# Flavour Physics at Hadron Colliders

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

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Future Flavours, ICTS
29 April – 5 May 2022

# 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: $b\rightarrow c\tau\bar{\upsilon}$
- Conclusions

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

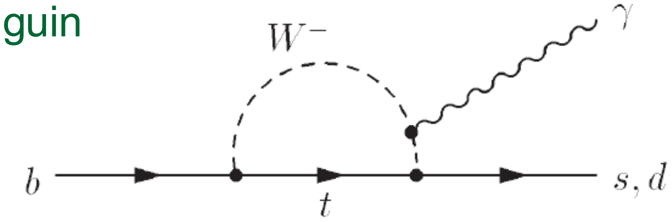
FCNC decays proceed through higher order diagrams → suppressed in SM and susceptible to New Physics contributions.

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

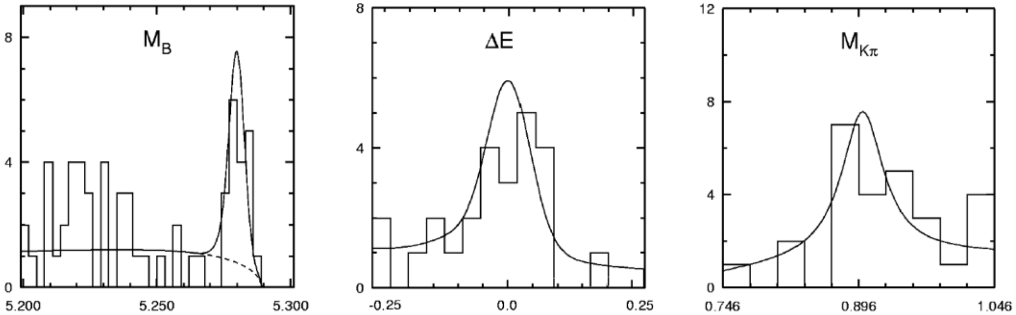
gluonic
Penguin

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

(EM) Radiative
penguin



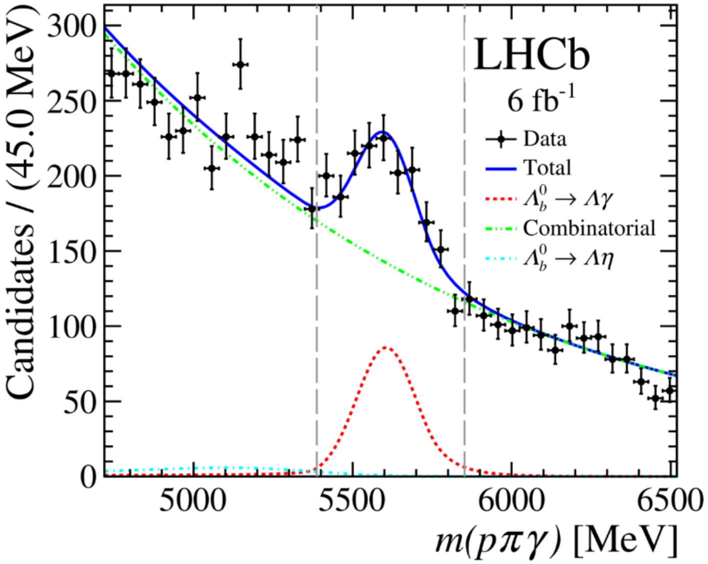
EM penguin first discovered by CLEO in B→K*(892)γ (BR~$10^{-5}$) [CLEO, PRL 71 (1993) 674].

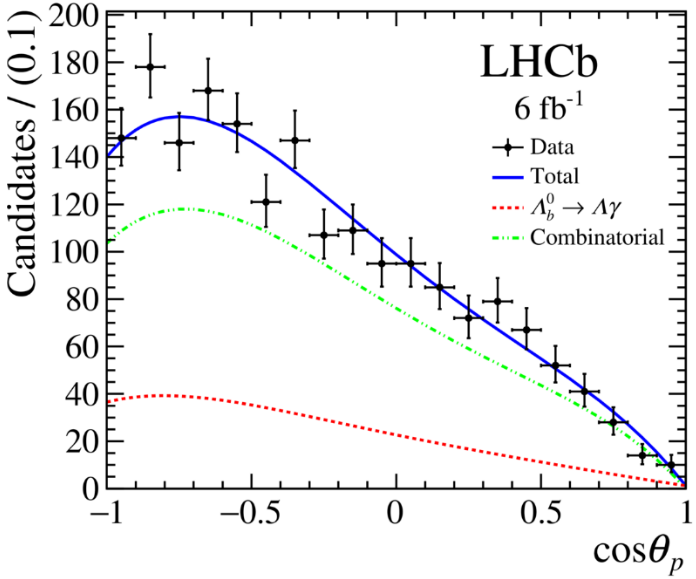


# Hadron machines can study b→sγ too

Despite the high background from combinatoric $\pi^0$ 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.





$\theta_p$ is angle between $p$ momentum and negative $\Lambda^0_b$ momentum in $\Lambda$ rest frame

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

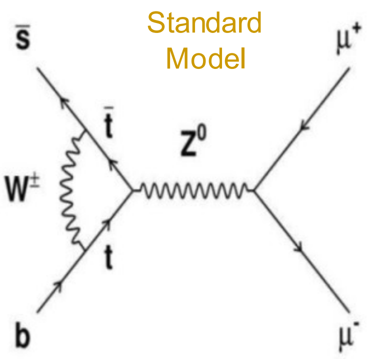
$$\boxed{\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})\,^{+0.04}_{-0.13}\,(\text{syst.}),}$$

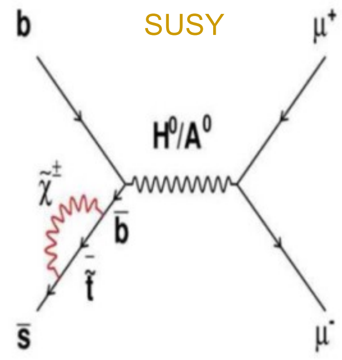
*i.e.* SM like

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

These decay modes can only proceed through suppressed loop diagrams.

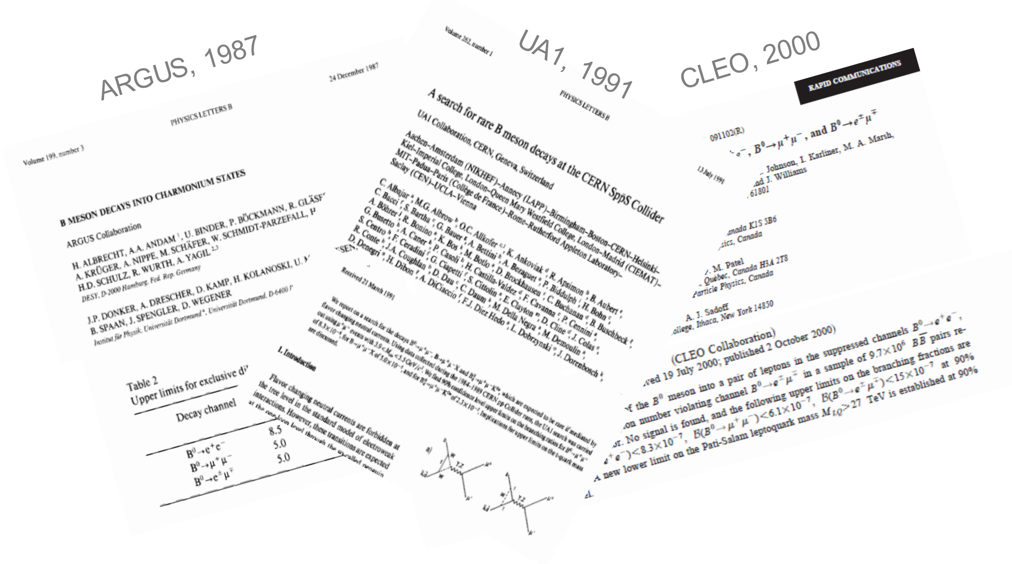
In SM they happen extremely rarely ($B_s \to \mu\mu$ ~$4 \times 10^{-9}$, $B^0 \to \mu\mu$ 30x lower), but the rate is very well predicted (*e.g.* <5% for $B_s \to \mu\mu$).





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.



Volume 199, number 3 PHYSICS LETTERS B 24 December 1987

B MESON DECAYS INTO CHARMONIUM STATES

ARGUS Collaboration

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A. KRÜGER, A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H
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Table 2
Upper limits for exclusive d

| Decay channel | |
|---|---|
| $B^0 \to e^+e^-$ | 8.5 |
| $B^0 \to \mu^+\mu^-$ | 5.0 |
| $B^0 \to e^\pm\mu^\mp$ | 5.0 |

Volume 262, number 1 PHYSICS LETTERS B

A search for rare B meson decays at the CERN SppS Collider

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–Boston–CERN–Helsinki–Kiel–Imperial College, London–Queen Mary Westfield College, London–Madrid (CIEMAT)–MIT–Padua–Paris (Collège de France)–Rome–Rutherford Appleton Laboratory–Saclay (CEN)–UCLA–Vienna

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Received 21 March 1991

1. Introduction

Flavor changing neutral currents are forbidden at the tree level in the standard model of electroweak interactions. However, these transitions are expected

RAPID COMMUNICATIONS

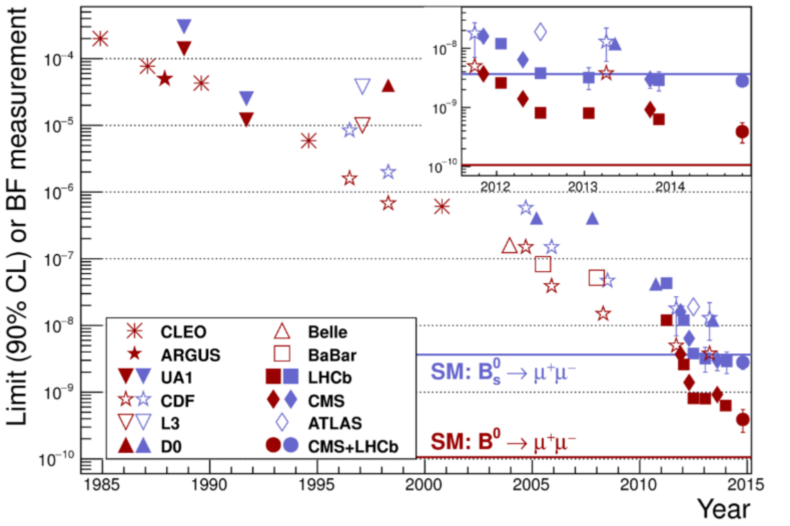
$B^0 \to \mu^+\mu^-$, and $B^0 \to e^\pm\mu^\mp$

Johnson, I. Karliner, M. A. Marsh, J. Williams

(CLEO Collaboration)

ved 19 July 2000; published 2 October 2000)

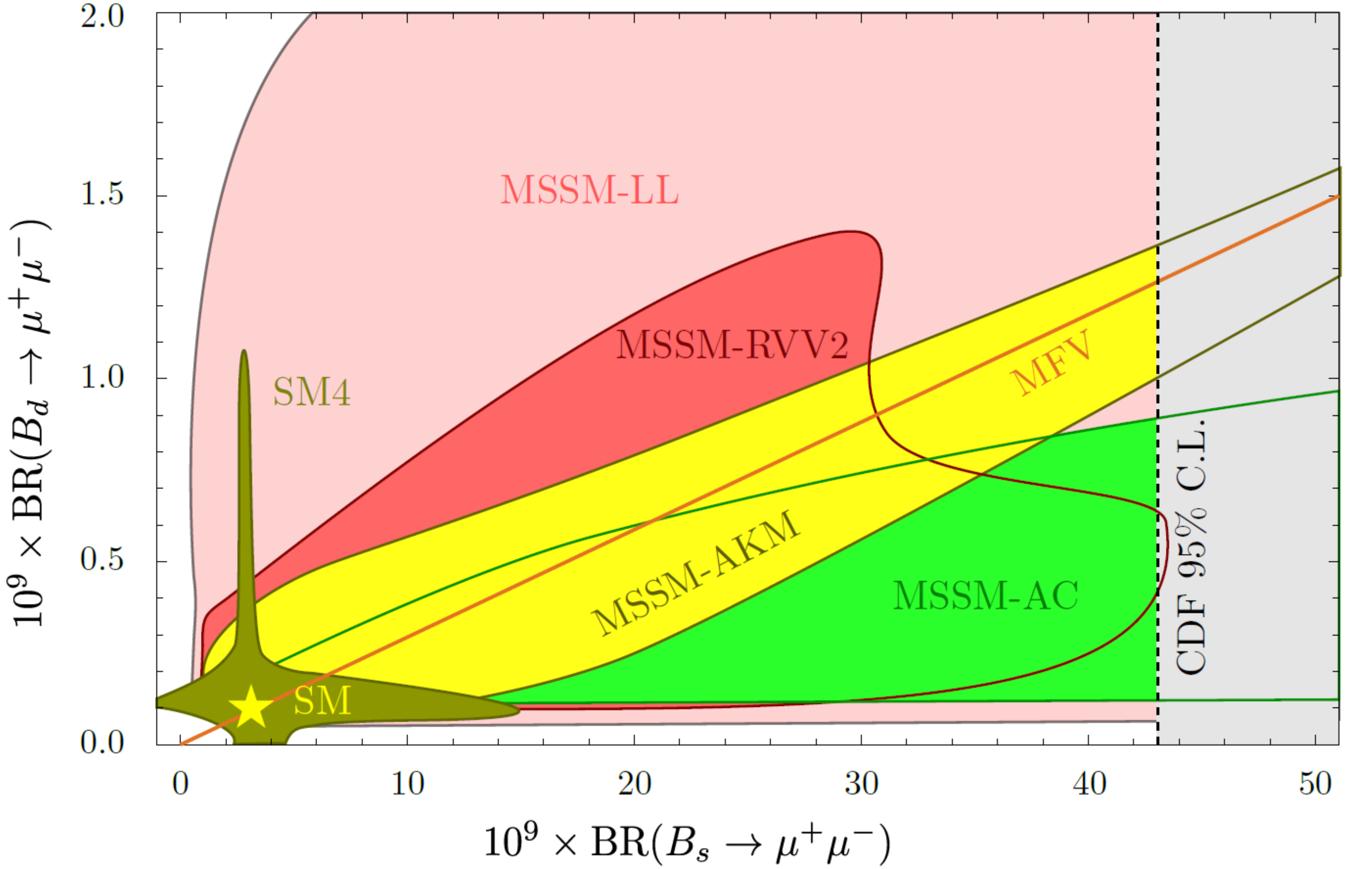
of the $B^0$ meson into a pair of leptons in the suppressed channels $B^0 \to e^+e^-$, on number violating channel $B^0 \to e^\pm\mu^\mp$ in a sample of $9.7 \times 10^6$ $B\bar{B}$ pairs re-. No signal is found, and the following upper limits on the branching fractions are $e^+e^-) < 8.3 \times 10^{-7}$, $B(B^0 \to \mu^+\mu^-) < 6.1 \times 10^{-7}$, $B(B^0 \to e^\pm\mu^\mp) < 15 \times 10^{-7}$ at 90% A new lower limit on the Pati-Salam leptoquark mass $M_{LQ} > 27$ TeV is established at 90%



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

# $B_s \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \mu^+\mu^-$: 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.



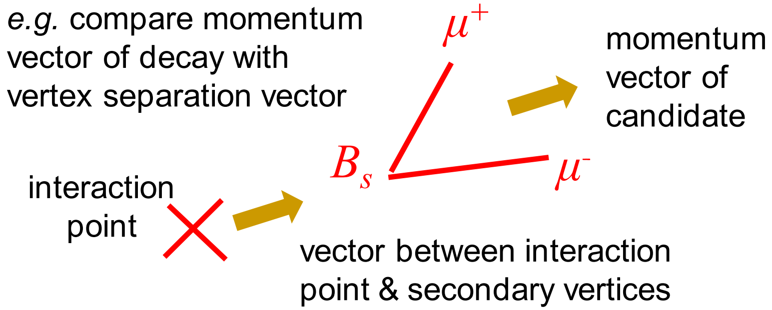
[D. Straub, arXiv:1012.3893]

# 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 $B_s \to \mu\mu$

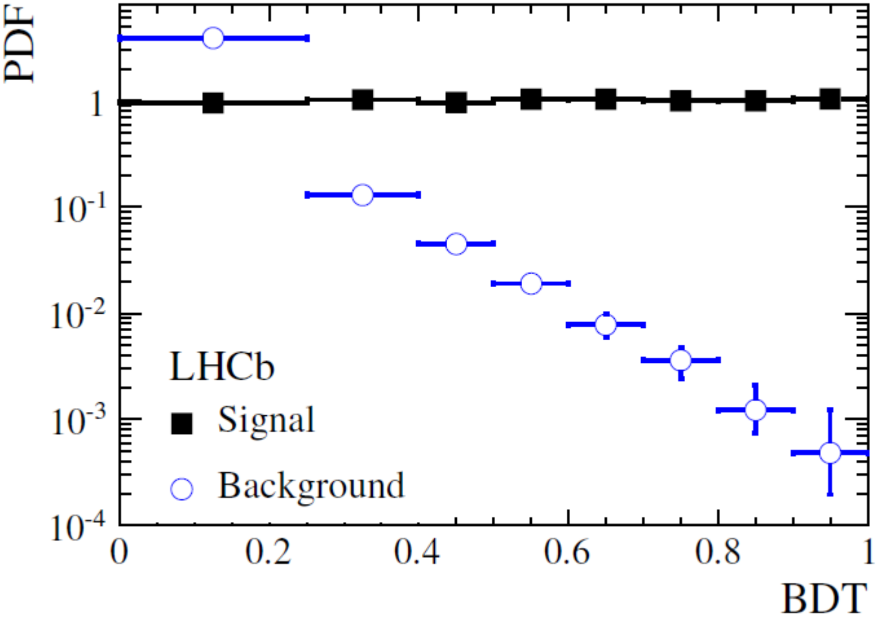


*e.g.* compare momentum vector of decay with vertex separation vector

momentum vector of candidate

interaction point

vector between interaction point & secondary vertices

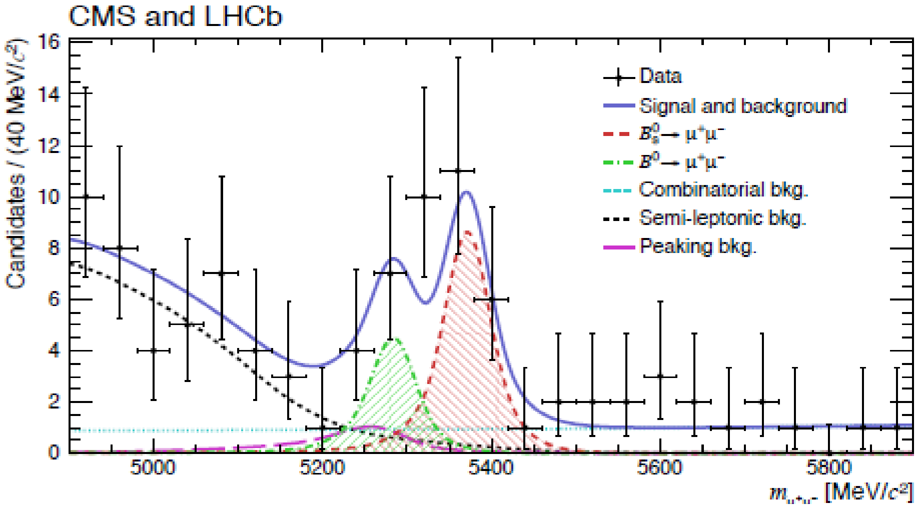


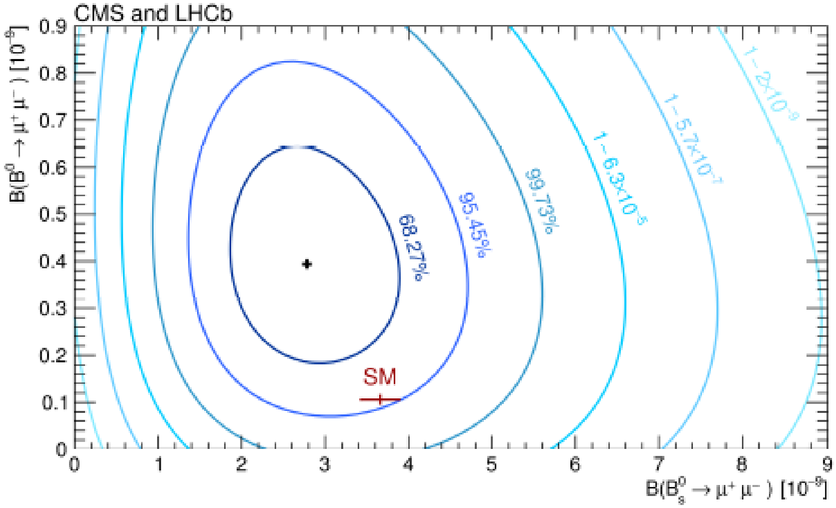
[LHCb, PRL 111 (2013) 101805]

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: $B_s \rightarrow \mu^+\mu^-$ 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…





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

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

[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 !

# LHCb $B^0_{(s)}\to\mu^+\mu^-$ run 1 & 2

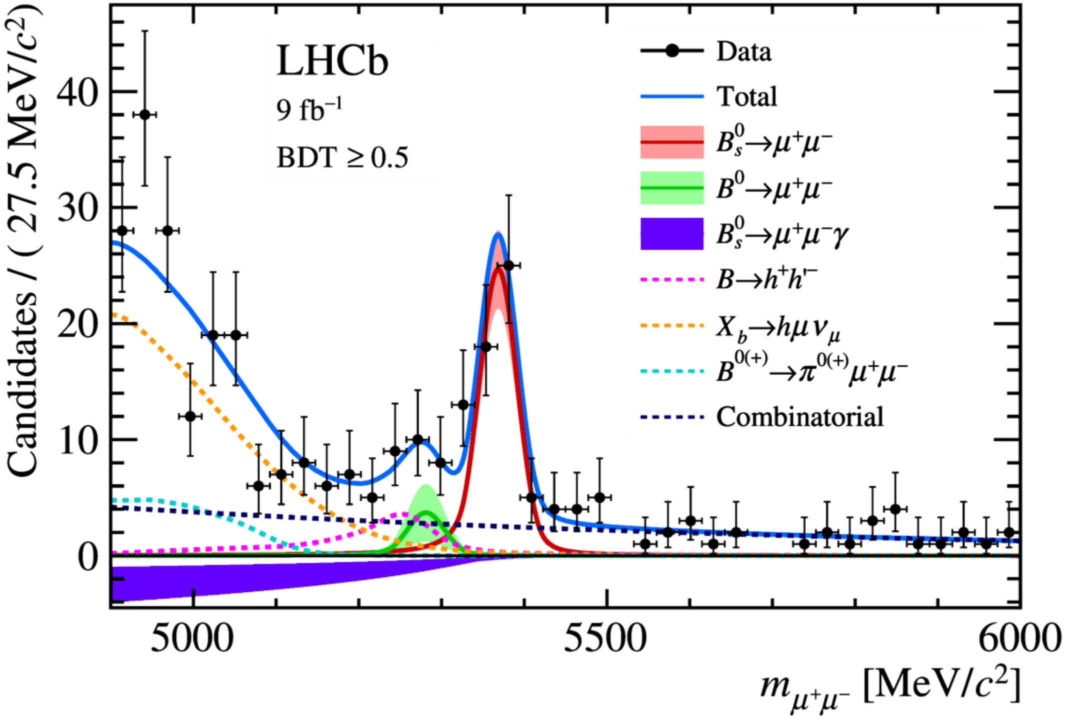
[PRL 128 (2022) 041801]

In Run 2 LHCb returned to this critical observable with an improved analysis (~50% combinatoric background than previously). Full data set now analysed.

- ~10 σ signal significance
- Precise measurement of branching fraction

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

- No evidence yet of the corresponding $B^0$ decay ('bump' has 1.7σ significance).



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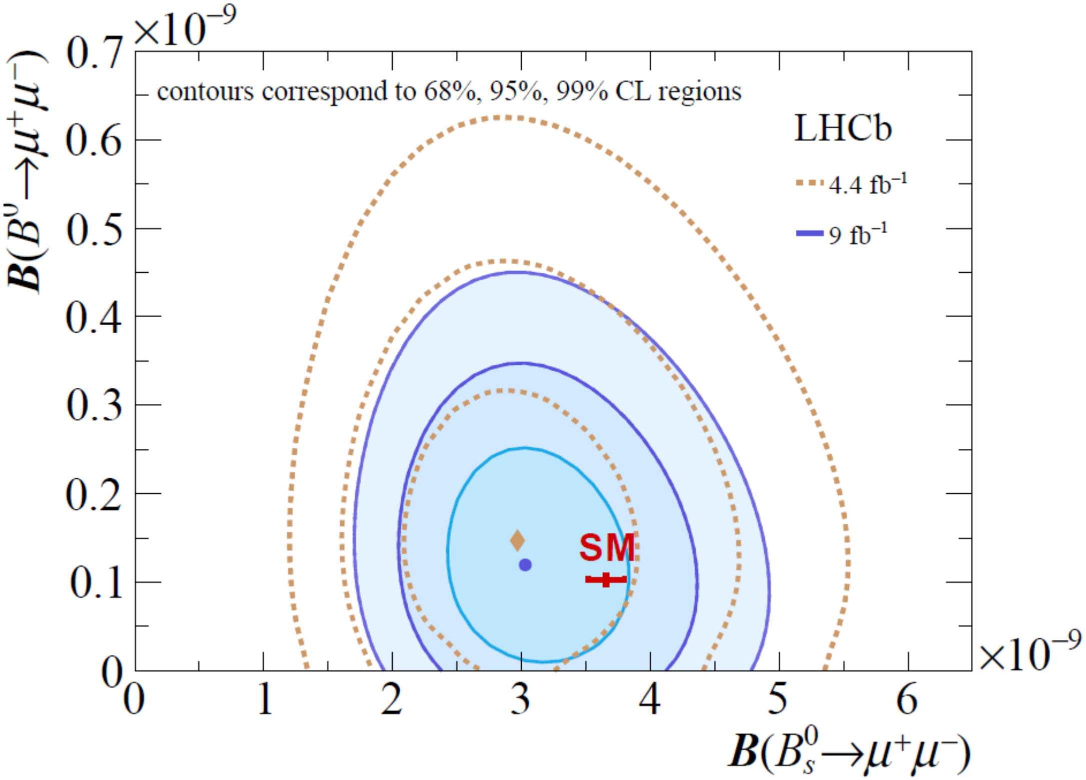


# CMS $B^0_{(s)}\to\mu^+\mu^-$ run 2 update

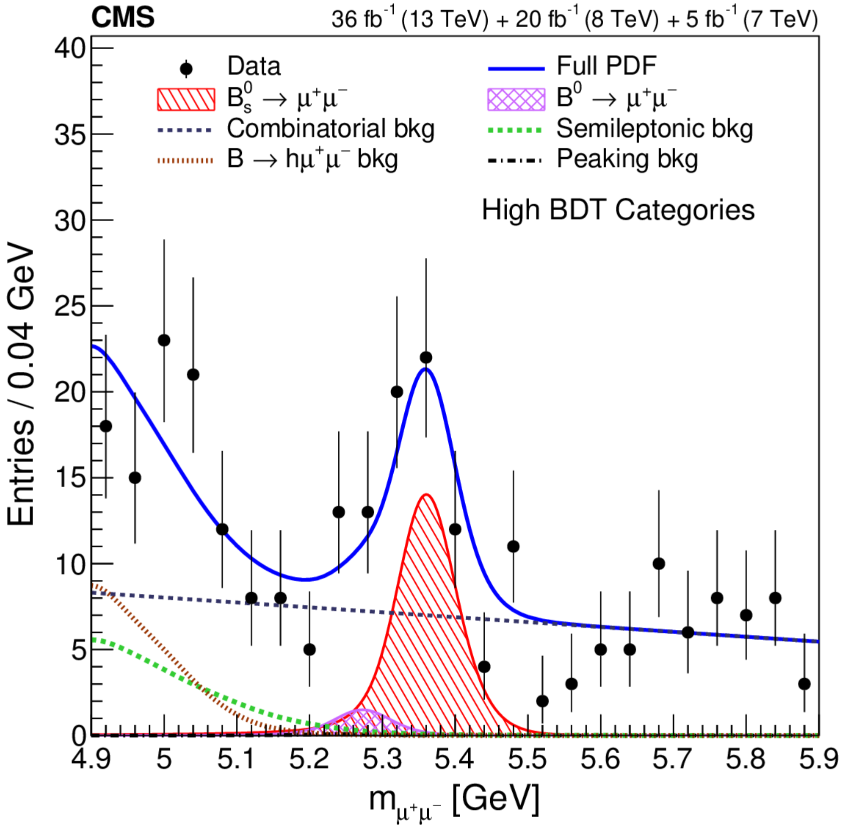
[JHEP 03 2020 188]

CMS have now extended their analysis to 2016 from Run 2 data taking.

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) =$$
$$[2.9^{+0.7}_{-0.6}\,(\mathrm{exp}) \pm 0.2\,(\mathrm{frag})] \times 10^{-9}$$

The 'frag' systematic concerns knowledge of ratio of production of $B_s$ to $B^+$ mesons (*i.e.* fragmentation). This enters because of $B^+\to J/\psi K^+$ normalisation mode.

Measured by LHCb and extrapolated into kinematic acceptance of CMS.



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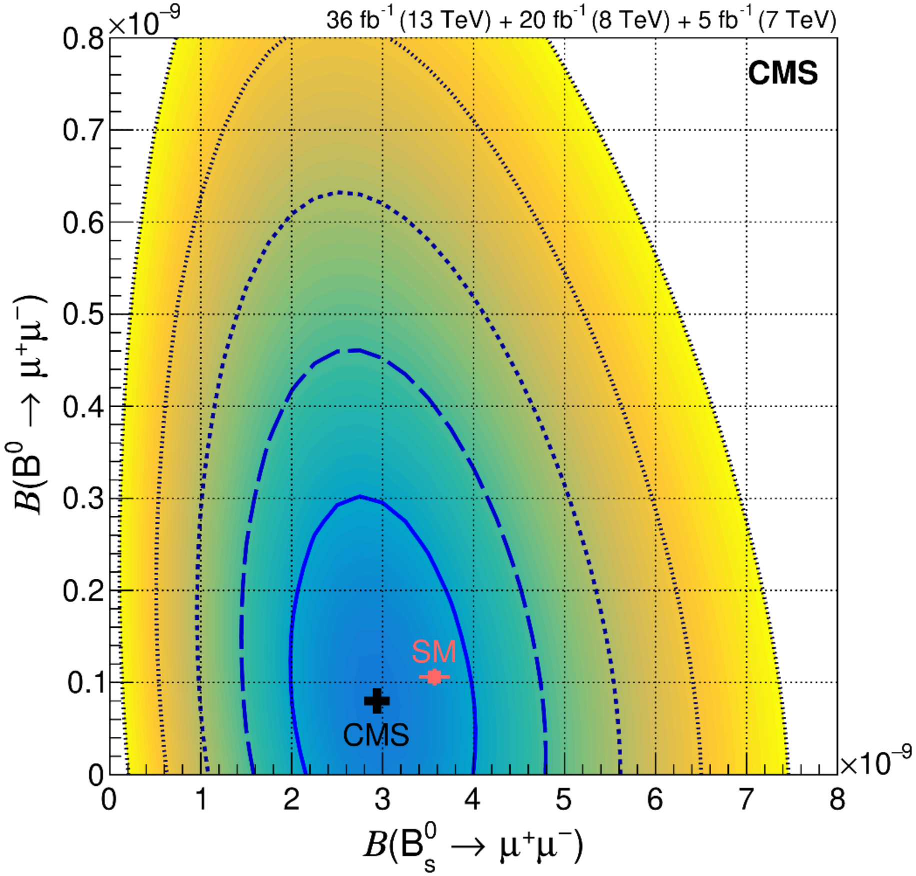


# ATLAS $B^0_{(s)} \rightarrow \mu^+\mu^-$ run 2 update

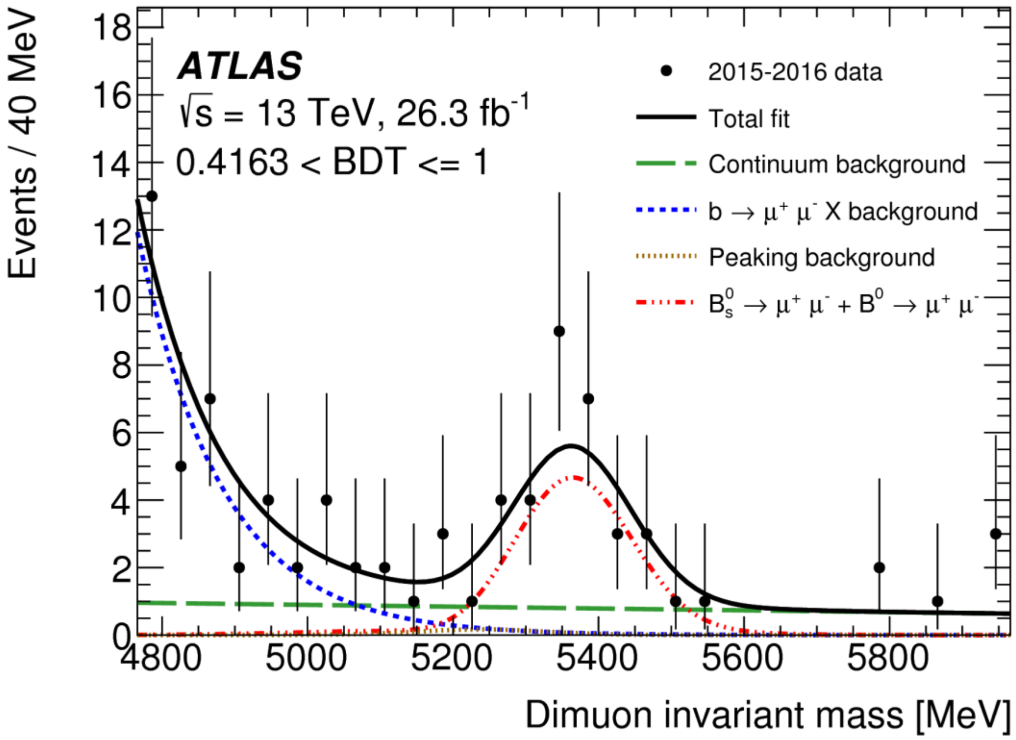
[JHEP 04 (2019) 098]

ATLAS have now extended their analysis to 2015 & 2016 from Run 2 data taking.

When combined with Run-1 result [EPJ C 76 (2016) 513].

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

Note that mass resolution does not allow for sensitivity to individual $B^0$ and $B^0_s$ peaks.



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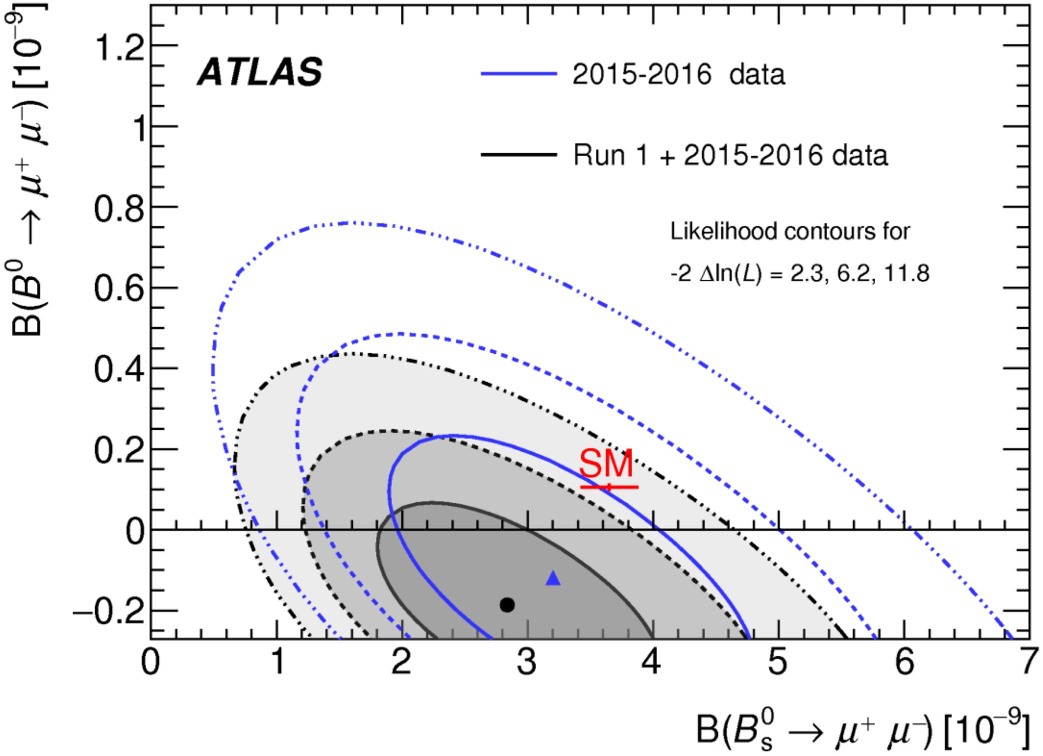
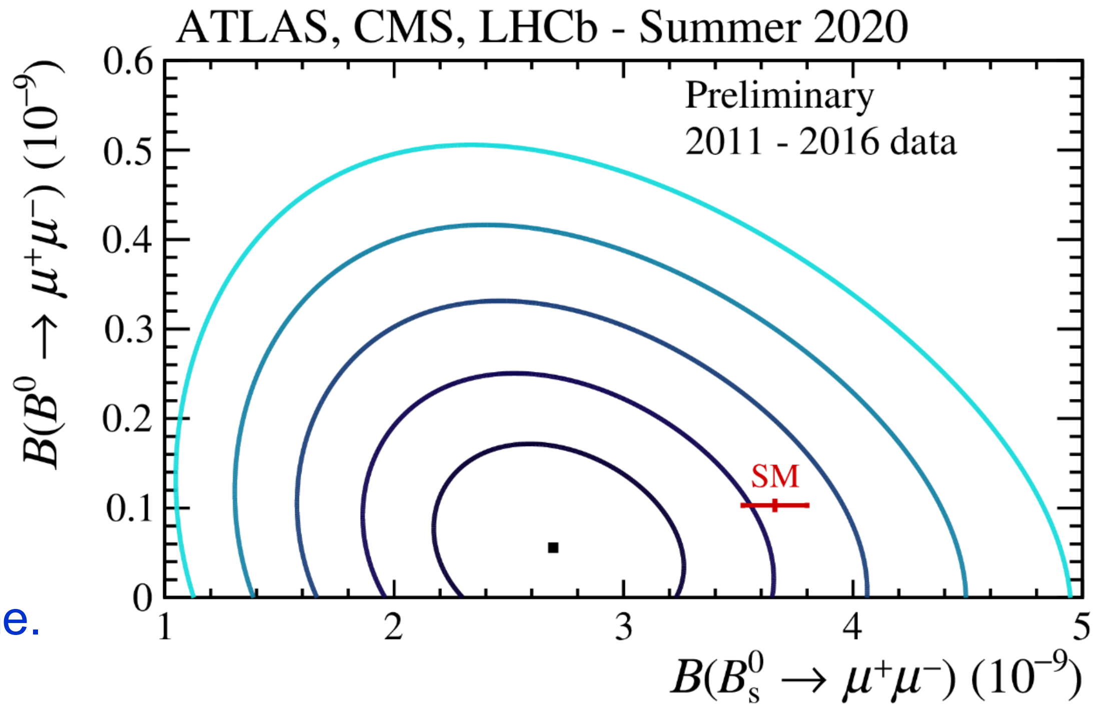


# LHC $B^0_{(s)} \rightarrow \mu^+\mu^-$ combination

[CMS PAS BPH-20-003; LHCb-CONF-2020-002; ATLAS-CONF-2020-049]

A combination has been performed of the B→μμ results from the three experiments. (NB: for LHCb this only makes use of data collected up to 2016 [PRL 118 (2017) 191801], which contains a result less sensitive, though qualitatively similar, to the final one. )

- Good consistency between experiments;
- $B_s \rightarrow \mu\mu$ is somewhat low compared to SM;
- No sign of $B^0 \rightarrow \mu\mu$ yet, but this is expected given current sensitivity;
- Overall consistency with SM is 2.1σ in $B^0$ vs $B_s$ plane.



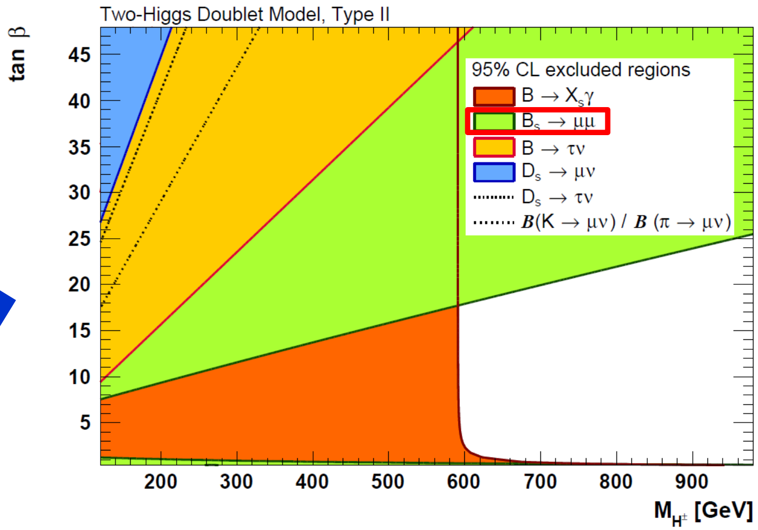
Worth watching carefully as more precise results emerge !

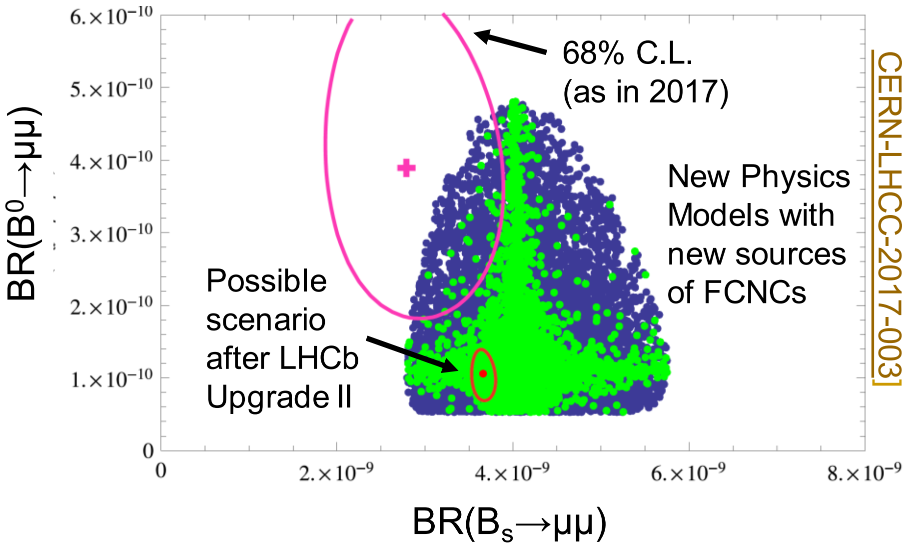
# Lessons from, & future of, $B^0_{(s)}\to\mu\mu$ measurements

- 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].





68% C.L. (as in 2017)

New Physics Models with new sources of FCNCs

Possible scenario after LHCb Upgrade II

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

- Better measurements are *essential*, as we are still far from 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 $B_s \rightarrow \mu^+\mu^-$

Remarkably, the sample of $B_s \rightarrow \mu\mu$ 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.

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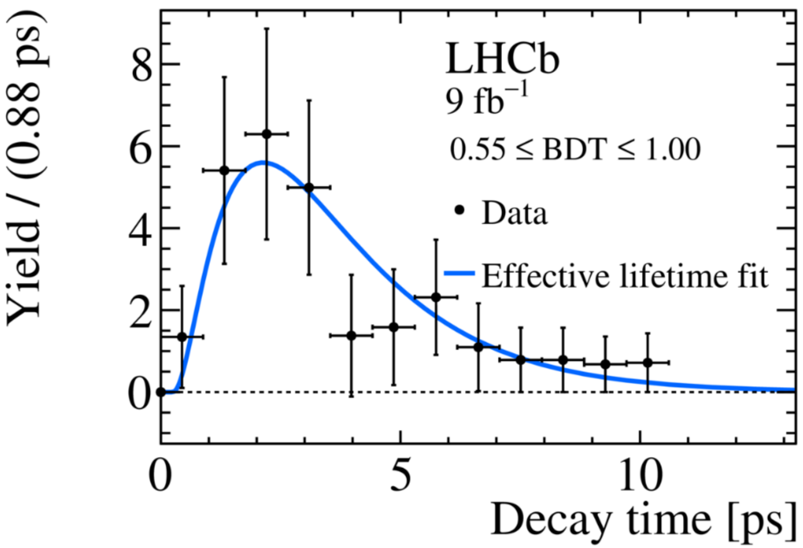
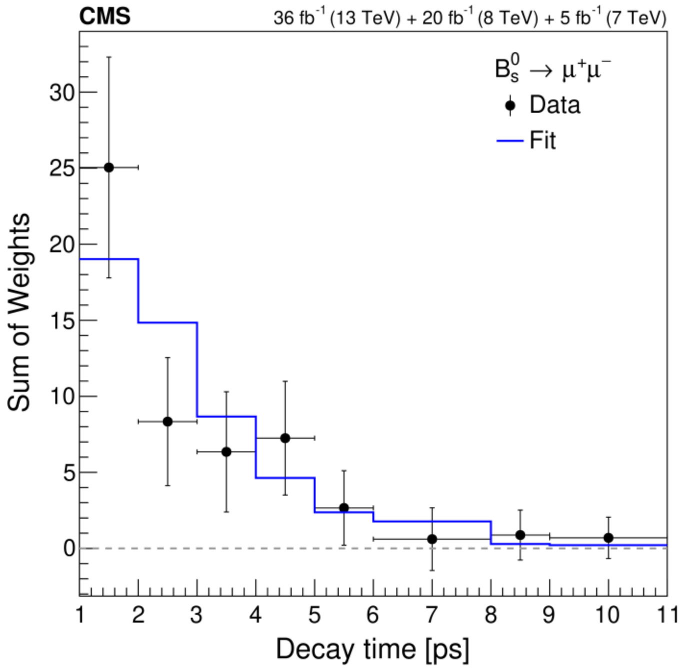
Proof-of-principle measurements conducted by LHCb and CMS:



[PRL 128 (2022) 041801]

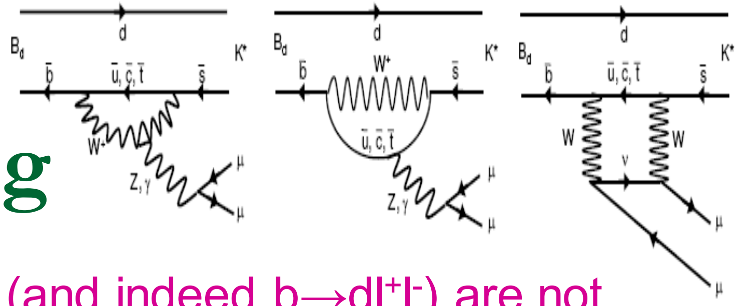


[JHEP 04 (2020) 188]

During HL-LHC era these will reach very interesting levels of precision.

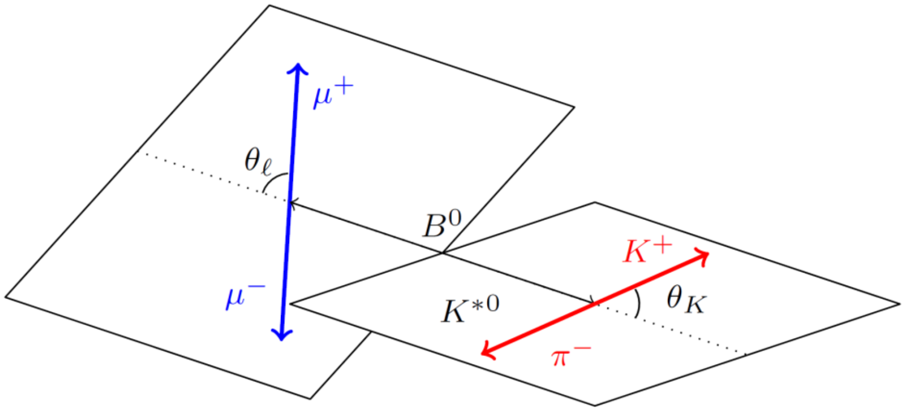
One may also dream of performing flavour-tagged CP asymmetry measurements !

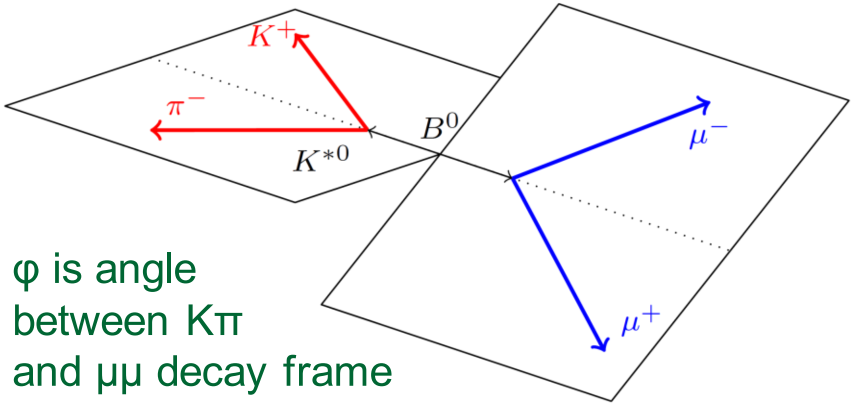
# $B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



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 $K^{*0} \rightarrow K^+ \pi^-$.

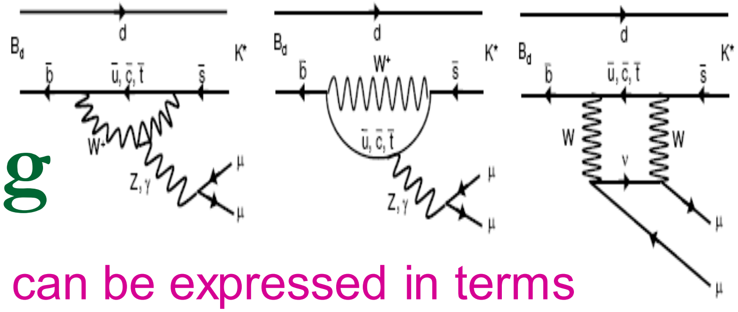




φ is angle between Kπ and μμ decay frame

Four-body final state can be characterised in terms of three angles, $\Theta_l$, $\theta_K$ and $\varphi$, & $q^2$, & 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):

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$

$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$

$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

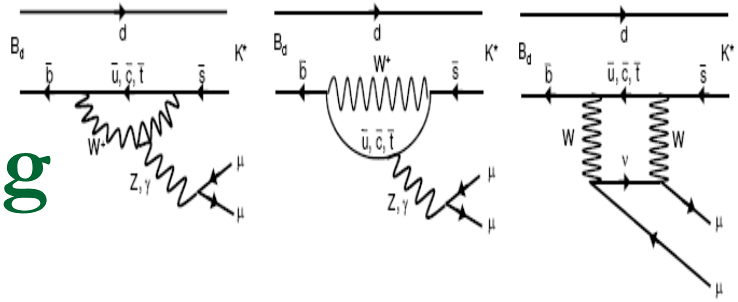
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

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

# $B^0 \rightarrow K^* l^+ l^-$ 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:

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

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

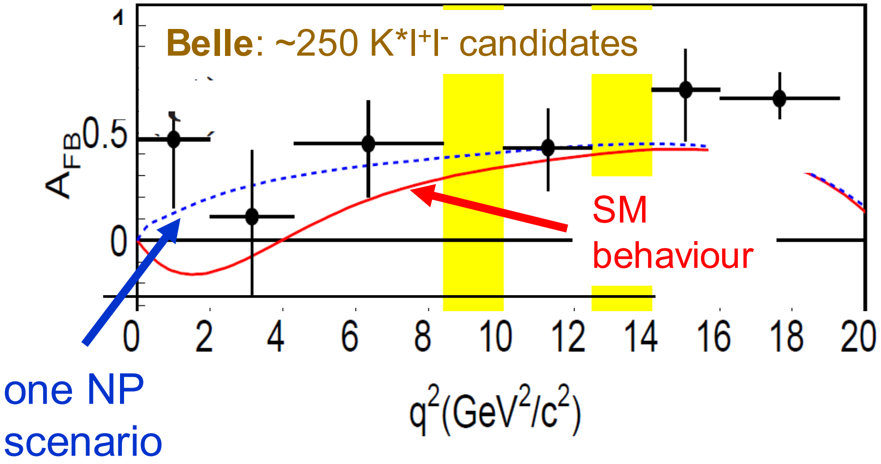
( LHCb definitions, see [JHEP 02 (2016) 104] )

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 !

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

The B factories studied $B^0 \to K^* l^+ l^-$ 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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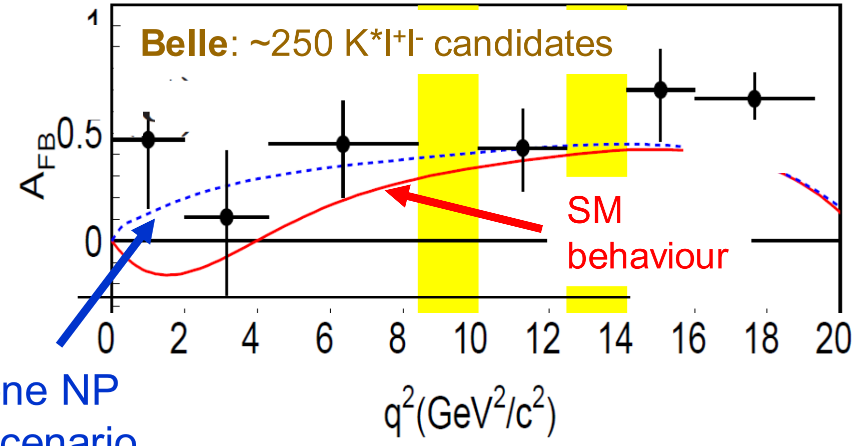
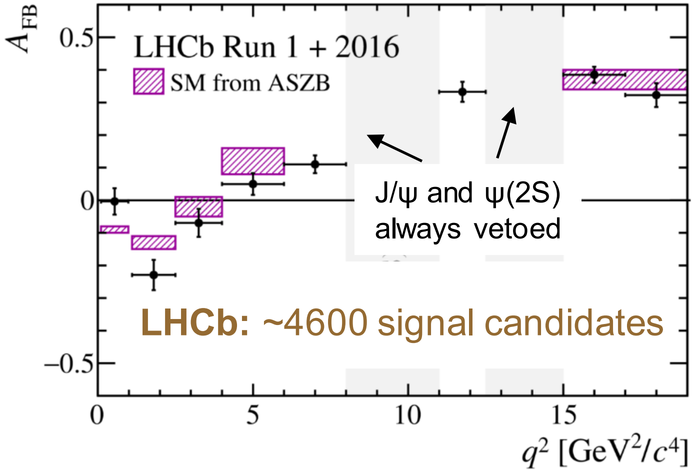


**Belle**: ~250 $K^* l^+ l^-$ candidates

SM behaviour

one NP scenario

[PRL 125 (2020) 011802]



J/ψ and ψ(2S) always vetoed

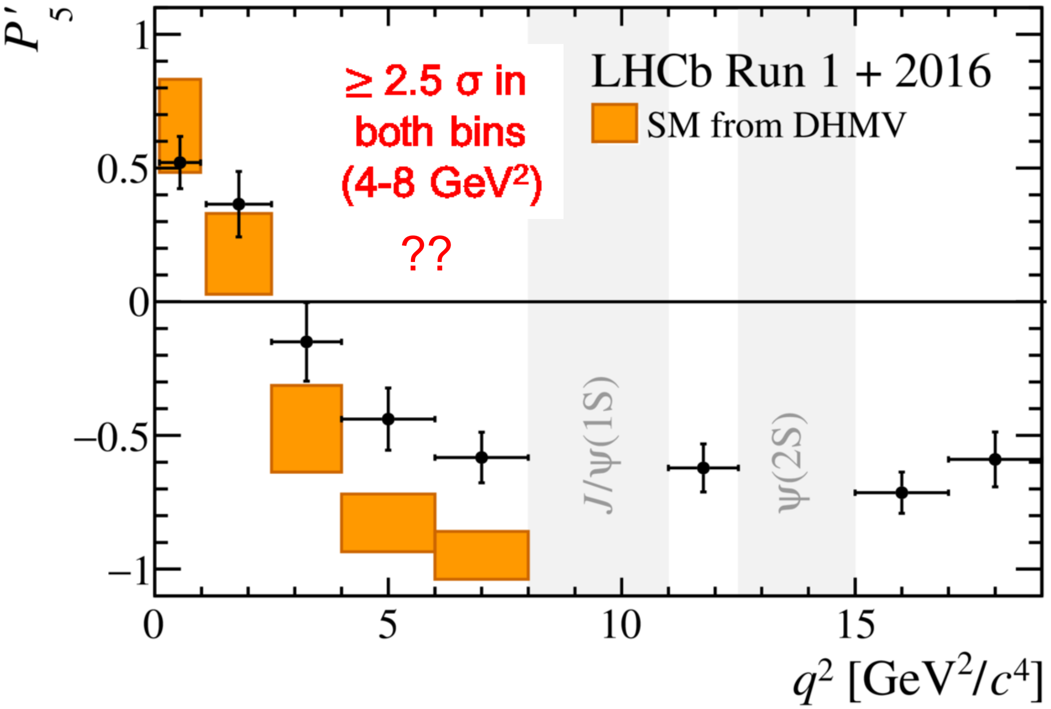
**LHCb:** ~4600 signal candidates

(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.)

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.



≥ 2.5 σ in both bins (4-8 GeV²)

??

[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].

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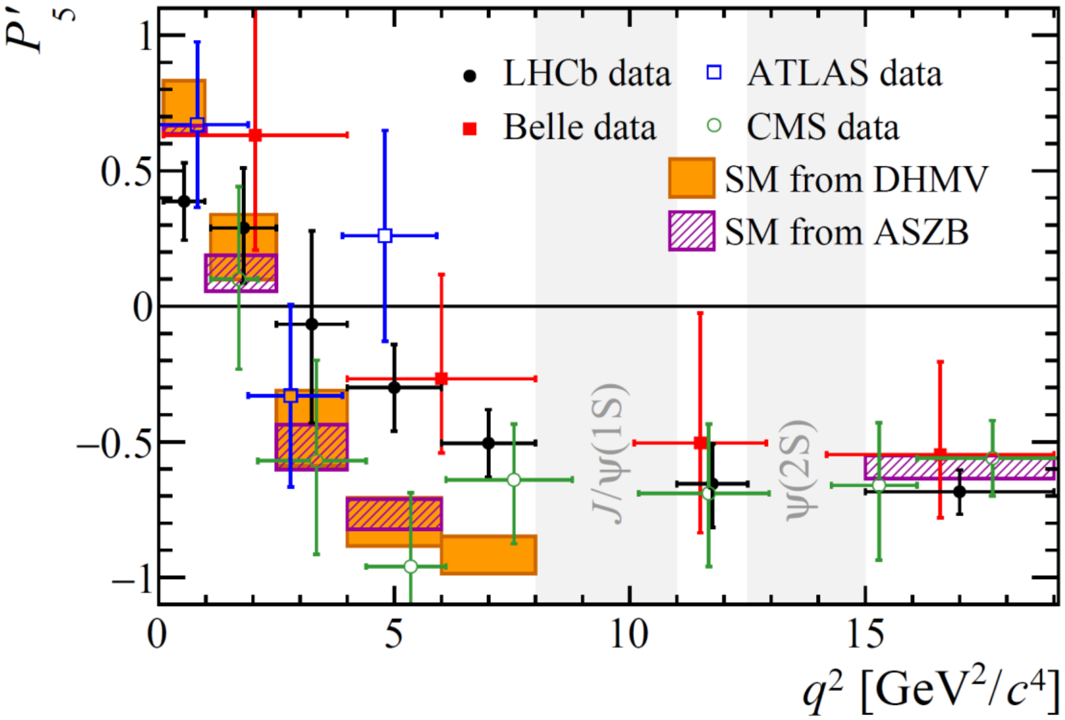
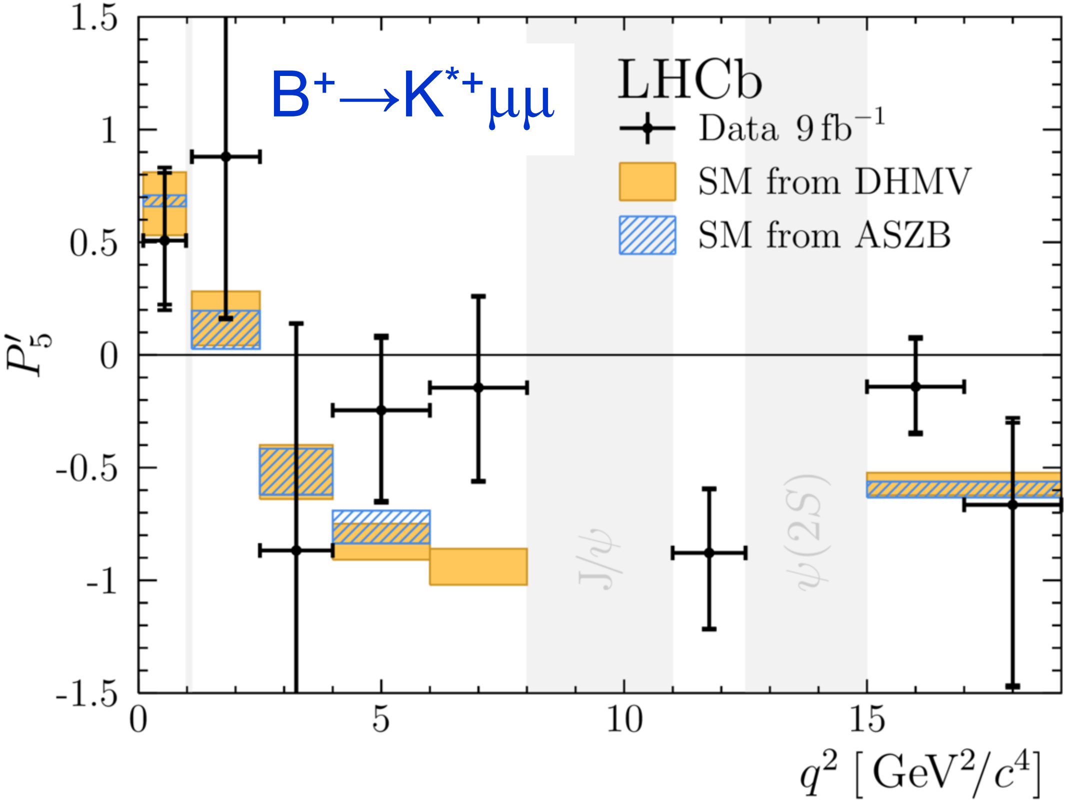


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

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…

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

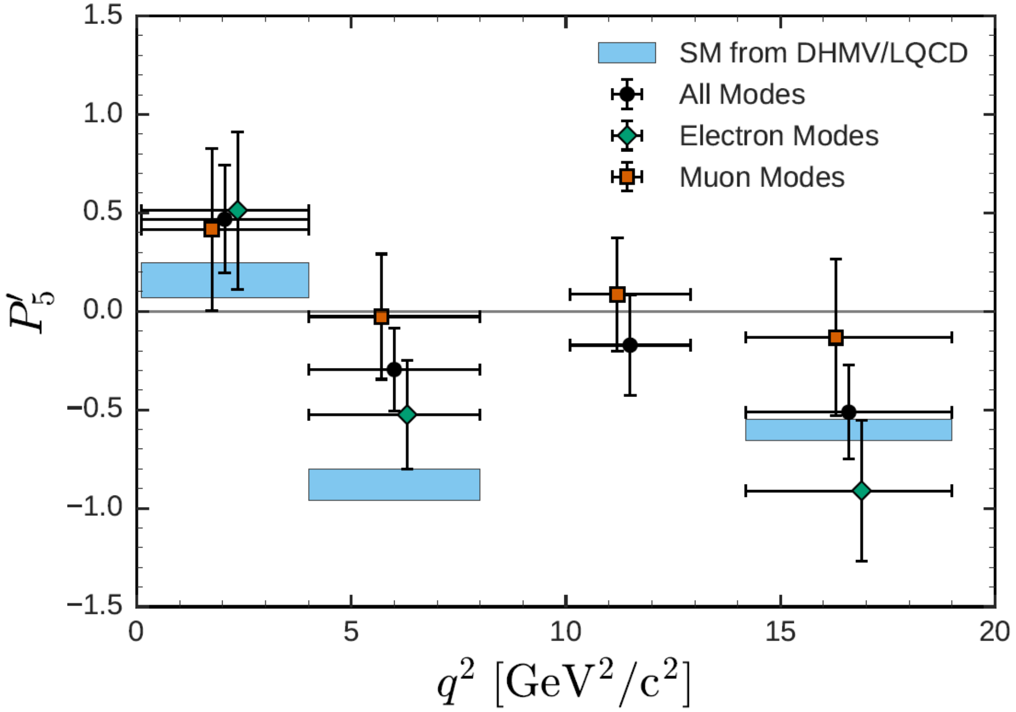
Measurements of the same / similar observables in different channels (*e.g.* $B^+ \rightarrow K^{*+}\mu\mu$ [PRL 126 (2021) 161802], $B_s \rightarrow \phi\mu\mu$ [JHEP 11 (2021) 043]) although less precise, provide a qualitatively similar picture.



[LHCb, PRL 126 (2021) 161802]

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

There is another interesting observation. All the LHC measurements are made with dimuons, whereas the Belle result comes from dimuons and dielectrons. Individual results are also available for each lepton final state.



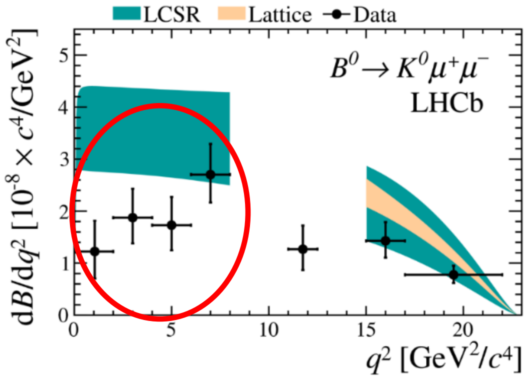
[Belle, PRL 118 (2017) 111801]

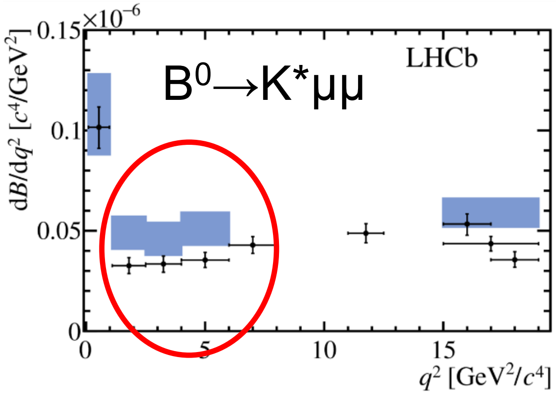
In the bin of interest it is the dimuon result that is most discrepant, although with the small sample size there is consistency between both final states.

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

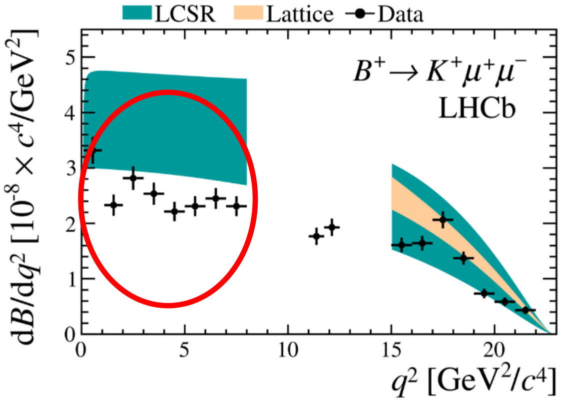
$P_5'$ is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

JHEP 06 (2014) 133



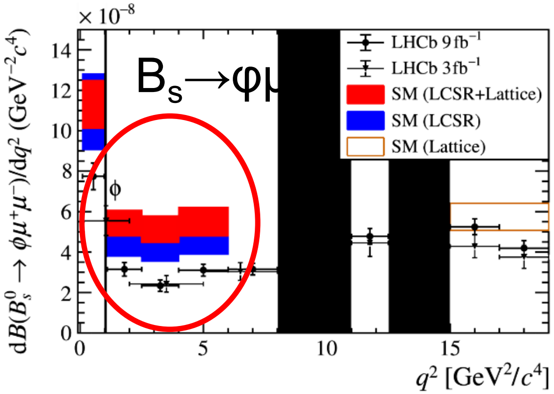


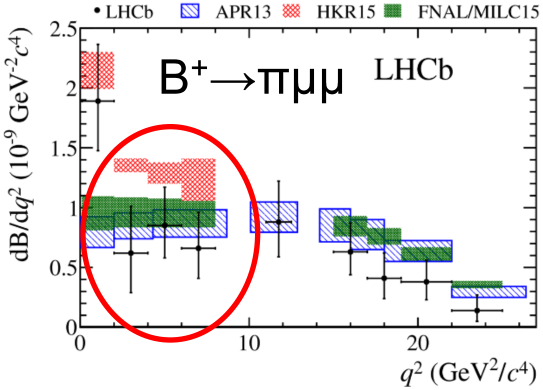
JHEP 04 (2017) 142



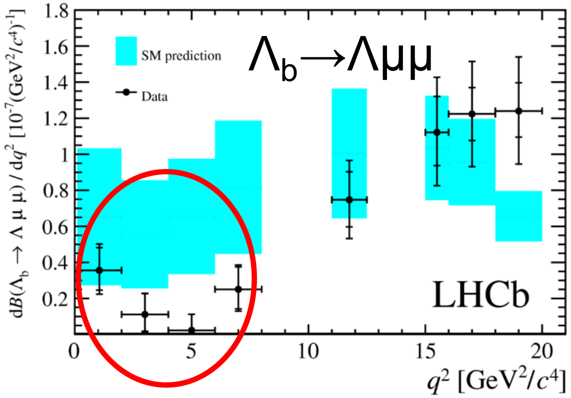
JHEP 06 (2014) 133

PRL 127 (2021) 151801





JHEP 10 (2015) 034



JHEP 06 (2015) 009

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 ?

# $B^0 \to K^* l^+ l^-$ 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 $b \to s\mu^+\mu^- / b \to s e^+ e^-$ for ~$1 < q^2 < 6$ GeV$^2$ for both $B \to K l^+ l^-$ ($R_K$) and $B^0 \to K^* l^+ l^-$ ($R_{K^*}$). In SM we expect 1 for both.

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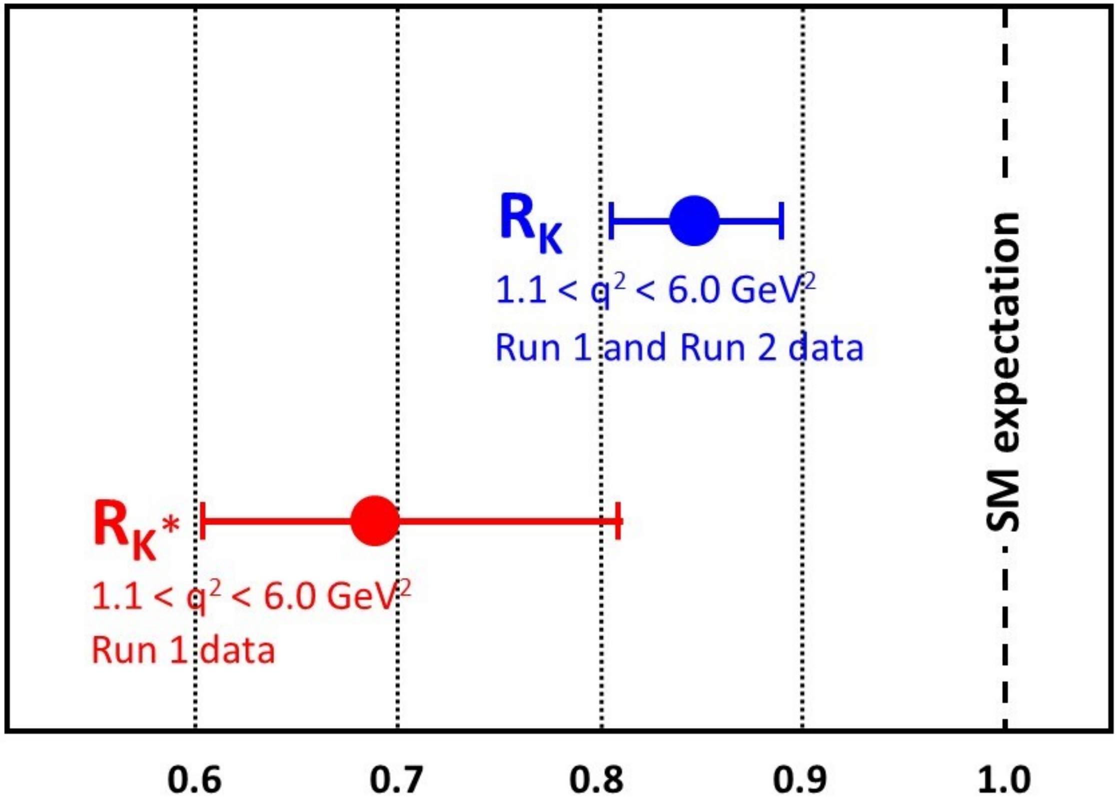
3.1 σ
below SM

~2.5 σ
below SM



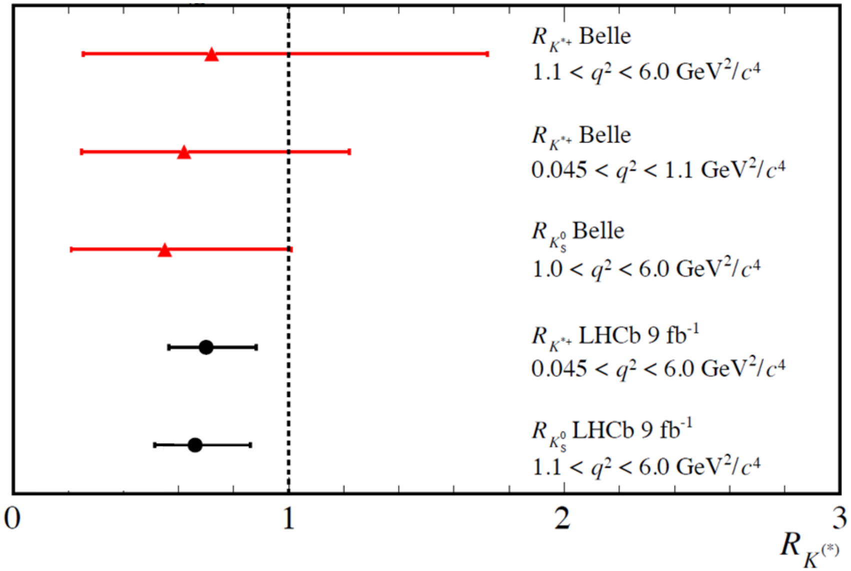
[arXiv:2103.11769] [JHEP 08 (2017) 055]

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

The rather precise $R_K$ and $R_{K^*}$ measurements have been complemented by studies made in other modes, with lower precision, but qualitatively similar results.

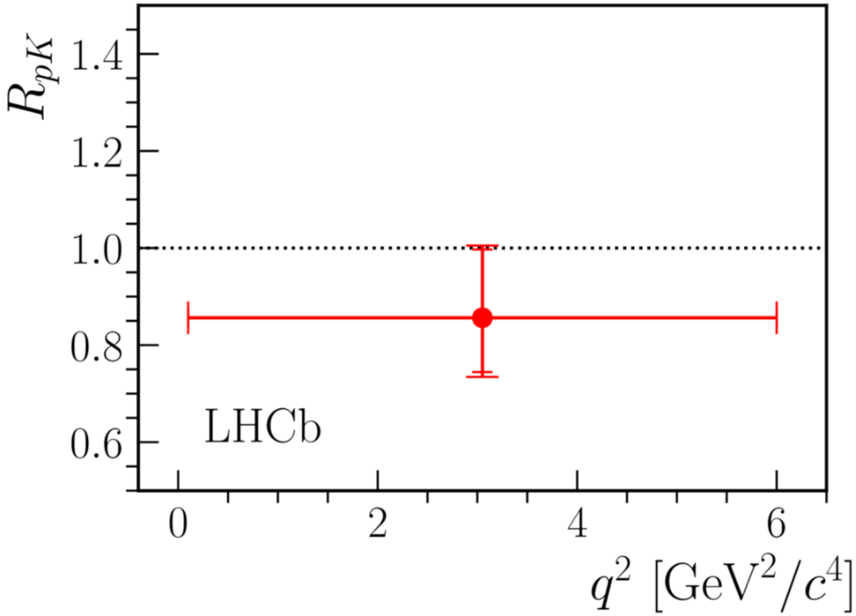
$B^+ \to K^{*+} l^+ l^-$ and $B^0 \to K_s^0 l^+ l^-$

[arXiv:2110.09501]



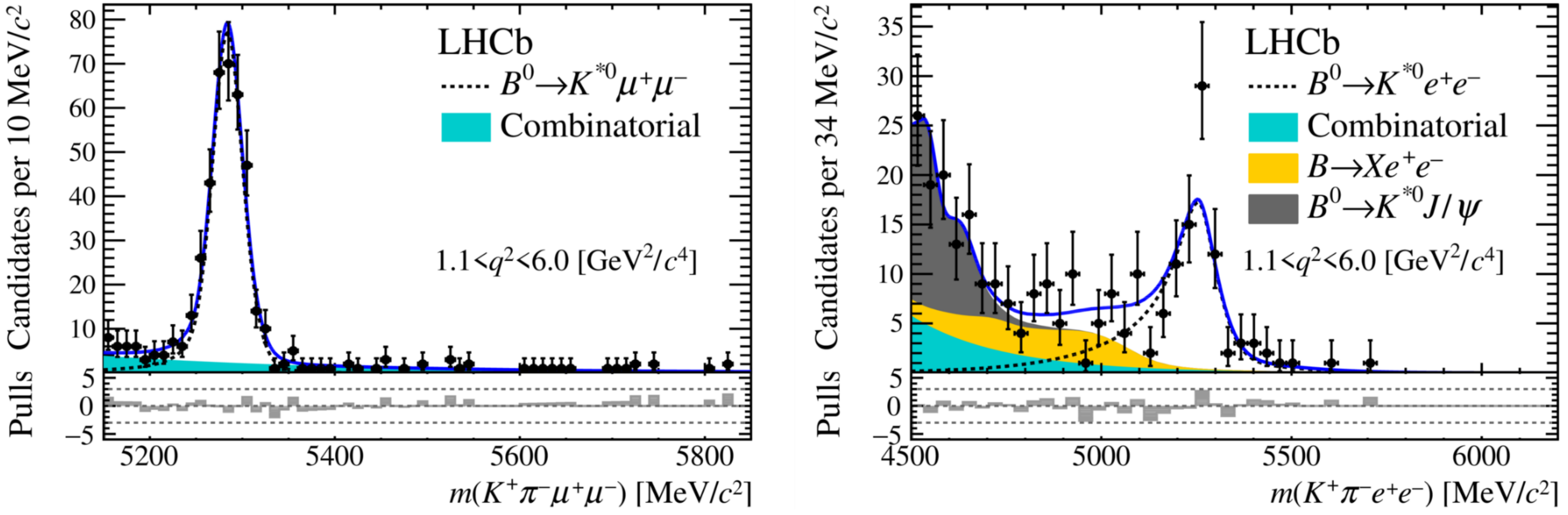
$\Lambda_b^0 \to p K^- l^+ l^-$

[JHEP 05 (2020) 040]



# $b \rightarrow s l^+ l^-$ lepton universality tests – more about the measurements (with focus on $R_{K*}$) [JHEP 08 (2017) 055]

Precision is limited by size of electron sample, which is ~100 decays in bin of measurement (muon sample is around 3-4 x larger).



# b→sl$^+$l$^-$ lepton universality tests – more about the measurements (with focus on R$_{K*}$) [JHEP 08 (2017) 055]

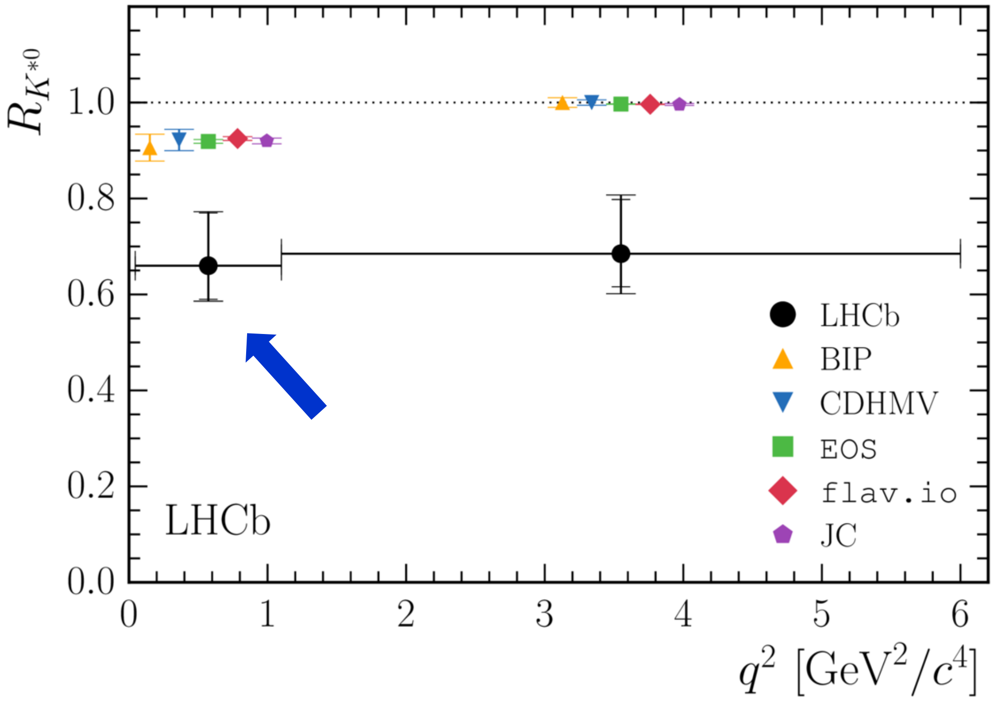
Isn't measurement vulnerable to knowledge of lepton id efficiency? No, because R$_{K*}$ is normalised to B$^0$→K*J/ψ (and its known J/ψ→l$^+$l$^-$ obeys lepton universality) which makes all such dependencies second order.

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))}$$

Nonetheless, checks are made by measuring whether the relevant ratios for B$^0$→K*J/ψ and indeed B$^0$→K*ψ(2S) are compatible with unity – they are.

# $b \rightarrow s l^+ l^-$ lepton universality tests – more about the measurements (with focus on $R_{K*}$) [JHEP 08 (2017) 055]

Measurements are made below J/ψ – it is the low $q^2$ region where odd behaviour has been seen in other studies. High $q^2$ measurements will come in future.



various calculations of SM prediction

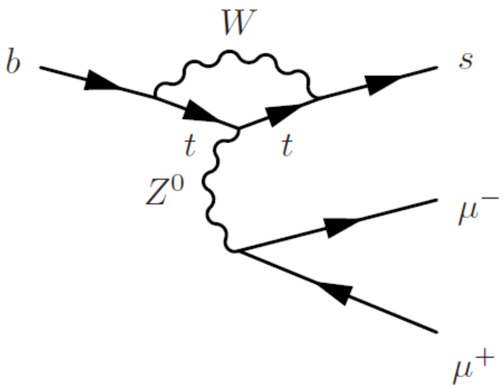
However a second $R_{K*}$ measurement exists at very low $q^2$. This also is >2σ low w.r.t. SM. Interesting! However, any deviation in this region is harder to explain by New Physics (see later), as 'photon pole' dominates decay process.

# Analysing FCNC data in context of effective field theory

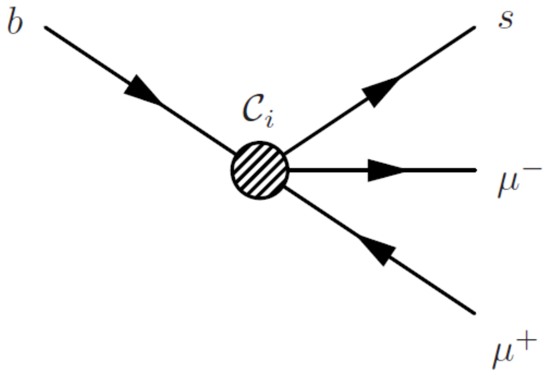
The $b \to s l^+ l^-$ results can be qualitatively ‘explained’ by hypothesising that $b \to s e^+ e^-$ largely obeys the SM, but New Physics intervenes for $b \to s \mu^+ \mu^-$ at low $q^2$.

A more quantitative analysis can be made 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.

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

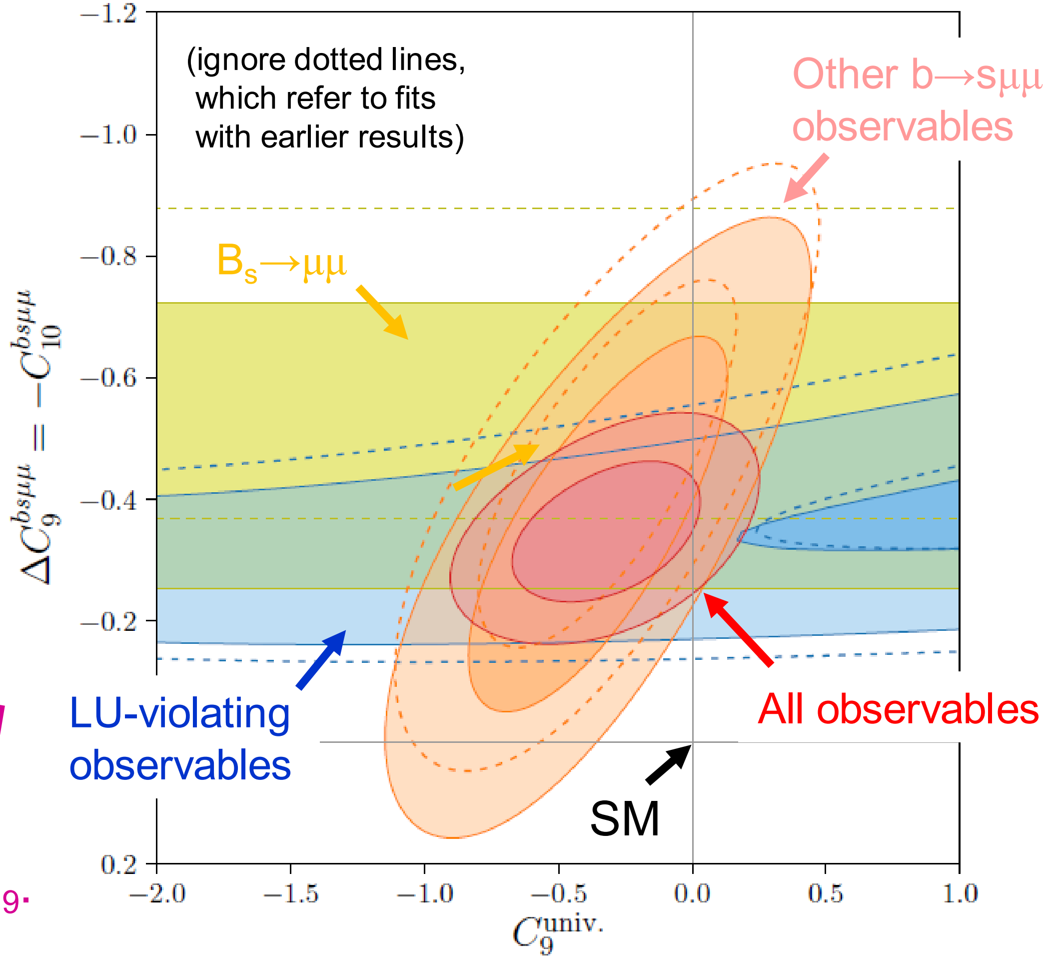
| Transition | $C_7^{(\prime)}$ | $C_9^{(\prime)}$ | $C_{10}^{(\prime)}$ | $C_{S,P}^{(\prime)}$ |
|---|---|---|---|---|
| $b \rightarrow s\gamma$ | X | | | |
| $b \rightarrow \ell^+\ell^-$ | | | X | X |
| $b \rightarrow s\ell^+\ell^-$ | X | X | X | |

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

# Current status of fits to FCNC data

- Ensemble of *all* FCNC data gives a fairly consistent picture
- Best fit is inconsistent with SM by more than 5σ !
- *BUT*, this assumes taking uncertainties on SM predictions for, *e.g.*, $P_5'$ at face value.
- One typical fit allows for NP shift for muons alone of opposite sign in $C_9$ & $C_{10}$, & a modest lepton-universal shift in $C_9$.

[Altmannshofer, Stangl, arXiv:2103.13370]



(ignore dotted lines, which refer to fits with earlier results)

# Current status of fits to FCNC data

[Altmannshofer, Stangl, arXiv:2103.13370]

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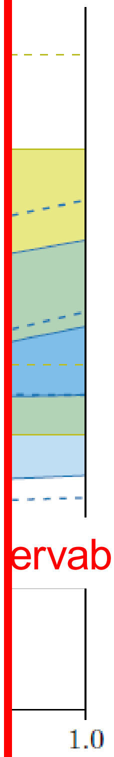


Popular explanations of these effects include:

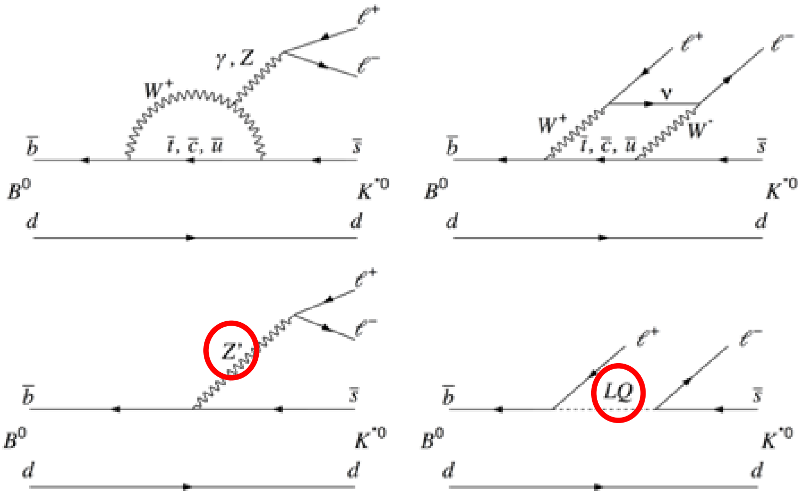
- Flavour-changing Z’

*e.g.* [Altmannshofer & Straub, EPJC 73 (2013) 2646], [Gauld, Goertz & Haisch, PRD 89 (2014) 015005], [Altmannshofer & Straub, EPJC 75 (2015) 382], [Crivellin *et al.*, PRD 92 (2015) 054013].

- Leptoquarks

*e.g.* [Hiller & Schmaltz, PRD 90 (2014) 054014], [Alonson *et al.*, arXiv:1505.05164], [Fajfer & Ksnik, PLB 755 (2016) 270].

Standard Model



New Physics

These may be within reach of direct detection at ATLAS & CMS.

# $b\rightarrow(s,d)l^+l^-$ : near-term experimental prospects

New experimental input is mandatory to conclude on the $b\rightarrow sl^+l^-$ anomalies.

- LHCb Run-2 dimuon results on $P_5$' and other optimal observables, and equivalent studies with dielectrons.
- LHCb full Run-2 results on $R_{K^*}$ , measurements in different $q^2$ regions, and with additional modes *e.g.* $B_s\rightarrow\varphi l^+l^-$ .
- $R_K$ and $R_{K^*}$ results from other LHC experiments.
- Results from Belle II.

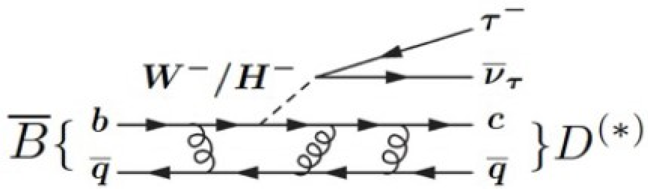
Most valuable will be *theoretically clean* observables that test lepton universality.

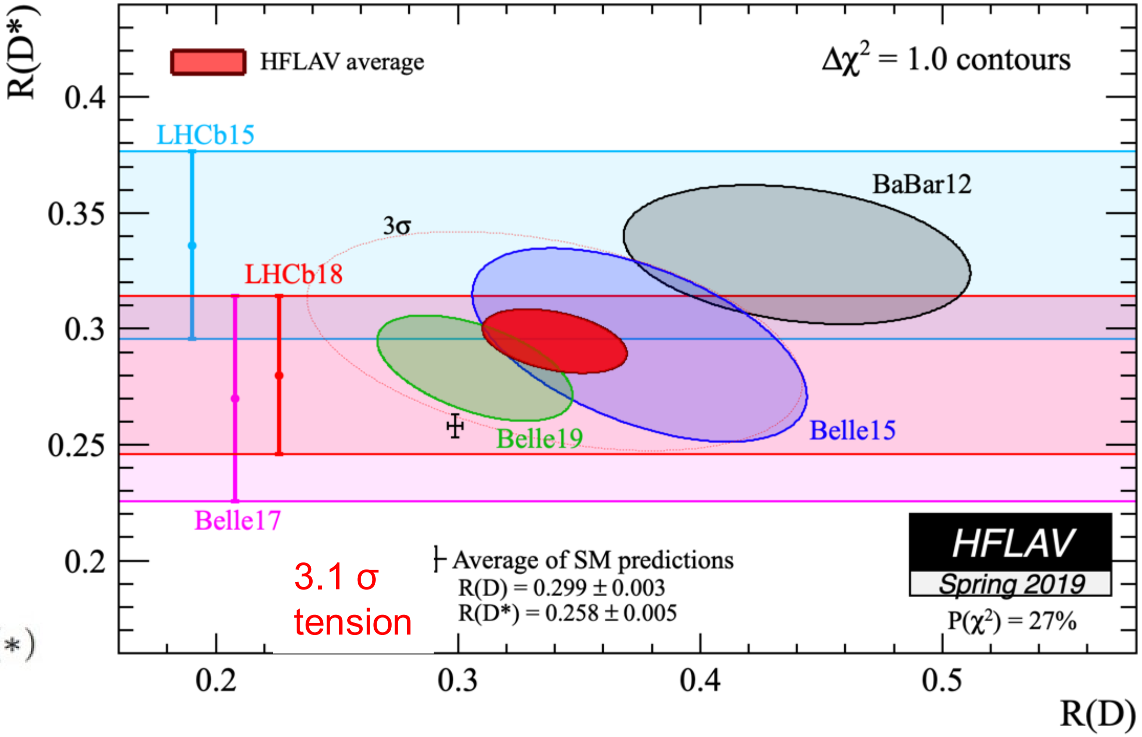
Personal opinion: even if current anomaly dissipates, the story has been very useful for focusing attention on one of the less well understood features of the SM (lepton universality), & also illustrating the power of a complementary ensemble of measurements. Whatever, $b\rightarrow(s,d)l^+l^-$ studies are sure to remain of great interest !

# Trouble with trees: more hints of LU violation

There is another class of decays, b→clν, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

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





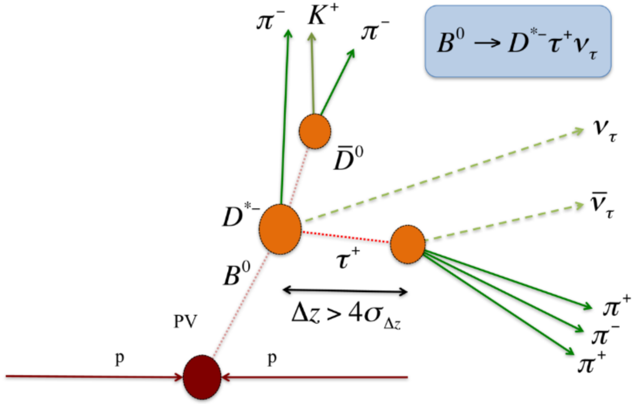
3.1 σ tension

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 $b\to sl^+l^-$ 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.

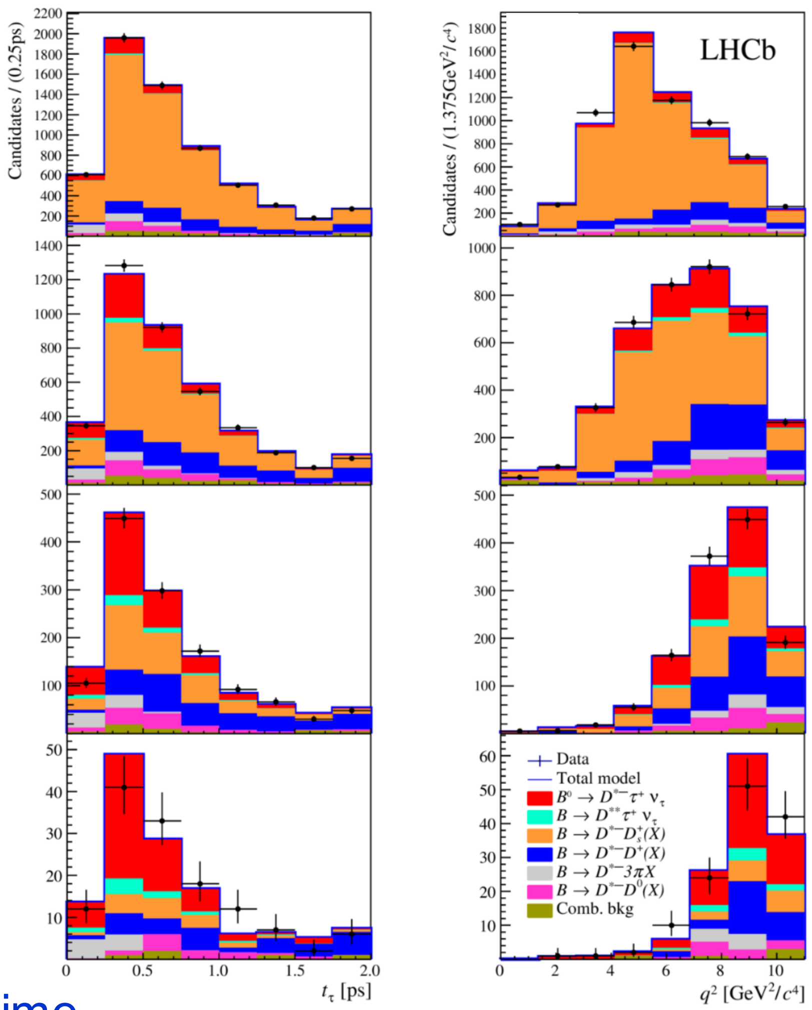
# LHCb contributions to the R(D), R(D*)… party

LHCb has made two measurements of R(D*), one using muonic tau decays [PRL 115 (2015) 159901], and one with the $\tau \rightarrow \pi\pi\pi\upsilon$ mode [PRD 97 (2018) 072013].



Difficult to do, as high backgrounds and no way of isolating a really pure sample. Use a multivariate BDT selection.

Then perform fits in different BDT bins to estimates of $q^2$ of lepton system and $\tau$ lifetime.



increasing signal purity from BDT

signal is red !

# LHCb contributions to the R(D), R(D*)… party

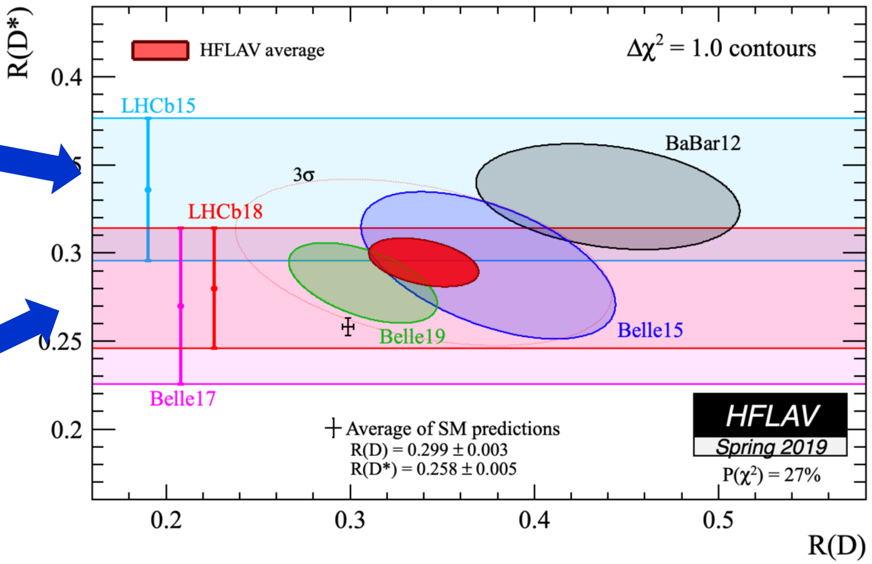
These two measurements have made an interesting contribution to overall picture…

Muonic tau decays [PRL 115 (2015) 159901]

$$\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$

3-prong tau decays [PRD 97 (2018) 072013]

$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$$



…without landing knockout blow. They are from Run 1 data only. New results soon !

What is also interesting is that proof-of-principle measurements have been performed in modes which are unique to LHCb.

$\Lambda^0_b \to \Lambda_c \tau \upsilon$ [arXiv:2201.03497]

$B_c \to J/\psi \tau \upsilon$ [PRL 120 (2018) 121801]

watch this space !

# 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 at the LHC, some with an intriguing status.

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

$b \rightarrow s l^+ l^-$ transitions.

Also of interest is the tree-level process $b \rightarrow c\tau\upsilon$, which has puzzled the community for many years. Although very challenging at hadron colliders, sensitive measurements can be performed, with much still to come from Runs 1 & 2.

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