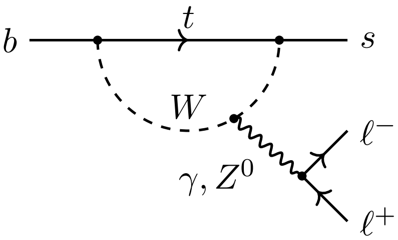
$b \to s\ell\ell$ and Lepton Flavour Universality at LHCb

C. Langenbruch[1]
on behalf of the LHCb collaboration
[1]Heidelberg University

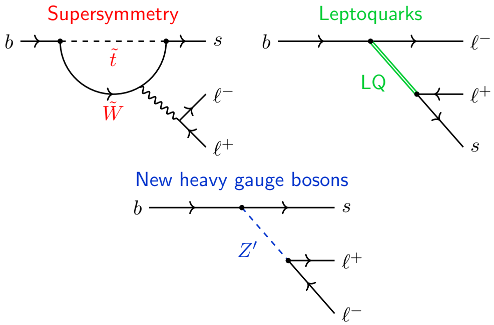
Moriond EW 2023
March 20$^{\text{th}}$ 2023

$b \to s\ell\ell$ decays as sensitive probes for New Physics

$b \to s\ell\ell$ decays in the SM

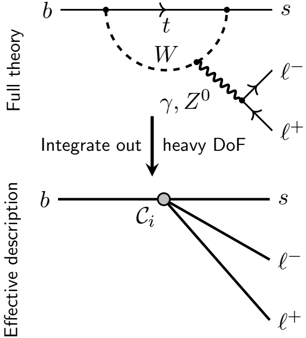


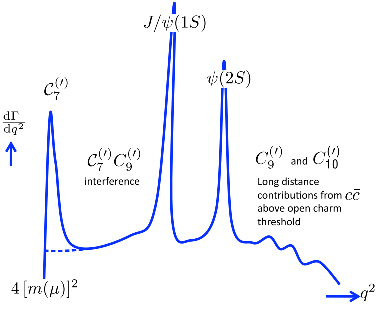
Possible contributions from NP



- $b \to s\ell\ell$ decays heavily (loop-)suppressed in the SM
- New heavy particles can significantly contribute and affect decay rates, angular distributions, and rate asymmetries

Effective field theory for $b \to s\ell\ell$ decays





- $b \to s\ell\ell$ transitions described model-independently in effective theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local operator ($\mathcal{O}_i$)

Wilson coefficient ("effective coupling") ($\mathcal{C}_i$)

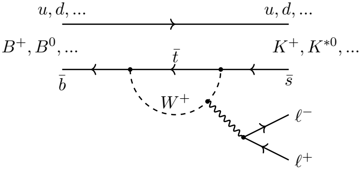
Effective couplings in $b \to s\ell\ell$ transitions		
Wilson coefficient		Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

For completeness

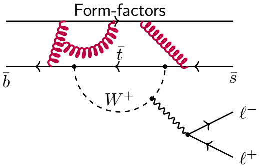
- Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations

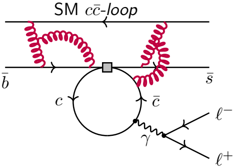
Observables in $b \to s\ell\ell$ decays and their cleanliness

Quarks bound in hadrons, *e.g.*



Hadronic uncertainties

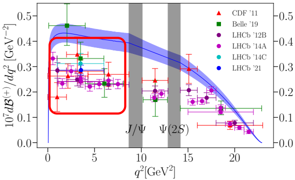




$b \to s\ell\ell$ Observables

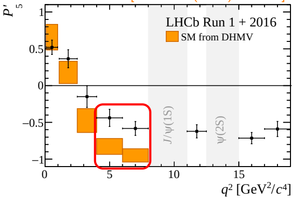
Increasing precision of SM prediction

[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



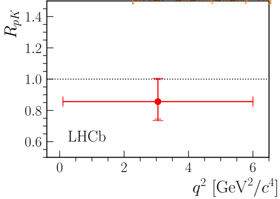
Branching fractions
affected by form-factors and $c\bar{c}$-loop

[PRL 125 (2020) 011802]



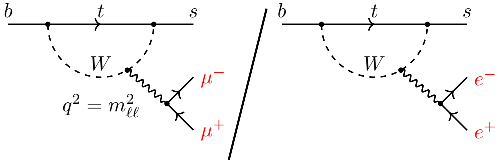
Angular observables
affected by $c\bar{c}$-loop

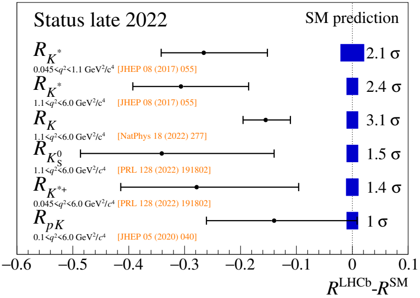
[JHEP 2020 (2020) 40]



Lepton Universality Tests
clean

Lepton Flavour Universality tests in $b \to s\ell\ell$ decays



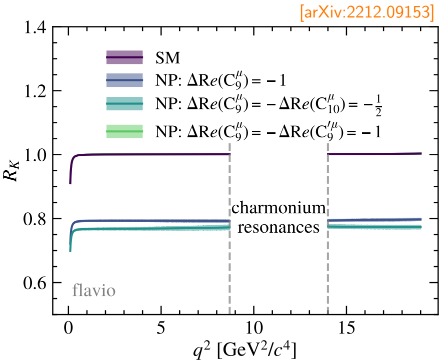


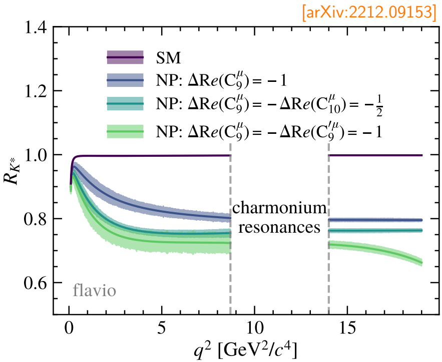
- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \to s\ell^+\ell^-$ decays:

$$R_{K,K^*} = \frac{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

- Exactly unity in SM, differences only through lepton mass effects
- QED corrections $\mathcal{O}(1\,\%)$ [EPJC 76 (2016) 440]
- Hadronic uncertainties (form-factors and $c\bar{c}$-loop) cancel in the ratio

R_K and R_{K^*} in different NP scenarios

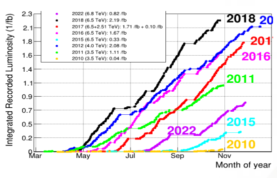


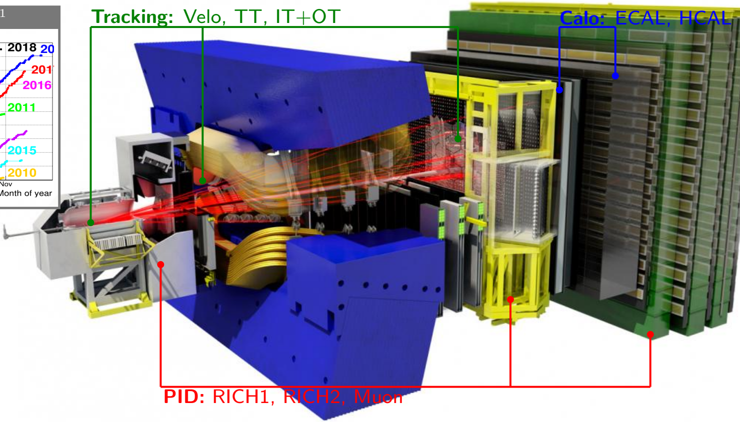


- Example NP models assuming NP only in muons
- Some ability to disentangle different scenarios with R_K and R_{K^*}
- Simultaneous R_K and R_{K^*} determination with $9\,\text{fb}^{-1}$ Run 1+2 data
  - low–q^2: $q^2 \in [0.1, 1.0]\,\text{GeV}^2/c^4$
  - central–q^2: $q^2 \in [1.1, 6.0]\,\text{GeV}^2/c^4$

The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\mathrm{fb}^{-1}$, Run 2: $6\,\mathrm{fb}^{-1}$

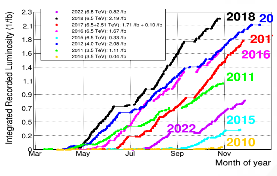




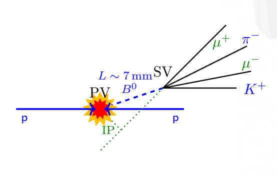
- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\mathrm{b}$ at $7\,\mathrm{TeV}$ and $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1 - 3\%$
- Low trigger thresholds: $p_{\mathrm{T}}(\mu) > 1.8\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 3.0\,\mathrm{GeV}$

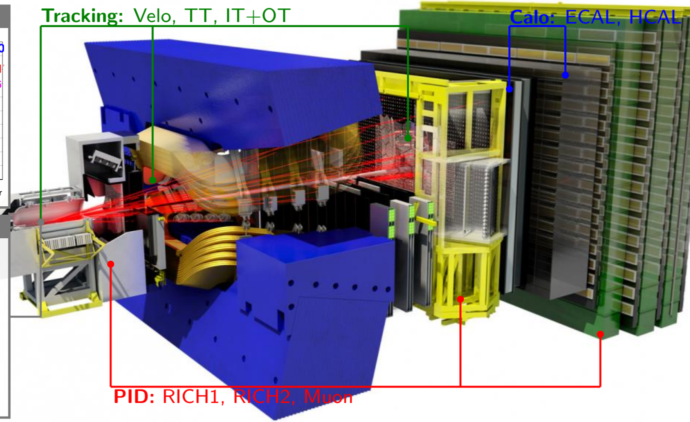
The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\text{fb}^{-1}$, Run 2: $6\,\text{fb}^{-1}$



Heavy flavour signature





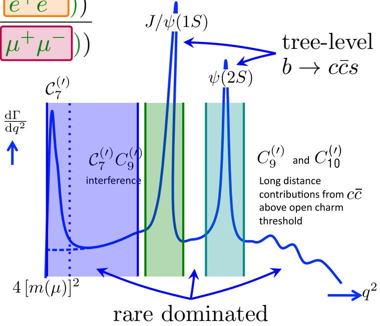
- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\text{b}$ at $7\,\text{TeV}$ and $(495 \pm 52)\,\mu\text{b}$ at $13\,\text{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\text{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Low trigger thresholds: $p_\text{T}(\mu) > 1.8\,\text{GeV}$, $E_\text{T}(e) > 3.0\,\text{GeV}$

Analysis strategy: Double ratio (Example: R_K)

- Analysis strategy: Double ratio of rare modes $B^+ \to K^+\ell^+\ell^-$ with resonant decays $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \times \underbrace{\frac{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}}_{r_{J/\psi}^{-1}=1 \text{ [PRD 88 (2013) 3]}}$$

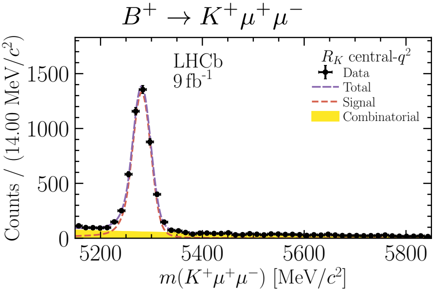
- Electron and Muon reconstruction very different at LHCb
- Efficiencies from corrected simulation
- Double ratio cancels most experimental systematic effects in efficiency ratios

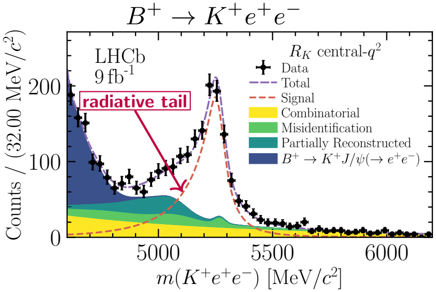


- Important cross-checks: $r_{J/\psi} = \frac{\mathcal{B}(B^+\to K^+J/\psi(\to\mu^+\mu^-))}{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}$ and

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+\to K^+\psi(2S)(\to\mu^+\mu^-))}{\mathcal{B}(B^+\to K^+\psi(2S)(\to e^+e^-))} \times \frac{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+\to K^+J/\psi(\to\mu^+\mu^-))}$$

Experimental challenges for electron modes at LHCb



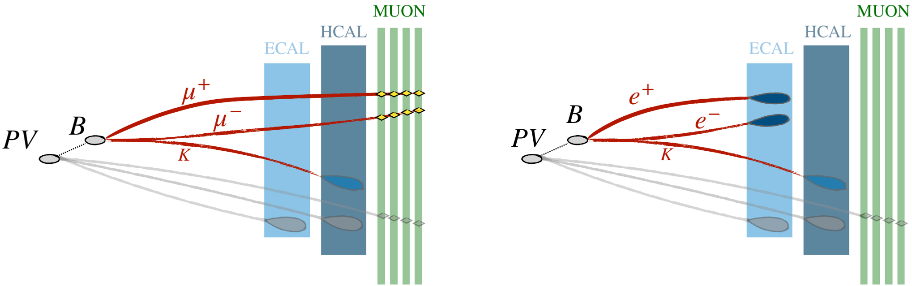


[arXiv:2212.09152] [arXiv:2212.09153]

Experimental Challenges for electron modes:

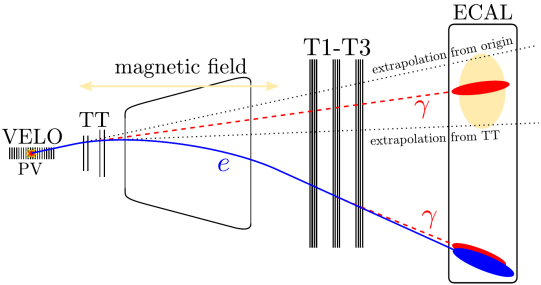
1. Low e trigger efficiencies due to higher thresholds compared to muons
2. Electrons strongly emit Bremsstrahlung traversing material
3. Contribution from several background sources, bkg. modeling critical

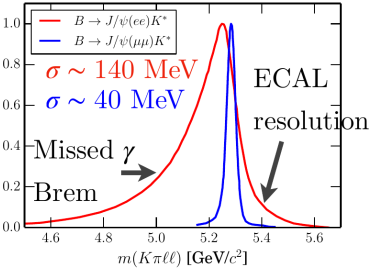
Experimental challenge: 1. Electron trigger



- Trigger signatures for muon and electron modes very different
- Lower L0 p_{T} thresholds for muons $(1.5–1.8\,\mathrm{GeV}/c)$ compared to electrons $(2.5–3.0\,\mathrm{GeV})$ $\rightarrow$ challenging for e^+e^- modes
- Combine exclusive trigger categories to improve ϵ for electron modes:
  1. Trigger on rest of event (independent of signal)
  2. Trigger on e/μ from signal

Experimental challenge: 2. Bremsstrahlung

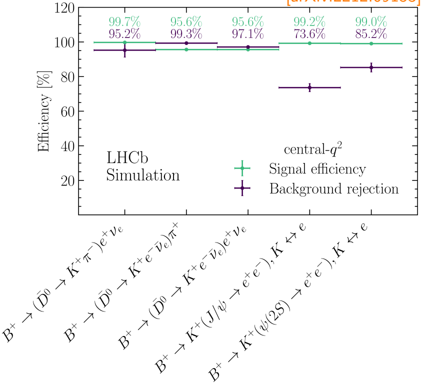




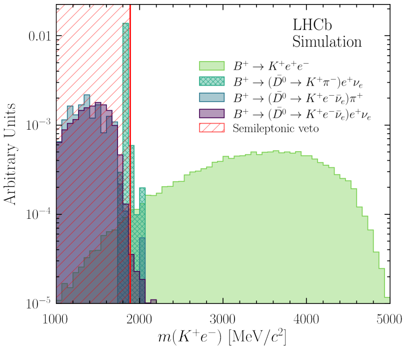
- Correct electron momentum by adding matching photons ($E_T > 75\,\mathrm{MeV}/c^2$) reconstructed in the ECAL
- Bremsstrahlung recovery $\sim 50\%$ efficient, well simulated
- Bremsstrahlung reconstruction impacts momentum resolution $\rightarrow$ higher background pollution and more sensitive to bkg. modeling

Experimental challenge: 3. Background suppression

[arXiv:2212.09153]

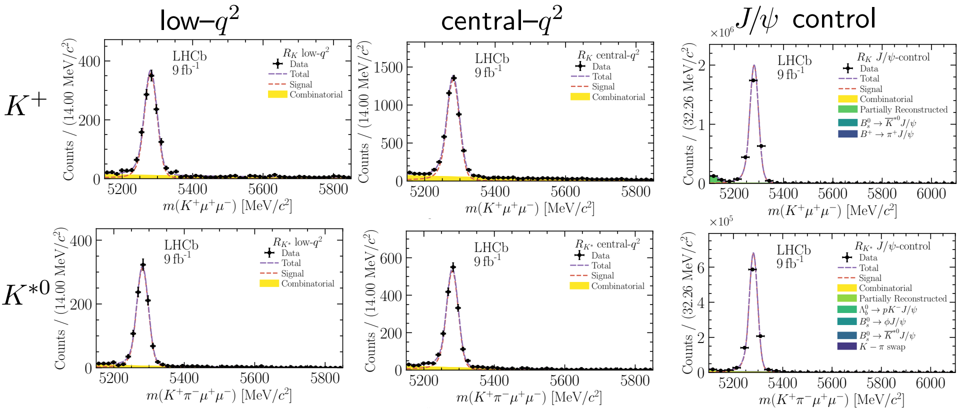


[arXiv:2212.09153]



- Combinatorial: multivariate classifier using kinematic quantities and vertex quality information
- Partially reconstructed: multivariate classifier in electron mode and corrected mass exploiting PV/SV reconstruction
- Misidentification: Lepton and hadron particle identification Residual backgrounds from misidentification explicitly modeled [see backup]

Muon mode fits

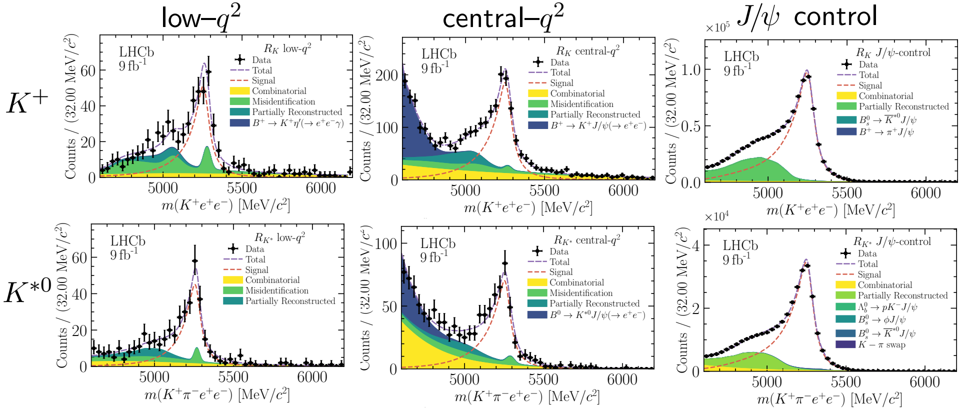


[arXiv:2212.09152] [arXiv:2212.09153]

- Muon mode is very clean!
- Muon branching fraction compatible with published results

[JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

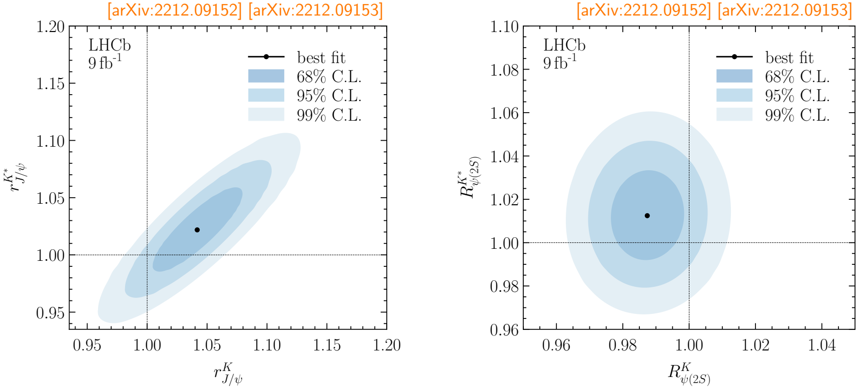
Electron mode fits



[arXiv:2212.09152] [arXiv:2212.09153]

- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bgk. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

Crosschecks $r_{J/\psi}$ and $R_{\psi(2S)}$



- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$

R_K and R_{K^*} results

- Most precise test of Lepton Flavour Universality in $b \to s\ell^+\ell^-$ transitions
- Supersedes previous results
- Compatible with the SM at $0.2\,\sigma$ using a simple χ^2 test
- Statistical uncertainty dominates
- Scaling R_{K,K^*} with measured muon $\mathcal{B}$: [JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

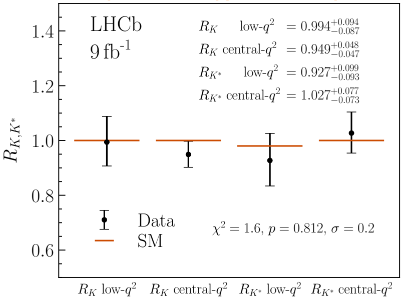
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2} = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

$$\frac{\mathrm{d}\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathrm{d}q^2} = (33.3^{+2.7}_{-2.6} \pm 2.2) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

- Dedicated $\mathcal{B}$ measurements of ee modes and angular analyses ongoing

see also [talk by A. Snoch]

[arXiv:2212.09152] [arXiv:2212.09153]



R_K and R_{K^*} results

- Most precise test of Lepton Flavour Universality in $b \to s\ell^+\ell^-$ transitions
- Supersedes previous results
- Compatible with the SM at $0.2\,\sigma$ using a simple χ^2 test
- Statistical uncertainty dominates
- Scaling R_{K,K^*} with measured muon $\mathcal{B}$:

[JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

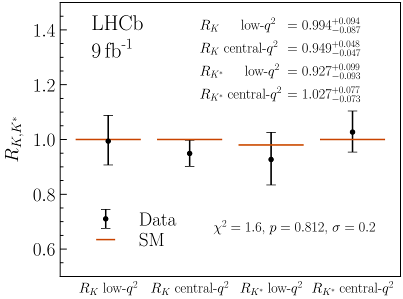
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2} = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

$$\frac{\mathrm{d}\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathrm{d}q^2} = (33.3^{+2.7}_{-2.6} \pm 2.2) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

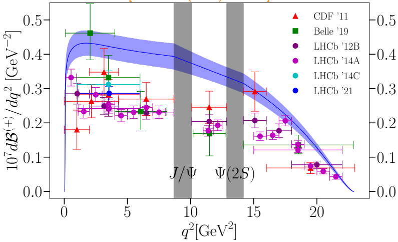
- Dedicated $\mathcal{B}$ measurements of ee modes and angular analyses ongoing

see also [talk by A. Snoch]

[arXiv:2212.09152] [arXiv:2212.09153]



[PRD 107 (2023) 014511]



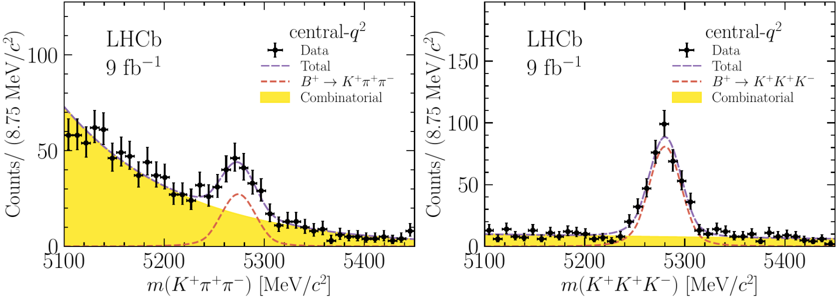
Conclusions

- $b \to s\ell\ell$ decays powerful probes of the SM
- Lepton Flavour Universality tests exhibit the most precise SM prediction in this area
- Data in excellent agreement with lepton flavour universality
- Tensions in muon branching fractions and angular analyses remain
- Measurement statistically limited
  $\to$ More precision needed
- Run 3 just started with brand new LHCb detector
- Will increase $\int \mathcal{L}\mathrm{d}t$ by more than factor 5 during Runs 3–4, allowing for unprecedented reach with precision flavour observables

cc-by-2.0, Christopher Michel

Residual backgrounds from misidentification

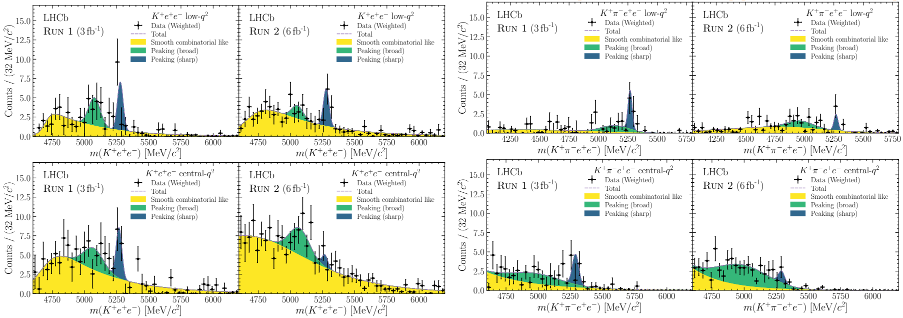
[arXiv:2212.09152] [arXiv:2212.09153]



- Misidentified backgrounds can be isolated by inverting particle ID cuts: Examples are (left) $B^+ \to K^+\pi^+\pi^-$ and (right) $B^+ \to K^+K^+K^-$
- Similar backgrounds for $K^{*0}e^+e^-$, however Dalitz structure not well known
- Backgrounds from single misidentification less well known, complex shape
- Developed new inclusive data-driven treatment of misidentified residual backgrounds

Residual backgrounds from misidentification

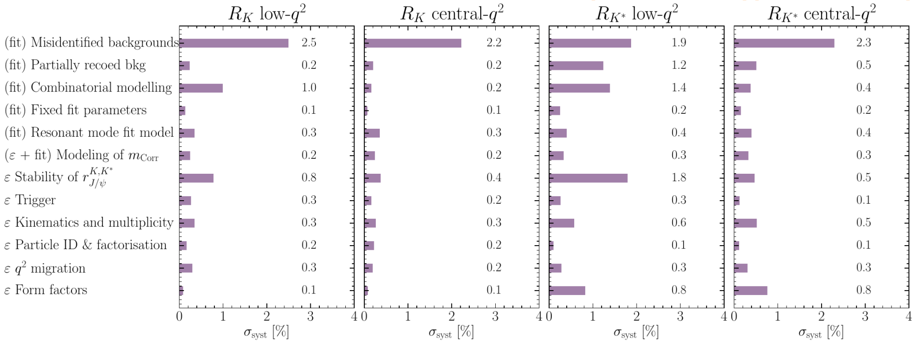
[arXiv:2212.09152] [arXiv:2212.09153]



- Invert electron PID selection to obtain control region
- Use control samples from data to weight control region events according to their misidentification probability $w_e = \epsilon_{\text{pass PID}}/\epsilon_{\text{fail PID}}$
- Resulting distribution and expected background yield used in nominal rare electron mode fit

Systematic uncertainties

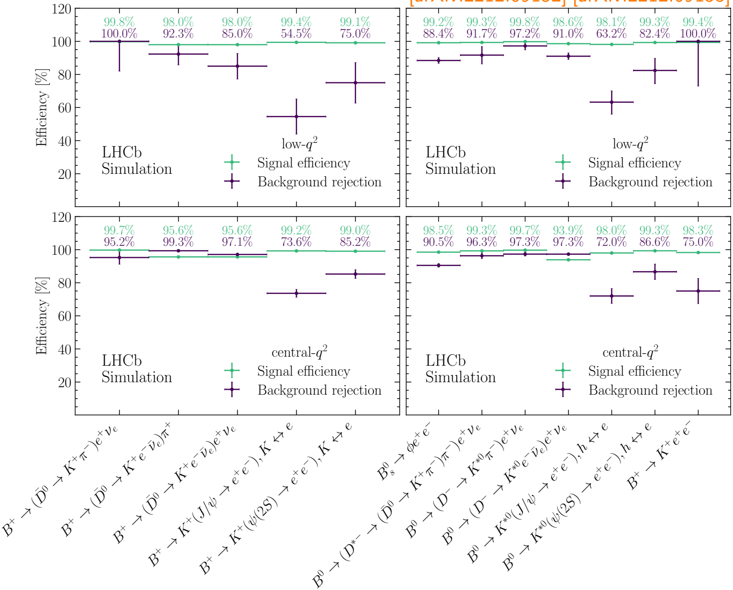
[arXiv:2212.09152] [arXiv:2212.09153]



- Dominant systematic: Modeling of residual misidentified bgks.
- Measurement statistically limited

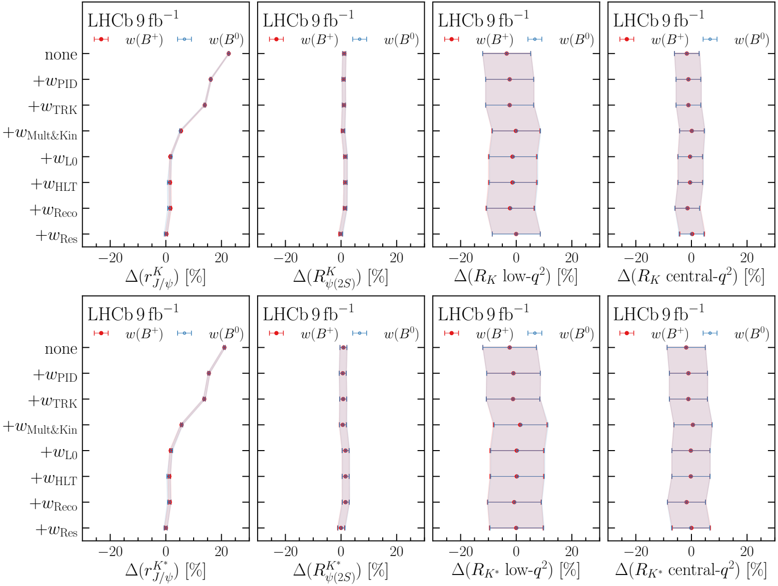
R_{K,K^*} specific background vetos

[arXiv:2212.09152] [arXiv:2212.09153]



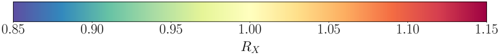
R_{K,K^*} efficiency corrected ratios

[arXiv:2212.09152] [arXiv:2212.09153]



R_{K,K^*} PID dependence

LHCb



R_K low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 5	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 2	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093

ProbNN(e)

R_K central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.948 ± 0.051	0.944 ± 0.051	0.944 ± 0.051	0.939 ± 0.051	0.939 ± 0.051	0.941 ± 0.051	0.934 ± 0.051	0.935 ± 0.051	0.937 ± 0.052
DLL(e) > 5	0.941 ± 0.044	0.938 ± 0.044	0.942 ± 0.044	0.933 ± 0.044	0.939 ± 0.045	0.951 ± 0.046	0.946 ± 0.046	0.953 ± 0.047	0.949 ± 0.048
DLL(e) > 2	0.906 ± 0.040	0.902 ± 0.040	0.907 ± 0.040	0.895 ± 0.040	0.904 ± 0.041	0.916 ± 0.042	0.920 ± 0.043	0.925 ± 0.044	0.919 ± 0.044

ProbNN(e)

R_{K^*} low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.985 ± 0.112	0.982 ± 0.112	0.966 ± 0.109	0.952 ± 0.107	0.971 ± 0.111	0.975 ± 0.112	0.984 ± 0.114	0.970 ± 0.112	0.960 ± 0.111
DLL(e) > 5	0.980 ± 0.097	0.993 ± 0.100	0.978 ± 0.099	0.979 ± 0.100	1.007 ± 0.103	1.014 ± 0.105	1.010 ± 0.106	1.010 ± 0.108	1.019 ± 0.110
DLL(e) > 2	0.855 ± 0.080	0.848 ± 0.079	0.830 ± 0.076	0.847 ± 0.080	0.883 ± 0.086	0.901 ± 0.088	0.915 ± 0.089	0.925 ± 0.092	0.934 ± 0.117

ProbNN(e)

R_{K^*} central-q^2

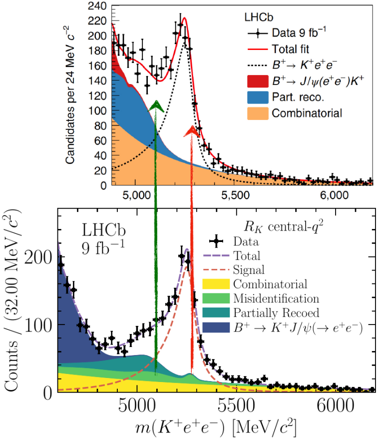
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	1.012 ± 0.077	1.035 ± 0.081	1.049 ± 0.084
DLL(e) > 2	0.965 ± 0.066	0.990 ± 0.069	0.986 ± 0.069	0.993 ± 0.071	1.024 ± 0.075	1.006 ± 0.073	1.014 ± 0.075	1.038 ± 0.079	1.039 ± 0.081

ProbNN(e)

[arXiv:2212.09152] [arXiv:2212.09153]

R_K comparison with previous measurement (credit R. Quagliani)

[Nat. Phys. 18, 277-282 (2022)]



- Different PID cut used ➡ Allowed σ_{stat} : ±0.033
- Mis-ID rate from $D^{*-} \to D^0(K\pi)\pi$
- With new(previous) analysis requirements

	Sample	$\pi \to e$	$K \to e$
(11+12)	Run 1	1.78 (1.70) %	0.69 (1.24) %
(15+16)	Run 2p1	0.83 (1.51) %	0.18 (1.25) %
(17+18)	Run 2p2	0.80 (1.50) %	0.16 (1.23) %

	$\pi \to e$	$K \to e$
single-misID	**× 1 (Run1)** **× 2 (Run2)**	**× 2 (Run1)** **× 7 (Run2)**
double-misID	**× 1^2 (Run1)** **× 2^2 (Run2)**	**× 2^2 (Run1)** **× 7^2 (Run2)**

- Shift due to contamination at looser working point : $+$**0.064**
- Shift due to not inclusion of background in mass fit: $+$**0.038**

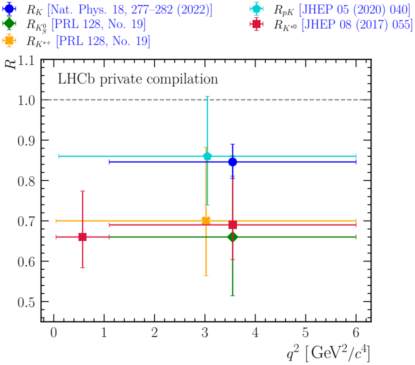
Adds linearly

LHCb presentation at ICHEP 2022

On the R_K and $R_{K^{*0}}$ Update

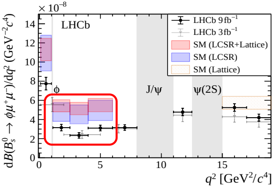
ICHEP 2022 BOLOGNA

- Working on **unified analysis** of R_K and $R_{K^{*0}}$
- Will provide **final** Run 1 and Run 2 results
- Efforts lead to a deeper understanding of the LFU measurements
- This will be reflected in the results
- Work is **high priority** for the collaboration
- We appreciate your patience until the results become available

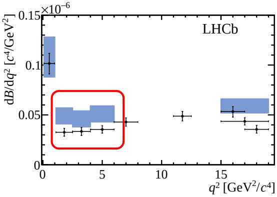


Low $\mathcal{B}$ also found for other $b \to s\mu^+\mu^-$ decays

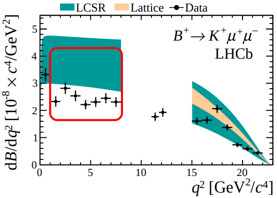
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



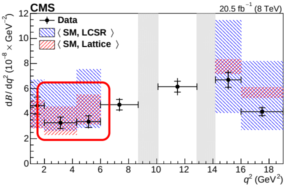
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



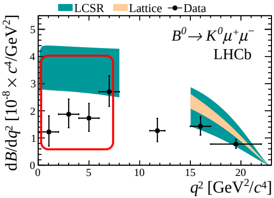
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



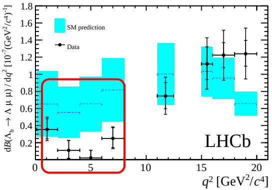
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



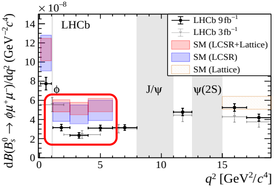
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



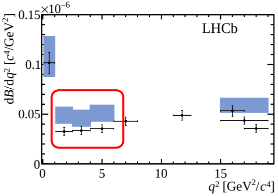
- Data consistently below SM predictions (particularly at low q^2)
- Tensions at 1–3σ level, SM predictions exhibit sizeable had. uncertainties
- Exciting recent developements on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, arXiv:2207.13371]
- Work on updates with full data sample, clean observables like A_I

Low $\mathcal{B}$ also found for other $b \to s\mu^+\mu^-$ decays

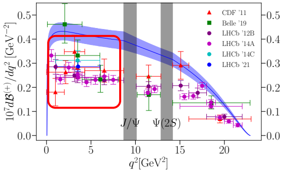
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



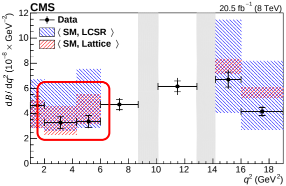
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



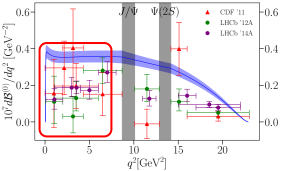
Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



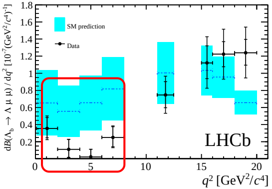
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]

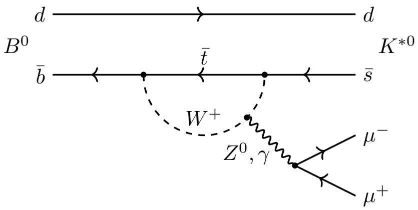


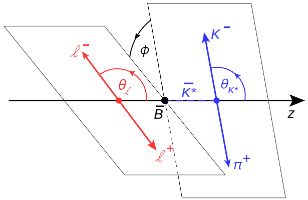
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



- Data consistently below SM predictions (particularly at low q^2)
- Tensions at 1–3σ level, SM predictions exhibit sizeable had. uncertainties
- Exciting recent developements on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, arXiv:2207.13371]
- Work on updates with full data sample, clean observables like A_I

Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$



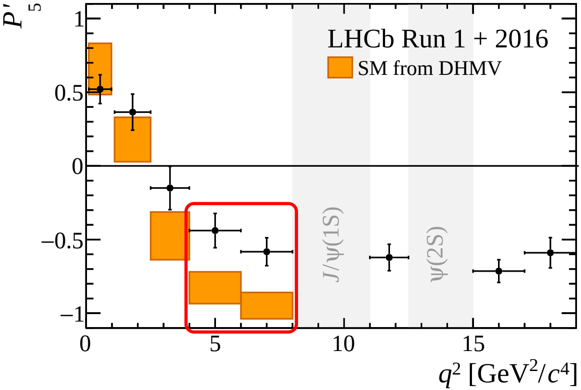


- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$
- Angular observables $F_{\mathrm{L}}, A_{\mathrm{FB}}, S_i$ sensitive to NP contributions
- Perform ratios of observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

For completeness

Angular observable P'_5 from $B^0 \to K^{*0}\mu^+\mu^-$

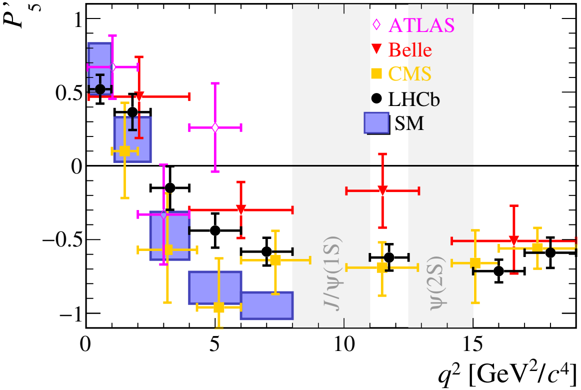
[PRL 125 (2020) 011802]



- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local tensions of $2.5\,\sigma$ and $2.9\,\sigma$
- Global $B^0 \to K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to $3.3\,\sigma$
- [LHCb, PRL 125 (2020) 011802] consistent with [Belle, PRL 118 (2017) 111801] [CMS, PLB 781 (2018) 517] [ATLAS, JHEP 10 (2018) 047]

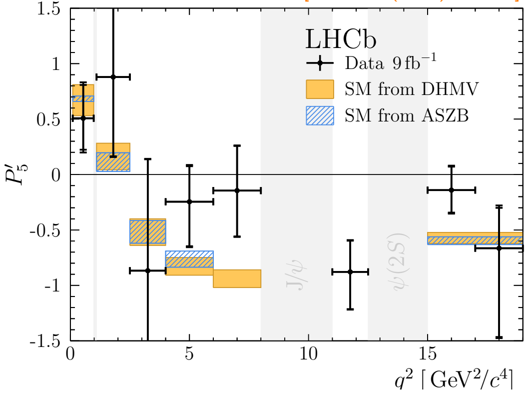
Angular observable P_5' from $B^0 \to K^{*0}\mu^+\mu^-$

[PIPNP 120 (2021) 103885]



- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\text{GeV}^2/c^4$ local tensions of $2.5\,\sigma$ and $2.9\,\sigma$
- Global $B^0 \to K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to $3.3\,\sigma$
- [LHCb, PRL 125 (2020) 011802] consistent with [Belle, PRL 118 (2017) 111801] [CMS, PLB 781 (2018) 517] [ATLAS, JHEP 10 (2018) 047]

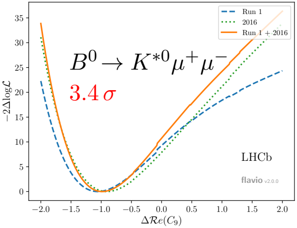
Angular observable P_5' from $B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$



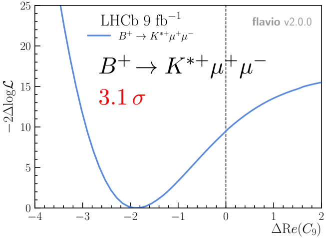
- Recent LHCb measurement using Run 1+2 data [PRL 126 (2021) 161802]
- Global tension corresponding to $3.1\,\sigma$, consistent with $B^0 \to K^{*0}\mu^+\mu^-$
- Angular analysis ($F_L + A_{FB}$) also by CMS [JHEP 04 (2021) 124]

Consistency of $b \to s\mu^+\mu^-$ angular analyses

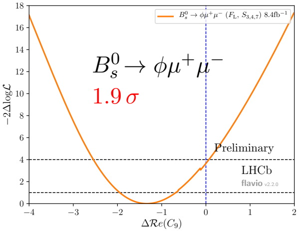
[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]

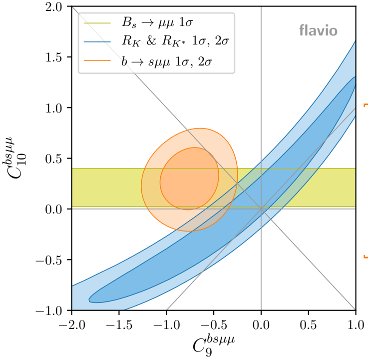


[JHEP 11 (2021) 043]



- Use `flavio` [arXiv:1810.08132] to determine tension with SM hypothesis
- Variation of vector coupling $\mathcal{R}e(\mathcal{C}_9)$ results in improved description of data
- Consistent trend for $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802], $B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802] and $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 11 (2021) 043] angular observables
- However, significant hadronic theory uncertainties, charm-loop effect?

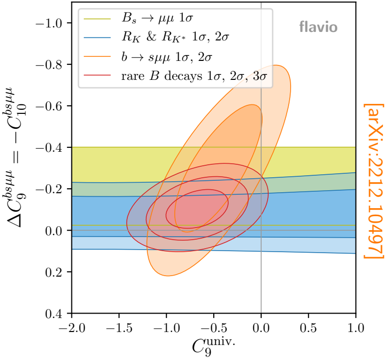
Interpretation in global fits

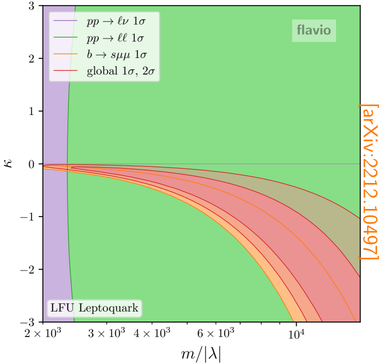


[arXiv:2212.10497]

- $b \to s\ell^+\ell^-$ data can be interpreted using *global fits* of Wilson coefficients
- Assuming NP only in muon-sector ($\mathcal{R}e(C_9^{bs\mu\mu})$ and $\mathcal{R}e(C_{10}^{bs\mu\mu})$) reveals tension between $b \to s\mu^+\mu^-$ angular and $\mathcal{B}$ measurements and R_{K,K^*}
- Can be resolved in presence of LFU NP which does not affect R_{K,K^*}
- Data prefers negative $C_9^{\text{univ.}}$, tension depends on hadronic uncertainties

Interpretation in global fits





- $b \to s\ell^+\ell^-$ data can be interpreted using *global fits* of Wilson coefficients
- Assuming NP only in muon-sector ($\mathcal{R}e(C_9^{bs\mu\mu})$ and $\mathcal{R}e(C_{10}^{bs\mu\mu})$) reveals tension between $b \to s\mu^+\mu^-$ angular and $\mathcal{B}$ measurements and R_{K,K^*}
- Can be resolved in presence of LFU NP which does not affect R_{K,K^*}
- Data prefers negative $C_9^{\text{univ.}}$, tension depends on hadronic uncertainties