Rare decays, radiative decays and *b* → *sll* transitions at LHCb

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on behalf of the LHCb collaboration

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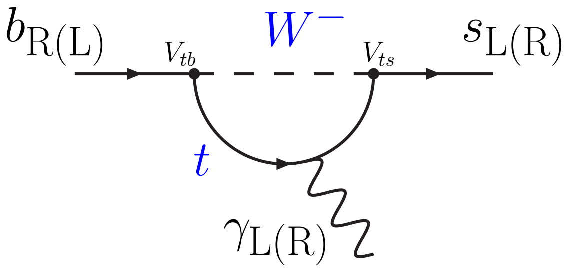
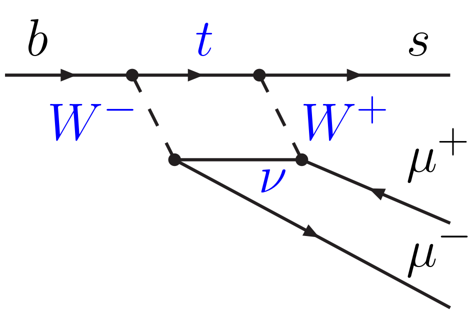
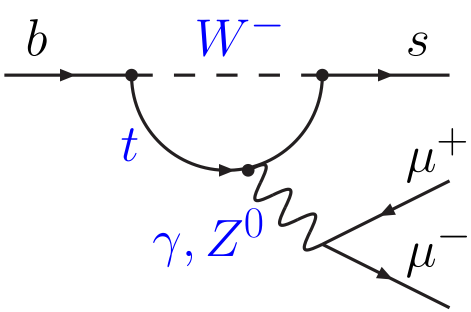
Rare decays - Searching for new physics

- Rare decays are rare in the context of the Standard Model (SM)
- Flavour-changing neutral current (FCNC) processes are of particular interest
- They are heavily suppressed and so new physics (NP) can appear at a similar or larger level as SM contributions
- New particles can appear at loop or tree level
- Search both for small deviations in precisely predicted SM processes and for forbidden processes that can only occur through NP

- A rich field with many interesting current anomalies and prospects
- For results on lepton flavour universality see talk by J. Albrecht







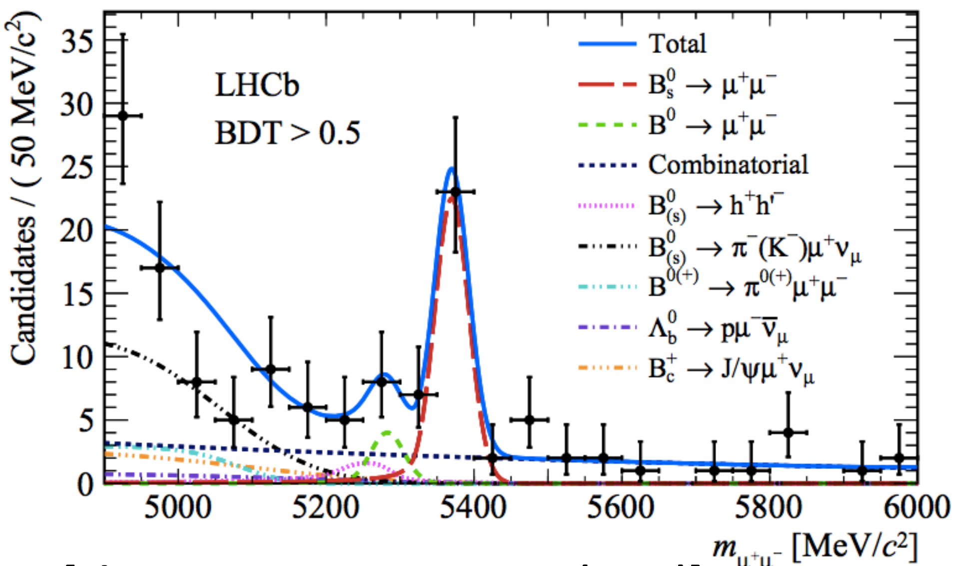
$B^0_{(s)} \to \mu^+\mu^-$

- A “golden channel” rare decay mode, loop and helicity suppressed in the SM
- Both theoretically and experimentally clean
- Search carried out with 3 fb^{-1} Run 1 and 1.4 fb^{-1} Run 2 data
- Results in the first single experiment observation of $B^0_s \to \mu^+\mu^-$ (with a significance of 7.8σ), first measurement of the $B^0_s \to \mu^+\mu^-$ effective lifetime and sets a limit on $B^0 \to \mu^+\mu^-$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

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

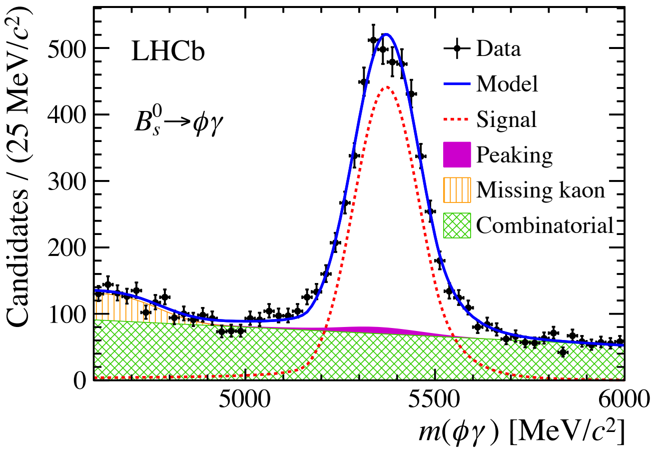
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ [95\% C.L]}$$

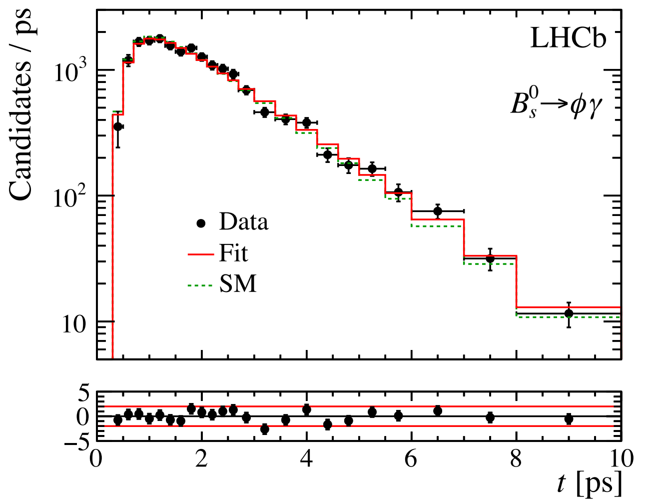


[Phys. Rev. Lett. 118, 191801 (2017)]

- All of these are consistent with SM predictions, setting stringent limits on possible NP models

Photon polarisation in $B_s^0 \to \phi\gamma$





[Phys. Rev. Lett. 118, 021801 (2017)]

- First study of photon polarisation in a radiative B_s^0 decay
- Study carried out with 3 fb^{-1} Run 1 data
- Extract the polarisation parameter $\mathcal{A}^{\Delta}$ from the decay time distribution of events

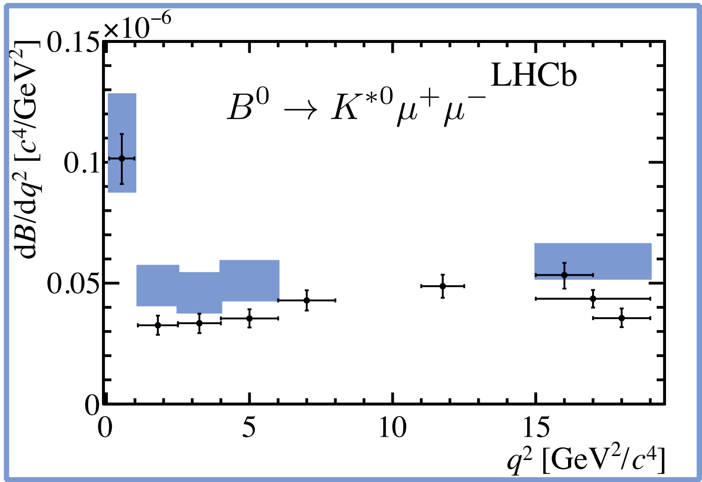
$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

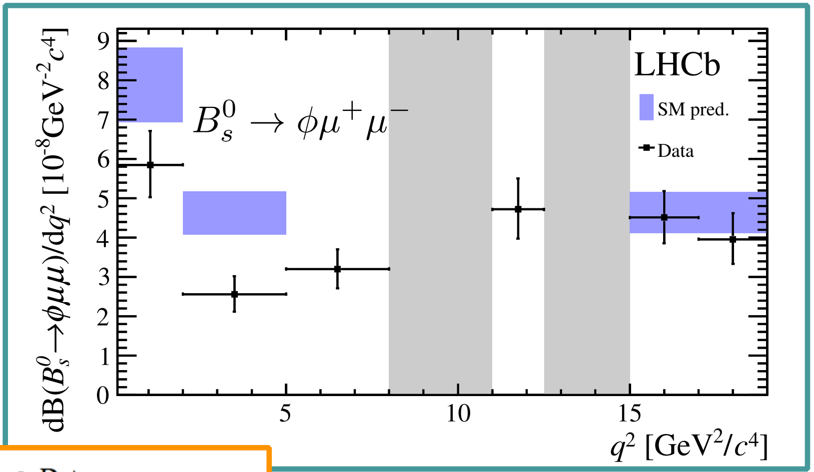
- Agrees with the SM expectation within 2 standard deviations

$$\mathcal{A}^{\Delta}_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$$

Muheim et al.
[Phys. Lett. B664 (2008) 174-179]

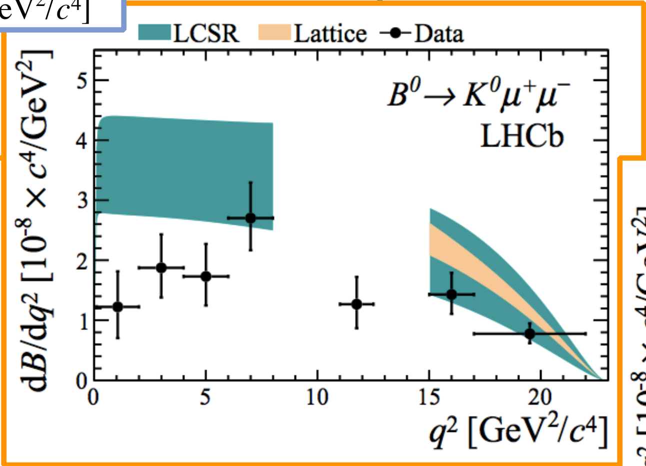
Branching fractions in $b \to sll$ decays

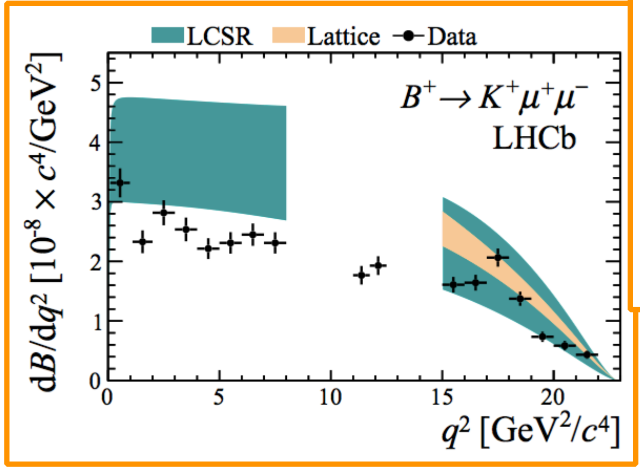




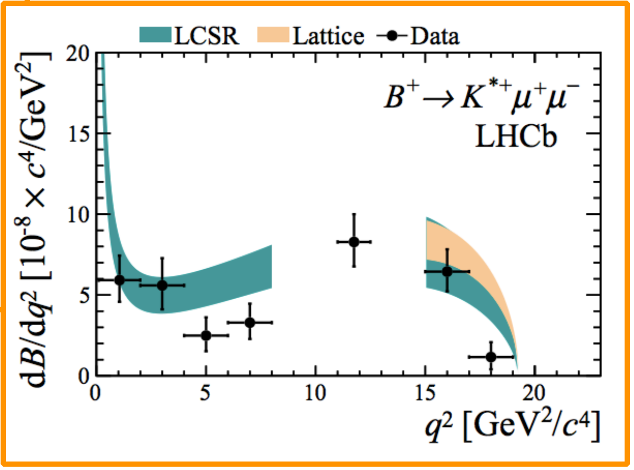
[JHEP 11 (2016) 047]
[JHEP 04 (2017) 142]

[JHEP 09 (2015) 179]

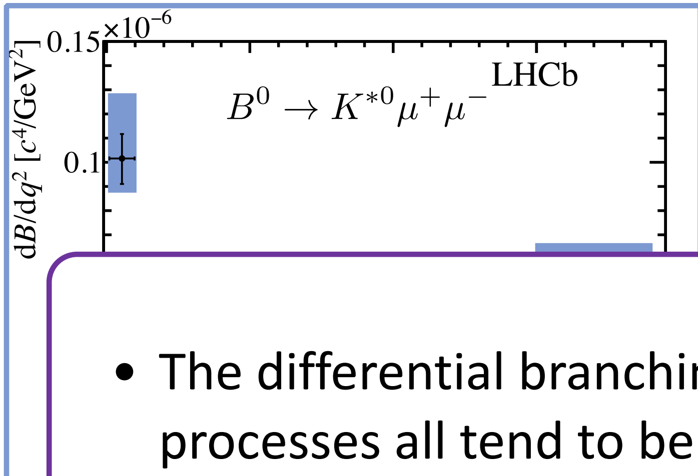


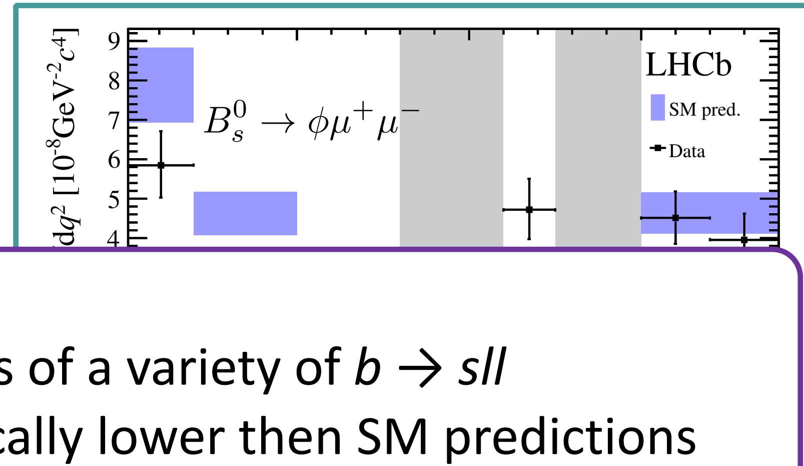


[JHEP 06 (2014) 133]

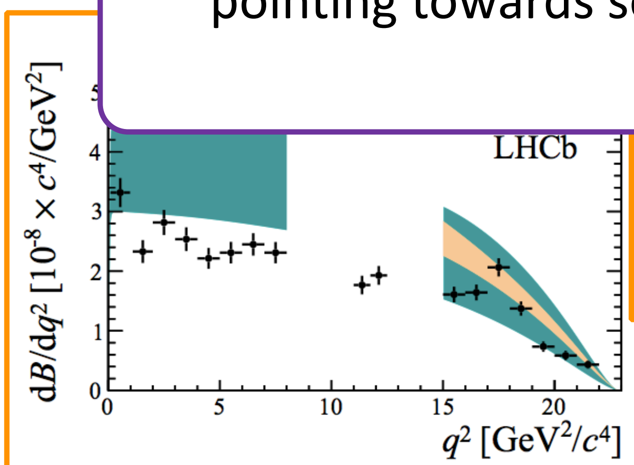


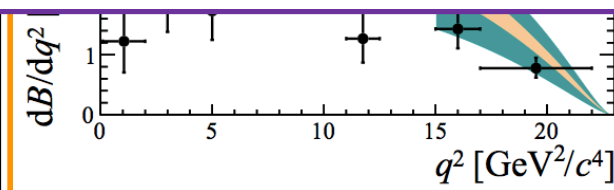
Branching fractions in $b \to sll$ decays



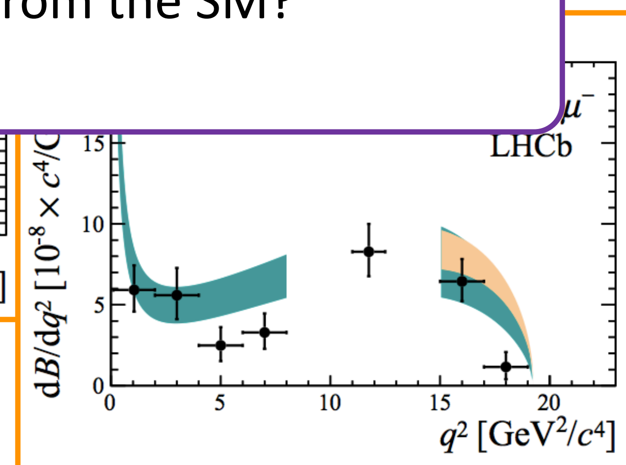


- The differential branching fractions of a variety of $b \to sll$ processes all tend to be systematically lower then SM predictions
- While there is no individually large tension, perhaps this is pointing towards some consistent deviation from the SM?



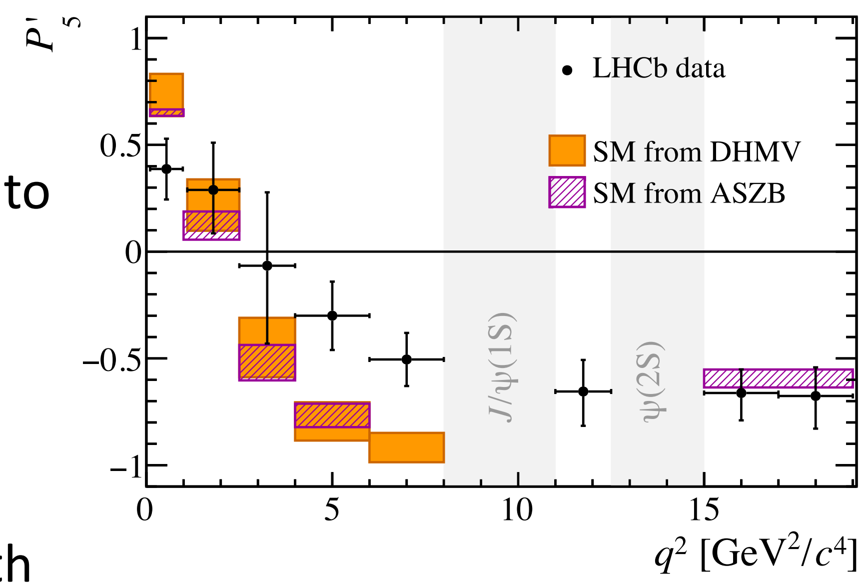


[JHEP 06 (2014) 133]



$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- Four body final state, with the system described by 3 angles and the invariant mass squared of the dimuon system (q^2)
- The angular distribution provides access to observables that are sensitive to new physics
- These observables depend on Wilson coefficients and hadronic form factors
- Try to construct ratios of observables with less form factor dependence (e.g. P_5')
- LHCb measurement of P_5' from run 1 data (3 fb^{-1}) shows local tensions with the SM at a combined significance of 3.4σ



[JHEP 02 (2016) 104]

Descotes-Genon et al. [JHEP 12 (2014) 125]

Altmannshofer and Straub [Eur. Phys. J. C75 (2015) 382]

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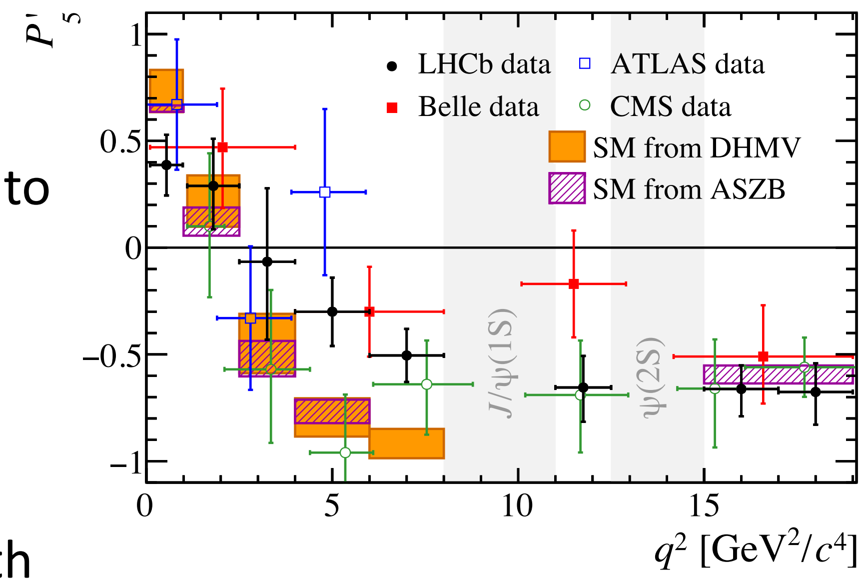


[JHEP 02 (2016) 104]

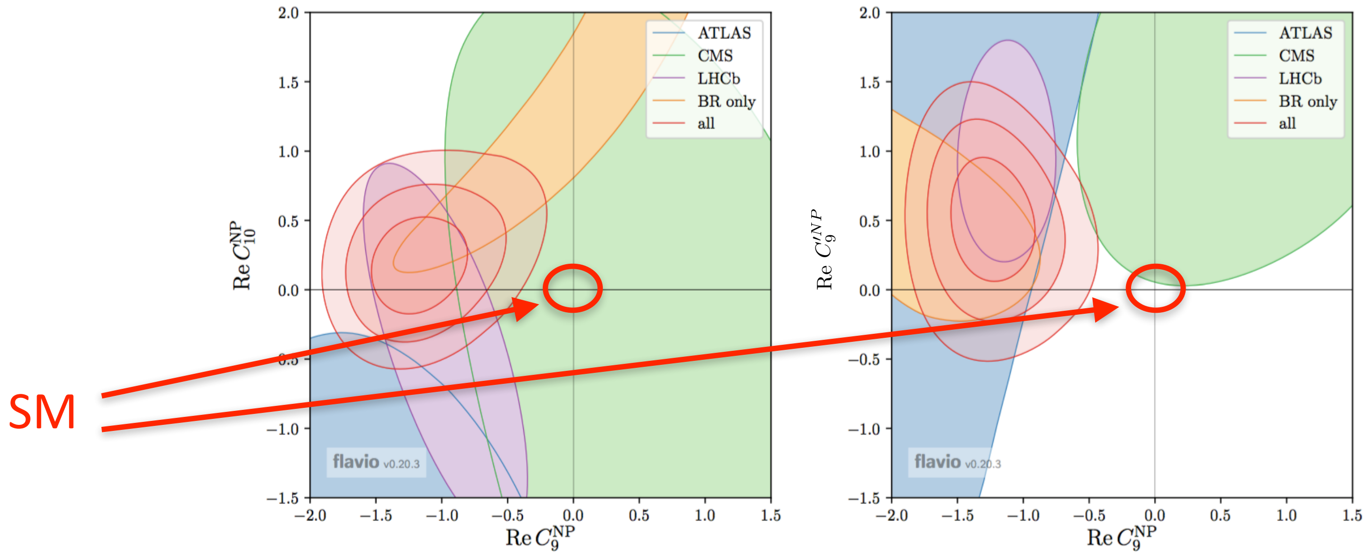
[CMS-BPH-15-008]

[ATLAS-CONF-2017-023]

[Phys. Rev. Lett. 118, 111801 (2017)]

Global fits

- Global fits can be carried out to take into account multiple measurements

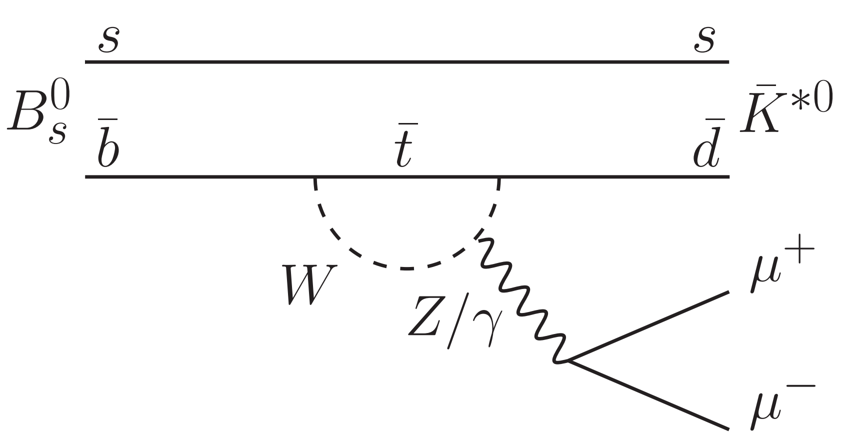


Altmannshofer et al. [Eur.Phys.J. C77 (2017) 377]

- Global fits favour a modified SM vector-current C_9^{NP} up to 4.9σ
- Whether this is new physics or the effect of underestimated QCD uncertainties remains to be seen

b → *dll* transitions

- Further suppressed in SM by CKM factor $|V_{td}/V_{ts}|^2$ compared to *b* → *sll*
- Provide similar but complementary information
- Some of the rarest decays that we have the potential to observe at the moment, will require more data for angular analyses
- Will be important to see if similar anomalies are seen in these decay as are seen in their *b* → *sll* counterparts



b → *dll* transitions

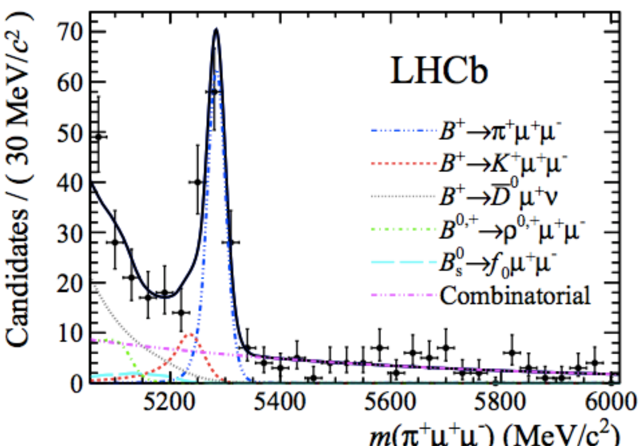
- So far the decay $B^+ \to \pi^+\mu^+\mu^-$ has been observed by LHCb and can be used in combination with $B^+ \to K^+\mu^+\mu^-$ and lattice results to measure $|V_{td}/V_{ts}|$
- Also have observed $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ and seen evidence for $B^0 \to \pi^+\pi^-\mu^+\mu^-$ at LHCb

$$\mathcal{B}(B^\pm \to \pi^\pm\mu^+\mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$
$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51 \pm 0.15 \pm 0.16) \times 10^{-8}$$

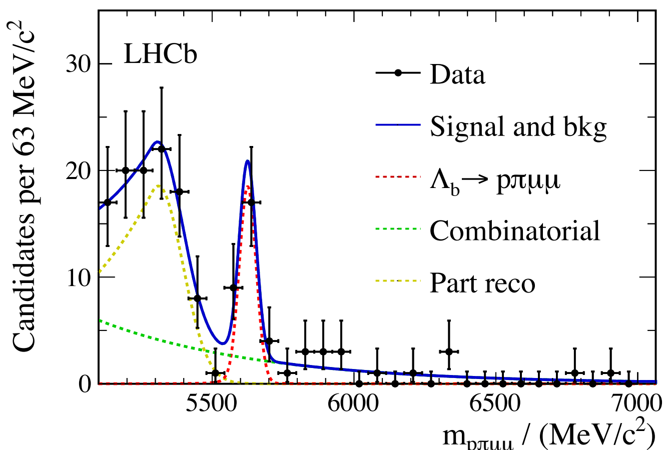
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.201 \pm 0.020$$

Du et al

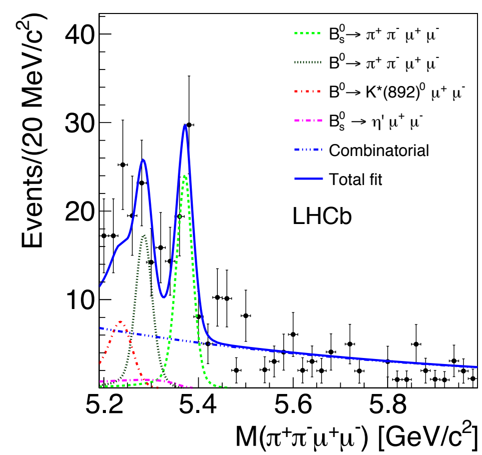
[Phys. Rev. D93 (2016) 034005]



[JHEP 10 (2015) 034]



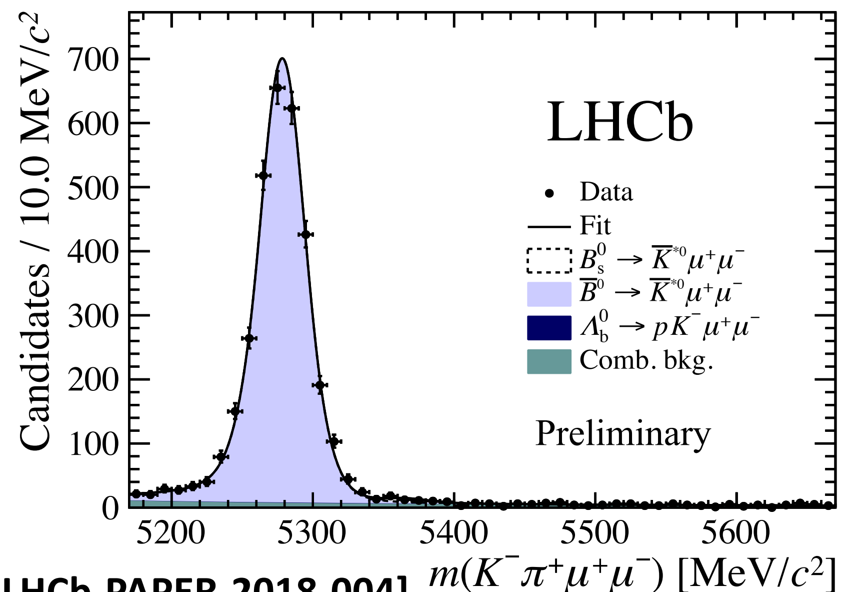
[JHEP 04 (2017) 029]

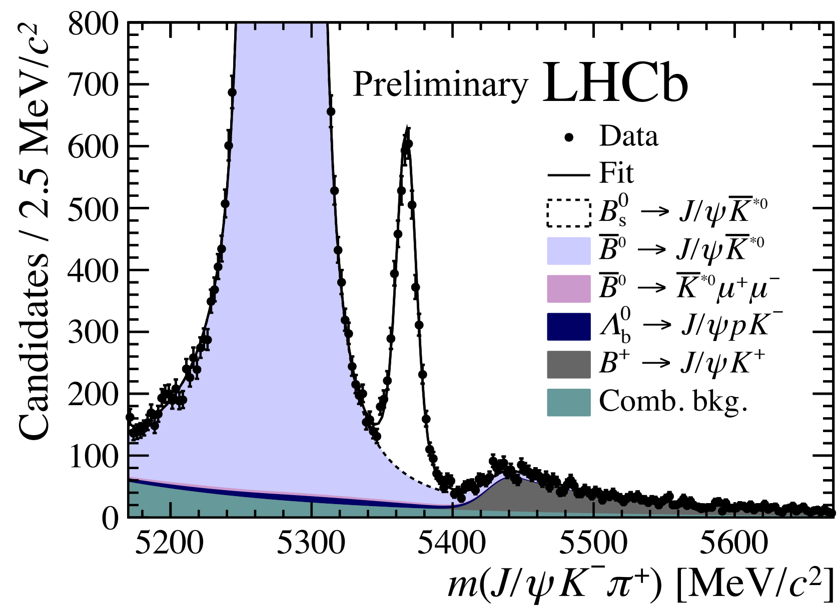


[Phys. Lett. B743 (2015) 46]

$B_s \to \overline{K}^{*0}\mu^+\mu^-$

- Further CKM suppressed version of $B^0 \to K^{*0}\mu^+\mu^-$
- Could be used to measure $|V_{td}/V_{ts}|$ in a similar way as done between $B^+ \to \pi^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$
- Perform a search using 3 fb^{-1} Run 1 and 1.6 fb^{-1} Run 2 data
- Normalise the decay to $B^0 \to J/\psi[\to \mu^+\mu^-]K^{*0}$





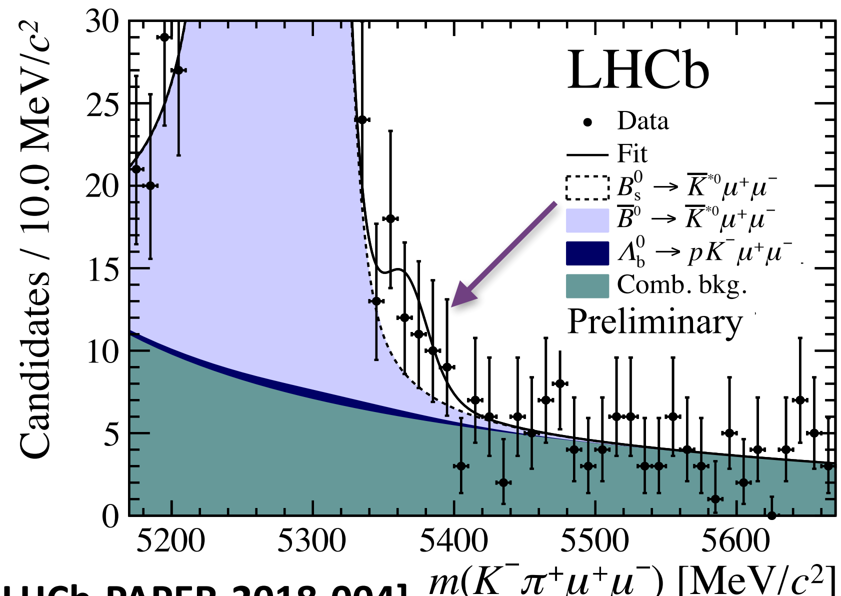
[LHCb-PAPER-2018-004]

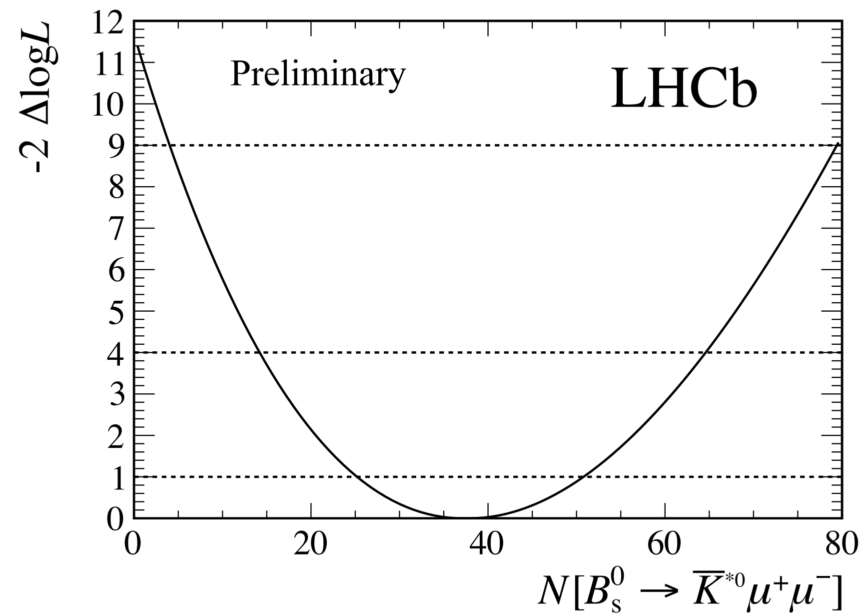
First evidence for $B_s \to \overline{K}^{*0}\mu^+\mu^-$

- Provides first evidence for this decay with significance of 3.4σ
- First measurement of the branching fraction:

NEW!

$$\mathcal{B}(B_s \to \overline{K}^{*0}\mu^+\mu^-) = (3.0 \pm 1.0(\text{stat}) \pm 0.2(\text{sys}) \pm 0.3(\text{norm})) \times 10^{-8}$$





[LHCb-PAPER-2018-004]

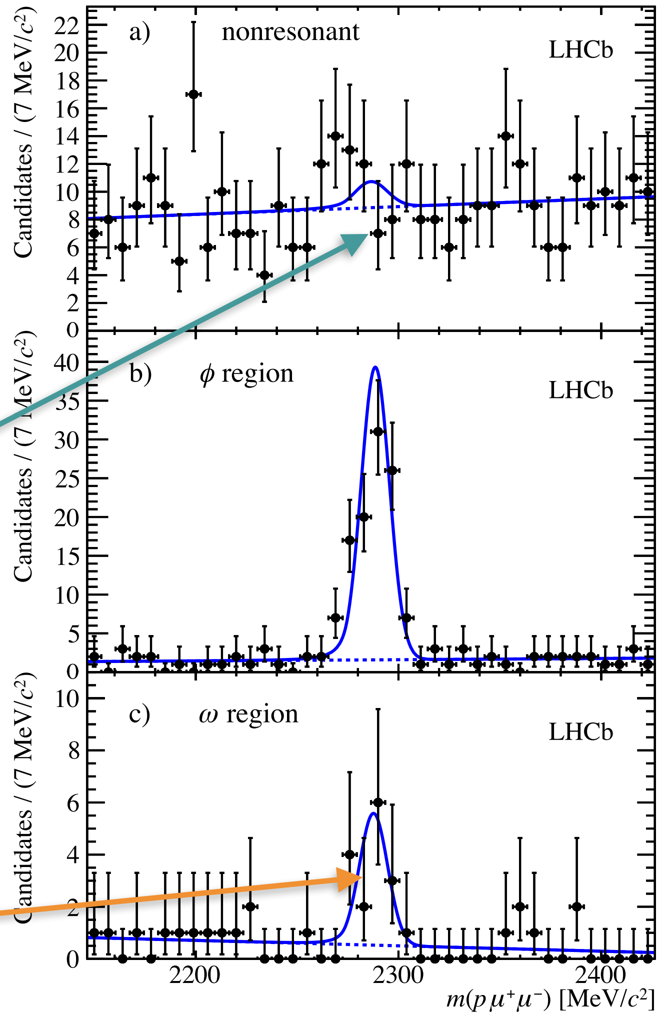
Search for $\Lambda_c^+ \to p\mu^+\mu^-$

- Rare baryonic c → *ull* FCNC process
- Search for non-resonant component carried out on 3 fb^{-1} Run 1 data
- Normalise to the resonant $\Lambda_c^+ \to p\phi$ mode
- No significant non-resonant component is found, as such a limit is set:

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ [95\% C.L.]}$$

- This is the best set limit on this mode
- In addition, the resonant $\Lambda_c^+ \to p\omega$ mode is observed for the first time at 5σ with branching fraction:

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$$

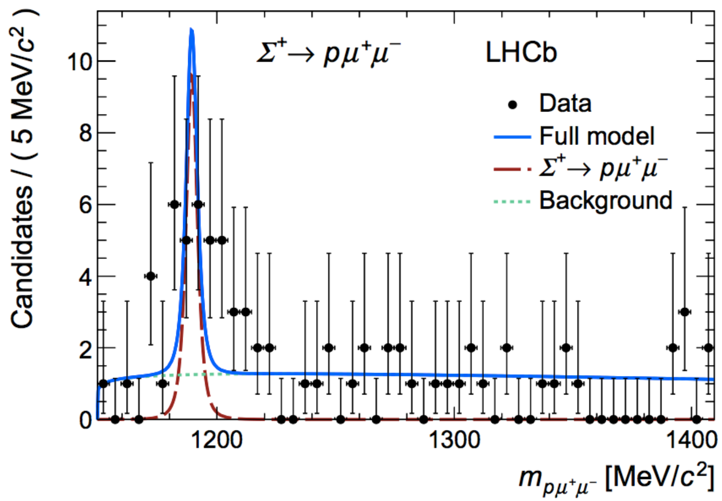


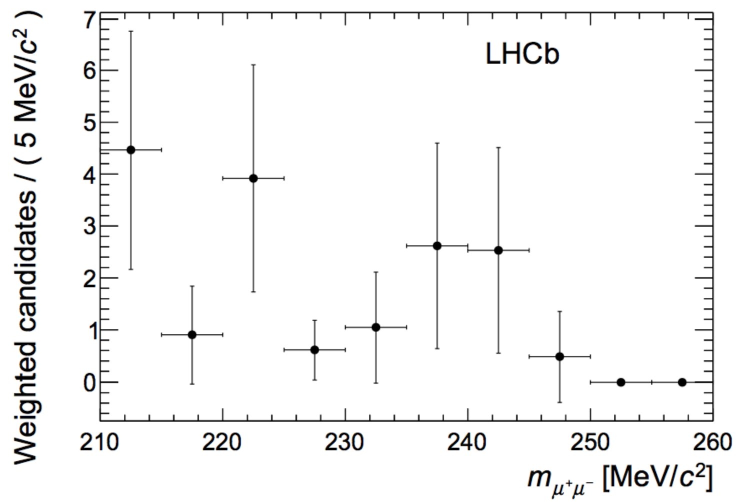
[arXiv:1712.07938, Submitted to Phys. Rev. Lett.]

Evidence for $\Sigma^+ \to p\mu^+\mu^-$

- Rare baryonic s → *dll* FCNC process
- Previous evidence for this decay reported by the HyperCP collaboration, with the observed events all having very similar dimuon invariant mass **[Phys. Rev. Lett. 94, 021801 (2005)]**
- LHCb search carried out on 3 fb^{-1} Run 1 data
- Evidence for the decay at the level of 4σ, no significant structure in $m_{\mu^+\mu^-}$

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.1^{+1.6}_{-1.2}) \times 10^{-8}$$





[arXiv:1712.08606, Submitted to Phys. Rev. Lett.]

Summary

- Rare decays provide powerful probes of the SM and potential NP scenarios
- LHCb has the ability to make a wide variety of rare decay measurements
  - Rare decay observables can provide stringent limits on NP models
  - Measurements in $b \to sll$ transitions seem to be pointing towards a modification of the SM
  - The range of $b \to dll$ measurements that are possible are opening up with more data, will tensions be seen here as well?
  - Baryonic charm and strange FCNC decays are probing largely unexplored CKM transitions
- More and more analyses are being carried out with the larger LHC Run 2 datasets, keep watching for more results from LHCb!

Backup

Angular observables

- Complex angular distribution

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

$$P_1 = \frac{2\,S_3}{(1-F_{\mathrm{L}})} = A_{\mathrm{T}}^{(2)},$$
$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}}{(1-F_{\mathrm{L}})},$$
$$P_3 = \frac{-S_9}{(1-F_{\mathrm{L}})},$$
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}},$$
$$P'_6 = \frac{S_7}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}.$$

Observables with reduced form factor dependence

Wilson coefficients

- Can parameterise an effective field theory for *b* → *s* transitions with the Hamiltonian:

$$\mathcal{H}_{\text{eff}} \propto V_{tb}V_{ts}^{*}\sum_{i}(C_i\mathcal{O}_i + C_i'\mathcal{O}_i')$$

C_i
Wilson coefficient
(short distance physics)

$\mathcal{O}_i$
Local operators

$C_i'\mathcal{O}_i'$
Right handed counterparts
(suppressed in SM)

- New physics can either modify the existing Wilson coefficients or add new operators
- C_9 and C_{10} quantify contributions through the vector and axial-vector couplings