Experimental Flavour Physics

Lecture III: New Physics searches through studies of Flavour-Changing Neutral Currents (& other processes)

Guy Wilkinson
University of Oxford

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Lecture plan

Lecture I — Why study flavour and where ? Focus on how to do this at hadron machines, in particular the LHC and LHCb. Closing digression on hadron spectroscopy.

Lecture II — Unitarity Triangle metrology and CPV measurements

Today !

Lecture III — New Physics searches through studies of Flavour-Changing Neutral Currents (and other processes)

Lecture IV — Charm physics, and future prospects for experimental flavour studies

Upfront admission: I will be saying a lot about LHCb.

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Lecture II Unitarity Triangle metrology and CPV measurements

Lecture ... anging

Last time

Lecture ... for experimental flavour studies

But first, tagging question from last time:

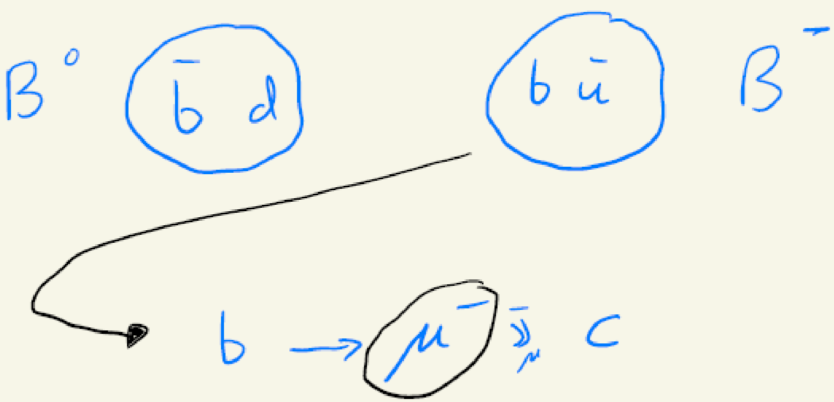
Why is flavour tagging performance always better at Υ(4S), than at LHC (or indeed Z^0) ?

Upfront admission: I will be saying a lot about LHCb.

FLAVOUR TAGGING AT LHC

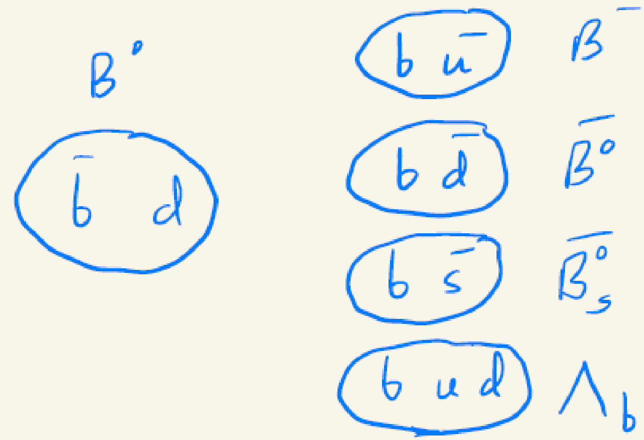
Recall, to determine whether meson of interest was a B^0 or $\bar{B}^0$ at birth, we (in simplest case) look at <u>other</u> b-hadron in event.

At production, say



Muon charge tags flavour of B^0.

Now at LHC, other b-hadron can be one of many possibilities



Now $\bar{B}^0$ and $\bar{B}^0_s$ mesons can oscillate. This can give tag of <u>wrong</u> flavour: <u>dilution</u>!

FLAVOUR TAGGING AT $\Upsilon(4S)$

At $\Upsilon(4S)$ there are no fragmentation particles.

This means identity of other meson is fixed.

Moreover, no mixing can occur until one meson decays!

$\Upsilon(4S) \to B^0 \bar{B}^0 \quad \therefore \ell = 1$ state

spin 1 → spin 0, spin 0

The two B mesons exist in a coherent wavefn. If one were to oscillate, we would have two identical bosons. B-E statistics requires such a wavefn. to be symmetric, but $\ell = 1$ is antisymmetric

$\Rightarrow$ no mixing allowed until one B decays!

This means less dilution of tagging, an asset of $\Upsilon(4S)$ environment.

Lecture-III outline

- Introduction to FCNCs – radiative decays
- The ultra rare: $B^0_{(s)}\rightarrow\mu^+\mu^-$
- $B^0\rightarrow K^{*0}\mu^+\mu^-$ and friends: the gift that keeps on giving
- Trouble with trees: $b\rightarrow c\tau\bar{\nu}$
- Conclusions

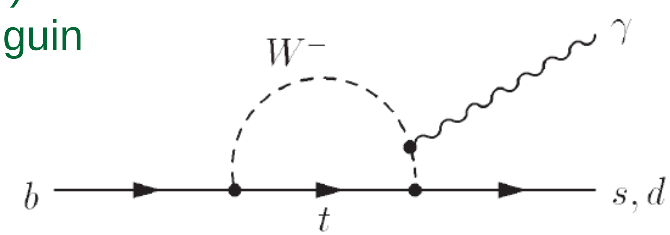
Flavour-changing Neutral Currents (FCNCs) or 'rare decays' as a probe of New Physics

FCNC decays proceed through higher order diagrams → suppressed in SM and susceptible to New Physics contributions.

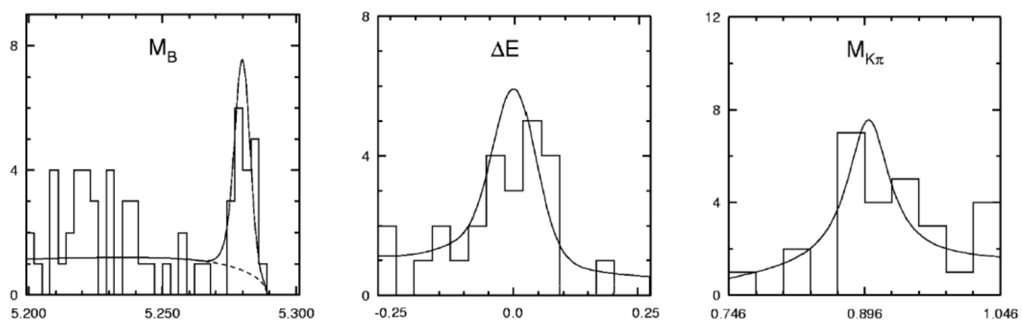
e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [Ellis *et al.*, NPB 131 (1977) 285].)

Most interesting measurements involve EM & weak penguins, with photon or dileptons – precise predictions.

(EM) Radiative penguin



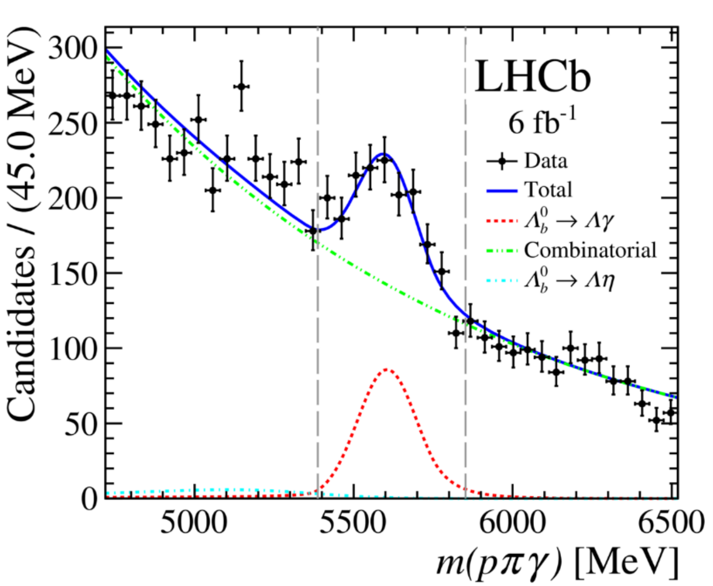
EM penguin first discovered by CLEO in B→K*(892)γ (BR~10^{-5}) [CLEO, PRL 71 (1993) 674].

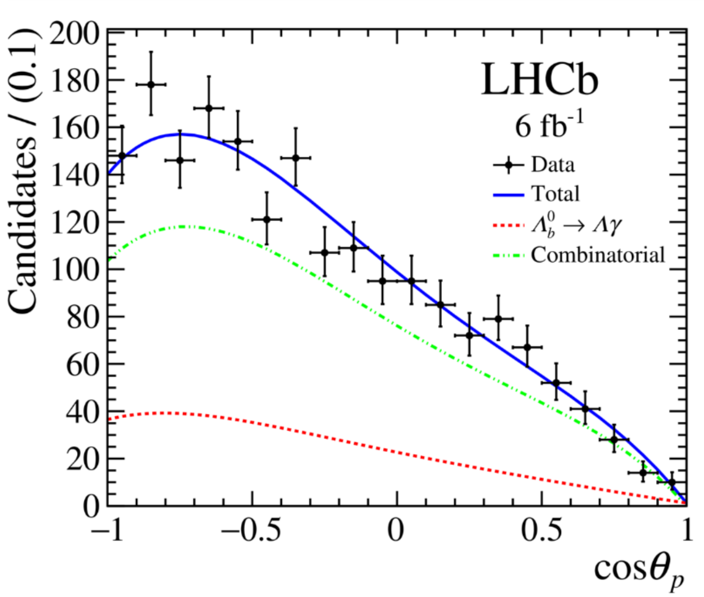


Hadron machines can study b→sγ too

Despite the high background from combinatoric π^0 decays, it is possible to study radiative penguins at the LHC, as the photon is reasonably hard. (what is much more challenging is to look at final states with > 1 neutral, or study b→sγ inclusively – that remains the province of the e^+e^- machines). Unique contributions possible.

e.g. [LHCb, PRD 105 (2022) L051104] reconstruction of $\Lambda^0_b \to \Lambda\gamma$ and measurement of photon polarisation, which is expected to be almost completely left-handed in the SM.





θ_p is angle between p momentum and negative Λ^0_b momentum in Λ rest frame

$$\alpha_\gamma \equiv \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R},$$

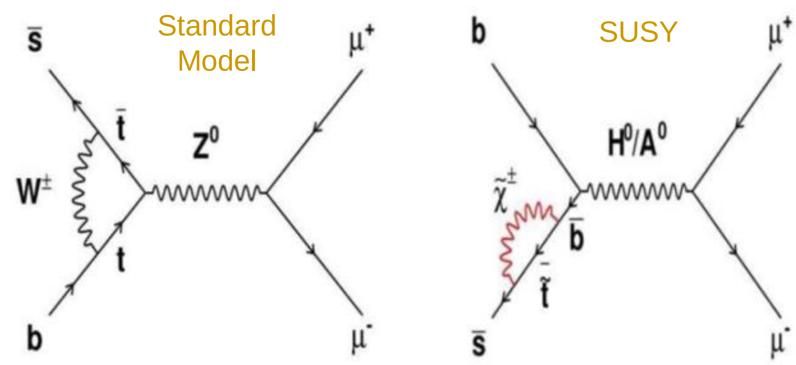
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.}).$$

i.e. SM like

The golden modes: $B_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$

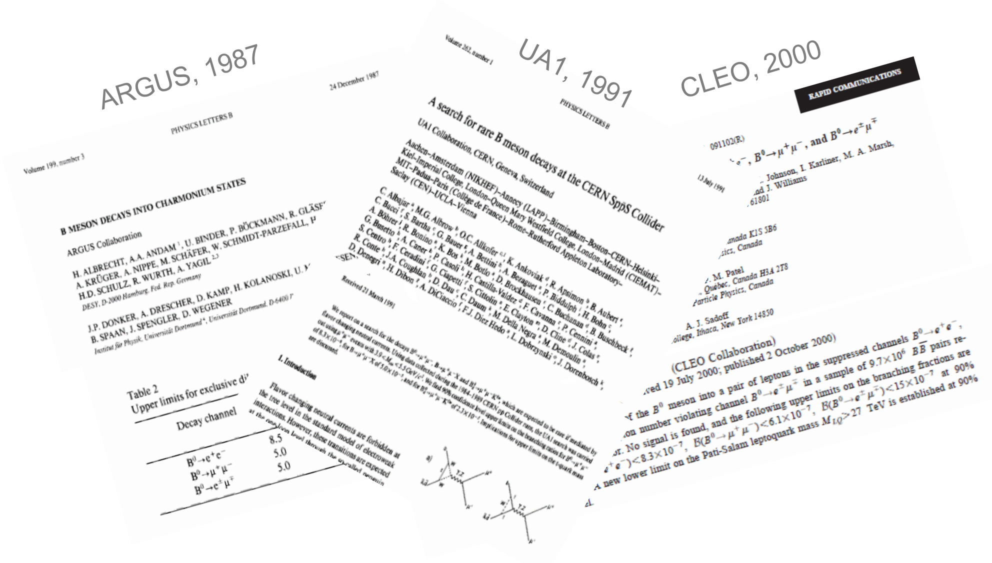
These decay modes can only proceed through suppressed loop diagrams.

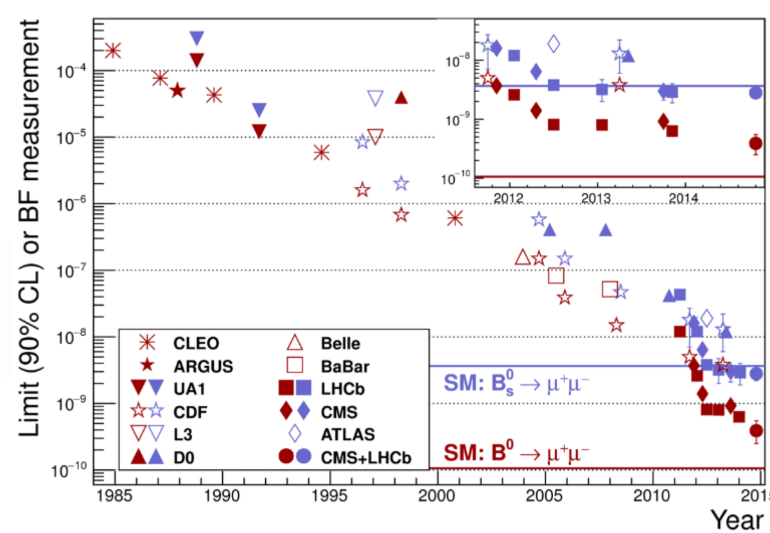
In SM they happen extremely rarely ($B_s \to \mu\mu$ ~4×10^{-9}, $B^0 \to \mu\mu$ 30x lower), but the rate is very well predicted (*e.g.* <5% for $B_s \to \mu\mu$).



Many models of New Physics (*e.g.* SUSY) can modify rate significantly !

A ‘needle-in-the haystack’ search, which has been pursued for over 25 years.

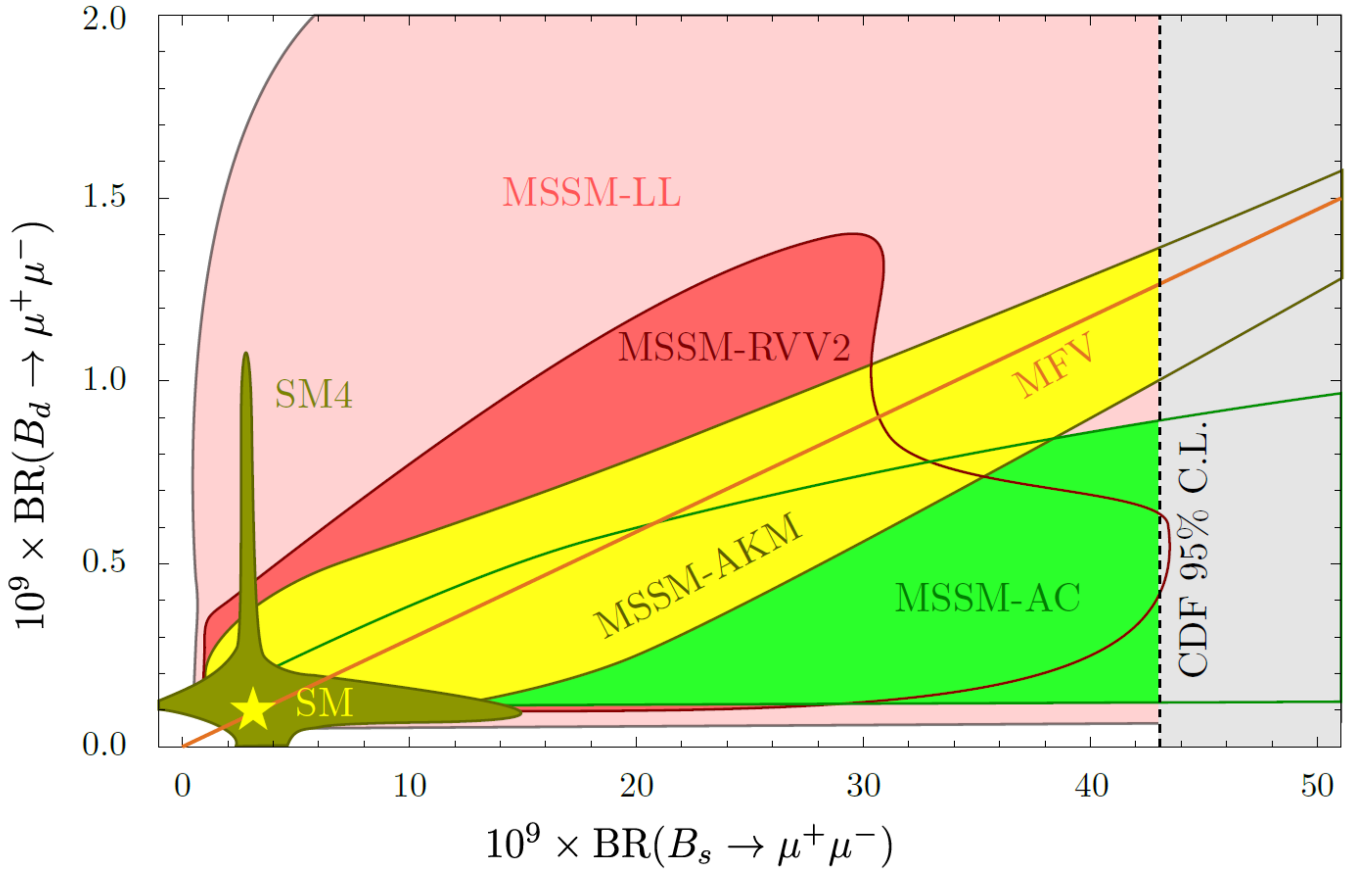




Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

$B_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$: the model killer

Historical plot from around the turn-on of the LHC, showing how a measurement of the BR of both modes provides powerful discrimination between New Physics models.



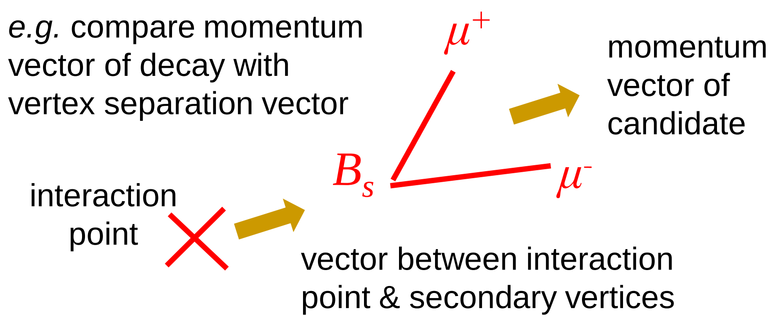
[D. Straub, arXiv:1012.3893]

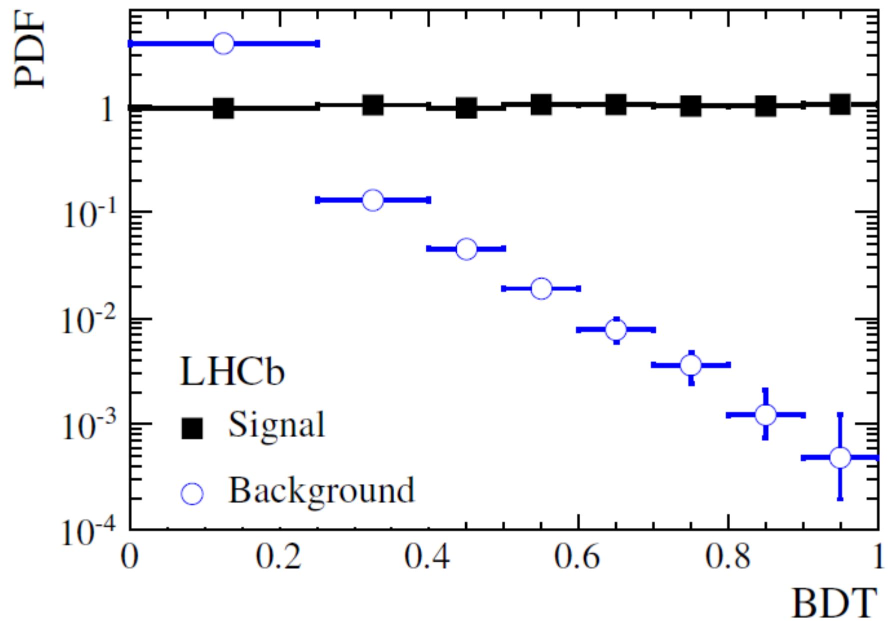
Finding the needle in the haystack

There are lots of B-decays that look rather similar to $B_s \to \mu\mu$. And 'rather similar' is very dangerous when you are searching for such a rare decay.

Most sensitive analyses (pioneered by LHCb & CMS) are not 'cut-based' . Rather, they employ a sequence of two boosted decision trees (BDTs).

BDTs must not just search for a B-decay, as in trigger, but must look for one which is $B_s \to \mu\mu$



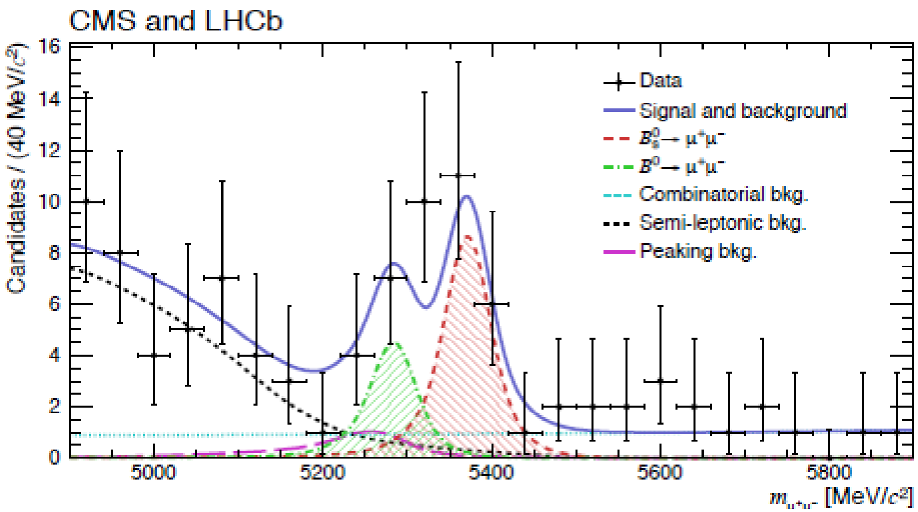


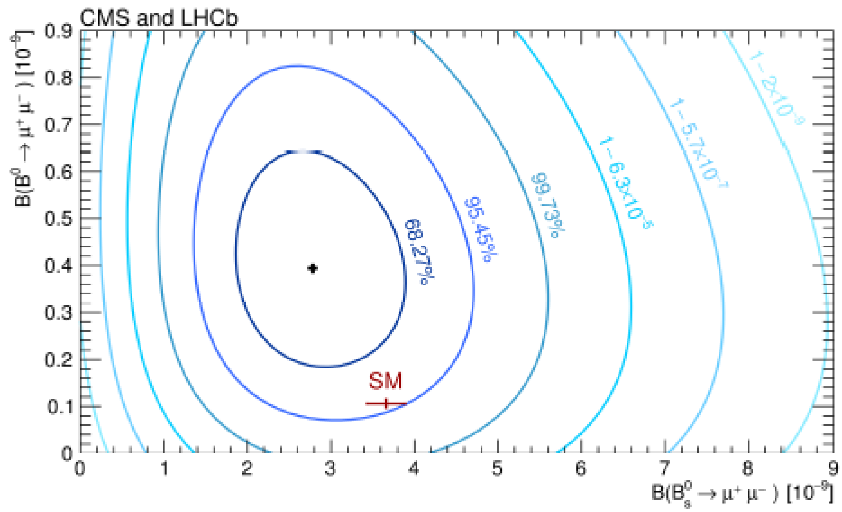
[LHCb, PRL 111 (2013) 101805]

Above, just one of many signatures that are used. Where possible calibrate BDTs on data (*e.g.* same topology $B^0 \to K\pi$ decays). Normalise signal yield to $B_s \to J/\psi K$ or $B^0 \to K\pi$ to determine BR.

The search is over: $B_s \to \mu^+\mu^-$ observed !

The signal finally showed up during Run 1, where LHCb found first evidence [PRL 110 (2013) 021801], & then a combined LHCb-CMS analysis yielded a 5σ observation [Nature 522 (2015) 68]. The BR, measured to 25%, agrees with the SM…





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

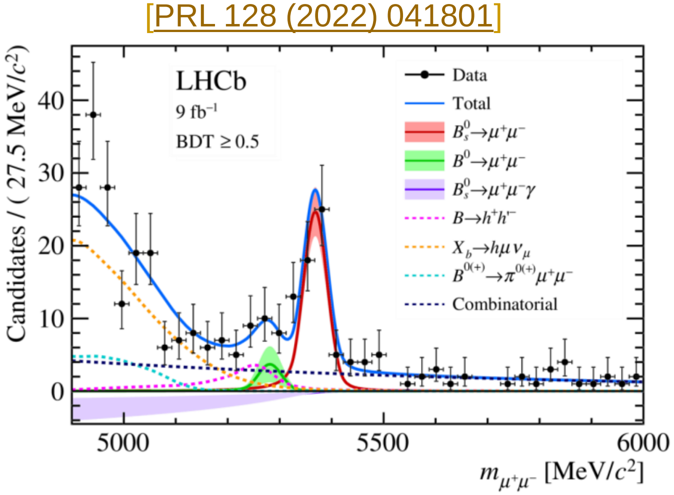
[Nature 522 (2015) 68]

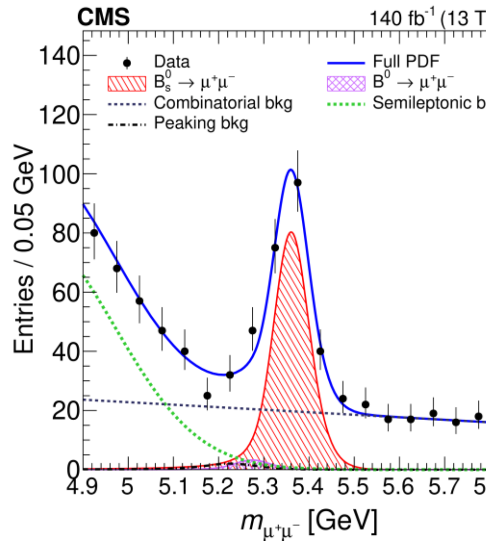
…however the analysis also searched for the even rarer $B^0 \to \mu\mu$. Here there is also a hint of a signal. Picture is intriguing & provided encouragement for Run 2 !

$B^0_{(s)} \to \mu^+\mu^-$ at the LHC: state of play

Recent results available from all experiments. Run 1 & 2 fully analysed by LHCb & CMS. Indicative plots below – these made for different data sets and BDT cuts, so take care when comparing absolute yields, but note different mass resolutions.

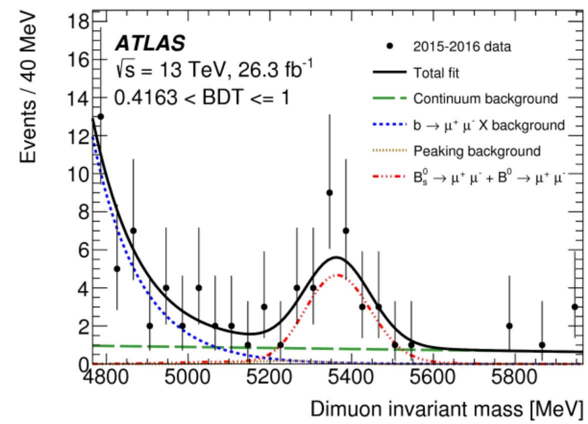
[PRL 128 (2022) 041801]





[PLB 842 (2023) 137955]

[JHEP 04 (2019) 098]



When combined with Run 1:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09 \,{}^{+0.46}_{-0.43}\,{}^{+0.15}_{-0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\mathrm{stat})\,{}^{+0.19}_{-0.16}\,(\mathrm{syst})\,{}^{+0.14}_{-0.13}\,(f_\mathrm{s}/f_\mathrm{u})\right] \times 10^{-9}$$

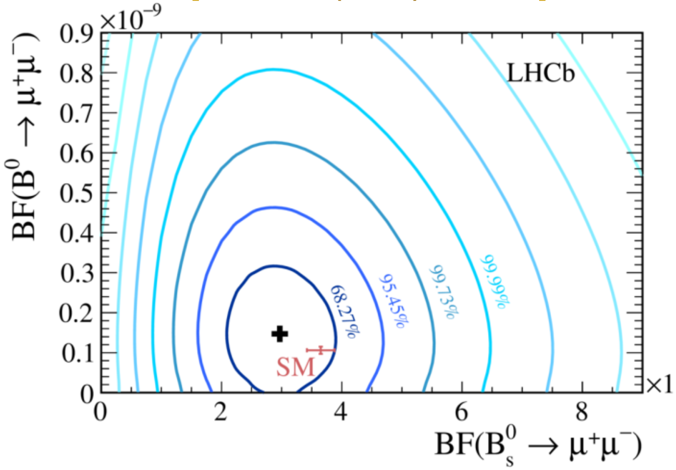
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

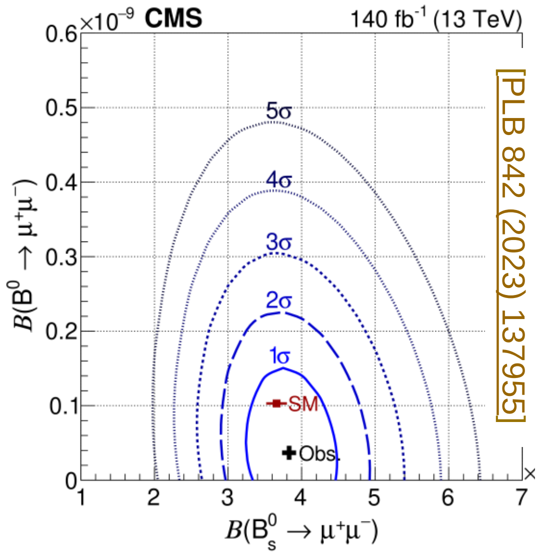
CMS currently has best measurement (this is a flavour-physics measurement well suited to the General Purpose Detectors). Precision ~10%. No sign yet of $B_d \to \mu\mu$.

$B^0_{(s)} \rightarrow \mu^+\mu^-$ at the LHC: state of play

No combination of the current individual LHC measurements yet exists…

[PRL 128 (2022) 041801]





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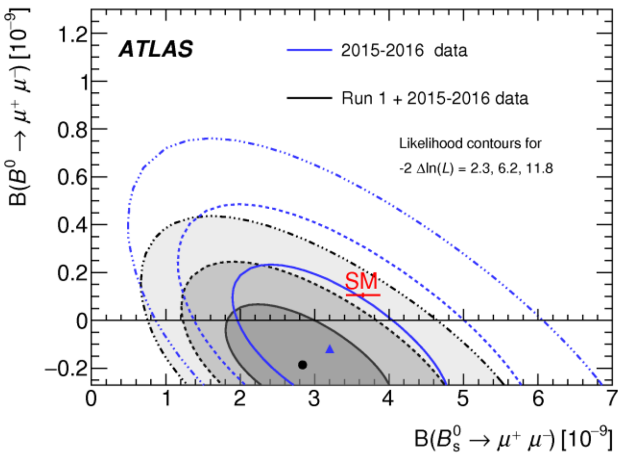


…but the overall picture is clear: broad consistency with the Standard Model.

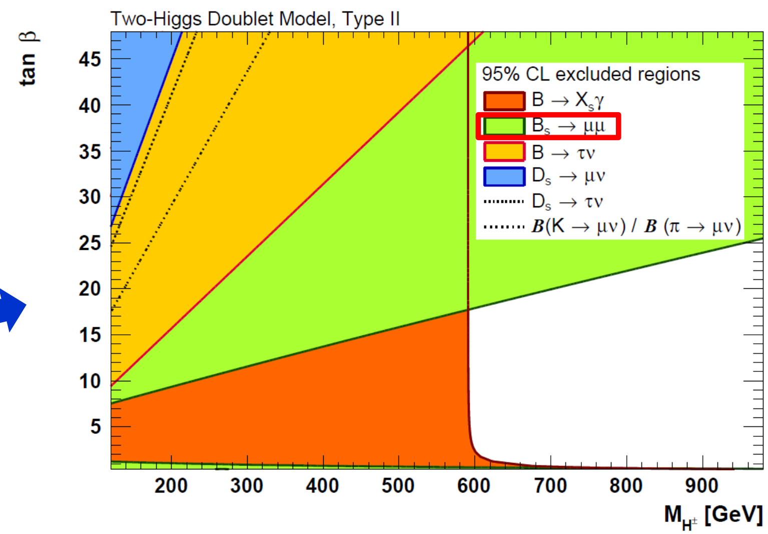
Achieving such precision on this rare process is a major achievement of LHC era !

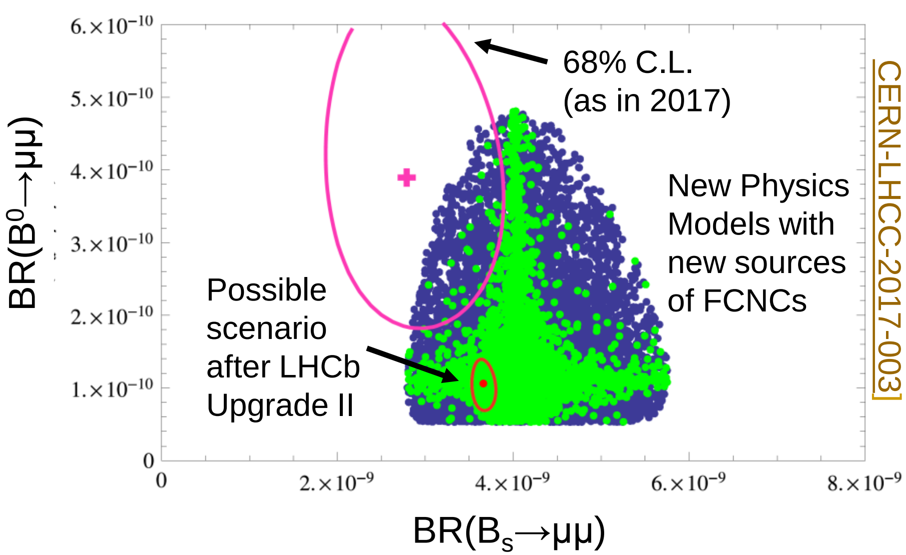
Lessons from, & future of, $B^0_{(s)}\to\mu\mu$ measurements

- Prior to LHC turn on, an enhanced BR($B_s\to\mu\mu$) was one of the great hopes for a rapid discovery of New Physics. This hope has not been realised.

- Nonetheless, the absence of an enhancement is a very powerful input in excluding certain classes of New Physics model.

  e.g. 95% CL excluded region in $M_{H^\pm}$ vs. tanβ space for two-Higgs doublet model [Gfitter group, Hallet *et al.*, EPJC 78 (2018) 675].





[LHCb, Upgrade II EoI, CERN-LHCC-2017-003]

- Better measurements are *essential*, as we are still above the theory limit (which will improve). Even truer for ratio BR($B_s\to\mu\mu$)/BR($B^0\to\mu\mu$). These decays still have much to tell us!

- Next step in the journey will be observation of $B^0\to\mu\mu$.

Unlocking new observables with $B_s \to \mu^+\mu^-$

Remarkably, the sample of $B_s \to \mu\mu$ decays now available is sufficient to begin probing new observables. *E.g.*, since the sample is in fact constituted of both B_s & $B_s$bar mesons, a lifetime measurement brings very valuable new information.

The effective lifetime [K. De Bruyn *et al.*, PRL 109 (2012) 041801]:

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + 2A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right)$$

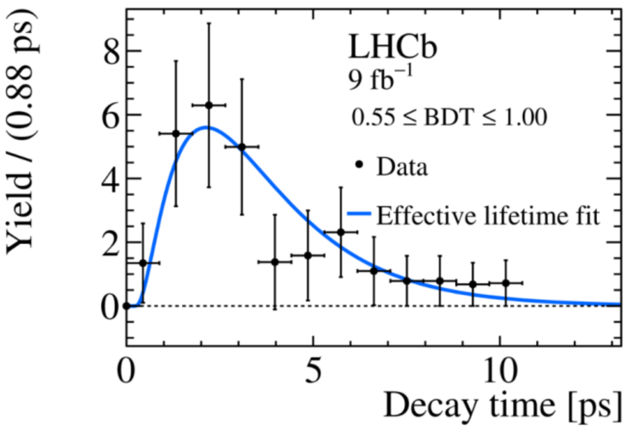
where

- $y_s \equiv \tau_{B_s^0} \Delta\Gamma/2 \approx 0.06$, $\Delta\Gamma$ being the lifetime splitting between the mass eigenstates;
- $A^{\mu\mu}_{\Delta\Gamma}$ is a term that is 1 in SM, but can take any value between -1 & 1 for New Physics.

Accessing $A^{\mu\mu}_{\Delta\Gamma}$ through $\tau_{\mu\mu}$ tells us things that the BR alone does not.

Unlocking new observables with $B_s \to \mu^+\mu^-$

Measurements of effective lifetime now available from all three experiments.



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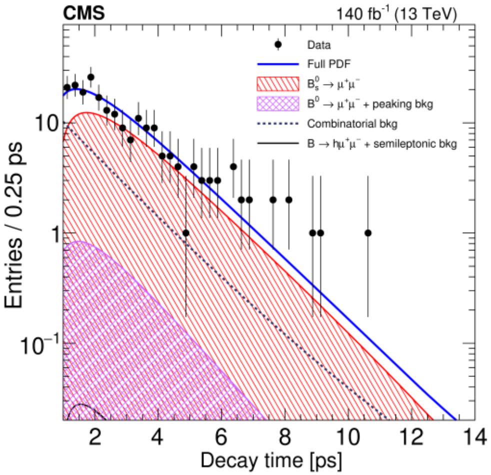

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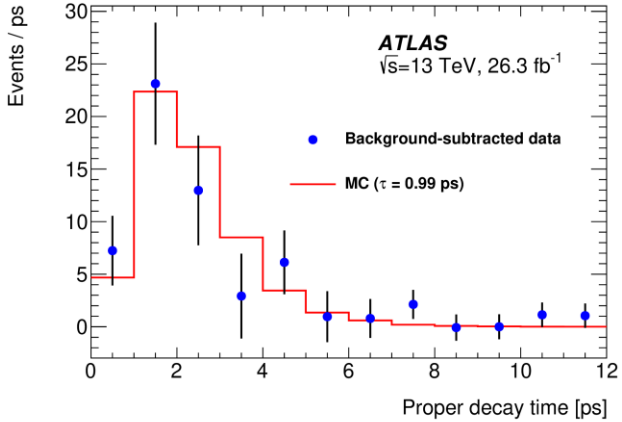
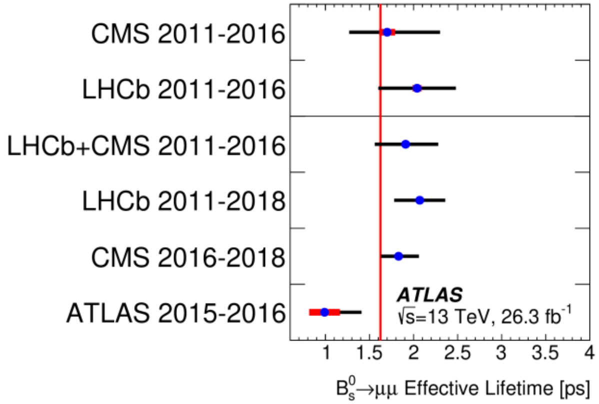
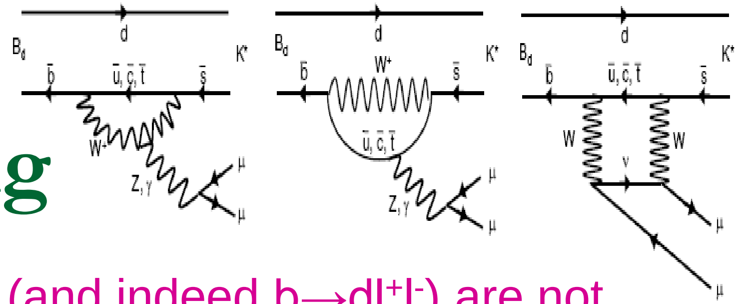


[arXiv:2308.01171]



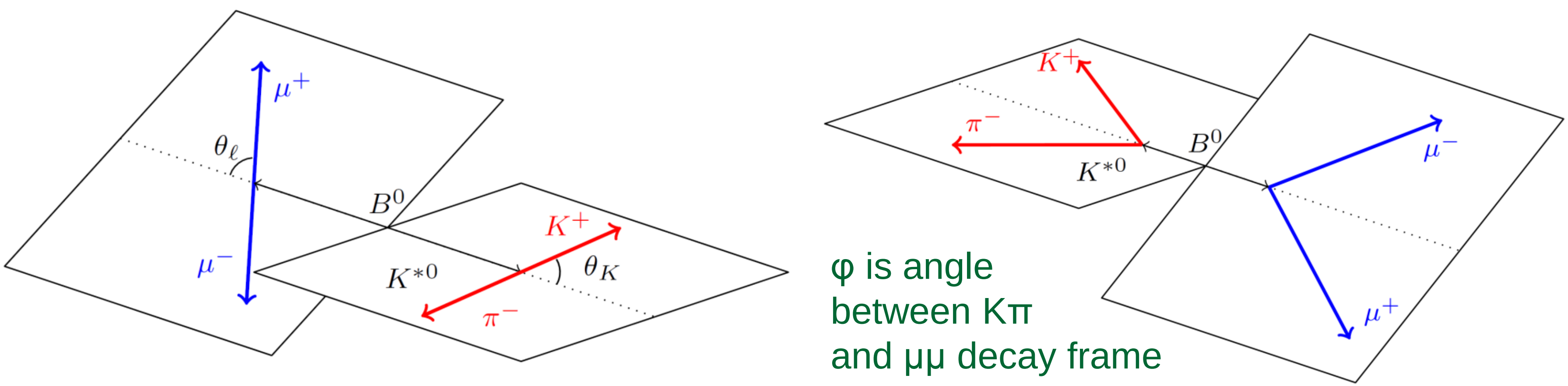
Precision now similar to lifetime splitting $\Delta\Gamma_s$. Very interesting prospects for HL-LHC era. Also, can start to plan for flavour-tagged CP asymmetry measurements !

$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



FCNC processes involving the transition $b \rightarrow s l^+ l^-$ (and indeed $b \rightarrow d l^+ l^-$) are not ultra rare, but provide an exceedingly rich set of observables to probe for NP effects, that are sensitive to non-SM helicity structures (and more).

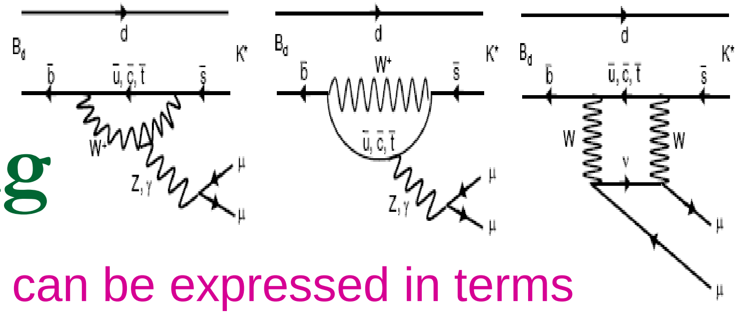
Many realisations, but the poster-child decay is $B^0 \rightarrow K^{*0} l^+ l^-$, with $K^{*0} \rightarrow K^+ \pi^-$.



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]).

$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



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):

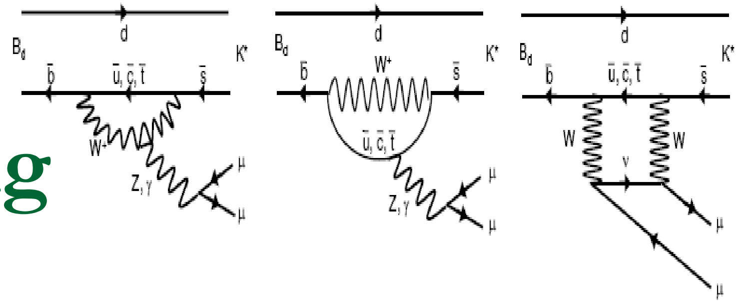
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos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

Note, this is the 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

$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



Three practical considerations:

1. Analysis must allow for an S-wave contribution in Kπ system, in addition to P wave that comes from K*(892) – important, but we won't discuss it here.
2. In pp environment, it is easier to reconstruct muons than electrons, so unless stated, measurements are made with di-muon final state.
3. Form-factor (*i.e*. QCD) uncertainties in predictions of coefficients can be reduced by changing to a set of optimised observables [Descotes-Genon *et al.*, JHEP 01 (2013) 048], in which first order uncertainties cancel, *i.e.* more robust:

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \qquad P_3 = \frac{-S_9}{(1-F_{\rm L})}\,, \qquad P_6' = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,.$$

$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \qquad P_{4,5,8}' = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,,$$

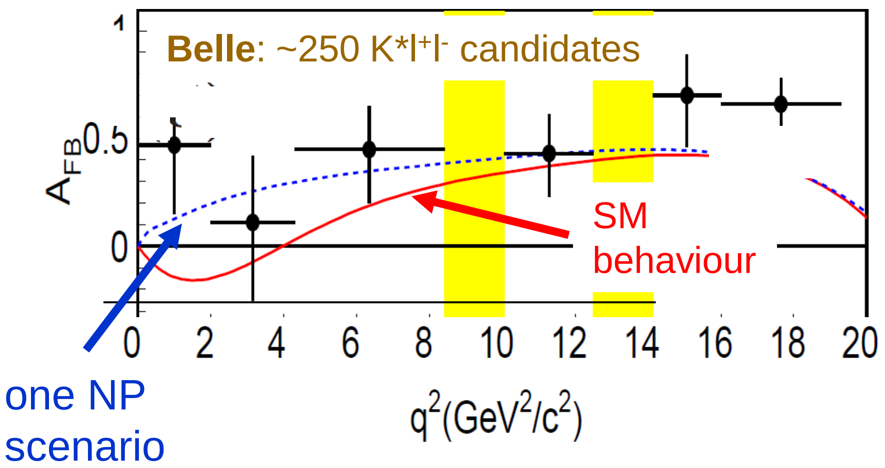
(LHCb definitions, see [JHEP 02 (2016) 104])

Hard to visualise what these mean, but they can be predicted in SM, & in terms of general NP predictions, rather well. Also very robust against detector bias !

$B^0 \rightarrow K^* l^+ l^-$ - impact of the LHC

The B factories studied $B^0 \rightarrow K^* l^+ l^-$ with enthusiasm. Initial results, *e.g.* for forward-backward asymmetry, were intriguing. But sample sizes inadequate for firm conclusions. Situation changed with the turn-on of the LHC.

[PRL 103 (2009) 171801]



(NB: the J/ψ and ψ' regions are excluded, as these ccbar resonances occur through tree-level processes and do not probe physics we are interested in.)

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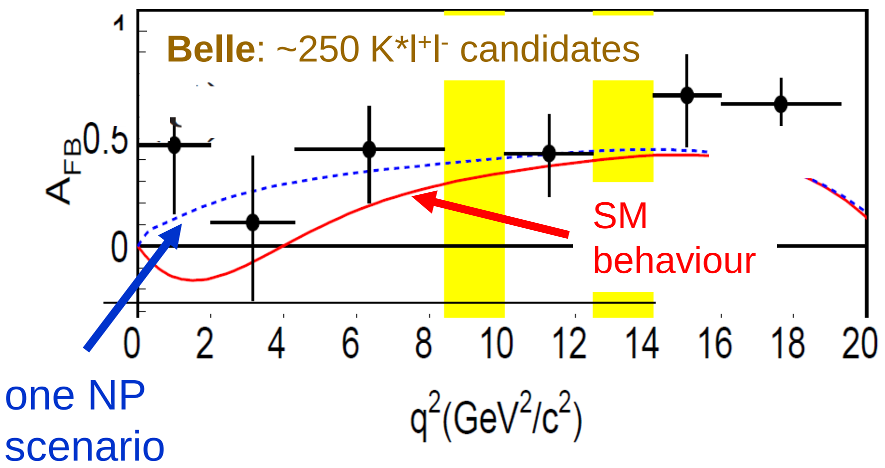
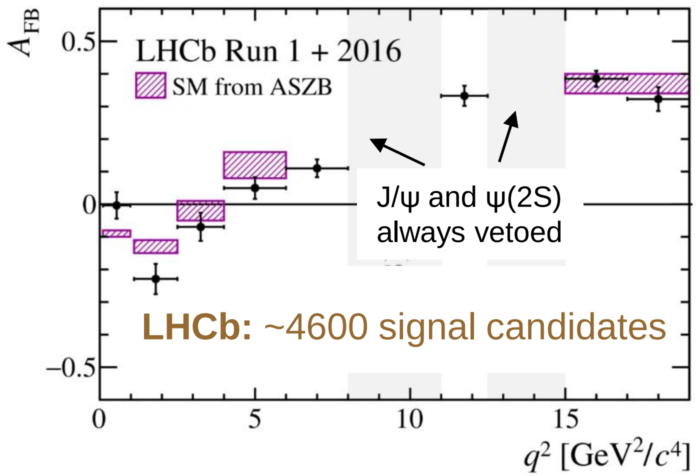


[PRL 125 (2020) 011802]



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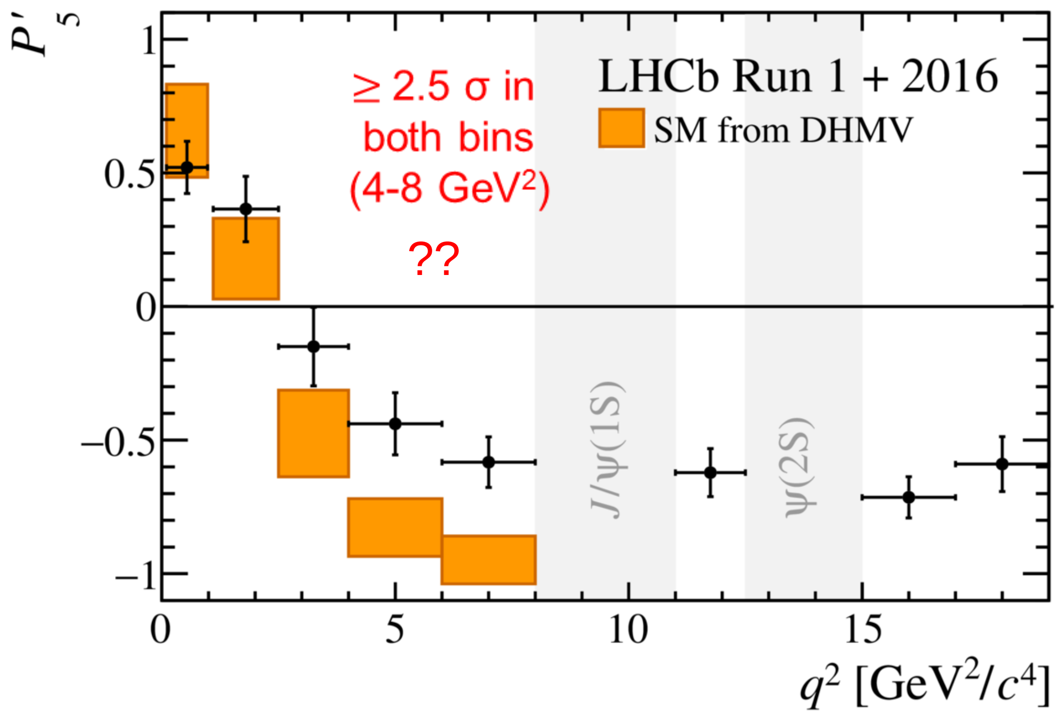
Hints of non-SM behaviour in early analyses not confirmed by high-statistics measurement (although mild tension at low q^2). What about 'optimal observables' ?

$B^0 \rightarrow K^* l^+ l^-$ and friends: the $P_5^{/}$ puzzle

The 'optimum observable' that has attracted most attention is $P_5^{/}$. A deviation at low q^2, first seen in early LHCb analysis [PRL 108 (2012) 181806], persisted with full Run 1 + early Run 2 data set [PRL 125 (2020) 011802], & is not contradicted by other experiments.

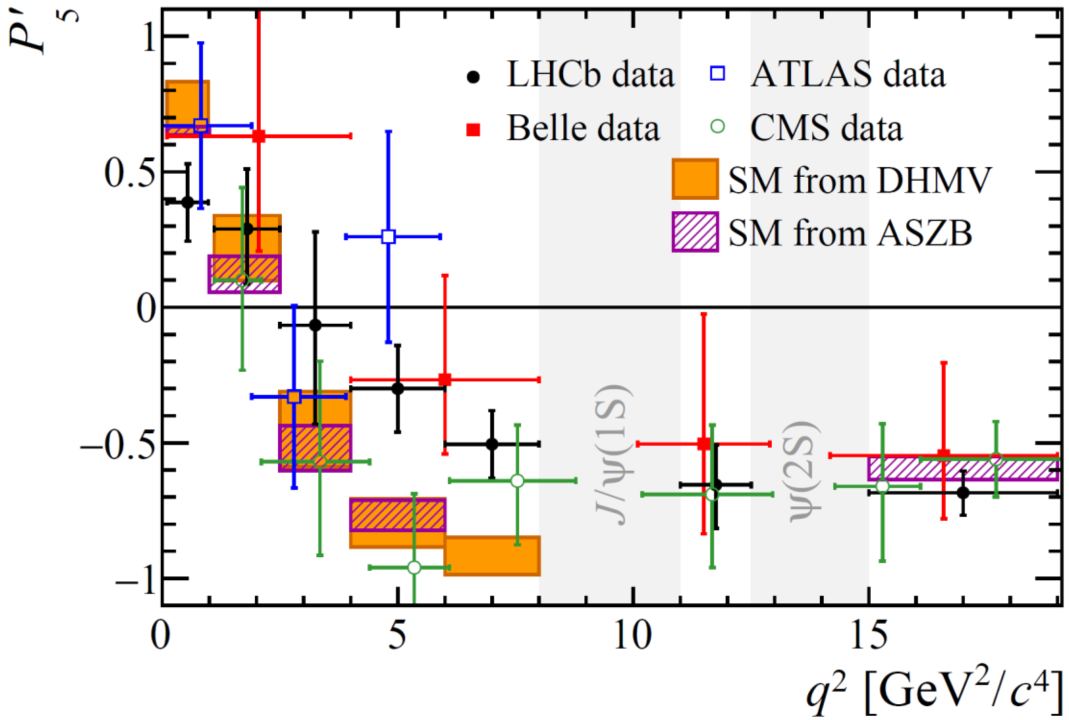


[PRL 108 (2012) 181806]

A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative. Meanwhile, work is ongoing to constrain QCD uncertainties from data, *e.g.* [LHCb, EPJ C77 (2017) 161].

$B^0 \to K^* l^+ l^-$ and friends: the $P_5^{/}$ puzzle

The ‘optimum observable’ that has attracted most attention is $P_5^{/}$. A deviation at low q^2, first seen in early LHCb analysis [PRL 108 (2012) 181806], persisted with full Run 1 + early Run 2 data set [PRL 125 (2020) 011802], & is not contradicted by other experiments.

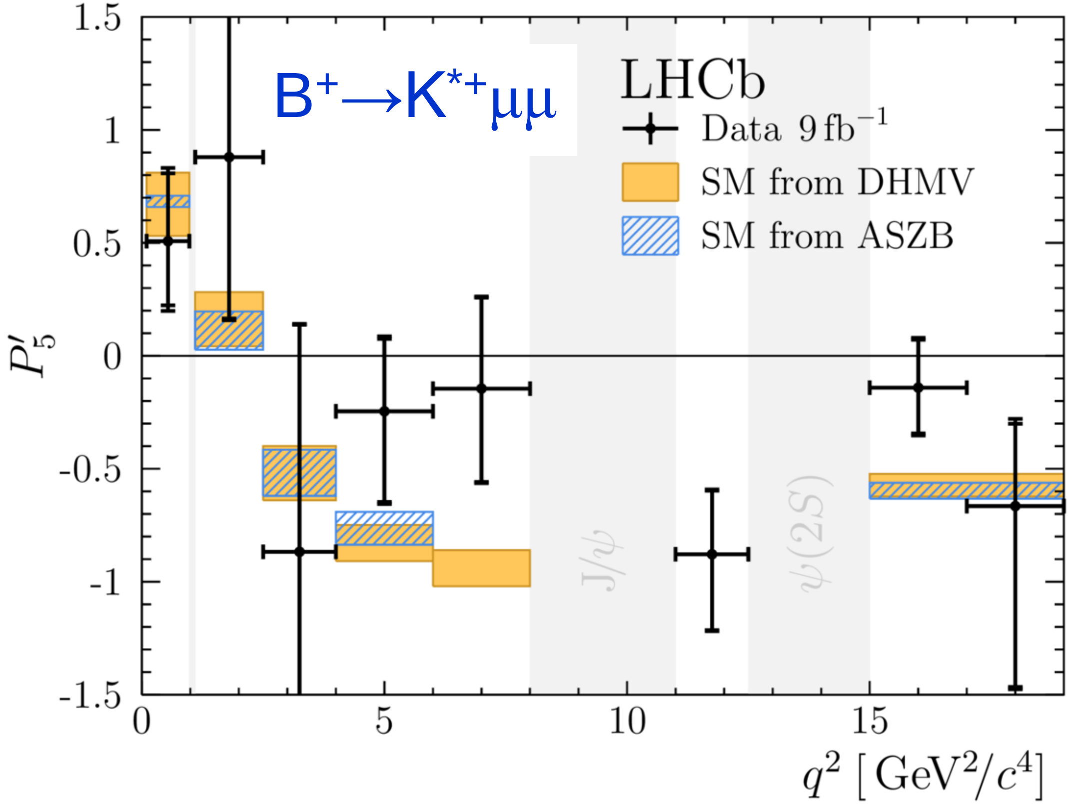


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

Same pattern seen by Belle and ATLAS, whereas CMS sees more SM-like behaviour. None of these measurements are individually precise, but the overall picture is very similar to LHCb. Does not smell like a statistical fluctuation…

$B^0 \to K^* l^+ l^-$ and friends: the P_5' puzzle

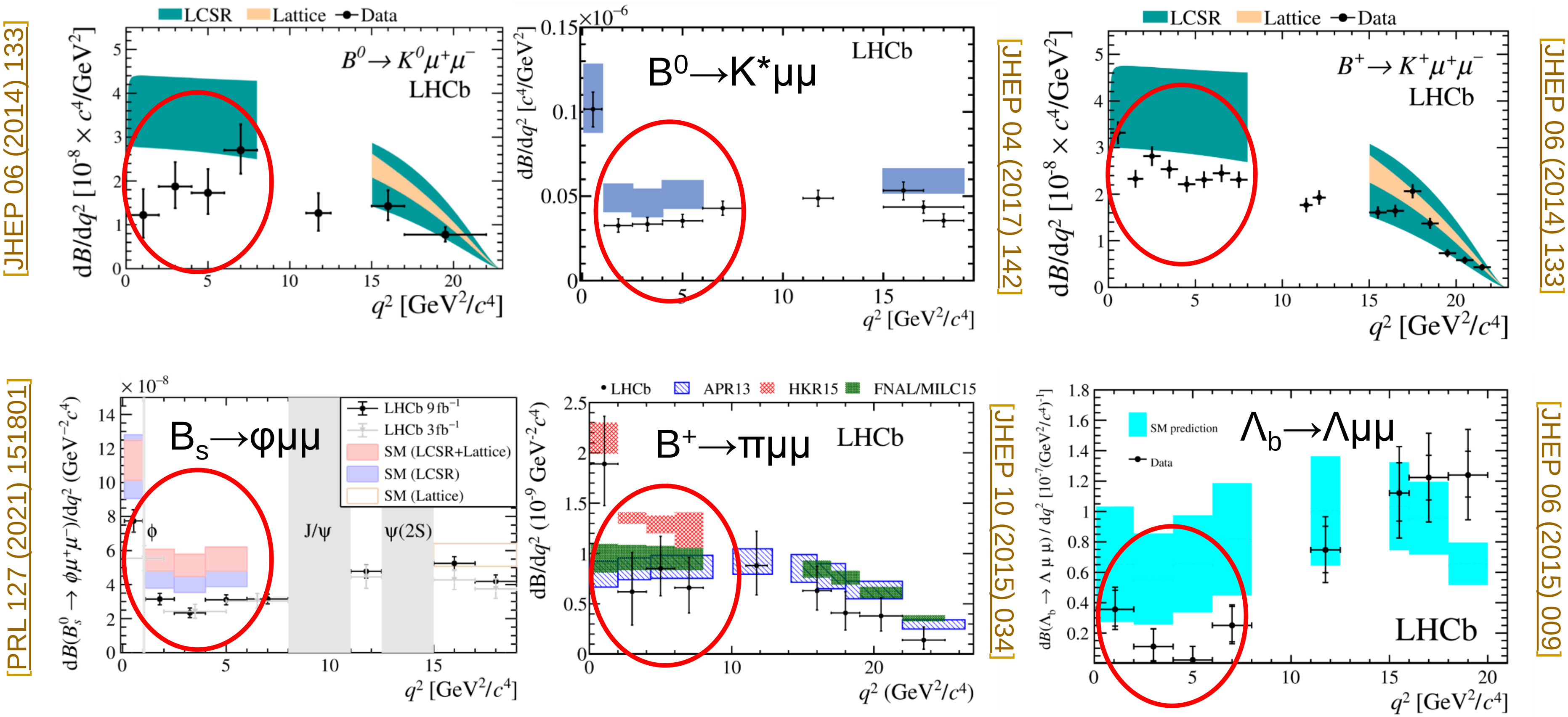
Measurements of the same / similar observables in different channels (*e.g.* $B^+ \to K^{*+}\mu\mu$ [PRL 126 (2021) 161802], $B_s \to \phi\mu\mu$ [JHEP 11 (2021) 043]) although less precise, provide a qualitatively similar picture.



[LHCb, PRL 126 (2021) 161802]

$B^0 \to K^* l^+ l^-$ and friends: differential x-secs

P_5' is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.



All measurements undershoot prediction at low q^2. (BTW, all made with *dimuons*…)
Intriguing – but maybe the uncertainties in theory are larger than claimed ?

Can we identify an observable where the theory uncertainties are negligible ?

$B^0 \rightarrow K^* l^+ l^-$ and friends: lepton-universality tests

The cleanest way to probe these decays are with lepton-universality (LU) tests, *i.e.* comparing decays with di-electrons and di-muons. Negligible theory uncertainty.

Ratios of decay rates have been measured for $b \rightarrow s\mu^+\mu^-/b \rightarrow se^+e^-$ for $\sim 1 < q^2 <$ 6 GeV^2 for both $B \rightarrow Kl^+l^-$ (R_K) and $B^0 \rightarrow K^*l^+l^-$ (R_{K^*}). In SM we expect 1 for both.

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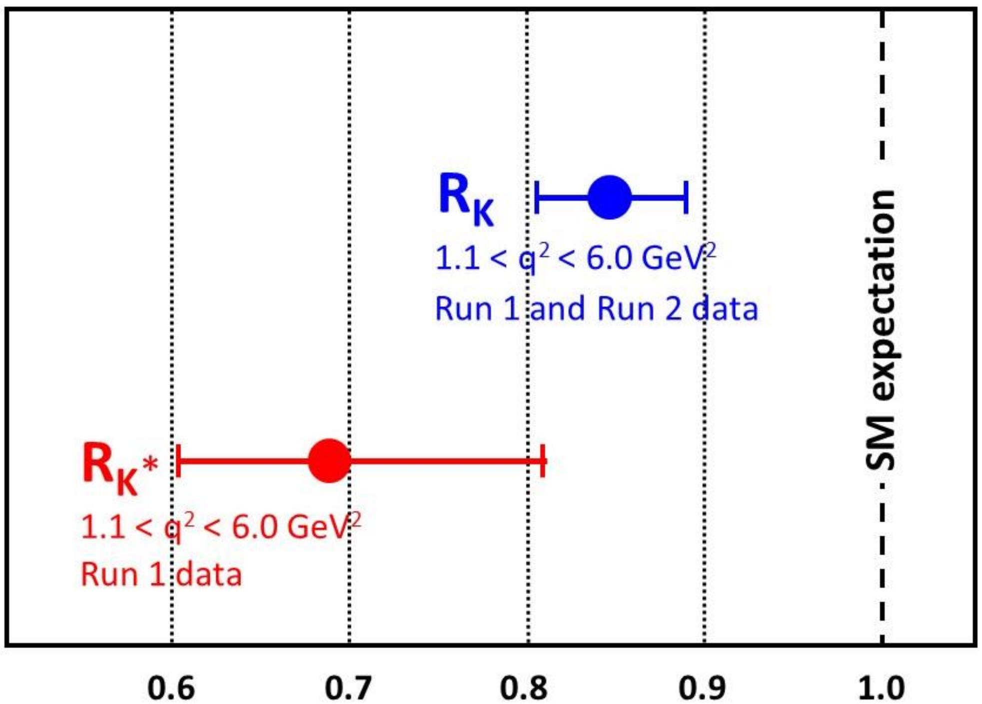
3.1 σ below SM

~2.5 σ below SM



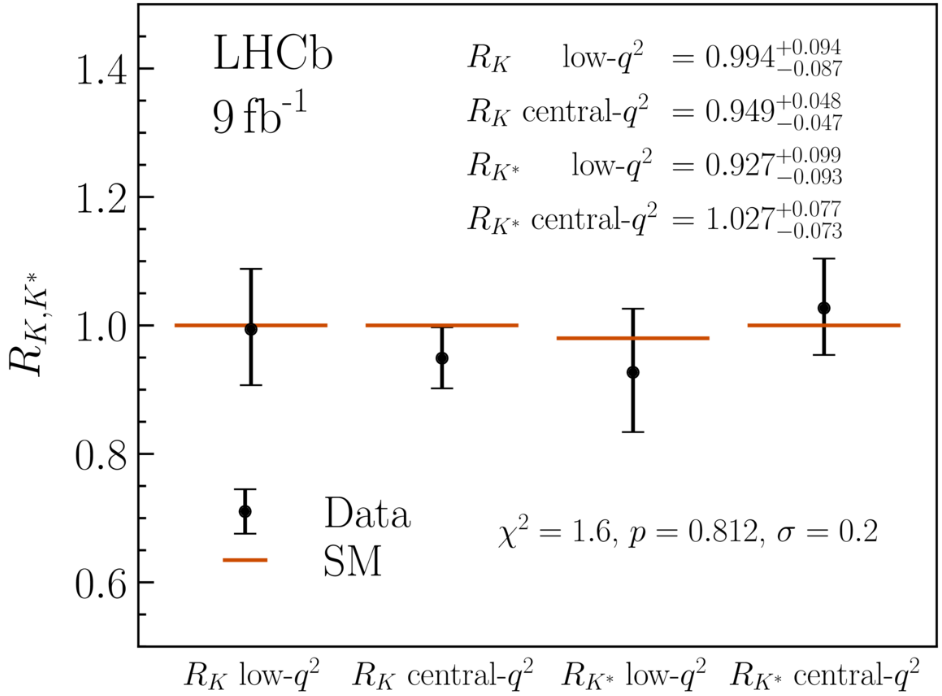
[Nat. Phys. 18 (2022) 277]

[JHEP 08 (2017) 055]

For a long time, these results generated great interest and many theory papers.

$B^0 \to K^* l^+ l^-$ and friends: lepton-universality tests

But measurements involving electrons at hadron colliders are hard, and a re-analysis of LHCb data involving both modes (and now two q^2 bins for each mode), revealed an unexpectedly large background and led to revised results.



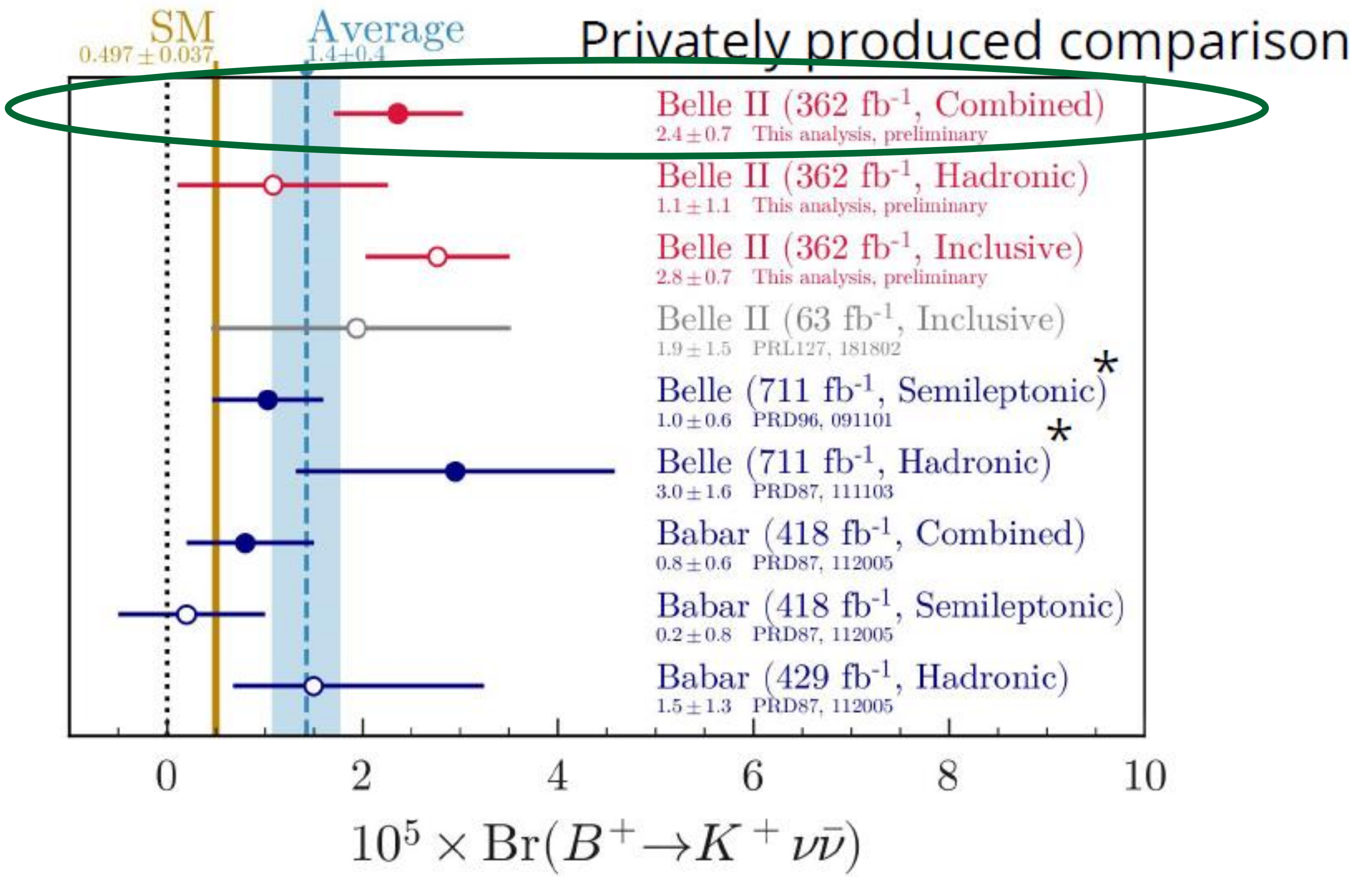
[arXiv:2212.09153]

Naturally this is disappointing, but we should celebrate that the scientific method always wins out. Nonetheless, the other $b \to s l^+ l^-$ puzzles remain, and indeed, soon after the world had thought these anomalies dead and buried…

When we dead awaken

Hot news: $B^+ \to K^+ \nu\bar{\nu}$ from Belle II

Announced at EPS Hamburg in August, 3.6σ evidence for $B^+ \to K^+$vvbar, at a rate 2.8σ above the SM. Await for confirmation in other channels and Belle data.

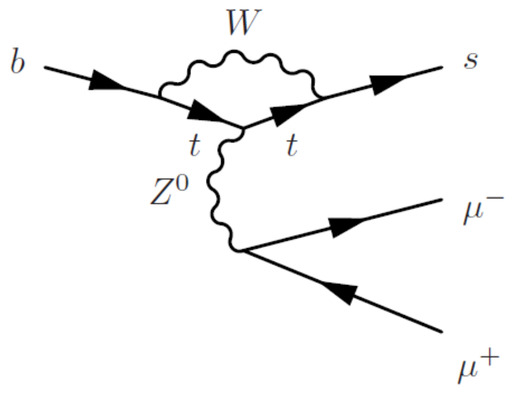


This is a measurement where LHCb cannot contribute ! Again, the message is that it is vital to have more than one flavour experiment, in different environments.

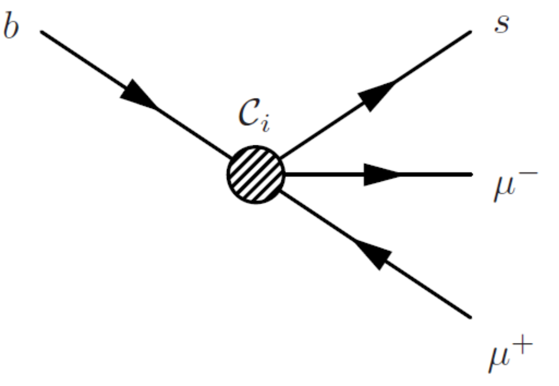
Analysing FCNC data in context of effective field theory

FCNC results can be analysed as a whole in context of effective field theory.

Real theory



Effective theory



$$\mathcal{A}(i \to f) = \langle f \,|\mathcal{H}_{eff}|\, i\rangle$$

See, *e.g.* [Buchalla *et al*., Rev. Mod. Phys. 68 (1996) 1125].

Analysing FCNC data in context of effective field theory

Operator product expansion:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

Model independent ! Expansion performed in a complete basis of four-body operators that contribute differently to each FCNC process.

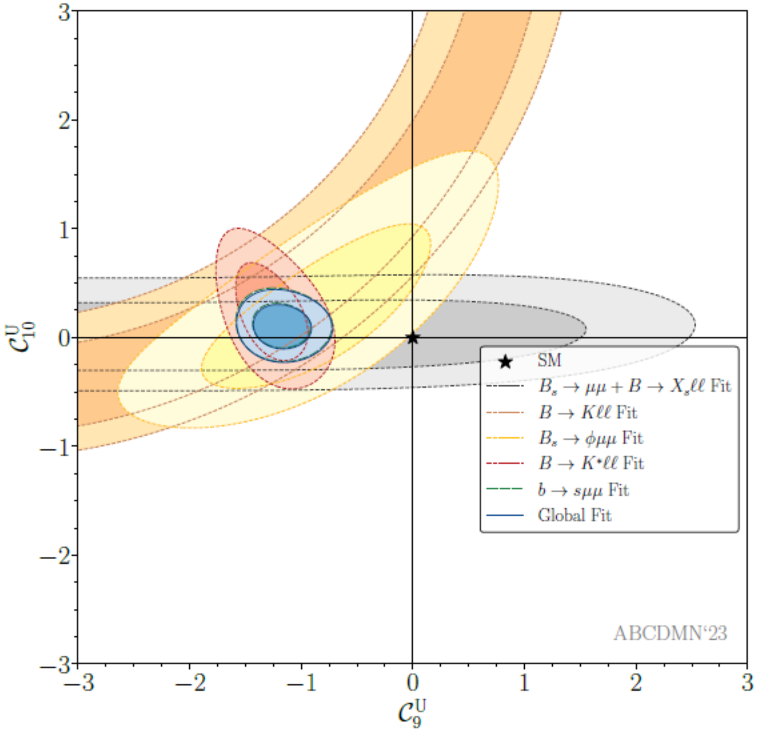
$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$
$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$
$$O_S^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l} l)$$
$$O_P^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l}\gamma_5 l)$$

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

C_i are the *Wilson coefficients*. Calculable in SM, but can be affected by New Physics.

Example Wilson coefficient fit

We will not dwell on the results of such fits today, partly because we are still awaiting a treatment that pays attention to the new experimental landscape.



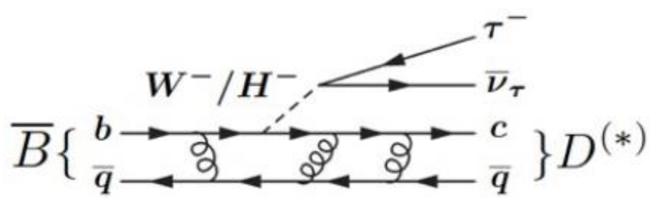
[Capdevila, Crivellin and Matias, arXiv:2309.0131]

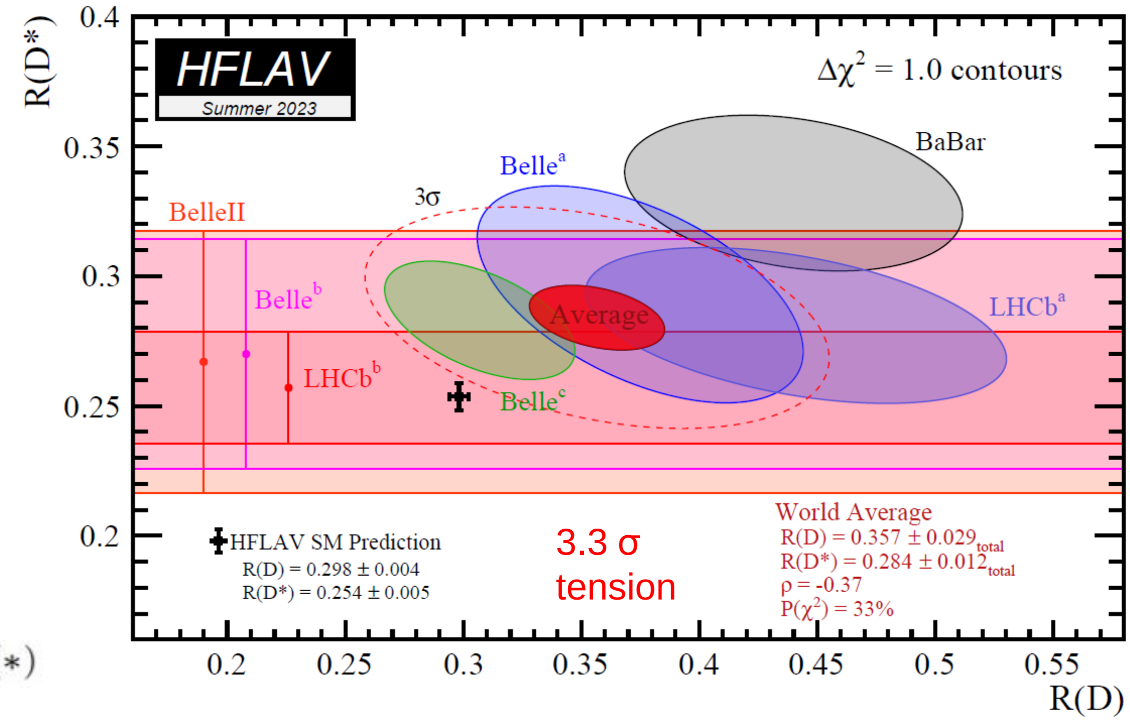
Deviations of Wilson coefficients from SM values can also be interpreted in terms of new particles, such as leptoquarks, or Z primes.

Trouble with trees: more hints of LU violation

There is another class of decays, $b \to c l \nu$, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

$$R(D^{(*)}) \equiv \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$



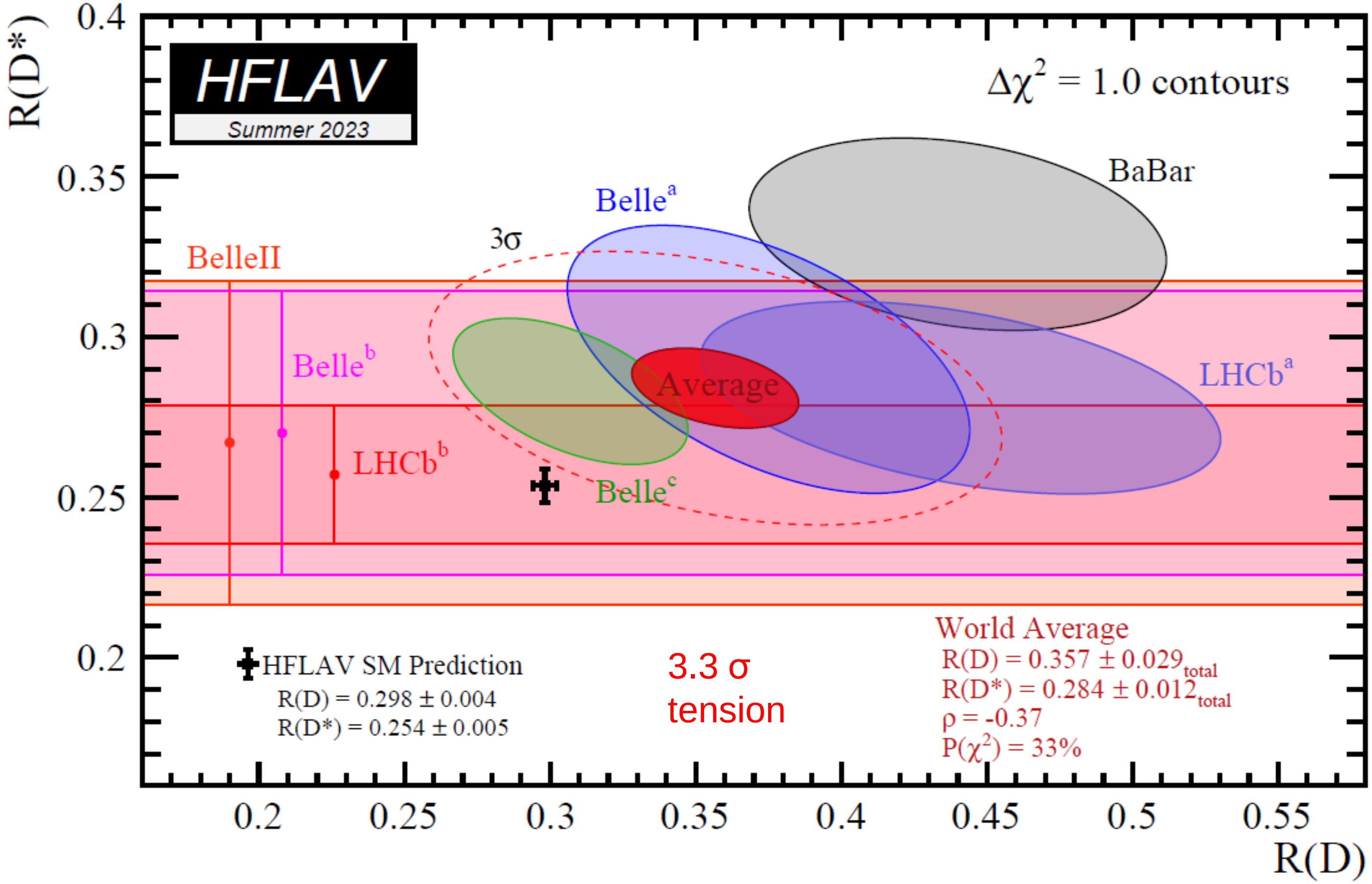


Studies originally motivated by sensitivity to charged Higgs, but results do not favour this explanation and fit better with leptoquark explanation, but requires some ingenuity to simultaneously explain this and $b \to s l^+ l^-$ anomaly. Tree-level process, so this New Physics particle has to be quite light to compete with SM.

Missing energy means that measurements are ideal for B-factories, but competitive studies have come from LHCb in a variety of channels.

Trouble with trees: more hints of LU violation

Situation is intriguing, and has been so for >10 years, but what is required is a truly precise single measurement to land a knockout blow, one way or another.



Conclusions

Some of the most powerful probes for New Physics, which are sensitive to the highest mass scales, are from studies of Flavour-Changing Neutral Currents.

Very many studies are underway, some with an intriguing status.

The most powerful and interesting concern: $B^0_{(s)} \to \mu^+\mu^-$

$b \to s l \bar{l}$ transitions.

Also of interest is the tree-level process $b \to c\tau\bar{\nu}$, which has puzzled the community for many years. Contributions from both B-factories and LHCb.
Awaiting truly precise single measurement to land knockout blow.

In all cases, more data and more precise measurements are required.

Backups