Overview of Rare B Decays

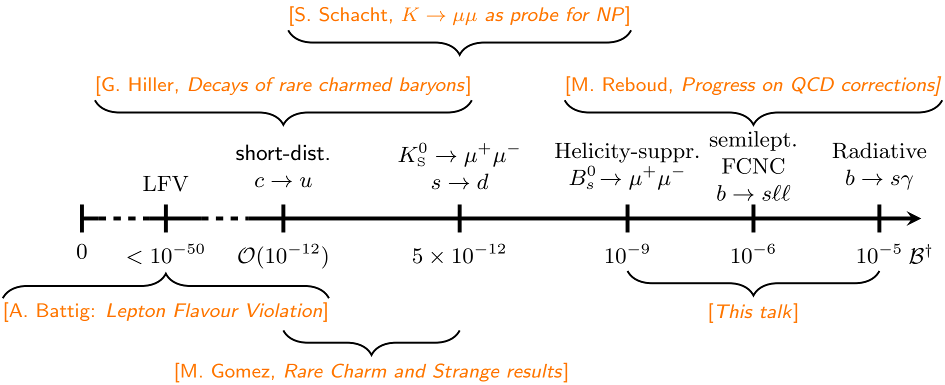
C. Langenbruch[1] on behalf of the LHCb collaboration

[1]RWTH Aachen

LHCb Implications workshop

CERN, October 20th 2022

An overview of Rare Decays



+Model building: [B. Allanach, *Overview of BSM models*] [M. Pestanadaluz, *Neutral current anomalies and alps*] [N. Selimovic, *Flavor and mass hierarchies from extra dim*] [F. Jaffredo, *On a model with two scalar leptoquarks R2 and S3*] [P. Olgoso, *Bridge solutions for (g-2) and $b \to s\ell\ell$ anomalies*] [A. Thomsen, *Muonic forces and flavor universality*]

† not to scale

Overview of Rare B Decays

NP searches with Rare B Decays

$\mathcal{B}(b \to s\mu^+\mu^-)$

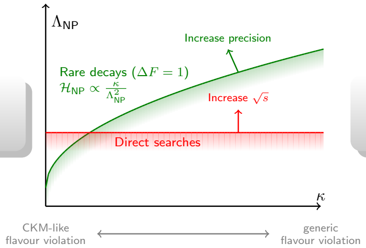
Angular analyses of $b \to s\mu^+\mu^-$

Lepton universality in $b \to s\ell^+\ell^-$

Radiative Decays

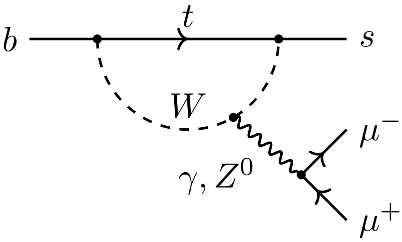
Conclusions

Exclusion limits for NP searches

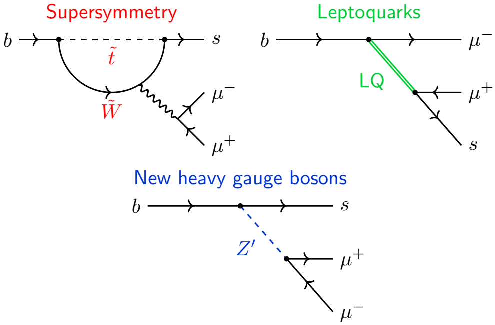


Rare B decays as sensitive probes for New Physics

Rare decays in the SM



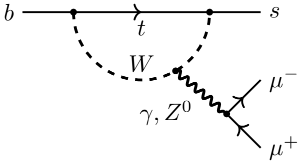
Possible contributions from NP



- Rare decays are so called Flavour Changing Neutral Currents
- In the SM: Only allowed via quantum fluctuations (loop suppressed)
- New heavy particles can significantly contribute and change rates, asymmetries, and angular distributions

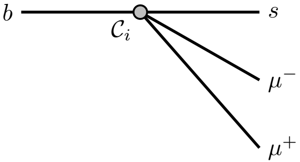
Rare B decays in effective field theory

Full theory



$\longrightarrow$

Effective description



- Model-independent description in effective field theory

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

Local operator → $\mathcal{O}_i$

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

Flavour-violating coupling → κ

NP scale → Λ_{NP}^2

- Rare B decays allow to probe several operators $\mathcal{O}_i^{(\text{NP})}$
- Λ_{NP} up to $\mathcal{O}(100\,\text{TeV})$ reachable [JHEP 11 (2014) 121]

Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
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	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

$b \to s\gamma$ ($\mathcal{C}_7$); $b \to s\ell\ell$ ($\mathcal{C}_7$, $\mathcal{C}_9$, $\mathcal{C}_{10}$); $B_s^0 \to \mu^+\mu^-$ ($\mathcal{C}_{10}$, $\mathcal{C}_S$, $\mathcal{C}_P$)

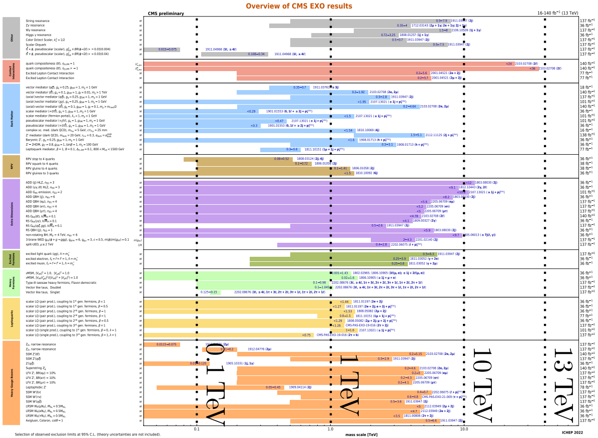
The complementarity of NP searches with rare decays

Dark Matter

Extra Dimensions

Leptoquarks

Heavy Gauge Bosons

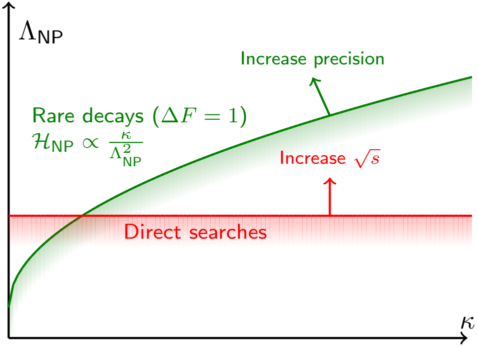


- Direct searches limited by beam energy, $\Lambda_{\rm NP} < \sqrt{s}$
- Reach with rare decays depends on coupling κ and measurement precision[1]: $\Lambda_{\rm NP} \propto \sqrt{\kappa/\sigma(\mathcal{C}_i)} \propto \sqrt[4]{\int \mathcal{L}dt}$

[1] Assuming clean SM prediction, no limiting exp. systematics

The complementarity of NP searches with rare decays

Exclusion limits for NP searches



NP scenario	κ
Tree generic	1
Tree MFV	$V_{\text{tb}}V_{\text{ts}}$
Loop generic	$\frac{1}{16\pi^2}$
Loop MFV	$\frac{V_{\text{tb}}V_{\text{ts}}}{16\pi^2}$

CKM-like flavour violation ⟷ generic flavour violation

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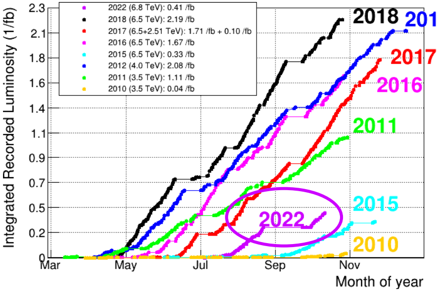
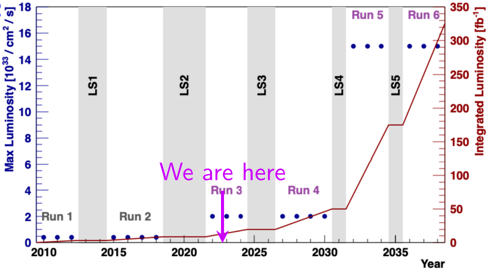
LHCb Upgrade schedule





- The **Upgrade** has arrived! Much improved detector, 40 MHz readout, full software trigger, and much more, see [M. Fontana, *LHCb Overview*]
- Will increase $\int \mathcal{L}\mathrm{d}t$ from $9\,\mathrm{fb}^{-1}$ (Run 1+2) to $50\,\mathrm{fb}^{-1}$ (Run 3+4)
- Upgrade II: $300\,\mathrm{fb}^{-1}$ (Run 5), summarised in FTDR [CERN-LHCC-2021-012], Physics case [CERN-LHCC-2018-027], see also [arxiv:1812.07638]
- Λ_{NP} reach increases by around $1.6_{50\,\mathrm{fb}^{-1}}$ and $2.5_{300\,\mathrm{fb}^{-1}}$ wrt. Run 1+2[2]

[2] Naive private extrapolation using clean observables.

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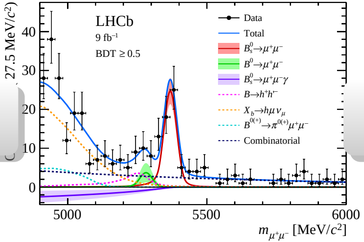
NP searches with Rare B Decays

$\mathcal{B}(b \to s\mu^+\mu^-)$



Angular analyses of $b \to s\mu^+\mu^-$

Lepton universality in $b \to s\ell^+\ell^-$

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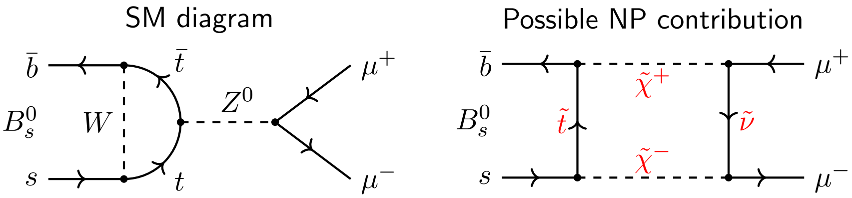
The very rare decay $B_s^0 \to \mu^+\mu^-$



- Loop-, helicity- and CKM suppressed
- Purely leptonic final state, theoretically and experimentally very clean
- Precise SM prediction[3] [PRL 112 (2014) 101801] [JHEP 10 (2019) 232]

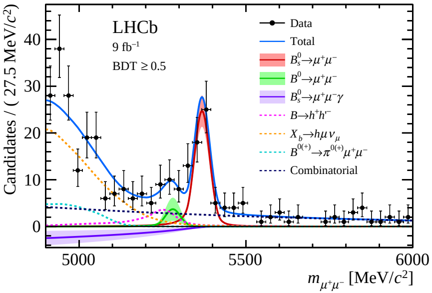
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

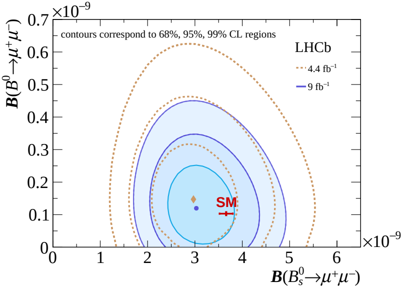
- Very sensitive to new scalar sector (*e.g.* extended Higgs sector, SUSY)

[3] SM prediction without V_{cb} dependence available, in good agreement [APP B 53 (2021) 6]

Measurements of $B^0_{(s)} \to \mu^+\mu^-$

[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]





- Recent LHCb measurement [PRL 128 (2022) 041801] [PRD 105 (2022) 012010]

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

  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$ ($\mathcal{B} < 2.6 \times 10^{-10}$ @ 95% CL)

  in good agreement with SM

- New precise CMS measurement [CMS-PAS-BPH-21-006] moves average further to SM

  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.83^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$

  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.37^{+0.75+0.08}_{-0.67-0.09}) \times 10^{-10}$ ($\mathcal{B} < 1.9 \times 10^{-10}$ @ 95% CL)

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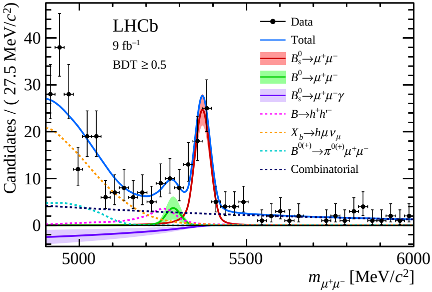

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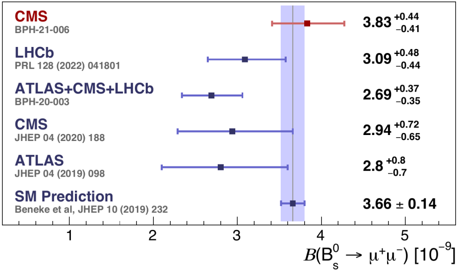

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Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

- $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) \overset{\text{SM}}{\sim} 10^{-12}(10^{-10})$ very rare in SM
- Many SM extensions with significant rates, *e.g.* MSSM [Phys. Rev. D 85, 077701] , axions [PRL 119 (2017) 031802] [JHEP 03 (2019) 008] [EPJC 79 (2019) 5]
- Using full Run 1–2 data set ($9\,\text{fb}^{-1}$)
- Search for non-resonant $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$, scalar-mediated $B^0_{(s)} \to aa$ with $m_a = 1\,\text{GeV}$, and $B^0_{(s)} \to J/\psi\,(\mu^+\mu^-)\mu^+\mu^-$
- Resulting limits at 95% CL:

$$\begin{aligned}
\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) &< 8.6\times10^{-10}\\
\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) &< 1.8\times10^{-10}\\
\mathcal{B}(B^0_s \to a(\mu^+\mu^-)a(\mu^+\mu^-)) &< 5.8\times10^{-10}\\
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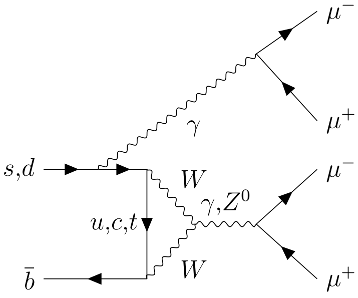
\end{aligned}$$



[JHEP 03 (2022) 109]

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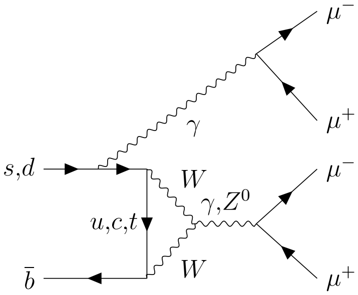
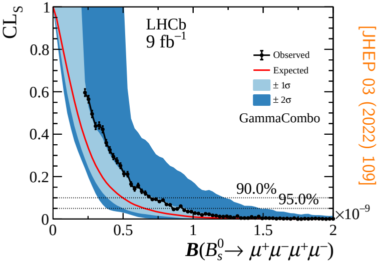
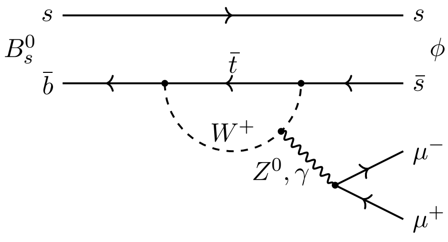


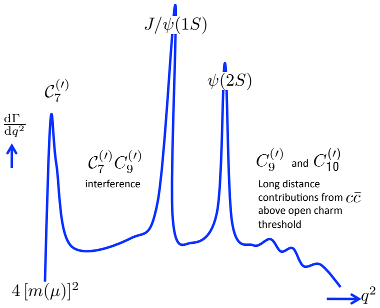
[JHEP 03 (2022) 109]



[JHEP 03 (2022) 109]

Semileptonic $b \to s\mu^+\mu^-$ decays: $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$





- $\mathcal{B}$ of semileptonic $b \to s\mu^+\mu^-$ decays can also be affected by NP
- Central: $q^2 = m(\ell^+\ell^-)^2$, different operators contribute depending on q^2
- SM predictions less clean than for leptonic decays, affected by significant form factor uncertainties
  Low q^2: LCSRs [PRD 71 (2005) 014029] [JHEP 08 (2016) 98] [PRD 75 (2007) 054013] [JHEP 09 (2010) 089] High q^2: Lattice [PRD 89 (2014) 094501] [PRD 88 (2013) 054509]

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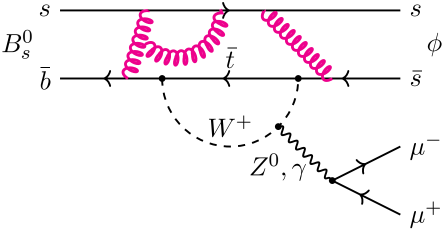

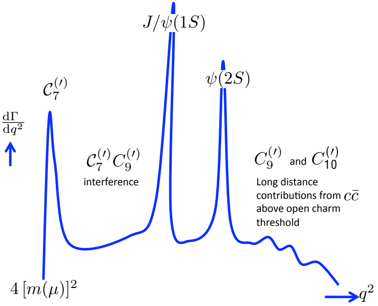

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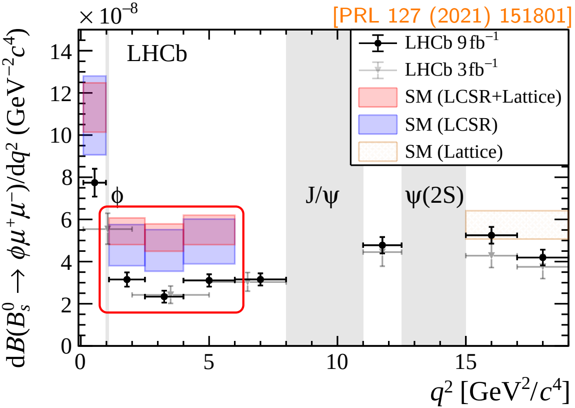
$B_s^0 \to \phi\mu^+\mu^-$ branching fraction

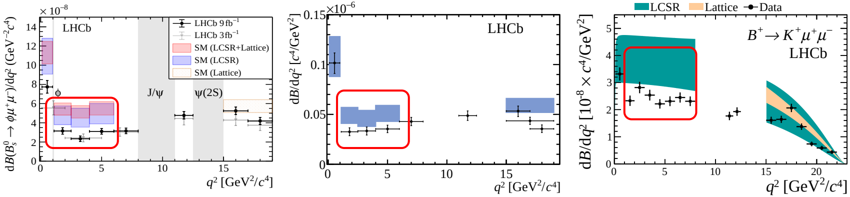


SM LCSR
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 8]
SM LCSR+Lattice
[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

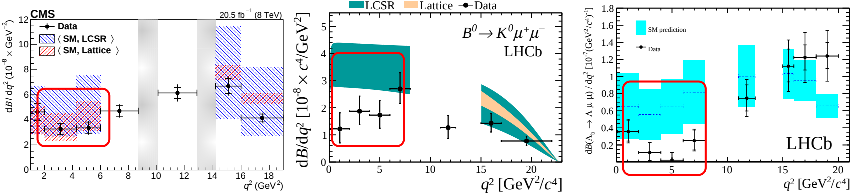
- Recent LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4) = (2.88 \pm 0.21)^{-8}\,\mathrm{GeV}^2/c^4$
- Tension with SM at $3.6\,\sigma$ (LCSR+Lattice) and $1.8\,\sigma$ (LCSR only)

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

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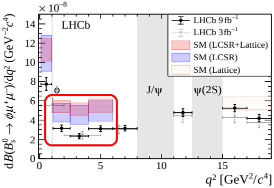
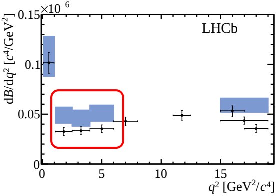
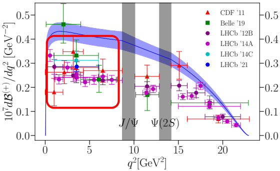
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



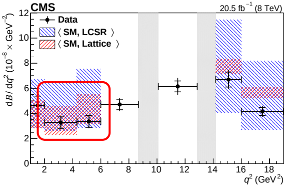
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



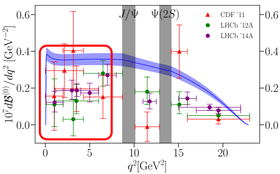
Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



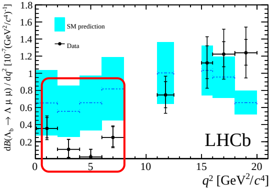
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



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



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



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Radiative Decays

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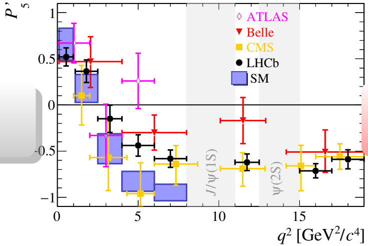
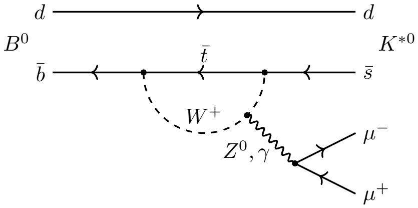
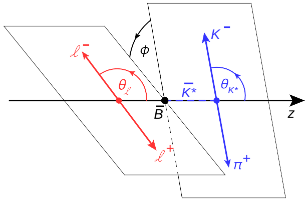


Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$



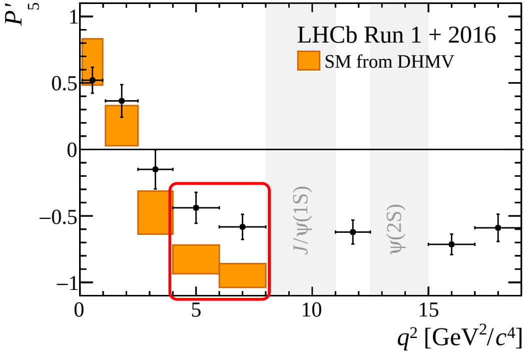


- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$
- 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]
- Update using full LHCb data sample coming soon, New q^2-unbinned analysis approaches ongoing

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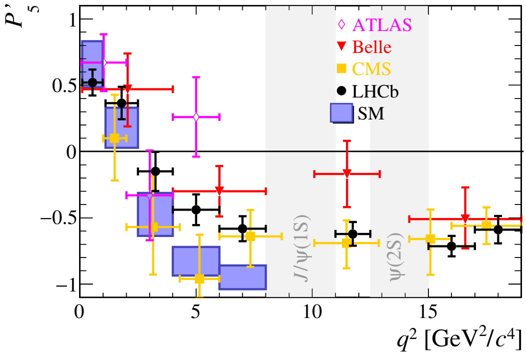
Angular observable P_5' from $B^0 \to K^{*0}\mu^+\mu^-$

[PIPNP 120 (2021) 103885]



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  New q^2-unbinned analysis approaches ongoing

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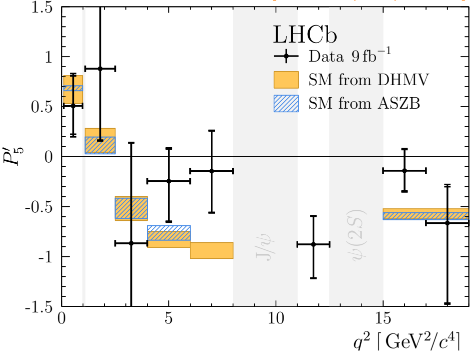
Angular observable P_5' from $B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$



- 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]

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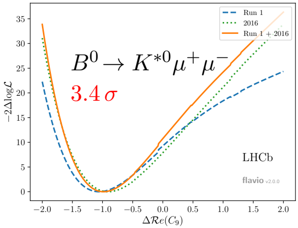
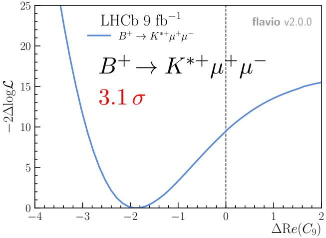
Consistency of $b \to s\mu^+\mu^-$ angular analyses

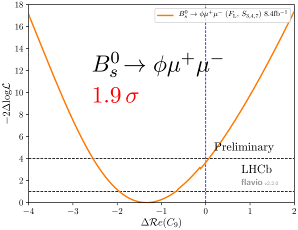
[PRL 125 (2020) 011802]



[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?

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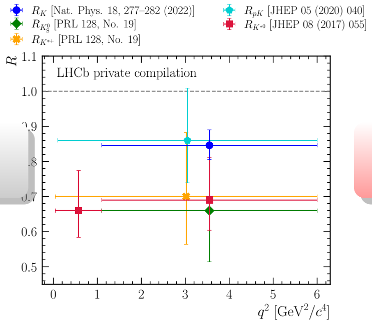
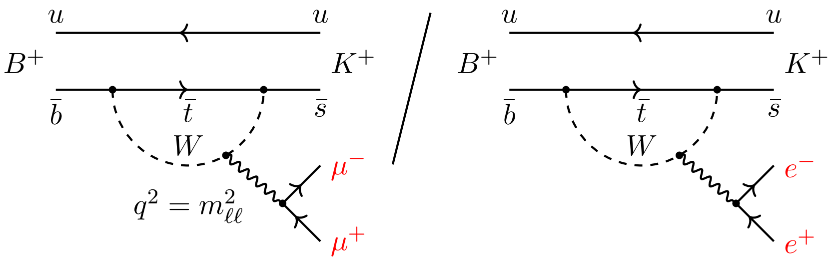


Lepton universality in rare decays

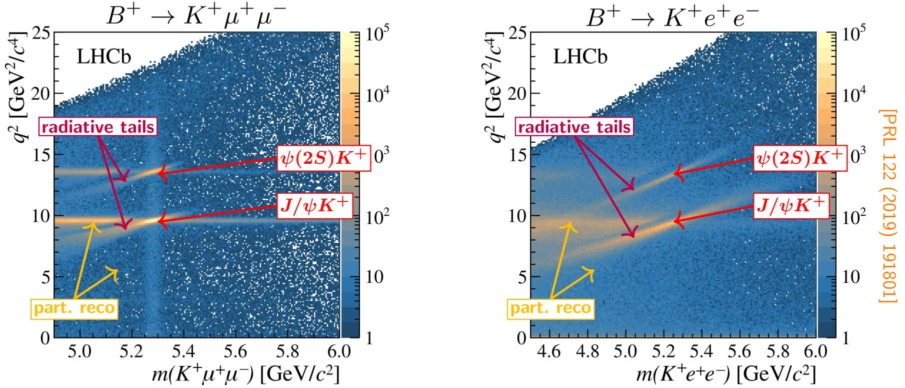


- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \to s\ell^+\ell^-$ decays:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

- Precisely predicted to be unity in SM, differences only through lepton mass effects
- QED corrections $\mathcal{O}(1\,\%)$ [EPJC 76 (2016) 440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio

Experimental challenges in $b \to s\ell^+\ell^-$ reconstruction



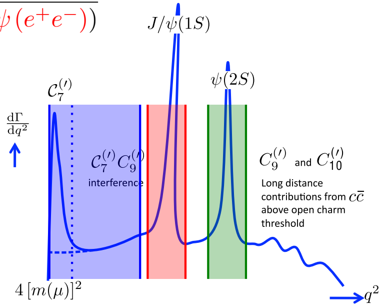
Experimental Challenges for electrons

1. Low trigger efficiencies:
   p_{T} thresholds $3\,\mathrm{GeV}$ for $e^{\pm}$ *vs.* $1.8\,\mathrm{GeV}$ for $\mu^{\pm}$
2. Electrons strongly emit Bremsstrahlung traversing material
   Brem-γ recovery has limited efficiency and degrades mass resolution
3. Backgrounds *e.g.* from partially reconstructed or misidentified decays

Analysis strategy: Double ratio

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

$$R_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}J/\psi\,(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to K^{(*)}J/\psi\,(e^+e^-))}$$
$$= \frac{N_{K^{(*)}\mu^+\mu^-}}{N_{K^{(*)}J/\psi\,(\mu^+\mu^-)}} \times \frac{\varepsilon_{K^{(*)}J/\psi\,(\mu^+\mu^-)}}{\varepsilon_{K^{(*)}\mu^+\mu^-}} \times \frac{N_{K^{(*)}J/\psi\,(e^+e^-)}}{N_{K^{(*)}e^+e^-}} \times \frac{\varepsilon_{K^{(*)}e^+e^-}}{\varepsilon_{K^{(*)}J/\psi\,(e^+e^-)}}$$



- Double ratio cancels most experimental systematic effects in ε ratios
- Important cross-checks:

$$r_{J/\psi} = \frac{\mathcal{B}(B\to K^{(*)}J/\psi\,(\mu^+\mu^-))}{\mathcal{B}(B\to K^{(*)}J/\psi\,(e^+e^-))} = 1$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B\to K^{(*)}\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B\to K^{(*)}J/\psi\,(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\psi(2S)(e^+e^-))}{\mathcal{B}(B\to K^{(*)}J/\psi\,(e^+e^-))} = 1$$

R_K [Nature Phys. 18 (2022) 277]

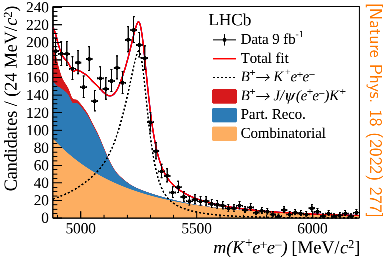
- Decay $B^+ \to K^+\ell^+\ell^-$
- $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$
- Run 1 and Run 2 data set $(9\,\mathrm{fb}^{-1})$
- Result:

$$R_K = 0.846^{+0.042}_{-0.039}(\mathrm{stat})^{+0.013}_{-0.012}(\mathrm{syst})$$

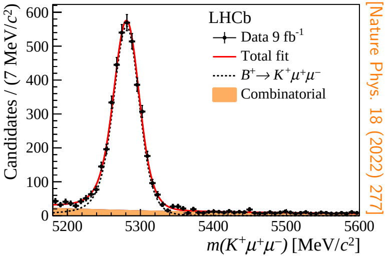
- Tension of $3.1\,\sigma$ with SM
- Crosschecks:

$$r_{J/\psi} = 0.981 \pm 0.020\ (\mathrm{stat} \oplus \mathrm{syst})$$
$$R_{\psi(2S)} = 0.997 \pm 0.011\ (\mathrm{stat} \oplus \mathrm{syst})$$

$N(B^+ \to K^+e^+e^-) = 1640 \pm 70$



$N(B^+ \to K^+\mu^+\mu^-) = 3\,850 \pm 70$



$R_{K^0_S}$ [PRL 128 (2022) 191802]

- Decay $B^0 \to K^0_S \ell^+ \ell^-$
- $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$
- Run 1 and 2016–2018 data ($9\,\mathrm{fb}^{-1}$)
- Result:

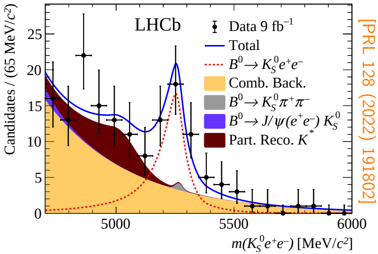
$$R_{K^0_S} = 0.66^{+0.20}_{-0.15}(\mathrm{stat})^{+0.02}_{-0.04}(\mathrm{syst})$$

- Agreement with SM at $1.5\,\sigma$
- Crosschecks:

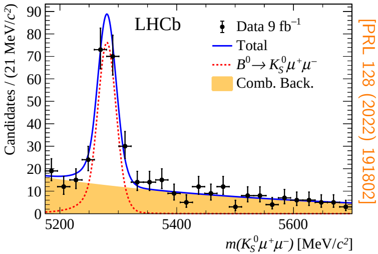
$$r^{-1}_{J/\psi} = 0.977 \pm 0.008(\mathrm{stat}) \pm 0.027(\mathrm{syst})$$

$$R^{-1}_{\psi(2S)} = 1.014 \pm 0.030(\mathrm{stat}) \pm 0.020(\mathrm{syst})$$

$N(B^0 \to K^0_S e^+ e^-) = 45 \pm 10$ ($5.3\,\sigma$ sign.)



$N(B^0 \to K^0_S \mu^+ \mu^-) = 155 \pm 15$



$R_{K^{*+}}$ [PRL 128 (2022) 191802]

- Decay $B^+ \to K^{*+}(\to K^0_S\pi^+)\ell^+\ell^-$
- $q^2 \in [0.045, 6.0]\,\mathrm{GeV}^2/c^4$
- Run 1 and 2016–2018 data ($9\,\mathrm{fb}^{-1}$)
- Result:

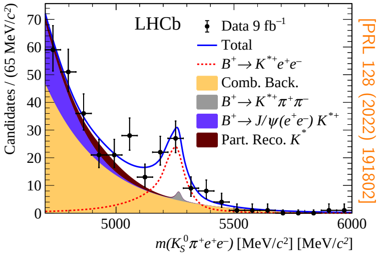
$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst})$$

- Agreement with SM at $1.4\,\sigma$
- Crosschecks:

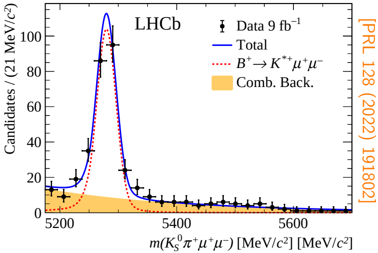
$$r^{-1}_{J/\psi} = 0.965 \pm 0.011(\mathrm{stat}) \pm 0.032(\mathrm{syst})$$

$$R^{-1}_{\psi(2S)} = 1.017 \pm 0.045(\mathrm{stat}) \pm 0.023(\mathrm{syst})$$

$N(B^+ \to K^{*+}e^+e^-) = 67 \pm 13$ (6.0 σ sign.)



$N(B^+ \to K^{*+}\mu^+\mu^-) = 221 \pm 17$



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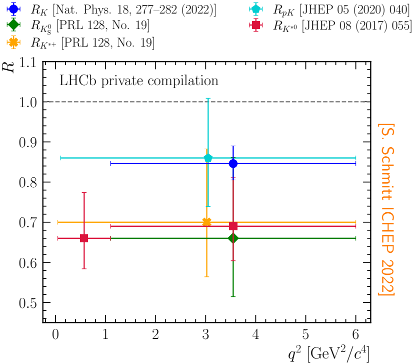
Overview and upcoming LFU tests

- Work ongoing with **high priority** on unified analysis of R_K and R_{K^*}
- Will provide final Run 1 and 2 results
- Efforts lead to deeper understanding of the LFU measurements
- This will be reflected in the results
- In addition, measurements of R_{pK}, R_ϕ, $R_{K\pi\pi}$ and more ongoing
- We appreciate your patience until results become available



[S. Schmitt ICHEP 2022]

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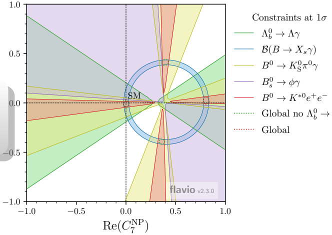
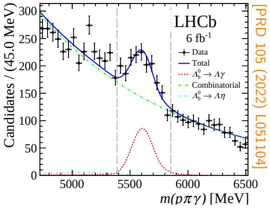
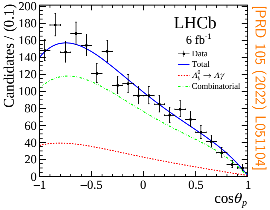


Measurement of photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

- $b \to s\gamma$ photon predominantly left-handed in SM (right-handed contributions $\propto m_s^2/m_b^2$)
- Angular distribution given by
  $$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$
  with α_γ photon-polarisation, $\alpha_\Lambda = 0.754 \pm 0.004$ the Λ asymmetry [Nature Phys 15 (2019) 631], $\theta_p \measuredangle(\vec{p}_p^{\,\Lambda}, -\vec{p}_{\Lambda_b^0}^{\,\Lambda})$
- Using $6\,\mathrm{fb}^{-1}$ of Run 2 data
- Results using Feldman-Cousins
  $$\alpha_\gamma = 0.82^{+0.17}_{-0.26}(\mathrm{stat})^{+0.04}_{-0.13}(\mathrm{syst})$$
  $$\alpha_\gamma^- > 0.56 \text{ at } 90\% \text{ CL}$$
  $$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}(\mathrm{stat})^{+0.16}_{-0.09}(\mathrm{syst})$$
- Consistent with SM predictions and CP-asymmetry
- Constraints on $C_7^{(\prime)}$ using Flavio, Resolving two-folded ambiguity





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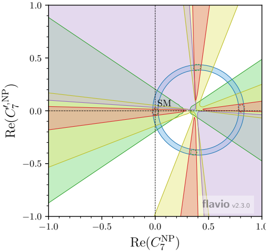

[PRD 105 (2022) L051104]

Constraints at 1σ
- $\Lambda_b^0 \to \Lambda\gamma$
- $\mathcal{B}(B \to X_s\gamma)$
- $B^0 \to K_S^0\pi^0\gamma$
- $B_s^0 \to \phi\gamma$
- $B^0 \to K^{*0}e^+e^-$
- Global no $\Lambda_b^0 \to \Lambda\gamma$
- Global

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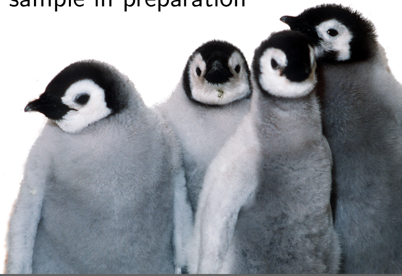
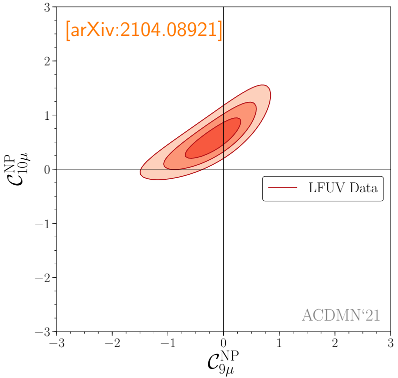
Conclusions

- Rare B decays an excellent laboratory to search for NP effects
- SM describes large majority of results with excellent precision
- But: A few tensions appeared in Rare Decays:
  - Low $\mathcal{B}$ of $b \to s\mu^+\mu^-$ decays
  - $b \to s\mu^+\mu^-$ angular observables
  - LFU tests in Rare Decays
- Most measurements are largely statistically limited, extensive program ongoing to clarify these anomalies
- Several updates with full Run 1 and 2 data sample in preparation
- LHC Run 3 has started, will allow for unprecedented NP reach with flavour
- Belle 2 will allow an independent clarification of anomalies
- Also looking forward to further heavy flavour measurements from ATLAS/CMS



Backup

Interpretation of $b \to s\ell^+\ell^-$ anomalies: Global fits

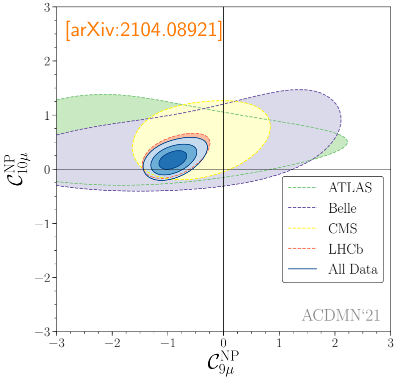


Only lepton universality tests [arXiv:2104.08921]			
coeff.	best fit	1σ	pull
$\mathcal{C}_{9\mu}^{\rm NP}$	-0.87	$[-1.11, -0.65]$	$4.4\,\sigma$
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.39	$[-0.48, -0.31]$	$5.0\,\sigma$
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.60	$[-2.10, -0.98]$	$3.2\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$	$(-0.16, +0.55)$	–	$4.7\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9\mu}')$	$(-1.82, +1.09)$	–	$4.5\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}')$	$(-1.88, -0.59)$	–	$5.0\,\sigma$

many other global fits: [EPJC 81 (2021) 952] [PLB 824 (2022) 136838]

- Interpretation in effective field theory via global fit of effective couplings
- Using only clean LFU tests result in 3–$4\,\sigma$ significance
- Anomalies in LFU tests, $\mathcal{B}$ and angular obs. form coherent picture
- Combining all data results in $> 5\,\sigma$ significance, however hadronic uncertainties of $\mathcal{B}$ and angular obs. under discussion [PRD 93 (2016) 014028][arXiv:1406.0566][JHEP 06 (2016) 116][EPJC 77 (2017) 10][JHEP 02 (2021) 088]

Interpretation of $b \to s\ell^+\ell^-$ anomalies: Global fits



All $b \to s\ell\ell$ data [arXiv:2104.08921]

coeff.	best fit	1σ	pull
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.01	$[-1.15, -0.87]$	$7.0\,\sigma$
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.45	$[-0.52, -0.37]$	$6.5\,\sigma$
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}'_{9\mu}$	-0.92	$[-1.07, -0.75]$	$5.7\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$	$(-0.92, +0.17)$	–	$6.8\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}'_{9\mu})$	$(-1.12, +0.36)$	–	$6.9\,\sigma$
$(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}'_{10\mu})$	$(-1.15, -0.26)$	–	$7.1\,\sigma$

many other global fits: [EPJC 81 (2021) 952] [PLB 824 (2022) 136838]

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- Using only clean LFU tests result in 3–$4\,\sigma$ significance
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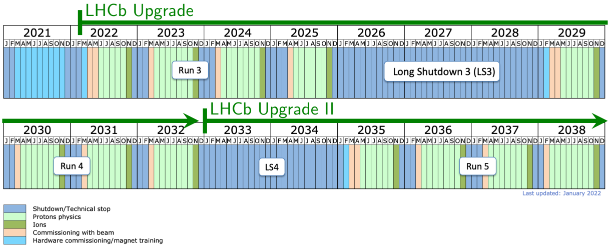
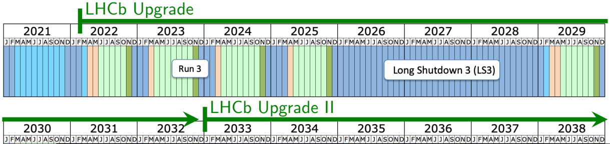
Outlook



Integrated luminosity [fb^{-1}]	LHCb	ATLAS/CMS
Run 1	3	25
Run 2	9	+140
Run 3	23	+300
Run 4	50	+300/year
Run 5(+)	300	+300/year

- Rare decays largely statistically dominated → requires more data
- Updates on anomalies with the full Run 1+2 data ongoing
- Run 3 has started with upgraded LHCb detector [Upgrade TDR]
- Belle II will deliver important complementary results
- Unprecedented precision in the HL-LHC era following LS3 [Yellow Report 7 (2019) 867]
- LHCb Upgrade II installation during LS4 [arXiv:1808.08865] [Upgrade II TDR]
  → expected integrated lumi. of $300\,\mathrm{fb}^{-1}$

Outlook



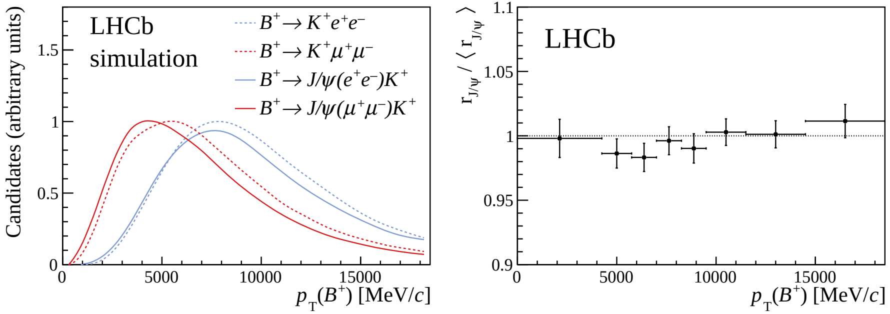
Integrated luminosity $[\mathrm{fb}^{-1}]$	LHCb	ATLAS/CMS
Run 1	3	25
Run 2	9	+140
Run 3	23	+300
		/year
		/year

Future prospects [arXiv:1808.08865] [PTEP 12 (2019) 123C01]

observable	LHCb 2025	Belle II	LHCb Upgrade II
$R(D^*)$	0.0072	0.005	0.002
$R(J/\psi)$	0.071	-	0.02
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	34%	-	10%
$R_K(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.025	0.036	0.007
$R_{K^*}(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.031	0.032	0.008

- Updates on anomalies with the full Run 1+2 data ongoing
- Run 3 has started with upgraded LHCb detector [Upgrade TDR]
- Belle II will deliver important complementary results
- Unprecedented precision in the HL-LHC era following LS3 [Yellow Report 7 (2019) 867]
- LHCb Upgrade II installation during LS4 [arXiv:1808.08865] [Upgrade II TDR] $\to$ expected integrated lumi. of $300\,\mathrm{fb}^{-1}$

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



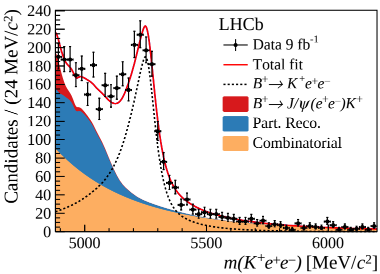
[Nature Phys. 18 (2022) 277]

- $r_{J/\psi} = \dfrac{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))} = 1$ important crosscheck for eff.
- $r_{J/\psi}$ single ratio, difference in e/μ reconstruction do not cancel
- Integrated $r_{J/\psi} = 0.981 \pm 0.020$, flat and independent of kinematics
- Also checked double ratio

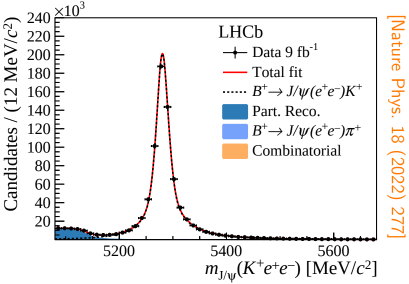
$$R_{\psi(2S)} = \frac{B^+ \to K^+\psi(2S)(\to \mu^+\mu^-))}{B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{B^+ \to K^+\psi(2S)(\to e^+e^-))}{B^+ \to K^+ J/\psi(\to e^+e^-))} = 0.997 \pm 0.011$$

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

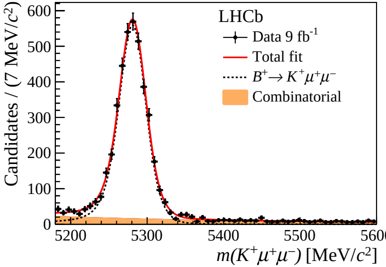
$N(B^+ \to K^+e^+e^-) = 1640 \pm 70$



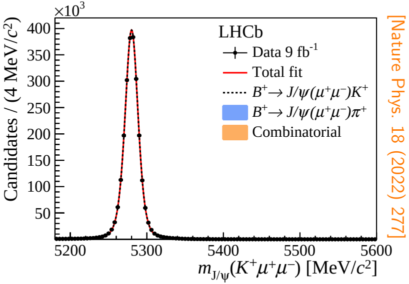
$N(B^+ \to K^+J/\psi(\to e^+e^-)) = (773.3 \pm 0.9)\,\mathrm{k}$



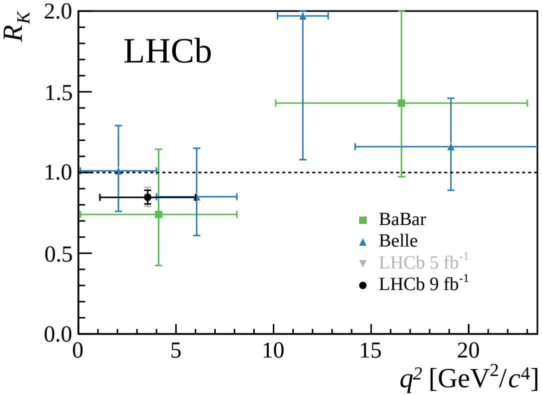
$N(B^+ \to K^+\mu^+\mu^-) = 3\,850 \pm 70$



$N(B^+ \to K^+J/\psi(\to \mu^+\mu^-)) = (2\,288.5 \pm 1.5)\,\mathrm{k}$



R_K Results

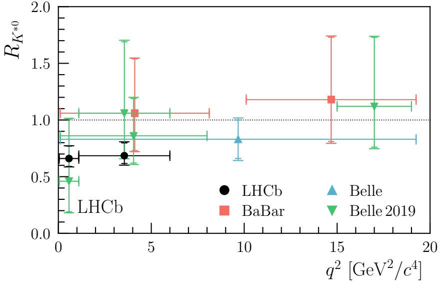


- LHCb 9 fb^{-1} [Nature Phys. 18 (2022) 277]
- LHCb 5 fb^{-1} [PRL 122 (2019) 191801]
- Belle [PRL 103 (2009) 171801]
- BaBar [PRD 86 (2012) 032012]

- LHCb determines R_K in central q^2 region $[1.1, 6.0]\,\mathrm{GeV}^2$: $R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.846^{+0.042+0.013}_{-0.039-0.012}$
- Tension with SM prediction at $3.1\,\sigma$

R_{K^*} Results

[JHEP 08 (2017) 055]



Babar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]
Belle 2019 [PRL 126 (2021) 161801]

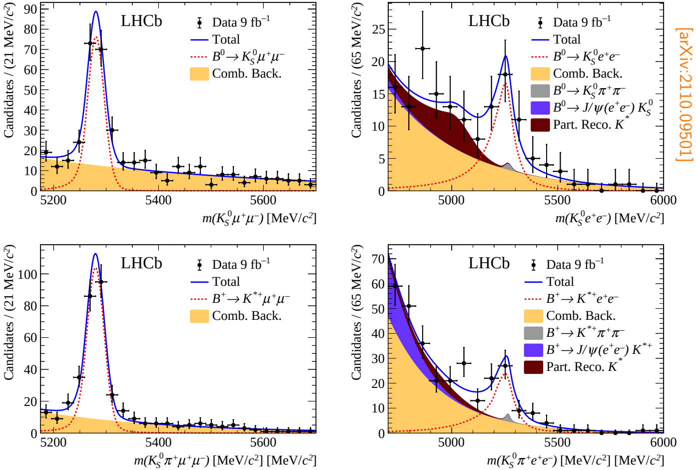
- Related LU ratio $R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$ also shows tension with SM

$$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad 2.1\text{-}2.3\,\sigma \text{ low } q^2$$

$$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad 2.4\text{-}2.5\,\sigma \text{ central } q^2$$

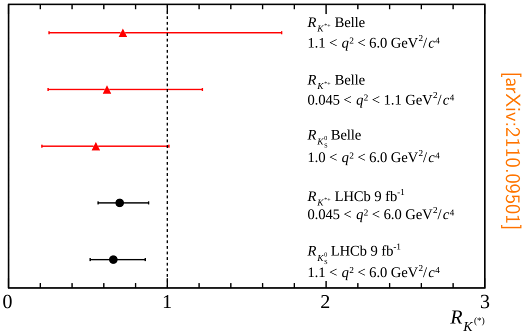
- Compatible with Babar [PRD 86 (2012) 032012] and Belle [PRL 103 (2009) 171801] [PRL 126 (2021) 161801]
- Update with full Run 1+2 data sample currently ongoing

Lepton universality tests $R_{K^0_S}$ and $R_{K^{*+}}$



- LHCb measurement of $R_{K^0_S}$ and $R_{K^{*+}}$ with Run 1+2 data [arXiv:2110.09501]
- Reconstructed via $K^0_S \to \pi^+\pi^-$ and $K^{*+} \to K^0_S(\to \pi^+\pi^-)\pi^+$
- First obs. of $B^0 \to K^0_S e^+e^-$ $(5.3\,\sigma)$ and $B^+ \to K^{*+}(\to K^0_S\pi^+)e^+e^-$ $(6.0\,\sigma)$

Lepton universality tests $R_{K^0_S}$ and $R_{K^{*+}}$



- New result by LHCb [arXiv:2110.09501]

$$R_{K^0_S}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.66^{+0.20}_{-0.15}(\mathrm{stat})^{+0.02}_{-0.04}(\mathrm{syst})$$
$$R_{K^{*+}}(0.045 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst})$$

- Consistent with SM at $1.5\,\sigma$ and $1.4\,\sigma$, lower than SM prediction
- Good agreement with Belle results [PRL 126 (2021) 161801] [JHEP 03 (2021) 105]