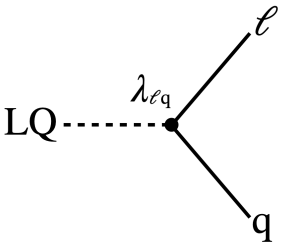
Searches for leptoquarks and other leptonic final states

Halil Saka (University of Cyprus) on behalf of the CMS Collaboration
May 23, 2023

LQs in BSM landscape



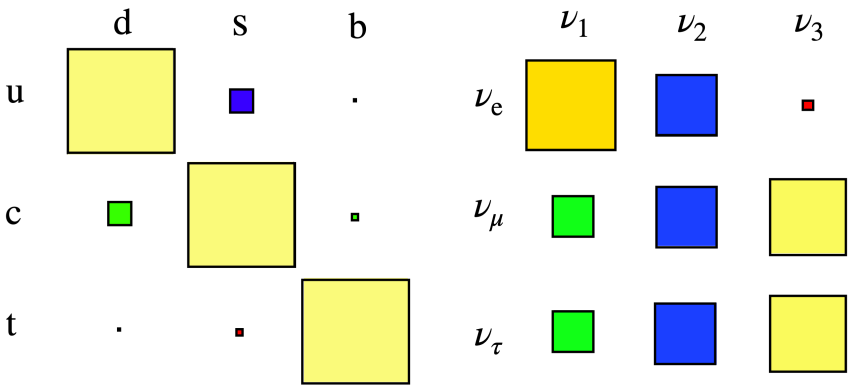
- Leptoquarks are colored states with both **baryon and lepton** quantum numbers

  - models with larger symmetry groups / **unification of matter** (leptons ↔ quarks)
    GUTs → **Vector LQs** may emerge as gauge bosons
    → **Scalar LQs** may emerge in the symmetry breaking sector

  - **compositeness** theories (LQs may emerge as bound states)

  - LQ-like states also appear in the **MSSM** Lagrangian with **R-parity violating** terms

  - allowed in SM Lagrangian when extended to all **renormalizable** interactions

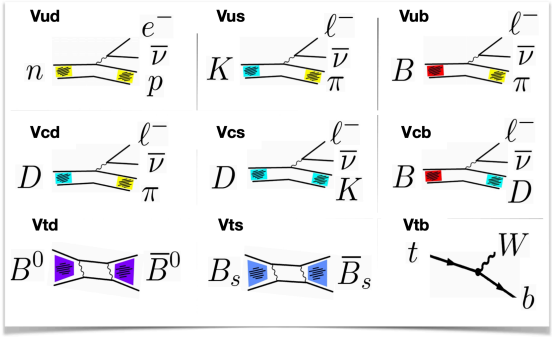


S.F. King https://inspirehep.net/literature/1388063

- At the LHC, novel **lepton+jet resonances**, among other signatures.

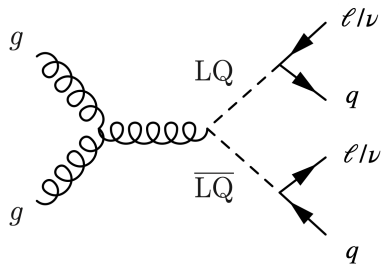
Low energy bounds, including proton decay, can be avoided by:
- couplings to **one generation of leptons/quarks**
- couplings to **third generation fermions** (generally weaker constraints)
- approximate **alignment** of couplings **with SM** Yukawa couplings

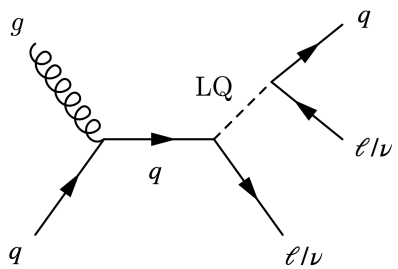
Simultaneous violation of these may lead to QLFV

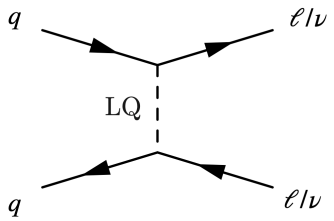


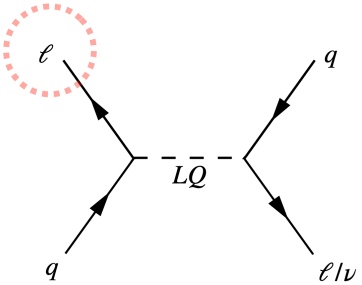
J. Brodzicka https://cds.cern.ch/record/2678400

LQ production at the LHC









LQ decays

$\beta = 1 : \text{LQ} \to \text{q}\ell$

$\beta = 0 : \text{LQ} \to \text{q}\nu$

Pair	Single	Nonresonant	Lepton-quark
			EXO-22-018
		EXO-21-009	
		HIG-21-001	
EXO-19-016	***EXO-19-016***	***EXO-19-016***	
EXO-19-015	*EXO-19-015*		
EXO-21-002			
SUS-19-005			

**all with Run 2 dataset*

Searches with full Run2 data from CMS cover:

- **off-diagonal** couplings in flavor
- **non-QCD production** modes → indirect signatures
- **non-minimal models** with more than one coupling (motivated by **tensions in LFU**)
- emphasis on couplings with **third generation fermions** today!

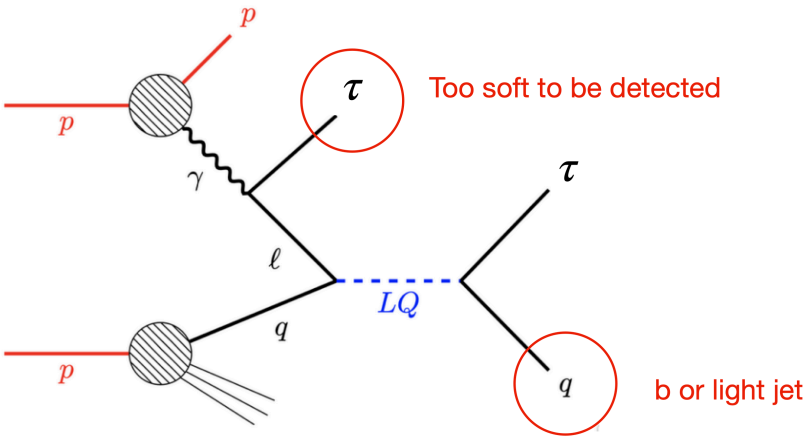
See session on "Joint (BSM1+Flavour)" on Thursday

- 11:30 AM- Lepton Flavour Universality tests in LHCb
  Speaker: Rizwaan Mohammed (University of Oxford (GB)
- 11:48 AM- Lepton Flavour Universality studies and related rare decays in CMS + ATLAS
  Speaker: Keith Ulmer (University of Colorado, Boulder (US))
- 12:06 PM- Theory lessons from flavour data
  Speaker: Dr Javier M. Lizana (University of Zurich)
- 12:24 PM- Searches for rare and forbidden decays in LHCb
  Speaker: Lex Greeven (Nikhef National institute for subatomic physics (NL))
- 12:42 PM- Leptoquarks (focus on high-pT)
  Speaker: Dr Nejc Košnik (J. Stefan Institute, University of Ljubljana)

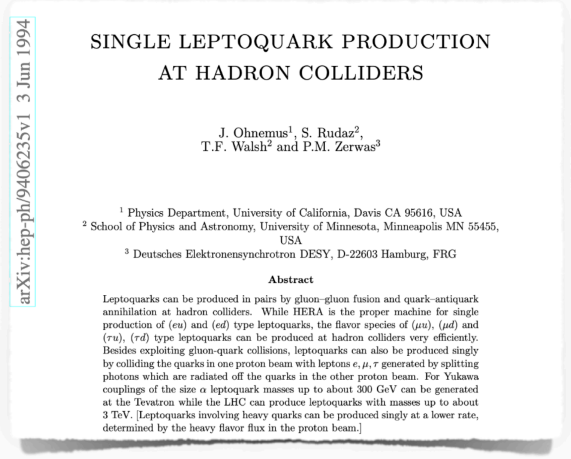
LQ-τ-b / LQ-τ-q

NEW RESULT! EXO-22-018

- First search for LQ using **lepton-quark** collisions!
  - possible due to recent advances in precision of lepton PDFs
- Event selection:
  - **single lepton** (e, μ, τ_h) + high p_T **jet**
  - veto events with additional leptons (**complementarity** to single/pair production)
- Two categories/models based on **"b-tag"** of leading **jet**
  - probes both $\lambda_{\tau b}$ and $\lambda_{\tau q}$
- **Unambiguous "LQ" resonance**:
  - require p_T^{miss} to be aligned with τ lepton



- A crucial aspect which prevented so far to fully explore the phenomenology offered by lepton initiated processes is **the lack of a precise determination of the lepton densities**



arXiv:hep-ph/9406235v1 3 Jun 1994

SINGLE LEPTOQUARK PRODUCTION AT HADRON COLLIDERS

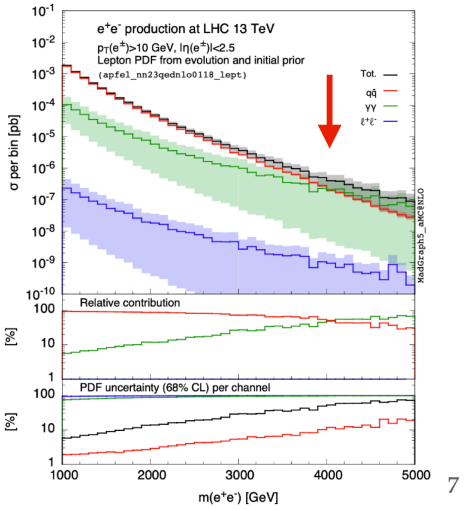
J. Ohnemus[1], S. Rudaz[2], T.F. Walsh[2] and P.M. Zerwas[3]

[1] Physics Department, University of California, Davis CA 95616, USA
[2] School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA
[3] Deutsches Elektronensynchrotron DESY, D-22603 Hamburg, FRG

Abstract

Leptoquarks can be produced in pairs by gluon–gluon fusion and quark–antiquark annihilation at hadron colliders. While HERA is the proper machine for single production of (eu) and (ed) type leptoquarks, the flavor species of (μu), (μd) and (τu), (τd) type leptoquarks can be produced at hadron colliders very efficiently. Besides exploiting gluon-quark collisions, leptoquarks can also be produced singly by colliding the quarks in one proton beam with leptons e, μ, τ generated by splitting photons which are radiated off the quarks in the other proton beam. For Yukawa couplings of the size α leptoquark masses up to about 300 GeV can be generated at the Tevatron while the LHC can produce leptoquarks with masses up to about 3 TeV. [Leptoquarks involving heavy quarks can be produced singly at a lower rate, determined by the heavy flavor flux in the proton beam.]

[Bertone,Carrazza,Pagani,Zaro, *JHEP* 11 (2015) 194]



1994 paper: very interesting, but almost forgotten...

7

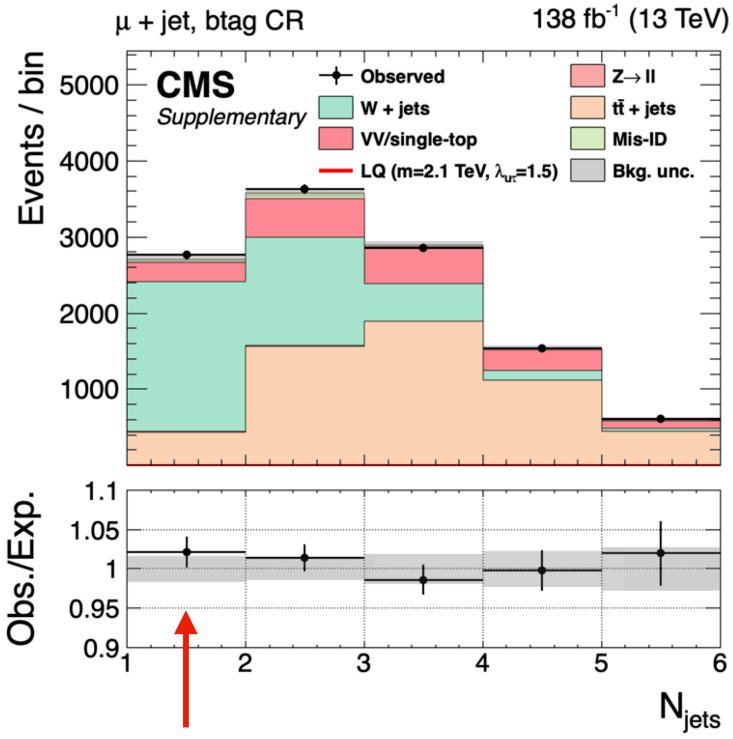
Slide borrowed from L. Buonocore et al.
https://indico.cern.ch/event/921962/

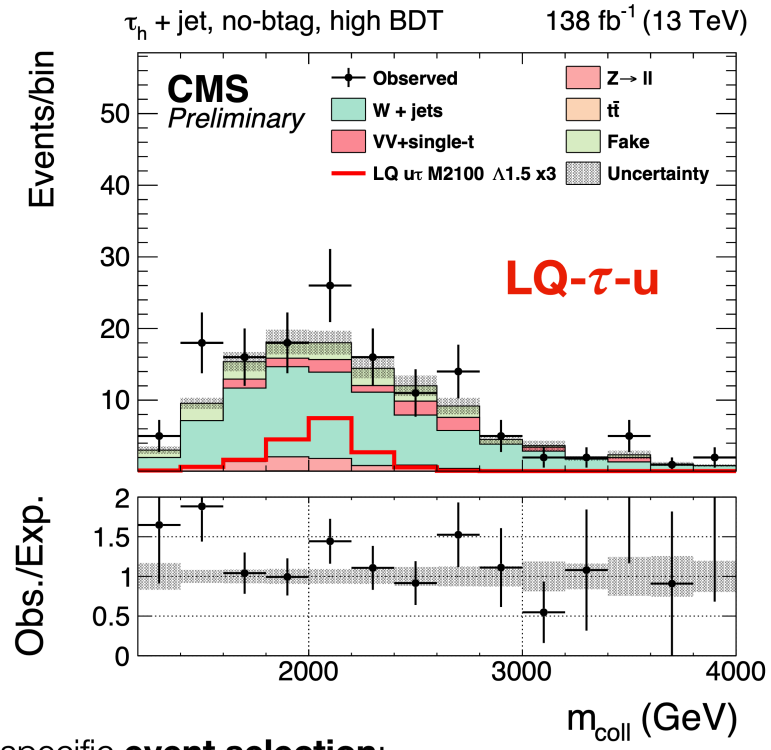
https://arxiv.org/abs/2005.06477

LQ-τ-b / LQ-τ-q

NEW RESULT! EXO-22-018

- Single-lepton + high p_T jet selection → **W+bb** background.
  - **normalization** is obtained **from data** in a dedicated selection (~7% unc.)
- Other irreducible backgrounds are from simulation, with theoretical cross-sections.
- **Data driven** estimate of **misidentified lepton** candidates (10-30% unc.)

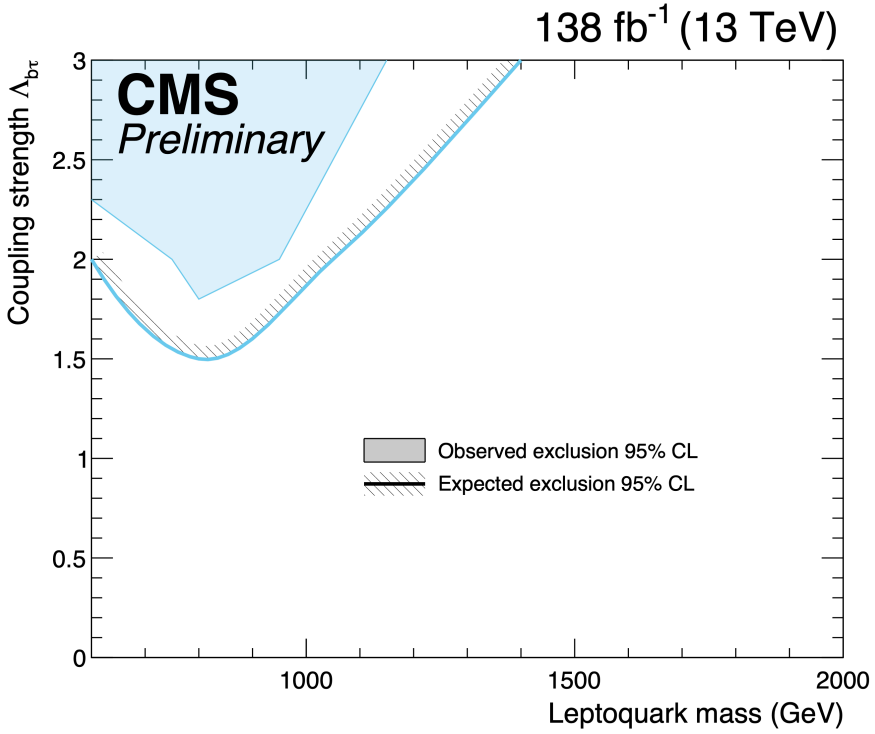




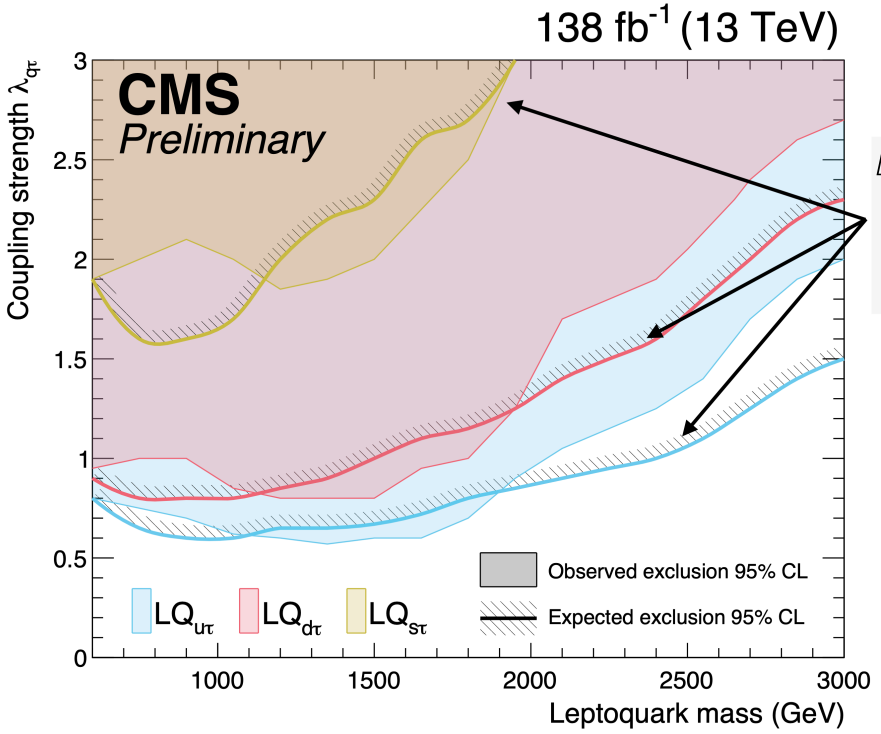
- **BDT** for model-specific **event selection**:
  - **angles** between physics objects
  - **ratios** of object p_Ts with respect to each other, or w.r.t. collinear mass
  - <u>limited dependency on LQ mass</u>
- **Collinear mass** is the final discriminant (resonance at the LQ mass)
  - $\gtrsim$10% resolution over the range of probed couplings

LQ-τ-b / LQ-τ-q

NEW RESULT! EXO-22-018



Constraints on $\mathrm{LQ} - \tau - b$ coupling, complementary to the dilepton searches (next)



Differences due to the quark content of the proton PDF

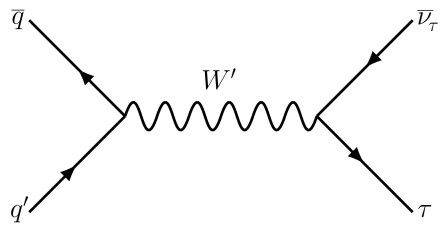
First direct limits on $\mathrm{LQ} - \tau - q$ couplings with light flavored quarks (similar acceptance)

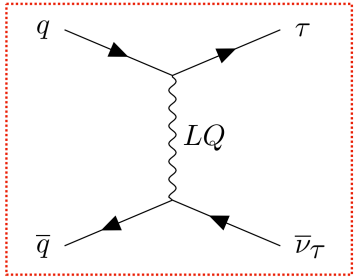
Probing multi-TeV LQ phase-space otherwise inaccessible for direct production at the LHC

LQ-τ-q / ν-q

EXO-21-009
e-print arXiv:2212.12604

- Benchmark analysis for a "**heavy W-like**" signature, with high p_T lepton and p_T^{miss}
  - traditionally interpreted for **W' of SSM (broad enhancement in M_T)**

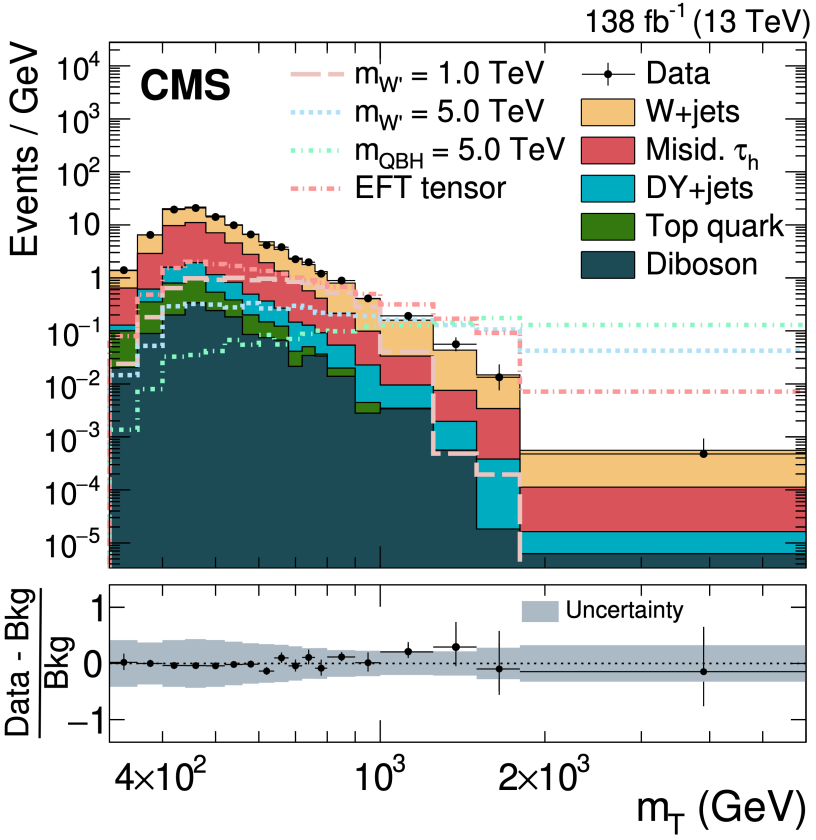




- Event selection:
  - one high p_T hadronic tau lepton candidate ($p_T > 130/190$ GeV)
  - require p_T^{miss} to be back to back with τ lepton, compatible in magnitude
  - veto events with additional electrons or muons

- Dominant background is **W+jets**:
  - estimated by MC (corrected to NNLO QCD + NLO EW)
  - mass dependent uncertainty (5-20%)
  - **PDF uncertainties** dominate at high m_T (50% beyond 1.8 TeV, from NNPDF3.1)

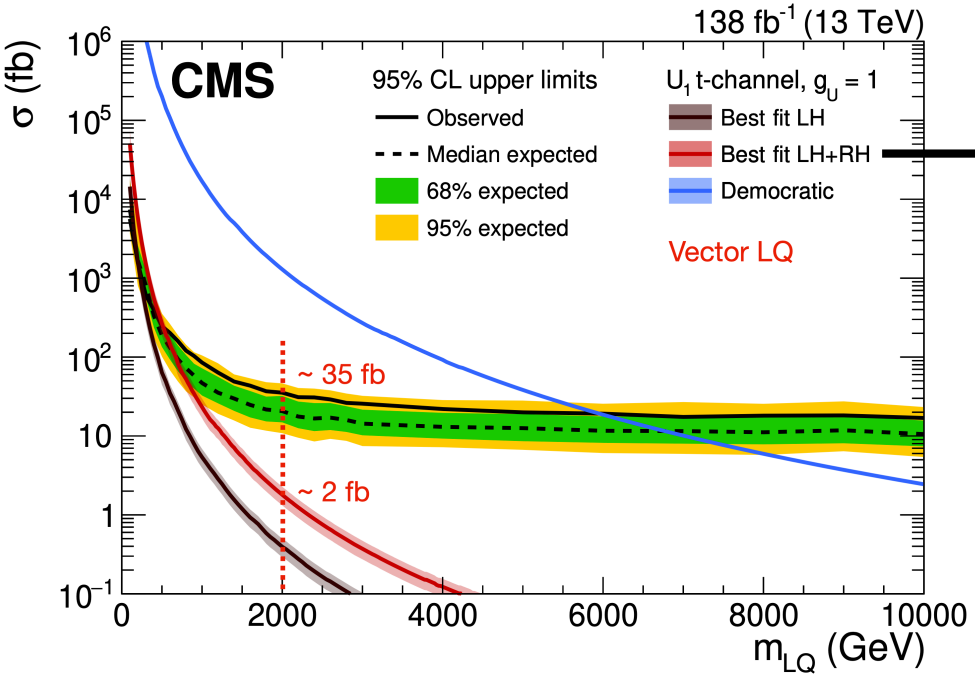
- **Data driven** estimate of **misidentified** τ_h candidates (10-30%)
  - developed in $\ell\tau_h$ events
  - normalization constrained in the fit (100% prefit uncertainty)

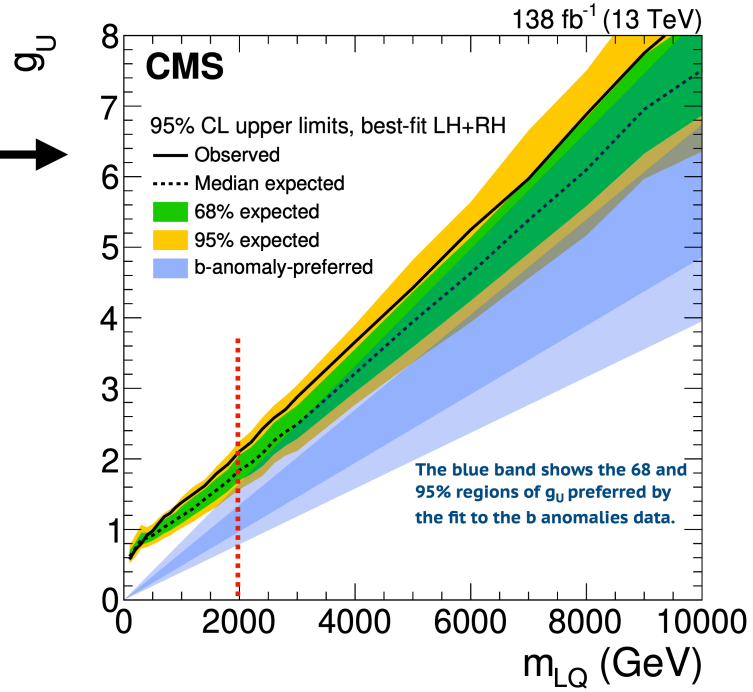


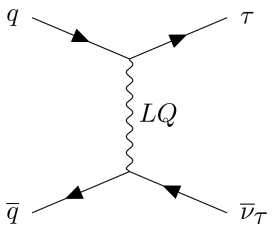
$$m_T = \sqrt{2 p_T^{\tau_h} p_T^{miss} [1 - \cos\Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{miss})]}$$

LQ-τ-q / ν-q

EXO-21-009
e-print arXiv:2212.12604







$\sigma \sim |g_U|^4$

Probing phase-space **favored by an LQ fit of the charged-current B decay anomalies**

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \quad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}$$

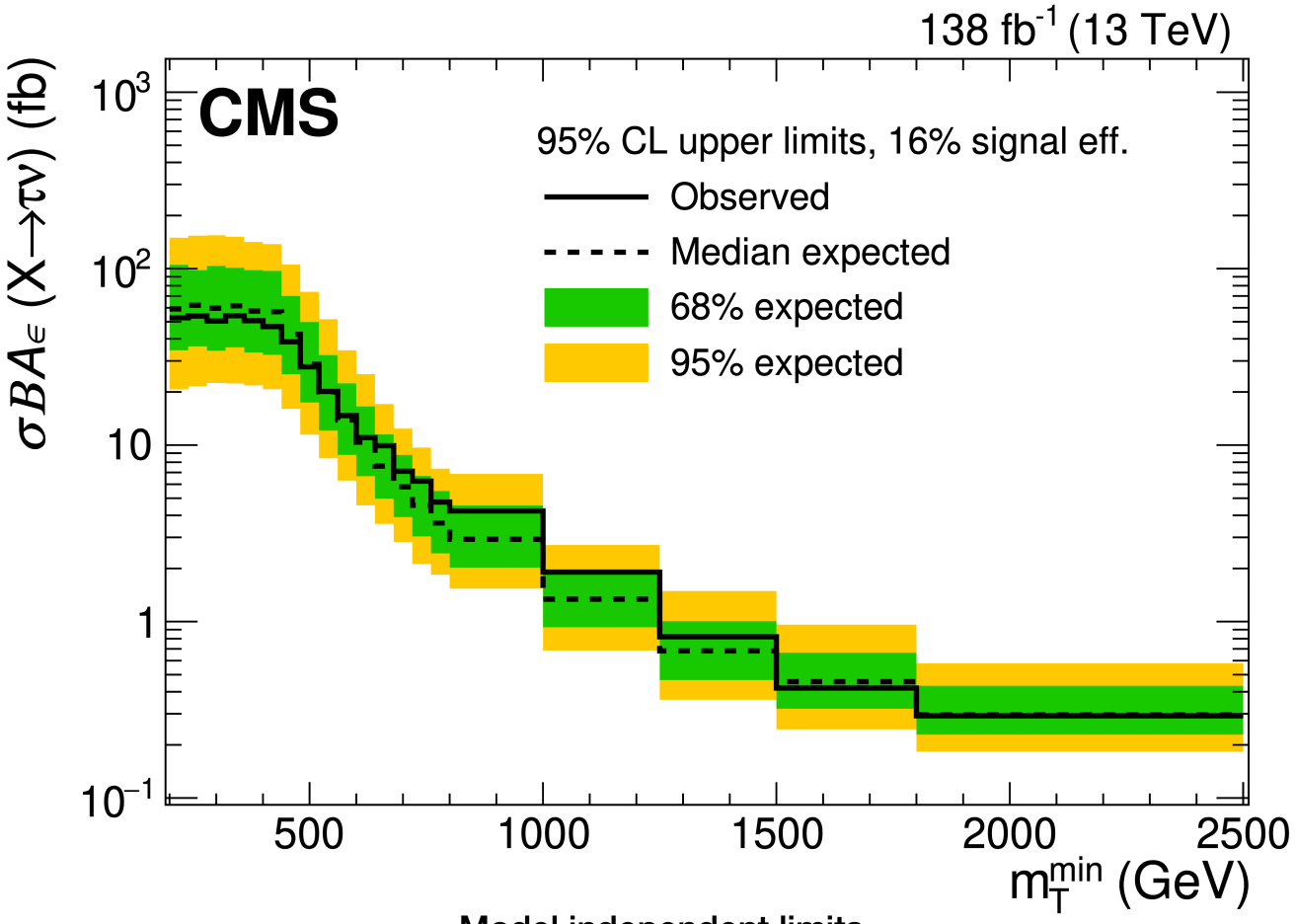
$$J_\mu^U = \beta_L^{i\alpha}\left(\bar{q}_L^i \gamma_\mu \ell_L^\alpha\right) + \beta_R^{i\alpha}\left(\bar{d}_R^{i\alpha} \gamma_\mu e_R^\alpha\right)$$

Model	Parameter	Expected Limit	Observed Limit
LQ best-fit LH+RH, g_U=1.0	m_{LQ}	645 GeV	515 GeV
LQ best-fit LH+RH, g_U=2.5	m_{LQ}	3.0 TeV	2.5 TeV

https://arxiv.org/abs/2103.16558

LQ-τ-q / ν-q

EXO-21-009
e-print arXiv:2212.12604



Model independent limits

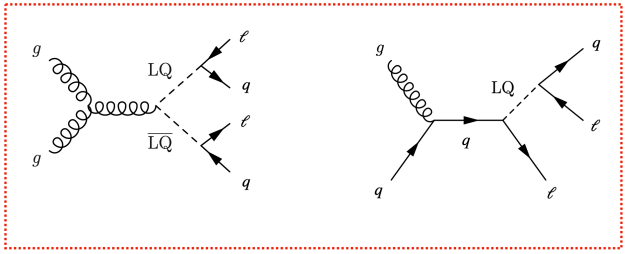
Signal efficiency includes the branching fraction of hadronic τ lepton decays and experimental efficiencies for the signal.

Valid for models with **back-to-back topology** of τ_h and p_T^{miss}

LQ-τ-b

EXO-19-016

- Targets **three production modes** simultaneously, with $\tau - \mathrm{b}$ couplings

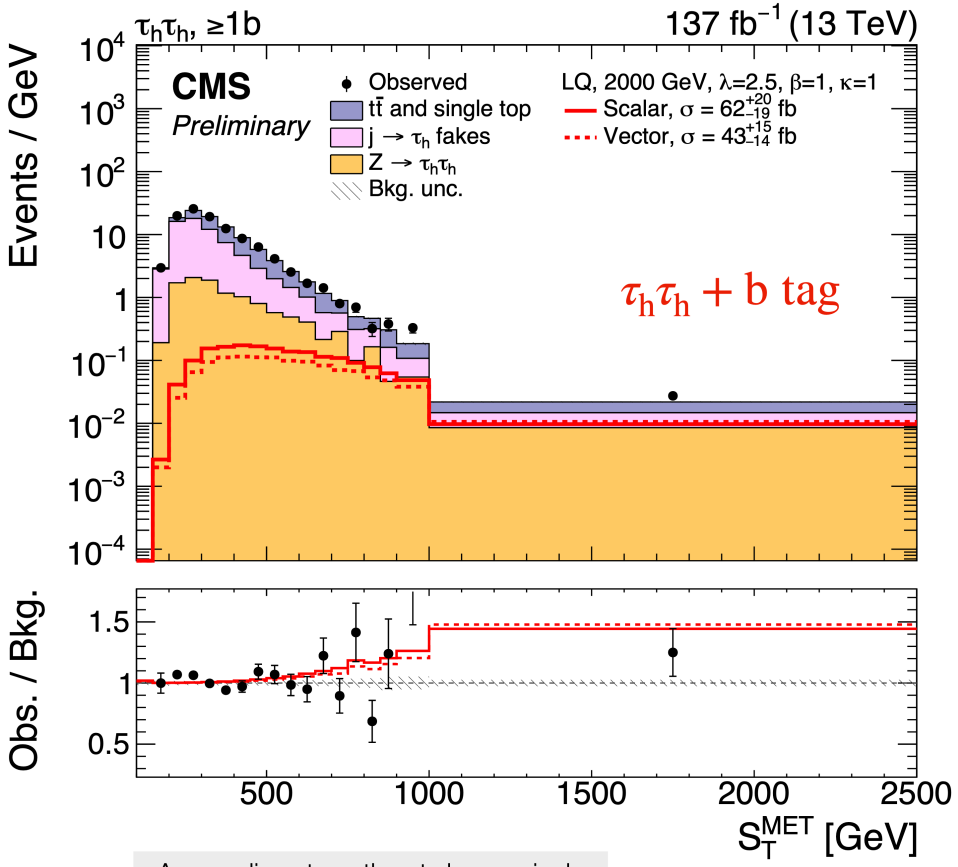


Resonant channels: $S_{\mathrm{T}}^{\mathrm{MET}}$

Nonresonant channel: χ

- Event selection:
  - **dilepton** signal regions ($\mathrm{e}\tau_{\mathrm{h}}$, $\mu\tau_{\mathrm{h}}$, $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$) **with(out)** a high p_{T} **jet**
  - light-flavored final states ($\mathrm{e}\mu$, $\mu\mu$) used as control selections
- Main categories:
  - **b-tagged** jet multiplicity (resonant ch.)
  - **visible mass** m_{vis} (200-400, 400–600, >600 GeV) (nonresonant ch.)
- Irreducible backgrounds are estimated by MC methods
  - normalized to theoretical cross-sections.
- **Data driven** estimate of **misidentified** lepton candidates (10-30%)
  - W+jets and QCD multijet contributions

$$S_{\mathrm{T}}^{\mathrm{MET}} \equiv p_{\mathrm{T}}(\tau_1) + p_{\mathrm{T}}(\tau_2) + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}^{\mathrm{miss}}$$

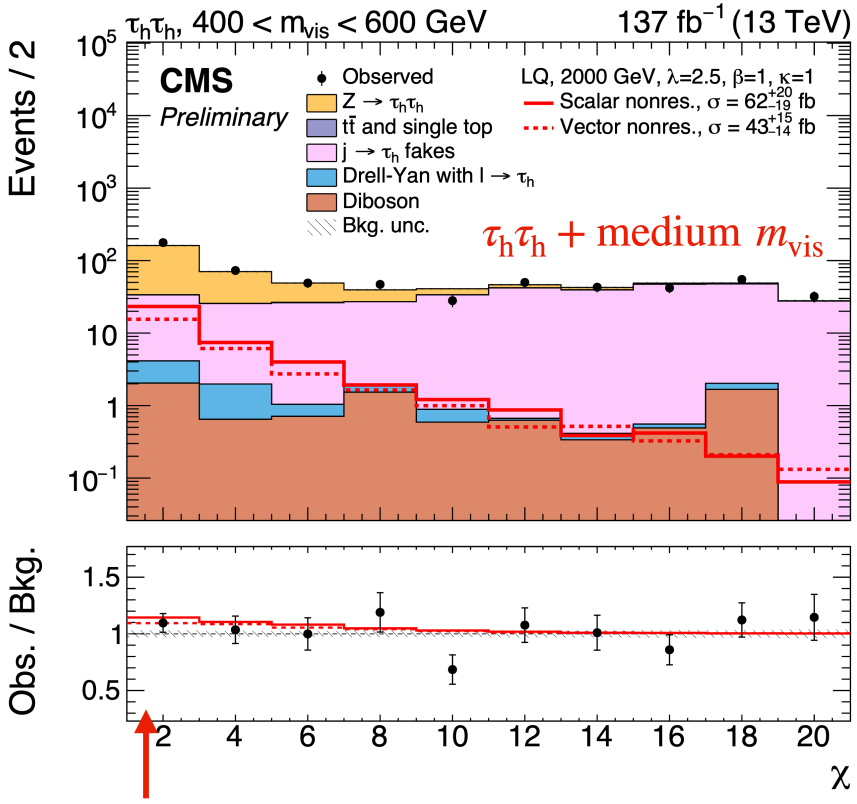


As coupling strength gets larger, single production moves towards lower $S_{\mathrm{T}}^{\mathrm{MET}}$

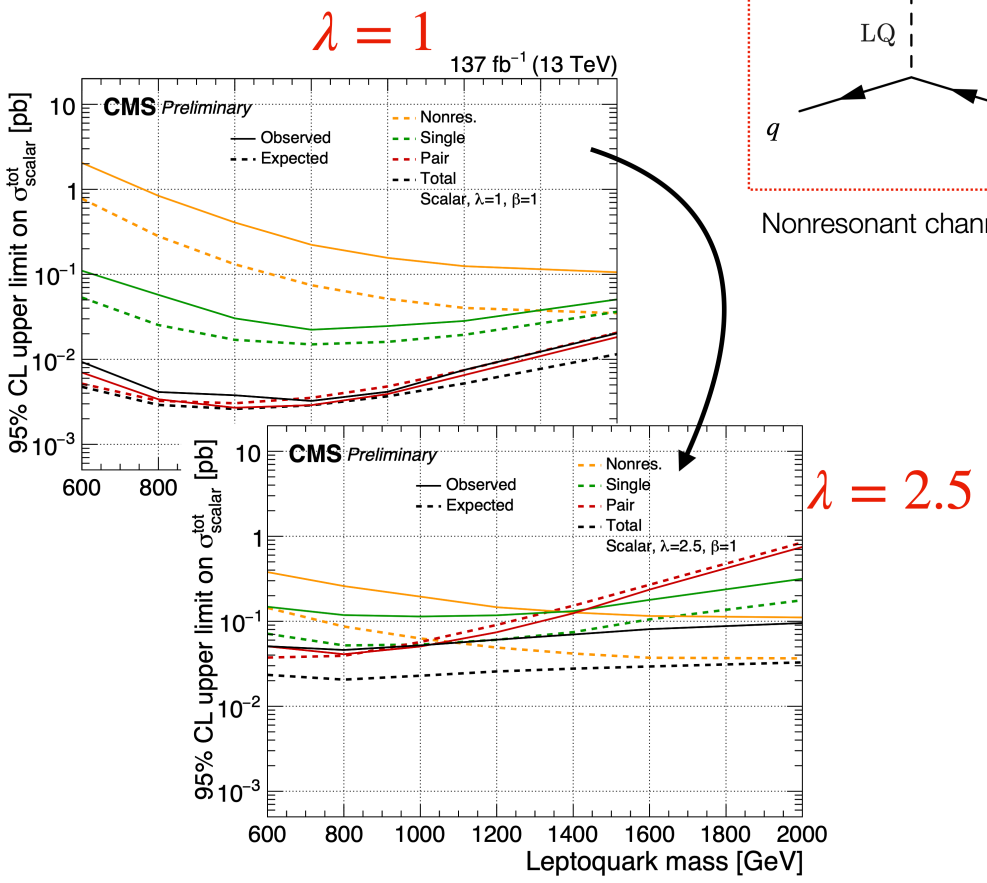
LQ-τ-b

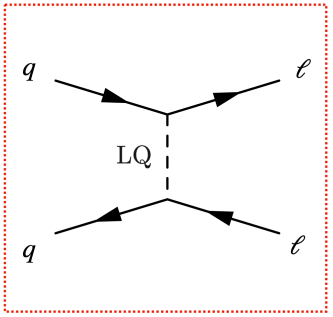
EXO-19-016

- **Angular χ variable** is used to probe **nonresonant** signal: $\chi \equiv \exp\left(|y(\tau_1) - y(\tau_2)|\right)$
- **LQ Yukawa coupling** dominate sensitivity at **large masse**



Small excess, with contributions from multiple dilepton channels



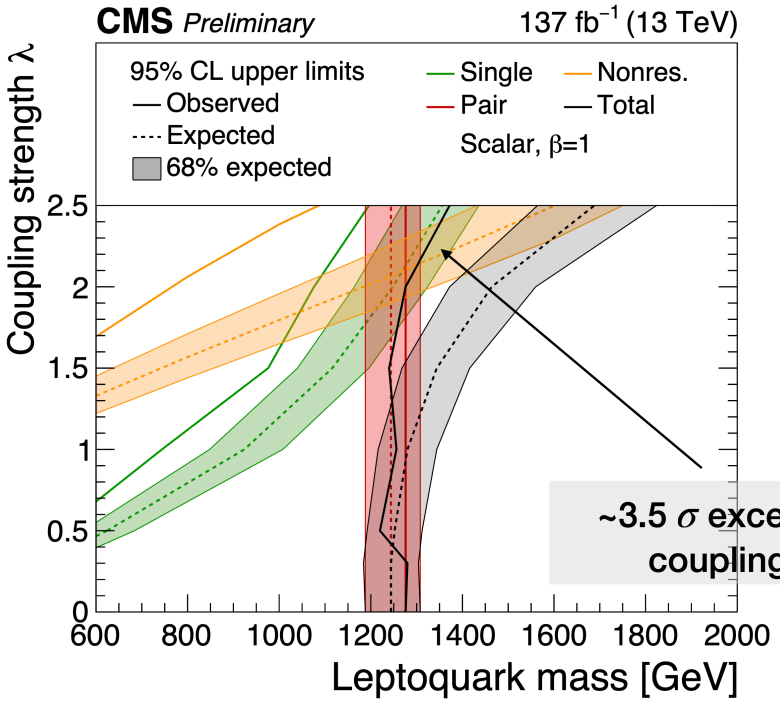


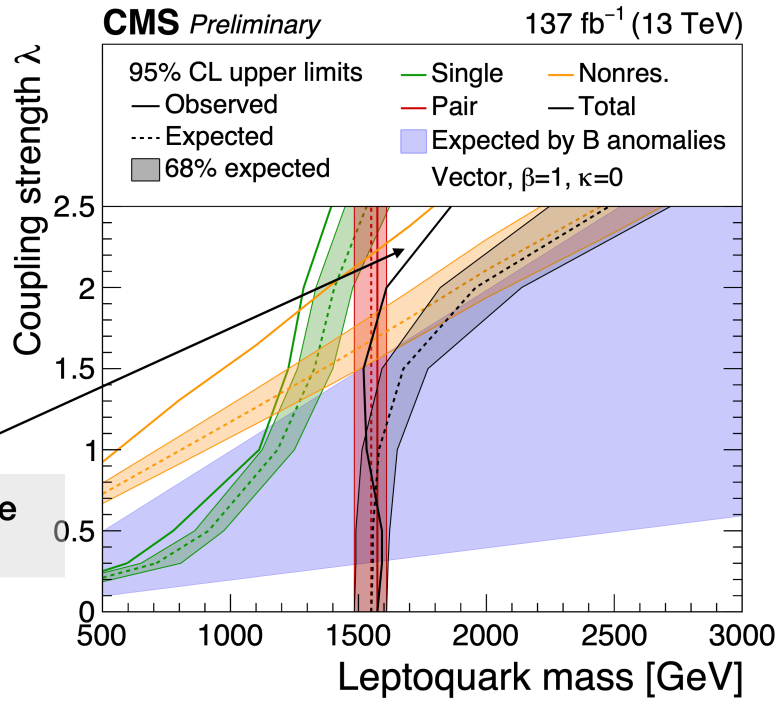
Nonresonant channel: χ

LQ-τ-b

EXO-19-016

Probing phase-space **favored by an LQ fit of the charged-current B decay anomalies**





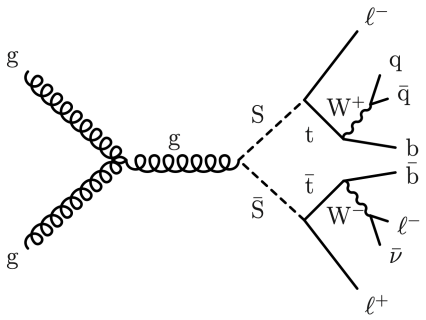
~3.5 σ excess at large coupling values

→ details are to **appear in a paper soon**!
- **not signal-like** in the strict sense of the probed LQ model
- mostly **insensitive to interference effects**, and **systematic uncertainties**

LQ-ℓ-t

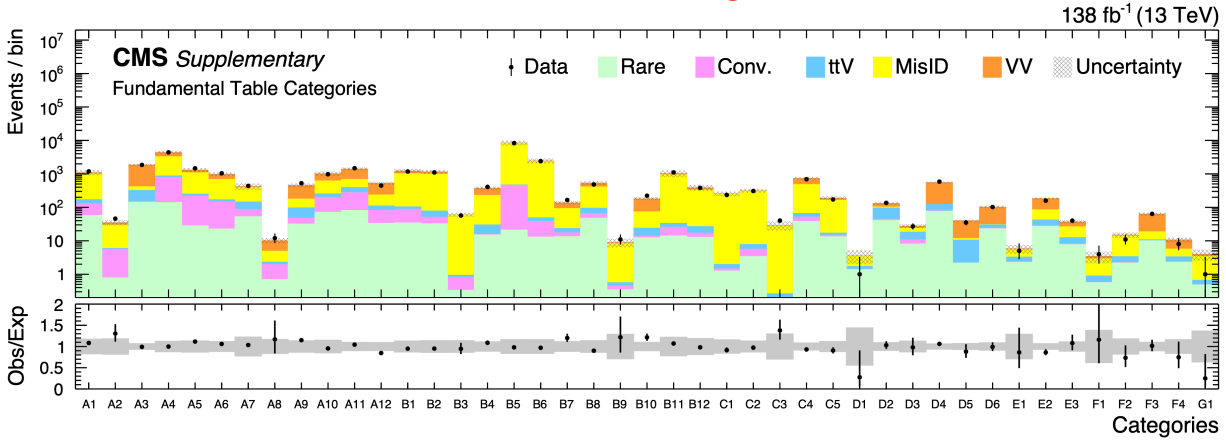
EXO-21-002
e-print arXiv:2202.08676

- A broad BSM search targeting **multilepton** events
  - Type-III seesaw heavy fermions
  - Vector-like leptons
  - **Leptoquarks (top-philic)**



- Event selection:
  - **three/four lepton** signatures (e, μ, τ_h) with minimum p_T of 10-20 GeV.
  - events are categories based on **lepton charge, mass, and flavor** characteristics.
- Irreducible bckg. processes are taken from simulation
  - WZ, ZZ, ttZ, ZG, (normalized to data)
- **Data driven** estimate of events with **misid. lepton**
  - jet $\rightarrow$ e, μ, τ_h (matrix method)

Inclusive categories

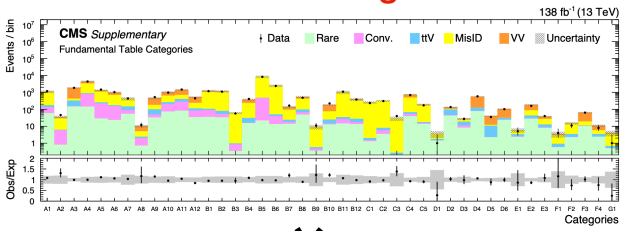


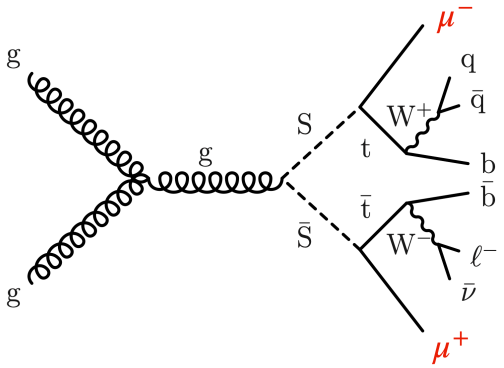
		OSSF0			OSSF1				OSSF2		
		BelowZ	AboveZ	SS	OnZ	BelowZ	AboveZ	MixedZ	Single-OnZ	Double-OnZ	OffZ
3L	Low p_T/M_T	A1	A1	A2	A3	A4	A5	A6	—	—	—
	High p_T/M_T	A7	A7	A8	A9	A10	A11	A12	—	—	—
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	—	—	—	—
	High p_T	B7	B8	B9	B10	B11	B12	—	—	—	—
1L2T		C1	C2	C3	—	C4	C5	—	—	—	—
4L		D1	D1	D1	D2	D3	D3	D3	D4	D5	D6
3L1T		E1	E1	E1	E2	E3	E3	E3	—	—	—
2L2T		F1	F1	F1	F2	F2	F2	—	F3	—	F4
1L3T		G1	G1	G1	—	G1	G1	—	—	—	—

LQ-ℓ-t

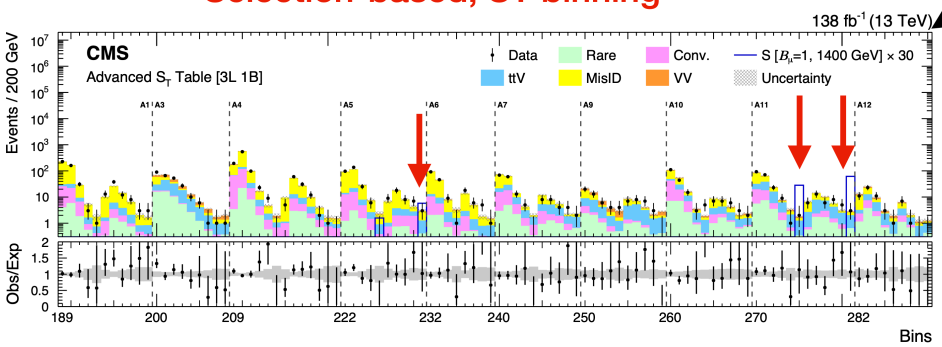
EXO-21-002
e-print arXiv:2202.08676

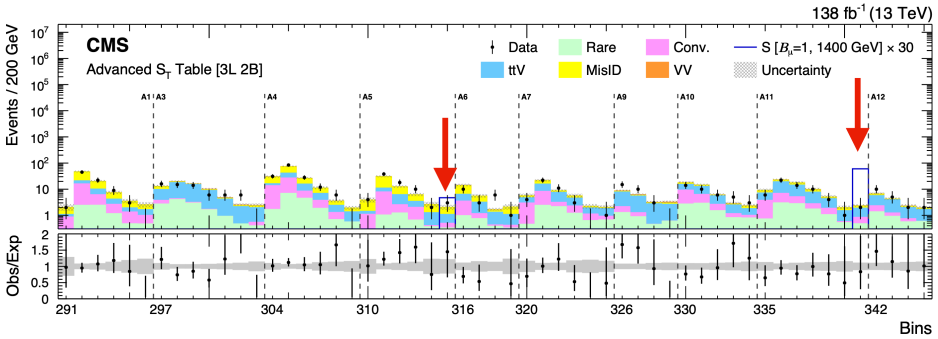
Inclusive categories

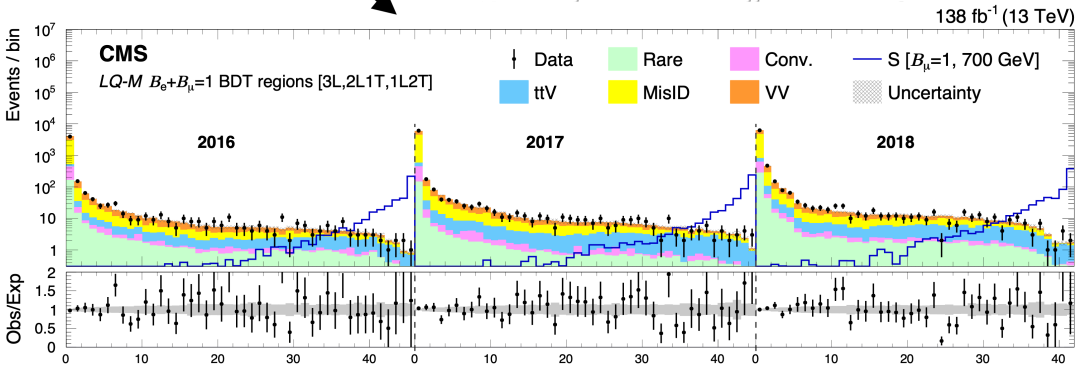




Selection-based, ST binning







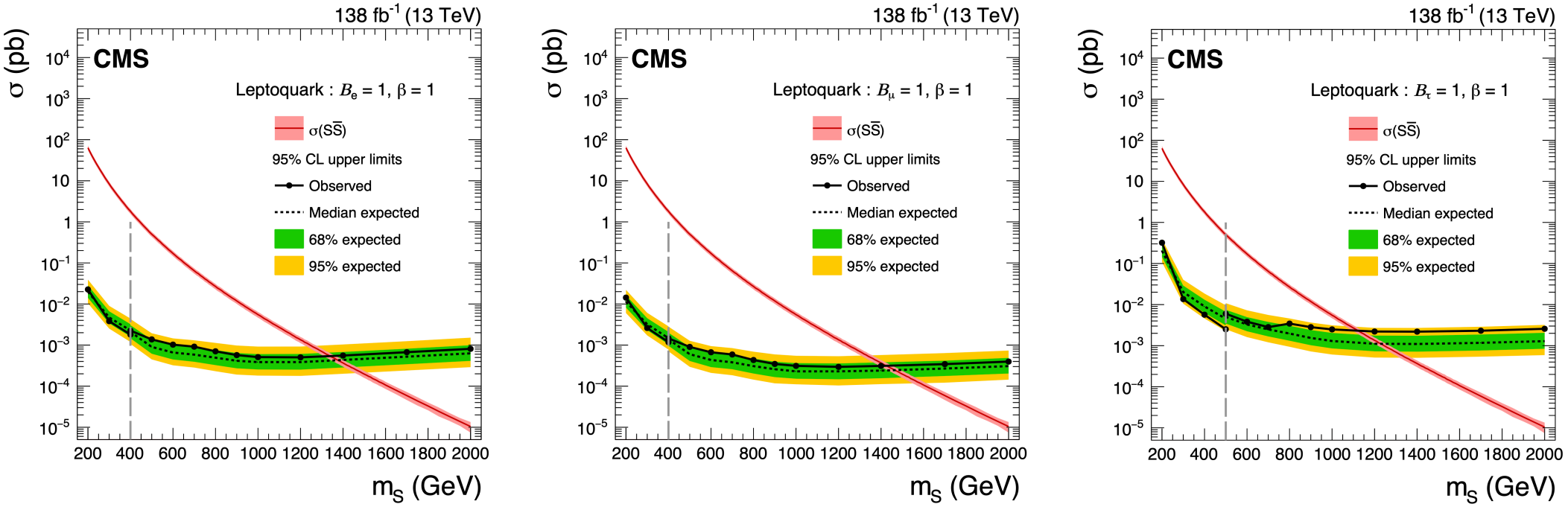
BDT-based binning

Signal discrimination via dual approach:

- selection based approach with L_T, p_T^{miss}, H_T, S_T (**transverse momentum variables**), and N_j, N_b
- machine learning based (**BDT**) discriminator is built for LQ signal (transverse or angular variables of physics objects

LQ-ℓ-t

EXO-21-002
e-print arXiv:2202.08676

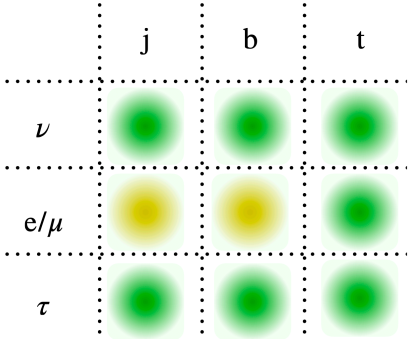


Limits on **pair-production** mode: $\mathrm{LQ} - \mathrm{e}/\mu - \mathrm{t} \sim 1.4$ TeV
$\mathrm{LQ} - \tau - \mathrm{t} \sim 1.1$ TeV

Summary

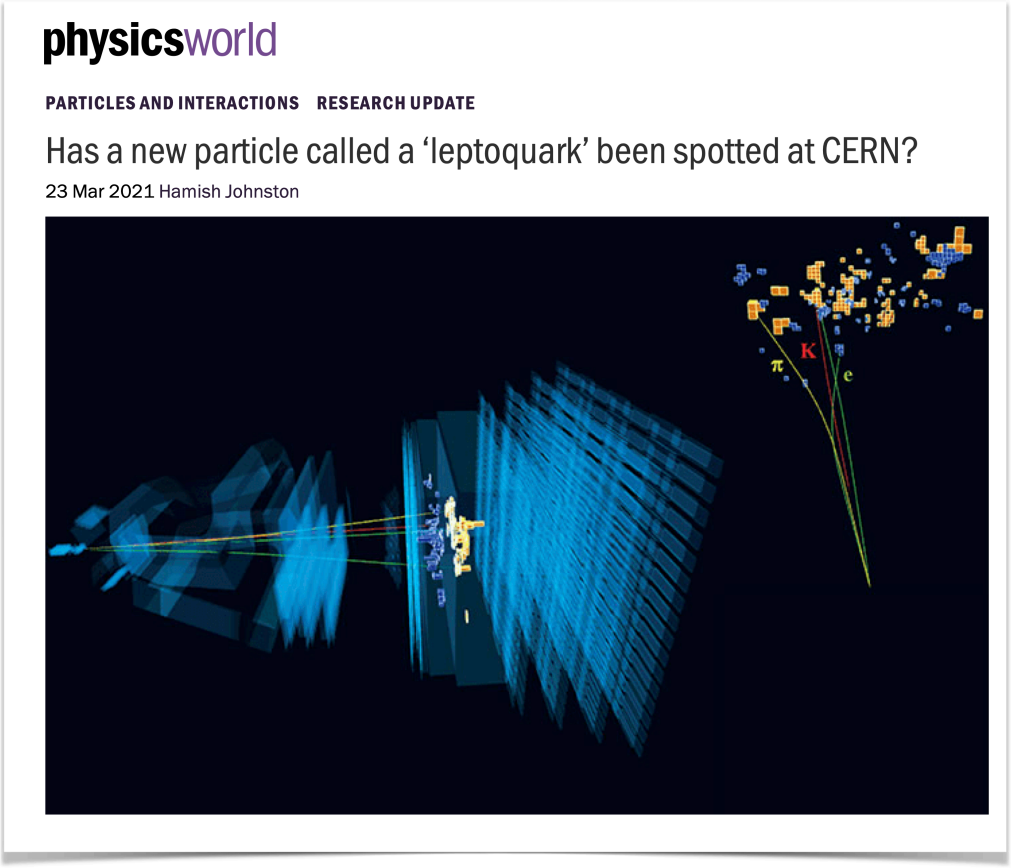
- **Leptoquarks** are among the **plausible/desirable extensions** of the SM boson sector:
  - matter **unification**
  - **revival** due to observed **tensions** in the **flavor sector**
  - provide **appealing detector signatures**

- A **multi-prong LQ search** program at CMS:
  - **lepton+jet & neutrino+jet** final states are both being targeted
  - models with **third generation fermion couplings**



- Breaking tradition with the most minimal models:
  - **non-QCD production** modes
  - flavor **off-diagonal** couplings
  - **simultaneous nonzero** couplings
  - *LQs with other BSM particles*

Stay tuned!


physicsworld

PARTICLES AND INTERACTIONS RESEARCH UPDATE

Has a new particle called a 'leptoquark' been spotted at CERN?

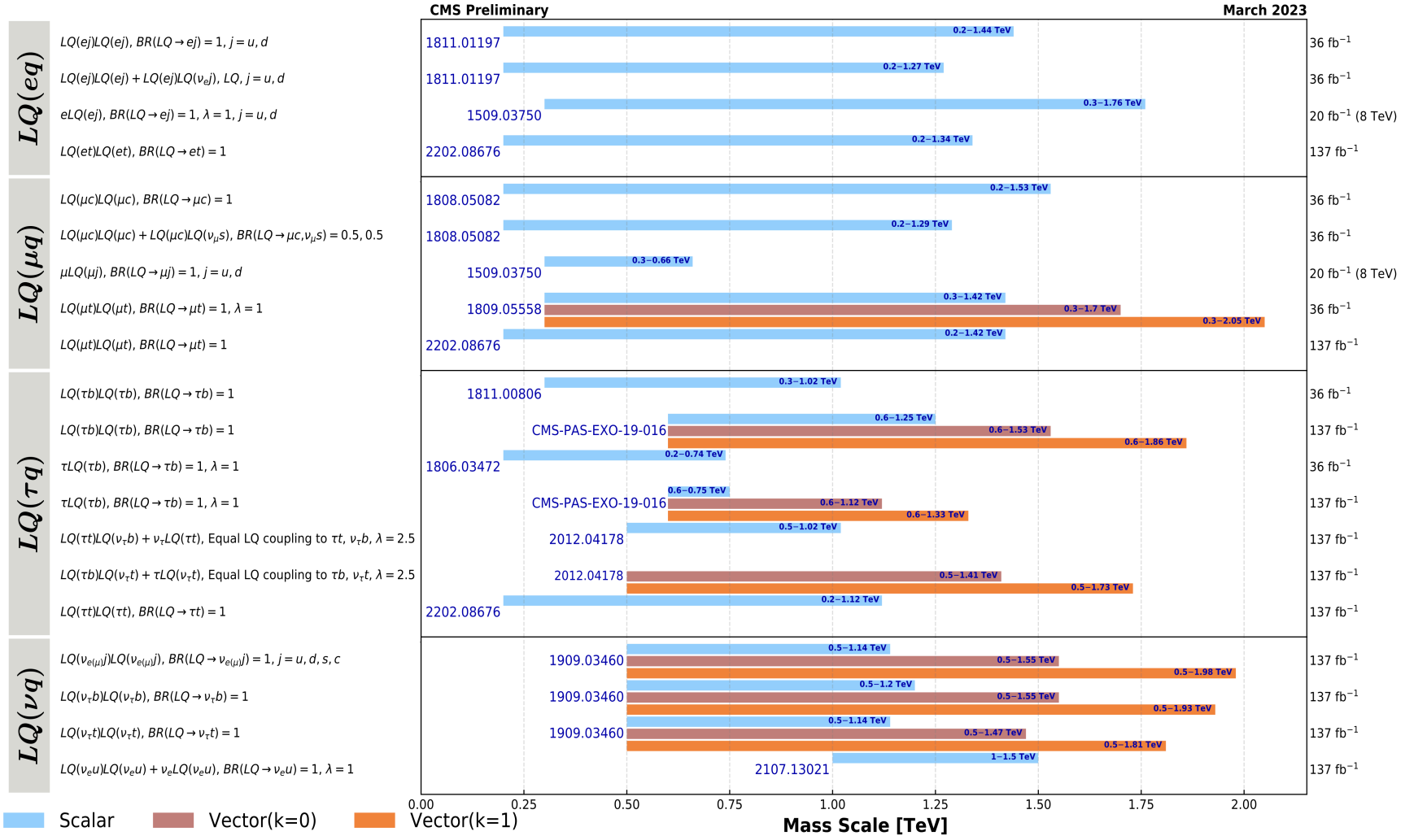
23 Mar 2021 Hamish Johnston

https://physicsworld.com/a/has-a-new-particle-called-a-leptoquark-been-spotted-at-cern/

Backup

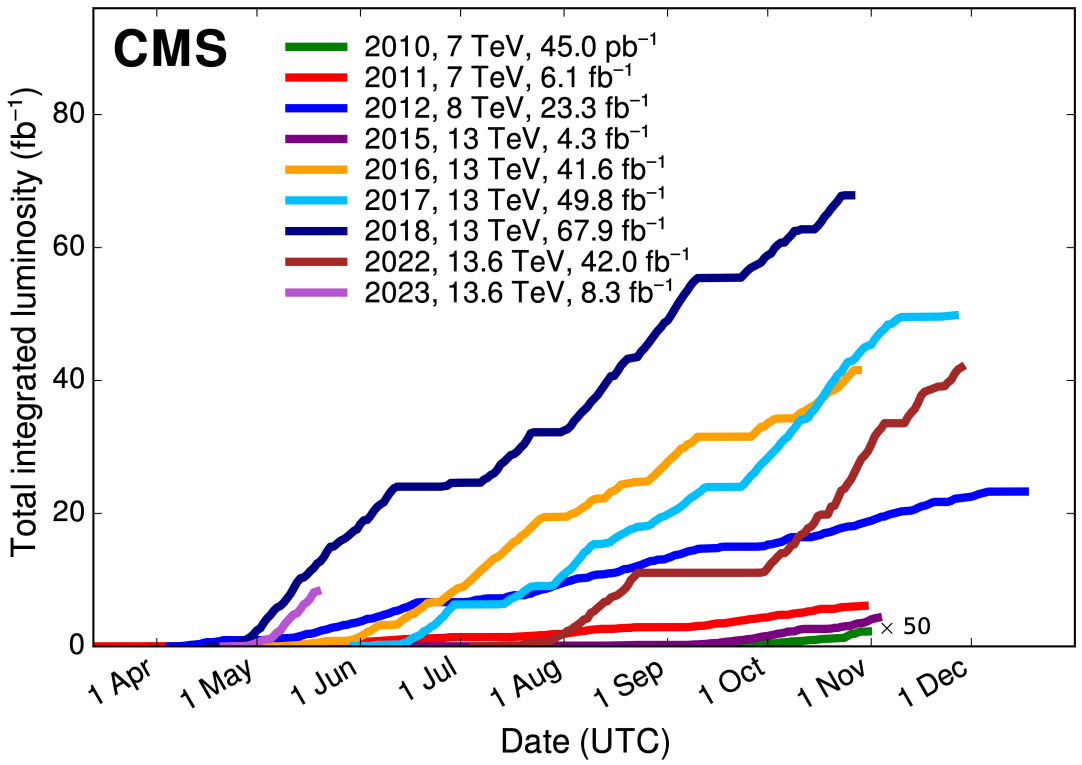
Overview of CMS LQ search program

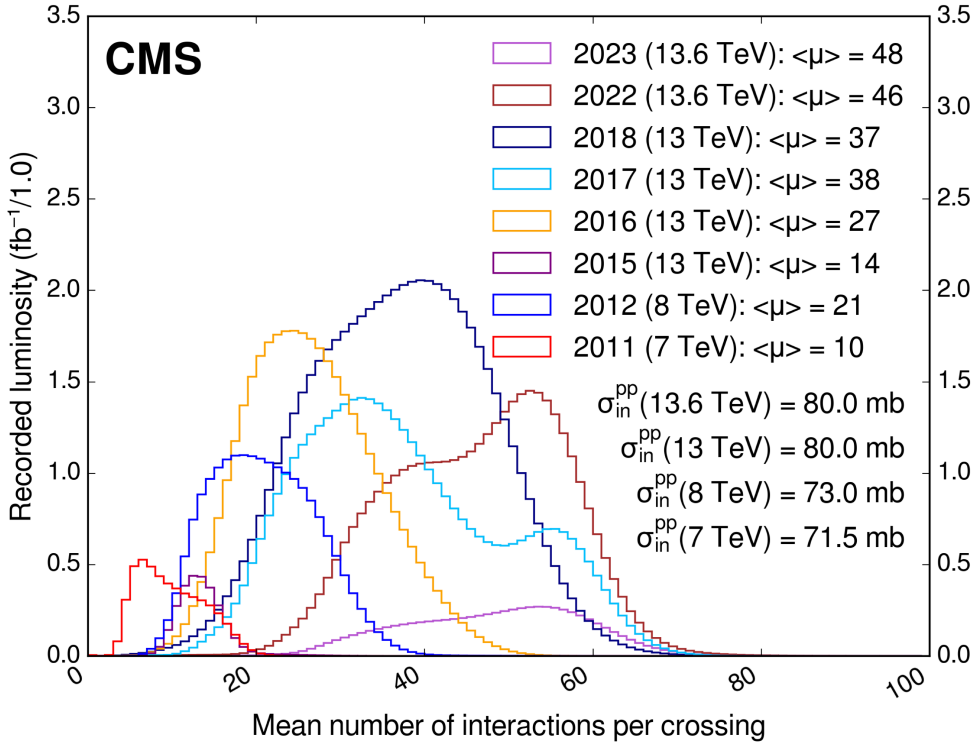
CMS Summary Plots



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Run1+2+3 pp collisions at a glance



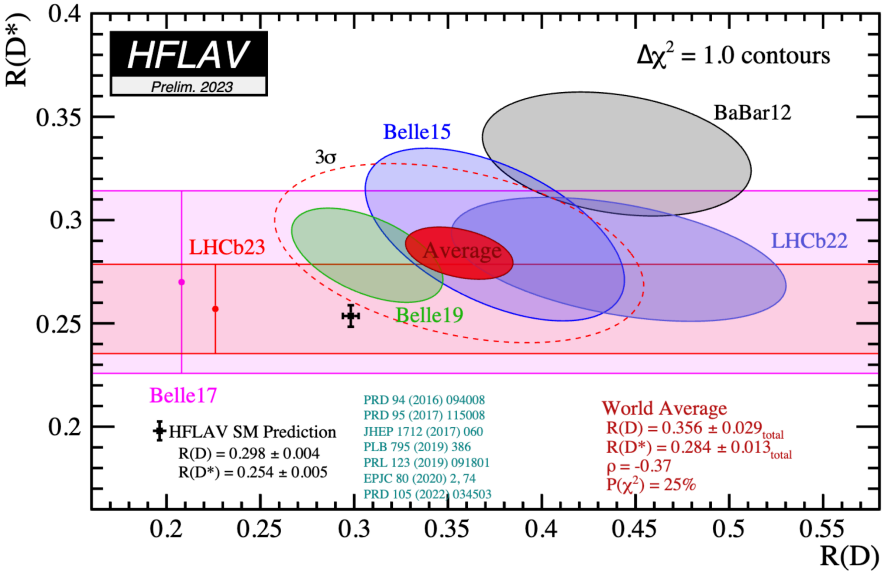


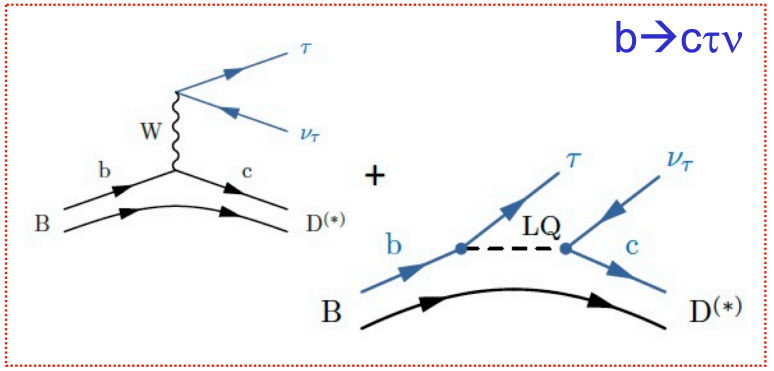
Leptoquark representations in mBRW

Leptoquark	Spin	F	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ representation	Q_{EM}	Coupling		Decay mode
S_1	0	2	$(\mathbf{3},\mathbf{1},-2/3)$	$-1/3$	$\lambda_{L,R}(u, e_{L,R})$,	$-\lambda_L(d, \nu_e)$	$t\tau^-$, $b\nu$
$\tilde{S}_1$	0	2	$(\mathbf{3},\mathbf{1},-8/3)$	$-4/3$	$\lambda_R(d, e_R)$		$b\tau^-$
S_2	0	0	$(\overline{\mathbf{3}},\mathbf{2},-7/3)$	$-2/3$ $-5/3$	$\lambda_L(u, \nu_e)$, $\lambda_{L,R}(u, e_{L,R})$	$\lambda_R(d, e_R)$	$\bar{t}\nu$, $b\tau^+$ $\bar{t}\tau^-$
$\tilde{S}_2$	0	0	$(\overline{\mathbf{3}},\mathbf{2},-1/3)$	$+1/3$ $-2/3$	$\lambda_L(d, \nu_e)$ $\lambda_L(d, e_L)$		$\bar{b}\nu$ $\bar{b}\tau^-$
S_3	0	2	$(\mathbf{3},\mathbf{3},-2/3)$	$+2/3$ $-1/3$ $-4/3$	$\sqrt{2}\lambda_L(u, \nu_e)$ $-\lambda_L(u, e_L)$, $-\sqrt{2}\lambda_L(d, e_L)$	$-\lambda_L(d, \nu_e)$	$t\nu$ $t\tau^-$, $b\nu$ $b\tau^-$
V_1	1	0	$(\overline{\mathbf{3}},\mathbf{1},-4/3)$	$-2/3$	$\lambda_{L,R}(d, e_{L,R})$,	$\lambda_L(u, \nu_e)$	$\bar{b}\tau^-$, $\bar{t}\nu$
$\tilde{V}_1$	1	0	$(\overline{\mathbf{3}},\mathbf{1},-10/3)$	$-5/3$	$\lambda_R(u, e_R)$		$\bar{t}\tau^-$
V_2	1	2	$(\mathbf{3},\mathbf{2},-5/3)$	$-1/3$ $-4/3$	$\lambda_L(d, \nu_e)$, $\lambda_{L,R}(d, e_{L,R})$	$\lambda_R(u, e_R)$	$b\nu$, $t\tau^-$ $b\tau^-$
$\tilde{V}_2$	1	2	$(\mathbf{3},\mathbf{2},+1/3)$	$+2/3$ $-1/3$	$\lambda_L(u, \nu_e)$ $\lambda_L(u, e_L)$		$t\nu$ $t\tau^-$
V_3	1	0	$(\overline{\mathbf{3}},\mathbf{3},-4/3)$	$+1/3$ $-2/3$ $-5/3$	$\sqrt{2}\lambda_L(d, \nu_e)$ $-\lambda_L(d, e_L)$, $\sqrt{2}\lambda_L(u, e_L)$	$\lambda_L(u, \nu_e)$	$\bar{b}\nu$ $\bar{b}\tau^-$, $\bar{t}\nu$ $\bar{t}\tau^-$

Table 2.1: Scalar and vector LQs as defined in the mBRW model. Representations under the SM gauge group are labelled by the dimensions of $SU(3)_C$ and $SU(2)_L$ representations, and the $U(1)_Y$ hypercharge Y, respectively. Fermion number is defined as $F = 3B + L$, and electric charge, $Q_{EM} = T^3 + Y/2$, is in units of proton charge, $|e|$, where T^3 is the third eigenvalue component of the SU(2) representation. Decay mode is provided assuming third generation LQs only.

The flavor issue: $R(D^{(*)}), R(K^{(*)})$





$R(D^*) = \beta(B \to D^* \tau^- \nu_\tau) / \beta(B \to D^* \mu^- \nu_\mu)$

The deviation w.r.t. the SM at **3.2σ** for the combination of $R(D)$-$R(D^*)$

https://hflav.web.cern.ch/content/semileptonic-b-decays

https://cds.cern.ch/record/2857546 (LHCb-PAPER-2022-052, for the most recent measurement)

Best-fit scenarios to 'b anomalies'

HIG-21-001
EXO-19-016

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \quad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}$$

$$J_\mu^U = \beta_L^{i\alpha} \left(\overline{q}_L^i \gamma_\mu \ell_L^\alpha \right) + \beta_R^{i\alpha} \left(\overline{d}_R^{i\alpha} \gamma_\mu e_R^\alpha \right)$$

ex/ https://arxiv.org/abs/2103.16558

Best-fit LH couplings

$$\beta_L = \begin{pmatrix} 0 & 0 & -0.04 \\ 0 & 0.014 & 0.19 \\ 0 & -0.15 & 1 \end{pmatrix}, \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Best-fit LH+RH couplings

$$\beta_L = \begin{pmatrix} 0 & 0 & -0.04 \\ 0 & 0.03 & 0.21 \\ 0 & -0.21 & 1 \end{pmatrix}, \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

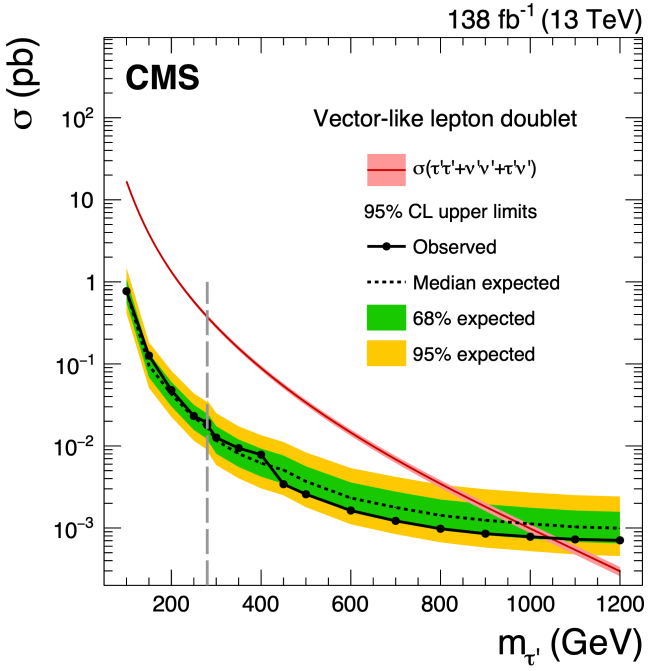
Democratic couplings

$$\beta_L = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

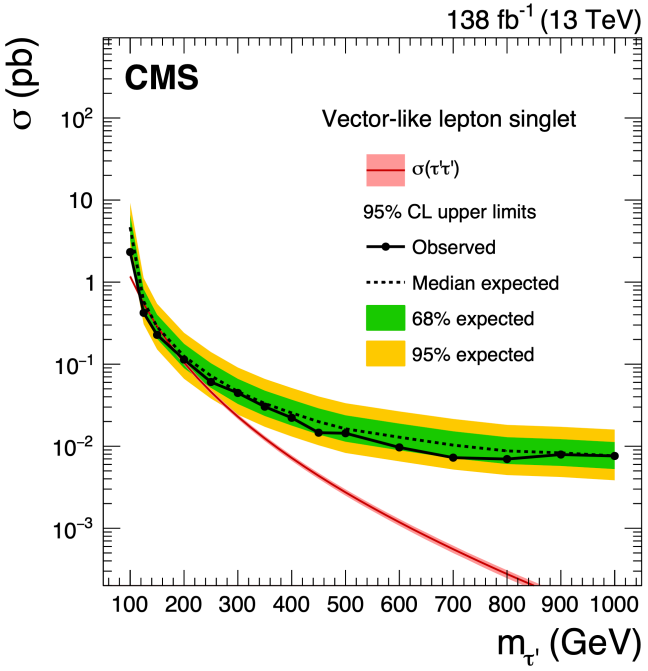
VLL / Type-III Seesaw

EXO-21-002
e-print arXiv:2202.08676

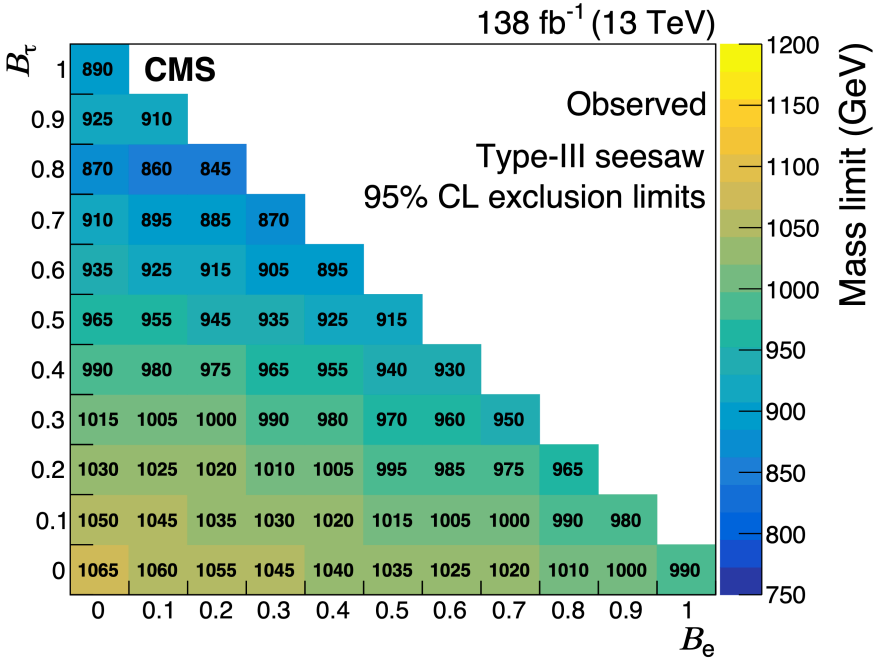
Doublet : τ', ν'



Singlet : τ'



$\Sigma^{\pm}\Sigma^{0}$

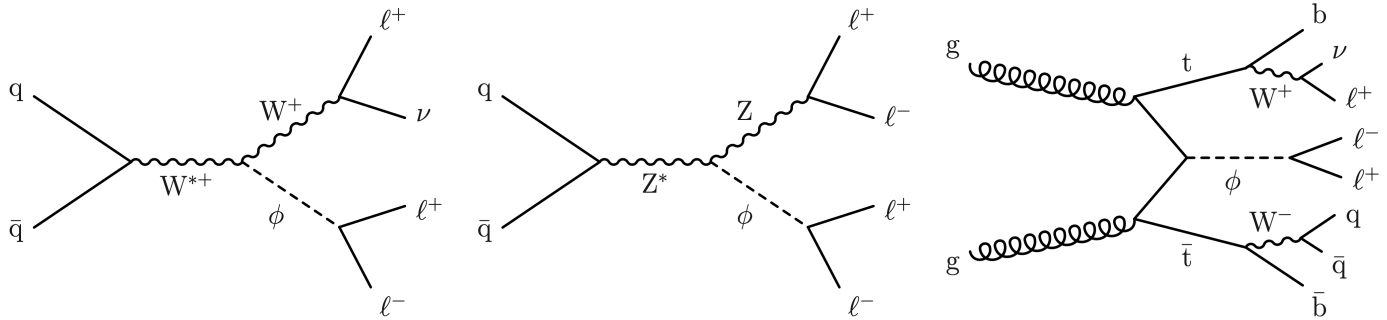


Limits on **VLL** doublet ~ 1 TeV
singlet ~ around 125-170 GeV

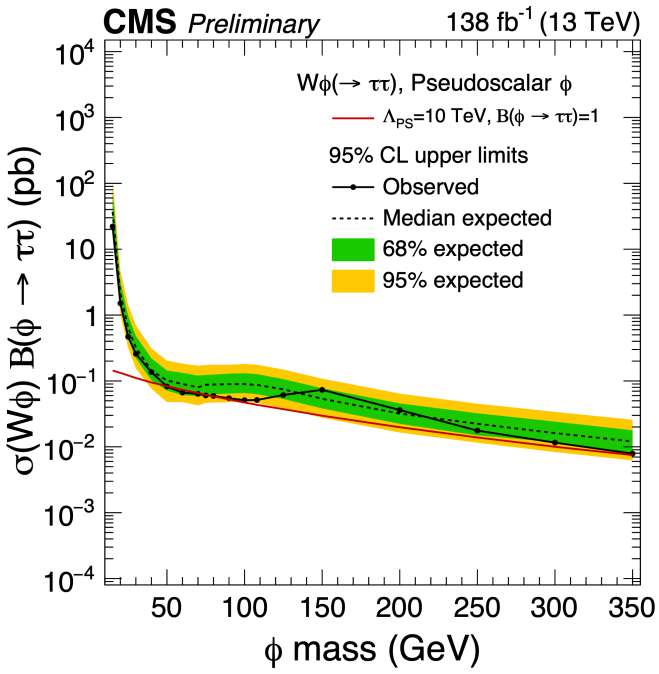
Limits on **Type-III Seesaw** heavy fermions:
~890-1065 GeV (per flavor scenario)

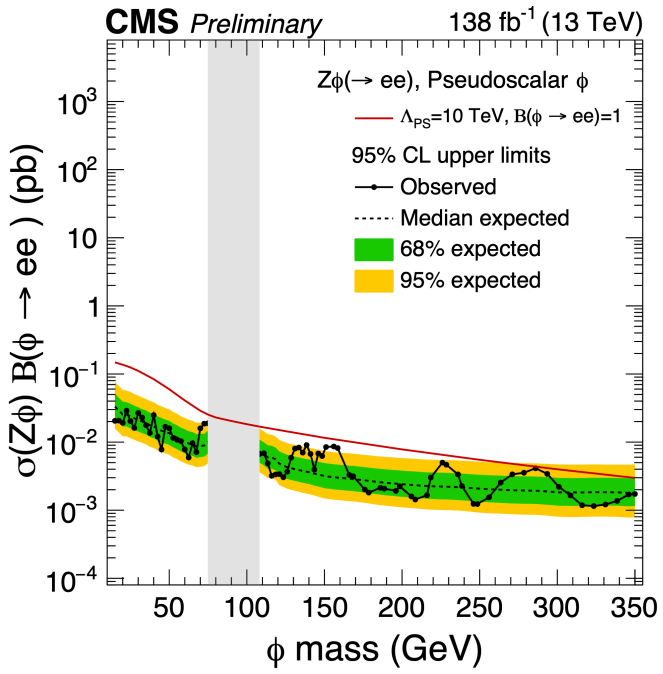
Resonances in multilepton events

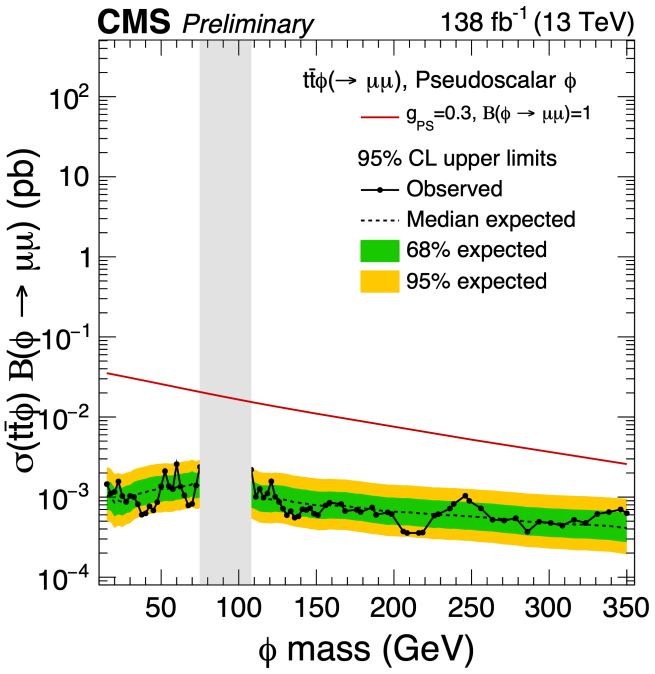
EXO-21-018



Same machinery as in EXO-21-002

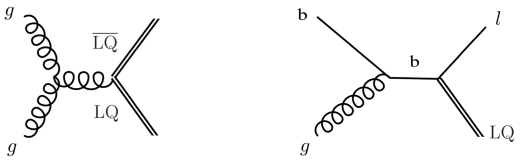




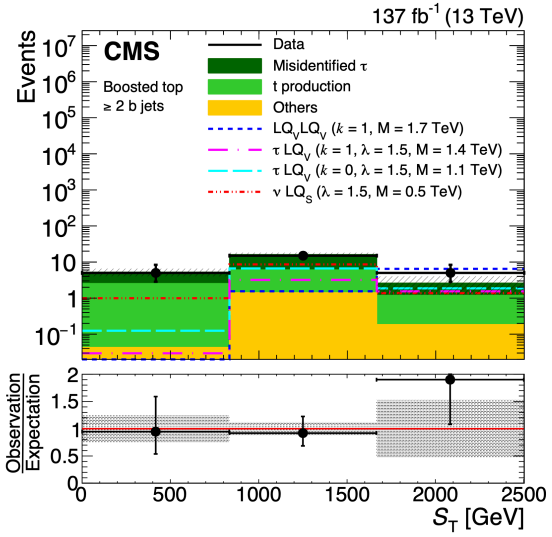


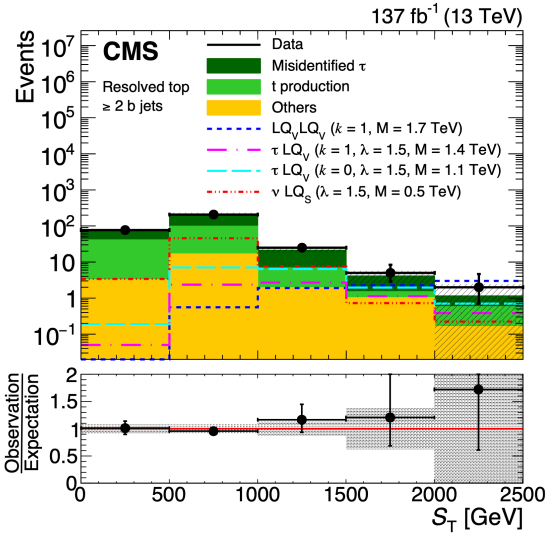
LQ-τ-b / ν-t

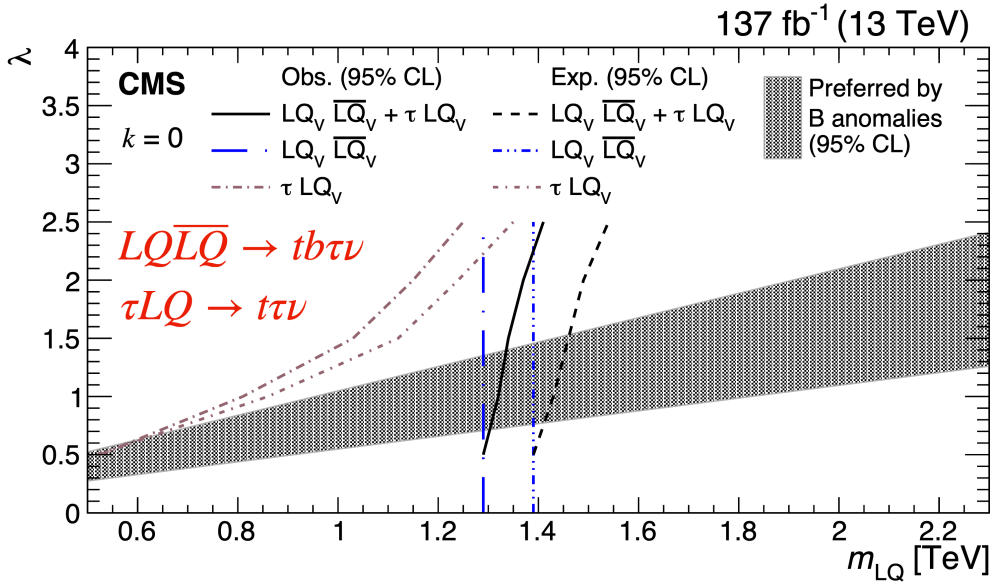
EXO-19-015



- "**Third** generation" **vector leptoquarks**
  - **pair + single** production mode, with $\beta = 0.5$
  - Couplings only to third generation fermions ($b\tau, t\nu$ or $b\nu, t\tau$)
- Dilepton final state, with **resolved/merged top** quark decays $\rightarrow t\tau\nu(b)$

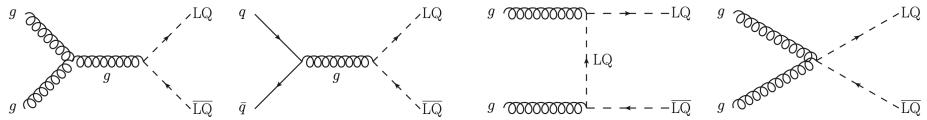






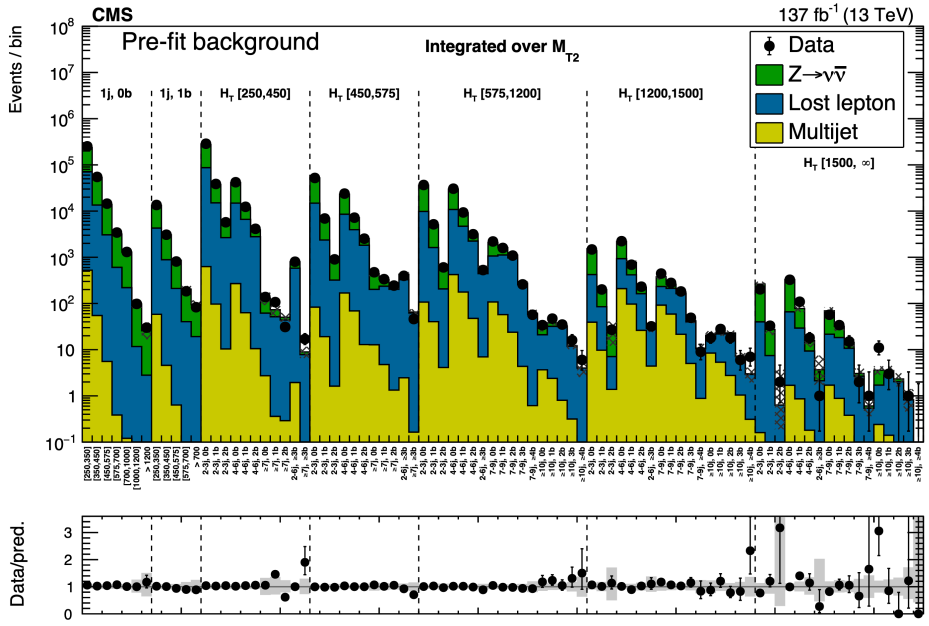
Most stringent limits on LQ mass ~1.4 TeV for $\beta = 0.5$

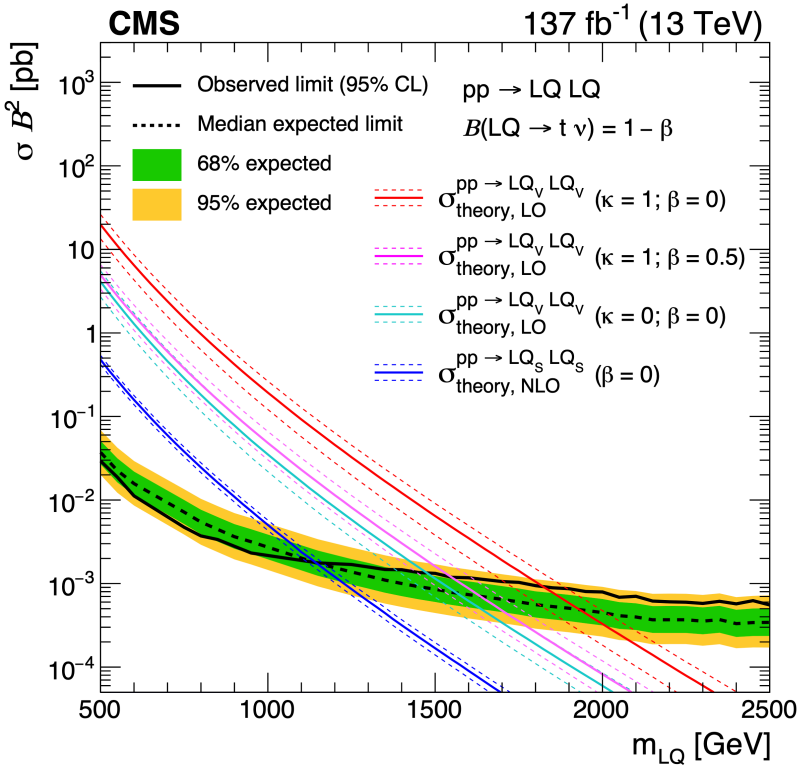
LQ-ν-q



SUS-19-005

- Targeting final states with **high hadronic activity** (jets and $p_{\mathrm{T}}^{\mathrm{miss}}$)
  - categories (b-tagged) jet multiplicity, and H_{T}
  - background estimated by data driven methods (lost lepton, QCD, $\mathrm{Z} \to \nu\nu$)





Constraints on $\mathrm{LQ} \to \mathrm{q}\nu$ decays for **all quark flavors**!

LQ-τ-b

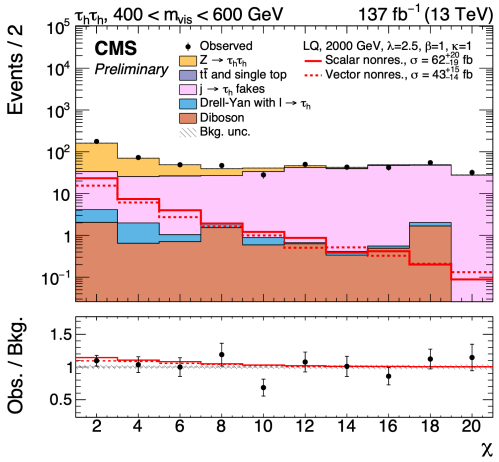
EXO-19-016

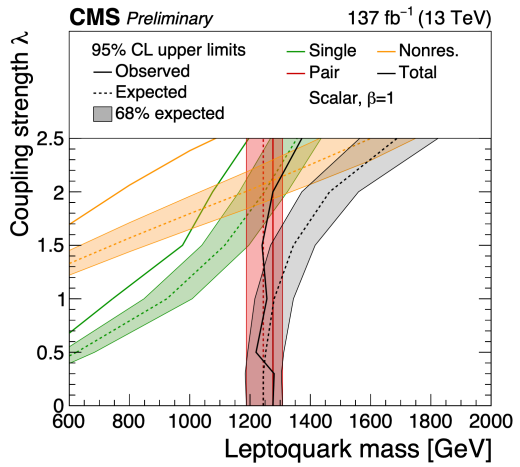
Table 2: Best-fit LQ cross sections σ for various masses and coupling strengths λ, and the corresponding significance z (given in standard deviations) for different production modes individually, as well as their combination.

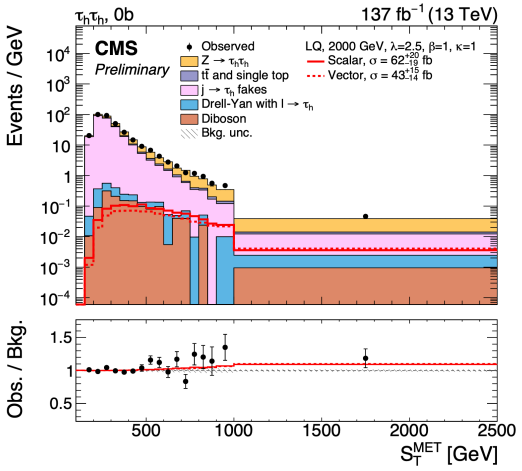
Signal	$m_{LQ} = 1400$ GeV		$m_{LQ} = 2000$ GeV	
	σ [pb]	z	σ [fb]	z
Scalar				
Pair	$0.24^{+0.47}_{-0.45}$	0.5	$0.22^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.15^{+0.95}_{-0.92}$	1.3	$0.64^{+0.68}_{-0.65}$	1.0
Single, $\lambda = 2.5$	$9.1^{+5.6}_{-5.3}$	1.7	18^{+11}_{-11}	1.7
Nonres.	70^{+23}_{-22}	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

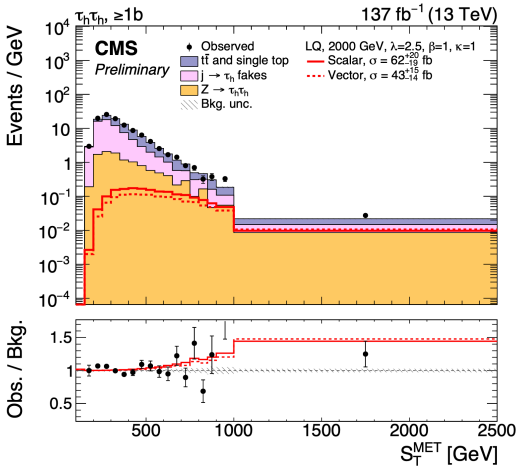
Criteria	Resonant		Nonresonant
	0b	≥1b	0j
Number of jets, $p_T > 50$ GeV	≥1j	≥1j	0
Number of b tags, $p_T > 50$ GeV, loose DeepCSV	0	≥ 1	0
`DeepTau2017v2p1VSjet`	Medium		
`DeepTau2017v2p1VSe`	Loose ($e\tau_h$)/ VVLoose ($\mu\tau_h$, $\tau_h\tau_h$)		
`DeepTau2017v2p1VSmu`	VLoose		
Extra lepton vetoes	Yes		Yes
Opposite charge	Yes		Yes
p_T of τ decay candidates	> 50 GeV		> 50 GeV
m_{vis}	> 100 GeV		Binned in $[200, 400, 600, +\infty[$
$\lvert\eta_\ell + \eta_{\ell'}\rvert/2$	—		< 1.1
$\Delta\eta_{\ell\ell'}$	—		< 3
Discriminating variable	S_T^{MET}		χ

Scalar interpretation





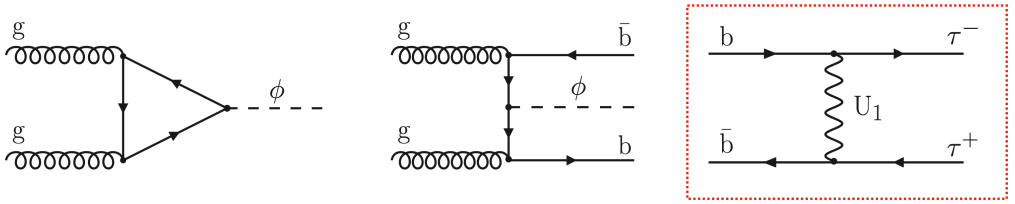




LQ-τ-b

HIG-21-001

- A broad search targeting **resonant and nonresonant ditau** signatures
  - **Vector leptoquark** with enhanced **LQ-tau-b/s** couplings (bb, bs, ss initiated production)

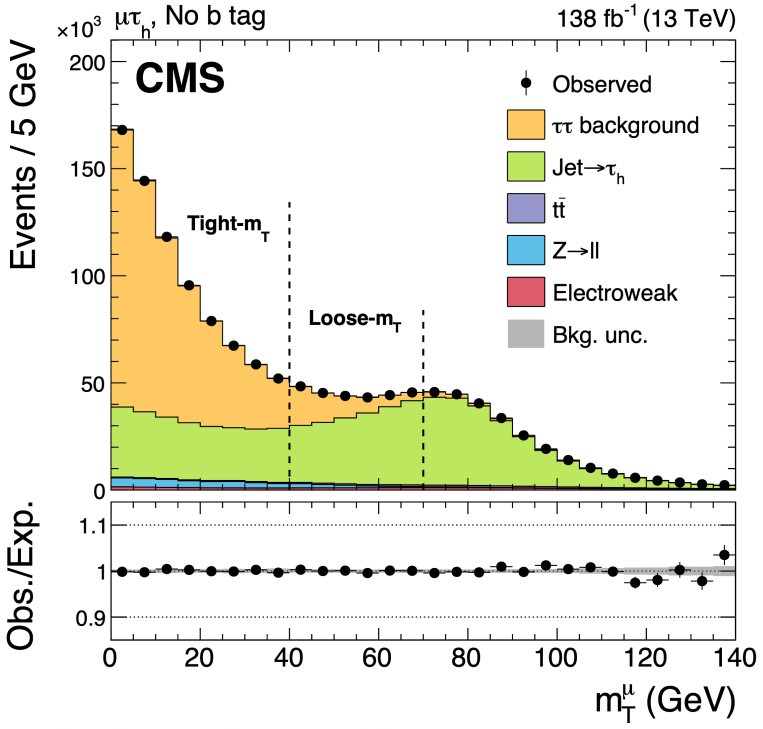


- Event selection:
  - **two lepton** final states ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)
  - events with additional e/μs are vetoed
  - two categories: 0, >0 "b-tagged" jets
  - further categorization on lepton-p_T^{miss} based variables (e.g. m_T)

- "**Tau-embedding**" for irreducible pp $\rightarrow \tau\tau$ background
  - Muons in pp $\rightarrow \mu\mu$ events are replaced with "simulated" tau lepton decays

- **Data driven** estimate of events with lepton **misID**
  - jet $\rightarrow$ e, μ, (same sign method), jet $\rightarrow \tau_h$ (fake factor)
  - typical uncertainty are $\mathcal{O}(10)$ %

- Other (irreducible) backgrounds are estimated by MC simulation



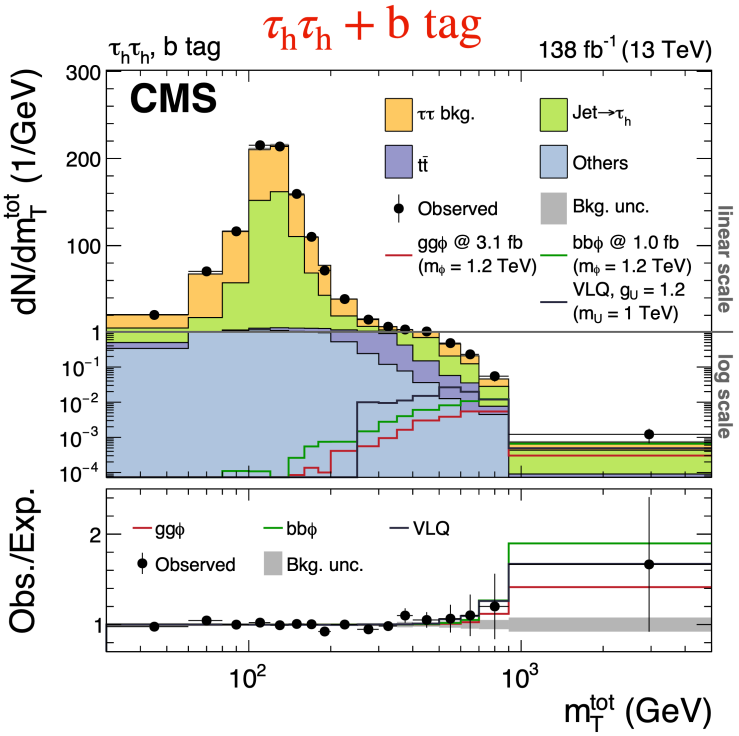
Background composition:

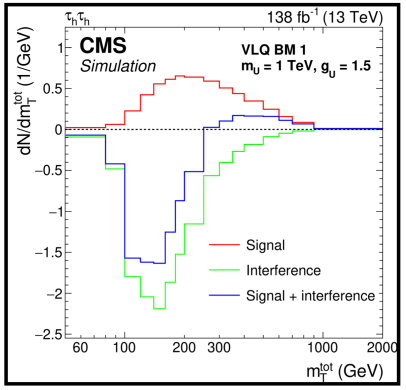
0 b-tagged jet: Z, jet $\rightarrow$ tau MisID (Loose-m_T)

>0 b-tagged jet: tt

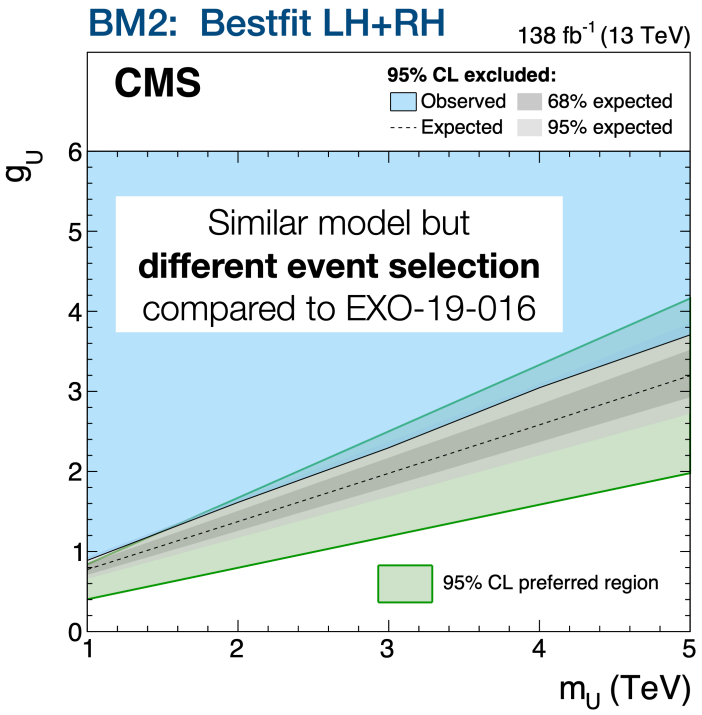
LQ-τ-b

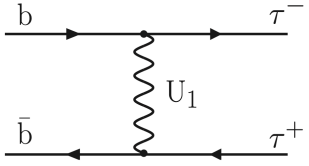
HIG-21-001





SM interference
→ reduced sensitivity at high mass.





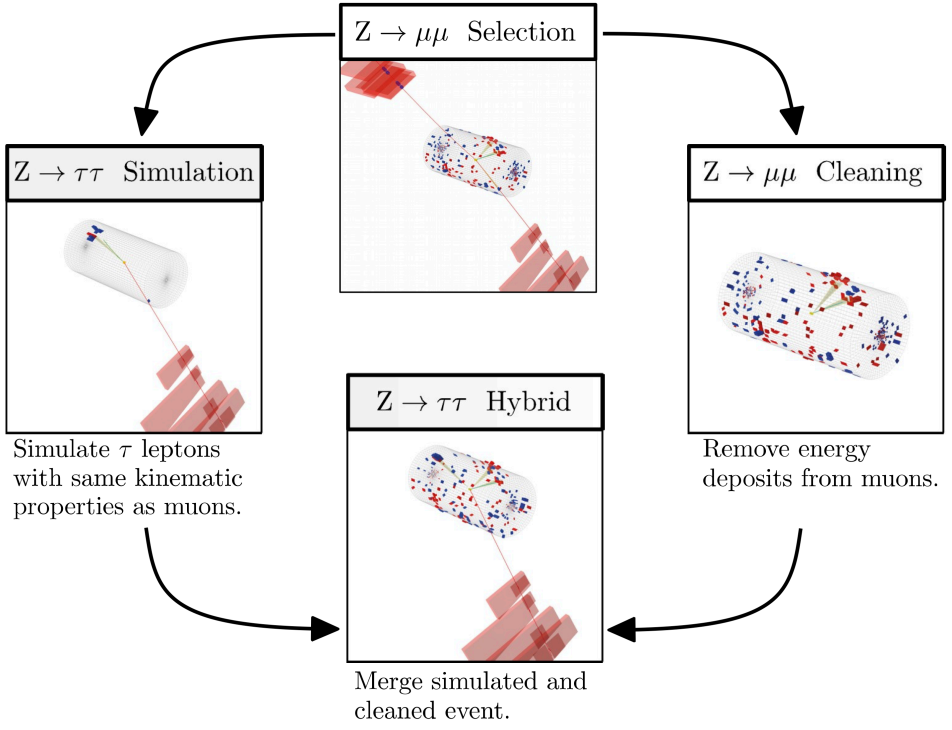
Signal discrimination:

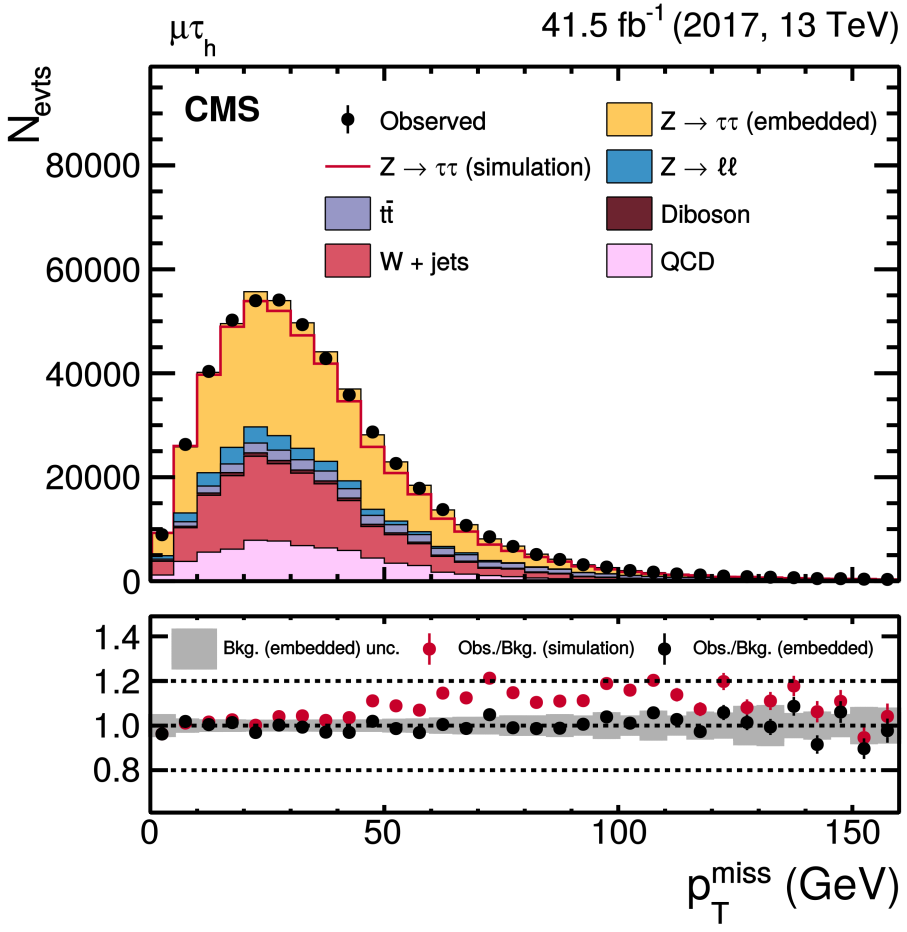
- total transverse mass m_T^{tot} is used as the final discriminant.

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

Tau embedding ($pp \to \tau\tau$)

TAU-18-001





Embedding technique eliminates possible issues with underlying event description, pileup contributions, or production of associated jets .

Summary plots from ATLAS on $LQ\overline{LQ}$

ATL-PHYS-PUB-2023-006