Searches for Vector-like Fermions and Leptoquarks with the ATLAS Experiment

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on behalf of the ATLAS Collaboration

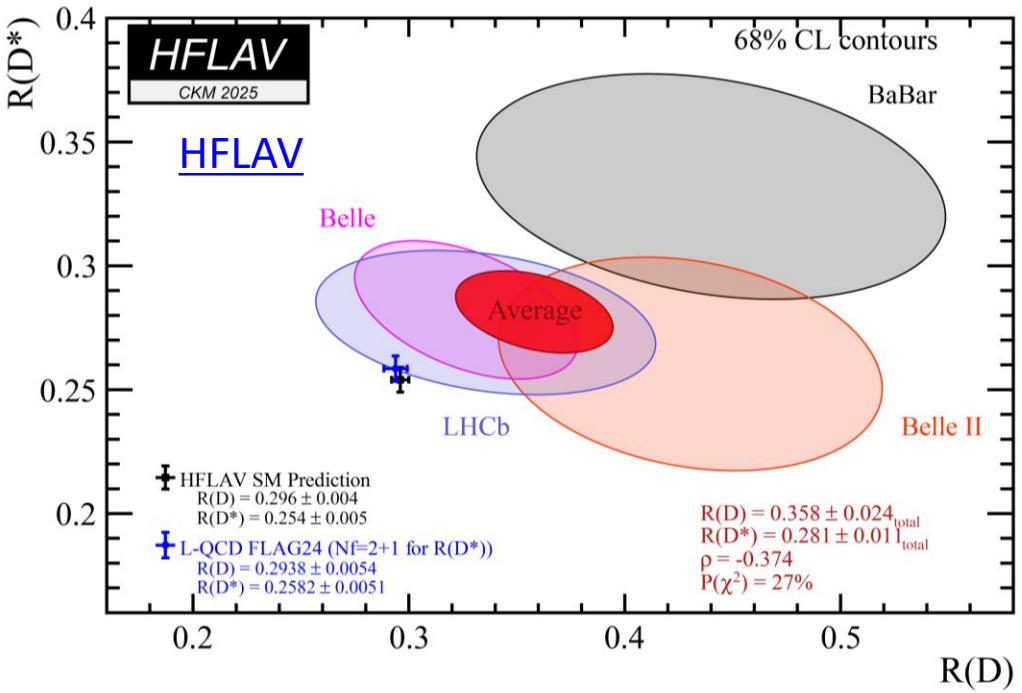
Pheno2026

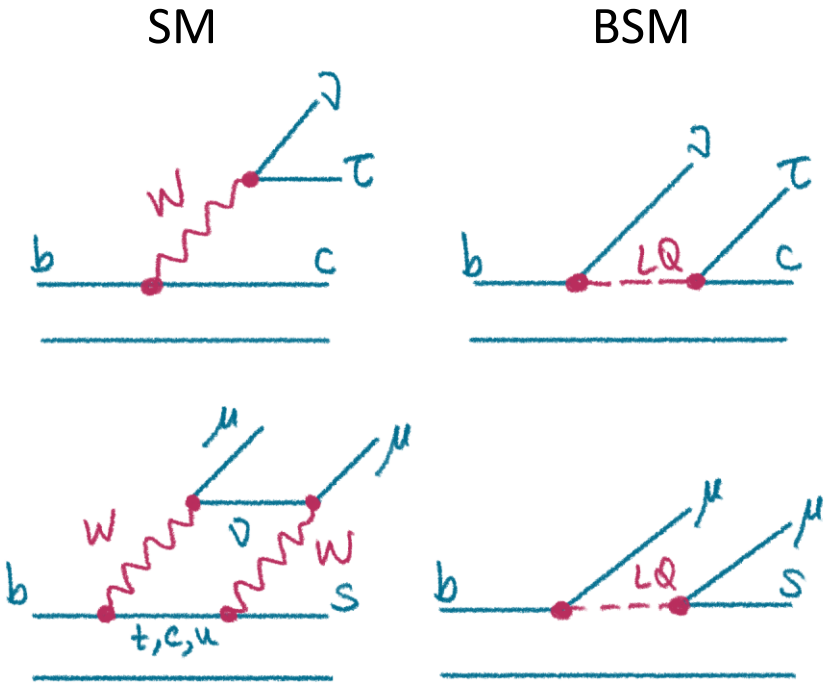
University of Pittsburgh, Pittsburgh

ICEPP
The University of Tokyo

Leptoquarks

Motivations





✓ **Hints for lepton flavour universality violation** is observed in charged and neutral current processes in B-physics.

- R_D/R_{D^*}: 3.8σ deviation (2.2σ at Moriond 2026…)
- R_K/R_{K^*}: Now SM consistent?
- B→Kμμ angular variable discrepancies, muon g-2

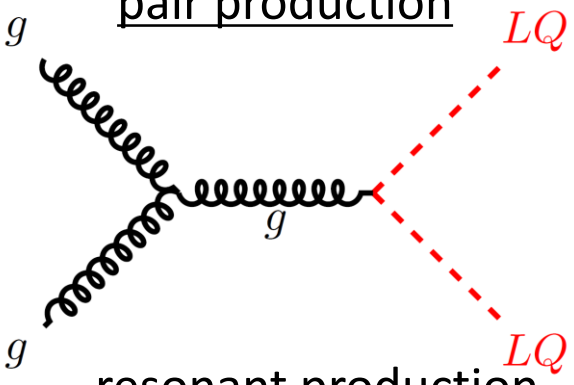
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}, (\ell = e \text{ or } \mu)$$

✓ One of the candidates to explain the deviation is a **leptoquark (LQ)**.

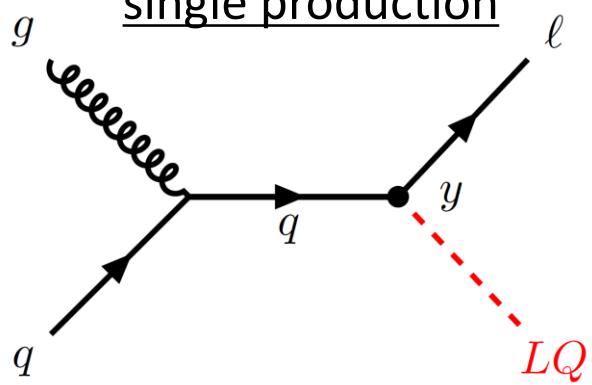
- Hypothetical particles that naturally arise in some beyond the Standard Model scenarios such as GUT.
- Introduces direct couplings between leptons and quarks.

LQ Search in Experiment

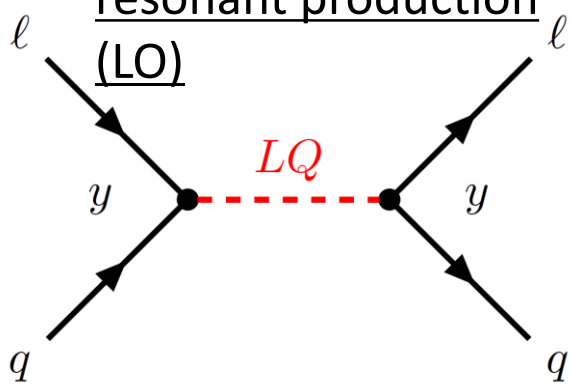
pair production

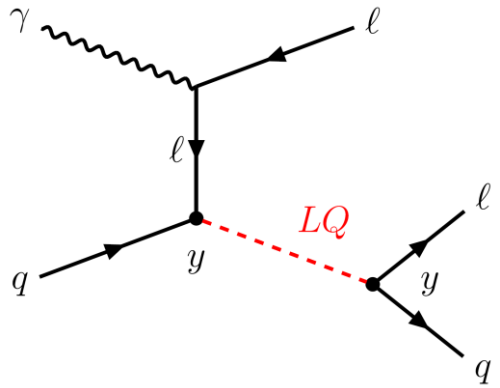


single production

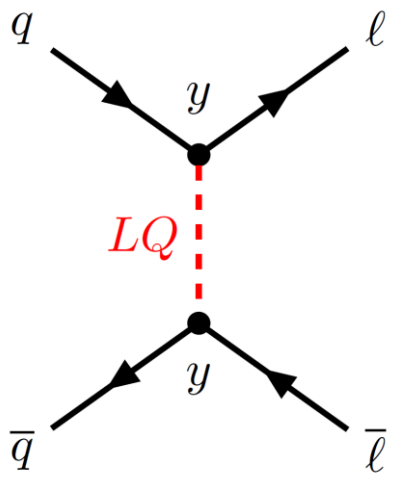


resonant production (LO)



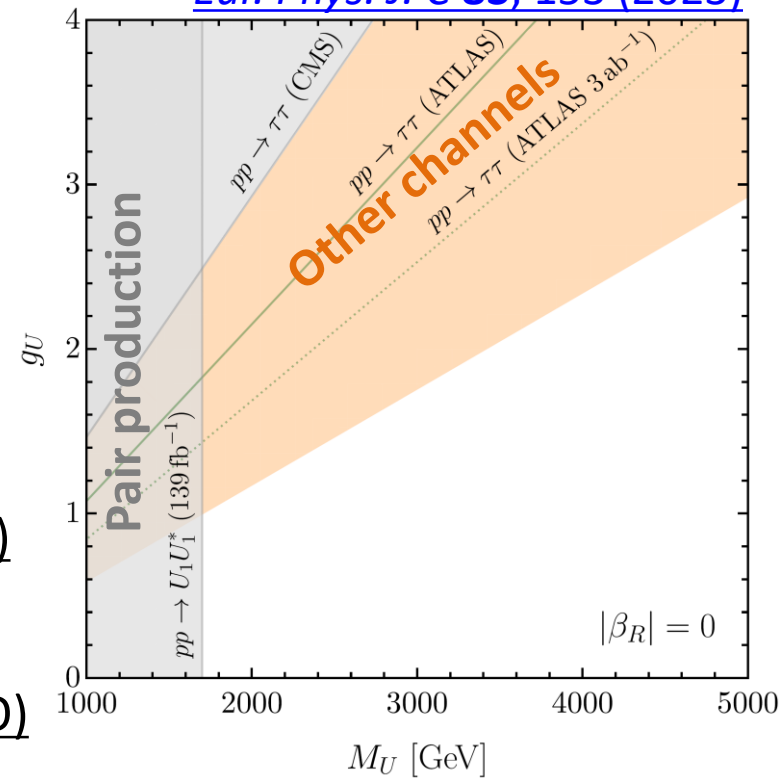


← resonant production (NLO)



non-resonant (t-channel) production

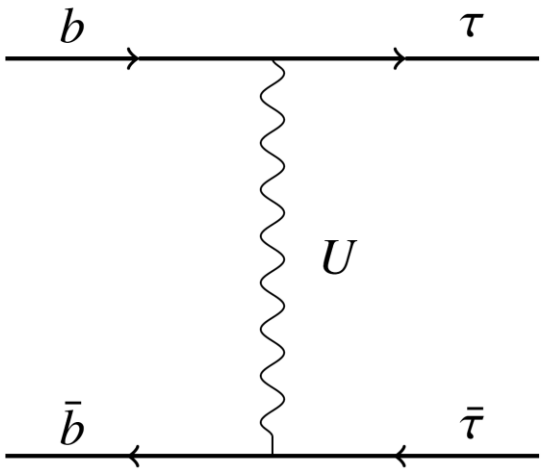
Eur. Phys. J. C **83**, 153 (2023)

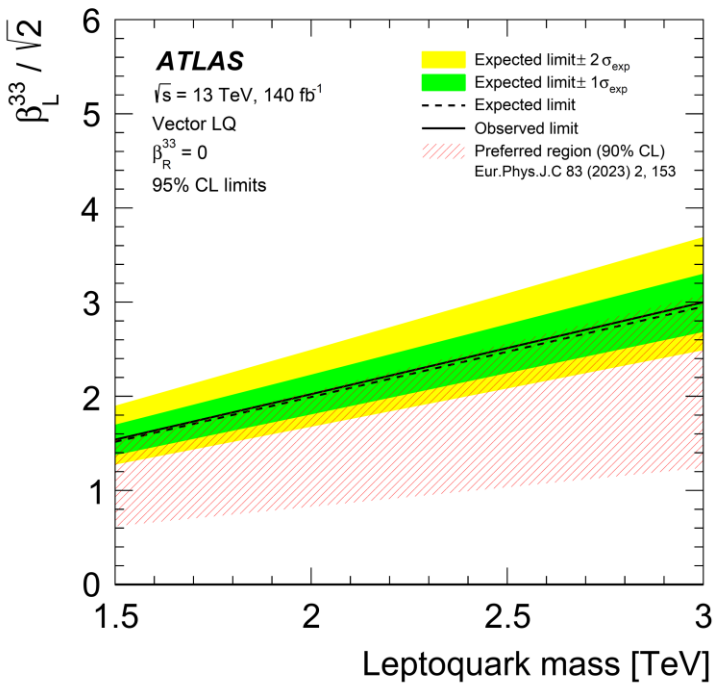


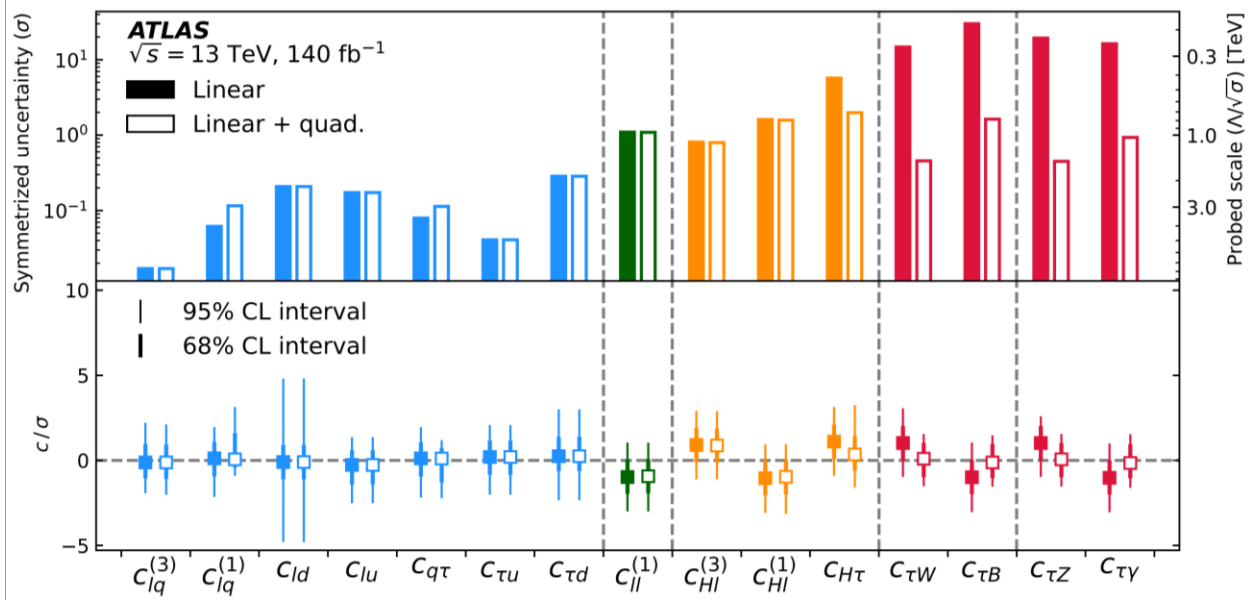
- ✓ **Scalar LQ** and **Vector LQ (of minimal coupling and Yang-Mills (YM) coupling)** scenarios are considered.
- ✓ LQs can be produced in **pair, single, non-resonant, and resonant**.
  - Pair and single productions have been searched for a long time.
- ✓ Decay modes also have variations. As experimental signature,
  - **quark** (top, bottom, charm, light-jet) and **lepton** (τ, μ, e, ν)

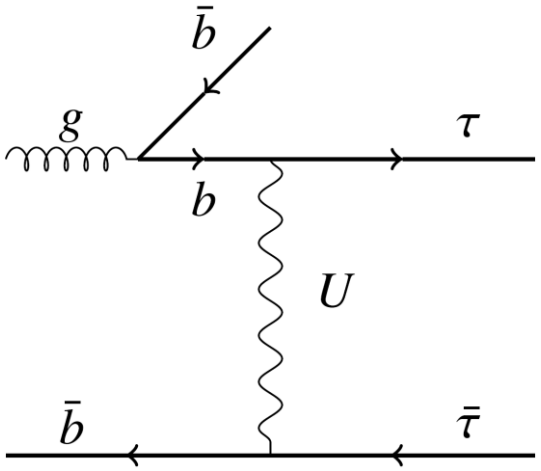
Non-Resonant Production

EXOT-2022-42





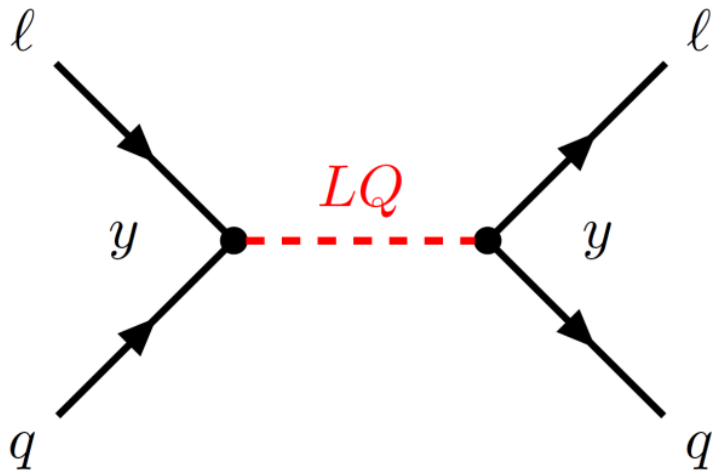


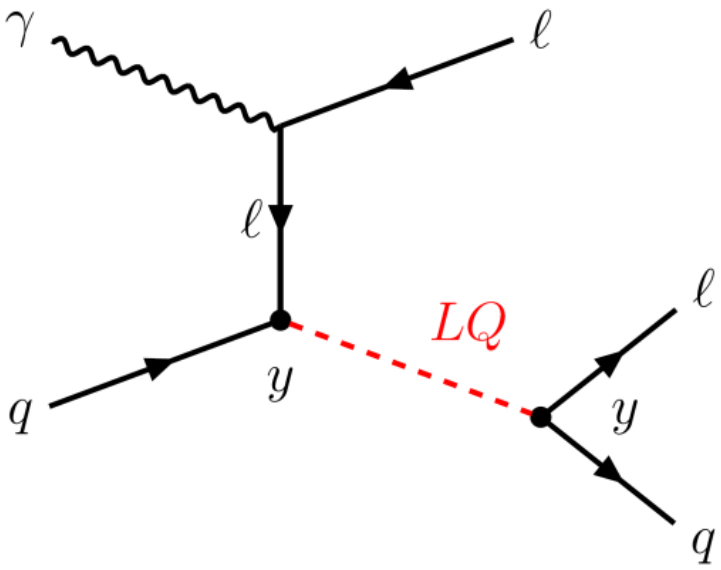


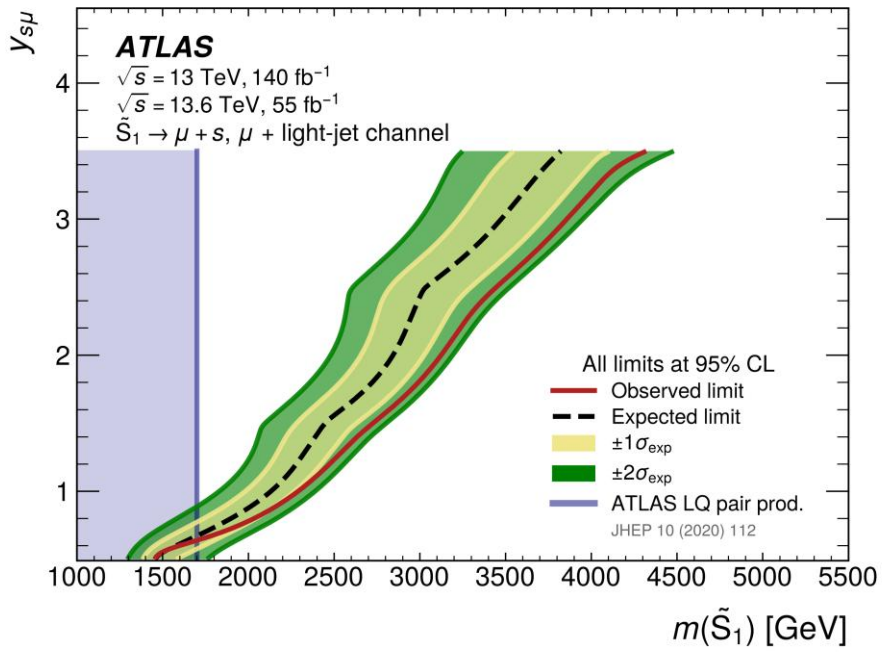
- ✓ **Higher mass region** can be searched for in non-resonant production depending on the couplings.
- ✓ **Differential cross section** in 2 tau final states is measured for the first time from run 1.
- ✓ **Constraints for several EFT coefficients** are also set.

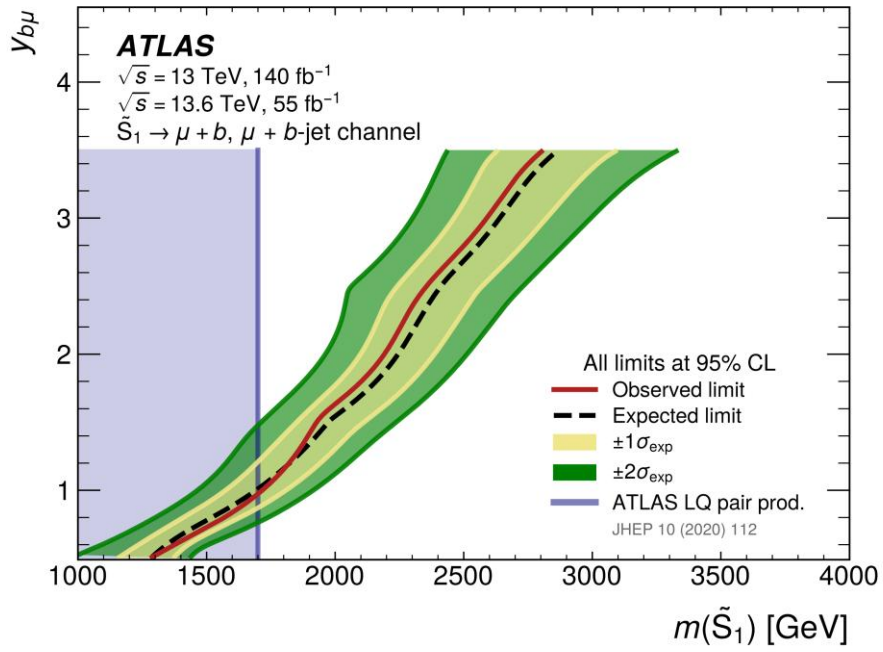
Resonant Production

EXOT-2024-12









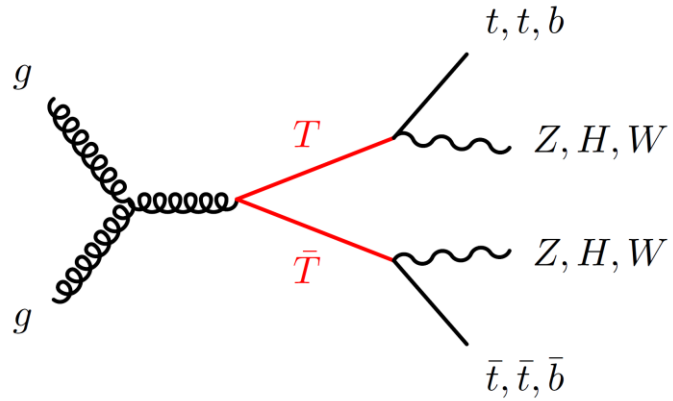
- ✓ Run2 + partial **run3 data** (2022, 2023)!
- ✓ The lepton content of the proton is becoming better understood (lepton PDF).
- ✓ **Covers complementary phase space** to other channels.
  - Especially in **high mass, high coupling region**.
- ✓ Good test for **generation and flavour structure of the LQs**

Vectorlike Fermions

Vectorlike Quark Introduction

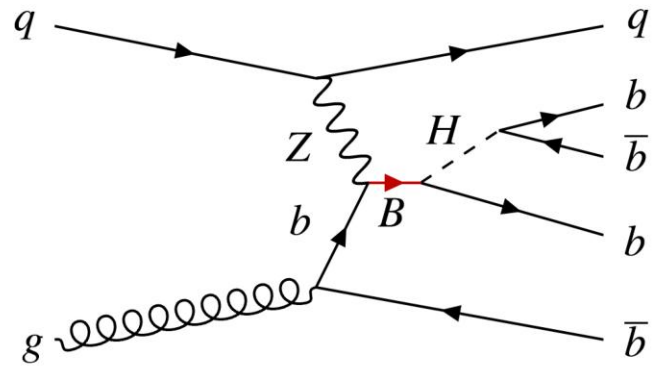
- ✓ **Vectorlike Quarks (VLQs)** are **color triplet, spin 1/2, fermionic partners of SM quarks** in many BSM models.
  - Composite Higgs, Little Higgs, Extra Dimensions, etc, to explain radiative divergences to the Higgs mass.

- ✓ VLQs can be SU(2) **singlets, doublets, or triplets** with specific charge assignments
- ✓ Typical branching ratios depend on the multiplet structure
  - e.g. **singlet: ξW≈0.5, ξZ≈ξH≈0.25**
- ✓ **T and B** have the same electric charge as the **SM t- and b-quarks**
- ✓ **X and Y** have electric charges **5/3 and -4/3**, respectively

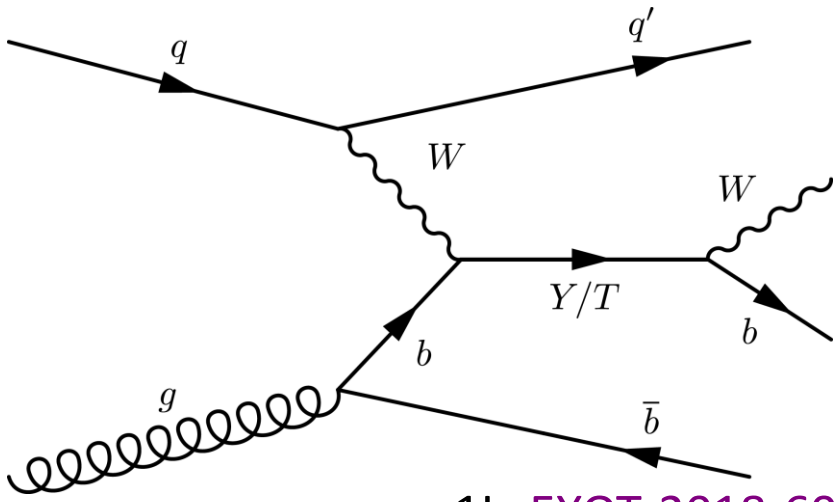


- ✓ **Pair production** (dominates at low mass) and **single production** (dominates at high mass and high coupling)
- ✓ **Preferential coupling to third generation SM quarks** is often assumed to cancel out the Higgs boson mass divergence from top-quark loops.
  - Possible decay channels: **T→Wb, T→Zt, T→Ht, B→Wt, B→Zb, B→Hb, X→Wt, Y→Wb**

- ✓ Parameters of model:
  - **$M_{T, B, X, Y}$**: Mass of the T, B, X, Y quark
  - **κ**: Global electroweak coupling parameter
  - **ξW, ξZ, ξH**: Relative couplings to W, Z, H bosons respectively
  - **Relative width**: $\Gamma/M \sim \kappa^2 M^2$



Single VLQ (T/Y) to Wb



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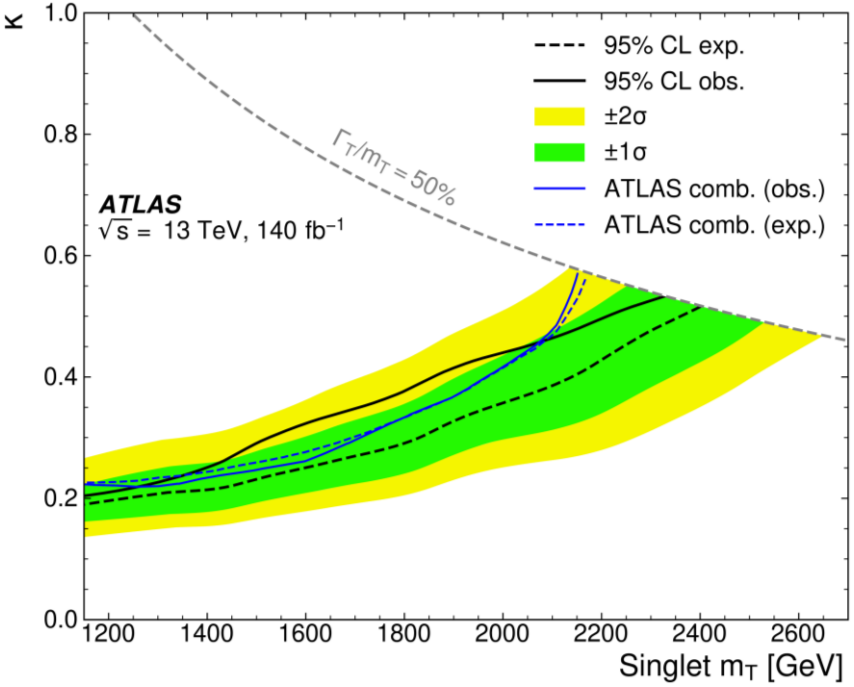
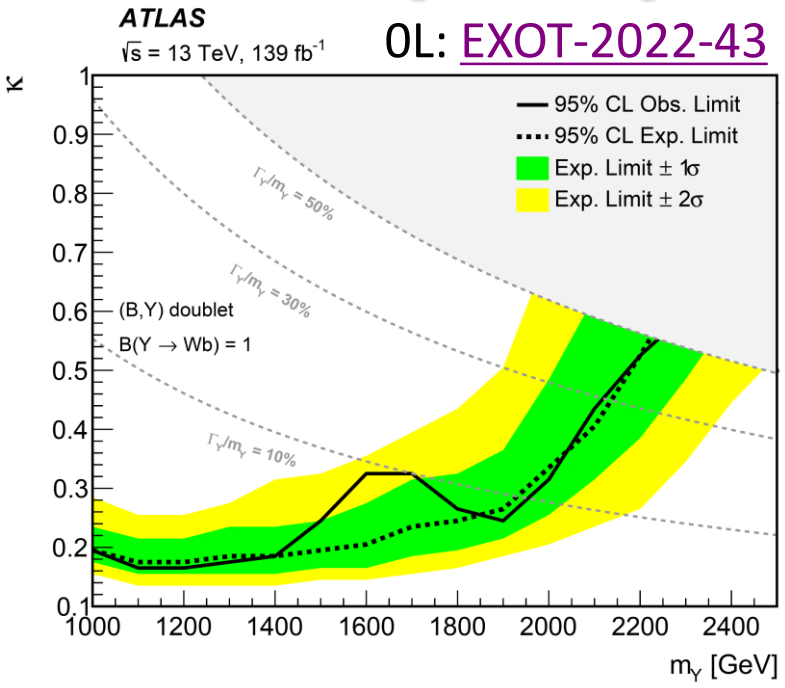


0L: EXOT-2022-43



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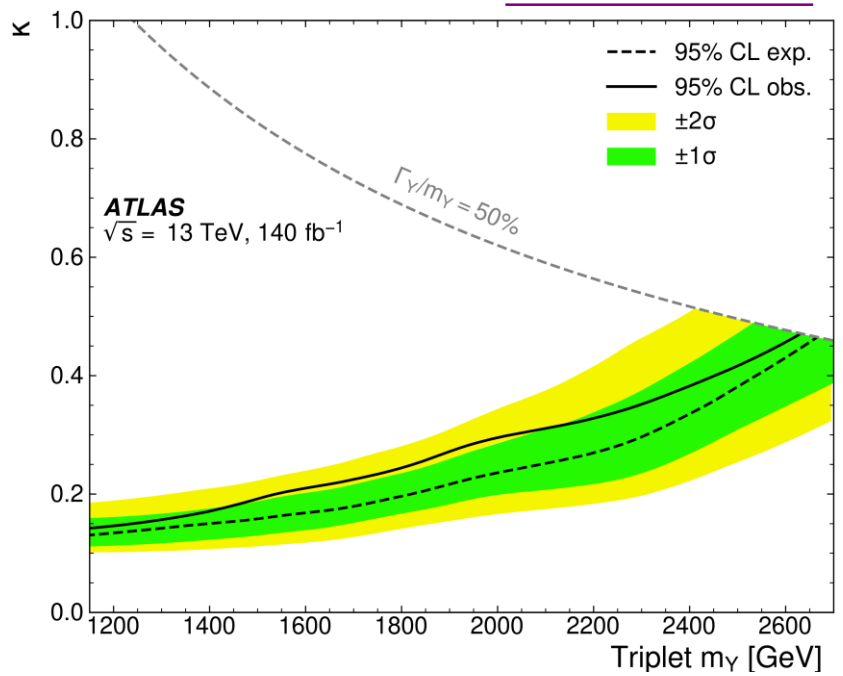


Searches for singlet T and Y in doublet (0L) and triplet (1L) scenarios

0-Lepton (0L) analysis

- ✓ Boosted large-R W tagging utilizing jet substructure information
- ✓ Data driven QCD background estimation is key

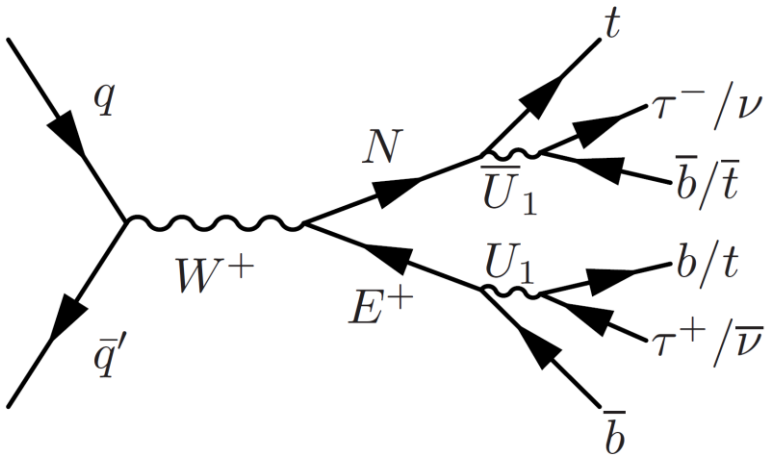
1-Lepton (1L) analysis

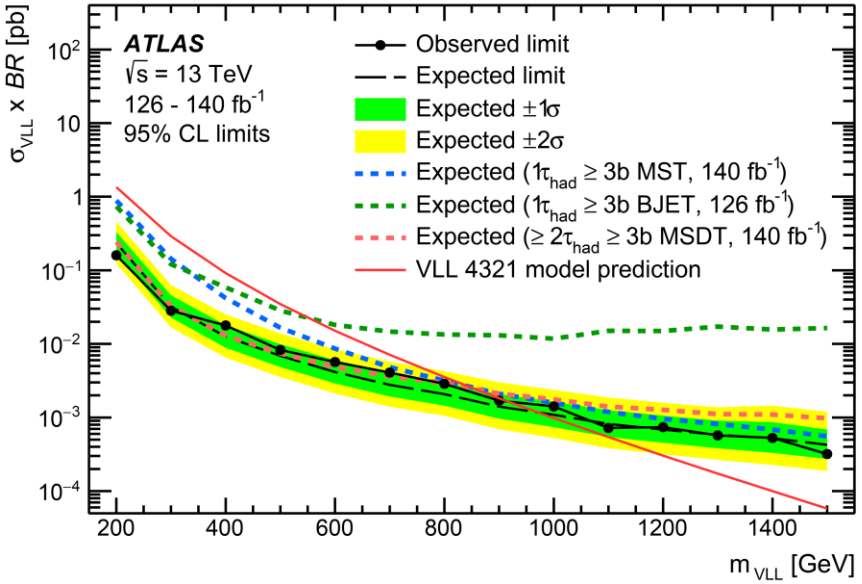
- ✓ Complementary sensitivity as 0L analysis
- ✓ Interference between the VLQs and SM processes is considered

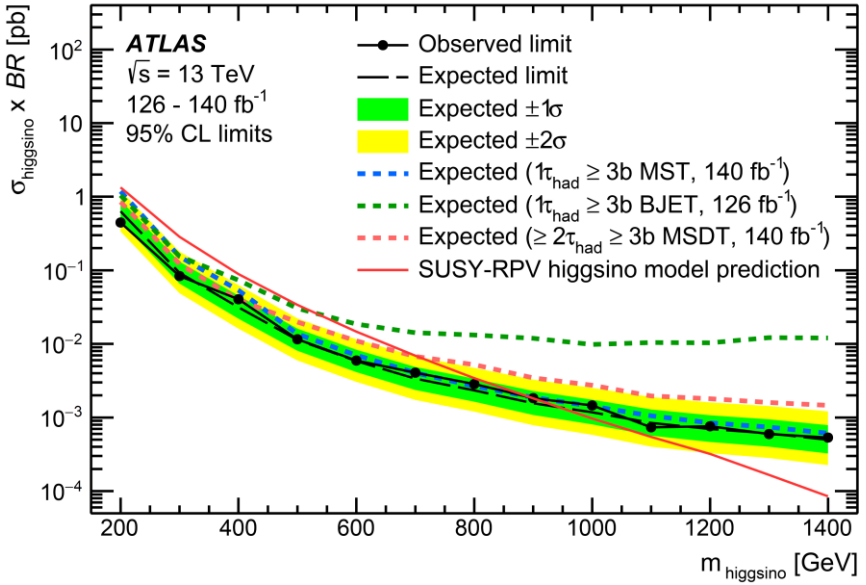
$$\mu \cdot S + \sqrt{\mu} \cdot I + B$$

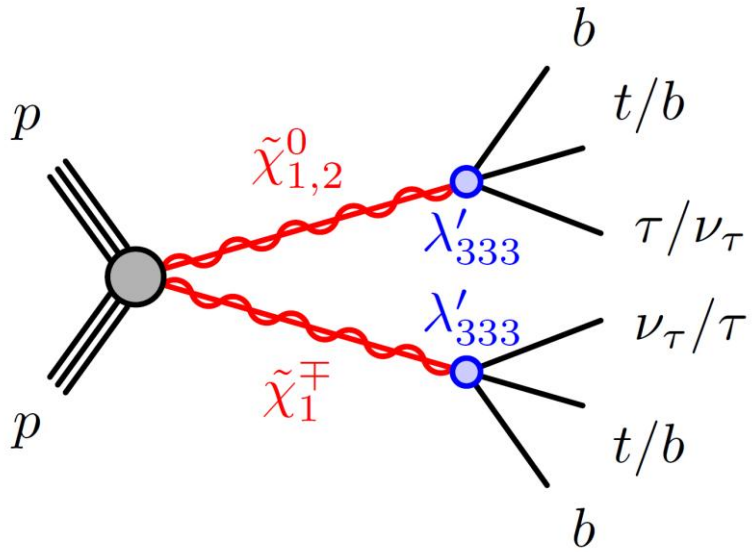
Vectorlike Lepton in b-jet and τ Final State

EXOT-2022-27







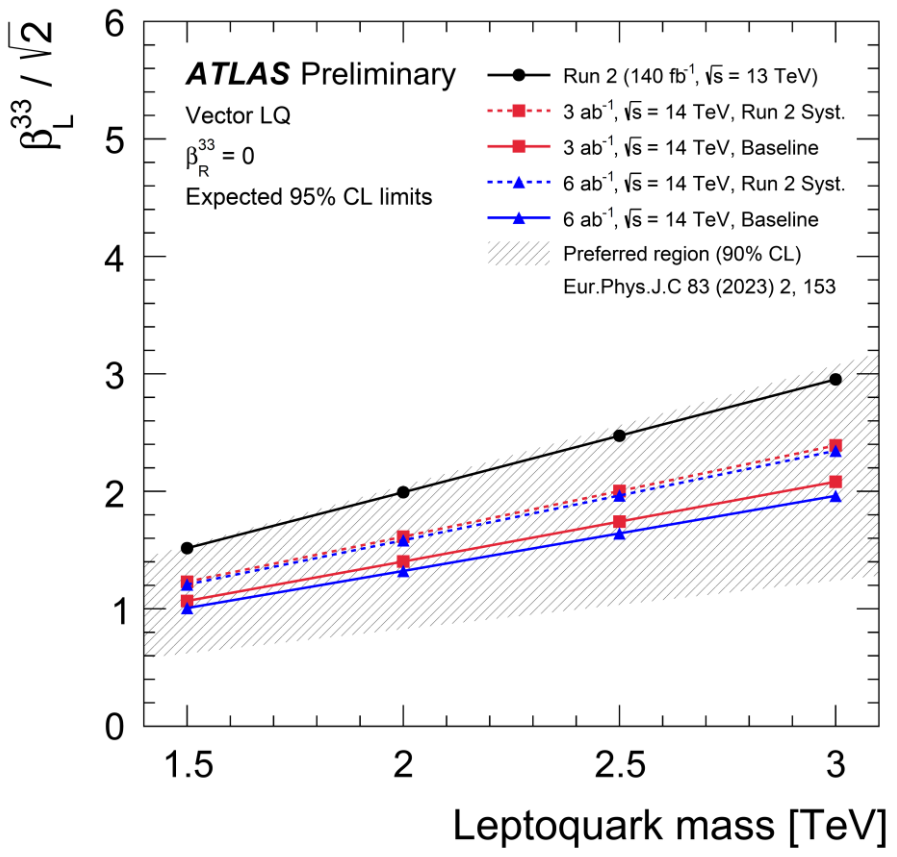


- ✓ One explanation of observed flavor anomalies is **4321 model**
  - **SU(4) × SU(3)' × $SU(2)_L$ × U(1)',** unitifies quarks and leptons
  - **Predicts vector LQ (U_1),** VLLs connect LQs to SM leptons
- ✓ VLL decays to U_1 Vector LQ, VLL (N, E^+) decays are as shown in the diagram
  - CMS reported 2.8σ excess at VLL mass 600 GeV, which is not observed
- ✓ **R-parity violating SUSY** is also searched for in the same analysis
- ✓ A paper is published with VLL search using **anomaly detection technique**
  - EXOT-2021-34

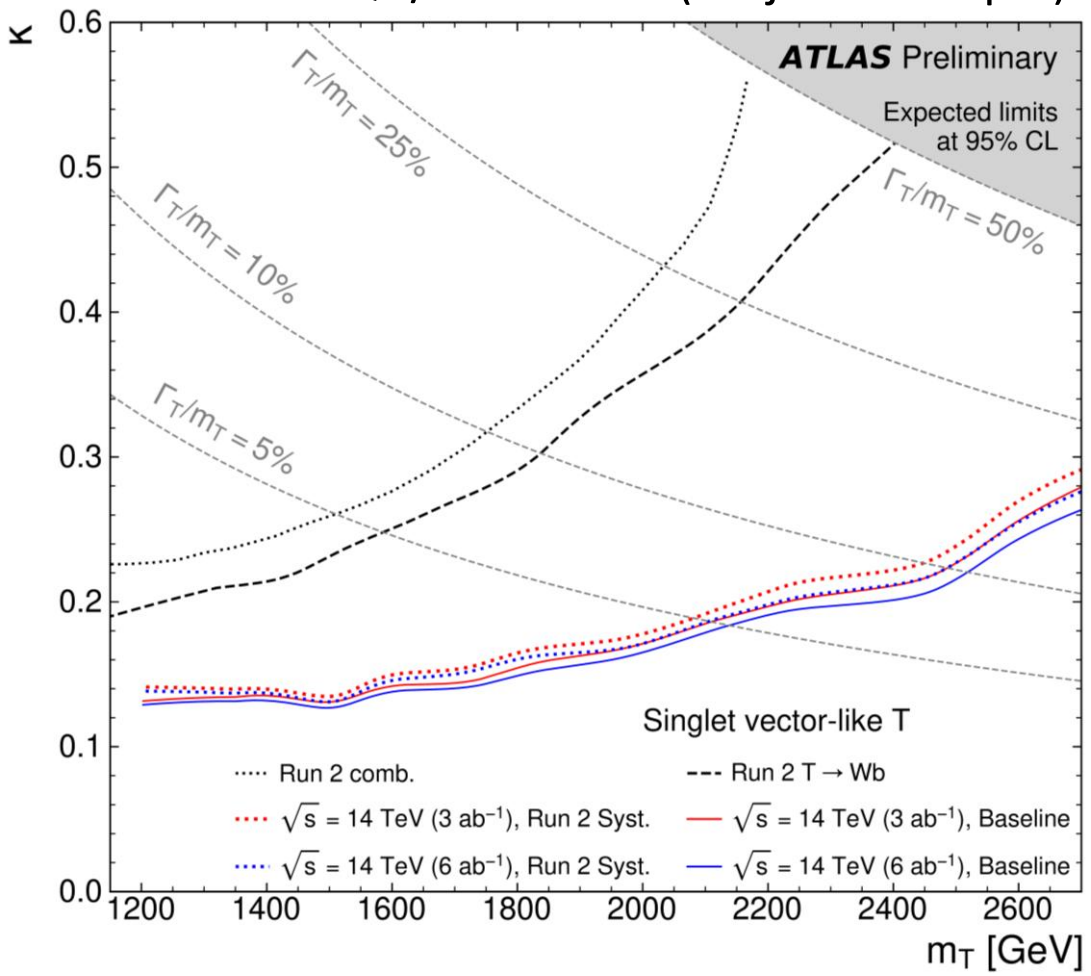
HL-LHC Projection

ATL-PHYS-PUB-2025-040

Non resonant LQ (Projection of p.5)



VLQ T/Y to WB 1L (Projection of p.9)



- ✓ Considering the following scaling:
  - Luminosity scale: **3000/139 (ATLAS only), 6000/139 (ATLAS + CMS)**
  - COM scale: considering cross section difference between **14/13 TeV**
- ✓ **Systematic uncertainties are scaled** according to the expected improvements with increased statistics and analysis techniques in the baseline scenario.

Summary

✓ Recent searches for Vector-like fermions and Leptoquarks at the ATLAS experiment are introduced.
- No significant excess is found, thus the strongest limits are set.

Leptoquarks

✓ First result from the non-resonant production searches.
- Differential cross-section is measured and the constraints are also set for the EFT coefficients.

✓ Resonant production search utilizing the lepton PDF knowledge is also conducted.
- Results using run 3 data are starting to emerge.

Vectorlike fermions

✓ VLQ (T/Y) decaying to Wb are searched for.

✓ VLL decaying to U_1 Vector Leptoquark as well as R-parity violating SUSY model are also searched for.

And HL-LHC projection study also performed.

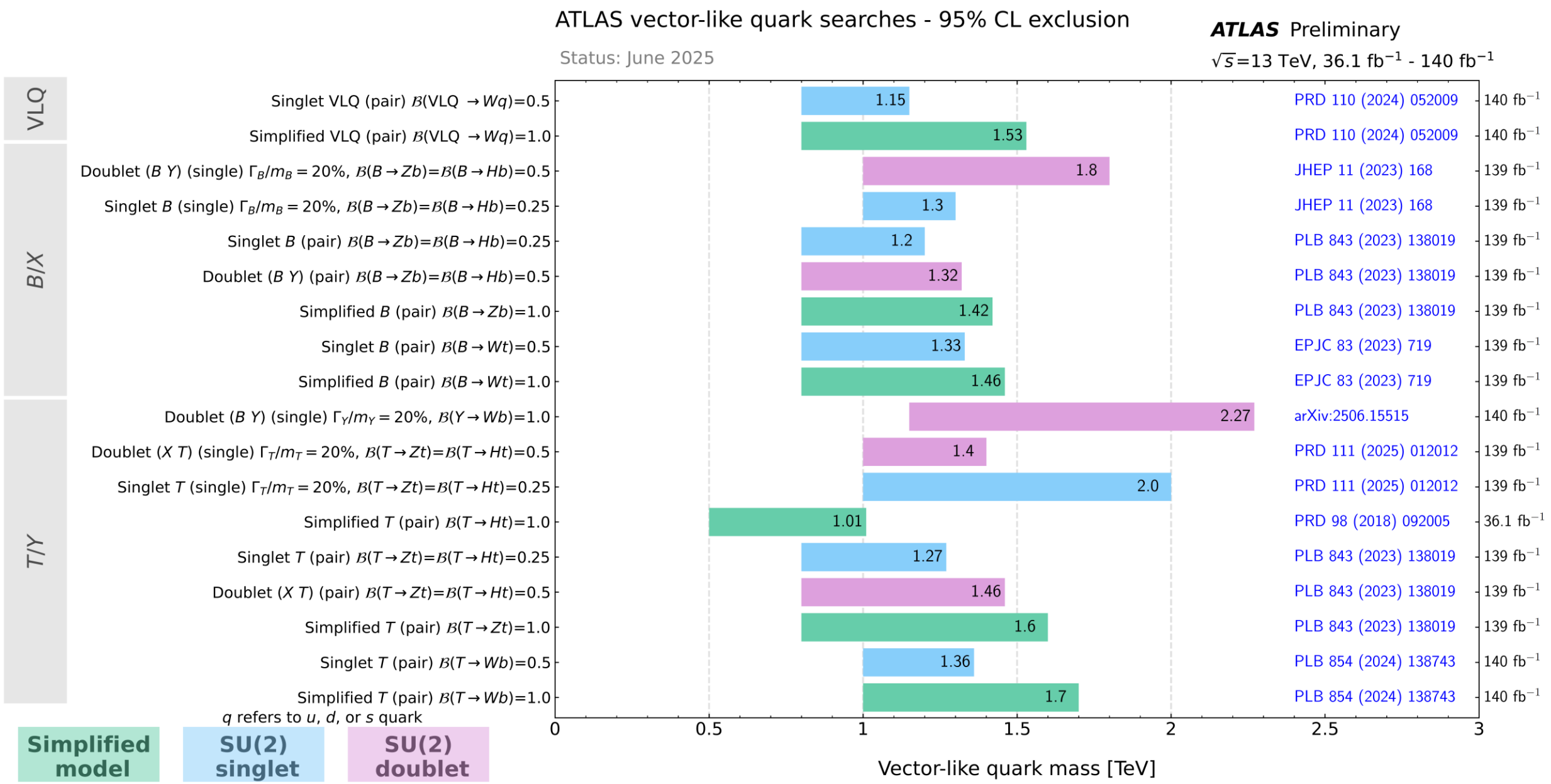
The ATLAS results can be found and have been updated in the ATLAS publication page, and…

Stay tuned for the upcoming new channels and Run-3 results!

Backup

VLQ Summary Plot

Link



LQ Summary Plot

Link