Extrapolation to LHCb Upgrades I/II

- LHCb Upgrade
- Some reminders
- Extrapolations [Hurth, Mahmoudi, Martínez Santos, Neshatpour, arXiv:2104.10058]

21/04/2021 — Beyond Flavour Anomalies
[indico]

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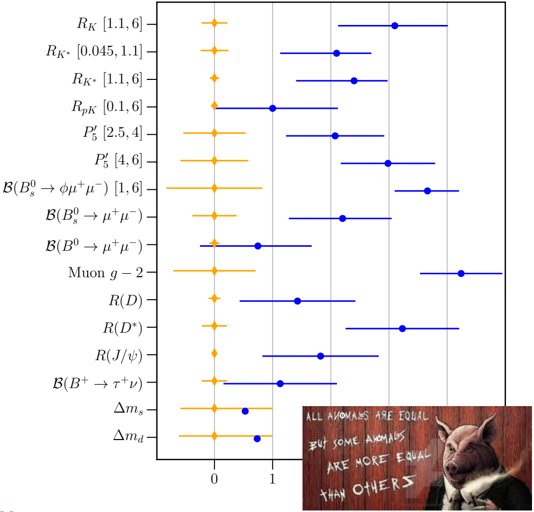
Pulls of flavour anomalies



R_K, R_{K*}: LHCb [arXiv:2103.11769] [JHEP 08 (2017) 055] vs [Bordone, Isidori, Pattori EPJC 76 (2016) 440].

R_{pK} LHCb [JHEP 05 (2020) 040].

P_5' my average of LHCb [PRL 125 (2020) 011802], CMS [PLB 781 (2018) 517], ATLAS [JHEP 10 (2018) 047] vs [Bharucha, Straub, Zwicky, JHEP 08 (2016) 098].

$B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179] vs FLAVIO [Straub, arXiv:1810.08132].

$B \to \mu^+\mu^-$ Combination [Altmannshofer, Stangl] of LHCb [LHCb-PAPER-2021-007], CMS [JHEP 04 (2020) 188], ATLAS [JHEP 04 (2019) 098] vs [Beneke, Bobeth, Szafron, JHEP 10 (2019) 232].

Muon $g-2$ [Muon $g-2$, PRL 126 (2021) 141801] vs [Aoyama et al., Phys. Rept. 887 (2020) 1].

$R(D^{(*)})$ [HFlav, arXiv:1909.12524].

$\mathcal{B}(B^+ \to \tau\mu)$ [UTFit].

Δm_q [arXiv:2104.04421] and [PDG] vs [Di Luzio, Kirk, Lenz, Rauh, JHEP 12 (2019) 009].

LHCb Upgrade

$\mathcal{L} = 2{\cdot}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ requires some new detectors and 40 MHz read-out clock new electronics

VELO: New pixel vertex detector

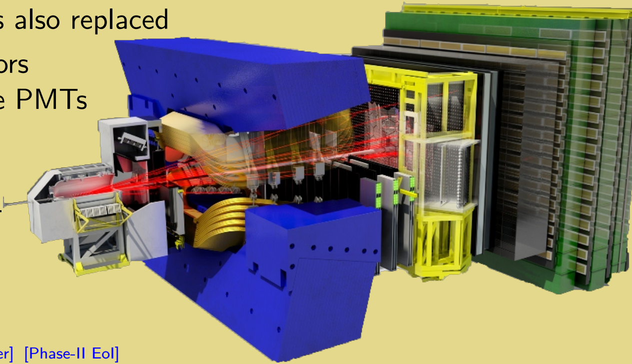
TRACKERS: New scintillating fibre tracker. The upstream tracker is also replaced

PID: Hybrid photodetectors replaced by multi-anode PMTs

➜ 50 fb^{-1} by Run 4.

✔ We are preparing another upgrade for Run 5

➜ 300 fb^{-1}

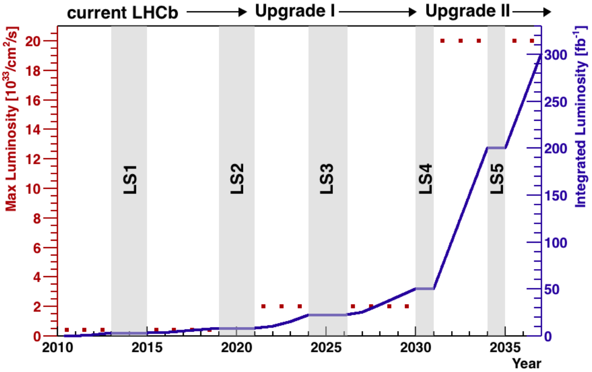


[Upgrade TDR] [Velo] [PID] [Sci-Fi] [Trigger] [Phase-II EoI]

LHCb Phase-II Upgrade

The plan is to record 300 fb^{-1} by the end of Run 5.

1. EoI [CERN-LHCC-2017-003]
2. Physics case [LHCb U2 Physics case, arXiv:1808.08865]
3. LHCC has approved LHCb to proceed to a framework TDR (2021)

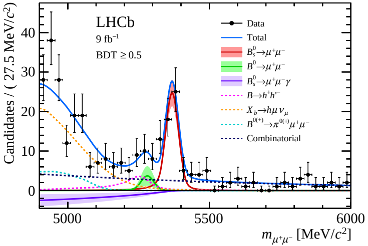


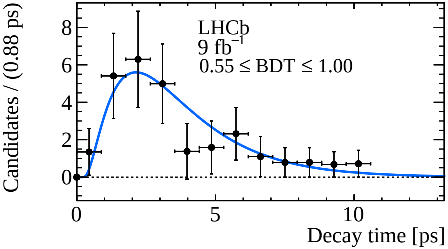
[LHC web]

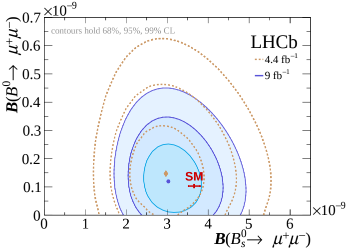
LHC schedule (Sep 2020)

$$B \to \mu^+\mu^-$$

Legacy measurement of $B_s^0 \to \mu^+\mu^-$







With 2011–2018 LHCb data ($9\,\text{fb}^{-1}$):

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

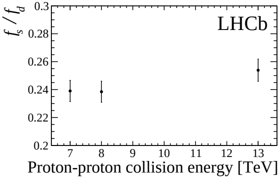
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.2\,^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$$

Effective lifetime:

$$\tau^{\text{eff}}_{B_s^0\to\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03\ \text{ps}$$

f_s/f_d Combination

1. Combine data from
   - $B^0_{(s)} \to D^-_{(s)}\pi^+$ at 7, 8, 13 TeV [EPJC 81 (2021) 314],
   - $B^0_s \to D^-_s\pi^+$ and $B^0 \to D^-K^+$ at 7 TeV [JHEP 04 (2013) 001],
   - $b \to c\mu^-\overline{\nu}$ at 7 TeV [PRD 85 (2012) 032008] and 13 TeV [PRD 100 (2019) 031102(R)],
   - $B^0_s \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ a 7, 8, 13 TeV [PRL 124 (2020) 122002]

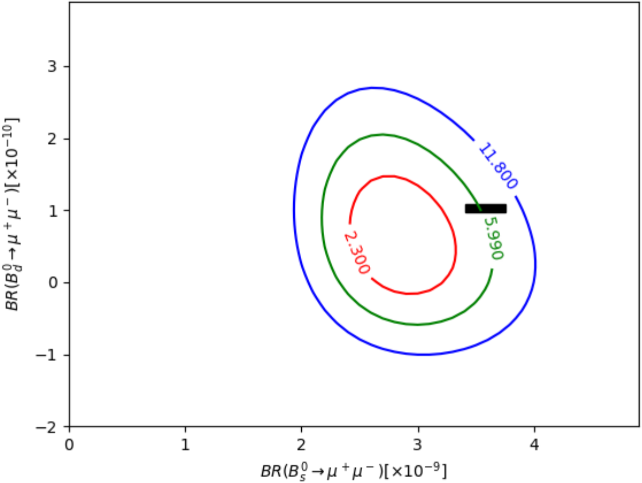


to get f_s/f_d versus p_{T} :

$$f_s/f_d(p_{\mathrm{T}}, 7\,\text{TeV}) = (0.263 \pm 0.008) + [(-17.6 \pm 2.1) \times 10^{-4}] \cdot p_{\mathrm{T}}$$
$$f_s/f_d(p_{\mathrm{T}}, 8\,\text{TeV}) = (0.244 \pm 0.008) + [(-10.3 \pm 2.7) \times 10^{-4}] \cdot p_{\mathrm{T}}$$
$$f_s/f_d(p_{\mathrm{T}}, 13\,\text{TeV}) = (0.240 \pm 0.008) + [(-\ \ 3.4 \pm 2.3) \times 10^{-4}] \cdot p_{\mathrm{T}}$$

With PDG-style error scaling, uncertainties on p_{T} slopes would increase by 25%

$B \to \mu^+\mu^-$ after Moriond 2021



The SM point is near the 2σ band

ATLAS [JHEP 04 (2019) 098], CMS [JHEP 04 (2020) 188], LHCb [LHCb-PAPER-2021-007]

LHCb Phase-II Upgrade : $B \to \mu^+\mu^-$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ has now 15% precision. Will get to 1.8% with 300 fb^{-1} ([LHCb U2 Physics case, arXiv:1808.08865] value). I get
The systematics are now 5%, dominated by f_s/f_d. Hard to predict how this will evolve.

$\mathcal{B}(B^0 \to \mu^+\mu^-)$ The statistical precision will be 10% with 300 fb^{-1}.

$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0 \to \mu^+\mu^-)$ suffers from the same f_s/f_d limitation, but is still statistics-dominated.

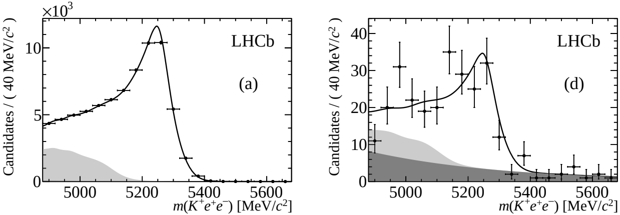
Lepton universality

R_K STRATEGY

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \mathrm{d}q^2 \frac{d\Gamma(B\to K\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{min}}^{q^2_{max}} \mathrm{d}q^2 \frac{d\Gamma(B\to K e^+e^-)}{\mathrm{d}q^2}} \overset{\text{measure}}{=} \frac{\frac{N(B^+\to K^+\mu^+\mu^-)}{\epsilon_{tot}(B^+\to K^+\mu^+\mu^-)}}{\frac{N(B^+\to K^+e^+e^-)}{\epsilon_{tot}(B^+\to K^+e^+e^-)}}$$

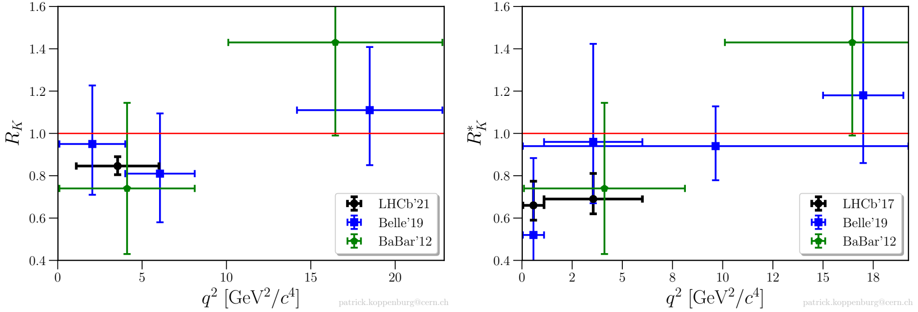
$$\overset{\text{measure}}{=} \frac{\frac{\epsilon_{tot}(B^+\to J/\psi(\mu^+\mu^-)K^+)}{\epsilon_{tot}(B^+\to K^+\mu^+\mu^-)} \times \frac{N(B^+\to K^+\mu^+\mu^-)}{N(B^+\to J/\psi(\mu^+\mu^-)K^+)}}{\frac{\epsilon_{tot}(B^+\to J/\psi(e^+e^-)K^+)}{\epsilon_{tot}(B^+\to K^+e^+e^-)} \times \frac{N(B^+\to K^+e^+e^-)}{N(B^+\to J/\psi(e^+e^-)K^+)}}$$

Efficiencies mostly cancel



LU in J/ψ decays:
1.0016 ± 0.0031 [PDG],
mostly [BESIII]

R_K and R_{K^*}



LHCb [JHEP 08 (2017) 055] [arXiv:2103.11769]. Belle [arXiv:1904.02440] [JHEP 03 (2021) 105]. BaBar [PRD 86 (2012) 032012].

Captain obvious says: the smaller the uncertainties the more precise the data point

$b \to s\ell^+\ell^-$ GLOBAL FIT

Theoretical uncertainties and correlations:

- Monte Carlo analysis Variation of the "standard" input parameters: masses, scales, CKM, ...
  Decay constants taken from the latest lattice results
  Form factors from the lattice+LCSR combinations, including correlations
- Parameterisation of uncertainties from power corrections
- Computation of a (theory + exp) correlation matrix

Observables: All $b \to s$ data from LHC and B factories (173 observables)

Using SuperIso public program

$b \to s\ell^+\ell^-$ GLOBAL FIT : RESULTS

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ **2021 data** ($\chi^2_{\rm SM} = 28.19$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

All observables except $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ **2021 data** ($\chi^2_{\rm SM} = 200.1$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.01 ± 0.13	158.2	6.5σ
δC_9^e	0.70 ± 0.60	198.8	1.1σ
δC_9^μ	-1.03 ± 0.13	156.0	6.6σ
δC_{10}	0.34 ± 0.23	197.7	1.5σ
δC_{10}^e	-0.50 ± 0.50	199.0	1.0σ
δC_{10}^μ	0.41 ± 0.23	196.5	1.9σ
$\delta C_{\rm LL}^e$	0.33 ± 0.29	198.9	1.1σ
$\delta C_{\rm LL}^\mu$	-0.75 ± 0.13	167.9	5.7σ

All observables **2021 data** ($\chi^2_{\rm SM} = 225.8$)			
δC_9	-0.99 ± 0.13	186.2	6.3σ
δC_9^e	0.79 ± 0.20	207.7	4.3σ
δC_9^μ	-0.95 ± 0.12	168.6	7.6σ
δC_{10}	0.32 ± 0.18	222.3	1.9σ
δC_{10}^e	-0.74 ± 0.18	206.3	4.4σ
δC_{10}^μ	0.55 ± 0.13	205.2	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.10	206.9	4.3σ
$\delta C_{\rm LL}^\mu$	-0.49 ± 0.08	180.5	6.7σ

↓ Clean observables

↓ ↓ Dependent on the assumptions on the nonfactorizable power corrections

[Hurth, Mahmoudi, Martínez Santos, Neshatpour, arXiv:2104.10058]

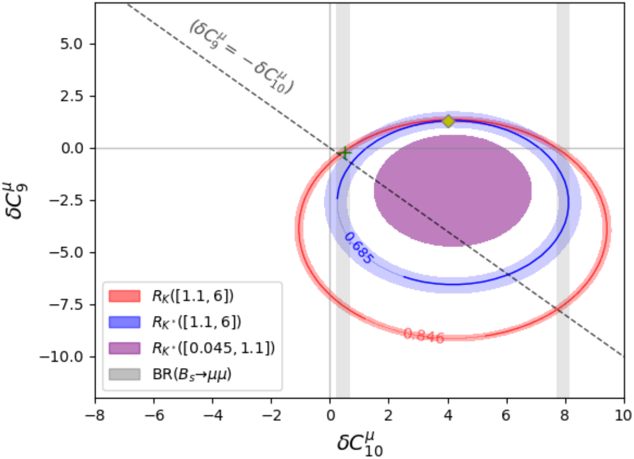
$b \to s\ell^+\ell^-$ GLOBAL FIT : $R_{K^{(*)}}$ AND $B_s^0 \to \mu^+\mu^-$

Red (blue) solid line: central value of $R_{K^{(*)}}^{\rm exp}$

Coloured regions: 1σ range (th+exp) with the experimental central value

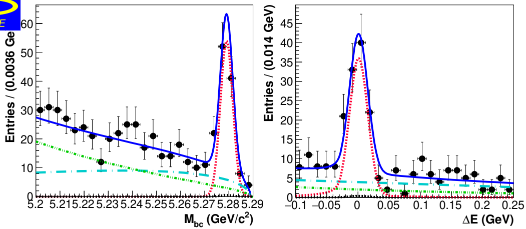
Yellow diamond ◇: best fit point of (C_9^μ, C_{10}^μ) of the fit to $R_{K^{(*)}}$

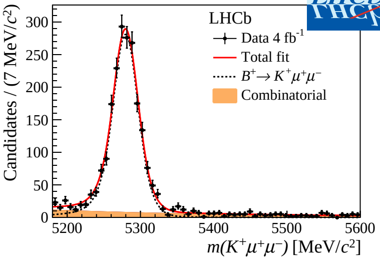
Green cross: best fit point of (C_9^μ, C_{10}^μ) of the fit to $R_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$



Outlook

BELLE VERSUS LHCb: $B^+ \to K^+\mu^+\mu^-$





✔ Two handles: B mass and B energy in $\Upsilon(4S)$ frame (ΔE)

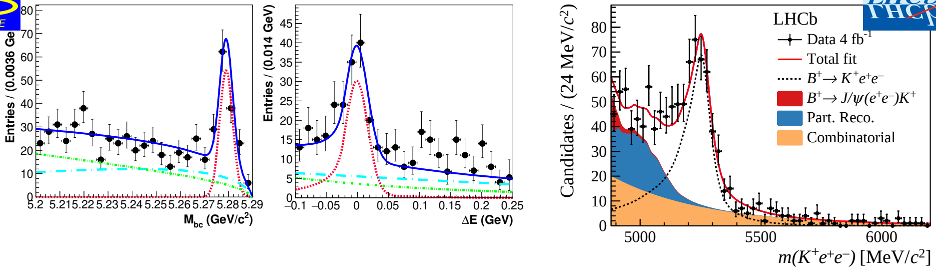
137 signal decays with 711 fb^{-1}

✔ Two handles: B mass and pointing to PV

1900 signal decays with 4 fb^{-1} at 13 TeV

Muons conversion factor: 2.5 ab^{-1} ↔ 1 fb^{-1}

Belle versus LHCb: $B^+ \to K^+ e^+ e^-$



✔ Electron channels are as "easy" as muonic

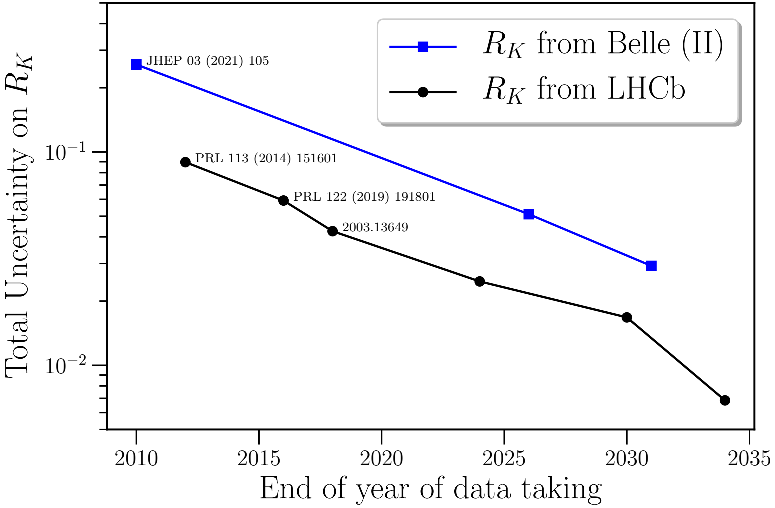
138 signal decays with 711 fb^{-1}

✗ Bremsstrahlung makes electrons much more difficult

800 signal decays with 4 fb^{-1} at 13 TeV

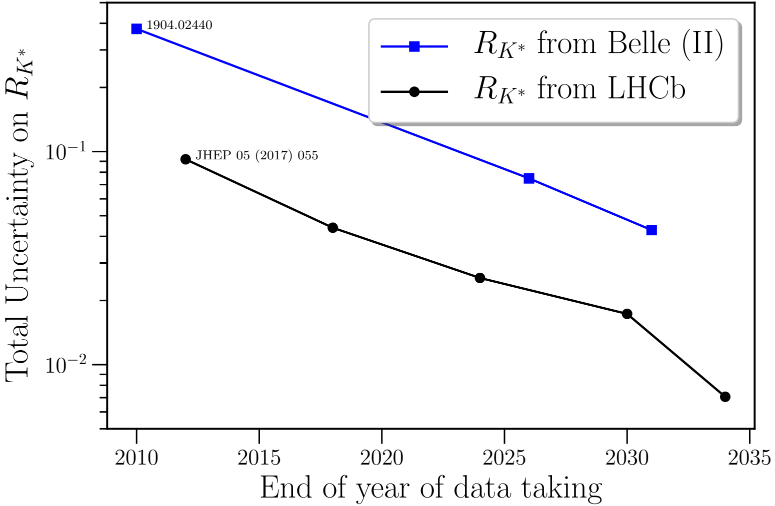
Electrons conversion factor: $1\,\text{ab}^{-1} \leftrightarrow 1\,\text{fb}^{-1}$

Projections for R_K in $1(.1) < q^2 < 6\,\mathrm{GeV}^2/c^4$



[B]

Projections for R_{K^*} in $1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4$



[B]

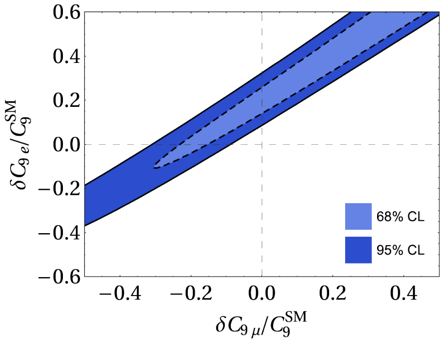
$b \to s\ell^+\ell^-$ GLOBAL FIT : PROJECTIONS

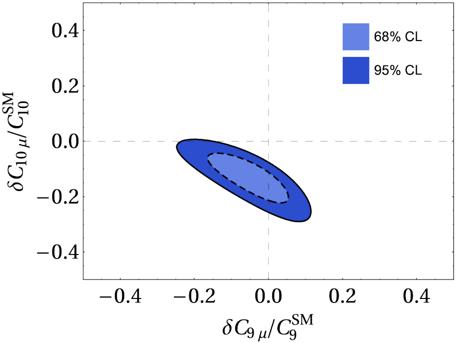
Using $R_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$ only

Pull_{SM} with R_K and R_K^* [+ BR($B_s \to \mu^+\mu^-$)] prospects			
LHCb lum.	18 fb^{-1}	50 fb^{-1}	300 fb^{-1}
δC_9^μ	6.5σ [6.5σ]	14.7σ [14.7σ]	21.9σ [21.9σ]
δC_{10}^μ	6.2σ [7.1σ]	16.1σ [16.6σ]	24.6σ [25.1σ]
δC_{LL}^μ	7.2σ [7.5σ]	17.5σ [17.7σ]	26.5σ [26.6σ]

$b \to s\ell^+\ell^-$ GLOBAL FIT : PROJECTIONS

Using $R_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$ only

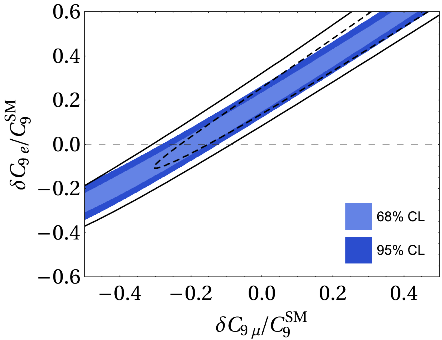


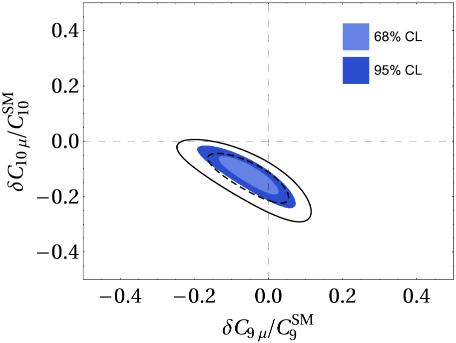


Current data

$b \to s\ell^+\ell^-$ GLOBAL FIT : PROJECTIONS

Using $R_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$ only

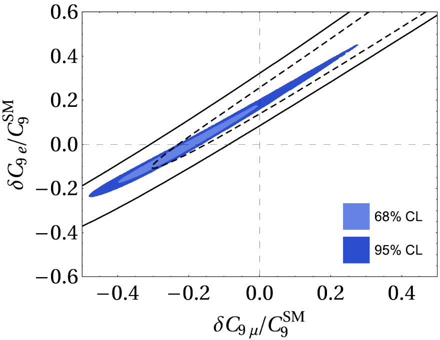


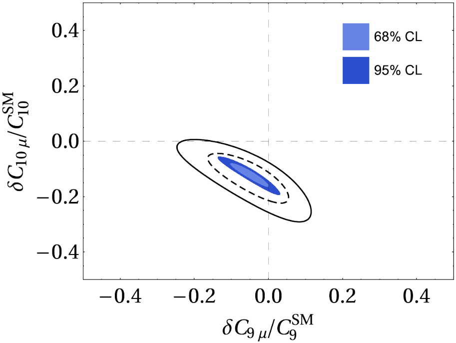


Projection for $18\,\mathrm{fb}^{-1}$

$b \to s\ell^+\ell^-$ GLOBAL FIT : PROJECTIONS

Using $R_{K^{(*)}}$ and $B^0_s \to \mu^+\mu^-$ only

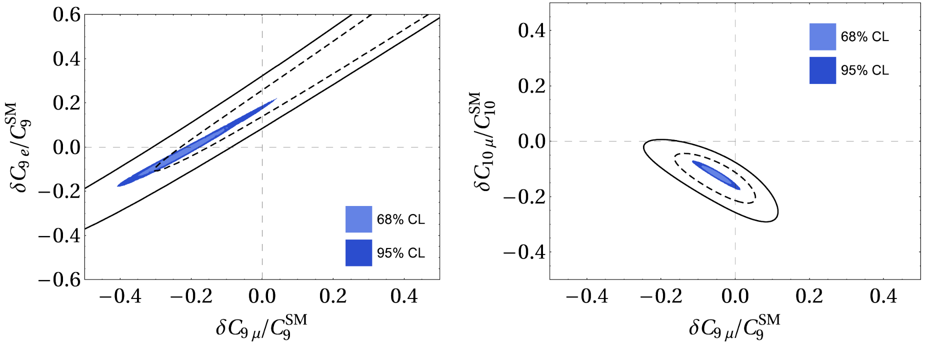




Projection for $50\,\text{fb}^{-1}$

$b \to s\ell^+\ell^-$ GLOBAL FIT : PROJECTIONS

Using $R_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$ only



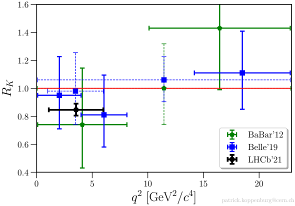
Projection for 300 fb^{-1}

$b \to s\ell^+\ell^-$ GLOBAL FIT : e/μ PREDICTIONS

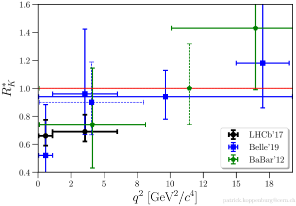
	Predictions assuming 50 fb^{-1} luminosity					
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e	C_{LL}^μ	C_{LL}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.922, 0.932]$	$[0.941, 0.944]$	$[0.995, 0.998]$	$[0.996, 0.997]$	$[0.961, 0.964]$	$[1.006, 1.010]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[4.791, 5.520]$	$[-0.416, -0.358]$	$[0.938, 0.939]$	$[0.963, 0.970]$	$[2.822, 3.089]$	$[0.279, 0.307]$
$R_{S_3}^{[1.1,6.0]}$	$[0.922, 0.931]$	$[0.914, 0.922]$	$[0.832, 0.852]$	$[0.858, 0.870]$	$[0.853, 0.870]$	$[1.027, 1.032]$
$R_{S_5}^{[1.1,6.0]}$	$[0.453, 0.543]$	$[0.723, 0.742]$	$[1.014, 1.014]$	$[1.040, 1.048]$	$[0.773, 0.801]$	$[1.298, 1.361]$
$R_{F_L}^{[15,19]}$	$[0.998, 0.999]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.929, 0.944]$	$[0.988, 0.989]$	$[1.009, 1.010]$	$[1.036, 1.042]$	$[0.996, 0.996]$	$[1.023, 1.028]$
$R_{S_3}^{[15,19]}$	$[0.998, 0.998]$	$[0.998, 0.998]$	$[0.999, 0.999]$	$[0.999, 0.999]$	$[0.999, 0.999]$	$[0.998, 0.998]$
$R_{S_5}^{[15,19]}$	$[0.929, 0.944]$	$[0.988, 0.989]$	$[1.009, 1.010]$	$[1.036, 1.042]$	$[0.996, 0.996]$	$[1.023, 1.028]$
$R_{K^*}^{[15,19]}$	$[0.825, 0.847]$	$[0.815, 0.835]$	$[0.828, 0.846]$	$[0.799, 0.820]$	$[0.804, 0.825]$	$[1.093, 1.107]$
$R_{K}^{[15,19]}$	$[0.823, 0.847]$	$[0.819, 0.838]$	$[0.854, 0.870]$	$[0.825, 0.844]$	$[0.820, 0.839]$	$[1.098, 1.113]$
$R_{\phi}^{[1.1,6.0]}$	$[0.862, 0.879]$	$[0.841, 0.858]$	$[0.824, 0.843]$	$[0.795, 0.816]$	$[0.819, 0.839]$	$[1.070, 1.080]$
$R_{\phi}^{[15,19]}$	$[0.825, 0.847]$	$[0.815, 0.835]$	$[0.826, 0.845]$	$[0.797, 0.819]$	$[0.803, 0.824]$	$[1.093, 1.107]$

[JHEP 08 (2017) 055] [PRL 122 (2019) 191801] [arXiv:1904.02440] [PRD 86 (2012) 032012]

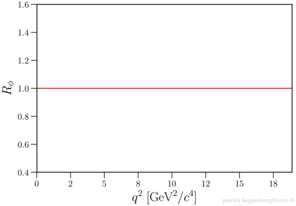
R_X: It's only the beginning



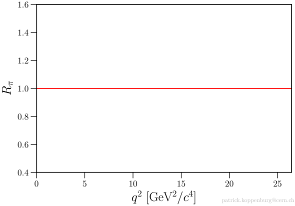
$B \to K\ell^+\ell^-$



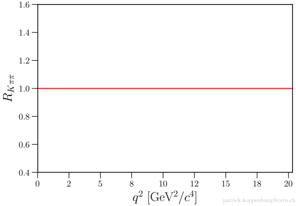
$B \to K^*\ell^+\ell^-$



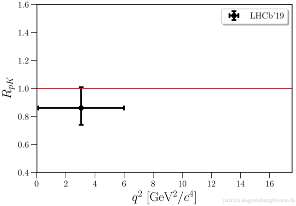
$B_s^0 \to \phi\ell^+\ell^-$



$B \to \pi\ell^+\ell^-$



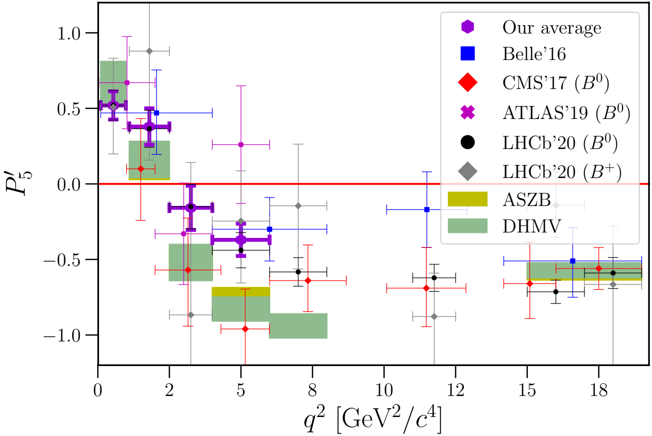
$B \to K\pi^+\pi^-\ell^+\ell^-$



$\Lambda_b^0 \to pK^-\ell^+\ell^-$

Angular Observables

B P_5'

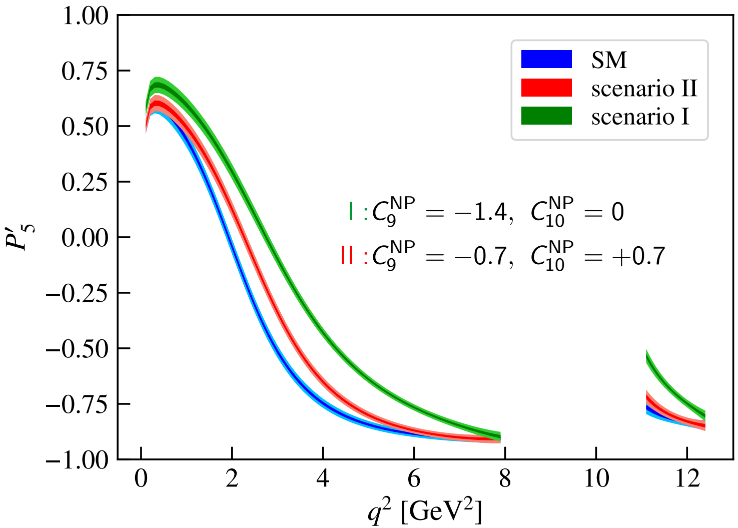


LHCb [PRL 125 (2020) 011802] Belle [PRL 118 (2017) 111801] CMS [PLB 781 (2018) 517] ATLAS [JHEP 10 (2018) 047] LHCb [arXiv:2012.13241]

Theory: [Bharucha, Straub, Zwicky, JHEP 08 (2016) 098] and [Descotes-Genon, Hofer, Matias, Virto, JHEP 12 (2014) 125].

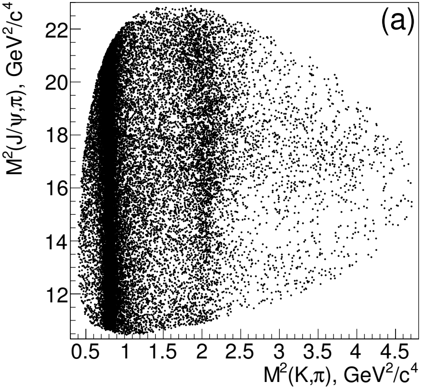
LHCb Phase-II Upgrade : $B \to K^{*}\mu^{+}\mu^{-}$

The problem of $B \to K^{*}\mu^{+}\mu^{-}$ is the understanding of charm loops

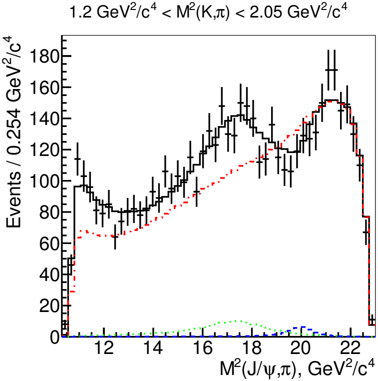


[Belle, PRD 90 112009 (2014), arXiv:1408.6457]

$Z_c(4200)^+$ IN $\bar{B}^0 \to J/\psi K^- \pi^+$



$K^*(890)^0$ and $K^*_{0,2}(1430)^0$ well visible



K^{*0} veto region: $Z_c(4200)^-$ very prominent. $Z_c(4430)^-$ visible via interference.

Conclusion

- ✔ Using clean observables we can pin down C_9, C_{10}
  …assuming that's where new physics is
- For a better picture we need less clean observables.
  - ✗ It's hard to be quantitative about those.


THE
OTHER SIDE
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Backup

Observables

More than 173 observables relevant for leptonic and semileptonic decays:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\mathrm{low}}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\mathrm{low}}(B \to X_s e^+ e^-)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s e^+ e^-)$
- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B_s \to e^+ e^-)$
- $\mathrm{BR}(B_d \to \mu^+\mu^-)$
- R_K in the low q^2 bin
- R_{K^*} in 2 low q^2 bins
- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^+\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^* e^+ e^-)$
- $B^0 \to K^{*0}\mu^+\mu^-$: BR, F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9 in 5 low q^2 and 2 high q^2bins
- $B^+ \to K^{*+}\mu^+\mu^-$: BR, F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9 in 5 low q^2 and 2 high q^2 bins
- $B_s \to \phi\mu^+\mu^-$: BR, F_L, S_3, S_4, S_7 in 3 low q^2 and 2 high q^2 bins
- $\Lambda_b \to \Lambda\mu^+\mu^-$: BR, A_{FB}^{ℓ}, A_{FB}^{h}, $A_{FB}^{\ell h}$, F_L in 1 high q^2 bin

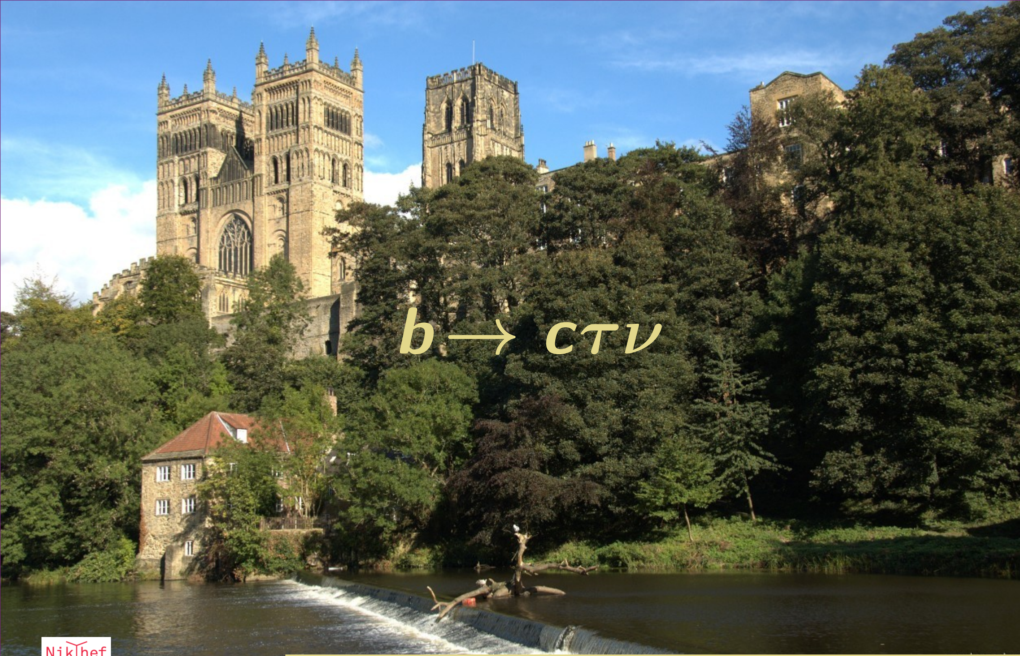
20D fit

Best fit values for the 20 operator global fit to the b → s data, assuming 10% error for the power corrections.
The Pull_{SM} in the parentheses corresponds to considering 19 effective d.o.f. instead of 20.
The numbers in the brackets refer to an alternative solution giving an equally good fit.

All observables with $\chi^2_{\text{SM}} = 225.8$ $\chi^2_{\text{min}} = 151.6$; $\text{Pull}_{\text{SM}} = 5.5(5.6)\sigma$			
δC_7 0.05 ± 0.03		δC_8 -0.70 ± 0.40	
$\delta C'_7$ -0.01 ± 0.02		$\delta C'_8$ 0.00 ± 0.80	
δC_9^μ -1.16 ± 0.17	δC_9^e -6.70 ± 1.20	δC_{10}^μ 0.20 ± 0.21	δC_{10}^e degenerate w/ $C_{10}^{\prime e}$
$\delta C_9^{\prime\mu}$ 0.09 ± 0.34	$\delta C_9^{\prime e}$ 1.90 ± 1.50	$\delta C_{10}^{\prime\mu}$ -0.12 ± 0.20	$\delta C_{10}^{\prime e}$ degenerate w/ C_{10}^e
$C_{Q_1}^\mu$ 0.04 ± 0.10 $[-0.08 \pm 0.11]$	$C_{Q_1}^e$ -1.50 ± 1.50 $[-0.20 \pm 1.60]$	$C_{Q_2}^\mu$ -0.09 ± 0.10 $[-0.11 \pm 0.10]$	$C_{Q_2}^e$ -4.10 ± 1.5 $[4.50 \pm 1.5]$
$C_{Q_1}^{\prime\mu}$ 0.15 ± 0.10 $[0.02 \pm 0.12]$	$C_{Q_1}^{\prime e}$ -1.70 ± 1.20 $[-0.30 \pm 1.10]$	$C_{Q_2}^{\prime\mu}$ -0.14 ± 0.11 $[-0.16 \pm 0.10]$	$C_{Q_2}^{\prime e}$ -4.20 ± 1.2 $[4.40 \pm 1.2]$

Predictions for different μ/e observables

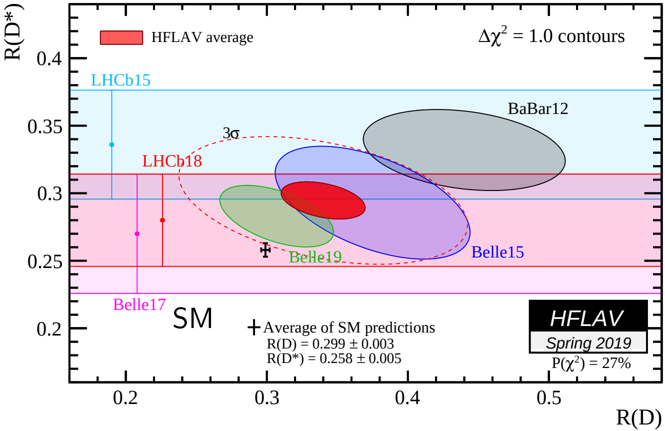
	Predictions assuming 50 fb^{-1} luminosity					
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e	C_{LL}^μ	C_{LL}^e
$D_{F_L}^{[1.1,6.0]}$	$[-0.059, -0.052]$	$[-0.047, -0.044]$	$[-0.004, -0.002]$	$[-0.003, -0.002]$	$[-0.029, -0.027]$	$[0.004, 0.007]$
$D_{A_{FB}}^{[1.1,6.0]}$	$[-0.061, -0.051]$	$[-0.047, -0.042]$	$[0.001, 0.001]$	$[0.000, 0.000]$	$[-0.028, -0.025]$	$[0.028, 0.032]$
$D_{S_3}^{[1.1,6.0]}$	$[0.001, 0.001]$	$[0.001, 0.001]$	$[0.002, 0.002]$	$[0.002, 0.002]$	$[0.002, 0.002]$	$[0.000, 0.000]$
$D_{S_4}^{[1.1,6.0]}$	$[-0.003, -0.003]$	$[-0.007, -0.006]$	$[-0.024, -0.021]$	$[-0.024, -0.021]$	$[-0.017, -0.015]$	$[0.000, 0.000]$
$D_{S_5}^{[1.1,6.0]}$	$[0.074, 0.089]$	$[0.056, 0.062]$	$[-0.002, -0.002]$	$[-0.007, -0.006]$	$[0.032, 0.037]$	$[-0.043, -0.037]$
$D_{F_L}^{[15,19]}$	$[-0.001, 0.000]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$
$D_{A_{FB}}^{[15,19]}$	$[-0.027, -0.021]$	$[-0.004, -0.004]$	$[0.003, 0.004]$	$[0.013, 0.015]$	$[-0.002, -0.001]$	$[0.009, 0.010]$
$D_{S_3}^{[15,19]}$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$
$D_{S_4}^{[15,19]}$	$[0.000, 0.000]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$
$D_{S_5}^{[15,19]}$	$[0.016, 0.020]$	$[0.003, 0.003]$	$[-0.003, -0.003]$	$[-0.012, -0.010]$	$[0.001, 0.001]$	$[-0.008, -0.006]$
$R_{P_2}^{[1.1,6.0]}$	$[4.221, 4.736]$	$[-0.373, -0.316]$	$[1.010, 1.018]$	$[1.031, 1.044]$	$[2.740, 2.976]$	$[0.311, 0.338]$
$R_{P_1}^{[1.1,6.0]}$	$[0.791, 0.820]$	$[0.807, 0.000]$	$[0.902, 0.917]$	$[0.924, 0.932]$	$[0.821, 0.845]$	$[1.133, 1.151]$
$R_{P_4}^{[1.1,6.0]}$	$[0.941, 0.948]$	$[0.918, -0.044]$	$[0.850, 0.871]$	$[0.879, 0.891]$	$[0.871, 0.888]$	$[1.047, 1.052]$
$R_{P_5}^{[1.1,6.0]}$	$[0.437, 0.528]$	$[0.701, -0.042]$	$[1.054, 1.058]$	$[1.079, 1.088]$	$[0.774, 0.804]$	$[1.359, 1.430]$
$R_{P_2}^{[15,19]}$	$[0.931, 0.946]$	$[0.990, 0.001]$	$[1.011, 1.012]$	$[1.038, 1.044]$	$[0.997, 0.998]$	$[1.025, 1.030]$
$R_{P_1}^{[15,19]}$	$[1.000, 1.000]$	$[1.000, -0.006]$	$[1.001, 1.001]$	$[1.001, 1.001]$	$[1.000, 1.001]$	$[1.000, 1.000]$
$R_{P_4}^{[15,19]}$	$[1.000, 1.000]$	$[1.000, 0.062]$	$[1.000, 1.000]$	$[1.000, 1.000]$	$[1.000, 1.000]$	$[1.000, 1.000]$
$R_{P_5}^{[15,19]}$	$[0.930, 0.946]$	$[0.990, -0.001]$	$[1.011, 1.012]$	$[1.038, 1.044]$	$[0.997, 0.998]$	$[1.025, 1.030]$
$Q_2^{[1.1,6.0]}$	$[0.121, 0.141]$	$[0.131, 0.148]$	$[0.000, 0.001]$	$[0.001, 0.001]$	$[0.066, 0.074]$	$[-0.079, -0.069]$
$Q_1^{[1.1,6.0]}$	$[0.018, 0.021]$	$[0.021, 0.024]$	$[0.008, 0.010]$	$[0.007, 0.008]$	$[0.016, 0.018]$	$[-0.013, -0.012]$
$Q_4^{[1.1,6.0]}$	$[-0.036, -0.032]$	$[-0.056, -0.048]$	$[-0.092, -0.079]$	$[-0.086, -0.076]$	$[-0.080, -0.069]$	$[0.028, 0.031]$
$Q_5^{[1.1,6.0]}$	$[0.180, 0.215]$	$[0.148, 0.165]$	$[-0.022, -0.021]$	$[-0.031, -0.028]$	$[0.075, 0.086]$	$[-0.117, -0.102]$
$Q_2^{[15,19]}$	$[0.021, 0.026]$	$[0.003, 0.004]$	$[-0.004, -0.004]$	$[-0.016, -0.014]$	$[0.001, 0.001]$	$[-0.011, -0.009]$
$Q_1^{[15,19]}$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[-0.001, -0.001]$	$[-0.001, -0.001]$	$[0.000, 0.000]$	$[0.000, 0.000]$
$Q_4^{[15,19]}$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$	$[0.000, 0.000]$
$Q_5^{[15,19]}$	$[0.033, 0.042]$	$[0.005, 0.006]$	$[-0.007, -0.007]$	$[-0.026, -0.022]$	$[0.001, 0.002]$	$[-0.018, -0.015]$



$b \to c\tau\nu$

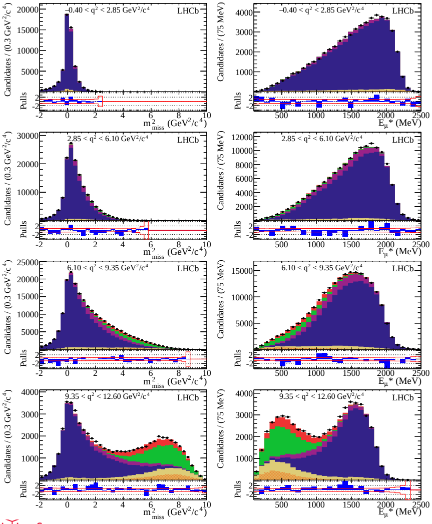
$B \to D^{(*)}\tau\nu$ HFLAV AVERAGE

HFLAV

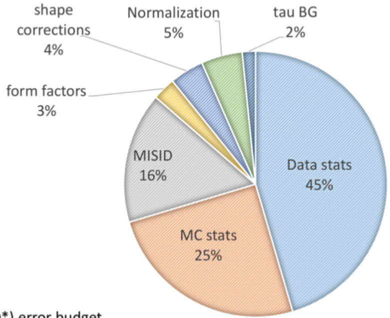


BABAR [PRL 109 101802 (2012)] [PRD 88 072012 (2013)] Belle [PRD 92 072014 (2015)] [PRL 118 211801 (2017)] [PRD 97 012004 (2018)] [PRL124 (2020) 161803] LHCb [PRL 115 (2015) 111803] [PRL 120 (2018) 171802]. Theory [FLAG EPJC77 (2017) 112], [Faijfer et al., PRD 85 094025 (2012)]

$\overline{B}^0 \to D^{*+}\tau\nu$ AT LHCb



- Get 36300 ± 1600 $B \to D^{*+}\mu^-\overline{\nu}$ decays and $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$
  - Dominant systematics are MC stats and mis-ID μ shapes



R(D*) error budget

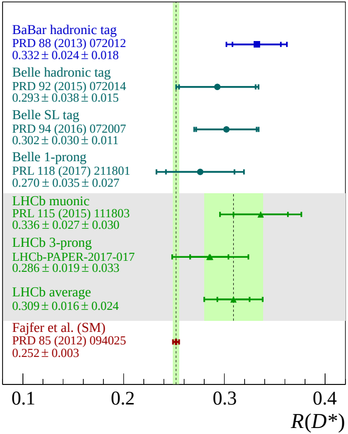
[LHCb, PRL 120 (2018) 171802, arXiv:1708.08856] [LHCb, PRD 97 (2018) 072013, arXiv:1711.02505]

$B^0 \to D^{*-}\tau^+\nu_\tau$ WITH $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$

Signal and backgrounds are determined by a three-dimensional binned fit to t_τ, q^2 and BDT output.

- signal yield: 1273 ± 85.
- Normalised to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ [PRD 87 (2013) 092001], yielding $\mathcal{B}(B \to D^*\tau^+\nu_\tau) = (1.40 \pm 0.09 \pm 0.12 \pm 0.10)\%$

$\mathcal{R}(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$, 1σ above the SM (0.252 ± 0.003 [Faijfer et al.]) and consistent with the world average.

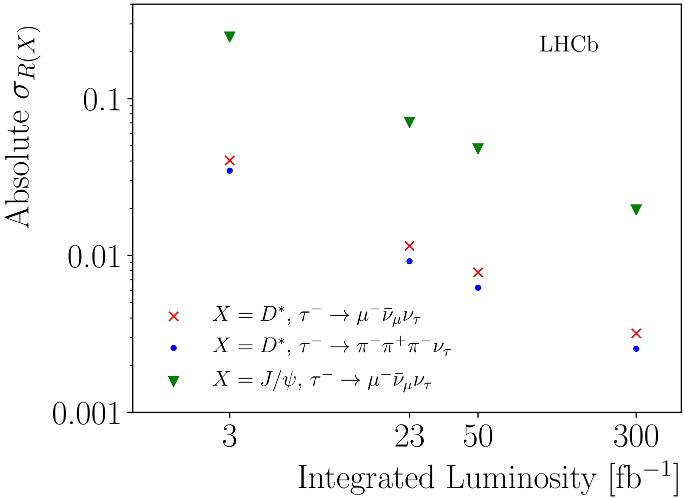


The world average becomes $\mathcal{R}(D^*)^{\text{WA}} = 0.304 \pm 0.013 \pm 0.007$

LHCb Phase-II Upgrade : $R(D^{(*)})$

It is assumed that all systematic uncertainties scale with $\sqrt{\mathcal{L}}$.

- ✔ No irreducible systematic uncertainty
- ✗ Improved form factors
- backgrounds from $B \to D\overline{D}$



[B]

More stuff

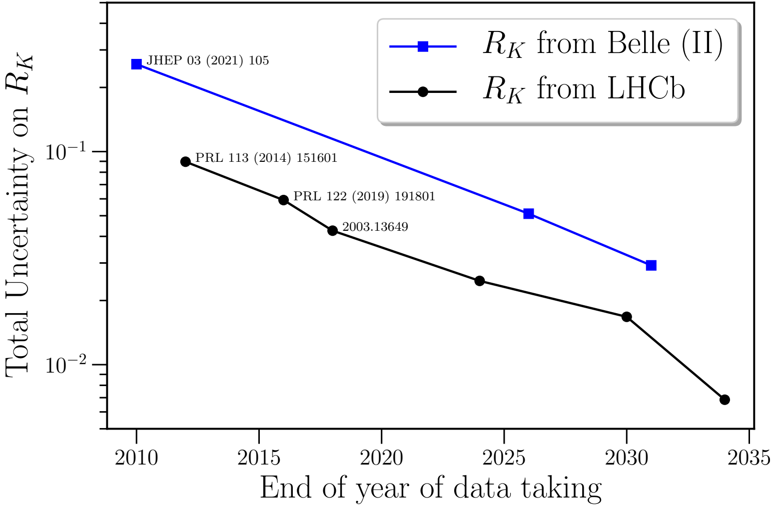
Projections for R_K in $1(.1) < q^2 < 6\,\mathrm{GeV}^2/c^4$

Experiment	$\int L dt$	N_{Kee}	R_K	Δ
Belle [Belle, JHEP 03 (2021) 105]	$711\,\mathrm{fb}^{-1}$	51 ± 10	$0.98\,^{+0.27}_{-0.23} \pm 0.06$	0.26
LHCb [PRL 113 (2014) 151601]	$3\,\mathrm{fb}^{-1}$	$254\,^{+29}_{-27}$	$0.745\,^{+0.090}_{-0.074} \pm 0.036$	0.09
LHCb [PRL 122 (2019) 191801]	$5\,\mathrm{fb}^{-1}$	770 ± 50	$0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$	0.059
LHCb [arXiv:2103.11769]	$9\,\mathrm{fb}^{-1}$	1640 ± 70	$0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$	0.042
Extrapolations				
LHCb Run 3 (2024)	$23\,\mathrm{fb}^{-1}$	4k		0.027
Belle II (2024)	$35\,\mathrm{ab}^{-1}$	2.5k		0.051
Belle II (2026)	$60\,\mathrm{ab}^{-1}$	4.3k		0.029
LHCb Run 4 (2030)	$50\,\mathrm{fb}^{-1}$	9k		0.018
LHCb Run 5 (2035)	$300\,\mathrm{fb}^{-1}$	55.0k		0.007

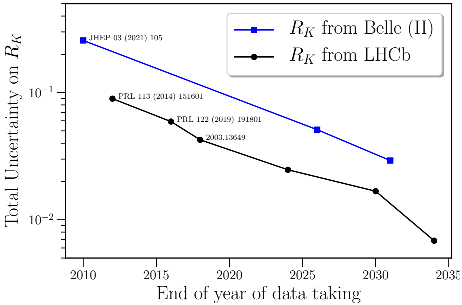
Yields at Belle sum K^+ and K^0_S. LHCb projections are similar to those in the Phase-II upgrade physics case [arXiv:1808.08865] based on the $3\,\mathrm{fb}^{-1}$ result [PRL 113 (2014) 151601].

[Scholarpedia, arXiv:1606.00999]

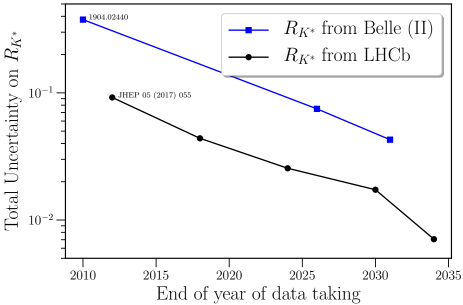
Projections for R_K in $1(.1) < q^2 < 6\,\mathrm{GeV}^2/c^4$



Projections for R_K in $1(.1) < q^2 < 6\,\mathrm{GeV}^2/c^4$



Uncertainty on R_K versus data taking year, based on [arXiv:2103.11769] and [Belle, arXiv:1908.01848]



Uncertainty on R_{K^*} versus data taking year, based on [JHEP 08 (2017) 055] and [Belle, arXiv:1904.02440]

Projections for R_{K^*} in $1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

Experiment	$\int L dt$	$N_{K^* ee}$	R_{K^*}	Δ
LHCb [1705.05802]	$3\,\mathrm{fb}^{-1}$	111 ± 14	$0.69\,^{+0.11}_{-0.07} \pm 0.03$	0.092
Belle [1904.02440]	$711\,\mathrm{fb}^{-1}$	103 ± 13 *	$0.96\,^{+0.45}_{-0.29} \pm 0.11$	0.39
Extrapolations				
LHCb Run 2 (2018)	$9\,\mathrm{fb}^{-1}$	500		0.044
LHCb Run 3 (2024)	$23\,\mathrm{fb}^{-1}$	1k		0.026
Belle II (2024)	$35\,\mathrm{ab}^{-1}$	2k		0.075
Belle II (2026)	$60\,\mathrm{ab}^{-1}$	3k		0.043
LHCb Run 4 (2030)	$50\,\mathrm{fb}^{-1}$	3k		0.017
LHCb Run 5 (2035)	$300\,\mathrm{fb}^{-1}$	20k		0.007

* in full q^2 range. I assume 1/3 goes into 1–6 GeV^2/c^4.
LHCb projections are similar to those in the Phase-II upgrade physics case [arXiv:1808.08865] based on the $3\,\mathrm{fb}^{-1}$ result [JHEP 08 (2017) 055].

Projections for R_{K^*} in $1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4$