Status and Prospect of Search for Lepton Flavour Universality Violation

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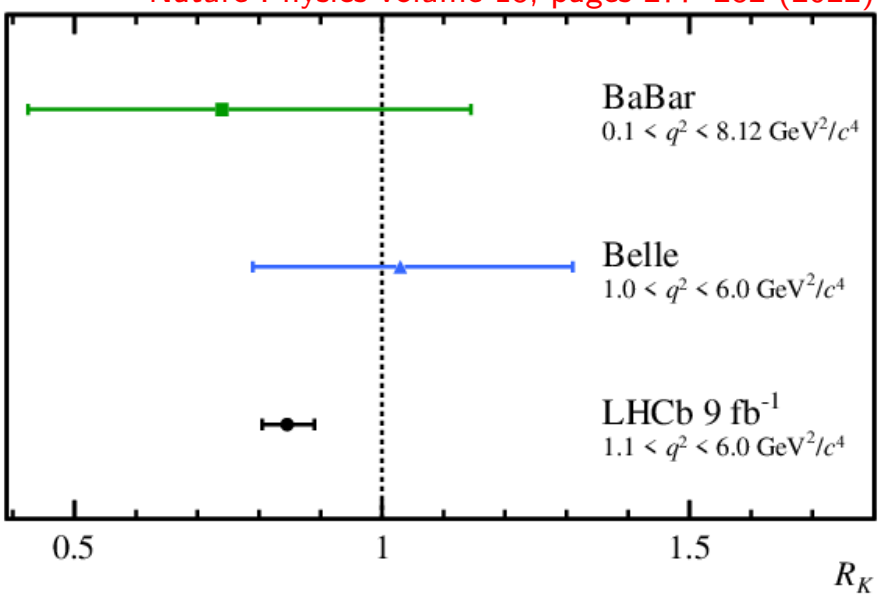
B-flavour anomalies with lepton universality violation (LFUV)

- In the standard model (SM), forces do not have different coupling strengths to different lepton flavours $\rightarrow$ lepton flavour universality (LFU)
- The currently most intriguing tests of LFU happen in the B-meson sector:

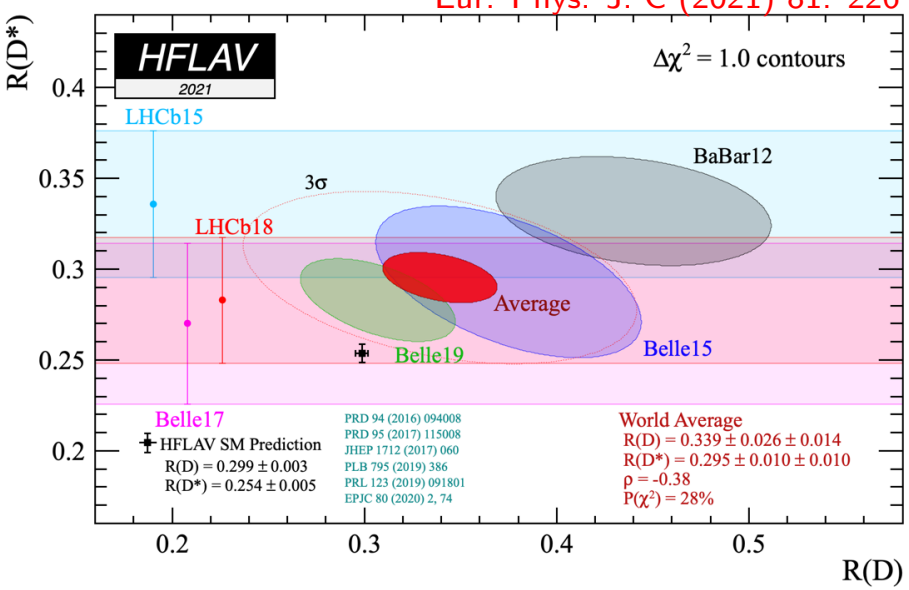
$b \rightarrow s\ell^+\ell^-$

Nature Physics volume 18, pages 277–282 (2022)



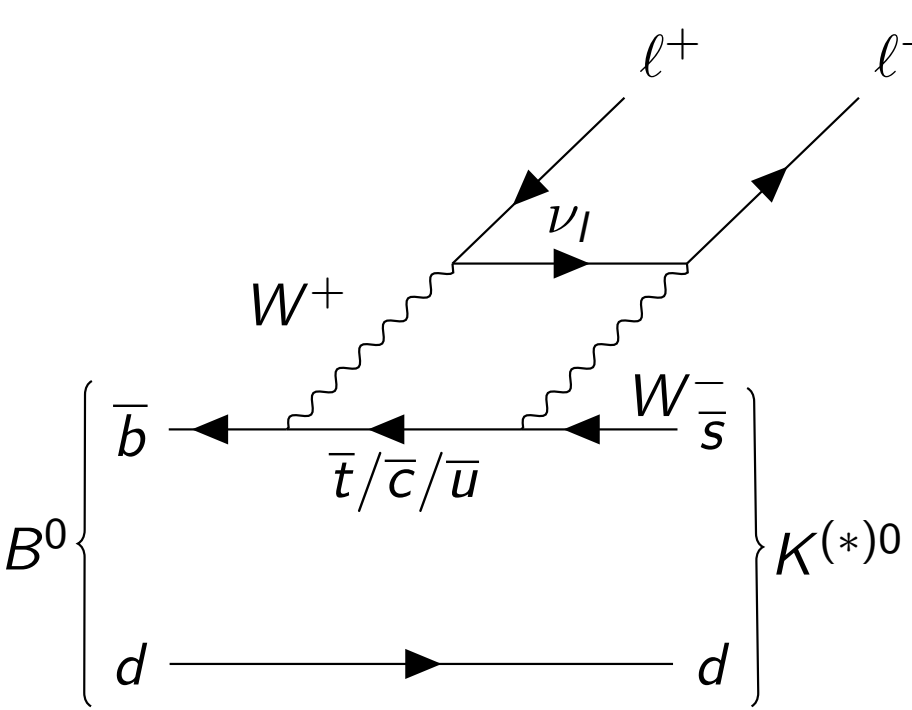
$b \rightarrow c\ell\nu$

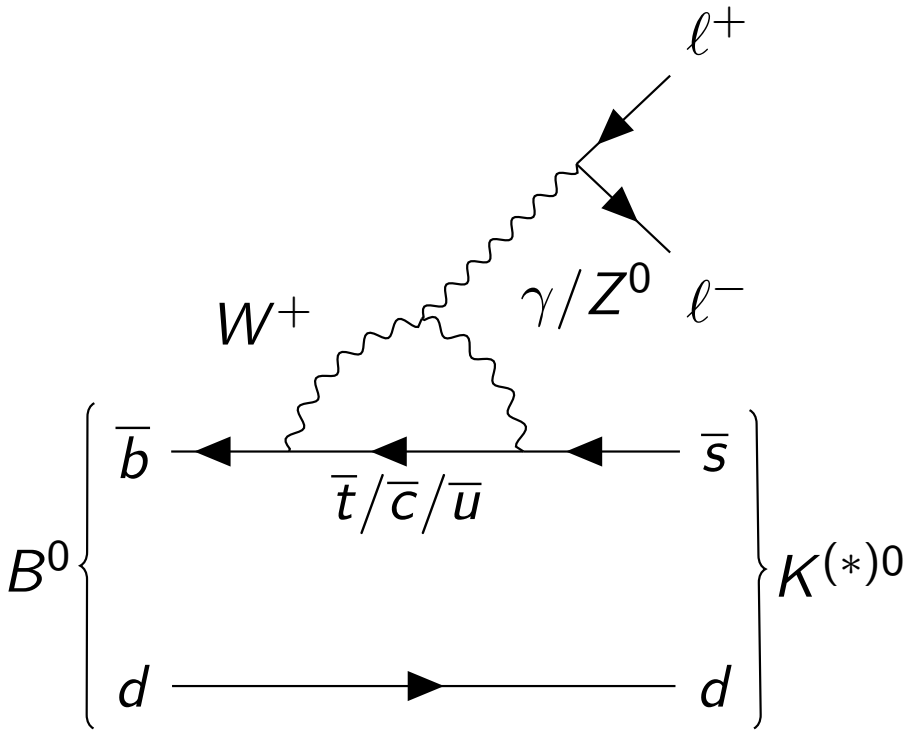
Eur. Phys. J. C (2021) 81: 226



$R(K)$ and $R(K*)$

- LHCb reports an excess in the muon to electron ratio of R_{K^*} (JHEP 08 (2017) 055) at $2.1 - 2.5\sigma$ and R_K (Nature Physics volume 18, pages 277–282 (2022)) at 3.1σ



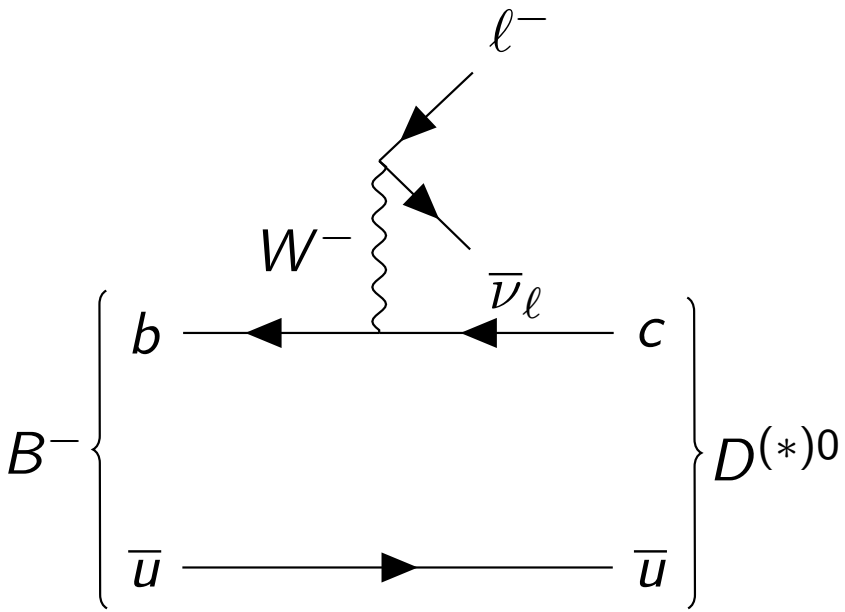


$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} \quad (1)$$

$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0})} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to J/\psi(\to e^+e^-)K^{*0})} \quad (2)$$

$R(D)$ and $R(D^*)$

- $R(D^{(*)})$ has been measured by BaBar, Belle ([1], [2]), and LHCb ($R(D^*)$ only) at various tensions and agreement with the SM



$$R(D^{(*)-}) = \mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu) \quad (3)$$

$$R(D^{(*)0}) = \mathcal{B}(B^- \to D^{(*)0}\tau^-\overline{\nu}_\tau)/\mathcal{B}(B^- \to D^{(*)0}\mu^-\overline{\nu}_\mu) \quad (4)$$

- All of this is low p_T physics at low luminosity experiments
- Can ATLAS and CMS also provide measurements for these?

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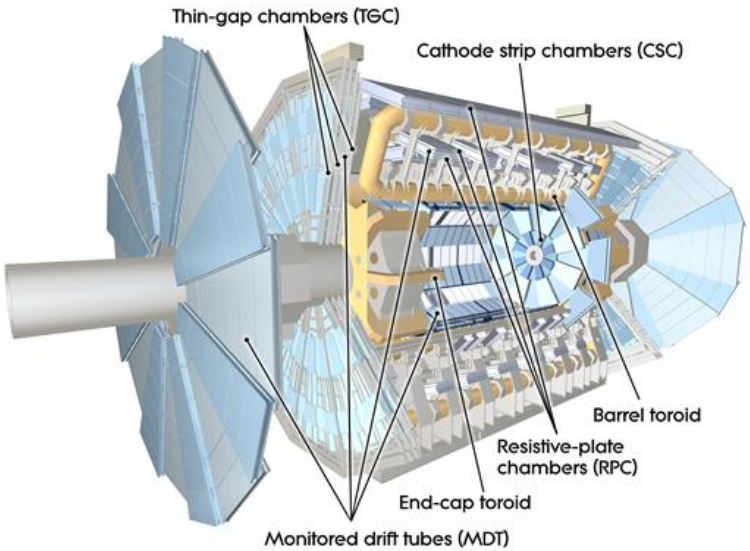
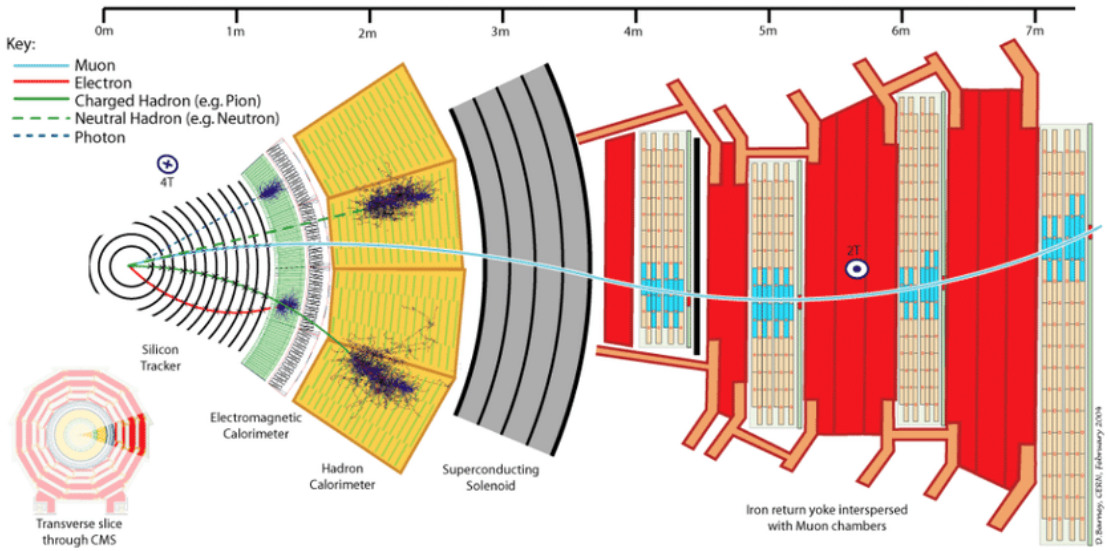
ATLAS and CMS detectors

ATLAS



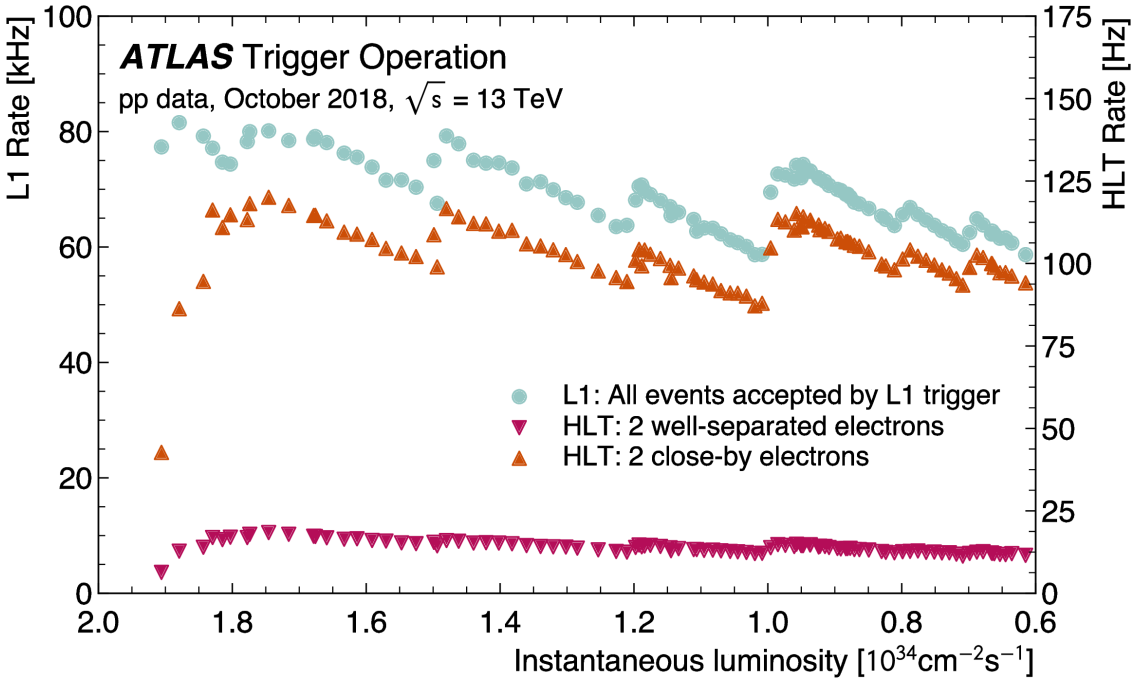
CMS

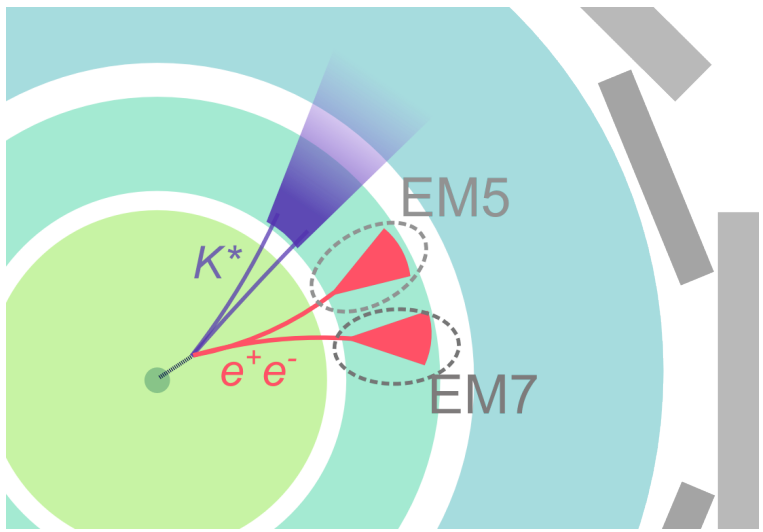


- General purpose detectors with different lever arms and magnetic fields for charged particle measurements
- Differing calorimeter designs (CMS ECAL-centric, ATLAS HCAL-centric)
- Common challenge for B-meson physics is triggering
- Unlike LHCb, both ATLAS and CMS run at high instantaneous luminosity for high-p_T-centric physics programme

ATLAS soft di-electron trigger

- General triggering strategy is multiple soft leptons and/or a mass-window constraint on dilepton-resonances like J/ψ or Φ
- New trigger in 2018 geared to $B \to K^* e^+ e^-$ events
  ATL-DAQ-PUB-2019-001

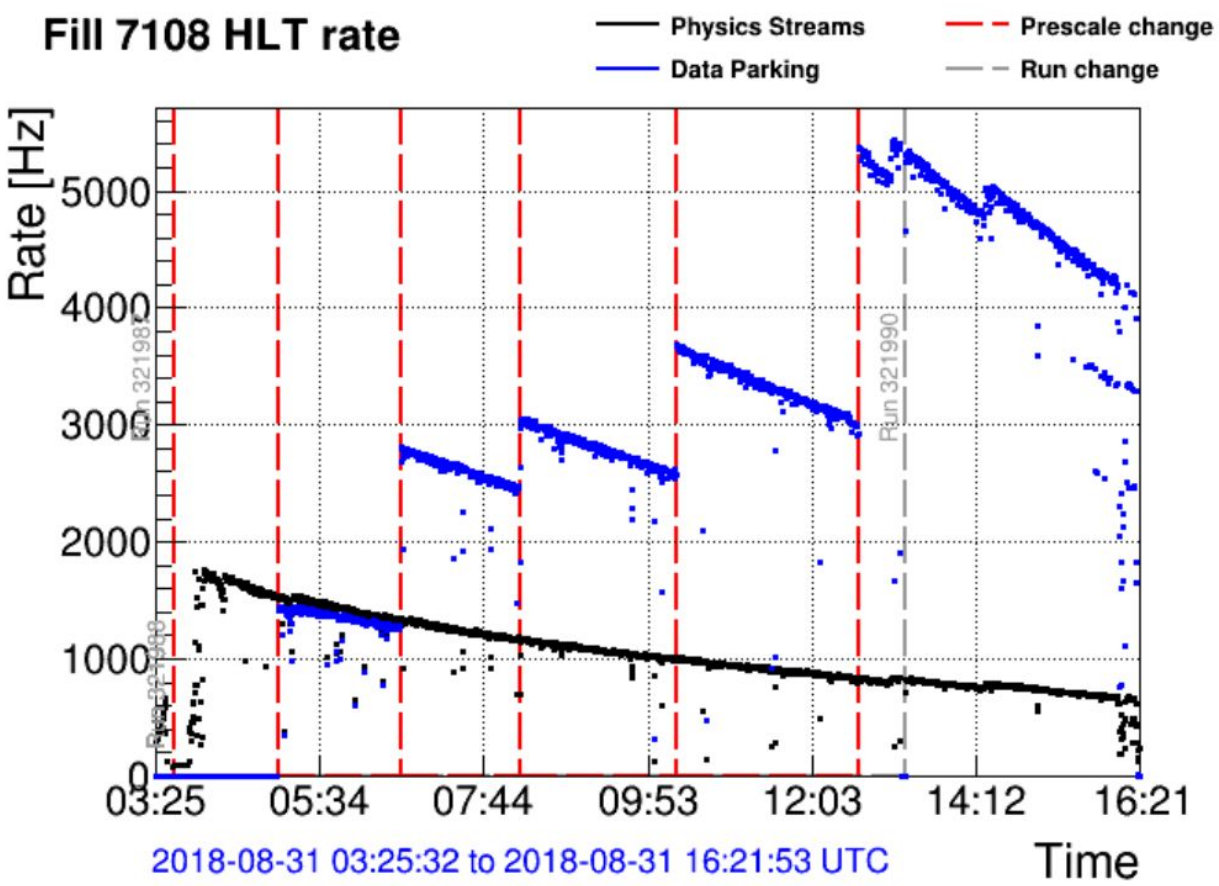


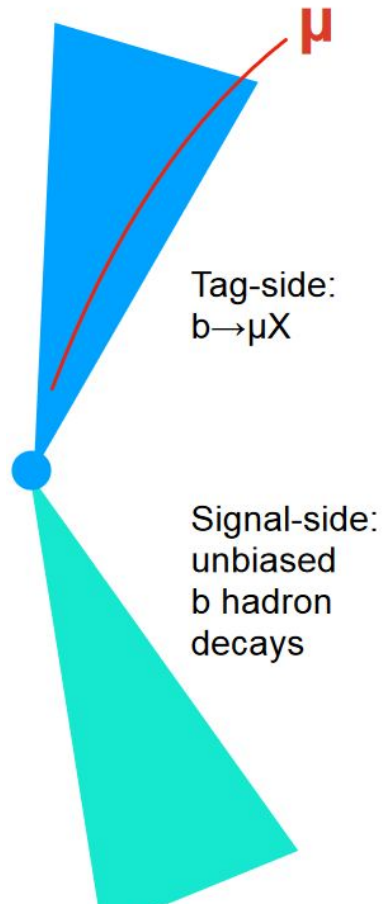


- Utilizes topology of the soft electron pair with low invariant mass
- Still necessitates a soft muon (or dimuon) L1 trigger from the other side of a B-meson pair production event for reasonable rates

CMS parked data with soft muon b-tagging

- CMS has implemented in 2018 data-taking a new trigger for soft muons from B-meson decays CMS-DP-2019/043
- Trigger requires low p_T μ ($12 - 7$ GeV) from displaced muons (impact parameter significance 4-6 σ) depending on peak luminosity to use "spare" bandwidth when luminosity falls





So, what can ATLAS and CMS do?

- Both have deployed B-anomaly-specific new triggers in 2018
- Work on analysing these datasets is ongoing and there has not yet been a publication on any of the LFUV ratios
- Low p_T electrons and τ are a reconstruction challenge for both experiments
- We can expect some results on $R(K^*)$, maybe even on $R(D^*)$ for the 2018 dataset from both
- Run3 though will have a high luminosity profile with more pileup and therefore higher thresholds
- People are actively working on this issue, but it only gets more challenging
  - ATLAS WIP on $R(K^*)$ and $R(D^*)$ triggers
  - CMS WIP on low p_T track-based electron (CMS-DP-2019-043) and hadronic $\tau \to \pi\pi\pi\nu$ (CMS-DP-2020-039) reconstruction

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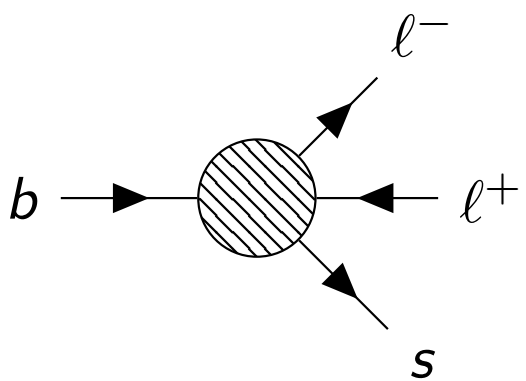
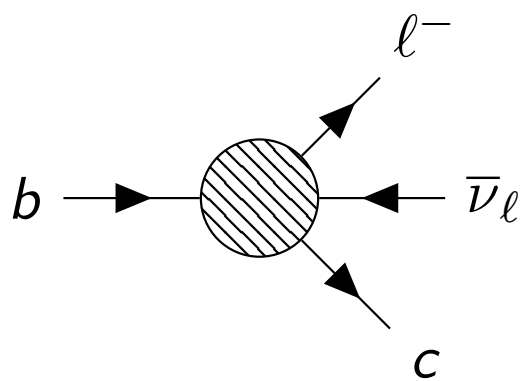
Effective Field Theory (EFT)

- Integrate out $> m_W$ and have four-fermion interaction described by effective couplings $C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{BSM}}$
- Effective couplings dominated by vector (C_9) and axial vector (C_{10}) leptonic currents to explain $R(D^{(*)})$ and $R(K^{(*)})$

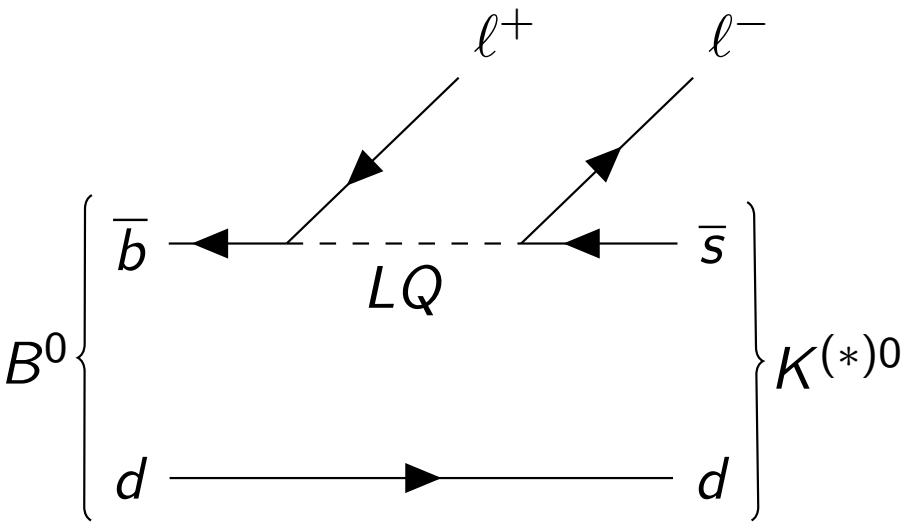


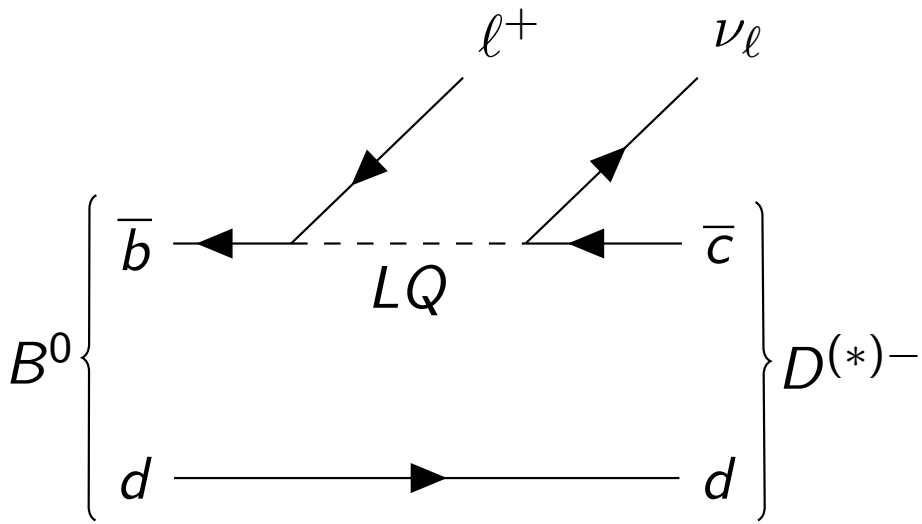


- Models can range from low mass narrow resonances to high mass wide resonances and anything in-between
- Limited by B_s-meson mixing on the hadronic coupling and neutrino trident production on the leptonic coupling

Leptoquarks

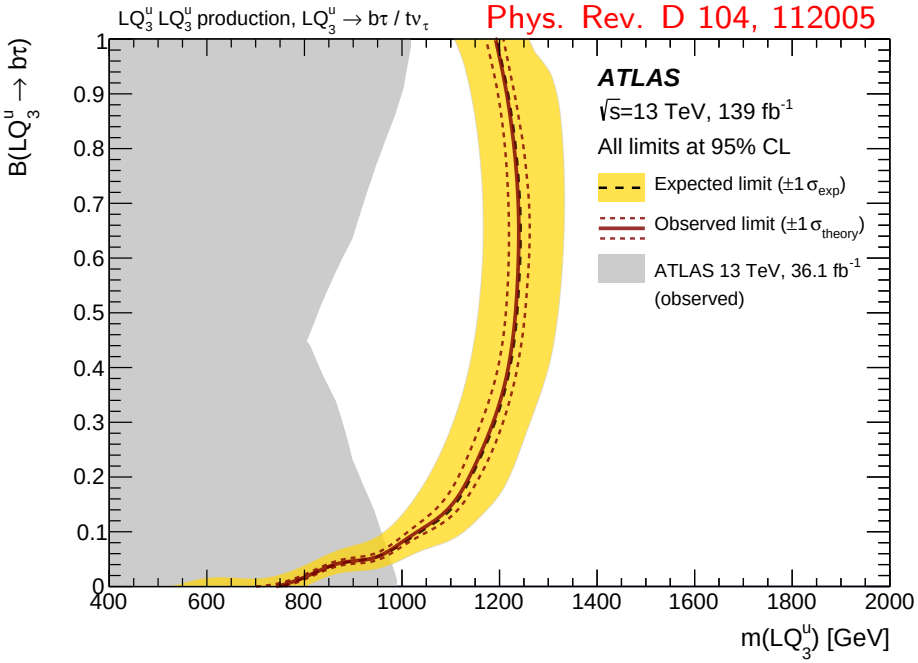
- Looking into the medium and high p_T regimes that ATLAS and CMS are better suited for, several BSM explanations are available and searched for
- One very straightforward idea are third generation leptoquarks (LQs)

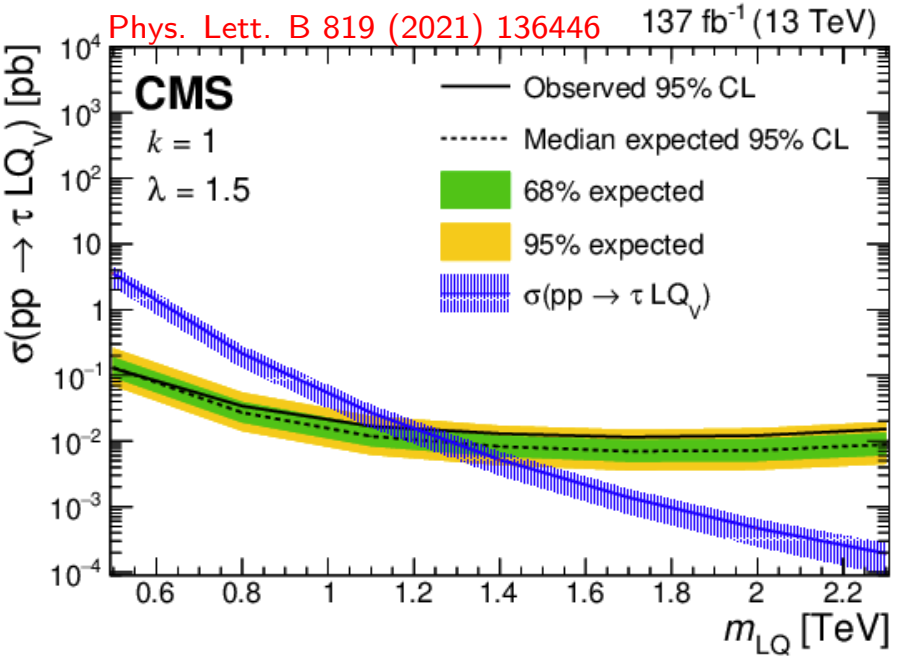




- Either way: Flavour non-universal couplings necessary

LQ searches

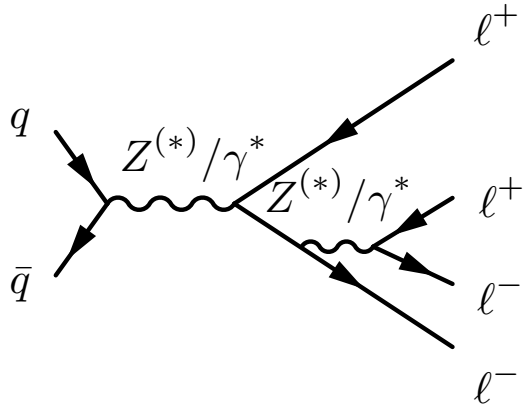




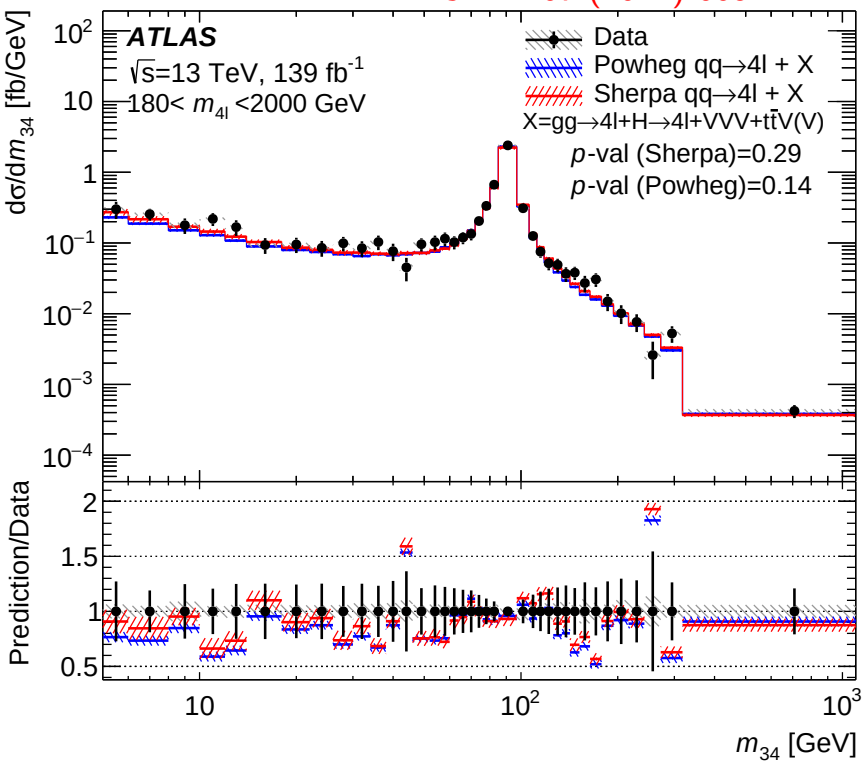
- ATLAS and CMS are both looking for LQs with third generation couplings (b, τ, t)
- Exclusion limits for these cases exist and are in the multi-TeV range for a large part of the parameter space
- LQ coupling λ-dependent and for B-flavour anomalies two different λ need to be at work
- Only examples, lots of LQ results and searches exist

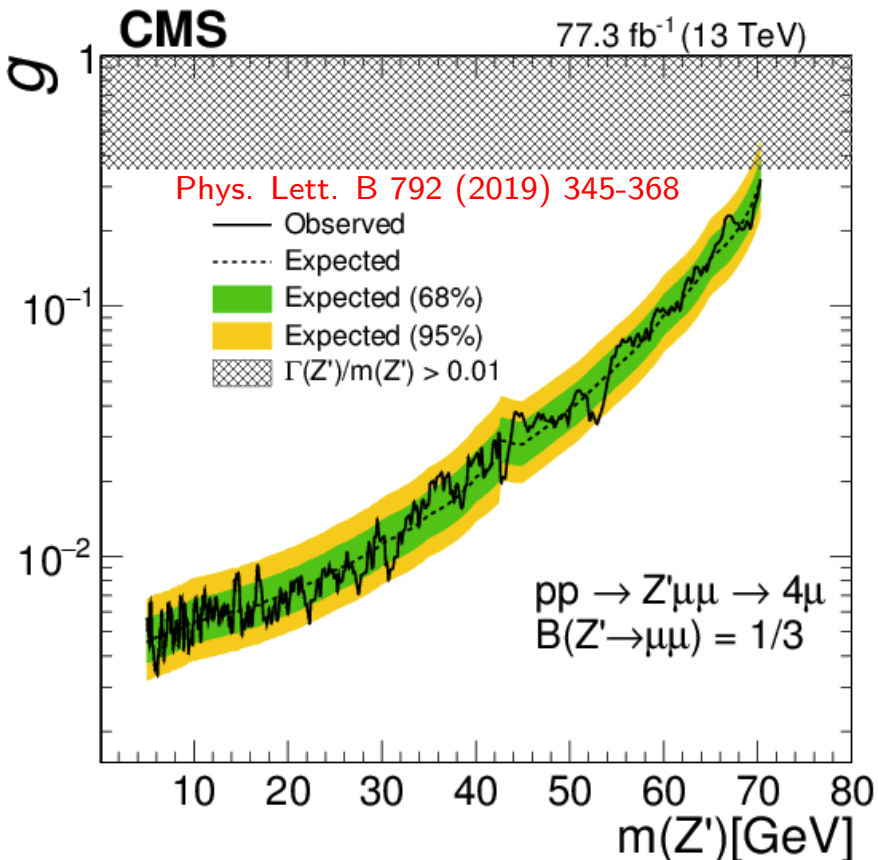
Low mass Z' di-μ coupling searches

- Leptonic coupling can be constrained in $Z \to 4\ell$ events
- Ideal for low mass Z' searches
- Easy to trigger, due to lepton multiplicity



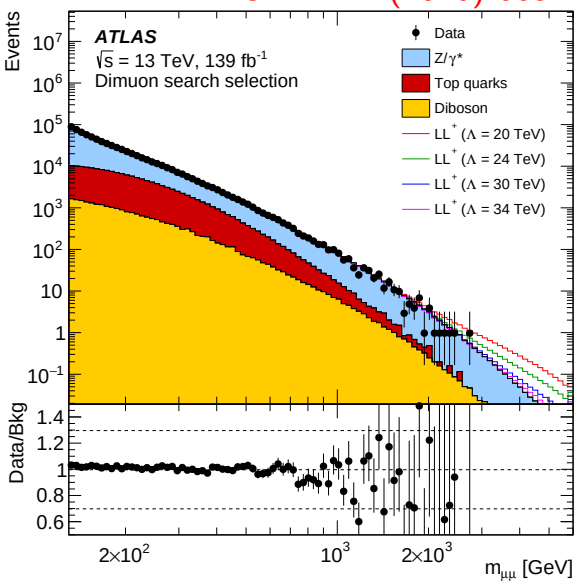
JHEP 07 (2021) 005



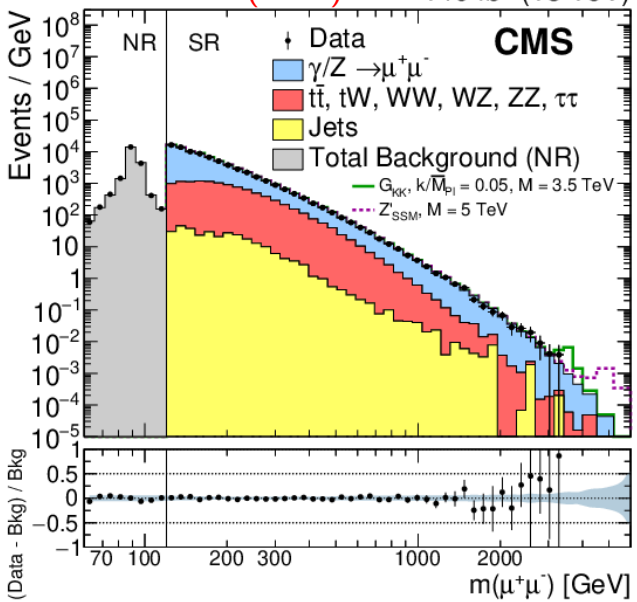


Flavour non-democratic Z'

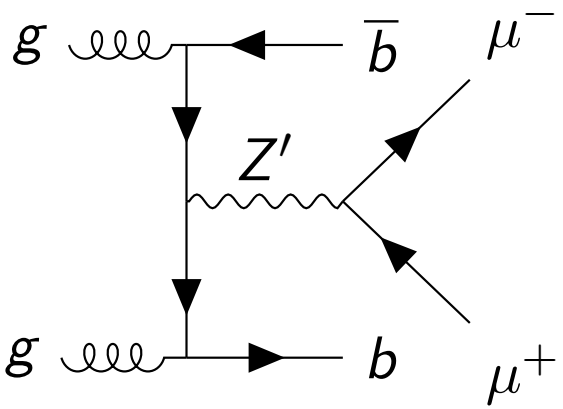
JHEP 11 (2020) 005



JHEP 2107 (2021) 208 140 fb^{-1} (13 TeV)



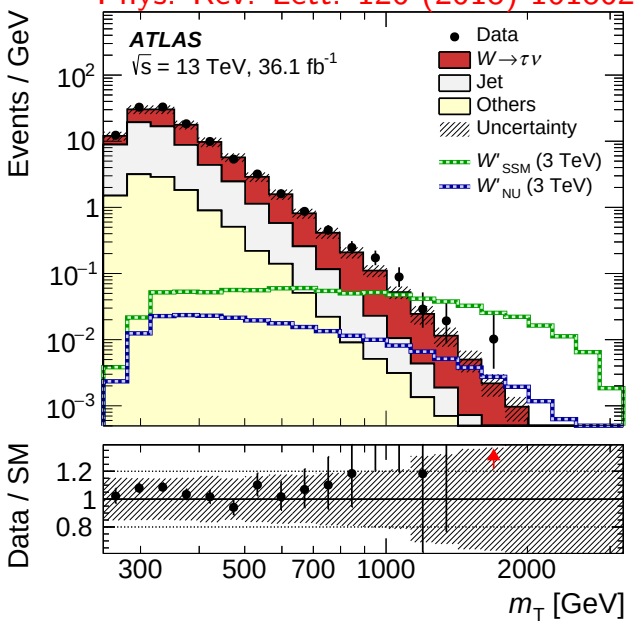
2 assoc. jets Z'



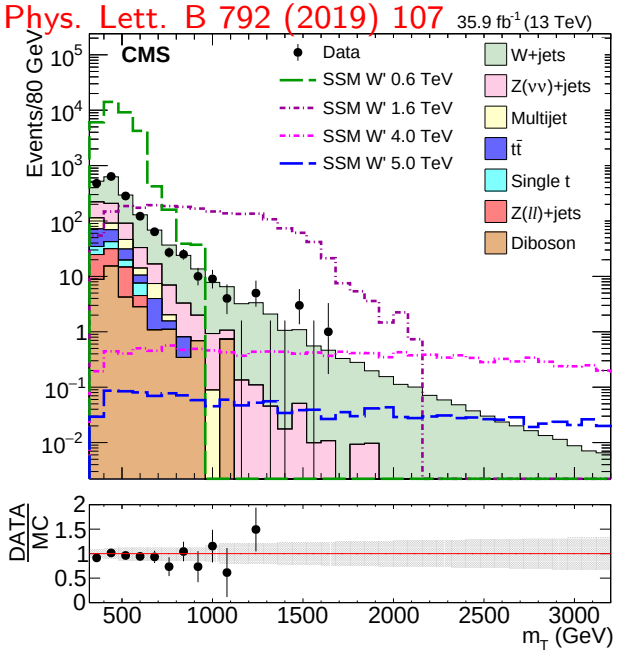
- Resonant and non-resonant searches for heavy new resonances with universal couplings to quarks exist
- Interpretation for B-anomaly purposes with flavour-violating *bs* quark coupling or third generation quark coupling viable
- Improvements by requiring one or two associated b-tags possible

Flavour non-democratic W'

Phys. Rev. Lett. 120 (2018) 161802



Phys. Lett. B 792 (2019) 107



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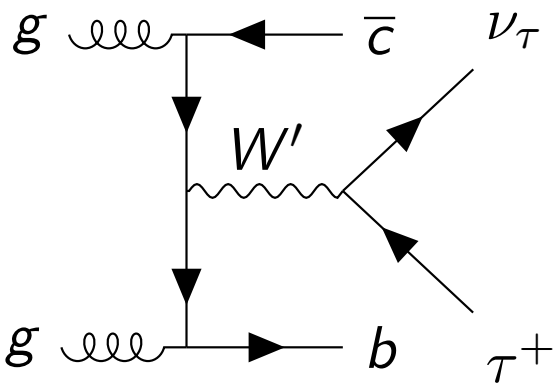

- Transverse mass is the search variable of choice here
- More difficult, since $R(D^{(*)})$ indicate abundance of τ indicating a lot of $\mathrm{p}_{\mathrm{T}}^{\mathrm{miss}}$
- Searches can be optimized looking for additional b- or even c-tagged jets

Conclusions and Outlook

- LFUV stays an exciting topic in the HEP community
- Using specialized triggers, some B-anomaly-related quantities can be measured independently of LHCb by ATLAS and CMS and this is WIP
- Run 3 is an even bigger challenge than Run 2 was in terms of instantaneous luminosity increasing pileup though
- On the other hand, various BSM models with higher masses will benefit from any increase in dataset size, mostly regardless of pileup
- More and more searches pinpointed at B-anomaly-related models are in the pipeline
- But old searches, including SUSY and four-lepton cross section SM measurements, can be reinterpreted with respect to B-anomalies, too