$b \to s\ell\ell$ exclusive decays

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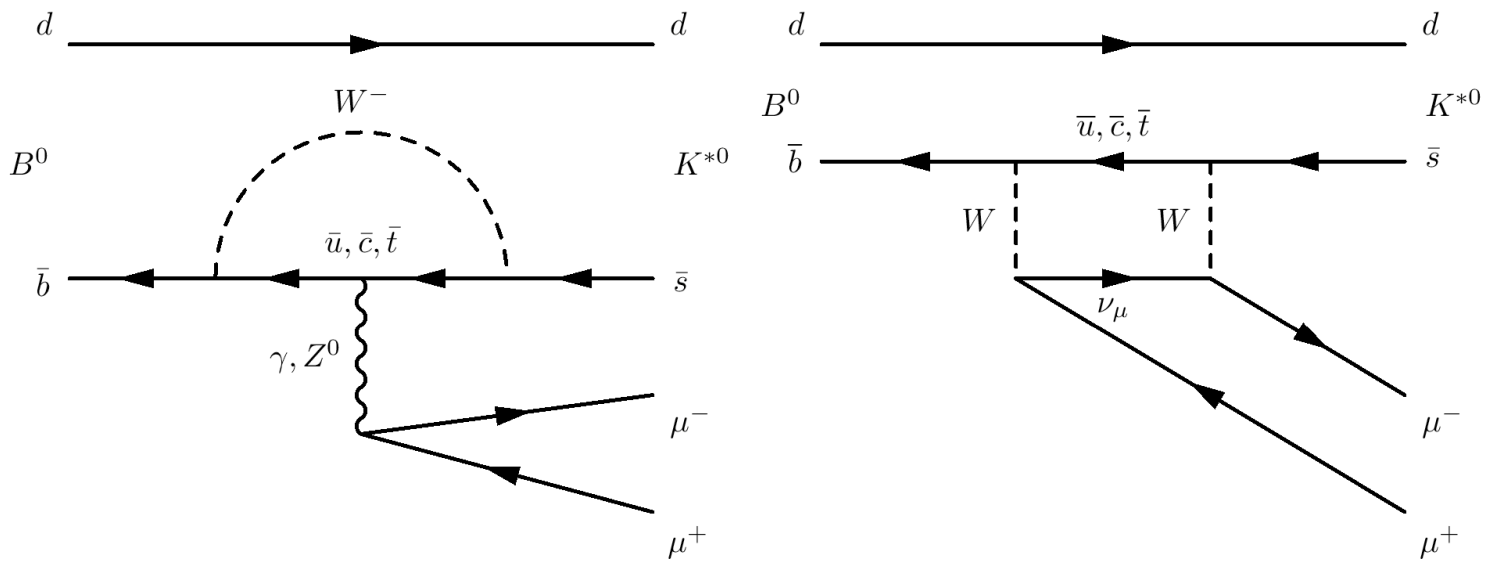
Electroweak penguin decays

- $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ proceed dominantly through penguin and box diagrams.



- Integrate out short distance dynamics $\to$ Wilson Coefficients:
  - $\mathcal{C}_7$ electromagnetic
  - $\mathcal{C}_9$ semi-leptonic vector
  - $\mathcal{C}_{10}$ semi-leptonic axial vector
- Observables depend on four-momentum transferred to dimuon, q^2.

Overview of measurements

- Angular analyses:
  - $B \to K \mu^+ \mu^-$: [arXiv:1403.8045]
  - $B^0 \to K^{*0} \mu^+ \mu^-$: [arXiv:1304.6325], [arXiv:1308.1707]
- Rate analyses:
  - $B^0 \to K^{*0} \mu^+ \mu^-$, [arXiv:1304.8045]
  - $B^+ \to K^{*+} \mu^+ \mu^-$, $B^+ \to K^+ \mu^+ \mu^-$, $B^0 \to K^0 \mu^+ \mu^-$: [arXiv:1403.8044]
  - $B \to K^{(*)} \mu^+ \mu^-$ isospin asymmetry [arXiv:1403.8044]
- CMS [arXiv:1308.3409], ATLAS [ATLAS-CONF-2013-038], BaBar [arXiv:1204.3933], Belle [arXiv:0904.0770] and CDF [arXiv:1108.0695] also made measurements.
  - Concentrate on most precise results today (LHCb).

$B \to K\mu^+\mu^-$ angular analysis - [arXiv:1403.8045]

The $B^+ \to K^+\mu^+\mu^-$ angular distribution can be written as

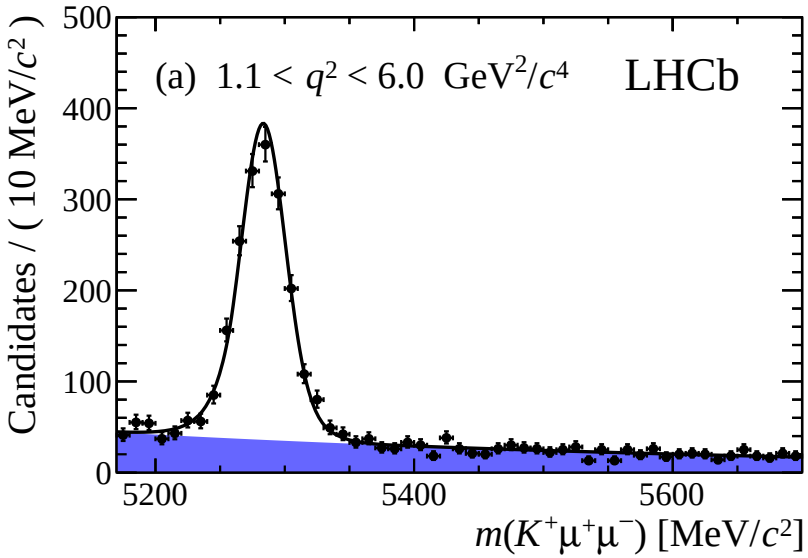
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1 - F_{\mathrm{H}})(1 - \cos^2\theta_l) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_l \quad ,$$

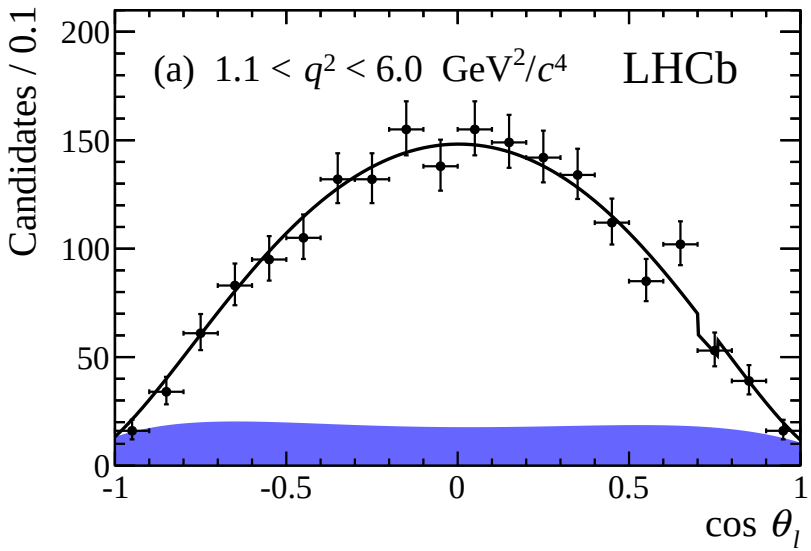
where A_{FB} is the forward-backward asymmetry and F_H is the "flat parameter".

- So far, $B_s^0 \to \mu^+\mu^-$ SM like.
  - Depends on (pseudo-)scalar Wilson coefficients $\mathcal{C}_s^{(\prime)}$ and $\mathcal{C}_p^{(\prime)}$
  - Rate proportional to $\mathcal{C}_s$-$\mathcal{C}'_s$ and $\mathcal{C}_p$-$\mathcal{C}'_p$
- Angular observables proportional to $\mathcal{C}_s$+$\mathcal{C}'_s$ and $\mathcal{C}_p$+$\mathcal{C}'_p$
- Also, clean place to look for tensor contributions.

$B \to K\mu^+\mu^-$ angular analysis - [arXiv:1403.8045]

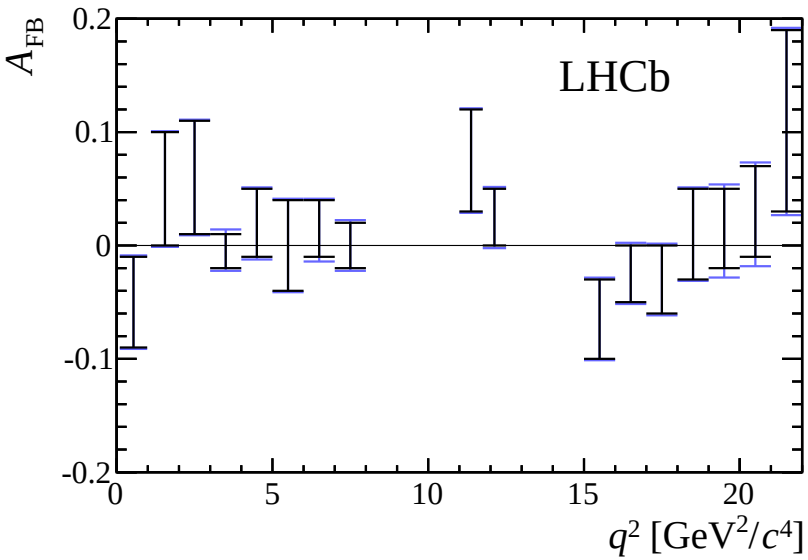
- Fit mass and angles to determine A_{FB} and F_H.
- Use 3 fb^{-1} of data.

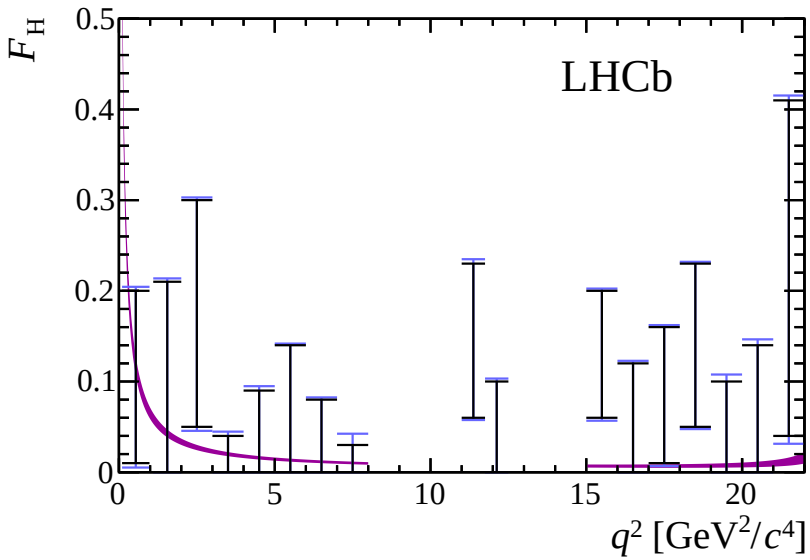




- Angular parameterisation of background biggest systematic.

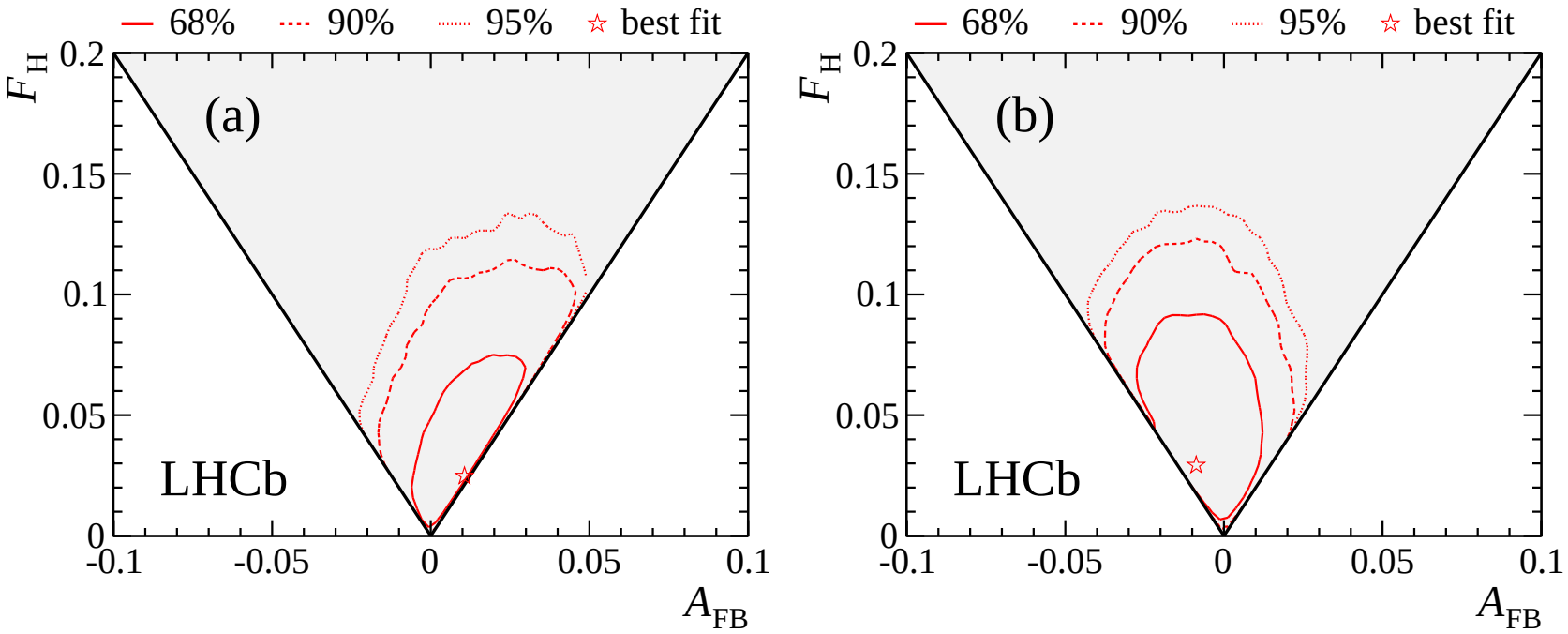
$B^+ \to K^+\mu^+\mu^-$ 1D results - [arXiv:1403.8045]





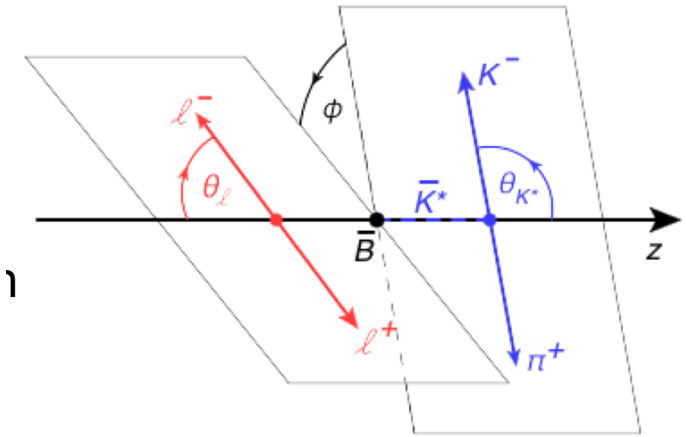
- Theory based on [arXiv:1111.2558], no predictions near charmonium resonances.
- 68% uncertainties obtained using Feldman-Cousins with plug-in method.
- No evidence for scalar or tensor couplings.

$B^+ \to K^+\mu^+\mu^-$ 2D results - [arXiv:1403.8045]



- 1D results with plugin method not guaranteed to cover due to unphysical region.
- 2D confidence regions provided for $B^+ \to K^+\mu^+\mu^-$.
- Data points available on preprint.

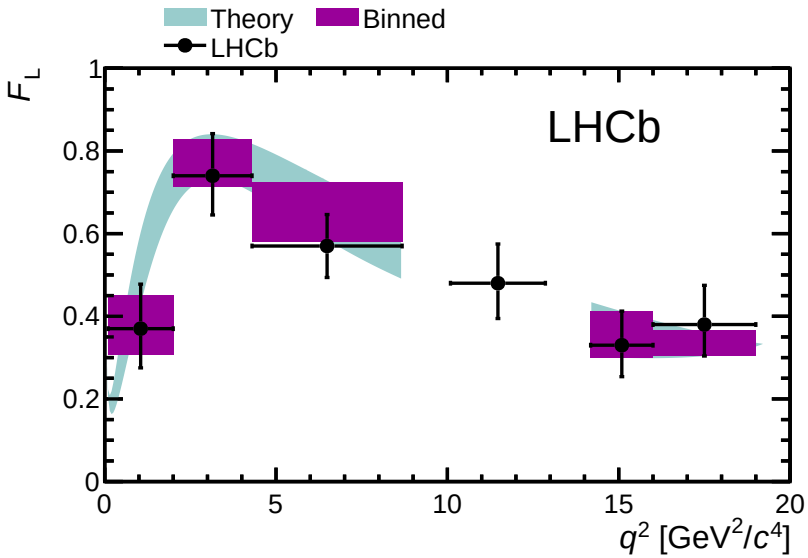
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

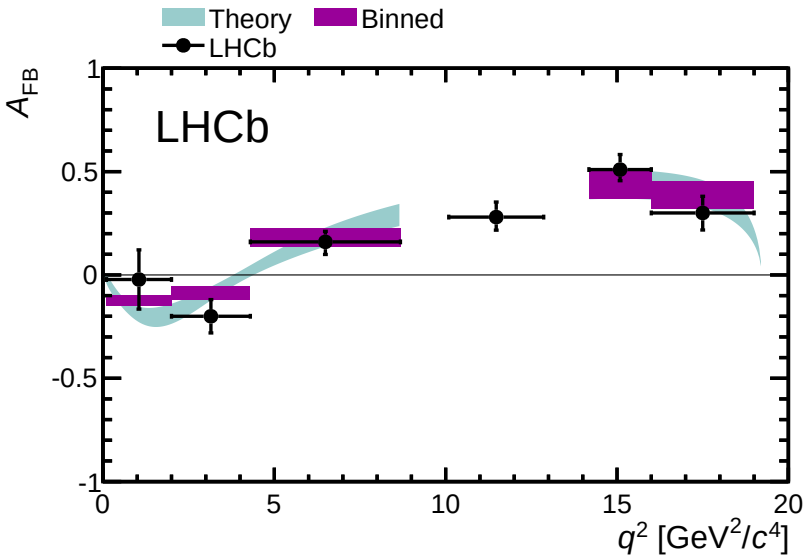


- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ allows separation between $\mathcal{C}_7$, $\mathcal{C}_9$ and $\mathcal{C}_{10}$.

- More degrees of freedom compared to $B \to K\mu^+\mu^-$, analysis complicated:
  - Three angles, θ_l, θ_k and ϕ.
  - If $m_\ell = 0$ and narrow width approximation, have 16 observables.

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

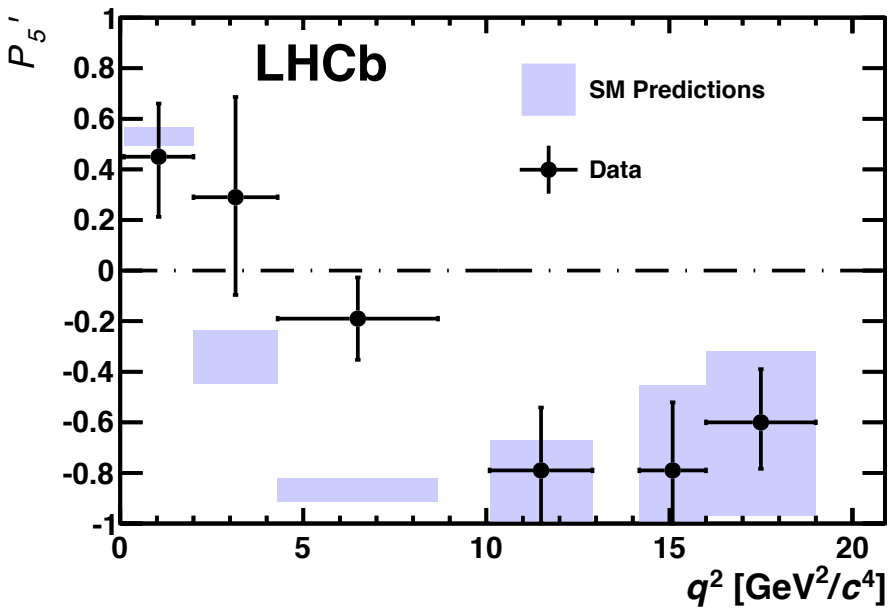




- Theory based on [arXiv:1105.0376].
- Most precise results found at [arXiv:1304.8045] ($1\,\text{fb}^{-1}$), no deviations from SM predictions.

$B^0 \to K^{*0}\mu^+\mu^-$ angular results [arXiv:1308.1707]

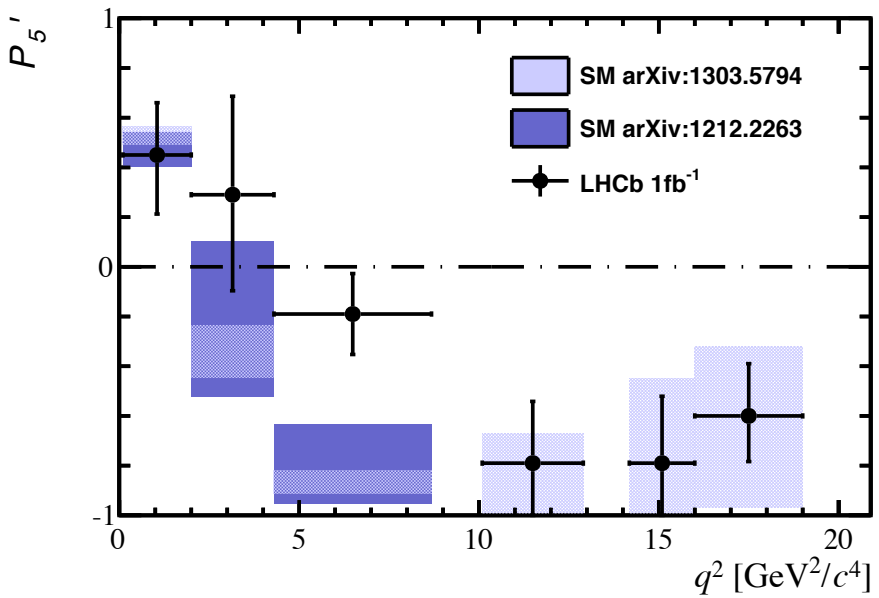
- Last summer, publish several "optimised" observables [arXiv:1202.4266] with $1\,\text{fb}^{-1}$.
- Designed to reduced form factor uncertainties.



- Large local deviation found in one bin of the observable P_5'.

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

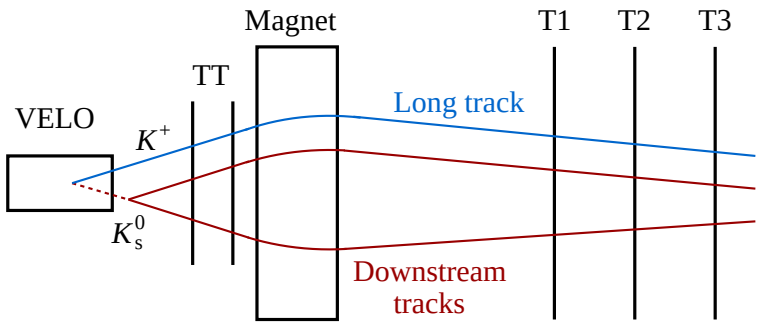
- Global fits to data suggest reduced value of C_9 (e.g. [arXiv:1307.5683],[arXiv:1308.1501] and [arXiv:1310.2478]).



- Theoretical uncertainty of observables a hot topic.
- Need sophisticated treatment of statistical uncertainties for global fit.
  - Measurements correlated.
  - Uncertainties not Gaussian.

Branching fractions [arXiv:1403.8044]

- Using $3\,\text{fb}^{-1}$, measure branching fractions of:
  - $B^+ \to K^+\mu^+\mu^-$
  - $B^0 \to (K^0_S \to \pi^+\pi^-)\mu^+\mu^-$
  - $B^+ \to (K^{*+} \to K^0_S\pi^+)\mu^+\mu^-$



- Split data into categories depending on whether the K^0_S daughters leave enough hits in the vertex detector (long (L) and down (D)).
- $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ branching fractions also shown use only $1\,\text{fb}^{-1}$ and different normalisation procedure.

Normalisation [arXiv:1403.8044]

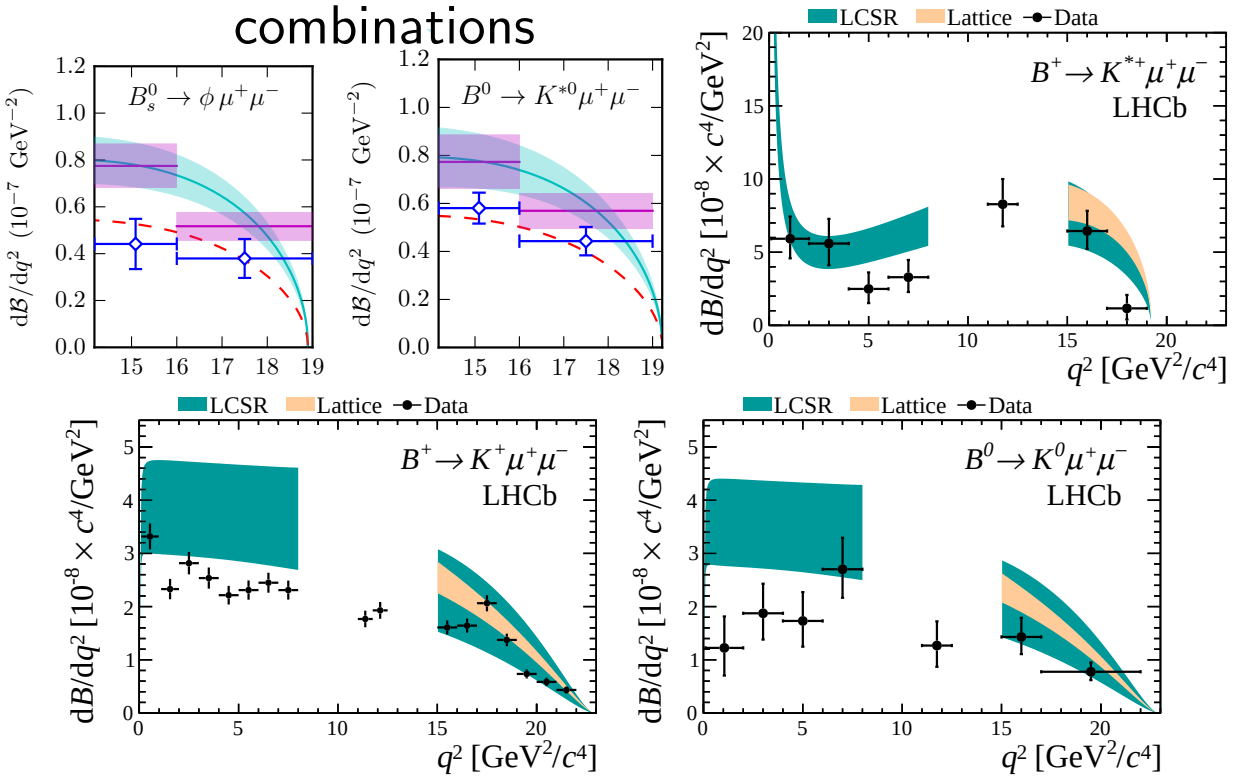
- Crucial issue is normalisation to $B \to J/\psi K^{(*)}$ decays.
- Previous measurements of $\mathcal{B}(B \to J/\psi K^{(*)})$ assume equal production of B^+ and B^0 at $\Upsilon(4S)$.
- Instead assume $B \to J/\psi K^{(*)}$ isospin asymmetry zero ($\sim$6% effect) [arXiv:0412062].

$$\mathcal{B}(B^+ \to J/\psi K^+) = (0.998 \pm 0.014 \pm 0.040) \times 10^{-3},$$
$$\mathcal{B}(B^0 \to J/\psi K^0) = (0.928 \pm 0.013 \pm 0.037) \times 10^{-3},$$
$$\mathcal{B}(B^+ \to J/\psi K^{*+}) = (1.431 \pm 0.027 \pm 0.090) \times 10^{-3},$$
$$\mathcal{B}(B^0 \to J/\psi K^{*0}) = (1.331 \pm 0.025 \pm 0.084) \times 10^{-3},$$

- Systematic uncertainties between isospin partners assumed to be 100% correlated.

Branching fraction results

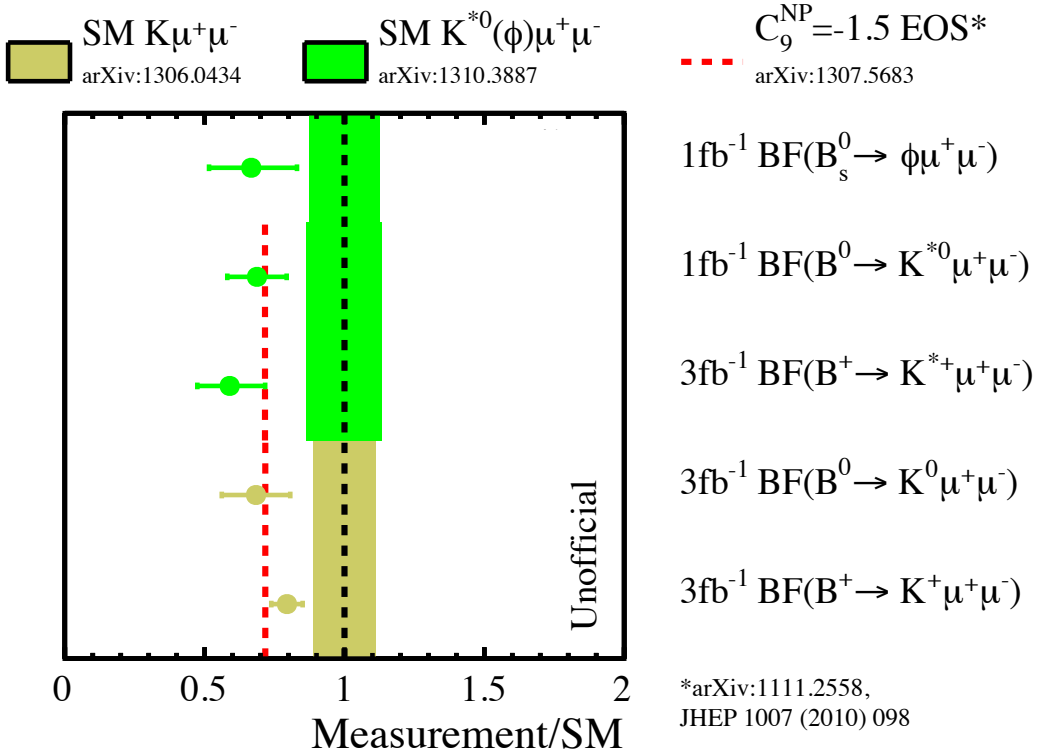
- $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$ results combinations, other LHCb results from [arXiv:1403.8044].



- Theory: [arXiv:1111.2558], [arXiv:1105.0376].
- Lattice QCD: [arXiv:1310.3207] ($B \to K\mu^+\mu^-$) and [arXiv:1310.3887] ($B \to K^*\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$).

Branching fraction summary

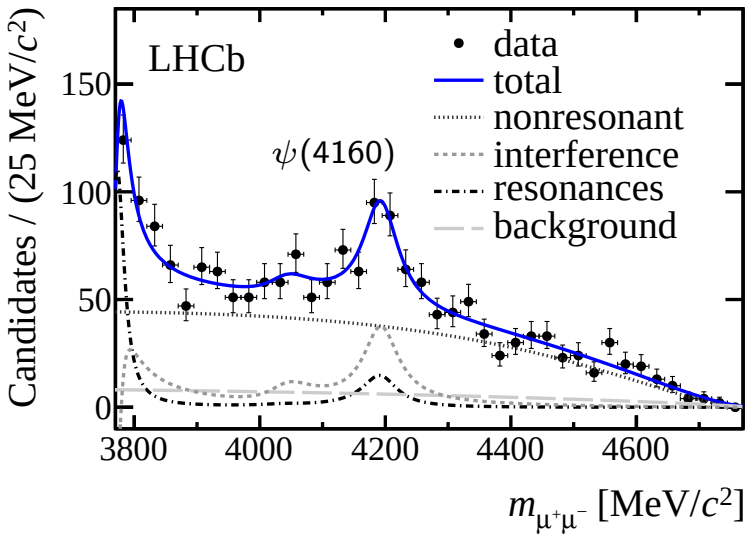
- All five measurements below theoretical predictions at high q^2.
- Tends to favour small $\mathcal{C}_9$ like angular results.
- Conclusion not dependent on $B \to J/\psi\, K^{(*)}$ assumption.



- Could be explained with a Z' particle [arXiv:1310.1082].
- However ..

Cold water

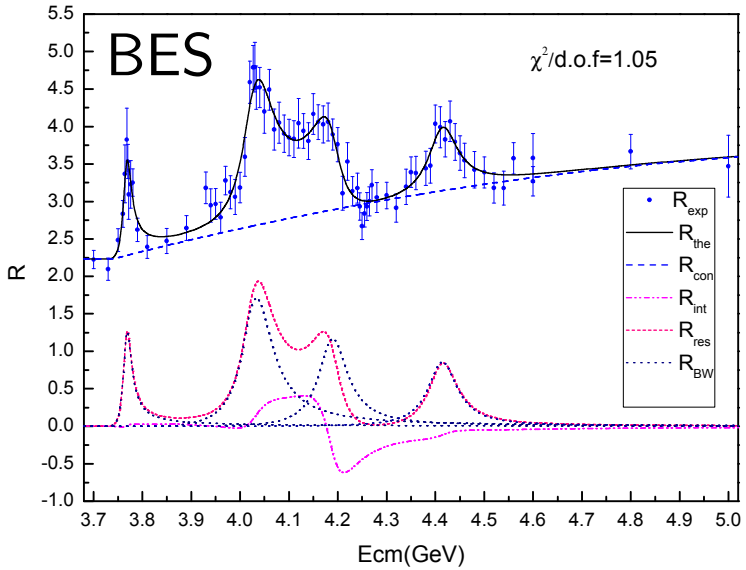
- Lattice predictions for $B \to K\mu^+\mu^-$ missing two-loop virtual corrections to effective part of $\mathcal{C}_9$.
- Taking this correction into account reduces the tension with SM.
- Large contribution from $\psi(4160)$ as well [arXiv:1307.7595].

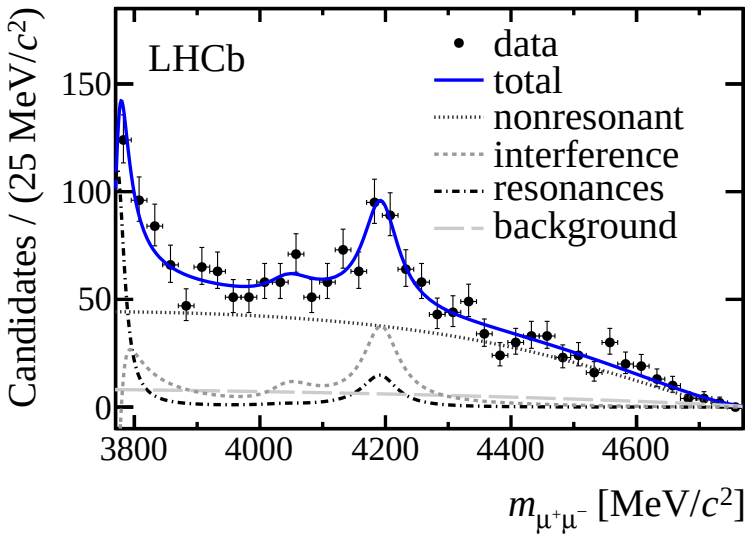


- $\sim$ 20% of the rate composed of resonance + interference.

Cold water

- Can we predict this theoretically?
  - In principle yes, they are dealt with an additional OPE at low recoil.
  - Assumes "quark-hadron duality" $\rightarrow$ smooth predictions.
  - Valid if integrated over a large q^2 region.
  - Also assumes QCDF - resonance structure should be the same in $e^+e^- \rightarrow$hadrons.
  - Clearly not the case!



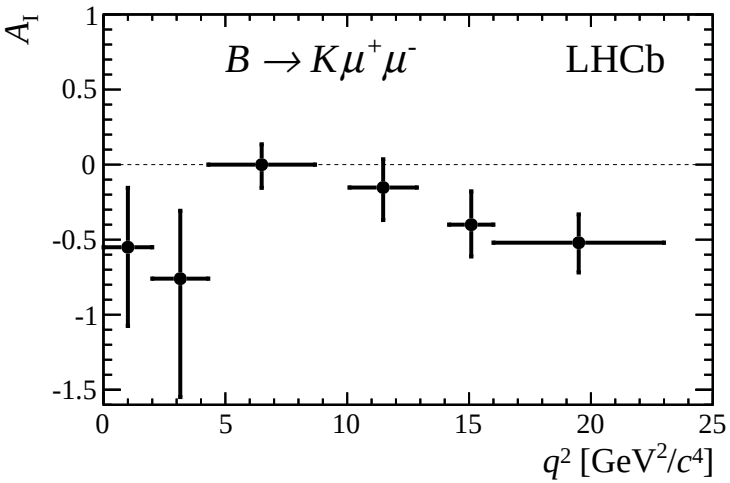


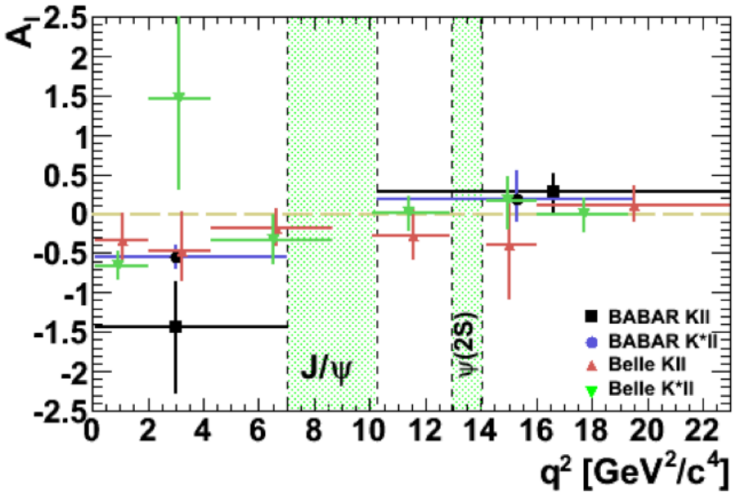
Isospin asymmetry of $B \to K^* \mu^+ \mu^-$

- Asymmetry in charged and neutral $B \to K^{(*)} \mu^+ \mu^-$ decays, defined as:

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0} \mu^+ \mu^-) - \frac{\tau_0}{\tau_+} \mathcal{B}(B^\pm \to K^{(*)\pm} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{(*)0} \mu^+ \mu^-) + \frac{\tau_0}{\tau_+} \mathcal{B}(B^\pm \to K^{(*)\pm} \mu^+ \mu^-)}$$

- A_I is predicted to be close to zero in the SM for both $B \to K \mu^+ \mu^-$ and $B \to K^* \mu^+ \mu^-$ [arXiv:1305.4797].

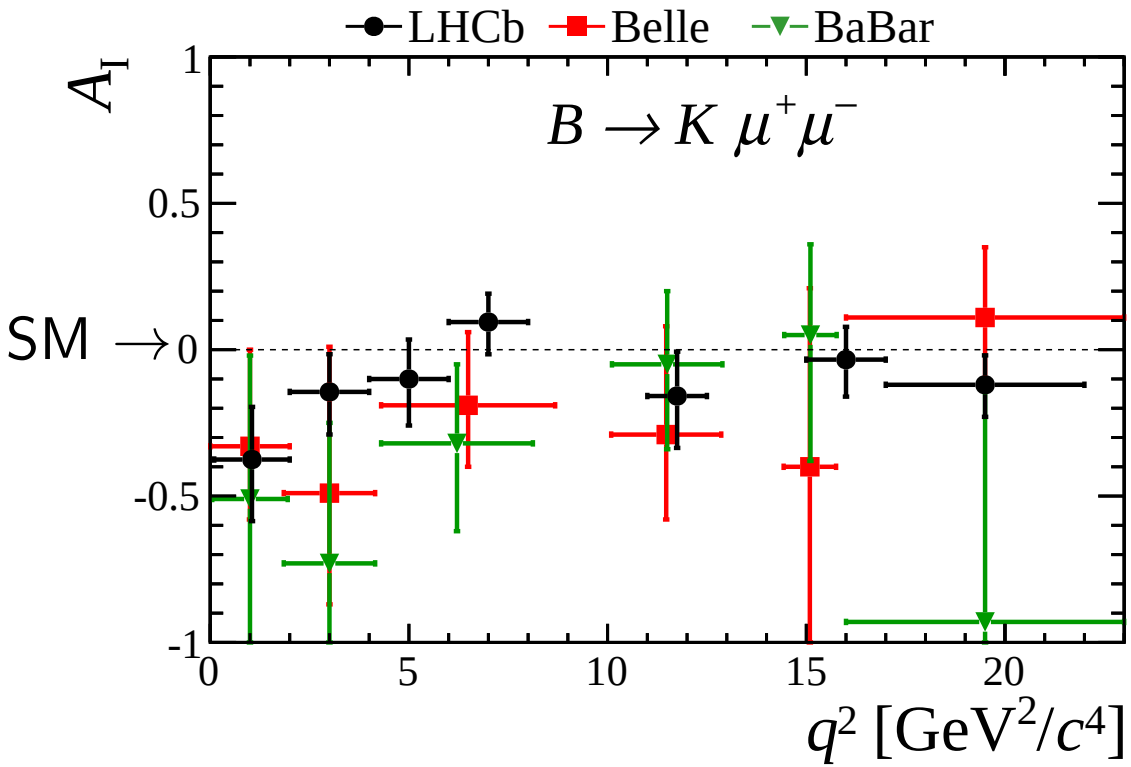




- Previously seen significantly negative results for $B \to K \mu^+ \mu^-$ from LHCb [arXiv:1205.3422] and BaBar [arXiv:0807.4119].

Isospin asymmetry of $B \to K^* \mu^+ \mu^-$

- Tension reduced when updating data.



- Still mild tension at low q^2 but measurement agrees much better with SM now.
- $B \to K^* \mu^+ \mu^-$ also consistant with SM (as previously).

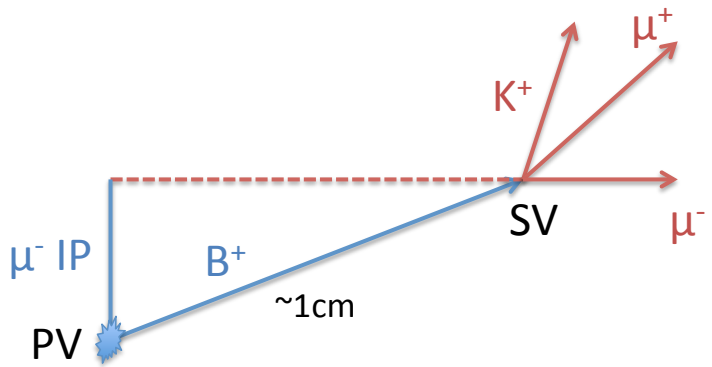
Summary

- Dominant SM contributions of $b \to s\ell\ell$ exclusive decays are $\mathcal{C}_7$, $\mathcal{C}_9$ and $\mathcal{C}_{10}$.
- $B \to K\mu^+\mu^-$ angular analysis sensitive to scalars and tensors.
  - No evidence seen.
- Angular and branching fraction measurements tend to favour a lower value of $\mathcal{C}_9$ than SM.
  - Theoretical and experimental work needed to confirm.
- Isospin asymmetry previously deviated from SM expectation.
  - Tension reduced with full $3\,\text{fb}^{-1}$ dataset.

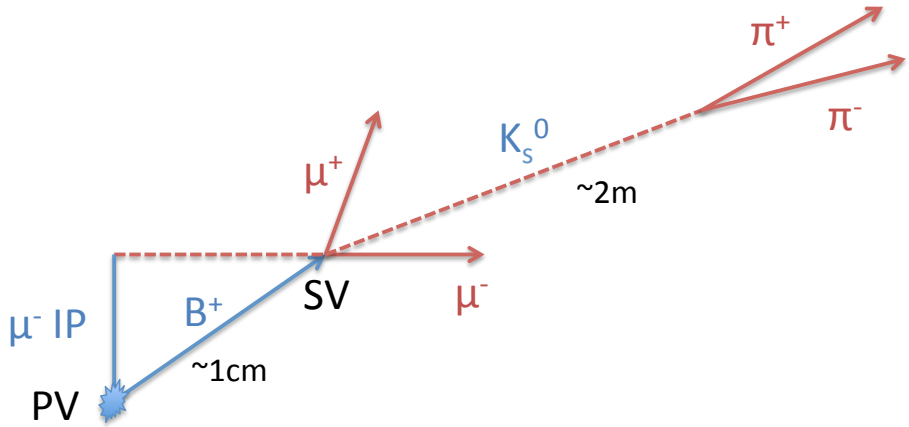
Backup

Selection

- Reduce combinatorial background using kinematic, geometric and particle identification (PID) information.
- Use multivariate techniques to boost sensitivity.
- Consider exclusive backgrounds and use PID/kinematics to reduce them - neglible after selection.



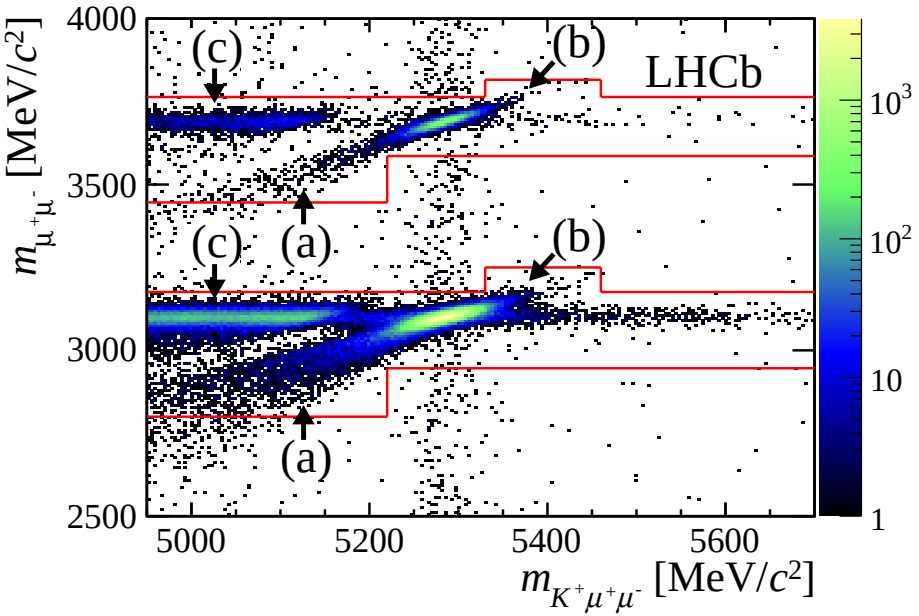
$B^+ \to K^+\mu^+\mu^-$



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

Charmonium resonances

- $B \to J/\psi K^{(*)}$ and $B \to \psi(2S)h$ are irreducible backgrounds and are $\sim$ 100 and 10 times more common than signal.



- Regions (a) due to FSR, (b) due to mis-reconstruction and (c) due to partially reconstructed background.