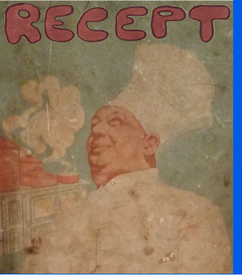
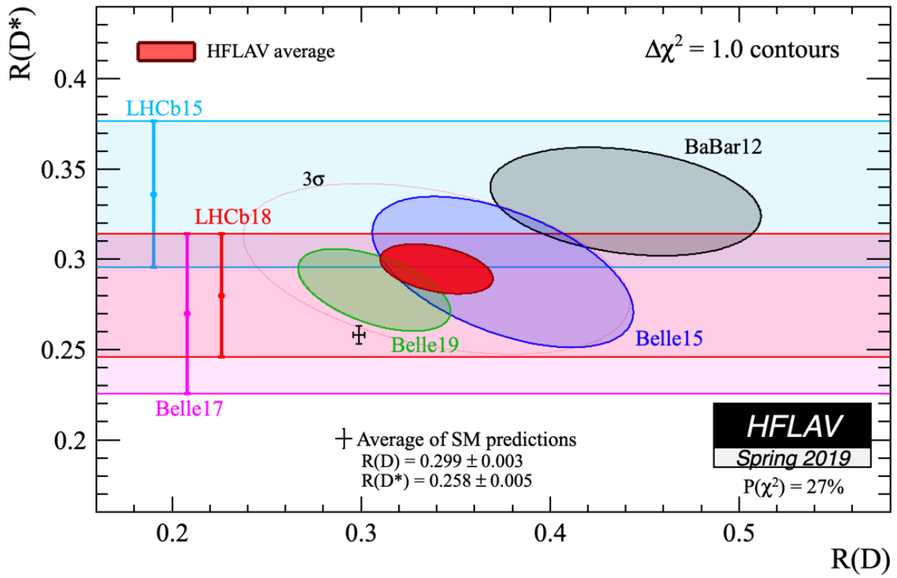
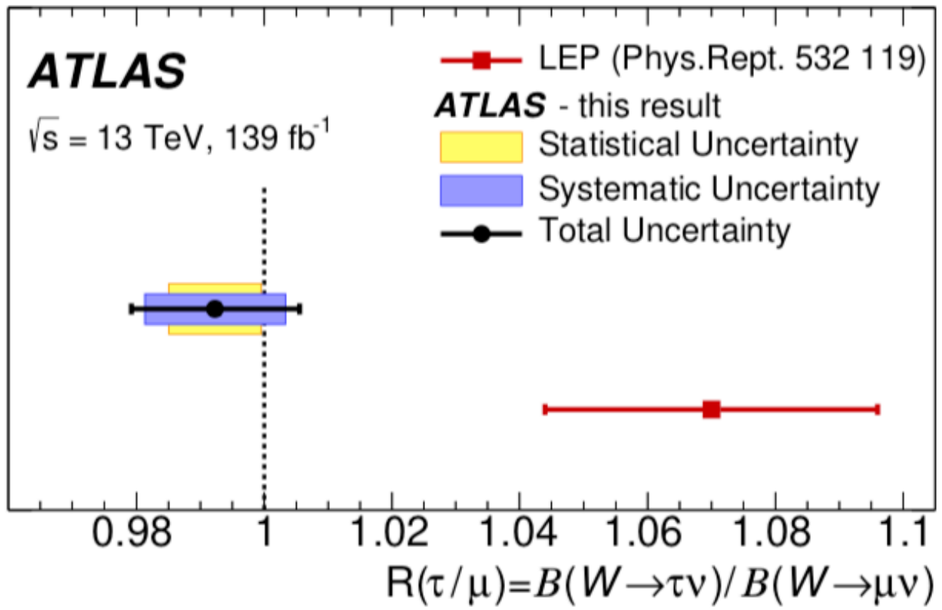


Lepton flavour at colliders experimental overview





Vladimir V. Gligorov, CNRS/LPNHE

On behalf of the LHCb, ATLAS, CMS, and Belle/Belle II collaborations

NuTau 2021 workshop, cyberspace, 28.09.2021

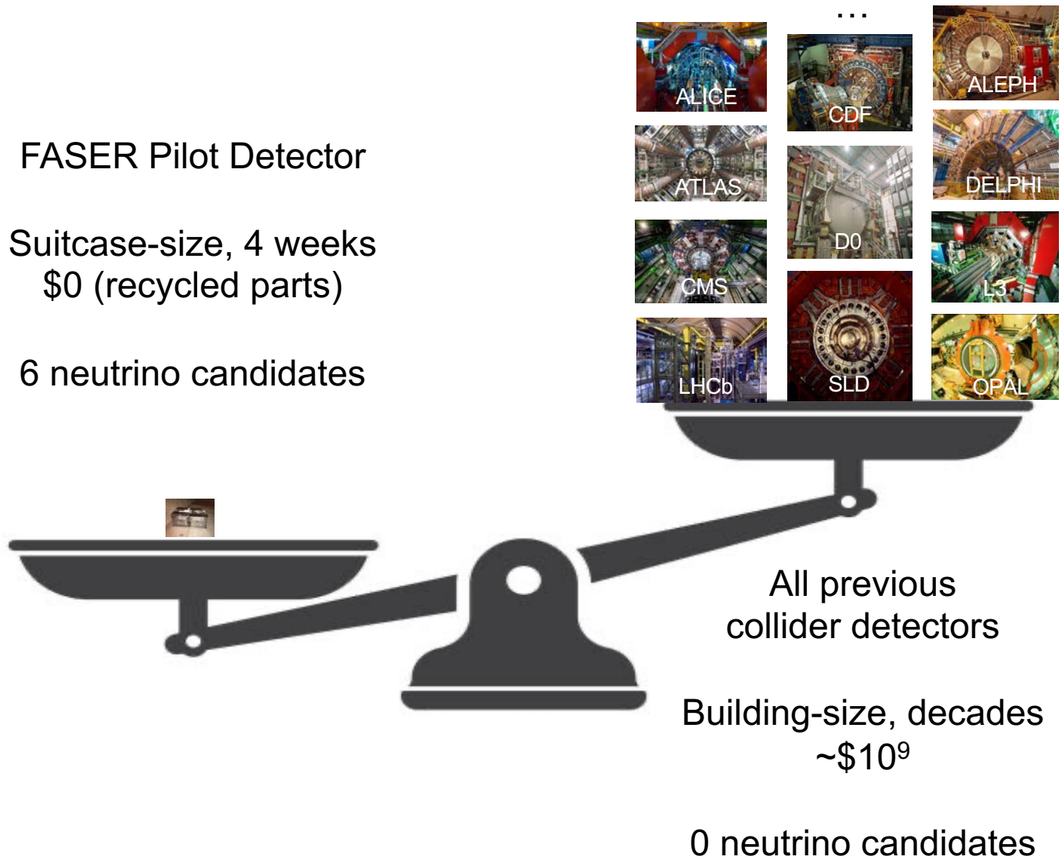
Talk overview

Collider physics does not naturally lend itself to studying neutrino properties… at least until FASERν will be in full swing

On the other hand the topic of lepton flavour is rather exciting these days

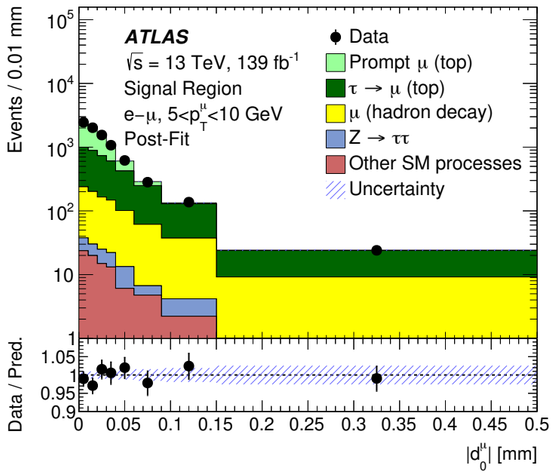
- The universality of electroweak lepton couplings in the Standard Model
- Searches for lepton flavour violation
- Connections to high-P_T direct searches for BSM particles

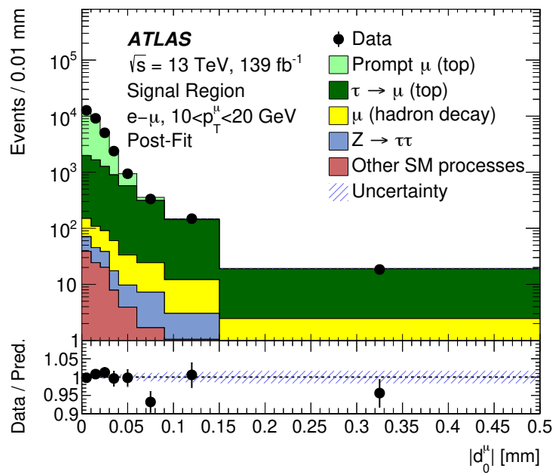
Jonathang Feng Quarks 2021 Online Workshop

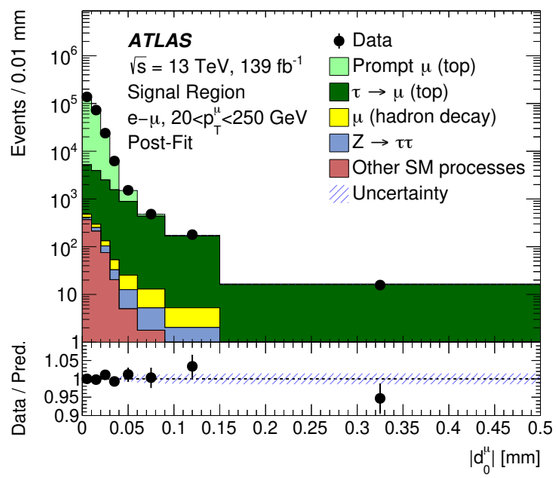


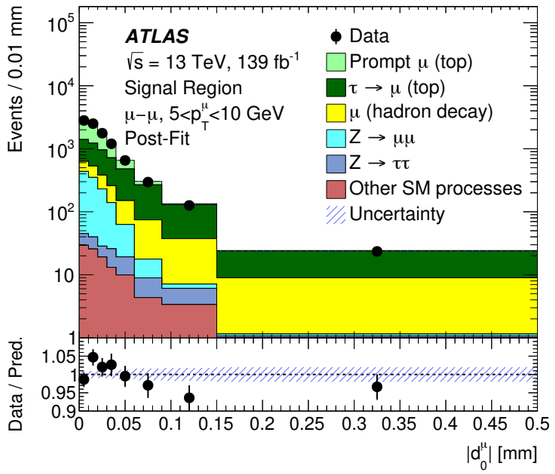
I will now attempt a whistlestop tour through this subject matter

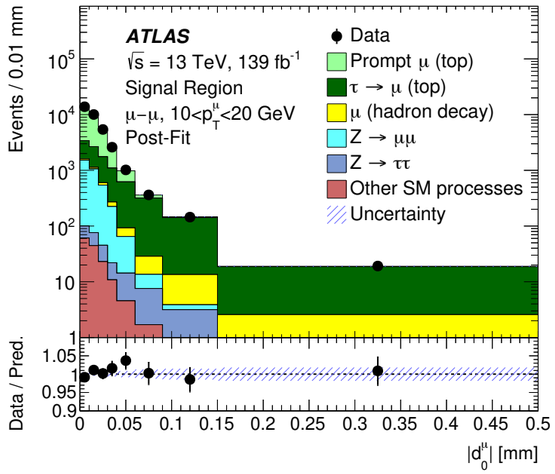
Universality of SM lepton couplings

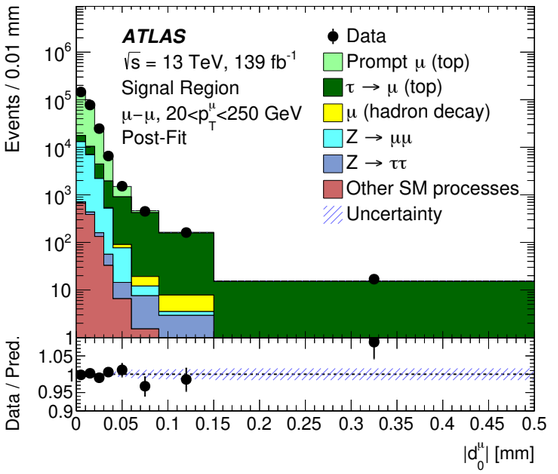










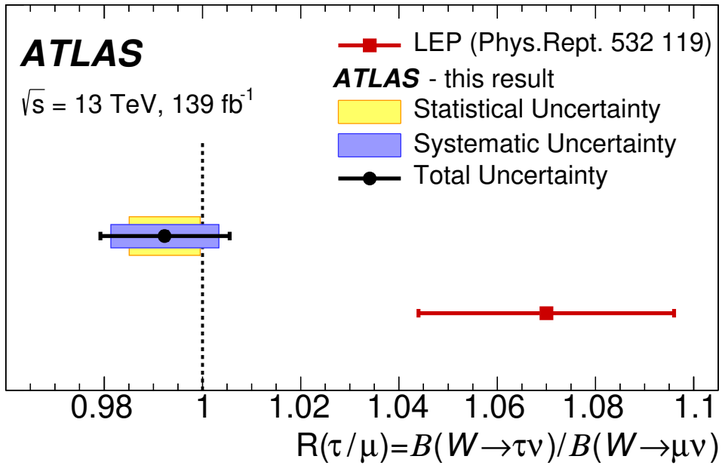


Nature Physics volume 17, pages 813–818 (2021)

Universality of Z couplings established at permille level since LEP

For W→τν a longstanding tension of ~2.5σ needed to be resolved however — exploit ttbar events at LHC!

Universality of SM lepton couplings



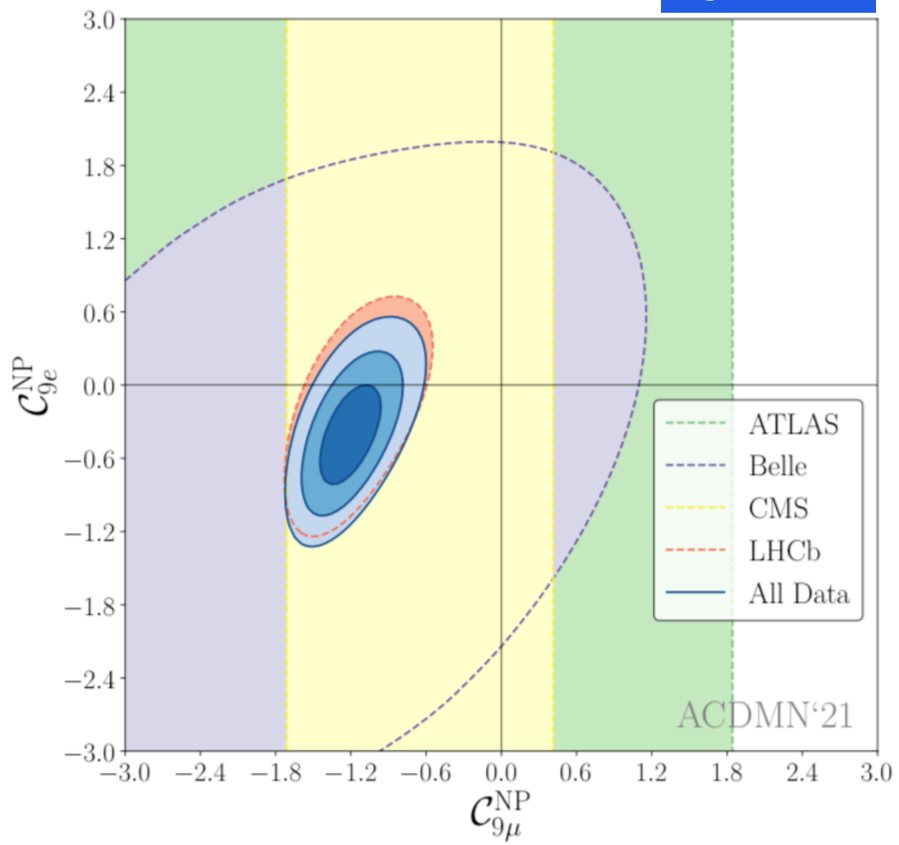
Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
μ_{prompt} and $\mu_{\tau(\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_{T} spectum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\to\mu)}$ and μ_{had} d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

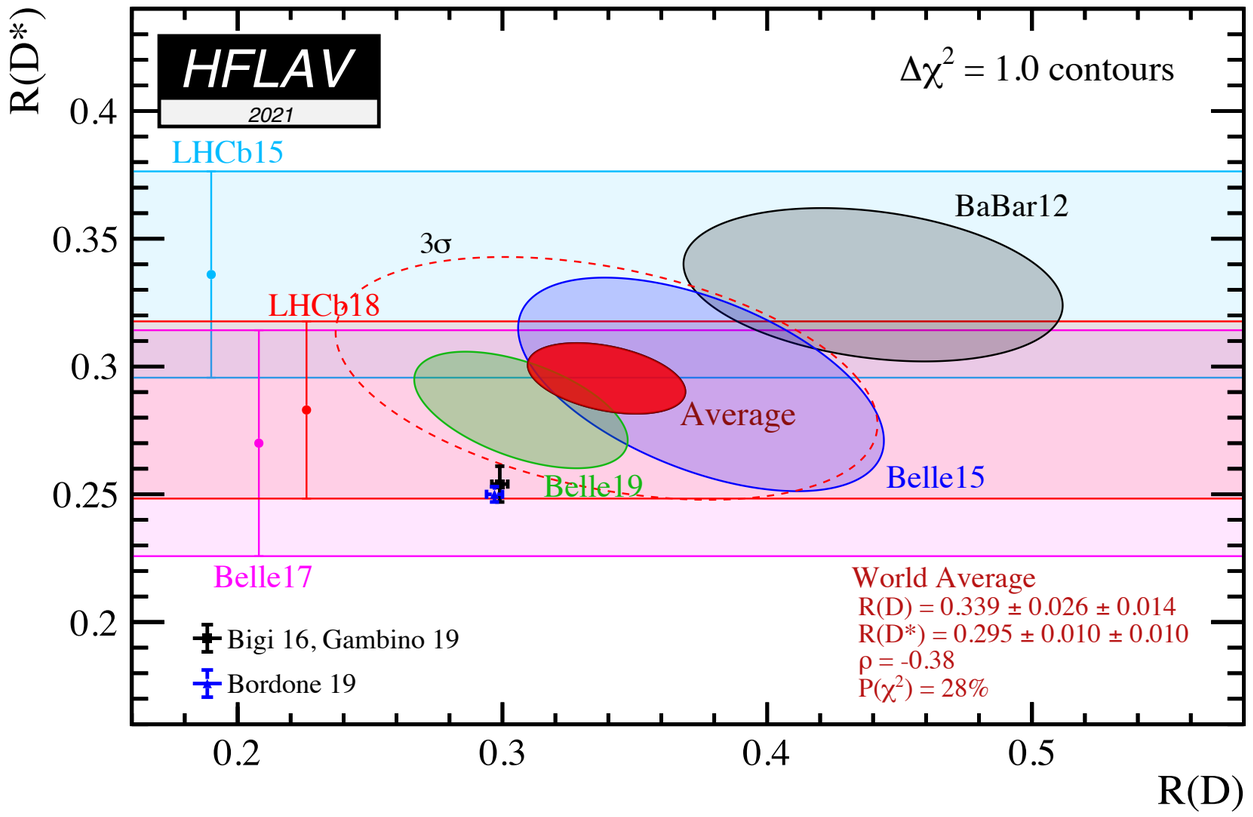
Nature Physics volume 17, pages 813–818 (2021)

Beautiful measurement by ATLAS with 1% systematic uncertainty (!) brings W→$\tau\nu$ into line with W→e/$\mu\nu$

And yet anomalies persist

Algueró et al



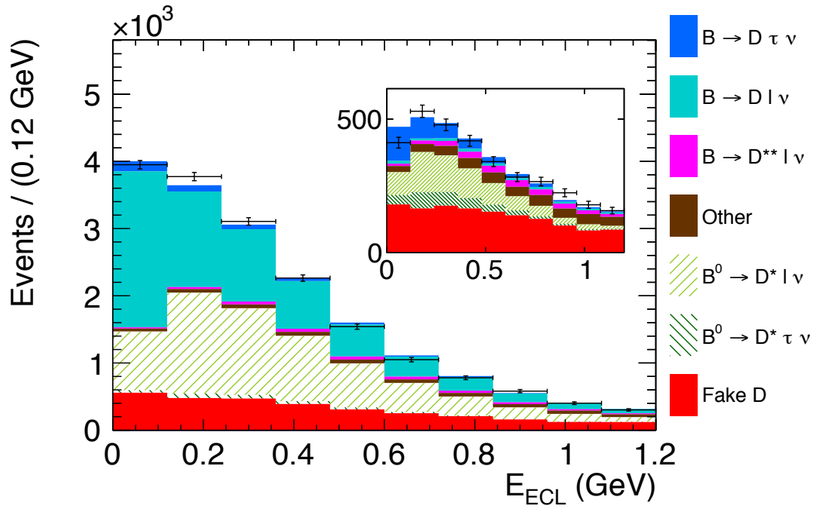


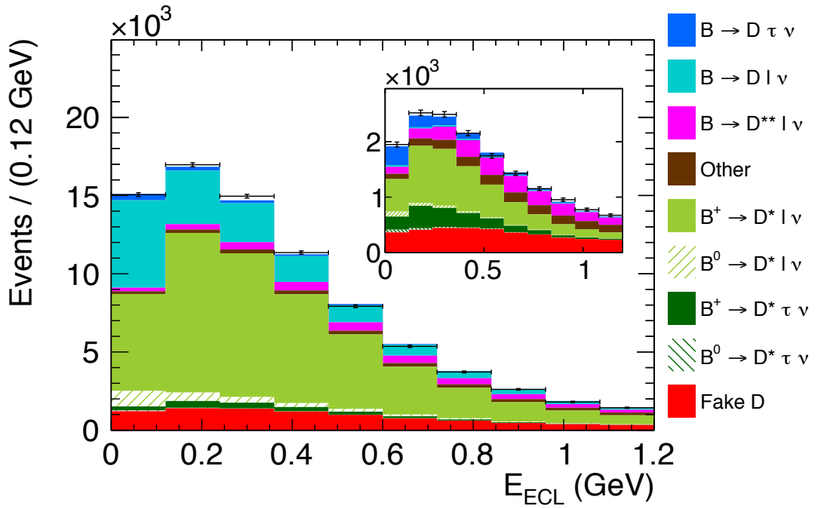
Despite many measurements over the past 9 years a 3σ tension persists in b→cτν processes. Improved theoretical calculations have not resolved the tension.

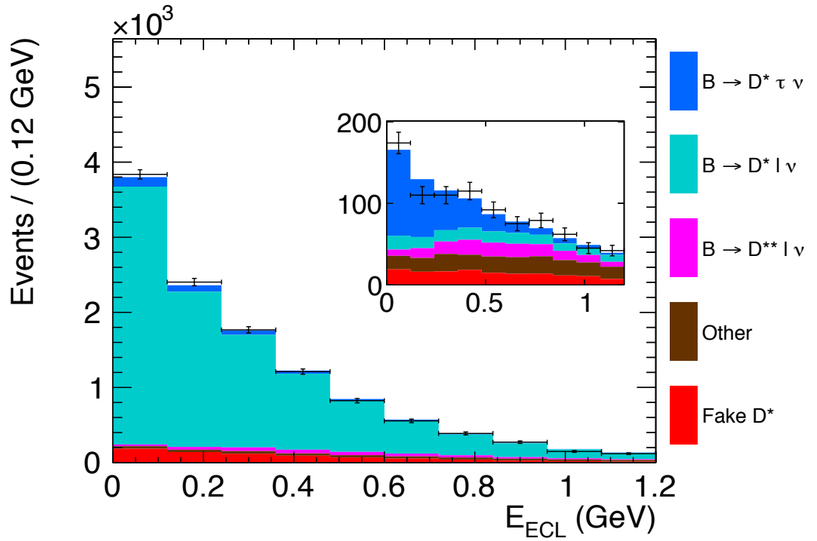
In b→sll processes recent evidence of lepton universality breaking is just one piece of a global tension with the Standard Model. So what is going on?

Apologies to teams whose b→sll results were omitted: blame HFLAV for not making a b→sll plot!

b→cτν LU: most recent Belle result







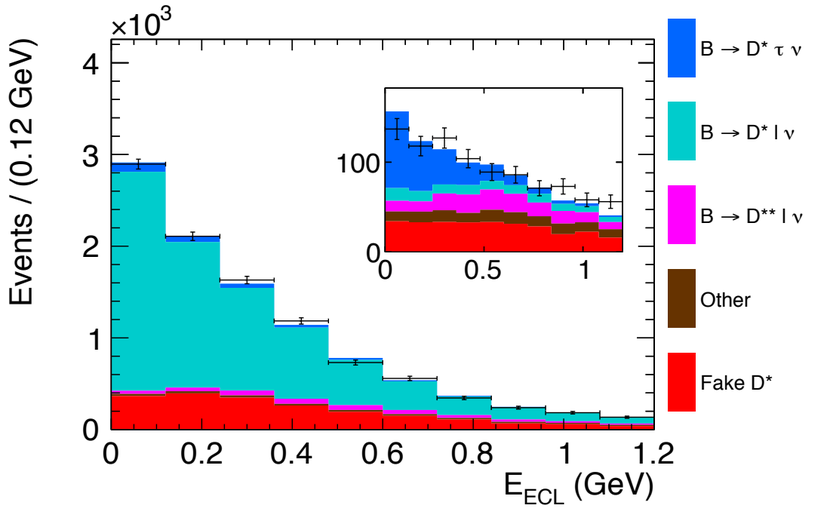


TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$ results, together with their correlation.

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)	Correlation
D^{**} composition	0.76	1.41	−0.41
PDF shapes	4.39	2.25	−0.55
Feed-down factors	1.69	0.44	0.53
Efficiency factors	1.93	4.12	−0.57
Fake $D^{(*)}$ calibration	0.19	0.11	−0.76
$B_{\rm tag}$ calibration	0.07	0.05	−0.76
Lepton efficiency and fake rate	0.36	0.33	−0.83
Slow pion efficiency	0.08	0.08	−0.98
B decay form factors	0.55	0.28	−0.60
Luminosity, f^{+-}, f^{00} and $\mathcal{B}(\Upsilon(4S))$	0.10	0.04	−0.58
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02	−0.69
$\mathcal{B}(D)$	0.35	0.13	−0.65
$\mathcal{B}(D^*)$	0.04	0.02	−0.51
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.15	0.14	−0.11
Total	5.21	4.94	−0.52

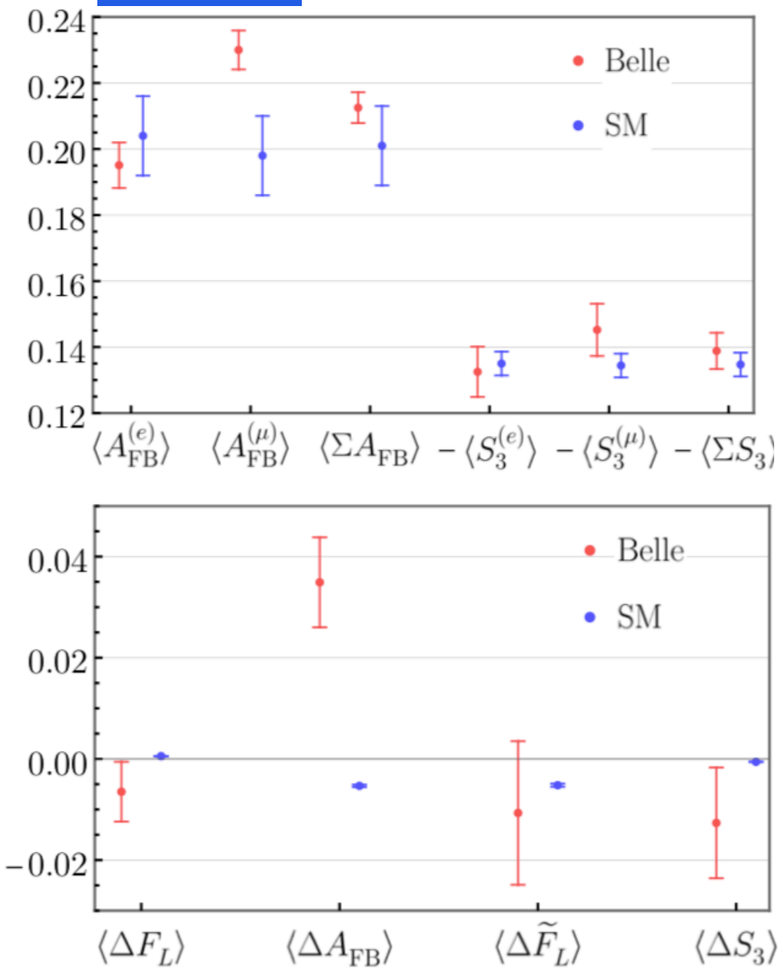
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014,$$

Phys. Rev. Lett. 124, 161803 (2020)

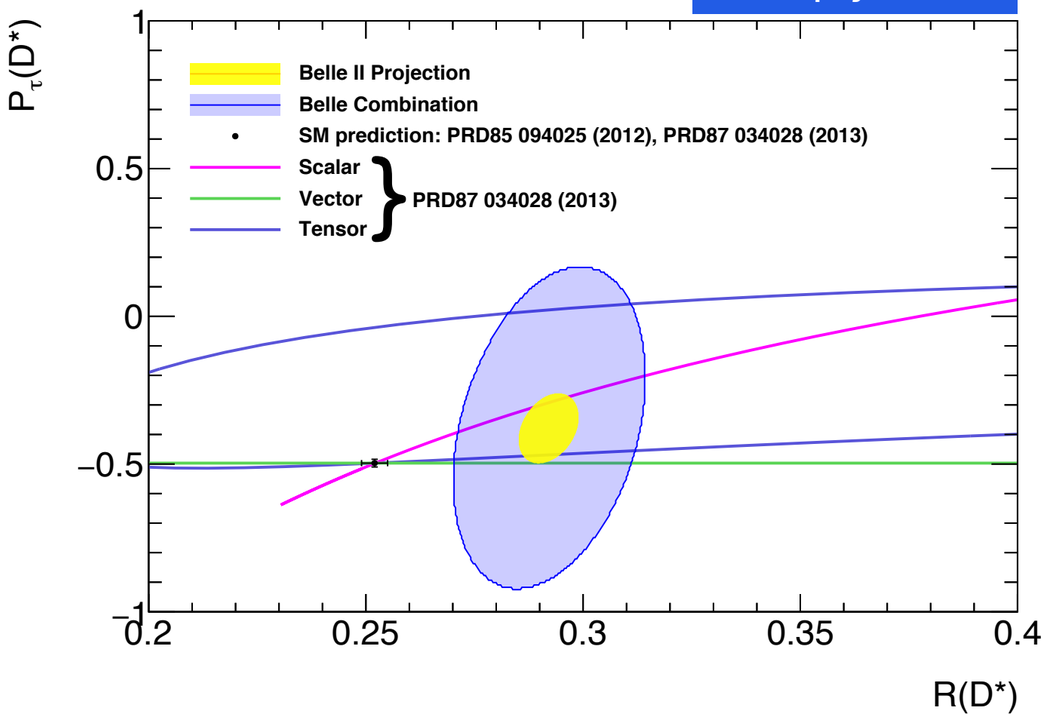
Still statistically limited, in particular for R_D. Single-measurement agreement with the SM at 0.8σ

b→clν LU: we need more observables

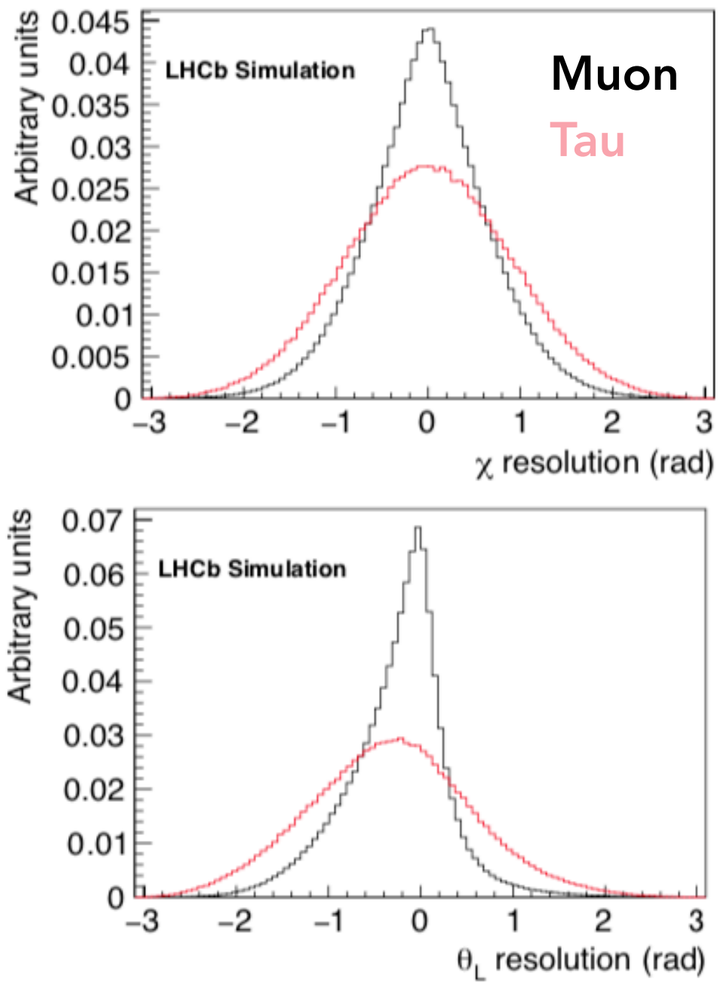
Bobeth et al



Belle 2 physics book



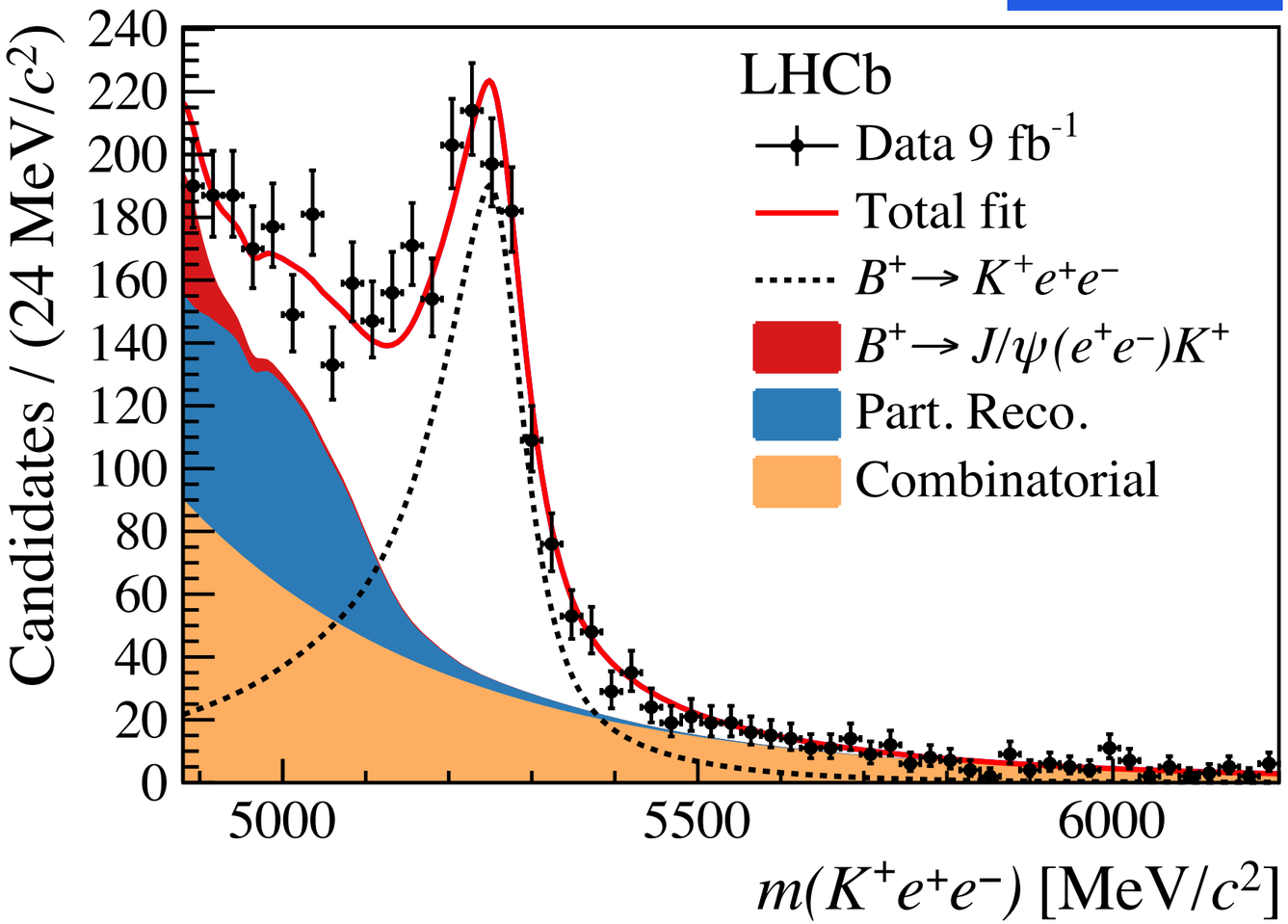
HL-LHC Yellow Report



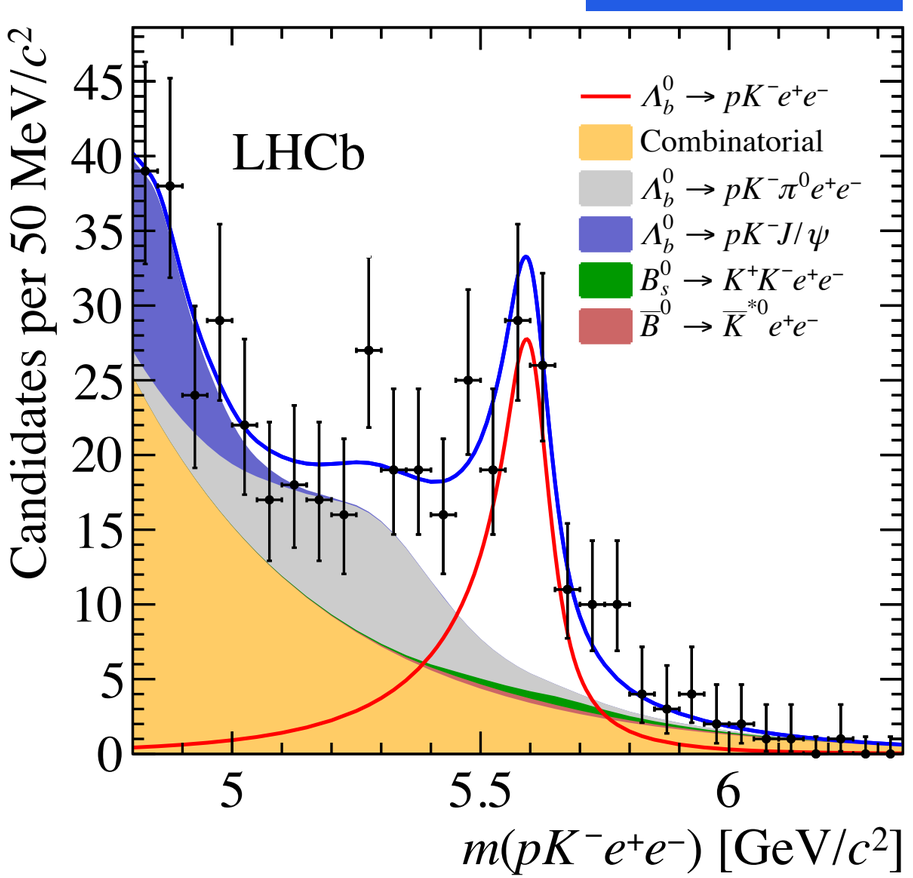
Angular b→sll and b→clν lepton universality tests are slowly starting. This is an area where Belle 2 has unique hadronic & semileptonic tag-side reconstruction capabilities, but LHCb will also have some sensitivity. Post-hoc analysis of Belle data by theory colleagues provides a strong motivation to publish our data in more detail!

b→sll lepton universality tests

arXiv 2103.11769



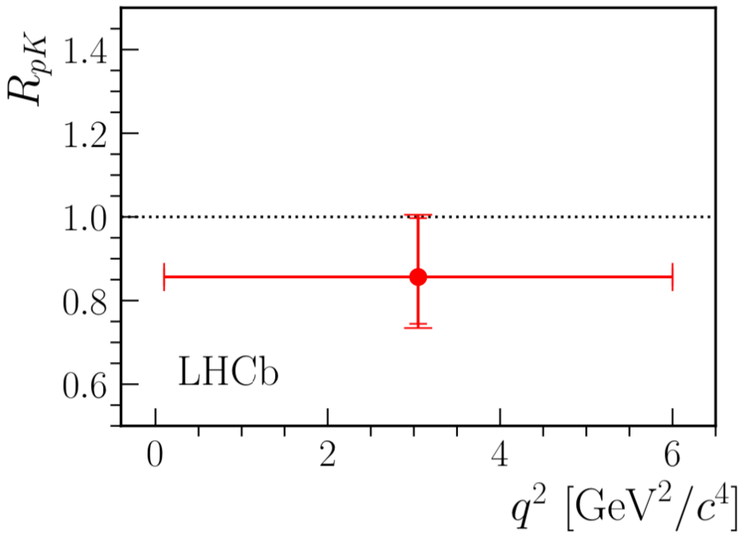
JHEP 05 (2020) 040

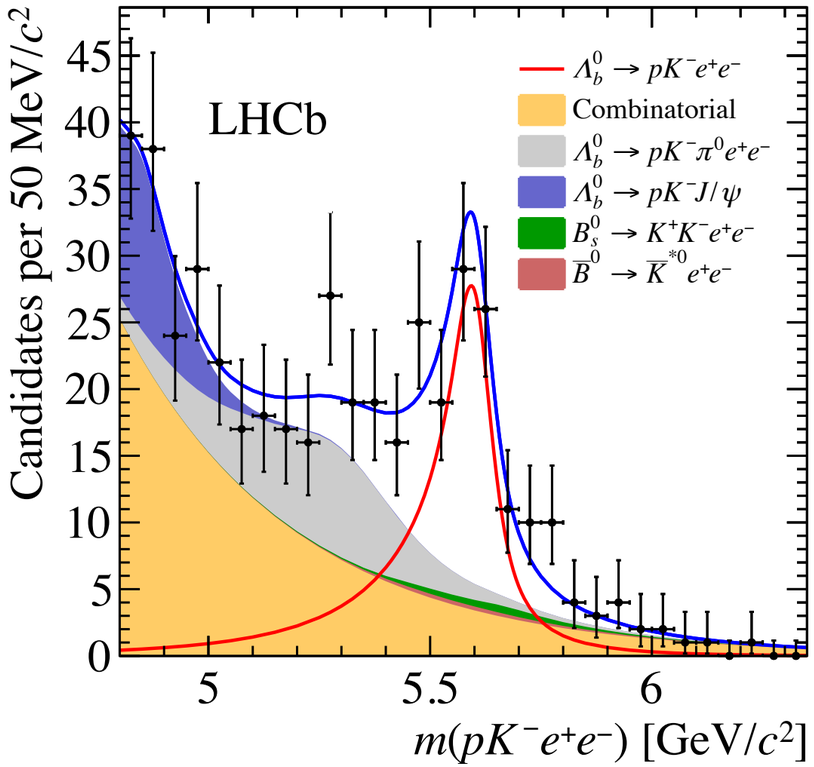


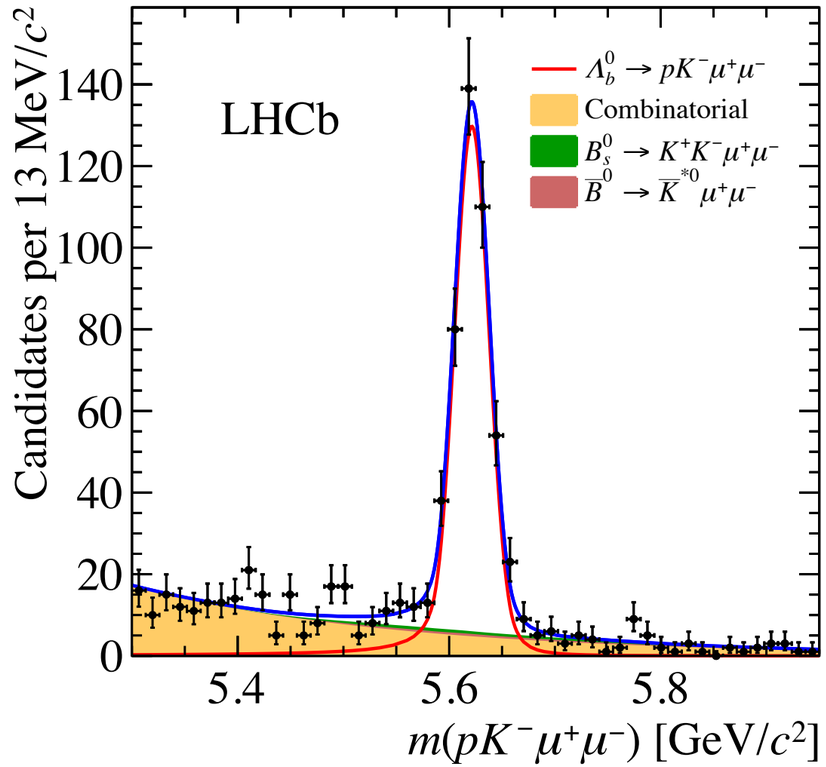
The data is mounting… almost entirely in one direction. Even baryon modes are entering the game.
The latest LHCb analysis of RK provides the first single-measurement evidence for LU in b→sll decays!

JHEP 05 (2020) 040

$\Lambda_b \to pKee/\mu\mu$





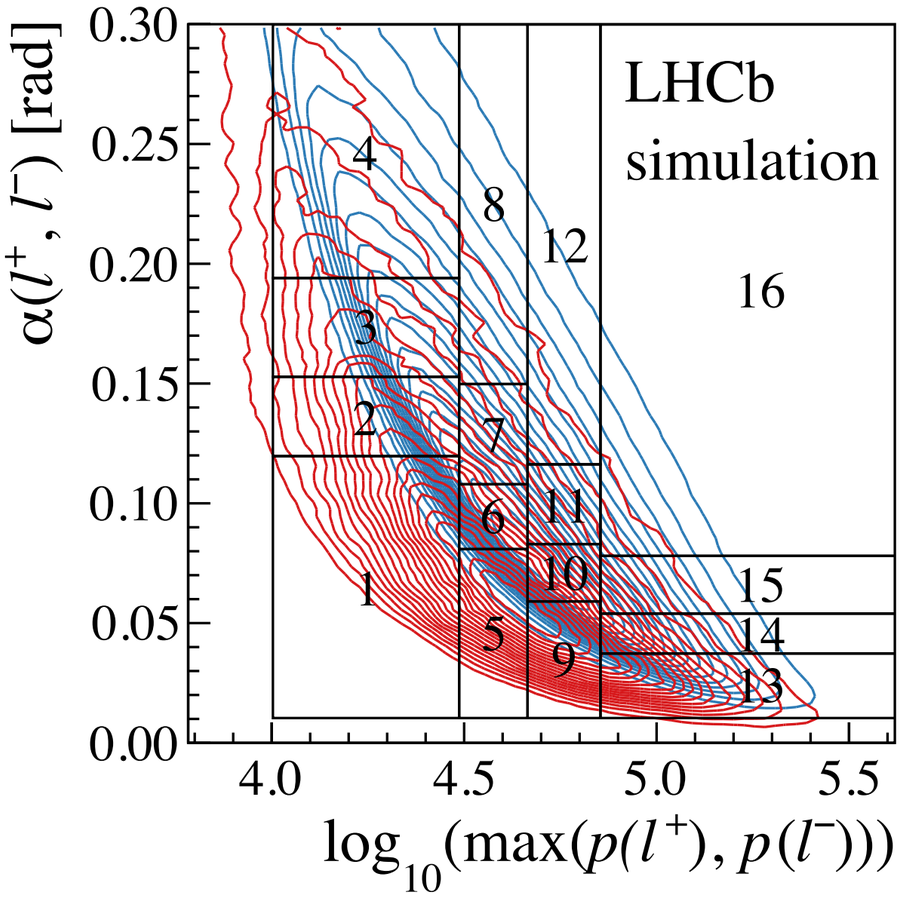


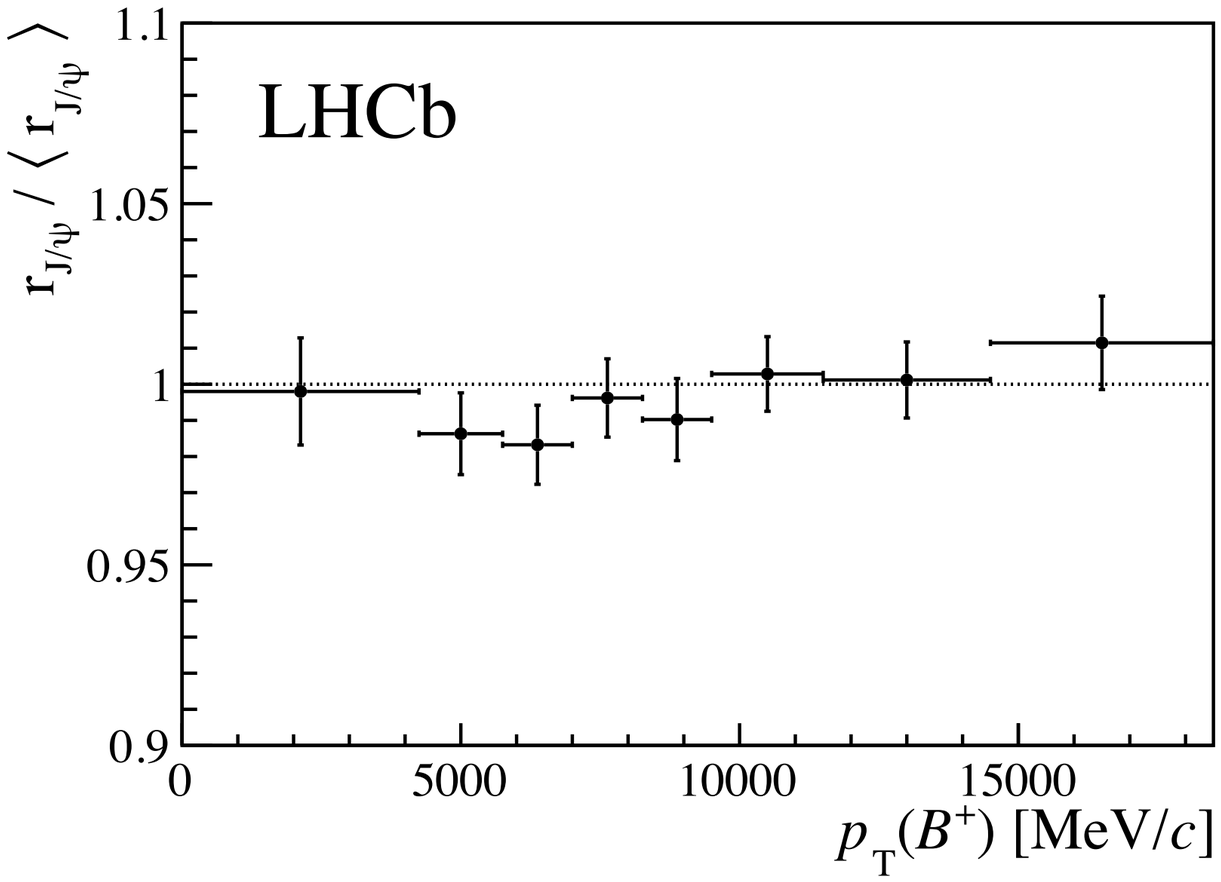
Decay mode	q^2 [GeV$^2/c^4$]	$pK^-\ell^+\ell^-$ invariant mass [GeV/c^2]
$\Lambda_b^0 \to pK^-e^+e^-$	0.1 – 6.0	4.80 – 6.32
$\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-)$	6.0 – 11.0	5.30 – 6.20
$\Lambda_b^0 \to pK^-\mu^+\mu^-$	0.1 – 6.0	5.30 – 5.95
$\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-)$	8.41 – 10.24	5.35 – 5.85

Measurement compatible with SM but central value goes in same direction as meson b→sll decays. Showcases the unique capabilities of the LHC to access high-statistics heavy flavour baryon decays

arXiv 2103.11769

R_K: first evidence for LU breaking

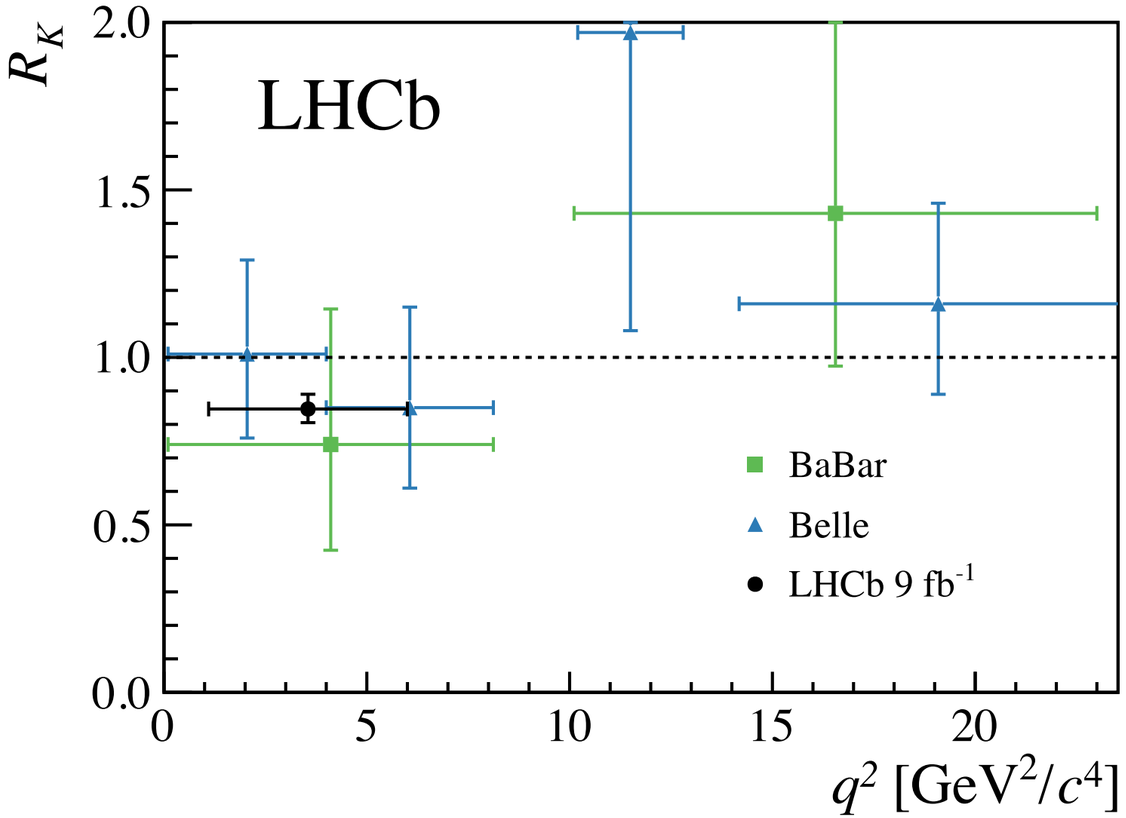


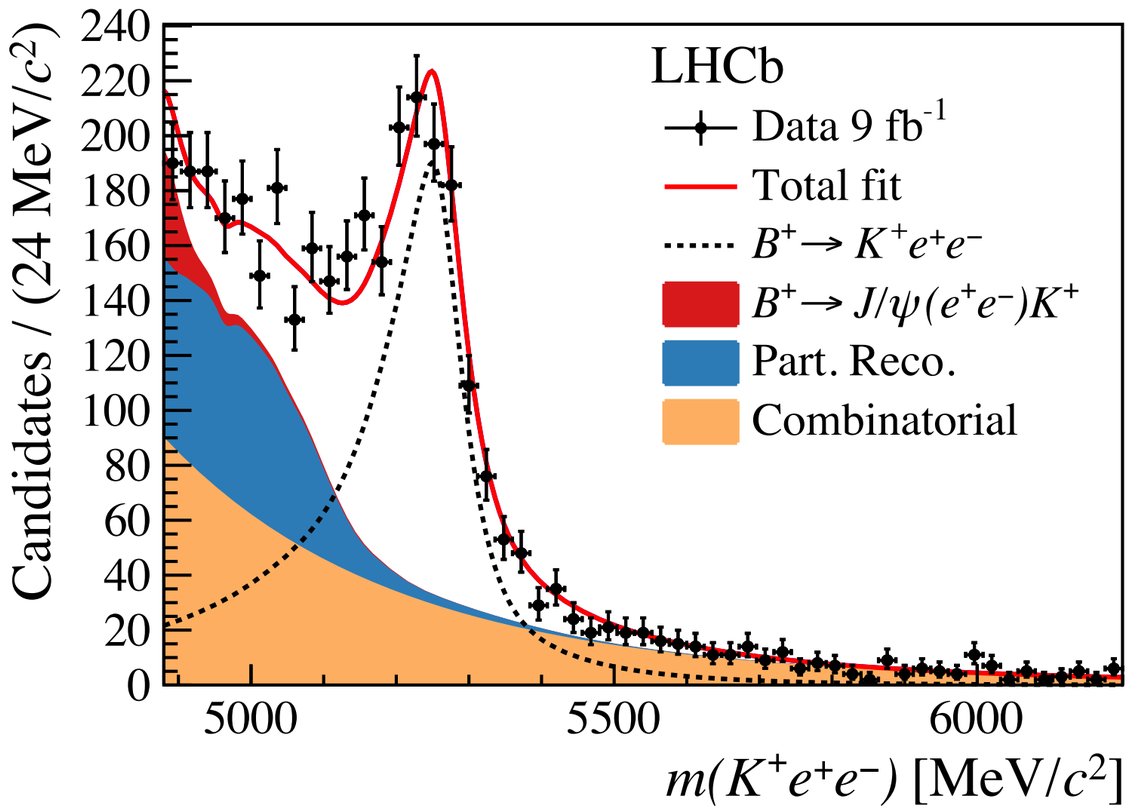


Electron efficiencies calibrated using a multi-step data-driven reweighting procedure, cross-checked differentially in 2D: the dilepton opening angle and maximum lepton momentum. Excellent stability observed with respect to a whole range of kinematic variables of interest.

R_K: first evidence for LU breaking

arXiv 2103.11769

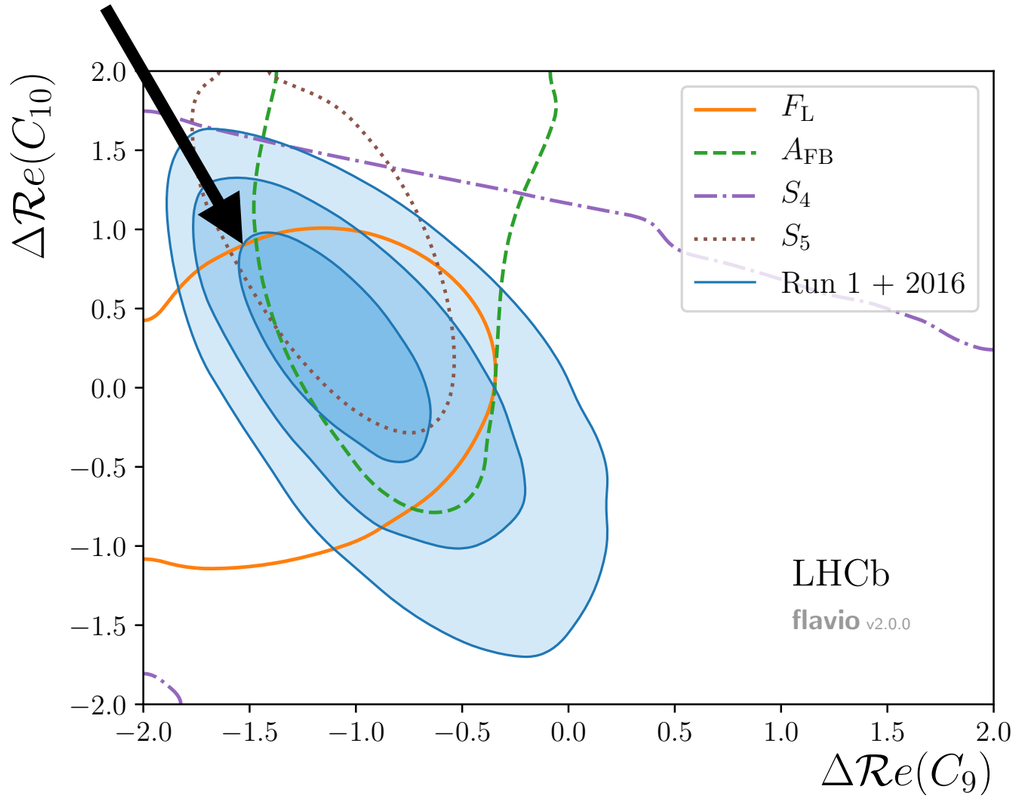


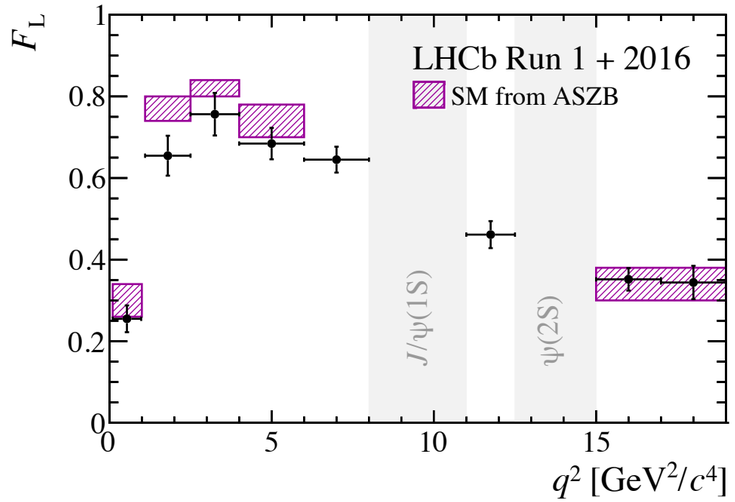


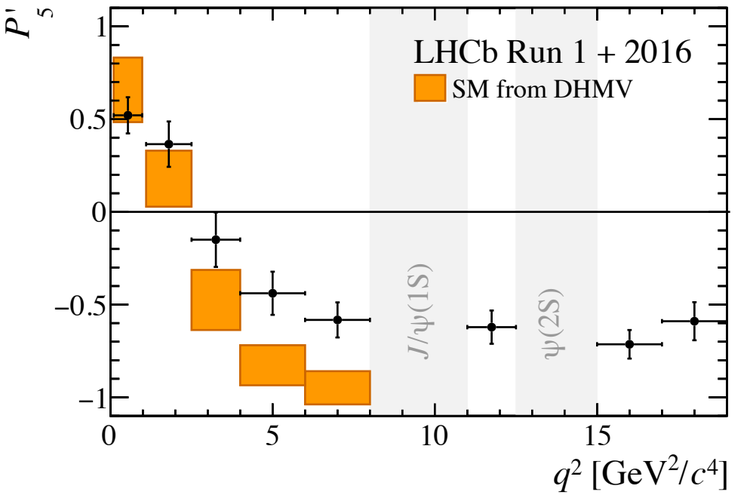
Could still be a fluctuation — Belle 2 input crucial but also fascinating to see what CMS (ATLAS?) can do!

LU in context of angular b→sll analyses

Notice that this is not just about P5′ — pattern seen in F_L is coherent and nearly as deviant! Interpretation as BSM physics or poorly understood hadronic effects remains controversial. (This is why link to the LU tests is so important, where hadronic effects cannot be the cause)







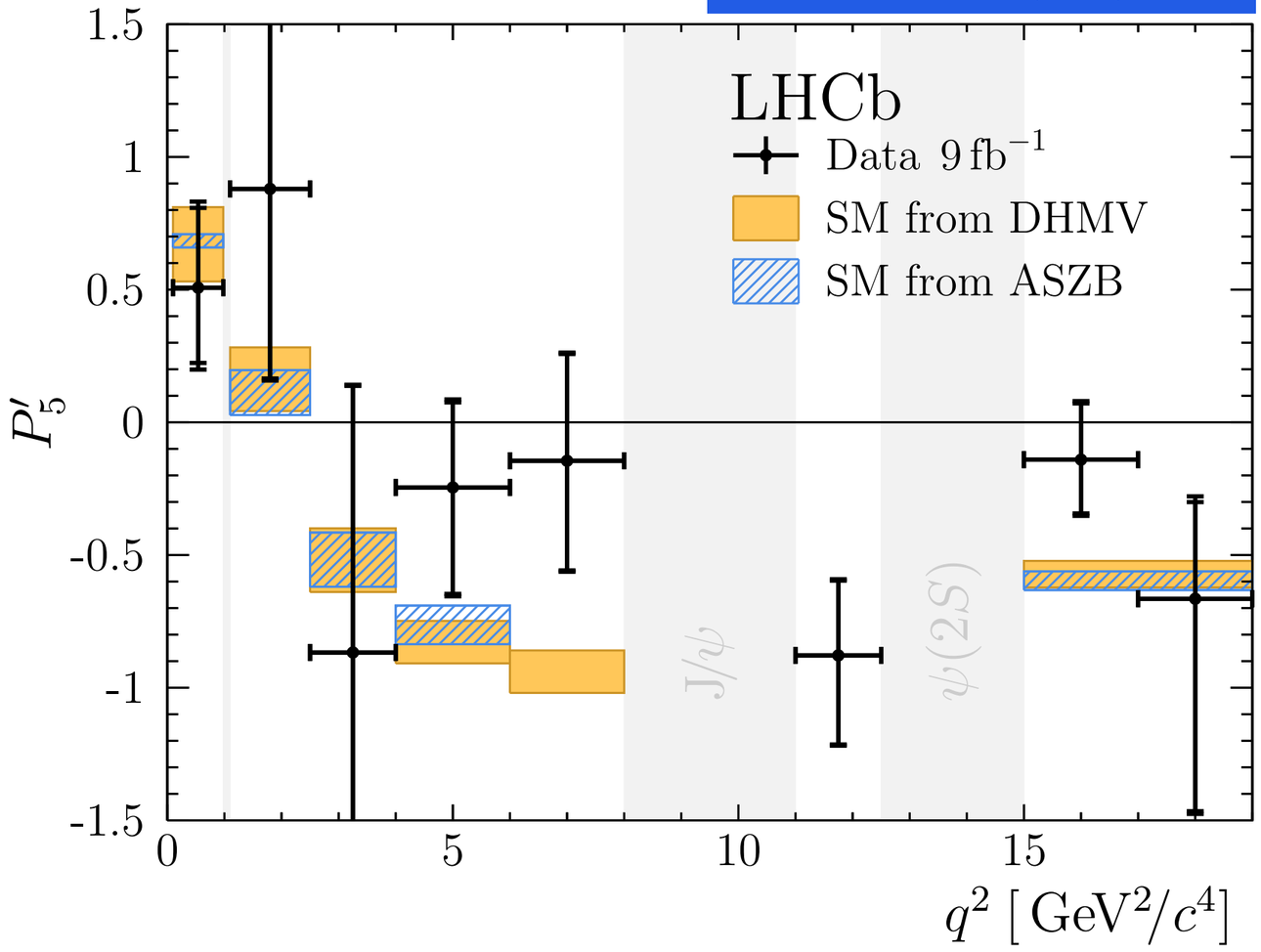
PHYS. REV. LETT. 125 (2020) 011802

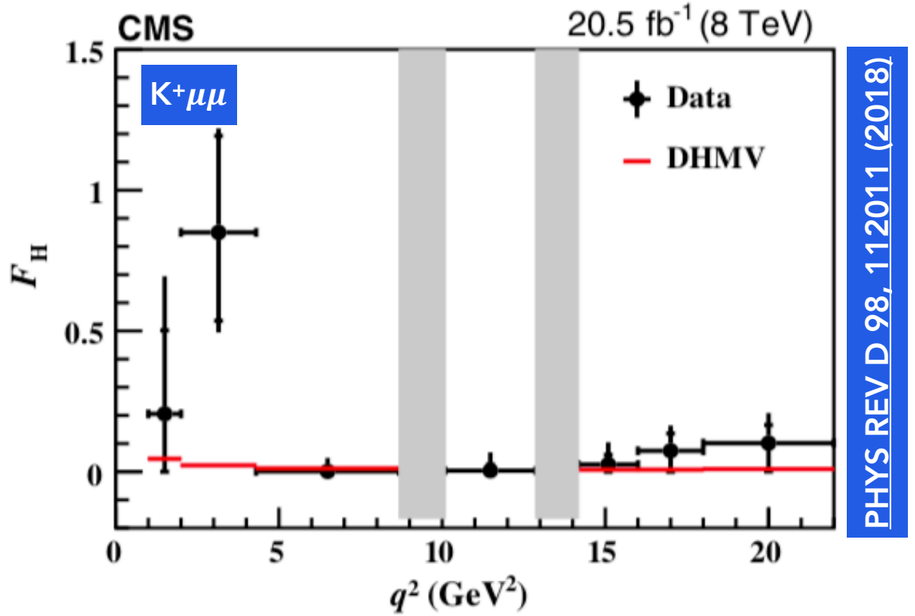
LU breaking in b→sll transitions is part of a wider pattern of anomalies seen in angular b→s$\mu\mu$ analyses

Latest high-statistics LHCb update of $B^0 \to K^{*0}\mu\mu$ confirms pattern of earlier deviations from SM picture

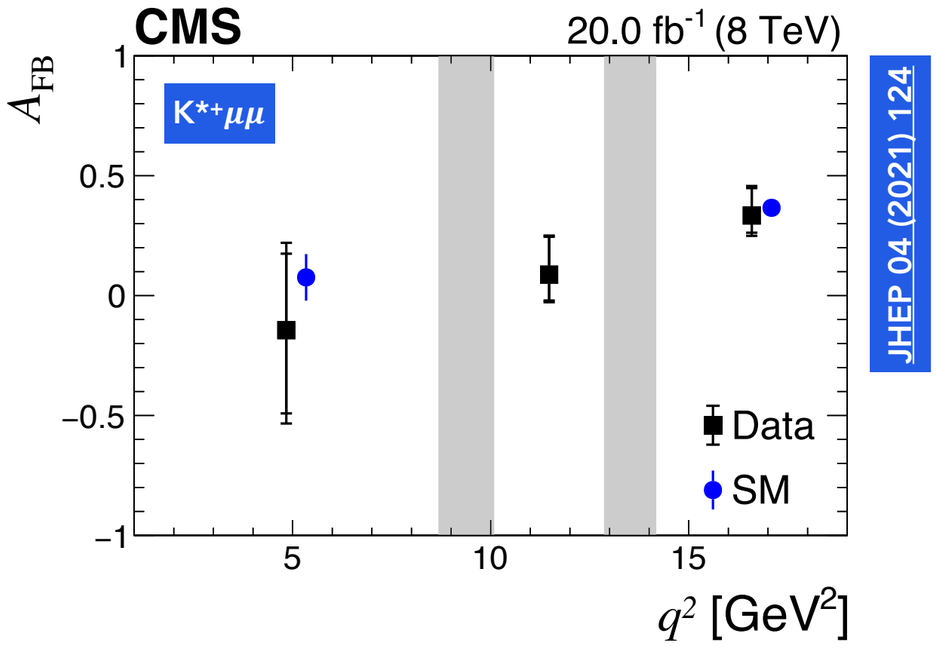
$K^{(*)+}\mu\mu$ angular analyses

PHYS. REV. LETT.126 (2021) 161802





PHYS REV D 98, 112011 (2018)



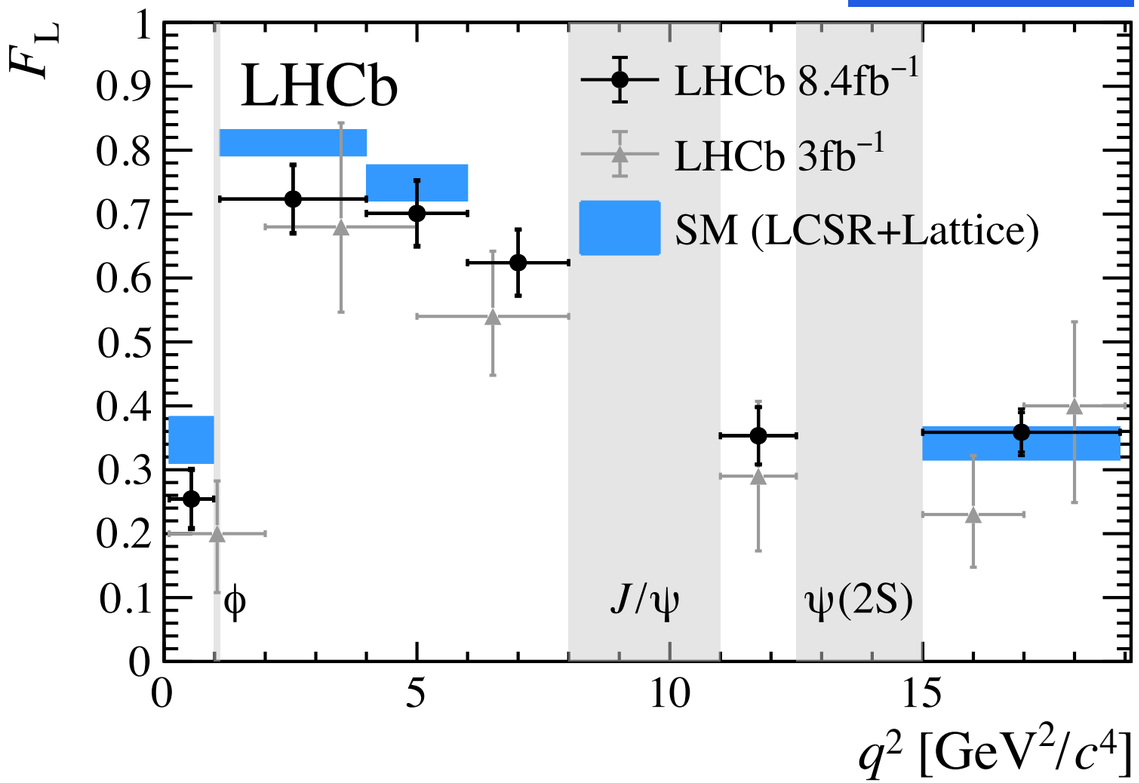
JHEP 04 (2021) 124

Great to see CMS entering the K*+ game!

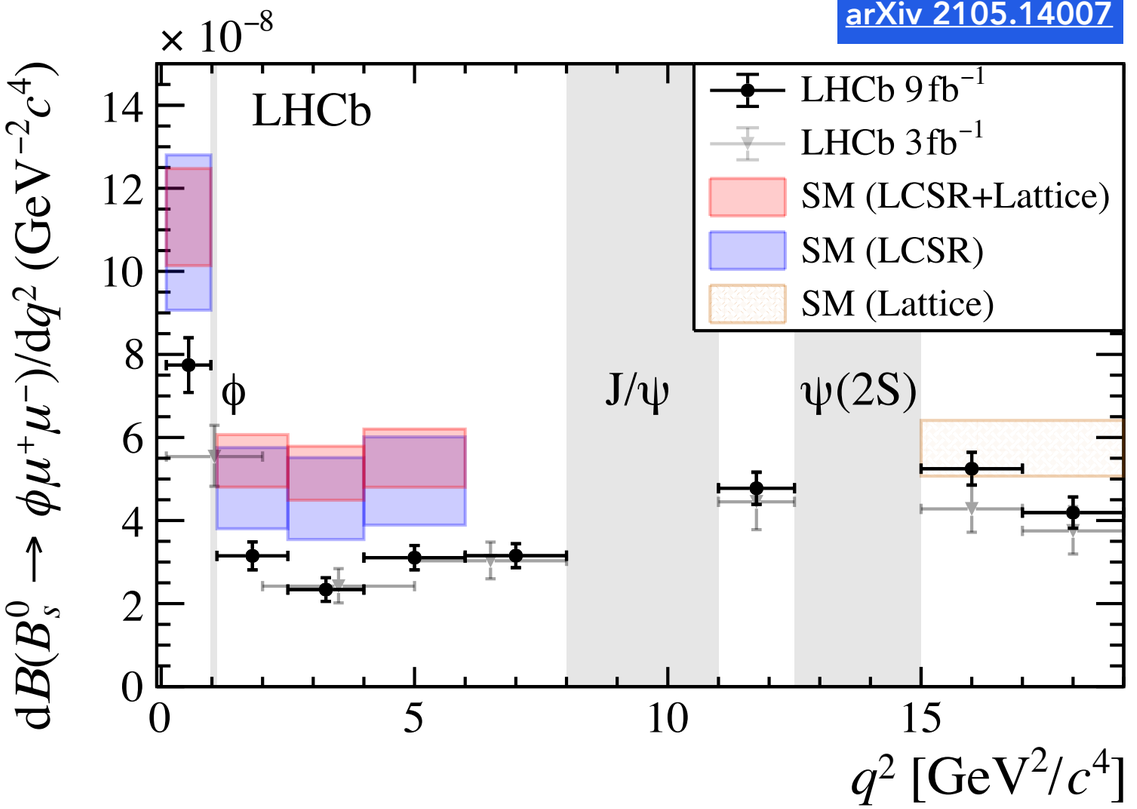
Results in very nice agreement with the picture observed in the neutral K* meson analyses

$\varphi\mu\mu$ angular analysis + branching fraction

arXiv 2107.13428



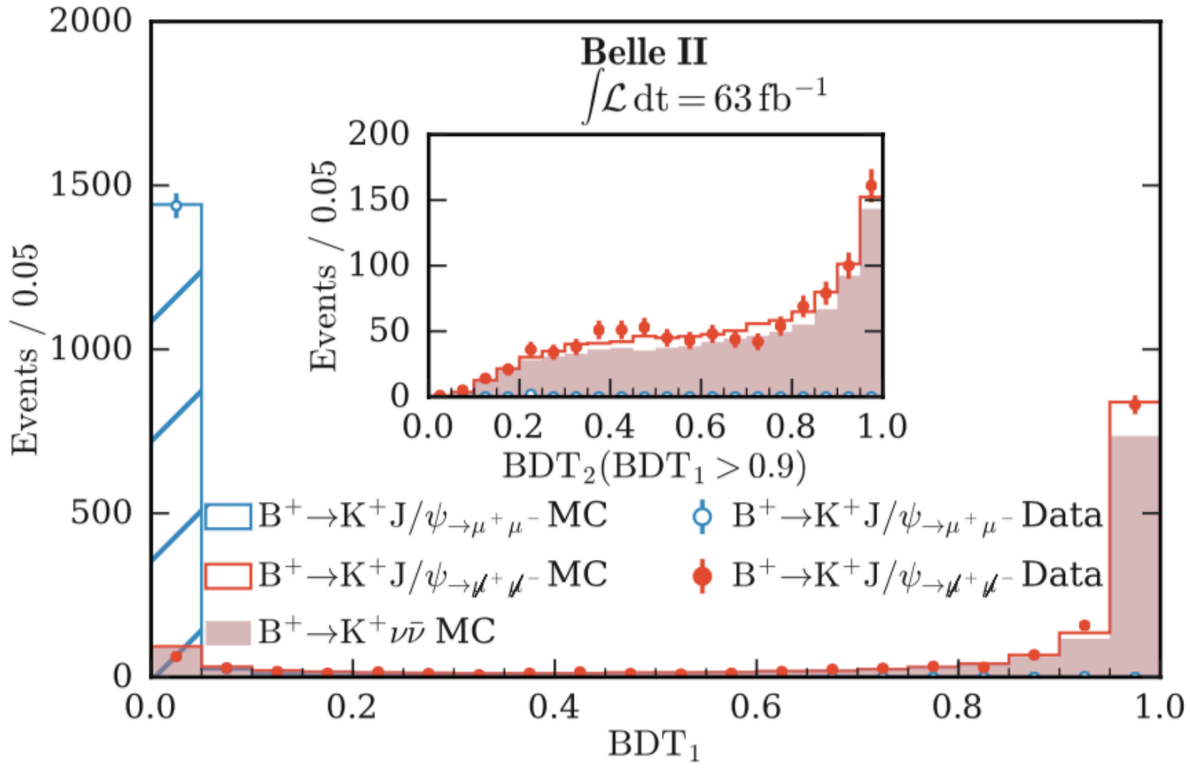
arXiv 2105.14007

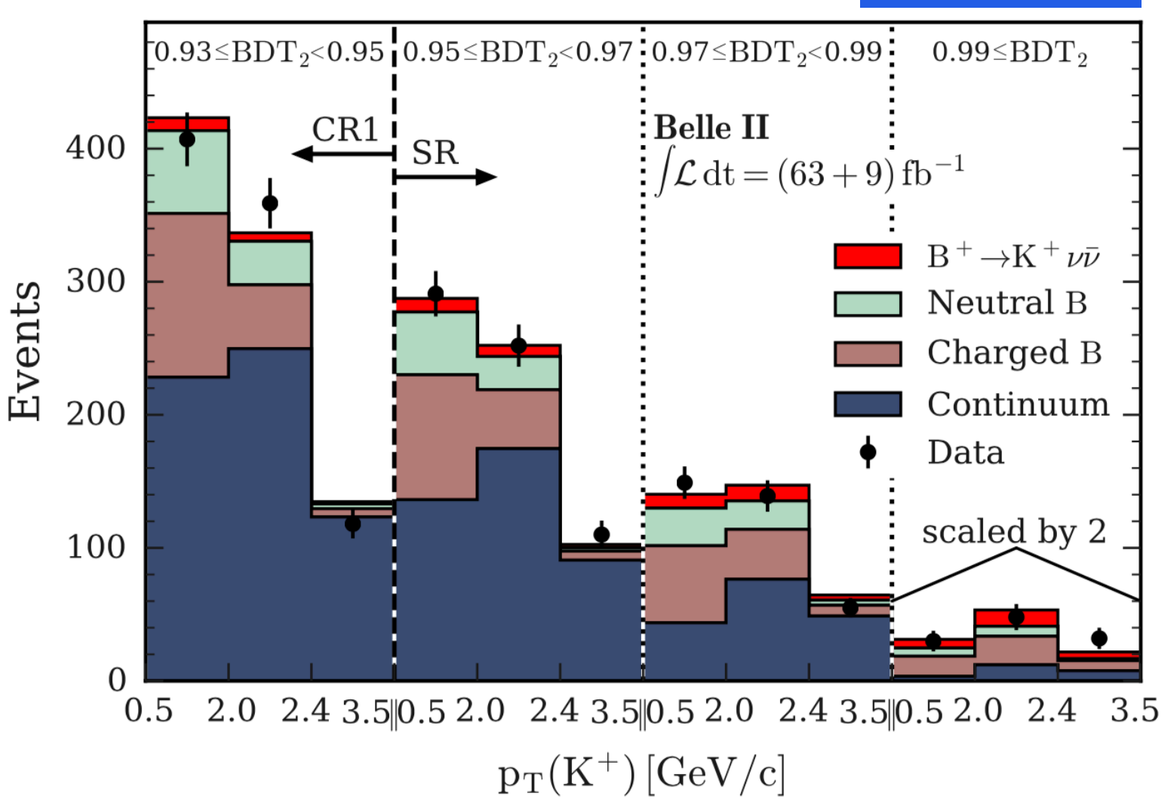


Pattern again consistent with other b→sll angular analyses. At this point fair to say that nobody really thinks these are a pure fluctuation — but more data is needed to determine what they are.

b→svv: first results from Belle 2

arxiv 2104.12624

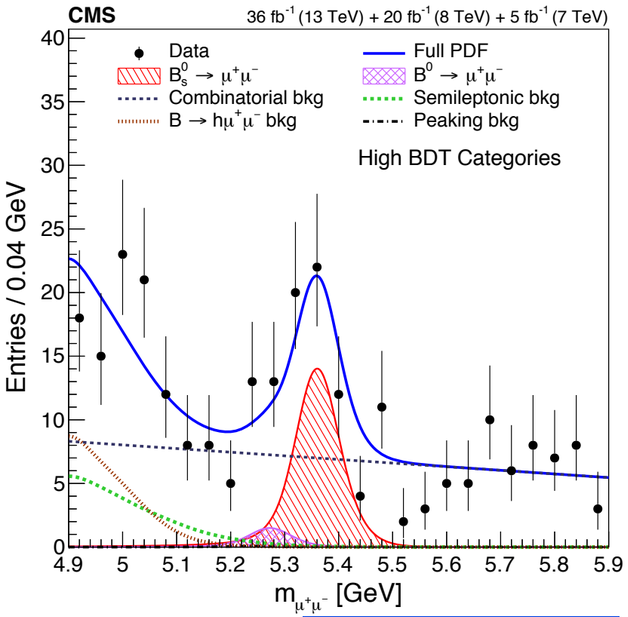




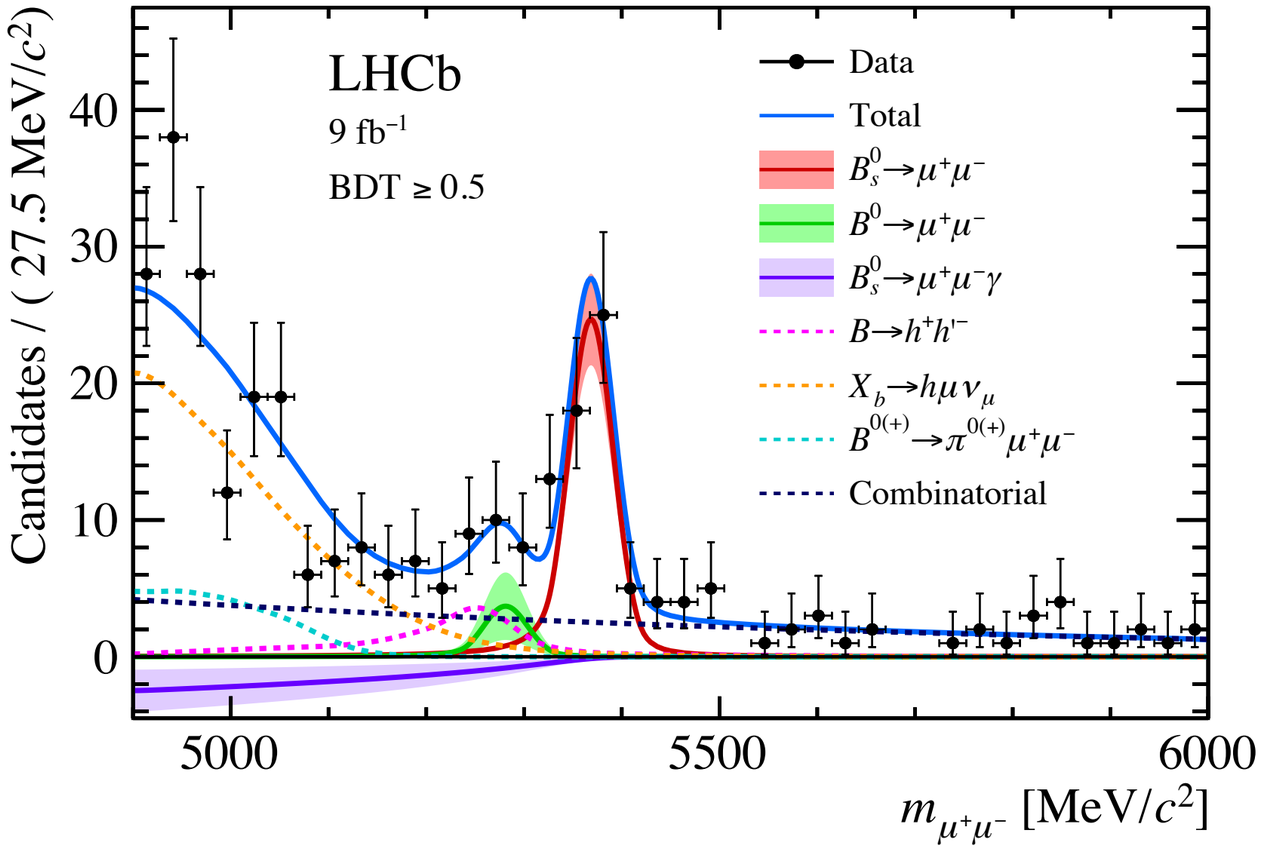
Competitive limits set with only 63 fb-1 of on-resonance data!

B→$\mu\mu$ legacy LHC measurements

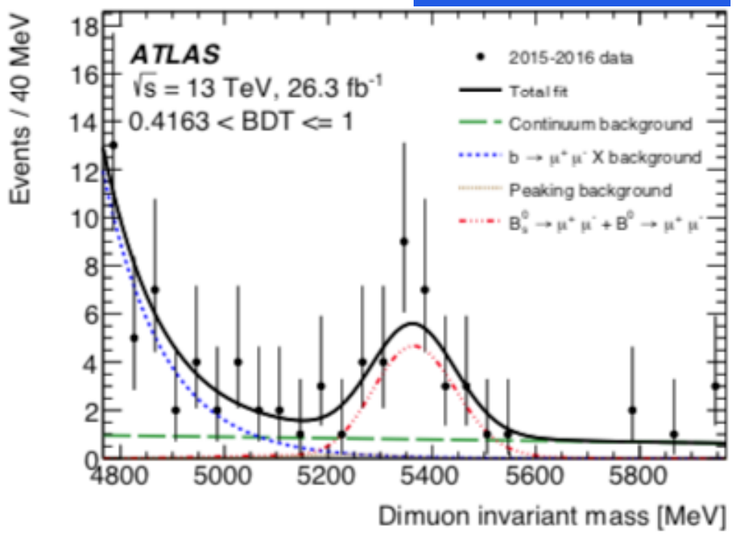
JHEP 04 (2020) 188



arXiv 2108.09284



JHEP 04 (2019) 098

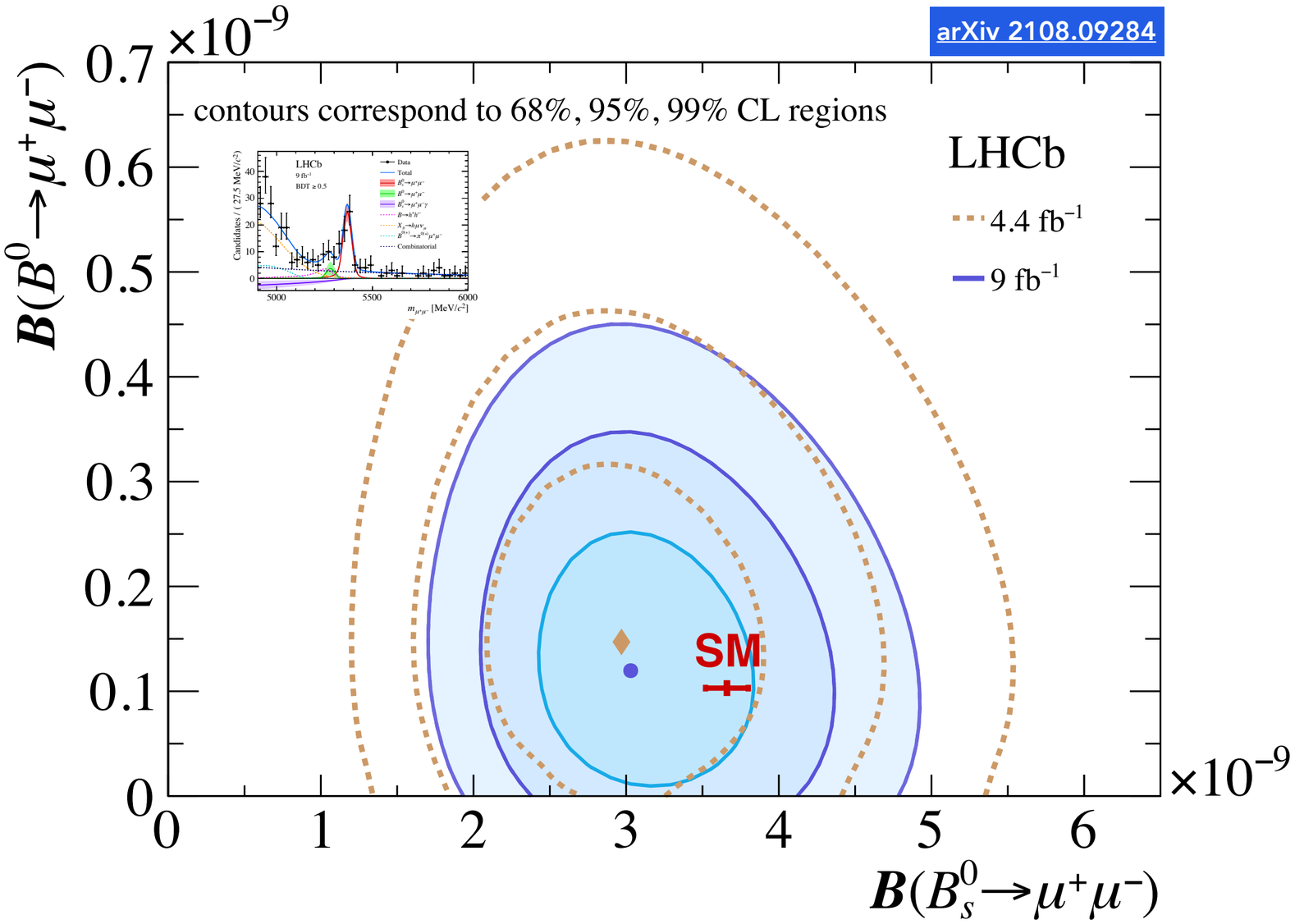


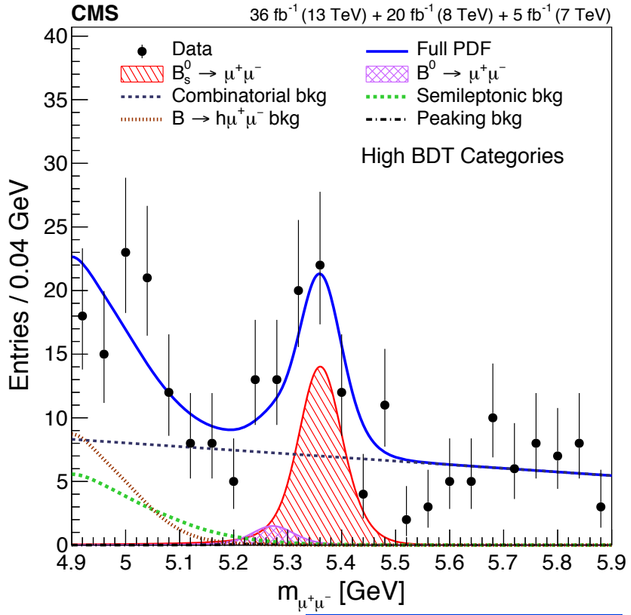
A beautiful (and SM-compatible) legacy of Runs 1 and 2

B→$\mu\mu$ legacy LHC measurements

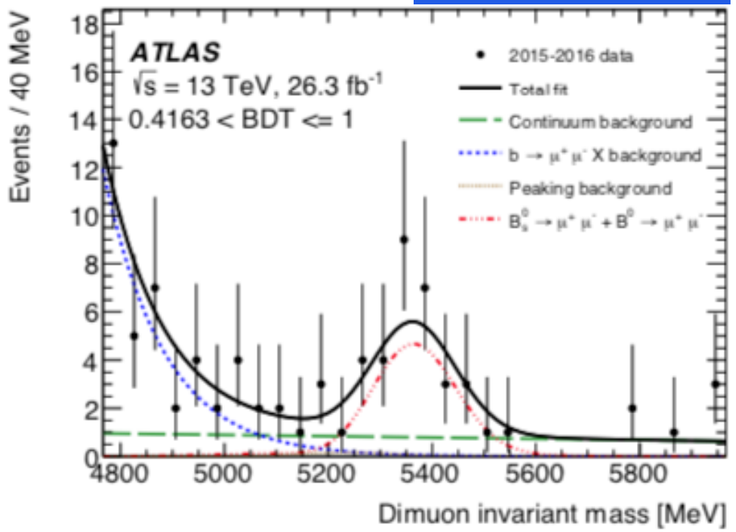
JHEP 04 (2020) 188

arXiv 2108.09284



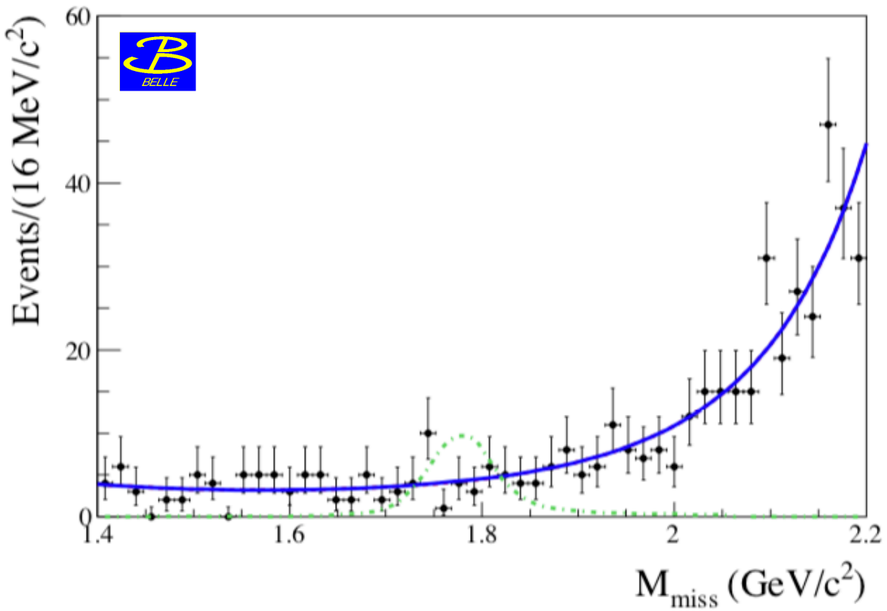


JHEP 04 (2019) 098



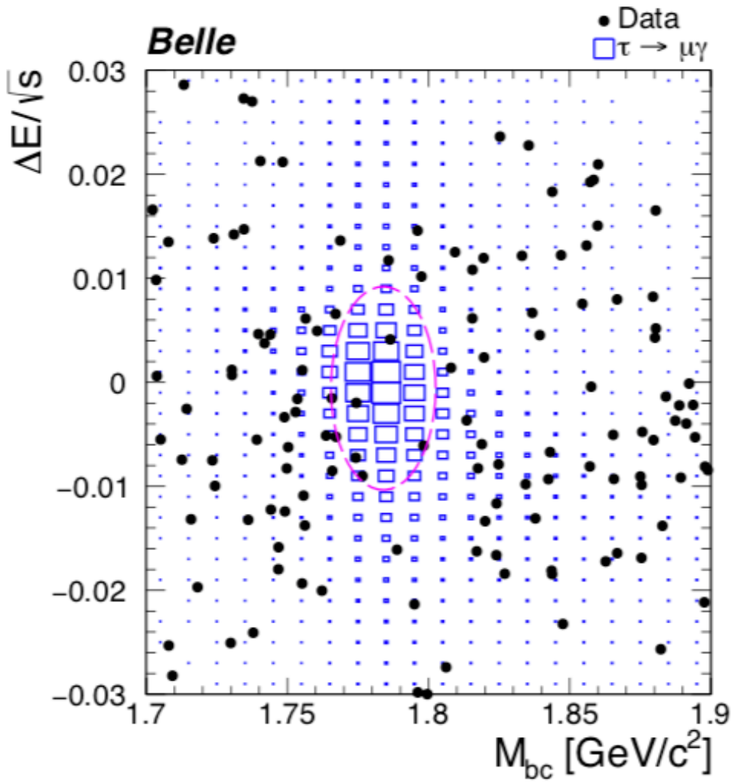
Coherent with the SM-compatible C_{10} Wilson coefficient seen in b→s$\mu\mu$ angular analyses

Searches for LFV



Mode	ε $(\times 10^{-4})$	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ $(\times 10^{-5})$
$B^0 \to \tau^\pm \mu^\mp$	11.0	$1.8\,^{+8.2}_{-7.6}$	12.4	1.5
$B^0 \to \tau^\pm e^\mp$	9.8	$0.3\,^{+8.8}_{-8.2}$	11.6	1.6

Belle Preprint 2021-23

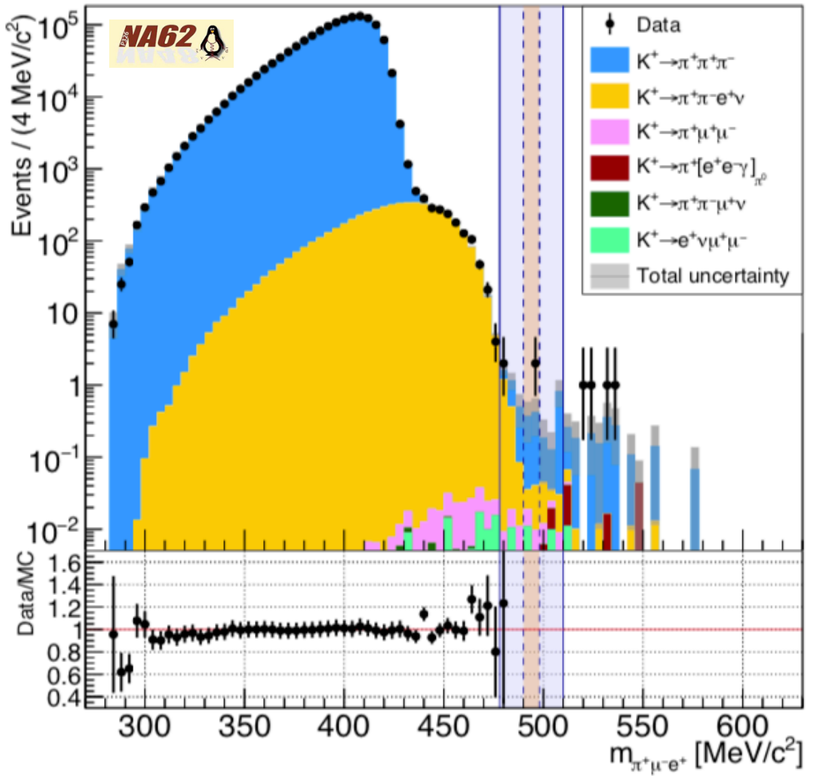


(a) $\tau^\pm \to \mu^\pm \gamma$

$$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 4.2 \times 10^{-8},$$

$$\mathcal{B}(\tau^\pm \to e^\pm \gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8},$$

Belle Preprint 2021-09



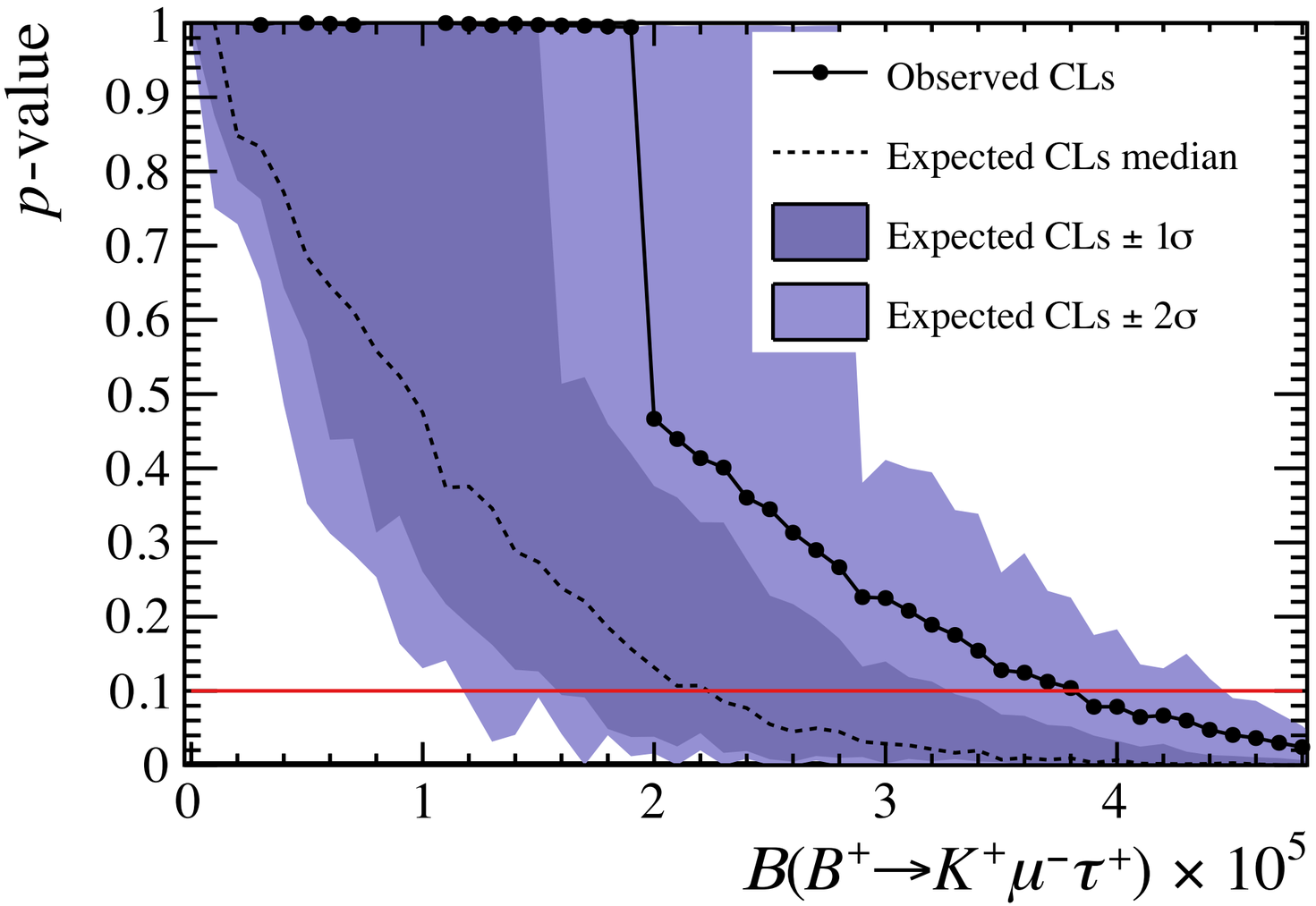
$$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11};$$
$$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11};$$
$$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}.$$

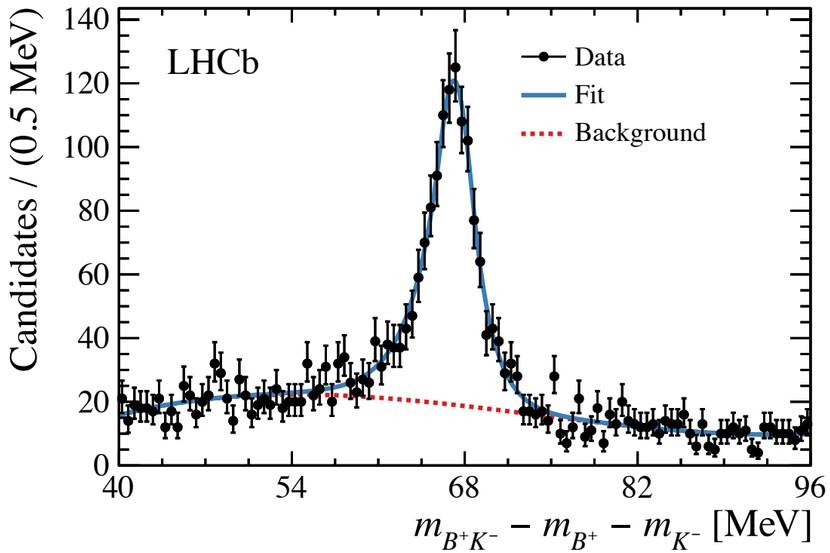
NA62 -- CERN-EP-2021-090

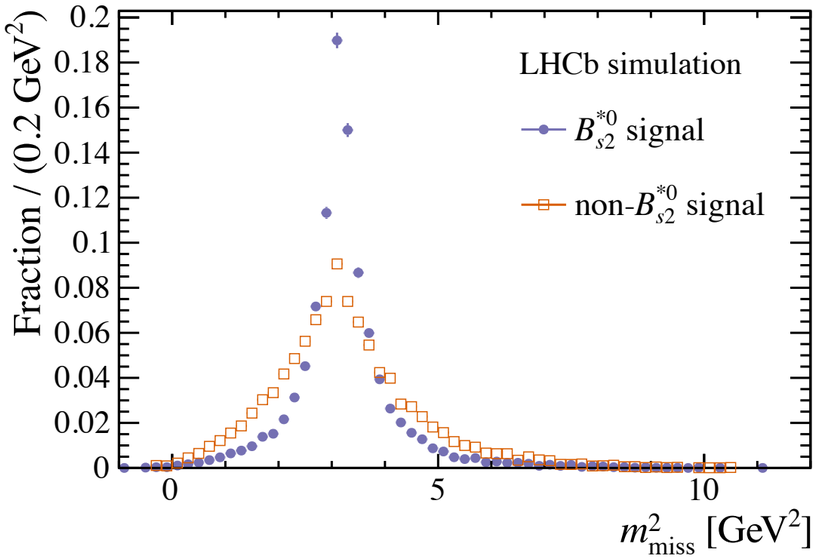
If we believe in evidence of LU should be natural to look for LFV! Many searches are ongoing

JHEP 06 (2020) 129

Searches for LFV in b→sτμ decays





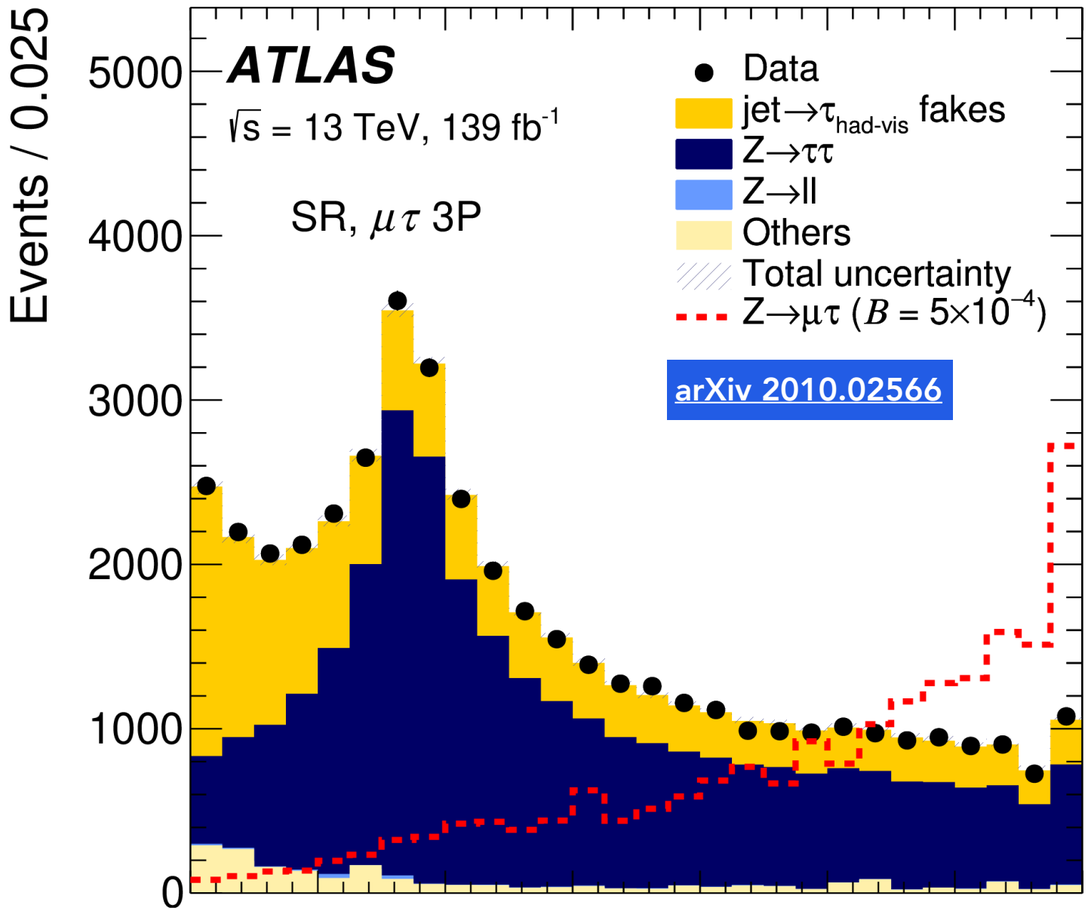


Despite presence of missing neutrinos, can reconstruct a relatively sharp peak using tagging decays

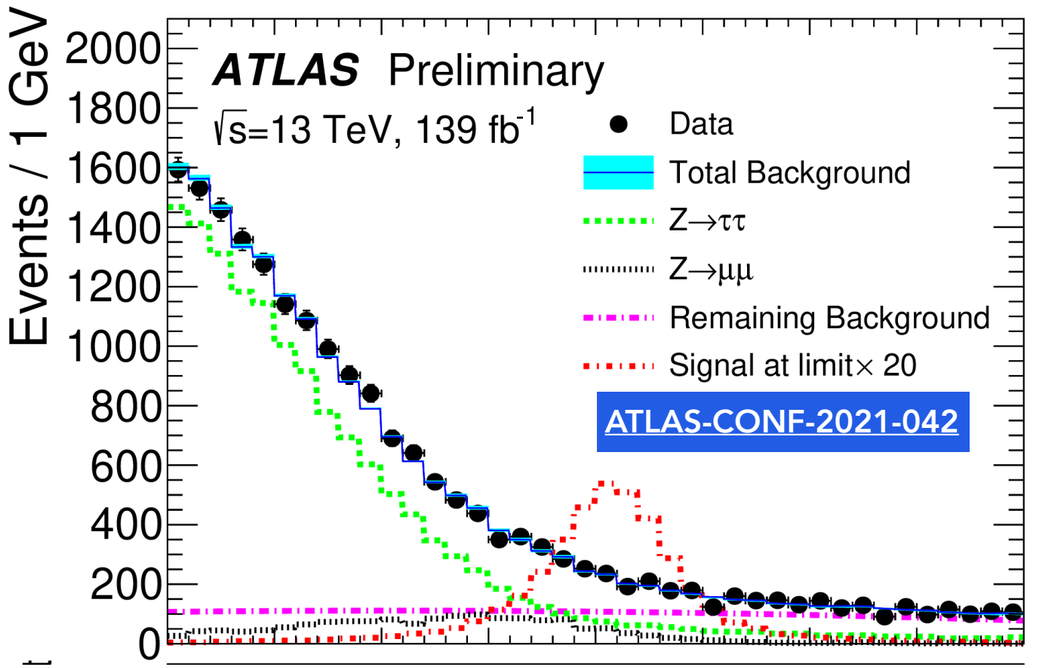
No signal seen and limits are set at $3.9 \cdot 10^{-5}$ @ 90% CL

Searches for LFV in Z decays

Nature Physics volume 17, pages 819–825 (2021)

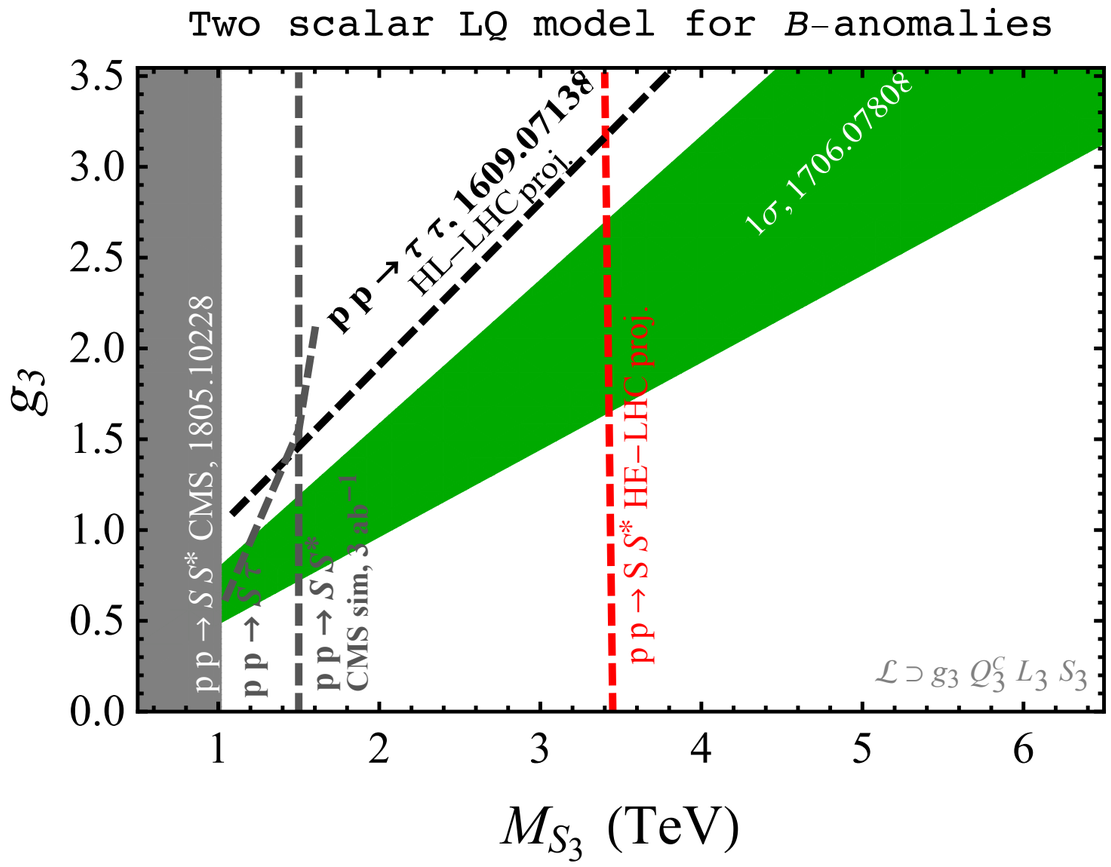


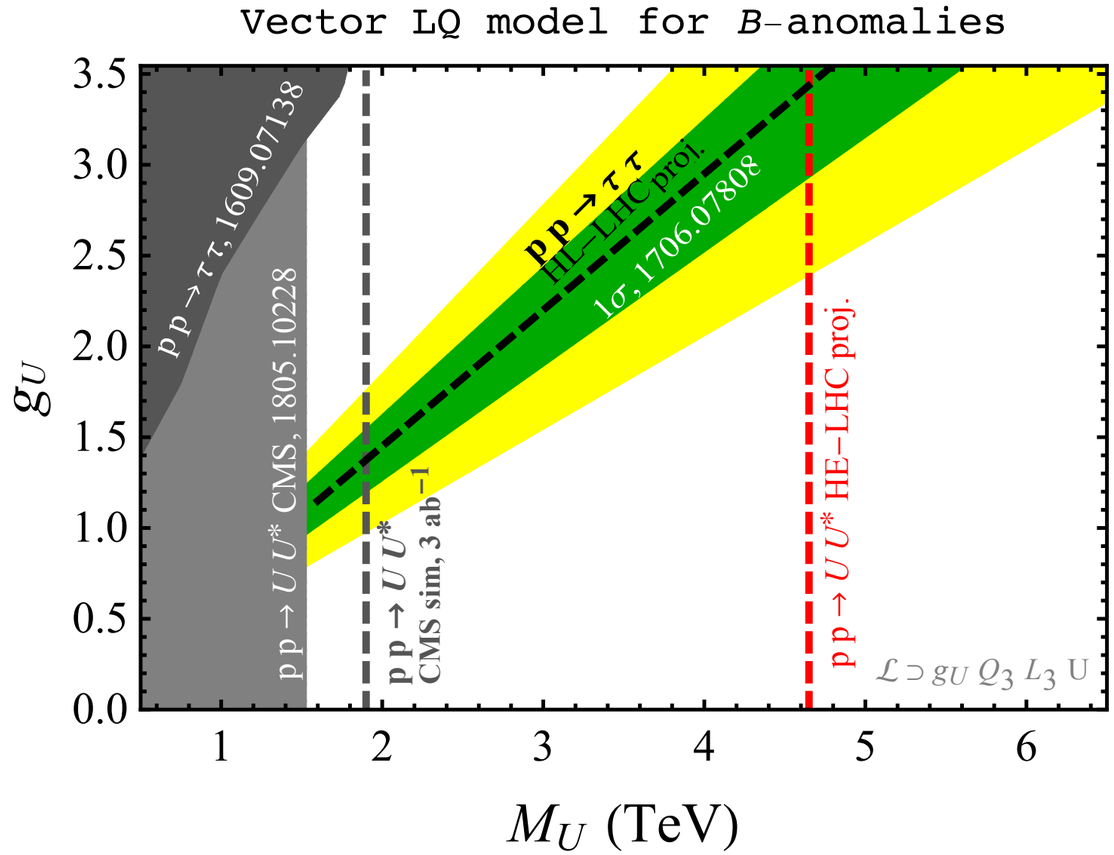
Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)



Most stringent limits on LFV decays of the Z boson

Connection to high-P_T searches

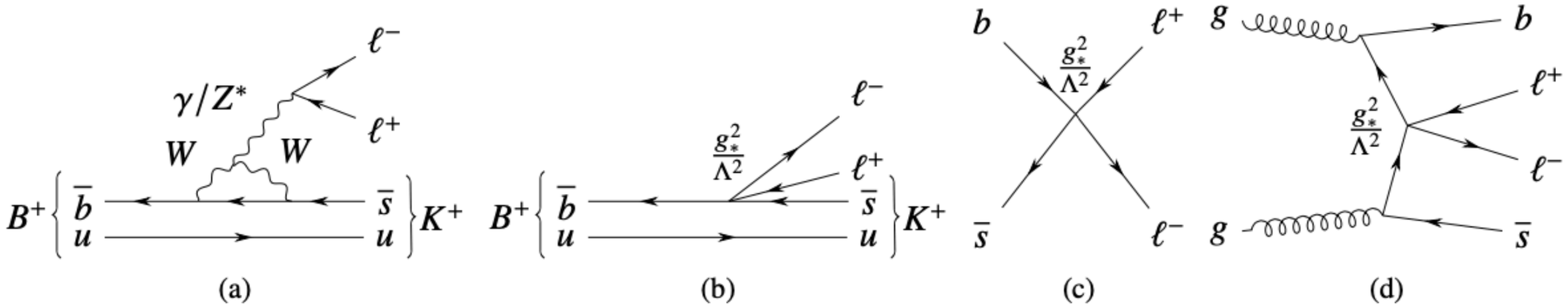


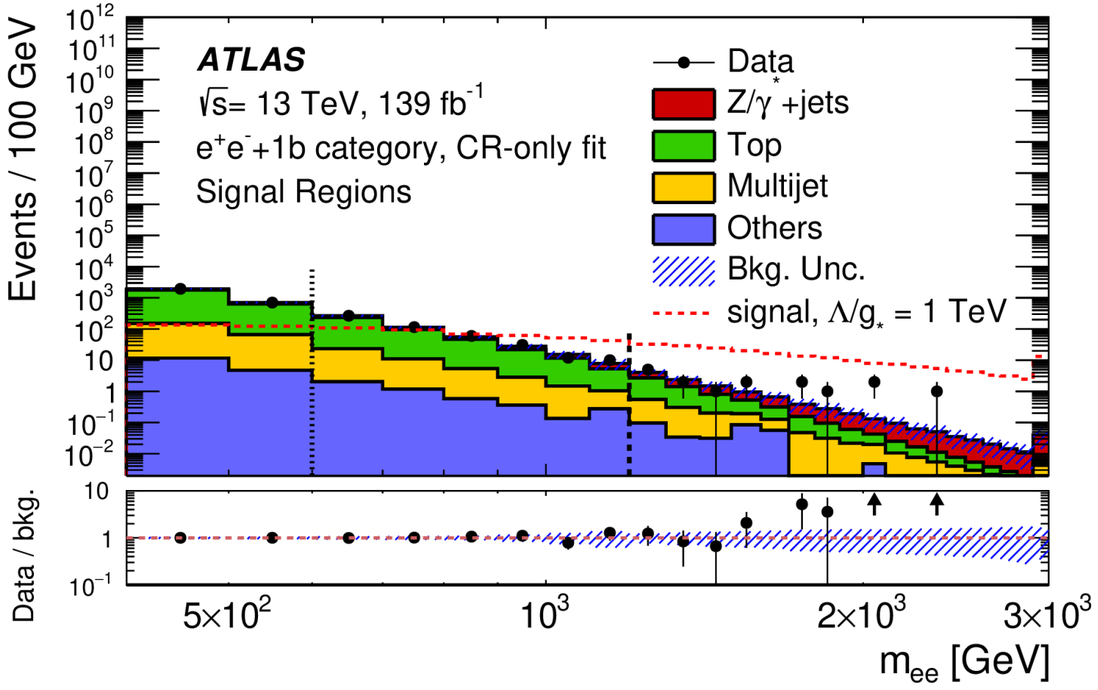


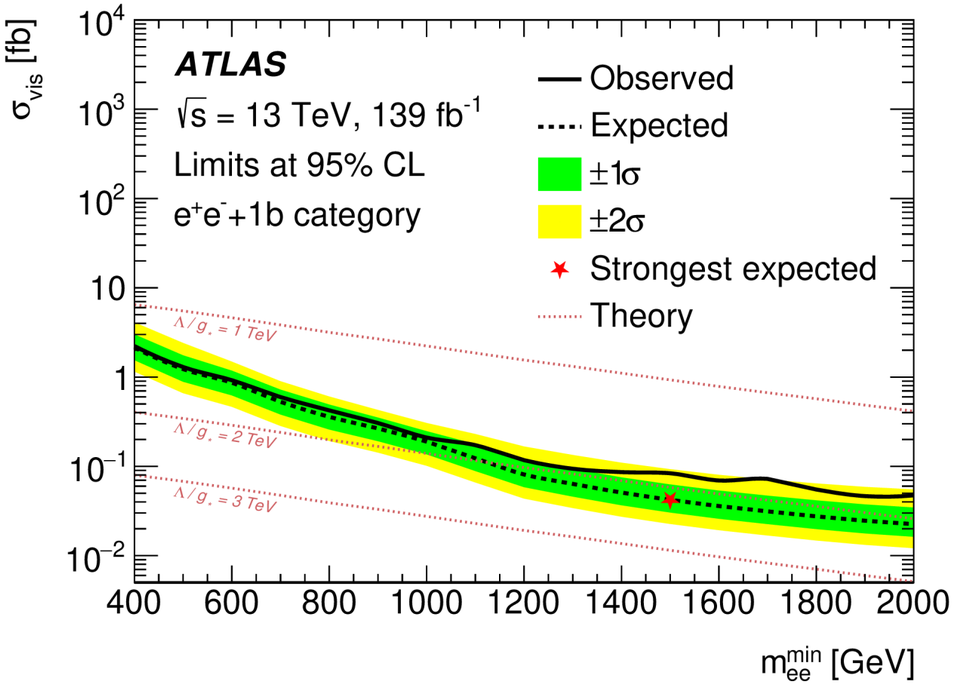
There is an immediate connection between the LU anomalies and direct searches at the LHC

Searches for bsll couplings at high mass

arXiv 2105.13847

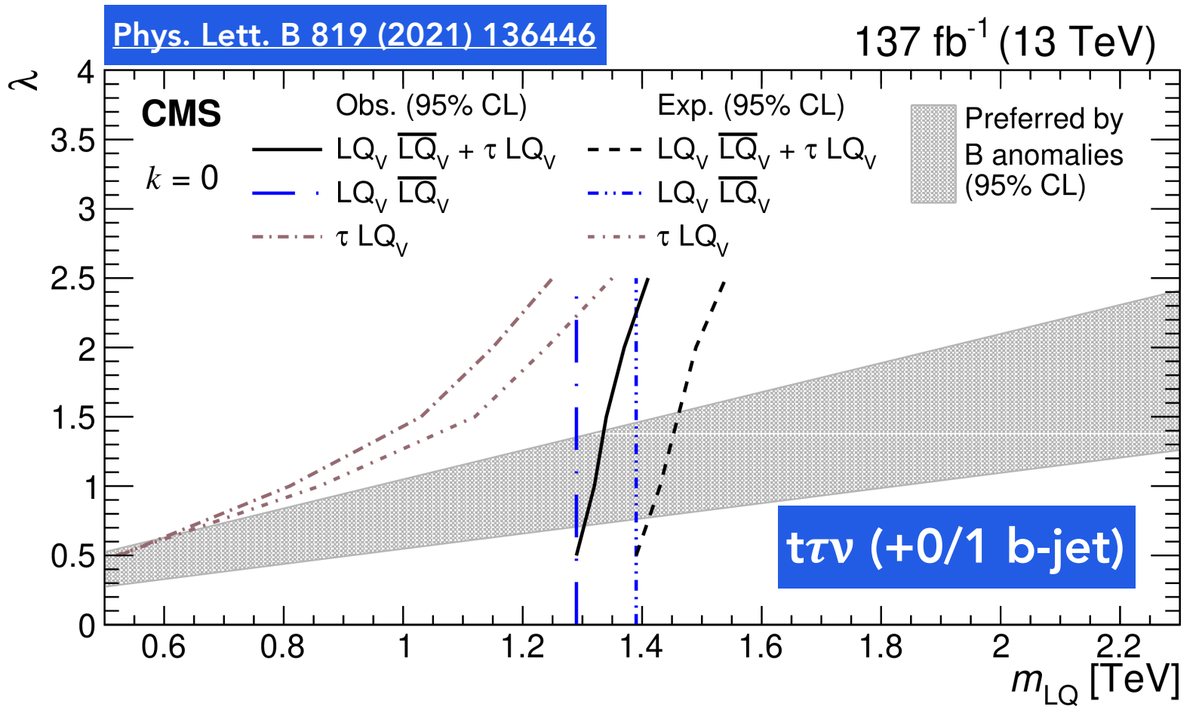


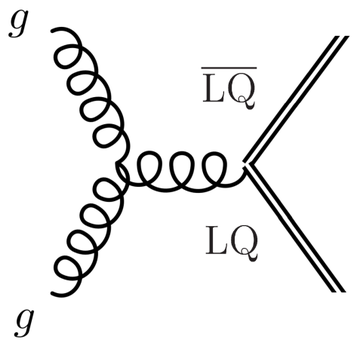


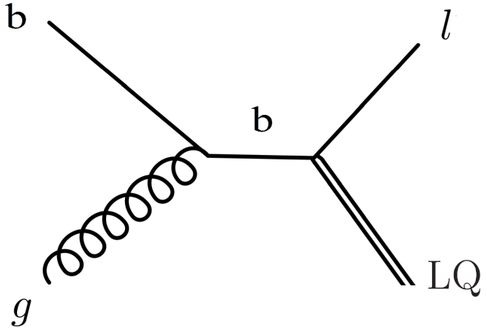


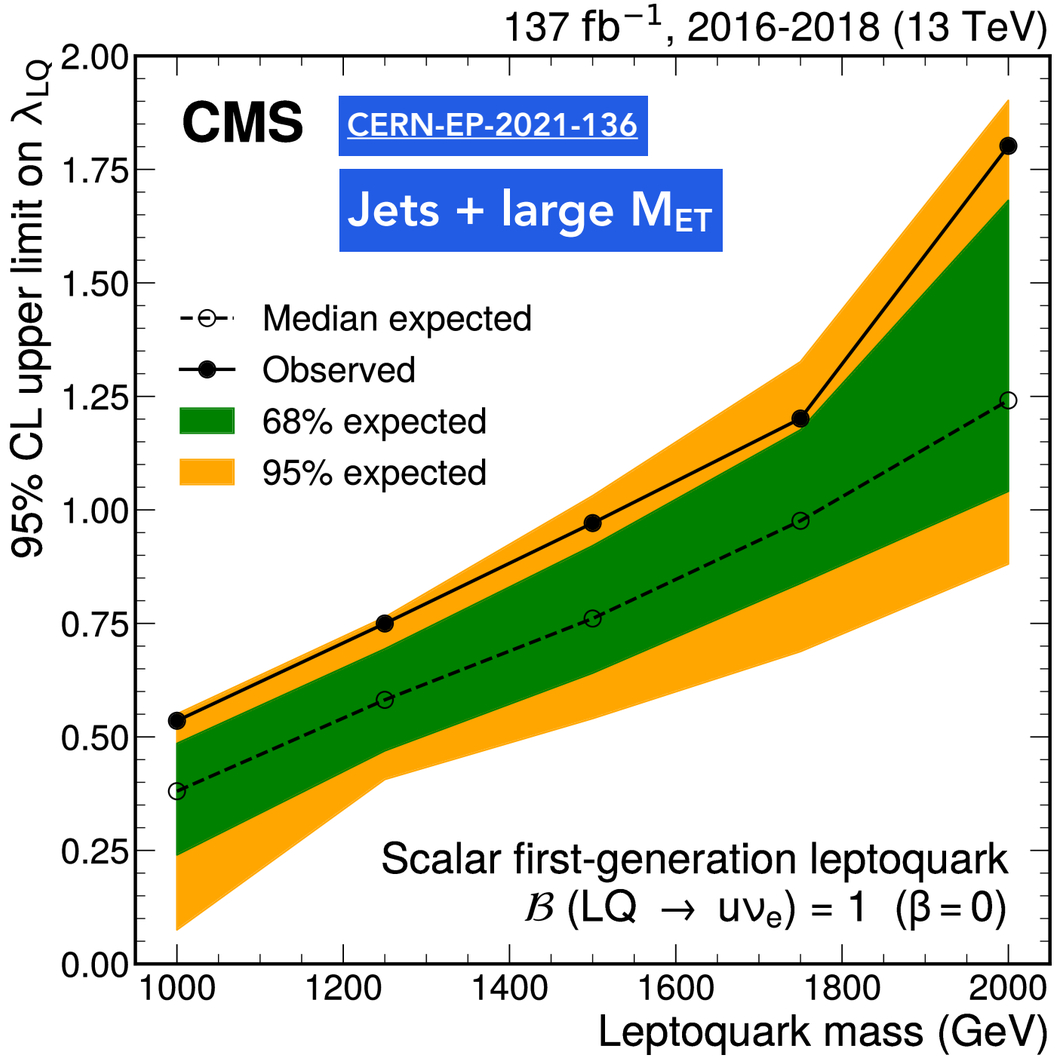
Searches carried out in ee and $\mu\mu$ (with 0/1 b jet) final states, no significant signal observed

Direct searches for leptoquarks



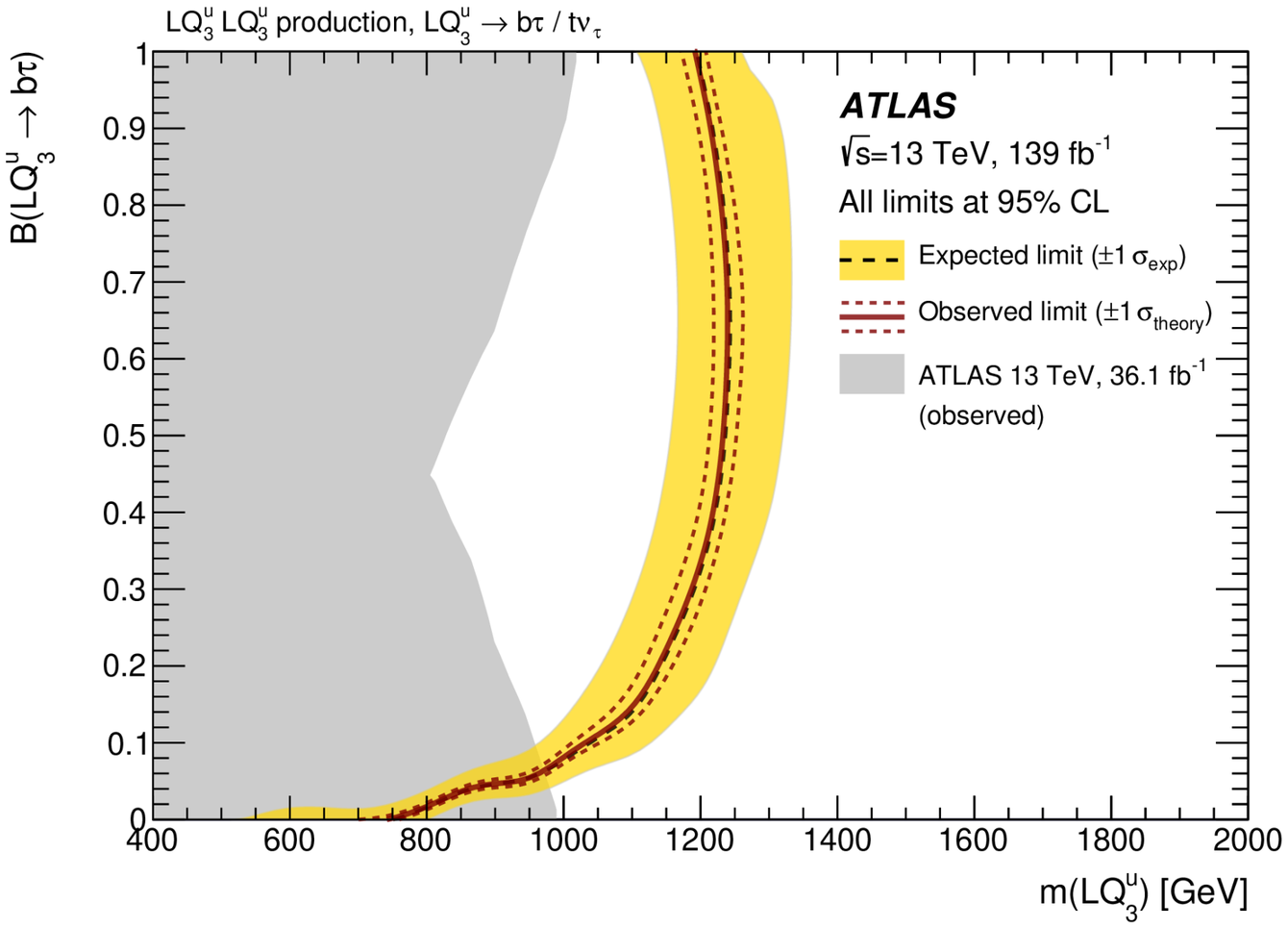


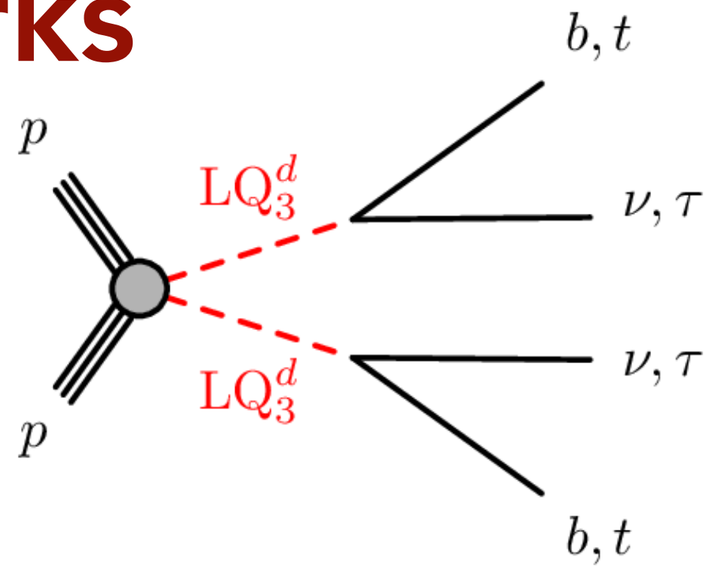


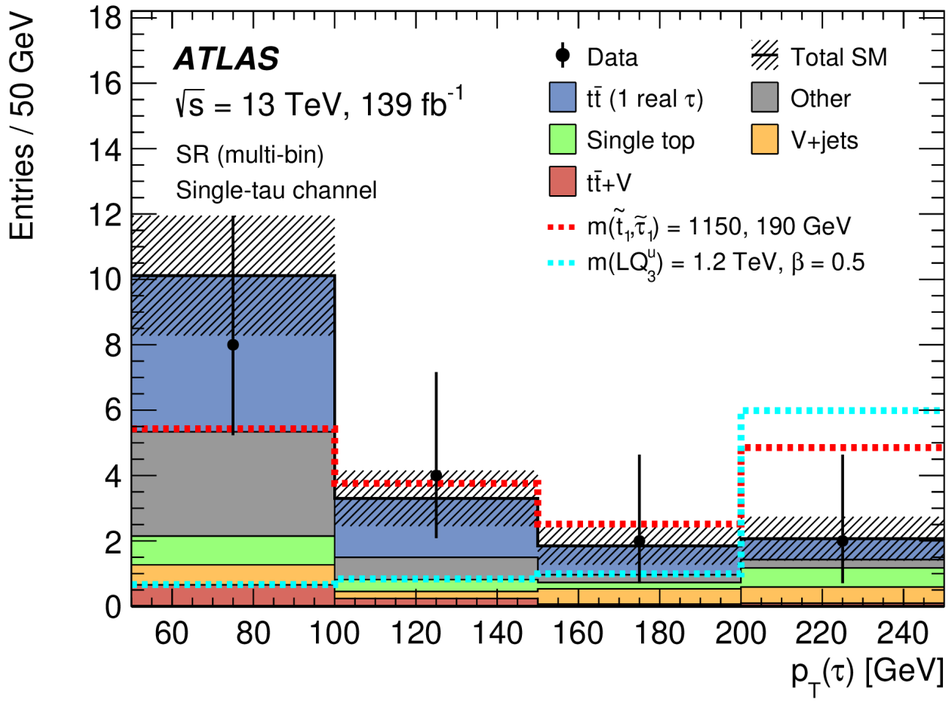


No signal observed so far, beginning to probe region of interest for the B anomalies

Direct searches for leptoquarks







Conclusions

Lepton flavour at colliders is a very hot topic at the moment

First on the agenda will be to resolve the situation in $b \to s\ell\ell$ decays, where further LHCb measurements can be expected even before Run 3 data becomes available

Hope for Belle 2 to make an impact in the coming years

Vital for us that CMS and ATLAS also enter this business in order to provide independent experimental validation of the picture

Angular LU analyses should get going in the next years and add further information

Similarly in $b \to c\ell\nu$ decays more measurements can be expected in the coming years. Again independent experimental validation of results will be crucial.

Any signals of LU breaking necessarily imply LFV and set a mass scale for direct searches.

Get ready for an exciting Run 3!

Backup