Searches for new physics with leptons using the ATLAS detector

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on behalf of ATLAS Collaboration

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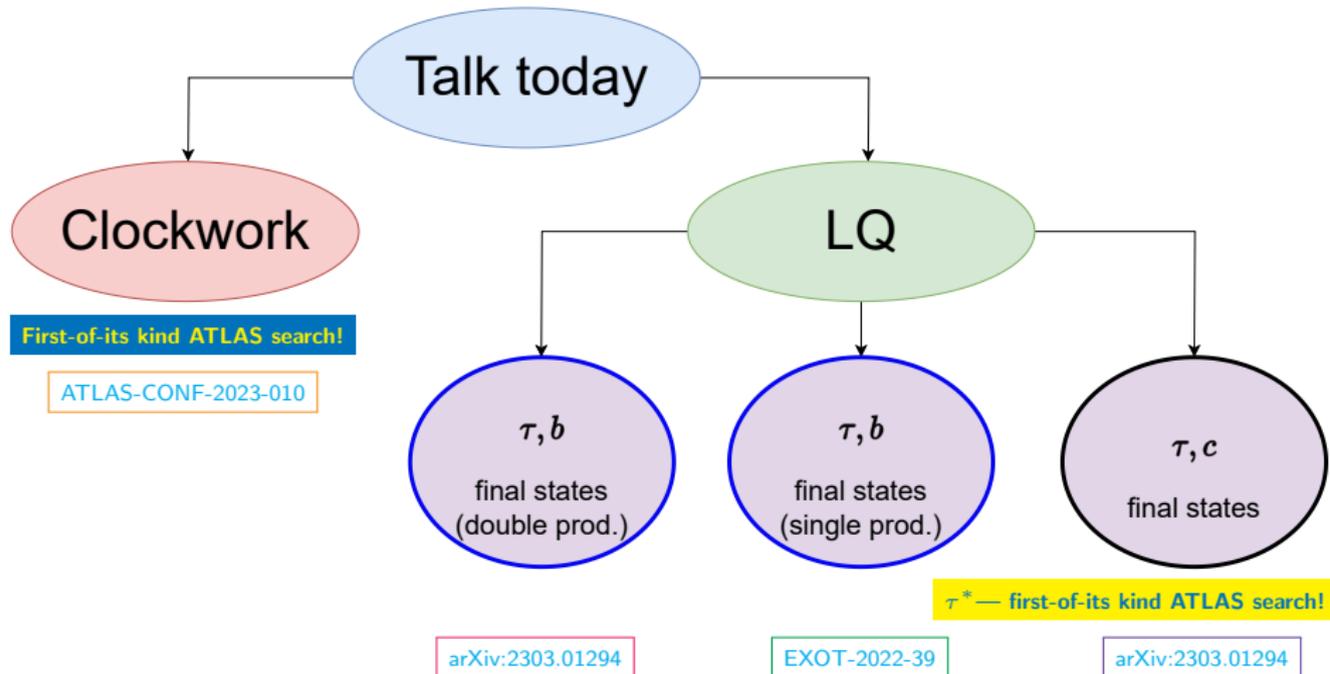Pheno2023, Pittsburgh
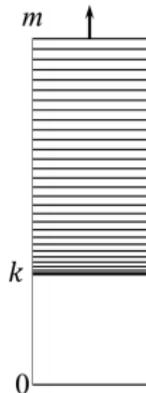
8 May 2023

All: new results w/ full LHC Run2 data

Search for signatures of quantum gravity models Clockwork/Linear dilaton

Masses

$m_0^2 = 0, \quad m_n^2 = k^2 + \frac{n^2}{R^2} \mid n = 1, 2, 3, ...$ Relates very small couplings to scales observable at LHC

k, R related to curvature, size of ED.

$\Lambda_N = q^N \Lambda$

Coupling to the SM

$\mathcal{L} \supset -\frac{1}{\Lambda_n} h_n^{\mu\nu} T_{\mu\nu}, \quad \Lambda_0^2 = M_{\mathrm{P}}^2, \ \Lambda_n^2 = M_5^3 \pi R \left(1 + \frac{k^2 R^2}{n^2}\right),$

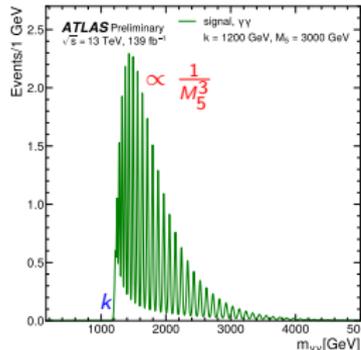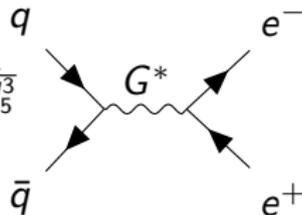Towers of resonances w/ small splittings in mass spectrum

$\boxed{G^* \to e^+ e^-, \gamma\gamma}$

Key model parameters

k, onset of KK graviton spectrum
M_5, 5D reduced Planck mass, $\sigma \propto \frac{1}{M_5^3}$

Signatures

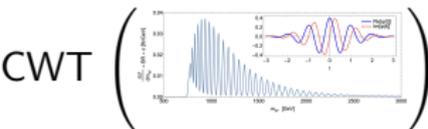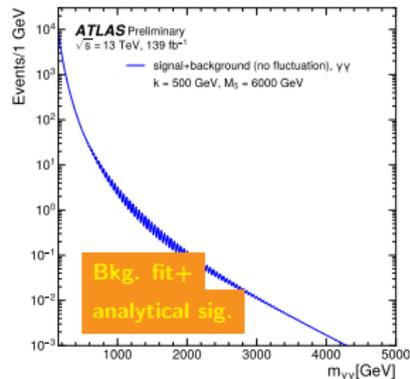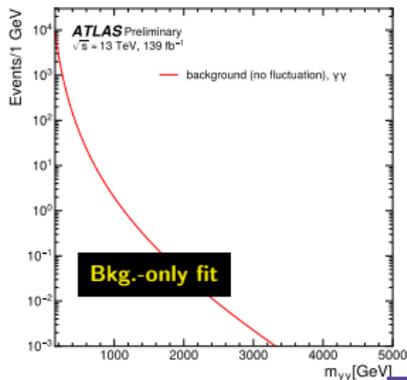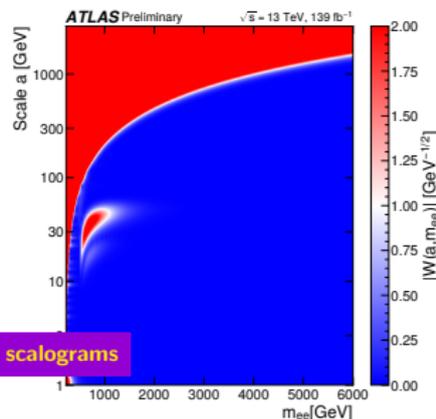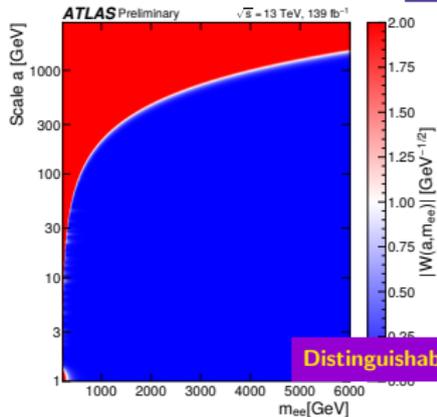Periodic signals $\to$ wavelet-like $m_{ee}, m_{\gamma\gamma}$

- Very low σ
- W/ fluctuations $\rightarrow$ signal "inseparable"
- Bump/tail-hunt-type searches suboptimal
- Idea to the rescue? Continuous Wavelet Transformation (CWT)

CWT $\left(\begin{array}{c} \text{[plot image]} \end{array} \right)$

Beauchesne, Kats [arXiv:1907.03676]

Mass-frequency scalograms perceptible by CNNs

NN score → test-statistic

test-statistic → p-value

NNs to distinguish S+B from B-only

Classifier
Trains on S(k, M5)+B and B
Supervised learning
Model-specific

Autoencoder
Trains on B-only
Unsupervised learning
Model-agnostic

Poisson-fluctuated
Indistinguishable by eye

↓ CWT ↓

Distinguishable by CNN

Clockwork search: results

AE model-independent results based on deviations from bkg.-only scalograms
Trains on bkg.-only and marks deviations from bkg.

Classifier model-dependent results by (k, M_5)

Thresholding to focus on periodic-nature sig. & avoid non-resonant tail effects

No observed deviations from SM
Very novel analysis; first ATLAS result of CW model

(CMS early Run2 search via non-resonant $\gamma\gamma$ arXiv:1809.00327)

Model-agnostic *p*-values by AE

(k, M_5) grid limits by Classifier

Motivation for LQ searches in $b\tau$ final states

Why LQ?

- LQ couple to quarks and leptons
- Scalar/vector models considered
- Appear in many NP theories

$b \to c\tau\nu$

Why 3rd-gen.?

- LFUV in $B \to D^*$ decays 1506.08614
- NP associated w/ b-quarks
- LQ couples to b and τ

arXiv:2303.01294

Pair-produced LQ

EXOT-2022-39

Singly-produced LQ

$LQ \to b\tau$ pairs search: event selection

Decay modes → final states

$$\tau_{\text{lep}}\tau_{\text{had}} \to \ell\tau_{\text{had-vis}}jj$$

$$\tau_{\text{had}}\tau_{\text{had}} \to \tau_{\text{had-vis}}\tau_{\text{had-vis}}jj$$

Key selections

$\geq 2j;\ p_{\text{T}}^{j} > 45(20)\ \text{GeV};\ \not{E} > 100\ \text{GeV}$

Background modelling

- Dominant: $t\bar{t}$ and single-t
- Subdominant: multijet with j as fake τ_{had} and $Z \to \tau\tau + (bb, bc, cc)$
- Simulation; validated in inverted regions of $s_{\text{T}} = \sum \not{E} + p_{\text{T}}^{\ell,\tau,b_1,b_2} > 600\ \text{GeV}$

Method

- Parameterised Neural Network (PNN) discrimination → **fit to PNN score**

R. S. Brener · Pheno2023 · 8 May 2023 · 8 / 15

$LQ \to b\tau$ pairs search: results arXiv:2303.01294

- High m_{LQ}: ~equal contribution by $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
- Low m_{LQ}: contribution by $\tau_{had}\tau_{had}$ up to 2 that of $\tau_{lep}\tau_{had}$
- σ limits assuming $\mathcal{B} = 1$

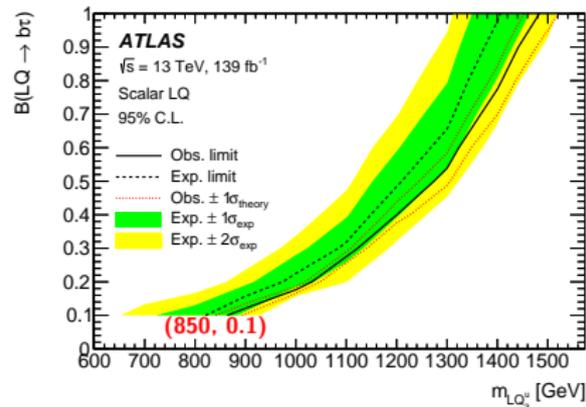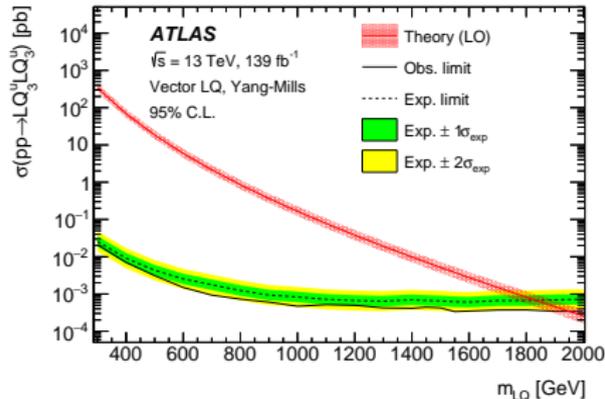
Observed limit stronger due to data deficit in high PNN score regions for $\tau_{had}\tau_{lep}$ channel

	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang–Mills)	1960	1840

m_{LQ}-limit improvements

450 GeV over 36 fb^{-1} result
More limits in backup

Singly-produced $LQ \to b\tau$ search EXOT-2022-39

$\tau_{\mathrm{had}}\tau_{\mathrm{had}}, \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channels

$s_{\mathrm{T}} = \sum p_{\mathrm{T}}(\ell\tau_{\text{had-vis}} || \tau_{\text{had-vis}}\tau_{\text{had-vis}}, j_b^1)$

Key selections

- $s_{\mathrm{T}} > 300$ GeV
- $\geq 1b; p_{\mathrm{T}}^b < (>) 200$ GeV for low (high) b-jet p_{T} SR
- $m(\ell || \tau_{\text{had-vis}}, \tau_{\text{had-vis}}) > 100$ GeV

Key results

- No significant excess
- $\tilde{S}_1$ (scalar) excluded to 1.26 TeV | $\lambda = 2.5$
- YM excluded to 1.56 TeV | $\lambda = 2.5$

First ATLAS search of singly-produced LQ in $b\tau\tau$ final states

Fit in s_T

Search for LQ and τ^* in τj final states

Why τ^*?

- Unexplained observations in LFU tests motivate CI fermion interactions.
- Compositeness of leptons and quarks up to scale Λ
- ℓ^* exist? τ^* produced at LHC

First Run2 ATLAS search for τ^*

Why cross-gen. LQ?

- LFUV in $B \to D^*$ decays 1506.08614
- LQ couples to $c/u/d$ and τ

First ATLAS search for $LQ \to c\tau c\tau$

EXOT-2020-18

$$\mathcal{L}_{\mathrm{CI}} = \frac{(4\pi)^2}{\Lambda^2} \frac{1}{2} j^\mu j_\mu$$

$\tau^* \to \tau q q$ **through CI**

(charm- or lighter- quark)

$LQLQ \to \tau c \tau c$

$(LQ, \tau^*) \to \tau j$ searches: analysis strategy

$$s_{\mathrm{T}} = \sum p_{\mathrm{T}}(\tau_{\mathrm{had}}\tau_{\mathrm{had}}, j^1 j^2)$$

Method

- Only τ_{had} considered
- $m_{\tau^*} > 300$ GeV, $m_{LQ} > 500$ GeV
- Fit on s_{T}

Z CR, VR in s_{T}

Background modelling

- Dominant: $Z \to \tau\tau$
- Subdominant: $t\bar{t}$ and single-t
- Simulation, validated in perpendicular regions of $m_{\tau\tau}, L_{\mathrm{T}}(= \sum p_{\mathrm{T}}(\tau\tau))$

t CR, VR in s_{T}

$(LQ, \tau^*) \to \tau j$ searches: results arXiv:2303.09444

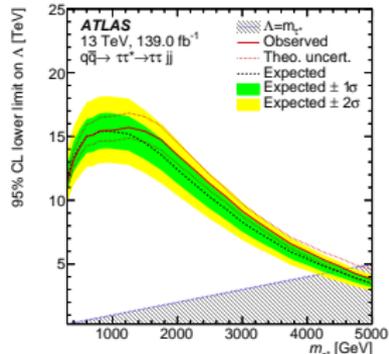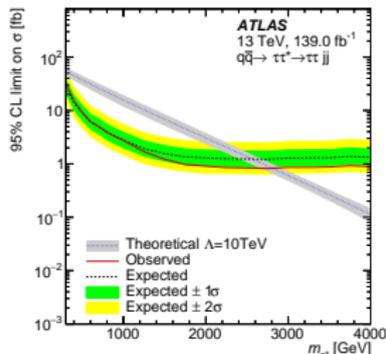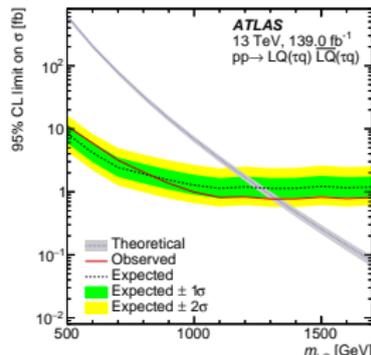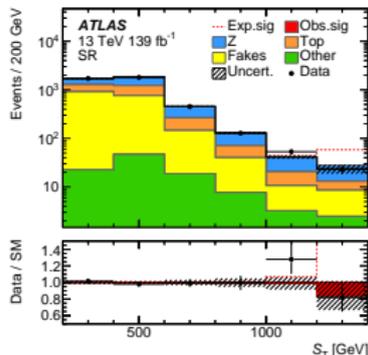$\underline{\tau\tau^* \to \tau\tau jj}$

- No significant excess
- Limits on m_{τ^*} vs. Λ

- τ^* excluded up to $m_{\tau^*} = 2.8 \text{ TeV} \mid \Lambda = 10 \text{ TeV}$
- τ^* excluded up to $m_{\tau^*} = 4.6 \text{ TeV} \mid \Lambda = m_{\tau^*}$

$\underline{LQLQ \to \tau\tau jj}$

- No significant excess
- LQ excluded up to $m_{LQ} = 1.3 \text{ TeV}$
  - $BR(LQ \to \tau c) = 1$

Summary

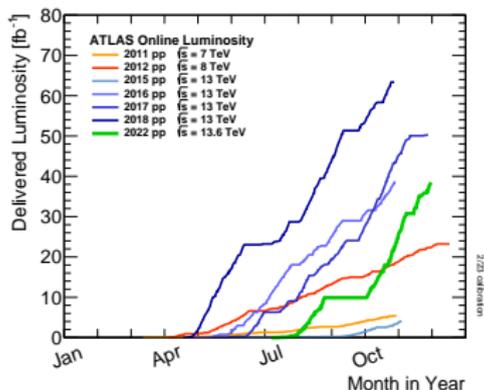**No evidence of NP**

Clockwork first-ever of its kind!
AE generic; detects periodic
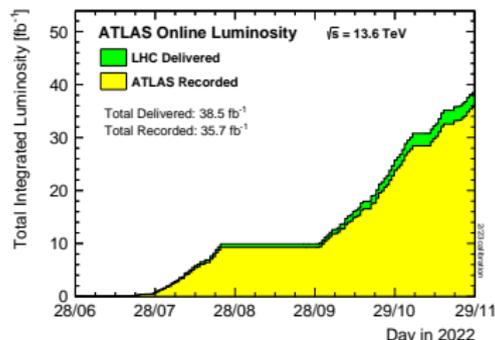deviations from fluctuating bkg.

Several $LQ \to \tau b$ investigations —
singly- and pair-produced LQ
$450 \ \mathrm{GeV}$ improvement in a m_{LQ}
limit over early Run2

τ^* searched through CI and limits
reach $4.6 \ \mathrm{TeV}$

The show goes on →

→ stay tuned!

Thank you for your attention.

Reference summary

Four investigations for New Physics with leptons

1. Periodic signals in *ee* and $\gamma\gamma$ final states ATLAS-CONF-2023-010

LQ {

2. Pair-produced LQ in final states with τ and *b*-jet(s) arXiv:2303.01294

3. LQ in final states with τ and *b*-jet(s) EXOT-2022-39

4. τ^* and LQ in final states with τ and jets arXiv:2303.09444

Common denominators include

- CoM LHC energy, $\sqrt{s} = 13 \text{ TeV}$
- Full LHC Run2 data; $\int_{2015}^{2018} \mathcal{L}\mathrm{d}t = 139 \text{ fb}^{-1}$

Arkani-Hamed, Dimopoulos, Dvali

ADD

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + dy^2$$
$$M_{\mathrm{P}}^2 = L_5 M_5^3$$

[arXiv:hep-ph/9803315]

Hierarchy is due to a large extra-dimensional volume.

Randall, Sundrum

RS

$$ds^2 = e^{2ky}g_{\mu\nu}dx^\mu dx^\nu + dy^2$$
$$M_{\mathrm{P}}^2 \simeq e^{2k\pi R}\frac{M_5^3}{k}$$

[arXiv:hep-ph/9905221]

Hierarchy is due to a warp factor.

Antoniadis, Arvanitaki, Dimopoulos, Giveon, Baryakhta, Giudice, McCullough, Kats, Torre, Urbano
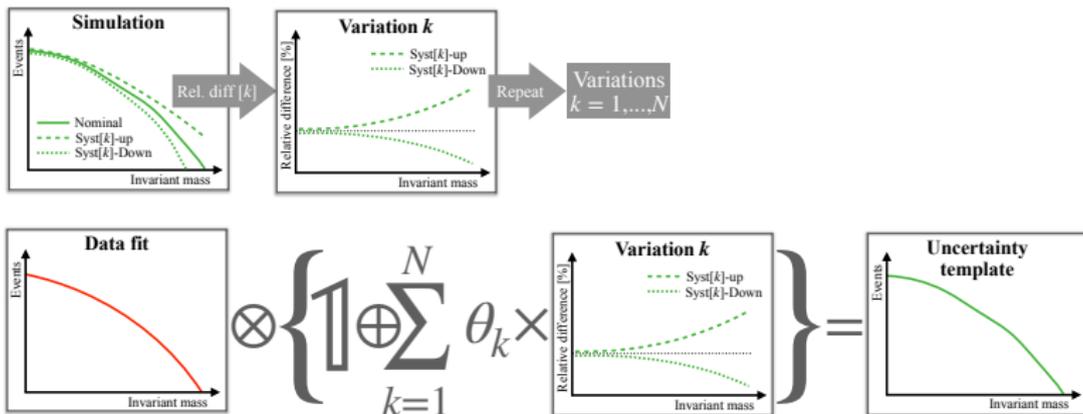
CW/LD

$$ds^2 = e^{\frac{4}{3}ky}(g_{\mu\nu}dx^\mu dx^\nu + dy^2)$$
$$M_{\mathrm{P}}^2 \simeq L_5 e^{\frac{4}{3}k\pi R}\frac{M_5^3}{3}$$
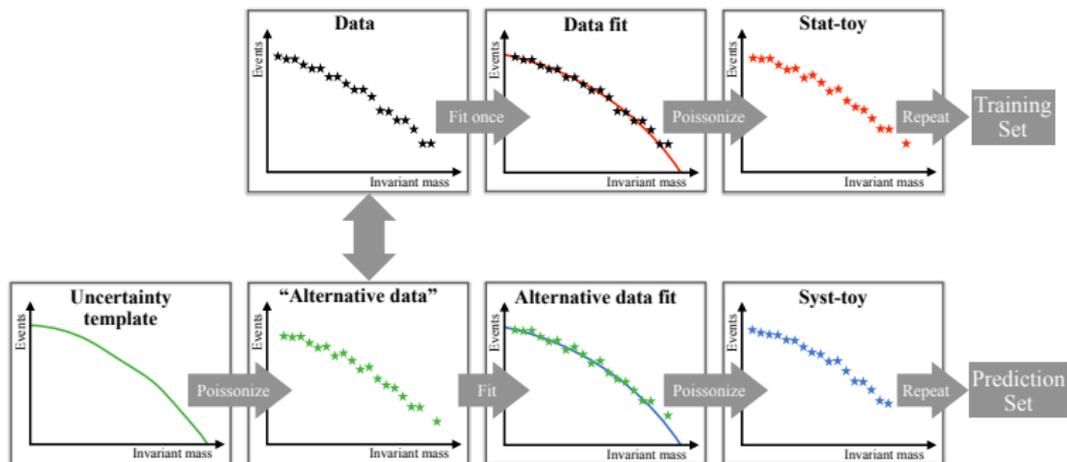$$L_5 \simeq e^{\frac{2}{3}k\pi R}\frac{3}{k}$$

[arXiv:1711.08437], [arXiv:1907.03676]

Hierarchy is due to a combination of the ED volume and the warp factor.

- Systematic uncertainties derived via MC in ATLAS diphoton (arXiv:2102.13405), dilepton (arXiv:1903.06248) searches used to generate toys
- **Dominant**: TH uncertainties on DY and $\gamma\gamma$ continuum backgrounds due to PDF variations. EX sub-dominant across full mass range.
- Experimental: PH, trigger eff., energy (scale, resolution), ID eff., iso.
- Theoretical: PDF (set, set choice, scale), α_{S} variations, EW corrections, γ-induced corrections

$LQ \to b\tau$ pairs search: event selection

Analysis strategy

- Event selection → PNN discrimination → **fit on PNN score**

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3 LQ models (all: $Q = +\frac{2}{3}, \beta = 0.5$)

- Scalar: BRW model, LQ Yukawa-interacts w/ same family f, coupling $\lambda = 0.3$ ($\Gamma(LQ) = 0.2\%$)
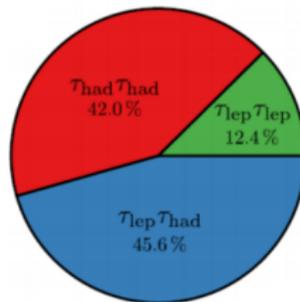- Vector (minimal coupling, Yang-Mills)

Background modelling

- Dominant: $t\bar{t}$ and single-t
- Subdominant: multijet with j as fake τ_{had} and $Z \to \tau\tau + (bb, bc, cc)$
- Modelled via simulation, validated in inverted regions of $s_{\text{T}} = \sum \not{E}_{\text{T}} + p_{\text{T}}^{\ell, \tau, j_1, j_2}$

Decay modes → final states

$$\tau_{\text{lep}}\tau_{\text{had}} \to \ell \tau_{\text{had-vis}} jj$$

$$\tau_{\text{had}}\tau_{\text{had}} \to \tau_{\text{had-vis}} \tau_{\text{had-vis}} jj$$

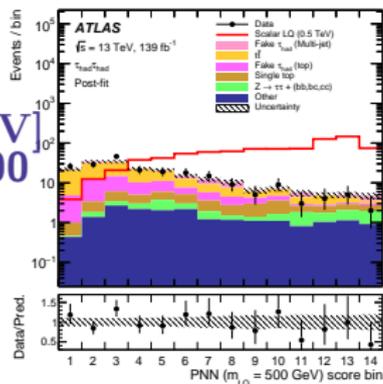$\tau_{\text{had}}\tau_{\text{had}}$ 42.0%

$\tau_{\text{lep}}\tau_{\text{lep}}$ 12.4%

$\tau_{\text{lep}}\tau_{\text{had}}$ 45.6%

Event selection		
	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
e/μ selection	= 1 'signal' e or μ $p_{\text{T}}^e > 25, 27$ GeV $p_{\text{T}}^\mu > 21, 27$ GeV	No 'veto' e or μ
$\tau_{\text{had-vis}}$ selection	= 1 $\tau_{\text{had-vis}}$ $p_{\text{T}}^\tau > 100$ GeV	= 2 $\tau_{\text{had-vis}}$ $p_{\text{T}}^\tau > 100, 140, 180$ (20) GeV
Jet selection	≥ 2 jets $p_{\text{T}}^{\text{jet}} > 45$ (20) GeV 1 or 2 b-jets	
Additional selection	Opposite charge $e, \mu, \tau_{\text{had}}$ and τ_{had} $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150$ GeV $E_{\text{T}}^{\text{miss}} > 100$ GeV $s_{\text{T}} > 600$ GeV	

$LQ \rightarrow b\tau$ pairs search: results arXiv:2303.01294

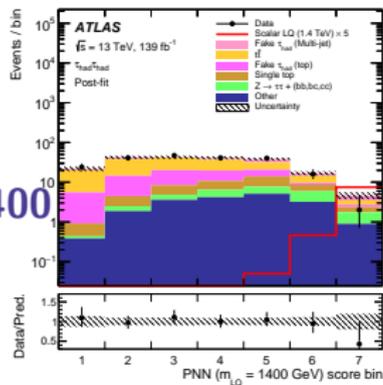$\tau_{\mathbf{had}}\tau_{\mathbf{had}}$

$m_{\mathbf{LQ}}$ [GeV]
500

- No sig. excess over SM.
- Top bkg. dominate at high PNN scores in $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$
- Bkg. composition fairly event thgouthout PNN scores in $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
- Data deficit at high PNN scores in $\tau_{\mathrm{hadd}}\tau_{\mathrm{had}}$

1400

$LQ \rightarrow b\tau$ pairs search: results arXiv:2303.01294

- High m_{LQ}: ~equal contribution by $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$

- Low m_{LQ}: contribution by $\tau_{had}\tau_{had}$ up to 2 that of $\tau_{lep}\tau_{had}$

- σ limits assuming $\mathcal{B} = 1$
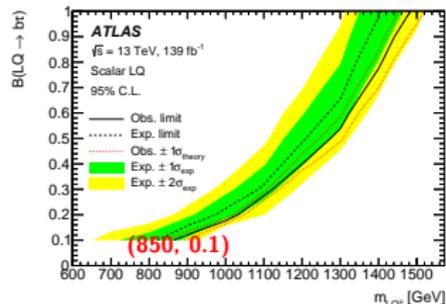
	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang–Mills)	1960	1840

m_{LQ}-limit improvements
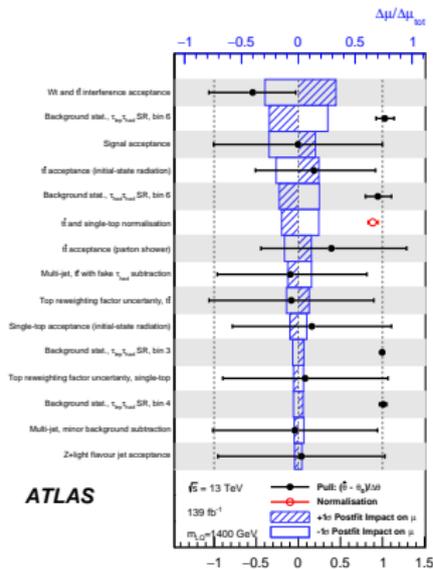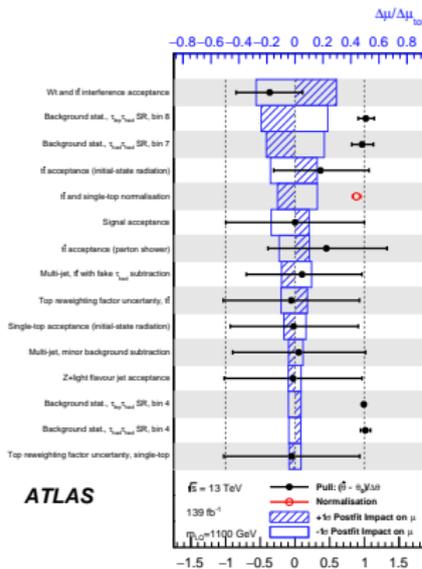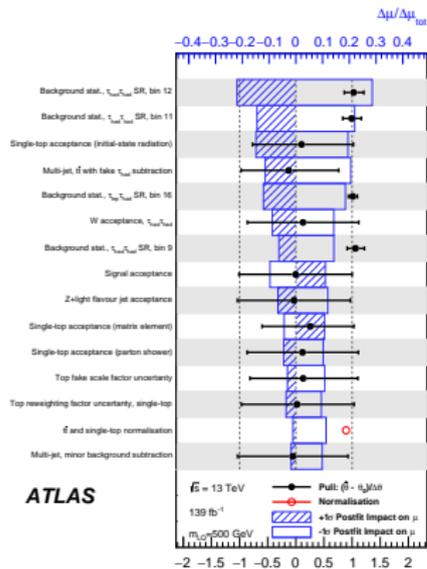
450 GeV over 36 fb^{-1} result

200 GeV over full Run2 result for $LQLQ \rightarrow t\nu$

Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$\tau_{\text{had-vis}}\ p_{\text{T}}^0$	✓	✓
s_{T}	✓	✓
$N_{b-\text{jets}}$	✓	✓
$m(\tau, \text{jet})_{0,1}$		✓
$m(\ell, \text{jet}),\ m(\tau_{\text{had}}, \text{jet})$	✓	
$\Delta R(\tau, \text{jet})$	✓	✓
$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	✓	
$E_{\text{T}}^{\text{miss}}\ \phi$ centrality	✓	✓

$LQ \rightarrow b\tau$ pairs search: uncertainties arXiv:2303.01294
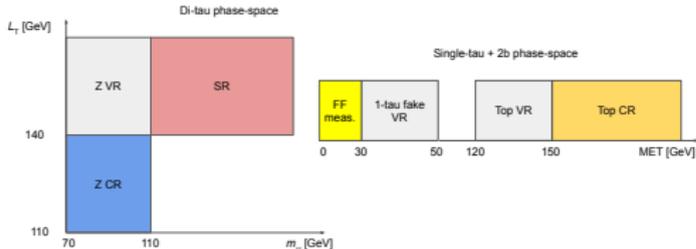
- Shifting central value +/- 1σ & propagating differences to zPNN
- Dominant: stat., increases w/ m_{LQ} *e.g.* 60–80% | lowest–highest m_{LQ} (scalar LQ)
- Dominant syst.: top modelling uncertainties (interference, normalisation) and $\mathcal{A}_{\text{sig.}}$ (increases w/ m_{LQ}, key for vector LQ)

$(LQ, \tau^*) \to \tau j$ searches: analysis strategy arXiv:2303.09444

Analysis strategy

- Only τ_{had} considered
- $m_{\tau^*} > 300 \text{ GeV}$, $m_{LQ} > 500 \text{ GeV}$
- Fit on s_{T}

$$s_{\mathrm{T}} = \sum p_{\mathrm{T}}(\tau_{\mathrm{had}}\tau_{\mathrm{had}}, j^1 j^2)$$
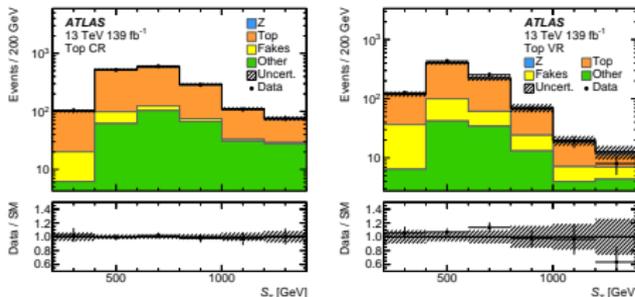

Z CR, VR in s_{T}

Background modelling

- Dominant: $Z \to \tau\tau$
- Subdominant: $t\bar{t}$ and single-t
- Modelled via simulation, validated in perpendicular regions of $m_{\tau\tau}$, $L_{\mathrm{T}}(= \sum p_{\mathrm{T}}(\tau\tau))$

t CR, VR in s_{T}

$(LQ, \tau^*) \to \tau j$ searches: uncertainties

- Estimating every NP pull on each bkg. included in fit to s_T
- **Dominant**: matching NLO matrix elements to PS in tW bkg. sim.
- **Subdominant**: interference of $t\bar{t}$ and tW bkgs.
- No NP strongly pulling