Searches for Leptoquarks with the ATLAS detector

Tatjana Lenz (University of Bonn)
on behalf of ATLAS Collaboration

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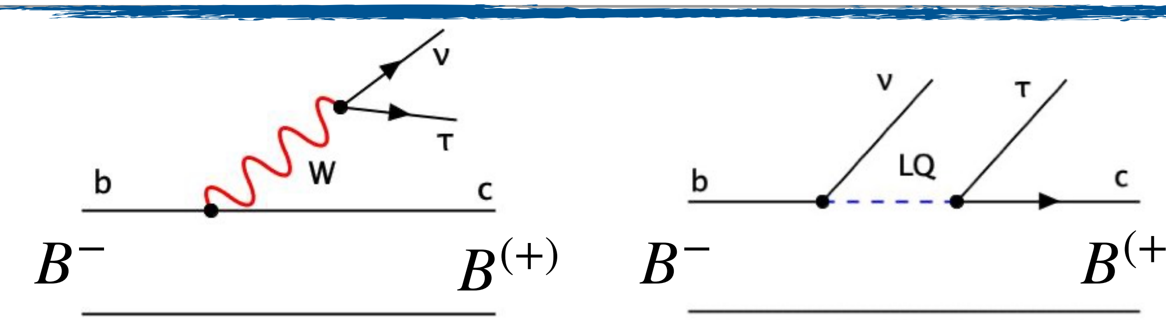
Lake Louise Winter Institute 2023

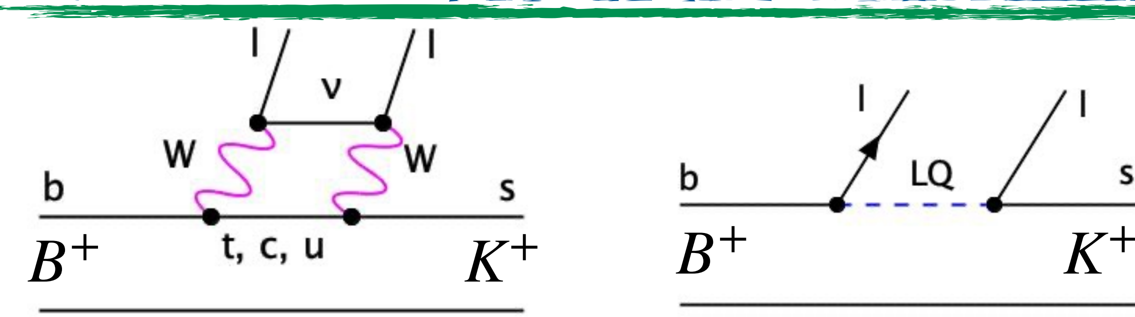
Anomalies - Hints for New Physics?

- Search for violation of symmetries
  ⇒ **New Physics (NP)**
- **Lepton Flavour Universality (LFU)**
  - Anomalies on charged and neutral current processes in B-physics
- **Anomalous magnetic dipole moment**
  - Could be connected to LFU
- **Leptoquarks (LQ)** - a good candidate to explain such anomalies
  - mediator of flavour-changing-neutral-currents
  - violation of LFU



$$R(D^{(*)}) = \frac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\ell\nu}, \quad \ell = e, \mu$$

3.1σ excess in $R(D)$ and $R(D^*)$ combination



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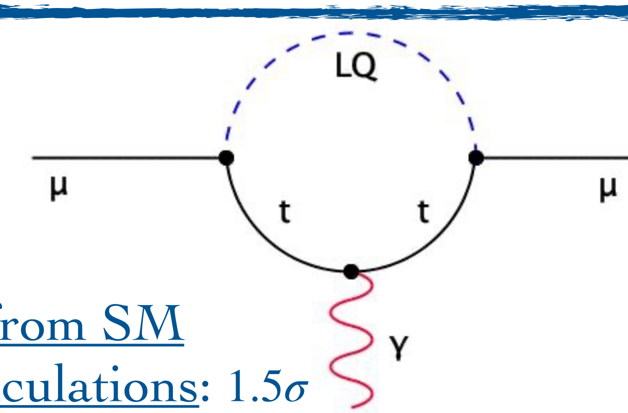
New LHCb result compatible with SM at 0.2σ



4.2σ deviation from SM
new lattice QCD calculations: 1.5σ

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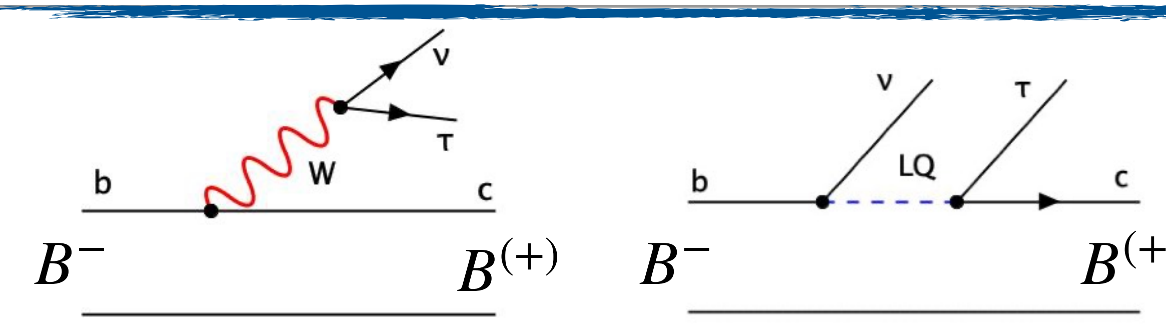

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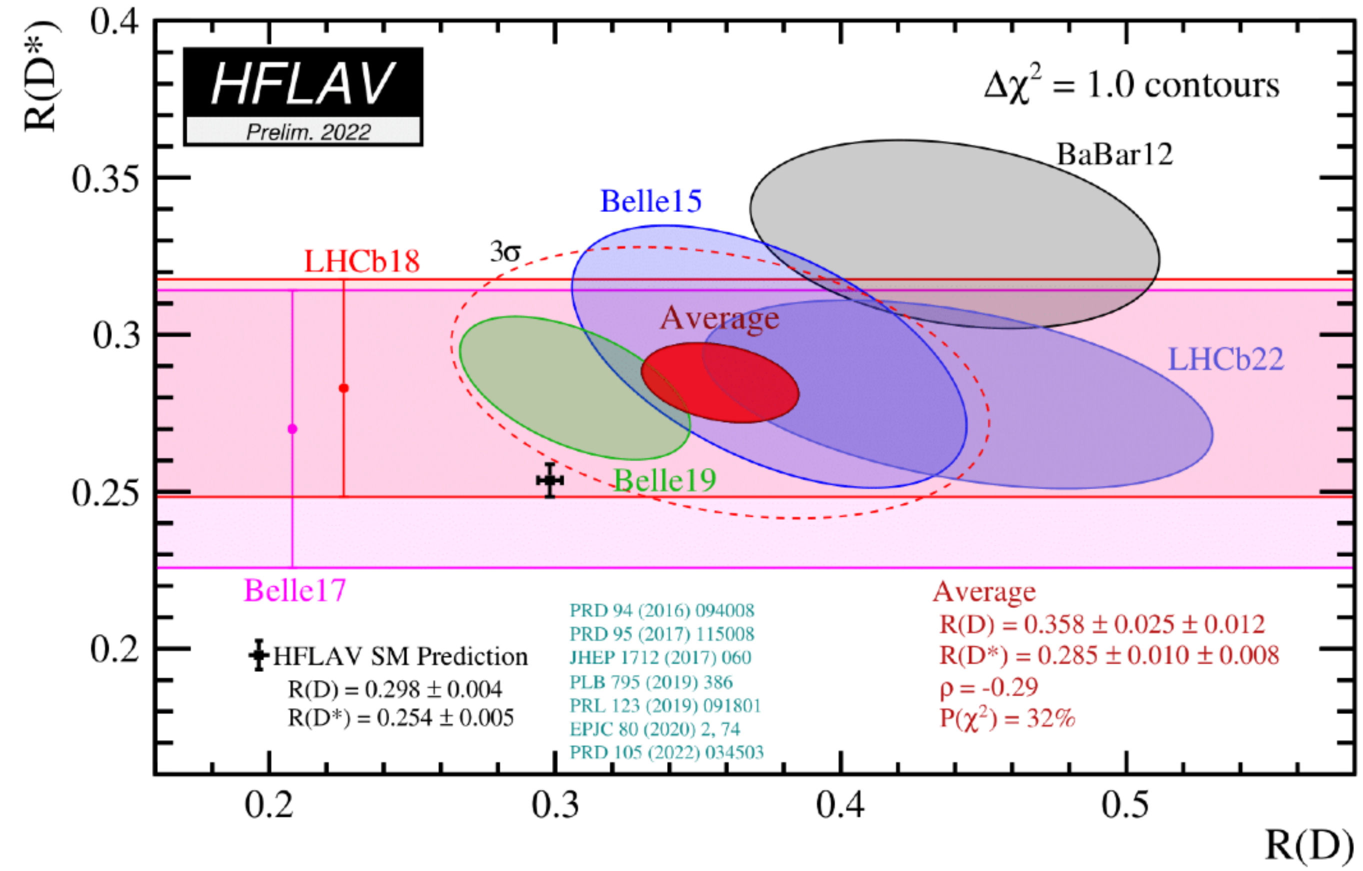

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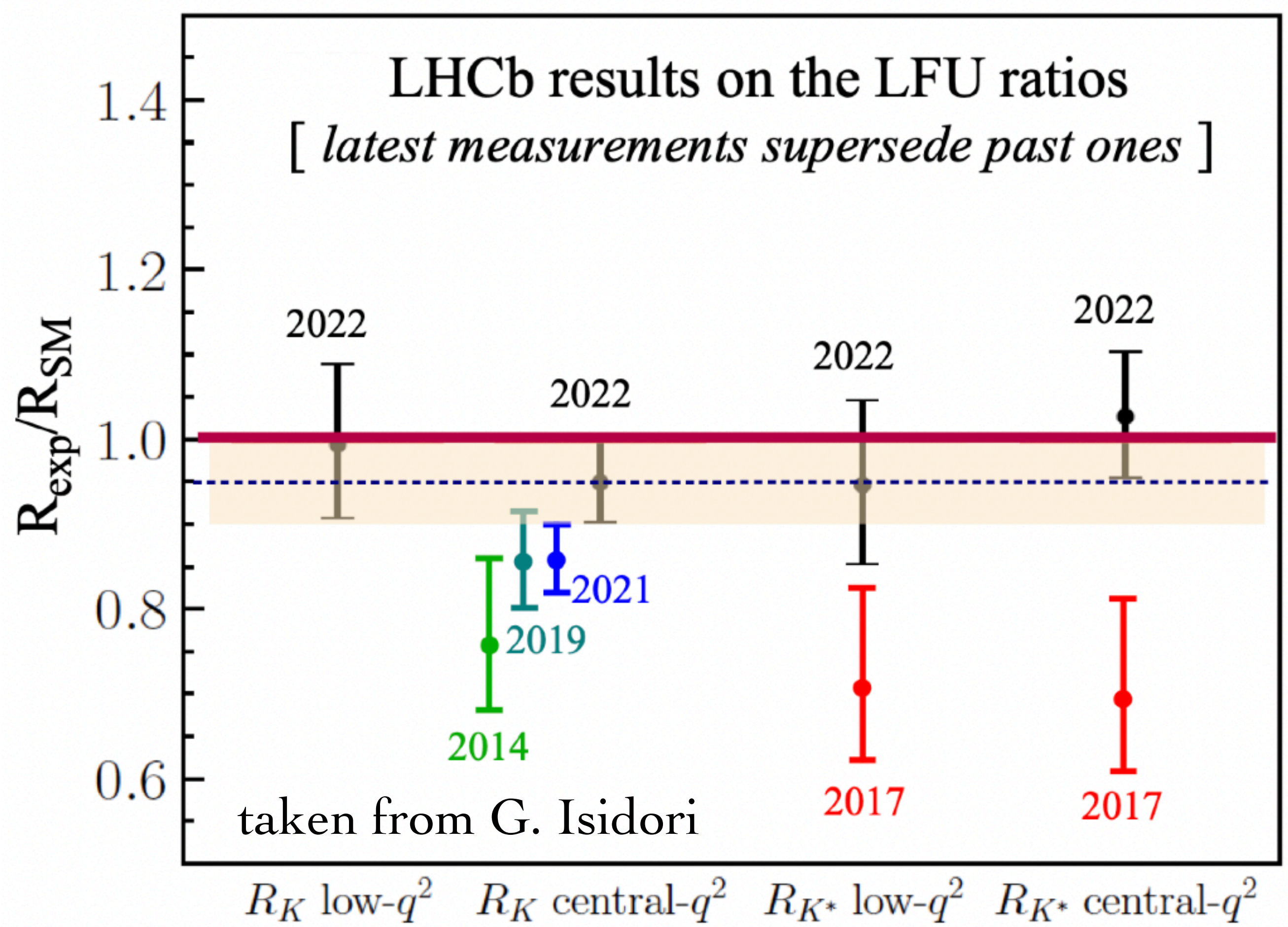

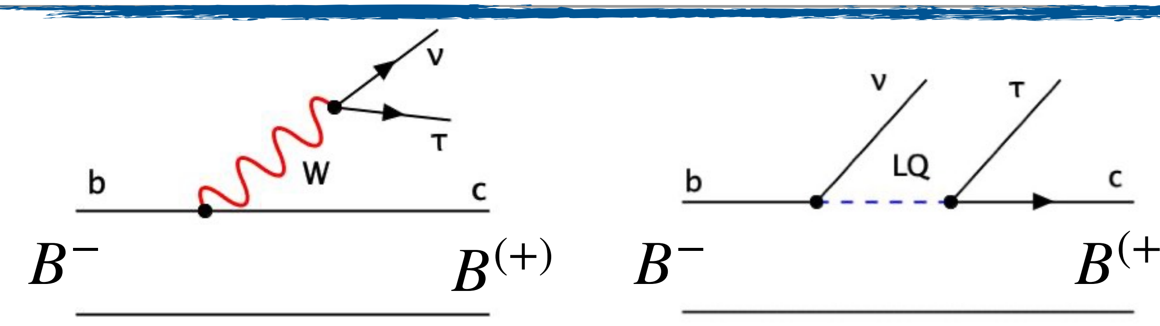

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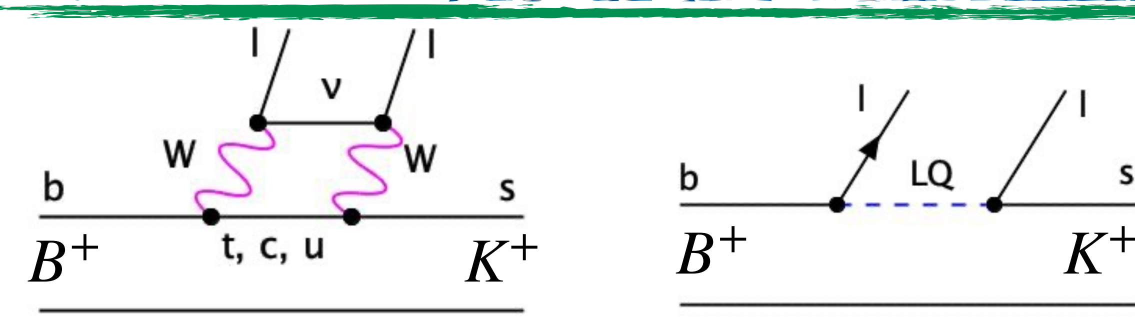

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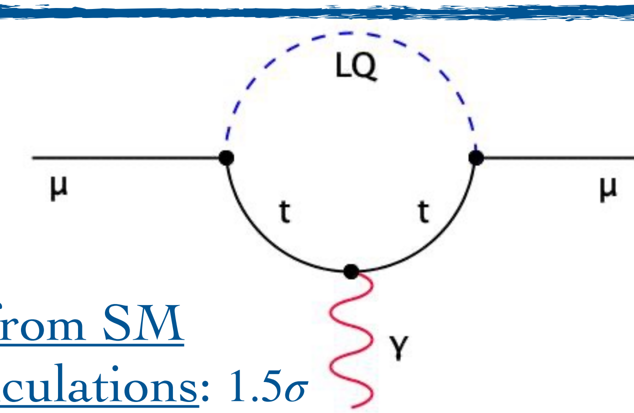

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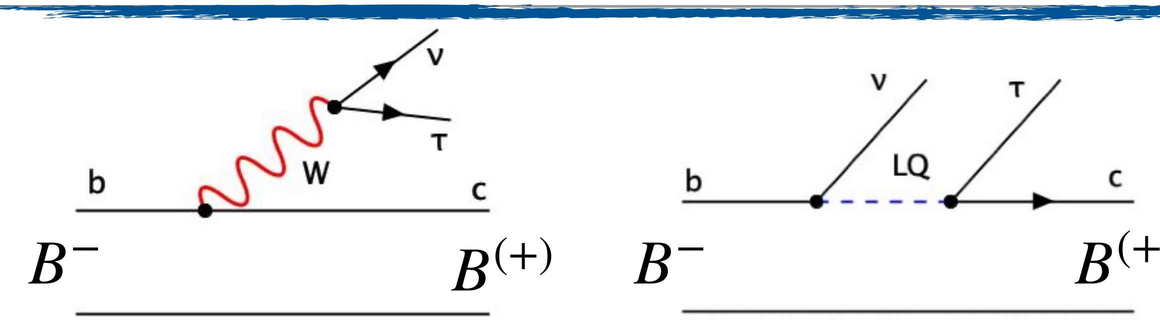

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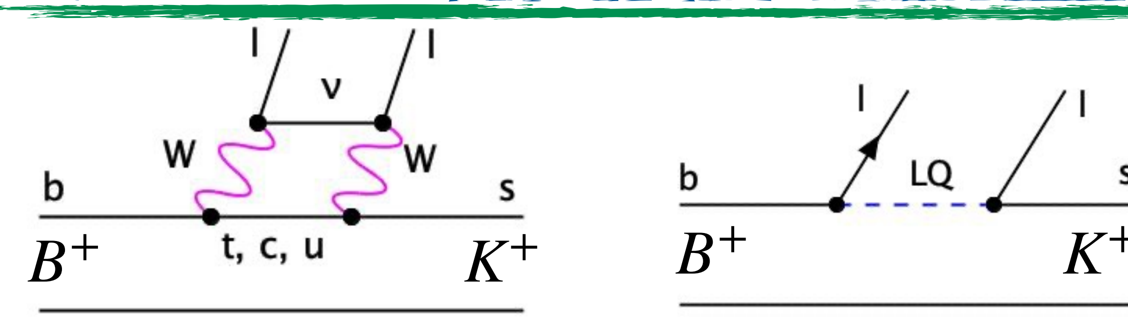

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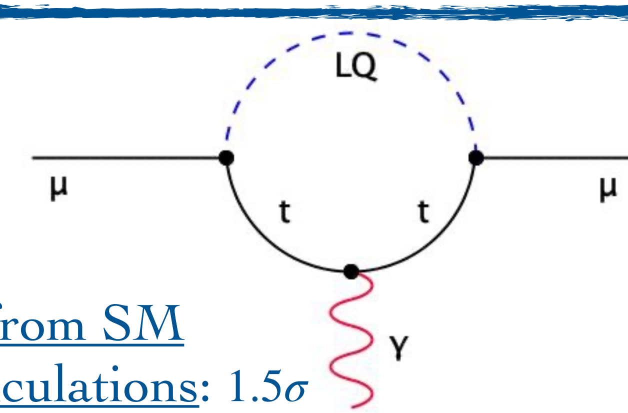

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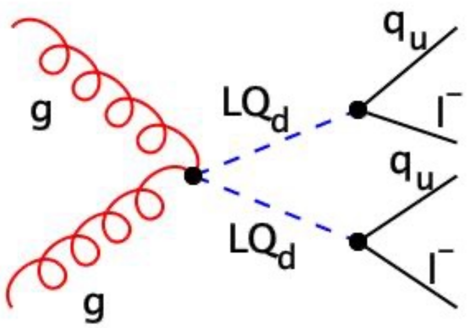
Leptoquarks

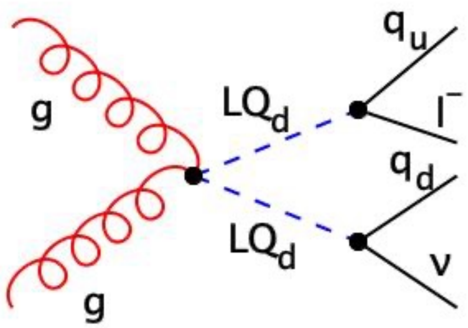
- Predicted by many grand unified theories: GUT SU(5), Pati-Salam SU(4), R-parity violating SUSY
- Connect the quark and lepton sectors
- **Degrees of freedom:**
  - mass, electrical charge, scalar/vector, Yukawa couplings (λ)
  - Branching fraction into charged lepton ($\beta = 1$) or neutrino ($\beta = 0$)
  - Production in pairs, singly, off-shell, s/t-channel

Pair Production

flavour-diagonal



cross-generational

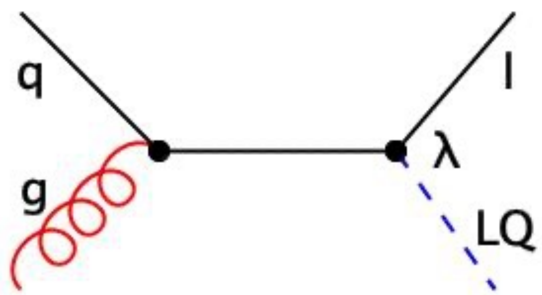


cross-section depends on m_{LQ}

Single Production

cross-section $\propto \lambda^2$

sensitive to higher m_{LQ} for high λ

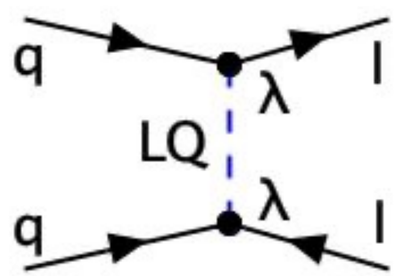


Non-resonant Production

cross-section $\propto \lambda^4$

sensitive to very high masses

interference with SM



Large Hadron Collider

ATLAS

New energy frontier: 7 - 13.6 TeV

Run-2: 13 TeV pp collisions, 139 fb^{-1}

ATLAS Search Program

- Focus on pair production, first results on single LQ
- **Grid**: LQ mass vs β or λ
- **Scalar LQ ($\tilde{S}_1$)**: up-type $(\frac{2}{3}e)$ and down-type$(-\frac{1}{3}e)$ charge; decays flavour-diagonal or cross-generational ("mix")
- **Vector LQ:** stronger model dependence (UV completion)
  - U_1 LQ is a favoured explanation for $R(D^{(*)})$ and $R(K^{(*)})$ anomalies
  - larger cross-section compared to scalar LQs
  - coupling to color can be suppressed
    - $\tilde{U}_1^{\mathrm{YM}}$, Yang Mills: nominal coupling to color ($\kappa = 0$)
    - $\tilde{U}_1^{\mathrm{min}}$, minimal coupling ($\kappa = 1$) to color: coupling to gluon only via covariant derivative

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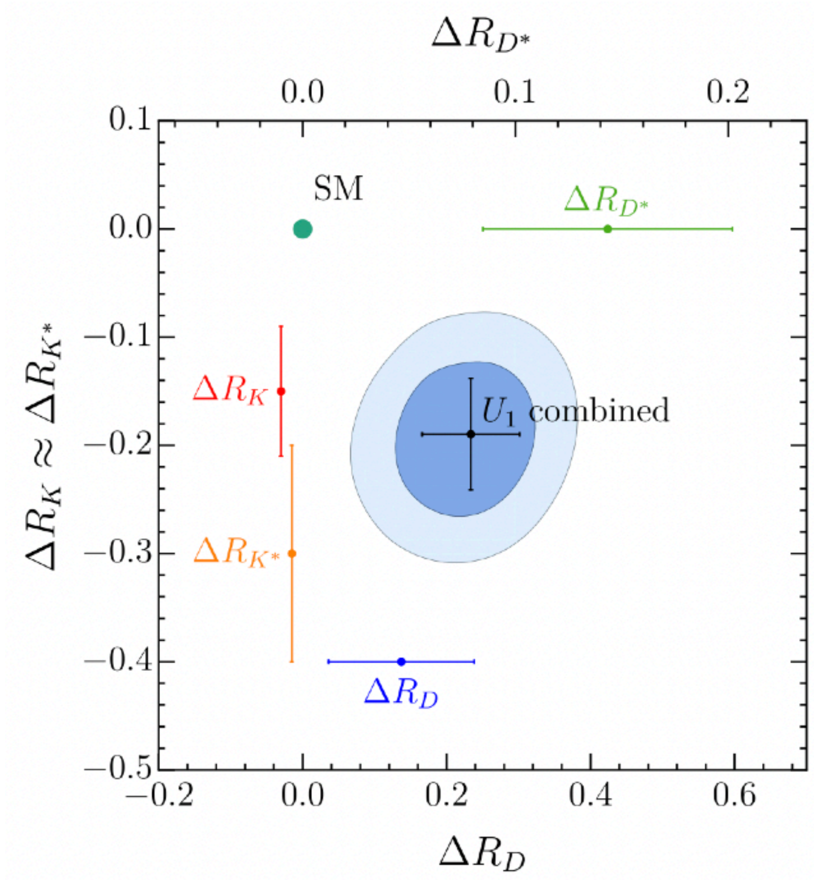
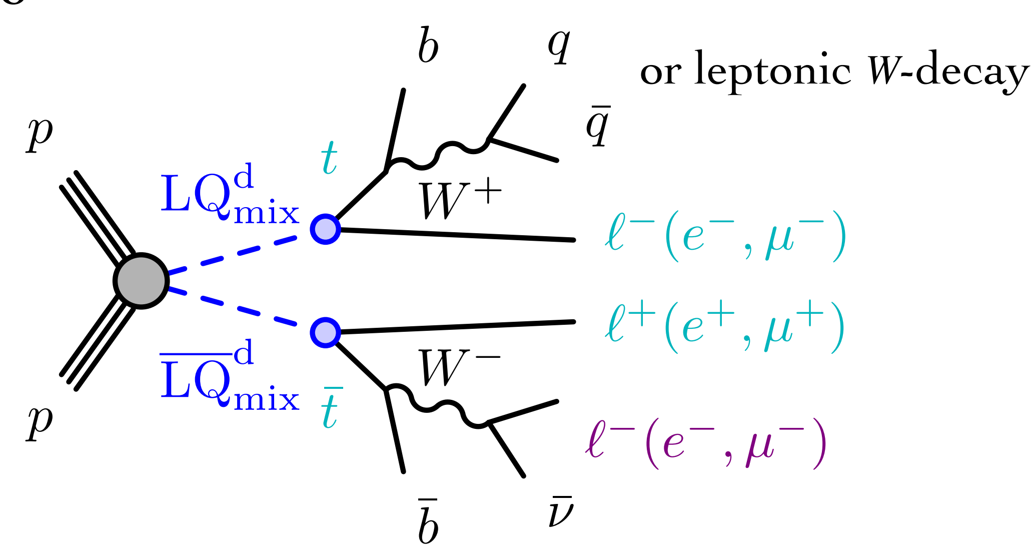
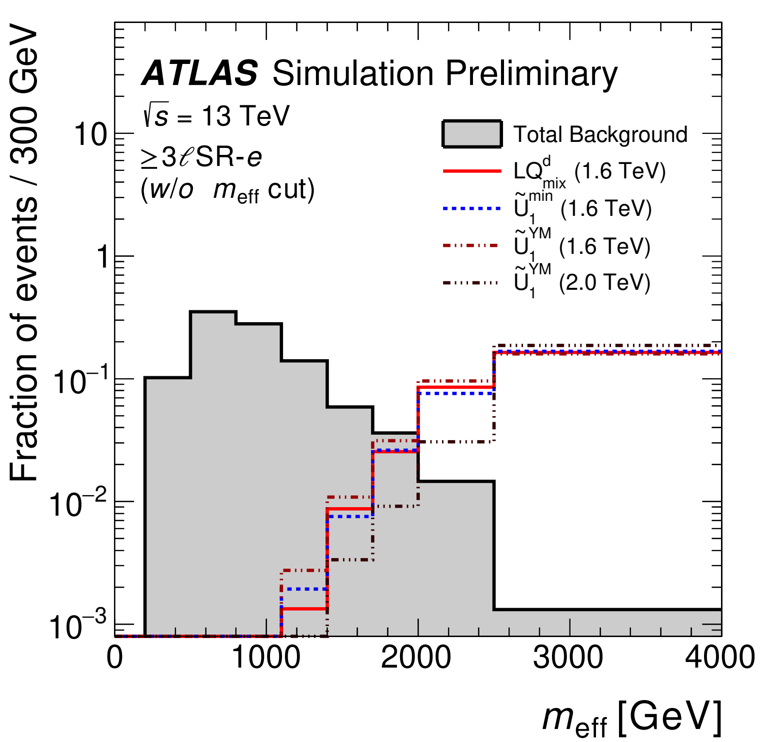


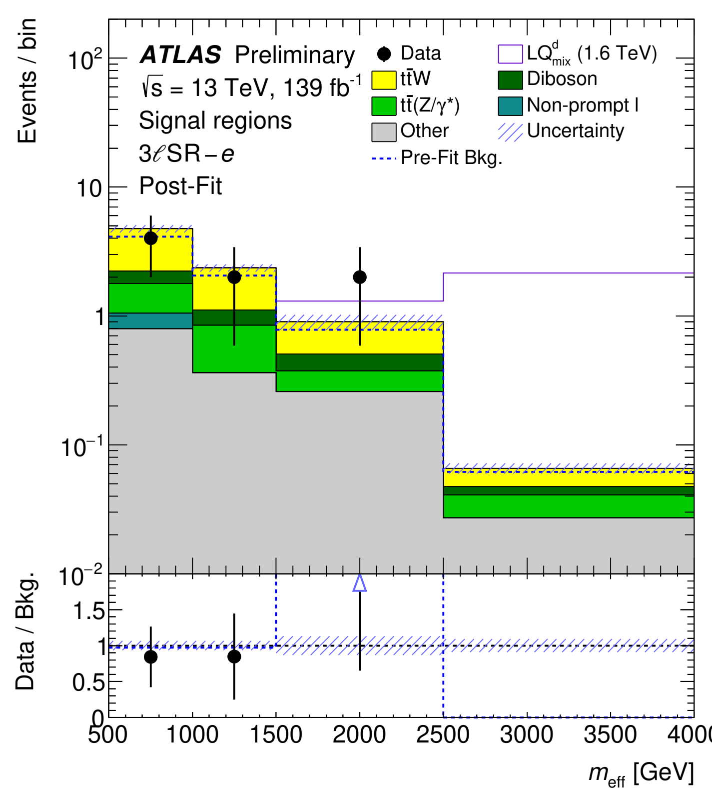
$R(K^{(*)})$ results outdated but new LHCb results can be explained as well (smaller couplings to 2nd generation)

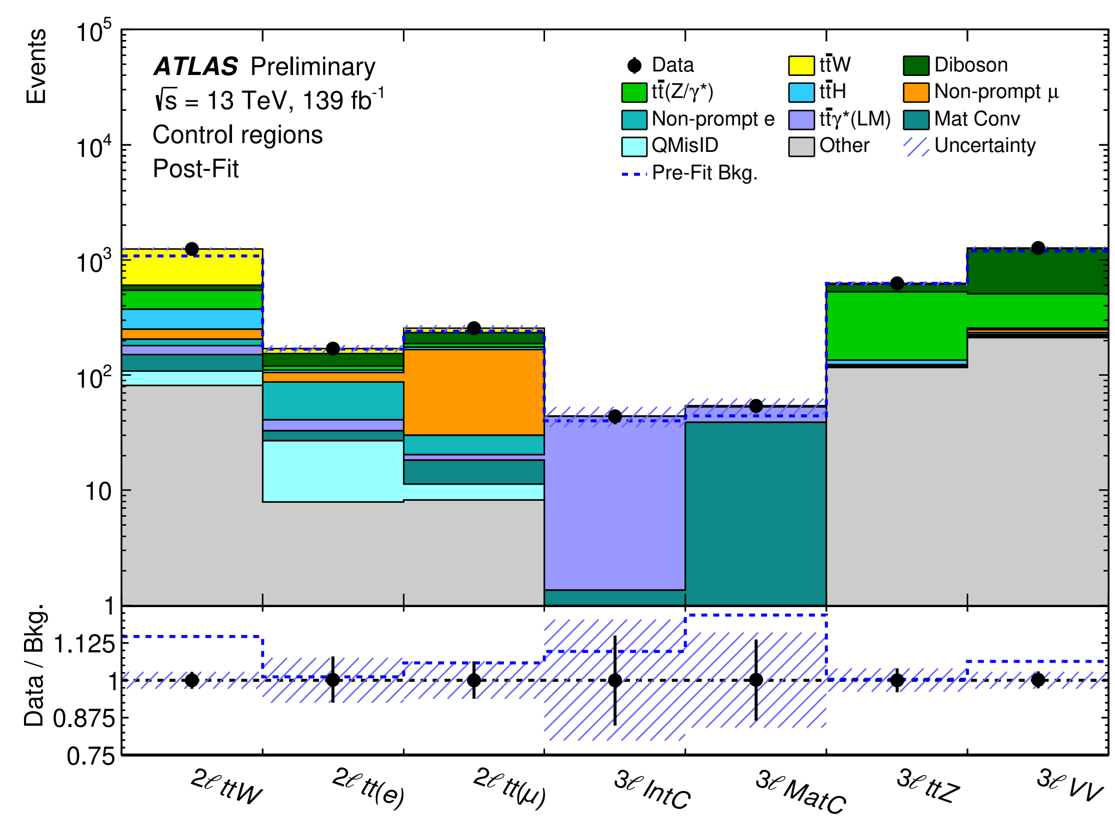
$LQ^{d}_{mix}LQ^{d}_{mix} \to t\ell t\ell$ Multilepton

- Pair-produced scalar ($\beta = 1$) and vector($\tilde{U}_1$) LQs decaying to top quark and multi-leptons($2\ell SS, 3\ell, 4\ell$)
- At least 2 jets, one b-tagged jet
- Main backgrounds: $t\bar{t}W, t\bar{t}Z, VV$, non-prompt ℓ
  - normalisation derived in data, modelling verified in validation regions
- Discriminant: $m_{eff} = \sum_{jets, e, \mu} p_T + E_T^{miss}$
- Signal regions: $m_{eff} > 500\,GeV$ and $m_{\ell\ell}^{min} > 200\,(100)\,GeV$ for $3\ell(4\ell)$



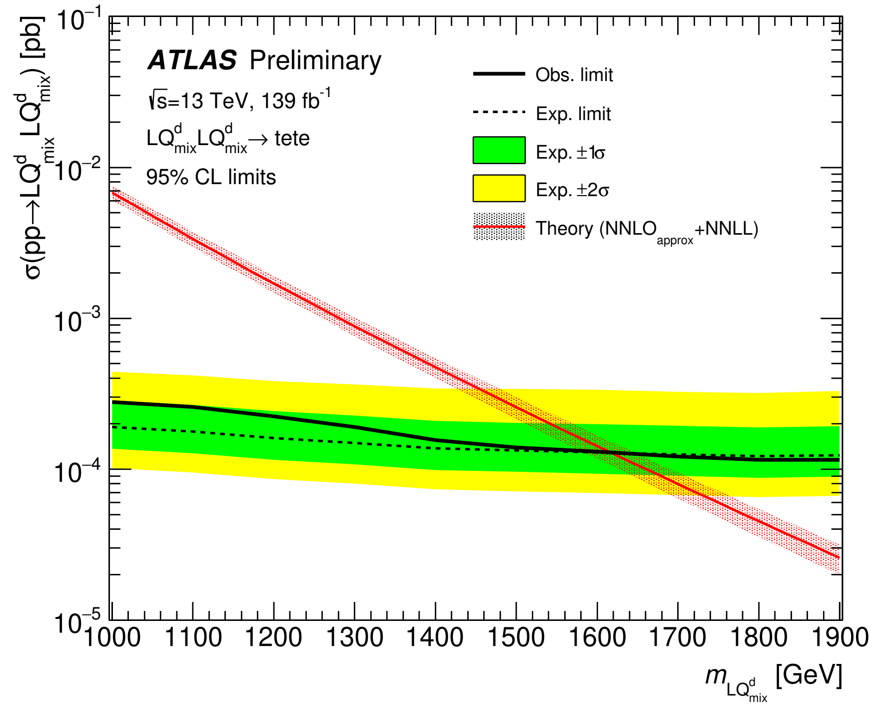


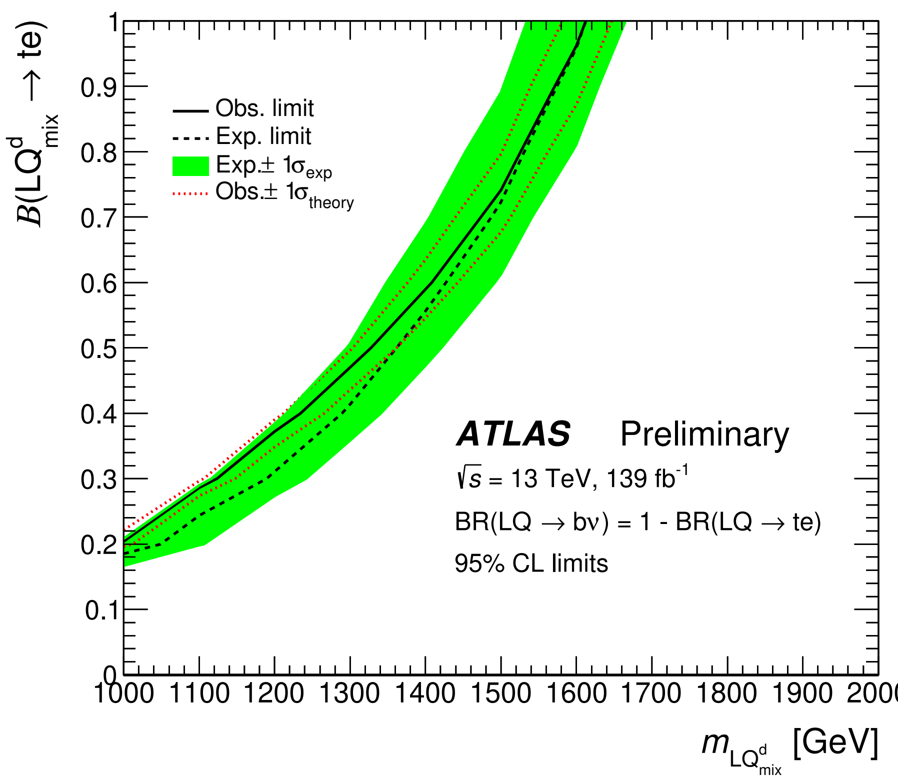


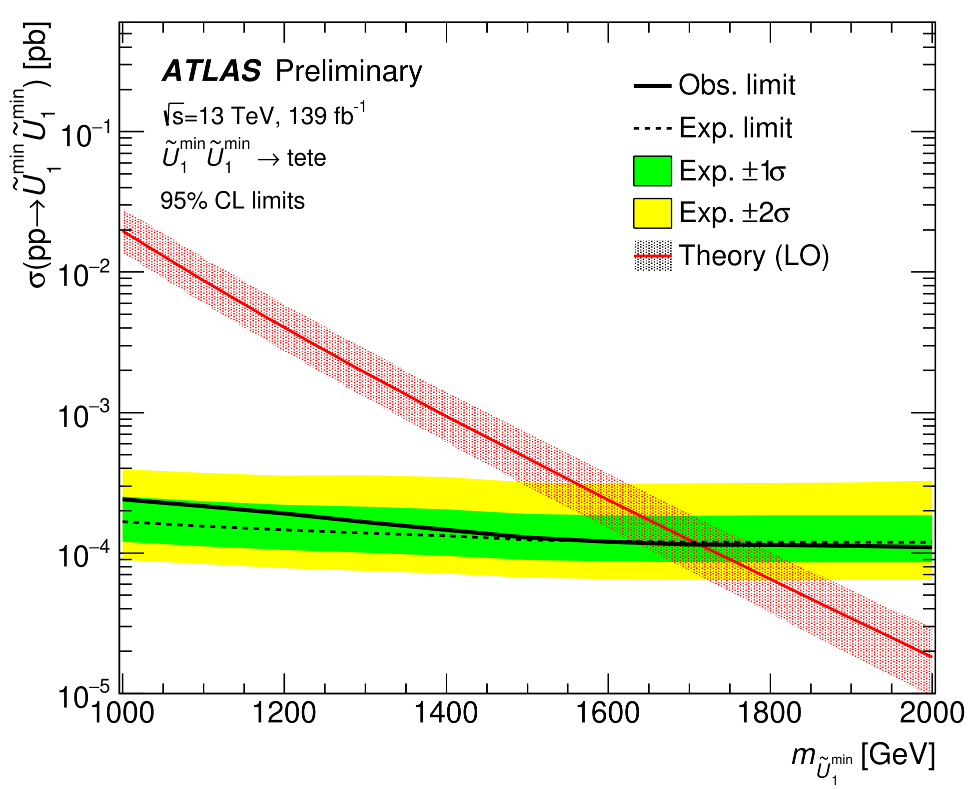


$LQ_d^{mix} LQ_d^{mix} \rightarrow t\ell t\ell$ Multilepton Results

- Statistically limited, largest systematic uncertainty - lepton identification
- Observed exclusions LQ $\rightarrow te\,(t\mu)$
  - Scalar LQ: $m_{LQ^d_{mix}} < 1.64\,(1.61)$ TeV
  - Yang-Mills vector LQ: $m_{LQ_{\tilde{U}_1^{YM}}} < 1.71\,(1.73)$ TeV
  - Minimal coupling vector LQ: $m_{LQ_{\tilde{U}_1^{min}}} < 2.0\,(2.0)$ TeV
- Most stringent limits

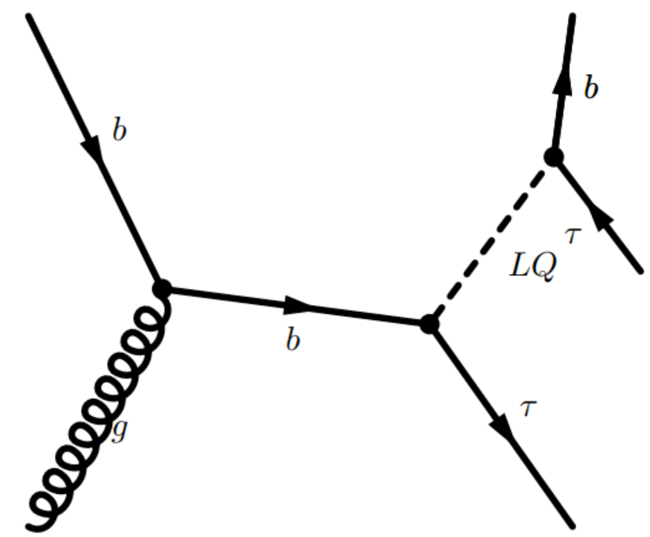


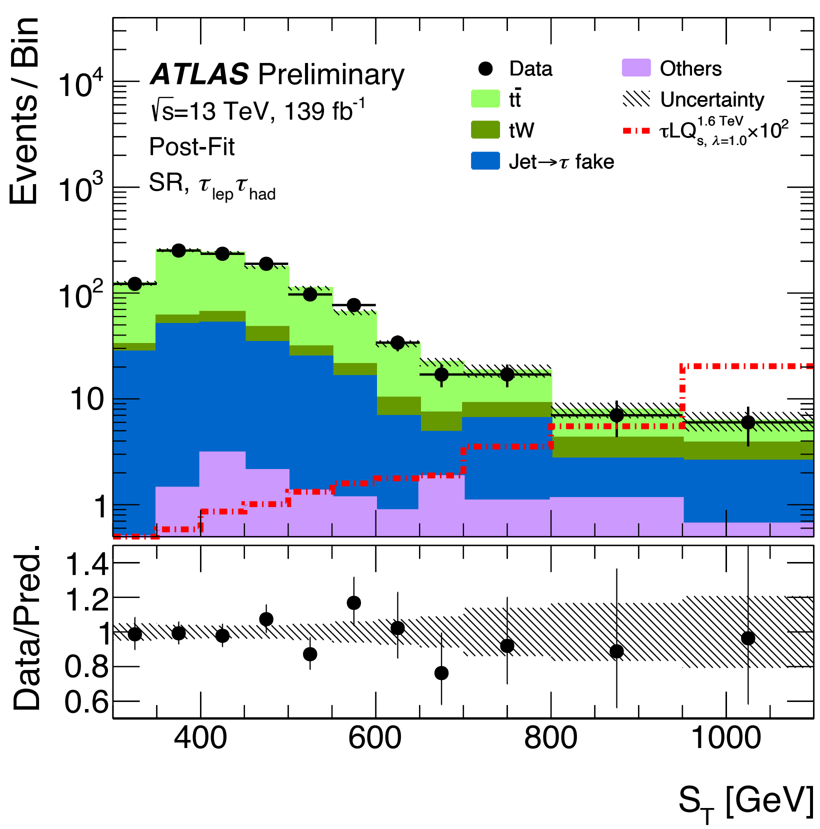


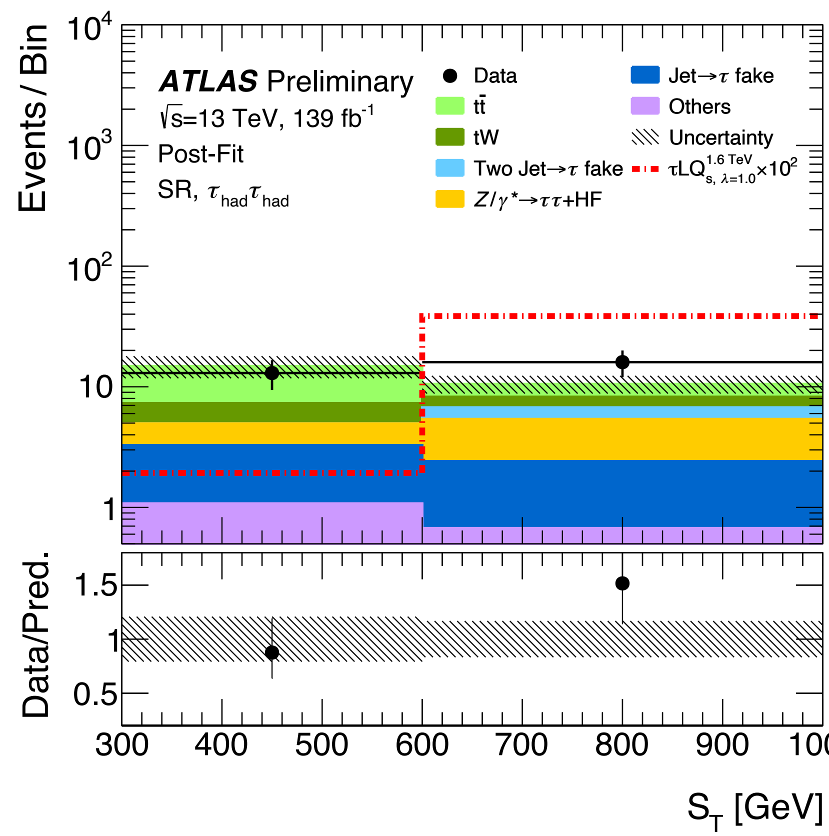


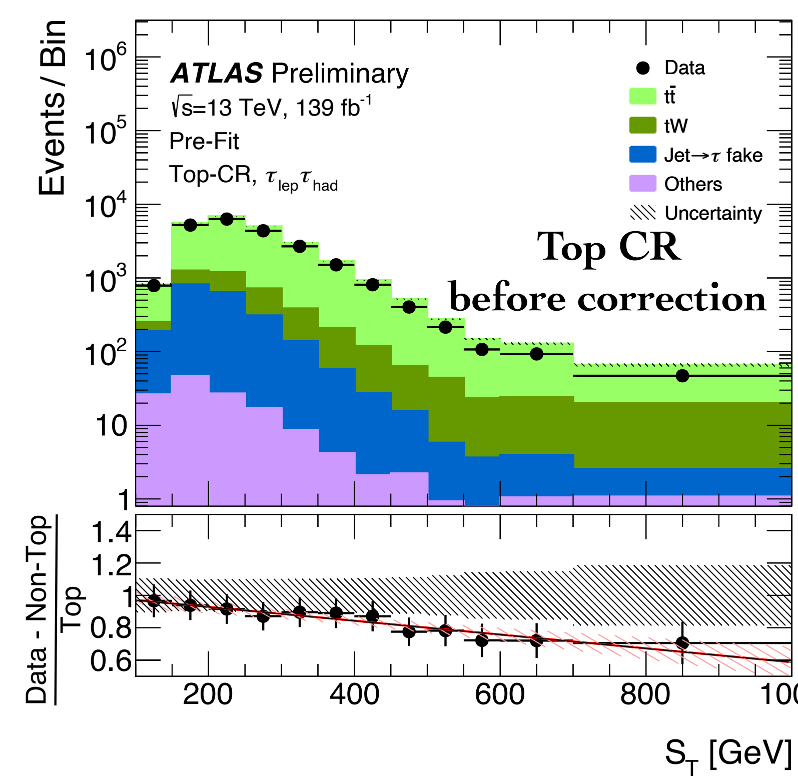
$\tau LQ^{\tilde{S}_1} \rightarrow b\tau_{had}\tau_{had}/\tau_{lep}\tau_{had}$

- Singly (and pair) produced LQs decaying into a τ-lepton and a b-hadron
  - $\lambda = 0.5 - 2.5, \beta = 1,\ \tilde{S}_1$ scalar LQ
- $\geq 2\,\text{jets},\ \geq 1\,\text{b}-\text{jet}, \Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5, m_{\text{vis}}^{\tau\tau} > 100\,\text{GeV}$
- $p_{\text{T, lead.}\,b\text{-jet}} > 200\,\text{GeV}$ to reduce SM interference with non-resonant production
- Discriminant: $S_{\text{T}} = \sum_{b\text{-jet},\ell,\tau} p_{\text{T}}$ & $S_{\text{T}} > 300\,\text{GeV}$ in the signal regions
- Main backgrounds:
  - $t\bar{t}$, single-top: data-driven correction as a function of S_{T}
  - data-driven fake τ-lepton estimate



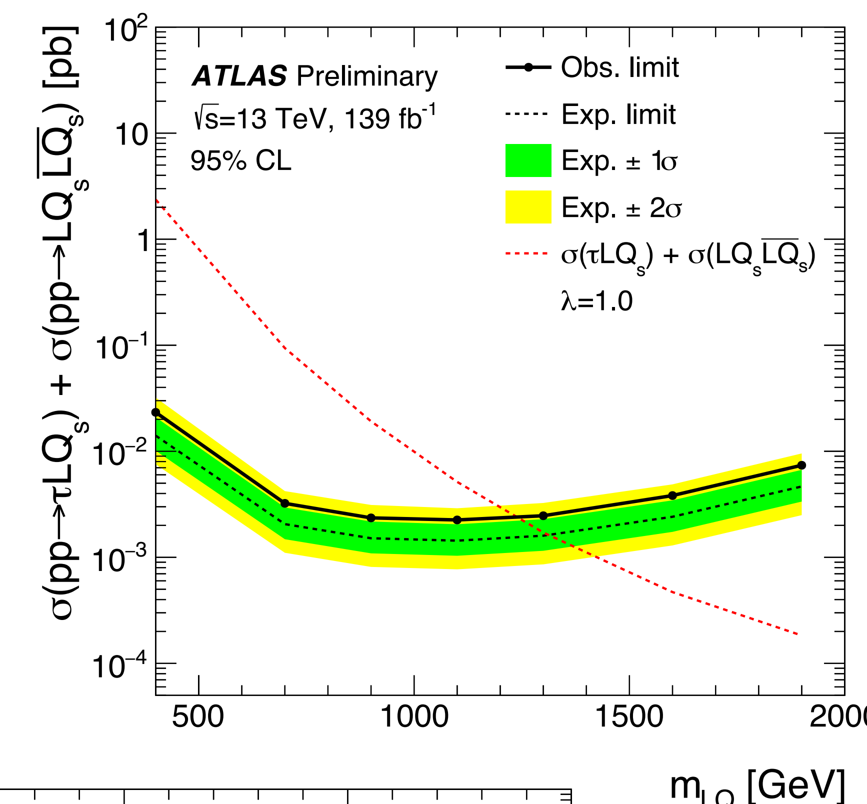


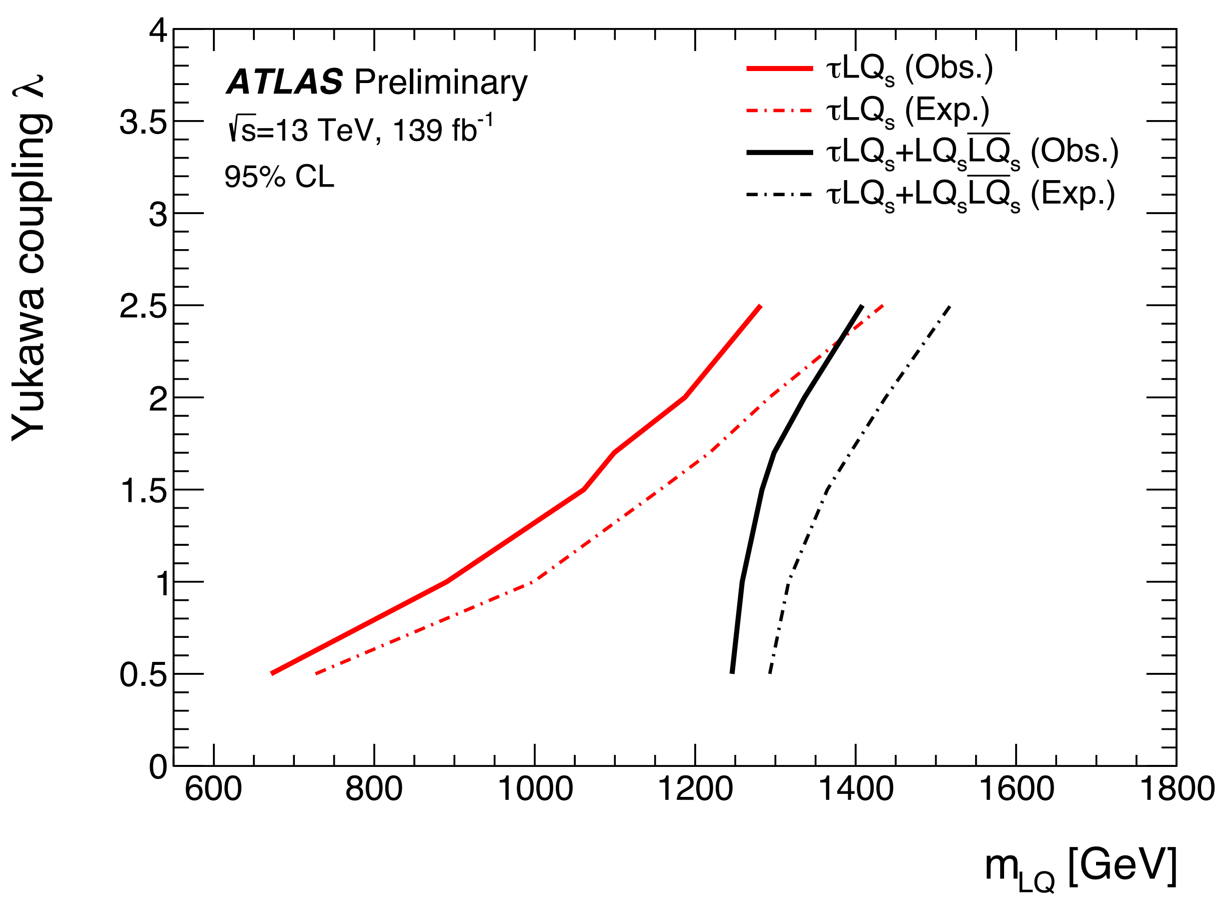


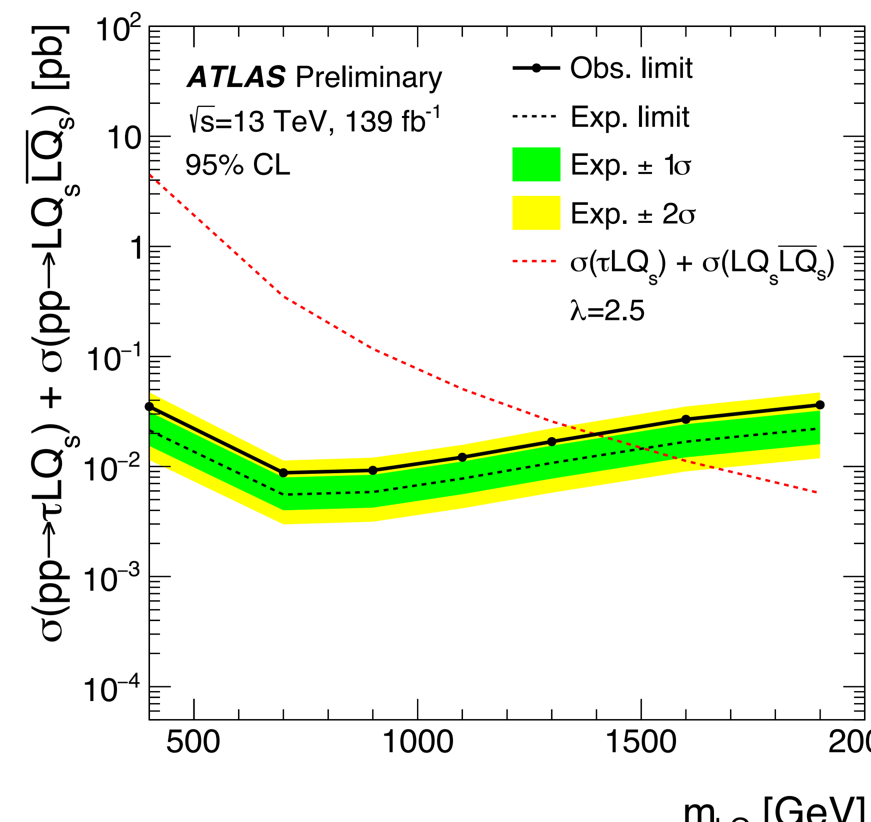


$\tau LQ^{\tilde{S}_1} \to b\tau_{\mathrm{had}}\tau_{\mathrm{had}}/\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ Results

- First ATLAS result for LQ in the $b\tau\tau$ final state
- statistically limited, top quark background modelling is largest systematic uncertainty
- Observed exclusions for LQ + LQLQ (single LQ) production
  - $m_{\mathrm{LQ}} < 1.25\,(0.89)$ TeV for $\lambda = 1$
  - $m_{\mathrm{LQ}} < 1.41\,(1.28)$ TeV for $\lambda = 2.5$

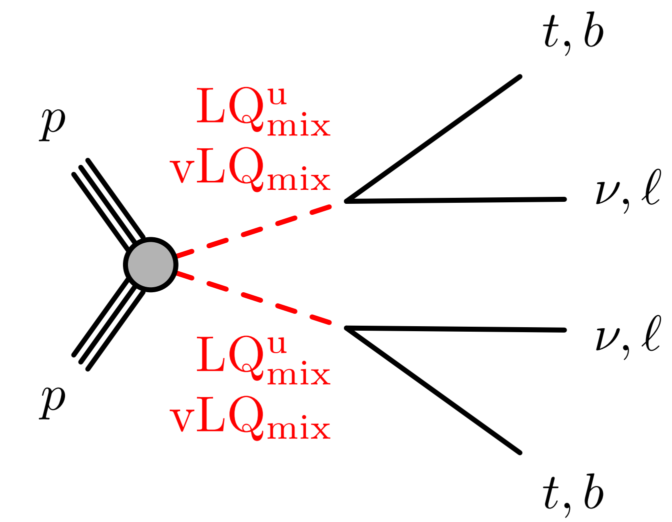


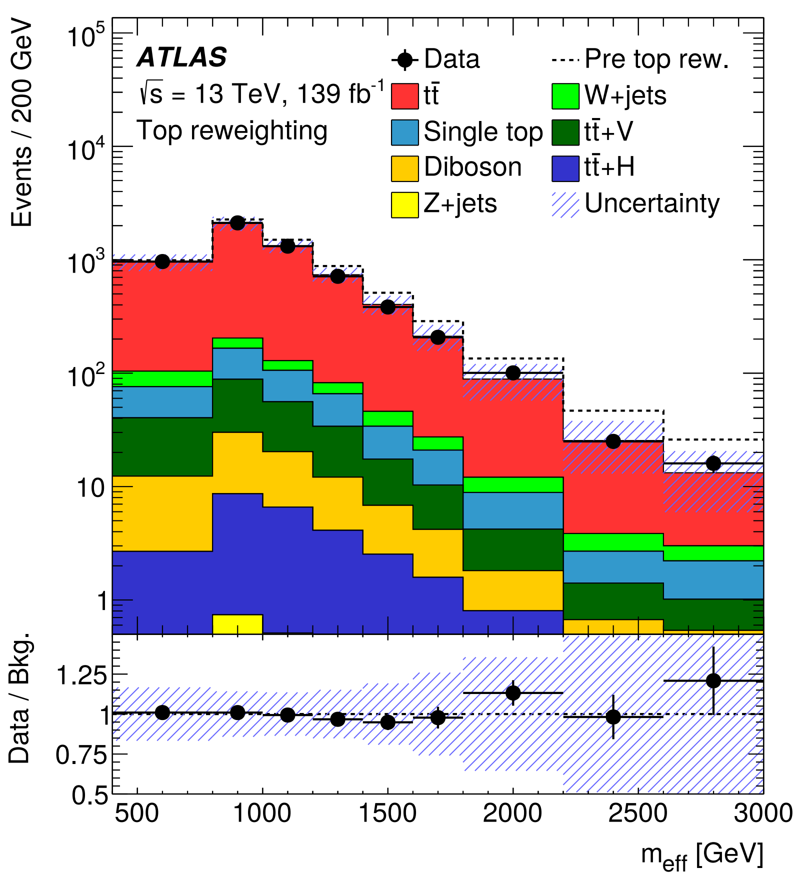


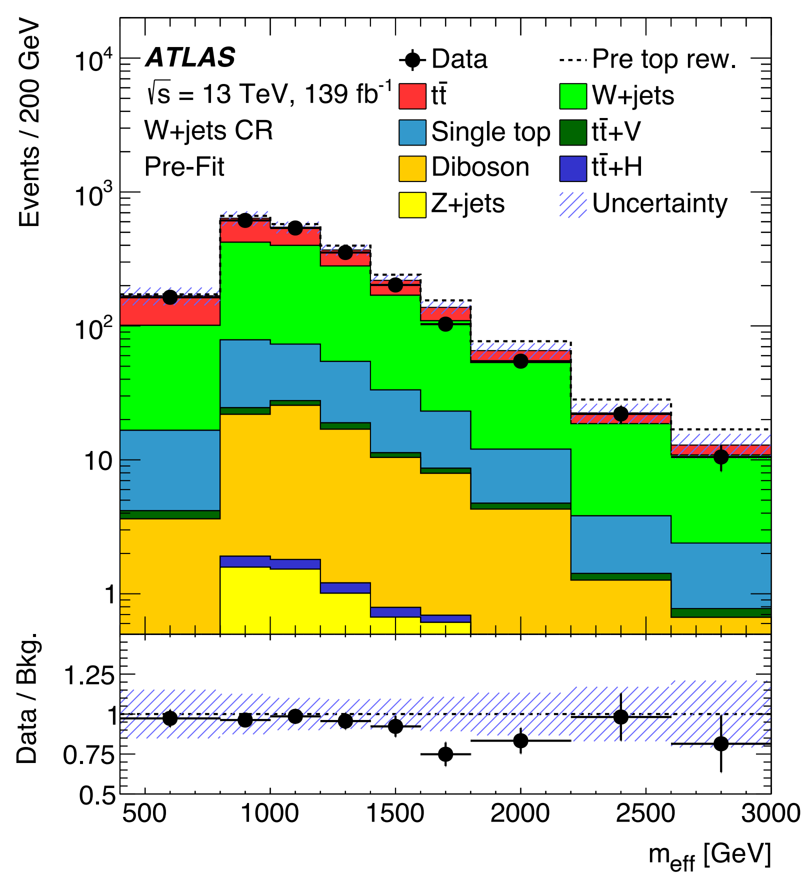


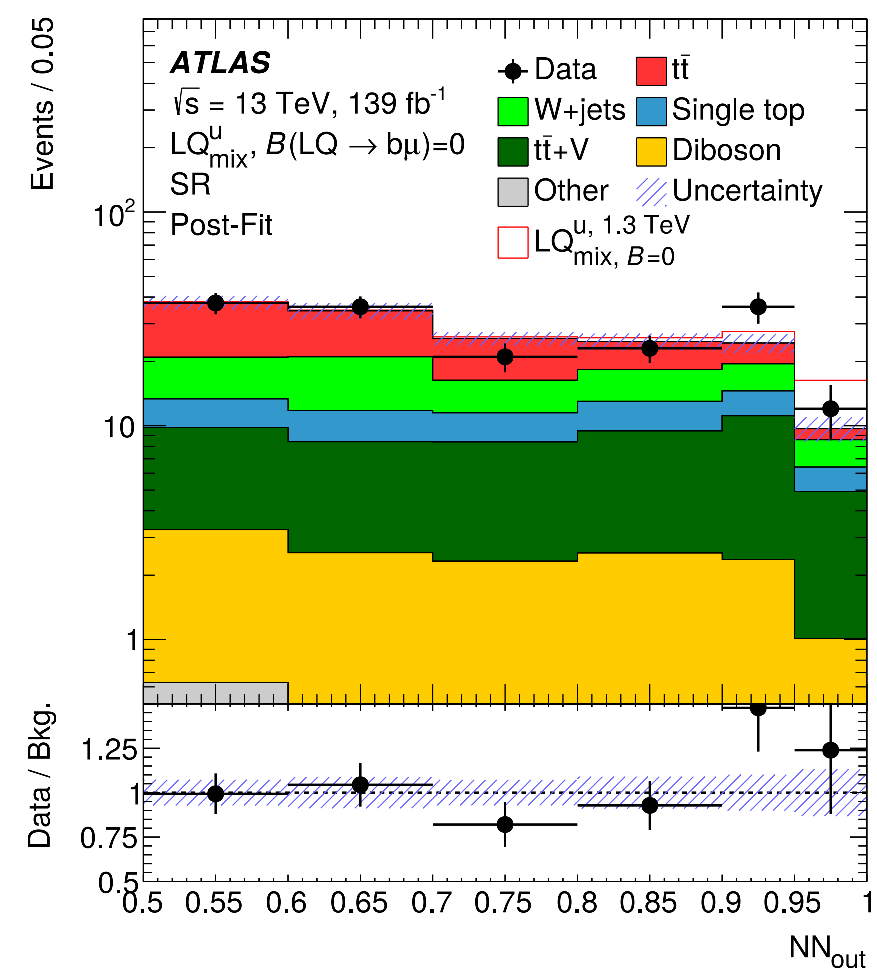
$\mathrm{LQ}^{d\,(u)}_{\mathrm{mix}}\mathrm{LQ}^{d\,(u)}_{\mathrm{mix}} \to t\nu b\ell\,/\,t\ell b\nu$

- Pair produced scalar and vector LQs decaying to *t*- or *b* -quarks and 1st or 2nd generation leptons in single lepton final states
- $E_{\mathrm{T}}^{\mathrm{miss}}$-trigger, ≥ 4 jets, ≥ 1 *b*-jet
- Main backgrounds: *W*+jets, single top (norm. to data), $t\bar{t}$ (data-driven correction as a function of m_{eff})
- Neural network trained for each signal hypothesis
- Discriminant: NN output used to define signal and control regions ⇒ simultaneous fit of all regions



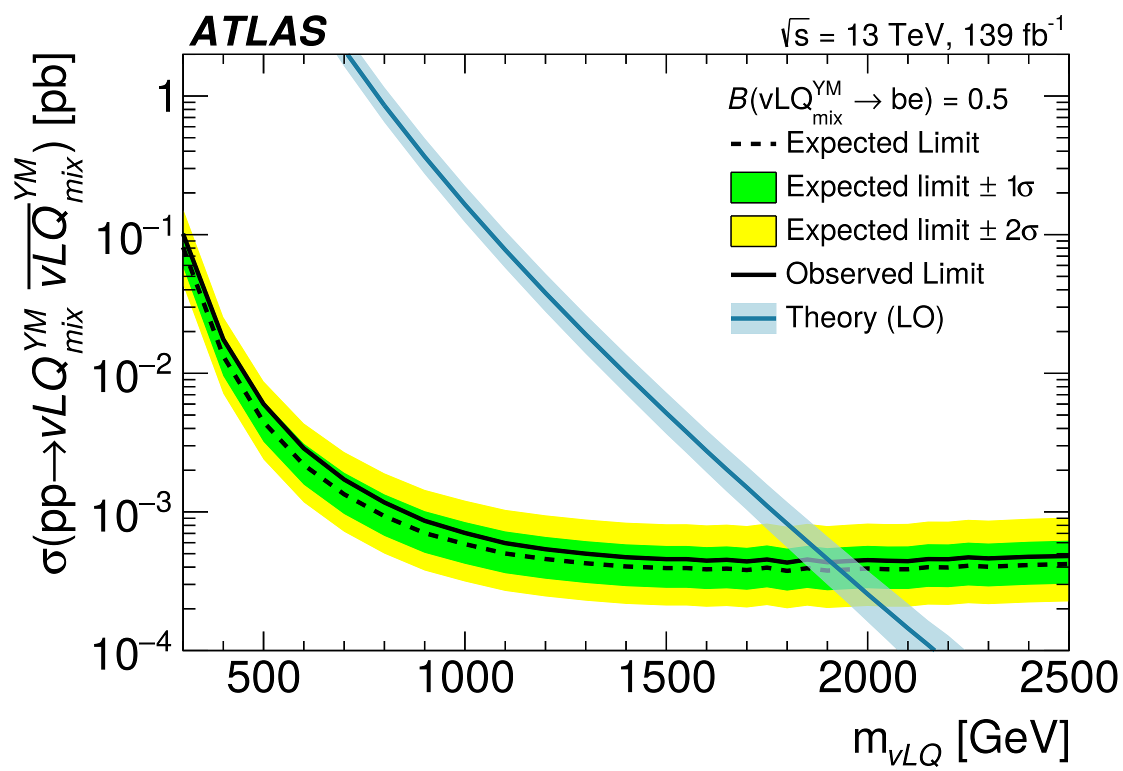


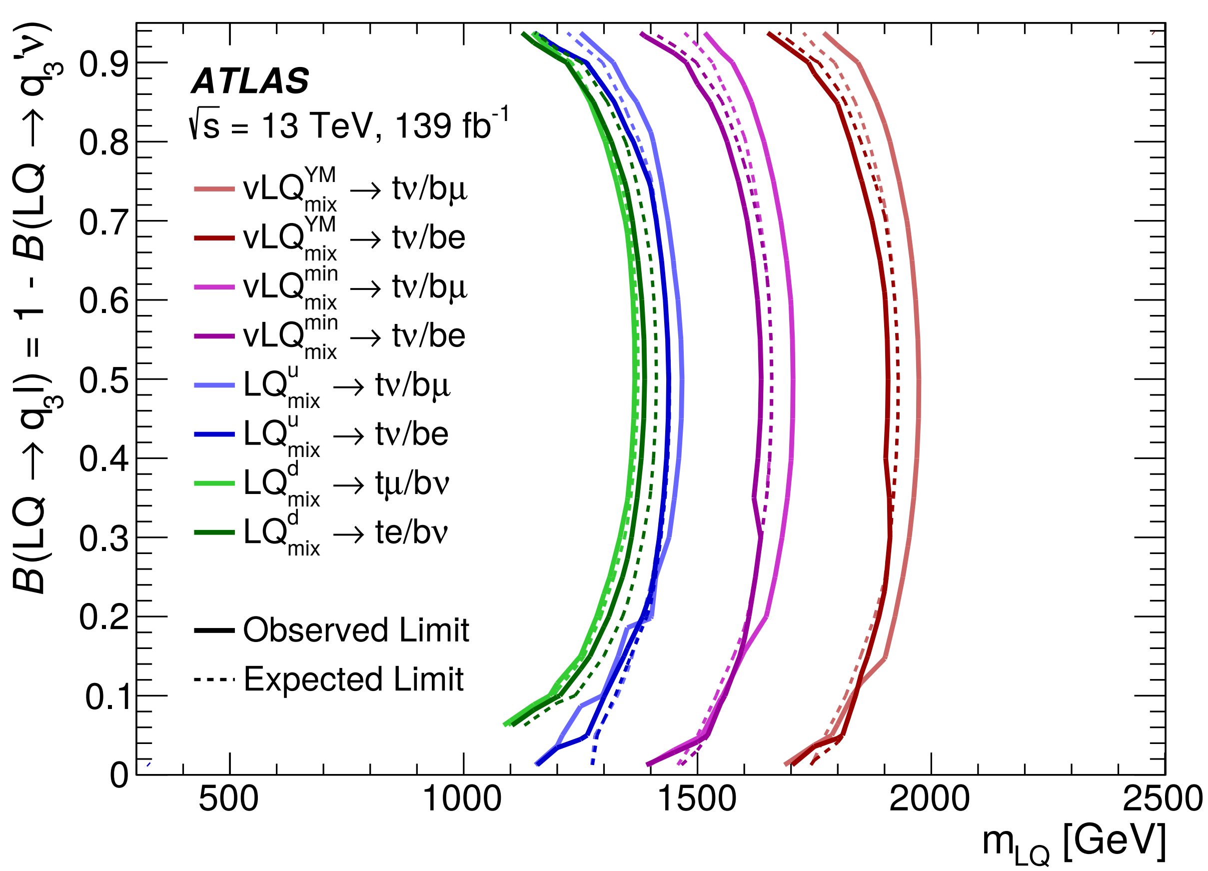


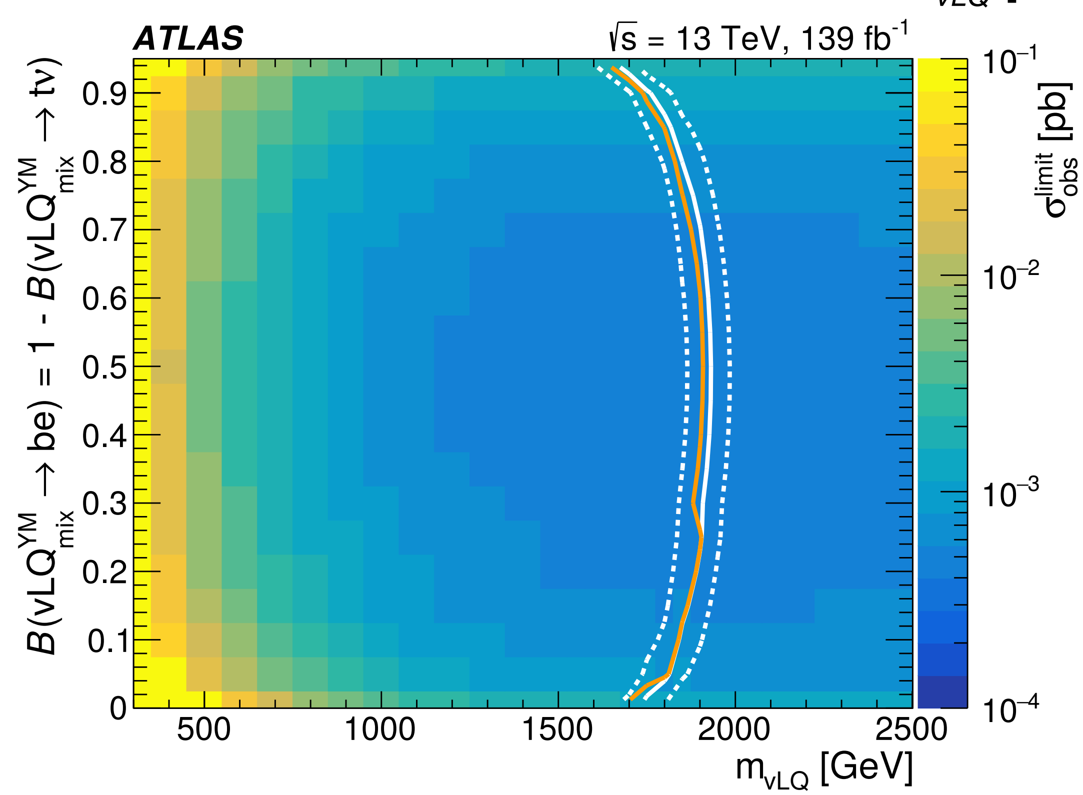


$\mathrm{LQ}_{\mathrm{mix}}^{d\,(u)}\mathrm{LQ}_{\mathrm{mix}}^{d\,(u)} \rightarrow t\nu b\ell / t\ell b\nu$ Results

- statistically limited at high masses, largest systematic uncertainties: top quark modelling and jet energy scale uncertainties
- Observed exclusions:
    - $m_{\mathrm{LQ}^{d}_{\mathrm{mix}}\rightarrow e(\mu)} < 1.39\,(1.37)$ TeV for $\beta = 0.5$
    - $m_{\mathrm{LQ}^{u}_{\mathrm{mix}}\rightarrow e(\mu)} < 1.44\,(1.46)$ TeV for $\beta = 0.5$
    - $m_{\mathrm{LQ}^{\mathrm{YM}}_{\mathrm{mix}}\rightarrow e(\mu)} < 1.90\,(1.98)$ TeV for $\beta = 0.5$







Conclusions

- Wide range of searches for LQs at ATLAS with 140 fb^{-1} pp collision data
  - benefit from improvements in flavour tagging and τ identification in Run-2
- Stringent limits set on scalar LQs with flavour-diagonal and cross-generational couplings

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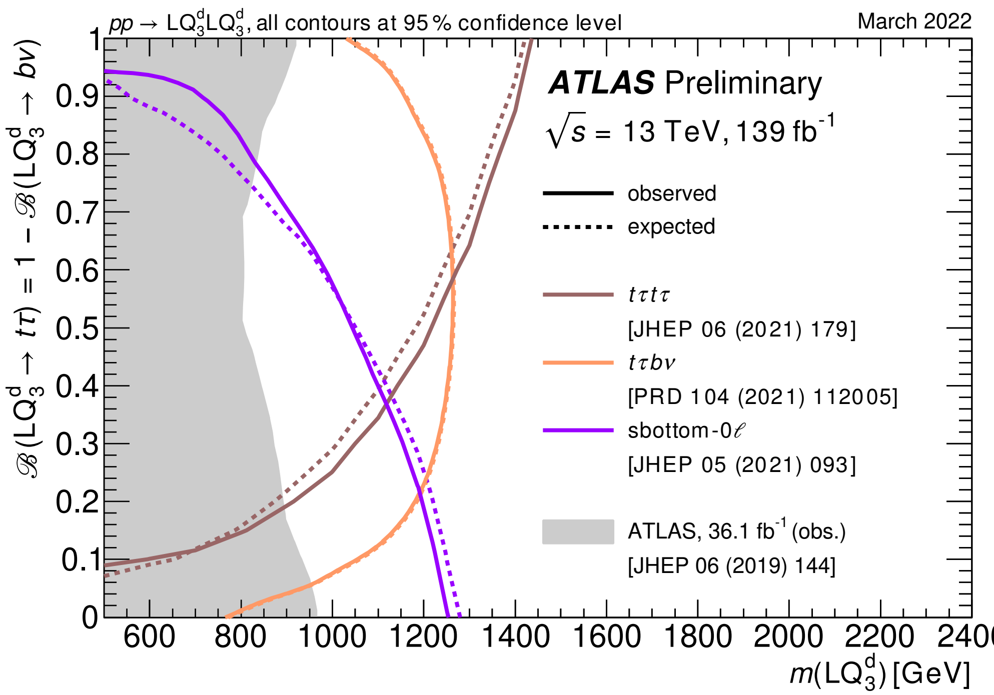
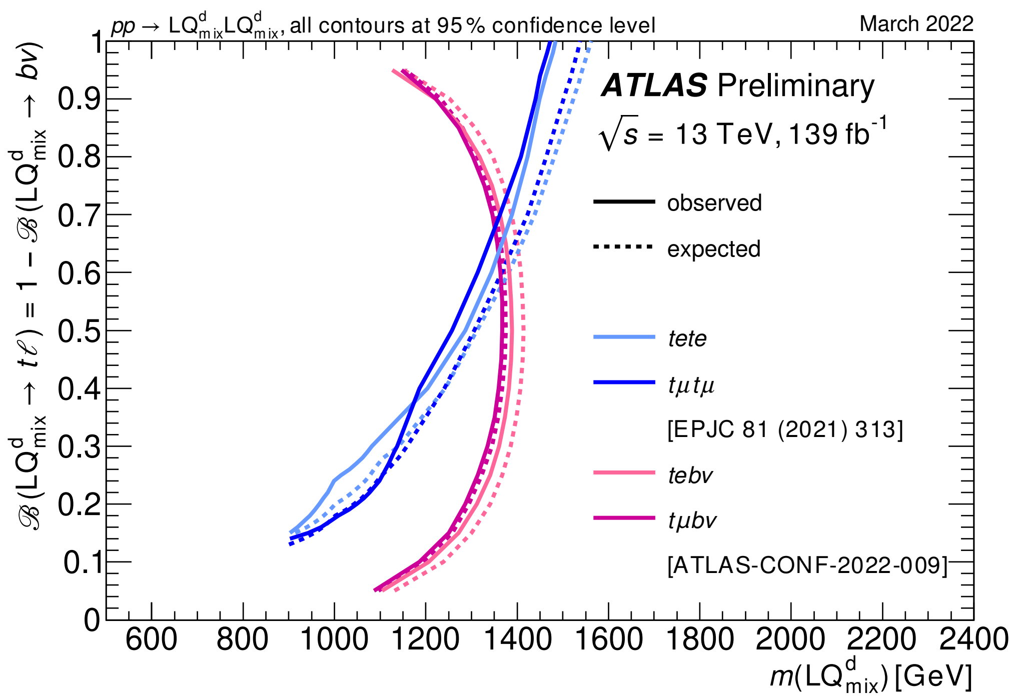
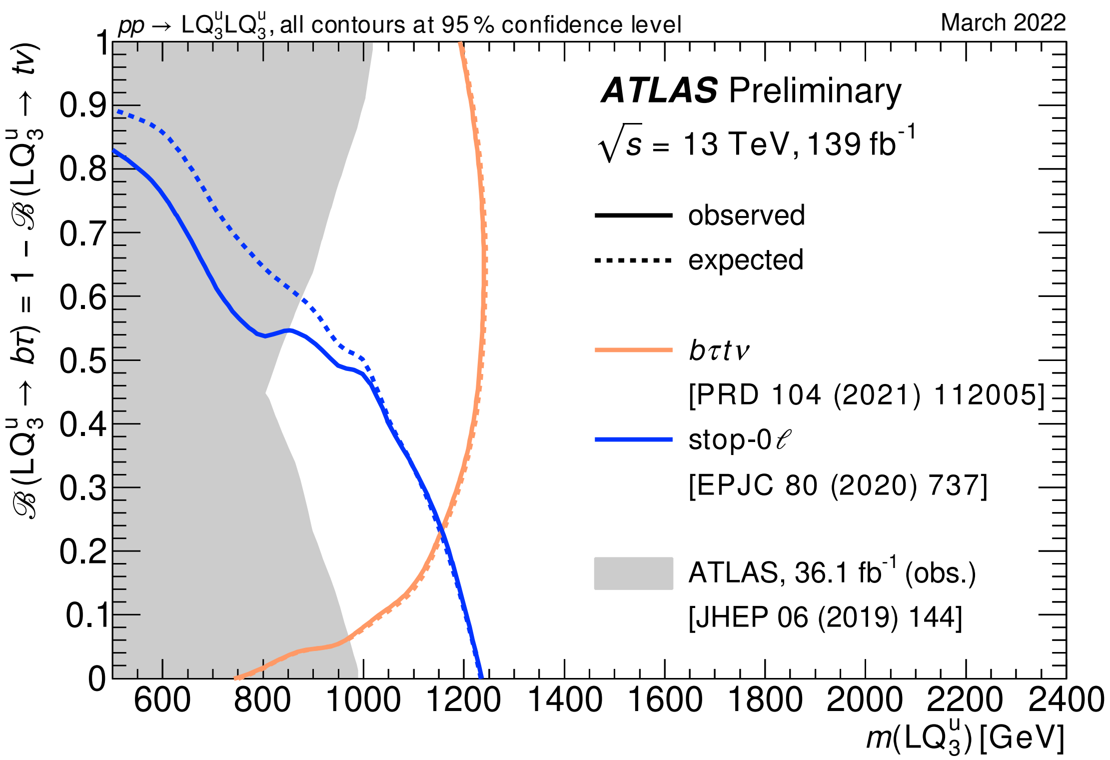


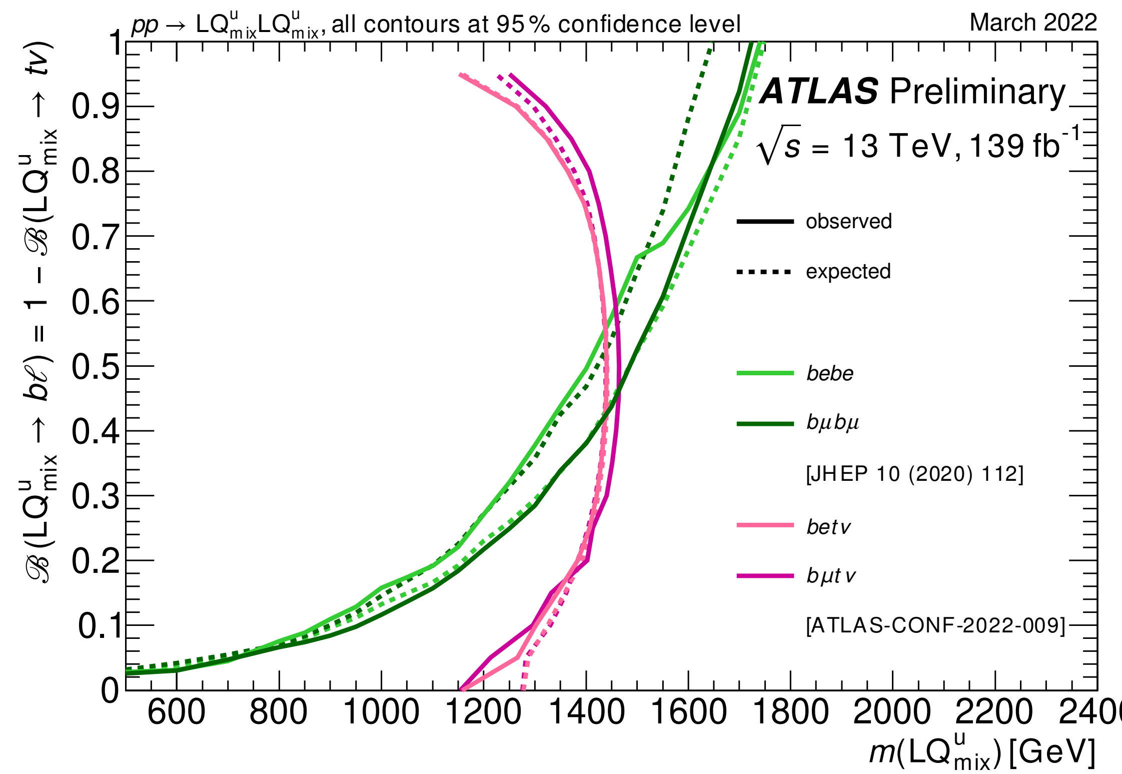


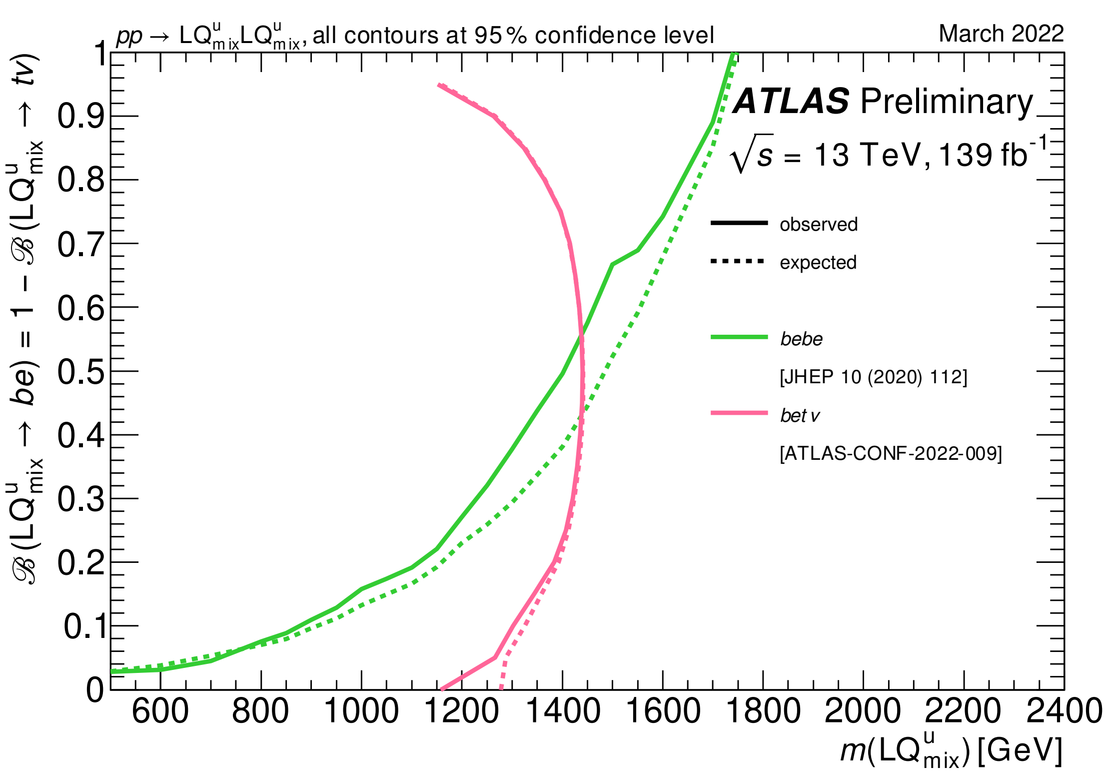
more summary plots in backup

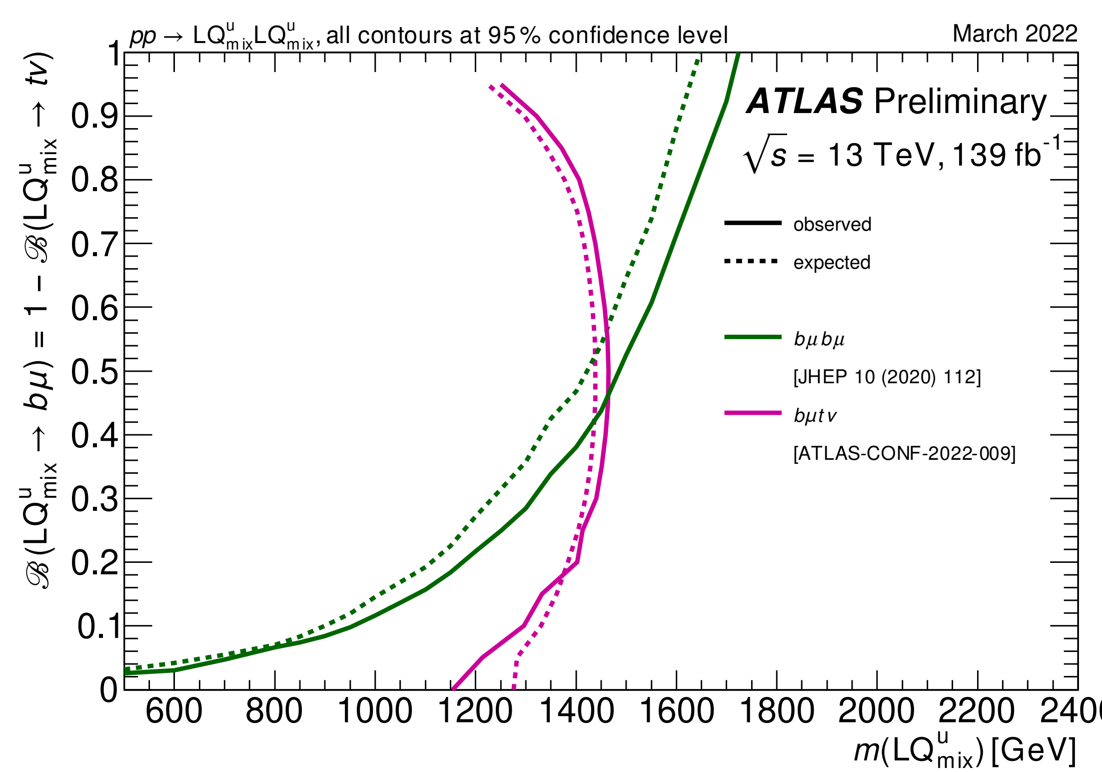
- More scenarios to cover: single LQs, non-resonant production, s-channel
- LQ analyses often statistically limited - will profit from Run-3 data set (or High-Luminosity LHC)

Summary Plots: Scalar LQ^u

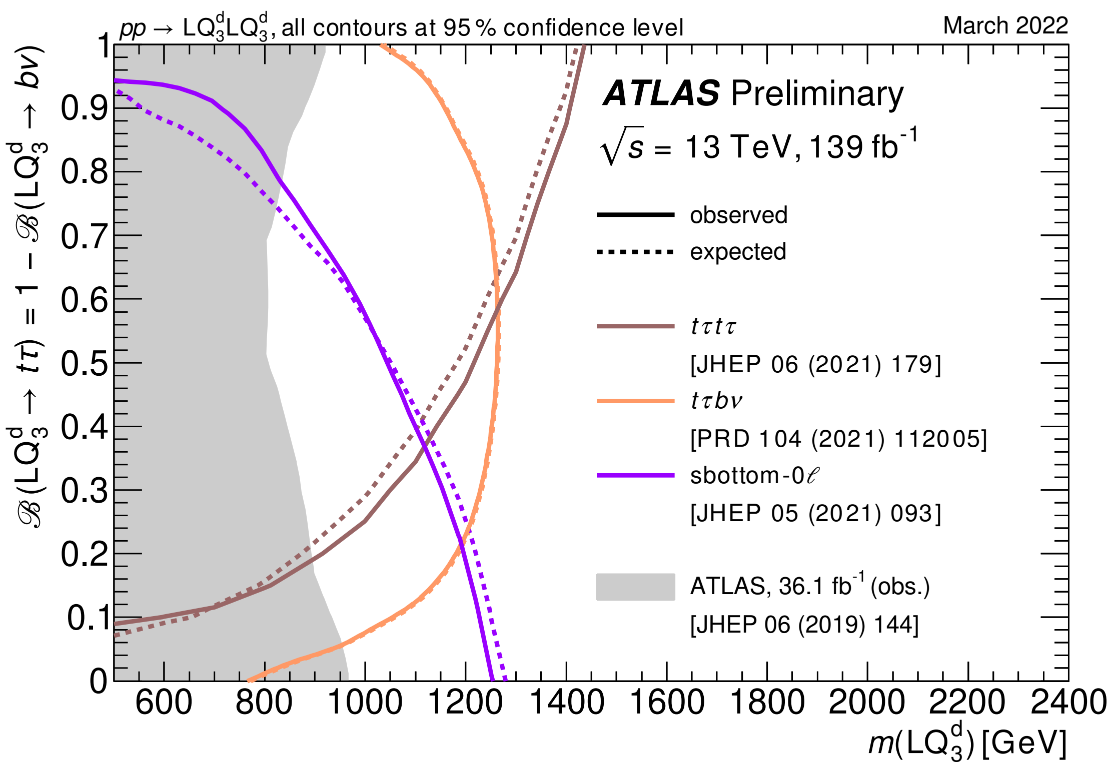


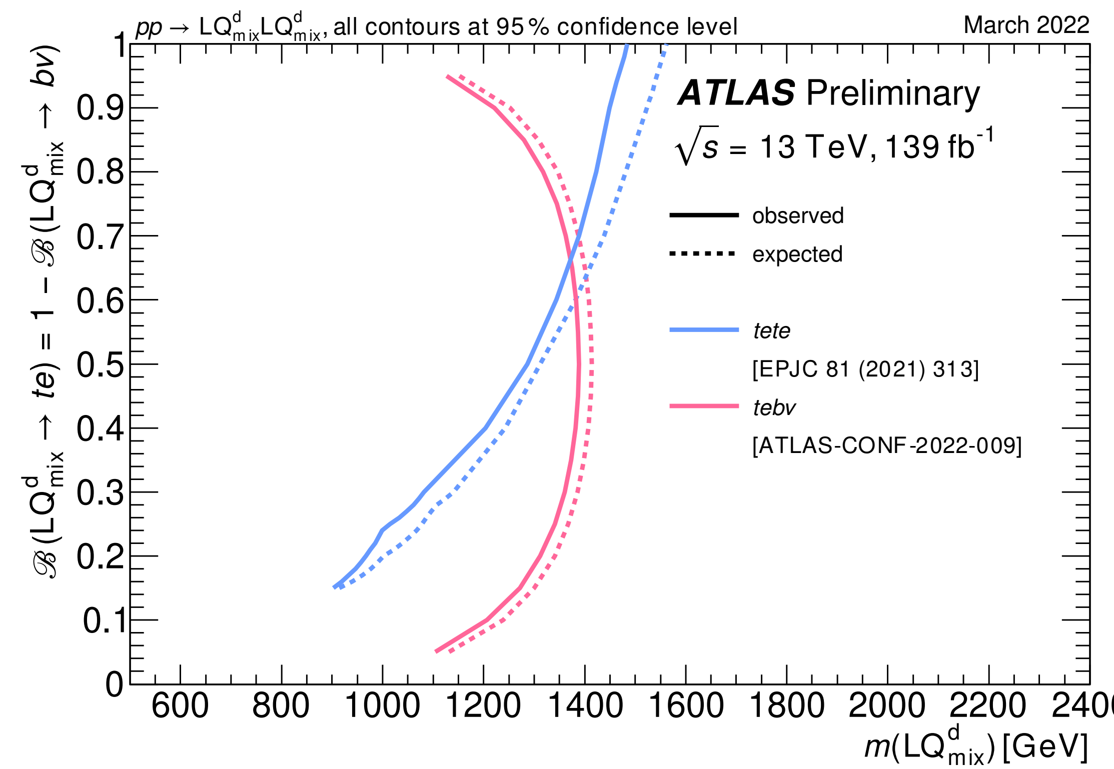


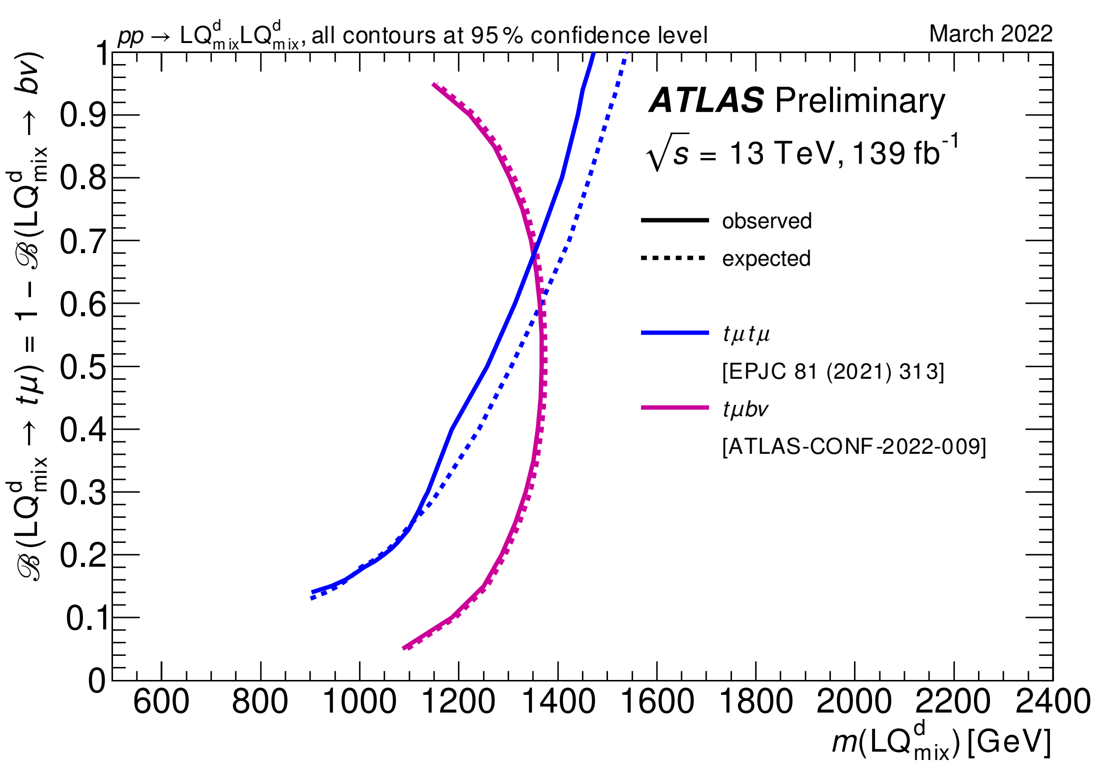


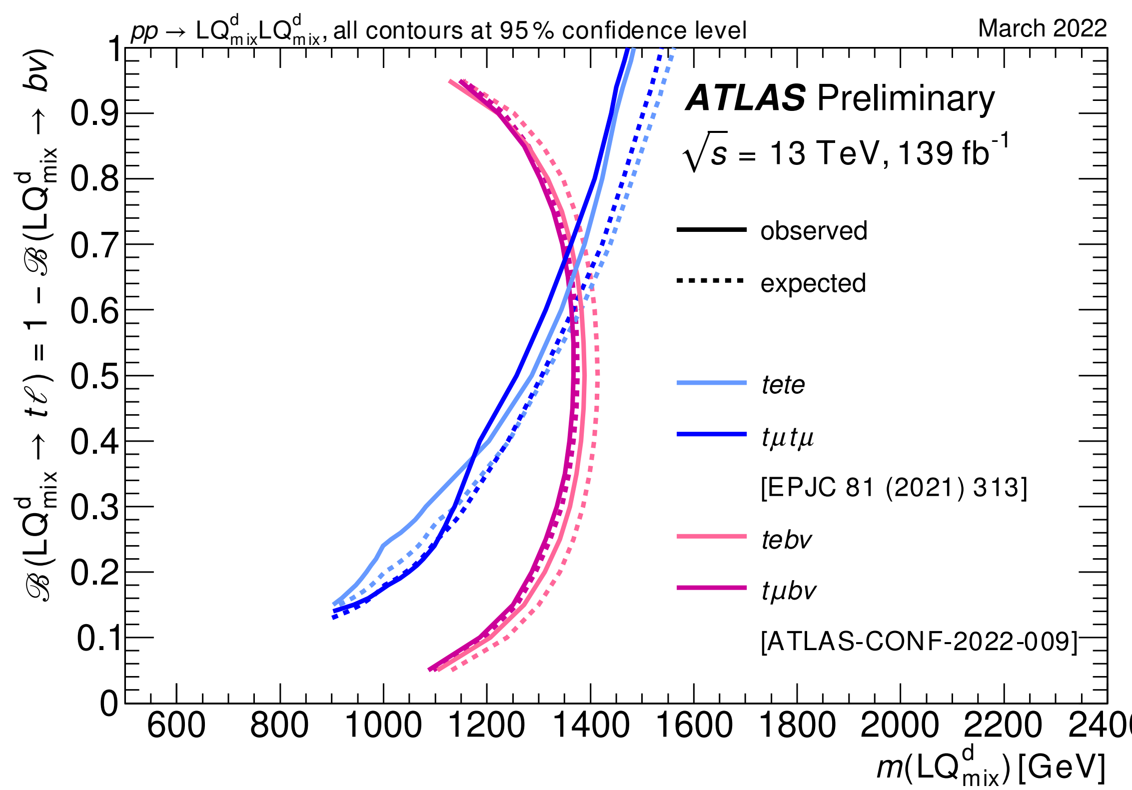


Summary Plots: Scalar LQ^d



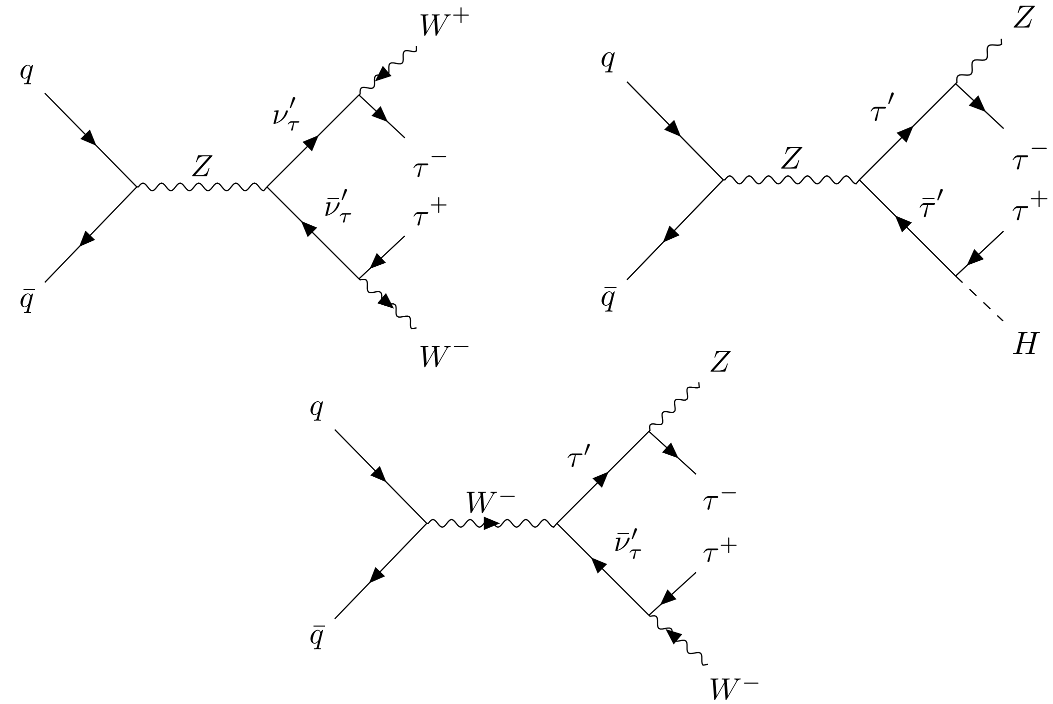




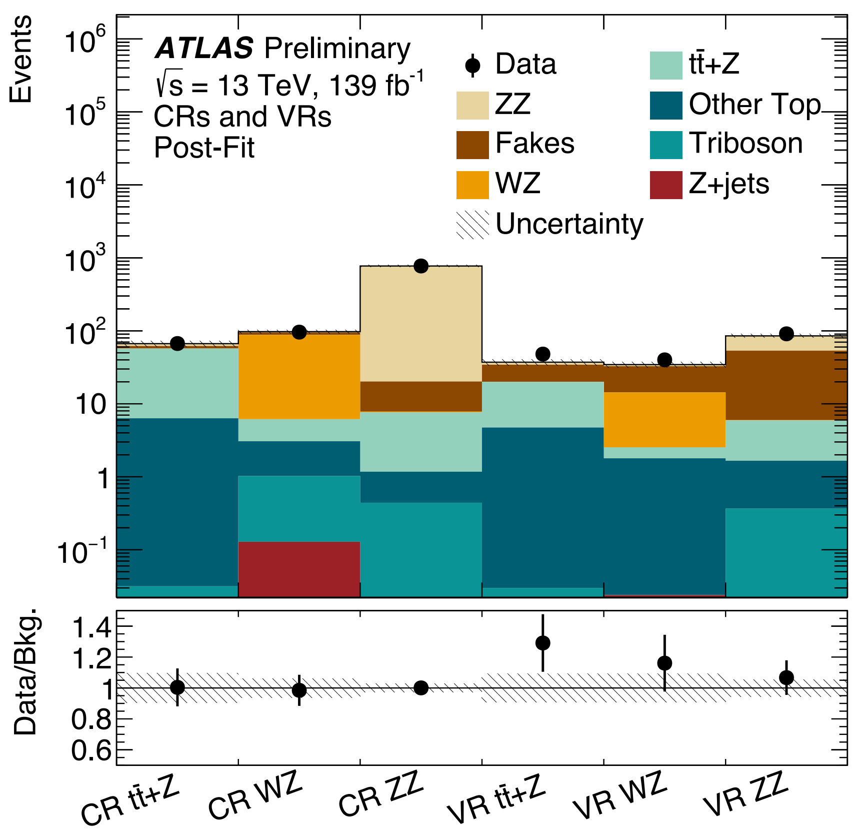


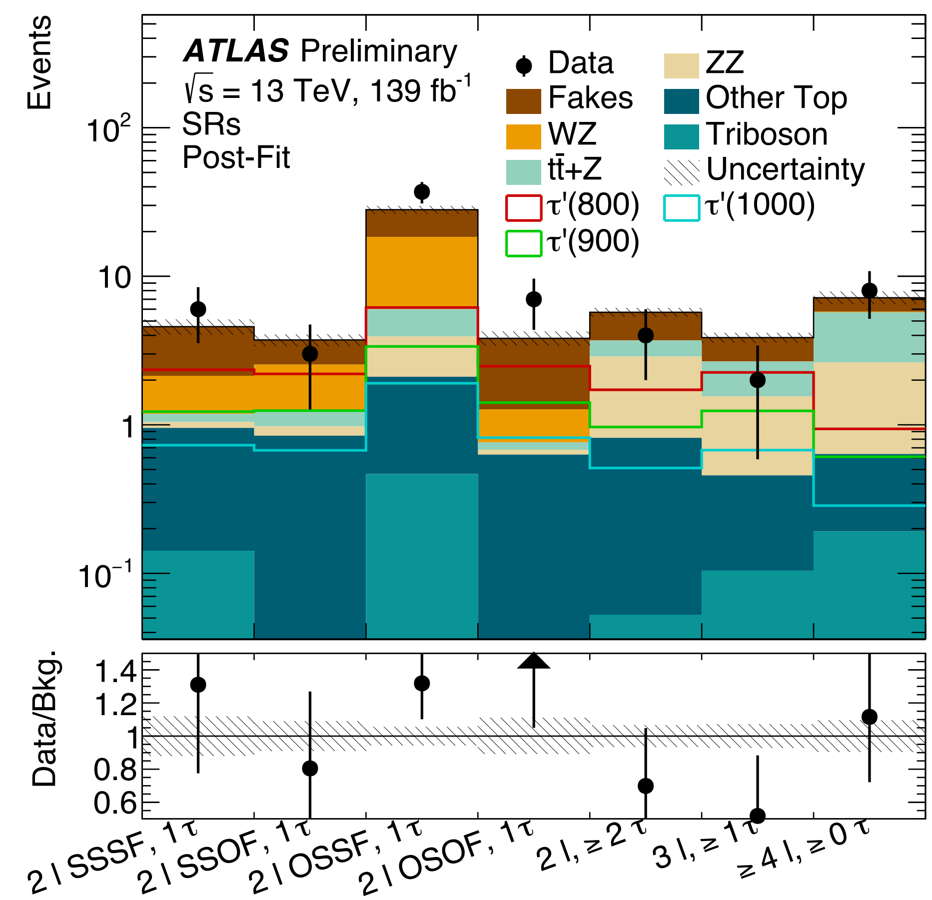
3rd Generation Vector-like Leptons

- Higgs branching ratios consistent with SM - little room for new particles with large Yukawa masses
- Non-chiral fermions with Dirac mass present in BSM (SUSY, string theories, extra dimensions)
- Case of a SM τ-coupling SU(2) double **V**ector-**L**ike **L**eptons (VLL) $(\tau', \nu'_{\tau'})$
- Focus on multilepton final states
- Main backgrounds: data-driven fake lepton, *WZ, ZZ,* $t\bar{t}Z$
- *7* BDTs trained for various states of lepton multiplicity



Normalisation of dominant bkgs derived in control regions
bkg modelling validated in data

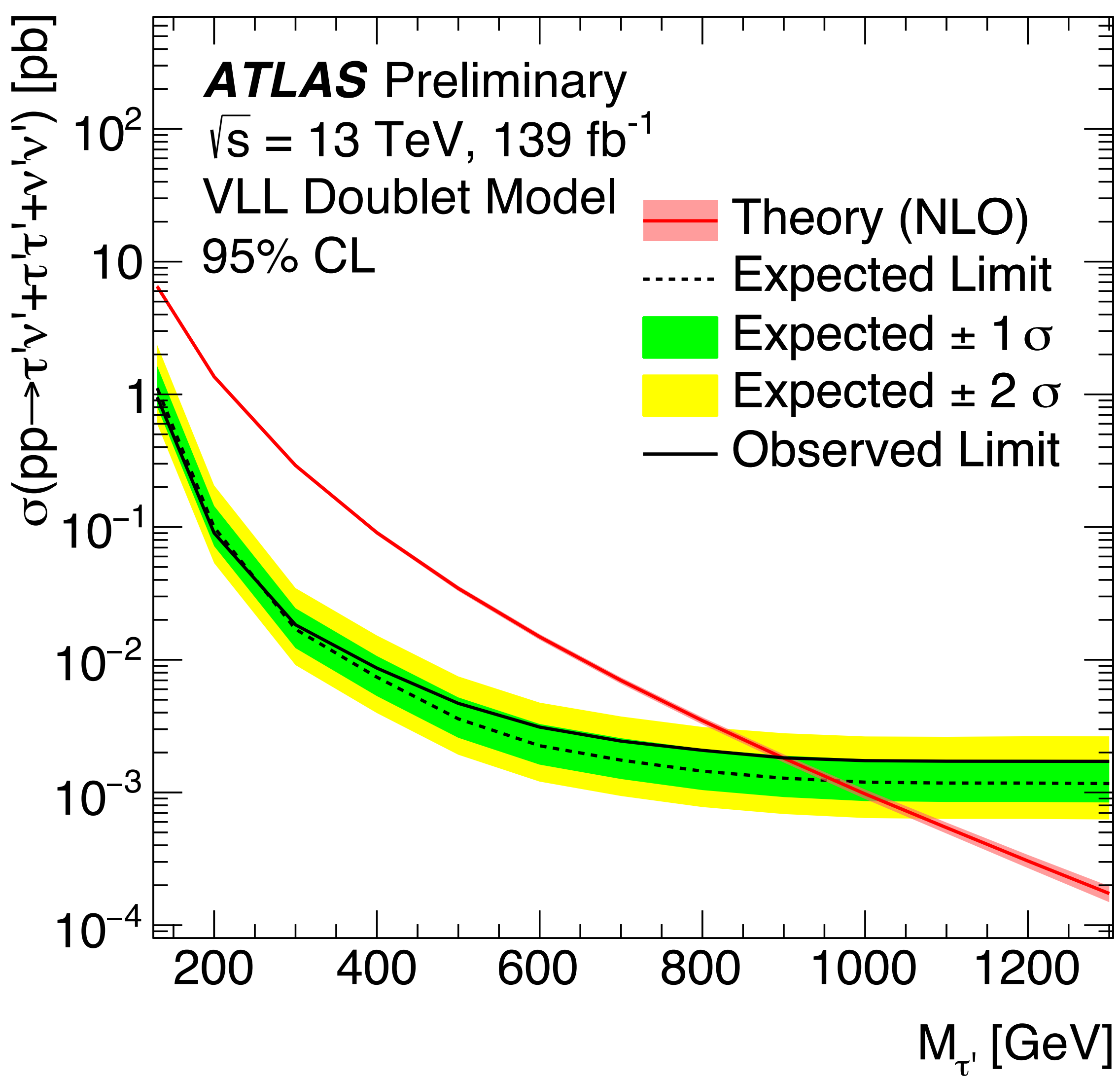




3rd Generation Vector-like Leptons

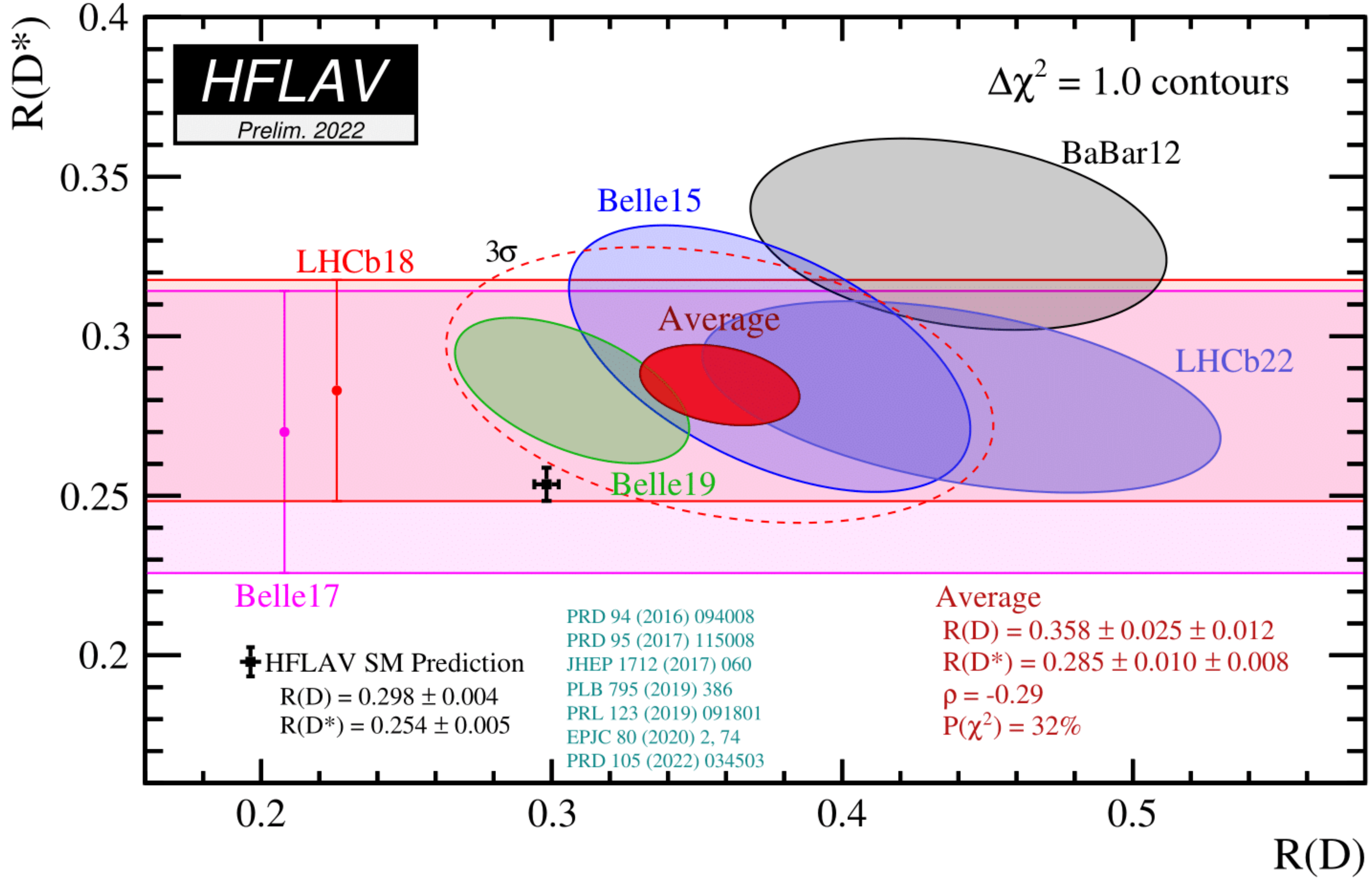
- statistically limited, largest systematic uncertainties: bkg. normalisation, fake lepton estimate

τ' Mass [GeV]	Significance		Exclusion Limit [nb]	
	Expected	Observed	Expected	Observed
130	5.9	−0.4	1110^{+520}_{-310}	953
200	12	−0.4	100^{+44}_{-28}	90
300	15	0.1	$17.0^{+7.5}_{-4.8}$	18
400	12	0.3	$7.4^{+3.3}_{-2.1}$	8.7
500	10	0.7	$3.6^{+1.6}_{-1.0}$	4.7
600	7.6	0.9	$2.3^{+1.0}_{-0.6}$	3.1
700	5.1	1.0	$1.8^{+0.8}_{-0.5}$	2.4
800	3.4	1.1	$1.5^{+0.7}_{-0.4}$	2.1
900	2.1	1.1	$1.3^{+0.6}_{-0.4}$	1.8
1000	1.3	1.2	$1.2^{+0.6}_{-0.3}$	1.7
1100	0.8	1.1	$1.2^{+0.6}_{-0.3}$	1.7
1200	0.5	1.1	$1.2^{+0.6}_{-0.3}$	1.7
1300	0.3	1.1	$1.2^{+0.6}_{-0.3}$	1.7



B-Physics Anomaly $R(D^{(*)})$

- LFU anomaly in charged current τ vs. e/μ: $R(D^{(*)}) = \dfrac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\ell\nu}$
- 3.1σ excess over Standard Model



B-Physics ~~Anomaly~~ $R(K^{(*)})$

- LFU anomaly in neutral current μ vs. e: $R(K^{(*)}) = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-}$
- New LHCb result compatible with SM