Constraining the leptoquark pair-production cross-section using tau leptons and *b*-jets with the ATLAS detector

Federico Morodei

on behalf of the ATLAS Collaboration

Standard Model at the LHC

8 May 2024

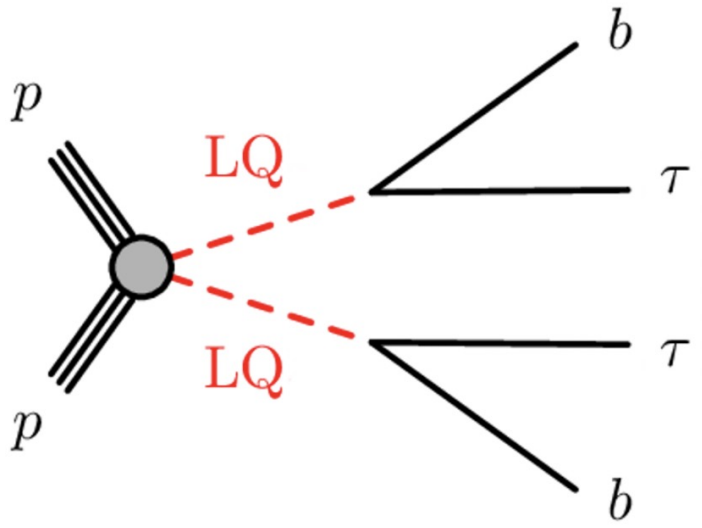
SAPIENZA
UNIVERSITÀ DI ROMA

Motivation

Analysis paper: Eur. Phys. J. C 83 (2023) 1075

Leptoquarks (LQs):

- Predicted by many SM extensions.
- Carry baryon and lepton quantum numbers.
- Could explain the observations of B-meson anomalies suggesting lepton universality violation.



Purpose of the analysis:

- Search for pair-production of third-generation up-type LQs.
- Consider both scalar and vector LQs (with minimal-coupling and Yang-Mills scenarios).
- Use the full Run 2 dataset collected by ATLAS (139 fb^{-1}) at $\sqrt{s} = 13\,\text{TeV}$.

Signal regions

2 orthogonal signal regions: $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$

$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
• One light-lepton (e/μ) and one $\tau_{\text{had-vis}}$. • Opposite charges. • Single-e/μ triggers. • e/μ minimum p_{T}: 21-27 GeV (depending on data period). • τ_{had} minimum p_{T}: 100 GeV.	• Two $\tau_{\text{had-vis}}$ with loose RNN working point (85% efficiency for 1-prong τ_{had}). • Opposite charges. • No light-leptons. • Single-τ_{had} trigger. • Offline triggered-τ_{had} minimum p_{T}: 100-180 GeV (depending on data period).

- >= 2 jet (at least one b-tagged).
- $m_{\tau\tau}^{\text{MMC}} \notin$ (40-150) GeV.
- $E_{\text{T}}^{\text{miss}} > 100$ GeV.
- $s_{\text{T}} > 600$ GeV.

$m_{\tau\tau}^{\text{MMC}}$: the Missing Mass Calculator (MMC) reconstructs the pre-decay $\tau\tau$ invariant mass using the momenta of the visible decay products and the $\boldsymbol{p}_{\text{T}}^{\text{miss}}$.

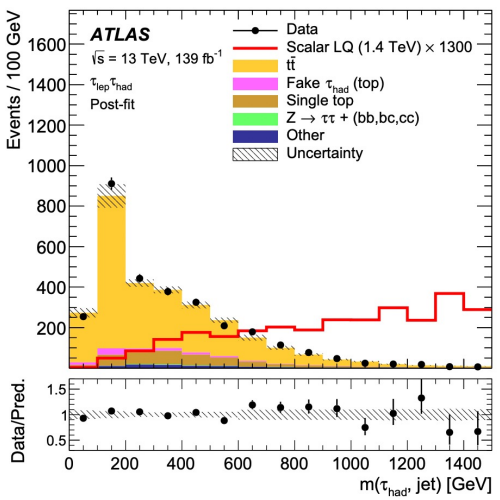
s_{T} : scalar sum of p_{T} of light-lepton (for $\tau_{\text{lep}}\tau_{\text{had}}$), $\tau_{\text{had-vis}}$, two jets and $E_{\text{T}}^{\text{miss}}$.

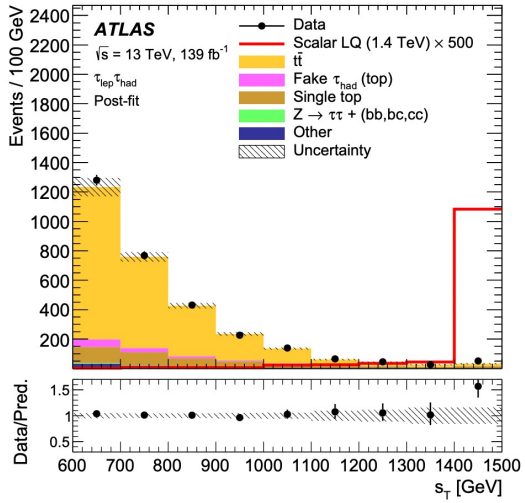
Multivariate signal extraction

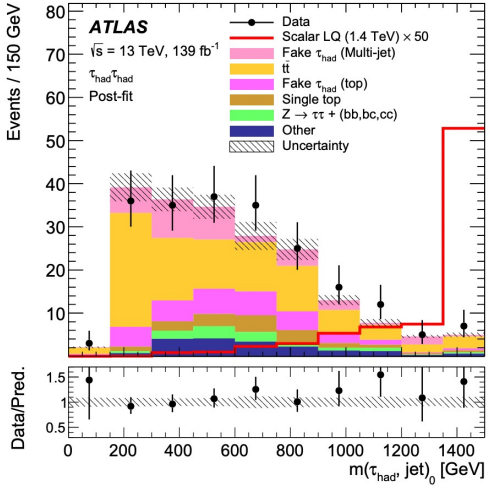
- Signal extracted using multivariate discriminant.
- Parameterised Neural Network (PNN) with generated LQ mass as parameter.
- PNN made of 3 hidden layers with 32 nodes each.
- PNN score distribution used as discriminant.
- PNN training:
  - Signal: scalar LQ samples (all masses simultaneously).
  - Background: $t\bar{t}$ and single-top MC samples.

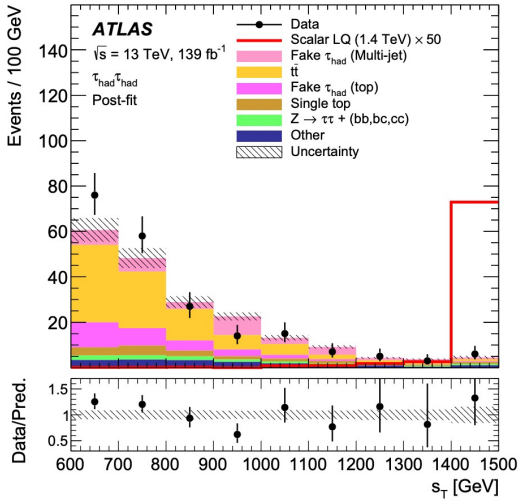
PNN input variables

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









Backgrounds

Main backgrounds:

- Top production (from MC + data-driven corrections).
- Z + heavy-flavour jets (from MC + data-driven corrections).
- Multijet (data-driven, in $\tau_{\text{had}}\tau_{\text{had}}$ only).

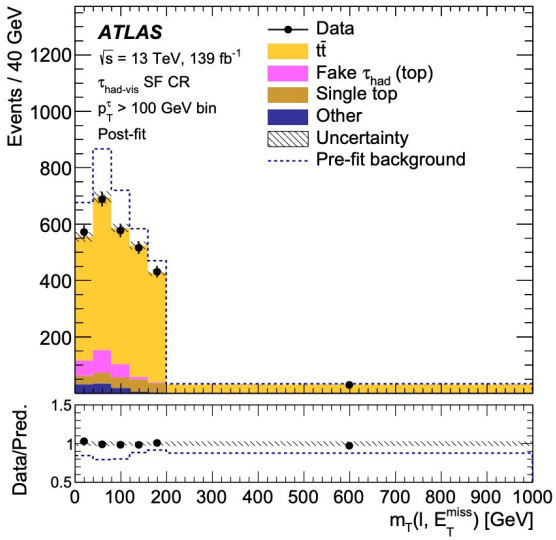
Top background corrections:

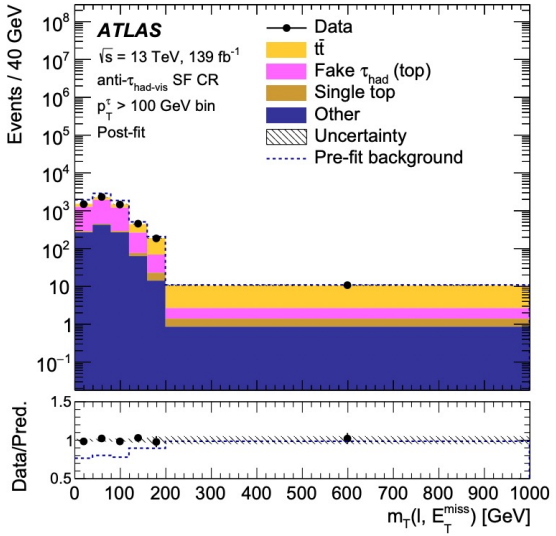
- Shape corrections from 99%-pure top CR: 2 b-jets, 2 light-leptons, $m_{\ell\ell} > 110$ GeV.
- Normalisation corrections from fit in 97%- pure $\tau_{\text{lep}}\tau_{\text{had}}$ CR: same SR selections but $s_{\text{T}} \in$ (400-600) GeV and any τ_{had} p_{T}.

Multijet background data-driven estimation:

- fake factors (FF) derived from same-charge data CR after subtracting all other MC contributions.
- FF applied to a region with 1 τ_{had}^{ID} and $1\tau_{had}^{\text{antiID}}$.

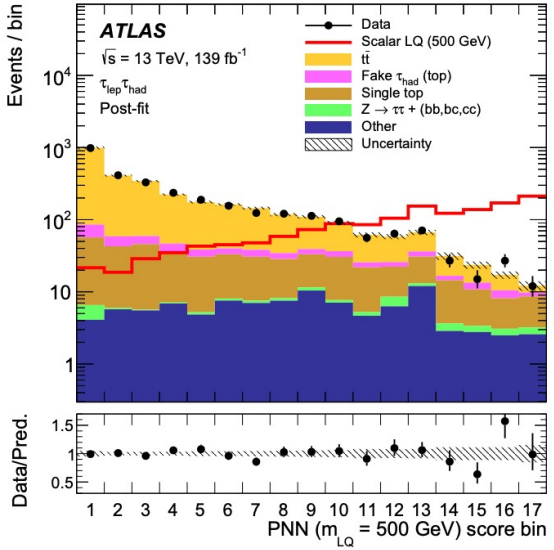
$$\text{FF} = \frac{N(\tau_{had}^{\text{ID}}, \tau_{had}^{\text{ID}})}{N(\tau_{had}^{\text{ID}}, \tau_{had}^{\text{antiID}})}$$

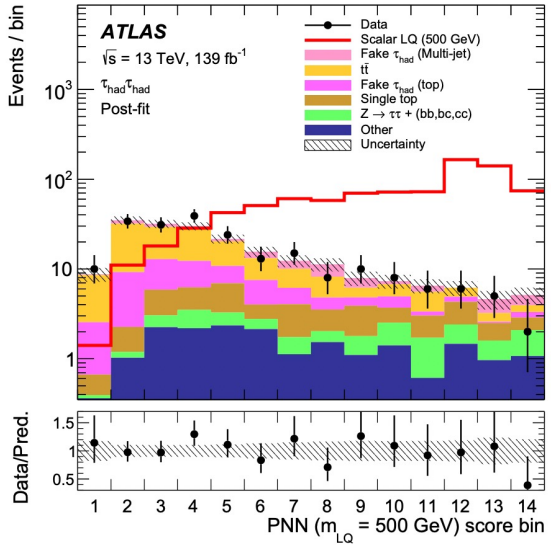




Results

- Binned profile-likelihood fit.
- Discriminant variable: PNN score distribution.
- 2 SRs: $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$.
- A separate fit for each LQ hypothesis.
- Top normalisation as free floating parameter.





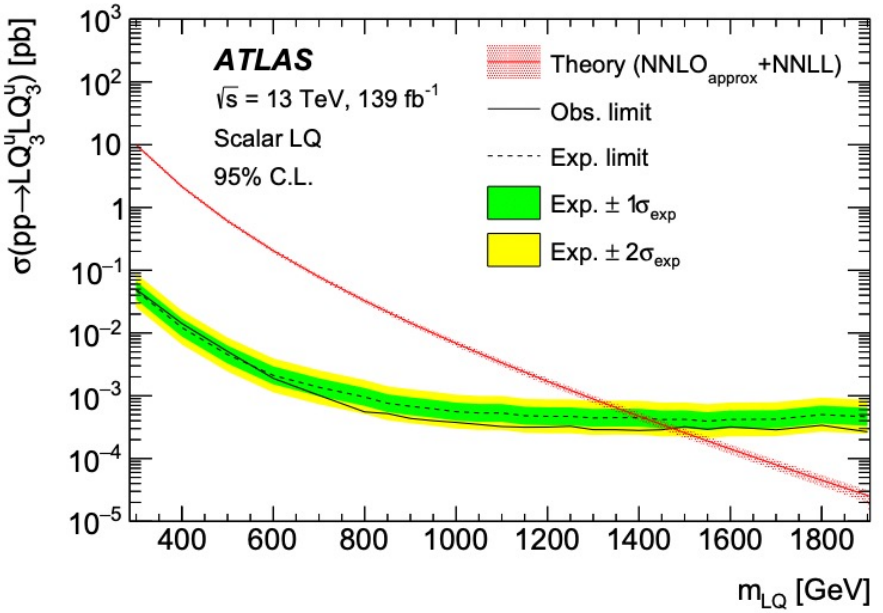
Event yields for background-only fit

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$	2430 ±110	94 ± 12
single-top	365 ± 26	20 ± 5
Fake τ_{had} (top)	140 ±100	36 ± 11
Z→ $\tau\tau$ + (bb, bc, cc)	13.1 ± 2.7	10.1 ± 1.3
Multi-jet	–	30 ± 16
Other	91 ± 35	18 ± 7
Total Background	3040 ± 60	207 ± 14
Data	3031	211

No significant excess observed

Interpretation

- No significant excess observed.
- LQ pair-production cross-section limits derived with CL_S method as a function of m_{LQ} (assuming $B(LQ \longrightarrow b\tau) = 1$).
- Limits derived combining both SRs.
- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ have equal sensitivity at high m_{LQ}.
- $\tau_{had}\tau_{had}$ is two times more sensitive than $\tau_{lep}\tau_{had}$ at low m_{LQ}.



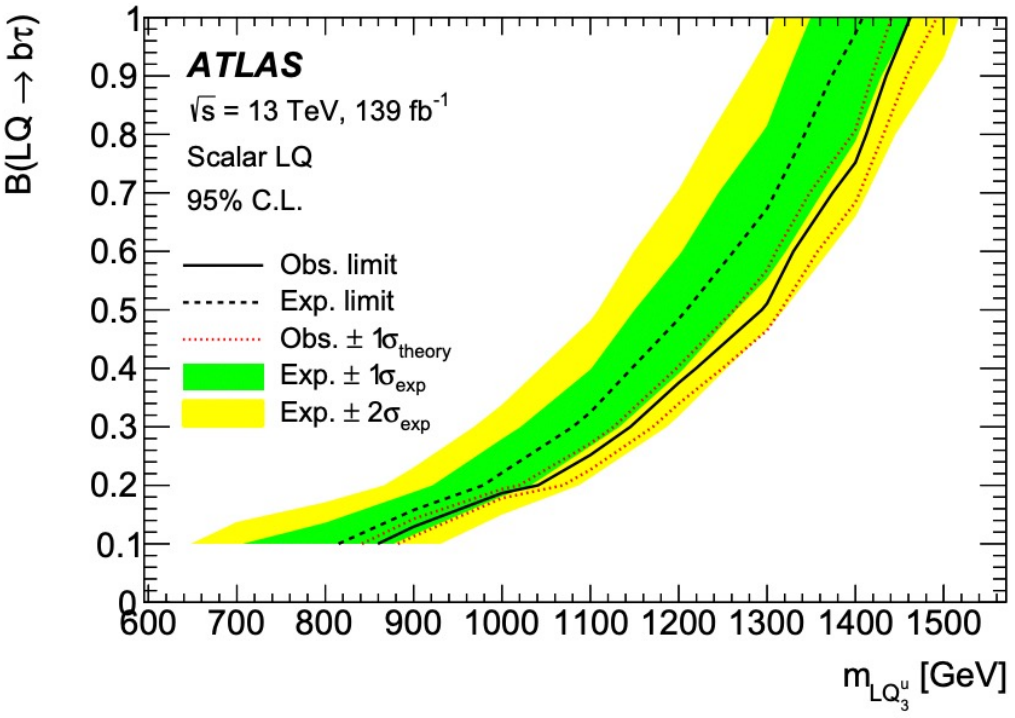
95% CL lower limits on LQ mass

	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1460	1410
Vector LQ (minimal-coupling)	1650	1590
Vector LQ (Yang–Mills)	1910	1820

- Improvement of 450 GeV for scalar LQs with respect to 36 fb^{-1} result [JHEP 06 (2019) 144].
- Improvement of 200 GeV in all three models with respect to $LQLQ \rightarrow tvtv$ result [Phys. Rev. D 104 (2021) 112005].

Conclusion

- Search for pair-produced LQs decaying to $\mathrm{b}\tau$.
- Signal extraction with multivariate discriminant based on PNN score.
- Use of data-driven techniques for background estimation.
- No significant deviations from SM expactions are observed.
- Improved exclusion limits on LQ mass with respect to previous ATLAS results.
- Results can be expressed as upper limits on the branching ratio to $\mathrm{b}\tau$ as a function of m_{LQ}.

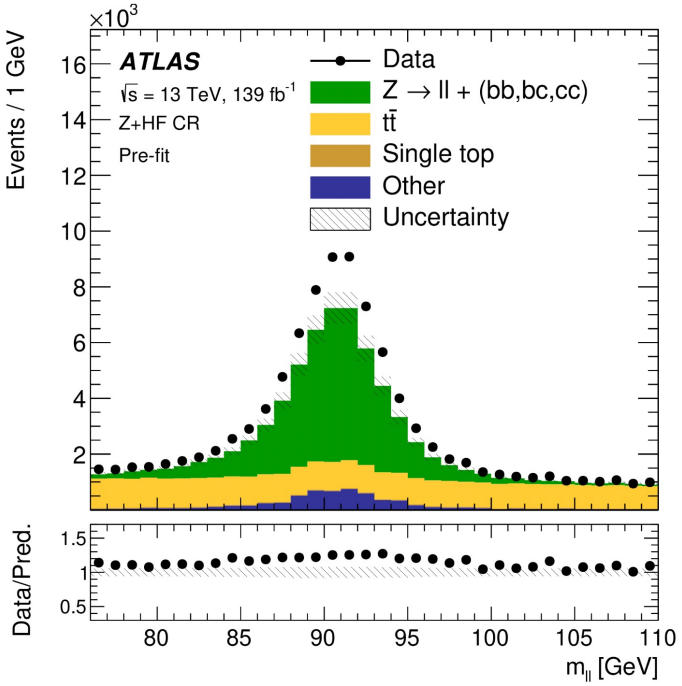


BACKUP

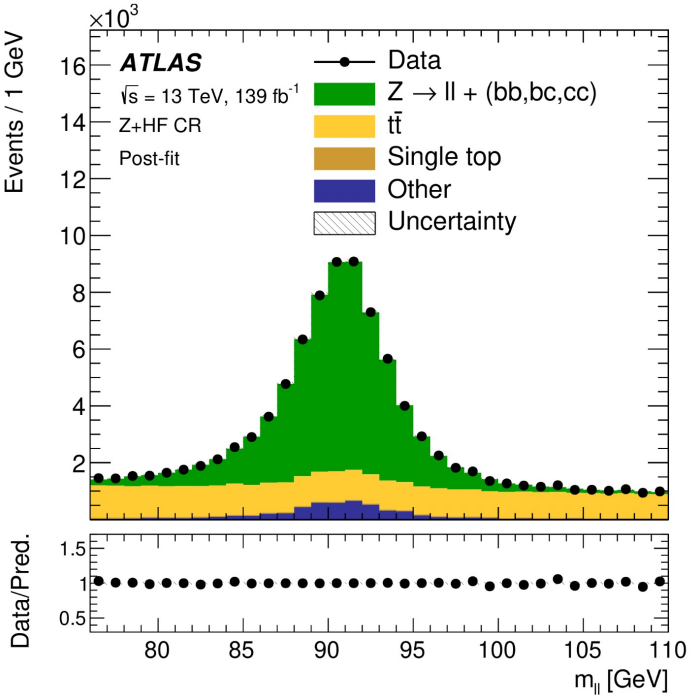
Z + jets background

Normalisation of Z+ heavy-flavour jets background from data with a fit in Z CR: 2 same-flavour light-leptons + 2 heavy-flavour jets, $m_{\ell\ell} \in (75,110)$ GeV (60% Z and 40% $t\bar{t}$ events)

Pre-fit

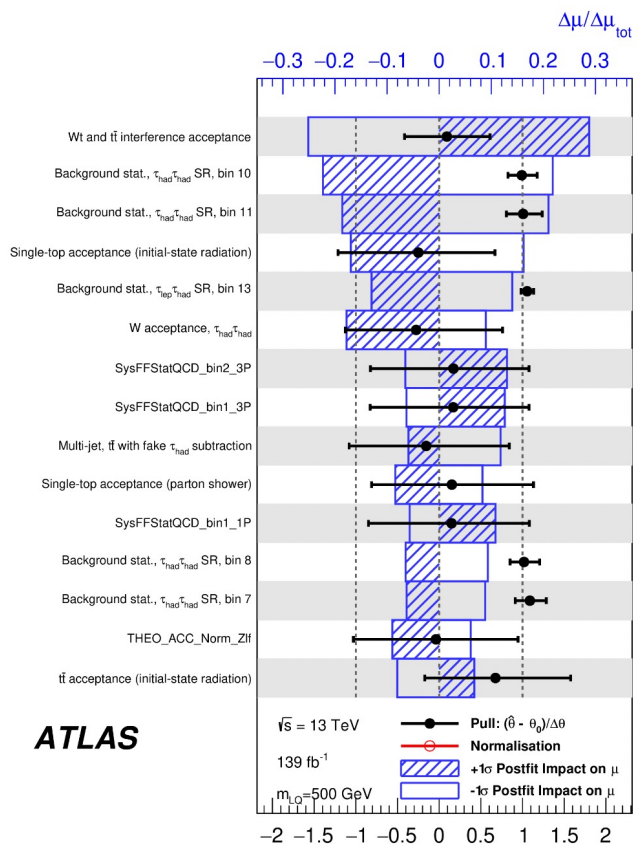


Post-fit

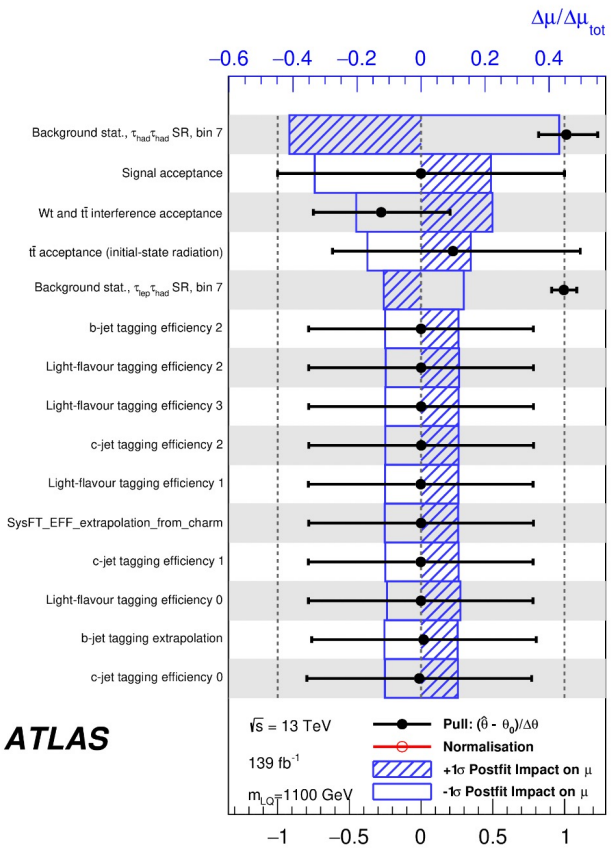


Ranking plots of systematics

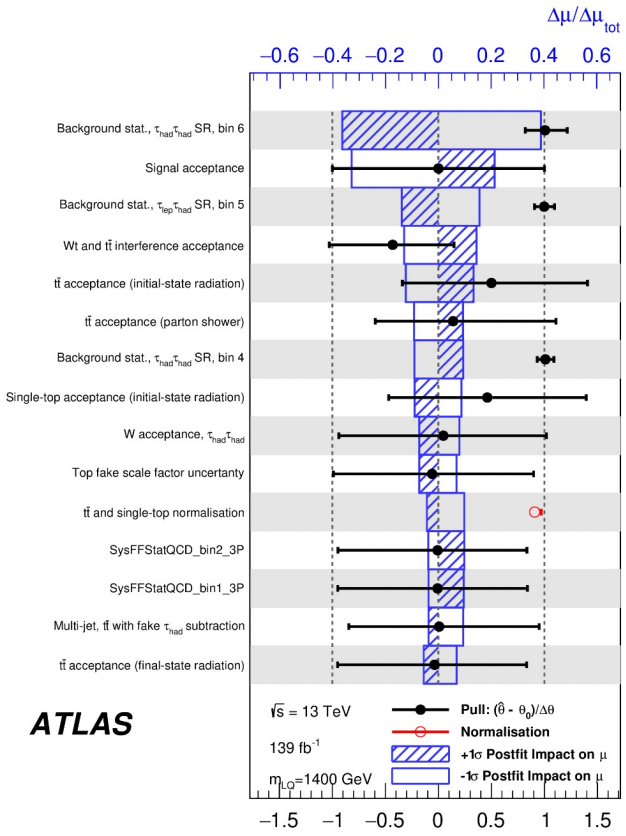
$m_{LQ} = 500$ GeV



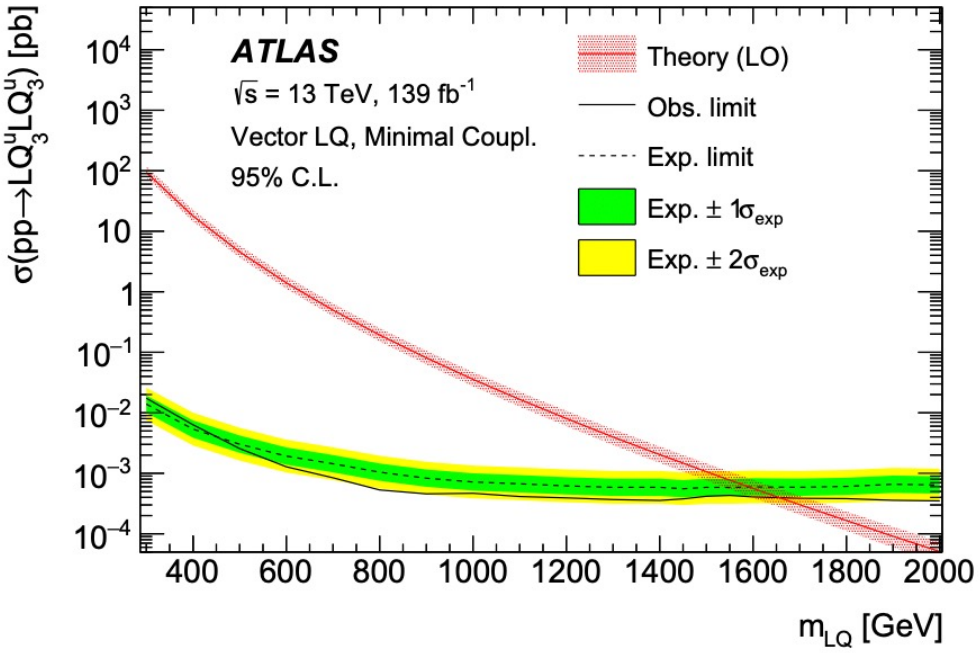
$m_{LQ} = 1100$ GeV

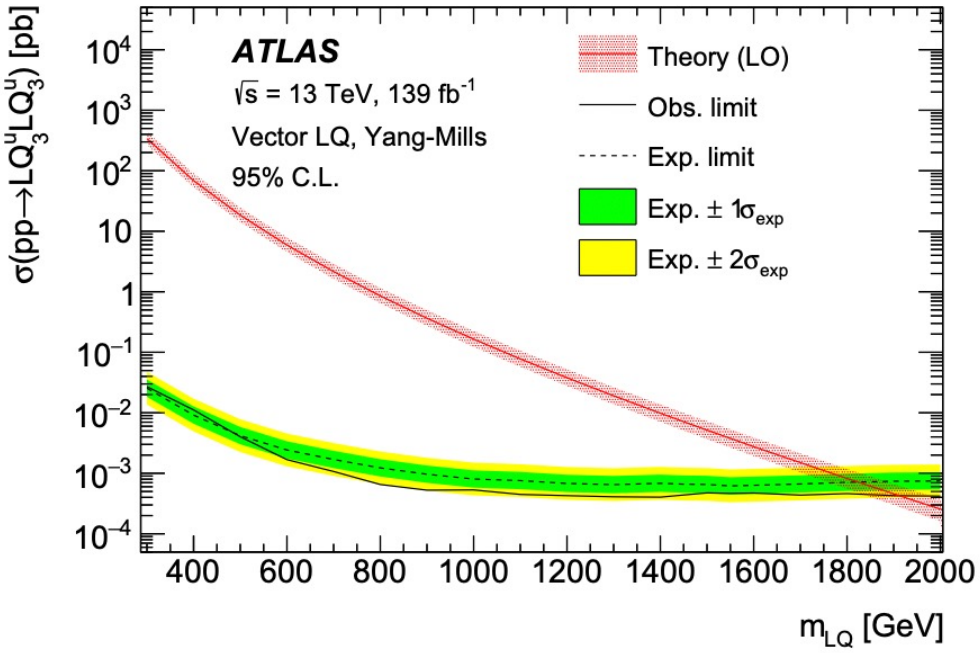


$m_{LQ} = 1400$ GeV



Cross-section limits (vector LQ)





Branching ratio limits (vector LQ)