Rare decays

A biased view...

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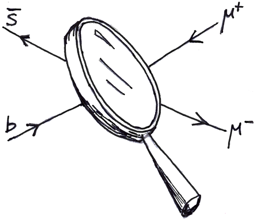
Why rare decays?

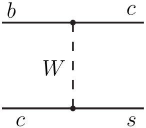
- Tiny effects in the SM $\Rightarrow$ NP can be at the same level
- Virtual particles $\Rightarrow$ High mass reach
- Precise predictions in SM
- Model independent searches
- Historically the laboratory of many particle physics discoveries



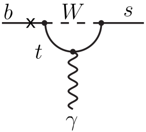
How are rare decays sensitive?

EFT, Wilson coefficients and other “boring” stuff

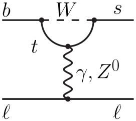
Complex interactions substituted with Fermi-like operators: couplings hide the high energy information



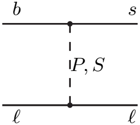
Charged current $G_F V_{cb} V_{cs}^* C_2 \bar{c}_L \gamma^\mu b_L \bar{s}_L \gamma_\mu c_L$



photon penguin $\frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$



EW penguin $G_F V_{tb} V_{ts}^* C_{9(10)} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$



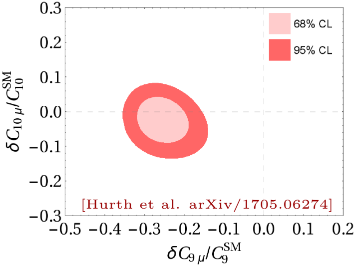
NP (pseudo)-scalar $\propto C_{S(P)} \bar{s}_L b_L \bar{\ell} (\gamma_5) \ell$

Plus chirally flipped operators...

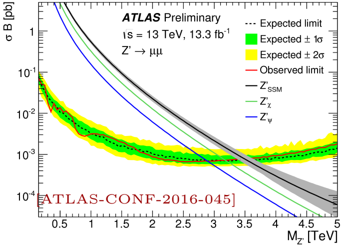
How are rare decays sensitive?

EFT, Wilson coefficients and other "boring" stuff (2)

- New physics interactions can enter through new operators $(S, P, \ldots)$ or modifying the coefficients of SM operators
- If Wilson coefficients are thought of effective couplings with a NP scale (e.g. for C_9):
  $\sim G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_9 = \frac{g^2}{\Lambda}$
- Probing scales (masses!) up to hundreds of TeV (depending how large the coupling you allow to be)
- Not necessarily having the CKM flavour structure (MFV)



[Hurth et al. arXiv/1705.06274]



[ATLAS-CONF-2016-045]

1. Branching fraction

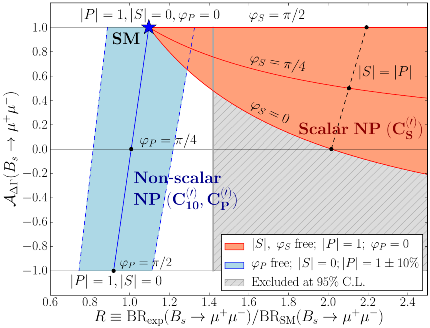
$$\mathcal{B}^{t=0}(B_s^0 \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{\pi^2} \tau_{B_s^0} f_{B_s}^2 m_{B_s}^3 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}V_{ts}^*|^2 \left(|2\frac{m_\mu}{m_{B_s}}(C_{10}-C'_{10}) + C_P - C'_P|^2 + |C_S - C'_S|^2 \right)$$

2. Ratio of branching fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{m_{B_d}\sqrt{1-\frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s}\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}}$$

3. Effective lifetime

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1-y_s^2)} \frac{1+2y_s\mathcal{A}_{\Delta\Gamma}+y_s^2}{1+y_s\mathcal{A}_{\Delta\Gamma}}$$



$B_s^0 \to \ell^+\ell^-$ Standard Model predictions

Most recent predictions (time integrated)

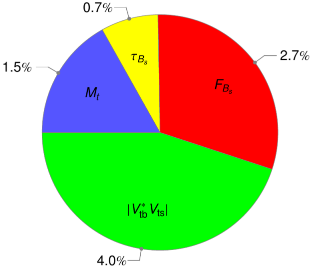
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\langle t\rangle} = (3.65 \pm 0.23) \cdot 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-)^{\langle t\rangle} = (1.06 \pm 0.09) \cdot 10^{-10}$$

$$\mathcal{R} = 0.0287 \pm 0.0026$$

$$A_{\Delta\Gamma} = 1$$

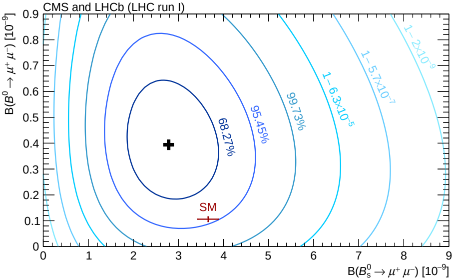
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-)^{\langle t\rangle} = (7.73 \pm 0.49) \times 10^{-7}$$

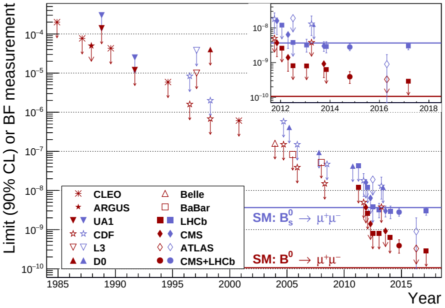


- Impressively precise predictions
- Any significant deviations from these values is sign of new interactions beyond the SM
- Main uncertainties are parametric, dominated by CKM matrix elements.

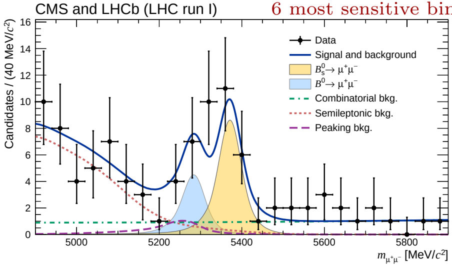
[Bobeth et al. PRL 112 (2014) 101801.] [Bobeth et al. PRD 89, 034023 (2014)] [Hermann et al. JHEP 1312 (2013) 097]

- 30 years search for $B^0_{d,s} \to \mu^+\mu^-$ decays
- First evidence in LHCb with 1 fb^{-1}
- Observation from CMS+LHCb combined analysis
- Good agreement with SM





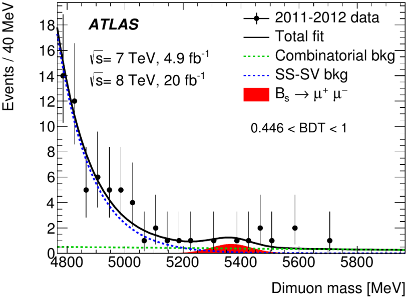
[CMS+LHCb - Nature 522, 6872 (2015)]

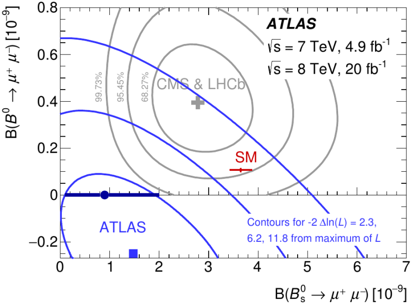


6 most sensitive bins

$B_s^0 \to \mu^+\mu^-$ in ATLAS

- 25 fb^{-1} of 7-8 TeV *pp* collisions
- Normalised to $B^+ \to J/\psi K^+$ events
- Search in three bins of a BDT operator





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9} \quad \mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at 95\% CL}$$

B_s^0 signal significance is 1.4σ
The 2D likelihood is compatible with SM at 2σ

[ATLAS - Eur. Phys. J. C 76 (2016) 513]

Observation of $B_s^0 \to \mu^+\mu^-$ at LHCb

And first measurement of the effective lifetime

- 3fb^{-1} Run 1 + 2 fb^{-1} Run 2 data
- Re-optimized particle identification and multivariate operator

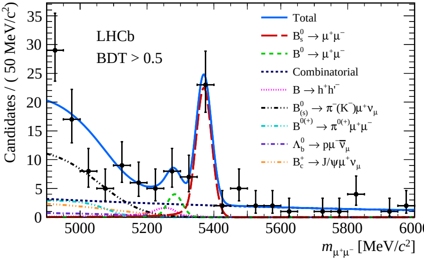
Results:

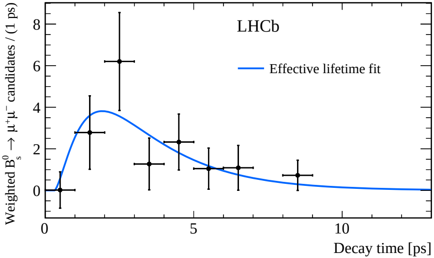
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} (95\% \text{ CL})$$

- First single-experiment observation of $B_s^0 \to \mu^+\mu^-$ with 7.8σ
- First measurement of effective lifetime

$$\tau(B_s^0 \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\text{ps}$$

Compatible with $A_{\Delta\Gamma} = 1(-1)$ at the 1.0 (1.4) σ level





[LHCb- Phys. Rev. Lett. 118 (2017) 191801]

Search for $B^0_{(s)} \to \tau^+\tau^-$ decays at LHCb

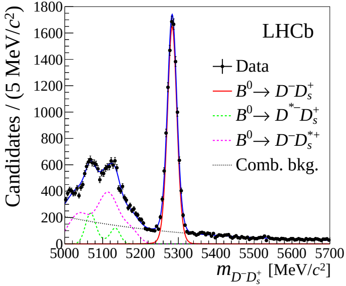
- Extremely difficult analyses
- Full Run 1 ($3\ \text{fb}^{-1}$)
- $\tau \to \pi\pi\pi\nu$ mode (10%)
- Search in NN output

Limits at 95% CL

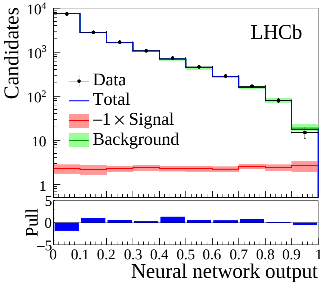
$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$$
$$\mathcal{B}(B^0_d \to \tau^+\tau^-) < 2.1 \times 10^{-3}$$

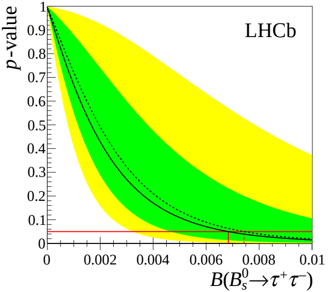
First (B^0_s) and world best (B^0) limits
Still very far from SM

Normalisation mode



[LHCb - arXiv:1703.02508]



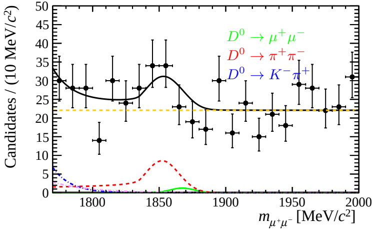


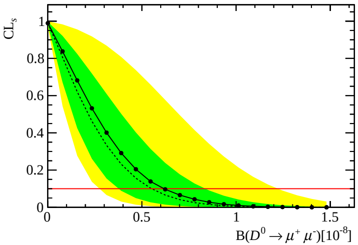
Search for $D^0 \to \mu^+\mu^-$ at LHCb

- $D^0 \to \mu^+\mu^-$ arises at tree levels in some leptoquarks model used for B decays: important complementary bounds! [Bauer et al. PRL116 (2016) no.14, 141802]
- $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$ search
- 0.9 fb^{-1} at 7 TeV

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

- Similar complementary constraints from other rare charm decays

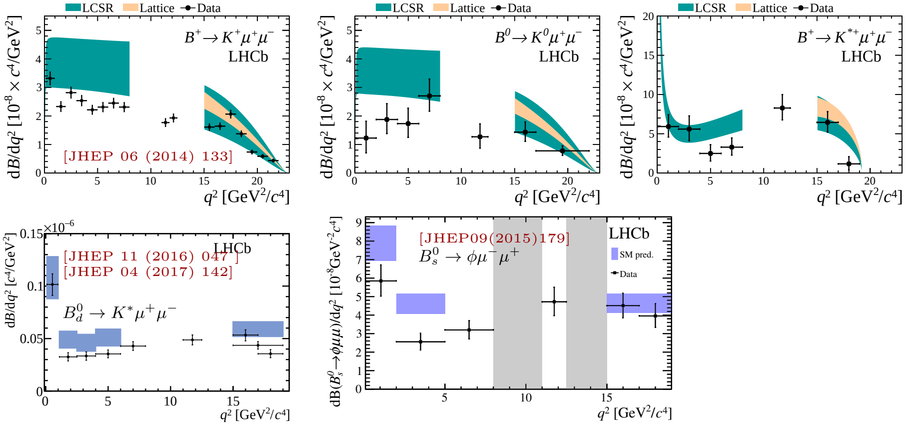




[LHCb - Phys.Lett. B725 (2013) 15-24]

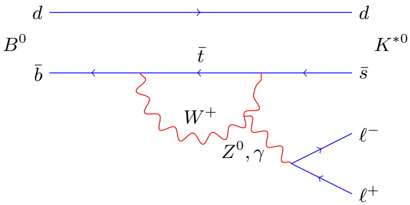
Branching fractions

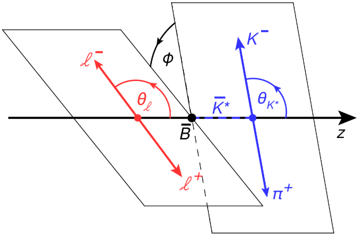
- Measurements of various $b \to s$ transitions systematically below the SM:
- Might be all due to modification of C_9



Angular analysis of $B_d^0 \to K^* \ell^+ \ell^-$ decays

- $b \to s$ transition with vector in the final state
- Final state described by $q^2 = m_{\mu\mu}^2$ and three angles $\Omega = (\theta_\ell, \theta_K, \phi)$
- F_L, A_{FB}, S_i sensitive to $C_7^{(\prime)}$ $C_9^{(\prime)}$ $C_{10}^{(\prime)}$



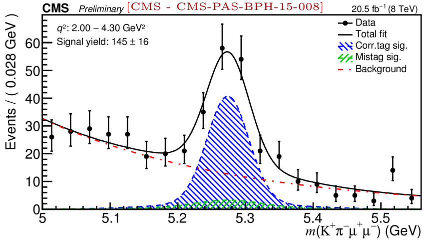


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

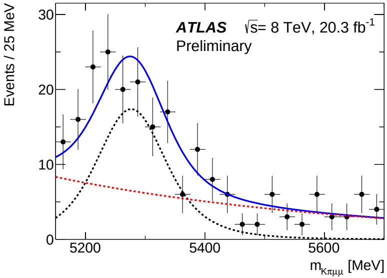
Angular analysis of $B_d^0 \to K^*\mu^+\mu^-$ decays

Many recent measurements

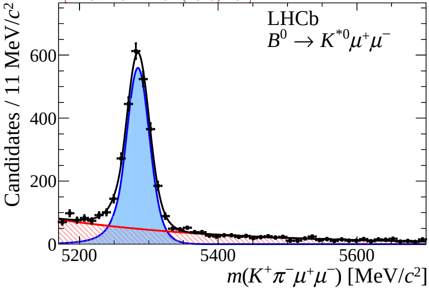
[CMS - CMS-PAS-BPH-15-008]



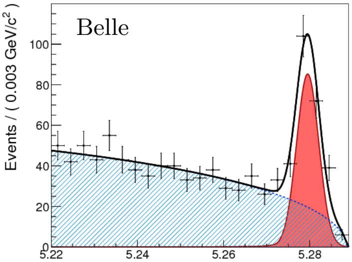
[ATLAS - ATLAS-CONF-2017-023]



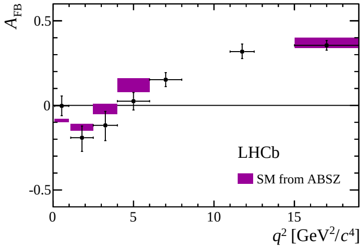
[LHCb - JHEP 02 (2016) 104]

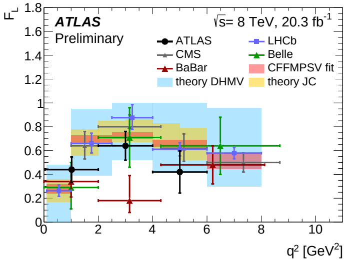


[Belle - Phys.Rev.Lett. 118 (2017) no.11, 111801]

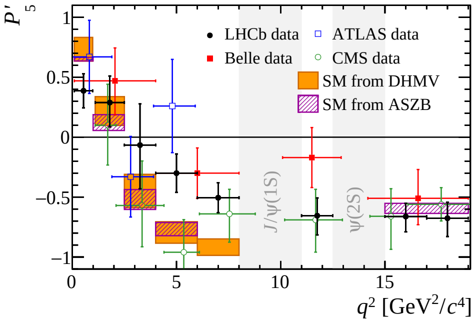


$B_d^0 \to K^* \mu^+ \mu^-$ results



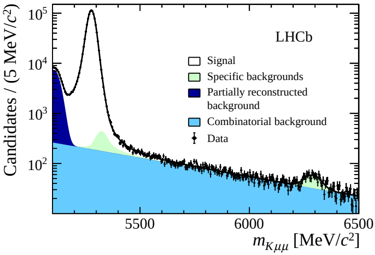


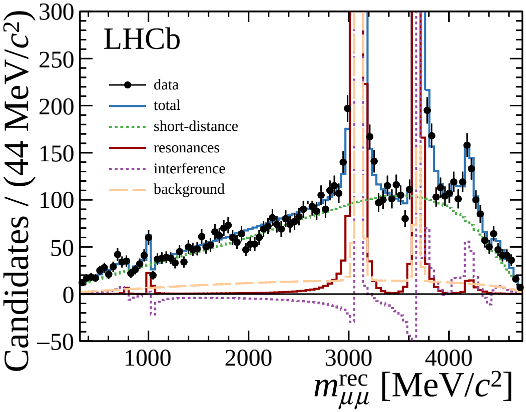
- Several observables appear different than SM
- In particular P_5' has significant discrepancy
- Global fits show large disagreement



- Fit to full dimuon mass distribution
  - Resonances: ρ, ω, ϕ, J/ψ, $\psi(2S)$
  - Broad charmonium states: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$,
- Four-fold ambiguity in J/ψ and $\psi(2S)$ phase signs:
  Compatible with $\pi/2$, hence low interference with non-resonant

[LHCb - Eur. Phys. J. C (2017) 77: 161]





Phase space difference in $B^+ \to K^+\mu^+\mu^-$ decays

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\mathbf{k}|\beta\left\{\frac{2}{3}|\mathbf{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\mathbf{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

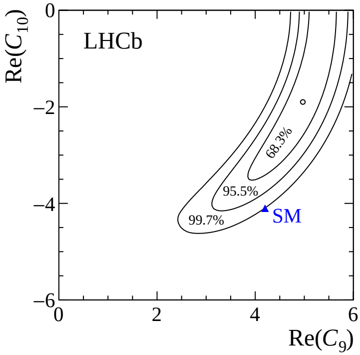
[Bailey et al. Phys. Rev. D 93, 025026 (2016)]

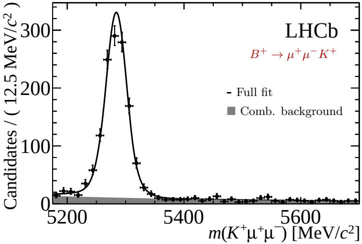
[LHCb - Eur. Phys. J. C (2017) 77: 161]

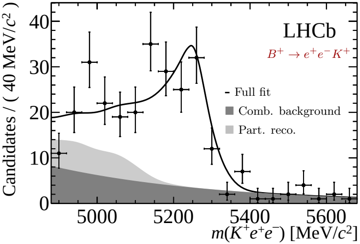
- Fit to Wilson coefficients
- Non resonant sensitive to C_9 and C_{10}
- Deviation of 3.0σ from SM
- Low $B^+ \to K^+\mu^+\mu^-$ BR not explained by resonance interferences

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37\pm0.15\pm0.23)\times10^{-7}$$

in agreement with previous measurement







$q^2 \in [1,6]\mathrm{GeV}^2/c^4$

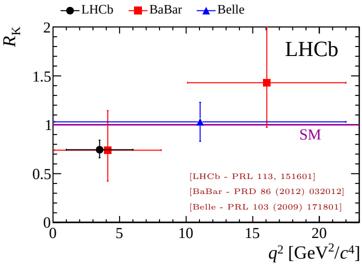
Electron Trigger

[LHCb - Phys. Rev. Lett. 113, 151601]

The combination of the various trigger channels gives:

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

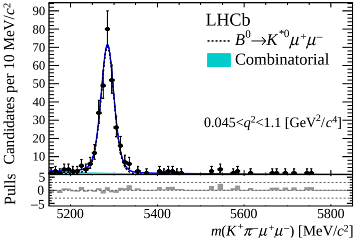
Most precise measurement to date, compatible with SM at 2.6σ level

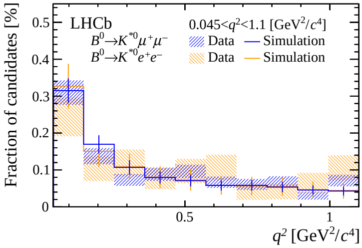


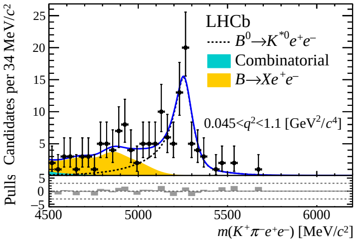
The branching fraction of $B^+ \to e^+e^-K^+$ is measured as
$\mathcal{B}(B^+ \to e^+e^-K^+) = 1.56^{+0.19}_{-0.15}(\mathrm{stat})^{+0.06}_{-0.05}(\mathrm{syst}) \times 10^{-7}$
well compatible with SM predictions

$$R_{K^*} = \frac{\mathcal{B}(B_d^0 \to K^* \mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^{*+})} \Big/ \frac{\mathcal{B}(B_d^0 \to K^* e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^{*+})}$$

- Very clean theoretical predictions
- Double ratio to cancel systematics
- Two q^2 bins and three independent triggers
- Excluded low q^2 region (dominated by photons)



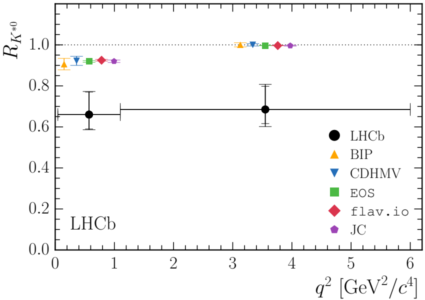


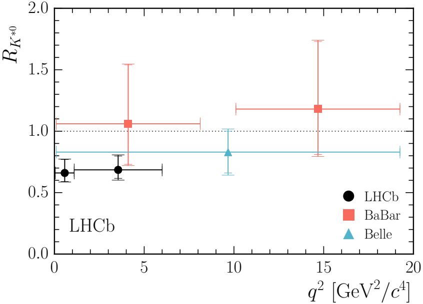


Lepton Universality Test in $B_d^0 \to K^* \ell^+ \ell^-$

[LHCb - arXiv/1705.05802]

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\,\text{GeV}^2/c^4 \end{cases}$$





- Statistically dominated
- SM compatibility: $[2.1 - 2.3]\sigma$ and $[2.4 - 2.5]\sigma$ for the two bins respectively

Summary of B anomalies

Are we there yet?

1. Low $b \to s\mu\mu$ branching fractions
2. Discrepancies in angular observables of $B_d^0 \to K^*\mu^+\mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+\mu^+\mu^-$ and $B_d^0 \to K^*\mu^+\mu^-$

- All seems to be related to a change in the C_9 coefficient (or maybe C_9 and C_{10}, but V-A)
- Global fits start to exhibit several standard deviations of discrepancy
- $c\bar{c}$ interference explanation seems not justified
- Additional discrepancies in tree-level $B \to D^{(*)}\ell\nu$ decays (See Victor Renaudin's talk)
- Many NP explanations: Z', leptoquarks, low mass resonances etc

See following talk by Joaquim Matias!

Summary

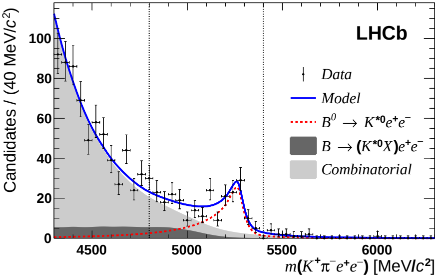
- Rare heavy flavour decays are a great laboratory to test the SM: precise predictions and clean experimental observables
- Model independent sensitivity to NP:
  - New (pseudo)-scalar interactions tightly constrained by $B_s^0 \to \mu^+\mu^-$ decays
  - Possible new vector (or V-A) interactions seem to explain several B anomalies
- Variety of complementary observables
- For some decays: healthy competition between 4 experiments!
- Vibrant field: many new results will come soon to confirm or disprove this tantalising results!

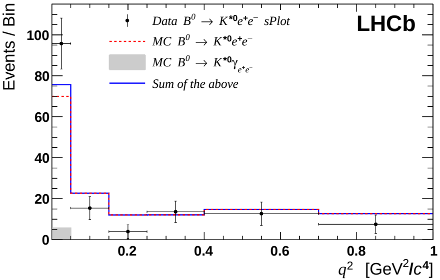
Backup

Angular analysis of $B_d^0 \to K^* e^+ e^-$ decays

[LHCb - JHEP04(2015)064]

- Angular analysis of $B_d^0 \to K^* e^+ e^-$ at very low q^2 ($\in [0.002, 1.120]\mathrm{GeV}^2/\mathrm{c}^4$)
- Folded angular observables ($\phi = \phi + \pi$ if $\phi < 0$)
- Measurement of F_L, $A_T^{(2)}$, $A_T^{(\mathrm{Im})}$, $A_T^{(\mathrm{Re})}$, * sensitive to C_7' as $q^2 \to 0$

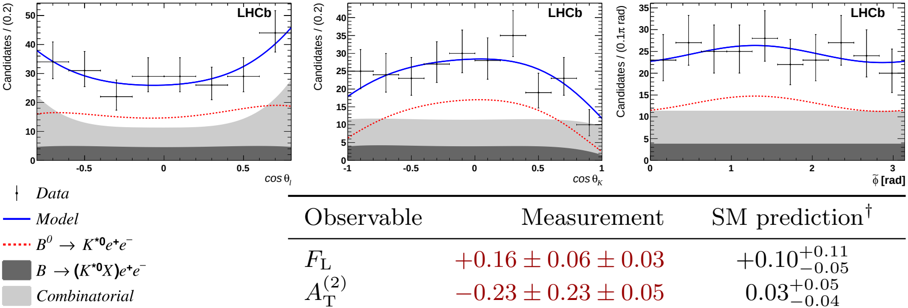




$^* A_T^{(\mathrm{Re})} = \frac{4}{3} A_{FB}/(1 - F_L)$, $A_T^{(2)} = \frac{1}{2} S_3/(1 - F_L)$ and $A_T = \frac{1}{2} S_9/(1 - F_L)$

Angular analysis of $B_d^0 \to K^* e^+ e^-$ decays

[LHCb - JHEP04(2015)064]

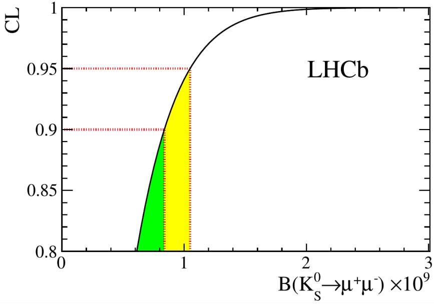


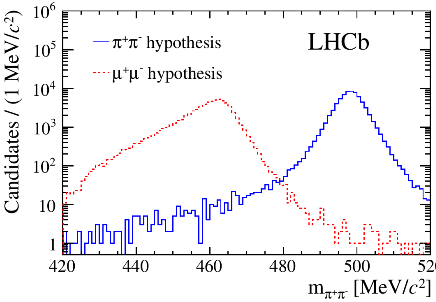
Observable	Measurement	SM prediction[†]
$F_{\rm L}$	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_{\rm T}^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$0.03^{+0.05}_{-0.04}$
$A_{\rm T}^{\rm Re}$	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
$A_{\rm T}^{\rm Im}$	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

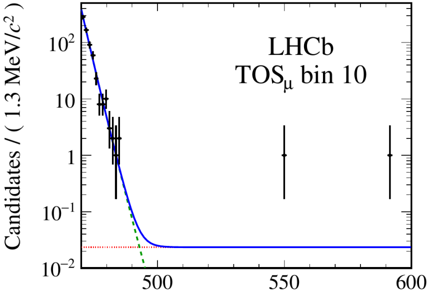
- Measurements well in agreement with SM predictions
- Constraints on $C_7^{(\prime)}$ competitive with radiative decays

[†] S. Jäger, J. M. Camalich [arXiv/1412.3283]

- NP can ber orders of magnitude the SM
- Full Run 1 statistics
- Normalisation and main background: $K^0_S \to \pi^+\pi^-$
- $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95% CL







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