5
Vector LQ (YM coupl., BR=0.5): m_{LQ}>2.09 TeV for λ=2.5

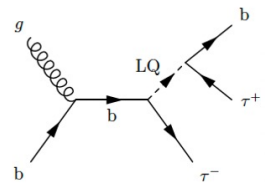
LQ-b-τ: Comparison of recent results

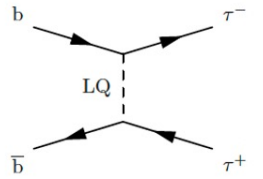
Including interference w/ SM bkg



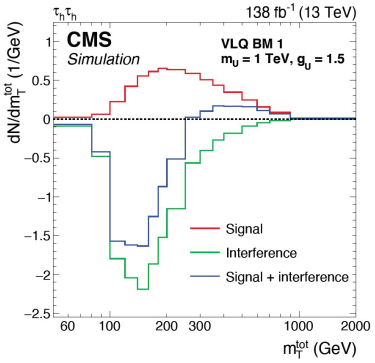
Neglecting interference w/ SM bkg

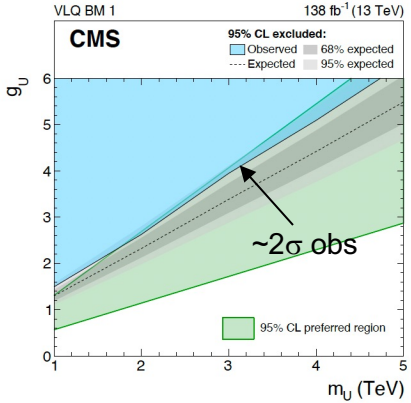




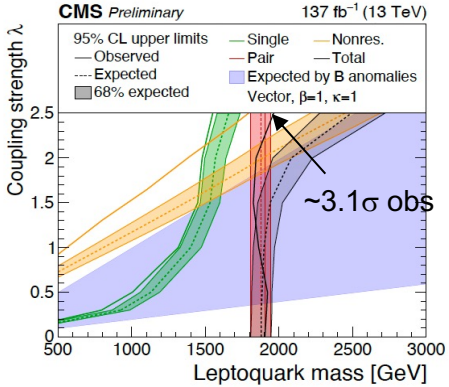


[CMS-HIG-21-001]





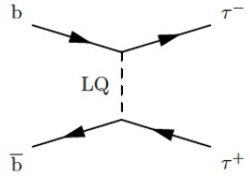
[CMS-PAS-EXO-19-016]



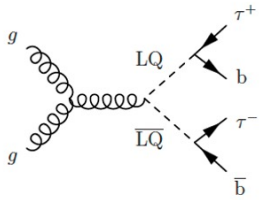
Shown at Moriond EW 2022

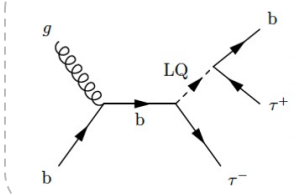
LQ-b-τ: Comparison of recent results

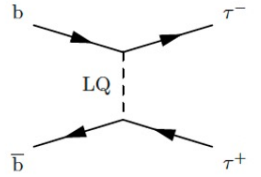
Including interference w/ SM bkg



Neglecting interference w/ SM bkg

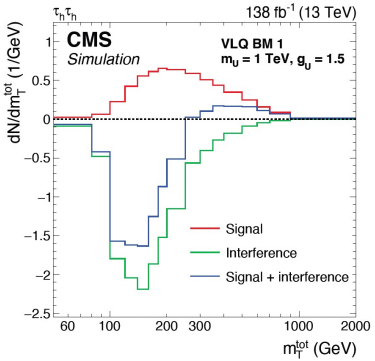


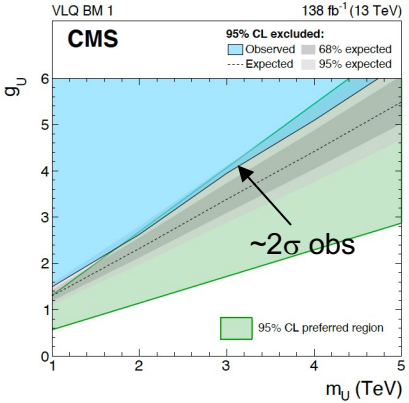




Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

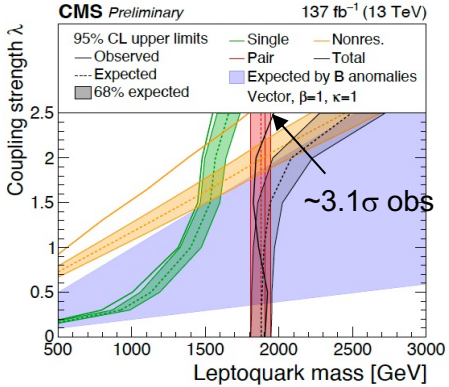
[CMS-HIG-21-001]



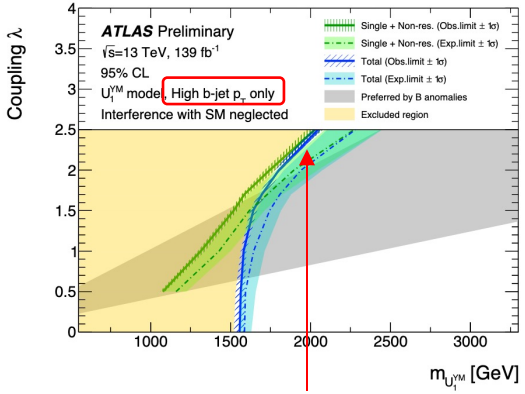


Shown at Moriond EW 2022

[CMS-PAS-EXO-19-016]



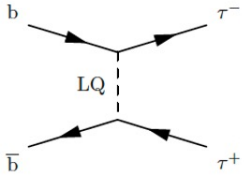
[EXOT-2022-39]



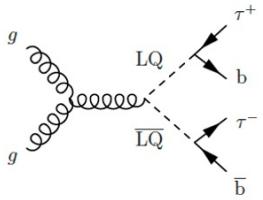
Doesn't exclude CMS' excess

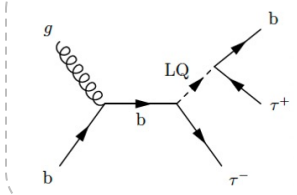
LQ-b-τ: Comparison of recent results

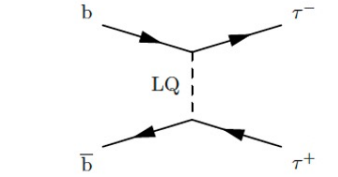
Including interference w/ SM bkg



Neglecting interference w/ SM bkg

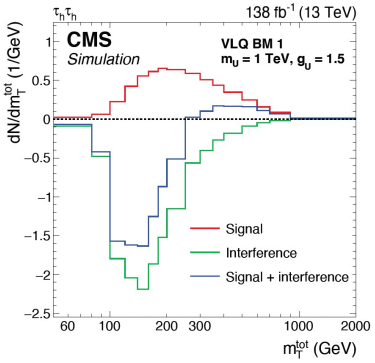


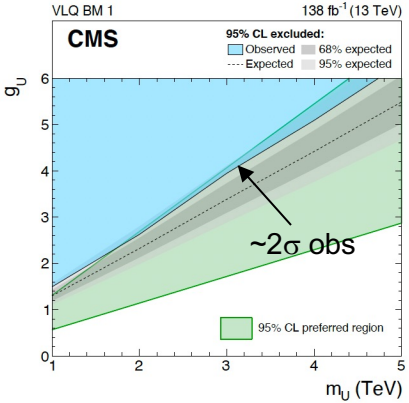




Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

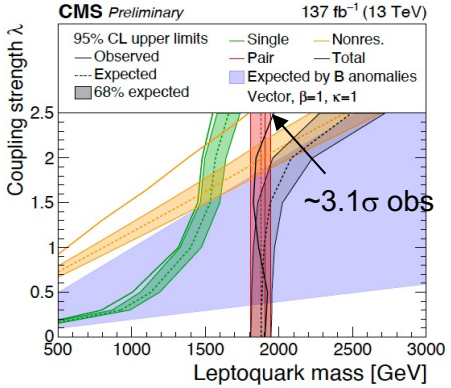
[CMS-HIG-21-001]



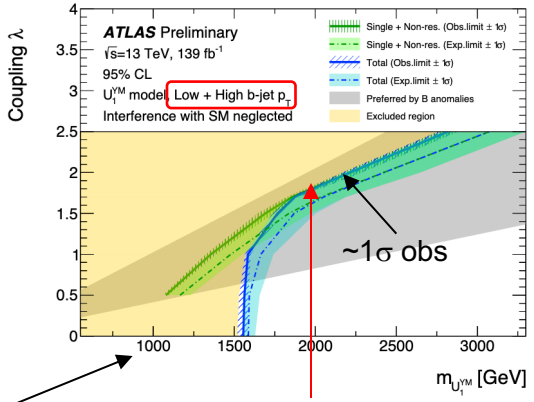


Shown at Moriond EW 2022

[CMS-PAS-EXO-19-016]



[EXOT-2022-39]



Large improvement in sensitivity when adding low b-jet p_T category

Excludes CMS' excess

Need to clarify interference issue for future interpretations

Conclusions

- The picture painted by flavour anomalies is exciting, but also quite confusing!
- More experimental information is needed and ATLAS and CMS have critical contributions to make.

- During Run 2 we have developed a broad search program probing relevant theory parameter space that can explain current anomalies (and beyond!).
  - Leptoquarks
  - Light and heavy vector bosons
  - High-mass Drell-Yan tails and EFT interpretations
  - Vector-like fermions, etc.

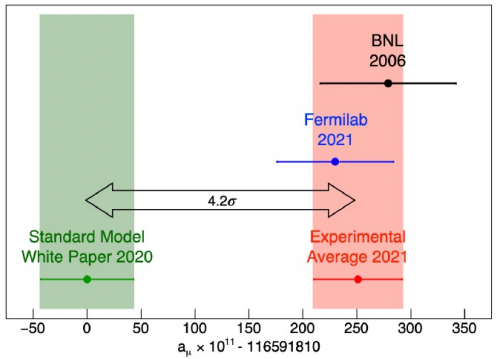
- For Run 3 we are building on the lessons learned and expect significantly improvements in sensitivity.

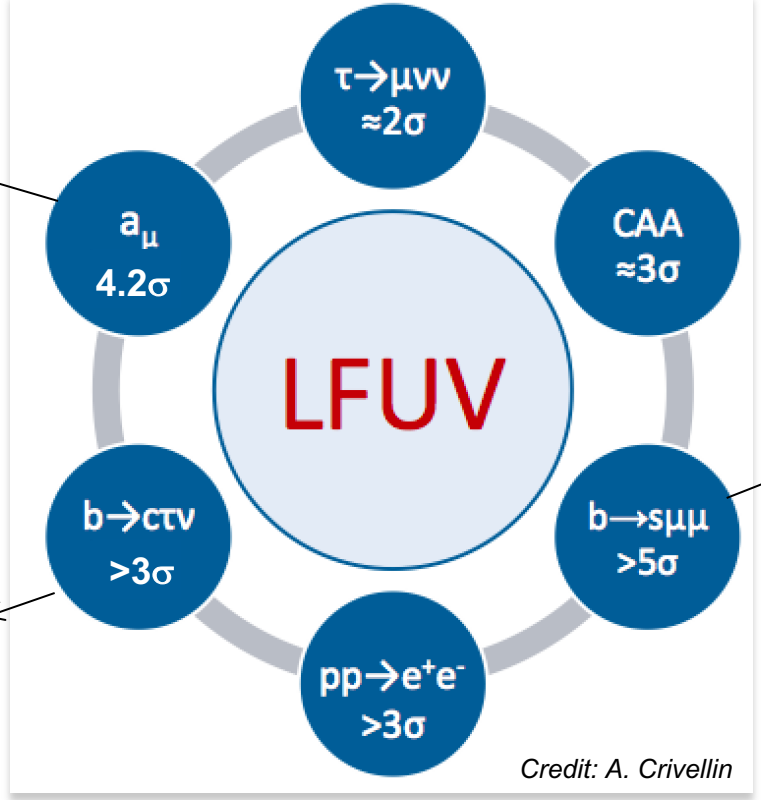
  ➔ Ambitious program with real discovery potential!

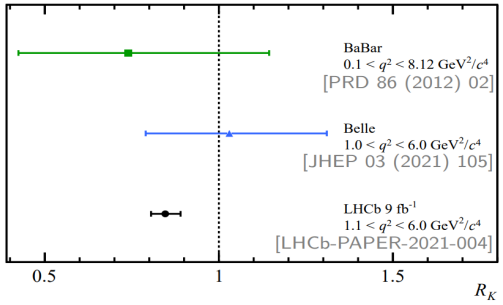
Stay tuned!

Backup

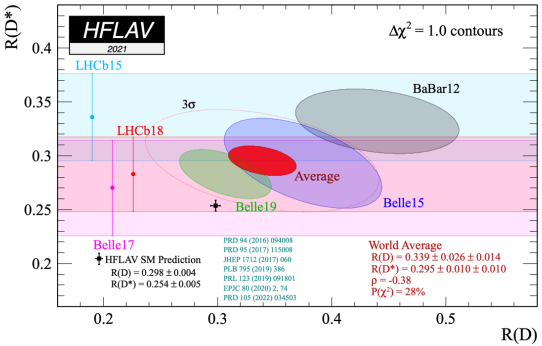
Flavour anomalies: Circa 2021

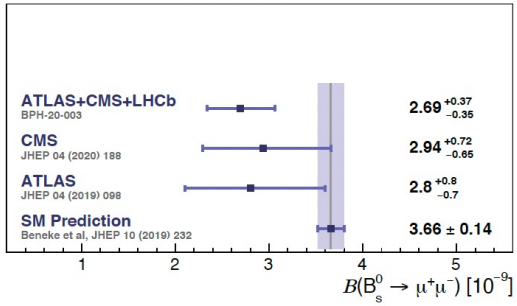






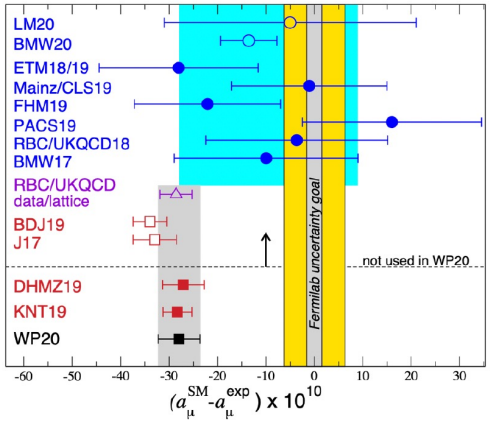
Also: R(K*), P_5', $B_s \to \mu\mu$, $B_s \to \mu\mu\phi$

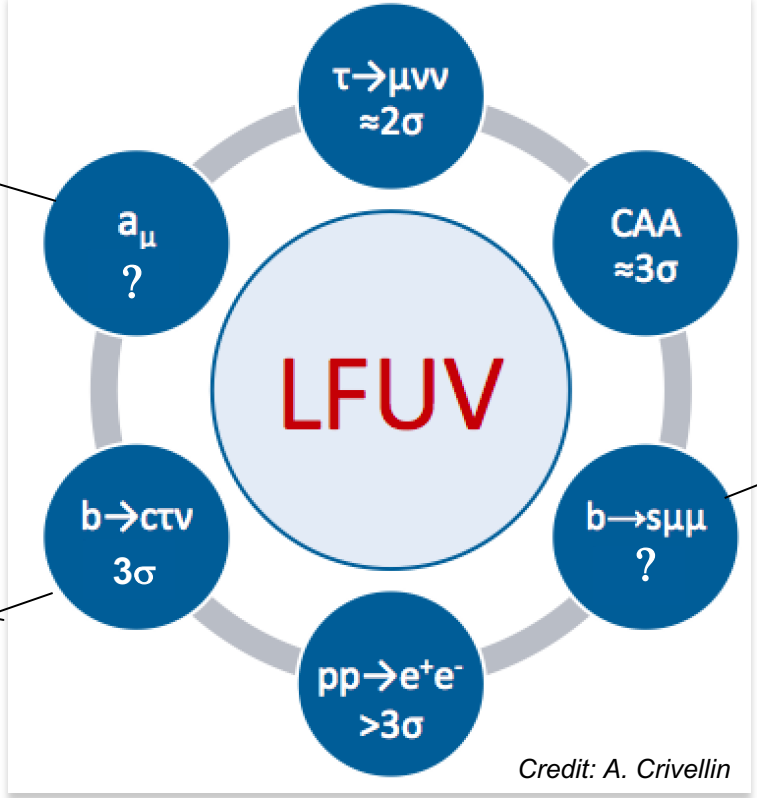




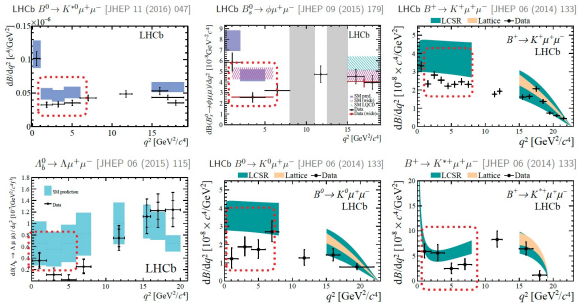
Flavour anomalies

arXiv:2106.06723

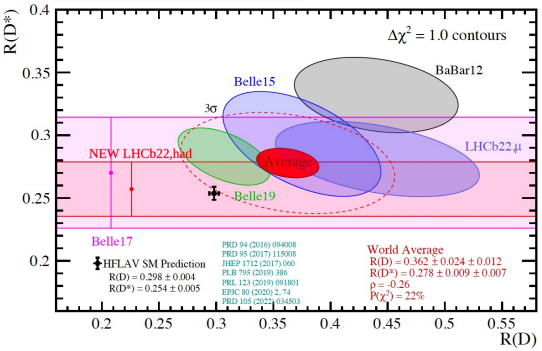


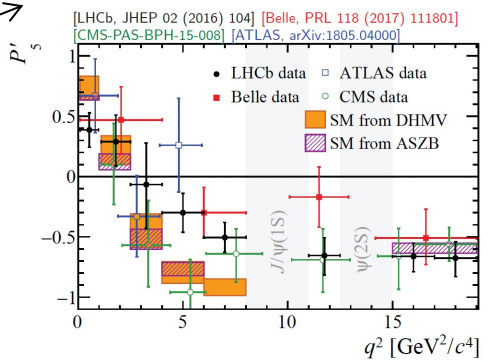


However, the other b→sμμ anomalies are still there!



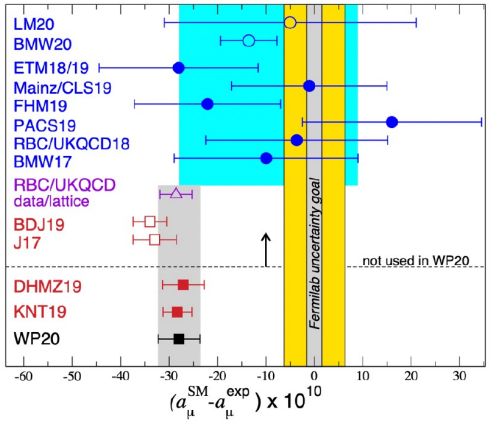
Updated at La Thuile 2023



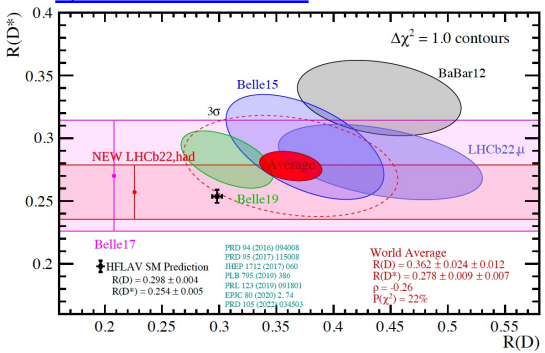


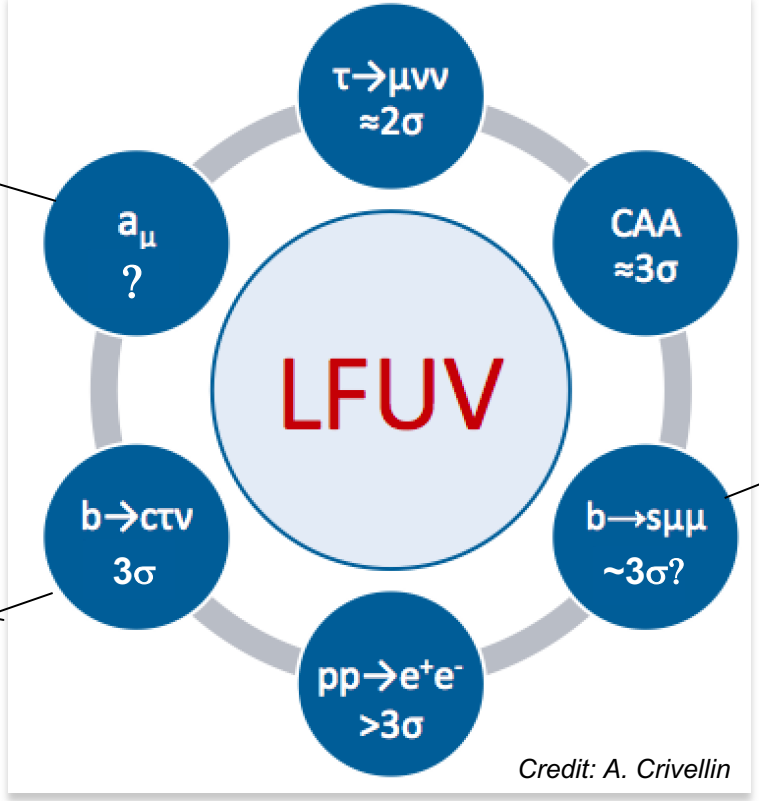
Flavour anomalies

arXiv:2106.06723



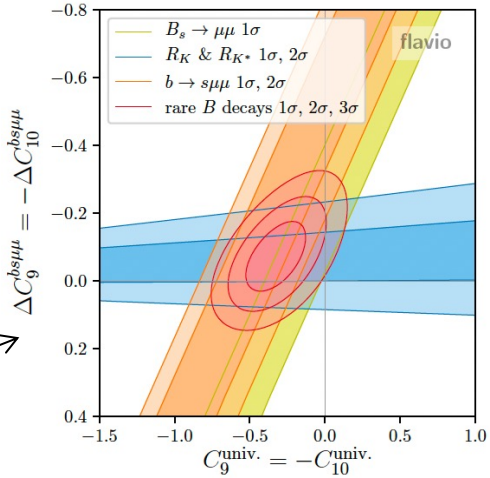
Updated at La Thuile 2023





Global fit to NP coupling purely to left-handed SM fields

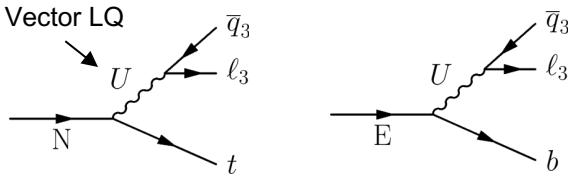
arXiv:2212.10497



e/μ–universal NP contribution

Vector-like leptons: Overview

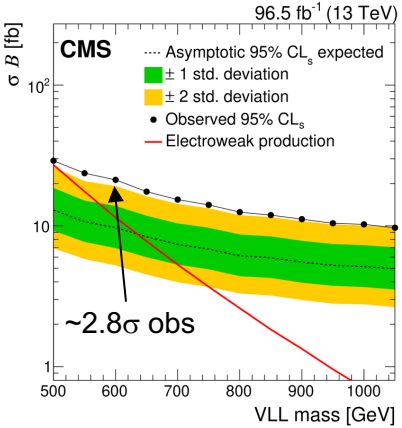
- Predicted in Composite Higgs models and other UV-complete constructions. Typical mass O(TeV).
- Can contribute to b→sμμ (via loop effects), a_μ, and/or CA anomalies.
- At the LHC dominantly produced in pairs via the EW interaction.
- Typically they are assumed to decay via charge-current and/or neutral-current SM interactions, depending on the $SU(2)_L$ representation.
- However, in particular models the phenomenology can be completely different, such as in the ”4321 model”.

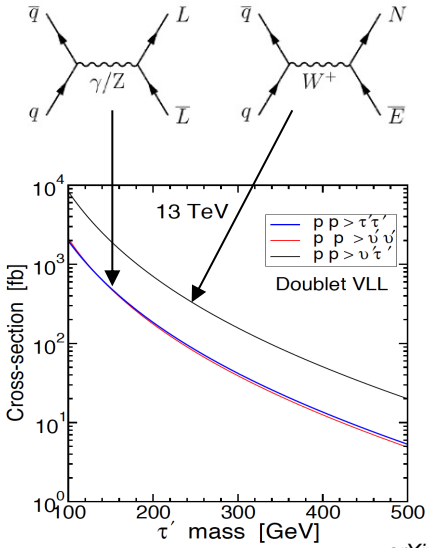


Complex cascades giving heavy-flavored multilepton+multijet final states

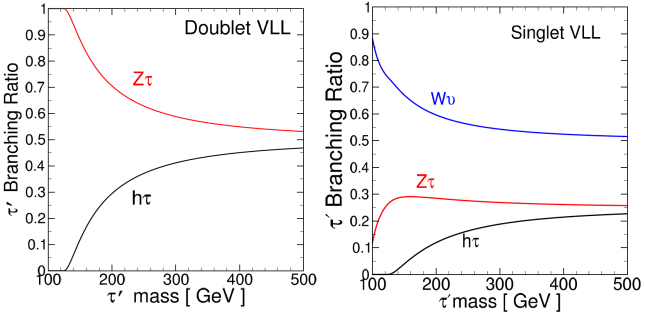
Shown at Moriond EW 2022

CMS-B2G-21-004



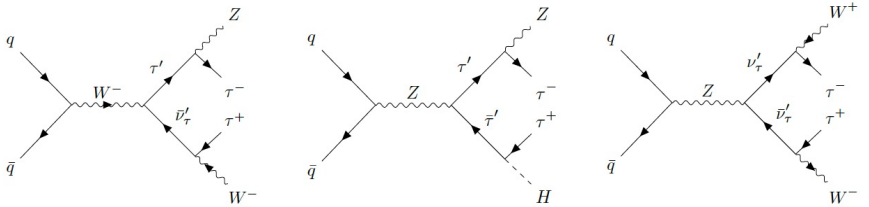


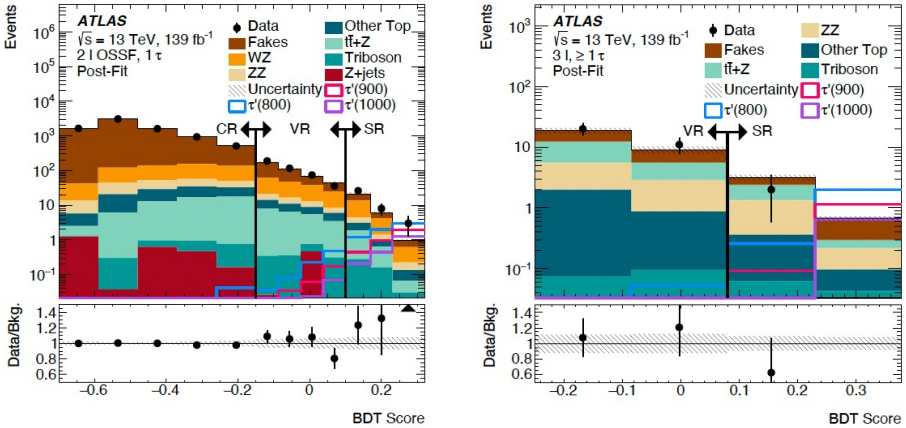
arXiv:1510.03456



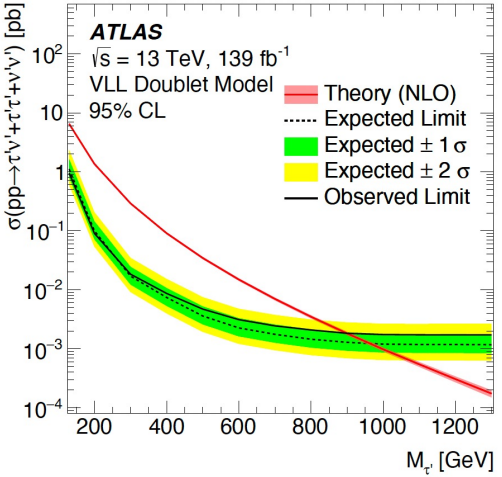
Vector-like taus

- Signature:
  - 2 or 3 light leptons (e or μ) and ≥1τ_{had}, or ≥4 light leptons.
  - Sizable E_T^{miss} and possibly additional jets.
- Main backgrounds: ttZ/γ*, WZ, ZZ, fake τ_{had}.
- Event categorization:
  - 7 signal regions depending on lepton multiplicity and charge/flavour combinations (for 2l events).
  - 4 control regions and 10 validation regions.
- Final discriminating variable:
  - BDT per signal region.





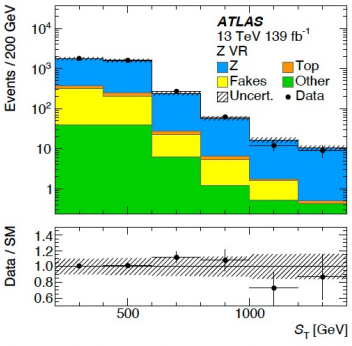
EXOT-2020-07

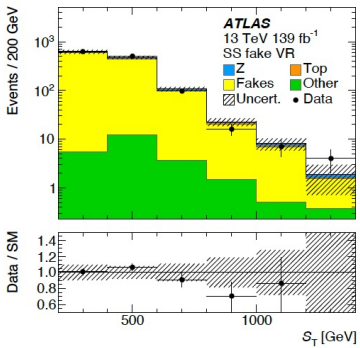


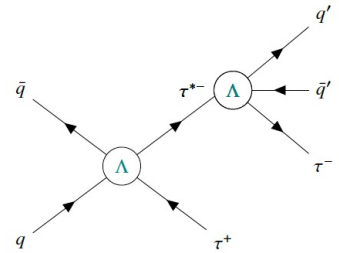
Obs. limit @95% CL:
VLL Doublet: m_{LQ}>900 GeV

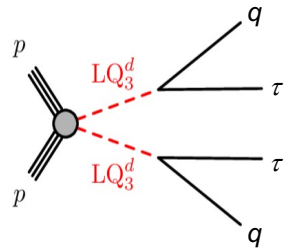
LQ-q-τ: Pair production

- Search for excited τ-leptons via a contact interaction. Also interpreted in the context of scalar LQLQ→qτqτ (q=u,d,s,c).
- Event preselection:
  - $\tau_{had}\tau_{had}$, ≥2 jets, di-τ_{had} trigger
- Main backgrounds: Z+jets, Top (tt/tW), Fake τ_{had}
- Event categorization:
  - Signal region: $m_{\tau\tau}^{coll}$>110 GeV, $p_{T,\tau}$>70/60 GeV.
  - Control regions for main backgrounds, along with dedicated validation regions.
- Final discriminating variable: $S_T = \sum_{\tau,jets} p_T$

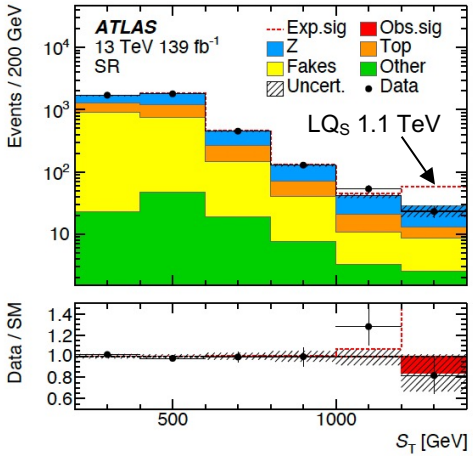


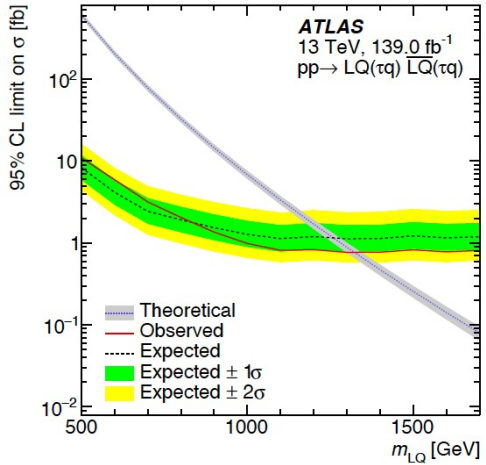






EXOT-2020-18

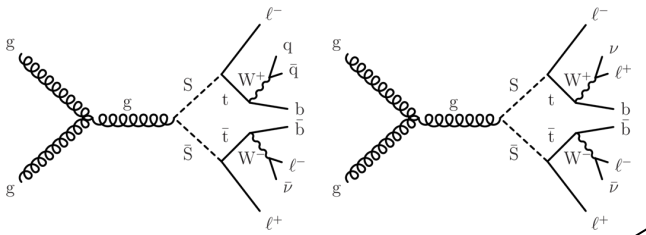




Obs. limit @95% CL (for BR=1):
Scalar LQ: m_{LQ}>1.3 TeV

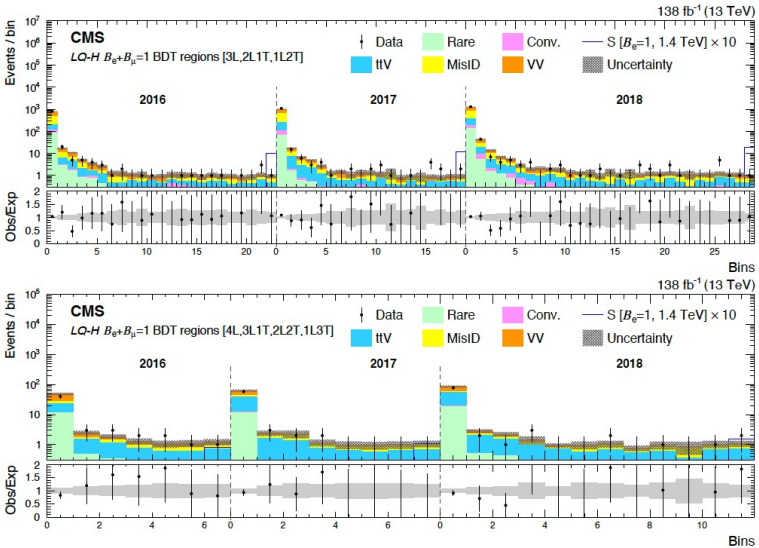
LQ-t-l (l=e,μ,τ): Pair production

- Event preselection:
  - 3 or 4 leptons (e, μ, or τ), ≥1 e/μ
- Main backgrounds: ttW, ttZ/γ*, diboson, non-prompt/fake leptons
- Final discriminating variable:
  - BDT (for model-dependent interpretations)

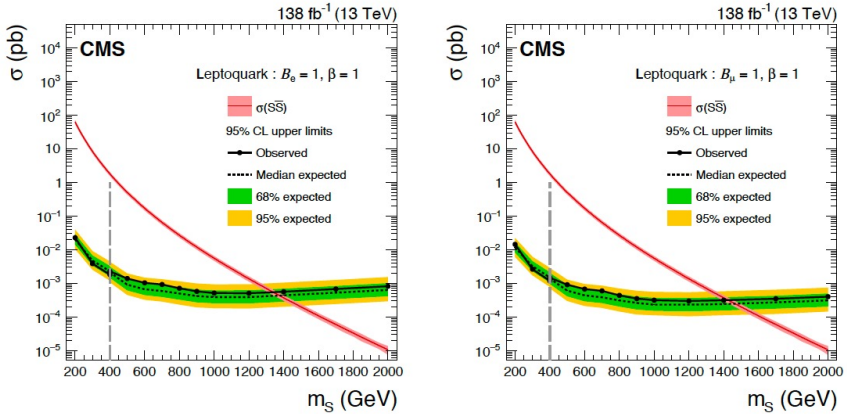


Includes broad model-indep search and additional BSM scenarios:
- Type-III seesaw heavy fermions
- Vector-like taus

[CMS-EXO-21-002]



No significant excess observed

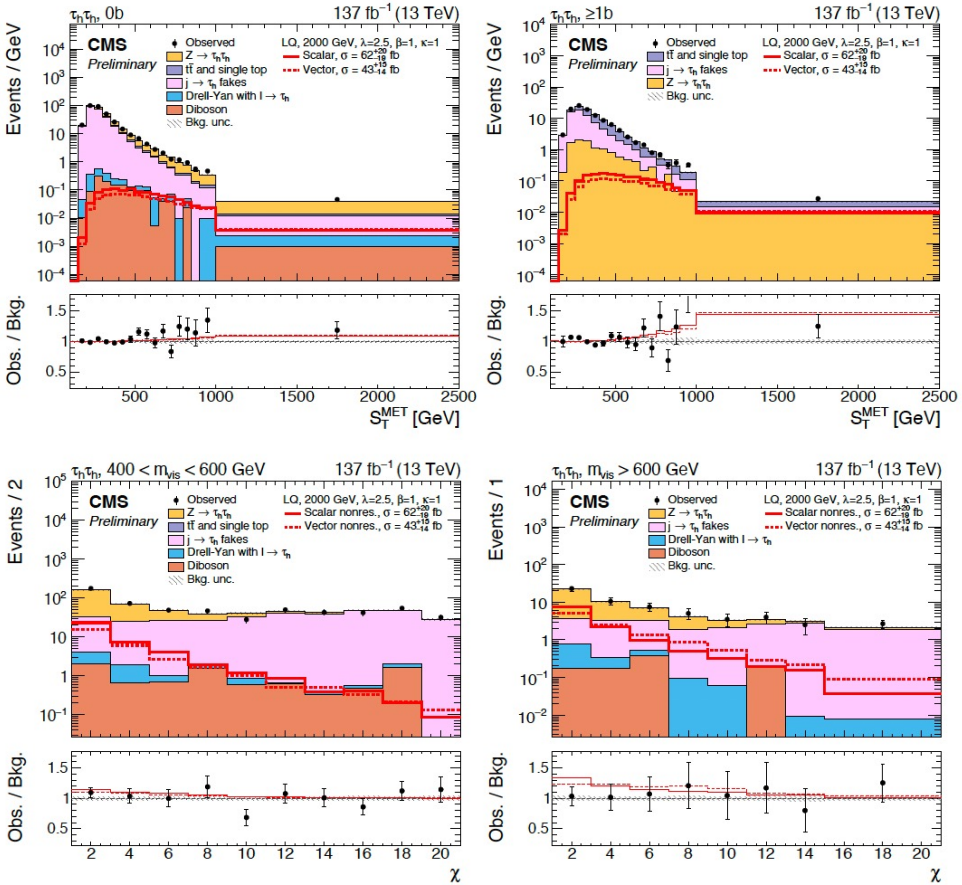


Obs. limits @95% CL (for BR=1):
Scalar LQ(→te): m_{LQ}>1.34 TeV
Scalar LQ(→tμ): m_{LQ}>1.42 TeV
Scalar LQ(→tτ): m_{LQ}>1.12 TeV

LQ-b-τ: All production modes

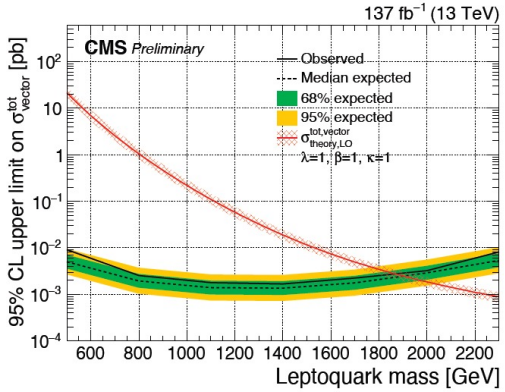
- Event preselection:
  - $\tau_{had}\tau_{had}$, $e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\mu\mu$ channels
  - Di-τ_{had} triggers and single-lepton triggers
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Event categorization:
  - Resonant: ≥1 jets (p_T>50 GeV), split in 2 categories: 0 and ≥1 b-jets (p_T>50 GeV)
  - Non-resonant: ≥0 jets (p_T>50 GeV), low boost & $\Delta\eta$, split in 3 m_{vis} categories
- Final discriminating variable:
  - Resonant: $S_T^{MET} = \sum_{\tau,j1} p_T + p_T^{miss}$
  - Non-resonant: $\chi = \exp(|y_{\tau 1} - y_{\tau 2}|)$

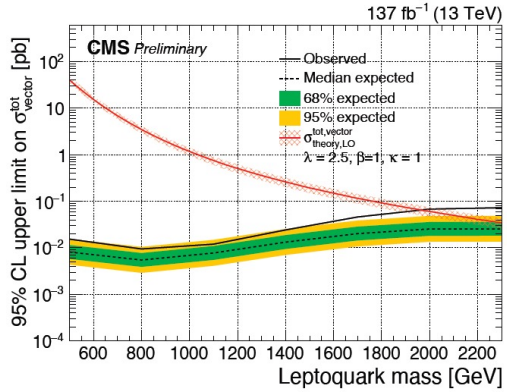
CMS-PAS-EXO-19-016

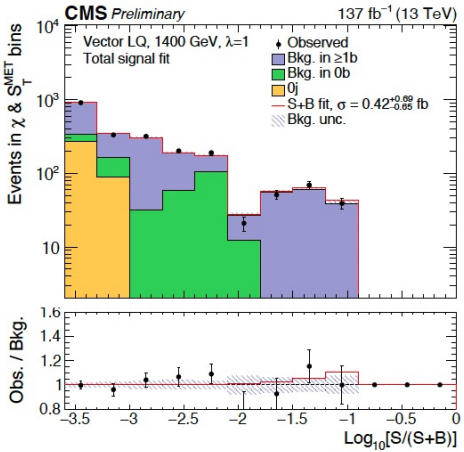


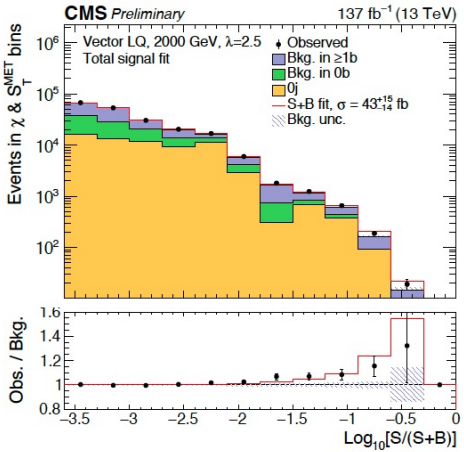
LQ-b-τ: All production modes

CMS-PAS-EXO-19-016







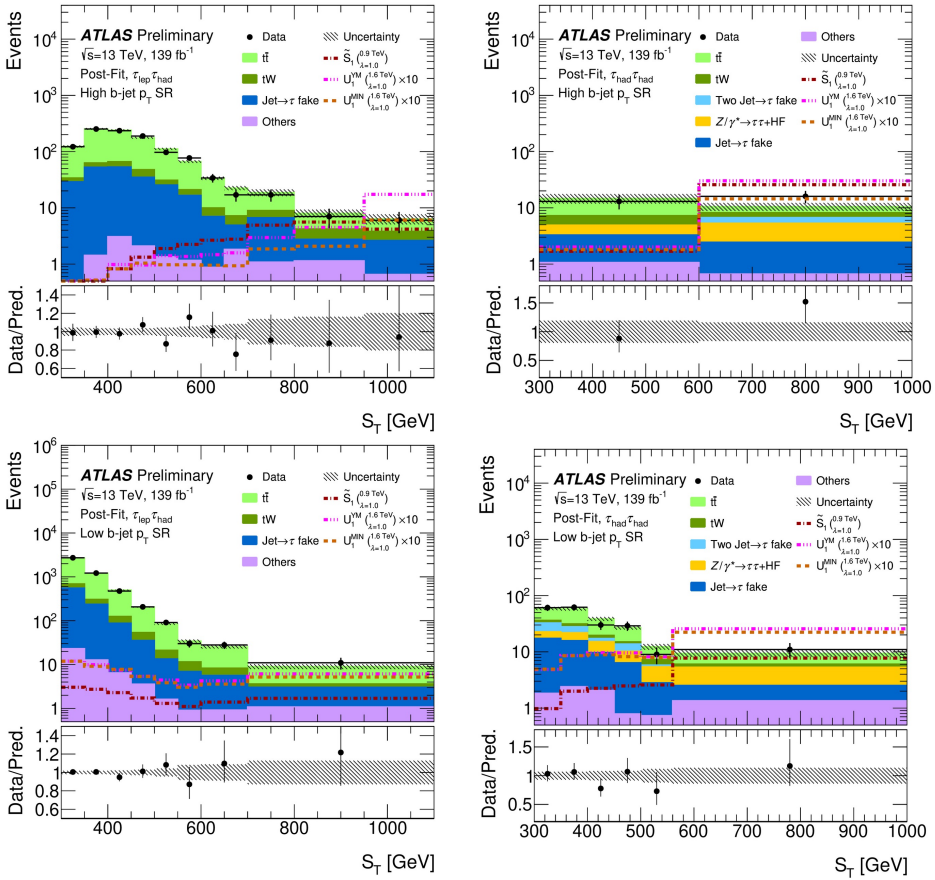


Signal	$m_{LQ} = 1400$ GeV		$m_{LQ} = 2000$ GeV	
	σ [pb]	z	σ [fb]	z
Scalar				
Pair	$0.24^{+0.47}_{-0.45}$	0.5	$0.22^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.15^{+0.95}_{-0.92}$	1.3	$0.64^{+0.68}_{-0.65}$	1.0
Single, $\lambda = 2.5$	$9.1^{+5.6}_{-5.3}$	1.7	18^{+11}_{-11}	1.7
Nonres.	70^{+23}_{-22}	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, $\lambda = 1$	$0.42^{+0.69}_{-0.66}$	0.0	$1.3^{+1.5}_{-1.4}$	0.5
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1

LQ-b-τ: All production modes

- Event preselection:
  - $\tau_{had}\tau_{had}$, $\tau_l\tau_{had}$ (l=e,μ) channels
  - ≥1 jets, ≥1 b-jets (p_T>25 GeV)
  - Single τ_{had} triggers and single-lepton triggers
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Event categorization:
  - High b-jet p_T: ≥1 b-jets (p_T>200 GeV)
  - Low b-jet p_T: ≥1 b-jets (25<p_T<200 GeV)
- Default interpretation considers only high b-jet p_T category to reduce impact from neglected interference w/ SM bkg.
- Final discriminating variable: $S_T = \sum_{\tau,b1} p_T + p_T^{miss}$

EXOT-2022-39



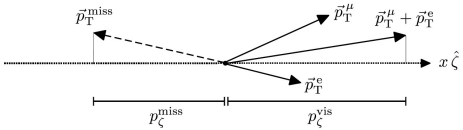
Non-resonant LQ in bb→ττ

CMS-HIG-21-001

	No b tag			b tag		
$e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$\mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$\tau_h\tau_h$						
$t\bar{t}(e\mu)$				$D_\zeta < -35$ GeV		

Signal region (SR)

Control region



$$D_\zeta = p_\zeta^{\text{miss}} + 0.85\, p_\zeta^{\text{vis}}; \qquad p_\zeta^{\text{miss}} = \vec{p}_T^{\,\text{miss}} \cdot \hat{\zeta}; \qquad p_\zeta^{\text{vis}} = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu}) \cdot \hat{\zeta},$$

$$m_T^{e(\mu)} = m_T(\vec{p}_T^{\,e(\mu)}, \vec{p}_T^{\,\text{miss}}), \quad \text{with} \quad m_T(\vec{p}_T^{\,i}, \vec{p}_T^{\,j}) = \sqrt{2\, p_T^i\, p_T^j\, (1 - \cos\Delta\varphi)},$$

$$m_T^{\text{tot}} = \sqrt{m_T^2(\vec{p}_T^{\,\tau_1}, \vec{p}_T^{\,\tau_2}) + m_T^2(\vec{p}_T^{\,\tau_1}, \vec{p}_T^{\,\text{miss}}) + m_T^2(\vec{p}_T^{\,\tau_2}, \vec{p}_T^{\,\text{miss}})},$$

Shown at Moriond EW 2022