B decay anomalies

Jusak Tandean

NTU & NCTS

Flavor/Collider Workshop

National Taiwan University, Taipei, Taiwan

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Outline

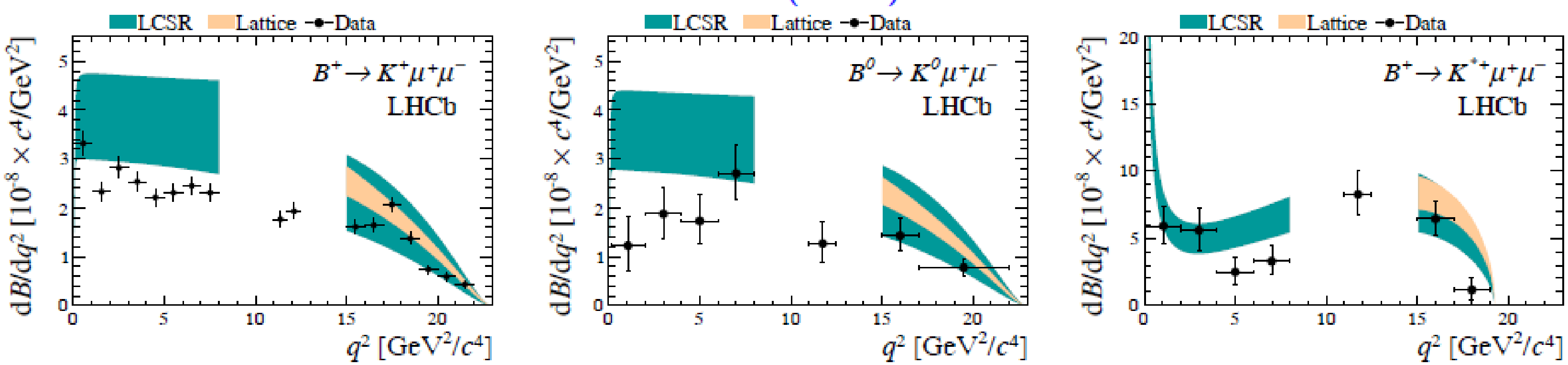
- Anomalies in earlier $b \to s\mu\mu$ data
- New results on $b \to s\mu\mu$ decays
- Anomalies in earlier $b \to c\nu\tau$ data
- New results on $b \to c\nu\tau$ decays
- Conclusions

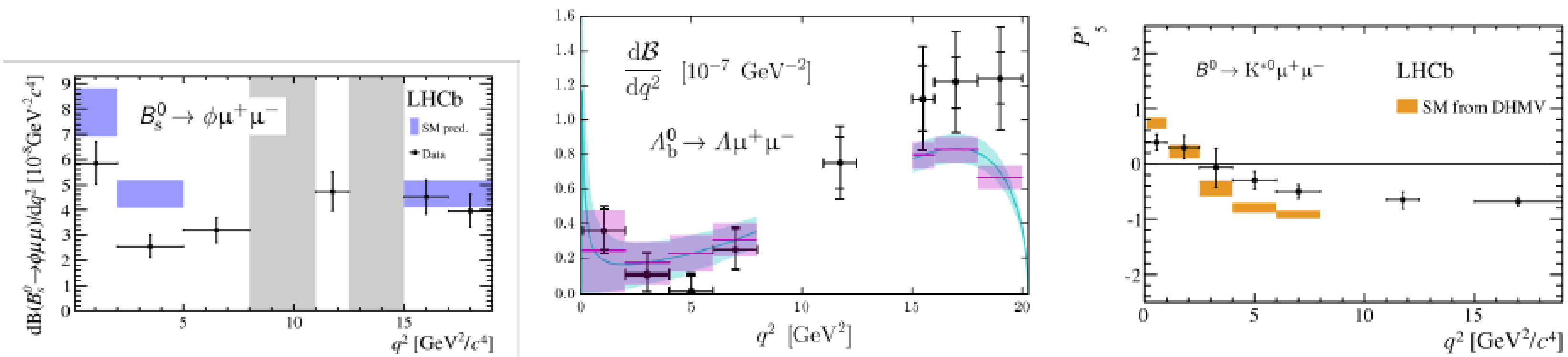
Experimental status

C Marin @ Moriond 2019

Several deviations in differential branching ratios (BR) and angular observables in $b \to s\ell^+\ell^-$:

LHCb JHEP 06 (2014) 133





JHEP 09 (2015) 179, JHEP 06 (2015) 115, PhysRevD.93.074501, JHEP 02 (2016) 104

LHCb LHCb Detmold & Meinel LHCb

- BR theory predictions affected by large uncertainties

Angular analysis of $\Lambda_b^0 \to \Lambda \mu^+ \mu^-$

JHEP 09 (2018) 146

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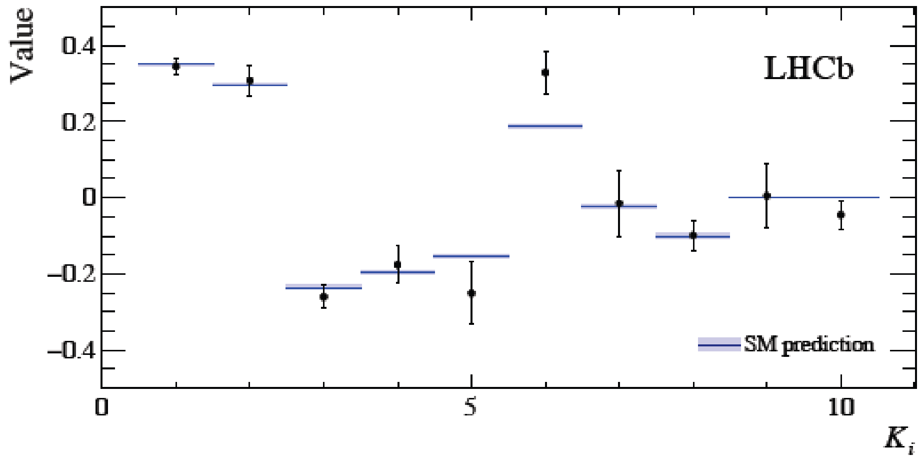
Full set of angular observables measured for the first time:

- All parameters compatible with SM predictions
- $K_{11,\ldots,34}$ compatible with no initial Λ_b^0 polarization

$$\frac{d^5\Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_i^{34} K_i f_i(\Omega)$$

- f_i angular functions
- K_i coefficients



Asymmetries measured from combination of observables

$$A_{FB}^{\ell} = \frac{3}{2} K_3 = -0.39 \pm 0.04 \pm 0.01$$
$$A_{FB}^{h} = K_4 + \frac{1}{2} K_5 = -0.30 \pm 0.05 \pm 0.02$$
$$A_{FB}^{h\ell} = \frac{3}{4} K_6 = +0.25 \pm 0.04 \pm 0.01$$

Experimental status

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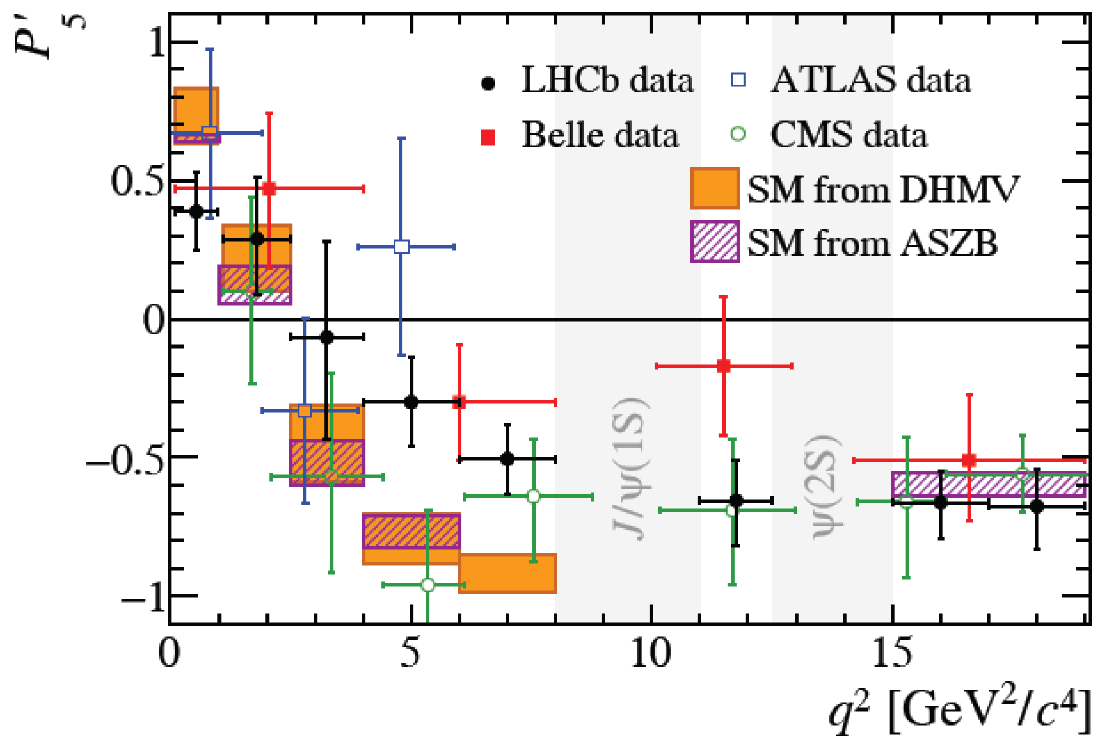
Deviations in optimised angular observable P'_5 in $B^0 \to K^{*0}\mu^+\mu^-$:

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP 05 (2013) 137]

Descotes-Genon *et al.*



LHCb & Belle: local 3.4σ & 2.6σ deviations

Atlas & CMS: SM compatible results

JHEP 02 (2016) 104, Phys.Rev.Lett.118(2017)11,111801,
LHCb / Belle

JHEP 10 (2018) 047, Phys.Lett.B781(2018)517-541
Atlas / CMS

Previous R_{K^*} and R_K results (LHCb Run 1 data)

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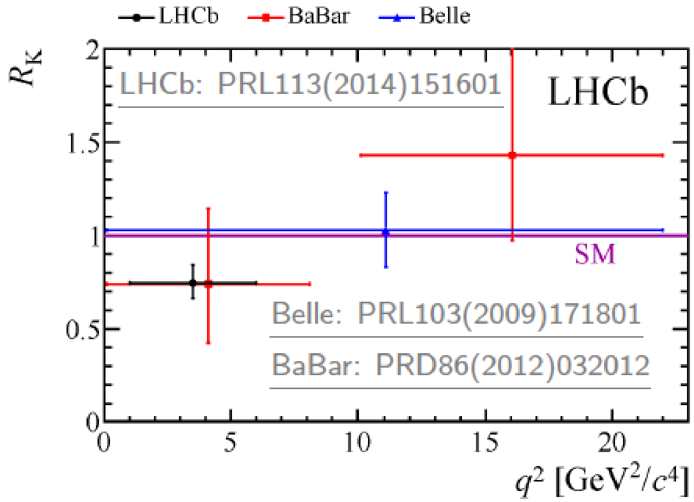

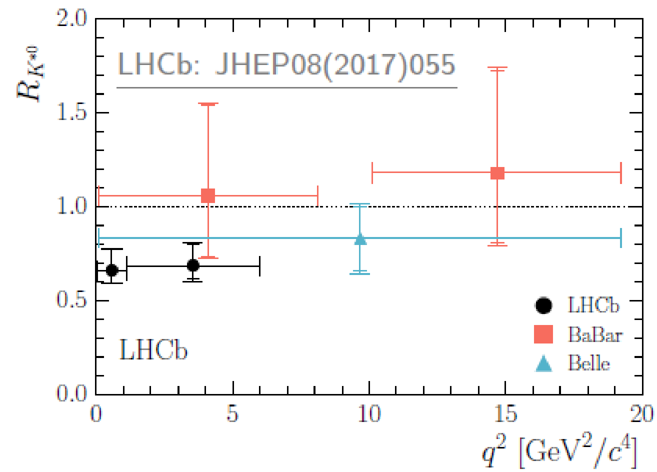

All LHCb results below SM expectations:

- $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ for $1.0 < q^2 < 6.0\ \mathrm{GeV}^2$, $\sim 2.6\,\sigma$ from SM;
- $R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ for $0.045 < q^2 < 1.1\ \mathrm{GeV}^2$, $\sim 2.2\,\sigma$ from SM;
- $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ for $1.1 < q^2 < 6.0\ \mathrm{GeV}^2$, $\sim 2.4\,\sigma$ from SM;

Together with $b \to s\mu\mu$ results, R_K and R_{K^*} constitute an interesting pattern of anomalies, but the significance is still low.

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{=} 1.0$$

R_K result with 2011 to 2016 data LHCb-Paper-2019-009

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Using 2011 and 2012 LHCb data, R_K was:

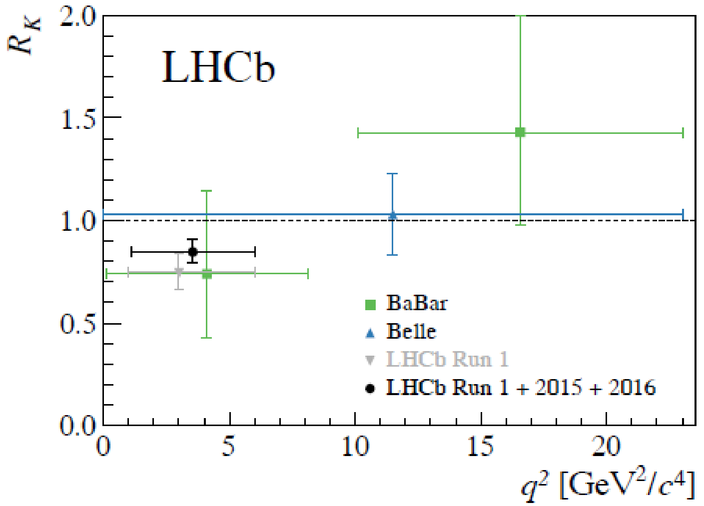
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

Adding 2015 and 2016 data, R_K becomes:

$$\boldsymbol{R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **2.5** σ from SM.



Branching fractions and other results LHCb-Paper-2019-009

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If instead the Run 1 and Run 2 were fitted separately:

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}, \qquad R_{K\ \mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017},$$

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{(PRL113(2014)151601)},$$

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\,\sigma$;
- Run 1 result vs. Run 2 result: $1.9\,\sigma$.

$B^+ \to K^+\mu^+\mu^-$ branching fraction:

- Compatible with previous result (JHEP06(2014)133) at $< 1\,\sigma$;
- Run 1 and Run 2 results compatible at $< 1\,\sigma$.

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- Updated R_K analysis has a significantly improved precision...
- ... but SM compatibility unchanged: LFU breaking not confirmed, nor ruled out.

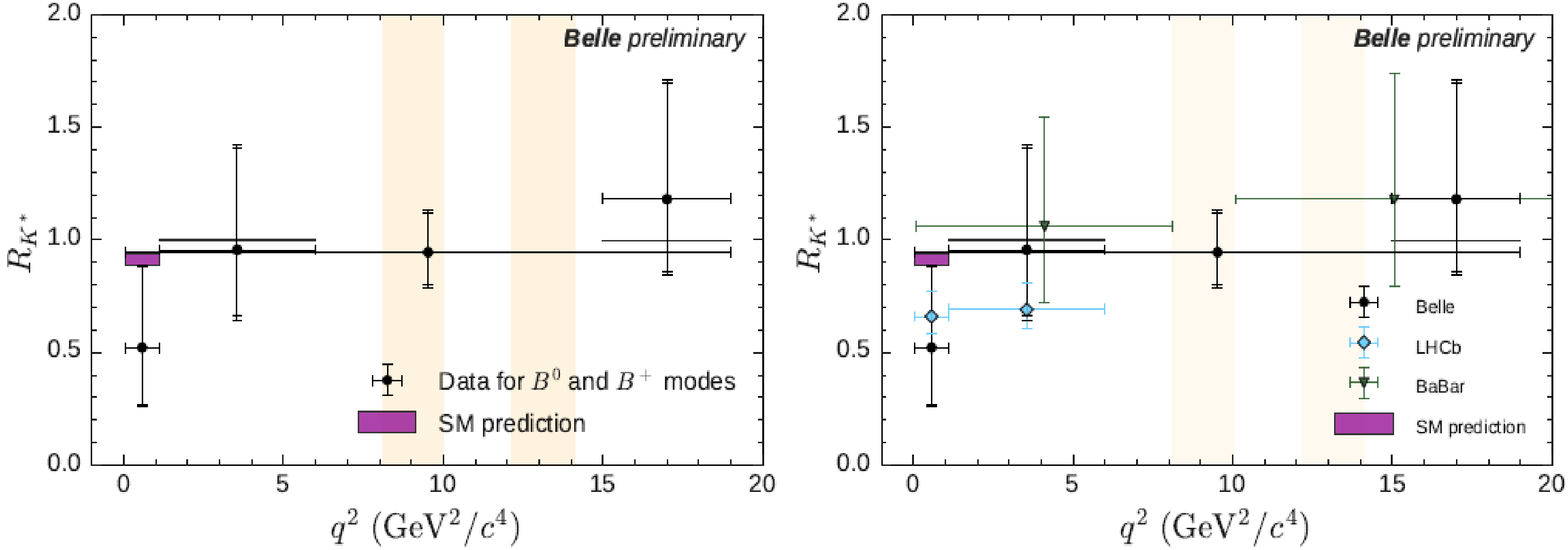
Much remains to be done with the LHCb data in hand:

- Update R_K and R_{K^*} with full Run 2 data
  $\Rightarrow 2\times$ as many B's as in present R_K update.
- Many other observables:
  - R_K and R_{K^*} in the high q^2 bin;
  - LFU in other $b \to s\ell^+\ell^-$ decays, e.g. $B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to p^+K^-\ell^+\ell^-$;
  - Full q^2 dependent $B^0 \to K^{*0}\mu^+\mu^-$ analysis;
  - LFU in charged currents ($R(D)$, $R(D^*)$).

With full LHCb Run 2 data available (up to 2018), the beginning of Belle 2 data taking, and LHCb upgraded detector starting data taking in 2021, we can expect the flavour anomalies to soon be understood.

$R(K^*)$: (Preliminary) Result

M Prim @ Moriond 2019

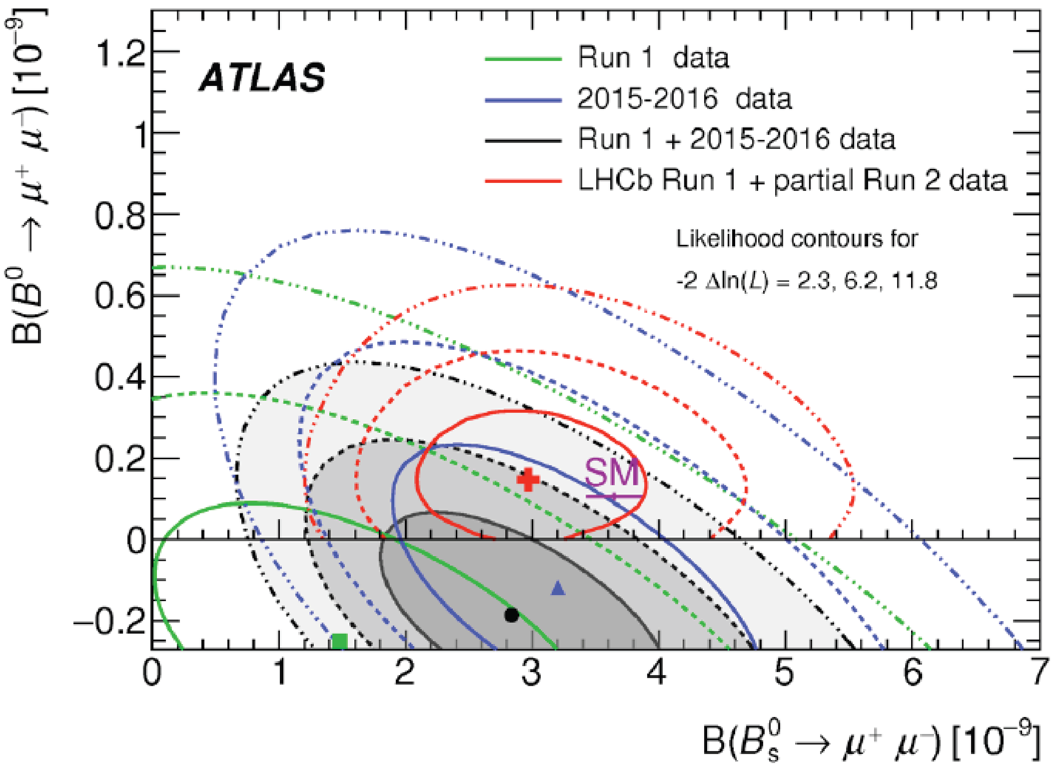


q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

- All measured values are in accordance with the SM and other recent measurements.
- First measurement of $R(K^{*+})$.

Results

O Igonkina @ Moriond 2019



- SM :

  $Br(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

  $Br(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

- Best fit of Run 2 data :

  $Br(B_s \to \mu\mu) = (3.2 \pm 0.9) \times 10^{-9}$

  $Br(B^0 \to \mu\mu) = (-1.3 \pm 2.1) \times 10^{-10}$

- Run 1 + Run 2 result @ 95% CL

  $Br(B_s \to \mu\mu) = (2.8 \pm 0.8) \times 10^{-9}$

  $Br(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$

PDG 2018: $\mathcal{B}(B_s \to \mu\mu) = \left(2.7^{+0.6}_{-0.5}\right) \times 10^{-9}$

B^0 limit is most stringent at the moment

B-decay discrepancies after Moriond 2019

Jason Aebischer[a], Wolfgang Altmannshofer[b], Diego Guadagnoli[c],
Méril Reboud[c], Peter Stangl[c], David M. Straub[a]

arXiv:1903.10434

Following the updated measurement of the lepton flavour universality (LFU) ratio R_K in $B \to K\ell\ell$ decays by LHCb, as well as a number of further measurements, e.g. R_{K^*} by Belle and $B_s \to \mu\mu$ by ATLAS, we analyse the global status of new physics in $b \to s$ transitions in the weak effective theory at the b-quark scale, in the Standard Model effective theory at the electroweak scale, and in simplified models of new physics. We find that the data continues to strongly prefer a solution with new physics in semi-leptonic Wilson coefficients. A purely muonic contribution to the combination $C_9 = -C_{10}$, well suited to UV-complete interpretations, is now favoured with respect to a muonic contribution to C_9 only. An even better fit is obtained by allowing an additional LFU shift in C_9. Such a shift can be renormalization-group induced from four-fermion operators above the electroweak scale, in particular from semi-tauonic operators, able to account for the potential discrepancies in $b \to c$ transitions. This scenario is naturally realized in the simplified U_1 leptoquark model. We also analyse simplified models where a LFU effect in $b \to s\ell\ell$ is induced radiatively from four-quark operators and show that such a setup is on the brink of exclusion by LHC di-jet resonance searches.

Aebischer *et al.*, 1903.10434

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\mathcal{N}\left(C_7^{bs}O_7^{bs} + C_7'^{bs}O_7'^{bs} + \sum_{\ell=e,\mu}\sum_{i=9,10,S,P}\left(C_i^{bs\ell\ell}O_i^{bs\ell\ell} + C_i'^{bs\ell\ell}O_i'^{bs\ell\ell}\right)\right) + \text{h.c.}$$

with the normalization factor

$$\mathcal{N} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}\,.$$

The dipole operators are given by[1]

$$O_7^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}\,, \qquad O_7'^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}\,,$$

where $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, and the semi-leptonic operators

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$

$$O_S^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_S'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,,$$

$$O_P^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,, \qquad O_P'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)\,.$$

- Approximate relations to linear order in NP coefficients

Belle II, 1808.10567

$$R_K[1,6] \simeq 1 + 0.24\left(C_{LL}^{\mathrm{NP}\,\mu} + C_{RL}^{\mu}\right) , \qquad C_{LL}^{\mathrm{NP}\,\ell} = C_9^{\mathrm{NP}\,\ell} - C_{10}^{\mathrm{NP}\,\ell} , \qquad C_{RL}^{\ell} = C_9^{\prime\ell} - C_{10}^{\prime\ell}$$

$$R_{K^*}[1,6] \simeq 1 + 0.24\left(C_{LL}^{\mathrm{NP}\,\mu} - C_{RL}^{\mu}\right) + 0.07\, C_{RL}^{\mu} ,$$

- Examples
  - $R_K = R_{K^*} \approx 1 + 0.24\,(C_9^{\mathrm{NP}} - C_{10}^{\mathrm{NP}})$
  - $R_K \approx 1 + 0.24\,(C_9^{\mathrm{NP}} + C_9') \;,\; R_{K^*} \approx 1 + 0.24\, C_9^{\mathrm{NP}} - 0.17 C_9'$

Alok *et al.*, 1903.09617

Best-fit values of single Wilson coefficients for NP

Aebischer *et al.*, 1903.10434

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10, -0.79]$	$[-1.26, -0.63]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$+0.09$	$[-0.07, +0.24]$	$[-0.23, +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59, +0.87]$	$[+0.46, +1.01]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	-0.19	$[-0.30, -0.07]$	$[-0.41, +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05, +0.35]$	$[-0.09, +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62, -0.45]$	$[-0.70, -0.36]$	6.5σ
C_9^{bsee}	$+0.88$	$[+0.62, +1.15]$	$[+0.36, +1.44]$	3.4σ
$C_9^{\prime bsee}$	$+0.32$	$[+0.09, +0.61]$	$[-0.16, +0.91]$	1.3σ
C_{10}^{bsee}	-0.82	$[-1.06, -0.59]$	$[-1.31, -0.37]$	3.7σ
$C_{10}^{\prime bsee}$	-0.27	$[-0.52, -0.05]$	$[-0.78, +0.17]$	1.2σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.65	$[-1.93, -1.36]$	$[-2.19, -1.02]$	4.0σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.45$	$[+0.31, +0.59]$	$[+0.19, +0.74]$	3.6σ
$(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ
$(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ

Table 1: Best-fit values, 1 and 2σ ranges, and pulls (cf. Eq. (12)) between the best-fit point and the SM point for scenarios with NP in a single Wilson coefficient (or Wilson coefficient combination). For the scalar Wilson coefficients, we show the SM-like solution, while also a sign-flipped solution is allowed, see [65].

Scenarios with pair of Wilson coefficients

Aebischer *et al.*, 1903.10434

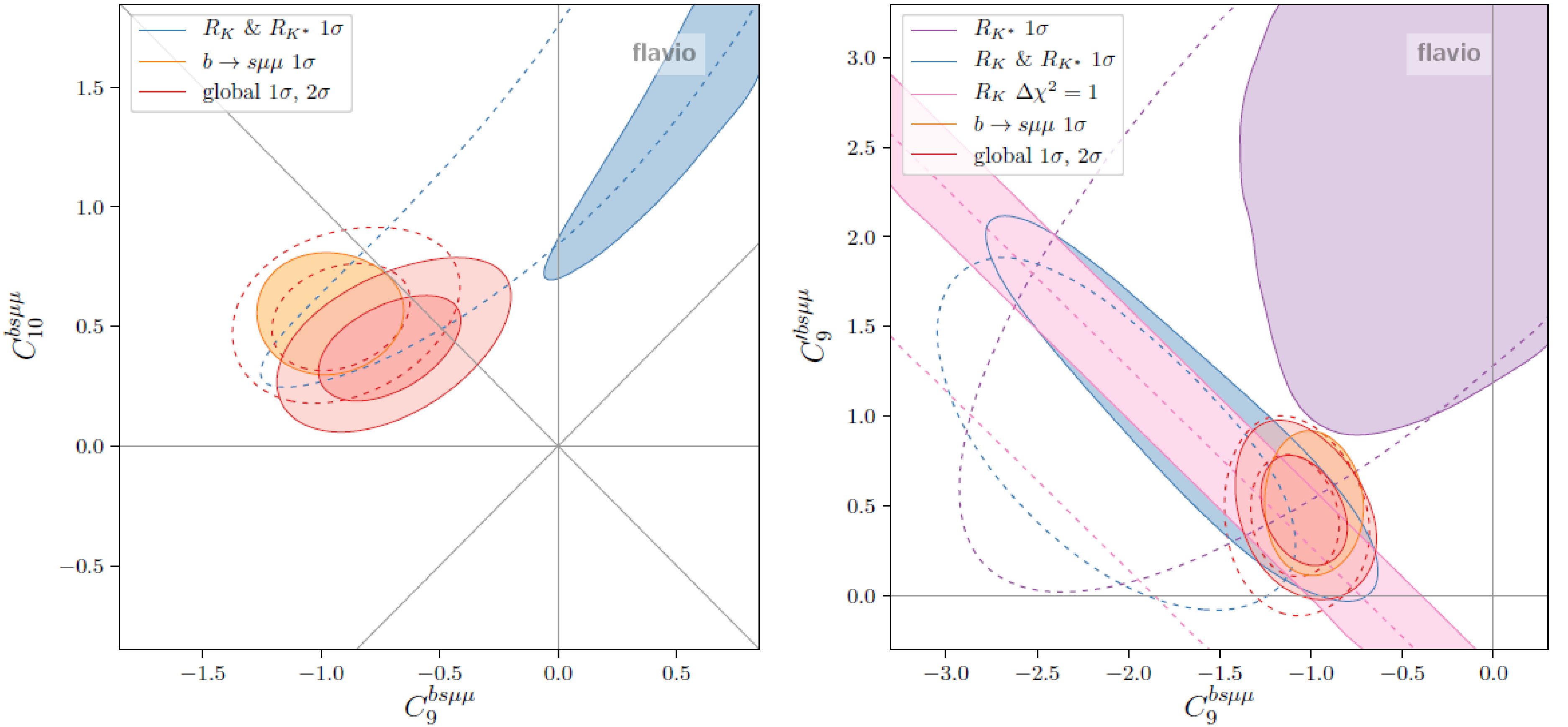
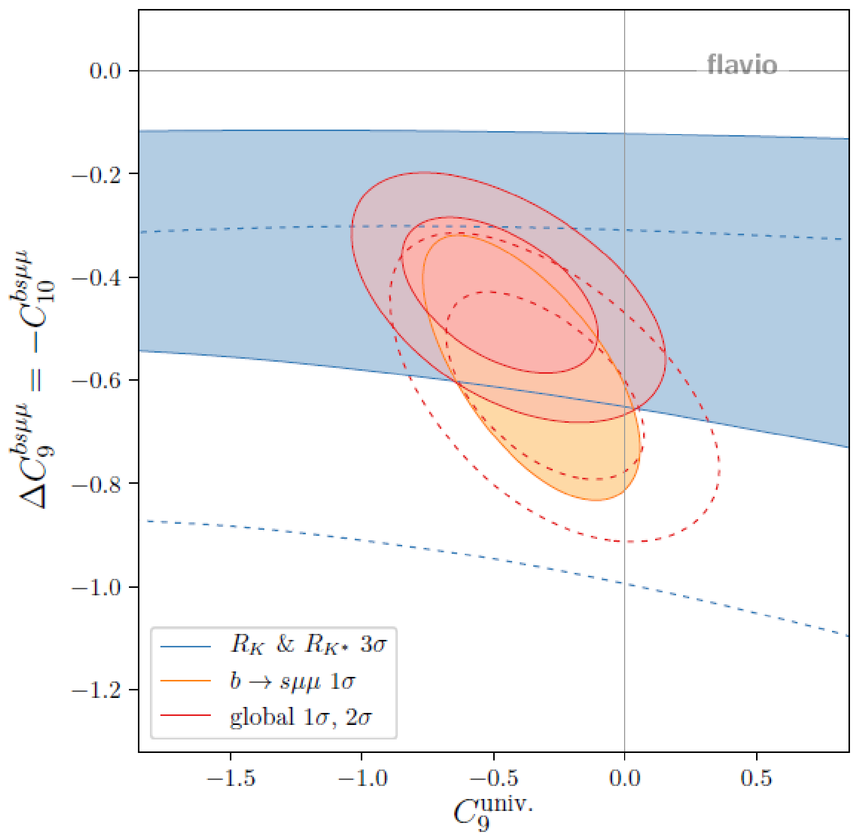


Figure 1: Two projections of the WET fit to $b \to s\mu\mu$ and $R_{K^{(*)}}$ in the plane of the Wilson coefficients $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$ (left), and $C_9^{bs\mu\mu}$ and $C_9^{\prime bs\mu\mu}$ (right). Solid (dashed) contours include (exclude) the Moriond-2019 results for R_K and R_{K^*}. Individual constraints are shown at 1σ, the result of the global fit is shown at 1 and 2σ. As R_K only constrains a single combination of Wilson coefficients in the right plot, its 1σ contour corresponds to $\Delta\chi^2 = 1$. For the other sets of data, 1 and 2σ contours correspond respectively to $\Delta\chi^2 \approx 2.3$ and 6.2.

- Example

$$C_9^{bs\mu\mu} = \Delta C_9^{bs\mu\mu} + C_9^{\text{univ.}} \,,$$
$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ.}} \,,$$
$$C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu} \,,$$
$$C_{10}^{bsee} = C_{10}^{bs\tau\tau} = 0 \,.$$



Projections of the WET fit to $b \to s\mu\mu$ and $R_{K^{(*)}}$ onto the plane of a lepton flavor universal contribution to $C_9^{\text{univ.}} \equiv C_9^{bs\ell\ell}, \forall \ell$, and a muon specific contribution to the linear combination $C_9 = -C_{10}$ (see text for details). Solid (dashed) contours include (exclude) the Moriond-2019 results for R_K and R_{K^*}.

Continuing search for new physics in $b \to s\mu\mu$ decays: two operators at a time

Ashutosh Kumar Alok, Amol Dighe, Shireen Gangal, Dinesh Kumar

(Submitted on 22 Mar 2019)

The anomalies in the measurements of observables involving $b \to s\mu\mu$ decays, namely R_K, R_{K^*}, P_5', and B_s^ϕ, may be addressed by adding lepton-universality-violating new physics contributions to the effective operators $\mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_9', \mathcal{O}_{10}'$. We analyze all the scenarios where the new physics contributes to a pair of these operators at a time. We perform a global fit to all relevant data in the $b \to s$ sector to estimate the corresponding new Wilson coefficients, $C_9^{\rm NP}, C_{10}^{\rm NP}, C_9', C_{10}'$. In the light of the new data on R_K and R_{K^*} presented in Moriond 2019, we find that the scenarios with new physics contributions to the ($C_9^{\rm NP}$, C_9') or ($C_9^{\rm NP}$, C_{10}') pair remain the most favored ones. On the other hand, though the competing scenario ($C_9^{\rm NP}$, $C_{10}^{\rm NP}$) remains attractive, its advantage above the SM reduces significantly due to the tension that emerges between the R_K and R_{K^*} measurements with the new data. The movement of the R_K measurement towards unity would also result in the re-emergence of the one-parameter scenario $C_9^{\rm NP} = -C_9'$.

Comments: 15 pages, 1 figure

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

Report number: TIFR/TH/19-6

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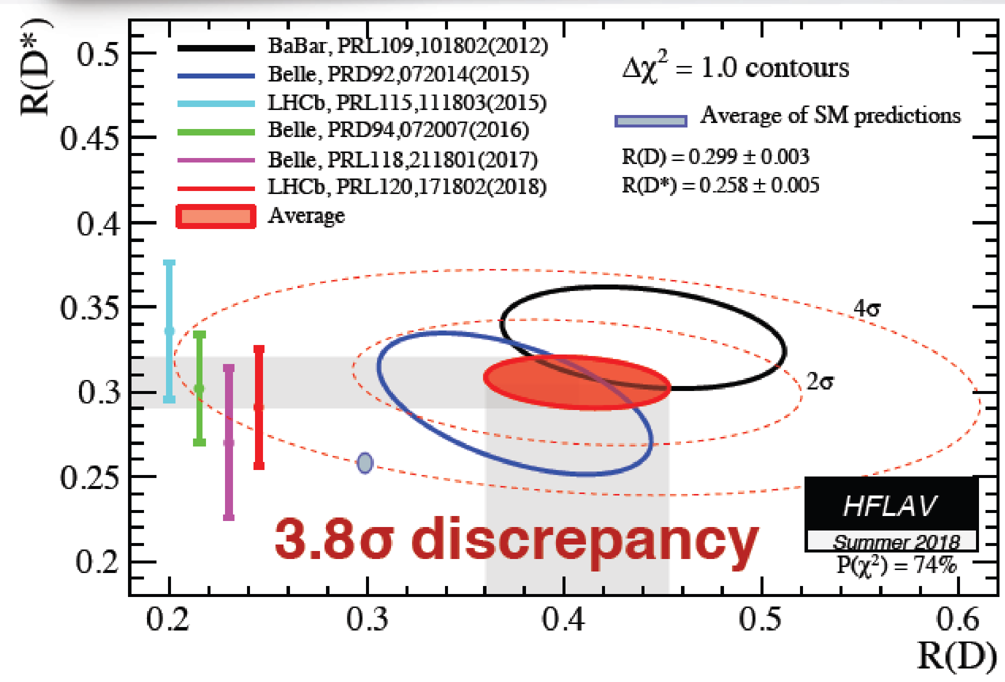
The R(D) and R(D*) puzzles



G Caria @ Moriond 2019

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)}$$

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

where ℓ = e,μ

Experiment	Tag method	τ mode	**R(D)**	R(D*)
Babar ‘12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018
Belle ‘15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015
LHCb ‘15	-	ℓ ν ν	-	0.336 ± 0.027 ± 0.030
Belle ‘16	**Semileptonic**	ℓ ν ν	-	0.302 ± 0.030 ± 0.011
Belle ‘17	Hadronic	π ν, ρ ν	-	0.270 ± 0.035 ± 0.027
LHCb ‘18	-	π π π	-	0.291 ± 0.019 ± 0.029
Average	-	-	**0.407 ± 0.039 ± 0.024**	0.306 ± 0.013 ± 0.007
SM			**0.299 ± 0.003**	0.258 ± 0.005

- LHCb:

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)} = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$$

1711.05623

  - SM: $\mathcal{R}(J/\psi)$ = [0.20,0.39] — Cohen *et al.*, 2018

- Belle: τ polarization in $B \to D^* \nu\tau$

$$P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst})$$

1612.00529

  - SM: $P_\tau(D^*) = -0.497 \pm 0.013$ — Tanaka & Watanabe, 2013

- Belle: longitudinal polarization of D^* in $B \to D^* \nu\tau$

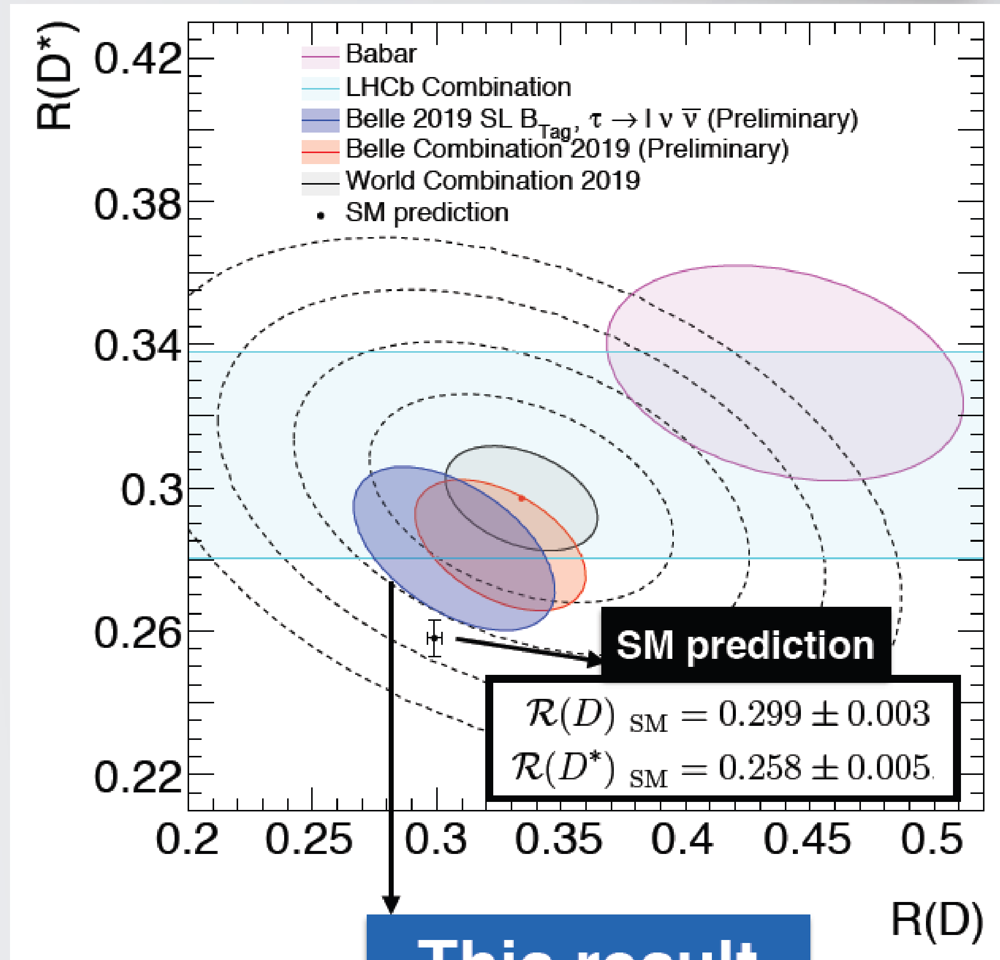
$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

1612.00529

  - SM: $F_L^{D^*} = 0.46 \pm 0.03$ — Alok *et al.*, 2017

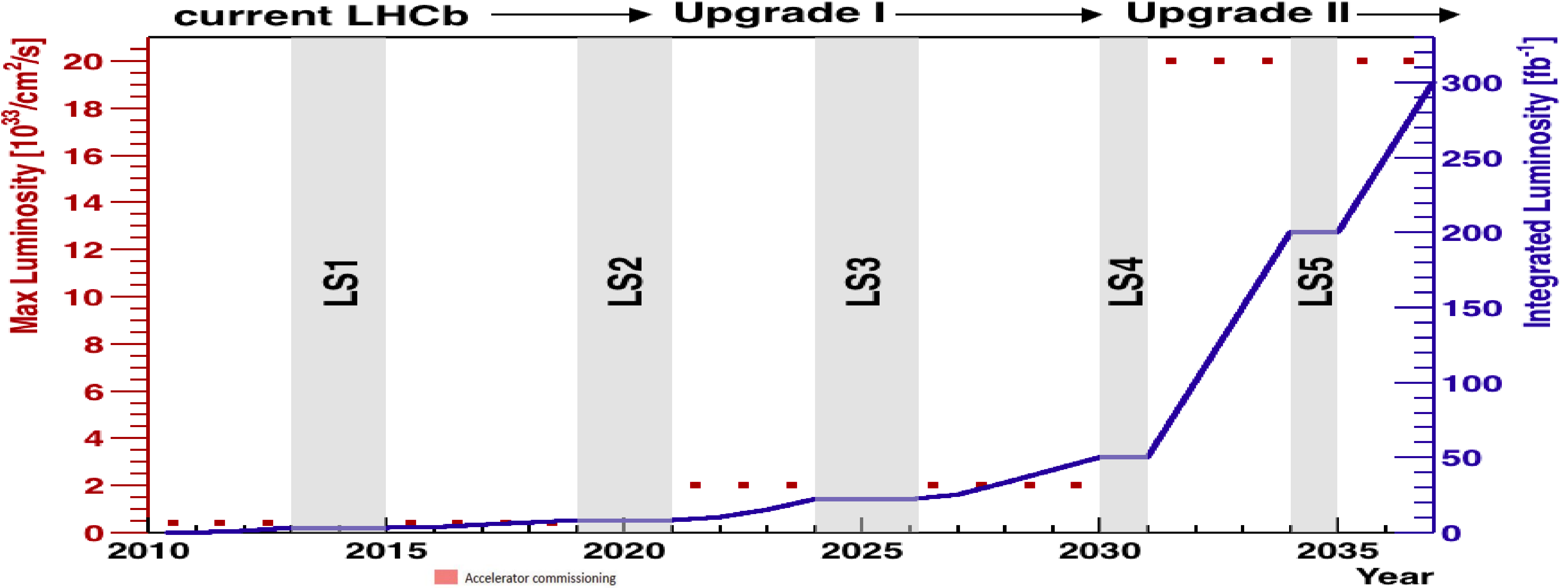
$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$$

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



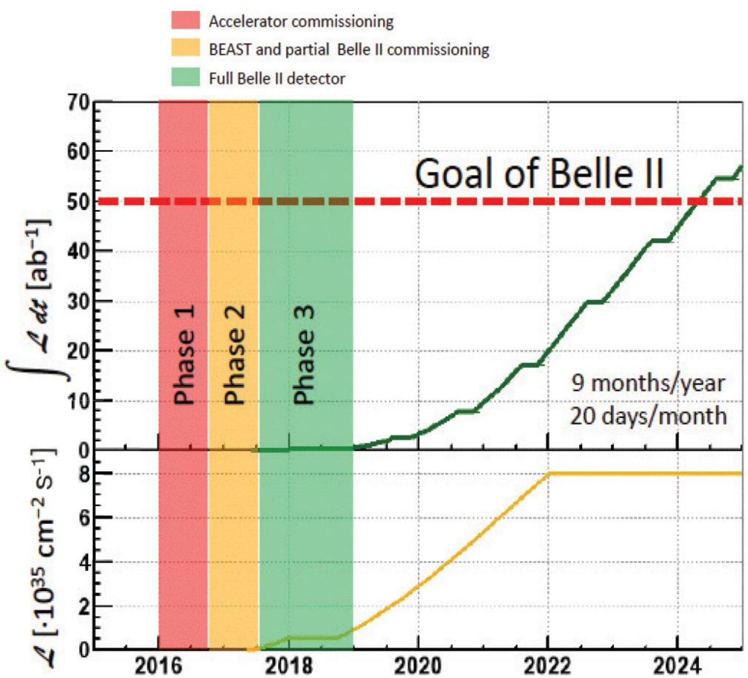
This result

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



Near future prospects

1808.08865



J Bennet, 2016

Figure 2. An overview of the projected luminosity and operation at SuperKEKB.

- New data related to the *B*-meson anomalies have recently appeared from LHCb and Belle.
  - Some of the tension with the SM in *B* decay data have decreased slightly.
  - Thus the anomalies still have not gone away.
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