Flavour anomalies – an introduction

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noun

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1. something that deviates from what is standard, normal, or expected.
   "there are a number of anomalies in the present system"

Guy Wilkinson
University of Oxford

ECFA Plenary Meeting, CERN
22 July 2022

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$b \to sll$ transitions
- Branching fractions
- Angular observables
- μ-e lepton-universality violating observables

$b \to c l \nu$ transitions
- τ-μ/e lepton-universality violating observables

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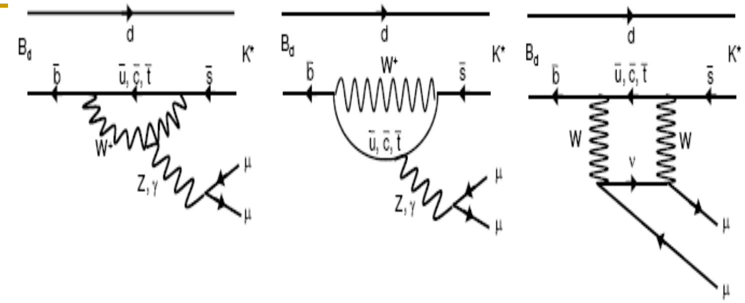
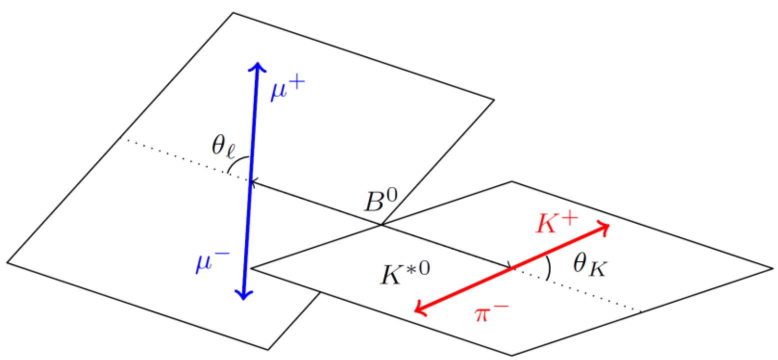
Searching for new physics in b⟶sll

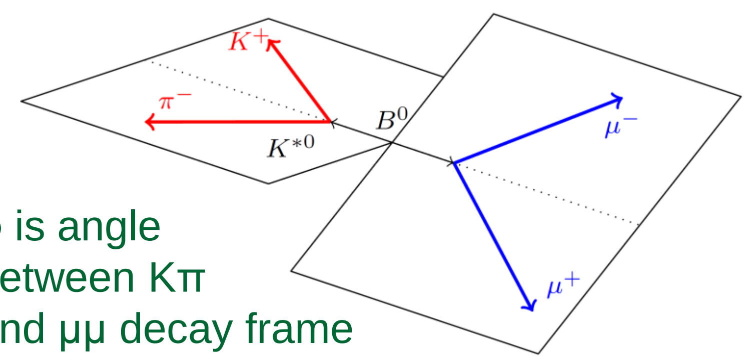


FCNC processes involving the transition $b \rightarrow s l^+ l^-$ (and indeed $b \rightarrow d l^+ l^-$) provide an exceedingly rich set of observables to probe for NP effects, that are sensitive to non-SM helicity structures (and more).

Many realisations, but the poster-child decay is $B^0 \rightarrow K^{*0} l^+ l^-$, with $K^{*0} \rightarrow K^+ \pi^-$.

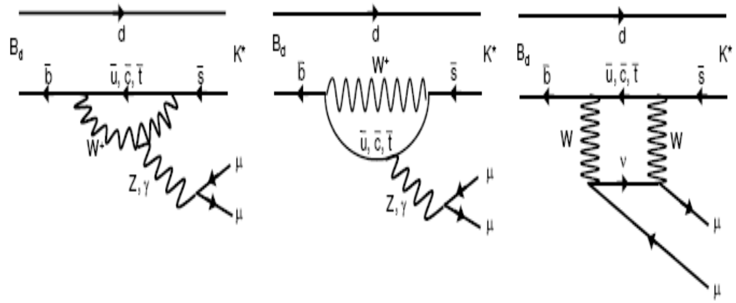


φ is angle between Kπ and μμ decay frame



Four-body final state can be characterised in terms of three angles, Θ_l, θ_K and φ, & q^2, & the invariant-mass of the dilepton pair (see *e.g.* [LHCb, JHEP 02 (2016) 104]).

Searching for new physics in b→sll



Differential cross-section w.r.t. solid angle and q^2 can be expressed in terms of eight coefficients: F_L, A_{FB} and S_i (other choices are available):

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

CP-averaged expression (*i.e.* assuming no CPV).

F_L – fraction of longitudinal polarisation of K*

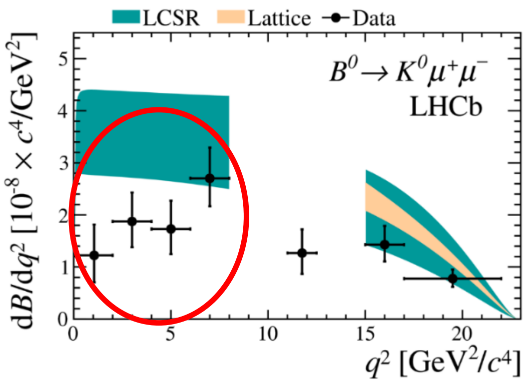
A_{FB} – forward-backward asymmetry of dilepton pair in B-meson frame

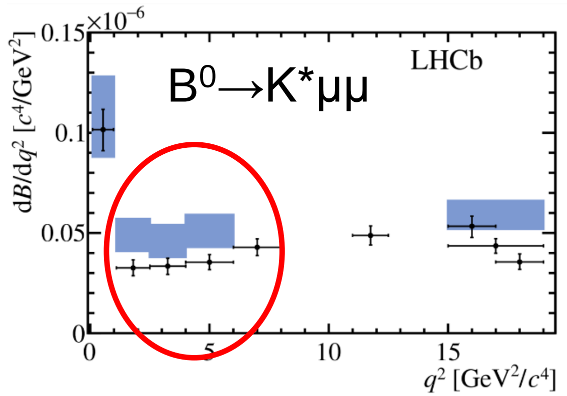
'Optimized observables' may be formed out of these coefficients that are more robust against QCD uncertainties (*e.g.* P_5') [Descotes-Genon *et al.*, JHEP 01 (2013) 048].

b→sll (& dll) exhibit A: differential BFs

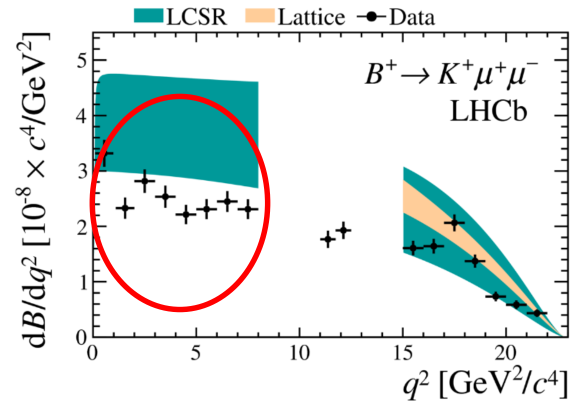
Systematic failure of theory to describe the differential branching fractions at low q^2.

JHEP 06 (2014) 133



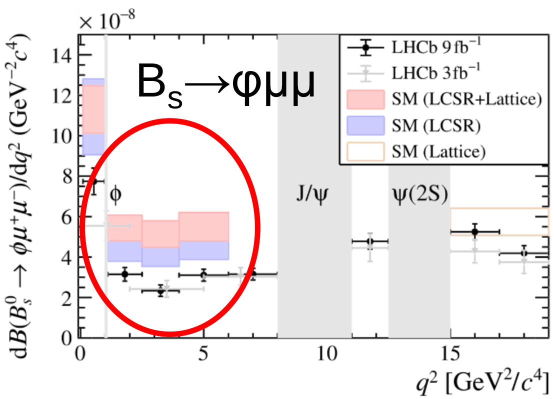


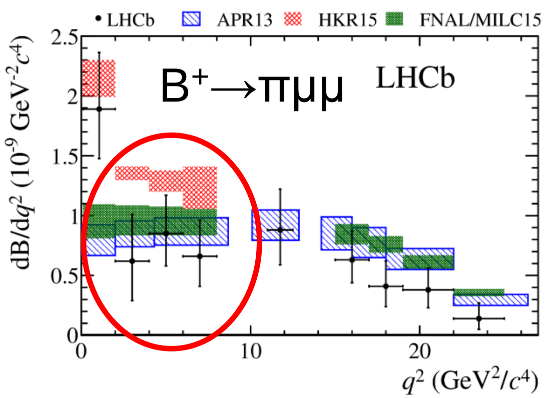
JHEP 04 (2017) 142



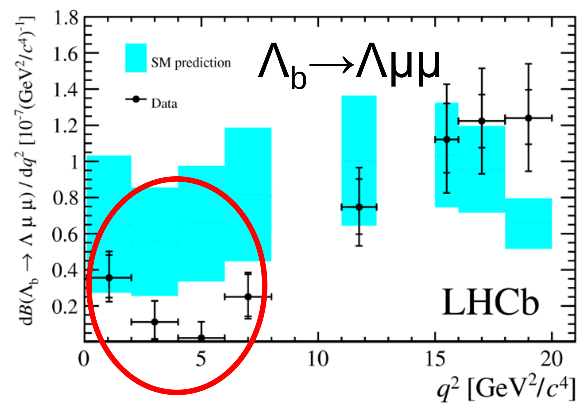
JHEP 06 (2014) 133

PRL 127 (2021) 151801





JHEP 10 (2015) 034



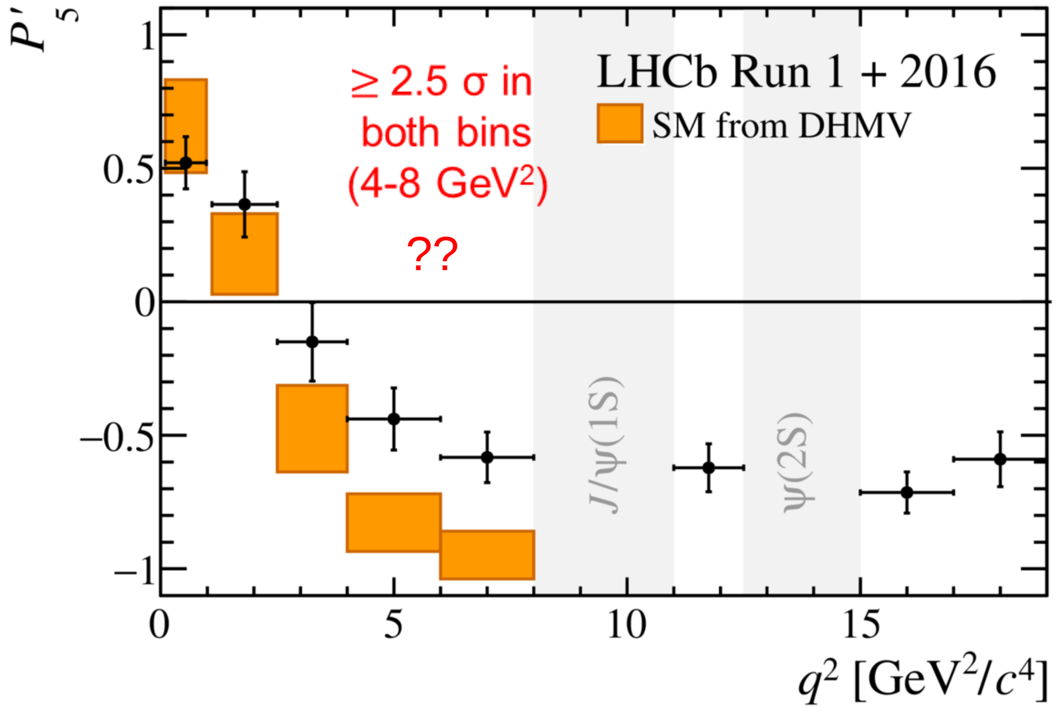
JHEP 06 (2015) 009

This is unquestionably a real effect. But maybe the theory uncertainties are underestimated. The differential BFs are not clean observables by any means.

Also, maybe relevant to note, these measurements were made with dimuons….

b→sll exhibit B: angular observables

Odd behaviour is also seen in the coefficients measured in the angular analysis, & the 'robust' optimised observables. The most discussed is the low q^2 anomaly in P_5' for $B^0 \to K^{*0}\mu\mu$ (again, dimuons) but effects found in other observables & channels.



[PRL 108 (2012) 181806]

The global picture from other experiments is not inconsistent with LHCb but more measurements, and full exploitation of LHCb data set is required.

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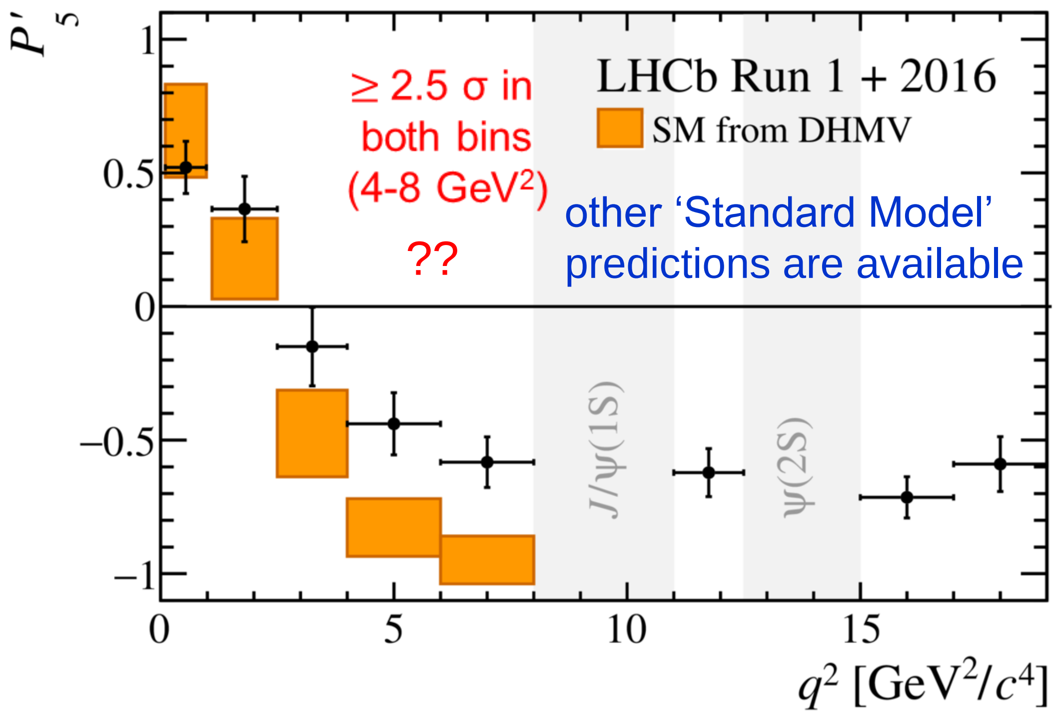


PRL 108 (2012) 181806

The global picture from other experiments is not inconsistent with LHCb but more measurements, and full exploitation of LHCb data set is required.

Much discussion about real size of theory uncertainties (*e.g.* charm loops).

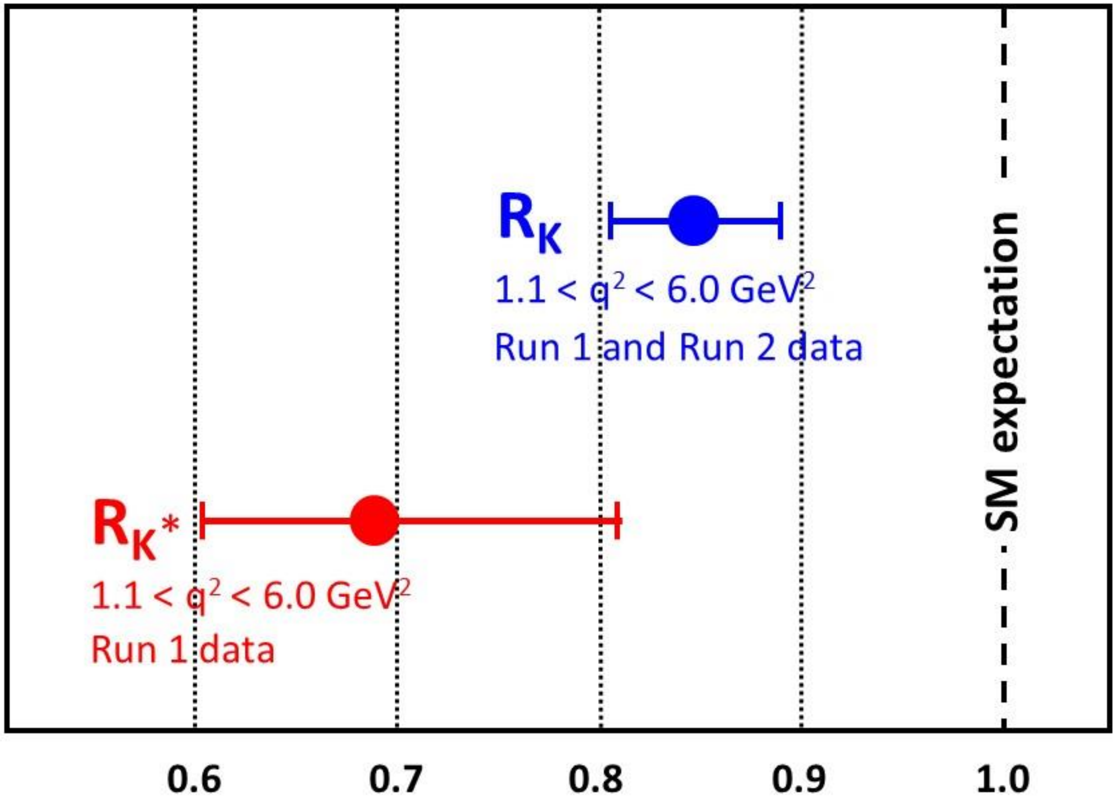
b→sll exhibit C: lepton-universality tests

Lepton-universality tests defined by R_K, which B→Kμμ / B→Kee ratio integrated over a range of q^2 at low values of q^2. R_{K^*} is an analogous quantity for B^0→K*ll.

These are the most important measurements from LHCb (others exist – next talk):

3.1 σ below SM

~2.5 σ below SM



[Nature Phys 18 (2022) 277]

[JHEP 08 (2017) 055]

General acceptance that these observables are theoretically pristine.

b→sll: the jury is out

There is a understandable desire to investigate whether all these oddities (and effects in other FCNC processes) have a common cause. This can be done with Wilson coefficients within Effective Field Theory - see later talks.

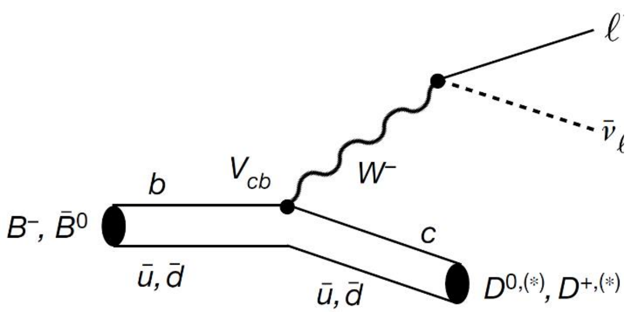
But let us continue to scrutinise each sub-anomaly on its own terms, paying careful attention to both the experimental and theoretical challenges,

experimental challenges ↓		theoretical challenges ↑
	Branching-fraction measurements	
	Observables from angular analysis	
	Lepton-universality tests	

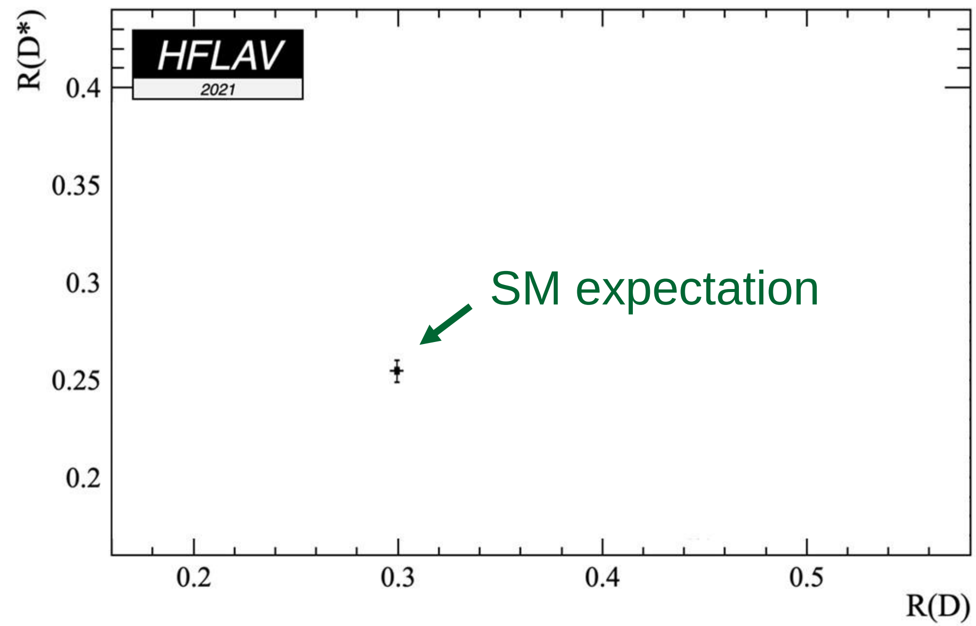
and let us see what further studies and analysis brings.

Searching for new physics in $b\rightarrow cl\upsilon$

The tree-level decay $\bar{B} \to D^{(*)} l^- \overline{\nu_l}$ is neither a FCNC nor rare. But measurement of the rate of decays with $l = \tau$ to $l = e, \mu$ is sensitive to New Physics which might couple differently to the τ, *e.g.* charged Higgs, a W' or a leptoquark.



$$R\left(D^{(*)}\right) = \frac{BF(\bar{B} \to D^{(*)}\tau^- \upsilon_\tau)}{BF(\bar{B} \to D^{(*)}\mu^- \upsilon_\mu)}$$



In SM $R(D) \approx 0.3, R(D^*) \approx 0.25$ (not unity because of phase-space effects).

Searching for new physics in b→clυ

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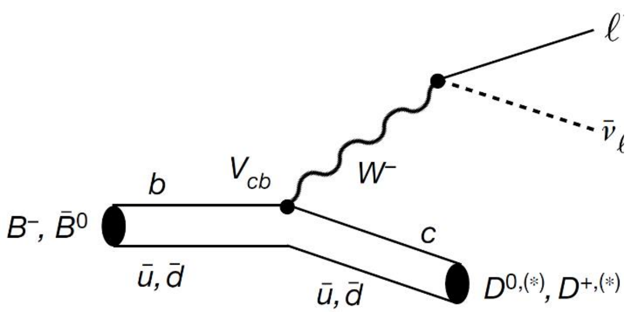

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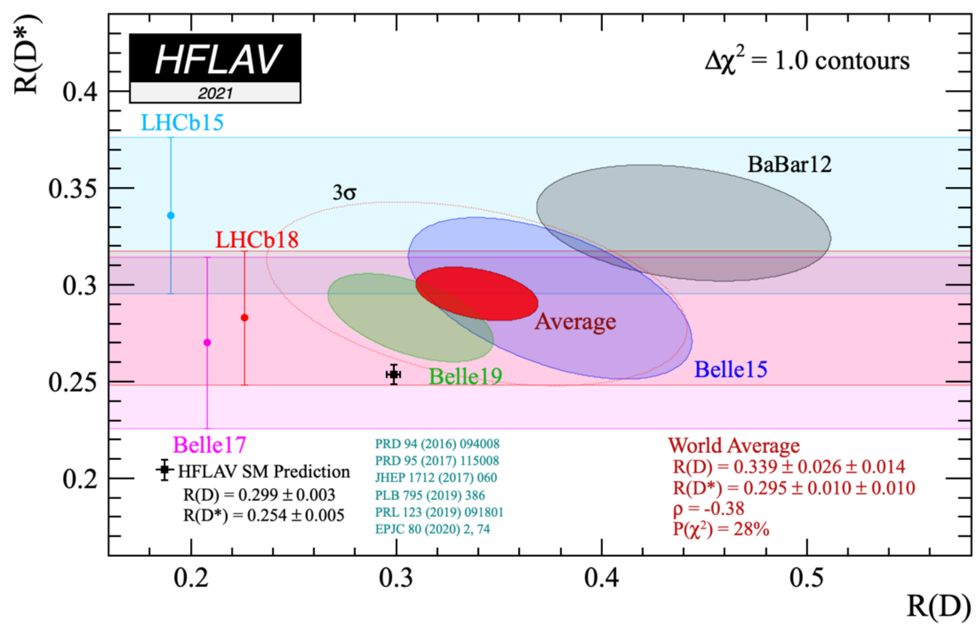
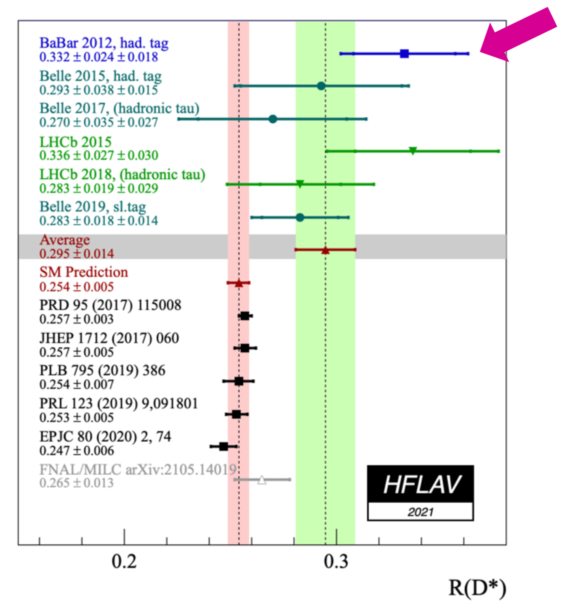


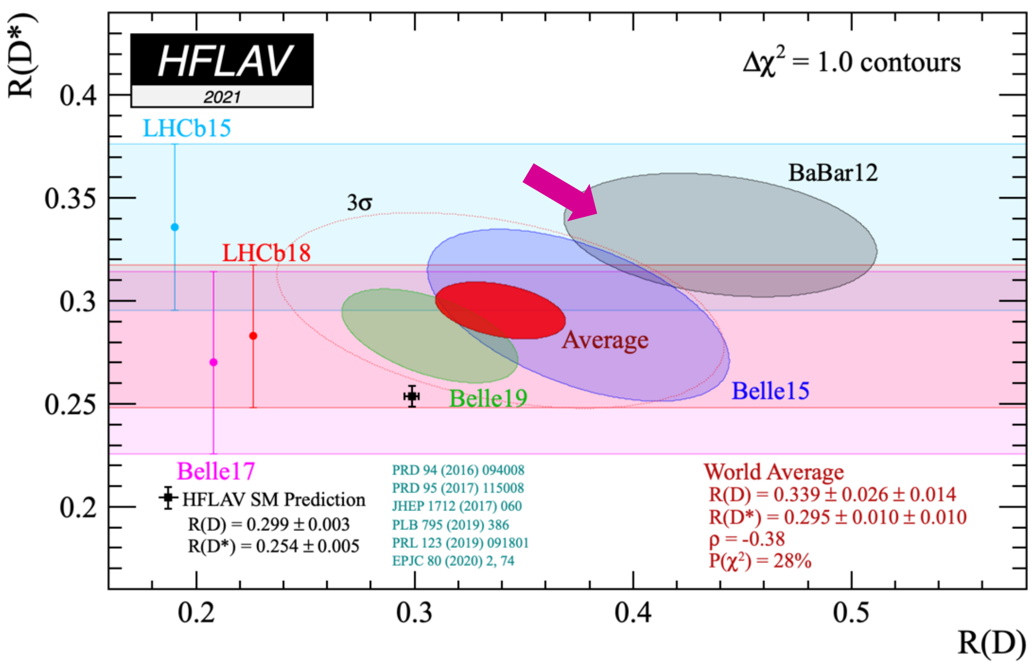
[HFLAV combination]

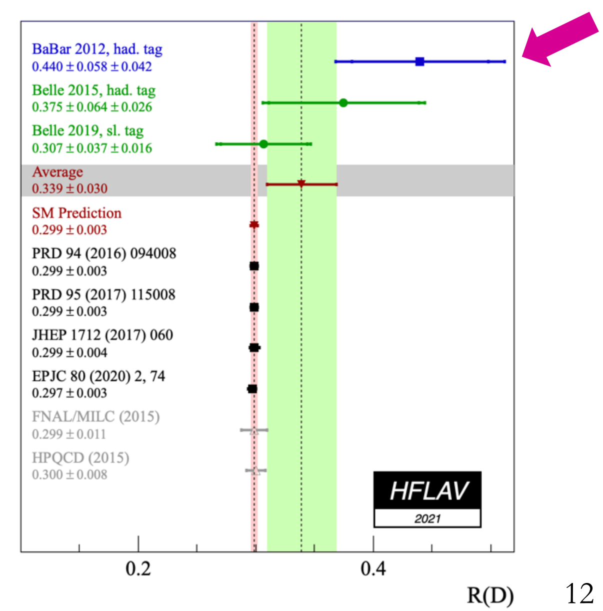
In SM $R(D) \approx 0.3, R(D^*) \approx 0.25$ (not unity because of phase-space effects). But current ensemble of measurements exhibits ~3 sigma tension with this expectation. In absolute terms the effect is very large for a tree-level decay !

Remarks on the R(D), R(D*) measurements

All measurements are high, but only one, the BaBar ‘hadronic tag’ [PRL 109 (2012) 101802] is individually anomalous.







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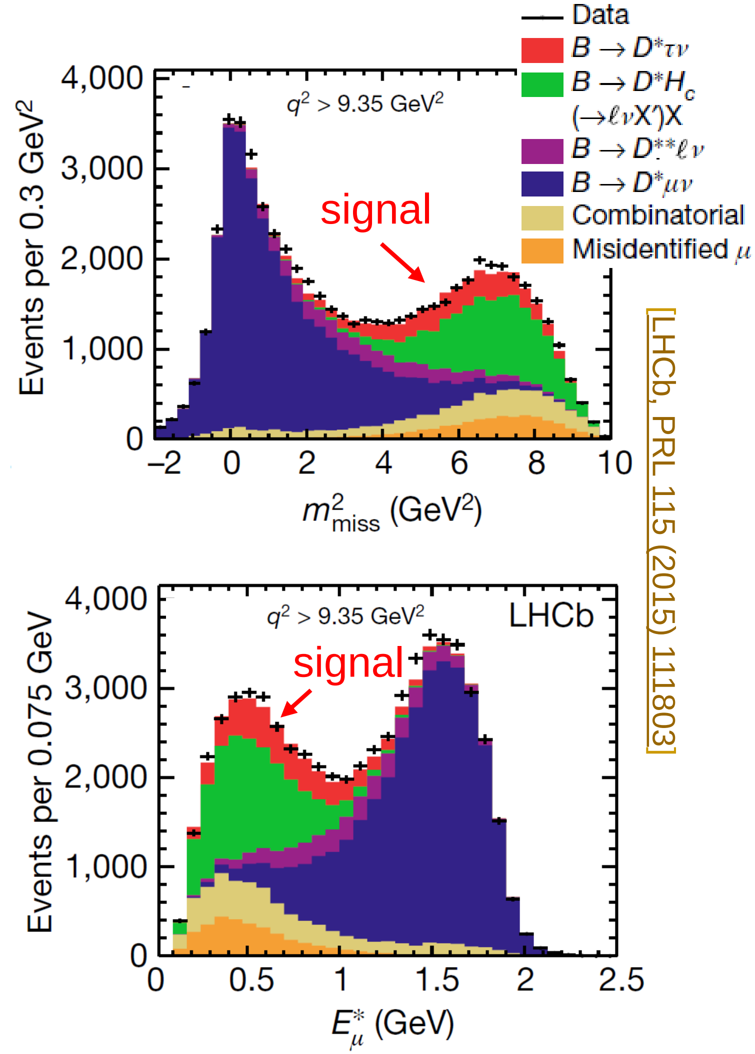
B factories control backgrounds by reconstructing other B in the event, by either hadronic or semileptonic tag.
Life is *much* harder at the LHC…

…indeed, many were amazed to see this measurement even being attempted.



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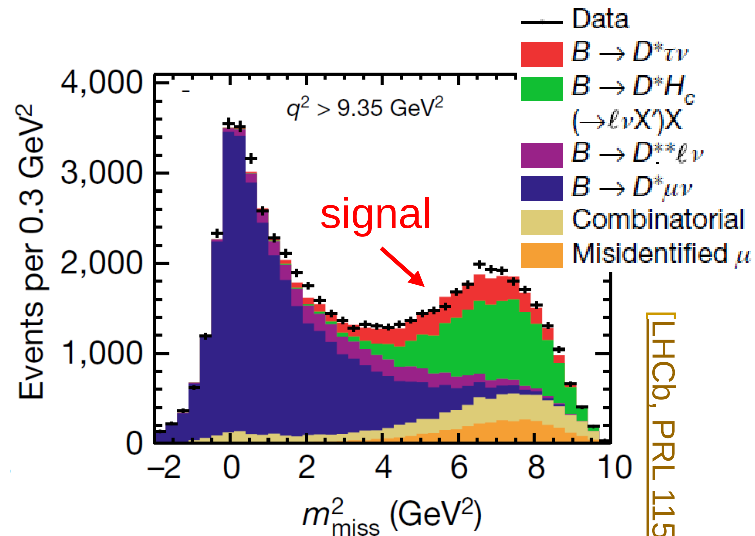
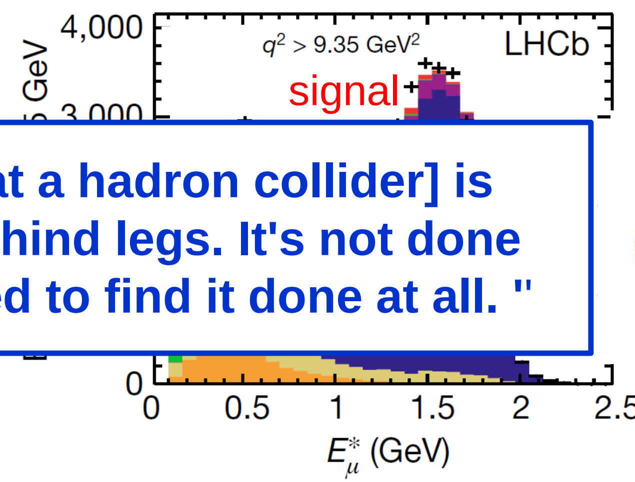


[LHCb, PRL 115 (2015) 11…



[Samuel Johnson, 1709-1784]

"Sir, a [B→D*τυ analysis at a hadron collider] is like a dog walking on his hind legs. It's not done well; but you are surprised to find it done at all. "

However it *is* done well ! It’s just hard, & takes time (so far only Run 1 R(D*) results).

Remarks on the R(D), R(D*) measurements

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Nonetheless, hadron colliders do open up new systems, in which tests can be made, such as $\Lambda_b \rightarrow \Lambda_c l\upsilon$ [LHCb, PRL 128 (2022) 191803] and $B_c \rightarrow J/\psi l\upsilon$ [LHCb, PRL 120 (2018) 121801].

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\,\mu^+\nu_\mu)}$$

$$= 0.71 \pm 0.17\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})$$

c.f. SM ~ 0.25 – 0.28

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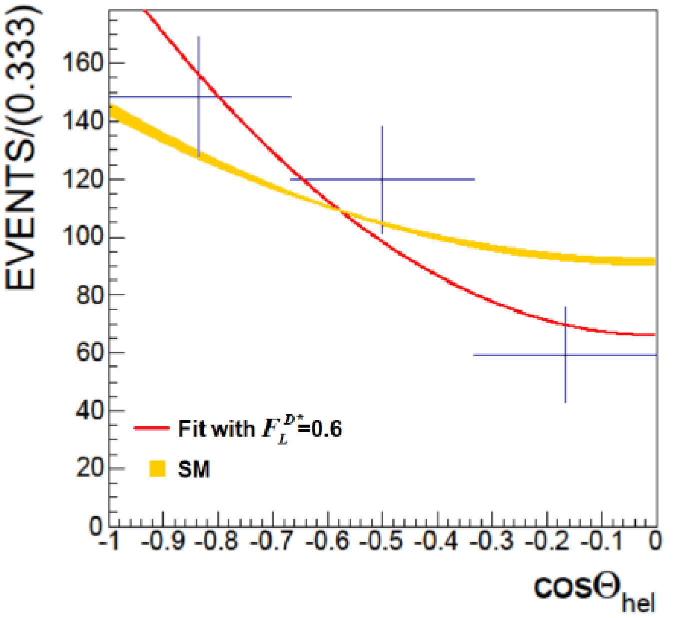
Many new measurements can still be performed on existing data sets.
Not only R(D) and R(D*), but those exploiting angular information in decay.

e.g. Belle measurement of D* longitudinal polarization fraction [arXiv:1903.03102].



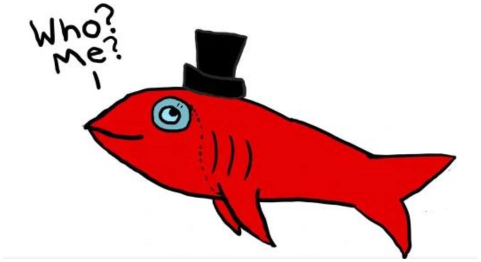
Also see JHEP 11 (2019) 133 for full angular analysis proposal.

Final words

The 'flavour anomalies' constitute a stimulating set of puzzles. Whatever their ultimate fate, confronting these questions is good for experimentalists & theorists.

'anomalies' – note the plural! It is tempting to view them as an interconnected whole, but there may be nothing linking the $b \to c l \upsilon$ and $b \to s l l$ puzzles despite the common theme of lepton-universality violation. And within $b \to s l l$ there are puzzles concerning BFs & angular observables, as well as lepton-universality violation.

- Each anomaly/puzzle should be scrutinised carefully, both in its experimental and theoretical aspects.
- They do not all need to stand (or fall) together.
- Beware of red herrings !



There is much that is still can be learned from the current LHCb and even the B-factory data sets, but any persistent effect will require confirmation in other experiments (Belle II, ATLAS/CMS) and, if genuine, must have other consequences *e.g.* in direct searches and the kaon sector - see next talks.