Rare *b*-hadron decays

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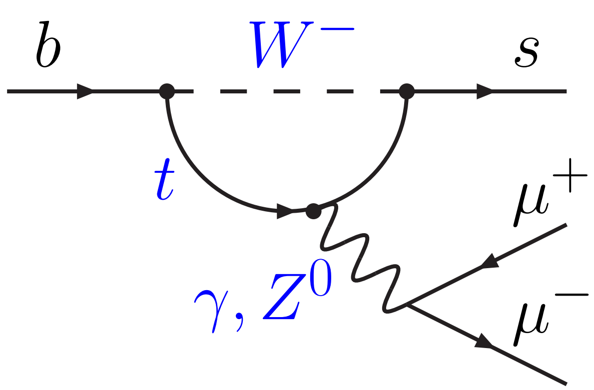
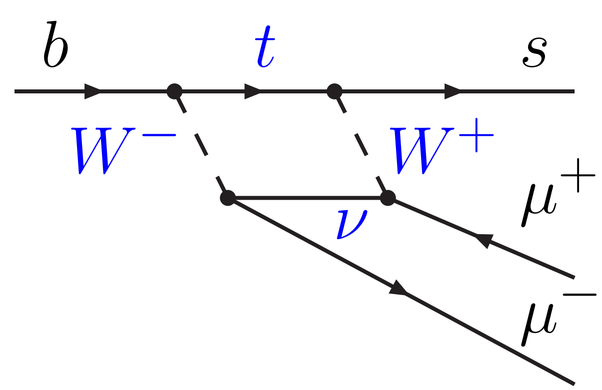
IoP HEPP and APP meeting
University of Sussex, March 2016

Exploring FCNC processes

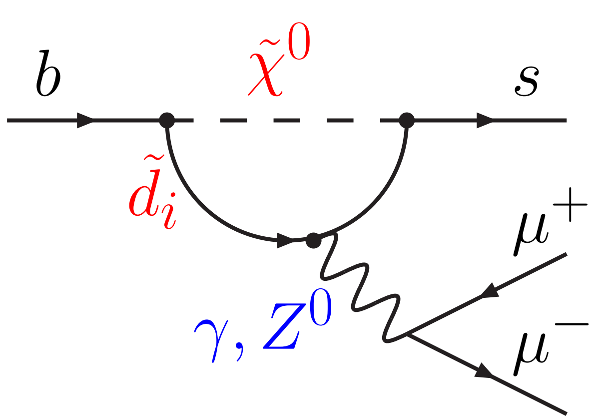
- Flavour changing neutral current transitions only occur at loop order (and beyond) in the SM.

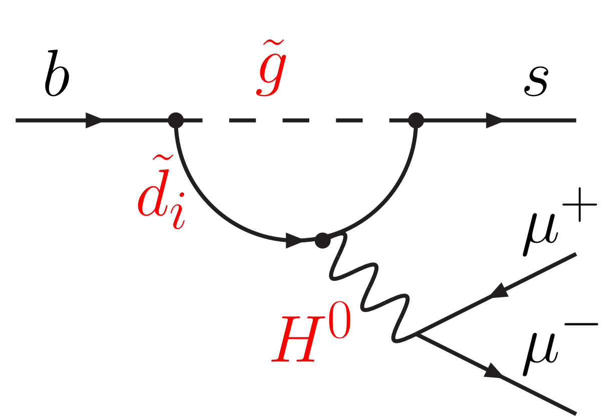


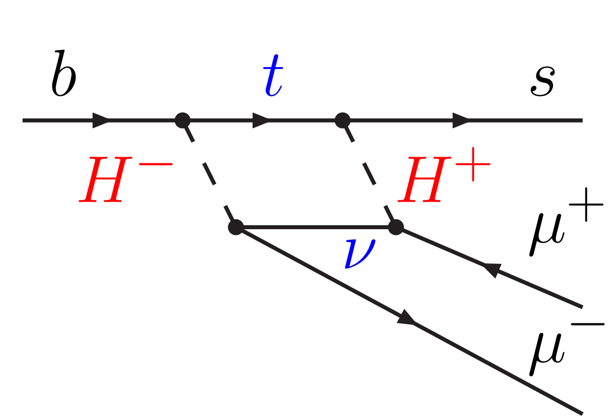


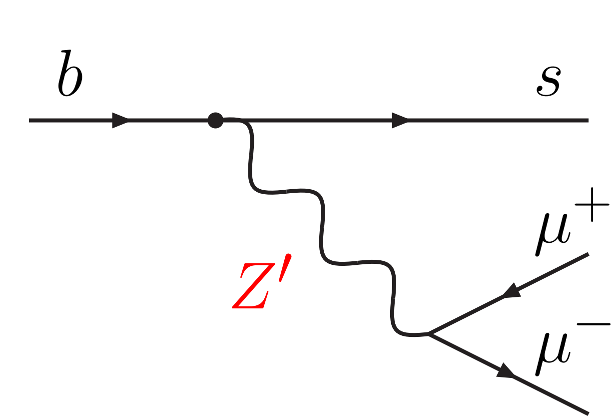
SM diagrams involve the charged current interaction.

- New particles can contribute at loop or tree level:







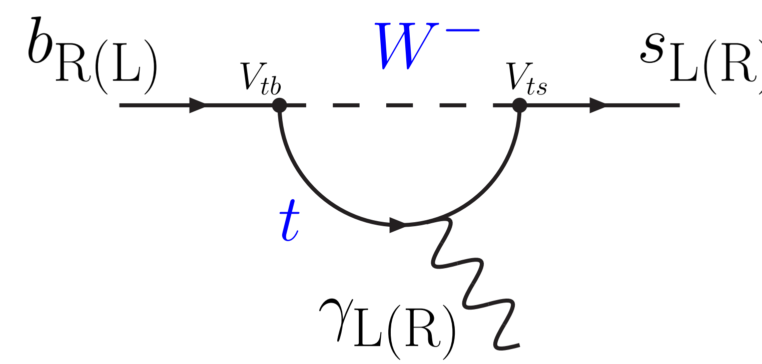


- Enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles

Properties of FCNC processes

Can also look at other properties of the decays:

- In the SM, photons from $b \rightarrow s\gamma$ decays are predominantly left-handed ($C_7/C'_7 \sim m_b/m_s$) due to the charged-current interaction.



- Flavour structure of SM implies that the rate of $b \rightarrow d$ processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to $b \rightarrow s$ processes.
- In the SM, the rate $\Gamma[B \to M\mu^+\mu^-] \approx \Gamma[B \to Me^+e^-]$ due to the universal coupling of the gauge bosons (except the Higgs) to the different lepton flavours. Any differences in the rate are due to phase-space.
- Lepton flavour violation is unobservable in the SM at any conceivable experiment due to the small size of the neutrino mass.

Outline

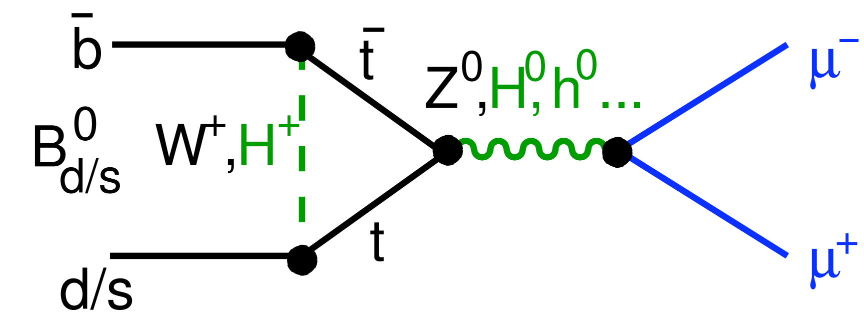
For more new results from LHCb see talk by Kostas Petridis.

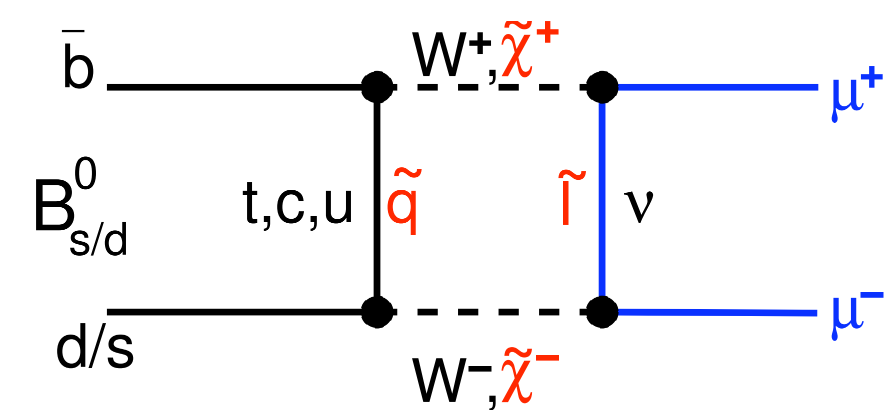
- B^0 and $B_s \to \mu^+\mu^-$ **[CMS & LHCb, Nature, 522 (2015) 68]**
- Recent measurements of $b \to s\, \ell^+\ell^-$ transitions:
  - ➡ $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis **[LHCb, JHEP 02 (2016) 104]**
  - ➡ $B_s \to \phi\mu^+\mu^-$ **[LHCb, JHEP 09 (2015) 179]**
  - ➡ $B \to K^{(*)}\mu+\mu-$ branching fractions **[LHCb, JHEP 1406 (2014) 133]**
- Lepton flavour universality in $b \to s\, \ell^+\ell^-$ transitions. **[LHCb, PRL 113 (2014) 151601]**
- Recent measurements of $b \to d\, \ell^+\ell^-$ transitions:
  - ➡ $B^+ \to \pi^+\mu^+\mu^-$ **[LHCb, JHEP 10 (2015) 034]**

NB Results are based on the LHCb Run 1 dataset ($3fb^{-1}$ of integrated luminosity collected at $\sqrt{s}$ of 7 and 8TeV).

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

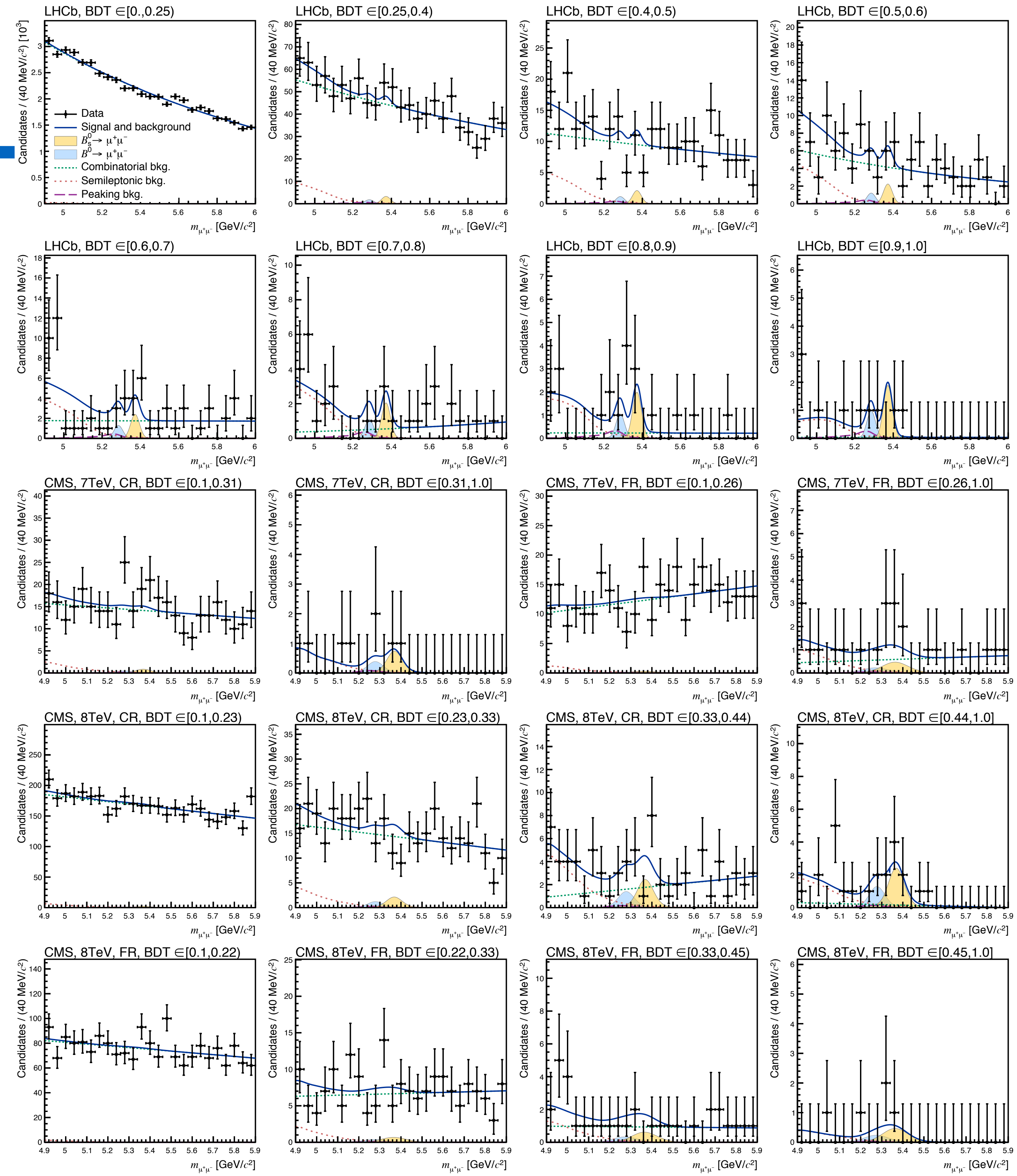
- $B_s \to \mu^+\mu^-$ is a golden mode to study FCNCs at the LHC.
  - ➡ CKM suppressed, GIM suppressed and helicty suppressed (pseudoscalar B meson producing two muons).
  - ➡ Predicted precisely in the SM (6% uncertainty on branching fraction). **[Bobeth et al. PRL 112 (2014) 101801]**
- Powerful probe of models with new or enhanced scalar/pseudoscalar interactions, e.g. SUSY at high tanβ.





CMS & LHCb combination

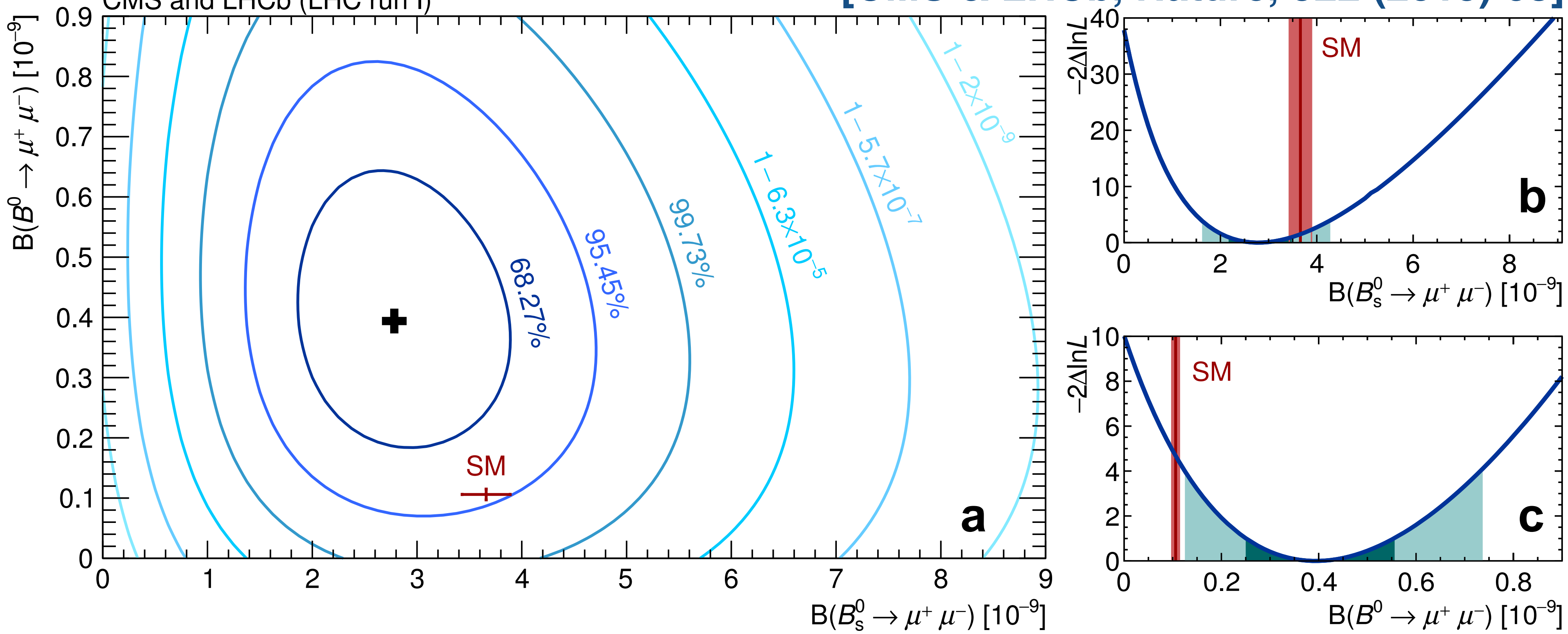
- CMS + LHCb have performed a simultaneous analysis of the datasets from the two experiments.
  - ➡ Binned in MVA response.
  - ➡ CMS data also split by barrel/end cap.
- Nuisance parameters (backgrounds, f_s/f_d) shared between the experiments.



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

CMS & LHCb $B_{(s,d)} \to \mu^+\mu^-$ result

[CMS & LHCb, Nature, 522 (2015) 68]



- Best fit results:

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

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

➡ Compatible with SM predictions at 1.2σ (Bs) and 2.2σ (B^0).

[SM predictions from Bobeth et al. Phys. Rev. Lett. 112 (2014) 101801]

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

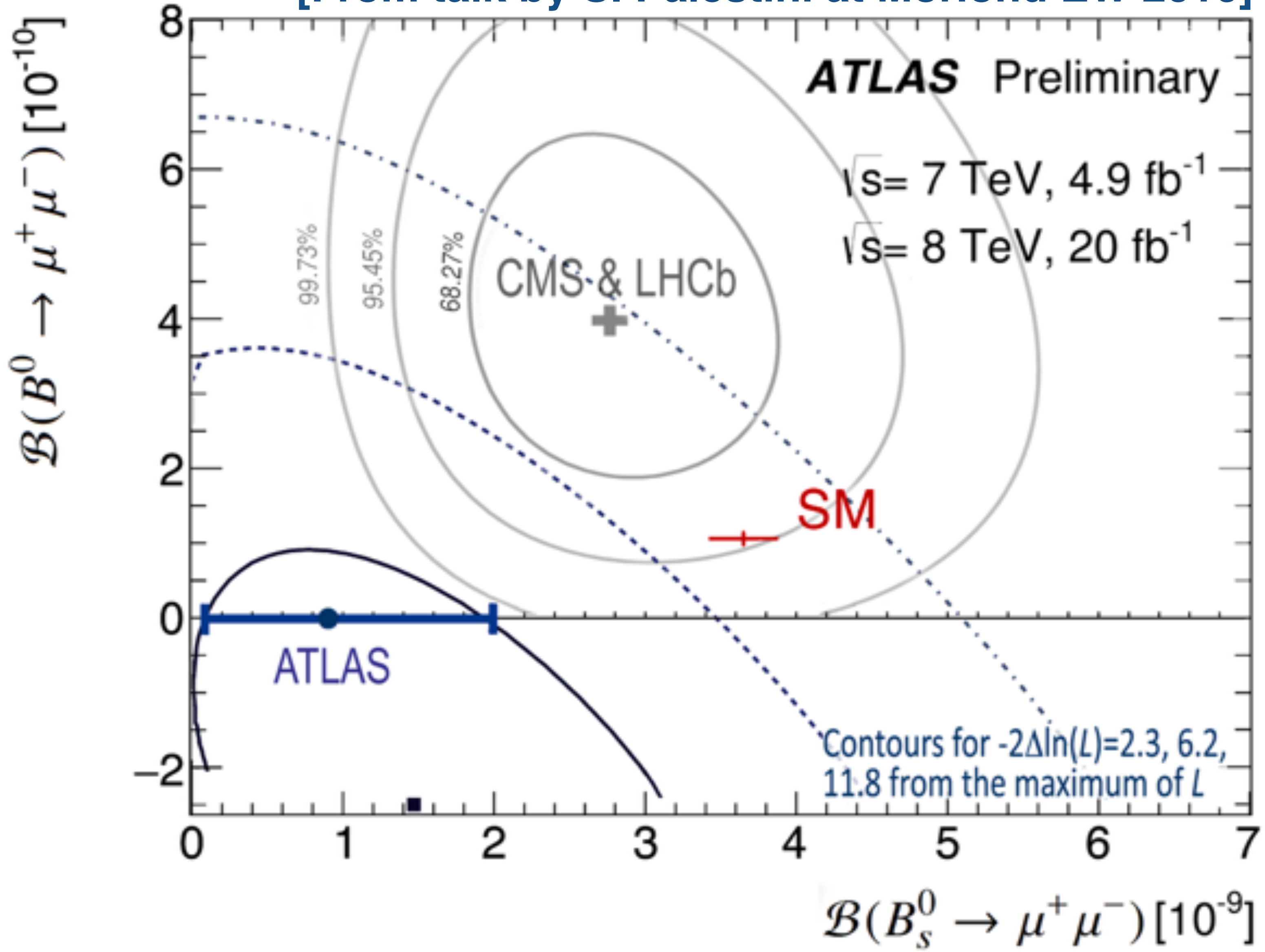
- A new result from ATLAS was presented last week at Moriond EW using their full Run 1 data sample

- Observed limit (95% CL): $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-9}$

- Expected limit (95% CL): $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.8 \times 10^{-9}$

NB ATLAS sensitivity is approaching that of LHCb and CMS.

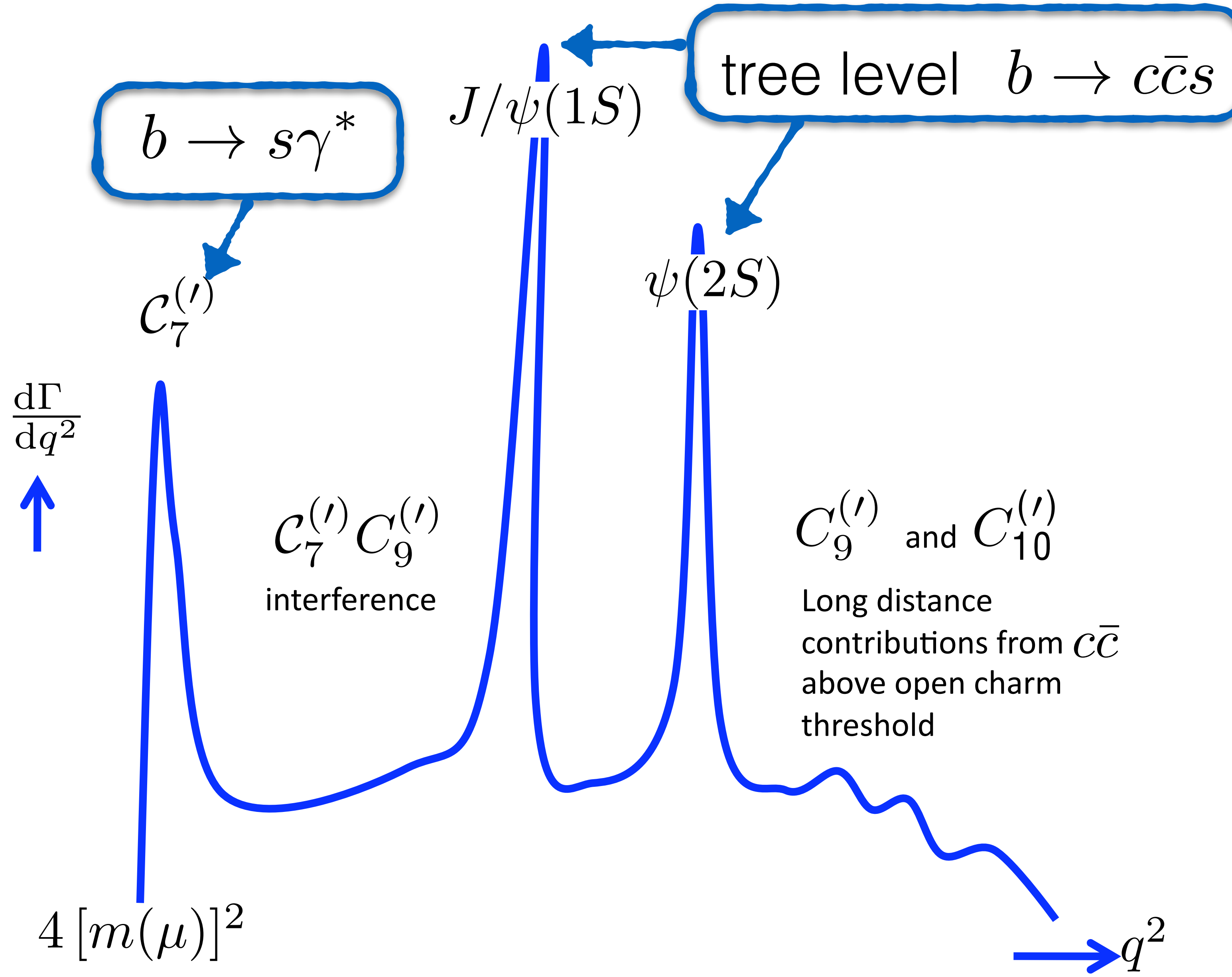
[From talk by S. Palestini at Moriond EW 2016]



For more details see the talk by Marcella Bona in parallel session 2B.

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

- Large number of observables: branching fractions, CP asymmetries and **angular observables**.
- Sensitive to new vector or axial-vector currents and virtual photon polarisation.
- Reconstructed as a four track final state containing a kaon, pion and dimuon pair.



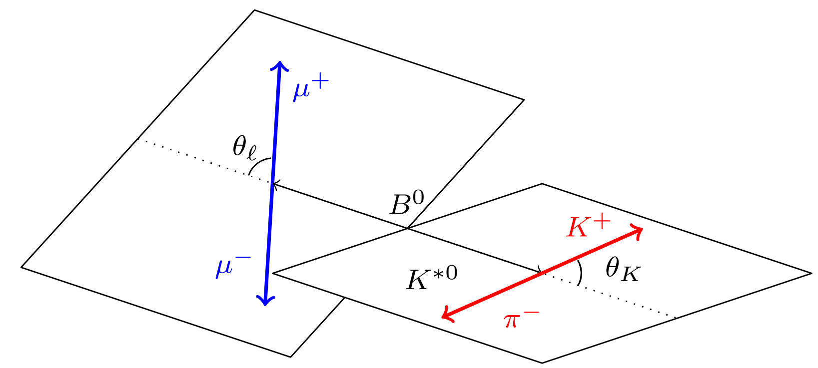
dimuon invariant mass squared, q^2

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

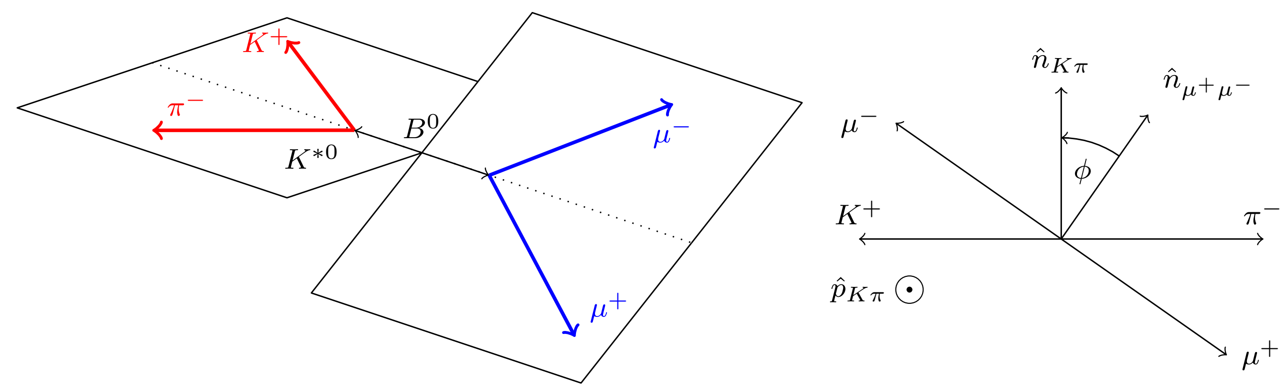
- Four-body final state.
  - ➡ Angular distribution provides many observables that are sensitive to NP.

  e.g. at low q^2 the angle between the decay planes, ϕ , is sensitive to the photon polarisation.

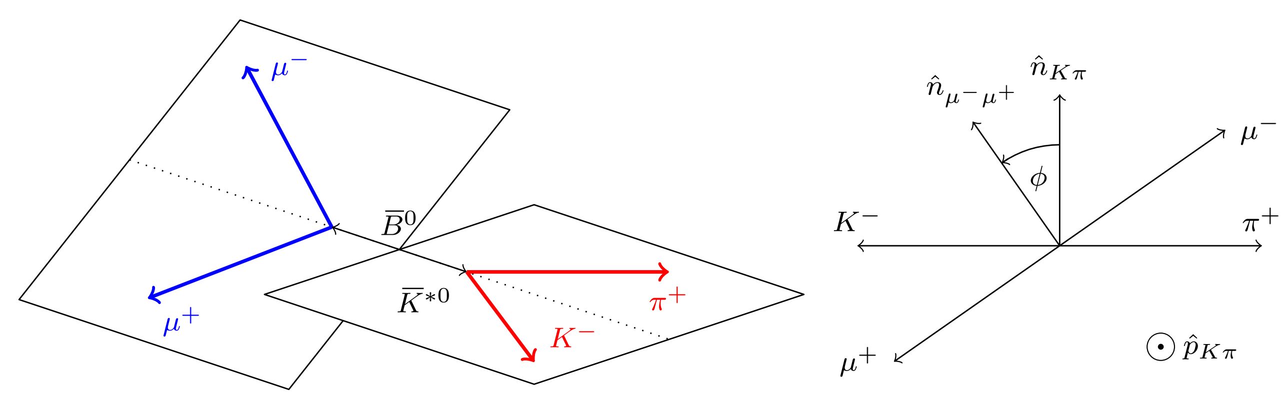
- System described by three angles and the dimuon invariant mass squared, q^2.
  - ➡ Use helicity basis for the angles.



(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

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

- Complex angular distribution:

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

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

The observables depend on form-factors for the $B \to K^*$ transition plus the underlying short distance physics (Wilson coefficients).

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

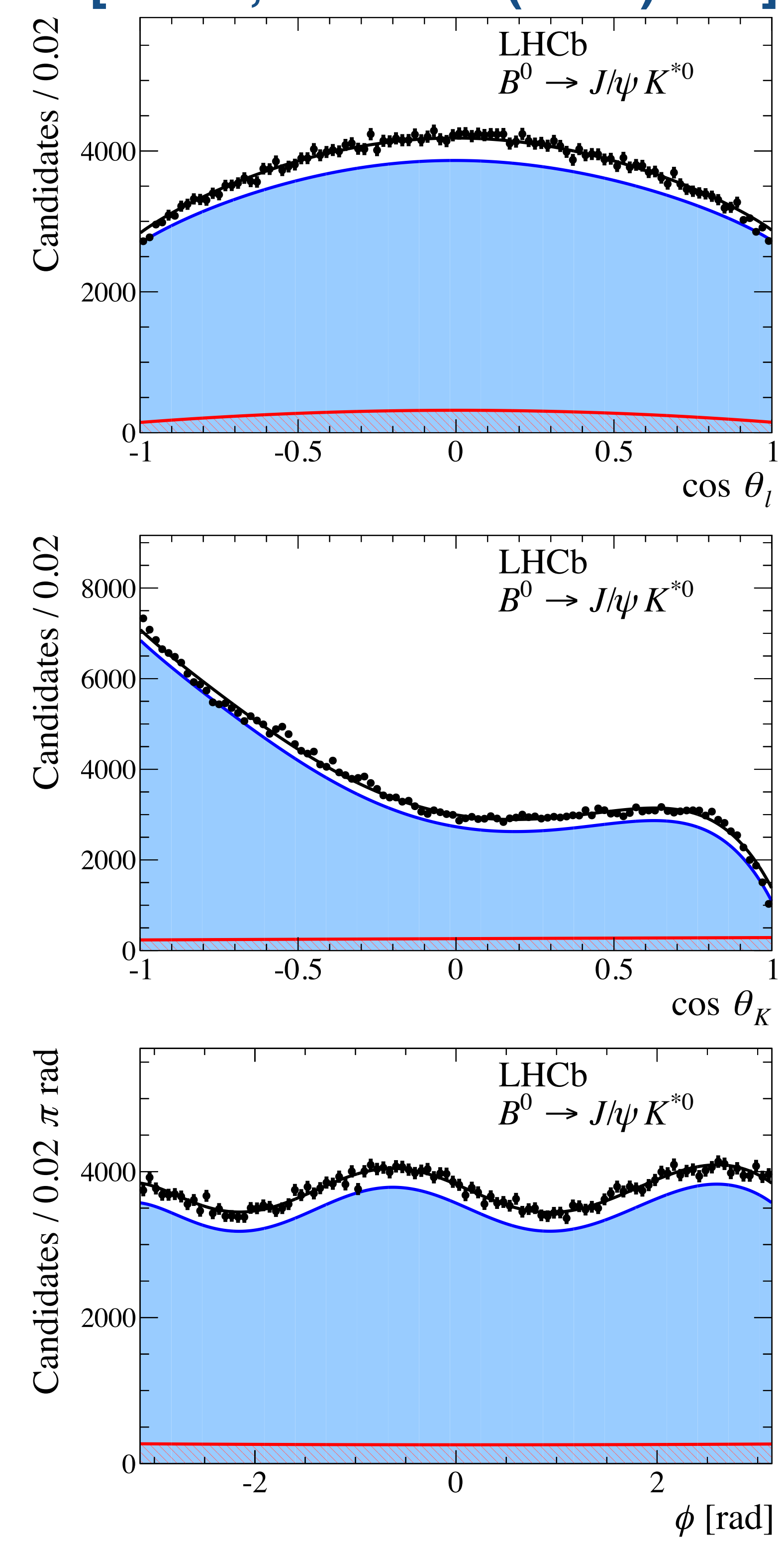
[LHCb, JHEP 02 (2016) 104]

- LHCb has performed the first full angular analysis of the decay.
- Perform an unbinned maximum likelihood fit to the $K^+\pi^-\mu^+\mu^-$ mass and the three decay angles in bins of q^2.
  - ➡ Simultaneously fit the $K\pi$ mass to constrain contributions where the $K\pi$ is in an S-wave configuration.
- Model efficiency in four-dimensions:

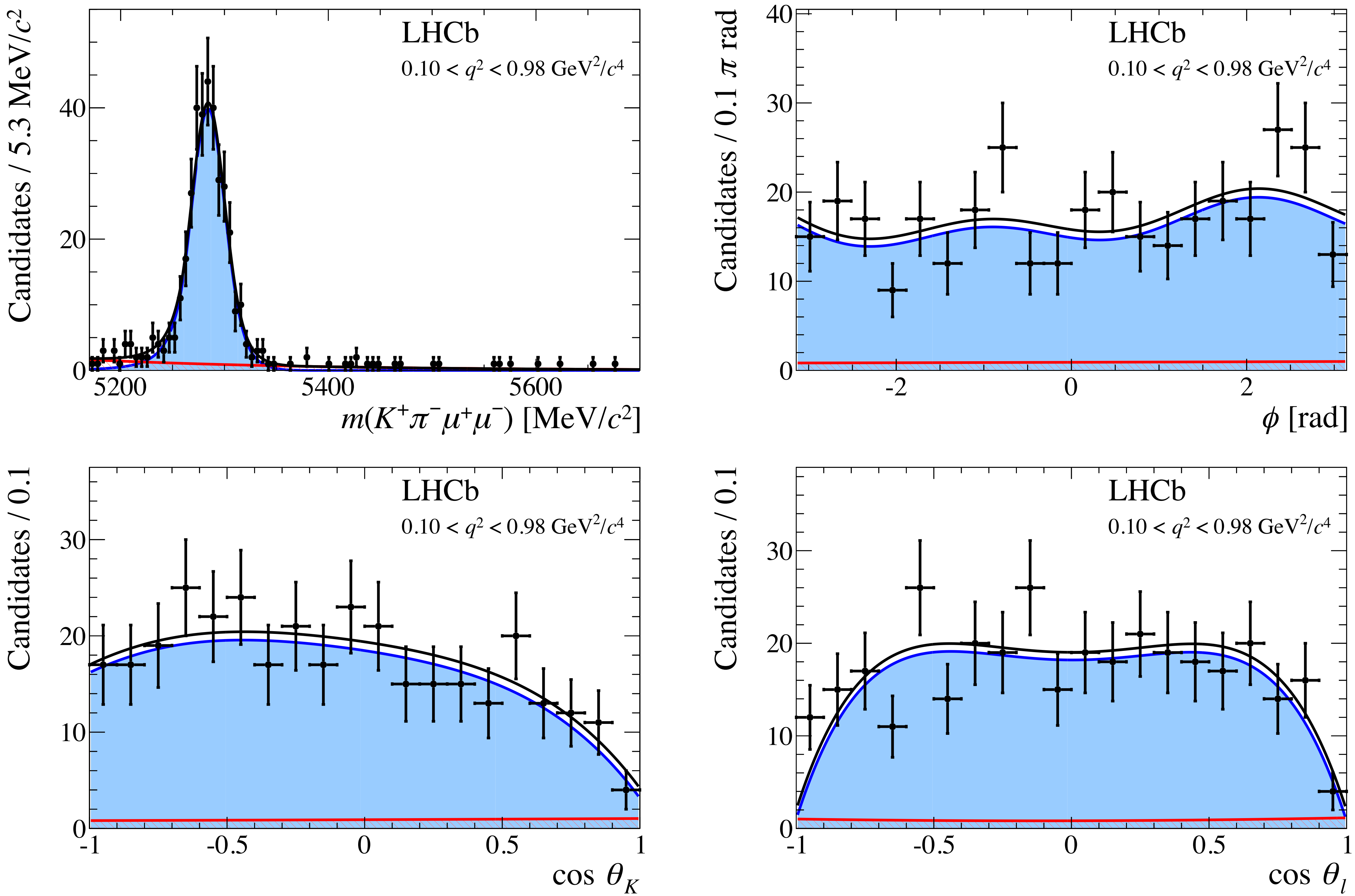
$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) \times L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

Legendre polynomial of degree *i*.

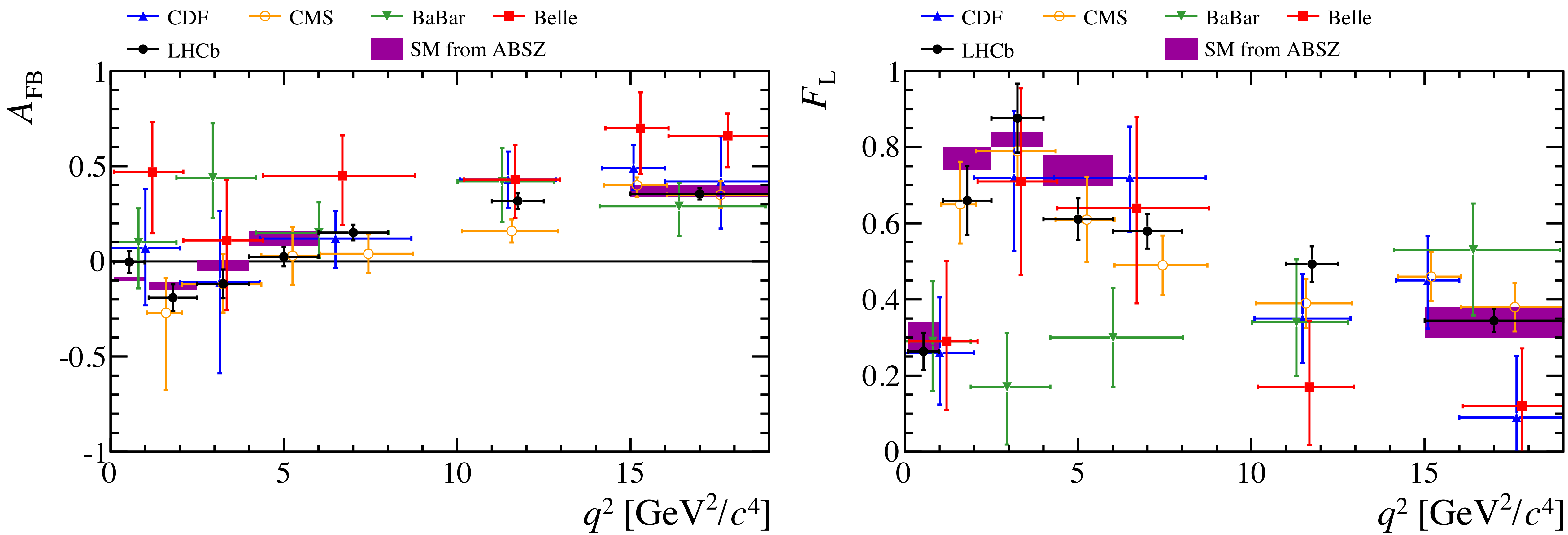
- Use $B^0 \to J/\psi K^{*0}$ as a control channel to understand the acceptance of the detector.



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



Results



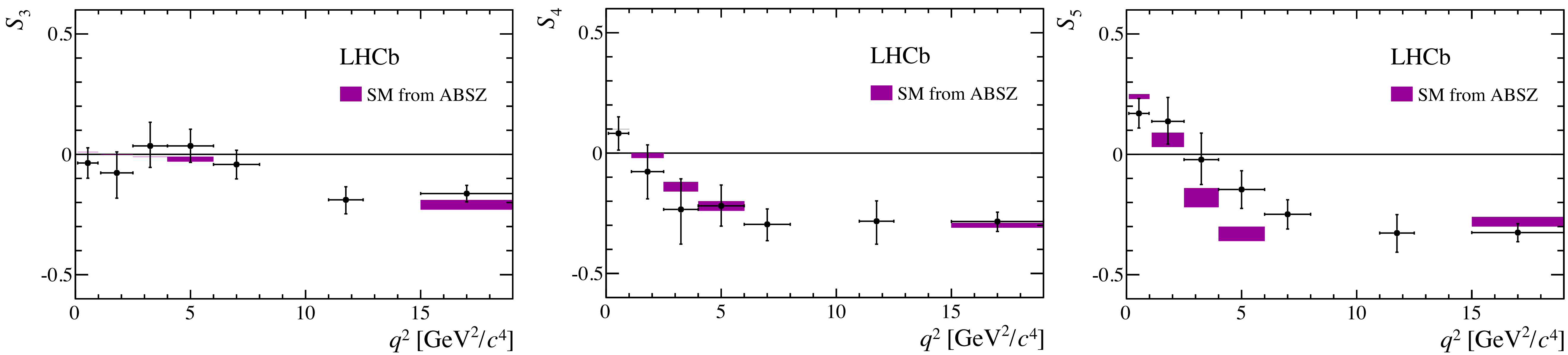
- New results for F_L and A_{FB} last year from LHCb **[JHEP 02 (2016) 104]** , CMS **[PLB 753 (2016) 424]** and BaBar **[arXiv:1508.07960]** + older measurements from CDF **[PRL 108 (2012) 081807]** and Belle **[PRL 103 (2009) 171801].**

- 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]

Results

- LHCb has performed the first full angular analysis of the decay:
  - ➡ Extract the full set of CP-averaged angular terms and their correlations.
  - ➡ Determine a full set of CP-asymmetries.

[LHCb, JHEP 02 (2016) 104]



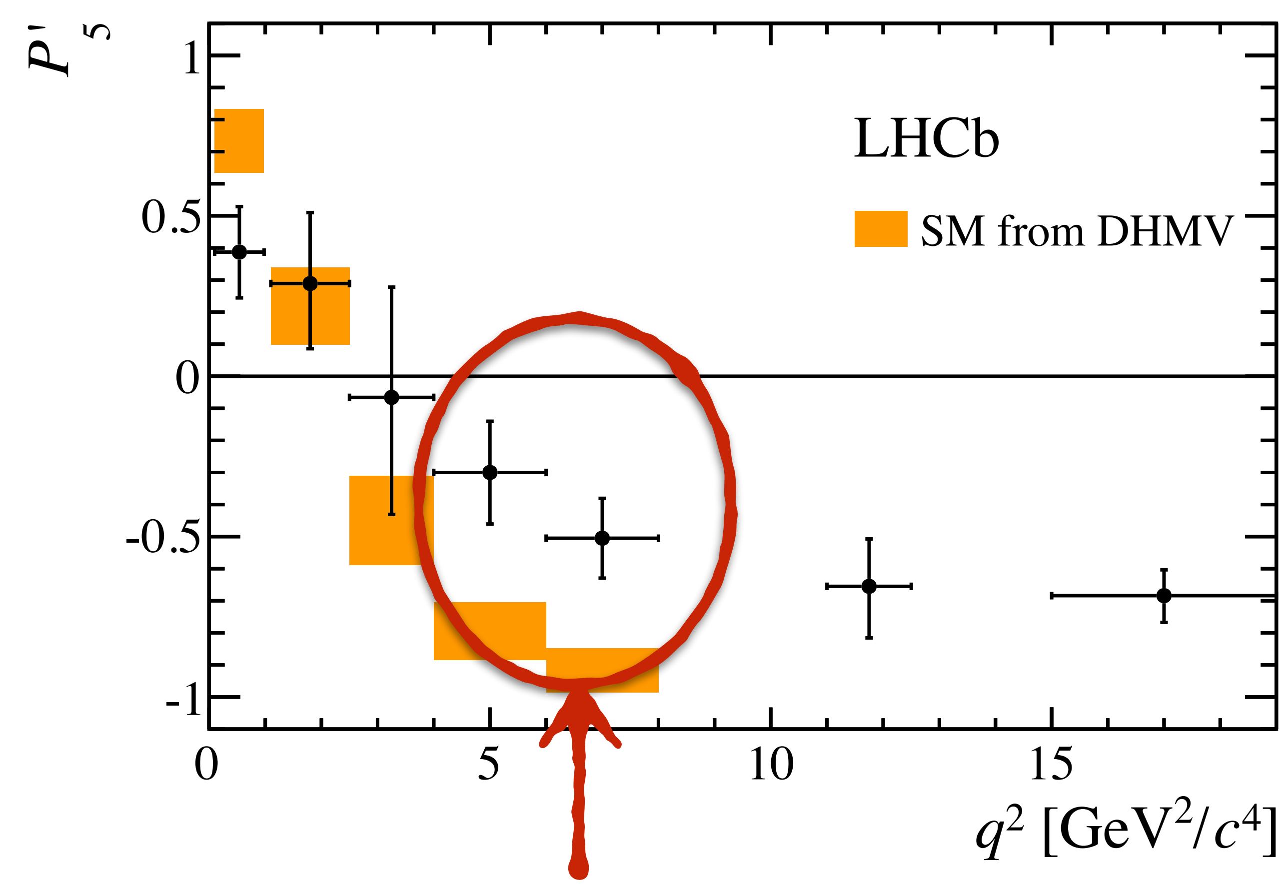
NB: These observables cancel when integrating over the ϕ-angle (e.g. in the CMS analysis).

Statistical coverage of the observables corrected using Feldman-Cousins (treating the nuisance parameters with the plug-in method).

Form-factor "free" observables

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

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



[LHCb, JHEP 02 (2016) 104]

local tension with SM predictions (2.8 and 3.0σ)

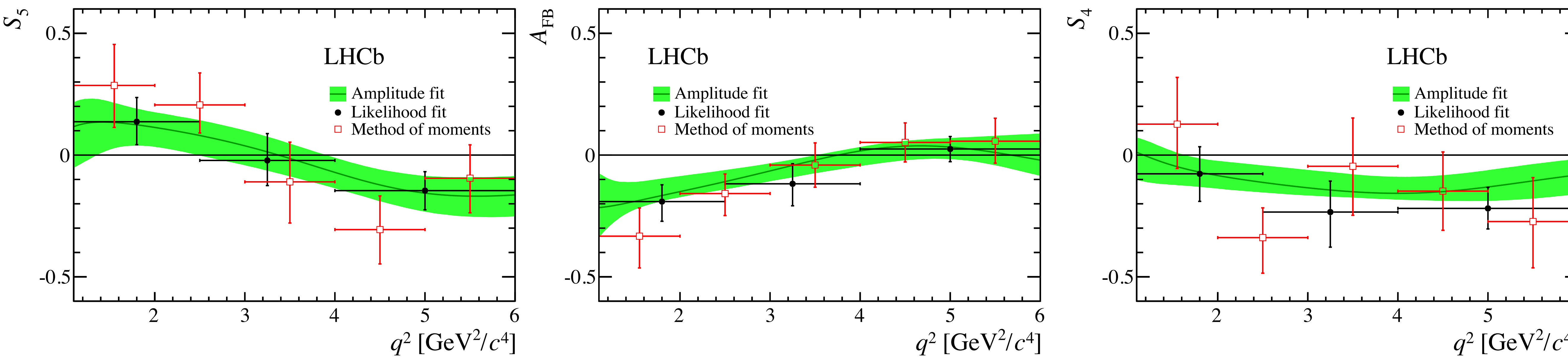
- P'_5 is one of a set of so-called form-factor free observables that can be measured **[S. Descotes-Genon et al. JHEP 1204 (2012) 104]**.

Zero-crossing points

- We determine the zero crossing points of S_4, S_5 and A_{FB} by parameterising the angular distribution with q^2 dependent decay amplitudes.
- Six complex helicity/transversity amplitudes modelled as:

$$A_{0,\|,\perp}^{\mathrm{L,R}} = \alpha_i + \beta_i/q^2 + \gamma_i q^2$$

[JHEP 02 (2016) 104]



- Zero crossing points are determined to be:

$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \text{ at 68\% confidence level (C.L.)}$$

$$q_0^2(A_{\rm FB}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \text{ at 68\% C.L.}$$

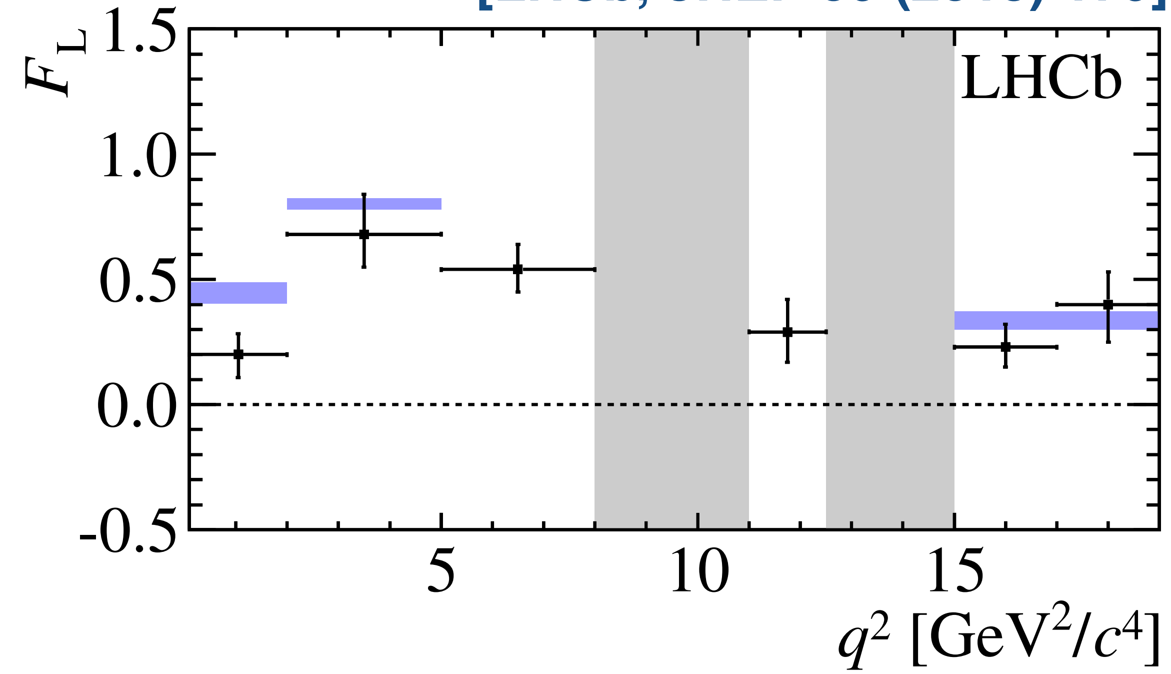
$$q_0^2(S_4) < 2.65\,\mathrm{GeV}^2/c^4 \text{ at 95\% C.L.}$$

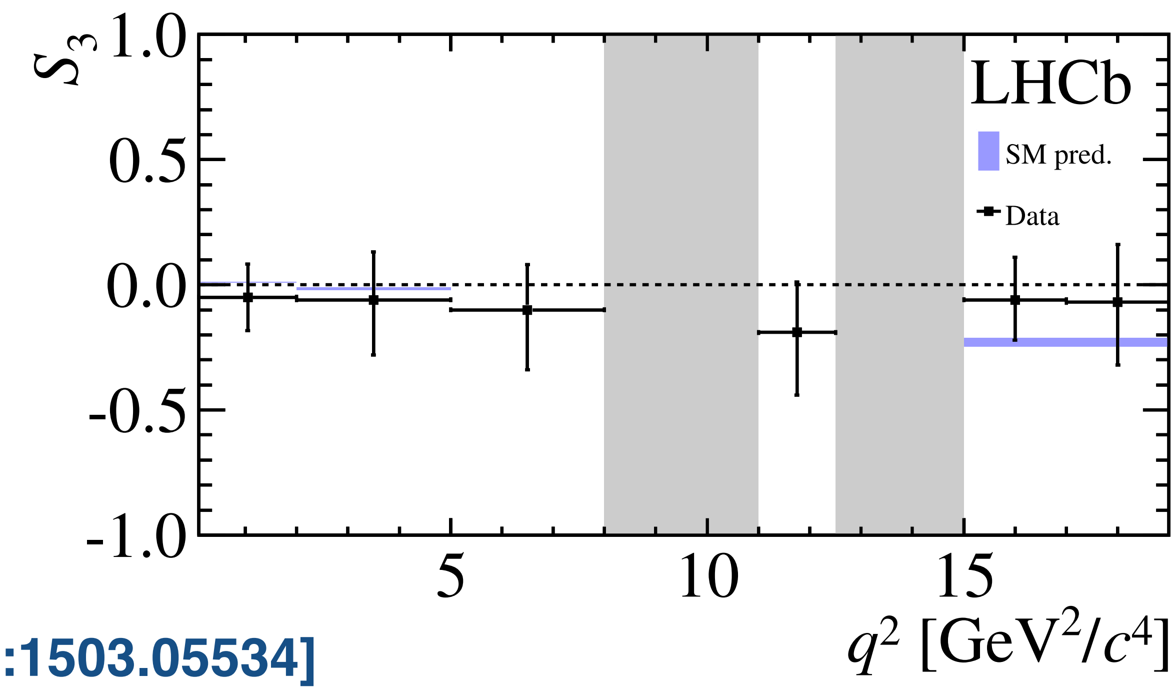
NB For S_4 the data are consistent with no zero crossing point in the $1 < q^2 < 6$ GeV^2/c^4

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

- Equivalent process for the B_s system is $B_s \to \phi\mu^+\mu^-$.
  - ➡ Angular observables are consistent with SM expectations.
  - ➡ Not a flavour specific final state so cannot determine P'_5.

[LHCb, JHEP 09 (2015) 179]





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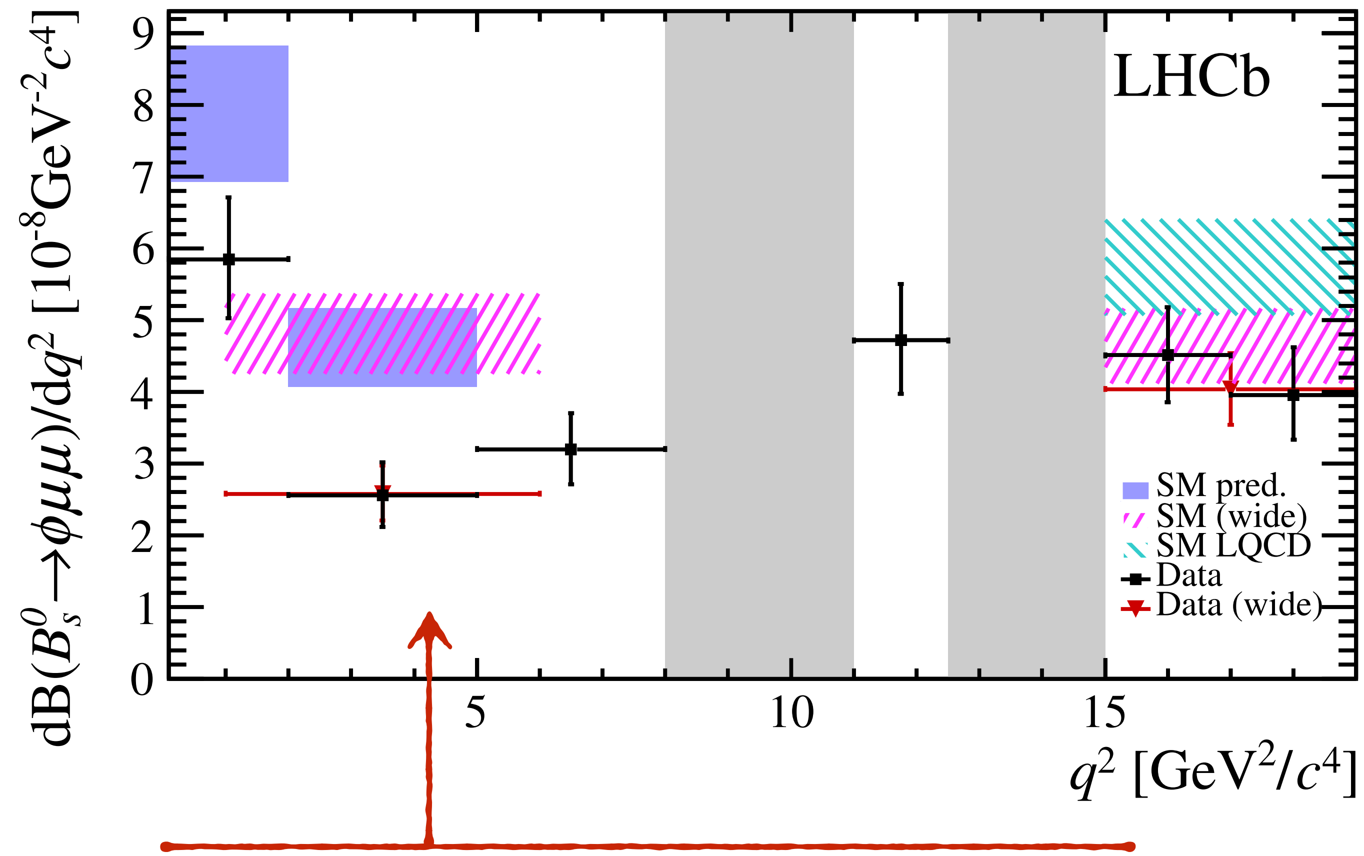
  [Lattice prediction from Horgan et al. arXiv:1310.3722]

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

- Equivalent process for the B_s system is $B_s \to \phi\mu^+\mu^-$.
    - ➡ Angular observables are consistent with SM expectations.
    - ➡ Not a flavour specific final state so cannot determine P'_5.
    - ➡ Branching fraction below SM predictions at low q^2 (similar trend seen in other $b \to s\mu^+\mu^-$ processes).

[LHCb, JHEP 09 (2015) 179]

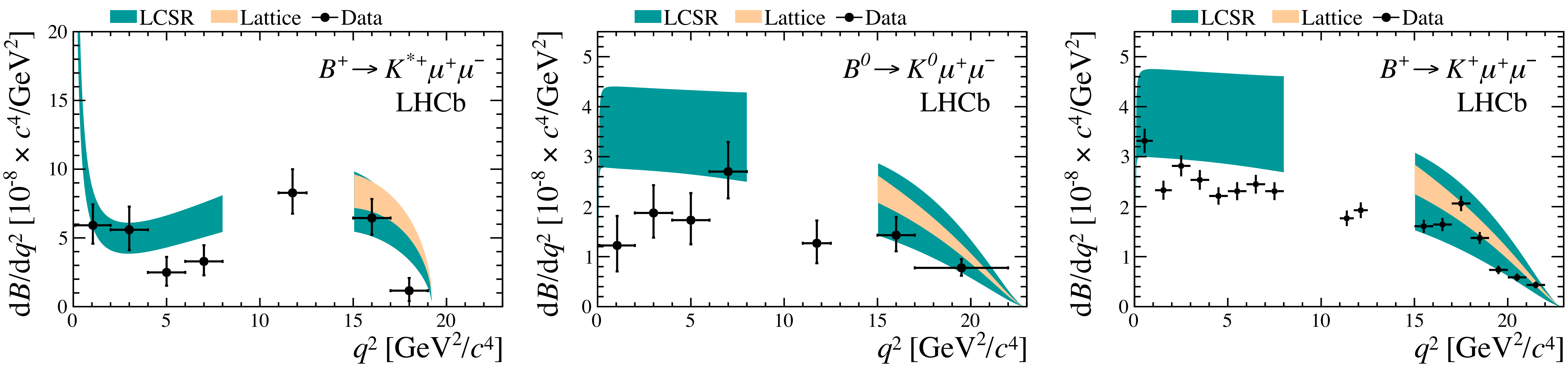


In a wide bin from $1 < q^2 < 6$ GeV$^2/c^4$, the data is 3.3σ from the SM prediction

- SM predictions based on
[Altmannshofer & Straub, arXiv:1411.3161]
[LCSR form-factors from Bharucha et al. arXiv:1503.05534]
[Lattice prediction from Horgan et al. arXiv:1310.3722]

$B \to K^{(*)}\mu^+\mu^-$ branching fraction

[LHCb, JHEP 1406 (2014) 133]

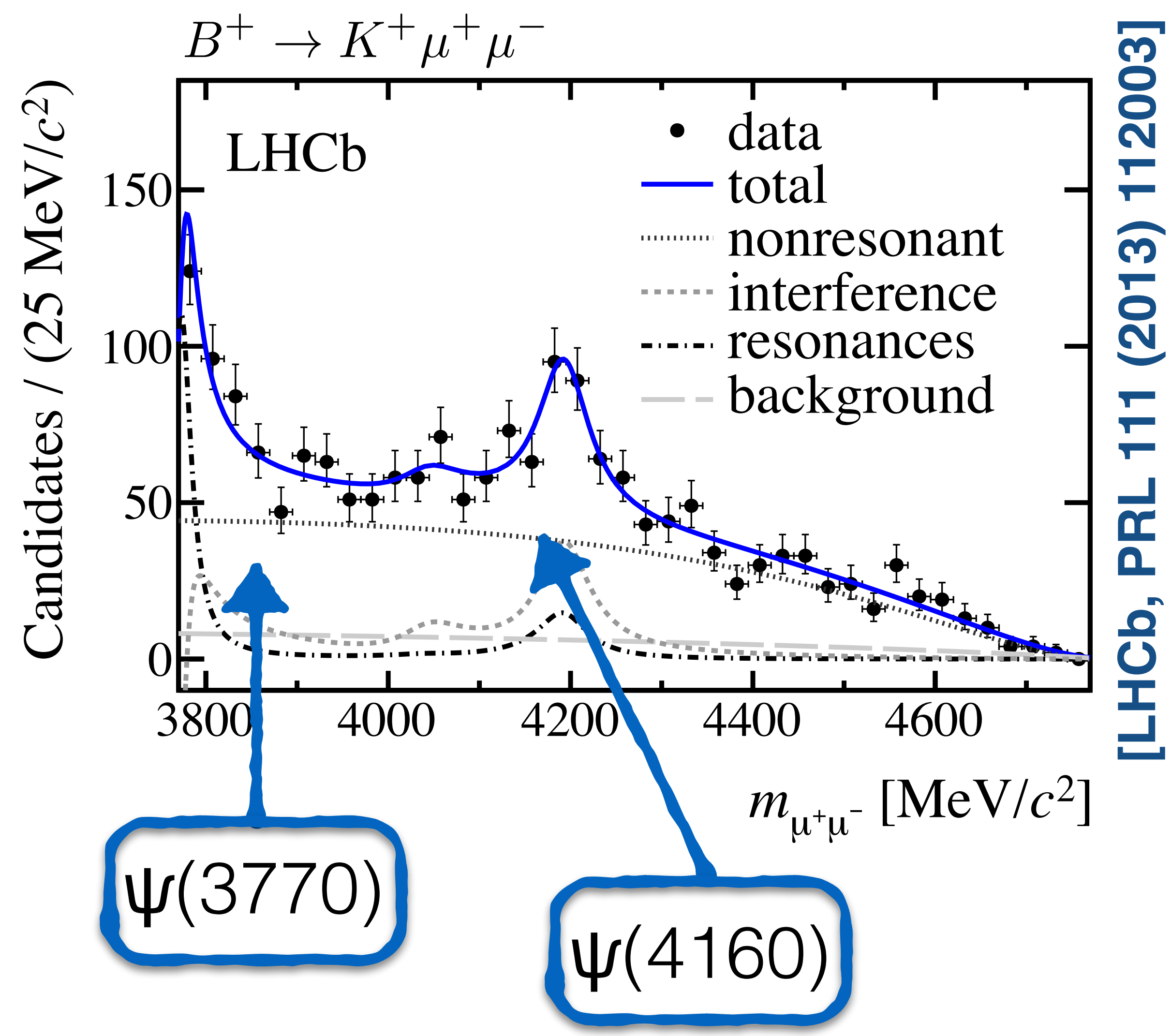


$B^+ \to K^{*+}\mu^+\mu^-$ $B^0 \to K^0\mu^+\mu^-$ $B^+ \to K^+\mu^+\mu^-$

- Branching fractions of other $b \to s\mu^+\mu^-$ processes also tend to be below SM predictions (although consistent with SM at 1σ).
- Decays with K^0 in the final state are experimentally challenging due to the lifetime of the K_S in the experiment (K_L escape the detector).
- We normalise the rate using $B \to J/\psi K^{(*)}$ decays to reduce experimental uncertainties.

Resonance structure

- See large resonant contributions from $c\bar{c}$ states at large dimuon masses.
- We can fit this with a Breit-Wigner ansatz (but only after assuming some q^2 parameterisation for the non-resonant part) to extract magnitudes and relative phases.



i.e. use a shape

$$\text{phsp} \times \left(|\mathcal{A}_{\rm V}(m_{\mu\mu}) + \sum_i e^{i\phi_i}\mathcal{A}_i(m_{\mu\mu},\mu_i,\Gamma_i)|^2 + |\mathcal{A}_A|^2\right) f_+^2(m_{\mu\mu})$$

for narrow states this needs to be convoluted by our experimental resolution

Effective theory

- Can write a Hamiltonian for an effective theory of $b \to s$ processes:

Wilson coefficient
(integrating out scales above μ)

Local 4 fermion operators with
different Lorentz structures

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

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

NP scale

NP can modify
SM contribution
or introduce
new operators

- $\kappa_{\rm NP}$ 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.

$$\mathcal{O}_7 = (m_b/e)\,(\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu})$$

photon (constrained by radiative decays and $b \to s\ell^+\ell^-$ processes at small q^2)

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

vector current (constrained by $b \to s\ell^+\ell^-$ processes)

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

axial vector current (constrained by leptonic decays and $b \to s\ell^+\ell^-$ processes)

$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\ell}\ell)$$

$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

scalar and pseudoscalar operators (constrained primarily by leptonic decays)

e.g.

$B^0_s \to \mu^+\mu^-$ constrains $C_{10} - C'_{10},\ C_S - C'_S,\ C_P - C'_P$

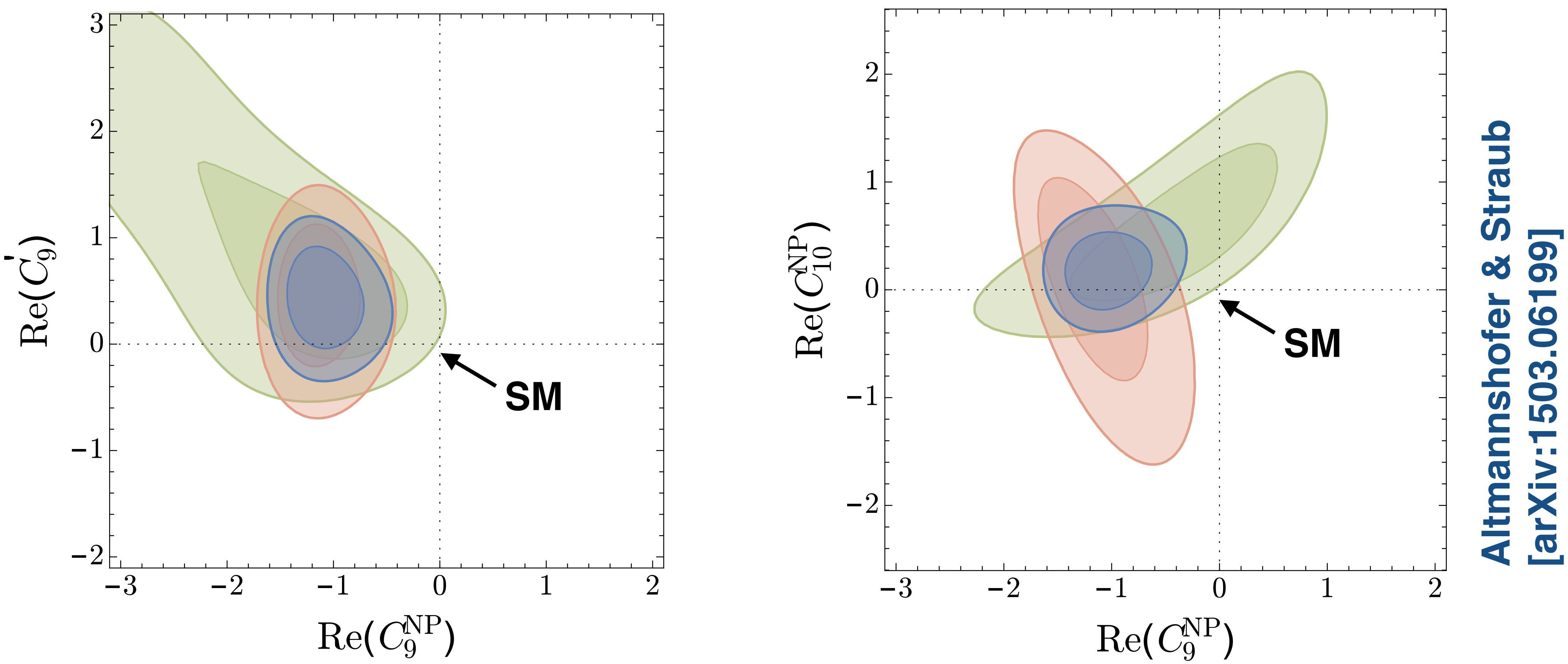
$B^+ \to K^+\mu^+\mu^-$ constrains $C_9 + C'_9,\ C_{10} + C'_{10}$

$B^0 \to K^{*0}\mu^+\mu^-$ constrains $C_7 \pm C'_7,\ C_9 \pm C'_9,\ C_{10} \pm C'_{10}$

The primes denote right-handed counterparts of the operators whose contribution is small in the SM.

Global fits

- Several attempts to interpret our results by performing global fits to $b \to s$ data (e.g. **[arXiv:1503.06199], [arXiv:1510.04239], [arXiv:1512.07157]**).

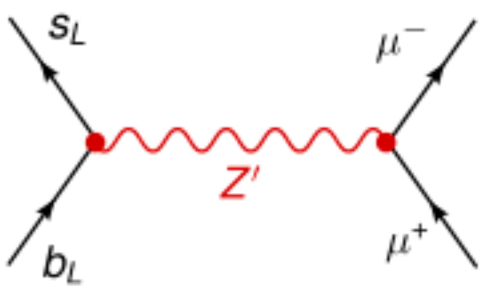


branching fractions, angular observables and combination

- Consistent picture, data favours modified vector coupling ($C_9^{NP} \neq 0$) at 3-4σ.

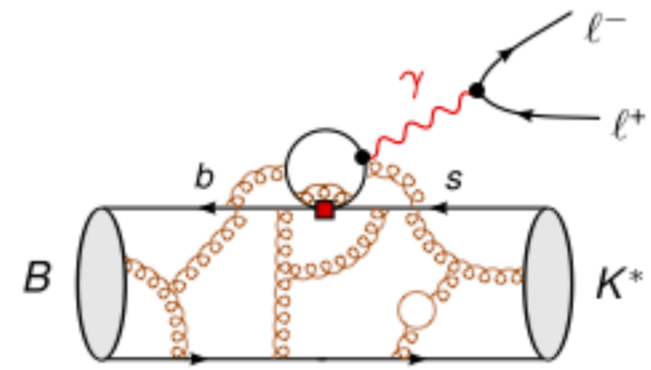
Interpretation of global fits

Optimist's view point



Vector-like contribution could come from new tree level contribution from a Z' with a mass of a few TeV (the Z' will also contribute to mixing, a challenge for model builders)

Pessimist's view point



Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

Lepton universality

- In the SM, ratios

$$R_{\mathrm{K}} = \frac{\int \mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int \mathrm{d}\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$$

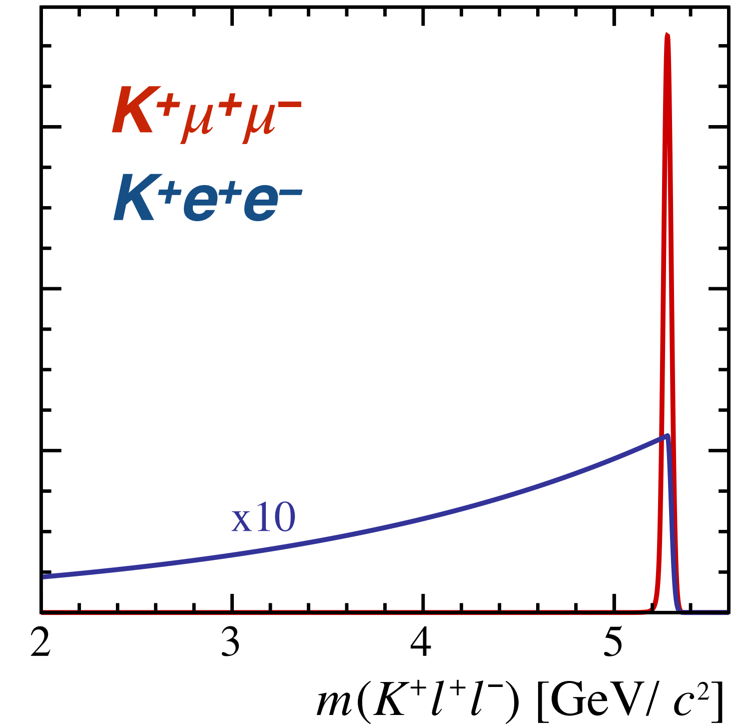
  only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours (with the exception of the Higgs).

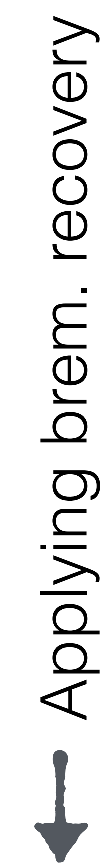
- Theoretically clean since hadronic uncertainties cancel in the ratio (same hadronic matrix element).

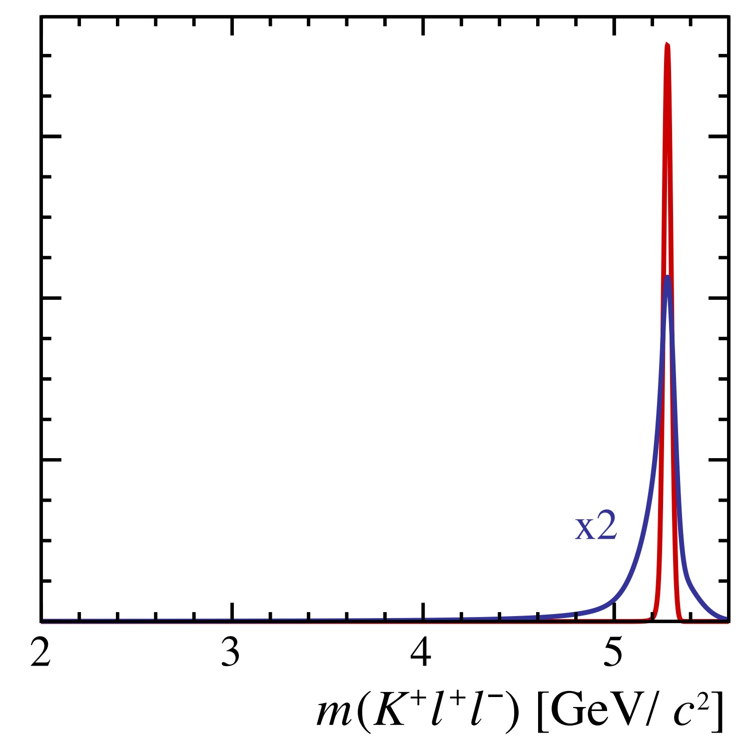
- Experimentally more challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).

Bremsstrahlung recovery

- Two big experimental differences between electrons/muons:
  - ➡ Bremsstrahlung/FSR from the electrons.
  - ➡ Typically require higher trigger thresholds for electrons than muons (E_T > 3 GeV c.f. p_T > 1.76 GeV/c in 2012) and have a lower tracking efficiency.
- Bremsstrahlung causes migration of events in q^2 and in reconstructed B mass.
  - ➡ Recover clusters with E_T > 75 MeV/c^2 to correct for Bremsstrahlung.



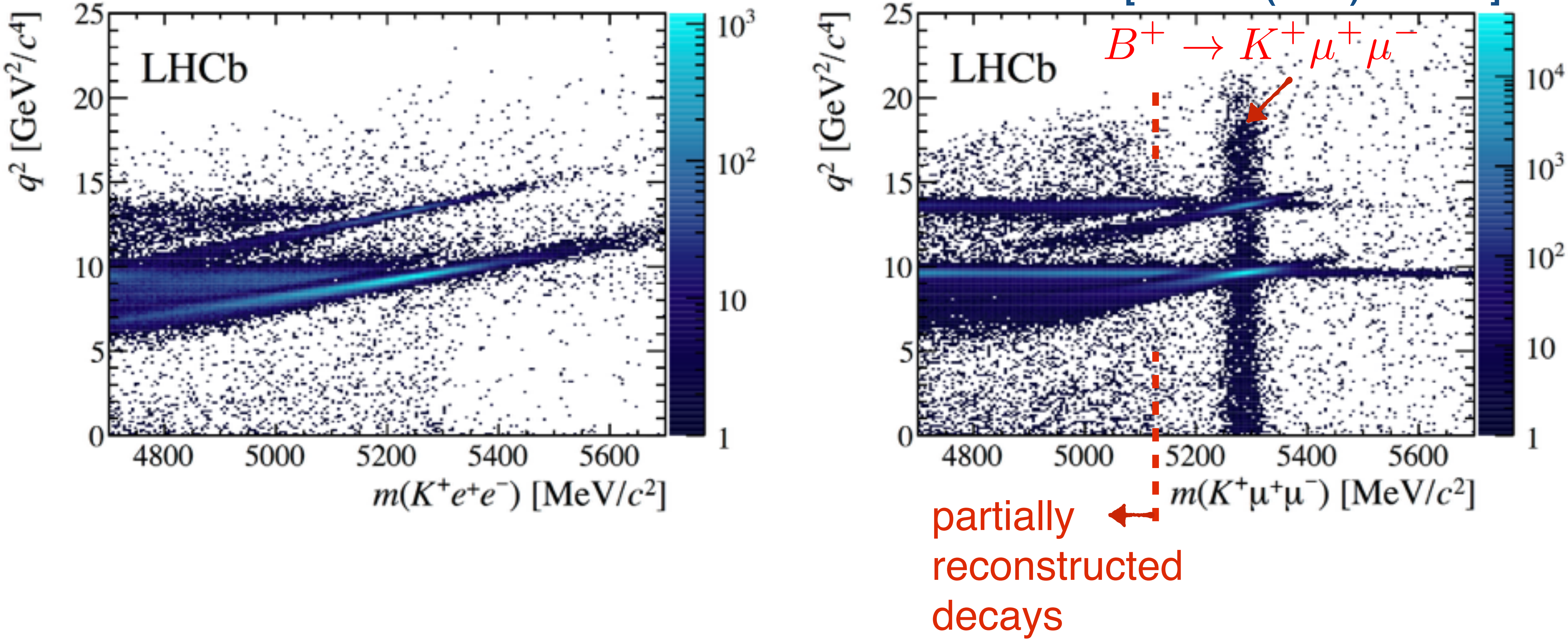




$B^+ \to K^+\ell^+\ell^-$ candidates

- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

LHCb [PRL113 (2014) 151601]



R_K result

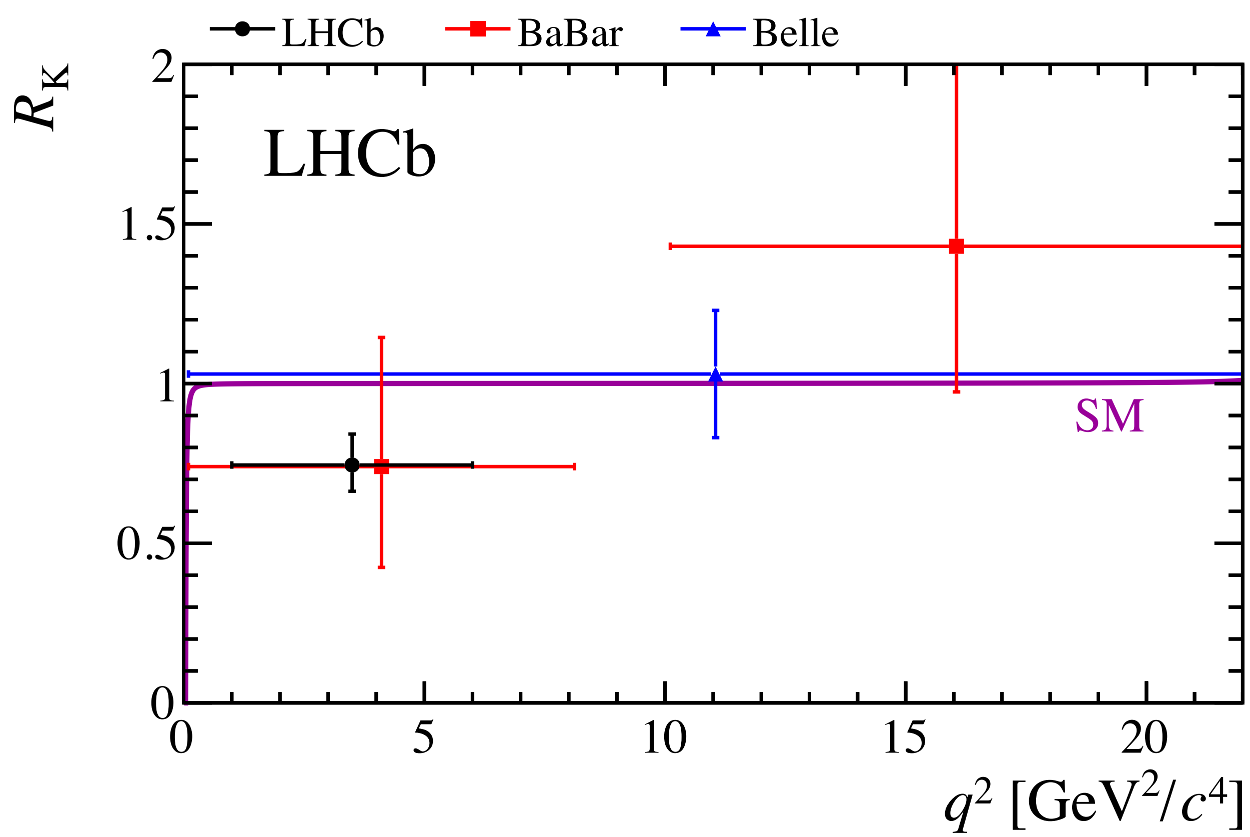
- In the Run 1 dataset, LHCb determines:

$$R_K = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}$$

in the range $1 < q^2 < 6$ GeV², which is consistent with the SM at 2.6σ.

- Take double ratio with $B^+ \to J/\psi K^+$ to cancel possible sources of systematic uncertainty.

- Correct for migration of events in q^2 due to Bremsstrahlung using MC (with PHOTOS).



LHCb [PRL113 (2014) 151601]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

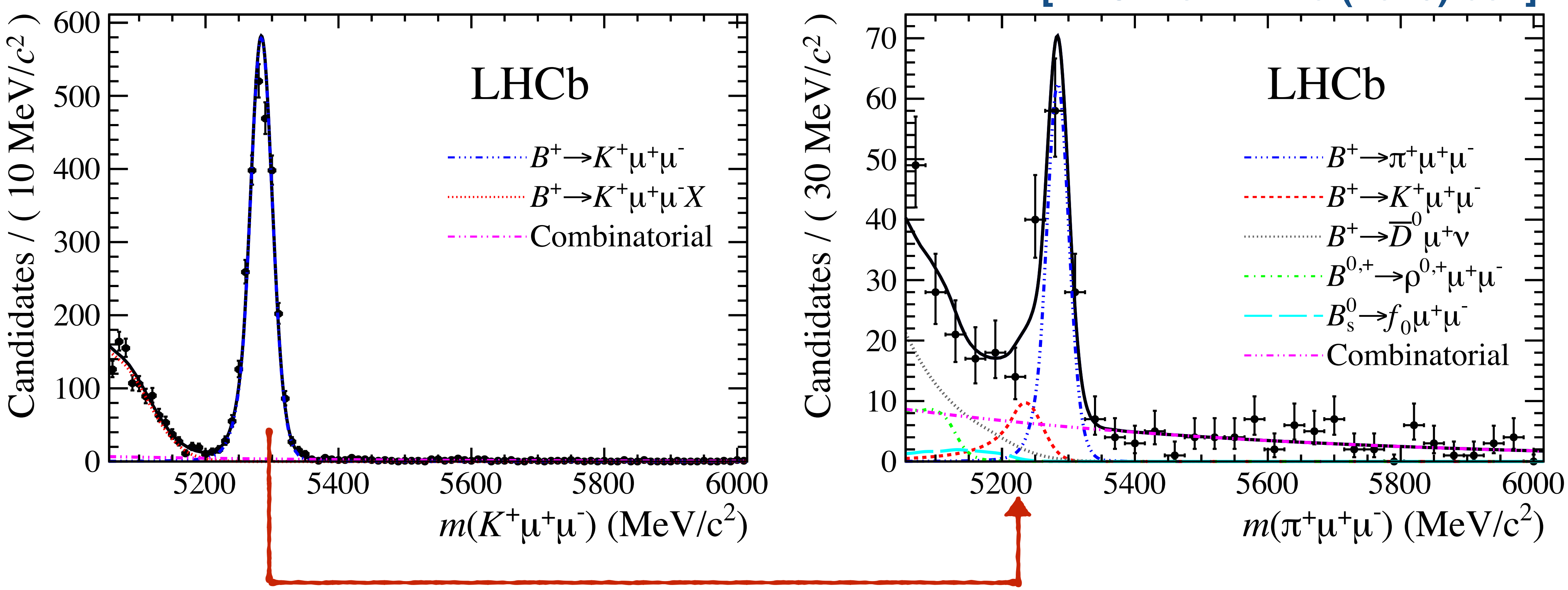
NB $R_K \simeq 0.8$ is a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

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

- Rare $b \to d$ FCNC process with a branching fraction:

$$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

[LHCb JHEP 10 (2015) 034]

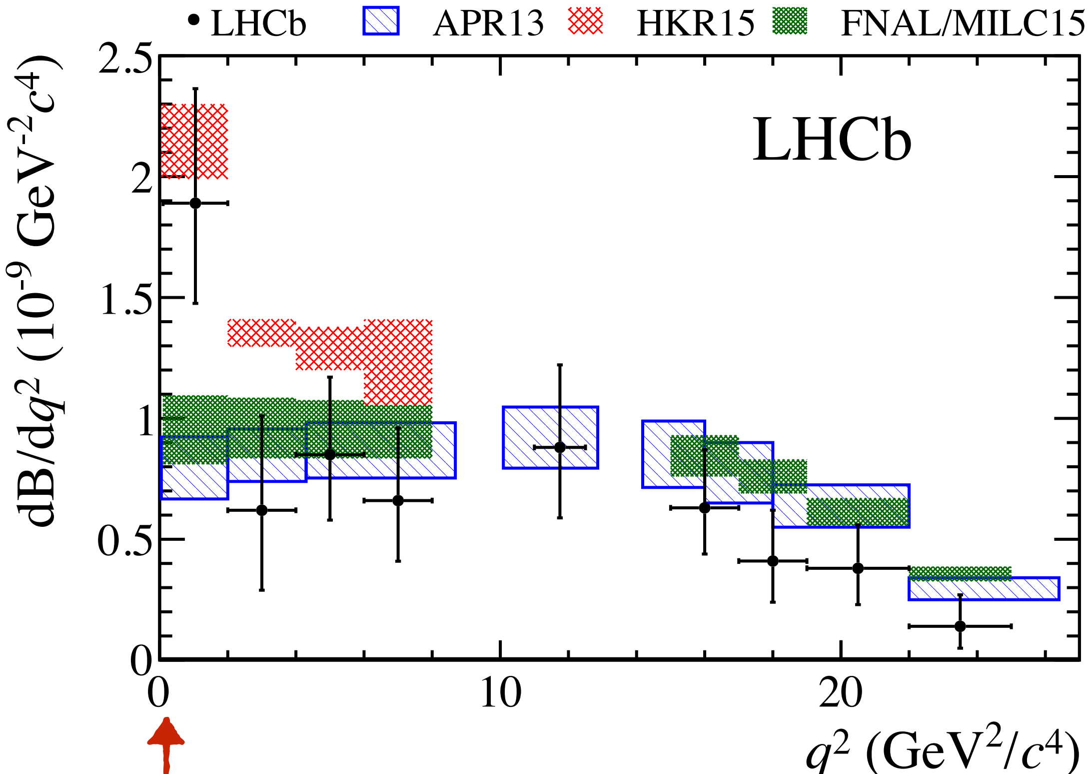


cross-feed suppressed by RICH PID in LHCb

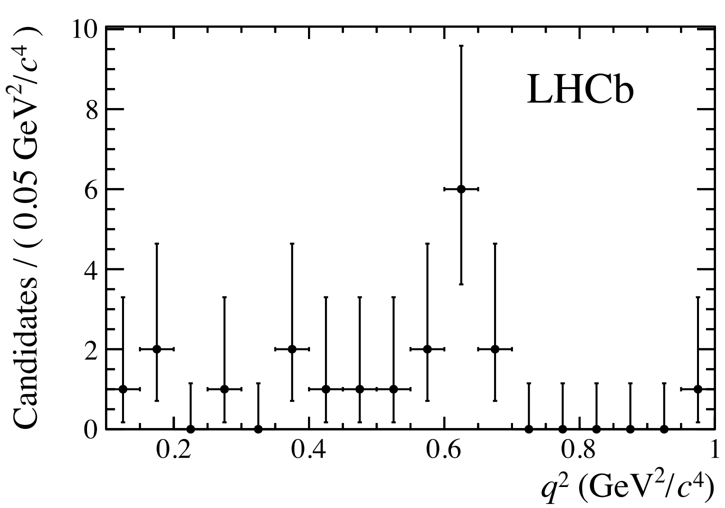
- Major experimental challenge is control of background from $B^+ \to K^+ \mu^+ \mu^-$ decays with $K \to \pi$ mis-id.

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

- Determine branching fraction by normalising to $B^+ \to J/\psi K^+$



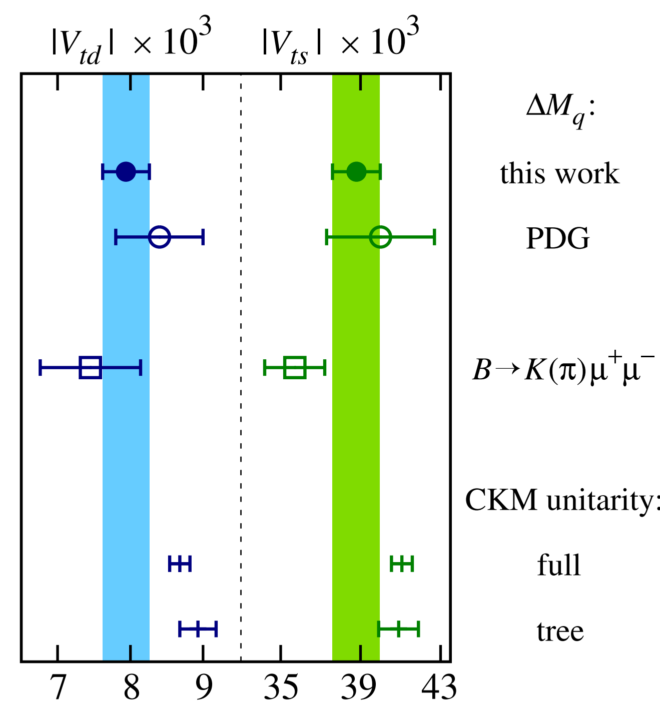
[LHCb JHEP 10 (2015) 034]



Enhancement for $q^2 < 1$ GeV$^2/c^4$ due to light resonances (ρ, ω).

These are included in HKR 15

Can also use and $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to \pi^+\mu^+\mu^-$ to determine the CKM elements V_{ts} and V_{td} (see e.g. **[Du et al arXiv:1510.02349]**)

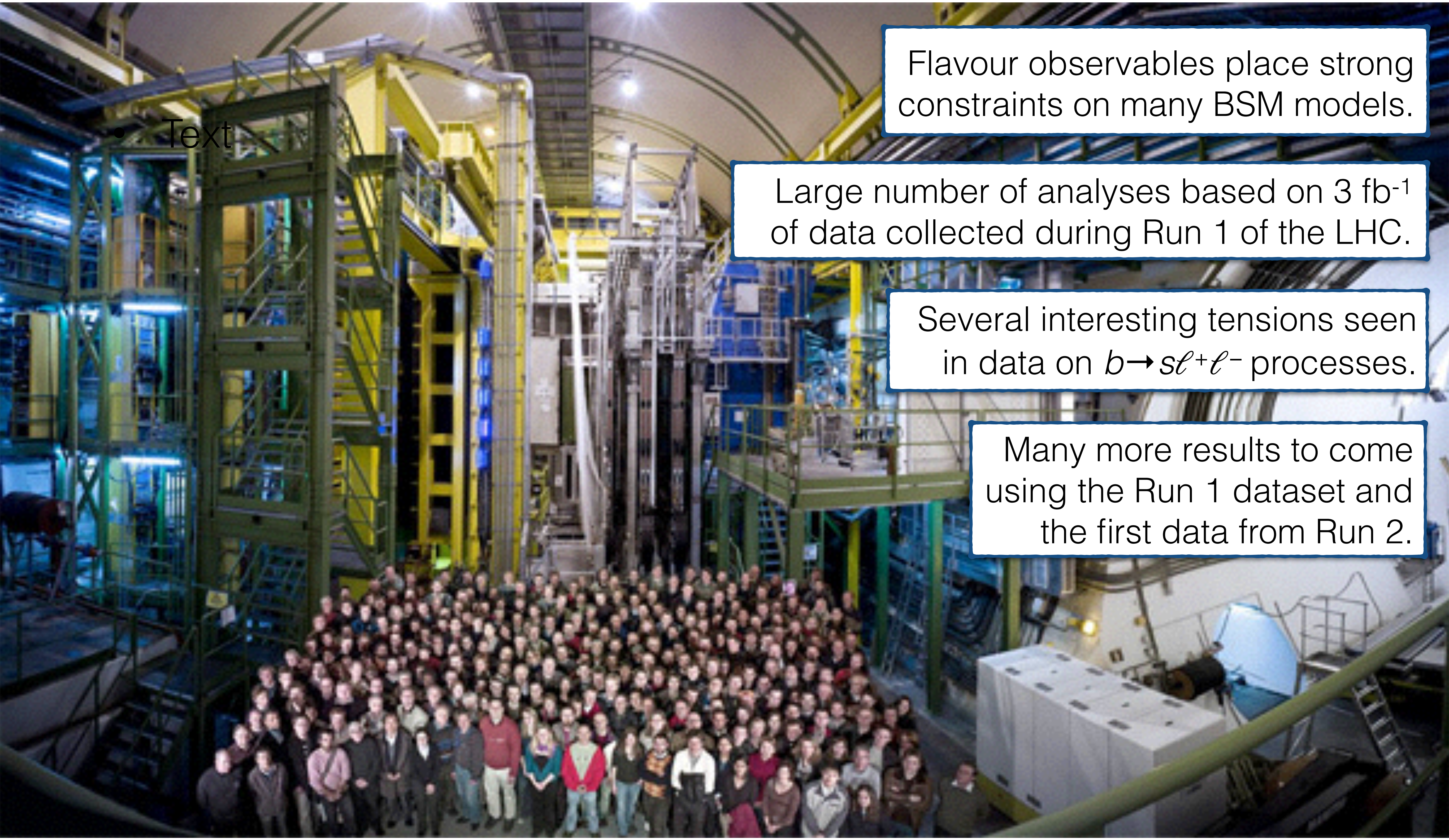


From **FNAL-MILC [arXiv:1602.03560]**

Ratio consistent with MFV hypothesis.

SM predictions [Ali et al. arXiv:1312.2523], [Hambrock et al. arXiv:1506.07760] and [Bailey et al. arXiv:1507.01618].

Summary



Flavour observables place strong constraints on many BSM models.

Large number of analyses based on 3 fb^{-1} of data collected during Run 1 of the LHC.

Several interesting tensions seen in data on $b \to s\ell^+\ell^-$ processes.

Many more results to come using the Run 1 dataset and the first data from Run 2.

References

Decay	Reference
$B^0 \to K^{*0}\mu^+\mu^-$	JHEP 08 (2013) 131
$B^0 \to K^0_S\mu^+\mu^-$	JHEP 06 (2014) 133
$B^0 \to \pi^+\pi^-\mu^+\mu^-$	Phys. Lett. B 743 (2015) 46
$B^0 \to \mu^+\mu^-$	Nature 522 (2015) 68
$B^+ \to K^{*+}\mu^+\mu^-$	HEP 06 (2014) 133
$B^+ \to K^+\mu^+\mu^-$	JHEP 06 (2014) 133
$B^+ \to K^+\pi^-\pi^+\mu^+\mu^-$	JHEP 10 (2014) 064
$B^+ \to \phi K^+\mu^+\mu^-$	JHEP 10 (2014) 064
$B^+ \to \pi^+\mu^+\mu^-$	JHEP 10 (2015) 034
$B^0_s \to \phi\mu^+\mu^-$	JHEP 09 (2015) 179
$B^0_s \to \pi^+\pi^-\mu^+\mu^-$	Phys. Lett. B 743 (2015) 46
$\Lambda^0_b \to \Lambda\mu^+\mu^-$	JHEP 06 (2015) 115
$B^0_s \to \mu^+\mu^-$	Nature 522 (2015) 68
$D^0 \to K^-\pi^+\mu^+\mu^-$	LHCb-PAPER-2015-043 (submitted to Phys. Lett. B)
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	Phys. Lett. B 728 (2014) 234
$D^0 \to \mu^+\mu^-$	Phys. Lett. B 725 (2013) 16
$D^+_{(s)} \to \pi^+\mu^+\mu^-$	Phys. Lett. B 724 (2013) 203

Branching fraction measurements (or limits)

References

- Much smaller range of measurements with electron final states. Expect this table to be slowly filled with the Run 2 data.

Decay	Reference
$B^0 \to K^{*0} e^+ e^-$	JHEP 05 (2013) 159
$B^+ \to K^+ e^+ e^-$	Phys. Rev. Lett. 113 (2014) 151601

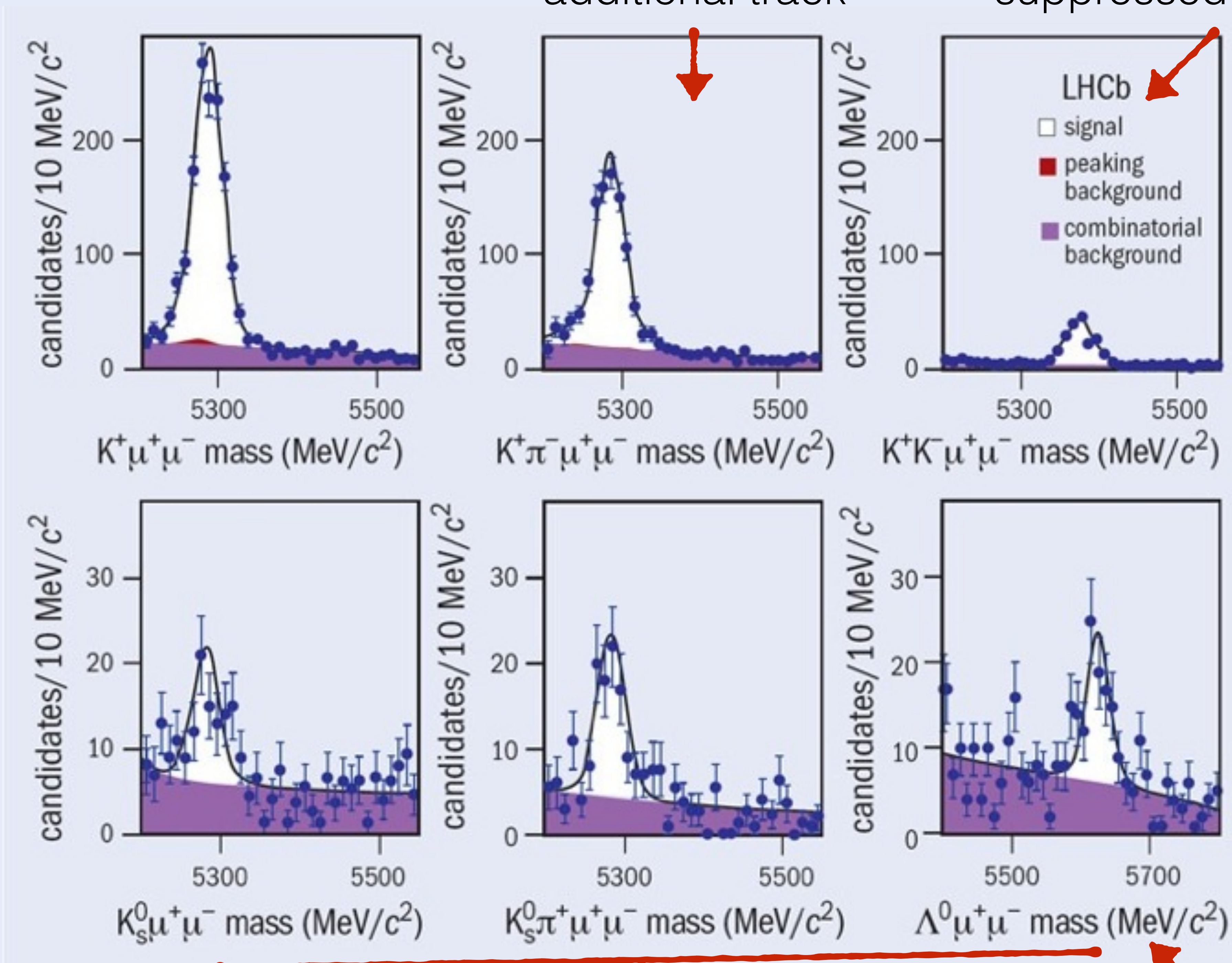
Backup

Signals in LHCb 1 fb-1 dataset

Can profit from a large $b\bar{b}$ production cross-section at the LHC to reconstruct large samples of these rare processes.

additional track

suppressed by f_s/f_d

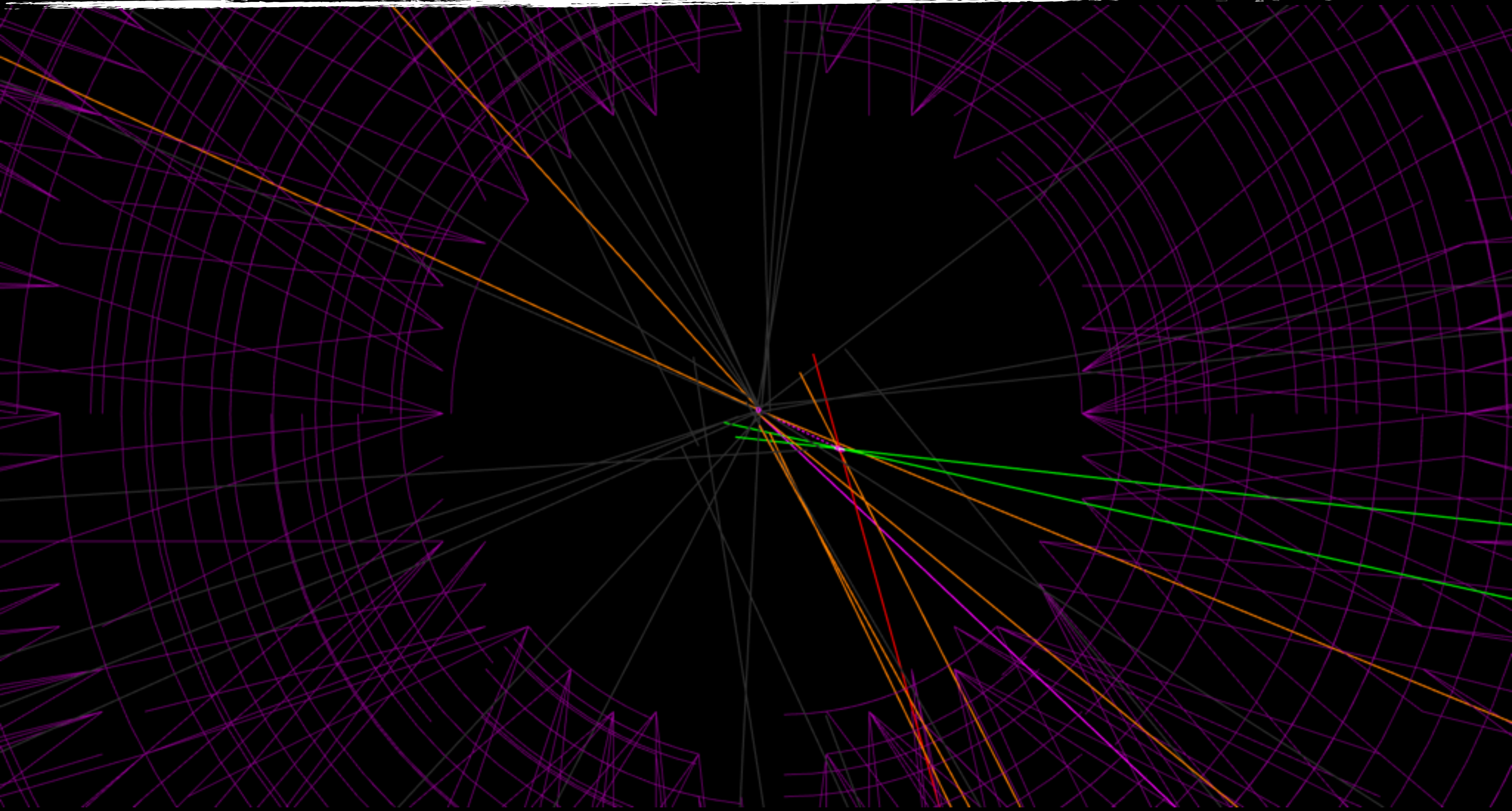


[from CERN courier, May 2013]

long-lived K_S^0 or Λ^0

suppressed by f_Λ/f_d

Candidate selection

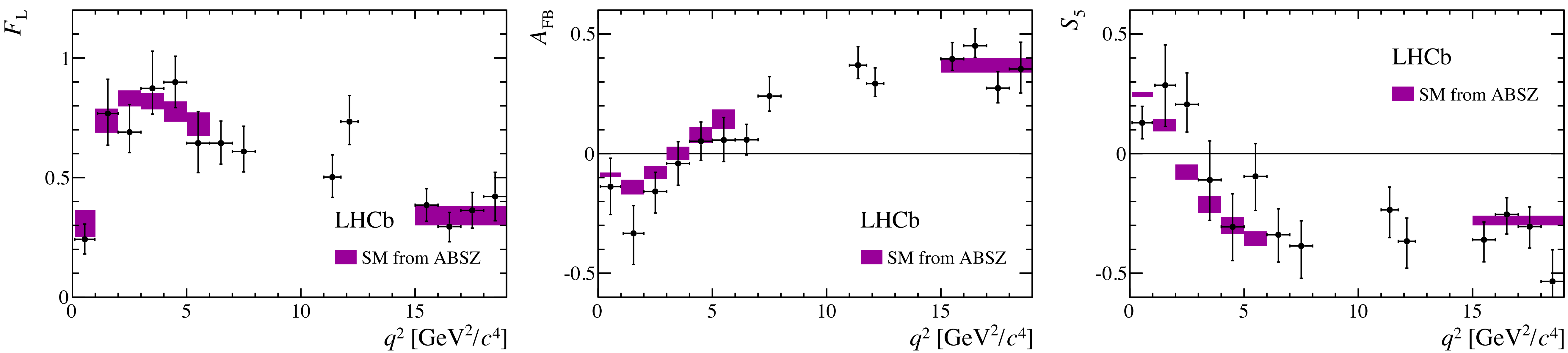


exploit the B lifetime to select candidates (~1cm decay length)

Moment analysis

- Can also determine the angular observables using principal moments of the angular distribution:
  - ✓ Robust estimator even for small datasets (allows us to bin more finely in q^2).
  - x Statistically less precise than the result of the maximum likelihood fit.

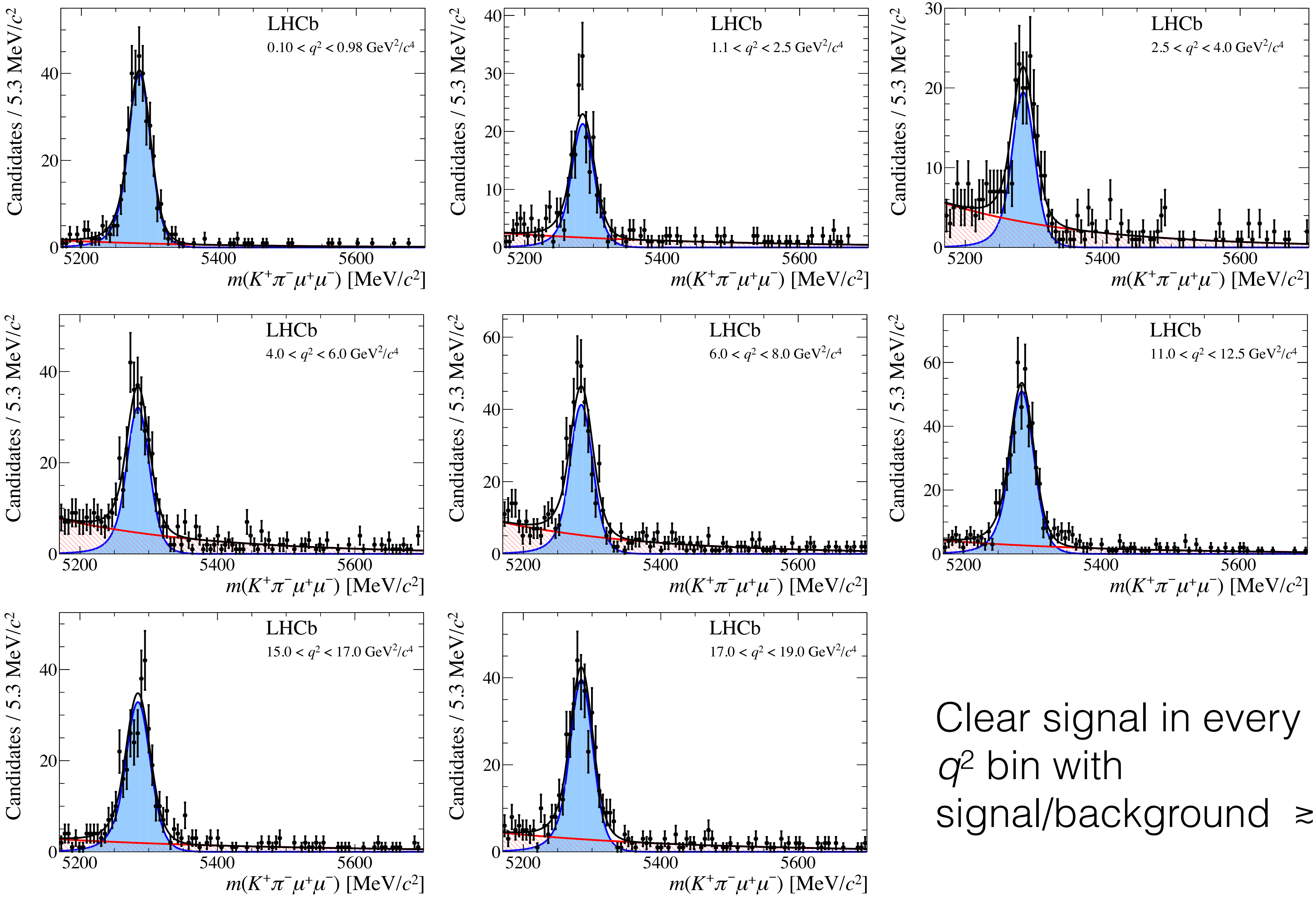
[LHCb, JHEP 02 (2016) 104]



- 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]

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

[LHCb, JHEP 02 (2016) 104]



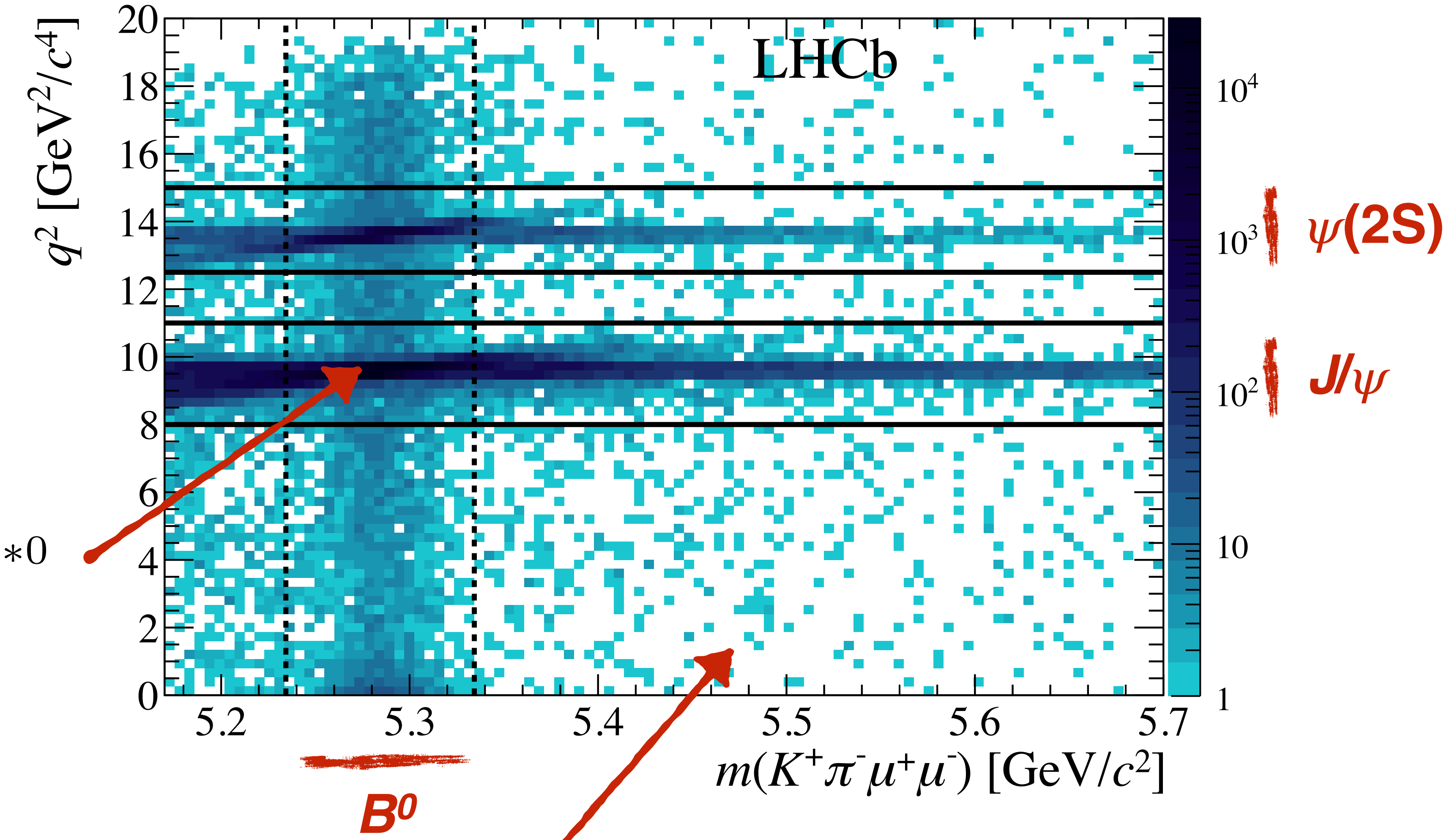
Clear signal in every q^2 bin with signal/background $\gtrsim 3$

Reconstructed candidates

Select clean sample of signal events using a multivariate classifier.

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

[LHCb, JHEP 02 (2016) 104]

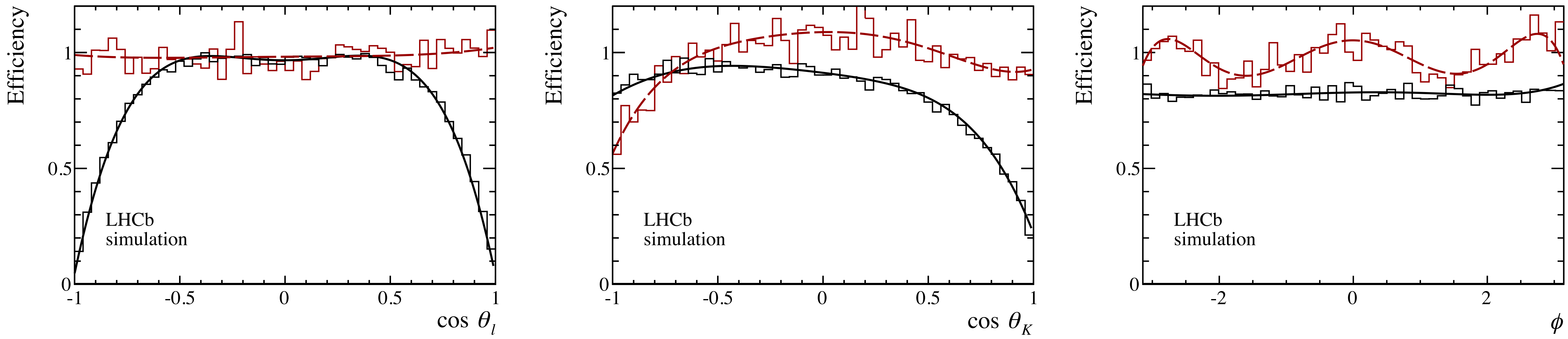


$B^0 \to J/\psi K^{*0}$

combinatorial background

Angular acceptance

[JHEP 02 (2016) 104]



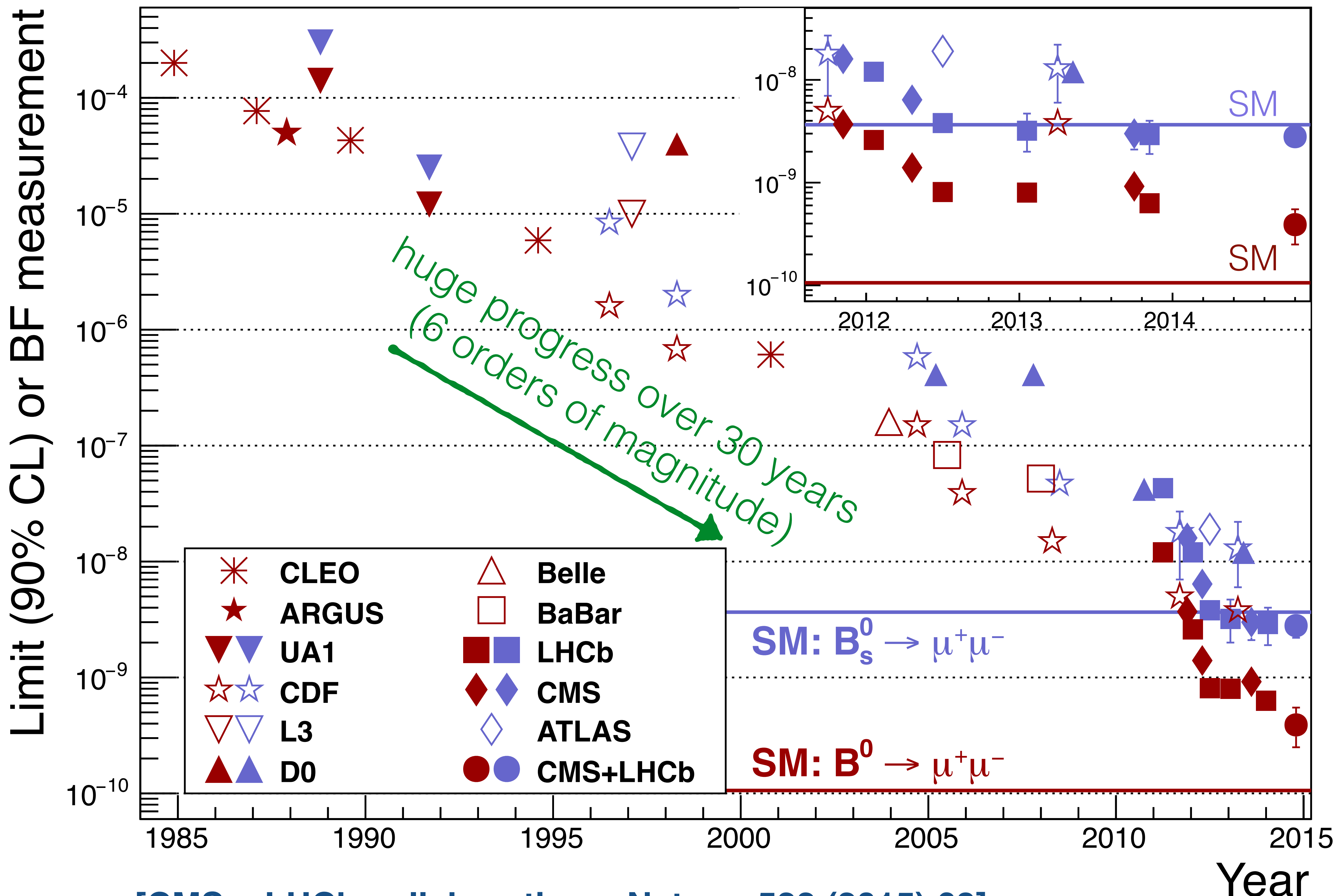
- Momentum/impact parameter requirements in the reconstruction/selection bias the angular distribution.
- We determine the acceptance using a large sample of phase-space events, with a model:

$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) \times L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

Legendre polynomial of degree *n*.

and cross check this using $B^0 \to J/\psi\, K^{*0}$ events in data.

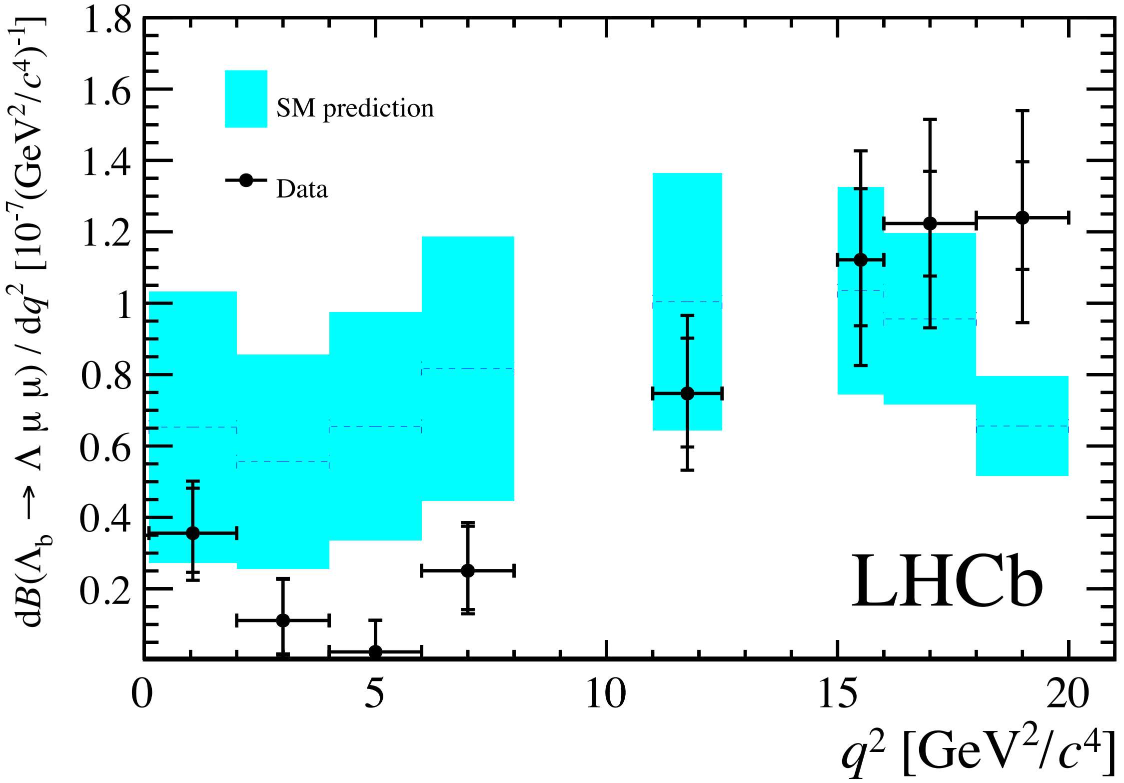
$B_{(s,d)} \to \mu^+\mu^-$ history



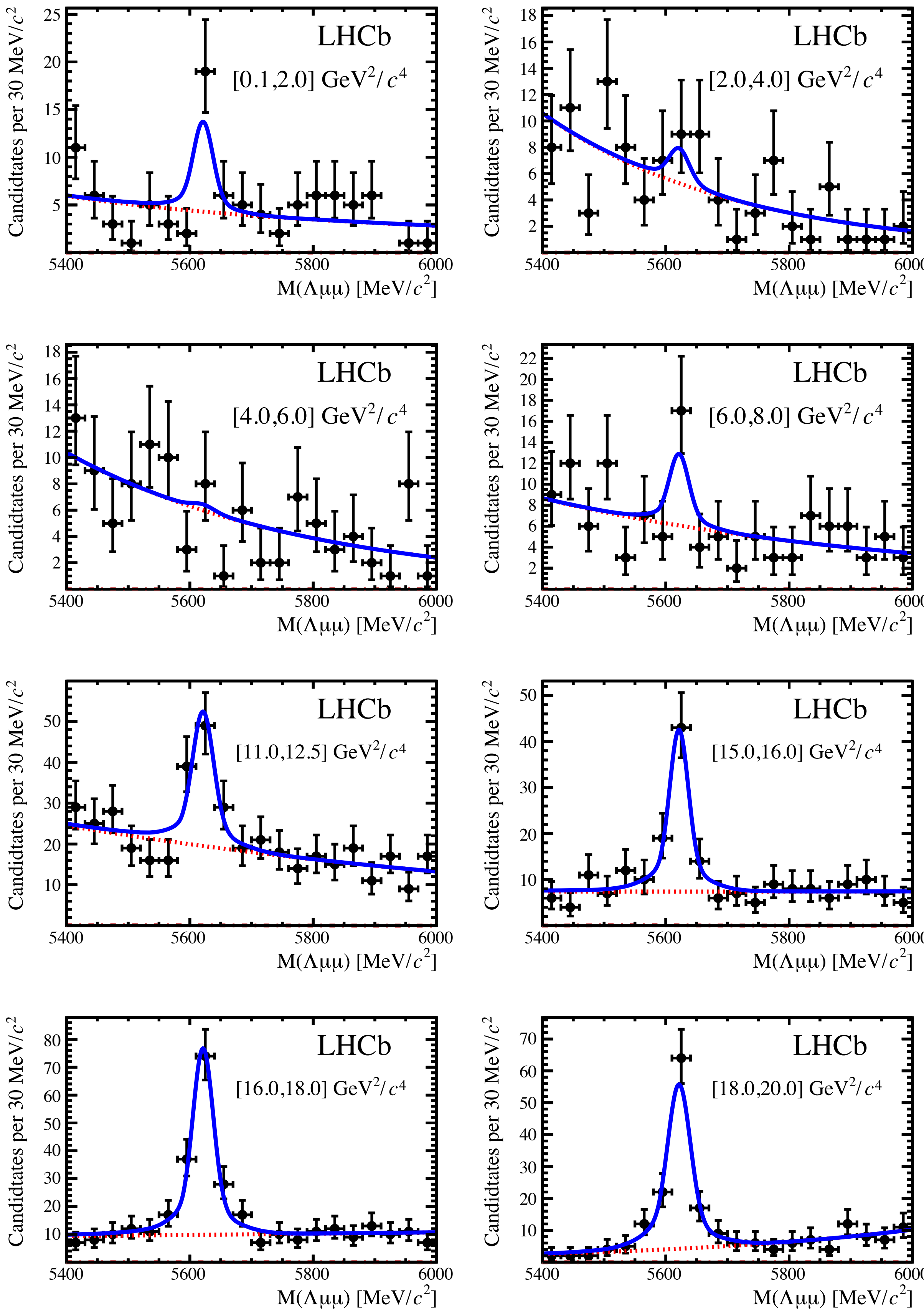
[CMS + LHCb collaborations, Nature, 522 (2015) 68]

Rare baryon decays

- We also now have precise measurements of the branching fraction of $\Lambda_b \to \Lambda\mu^+\mu^-$ decays.
  - ➡ Signal mainly at high q^2.



Poor agreement in shape between SM predictions and data (especially at low q^2)?



[LHCb, JHEP 06 (2015) 115]

[SM from Detmold et al. Phys. Rev. D87 (2013) 074502]

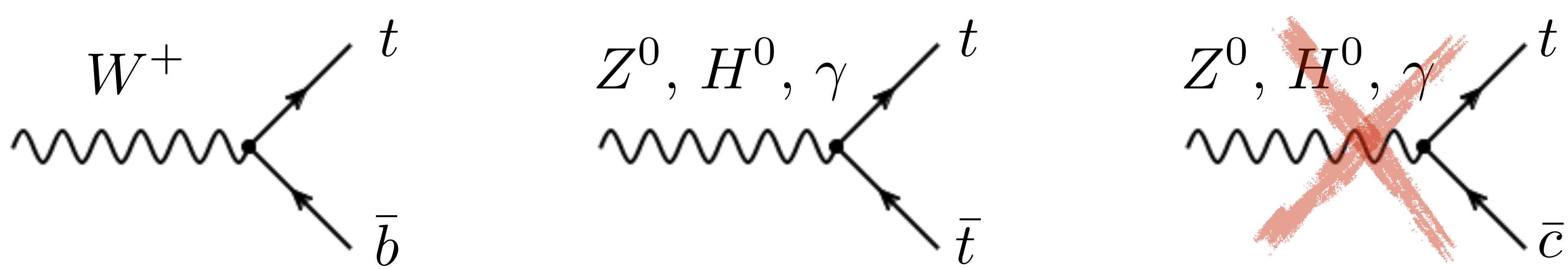
Flavour in the SM

- Particle physics can be described to excellent precision by a very simple theory:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_a, \psi_i)$$

- $\mathcal{L}_{\rm Higgs}$ is responsible for flavour in the SM. Without the Higgs, the three fermion families would be identical replicas.

- Yukawa matrices are the only source of flavour violation,



➡ Quark flavour-violating interactions governed by the CKM.

➡ No tree level FCNCs in the SM.

Small couplings?

- New flavour violating sources (if there are any) are highly tuned, i.e. must come with a small coupling constant or must have a very large mass.

$\kappa_{\rm NP}$

generic tree-level

$$\sim 1 \longrightarrow \Lambda_{\rm NP} \gtrsim 2\times 10^4\ {\rm TeV}$$

generic loop-order

$$\sim \frac{1}{(4\pi)^2} \longrightarrow \Lambda_{\rm NP} \gtrsim 2\times 10^3\ {\rm TeV}$$

tree-level with "alignment"

$$\sim (y_t V_{ti}^* V_{tj})^2 \longrightarrow \Lambda_{\rm NP} \gtrsim 5\ {\rm TeV}$$

loop-order with "alignment"

$$\sim \frac{(y_t V_{ti}^* V_{tj}^*)^2}{(4\pi)^2} \longrightarrow \Lambda_{\rm NP} \gtrsim 0.5\ {\rm TeV}$$

Theoretical Framework

- In leptonic decays the matrix element for the decay can be factorised into a leptonic current and *B* meson decay constant:

$$
\begin{aligned}
\langle \ell^+\ell^- | j_\ell \, j_q | B_q \rangle &= \langle \ell^+\ell^- | j_\ell | 0 \rangle \langle 0 | j_q | B_q \rangle \\
&\approx \langle \ell^+\ell^- | j_q | 0 \rangle \cdot f_{B_q}
\end{aligned}
$$

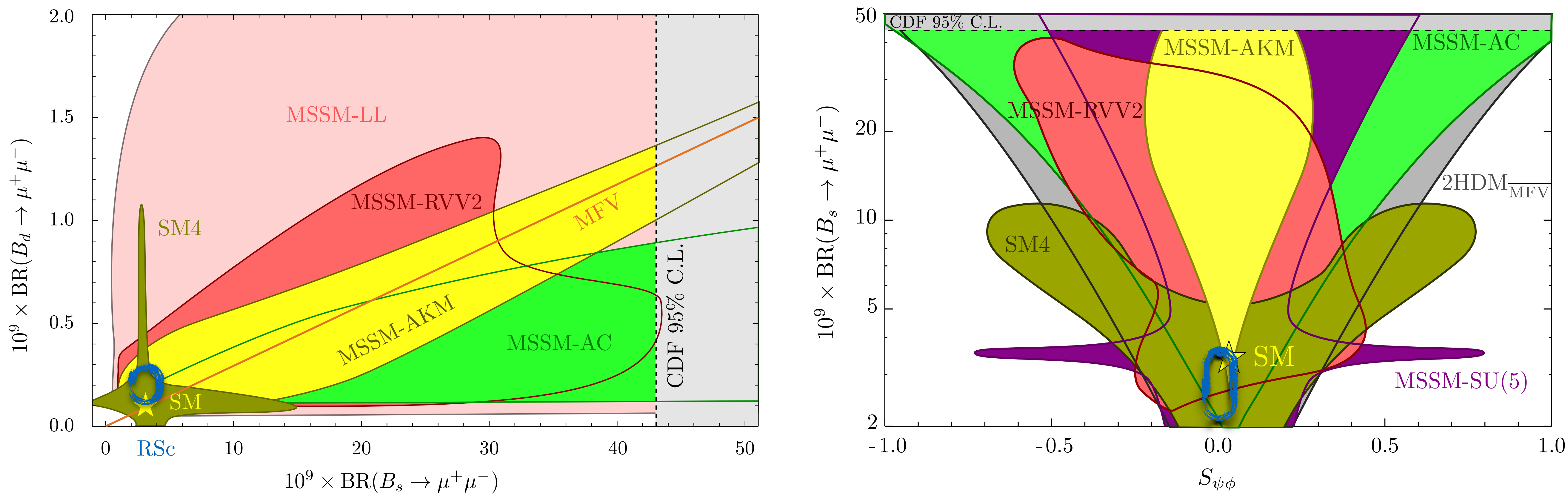
- In semileptonic decays, the matrix element can be factorised into a leptonic current times a form-factor:

$$
\begin{aligned}
\langle \ell^+\ell^- M | j_\ell \, j_q | B \rangle &= \langle \ell^+\ell^- | j_\ell | 0 \rangle \langle M | j_q | B_q \rangle \\
&\approx \langle \ell^+\ell^- | j_\ell | 0 \rangle \cdot F(q^2) + \mathcal{O}(\Lambda_{\rm QCD}/m_B)
\end{aligned}
$$

however this factorisation is not exact (due to hadronic contributions).

Flavour constraints

[Straub, arXiv:1107.0266]



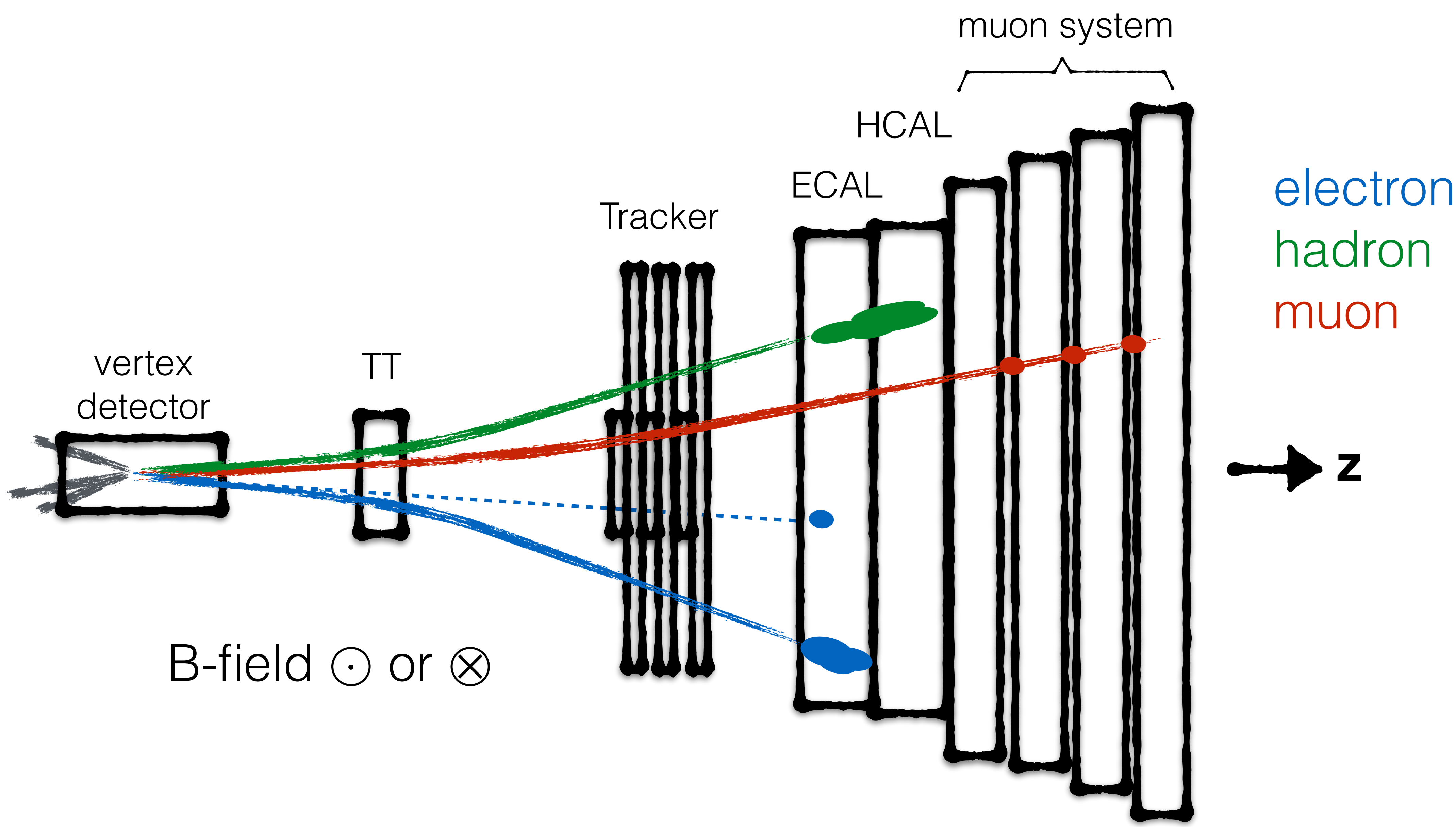
constraints prior to LHC, constraints at the end of Run 1

- FCNC processes can be highly sensitive to the presence of new TeV-scale particles.

  e.g. $B_s \to \mu^+\mu^-$ branching fraction or CP violation in Bs mixing.

Particle reconstruction

(in the LHCb detector)



Electron reconstruction includes recovery of Bremsstrahlung photons (for clusters with $E_T > 75$ MeV/c^2)

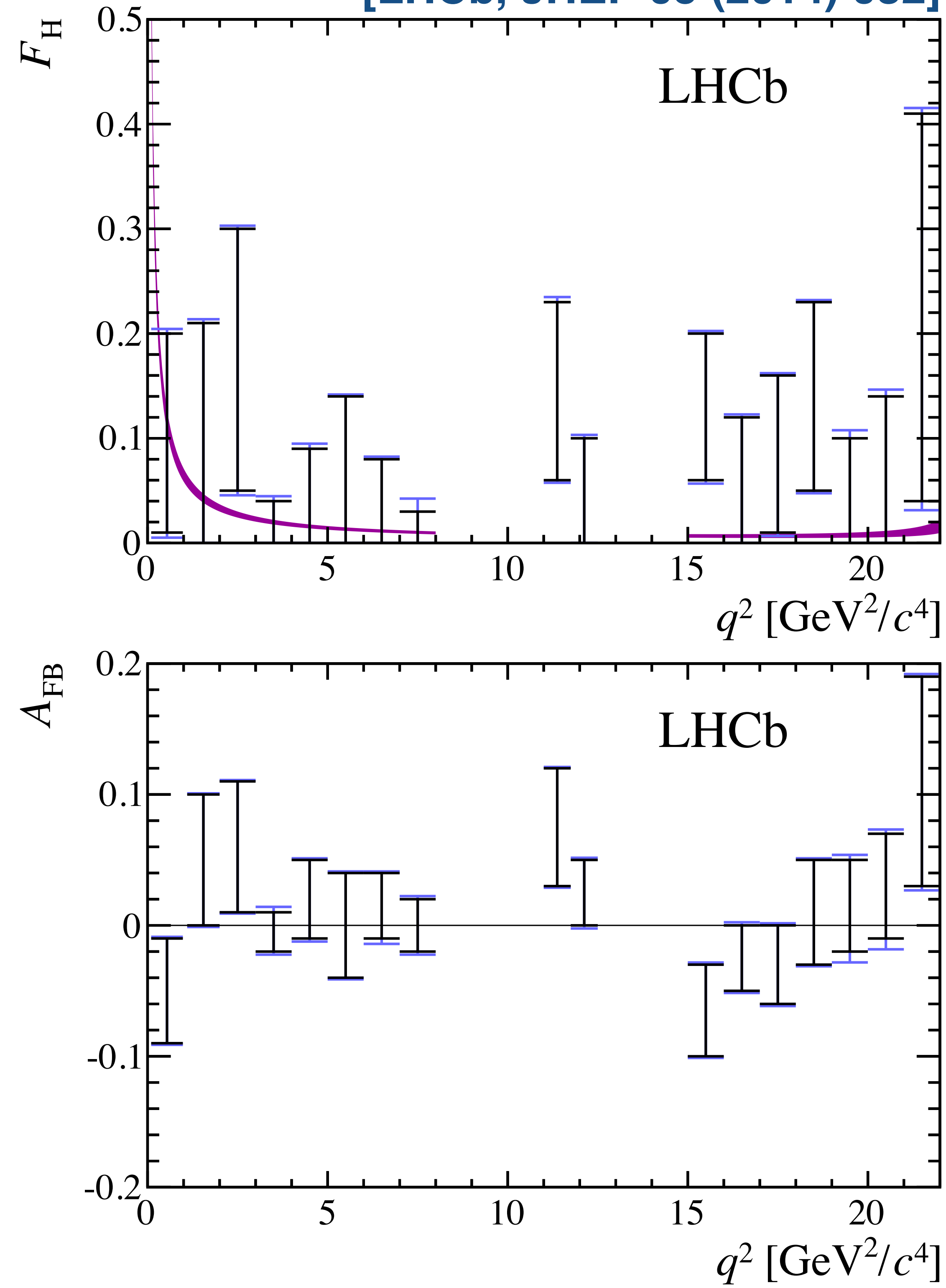
$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

[LHCb, JHEP 05 (2014) 082]

- Single angle and two parameters describe the decay:

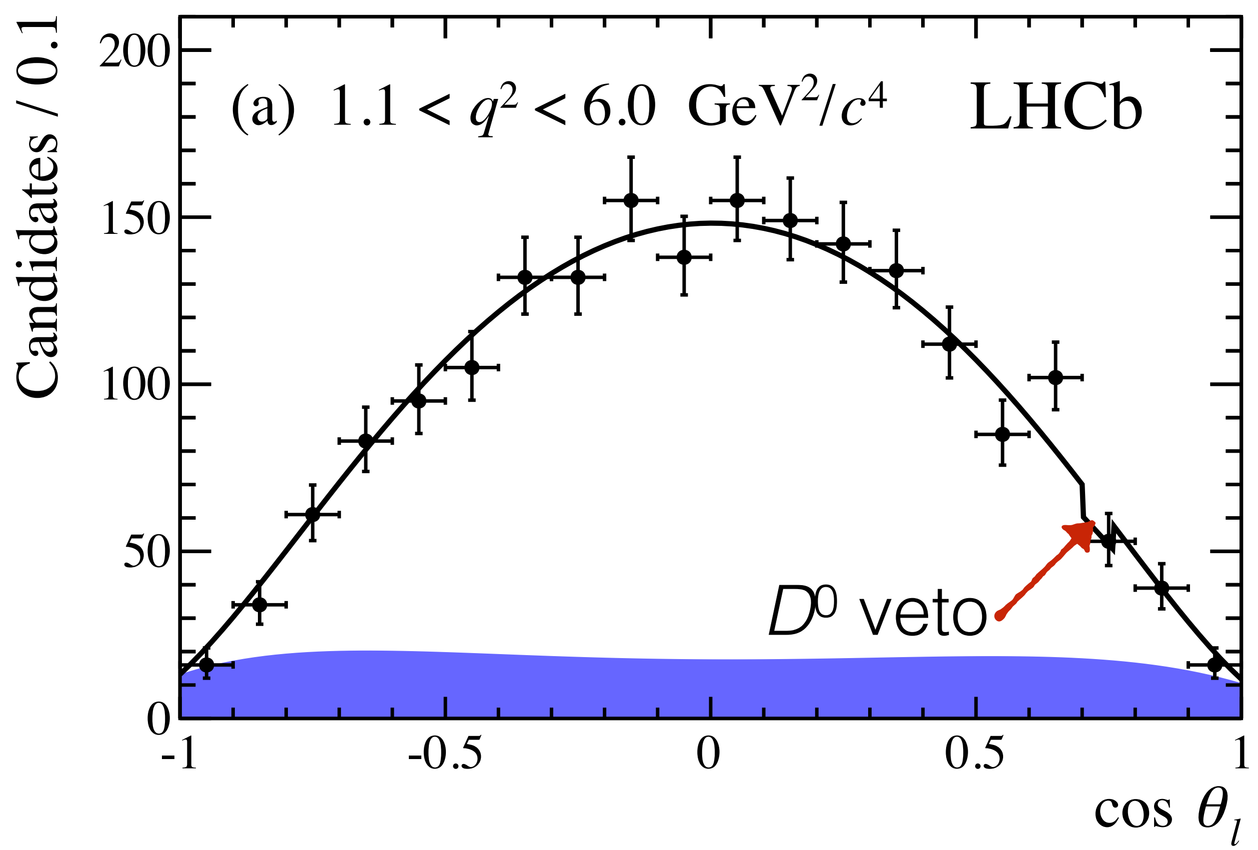
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_\mathrm{H})(1-\cos^2\theta_\ell) + \frac{1}{2}F_\mathrm{H} + A_\mathrm{FB}\cos\theta_\ell$$

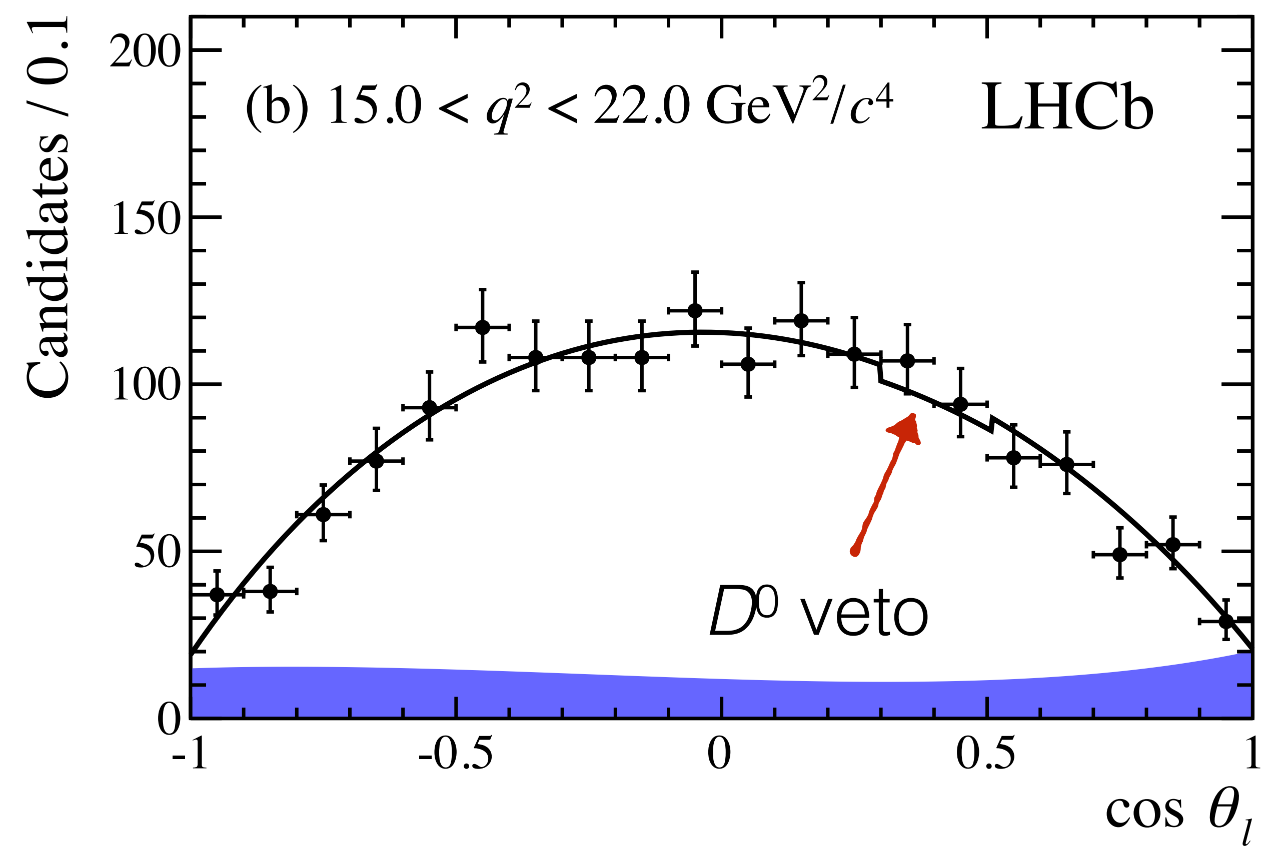
- F_H corresponds to the fractional contribution of scalar/pseudoscalar and tensor operators to Γ.
- Expect $A_\mathrm{FB} \approx 0$ and $F_\mathrm{H} \approx 0$ in the SM.
  - ➡ Result consistent with SM expectation.



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

[LHCb, JHEP 05 (2014) 082]





Isospin asymmetries

- In the SM expect the partial widths of B^+ and B^0 decays to be almost identical, i.e.

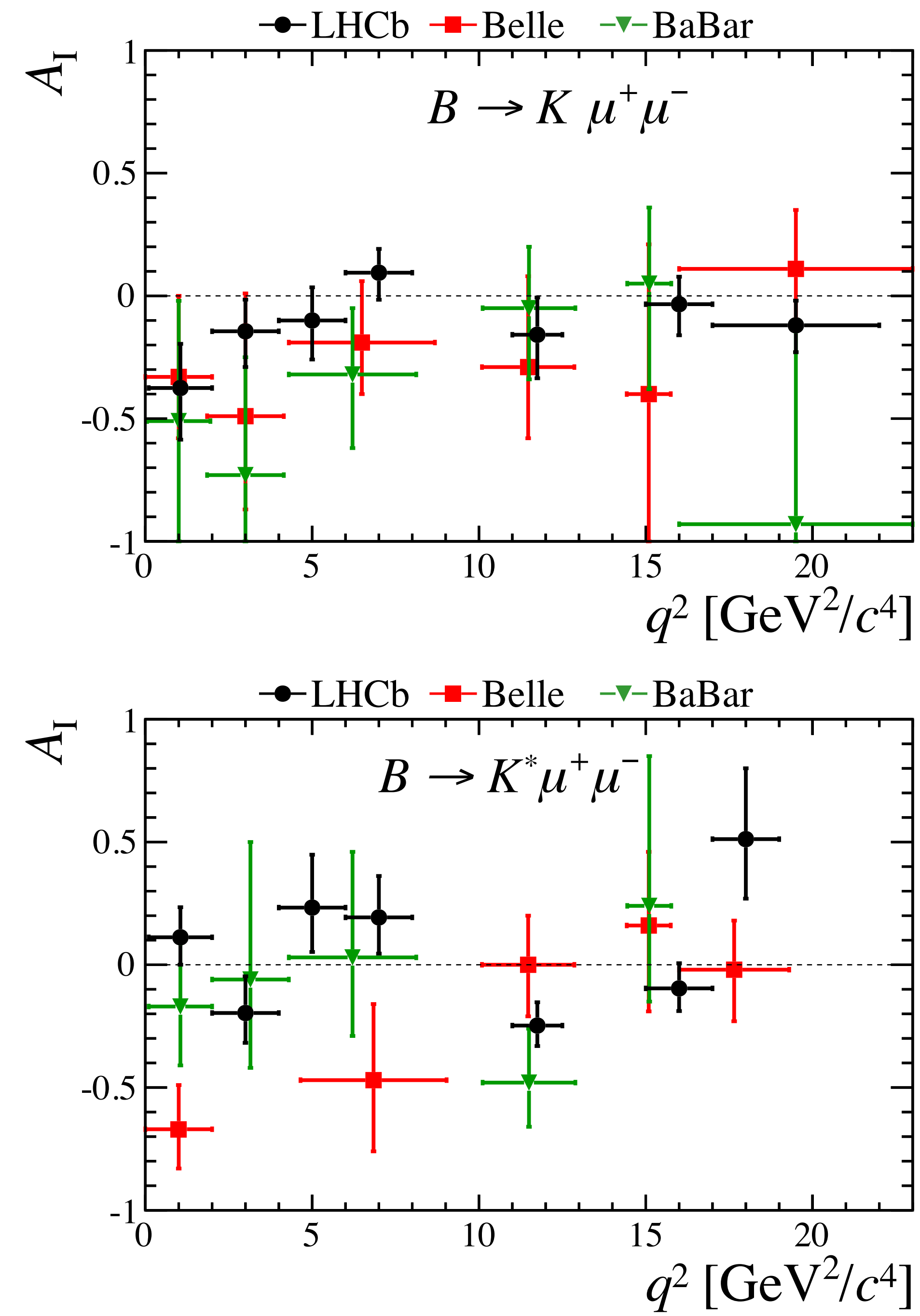
$$A_\mathrm{I} = \frac{\Gamma[B^0 \to K^{(*)0}\ell^+\ell^-] - \Gamma[B^+ \to K^{(*)+}\ell^+\ell^-]}{\Gamma[B^0 \to K^{(*)0}\ell^+\ell^-] + \Gamma[B^+ \to K^{(*)+}\ell^+\ell^-]}$$

should be O(1%).

- Sensitive to spectator quark differences between the decays (exchange and annihilation processes).

- To reduce experimental uncertainties measure the difference in A_I c.f. decays via a J/ψ meson (where $A_\mathrm{I} \ll 1\%$).

- Measurements are consistent with zero isospin asymmetry.



LHCb [JHEP 06 (2014) 133]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

CP asymmetries

[LHCb, JHEP 09 (2014) 177]

- Direct *CP* asymmetries

$$A_{CP} = \frac{\Gamma[\overline{B} \to \overline{K}\ell^+\ell^-] - \Gamma[B \to K\ell^+\ell^-]}{\Gamma[\overline{B} \to \overline{K}\ell^+\ell^-] + \Gamma[B \to K\ell^+\ell^-]}$$

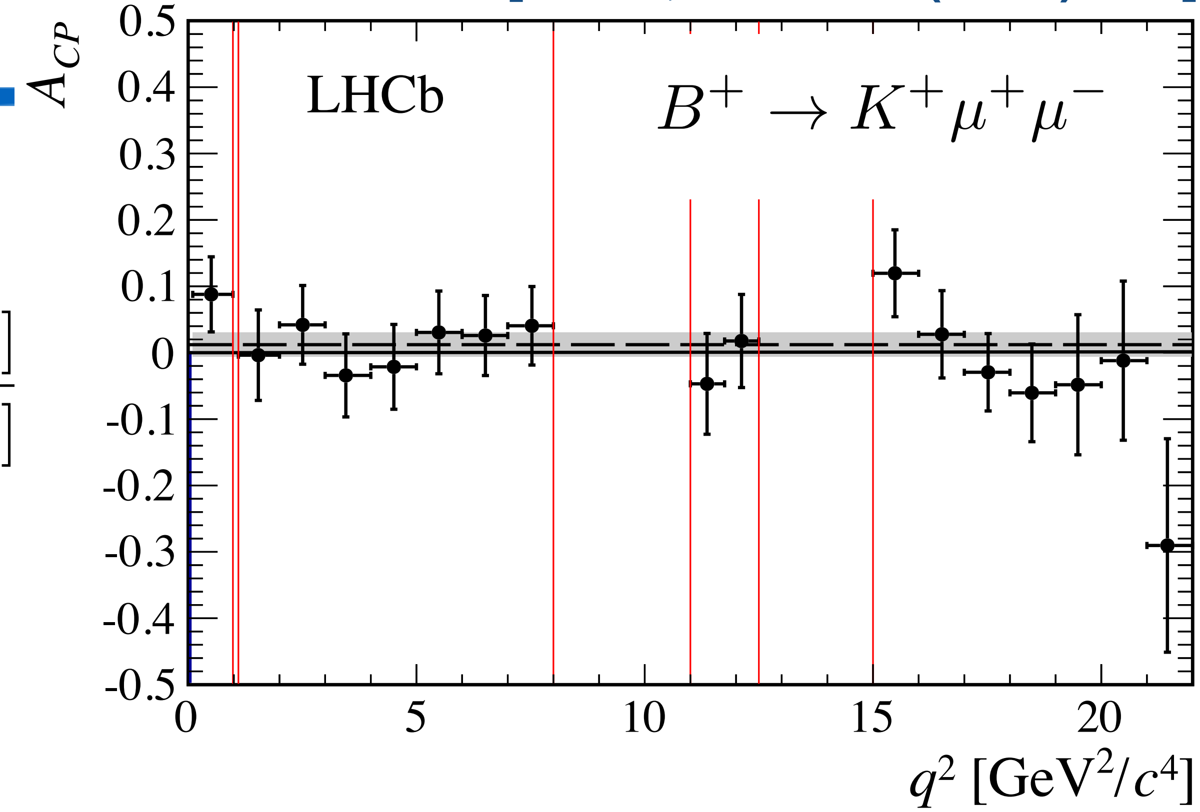
are tiny in SM due to size of $|V_{ub}V_{us}^*|$.

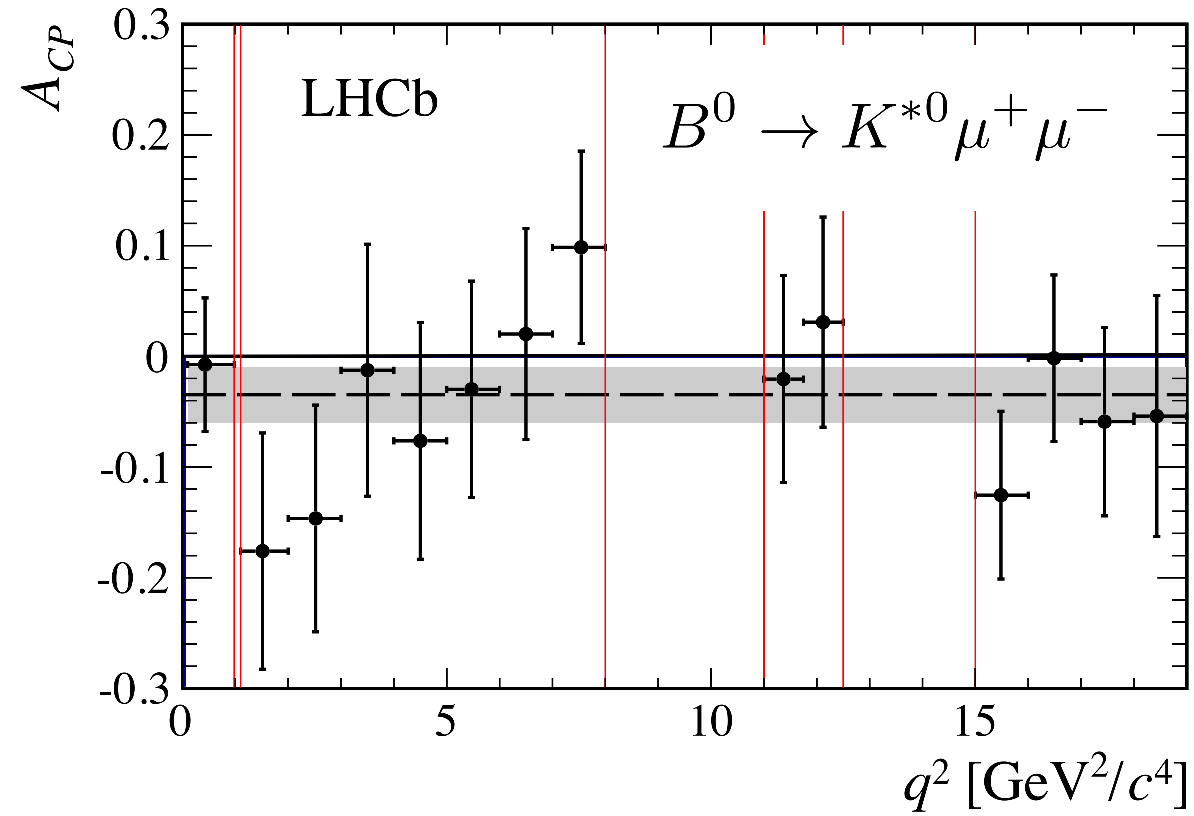
- Correct the observed asymmetry for production/detection asymmetries using $B \to J/\psi K^{(*)}$ events:

$$A_{CP} = A_{\rm raw} - A_D - \kappa A_P \approx A_{\rm raw} - A_{J/\psi K^{(*)}}$$

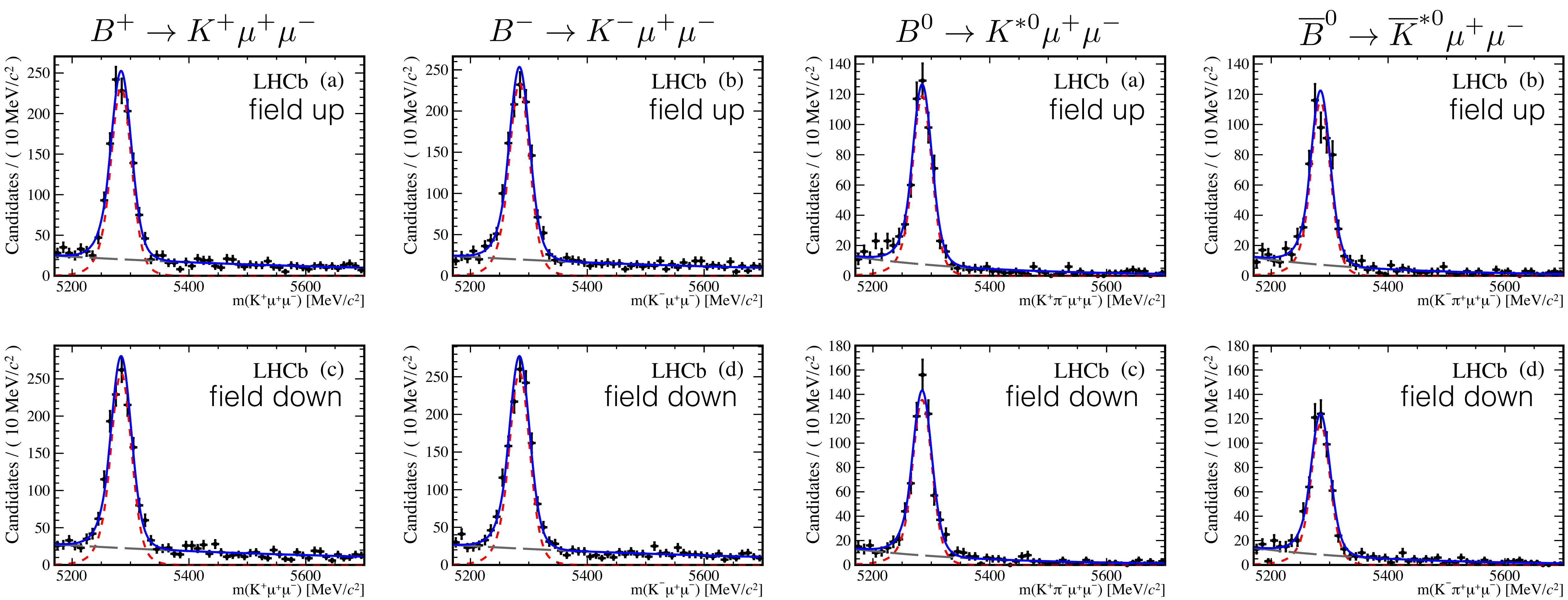
Dilution factor due to *B* oscillation.

- Additional cancellation of detection asymmetries by averaging data taken with positive and negative magnet polarities.





CP asymmetries



[LHCb, JHEP 09 (2014) 177]

- No visible CP asymmetry in the full dataset.