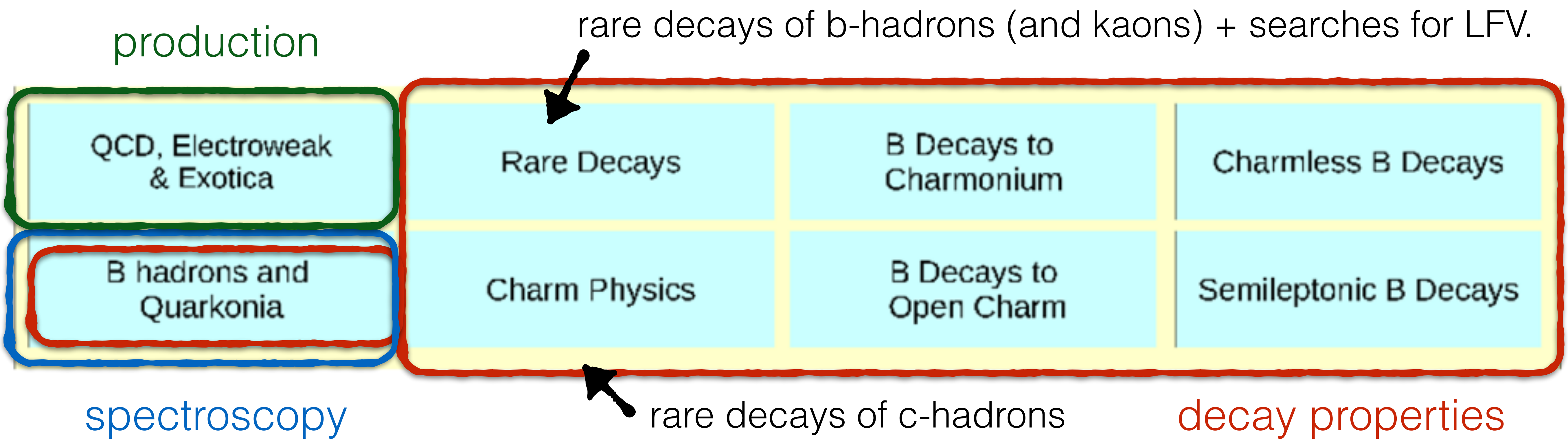
Decay properties of heavy hadrons and of τ leptons, and the search for rare or SM forbidden decays at LHCb

T. Blake on behalf of the LHCb collaboration

LHCFWG 10/11/15

LHCb WG structure

- The LHCb collaboration is organised loosely in 8 WGs.



- Top, EW and Quarkonia are in separate LPCC WGs.
- The WG's are arranged such that similar types of analysis are grouped together.

Disclaimer

- "Decay properties of heavy hadrons and of τ leptons, and the search for rare or SM forbidden decays" covers a large part of LHCb's physics programme (more than 200 papers).
- I will just pick (with some personal bias) a couple of example analyses/issues that might be of interest to the LHCFWG.
- For an exhaustive list of our results:
  - ➡ http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Decay properties?

- Branching fractions
  - ➡ Averaged by the Particle Data Group (http://pdg.lbl.gov/).
- Lifetimes (B_s, Λ_b, Ξ_b ,Ω_b and B_c etc)
  - ➡ Averaged by HFAG (http://www.slac.stanford.edu/xorg/hfag/)
- Mass and width differences
  - ➡ Averaged by HFAG
- CP violating phases
  - ➡ Averaged by HFAG, CKMFitter (http://ckmfitter.in2p3.fr/) or UTFit (http://www.utfit.org/UTfit/) for CKM angles.
  - ➡ Internal γ combination performed by LHCb.

$B_{(s,d)} \to \mu^+\mu^-$ branching fraction

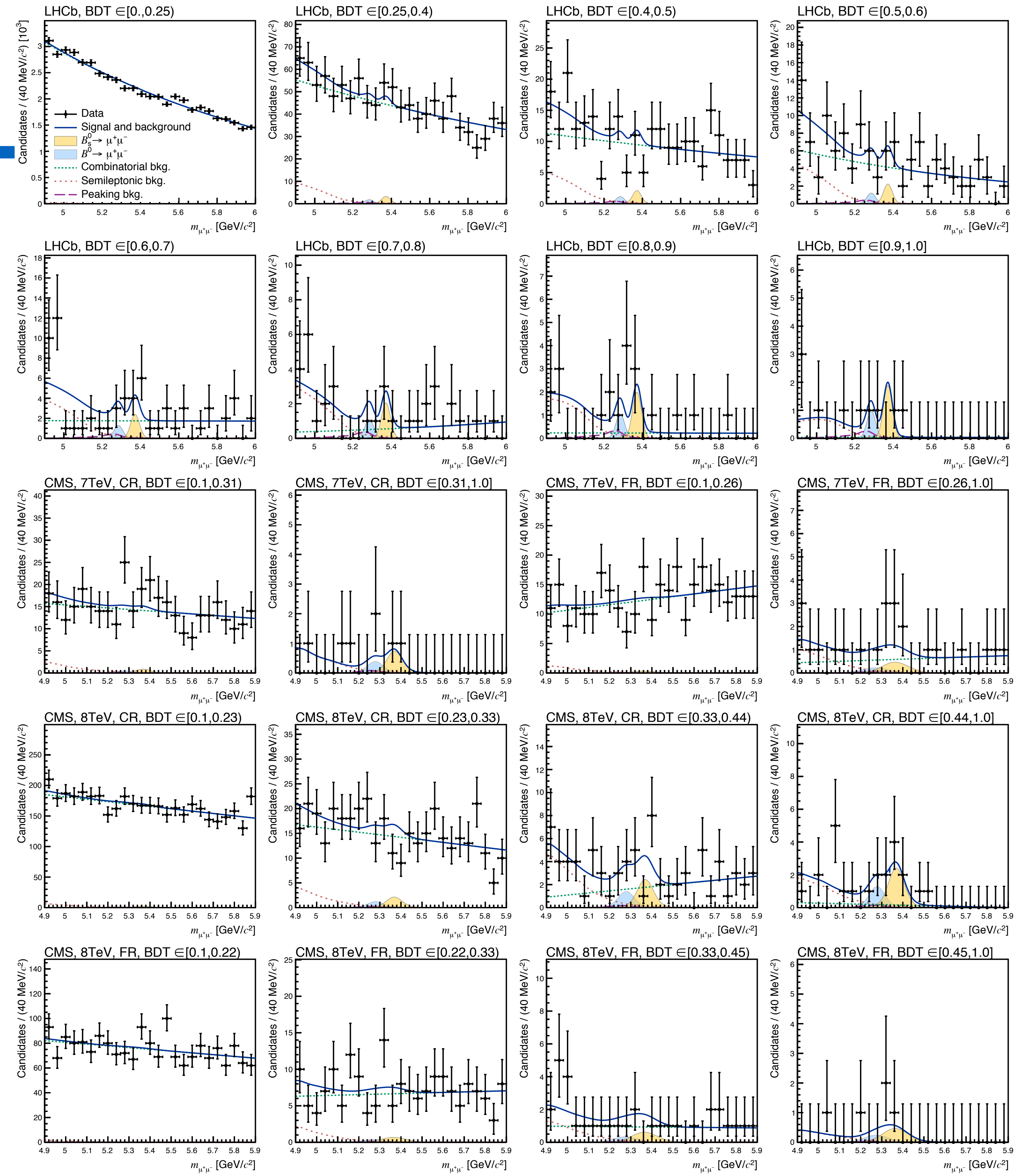
- Combination of branching fraction is straightforward with a well defined likelihood but there is (AFAIK) no good prescription to combine upper limits.
    - ➡ The PDG just uses the best single measurement.
- This was the motivation behind the joint analysis of $B_{(s,d)} \to \mu^+\mu^-$ performed by LHCb/CMS. This was a useful experience
    - ➡ Harmonisation of the analyses led to an improved understanding of background modelling ($\Lambda_b \to p\mu\nu$) and lifetime dependent effects (and the best possible result).

  but not without its problems:
    - ➡ It was an intensive process and there is no way to update the combination if an experiment updates one of its measurements.

This process convinced us that a LHCFWG would be useful.

$B_{(s,d)} \to \mu^{+}\mu^{-}$

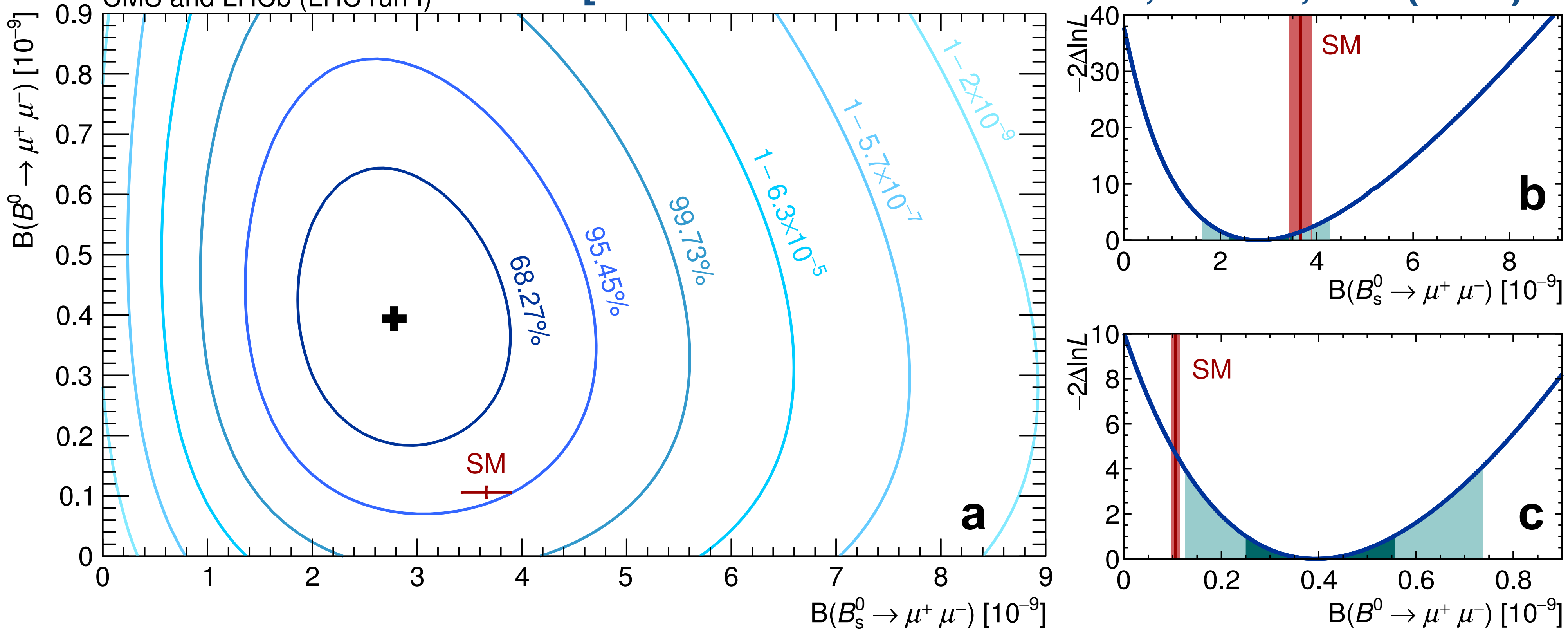
- Simultaneous analysis of the LHCb and CMS datasets.
  - ➡ Binned in MVA response.
  - ➡ CMS data also split by barrel/end cap.
- Nuisance parameters (background branching fractions, f_s/f_d) shared between the experiments.



[CMS + LHCb collaborations, Nature, 522 (2015) 68]

$B_{(s,d)} \rightarrow \mu^+ \mu^-$

[CMS + LHCb collaborations, Nature, 522 (2015) 68]



- Best fit results:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

➡ B_s decay observed at 6.2σ, evidence for B^0 decay at 3.0σ

Branching fractions

- We generally measure branching fractions w.r.t. to a control mode:

$$\mathcal{B}(\text{signal}) = \frac{f_{q'}(\text{control})}{f_q(\text{signal})} \frac{N(\text{signal})}{N(\text{control})} \frac{\varepsilon(\text{control})}{\varepsilon(\text{signal})} \mathcal{B}(\text{control})$$

ratio of hadronisation fractions

ratio of yields

ratio of efficiencies

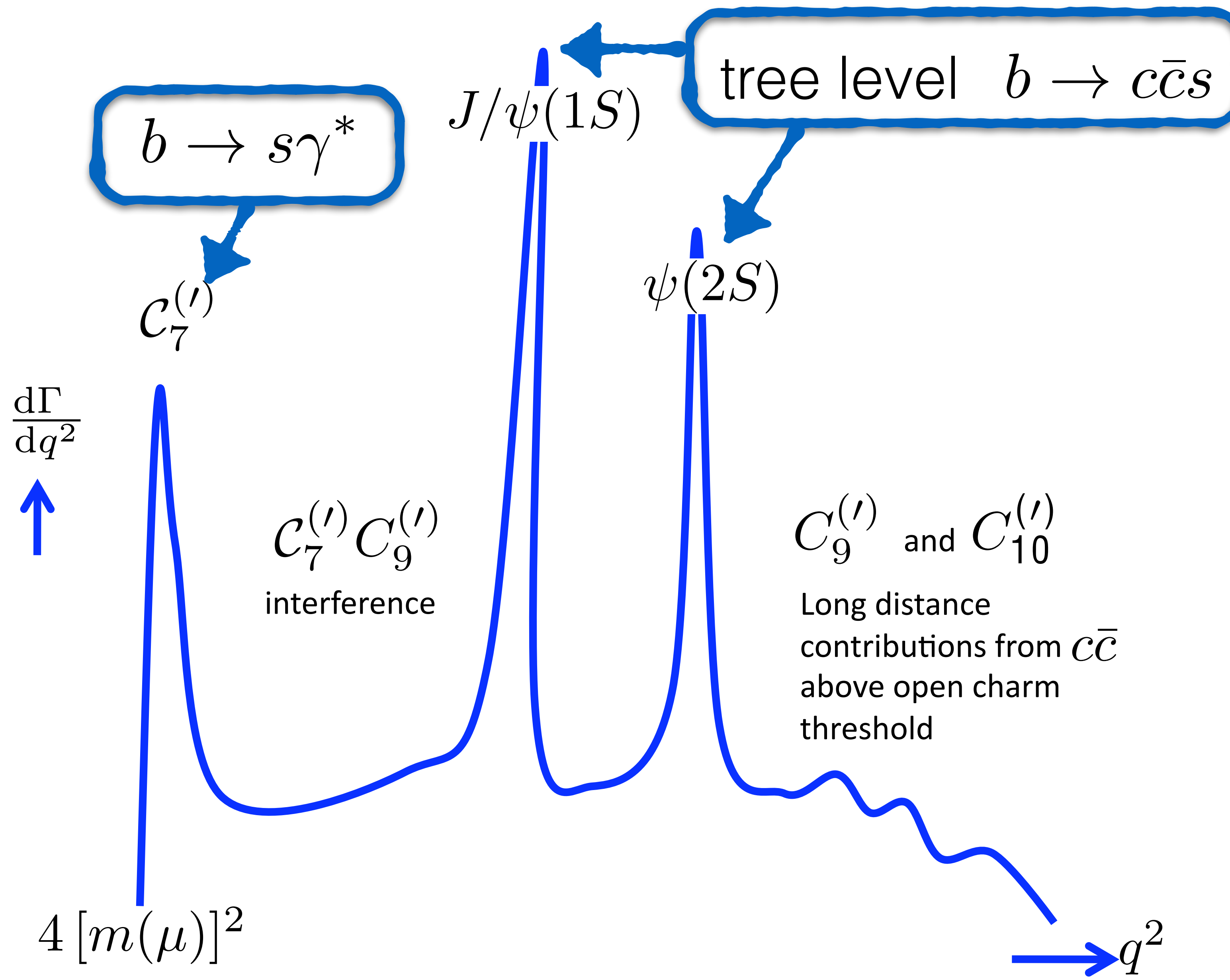
branching fraction of control mode

- The hadronisation fractions and control mode branching fraction are clearly correlated between experiments.

- We try to state the value of $\mathcal{B}(\text{control})$ in our papers (the PDG is a moving target so citing the PDG may not be sufficient for a future combination).

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

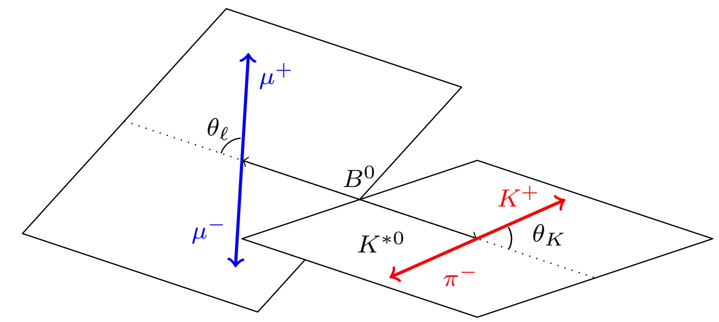
- Large number of observables: branching fractions, CP asymmetries and angular observables.
- Sensitive to new vector/axial-vector currents and virtual photon polarisation (left-handed in SM).
- Also receives contributions from intermediate hadronic states decaying to a dimuon pair.



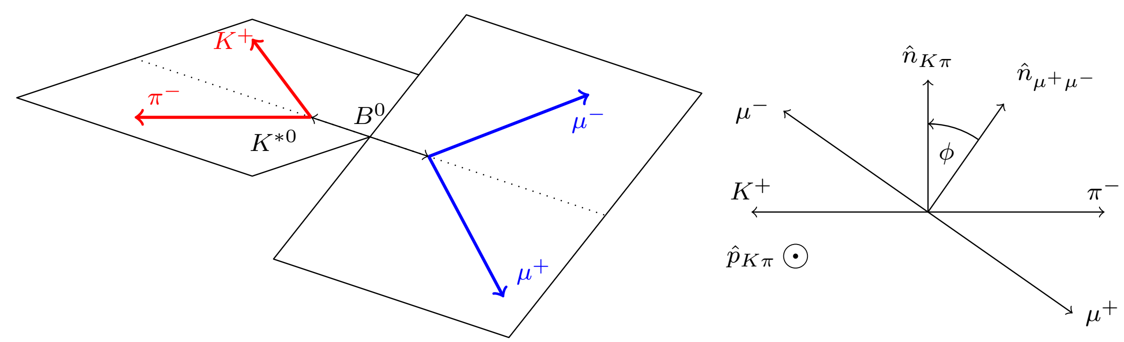
dimuon invariant mass squared, q^2

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

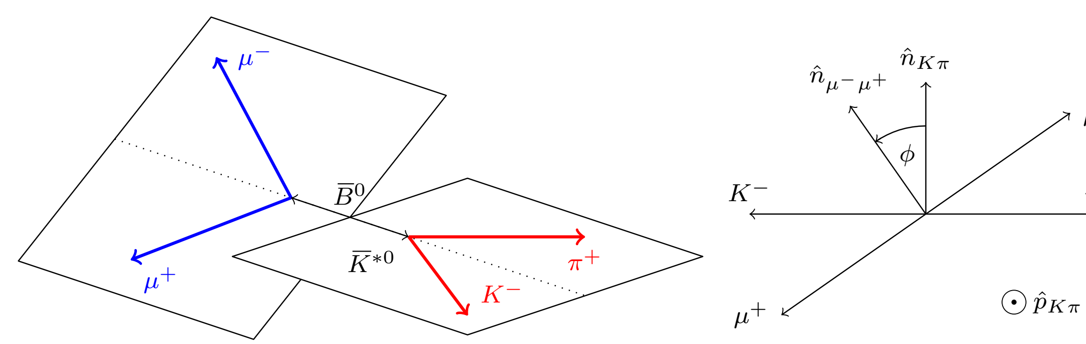
- Four-body final state.
  - ➡ Angular distribution provides many observables that are sensitive to NP.
- System described by three angles and the dimuon invariant mass squared, q^2.
  - ➡ Angular convention is important, it determines the sign convention for the observables (source of endless confusion when comparing theory/experiment).
  - ➡ It would be good to have a common convention between experiments.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

Our convention is defined in **[JHEP 08 (2013) 131]**

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

increasing dataset

increasing complexity

[PRL 108 (2011) 181806]
0.37 fb^{-1} analysis fitting single angle projections.

[JHEP 08 (2013) 131]
[PRL 101 (2013) 191801]
1 fb^{-1} analyses using angular folding to extract a larger number of angular observables.
Tension seen w.r.t SM predictions in P'_5.

[LHCb-CONF-2015-002]
[LHCb-PAPER-2015-051]
3 fb^{-1} full angular analysis

Amplitude analysis of $K\pi\mu^+\mu^-$?

We determine the full set of CP-averaged and CP-asymmetric angular observables. S-wave is included in the analysis (this was our largest source of systematic uncertainty).

We are statistically limited. Systematic uncertainties will remain negligible with the run II dataset.

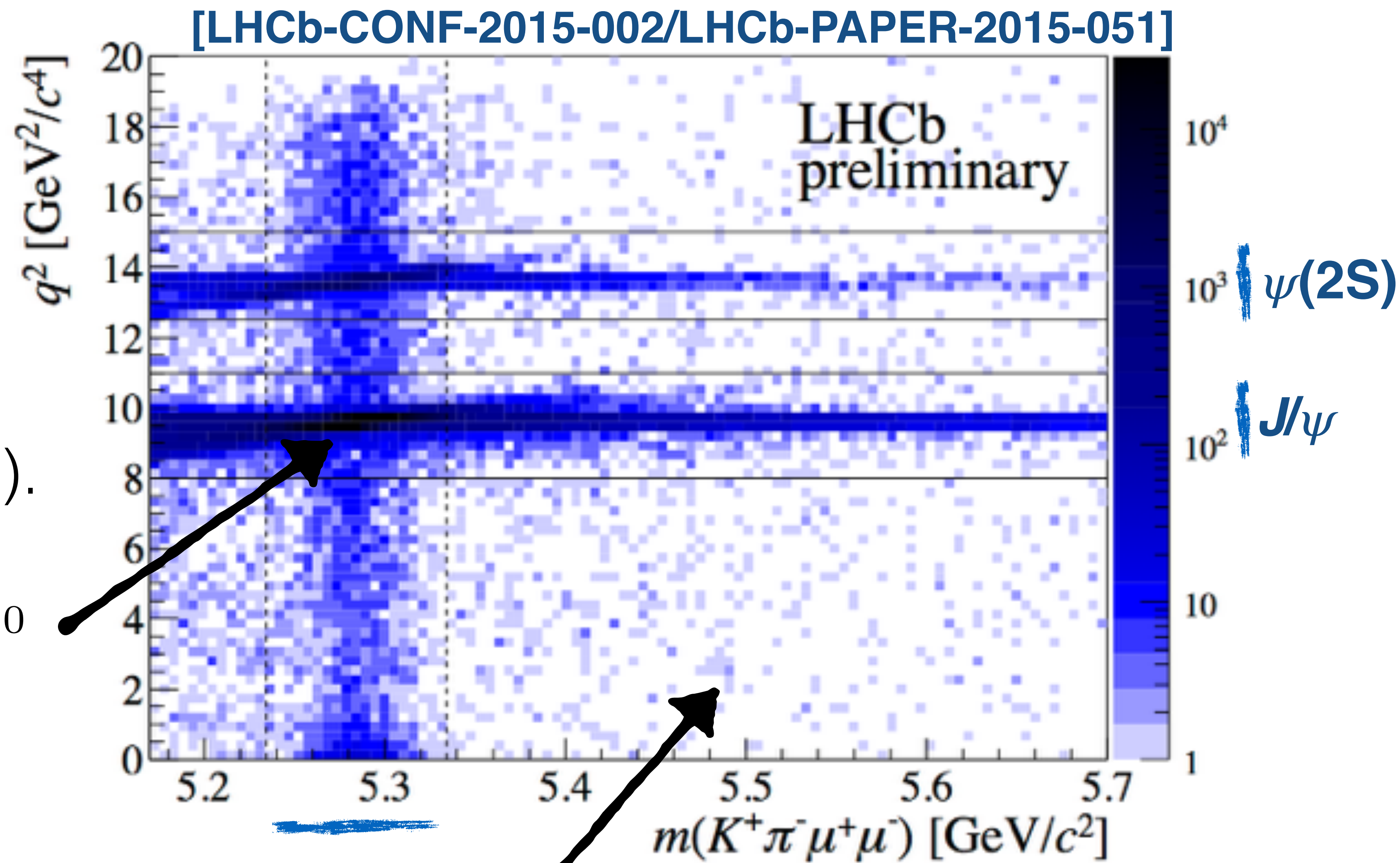
NB: Our q^2 binning has evolved with time, but we have used a ±100 MeV mass window for the K* throughout.

3fb^{-1} $B^0 \to K^{*0}\mu^+\mu^-$ analysis

Select clean sample of signal events using multivariate classifier.

2398 ± 57 candidates in $0.1 < q^2 < 19$ GeV^2 after removing the J/ψ and $\psi(2S)$.

$B^0 \to J/\psi K^{*0}$



combinatorial background

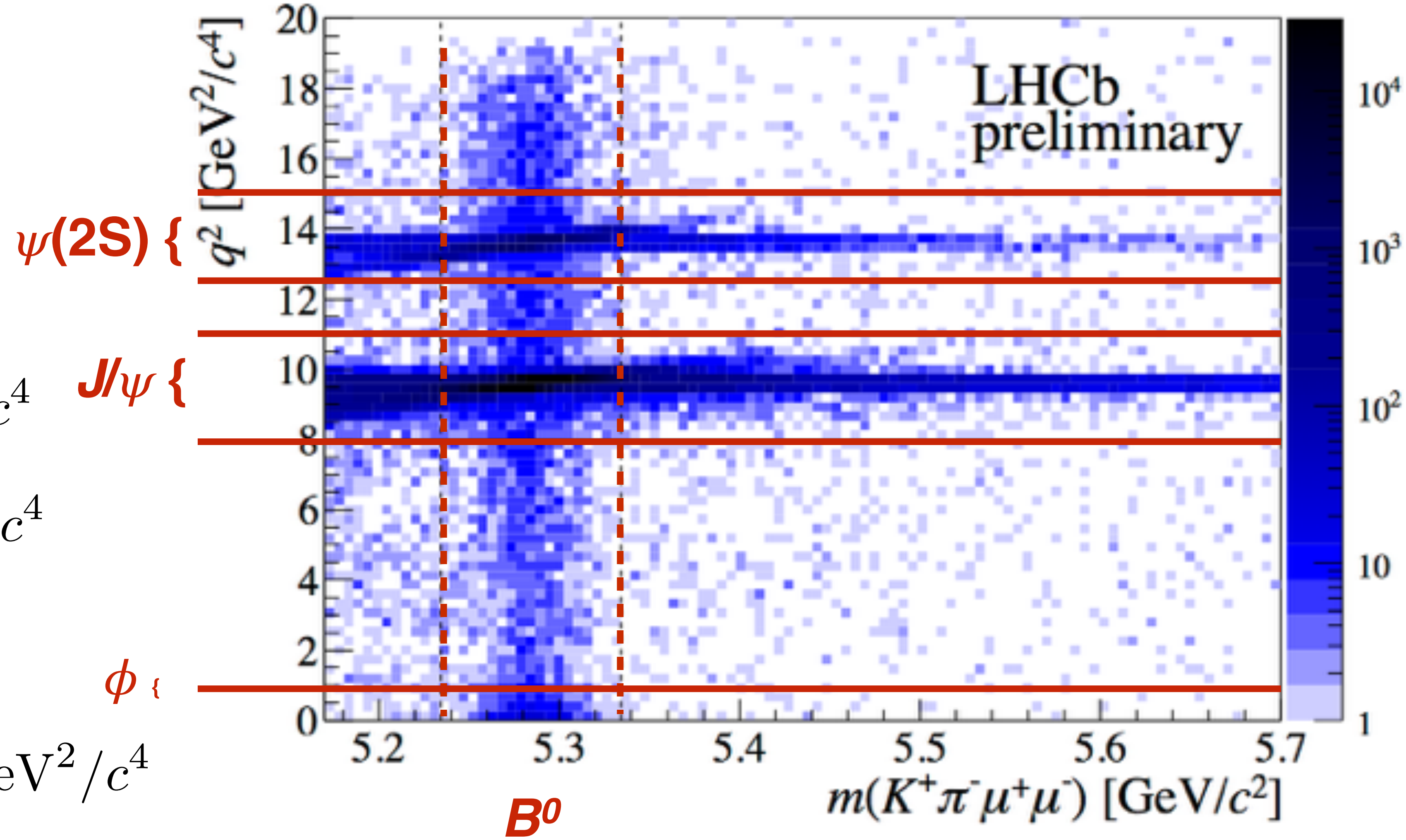
You can see the same structure in the data as in the cartoon.

We would ideally like to subdivide the data as finely as possible in q^2

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

We remove the narrow Charmonium states using the vetoes $8.0 < q^2 < 11.0~\mathrm{GeV}^2/c^4$ and $12.5 < q^2 < 15.0~\mathrm{GeV}^2/c^4$

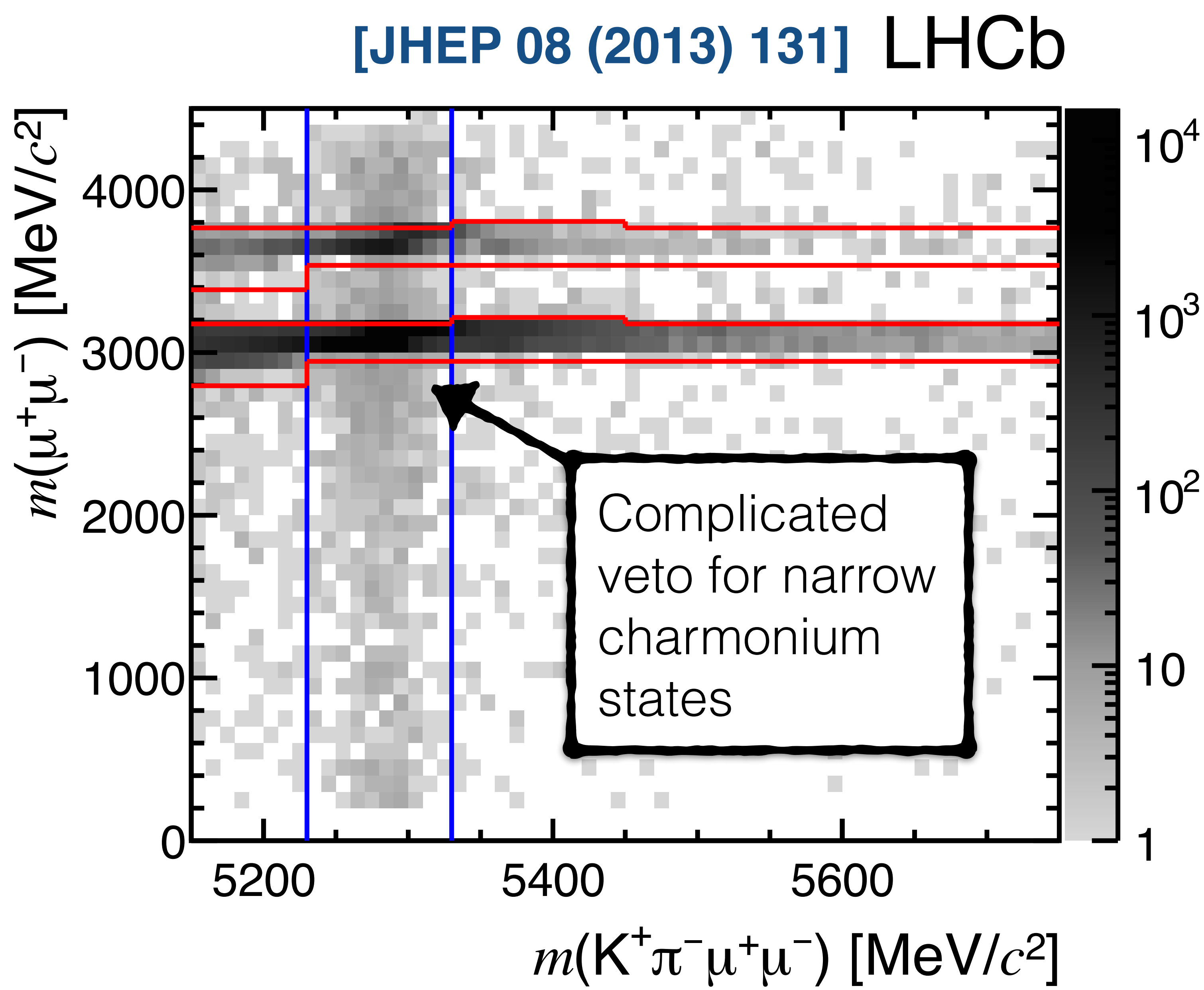
Veto $0.98 < q^2 < 1.1~\mathrm{GeV}^2/c^4$ to remove the ϕ (we can see this in our dataset).



Old 1 fb^{-1} analysis

- We have changed our q^2 binning scheme for this round of the analysis.
  - ➡ Obviously this is something that would be good to agree on between the LHC experiments.

[JHEP 08 (2013) 131]

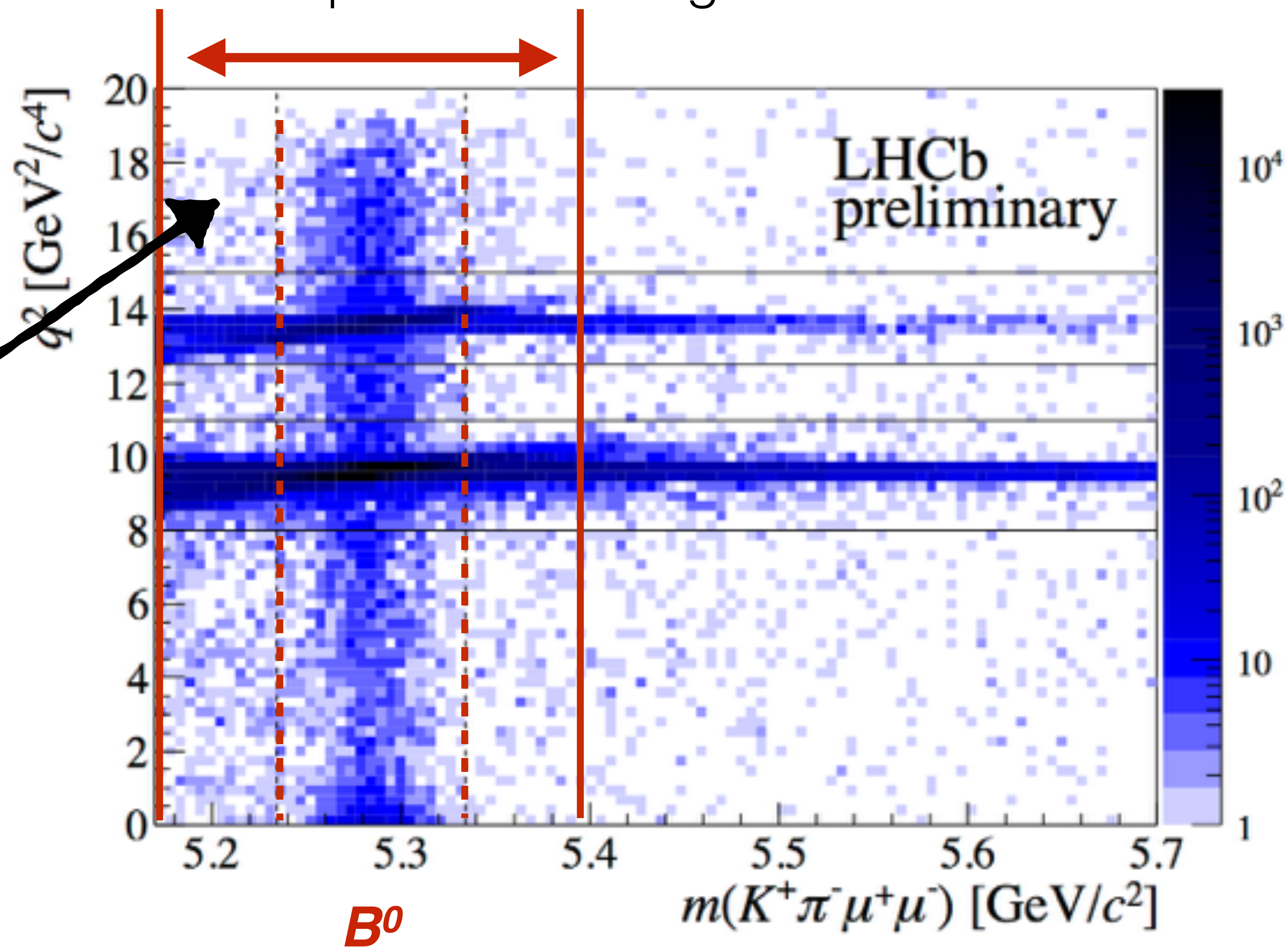


The old binning scheme came from Belle and is not ideal for LHCb (any of the LHC experiments?) due to our mass resolution.

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

forms a broad ‘peak’ in this region

Suppress backgrounds from e.g. $\Lambda_b^0 \to pK^-\mu^+\mu^-$ (if the p is misidentified as a π) using PID information.

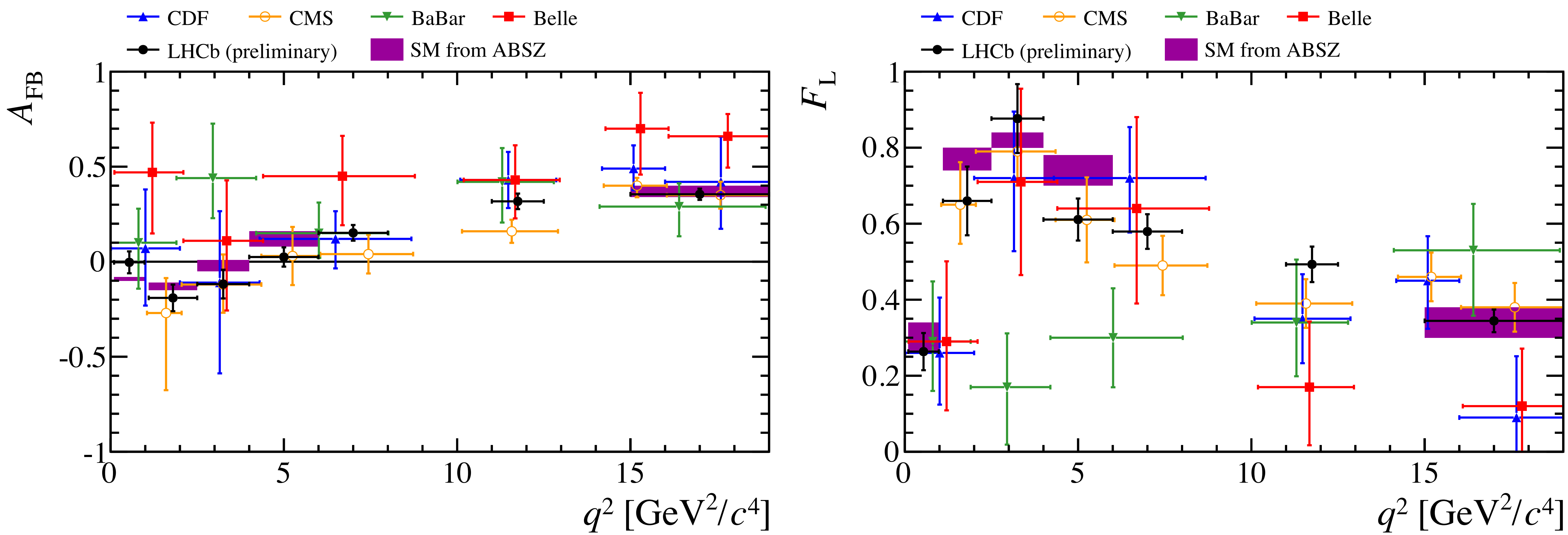


We can invert our PID requirements to measure the branching fractions of the different peaking backgrounds.

Would this be useful for future ATLAS/CMS analyses?

Results

- Majority of observables are consistent between experiment/SM predictions. Good degree of consistency between experiments.

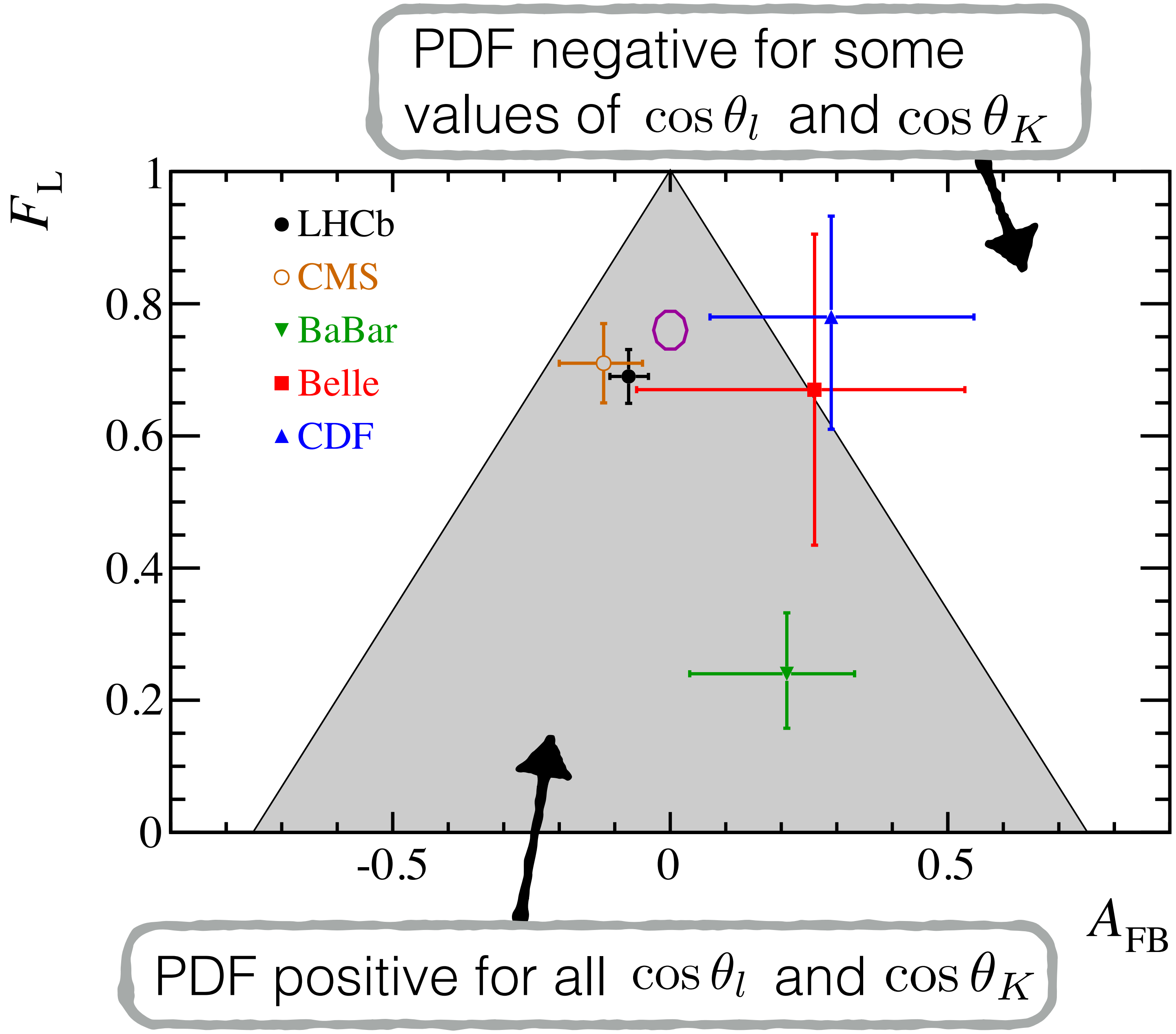


- SM predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
  [LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]
  [Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]

Beware naïve combinations

- In the $B^0 \to K^{*0}\mu^+\mu^-$ analysis we also need to be aware of boundary issues in the likelihood surface that come from the definition of the PDF.

- Experiments will be more/less sensitive depending on the exact distribution of events in their dataset and the construction of their likelihood.

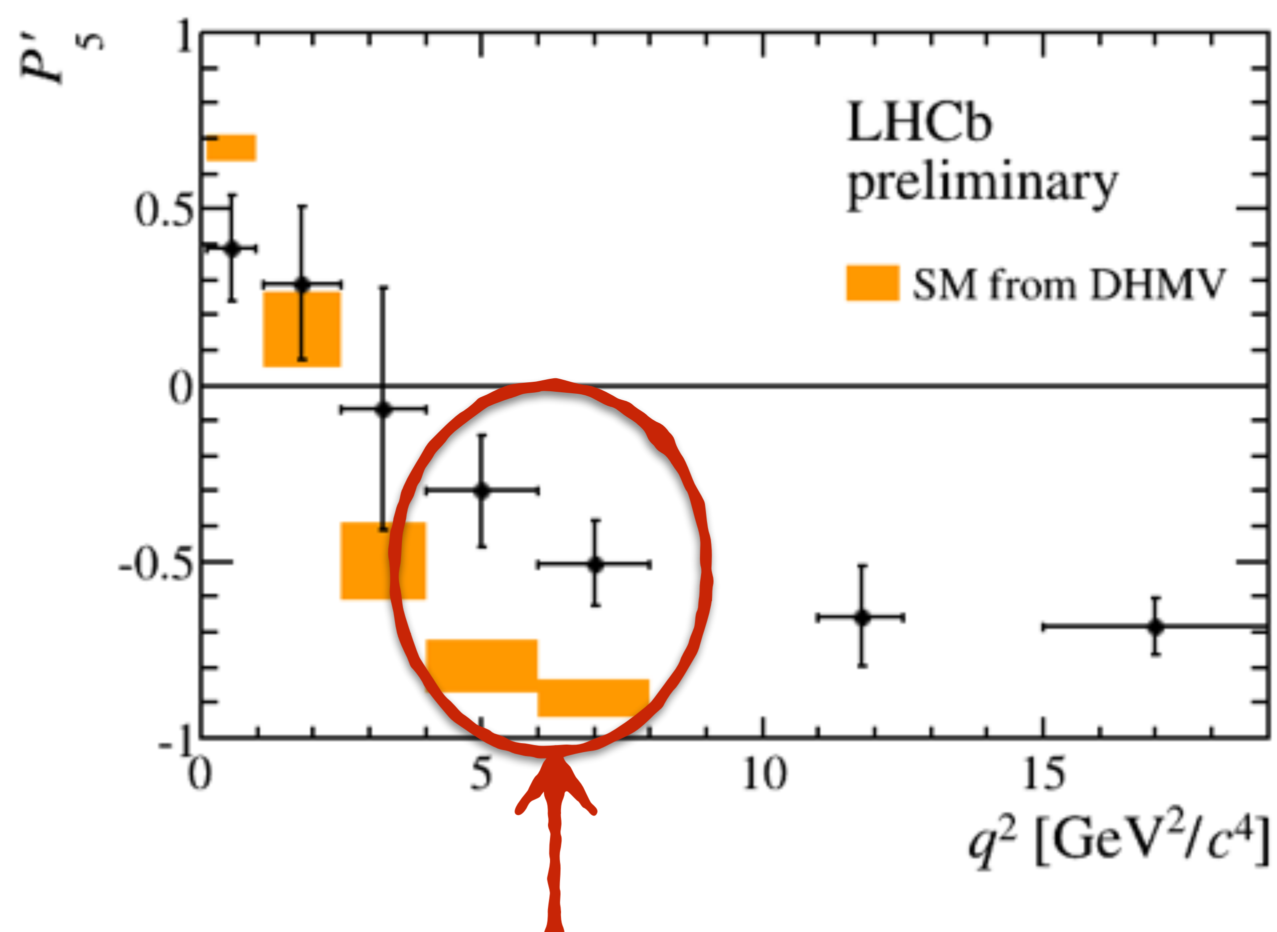


A_{FB} and F_L are **not** independent observables

Form-factor “free” observables

- In QCD factorisation/SCET there are only two form-factors
  - ➡ One is associated with A_0 and the other $A_{||}$ and $A_{\perp}$.
- Can then construct ratios of observables which are independent of form-factors, e.g.

$$P_5' = S_5/\sqrt{F_{\rm L}(1 - F_{\rm L})}$$



[LHCb-CONF-2015-002]

local tension with SM predictions (2.8σ and 3.0σ)

Obvious interest in ATLAS/CMS measuring this observable.

- P'_5 is one of a set of so-called form-factor free observables that can be measured **[S. Descotes-Genon et al. JHEP 1204 (2012) 104]**.

ϕ_s timeline

[PRL 108 (2012) 101803]

0.37 fb^{-1} result, time-dependent angular analysis of J/ψ ϕ.

[PRL 108 (2012) 241801]

0.37 fb^{-1} result, determining the sign of $\Delta\Gamma_s$ by exploiting S-wave interference in the KK system.

[PRD 87 (2013) 112010]

1fb^{-1} result, combining a time-dependent angular analysis of J/ψ KK with a time dependent measurement of J/ψ$\pi\pi$.

[PRL114 (2015) 041801]

3fb^{-1} analysis of J/ψ KK, allowing ϕ_s to be different for different polarisation states.

+ Many steps in between to understand the structure of the $\pi\pi$ and KK system (through amplitude analyses), possible penguin pollution of ϕ_s and for improvements in flavour tagging.

$\Delta\Gamma_s$ versus ϕ_s

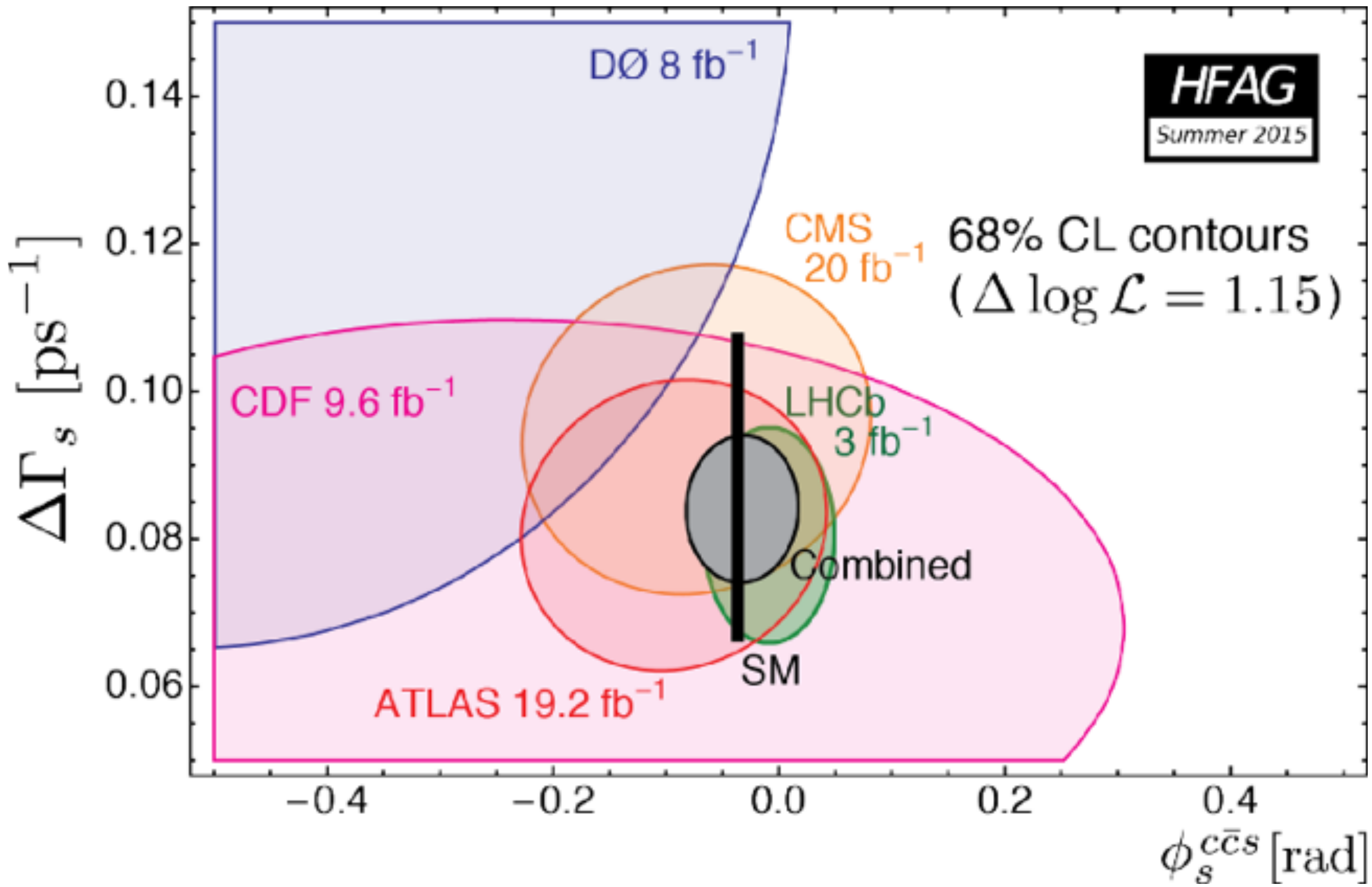
[D0, PRD 85 (2012) 032006]

[CDF, PRL 109 (2012) 171802]

[LHCb, PRL 114 (2015) 041801]

[CMS, CMS-BPH-13-012]

[ATLAS, EPS 2015]

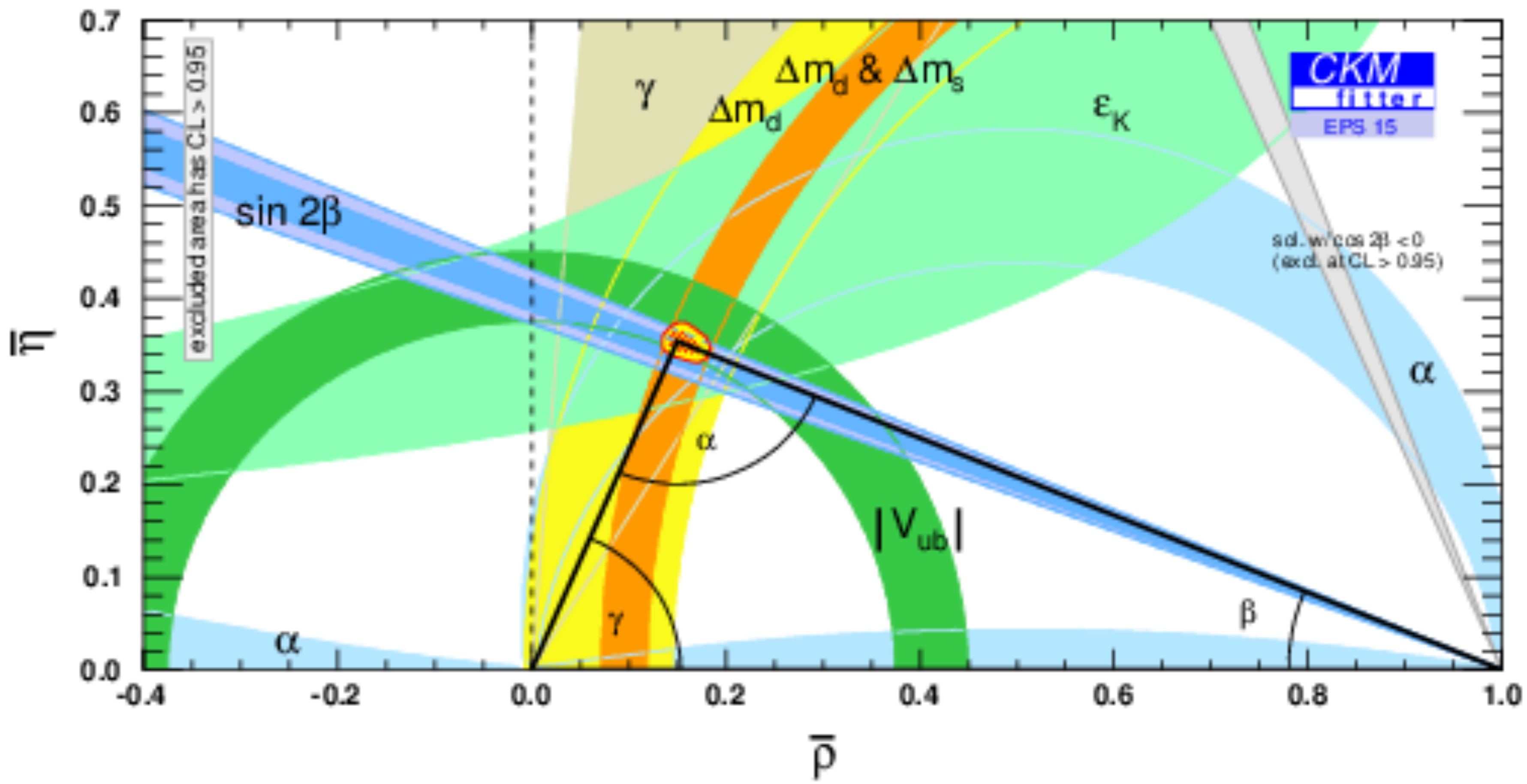


- Measurements are statistically limited. We will have to pay attention to systematic uncertainties with the larger run II datasets (including correlations between $\phi_s/\Delta\Gamma_s$ and $\Gamma_s/\Delta m_s$).

The unitarity triangle

- CKM matrix is the only source of CP violation in SM.

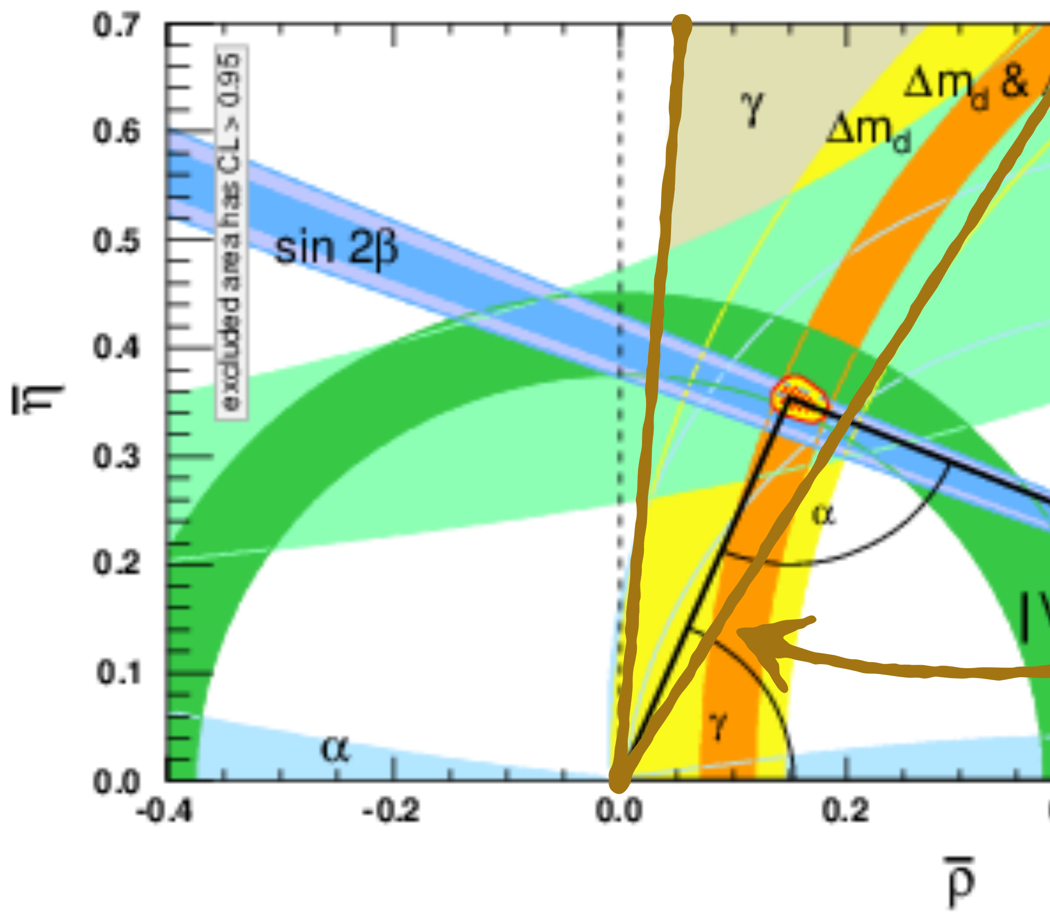
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



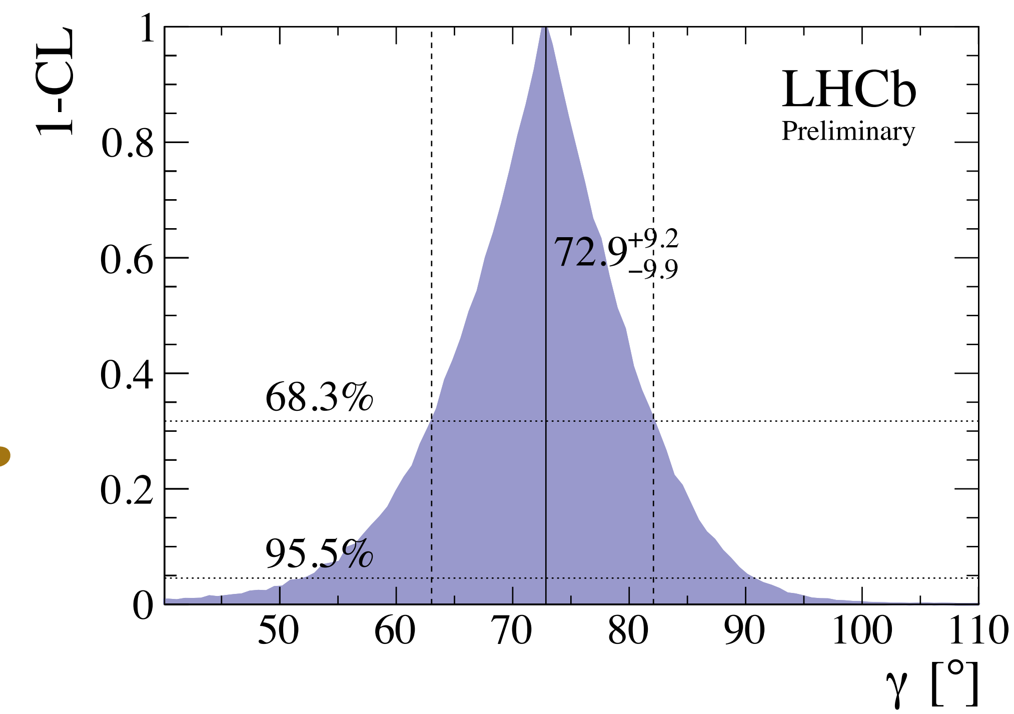
SM-like picture: data are consistent with a triangle in the complex plane

The unitarity triangle

- γ is the least well known of the angles of the unitarity triangle.
  - ➡ The only angle that can be determined from tree level processes.



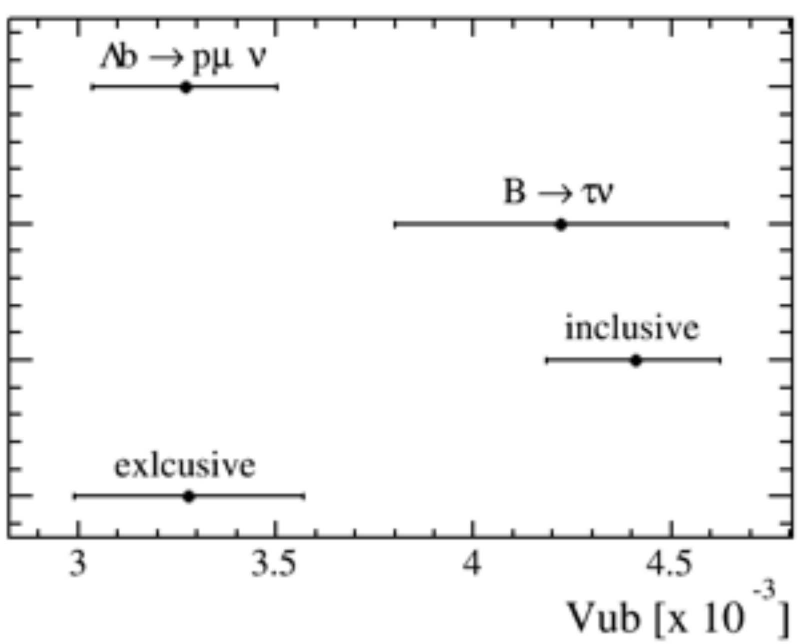
Summer 2014 combination
[LHCB-CONF-2014-004]



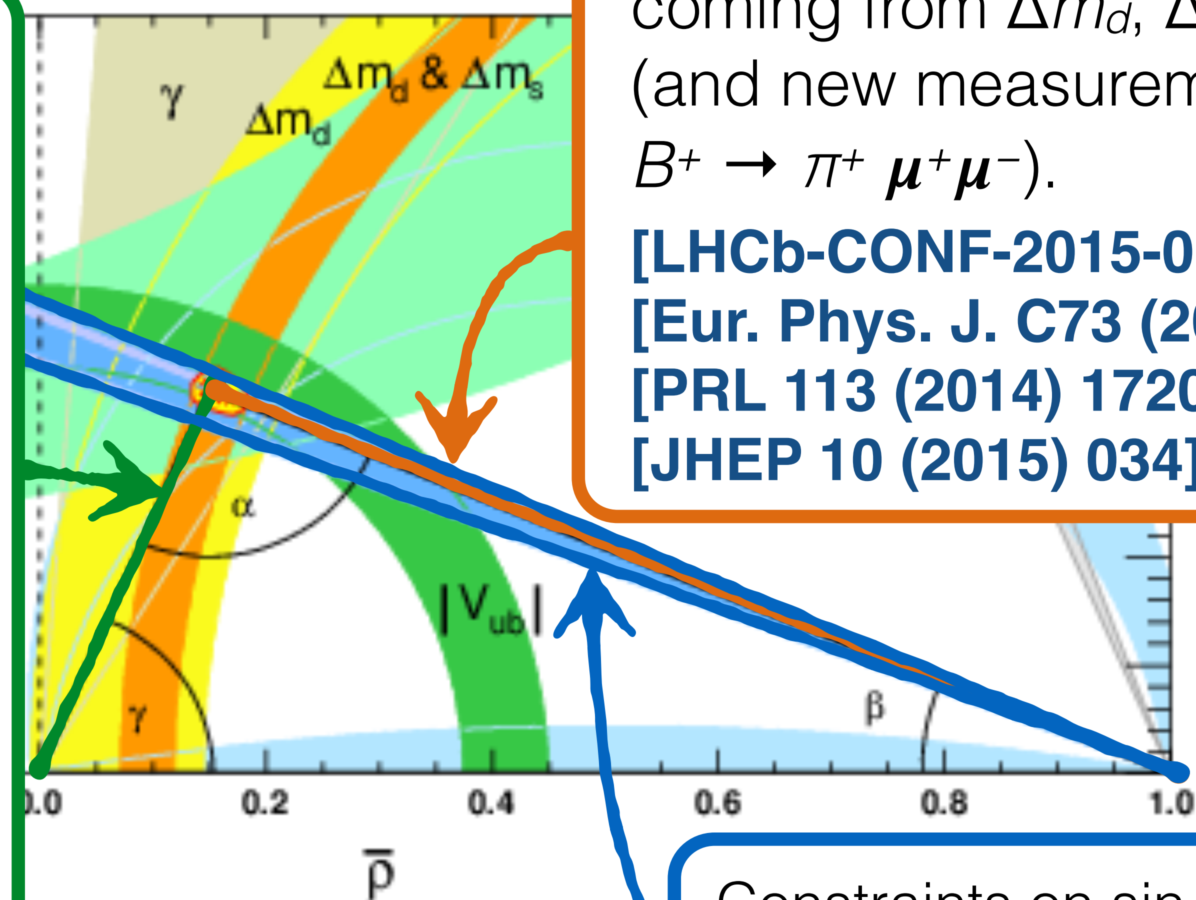
LHCb constraints are already competitive with the legacy B-factory measurements.

The unitarity triangle

We have measured $|V_{ub}|$ for the first time in $\Lambda_b \to p\mu\nu$ decays
[Nature Physics (2015) 3415]



NB: tension between inclusive and exclusive measurements.

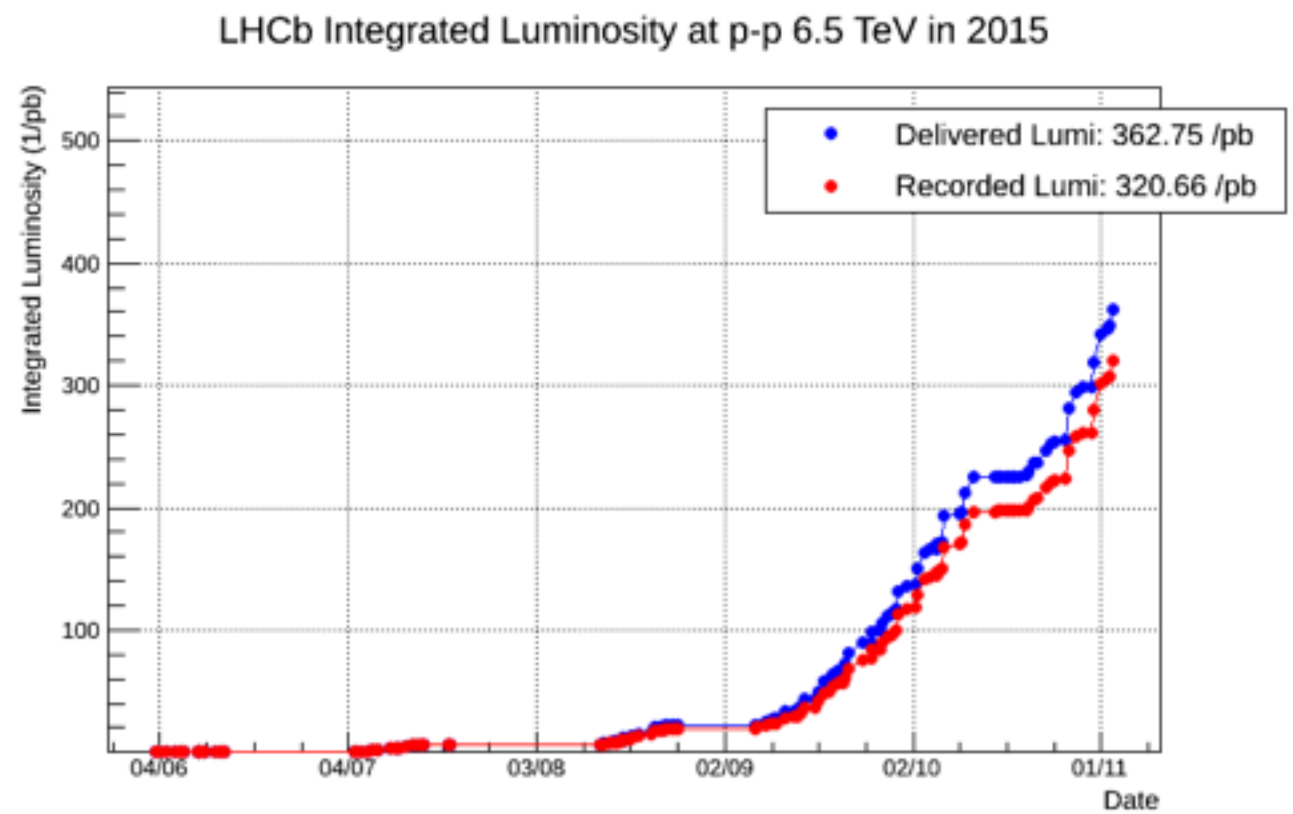


World leading constraints from LHCb on the top-side of triangle coming from Δm_d, Δm_s
(and new measurements from $B^+ \to \pi^+ \mu^+\mu^-$).
[LHCb-CONF-2015-003]
[Eur. Phys. J. C73 (2013)]
[PRL 113 (2014) 172001]
[JHEP 10 (2015) 034]

Constraints on sin 2β that are competitive with the results from the B-factories
[PRL 115 (2015) 031601]

Run II data taking

- LHCb runs at a much lower luminosity (lower pileup) than ATLAS and CMS, with a levelled luminosity that is stable throughout the run.
- We have collected 0.3 fb^{-1} of integrated luminosity this year.
  - ➡ For most channels we will not update our results until we have approximately doubled our dataset.
- Expect to have 4x larger dataset by the end of run II.



Final remark

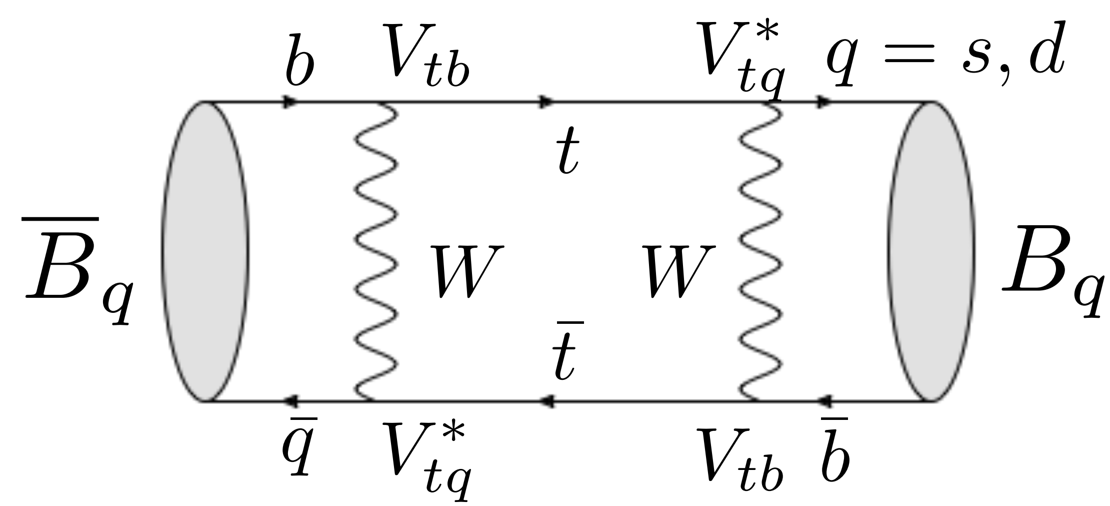
- One topic that might be useful to explore in the LHCFWG is benchmark models for run II and beyond.
  - ➡ Especially if we can find models that can be compared to direct searches at ATLAS and CMS.

Backup

Mixing induced $\not{CP}$

- To study mixing induced CP violation, look at tree level $b \to c\bar{c}s$ decays to a common final state.
  - ➡ Studied using $B_s \to J/\psi\, hh$ decays in the B_s system.
- Probes CP violation from interference between decays with and without mixing (and NP contributions to the box diagram).
- Mixing phase for B_s

$$\frac{q}{p} = \frac{V_{tb}^* V_{ts} V_{tb}^* V_{ts}}{|V_{tb}^* V_{td} V_{tb}^* V_{td}|} = e^{i\phi_s}$$

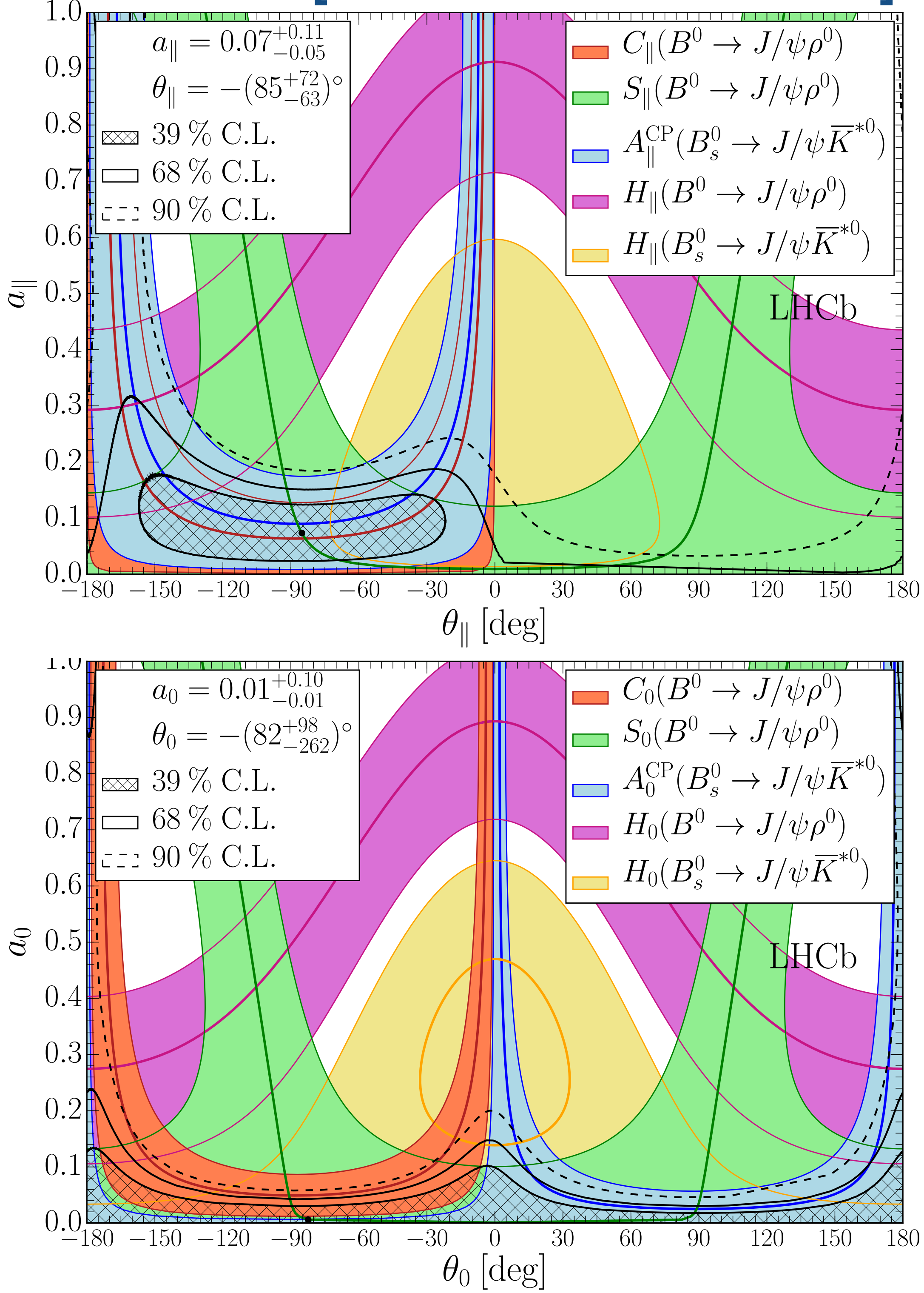


Requires a time-dependent flavour-tagged analysis.

Penguin pollution

- The theoretical uncertainty on ϕ_s is mainly due to penguin pollution of the decay (which can have a different weak phase).
- Can use $b \to c\bar{c}d$ processes to test the size of the penguin pollution.
- The pollution is found to be small
  - ➡ Consistent with zero within 0.01 rad c.f. statistical uncertainty on ϕ_s of 0.035 rad.

[LHCB-PAPER-2015-034]

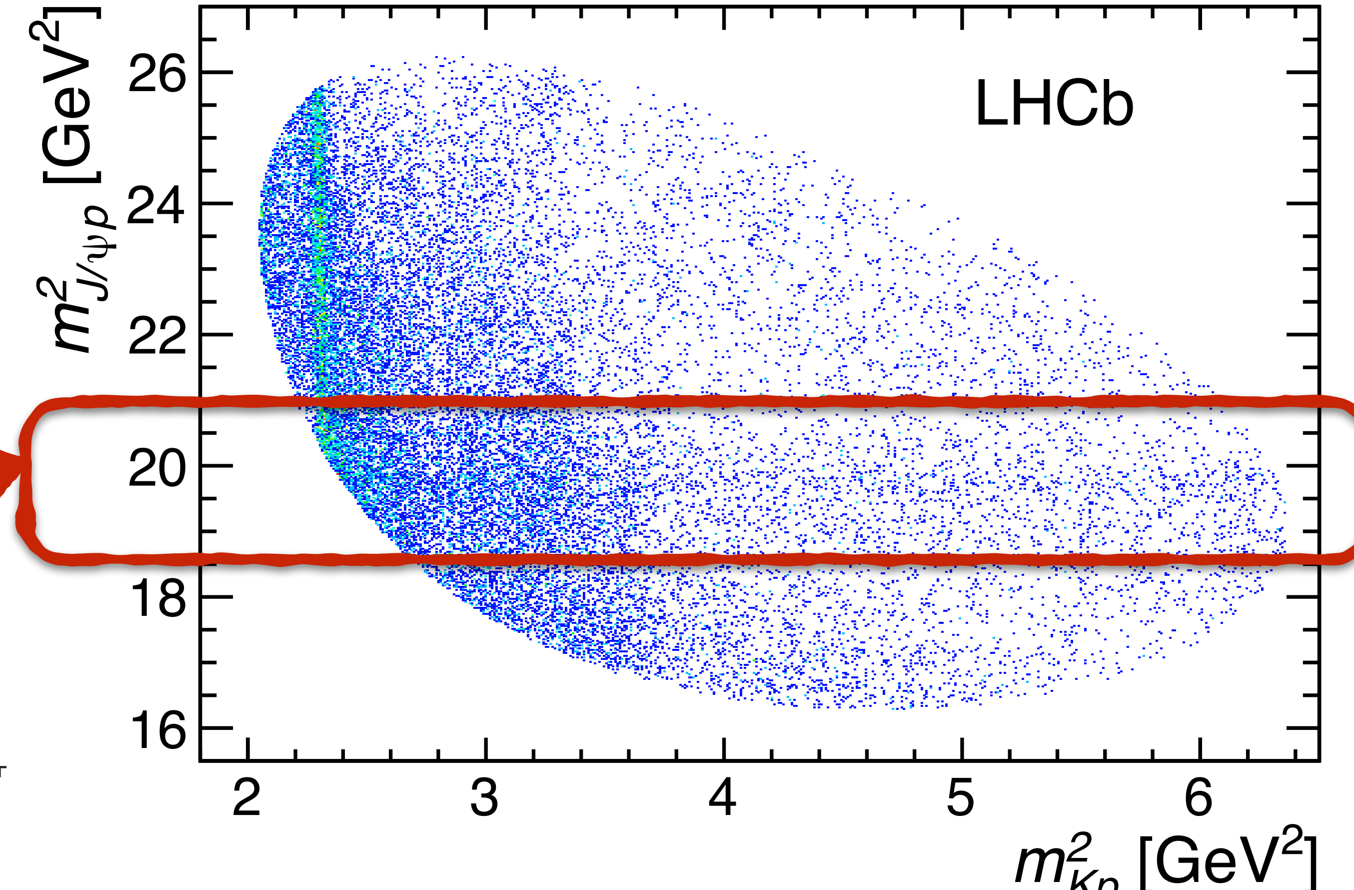


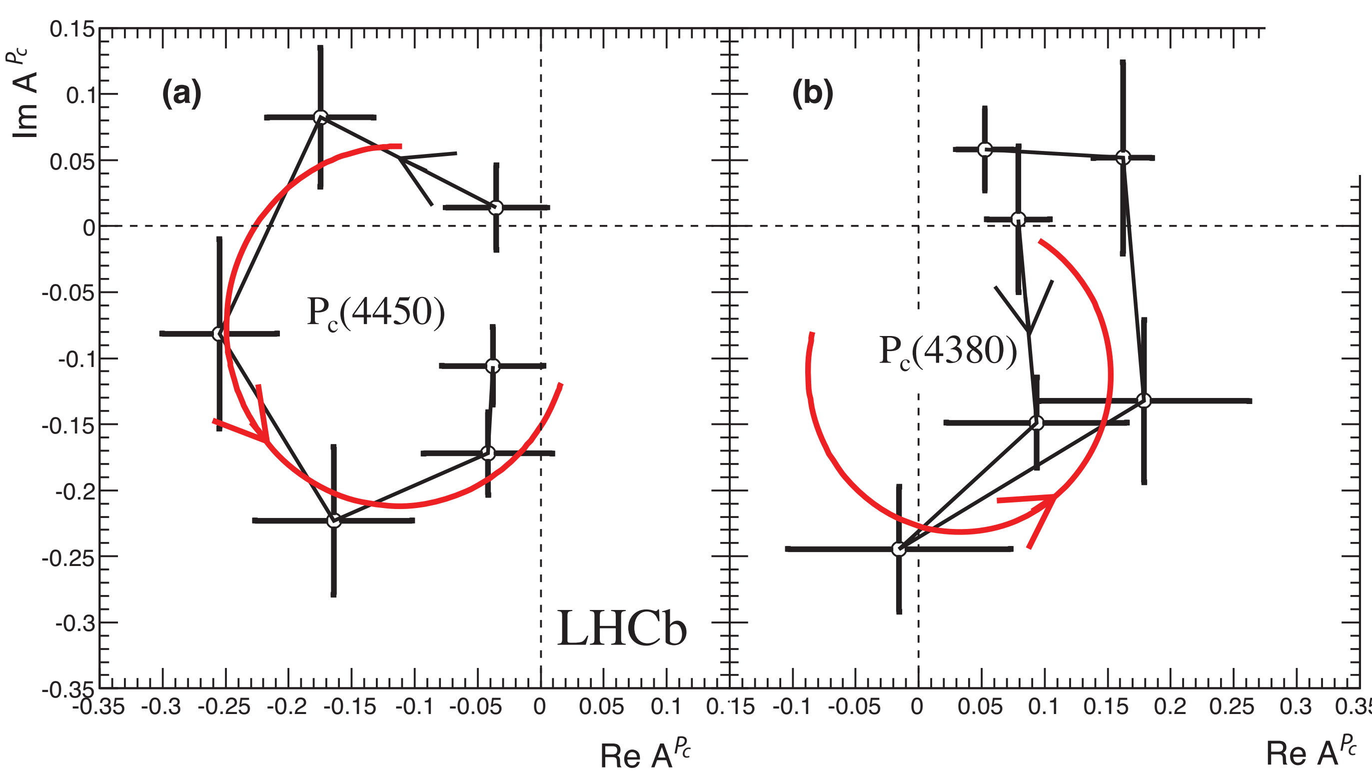
Charmonium pentaquark

[LHCb,Phys. Rev. Lett. 115 (2015) 072001]

- Recent LHCb result provided the first observation of possible 5 quark states in $\Lambda_b \to J/\psi\, pK$.

Structure in $m(J/\psi\, p)$ in the Dalitz plot.





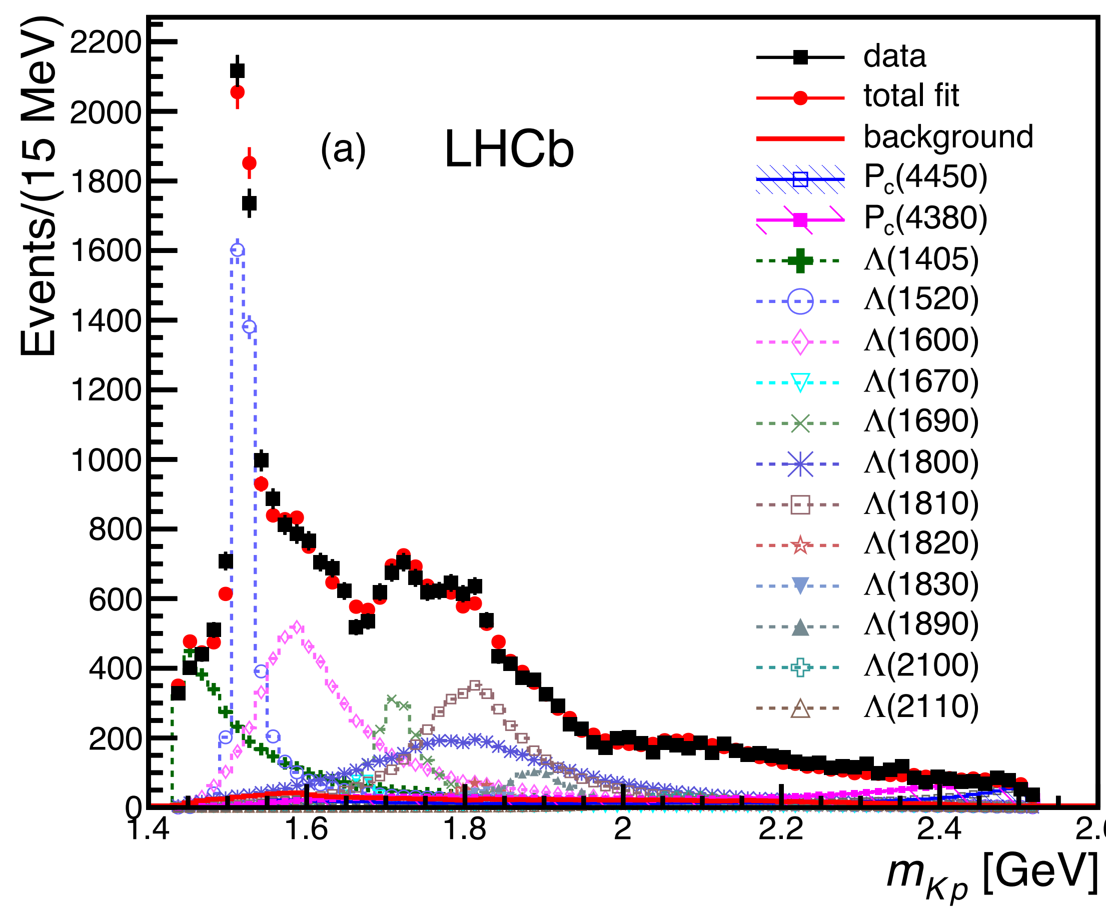
Phase motions consistent with resonance behaviour

$$m(4380) = (4380 \pm 8 \pm 9)\ \mathrm{MeV}$$
$$\Gamma(4380) = (205 \pm 18 \pm 86)\ \mathrm{MeV}$$
$$m(4450) = (4449.8 \pm 1.7 \pm 2.5)\ \mathrm{MeV}$$
$$\Gamma(4450) = (39 \pm 5 \pm 19)\ \mathrm{MeV}$$

Amplitude analyses

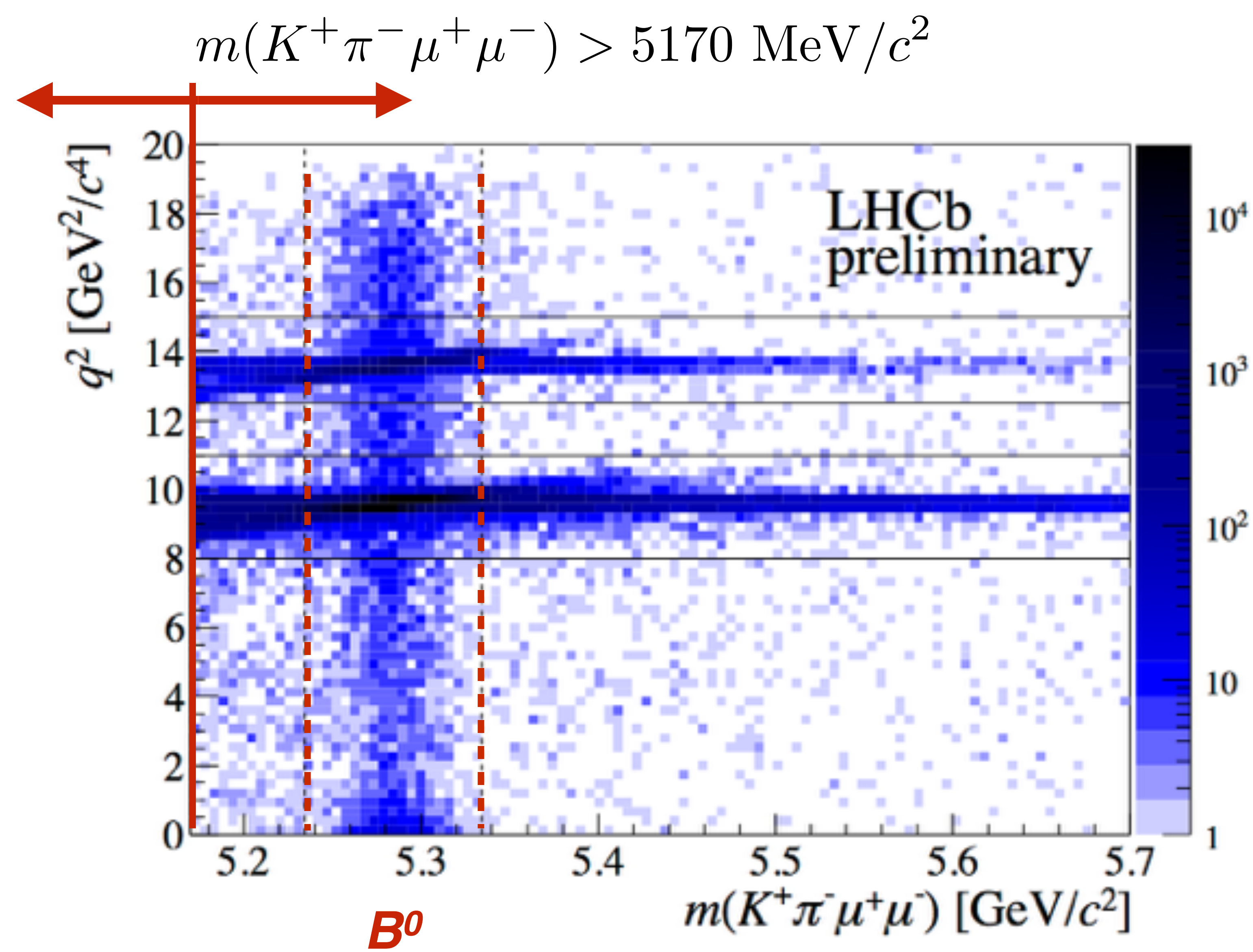
- In general results of amplitude analyses are difficult to combine and directly compare between experiments.
    - ➡ Interpretation of the decay properties depends on model assumptions.

e.g. for the Pentaquark analysis on the number of pentaquark states considered and their spin/parity. Any comparison also depends on the choice of model for the Λ* states.



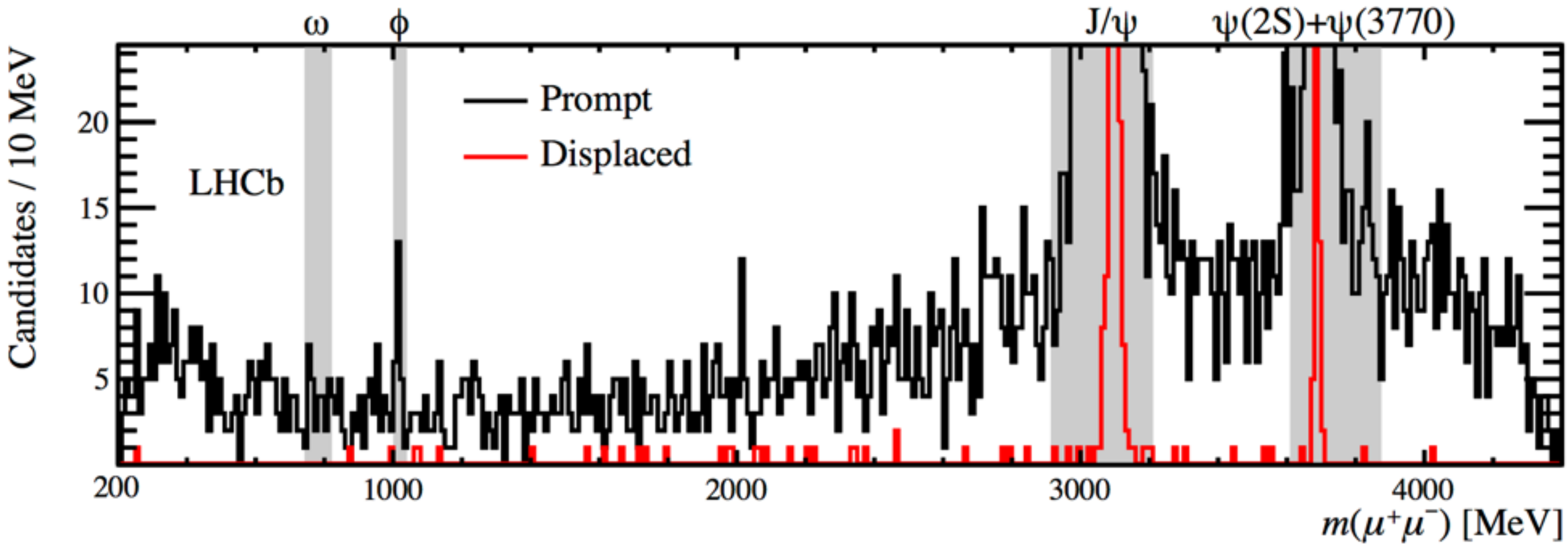
$B^0 \to K^{*0}\mu^+\mu^-$ binning

Remove partially reconstructed backgrounds, e.g. $B^+ \to K_1^+\mu^+\mu^-$ separated by $m(\pi)$. This has a different angular structure to the background under our signal.



Hidden sector search for displaced dimuon pairs

[LHCb, PRL 115 (2015) 161802]

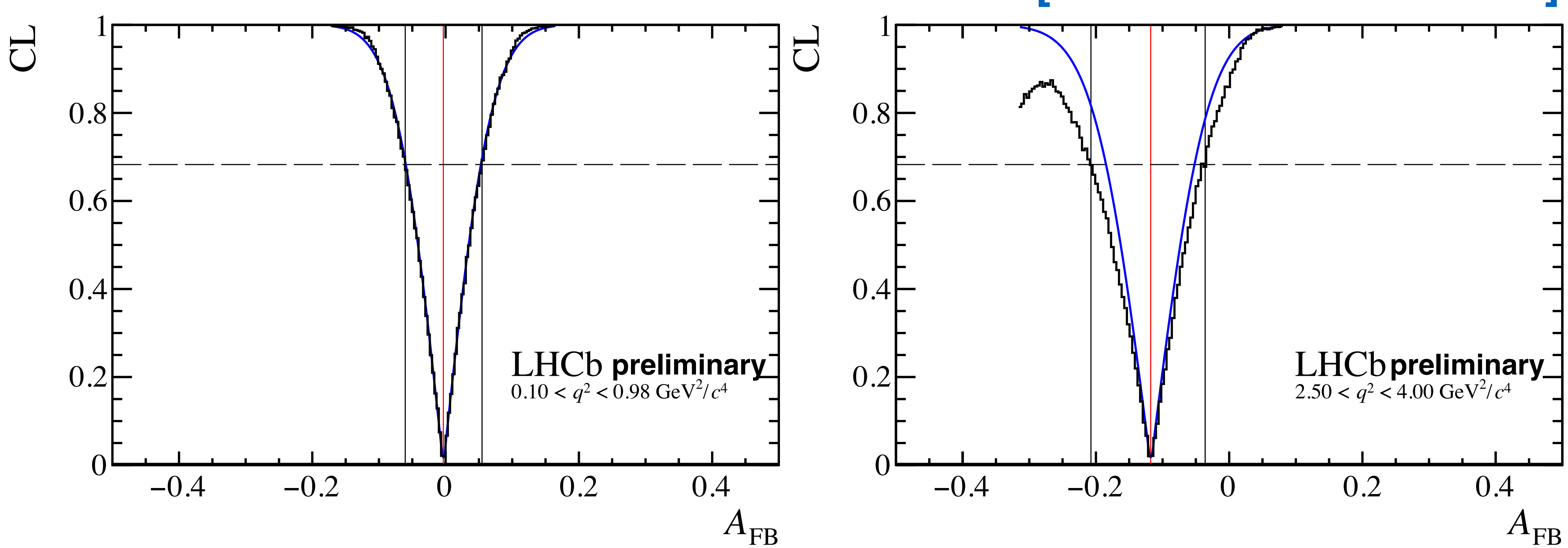


- Search for peak in dimuon spectrum, for either prompt and displaced (> $3\sigma_{t}$) dimuon pairs.
  - ➡ Data consistent with background only hypothesis.
- Sensitive in LHCb to lifetimes up-to 1 ns, but best sensitivity for lifetimes less than 10 ps.

Coverage issues?

- Relatively straightforward to combine likelihoods if correlations are known. However, in LHCb we use FC to define our confidence intervals due to coverage issues in the least populated q^2 bins.
    - ➡ AFAIK, there is no simple prescription to combine FC intervals.
- This should <u>not</u> be a problem in our run II analysis.

[LHCb-PAPER-2015-051]



Is this a specific problem for our fit or is this seen by ATLAS/CMS as well?

Profile likelihood, **Feldman-Cousins with plug-in treatment of nuisance parameters**