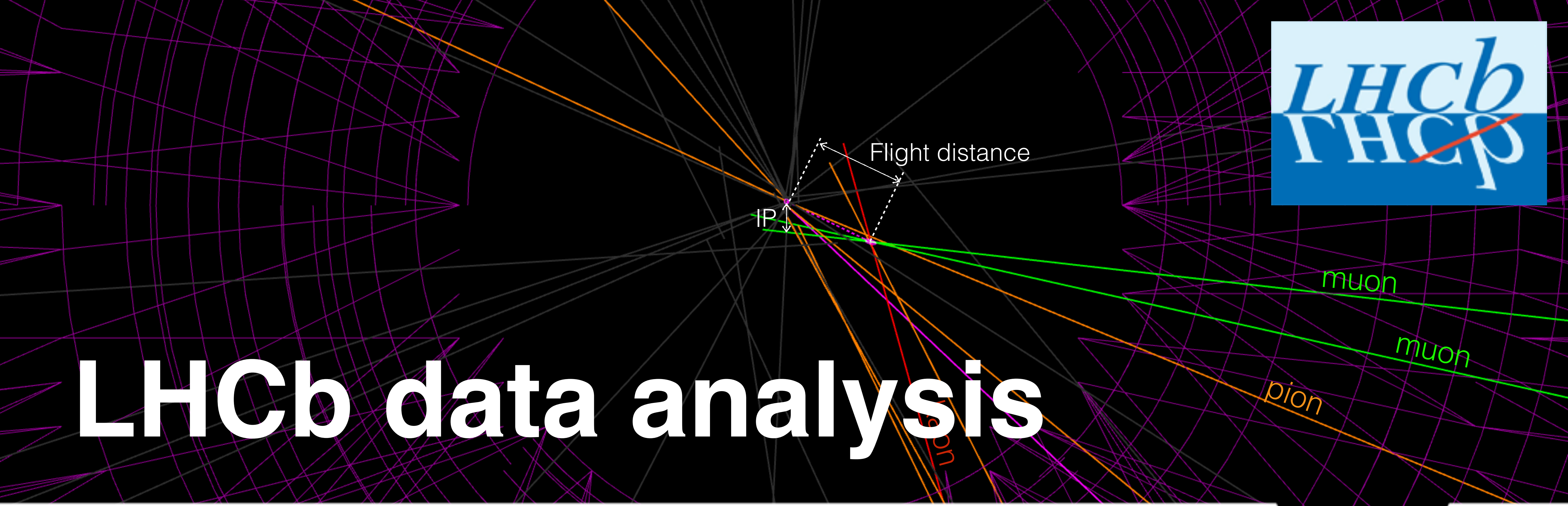


LHCb data analysis

T. Blake

Warwick Monash Alliance meeting
15th of December 2020

WARWICK
THE UNIVERSITY OF WARWICK

Overview

Warwick activities

Rare b-hadron decays **(TB, MK, AW)**

CP violation in charmless and open charm *B* hadron decays **(TG, TL, MK)**

Precision EW measurements **(MV, MRP)**

Semileptonic *B* decays **(MV, MK)**

Monash activities

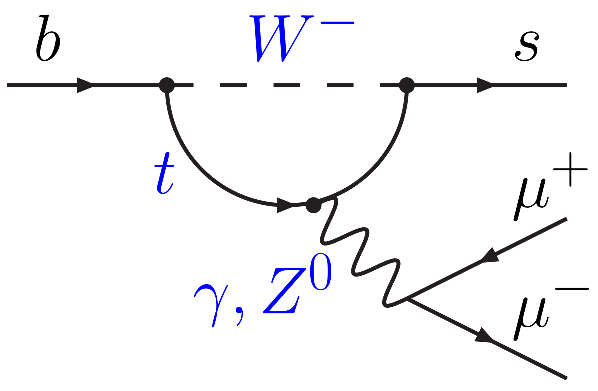
Rare b-hadron decays **(UE, TH)**

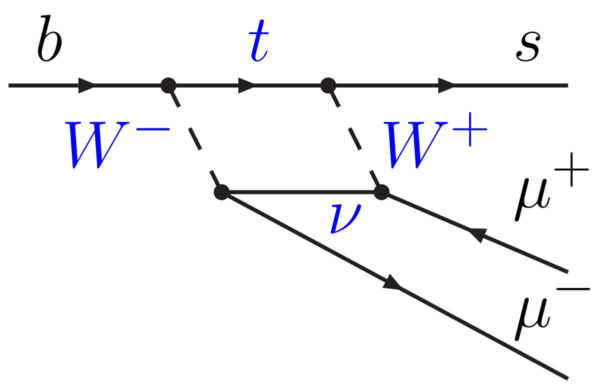
Deuteron production **(UE)**

Searches for (apparently) baryon number violating decays **(UE)**

Rare FCNC decays

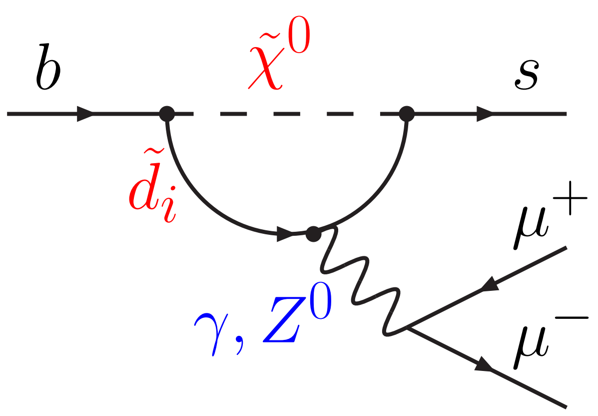
- Flavour changing neutral current transitions only occur at loop order (and beyond) in the SM.

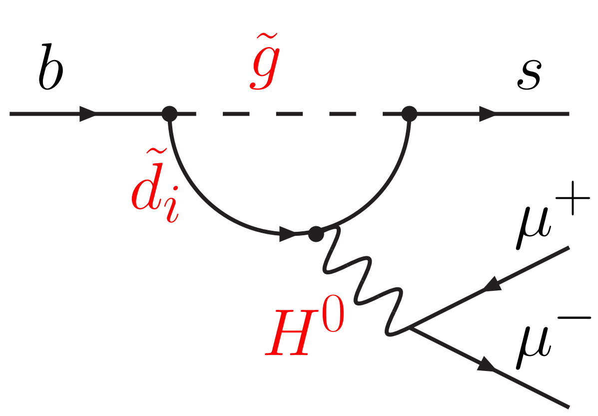


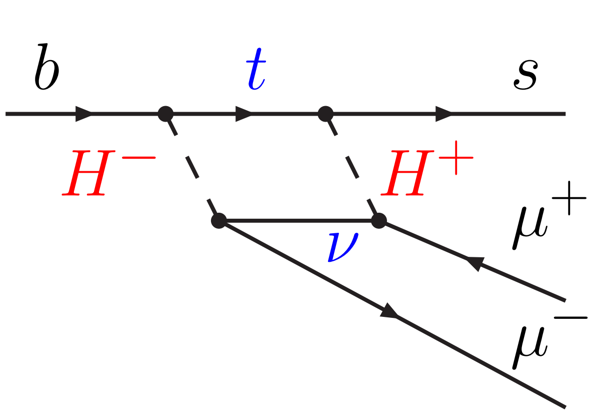


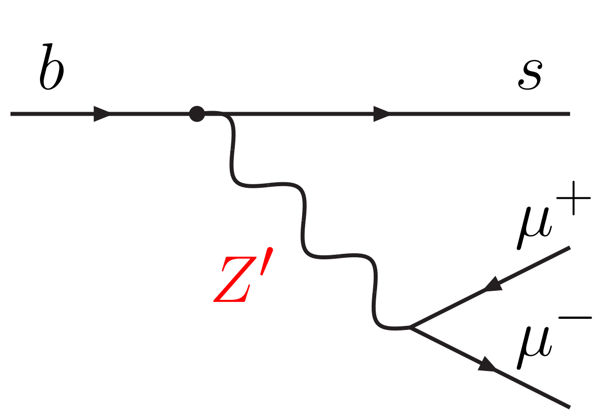
SM diagrams involve the charged current interaction.

- New particles can also contribute:





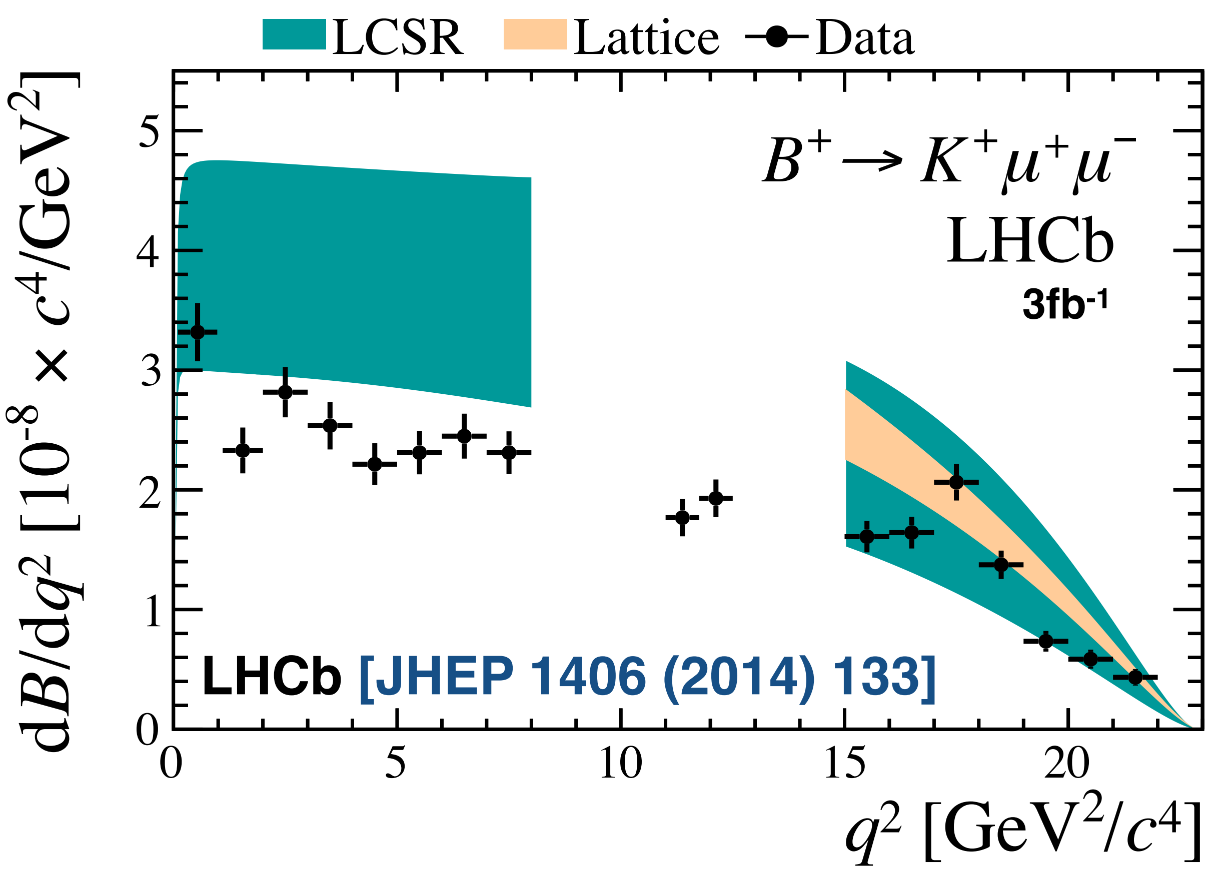


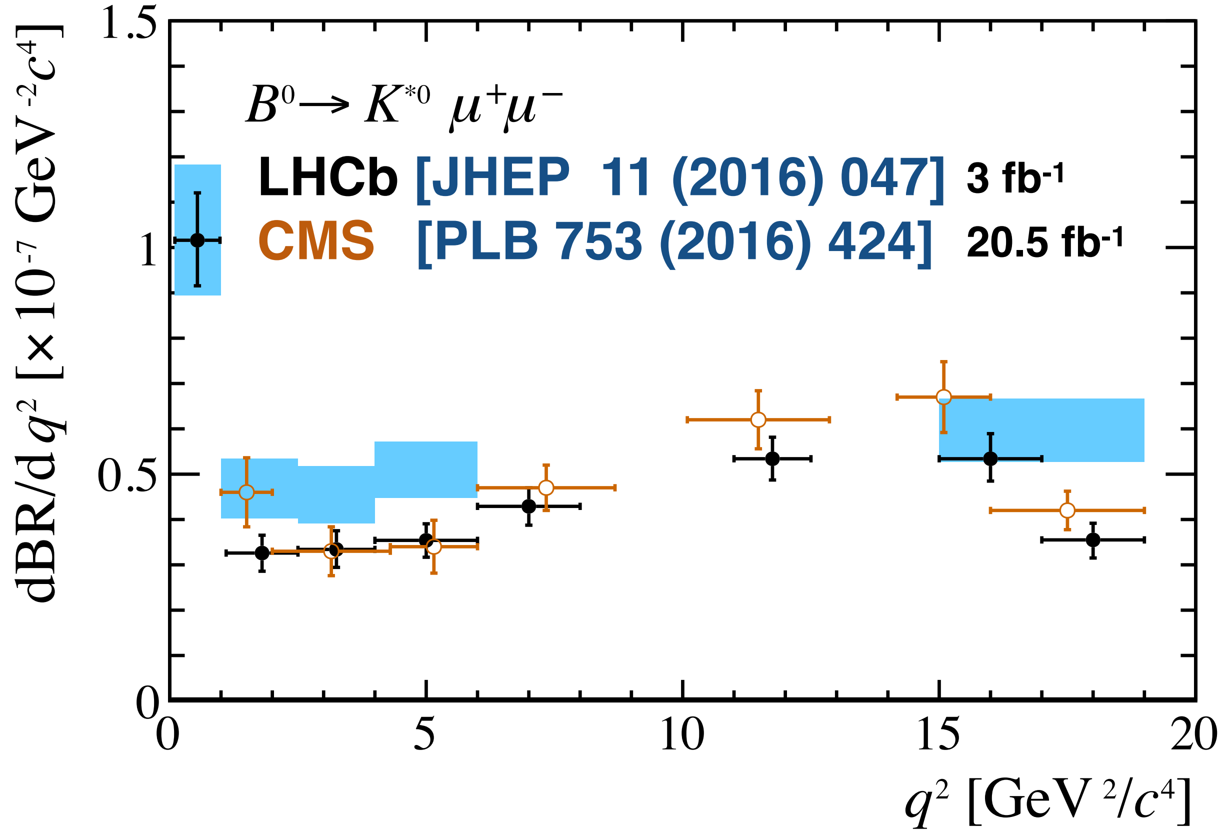


Enhancing/suppressing decay rates, introducing new sources of *CP* violation or modifying the angular distribution of the final-state particles.

Branching fraction measurements

- We already have precise measurements of branching fractions in the run1 datasets with at least comparable precision to SM expectations:



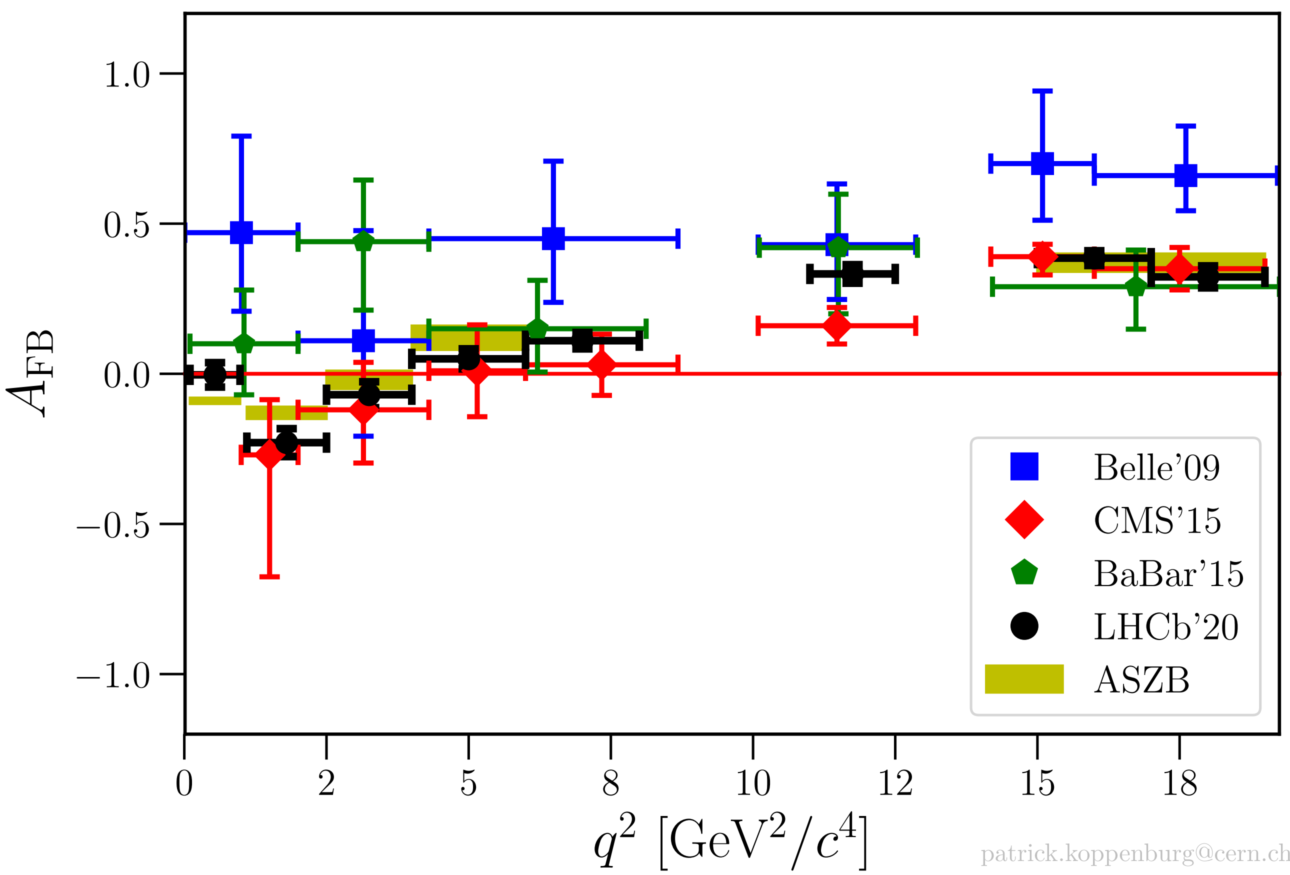


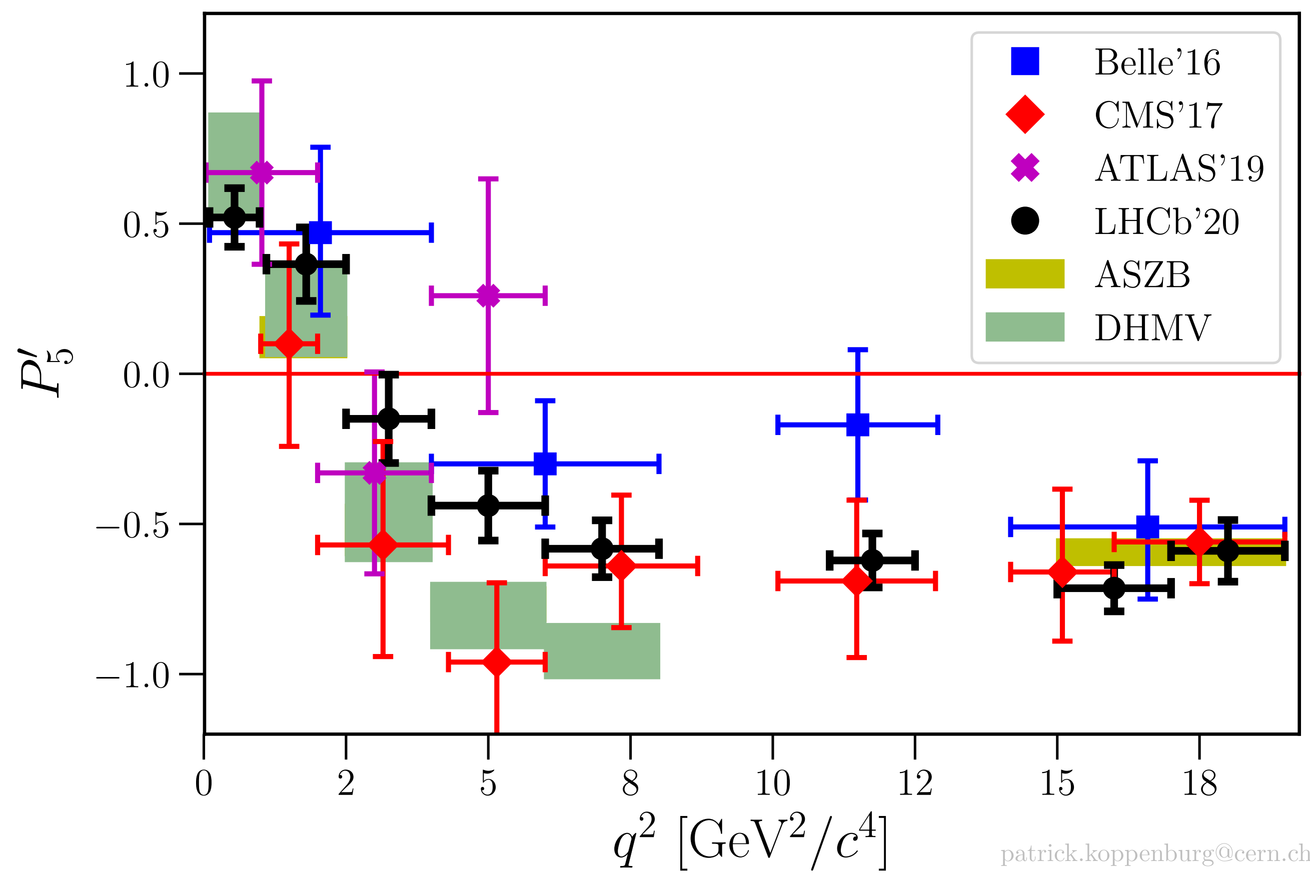
- SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B \to K$ and 7 for $B \to K^*$ decays).

- For details see **[Bobeth et al JHEP 01 (2012) 107], [Bouchard et al. PRL111 (2013) 162002], [Altmannshofer & Straub, EPJC (2015) 75 382]**.

Angular observables

- Get improved sensitivity by considering angular observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay.





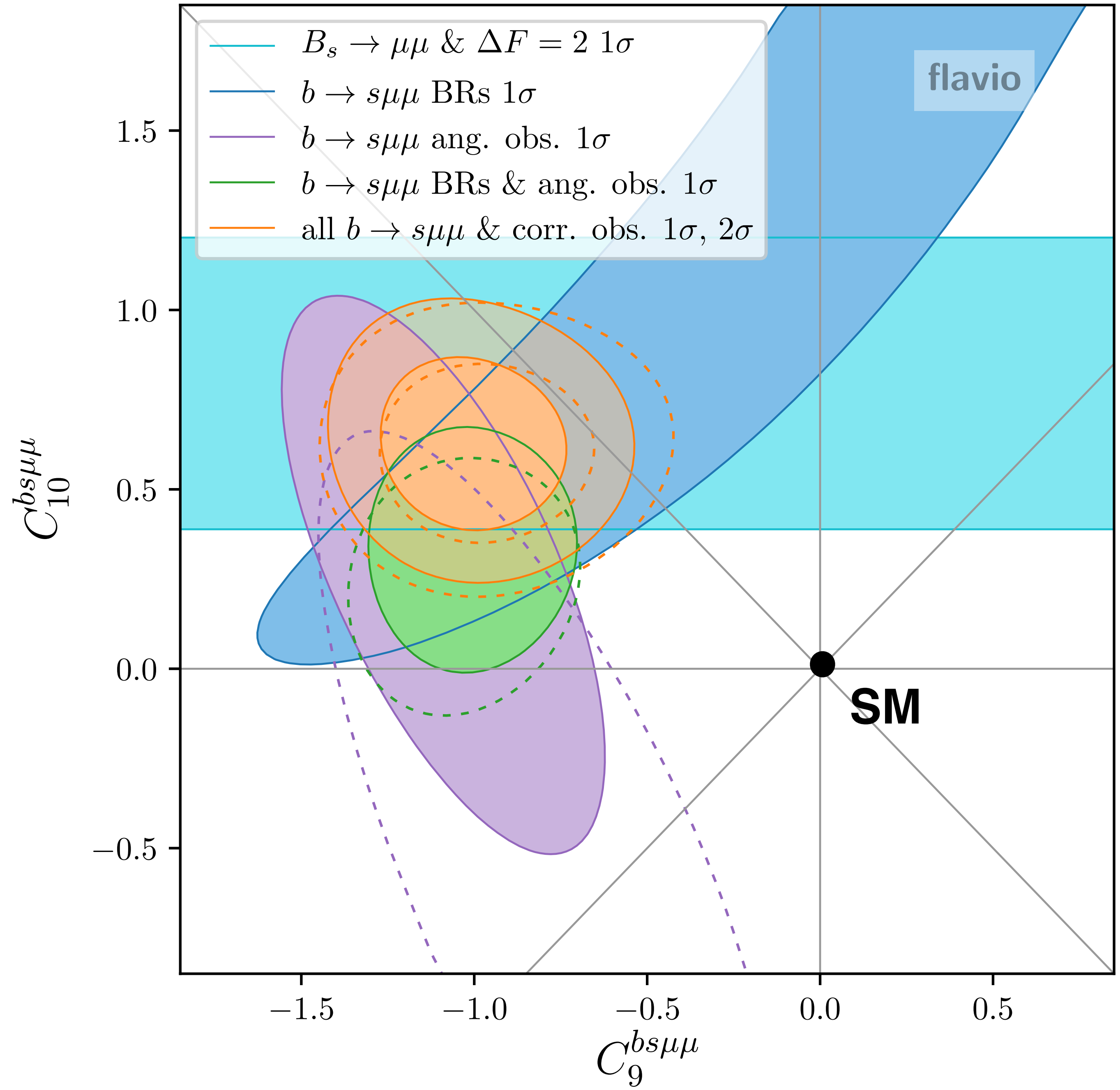
ASBZ [JHEP 08 (2016) 98], DHMV [JHEP 1204 (2012) 104], ATLAS [JHEP 10 (2018) 047], Belle [PRL 118 (2017) 111801], CMS [PLB 781 (2018) 517], LHCb [PRL 125 (2020) 011802]

- At low q^2, see some tension between the data and the SM predictions.

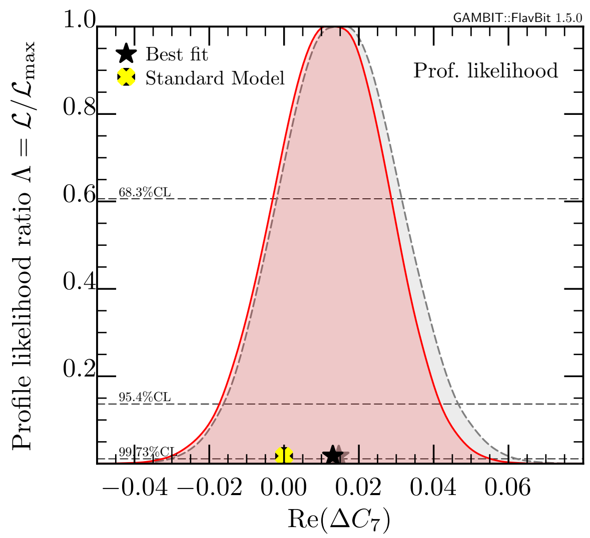
$b \to s\mu^+\mu^-$ interpretation

- Data favour either:
  - Modified C_9;
  - Modified C_9 and C_{10} (consistent with $\Delta C_9 = -\Delta C_{10}$).
- Dashed lines correspond to the previous Run 1 analysis.

From Talk by P. Stangl [https://conference.ippp.dur.ac.uk/event/876]

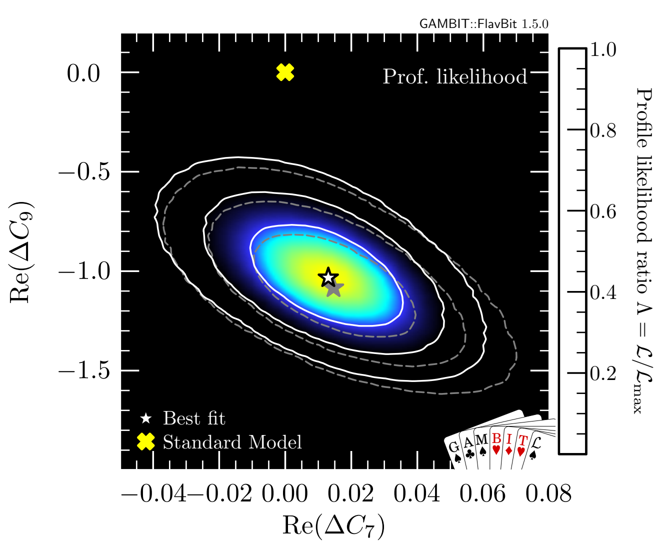


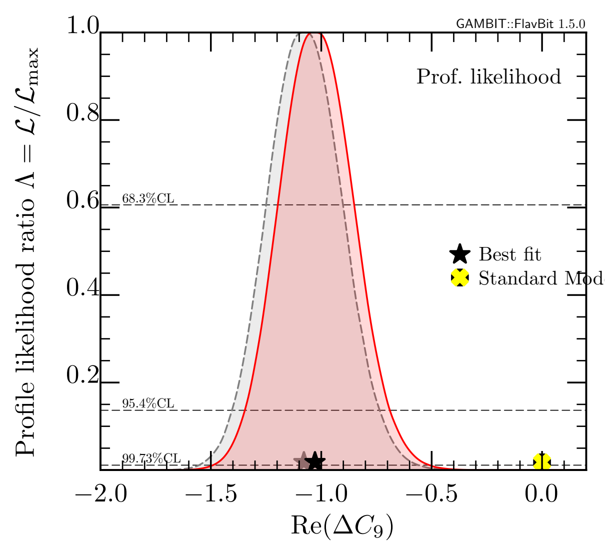
$b \to s\mu^+\mu^-$ interpretation

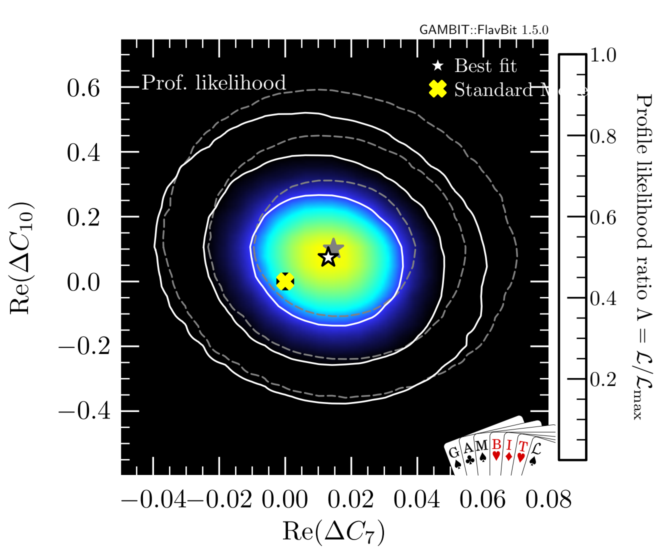


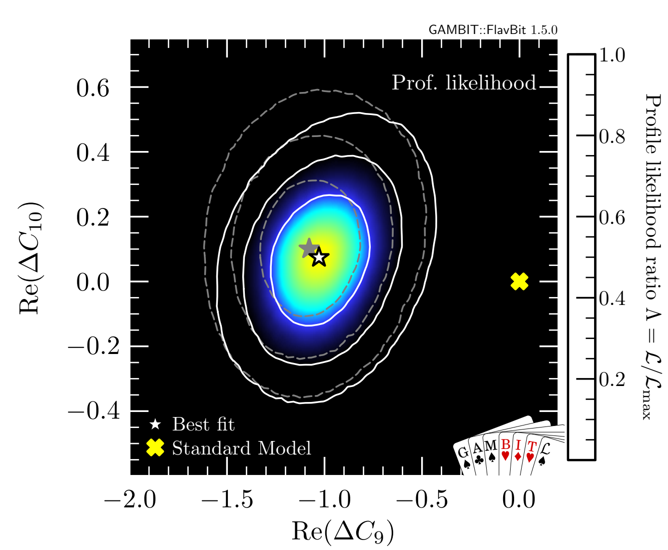
- A similar analysis has also been performed using GAMBIT in [arXiv:2006.03489]

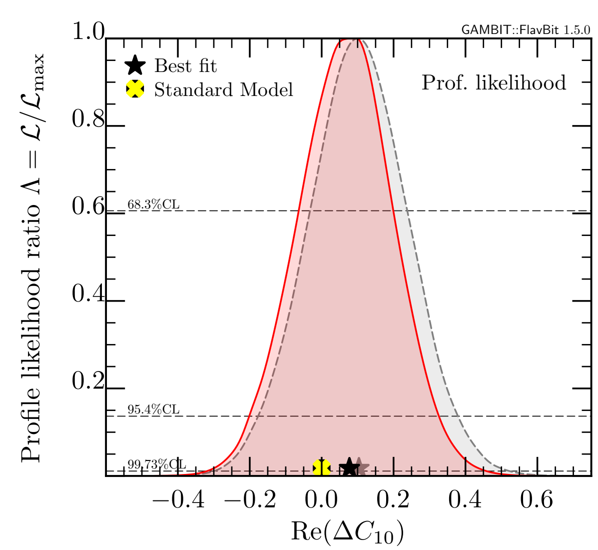
- Different behaviour in C_{10} due to differences in inputs/theory treatment.







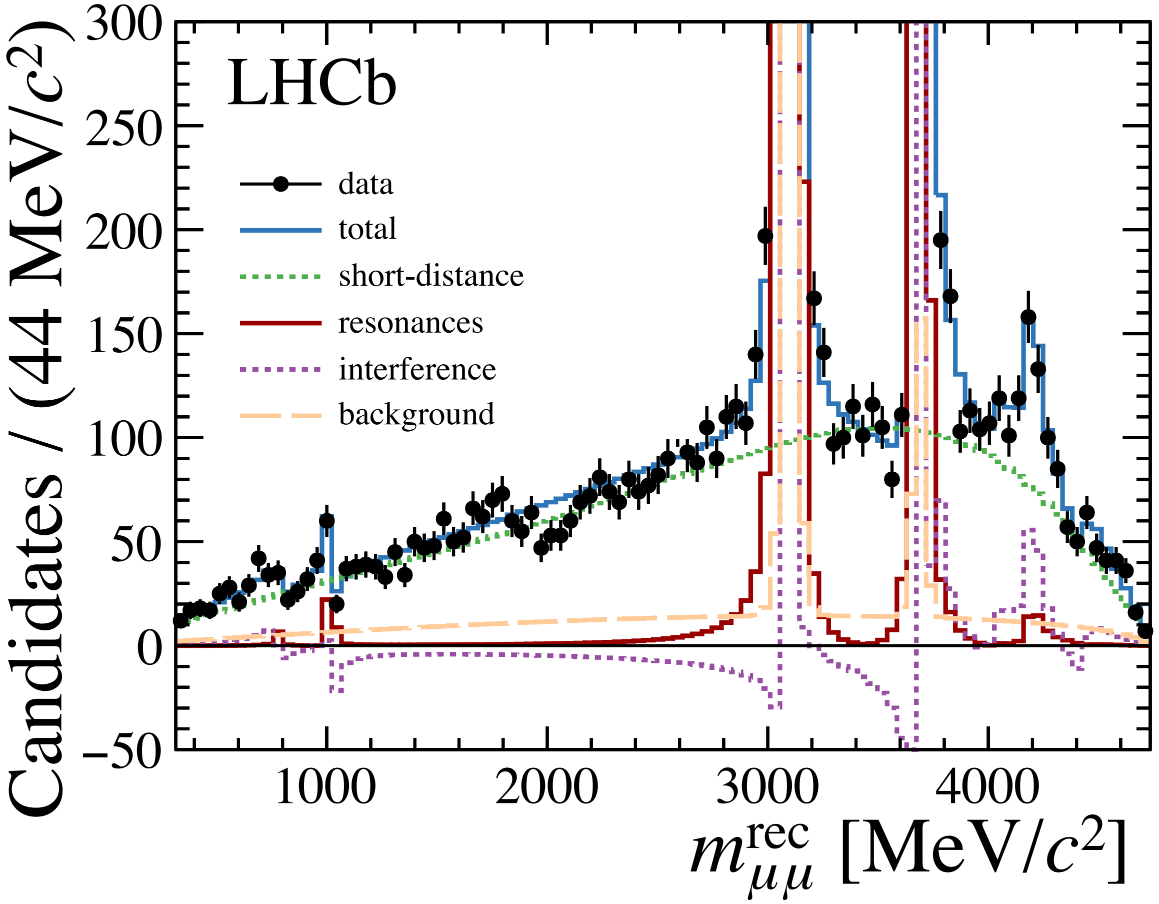




Extending the programme

- How well do we understand the SM predictions?
  - The spectrum in the data is complicated by resonance contributions.
  - Motivates using q^2-dependent models *e.g.* isobar models [EPJC 78 (2018) 6] or parametric expansions [arXiv:2011.09813].

LHCb [EPJC 77 (2017) 161]

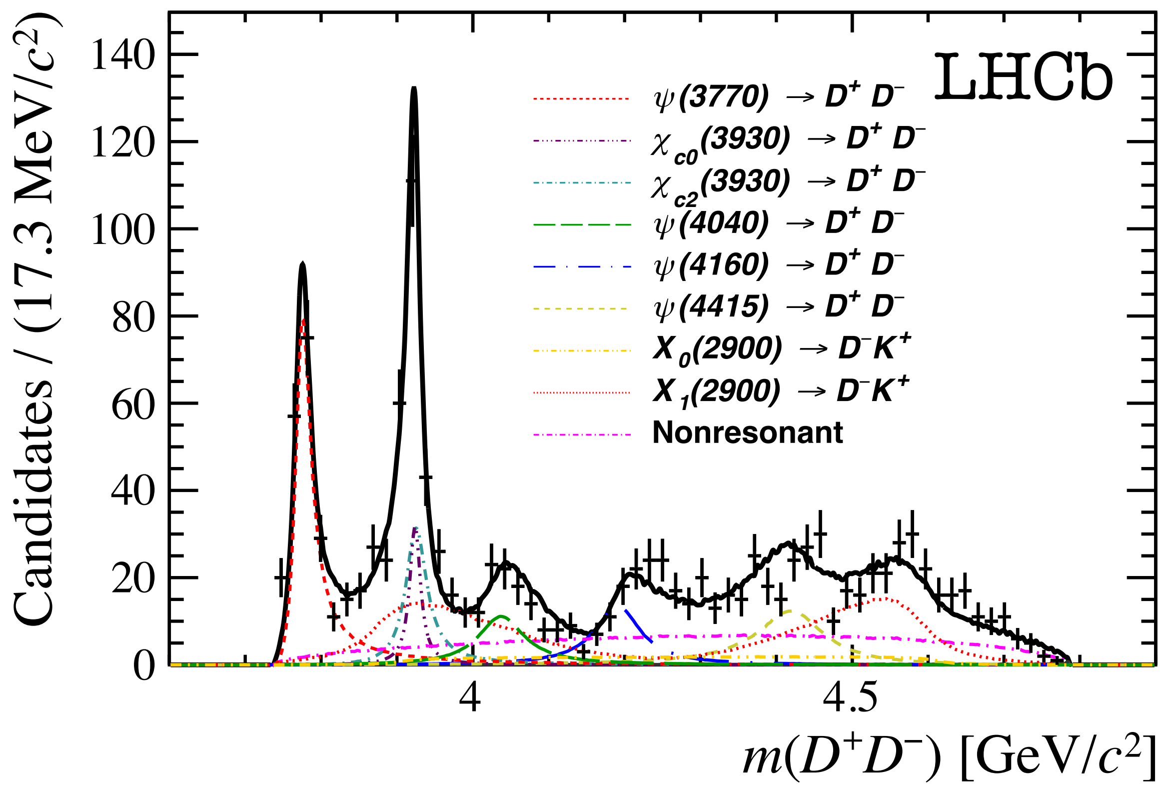


Extending the programme

- Are similar effects seen in $b \to d\mu^+\mu^-$ transitions?
  - Further suppressed by the small size of $|V_{td}|$ in the SM, could have increased sensitivity to BSM effects if the underlying theory doesn't have the same flavour structure as the SM.
  - Can get visible *CP* violating effects due to large weak phase differences (charmonium resonances and light-quark resonances provide sources of strong phase difference).
- Are similar effects seen in b-baryon transitions?

Hadronic B decays

- Extensive expertise in Warwick at carrying out so-called Dalitz plot analysis of decays with three pseudoscalars in the final state.
- Primary interest of the ongoing work is on studies of *CP* violation and hadron spectroscopy.
- We could also constrain charmonium contributions in rare b-hadron decays using information form hadronic $B \to D\bar{D}K$ decays.
- The $B^+ \to D^+D^-K^+$ analysis was carried out using `Laura++` with Warwick involvement.



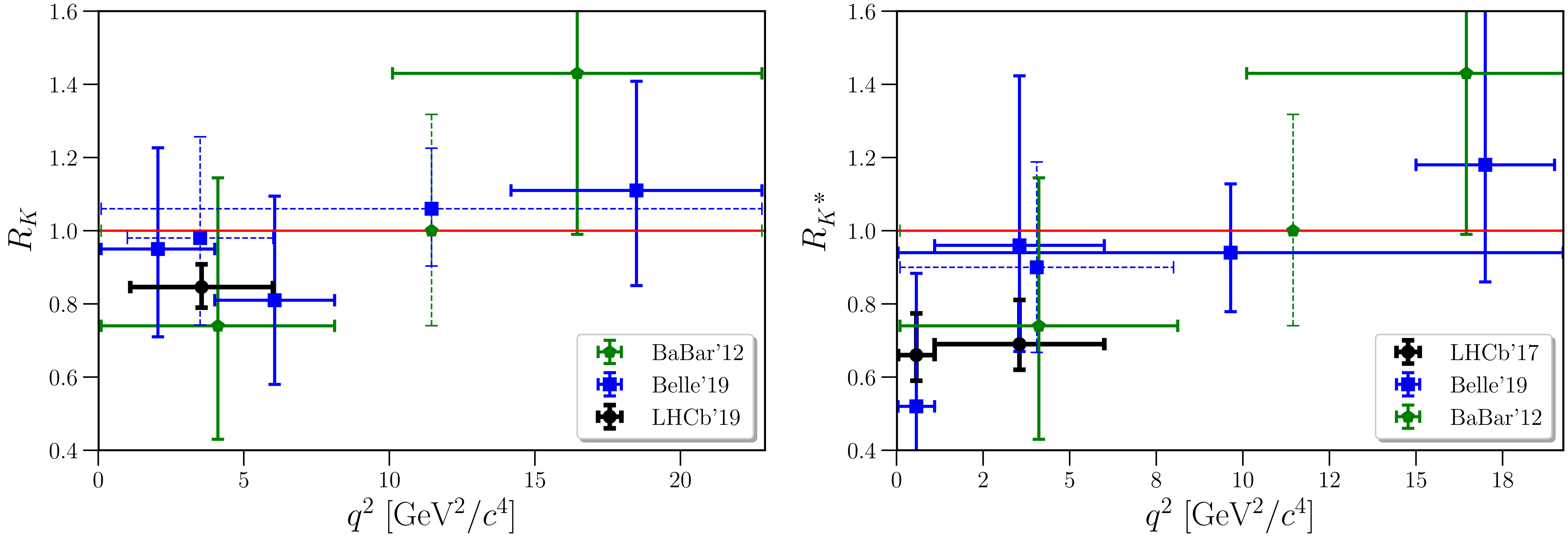
Charmonium states in $B^+ \to D^+D^-K^+$
[PRD102 (2020) 112003]

Hadronic *B* decays

- At Warwick we are also actively involved in measurements of:
  - γ using $B \to DK\pi$ decays.
  - β using $B \to D\pi\pi$ decays.
  - *CP* violation in 3-body b-hadron decays (*e.g.* in $B^+ \to \pi^+\pi^-\pi^+$ or $B \to K_S^0 h^+ h^-$ decays).
  - β_s in $B_s^0 \to K^{*0}\bar{K}^{*0}$ decays.

Lepton Universality Tests

- Theoretical uncertainties cancel ratios of decay rates between decays with dimuon and dielectron final-states:

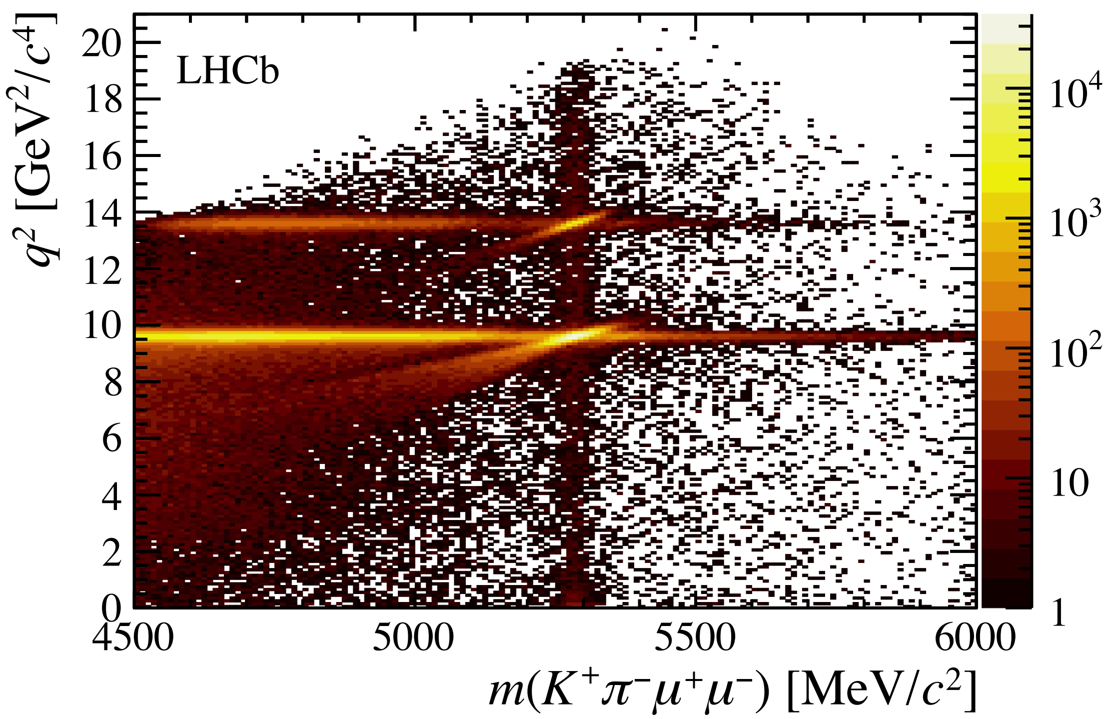


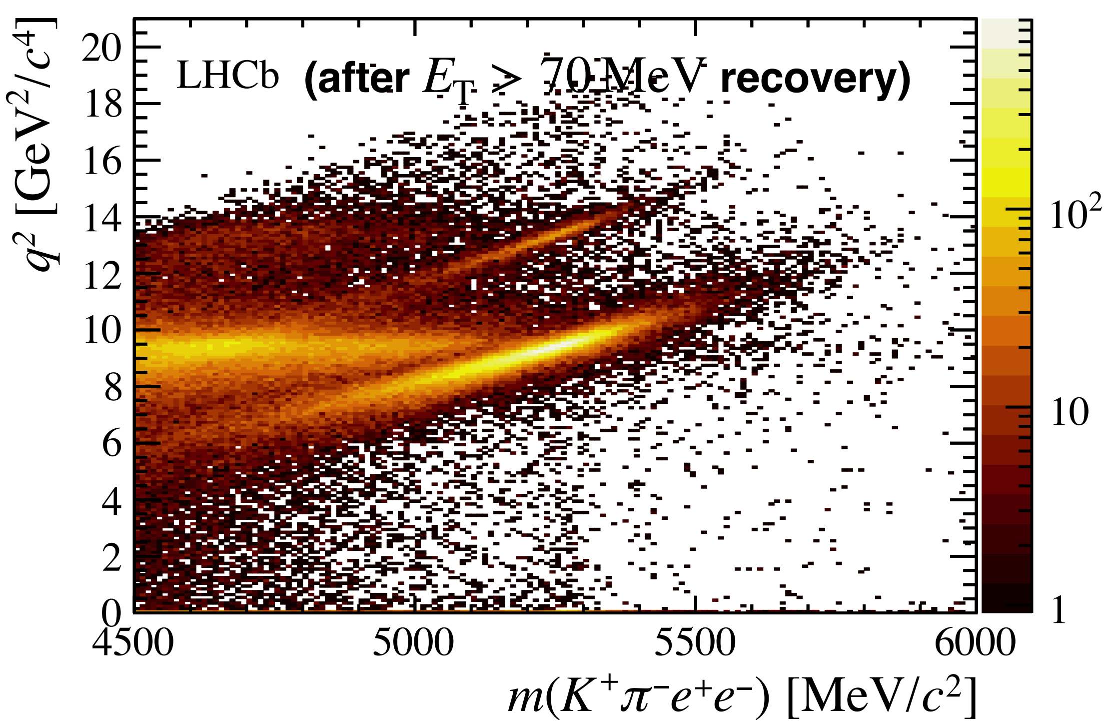
LHCb [PRL 122 (2019) 191801], [JHEP 08 (2017) 055],
BaBar [PRD 93 (2016) 052015], Belle [arXiv:1908.01848].

- LHCb data are approximately 2.5σ from SM expectations at low q^2

Lepton Universality Tests

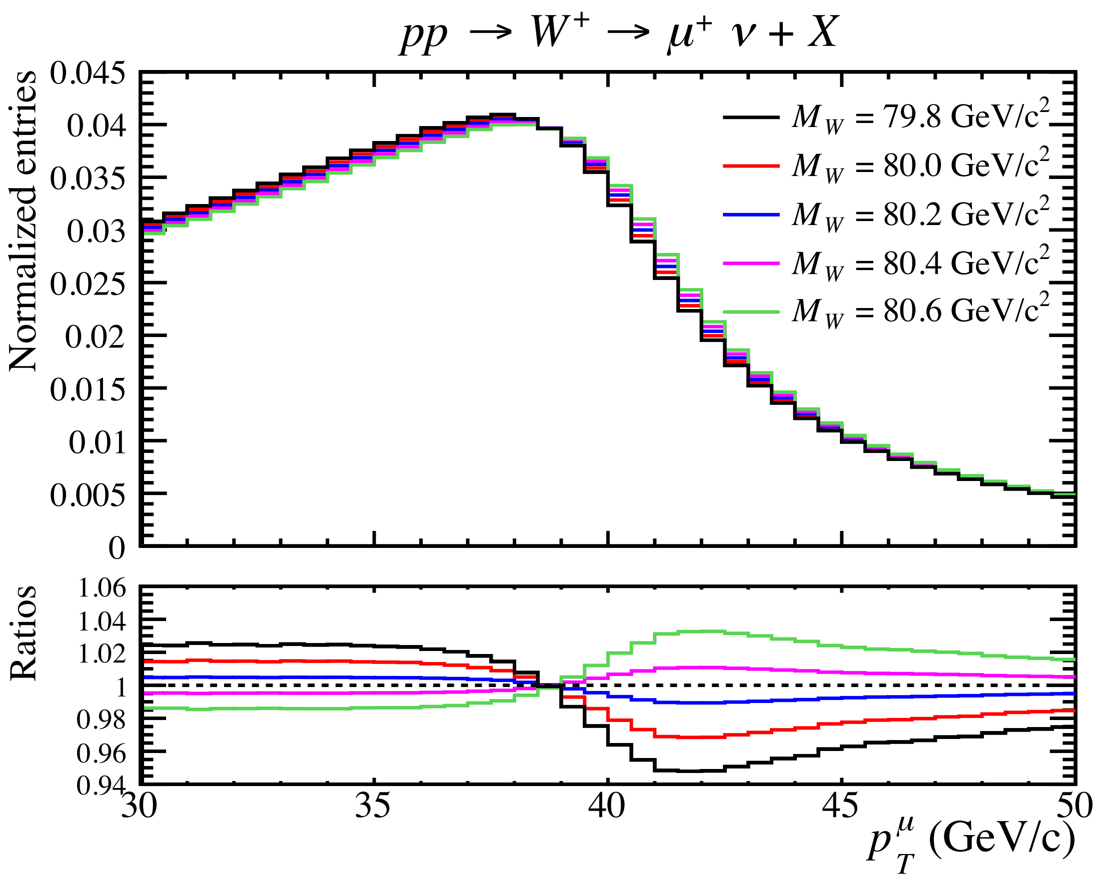
- Theoretically clean but experimentally challenging due to FSR and Bremsstrahlung from the electrons.
  - Need to unfold the measured distribution to compare rates in a region of q^2.
  - Rely on **GEANT4** to describe Bremsstrahlung due to detector material.
  - Rely on **PHOTOS** to describe QED emission.
- We are involved at Warwick in efforts to measure R_ϕ in $B_s^0 \to \phi \ell^+ \ell^-$ decays.





Electroweak precision tests

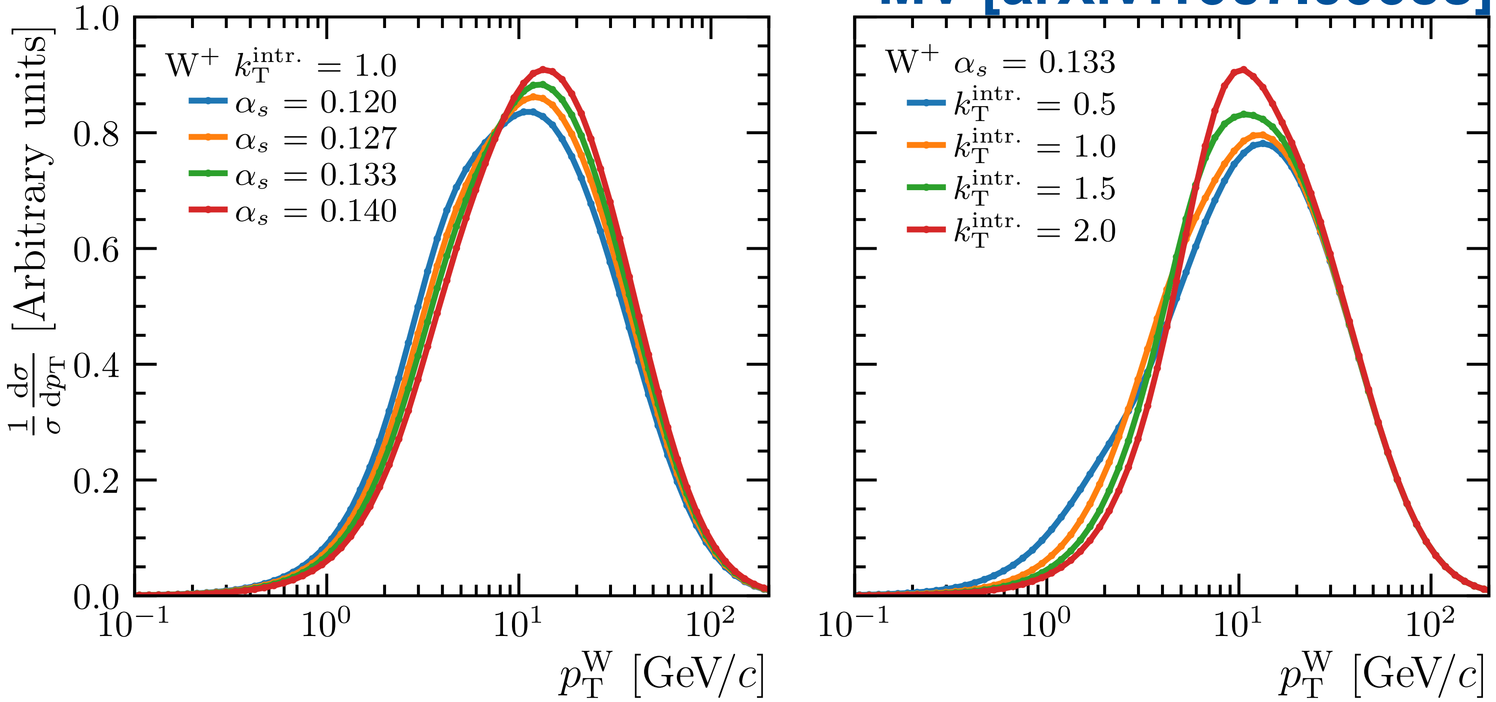
- Ongoing effort measure m_W, from the p_T spectrum of $\mu^\pm$ from $W^\pm$.
- Targeting an experimental precision of $\mathcal{O}(10\,\mathrm{MeV}/c^2)$.
- Profit from unique coverage of the LHCb detector and correlations between PDF sets in different pseudorapidity ranges to get an improved measurement of m_W [EPJ C75 (2015) 601].



Electroweak precision tests

- Use fixed-order QCD calculations to describe rapidity and angular distribution of the $W^{\pm}$ bosons.
- Non-perturbative effects are important — rely on parton showering.
- The p_{T} spectrum is sensitive to PYTHIA parameters.
- ATLAS tune the parameters based on the p_{T} spectrum of Z bosons **[EPJC 78 (2018) 110]**.

MV [arXiv:1907.09958]



- Also sensitive to effects from FSR (QED) radiation, currently modelled using PHOTOS.

Deuteron production

- Measure deuteron production rates in pp, heavy ion, p-ion and fixed target collisions.
  - Use PID capability of the RICH detectors to separate deuterons from other charged particle species.
- This could have an interesting overlap with work at Warwick on the TORCH detector, a proposed time-of-flight detector for a future upgrade of LHCb.

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Effective theory

- Can write a Hamiltonian for an effective theory of *b*→*s* processes:

Wilson coefficient
(integrating out scales above *μ*)

Local 4 fermion operators with
different Lorentz structures

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu),$$

$$\Delta\mathcal{H}_{\text{eff}} = \frac{\kappa_{\text{NP}}}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

NP scale

NP can modify
SM contribution
or introduce
new operators

κ_{NP} can have all/some/none of the suppression of the SM, e.g MFV inherits SM CKM suppression.

c.f. Fermi theory of weak interaction where at low energies:

$$\lim_{q^2 \to 0} \left(\frac{g^2}{m_W^2 - q^2} \right) = \frac{g^2}{m_W^2}$$

i.e. the full theory can be replaced by a 4-fermion operator and a coupling constant, G_F.

Operators

- Different processes are sensitive to different 4-fermion operators.
  - ➡ Can exploit this to over-constrain the system.

$$\mathcal{O}_7 = (m_b/e)\,(\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu})$$
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\ell}\ell)$$
$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

- $\mathcal{O}_7$: photon (constrained by radiative decays and $b \to s\ell^+\ell^-$ processes at small q^2)
- $\mathcal{O}_9$: vector current (constrained by $b \to s\ell^+\ell^-$ processes)
- $\mathcal{O}_{10}$: axial vector current (constrained by leptonic decays and $b \to s\ell^+\ell^-$ processes)
- $\mathcal{O}_S$, $\mathcal{O}_P$: scalar and pseudoscalar operators (constrained primarily by leptonic decays)

Can also have right-handed counterparts of the operators whose contribution is small in the SM.