Review of experimental results on $b \to d\ell^+\ell^-$ decays

Area 6 meeting on heavy flavour aspects in EFT fits

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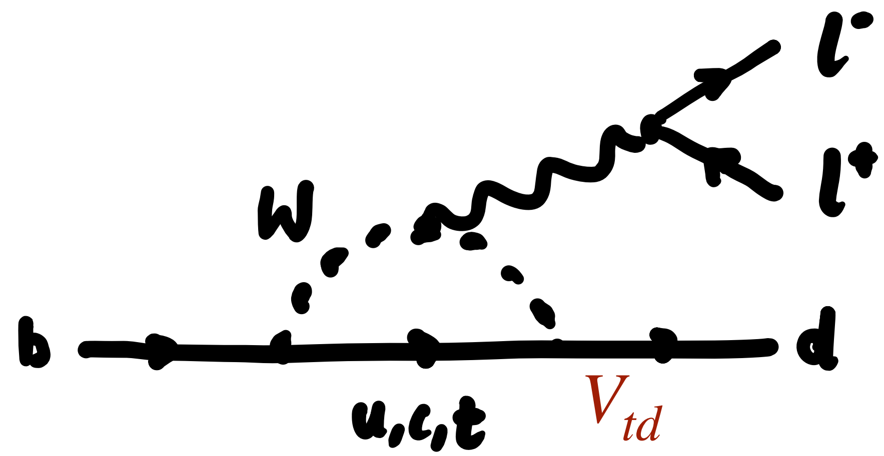
Why study $b \to d\ell^+\ell^-$ decays?

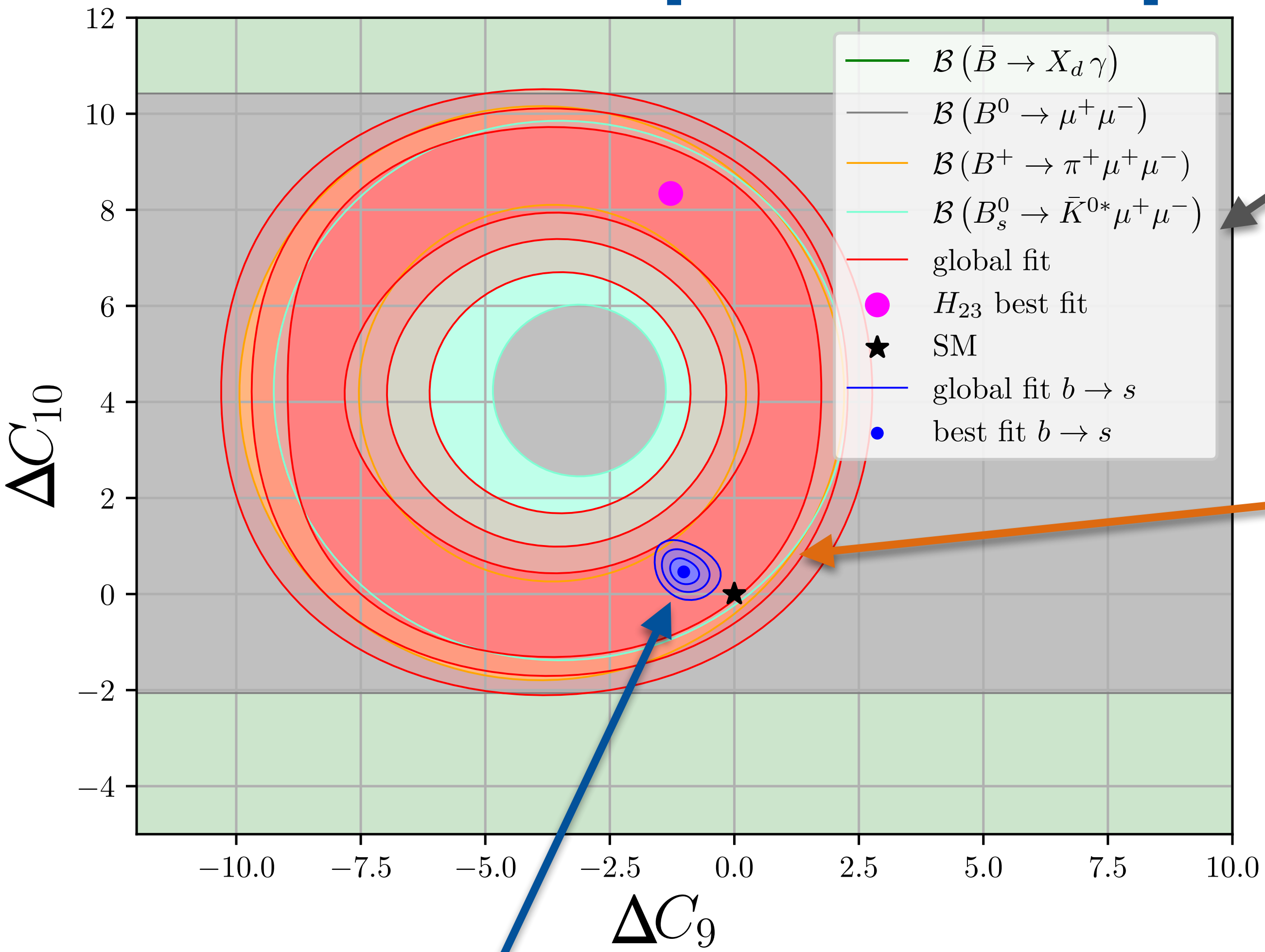
- Very rare FCNC transition.
  - Suppressed by small size of V_{td} in the SM.
- Tensions are seen in $b \to s\ell^+\ell^-$ processes between data and SM predictions.



- Comparisons between measurements of $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ processes probe the flavour structure of the underlying theory.
  - If the underlying theory does not share the same flavour structure as the SM, could see much larger deviations from SM predictions in $b \to d\ell^+\ell^-$ processes.

Existing constraints

R. Bause, H. Gisbert,
M. Golz & G. Hiller [arXiv:2209.04457]



Constraints from $b \to s\mu^+\mu^-$ processes.

$\mathcal{B}(B^0 \to \mu^+\mu^-) \propto |C_{10}|^2$
Constraint is a horizontal band in the $C_9 - C_{10}$ plane.

$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) \propto |C_9|^2 + |C_{10}|^2$
Constraint forms a donut shape in the $C_9 - C_{10}$ plane.

To distinguish C_9 and C_{10} need angular information, e.g. $A_{\rm FB} \propto {\rm Re}(C_9 C_{10})$, or precise information on C_7 and interference at low q^2.

Existing constraints?

$B^0 \rightarrow \mu^+\mu^-$

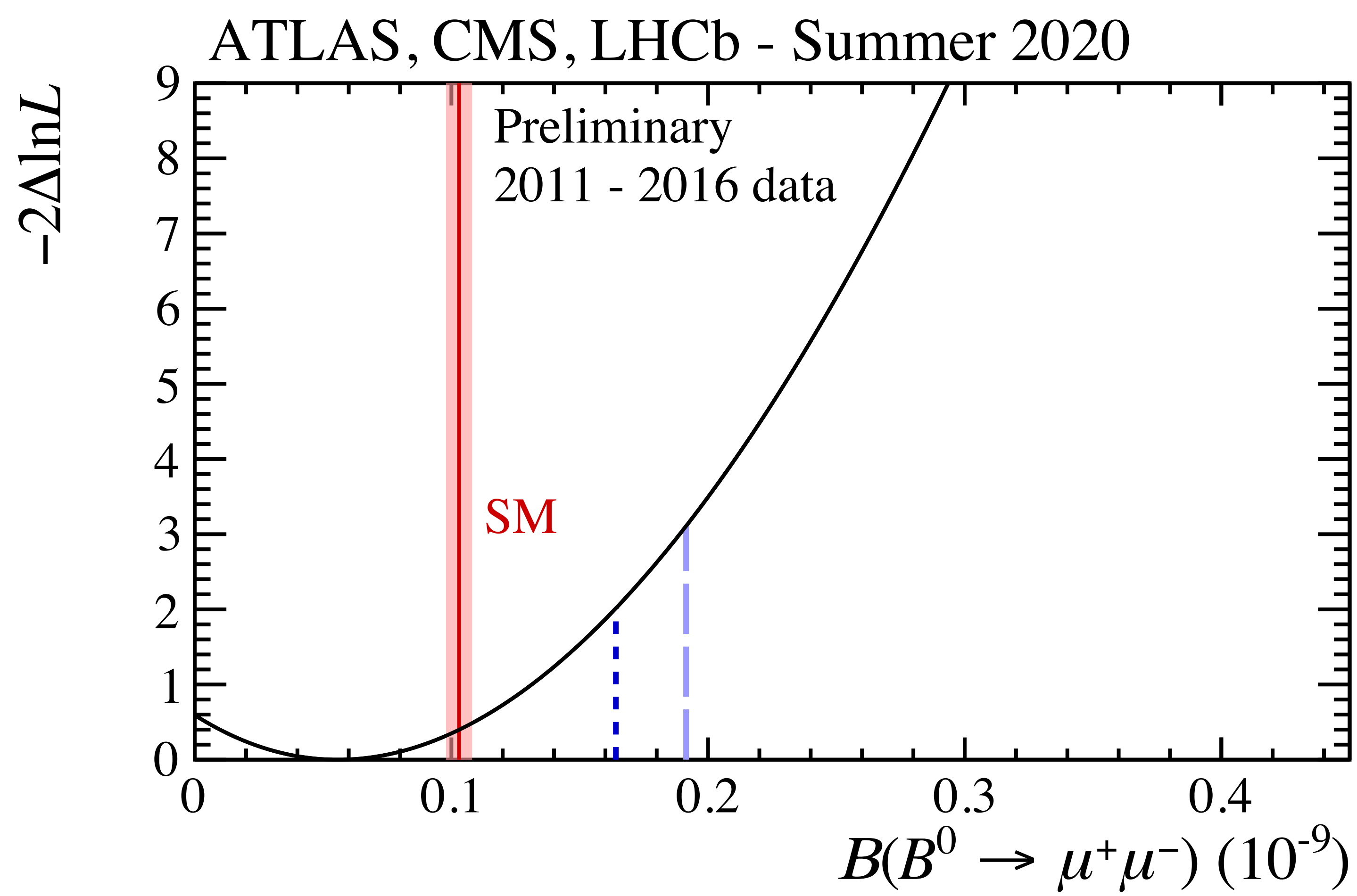
- Incredibly rare process in SM due to the small size of V_{td} and additional helicity suppression.
- No evidence of a statistically significant signal at any experiment.

  At 95% confidence level:

  - $\mathscr{B}(B^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-10}$ **[LHCb, Phys. Rev. Lett. 128, (2022) 041801]**
  - $\mathscr{B}(B^0 \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-10}$ **[CMS, CMS-PAS-BPH-21-006]**
  - $\mathscr{B}(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ **[ATLAS, JHEP 04 (2019) 098]**
- Comparable precisions achieved by ATLAS, CMS and LHCb.

$B^0 \to \mu^+\mu^-$

- Global analysis of experiment data using run 1 + 2015 & 2016 data sets is consistent with the SM prediction (and the background only hypothesis).
- Branching fraction measurement constrains C_{10}, C_S and C_P Wilson coefficients.

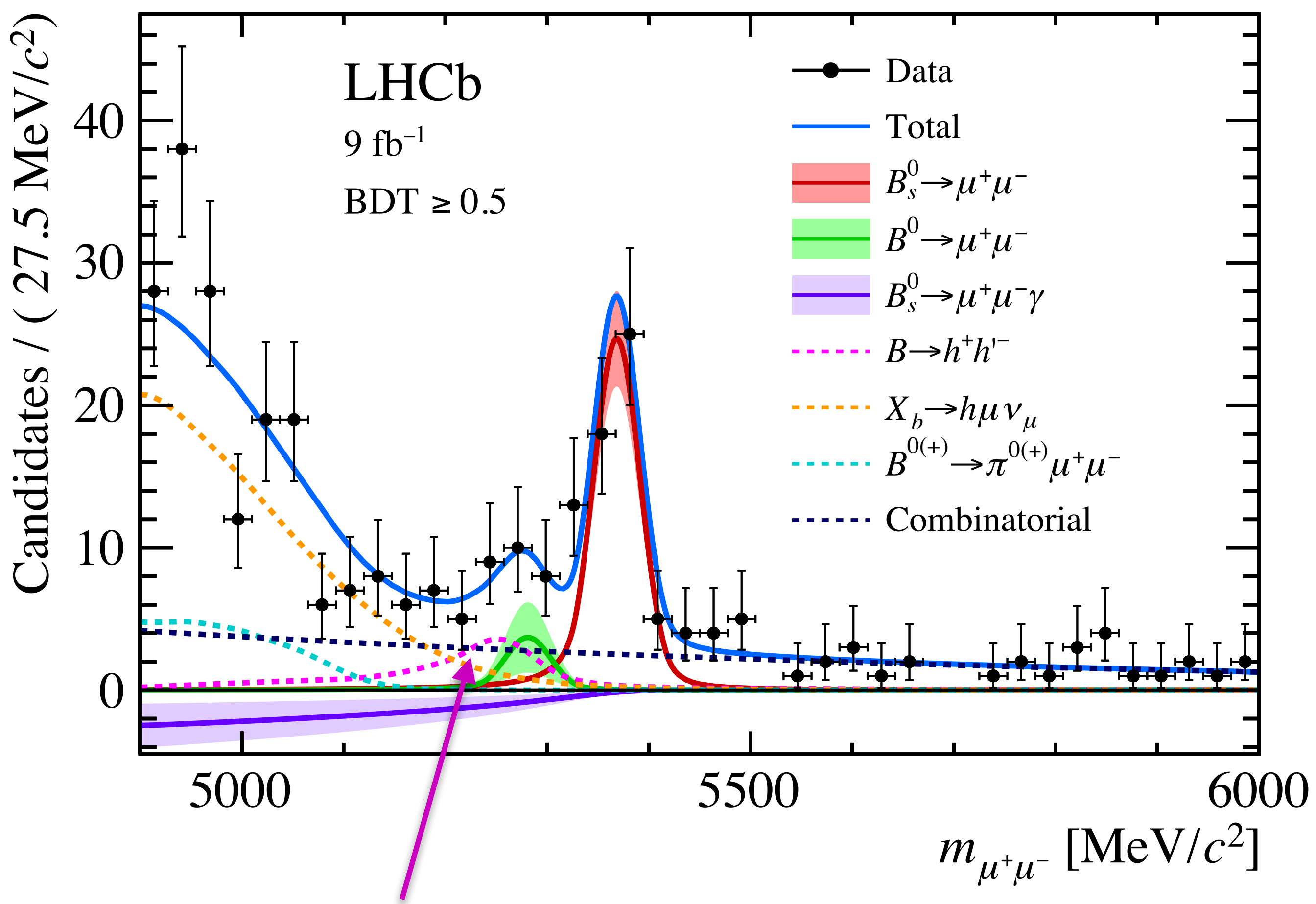


[https://cds.cern.ch/record/2727216]

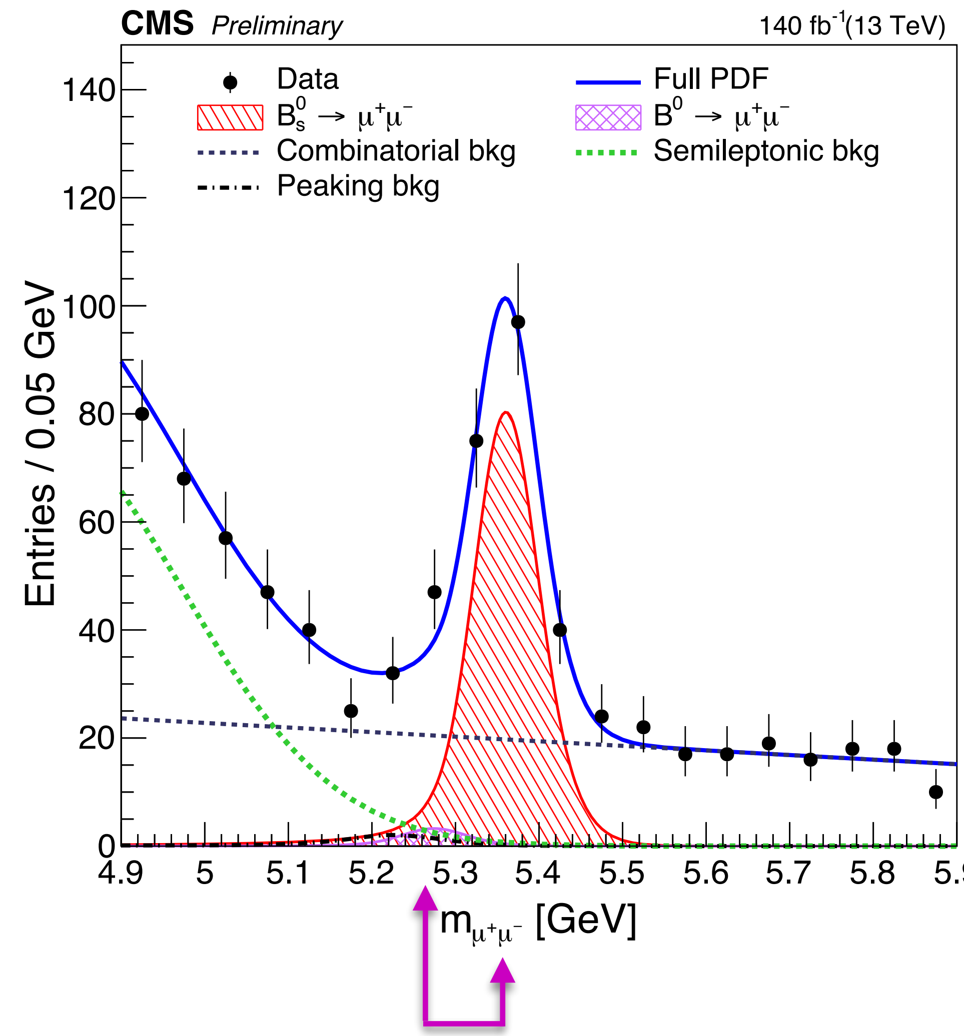
$B^0 \to \mu^+\mu^-$

- Main challenge (beside the small signal) is misidentified backgrounds:

[LHCb, Phys. Rev. Lett. 128, (2022) 041801]



Dangerous backgrounds from e.g. misidentified $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B_s^0 \to K^+K^-$ and $\Lambda_b \to pK^-$ decays.



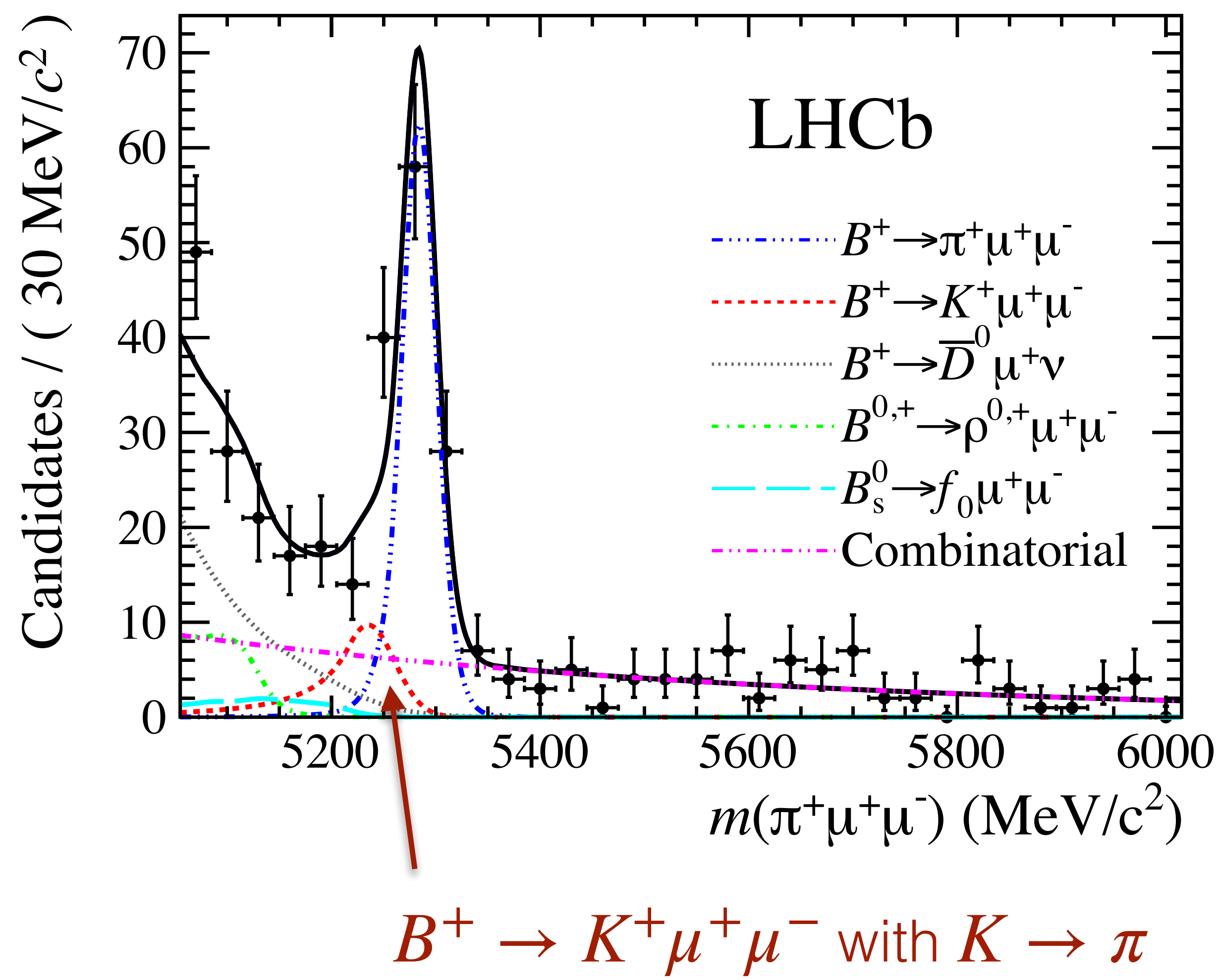
[CMS, CMS-PAS-BPH-21-006]

Experimental mass resolution can make separating B^0 and B_s^0 decays challenging.

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

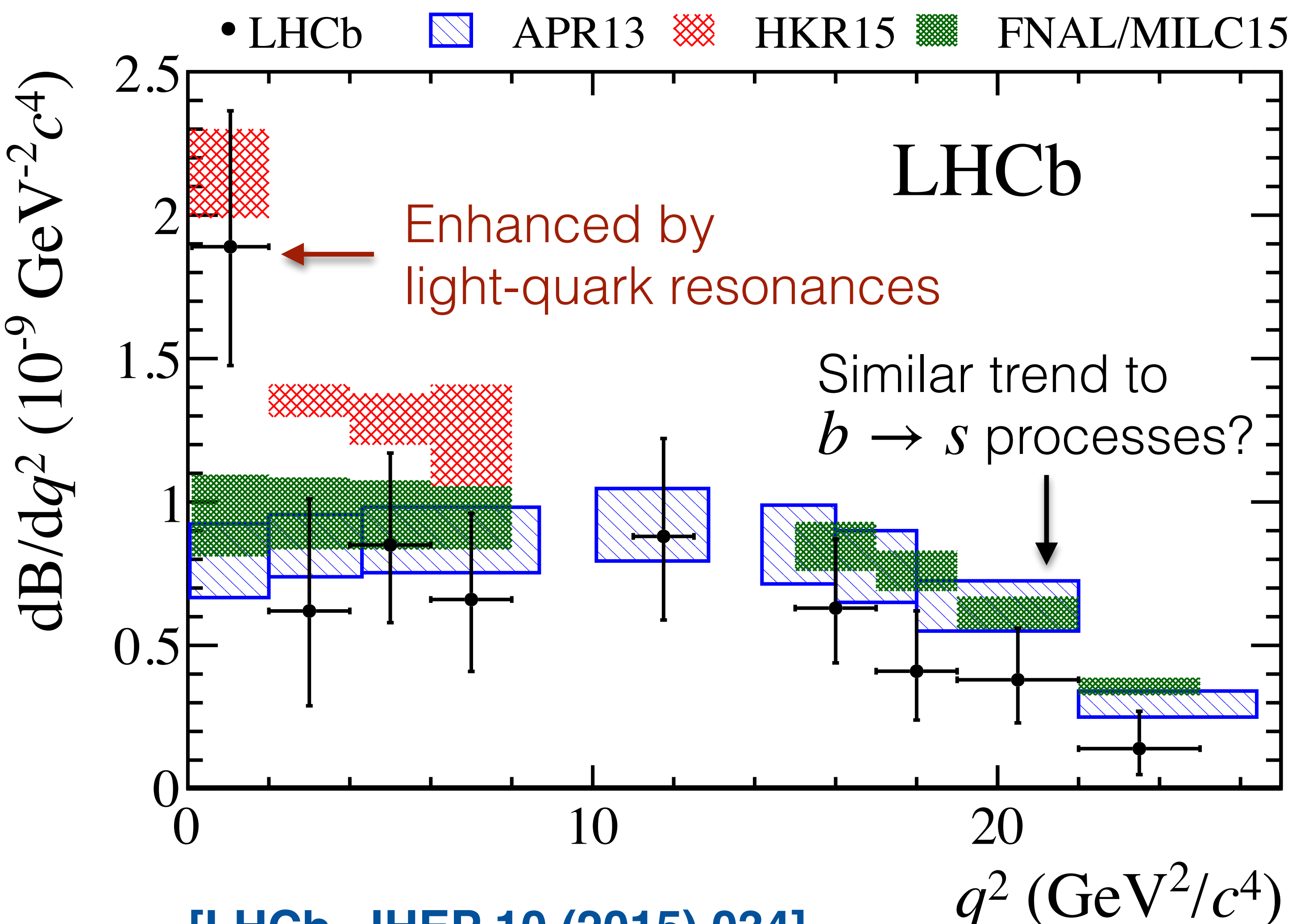
[LHCb, JHEP 10 (2015) 034]

- Measurement of the differential branching fraction of the $B^+ \to \pi^+\mu^+\mu^-$ decay in bins of q^2 performed by LHCb using data collected in run 1 (with 3 fb^{-1} of integrated luminosity).
- See important backgrounds from misidentified decays — in particular from $B^+ \to K^+\mu^+\mu^-$ which has a branching fraction that is $(|V_{ts}|/|V_{td}|)^2 \sim 25$ times larger than the signal.



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

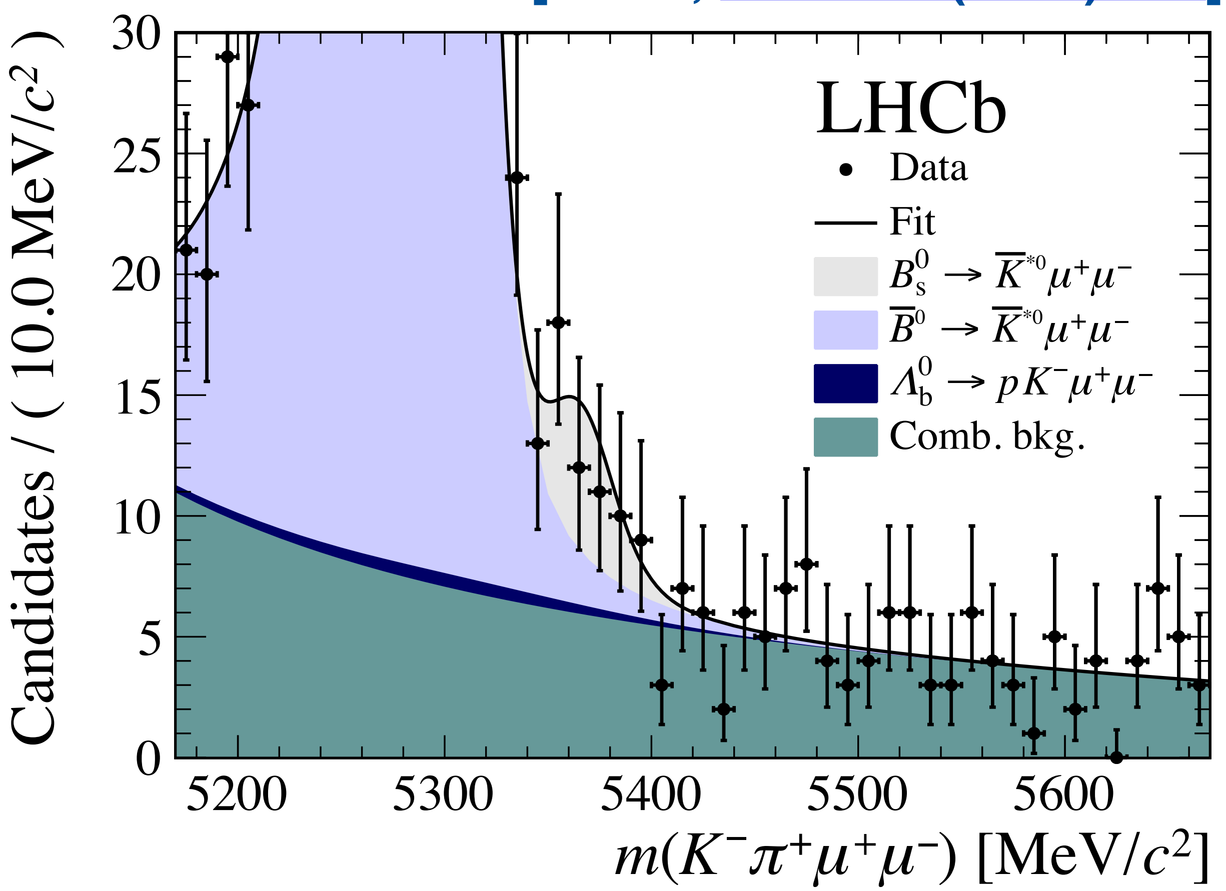
- Observed signal normalised w.r.t. to $B^+ \to J/\psi K^+$ decays in the same data set.
- Data are compatible with predictions given the statistical uncertainties on the measurements.
- Differential branching fraction measurement constrains C_9 and C_{10} Wilson coefficients.



[LHCb, JHEP 10 (2015) 034]
[Ali et. al, Phys .Rev. D 89 (2014) 094021]
[Hambrock et. al., Phys. Rev. D 92 (2015) 074020]
[FNAL/MILC, Phys. Rev. Lett. 115 (2015) 15]

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

[LHCb, JHEP 07 (2018) 020]



- First evidence of the $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ seen with a significance of 3.4σ by LHCb using its run 1 and 2016 data sets (with 4.6 fb^{-1} of integrated luminosity).

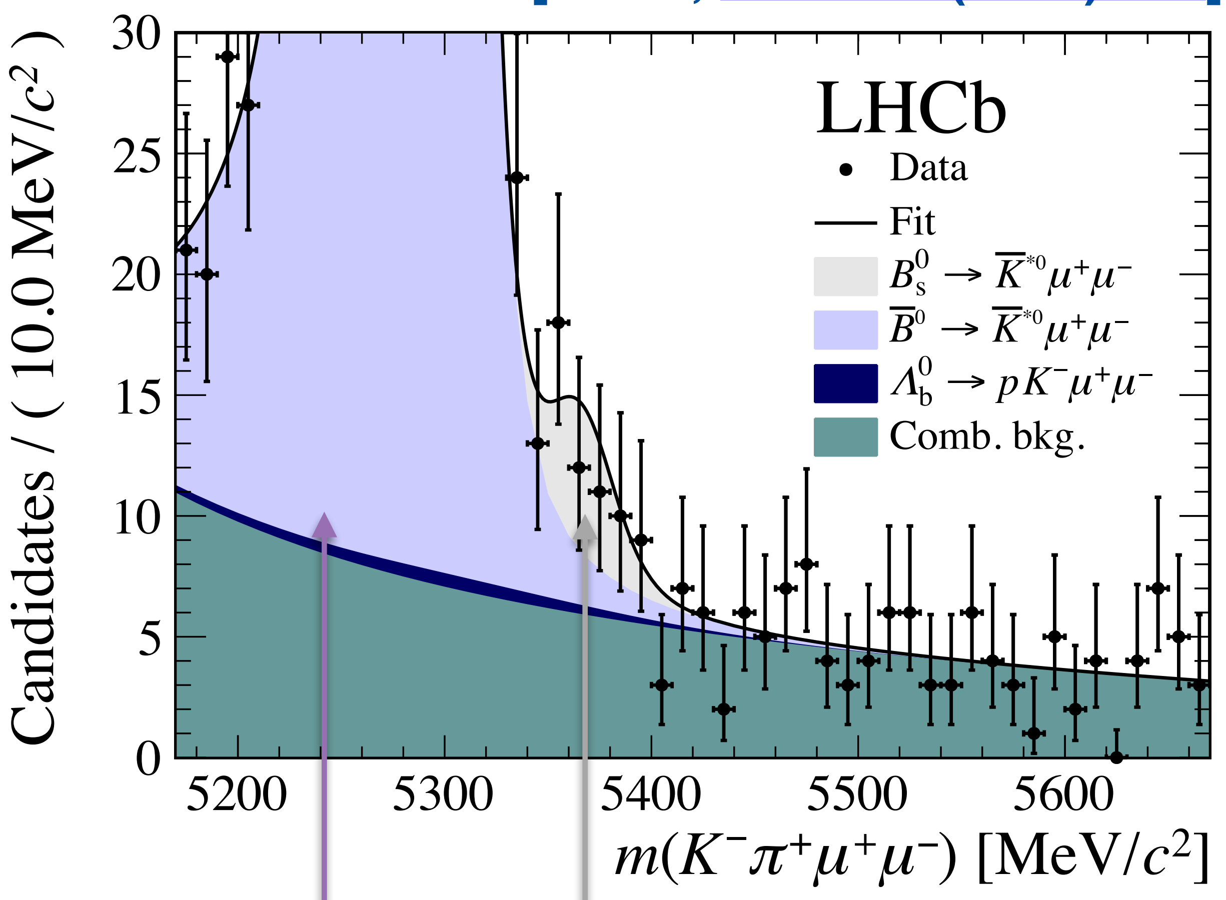
- Determine branching fraction using $B^0 \to J/\psi K^{*0}$ as a normalisation channel. Yields

$$\mathscr{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$

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

[LHCb, JHEP 07 (2018) 020]

- Main challenge is the understanding of the tails of the mass resolution and the background from $B^0 \to K^{*0}\mu^+\mu^-$ decays.
  - The $B^0 \to K^{*0}\mu^+\mu^-$ decay is ~100 times more prominent than the signal due to $|V_{td}/V_{ts}|$ and the B production fraction ratio (f_s/f_d) in *pp* collisions.

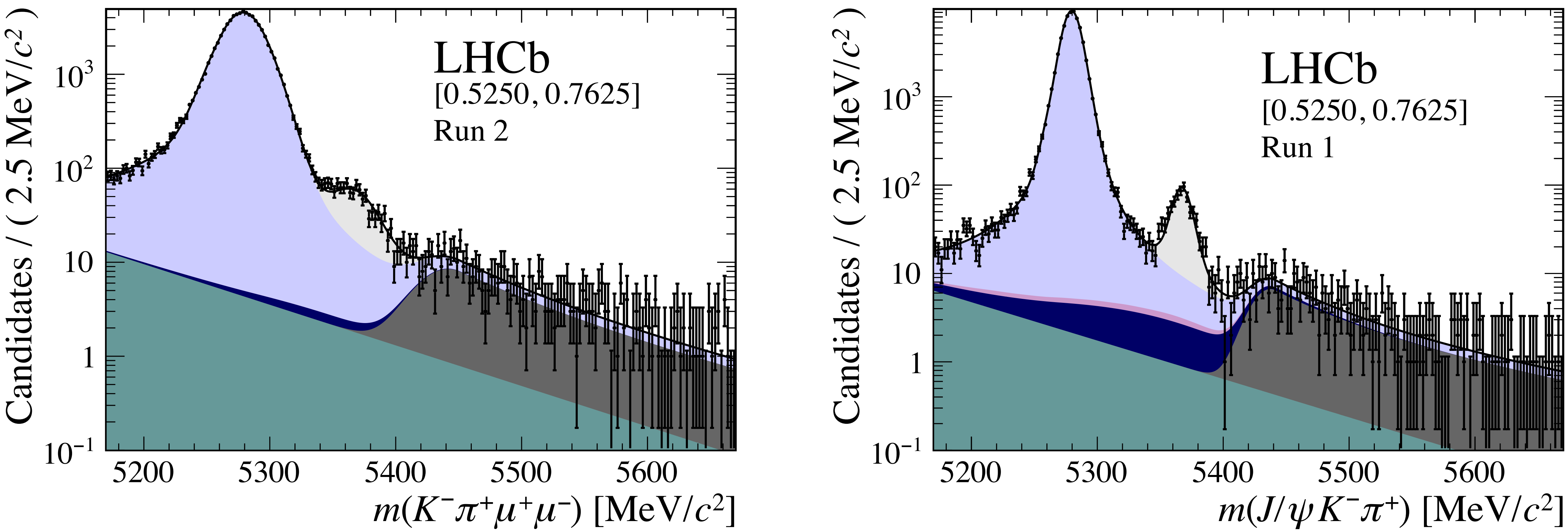


$\overline{B}_s^0 \to K^{*0}\mu^+\mu^-$ signal.

Dominant contribution is from $B^0 \to K^{*0}\mu^+\mu^-$ decays.

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

- Can gain an understanding of the modelling of the tails by comparing $\overline{K}^{*0}J/\psi$ reconstructed with and without a J/ψ mass constraint.



no mass constraint

with J/ψ mass constraint

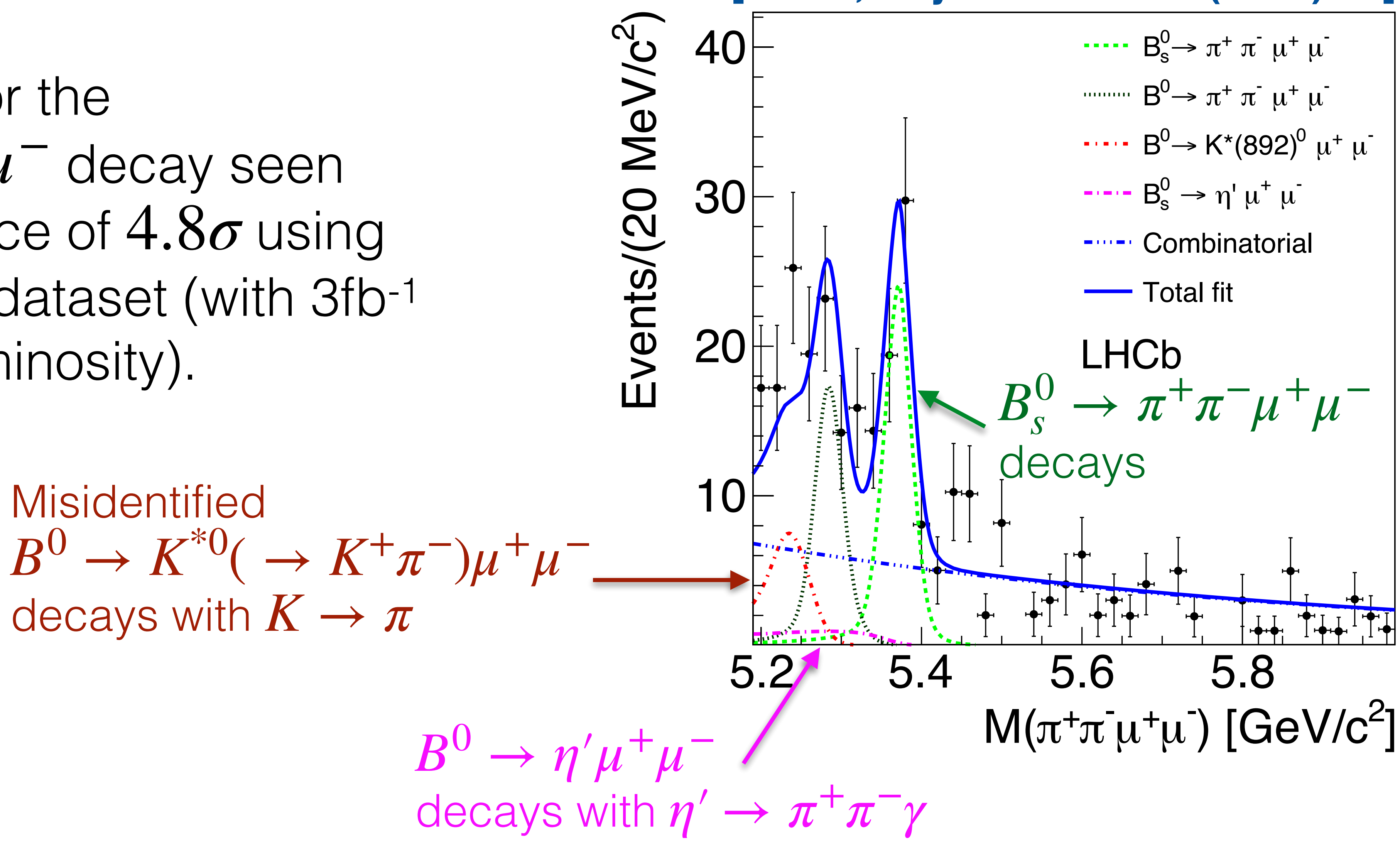
[LHCb, JHEP 07 (2018) 020]

Other constraints?

$B^0 \to \rho^0 \mu^+ \mu^-$

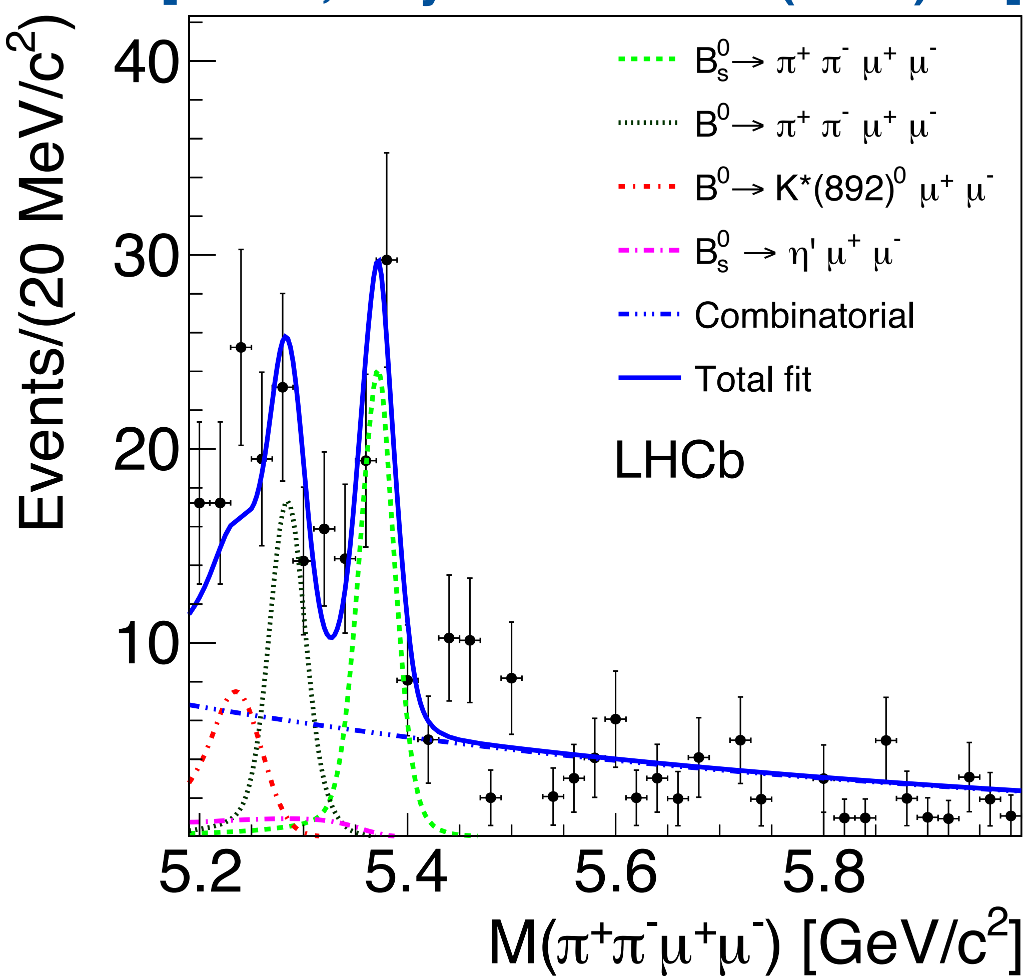
- First evidence for the $B^0 \to \pi^+\pi^-\mu^+\mu^-$ decay seen with a significance of 4.8σ using the LHCb run 1 dataset (with 3fb^{-1} of integrated luminosity).

[LHCb, Phys. Lett. B743 (2015) 46]



$B^0 \to \rho^0\mu^+\mu^-$

[LHCb, Phys. Lett. B743 (2015) 46]



- First evidence for the $B^0 \to \pi^+\pi^-\mu^+\mu^-$ decay seen with a significance of 4.8σ using the LHCb Run1 dataset (with 3fb^{-1} of integrated luminosity).

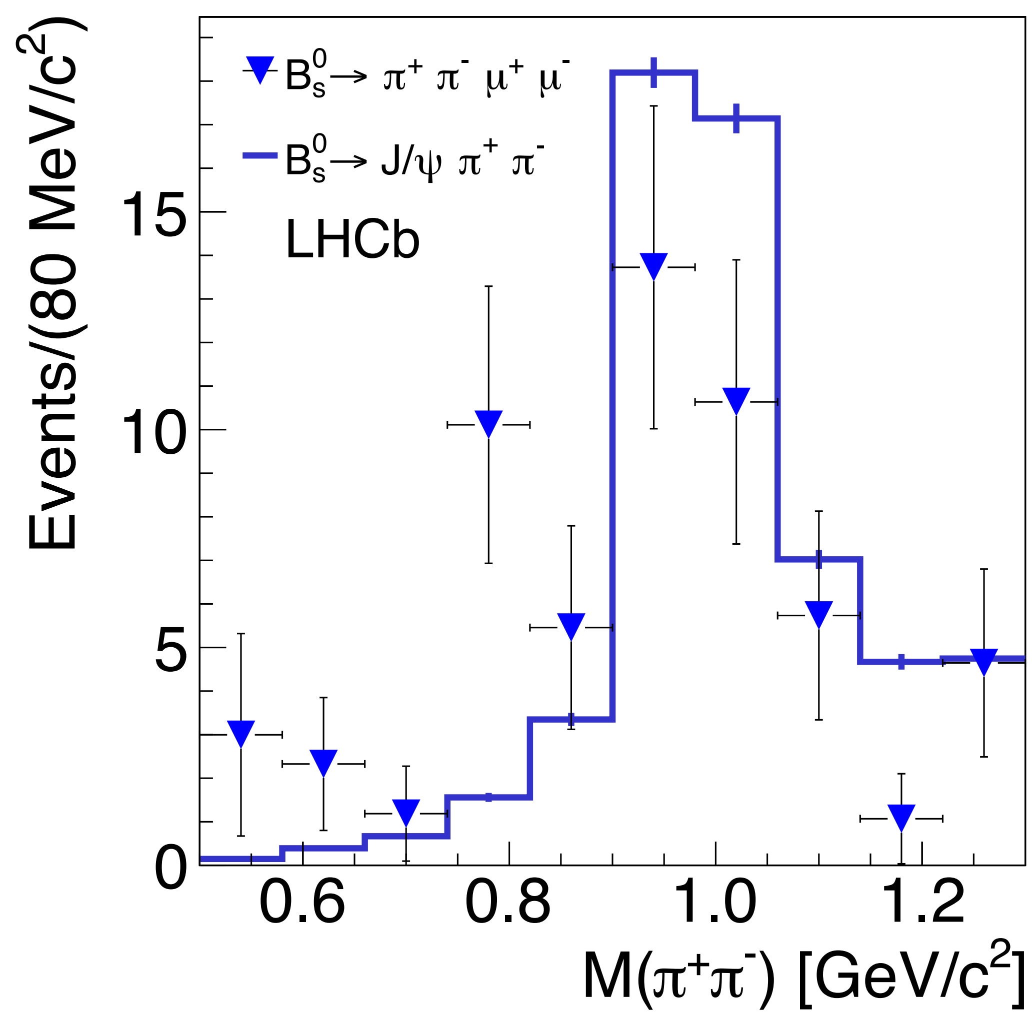
- Determine branching fraction with $B^0 \to J/\psi K^{*0}$ as a normalisation channel.

Yields:

$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = [2.11 \pm 0.51\,(\text{stat}) \pm 0.15\,(\text{syst}) \pm 0.16\,(\text{norm})] \times 10^{-8}$$

$B^0 \to \rho^0 \mu^+ \mu^-$

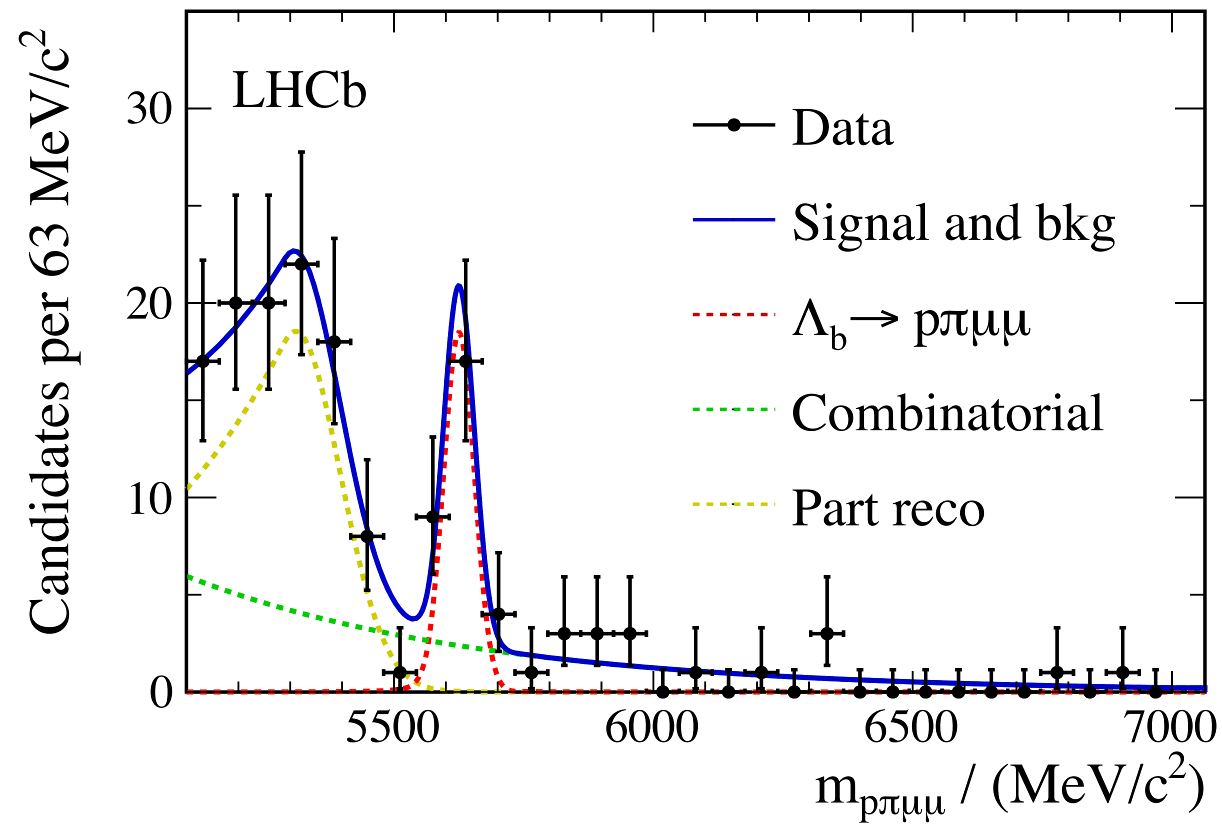
[LHCb, Phys. Lett. B743 (2015) 46]



- Unfortunately, given the large natural width of the ρ, it is hard to separate the signal from other $\pi^+\pi^-$ contributions.
  - No attempt was made to separate the ρ from other contributions in the LHCb analysis.

$\Lambda_b \to N\mu^+\mu^-$

[LHCb, JHEP 04 (2017) 029]



- First observation of the $\Lambda_b \to p\pi^-\mu^+\mu^-$ decay with a significance of 5.5σ using the LHCb run 1 data set (with 3fb^{-1} of integrated luminosity).

- Measured branching fraction ratio:

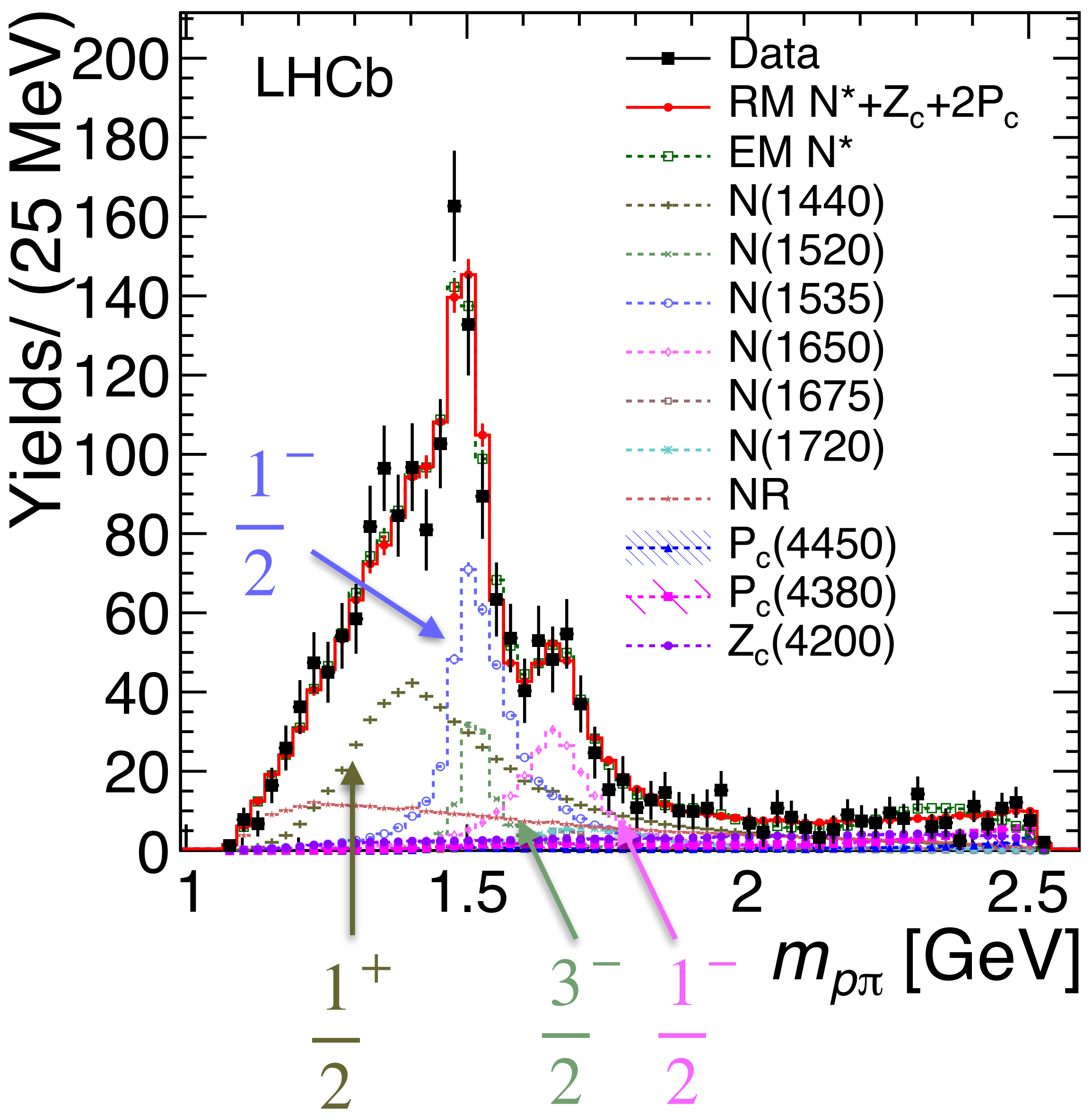
$$\frac{\mathcal{B}(\Lambda_b \to p\pi^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b \to J/\psi(\to \mu^+\mu^-)p\pi^-)} = 0.044 \pm 0.012(\text{stat}) \pm 0.007(\text{syst})$$

which corresponds to $\mathcal{B}(\Lambda_b \to p\pi^-\mu^+\mu^-) \approx 6 \times 10^{-8}$

$\Lambda_b \to N\mu^+\mu^-$

- Even bigger challenge in interpreting the result due to the large number of overlapping *N* states with different quantum numbers decaying to $p\pi^-$.
  - Would require an amplitude analysis to separate states, which is not possible with the current data set.
- For comparison, the figure shows the states used in the amplitude analysis of $\Lambda_b \to J/\psi p \pi^-$ decays.

[LHCb, Phys. Rev. Lett. 117 (2016) 082003]



Possible future constraints?

Lepton flavour universality tests

- Focus on $B^+ \to \pi^+ \ell^+ \ell^-$ as the cleanest experimental signatures.
- Expect $\mathcal{O}(25)$ $B^+ \to \pi^+ e^+ e^-$ decays in $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ with the LHCb Run 1+2 dataset (with $9\mathrm{fb}^{-1}$ of integrated luminosity).
- Main challenge is the small electron mode yield and backgrounds from:
  1. $B^+ \to K^+ e^+ e^-$ decays with $K \to \pi$.
  2. Semileptonic decays with missing neutrinos.
  3. Misidentified hadronic decays, e.g. $B^+ \to \pi^+ \pi^+ \pi^-$ with $\pi^\pm \to e^\pm$.

NB, expect to see a significant improvement in electron efficiency in data collected from next year due to the removal of LHCb's hardware trigger.

Angular distribution of $B^+ \to \pi^+\mu^+\mu^-$

- Simplified angular distribution, which depends on two parameters:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} = \frac{3}{4}(1 - F_\mathrm{H})(1 - \cos^2\theta) + \frac{F_\mathrm{H}}{2} + A_\mathrm{FB}\cos\theta$$

[Bobeth et. al. JHEP 12 (2007) 040]

- A_FB and F_H receive contributions from C_S, C_P, C_T and C_T5, which are absent in the SM.
  - C_S and C_P appear in different combinations in F_H and A_FB, compared to $\mathscr{B}(B^0 \to \mu^+\mu^-)$.

[Bobeth et. al. EPJC 75 (2015) 9]

Angular observables

- Most powerful constraints on C_9 and C_{10} in $b \to s\ell^+\ell^-$ decays come from the angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay.
  - Best sensitivity comes from A_{FB} and S_5/P_5'.
- Analog of $B^0 \to K^{*0}\mu^+\mu^-$ is $B^0 \to \rho^0\mu^+\mu^-$ **but** this decay is not self-tagging.
  - We can only gain information on the flavour of the *B* by tagging the flavour of the system at production.
  - We cannot measure A_{FB} and S_5/P_5' in an untagged analysis. We can measure F_{L} and S_4/P_4' in an untagged analysis.

[Descotes-Genon et. al., JHEP 04 (2015) 045]

- In time-dependent analyses, sensitivity is limited by the effective-tagging power of the experiment.
  - For LHCb in Run 1 + 2, this is $\varepsilon_{\mathrm{eff}} = \varepsilon_{\mathrm{tag}} D^2 \sim 5\,\%$, see e.g. **[LHCb, JHEP 11 (2017) 170]**.

Angular observables

- There are several self-tagging options but each has experimental difficulties:
  - $B_s^0 \to \overline{K}^{*0}\mu^-\mu^-$ is the best choice at LHCb but is limited by the small sample size and the background from $B^0 \to K^{*0}\mu^+\mu^-$.
  - $B^+ \to \rho^+\mu^+\mu^-$ is challenging at LHCb as it requires the reconstruction of a π^0.
  - $\Lambda_b \to N\mu^+\mu^-$ has a complex angular structure to the the overlapping (interfering) $p\pi^-$ resonances, see. e.g. **[A. Beck et. al., arXiv:2210.09988]**

Summary

- LHC Run 1+2 data has enabled measurements of $b \to d\ell^+\ell^-$ processes for the first time.
    - The challenge for Belle II is the small size of the branching fraction compared to the number of B^+B^- or $B^0\overline{B}^0$ produced.
- Expect updated measurements on several processes with the legacy run 1 + 2 data set.
- New opportunities will be possible with the data from runs 3 and 4.
    - There are also interesting opportunities for measurements of *CP* violation in $b \to d\ell^+\ell^-$ decays due to the large weak phase differences between contributions to the amplitude of the decay.