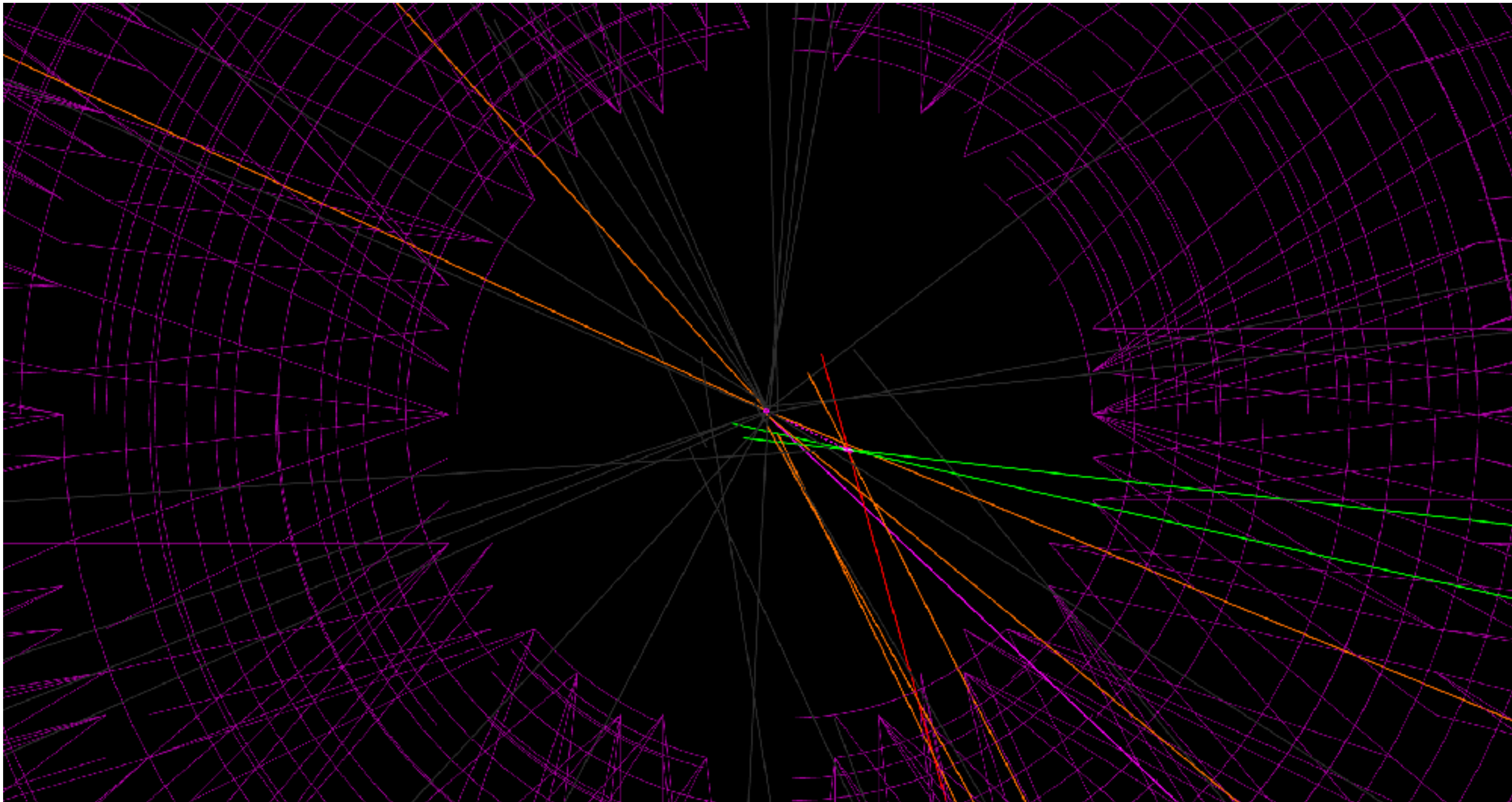
Status of B anomalies: Part II

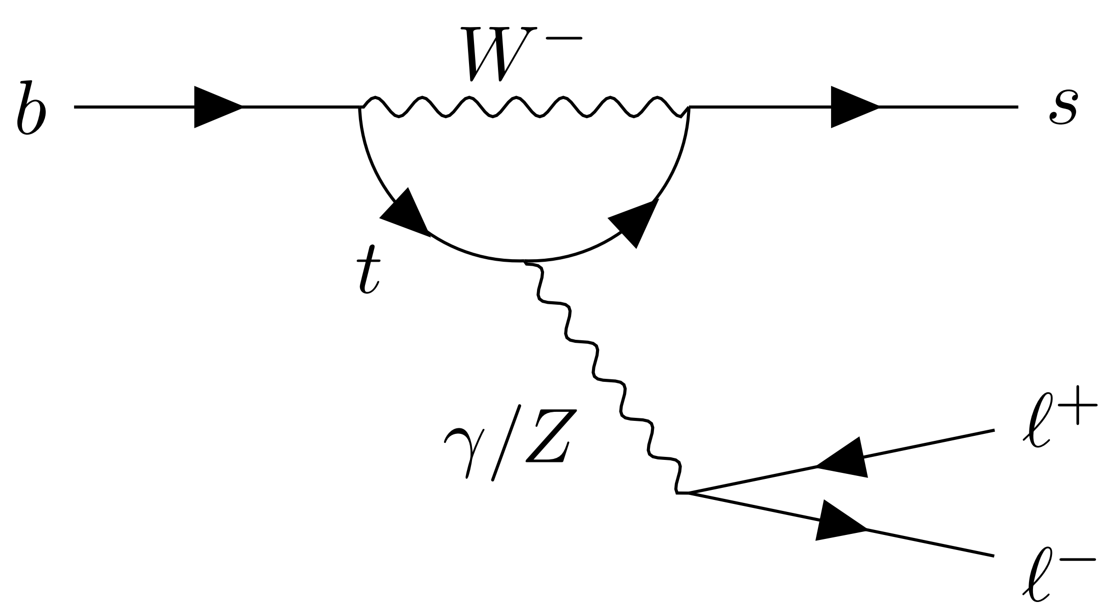
Loop-level $b \to s\ell\ell$ transitions



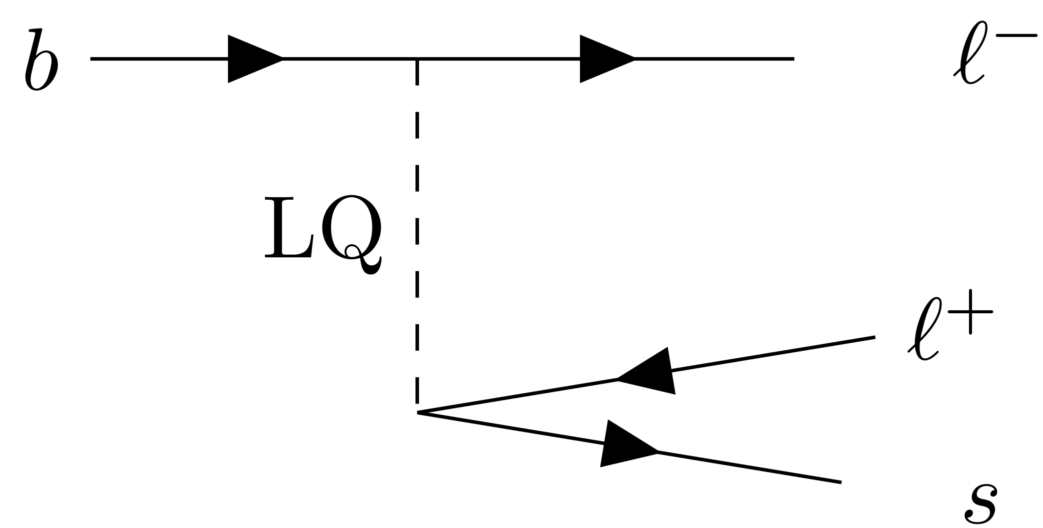
$b \to s\ell\ell$ transitions

- The idea is that because these are loop suppressed, NP can compete quite easily with the SM decay amplitude.

SM



NP



- If NP couples strongly and is light enough, it will significantly alter the behaviour compared to the SM expectation.

$b \to s\ell\ell$ transitions

- b—>s transitions have always played a prominent role in the LHCb physics programme, e.g. from our Wikipedia page:

Physics goals [edit]

The experiment has wide physics program covering many important aspects of Heavy Flavor (both beauty and charm), Electroweak and QCD physics. Six key measurements have been identified involving B mesons. These are described in a roadmap document [2] that form the core physics programme for the first high energy LHC running in 2010–2012. They include:

- Measuring the branching ratio of the rare $B_s \to \mu^+ \mu^-$ decay.
- Measuring the forward-backward asymmetry of the muon pair in the flavour changing neutral current $B_d \to K^* \mu^+ \mu^-$ decay. Such a flavour changing neutral current cannot occur at tree-level in the Standard Model of Particle Physics, and only occurs through box and loop Feynman diagrams; properties of the decay can be strongly modified by new Physics.
- Measuring the CP violating phase in the decay $B_s \to J/\psi\ \phi$, caused by interference between the decays with and without B_s oscillations. This phase is one of the CP observables with the smallest theoretical uncertainty in the Standard Model, and can be significantly modified by new Physics.
- Measuring properties of radiative B decays, i.e. B meson decays with photons in the final states. Specifically, these are again flavour changing neutral current decays.
- Tree-level determination of the unitarity triangle angle γ.
- Charmless charged two-body B decays.

- Fully reconstructed with charged final states is bread and butter for LHCb.

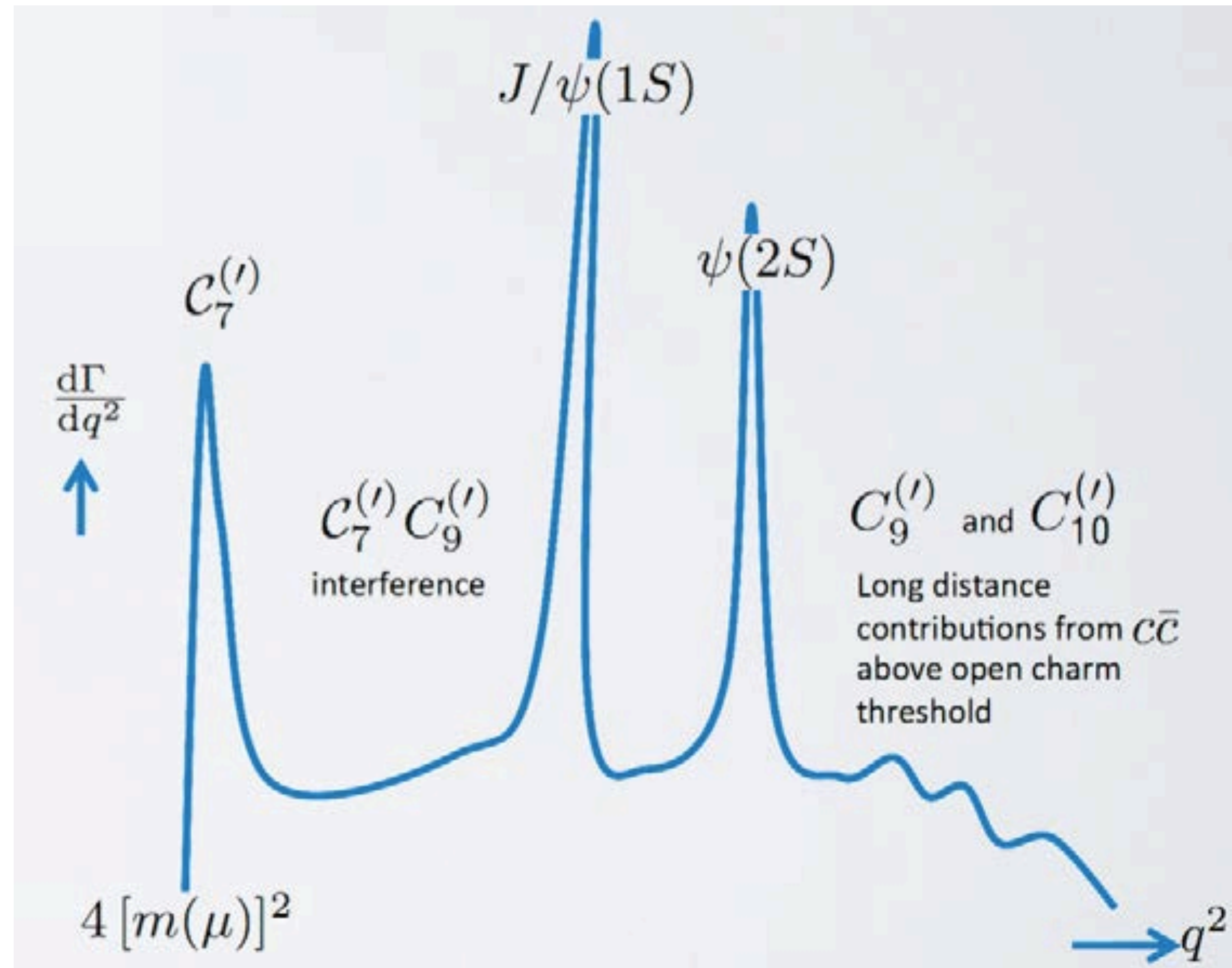
  - Only a real challenge if they are extraordinary rare (e.g. B_s—>μμ).

Example decays

- Example decays should result in low energy hadrons in order to get good theory predictions.

  - e.g.

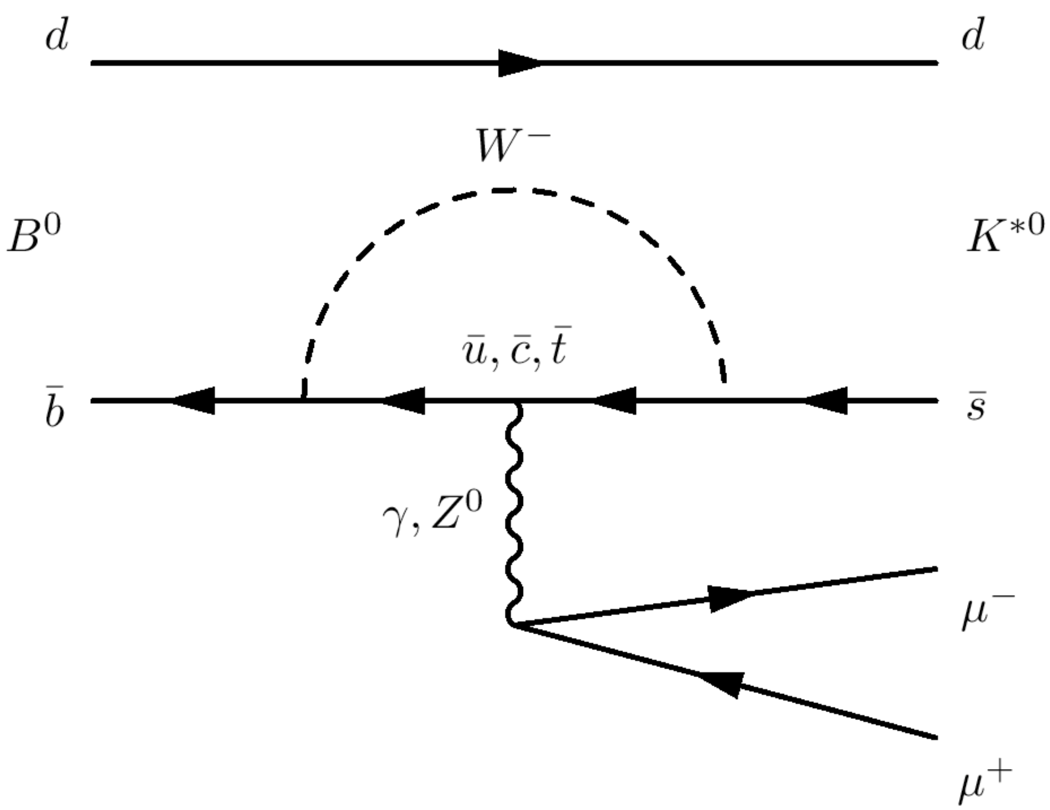
    - $B^+ \to K^+\mu^+\mu^-$
    - $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$
    - $B_s^0 \to \phi\mu^+\mu^-$
    - $B^0 \to K^{*0}\mu^+\mu^-$

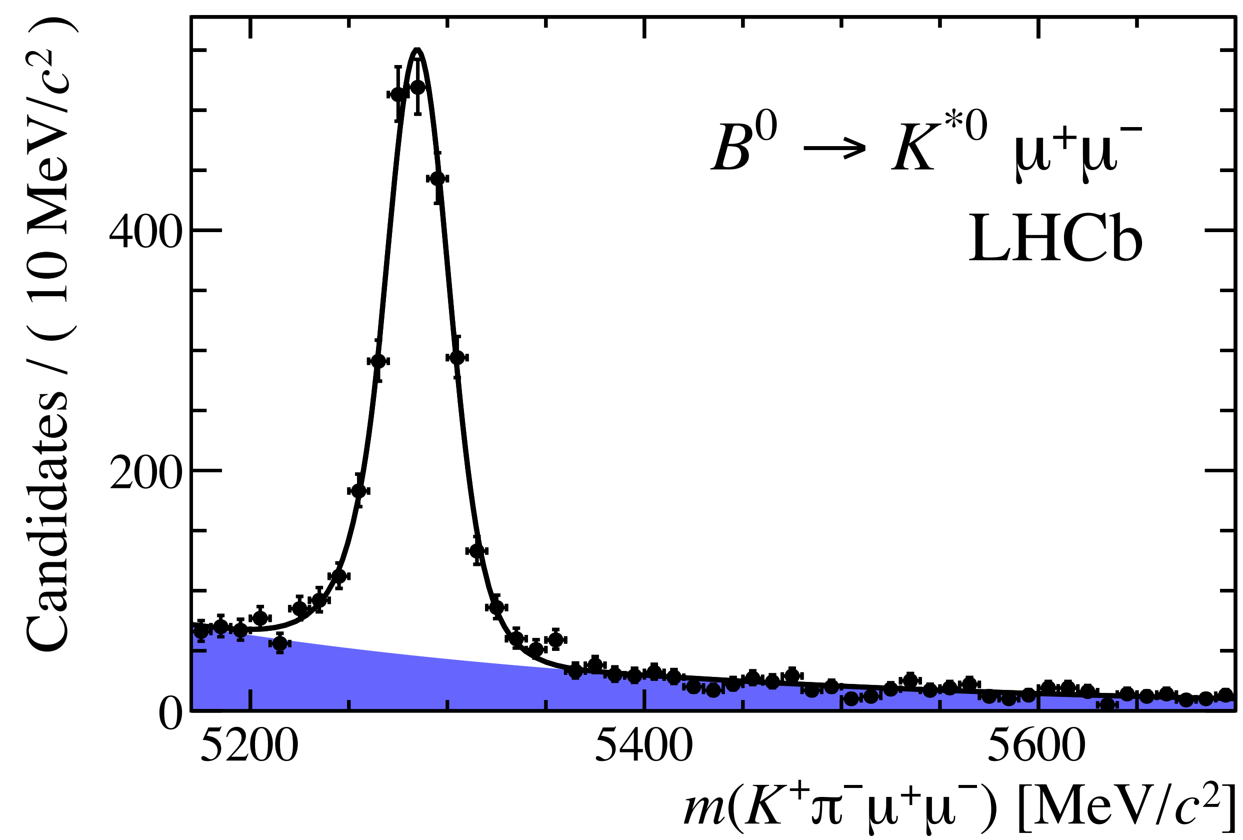


- Unlike CC decays, get spikes in the distribution, typically we veto these so that we are dominated by the semileptonic decay.

Branching fraction

- Is NP affecting the rate of these decays?
  - Measure the branching fraction as a function of q^2.





- Take the most experimentally appealing signature (muons and charged hadrons).

Normalisation

- At LHCb we normalise to the corresponding J/ψ decay mode.

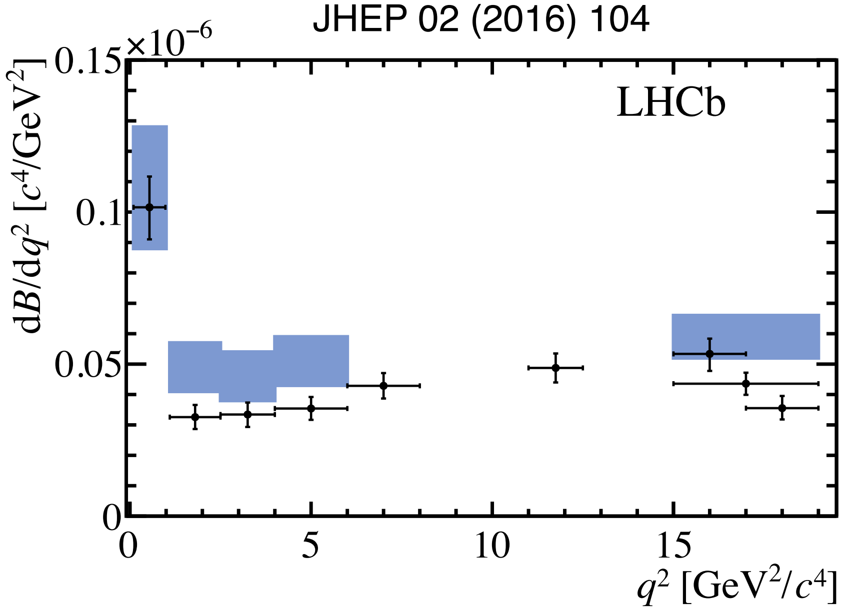
$$\frac{d\mathcal{B}}{dq^2} = \frac{N(B\to K^{(*)}\mu^+\mu^-)}{N(B\to J/\psi\, K^{(*)})} \cdot \frac{\varepsilon(B\to J/\psi\, K^{(*)})}{\varepsilon(B\to K^{(*)}\mu^+\mu^-)} \cdot \frac{\mathcal{B}(B\to J/\psi\, K^{(*)})\mathcal{B}(J/\psi \to \mu^+\mu^-)}{(q^2_{\rm max} - q^2_{\rm min})}$$

- This vastly simplifies systematic uncertainties, as both signal and normalisation have the same final state.
  - But: we are limited by the uncertainty on $\mathcal{B}(B \to J/\psi K^{(*)})$
- Good information for B^+ and B^0 mesons from B-factories, for B_s^0 and Λ_b^0 branching fractions we have to do a bit more work.

Branching fraction results

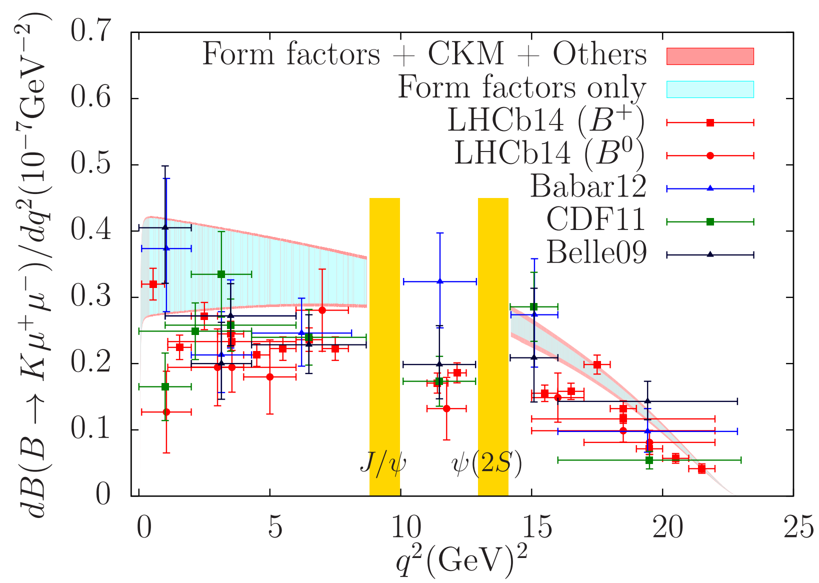
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104



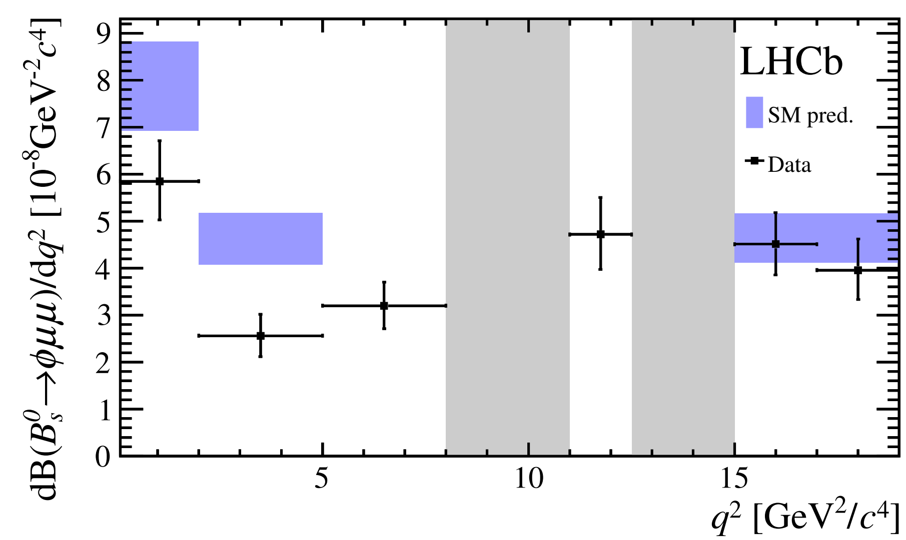
$B^+ \to K^+\mu^+\mu^-$

FNAL/MILC, Phys. Rev. D 93, 034005 (2016)

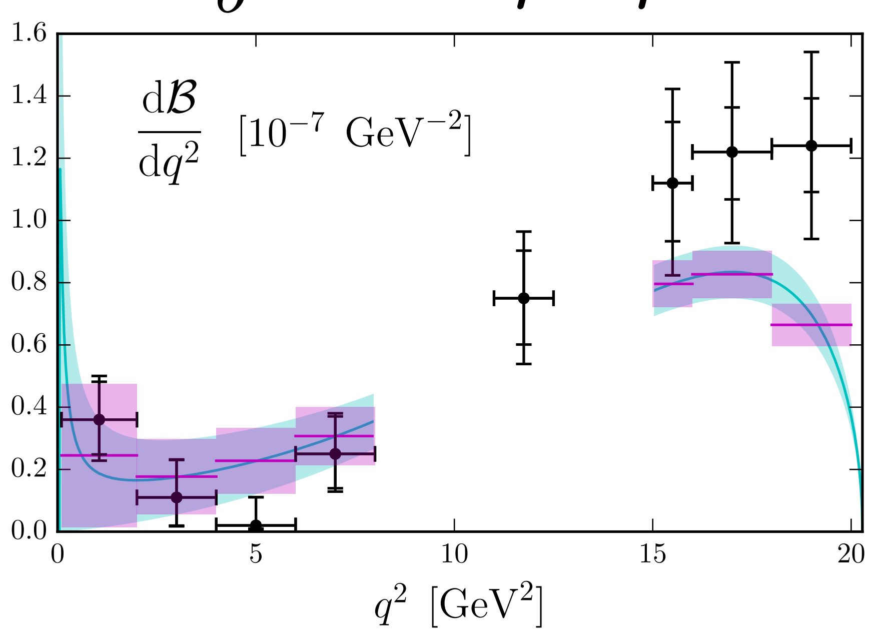


$B_s^0 \to \phi\mu^+\mu^-$

JHEP 09 179 (2015)



$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$

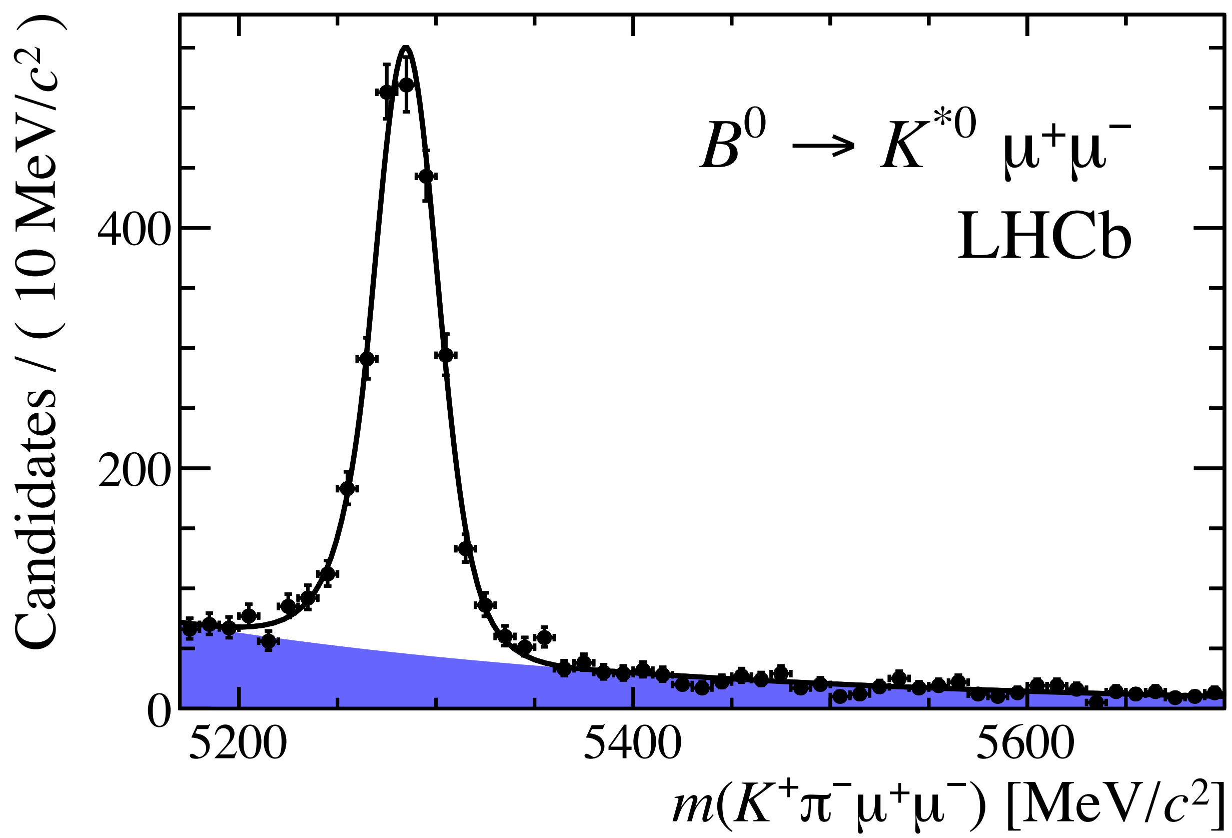


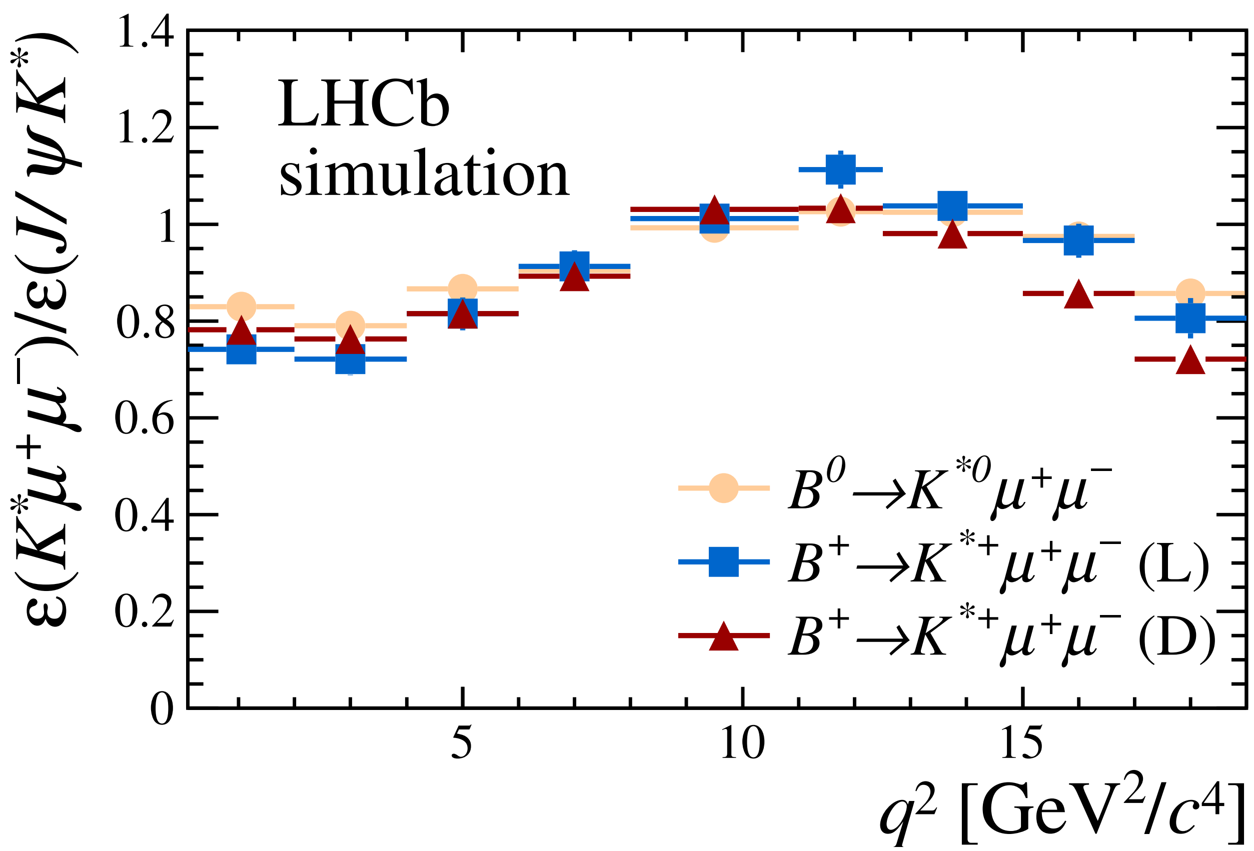
- Everything is below the SM, with the notable exception of $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$

Mode		Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda \times \mathrm{B}(b \to \Lambda_b^0)$	$(5.8 \pm 0.8) \times 10^{-5}$

The robustness of muons

- Fit the mass peak to obtain the signal yield and correct using the ratio of efficiencies.

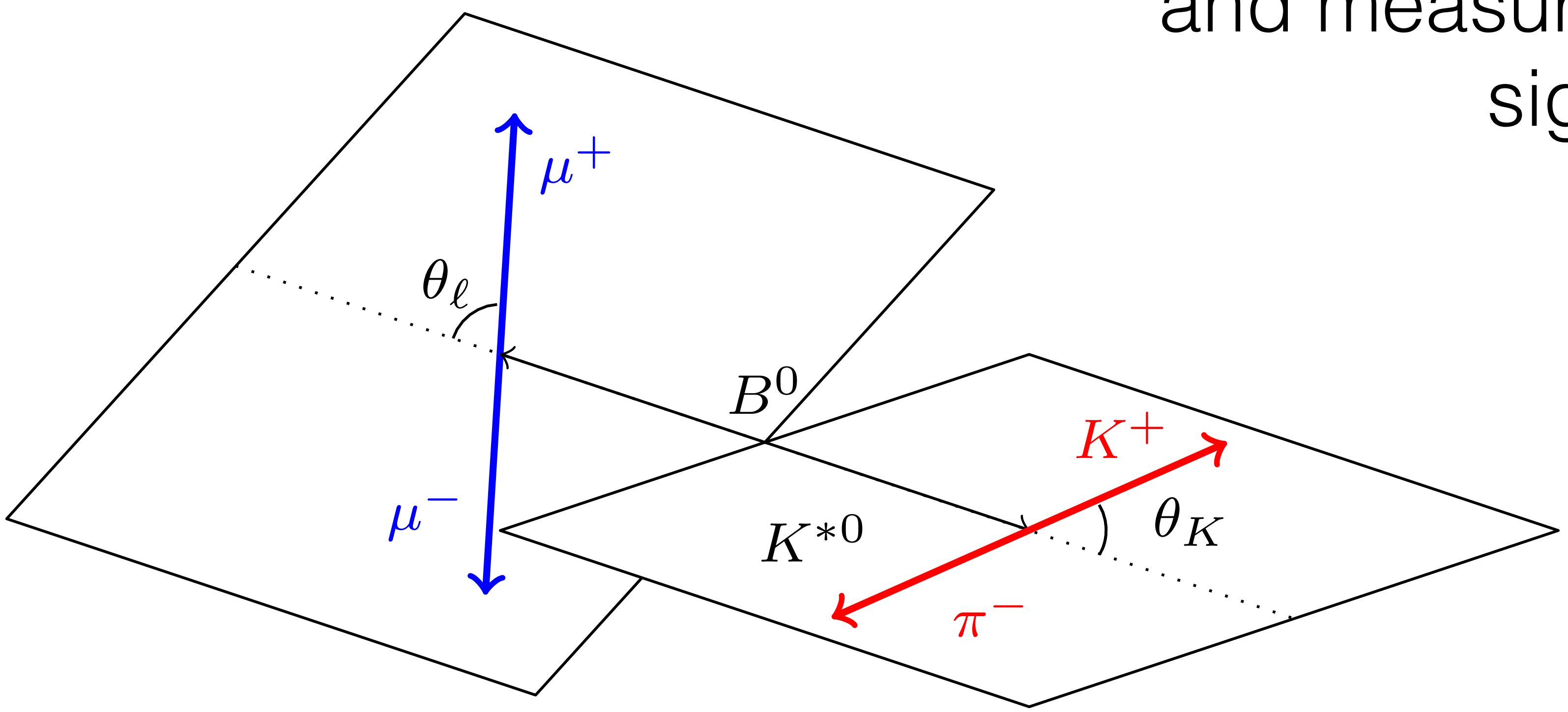




- The backgrounds and efficiency corrections for muonic modes is very robust.

Beyond branching fractions

- If NP is indeed changing the branching fractions of these decays, expect it also to change the angular distribution.



Boost into the rest frame of the B, and measure these angles for every signal candidate.

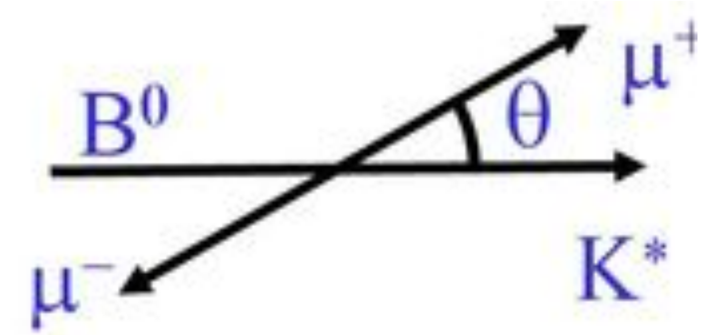
- The main decay is $B \to K^* \mu^+ \mu^-$, why not $B \to K \mu^+ \mu^-$ or $B_s^0 \to \phi \mu^+ \mu^-$?

First we write down the PDF

- The $B^0 \to K^{*0}\ell^+\ell^-$ angular distribution can be written down as follows

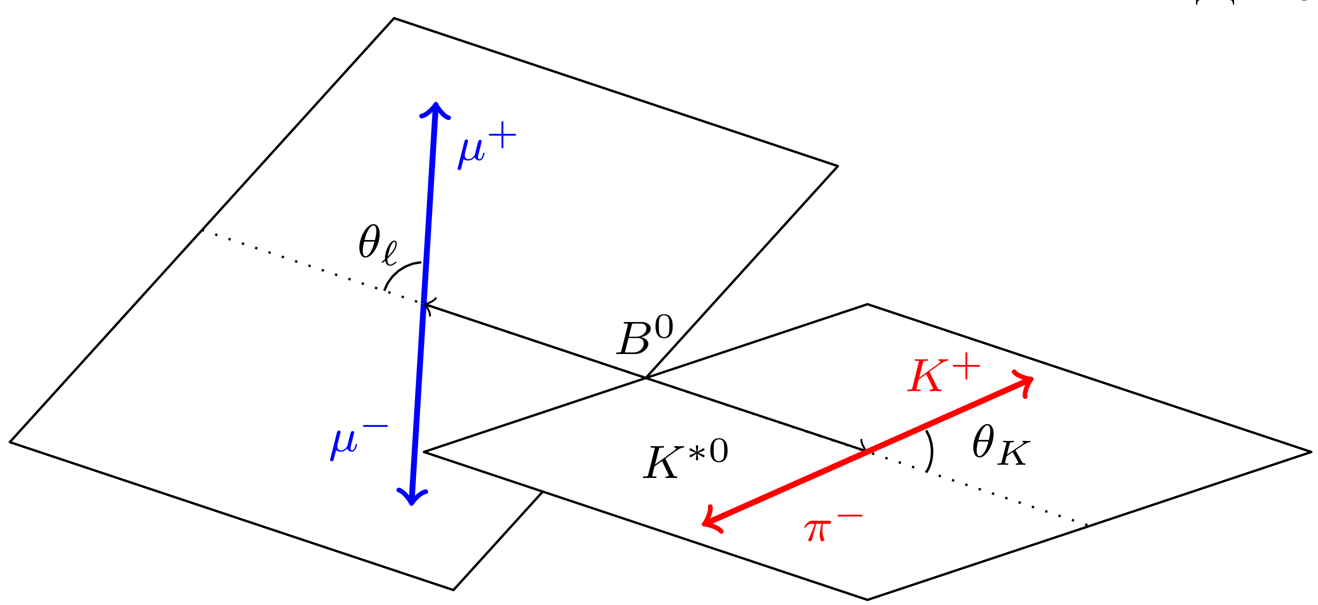
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$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

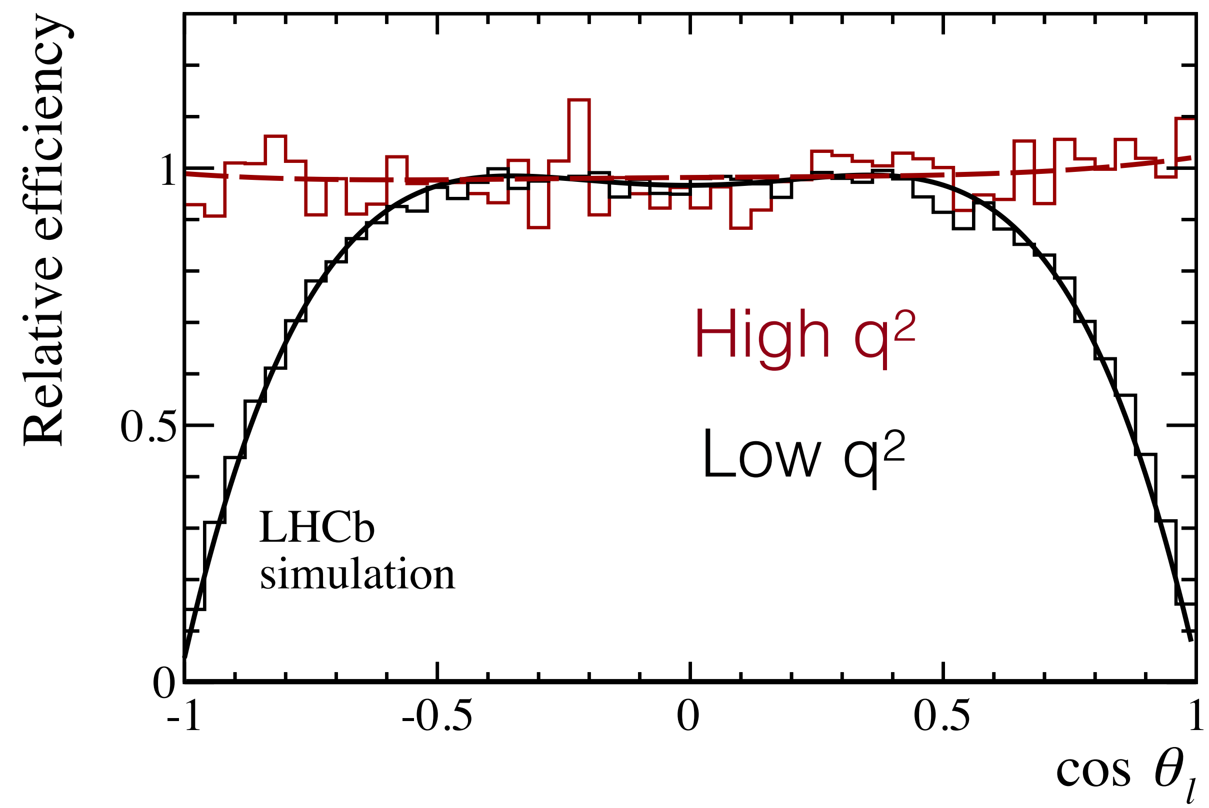
Probe observables such as the forward-backward asymmetry (A_{FB}) and and the fraction of longtitundal polarisation of the K* (F_L)



Need to correct for angular acceptance

- The requirements that the decay is reconstruction will bias the angular distribution.

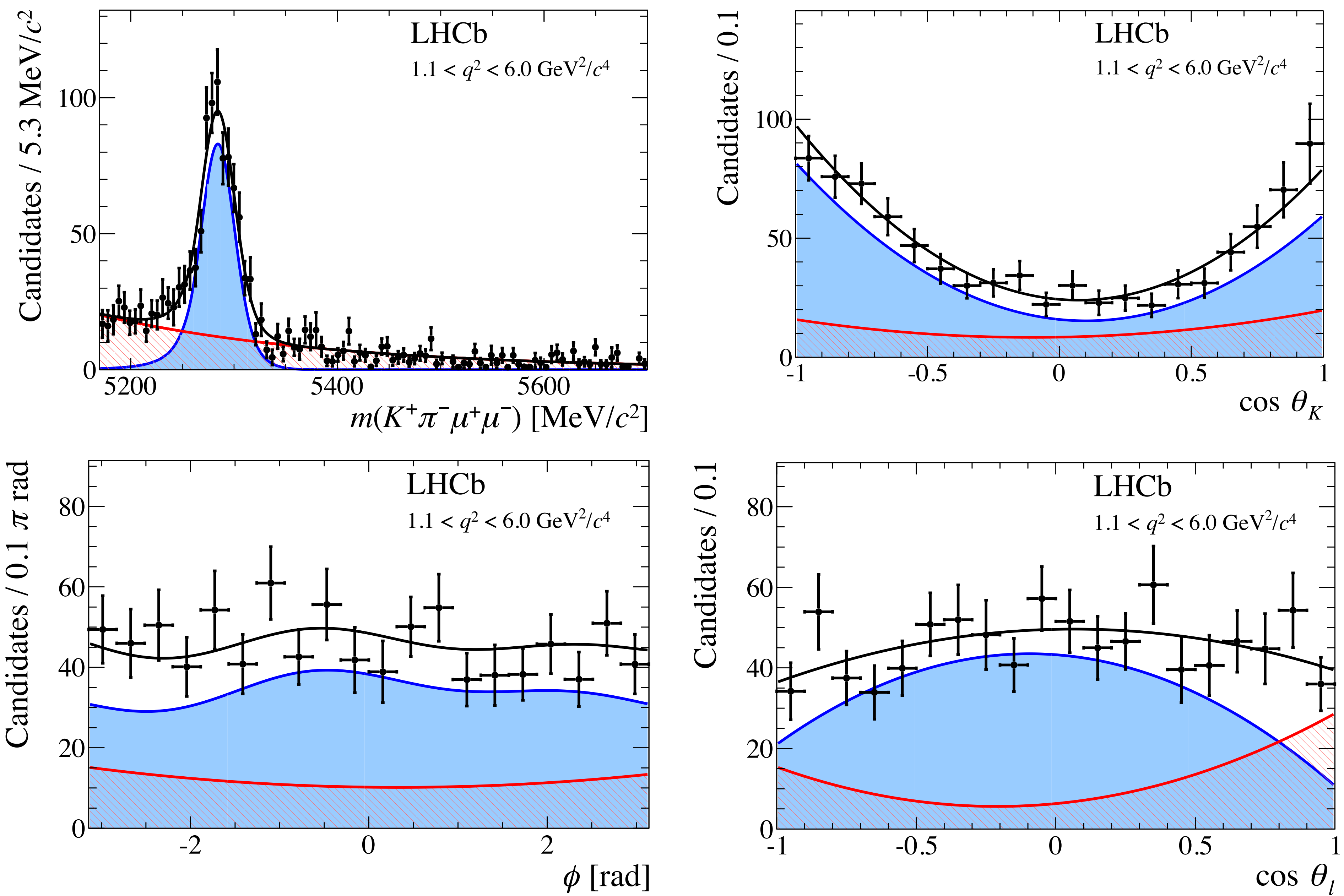




- This is corrected using simulation.

Then we fit the distribution

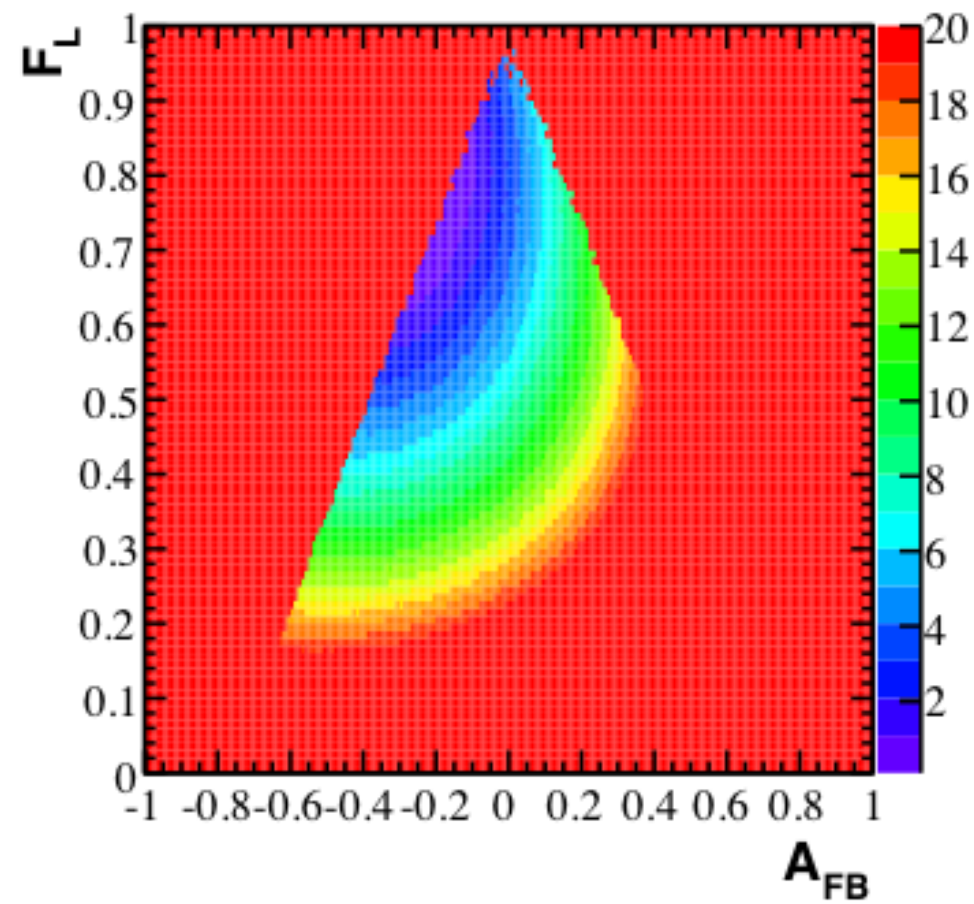
- Fit the 4D distribution of mass, three angles in bins of q^2.
  - We avoid fitting in q^2 to preserve independence on theory.



A tricky statistical issue

- The angular PDF is only positive in certain regions of phase-space.

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_l\,\mathrm{d}q^2} = \frac{3}{4}F_\mathrm{L}(1-\cos^2\theta_l) + \frac{3}{8}(1-F_\mathrm{L})(1+\cos^2\theta_l) + A_\mathrm{FB}\cos\theta_l$$



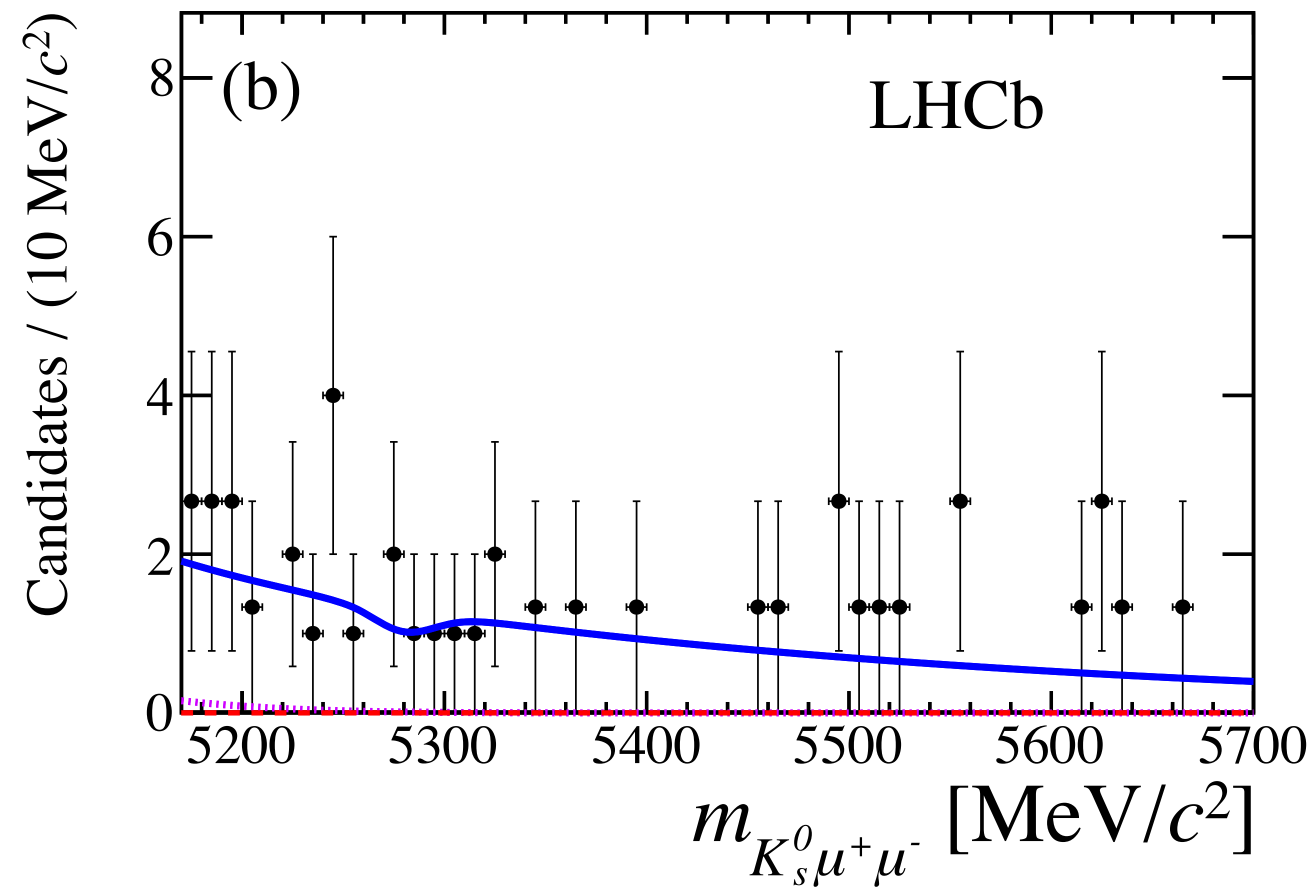
- Positive if:

$$A_{FB} \leq \frac{3}{4}(1-F_L)$$

This is not normally an issue

- Background can sometimes save you from these issues.

- Heres an example of the data preferring a negative signal PDF, but the total PDF staying positive.

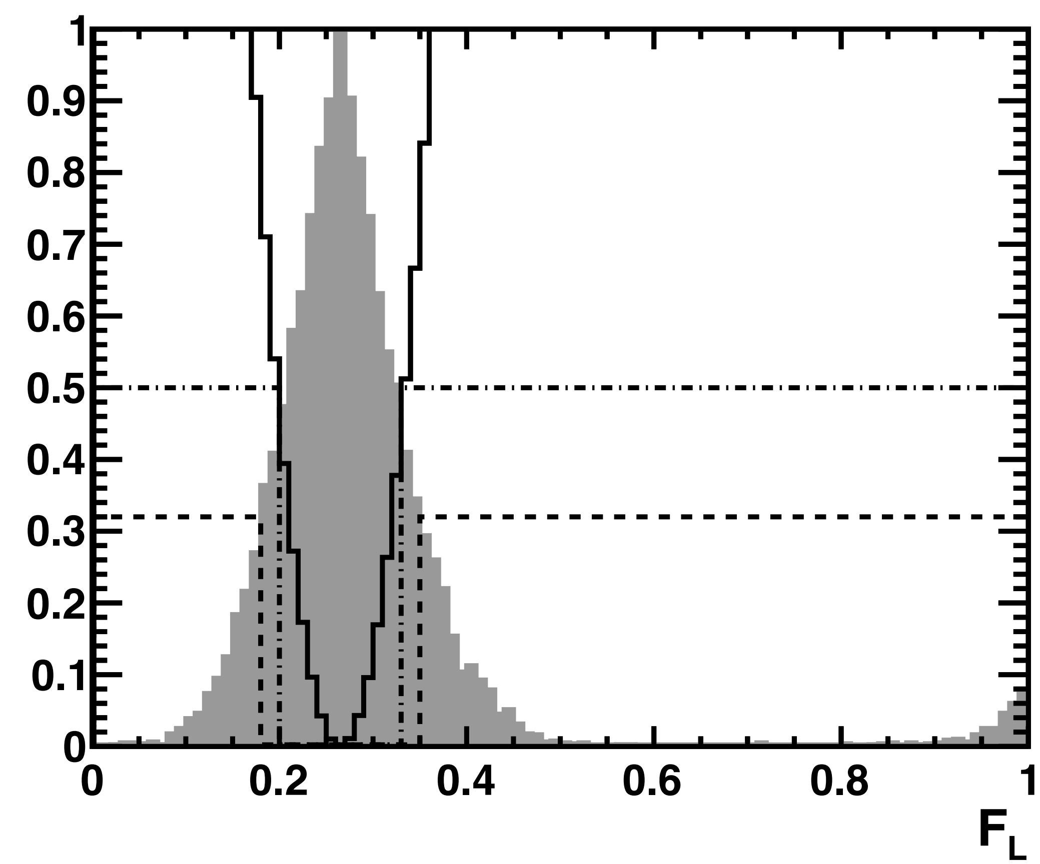


- For the angular analysis, however, its often impossible to keep the total PDF positive, which causes the uncertainties to be badly behaved.

Coverage issues

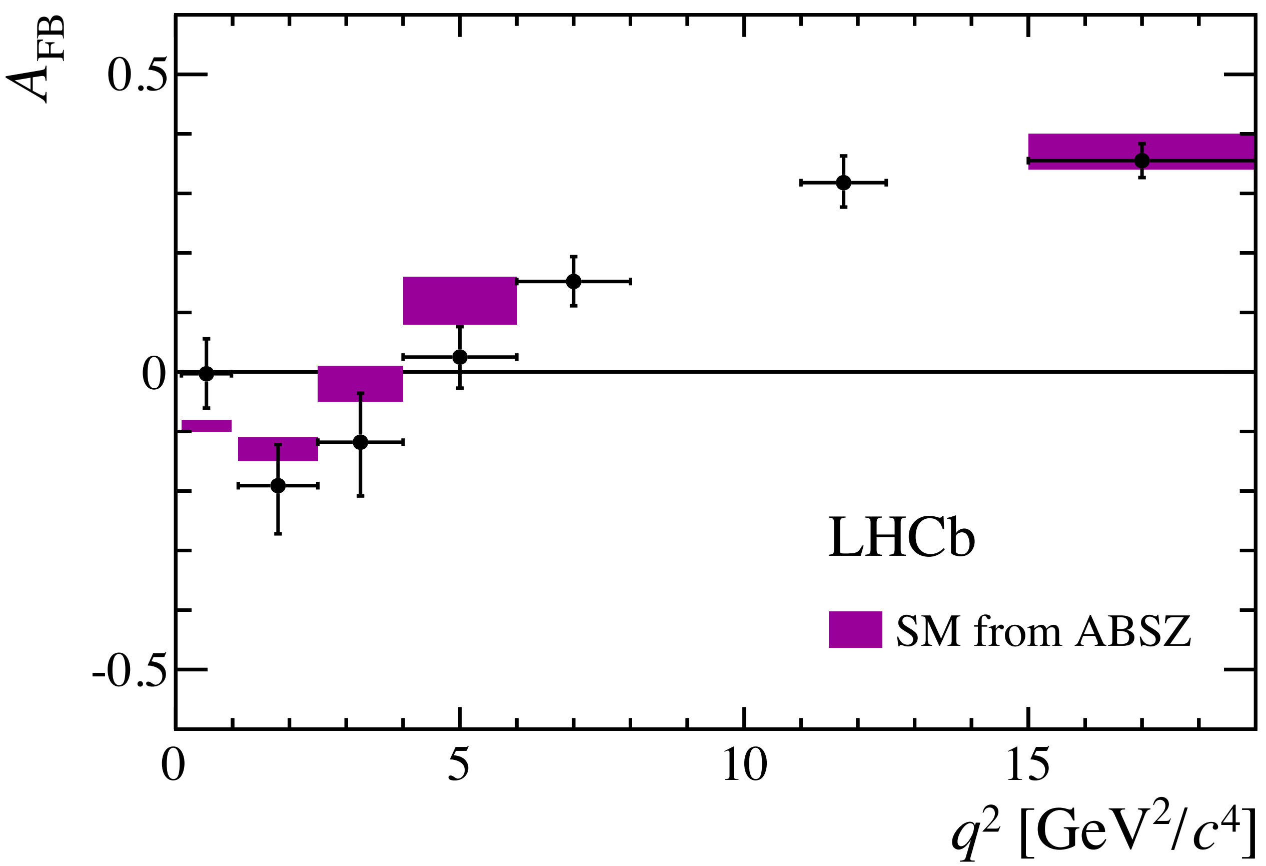
- Frequentist coverage is defined as the probability that the true value μ is contained within a confidence interval, you want this to be 68%.
  - If its above 68%, you are said to overcover, you are too conservative.
  - If its below, you are too aggressive (not a good situation to be in).

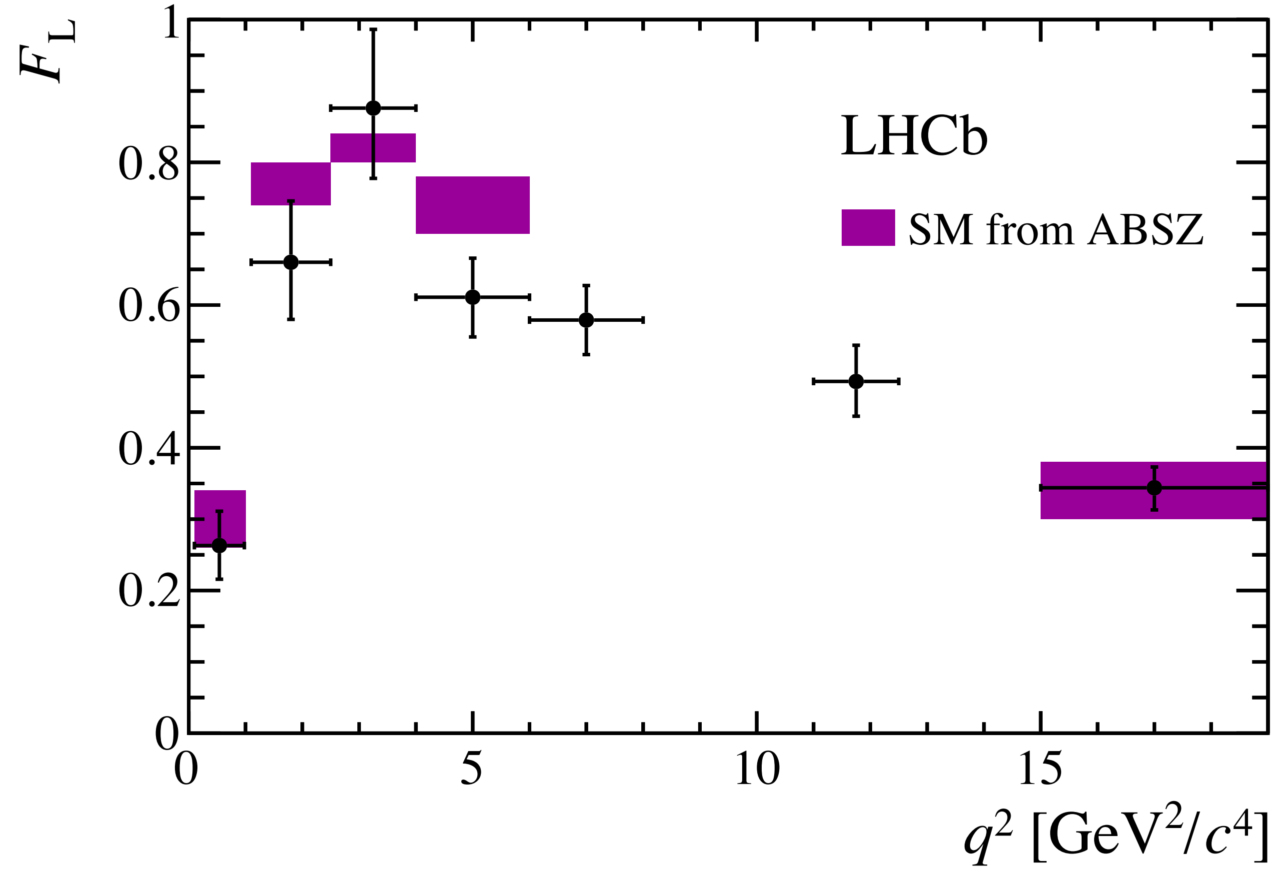
- Instead of relying on the likelihood to give you the uncertainty, throw toys to tell you how often you get a DLL worse than one at the point in the data.



Results

- Once that's sorted, add the systematics (small) and compare to theory.

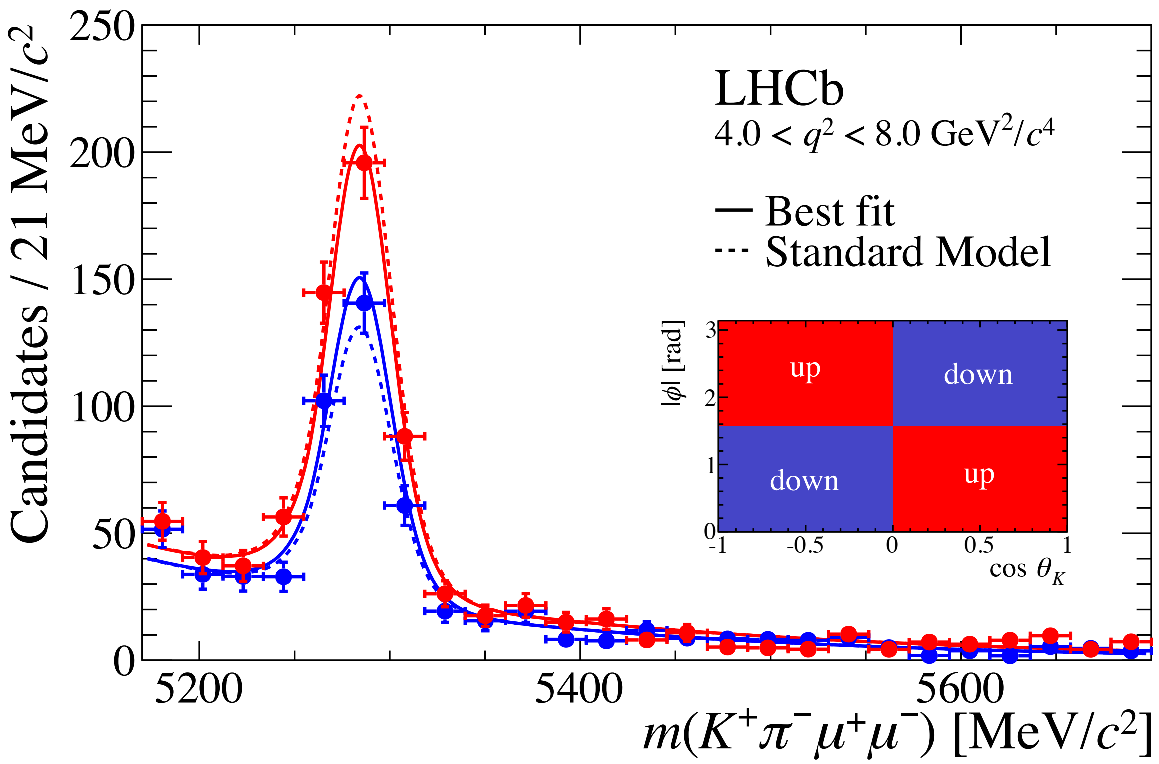


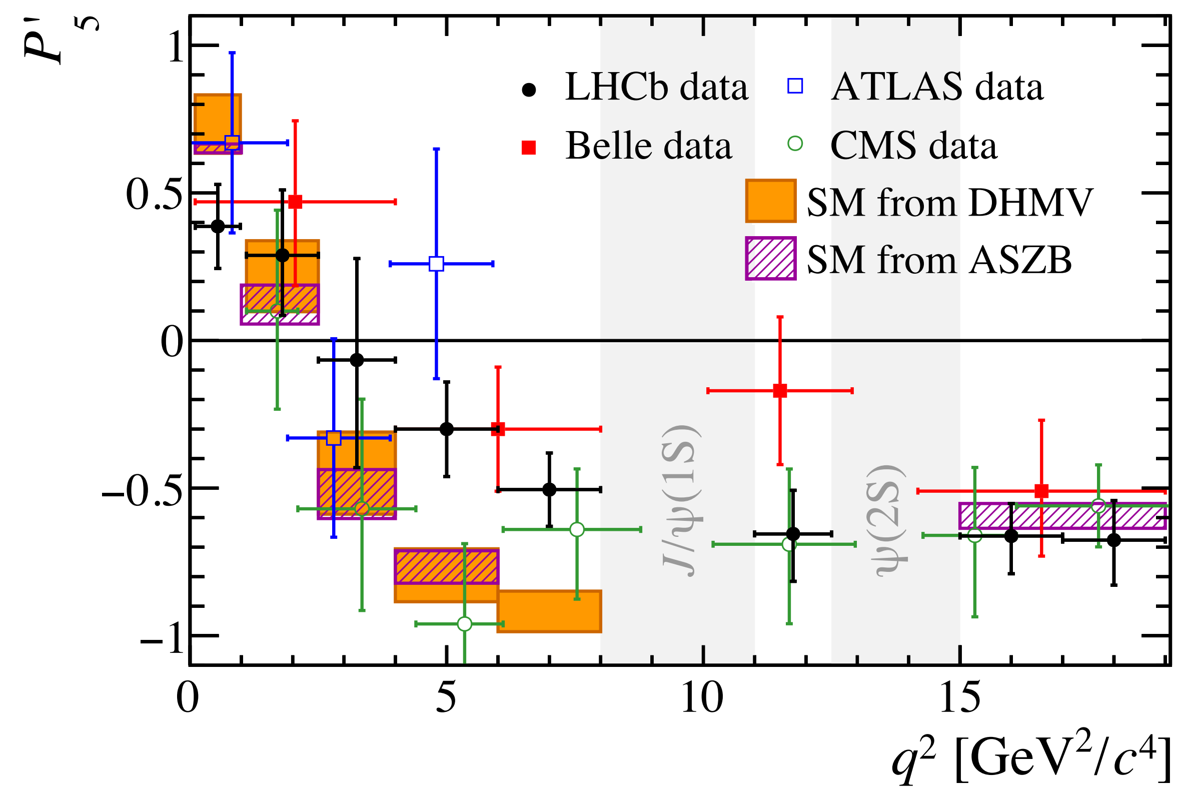


- Small shift in A_{FB} but overall things are consistent with the SM, apart from one observable …

P_5'

- Cancel leading form factor uncertainties by constructing 'optimised observables' (P observables).



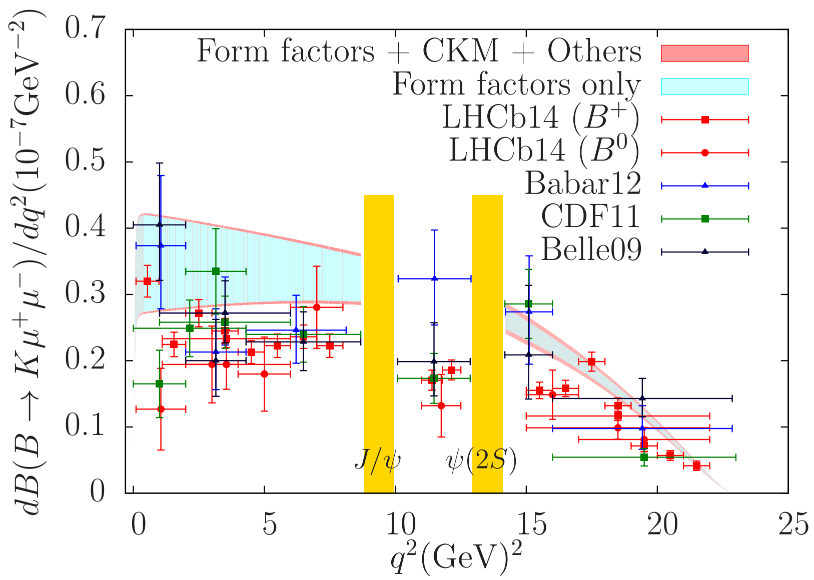


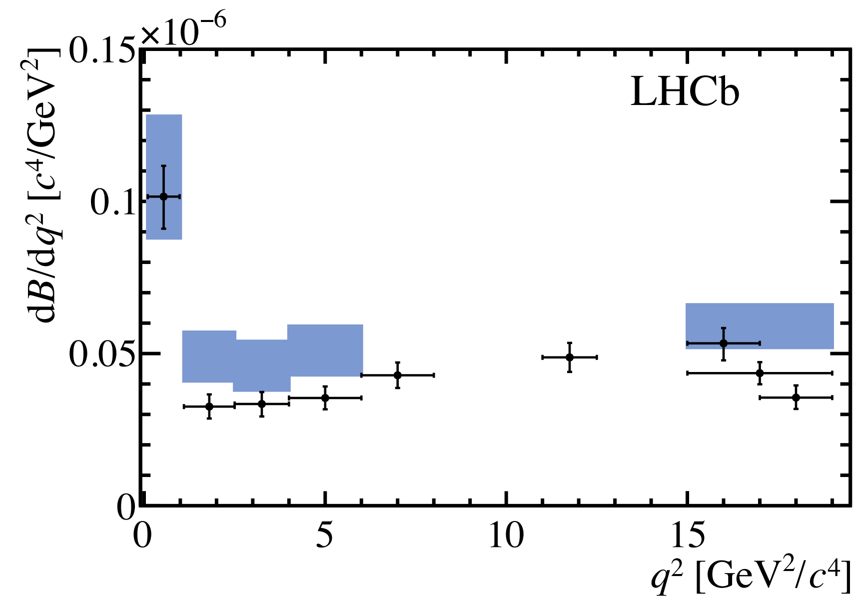
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}},$$

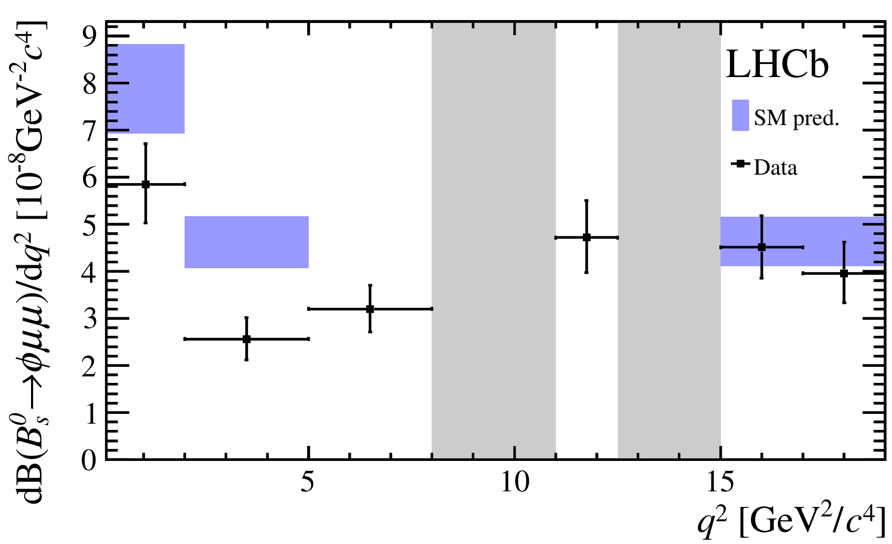
- Discrepancy just below the J/ψ peak.

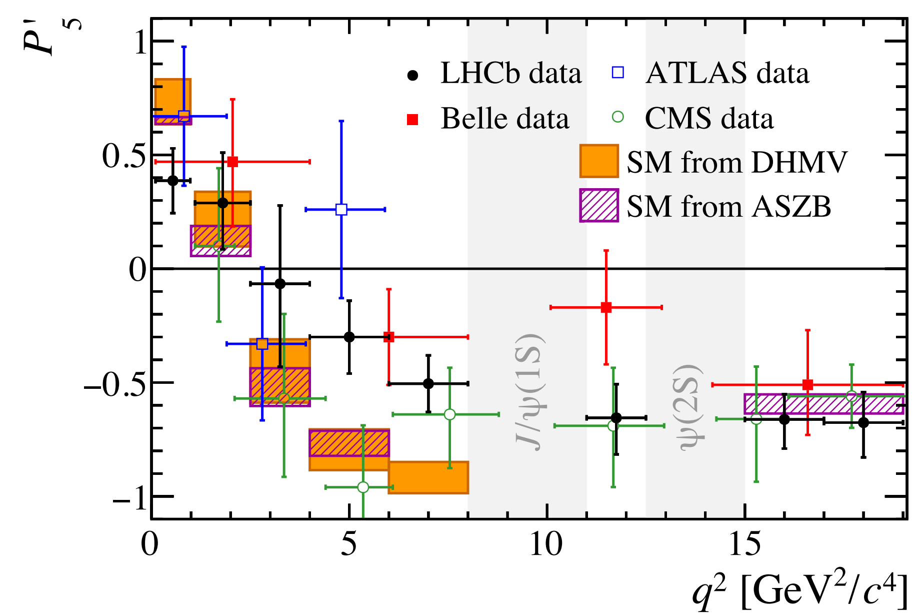
Coherent pattern?

- If the P_5' discrepancy is due to NP, it would also cause the branching fractions to be lower than the SM.





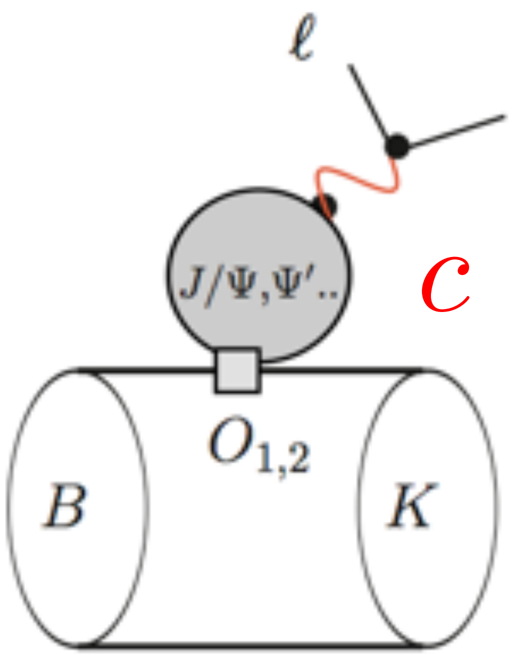


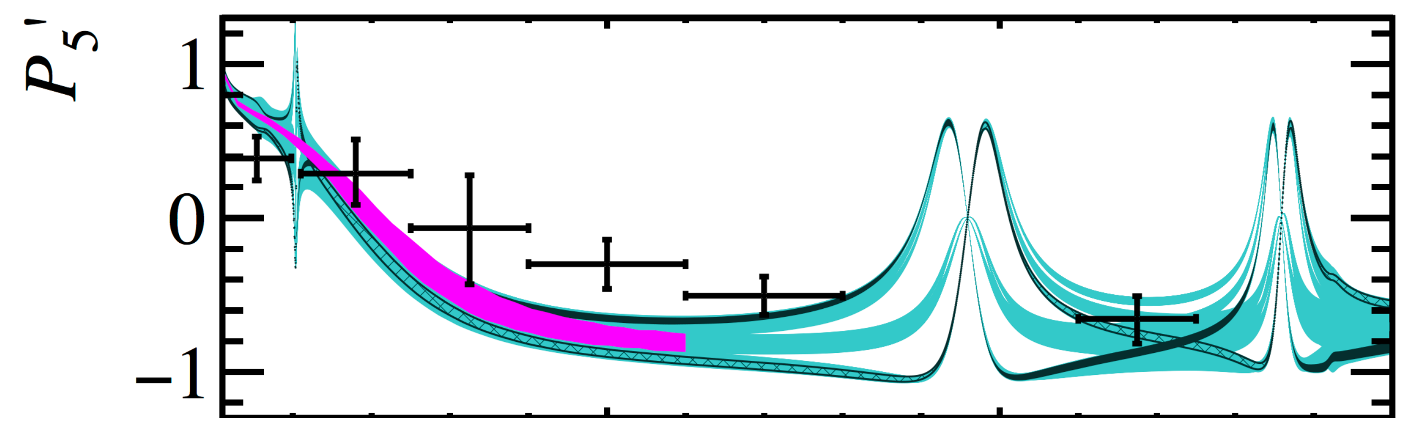


- Something appears to be negatively interfering with the SM b->sll decay amplitude, with a vector like coupling to the leptons.

A SM complication

- Unfortunately, there is also a SM contribution which can negatively interfere with the semileptonic amplitude.



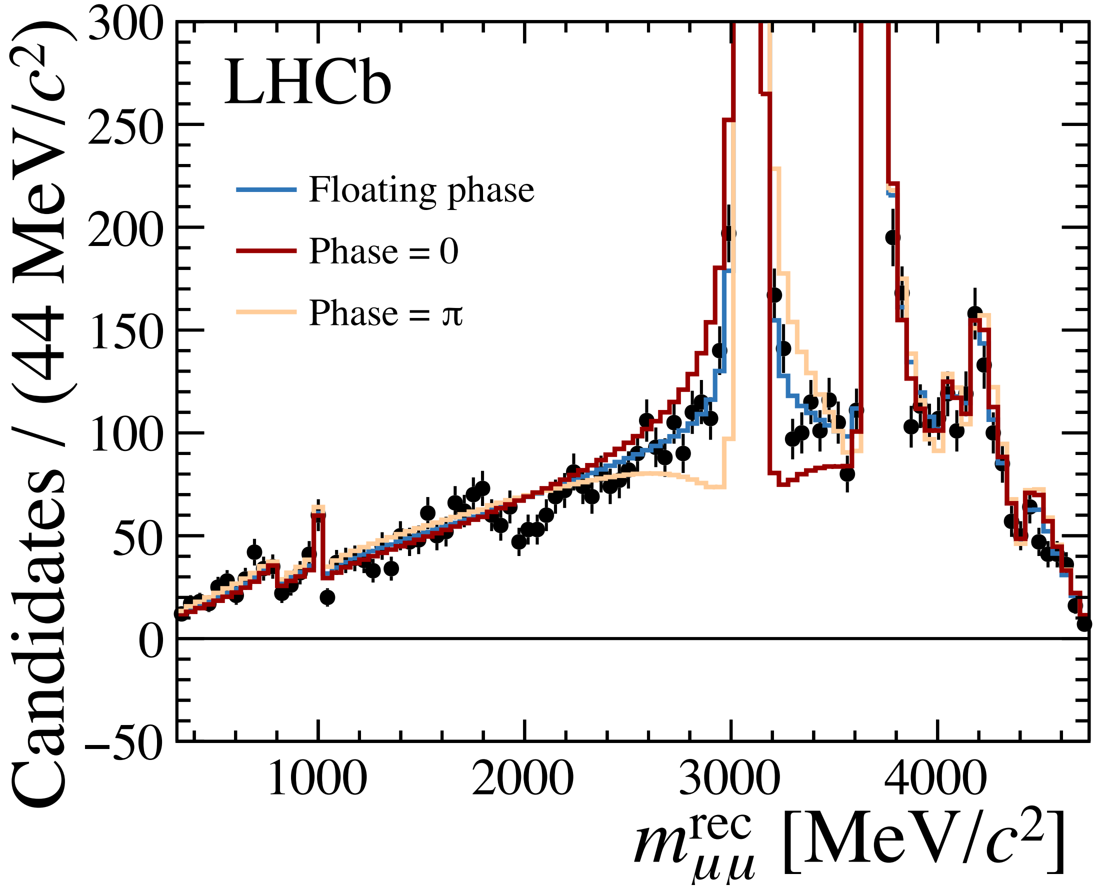


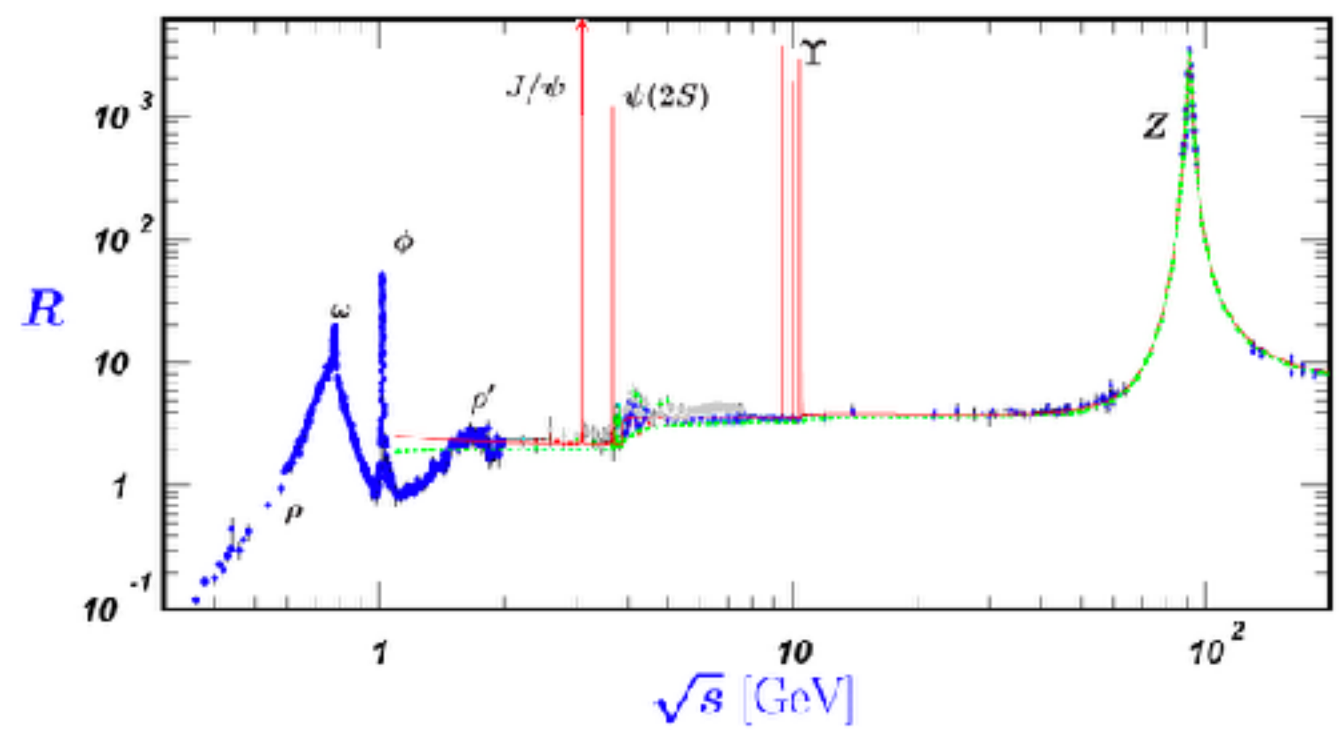
Blake et al, Eur. Phys. J. C (2018) 78: 453

- This contribution is very difficult to calculate as it is fully hadronic.

Handles with data

- We have tried experimentally to control this in $B \to K\mu^+\mu^-$ decays.



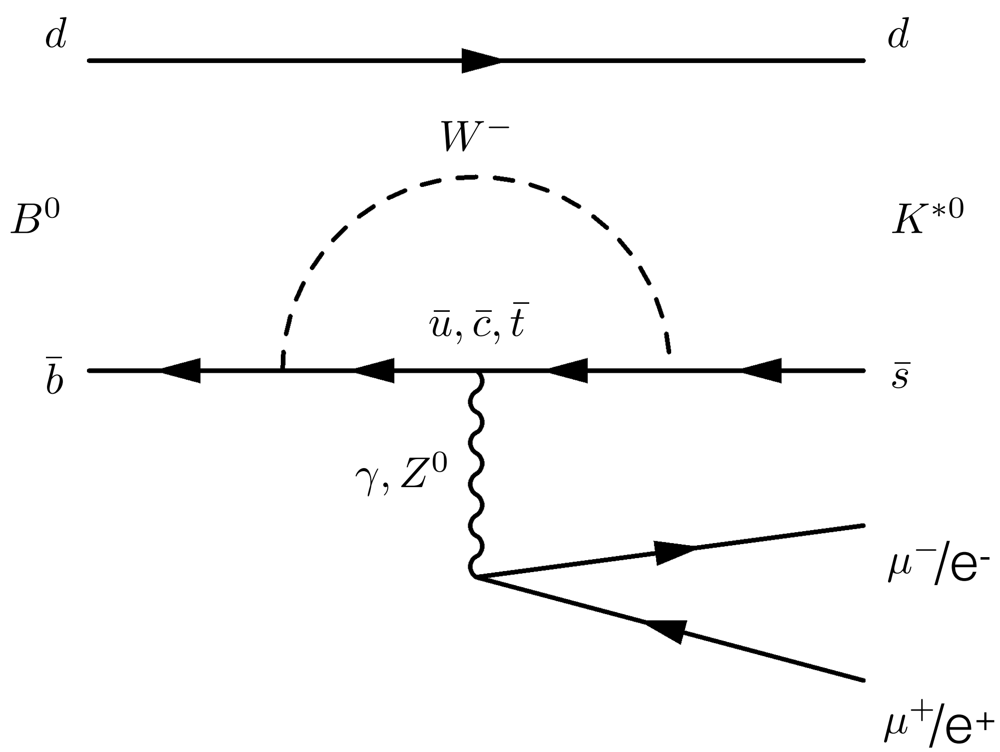


- No big effect from charmonium resonances seen, but model assumes a Breit-Wigner and only has a finite number of resonances included.

Lepton universality

- If we still can't come to a consensus, we can compare muons and electrons to see if the same discrepancies appear there.

- First test the BF disprenacies by measuring R ratios.



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

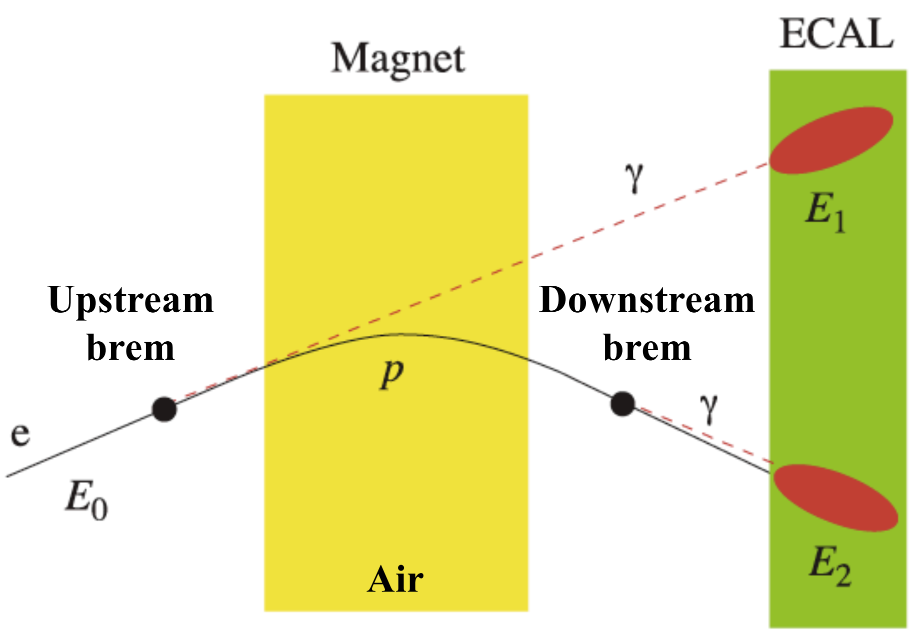
- Muon and electron masses small compared to b-quark: $R_{K(*)} \sim 1$

- Again normalise to simplify systematics (also $\mathcal{B}(B \to J/\psi K^{(*)})$ cancels).

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

The problem with electrons

- The main issue with electrons is their tendency to bremsstrahlung



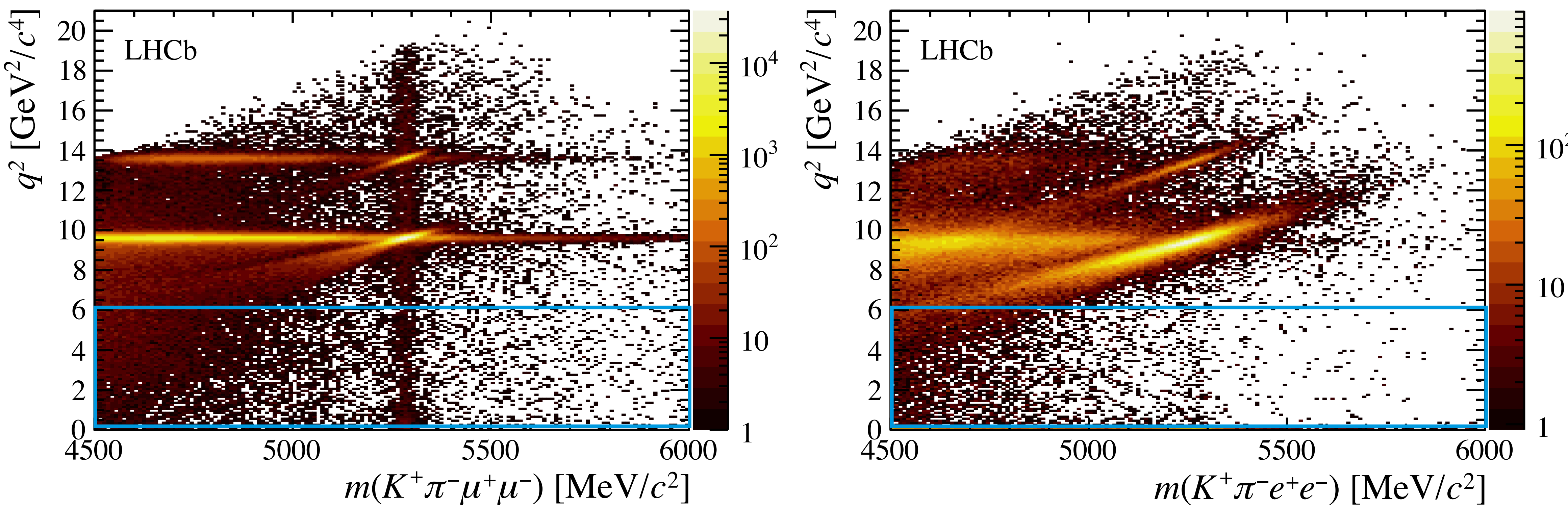
- Also get more FSR from electrons, but this is generally a smaller effect and is reproduced fairly well in our simulation (< 1% effect).
- Easier to confuse signal and background, due to a widening of the mass resolution.

- In addition, trigger and reconstruction efficiency worse for electrons
  - Electrons are more easily swept away by the magnet.
  - High ET ECAL cluster less distinguishing than a high PT muon.
- **Rule of thumb:** lose a factor three in signal when exchanging a muon with an electron.

Bremsstrahlung issues

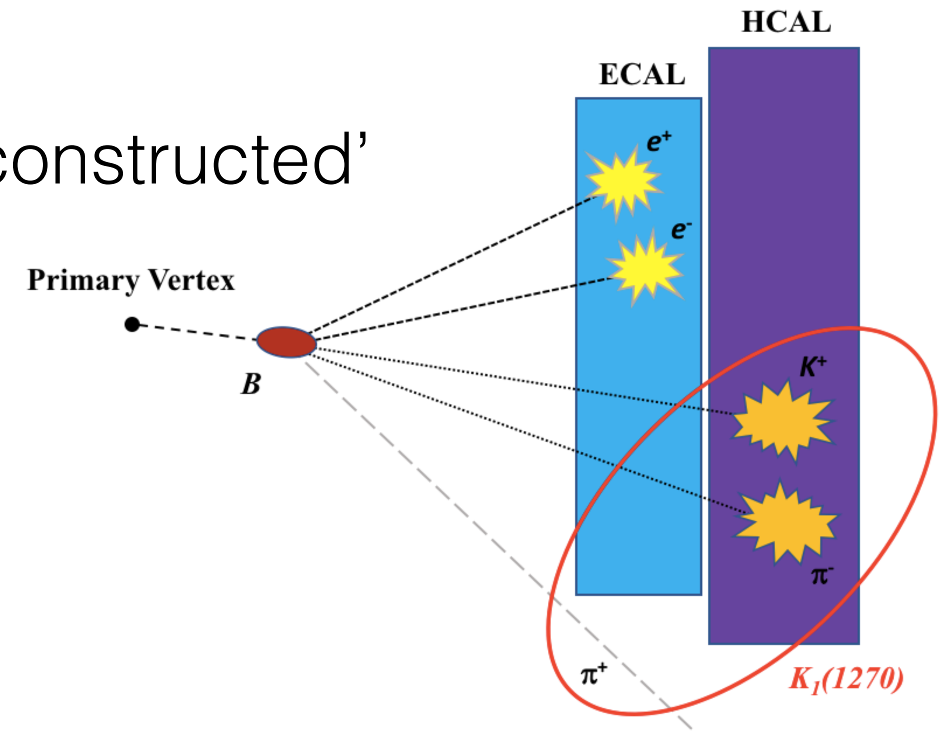
- Get background from the J/ψ and ψ(2S) leaking into signal region.

JHEP 08 (2017) 055

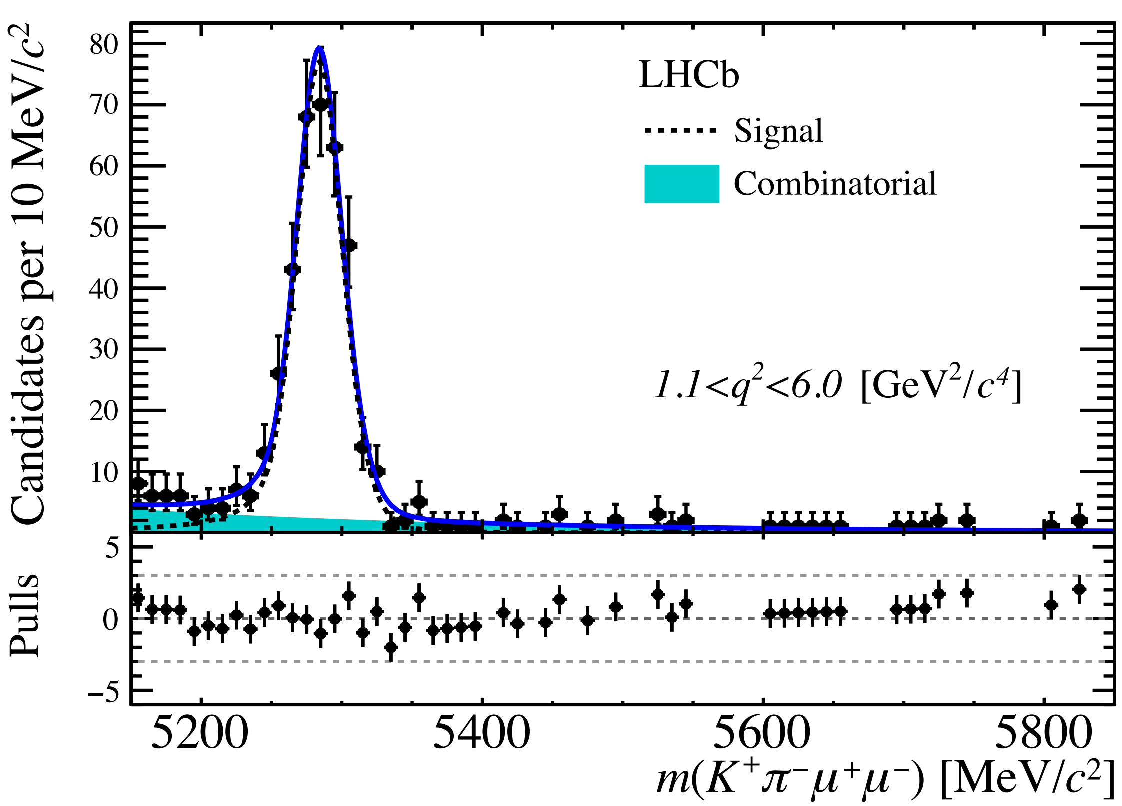


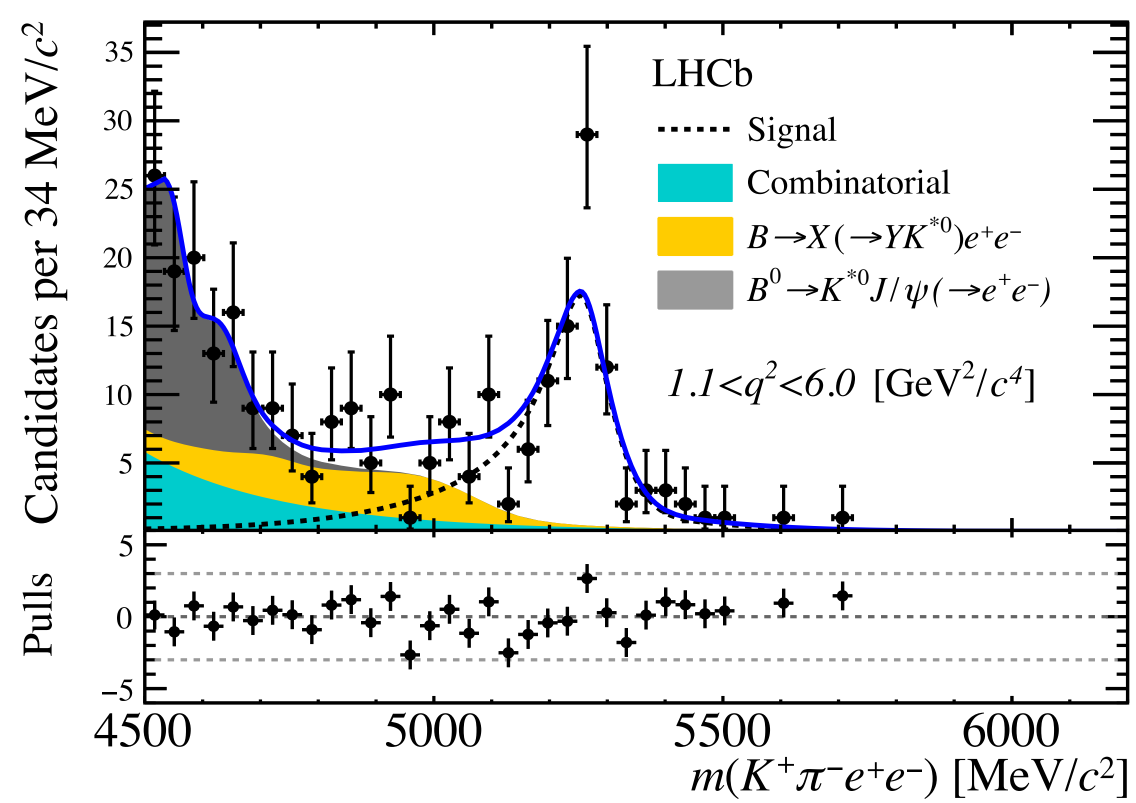
Bremsstrahlung issues

- Easier to confuse signal with 'partially reconstructed' background.



JHEP 08 (2017) 055





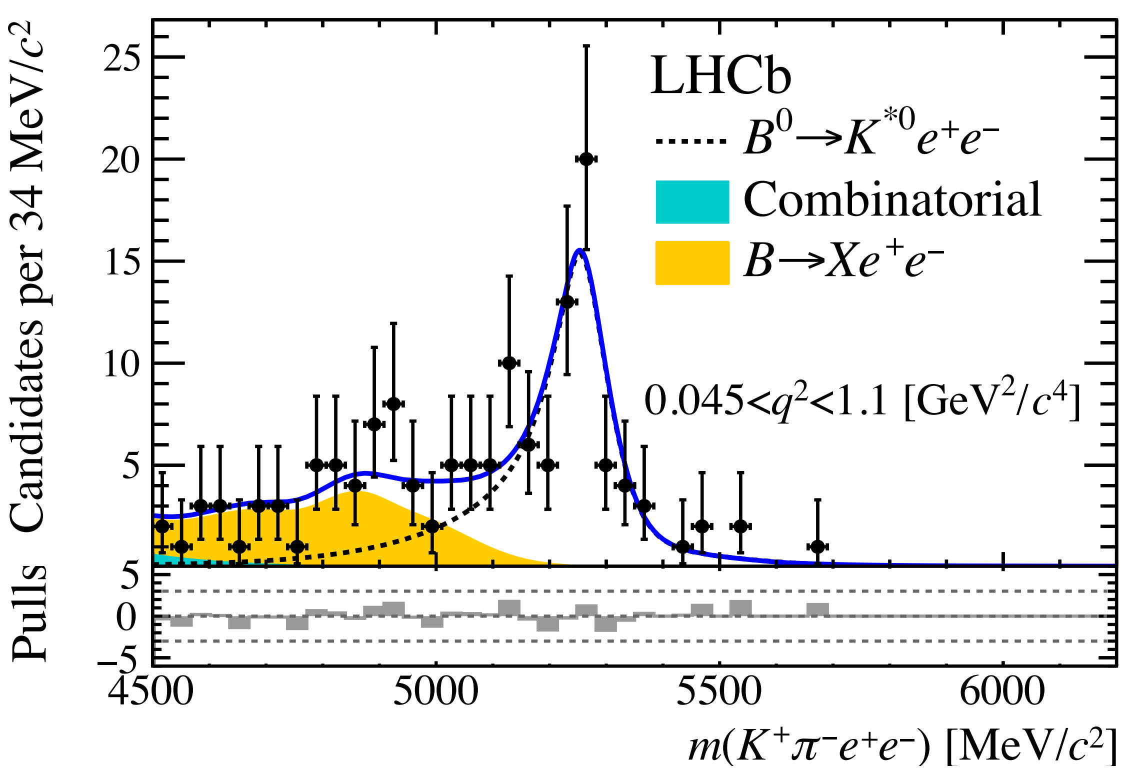
Measurement at LHCb

LHCb-PAPER-2017-013, arXiv:1705.05802

- Results use run 1 data - 3fb^{-1} of luminosity.
- Fit B mass in low and central q^2 regions:

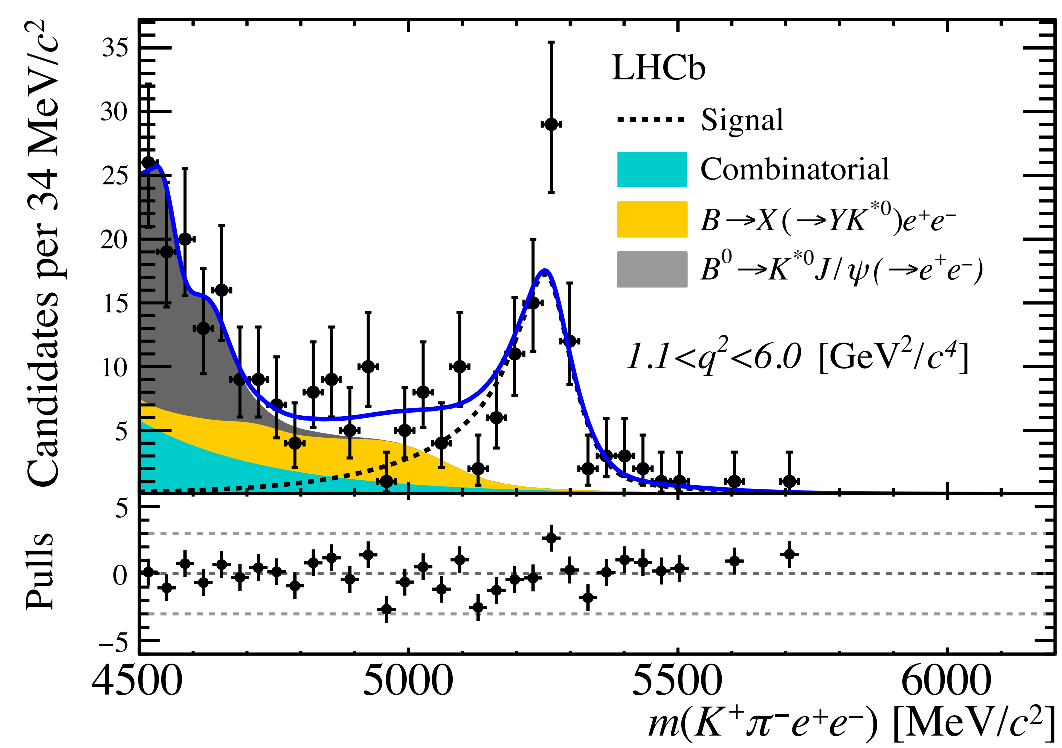
‘low’ region

$$0.045 < q^2 < 1.1\mathrm{GeV}^2/\mathrm{c}^4$$



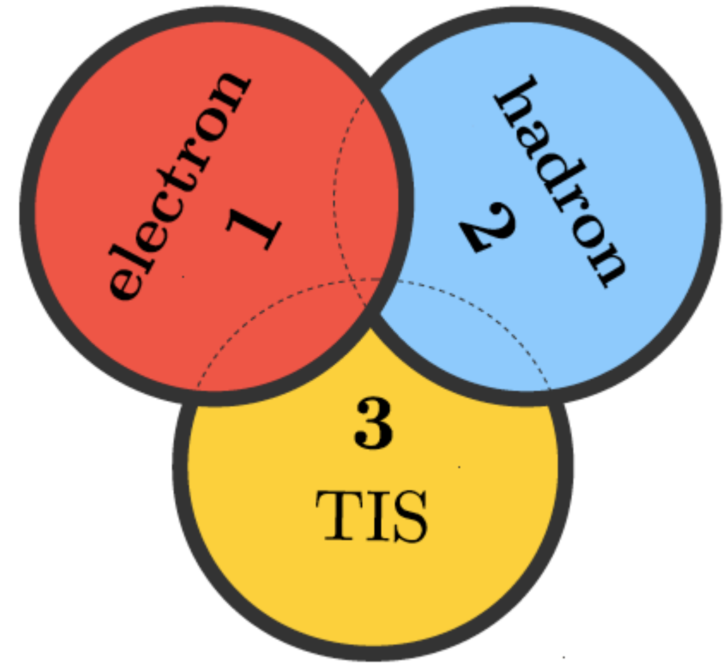
‘central’ region

$$1.1 < q^2 < 6.0\mathrm{GeV}^2/\mathrm{c}^4$$



Correcting for efficiency

- Split data depending on how event was triggered.
  - Important for cross-checks.



- The double ratio means that only efficiency differences due to kinematics can affect the result.
- Simulation is also corrected for using control samples.
  - If these corrections are not used, the result only changes by 5%.

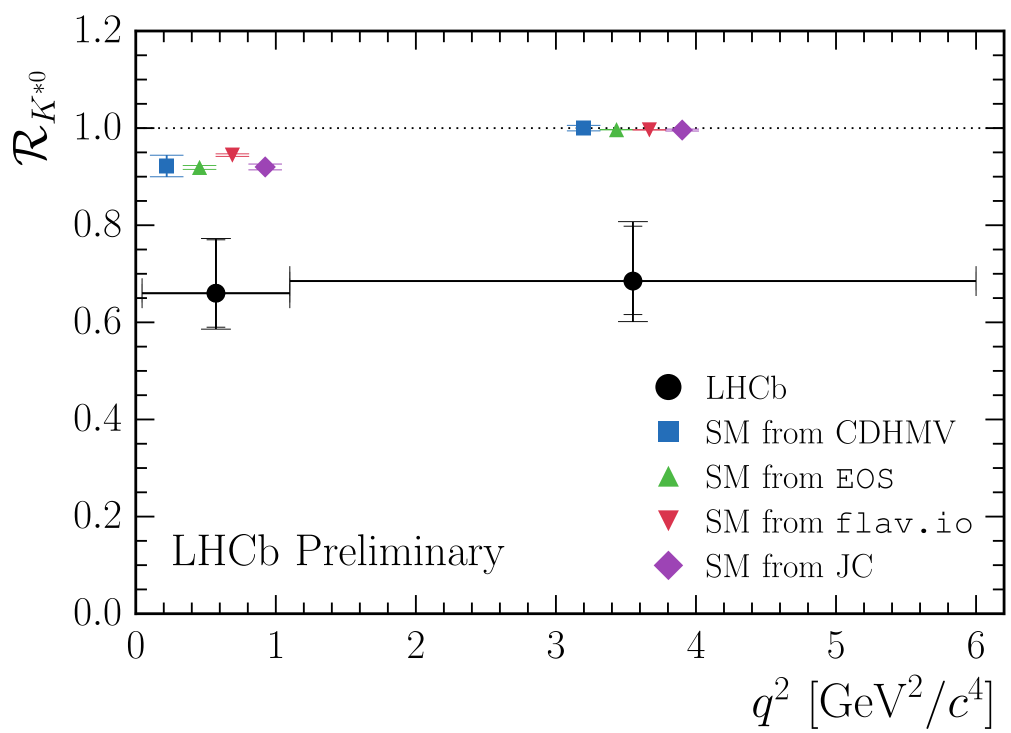
Results

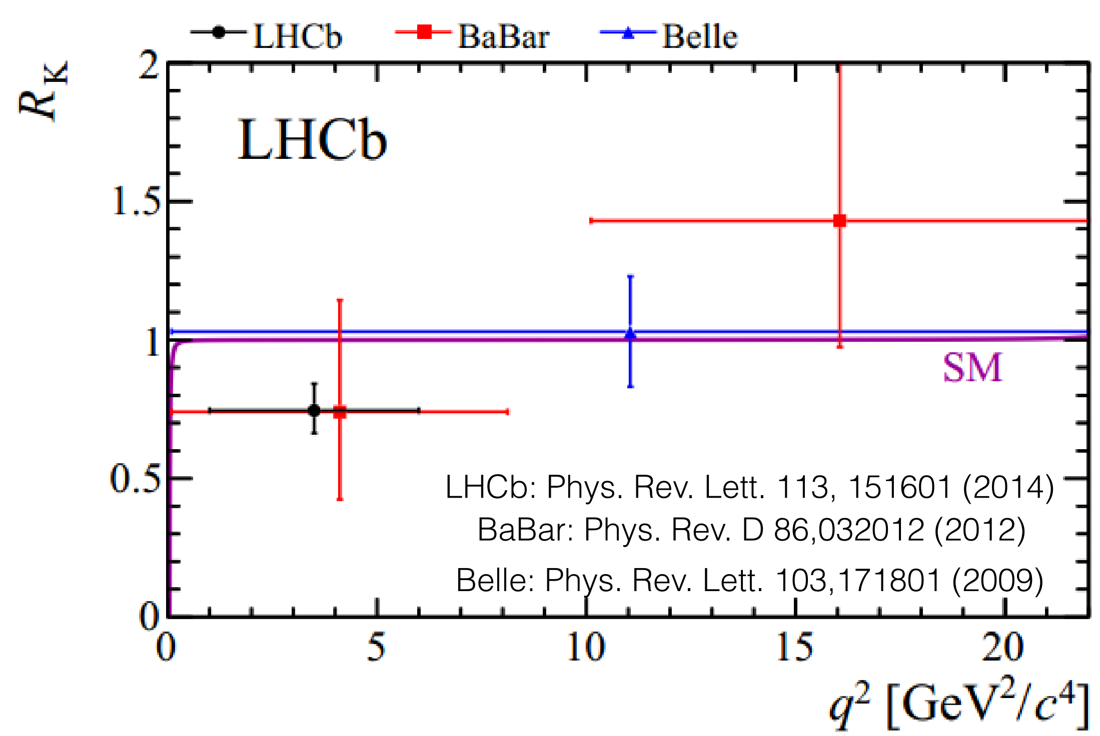
- Take ratio of signal yields and correct for efficiency to get $R_{K^{(*)}}$.

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$

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

LHCb-PAPER-2017-013





- LHCb results are 2.6 (R_K), 2.4 and 2.2σ from the SM predictions and all in the same direction.
- Error dominated by the statistical uncertainty.

What should we worry about?

- The master formula:

$$R_K = \frac{\dfrac{N(Ke^+e^-)}{N(KJ/\psi)_{ee}}}{\dfrac{N(K\mu^+\mu^-)}{N(KJ/\psi)_{\mu\mu}}} \frac{\epsilon_{\mu\mu}^{\mathrm{rel}}}{\epsilon_{ee}^{\mathrm{rel}}}$$

What should we worry about?

- The master formula:

$$R_K = \frac{\dfrac{N(Ke^+e^-)}{N(KJ/\psi)_{ee}}}{\dfrac{N(K\mu^+\mu^-)}{N(KJ/\psi)_{\mu\mu}}} \frac{\epsilon^{\text{rel}}_{\mu\mu}}{\epsilon^{\text{rel}}_{ee}}$$

- My opinion:

Easier | Harder

$$N(KJ/\psi)_{\mu\mu} \rightarrow N(KJ/\psi)_{ee} \rightarrow N(K\mu^+\mu^-) \rightarrow \epsilon^{\text{rel}}_{\mu\mu} \rightarrow N(Ke^+e^-) \rightarrow \epsilon^{\text{rel}}_{ee}$$

Cross-checks

LHCb-PAPER-2017-013

- Most powerful cross-check for efficiency, measure single ratio for the J/ψ modes.

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))} = 1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

Other cross-checks include other double ratios who's precision is known.

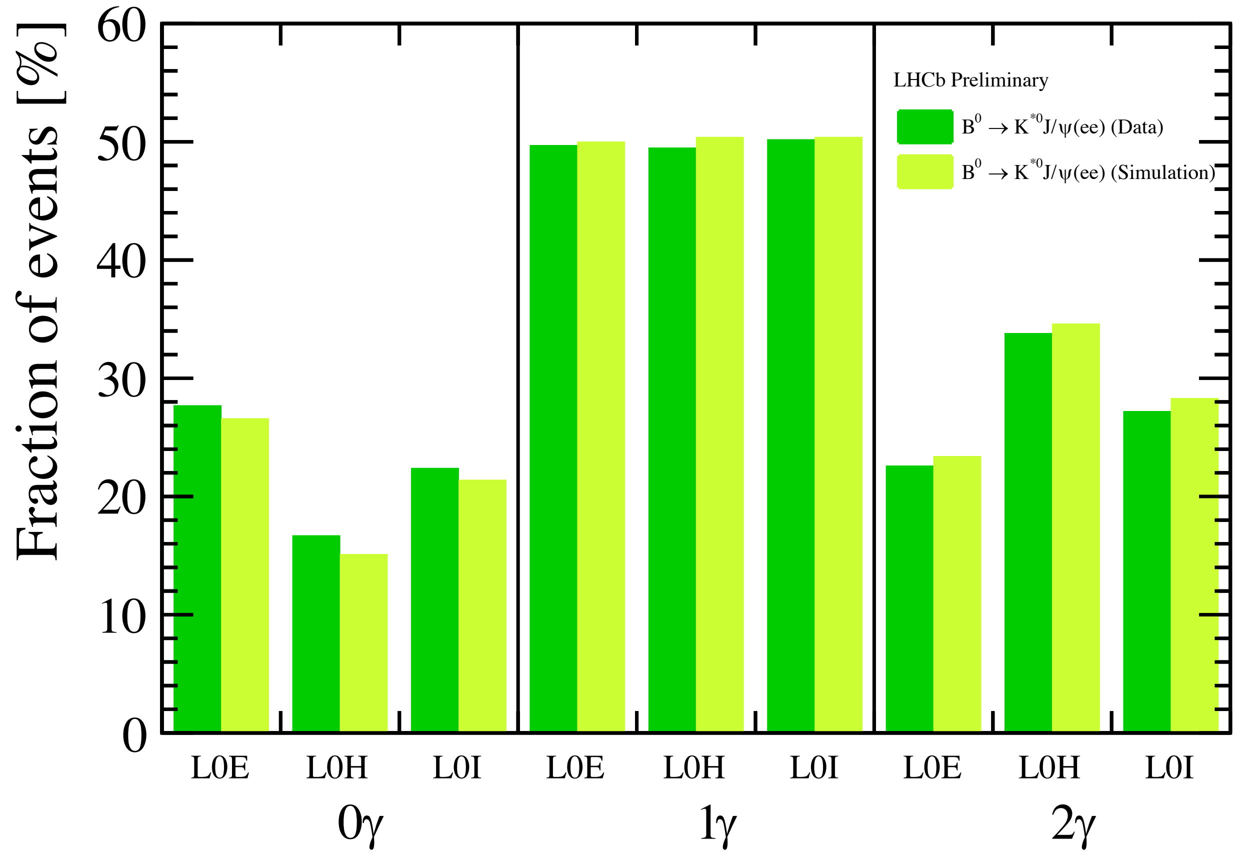
$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))}$$

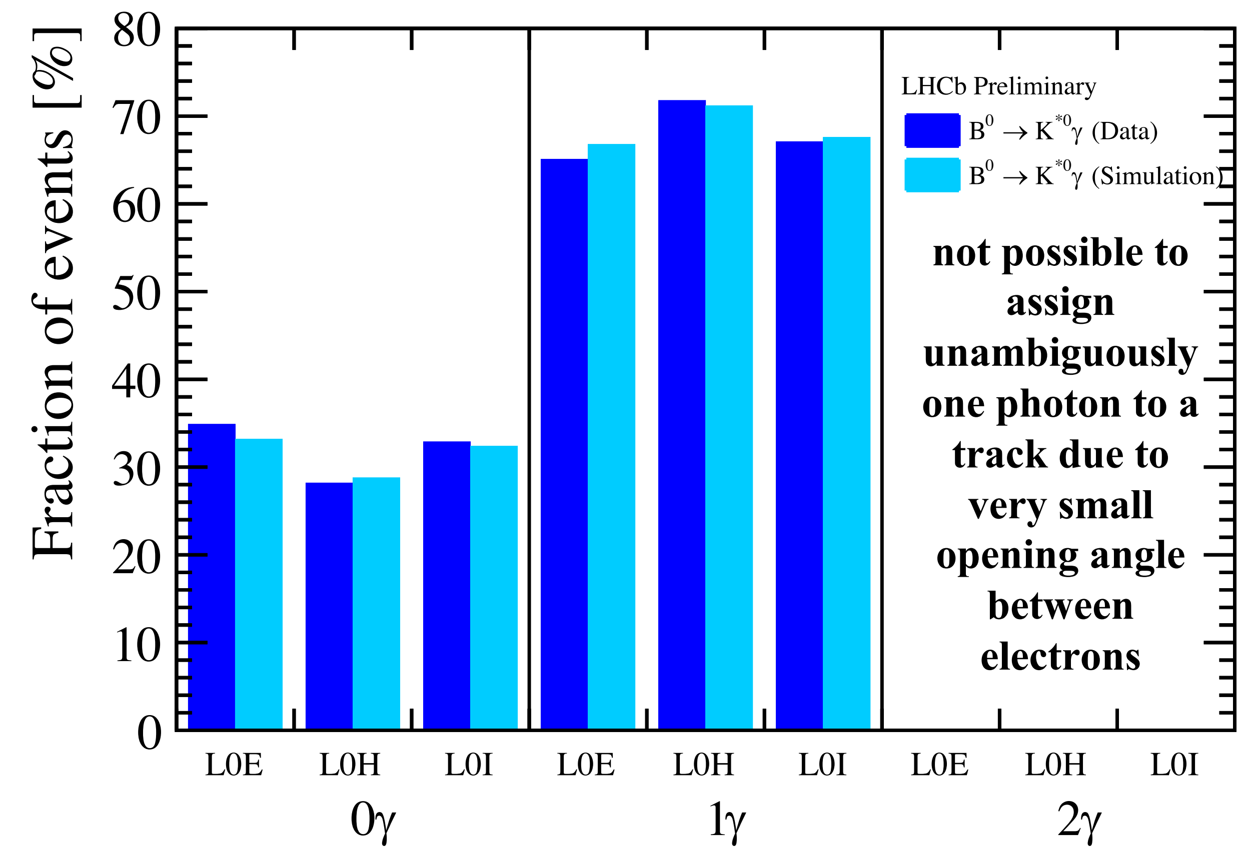
$$r_{\gamma} = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))}$$

Both of which are found to be compatible with expectations.

Cross-checks (II)

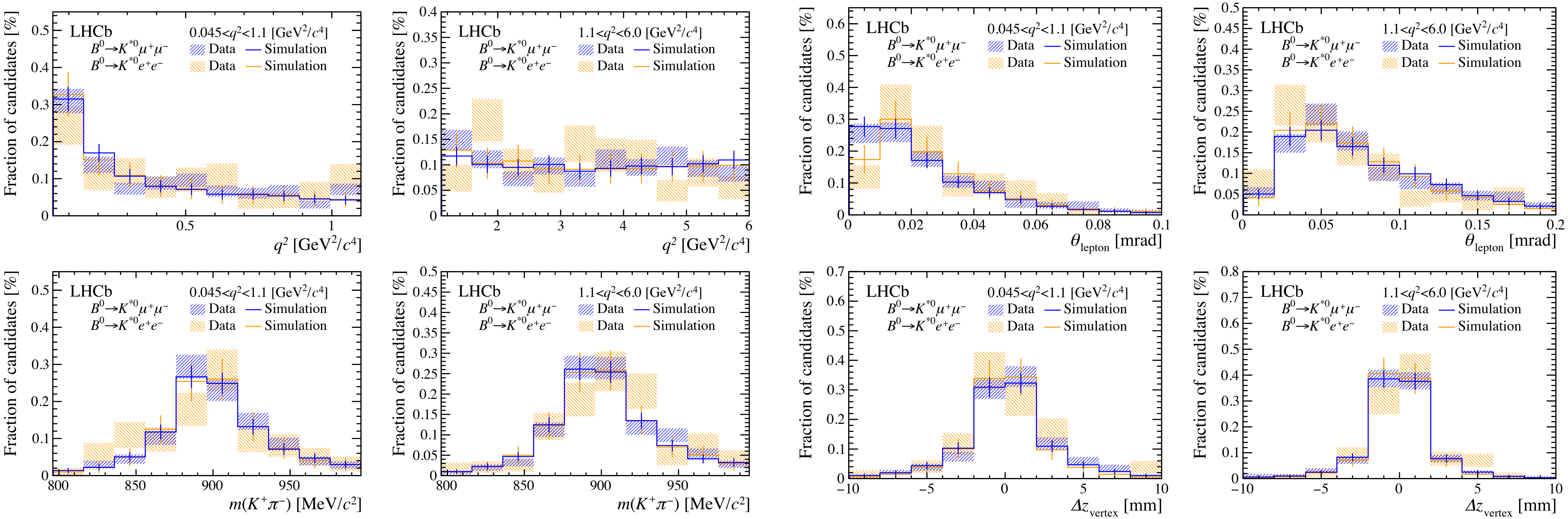
- Compare bremsstrahlung/trigger categories between data and simulation.





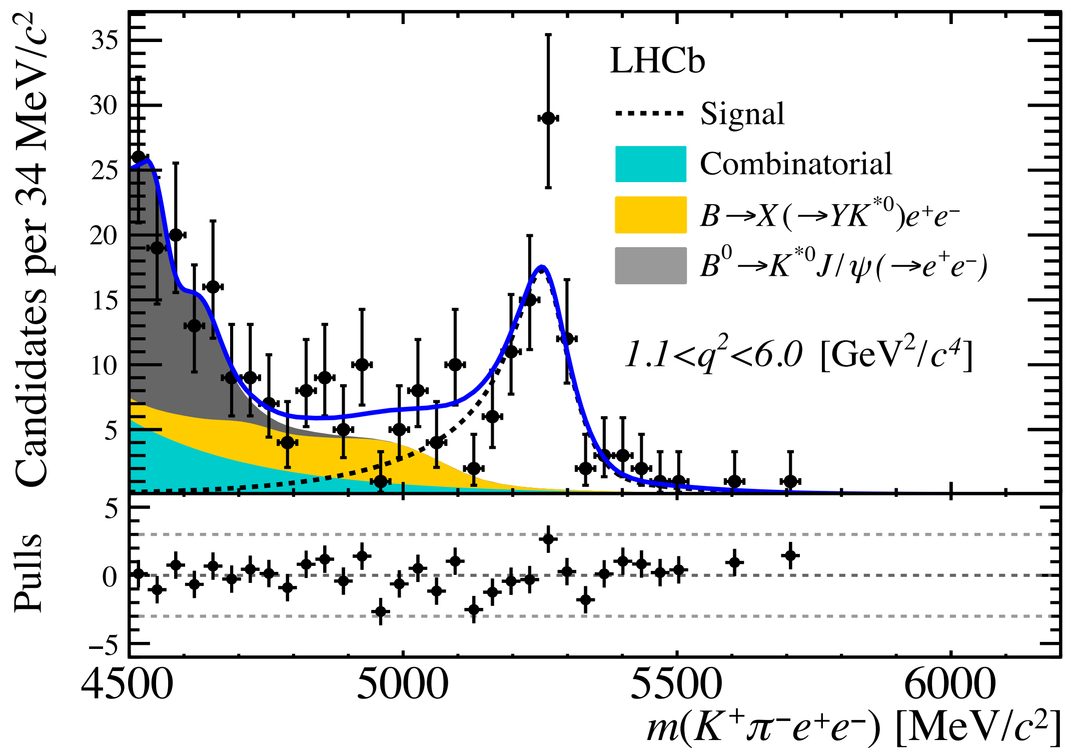
Cross-checks (III)

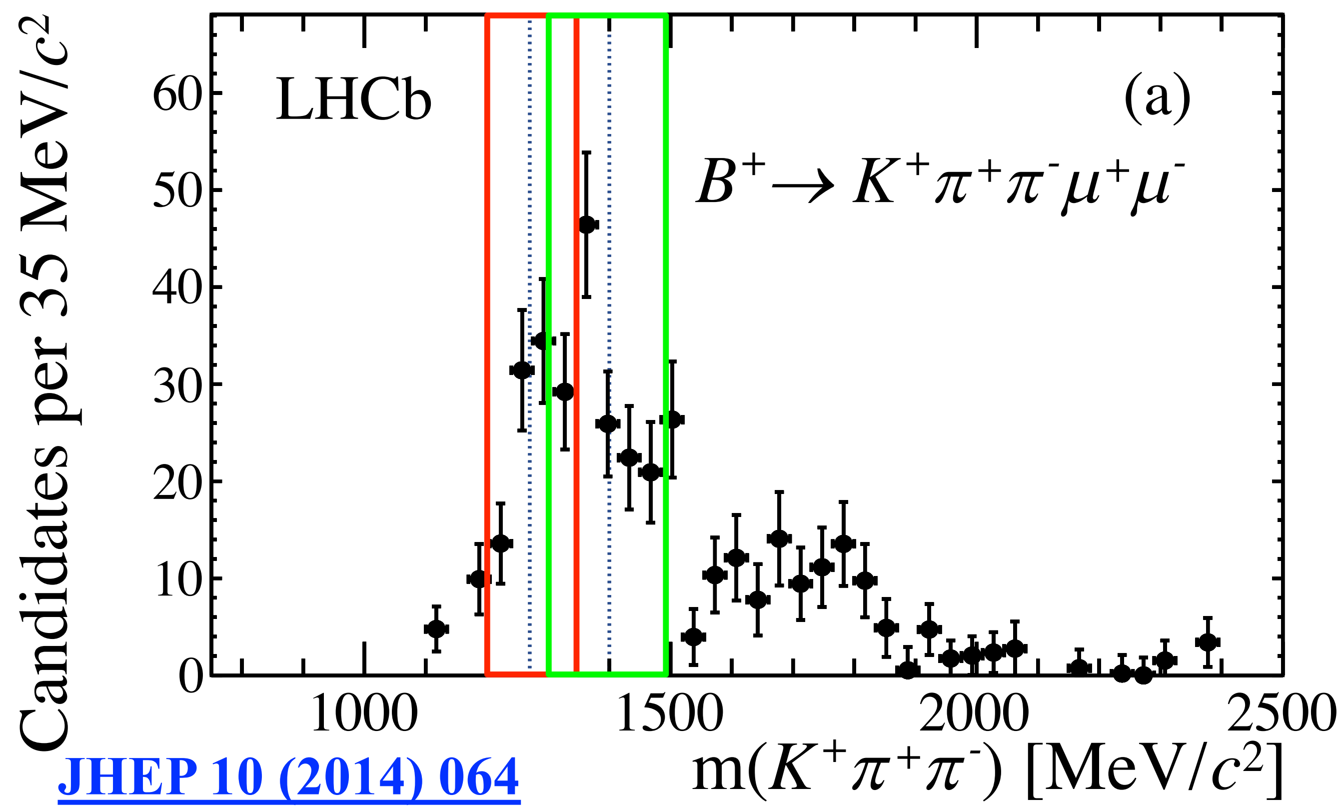
- Also compare kinematic distributions of signal peak between data/ simulation.



Cross-checks (IV)

- What about the signal yield?



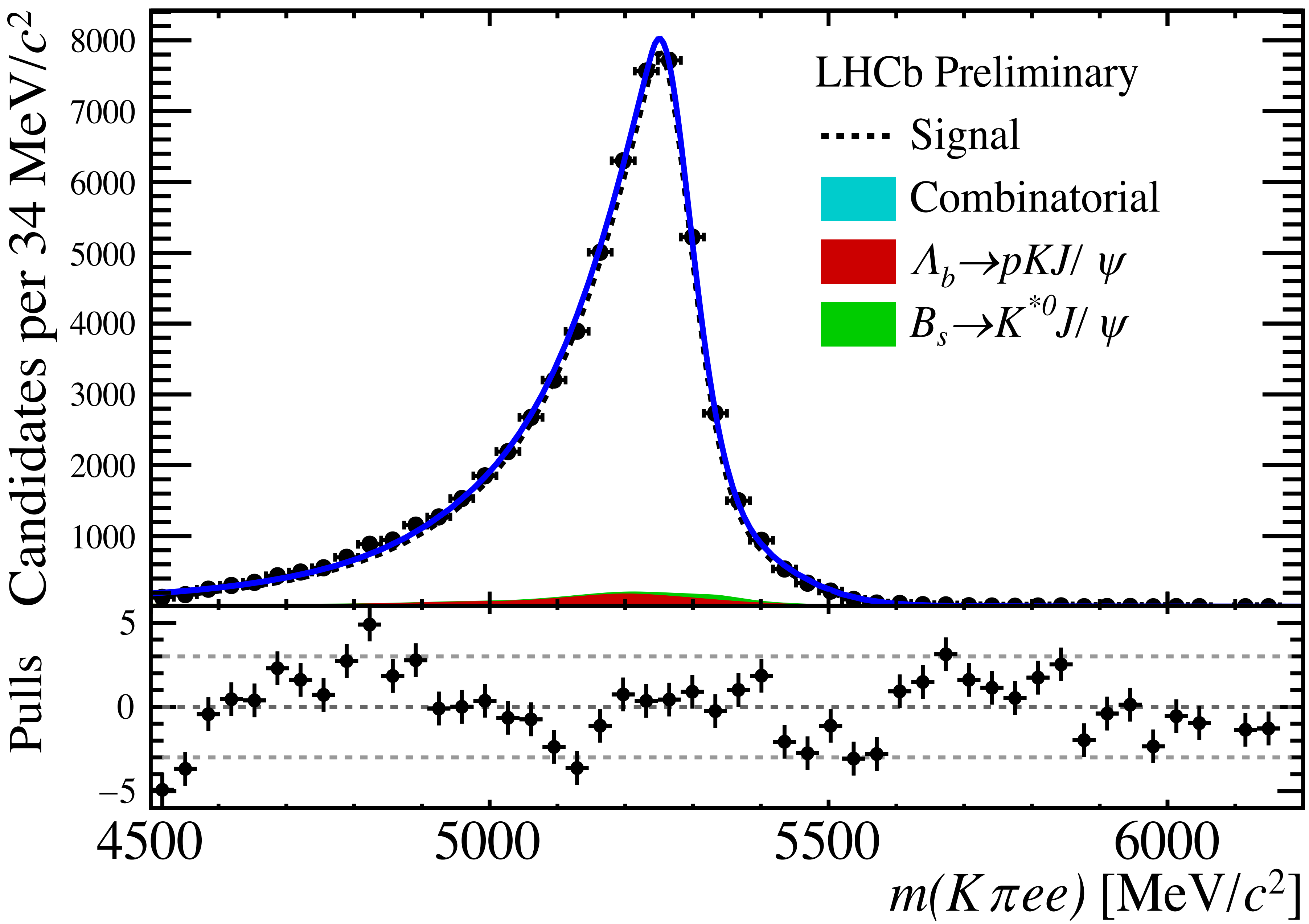


[JHEP 10 (2014) 064]

- Part. reco background controlled in two ways:
  - Using $B \to K^*(J/\psi \to e^+e^-)$
  - Using $B \to K\pi\pi\mu^+\mu^-$

Cross-checks (V)

- What about modelling of signal yield?

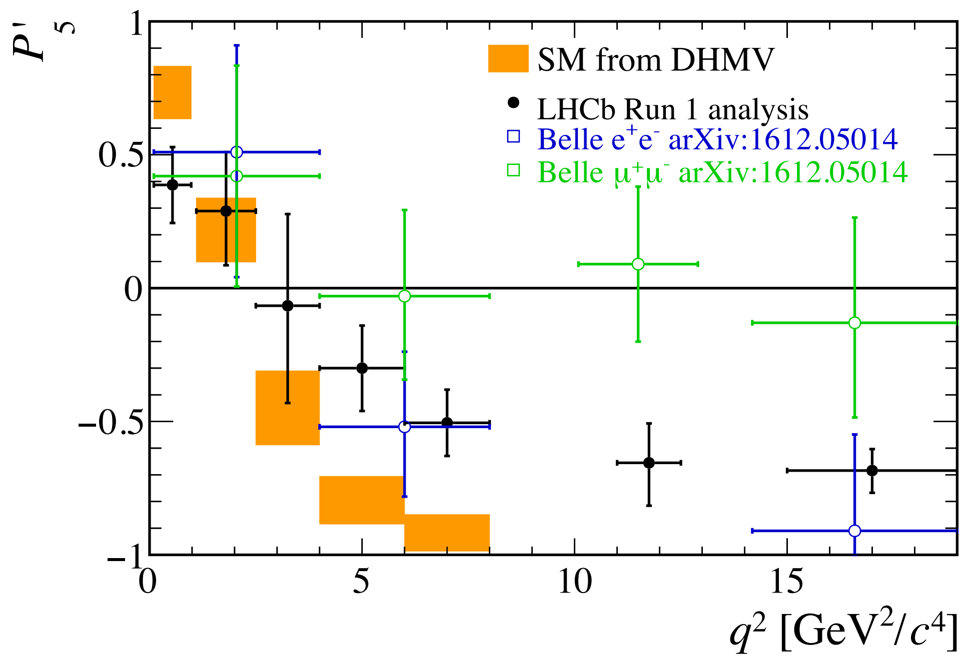


Residual worries?

$$R_K = \frac{\frac{N(Ke^+e^-)}{N(KJ/\psi)_{ee}}}{\frac{N(K\mu^+\mu^-)}{N(KJ/\psi)_{\mu\mu}}} \frac{\epsilon^{\mathrm{rel}}_{\mu\mu}}{\epsilon^{\mathrm{rel}}_{ee}}$$

Summary and outlook

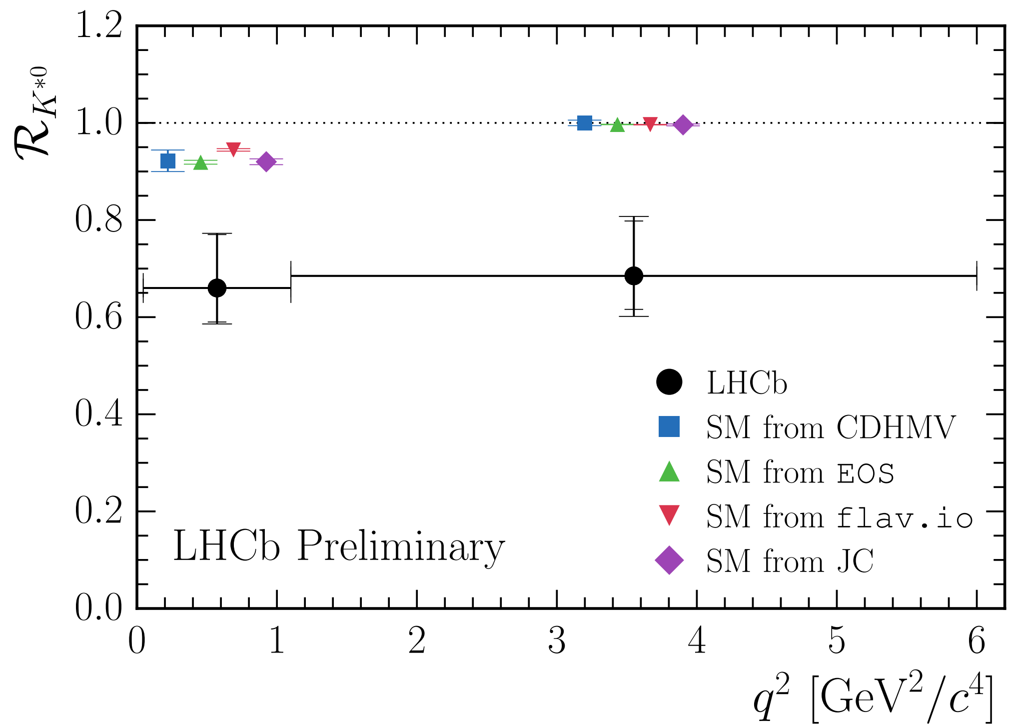
- We are three separate hints for NP in b—>sll decays, which different experimental and theoretical uncertainties.
    - Nothing is conclusive, but the fact that they are all consistent is encouraging.
- LHCb is looking forward to updating the R results with run II.
    - Also want to measure P_5' for electrons.
- Also might expect to see discrepancies in the B_s^0—>μμ branching fraction eventually.

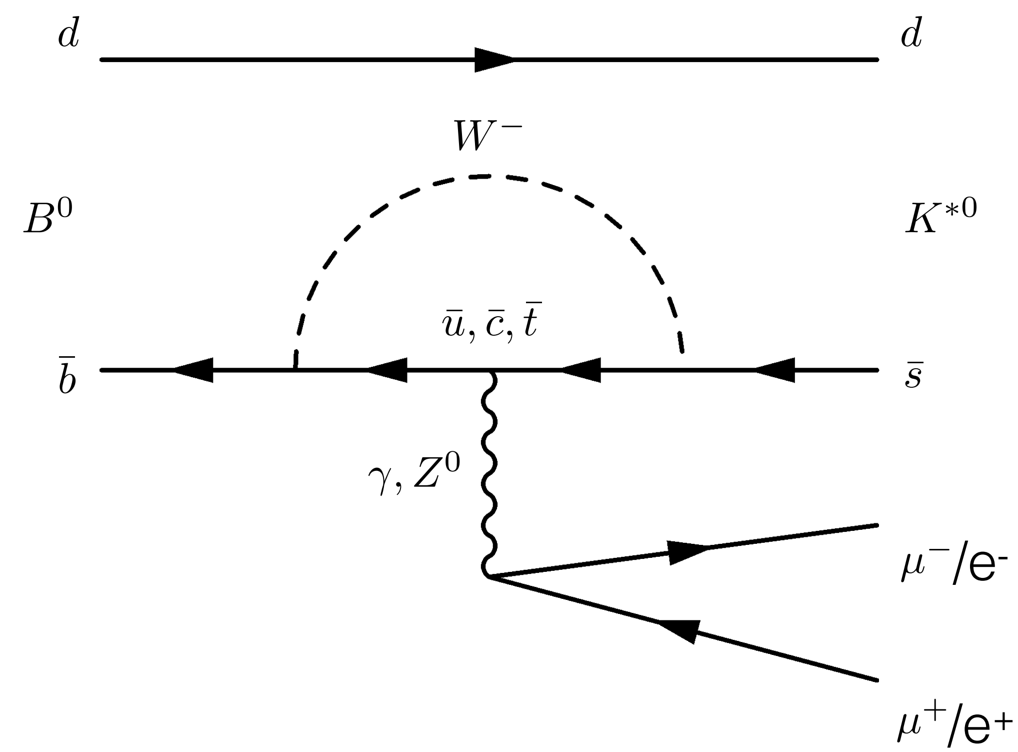


Back-ups

Remarks on the first bin

- If we assume NP is heavy, its hard to accommodate the shift in the first q^2 bin.





- At low q^2, the decay amplitude is dominated by the photon diagram - must be lepton universal!

- There are models which get around this with light mediators (see e.g. Sala, Straub, arXiv:1704.06188).