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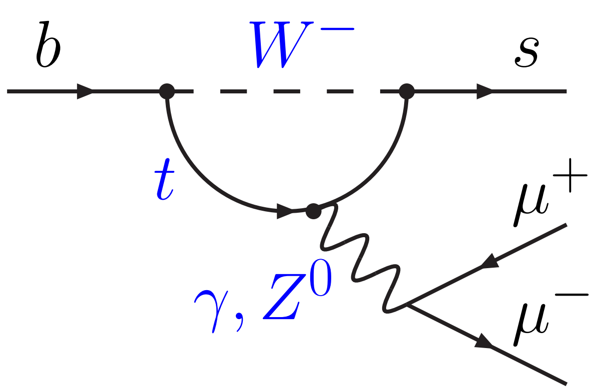
Rare beauty and charm decays

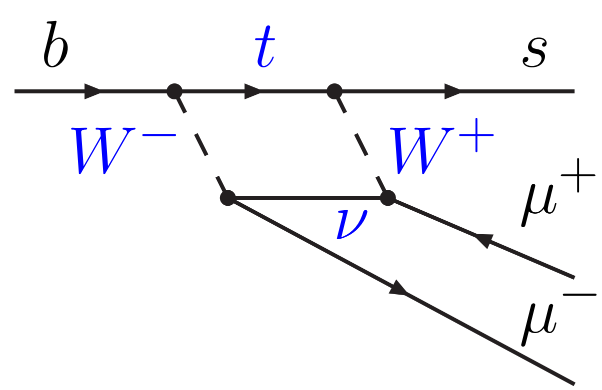
T. Blake on behalf of the LHCb collaboration

Les Rencontres de Physique de la Vallée d'Aoste 2016

Exploring FCNC processes

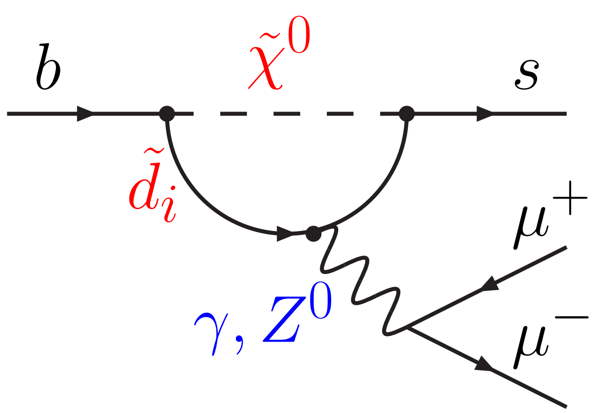
- Flavour changing neutral current transitions only occur at loop order (and beyond) in the SM.

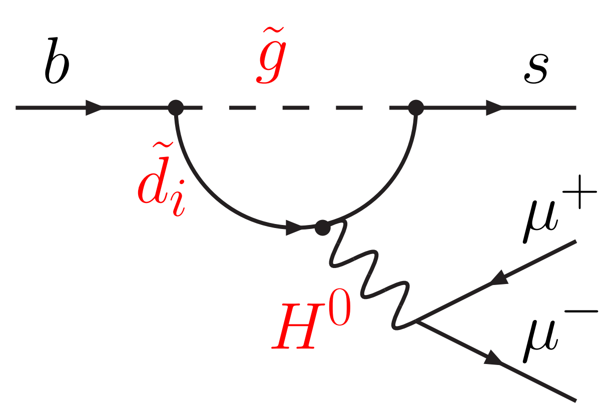


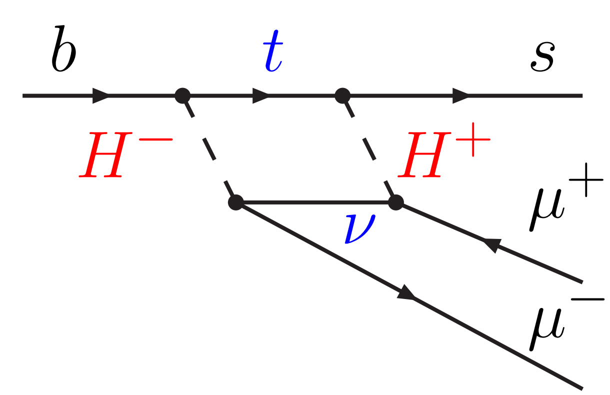


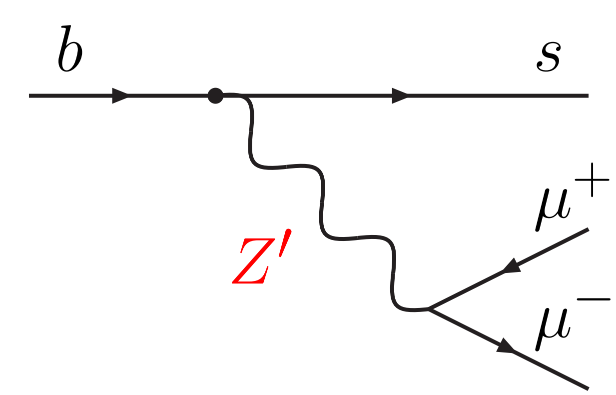
SM diagrams involve the charged current interaction.

- New particles can contribute at loop or tree level:







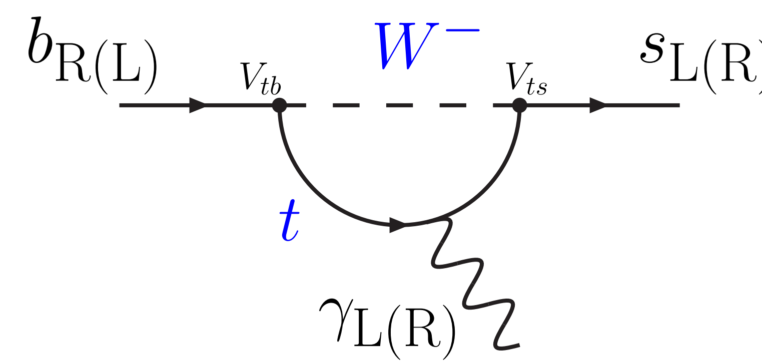


- Enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles

Properties of FCNC processes

Can also look at other properties of the decays:

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



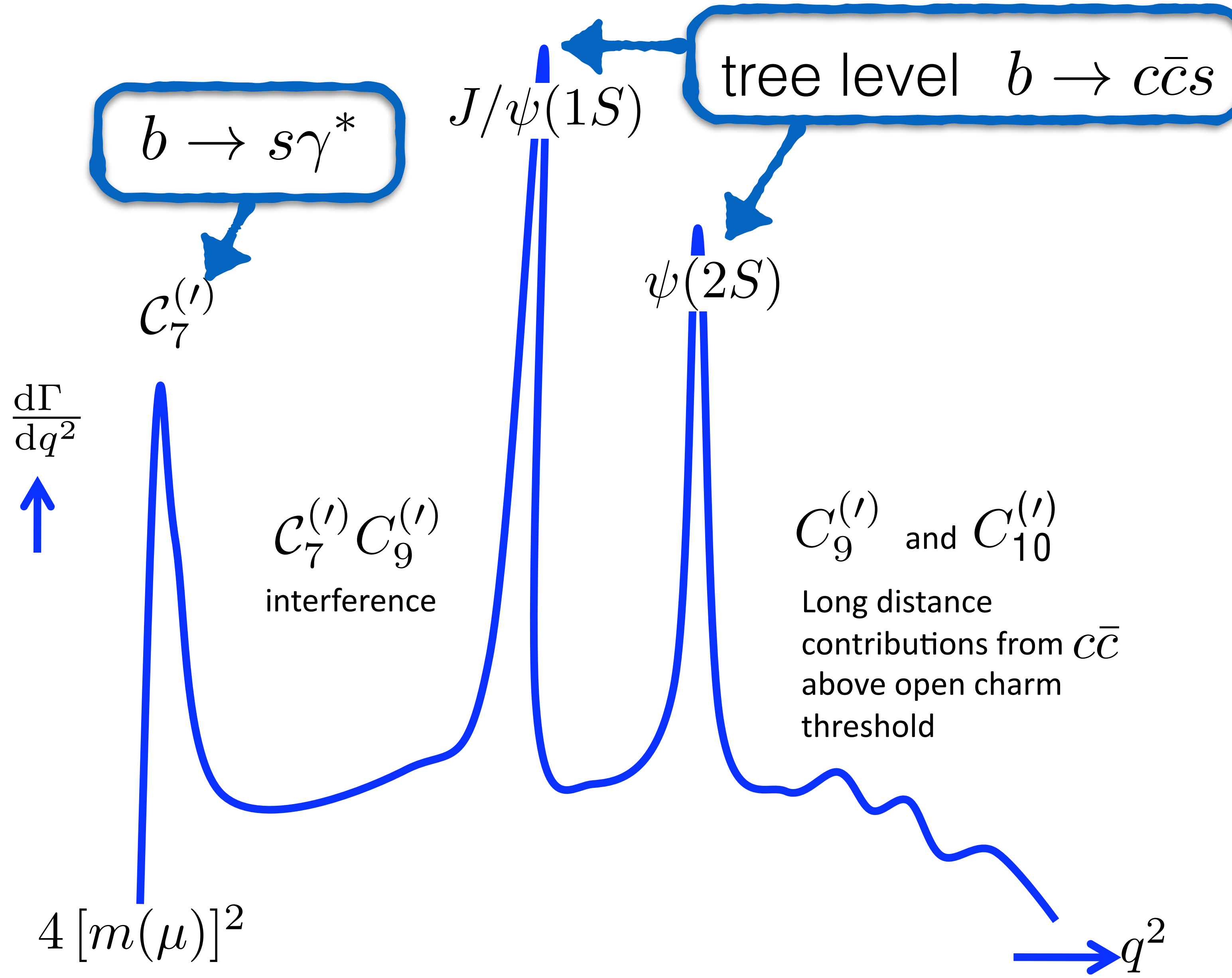
- Flavour structure of SM implies that the rate of $b \to d$ processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to $b \to s$ processes.
- In the SM, the rate $\Gamma[B \to M\mu^+\mu^-] \approx \Gamma[B \to Me^+e^-]$ due to the universal coupling of the gauge bosons (except the Higgs) to the different 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

- 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]**
- 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]**
- Rare charm decays:
  - ➡ $D^0 \to K^-\pi^+\mu^+\mu^-$ **[LHCb, arXiv:1510.08367]**
  - ➡ $D^0 \to \mu^\pm e^\mp$ **[LHCb, PLB 754 (2016) 167]**

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

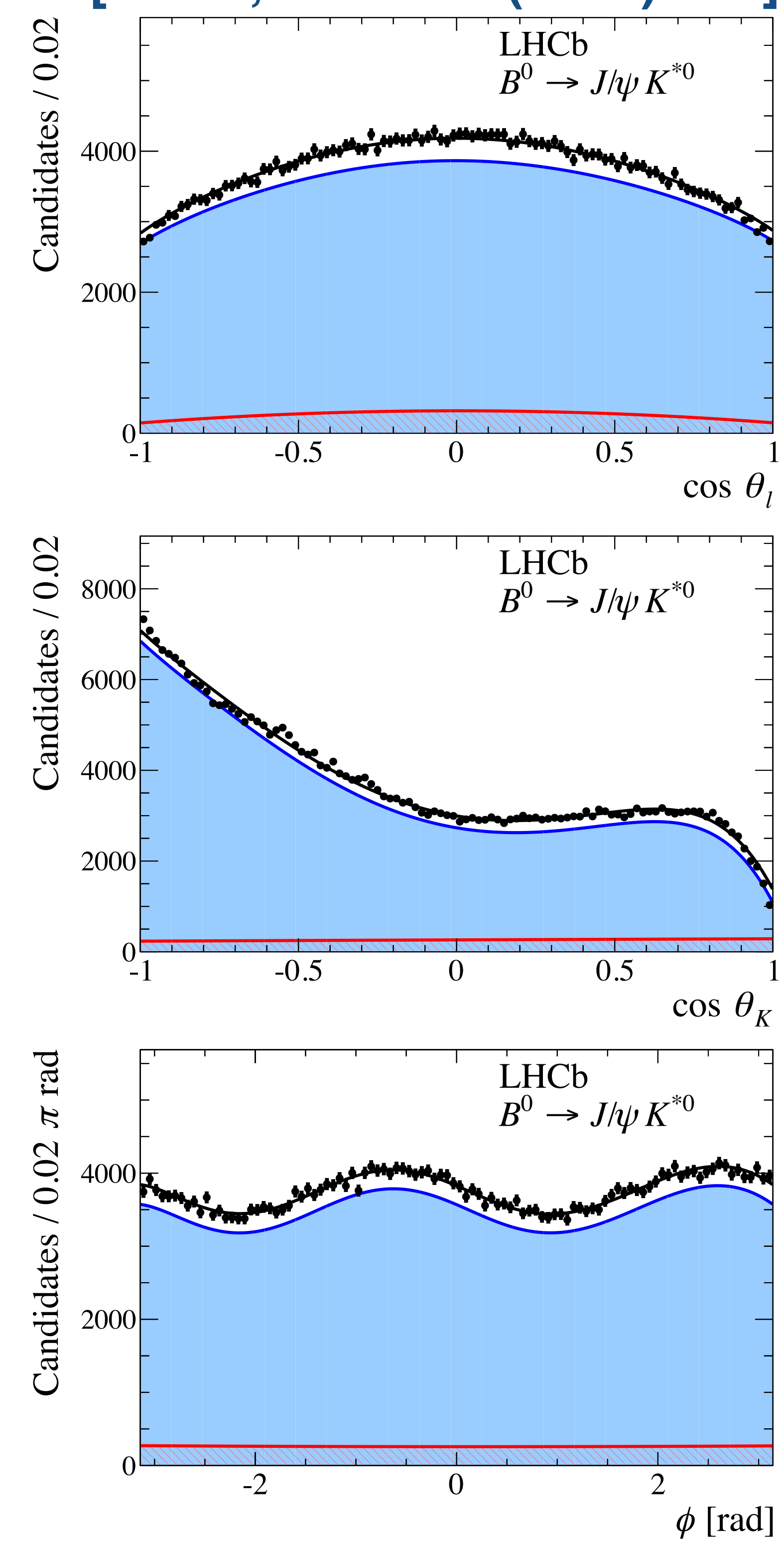
[LHCb, JHEP 02 (2016) 104]

- 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:

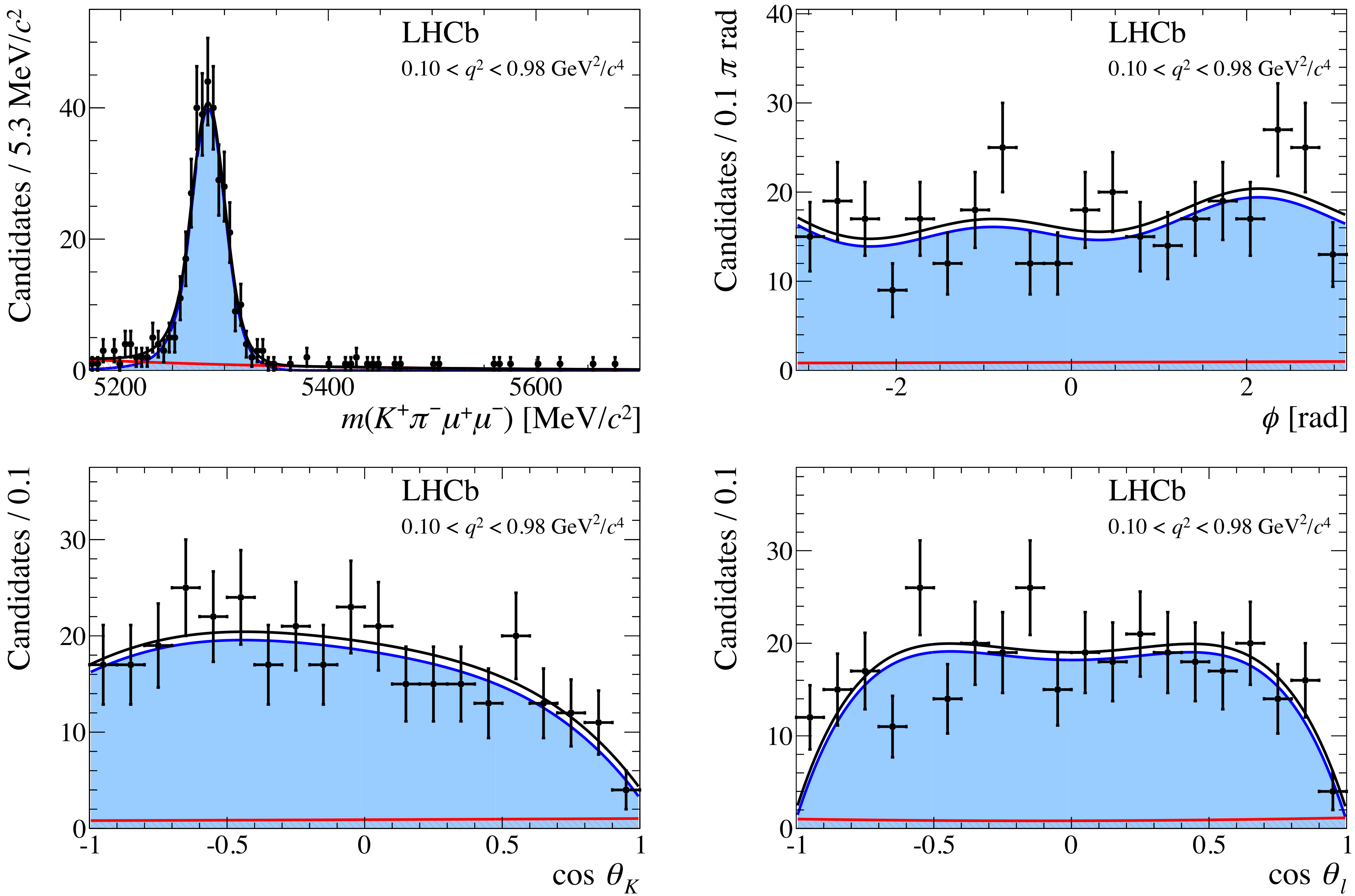
$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) \times L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

Legendre polynomial of degree *i*.

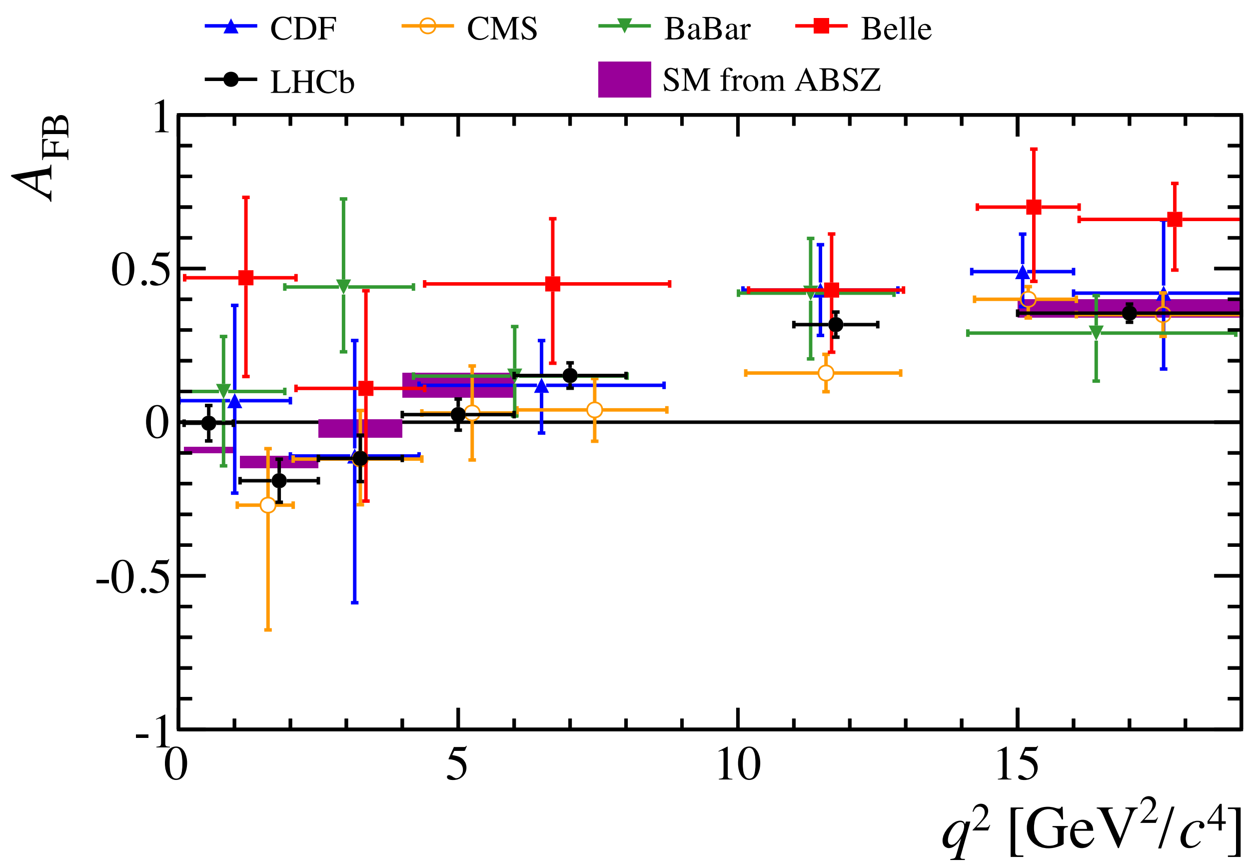
- Use $B^0 \to J/\psi\, K^{*0}$ as a control channel to understand the acceptance of the detector.

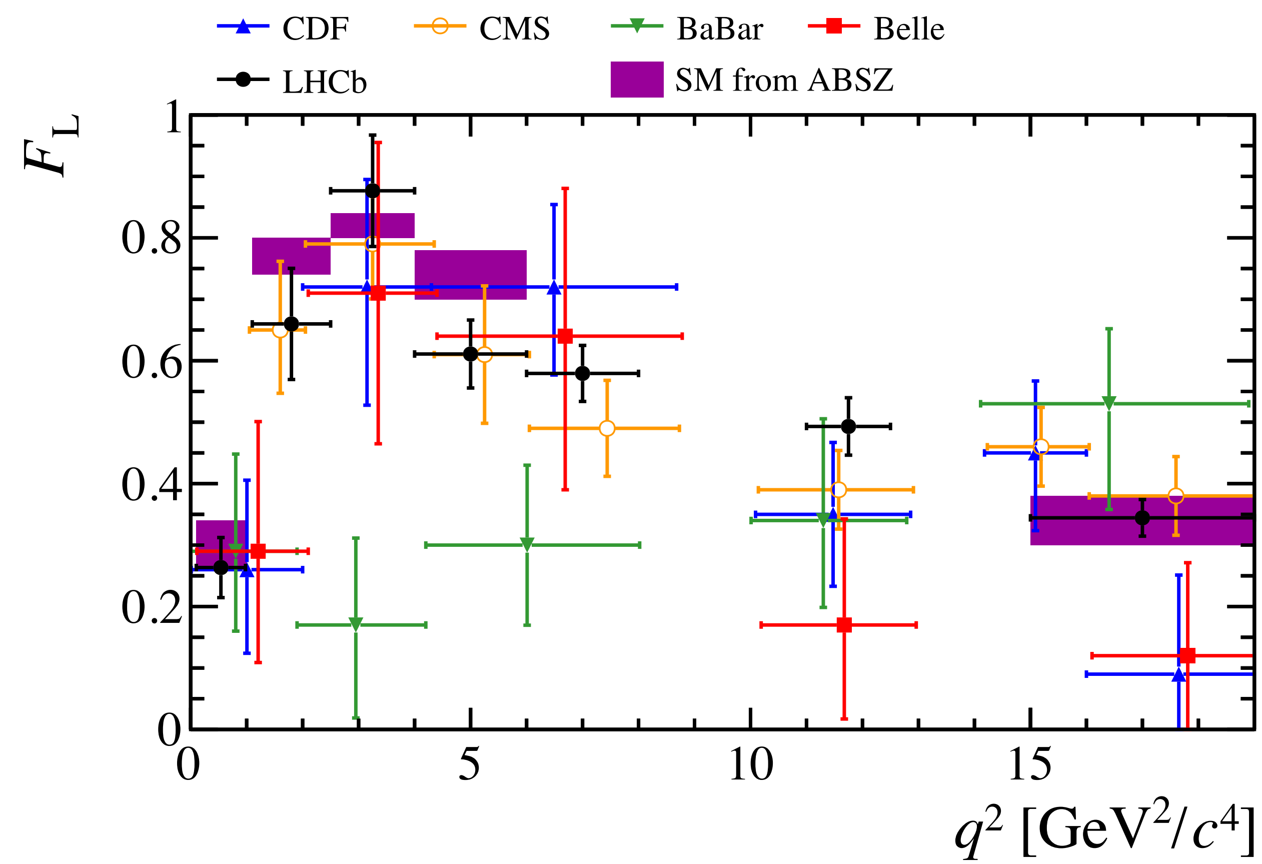


$B^0 \to K^{*0}\mu^+\mu^-$ example fit



Results



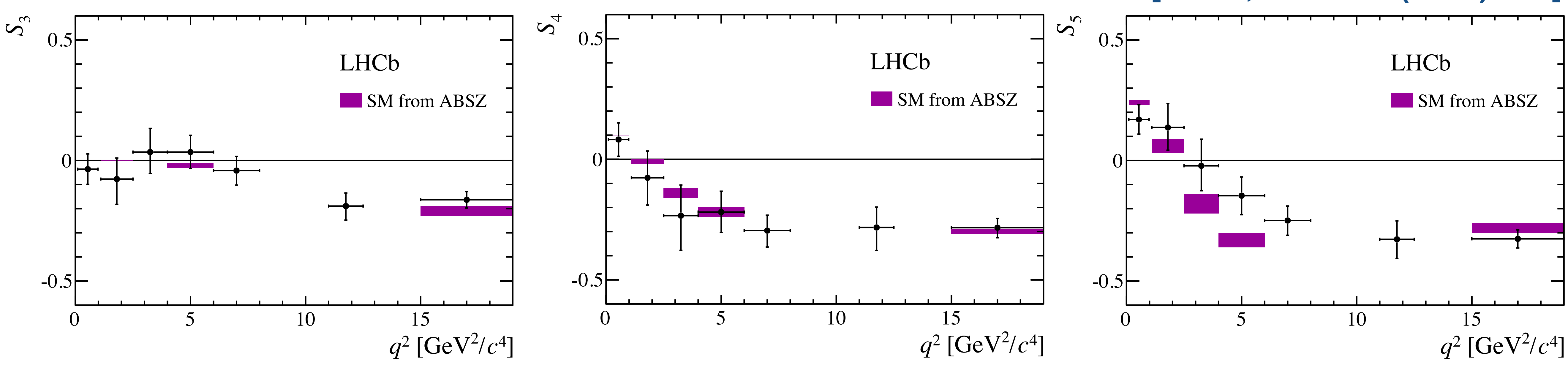


- New results for F_L and A_{FB} last year from LHCb **[JHEP 02 (2016) 104]** , CMS **[PLB 753 (2016) 424]** and BaBar **[arXiv:1508.07960]** + older measurements from CDF **[PRL 108 (2012) 081807]** and Belle **[PRL 103 (2009) 171801].**
- SM predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
  [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]



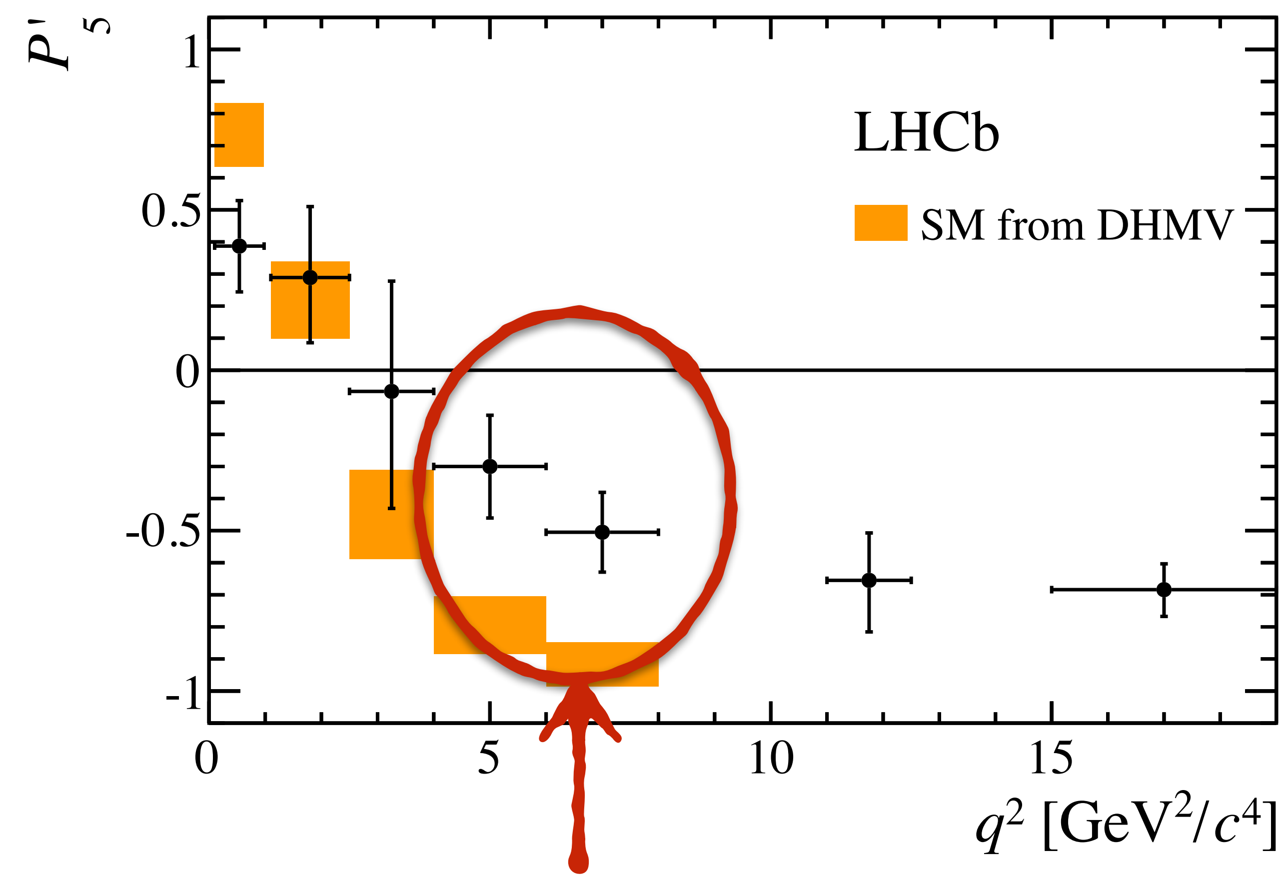
NB: These observables cancel when integrating over the ϕ-angle (e.g. in the CMS analysis).

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 $A_{\|}$ 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, JHEP 02 (2016) 104]

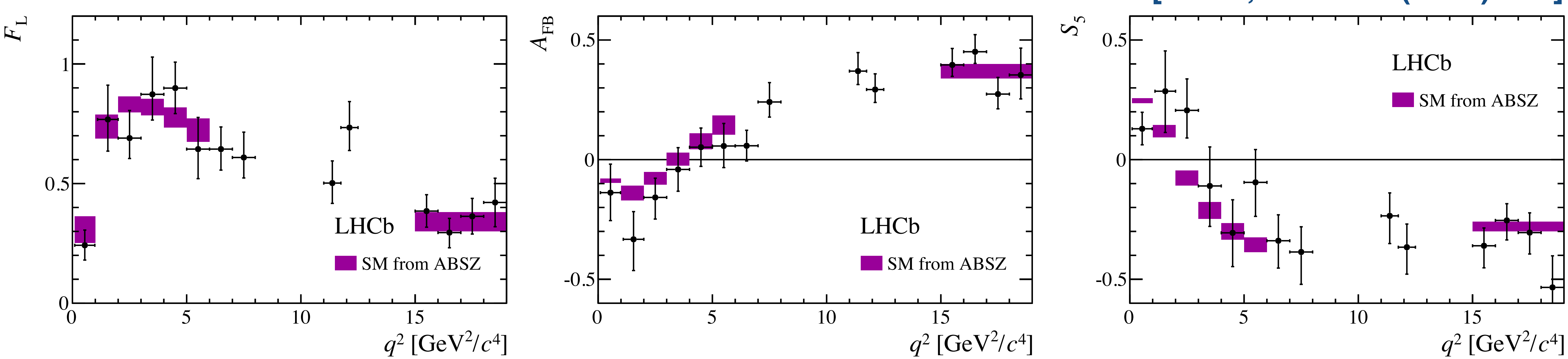
local tension with SM predictions (2.8 and 3.0σ)

- 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]**.

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]



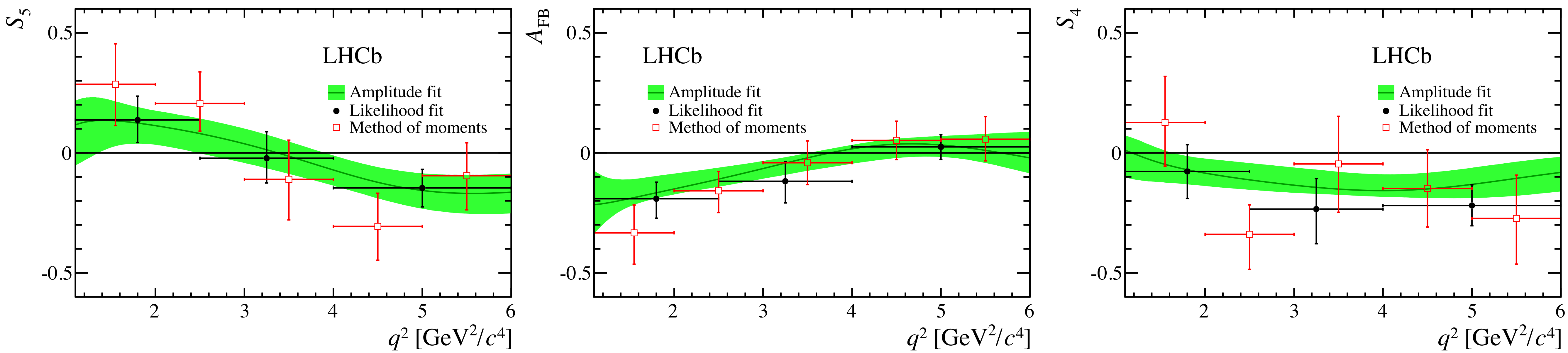
- SM predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
  [LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]
  [Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]

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:

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

[JHEP 02 (2016) 104]



- Zero crossing points are determined to be:

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

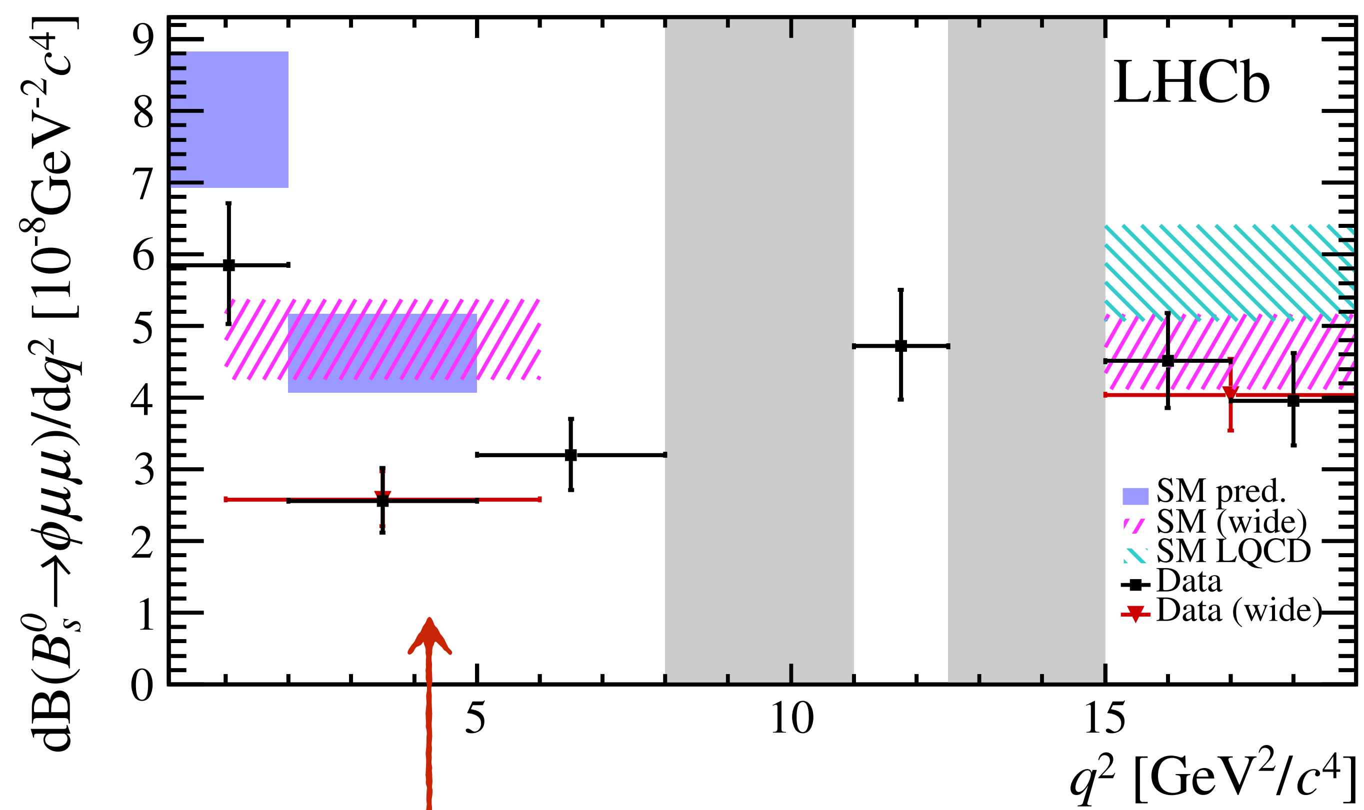
$$q_0^2(A_{FB}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \text{ at 68\% C.L.}$$

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

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

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

[LHCb, JHEP 09 (2015) 179]

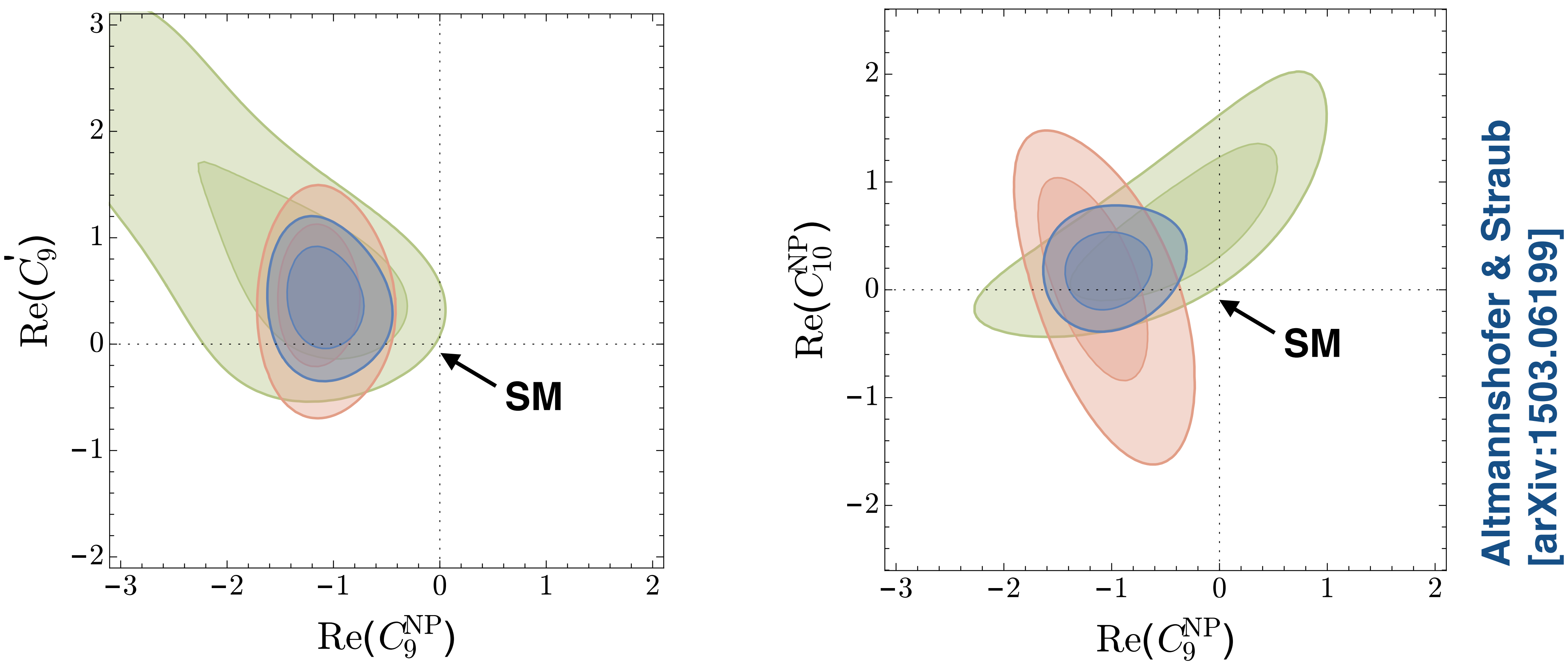


In a wide bin from $1 < q^2 < 6$ GeV$^2/c^4$, the data is 3.3σ from the SM prediction

- 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]

Global fits

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



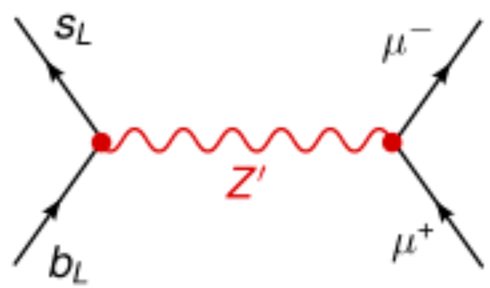
branching fractions, angular observables and combination

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

More details in talk by J. Matias

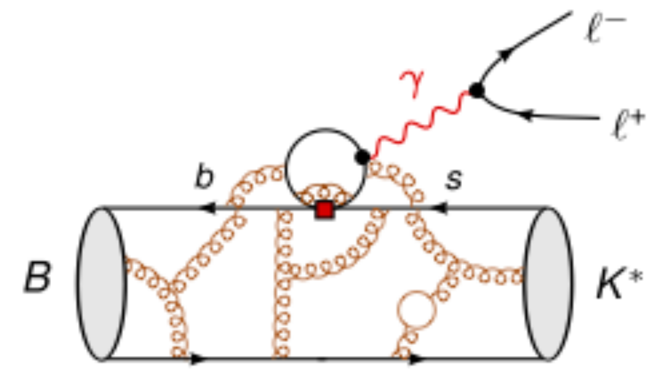
Interpretation of global fits

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).

R_K result

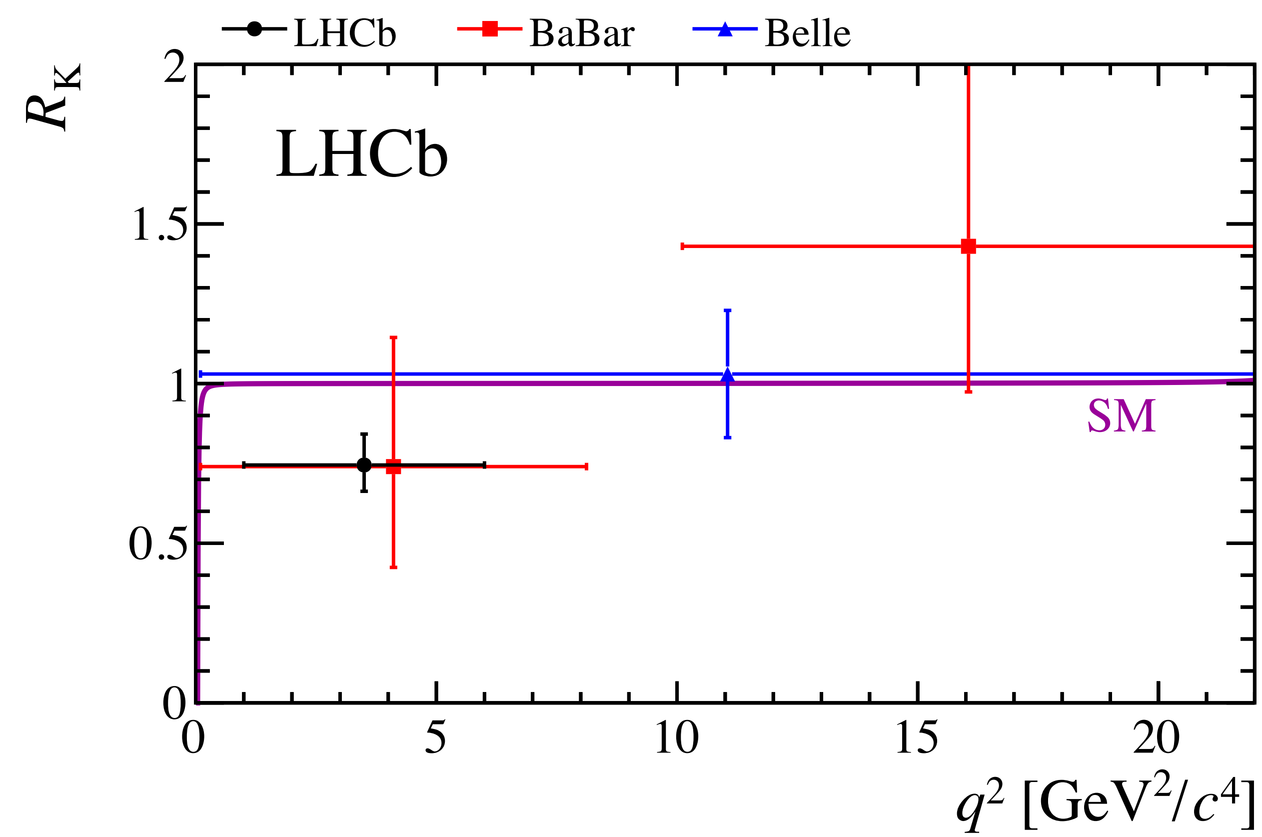
- In the run 1 dataset, LHCb determines:

$$R_{\mathrm{K}} = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}$$

in the range $1 < q^2 < 6$ GeV^2, 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]

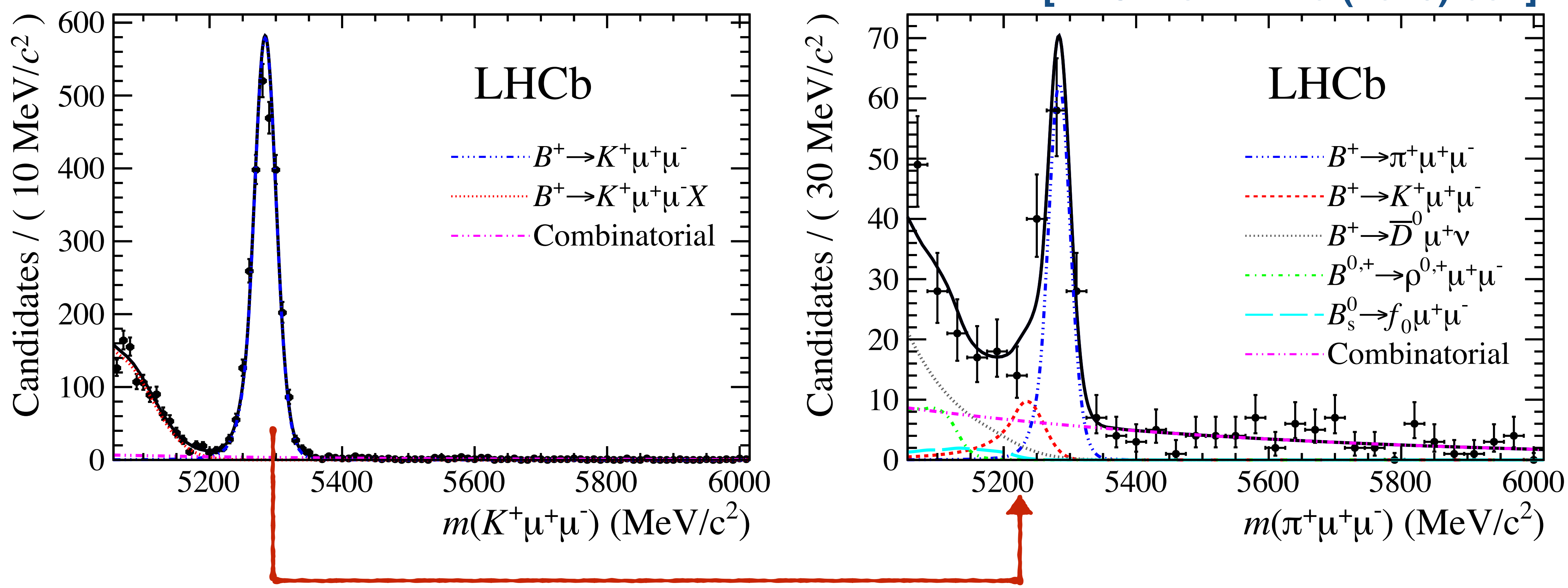
$R_K < 1$ implies a deficit of muons w.r.t. electrons.

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

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

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

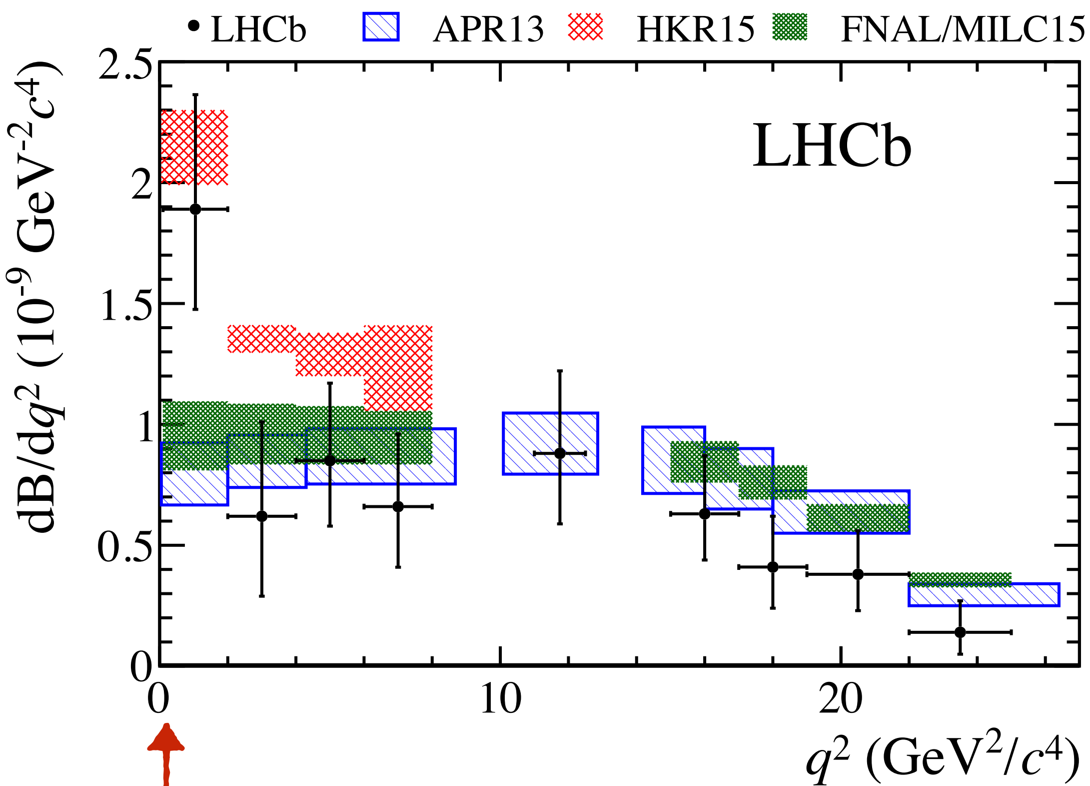
[LHCb JHEP 10 (2015) 034]



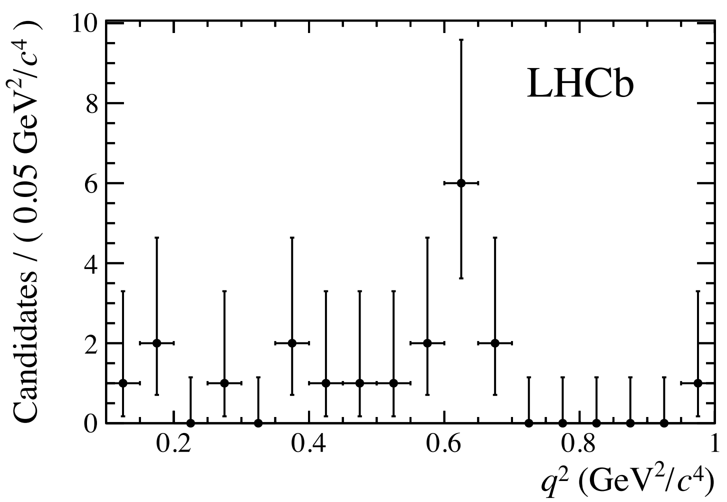
- Major experimental challenge is control of background from $B^+ \to K^+ \mu^+ \mu^-$ decays with $K \to \pi$ mis-id.

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

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



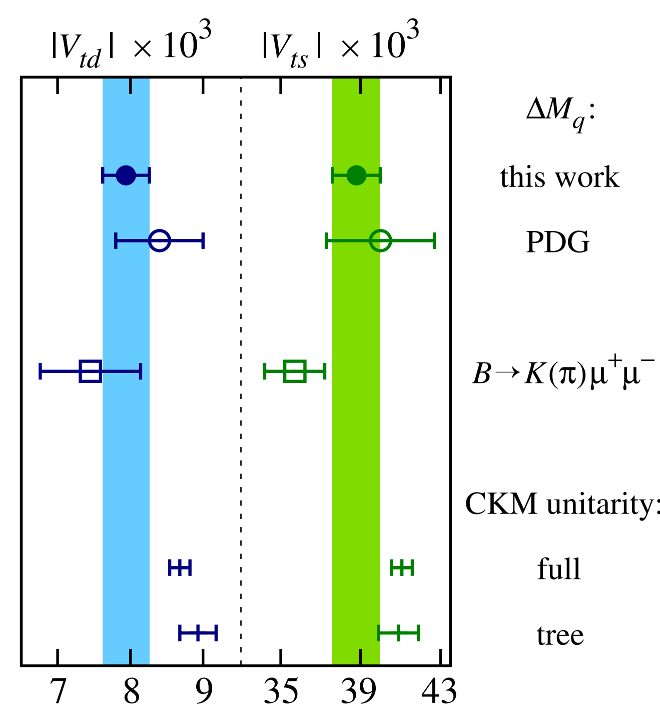
[LHCb JHEP 10 (2015) 034]



Enhancement for $q^2 < 1\ \mathrm{GeV}^2/c^4$ 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]**

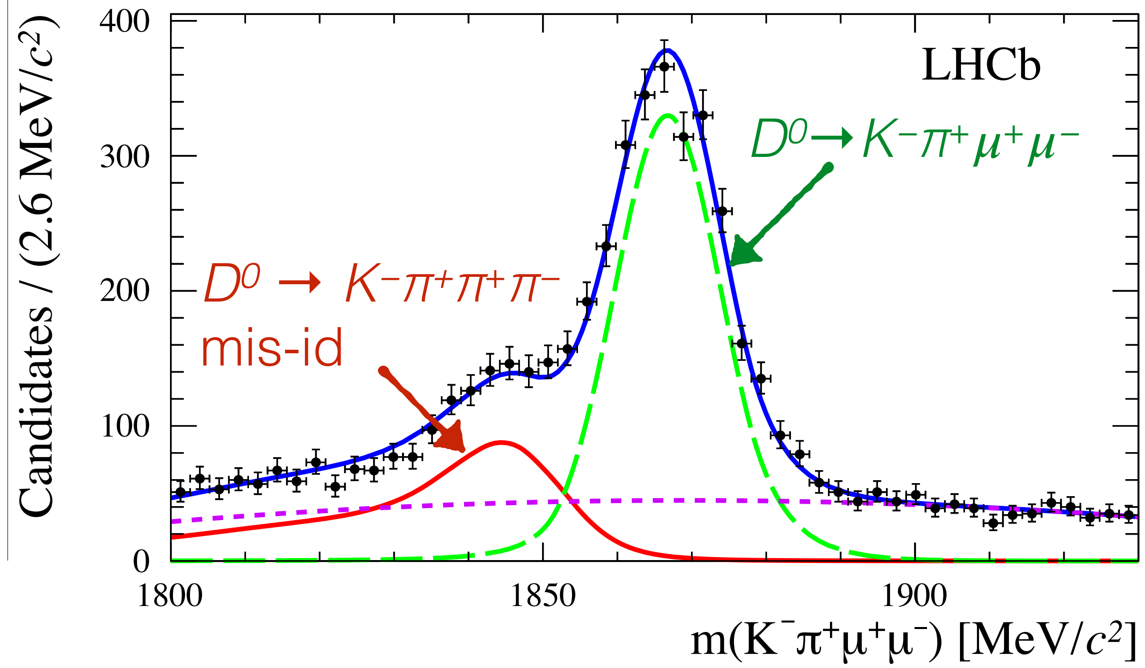
Ratio consistent with MFV hypothesis.

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

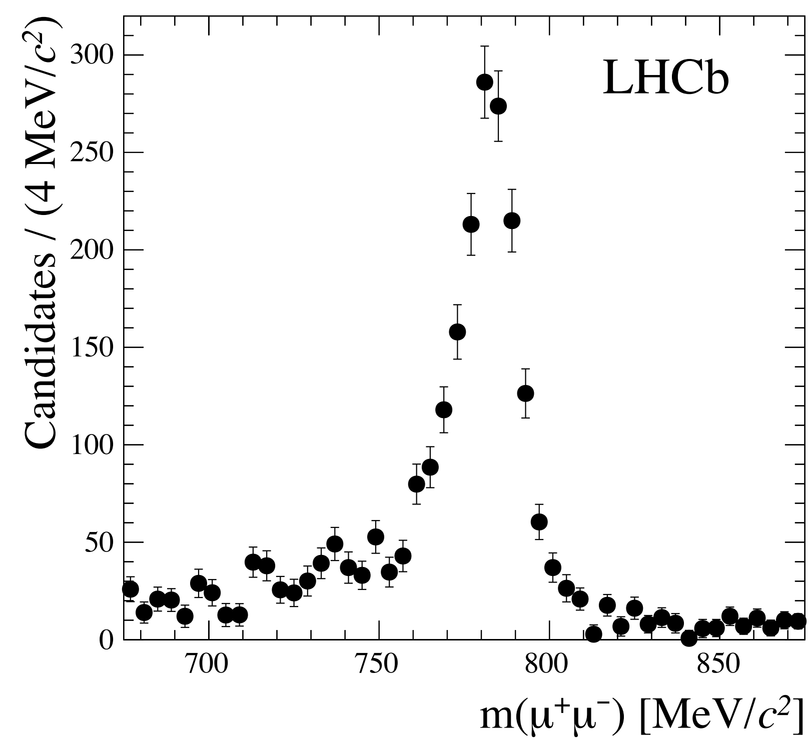
$D^0 \to K^- \pi^+ \mu^+ \mu^-$

- Short-distance contribution to rare charm decays is much smaller (stronger GIM suppression due to $m_b \ll m_t$).
- Long distance contributions can be larger.
- First measurement of branching fraction of $D^0 \to K^- \pi^+ \mu^+ \mu^-$ performed by LHCb in the ρ/ω region.
- Measured branching fraction:

$$\mathcal{B}(D^0 \to K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12(\text{stat}) \pm 0.40(\text{syst})) \times 10^{-6}$$



[LHCb, arXiv:1510.08367]



$D^0 \to \mu^\pm e^\mp$

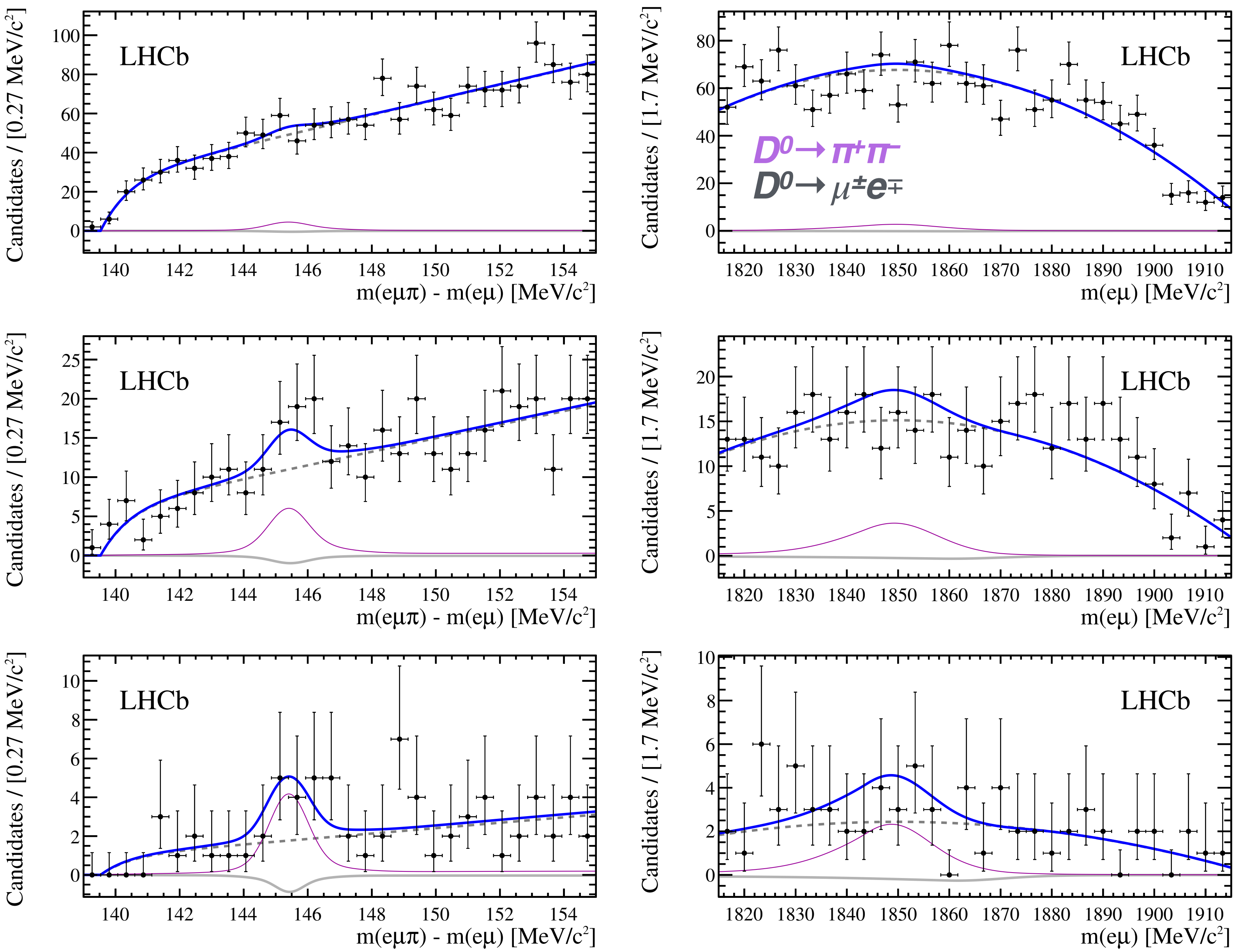
- Lepton flavour violation is unobservable in the SM at any conceivable experiment due to the small size of the neutrino mass.

- Search for the lepton flavour violating decay $D^0 \to \mu^\pm e^\mp$ using the 3fb^{-1} LHCb dataset.

- Exploit small Δm in $D^{*+} \to D\pi^+$ decays to suppress combinatorial background.

- Major challenge is the control of mis-id backgrounds

- Perform the analysis in bins on MVA response.



[LHCb, PLB 754 (2016) 167]

$D^0 \to \mu^{\pm} e^{\mp}$

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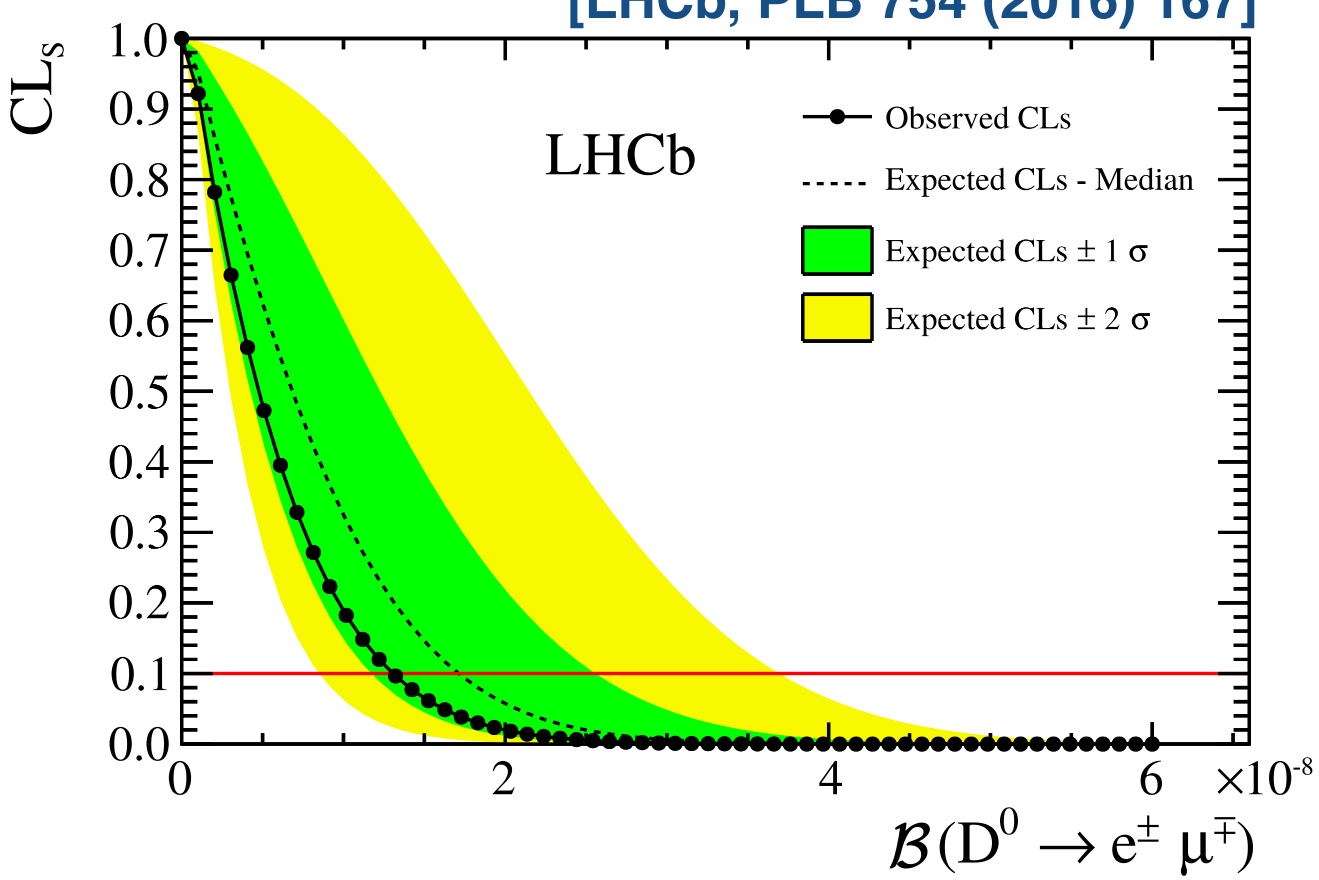
- Exploit small Δm in $D^{*+} \to D\pi^+$ decays to suppress combinatorial background.
- Major challenge is the control of mis-id backgrounds
- Perform the analysis in bins on MVA response.

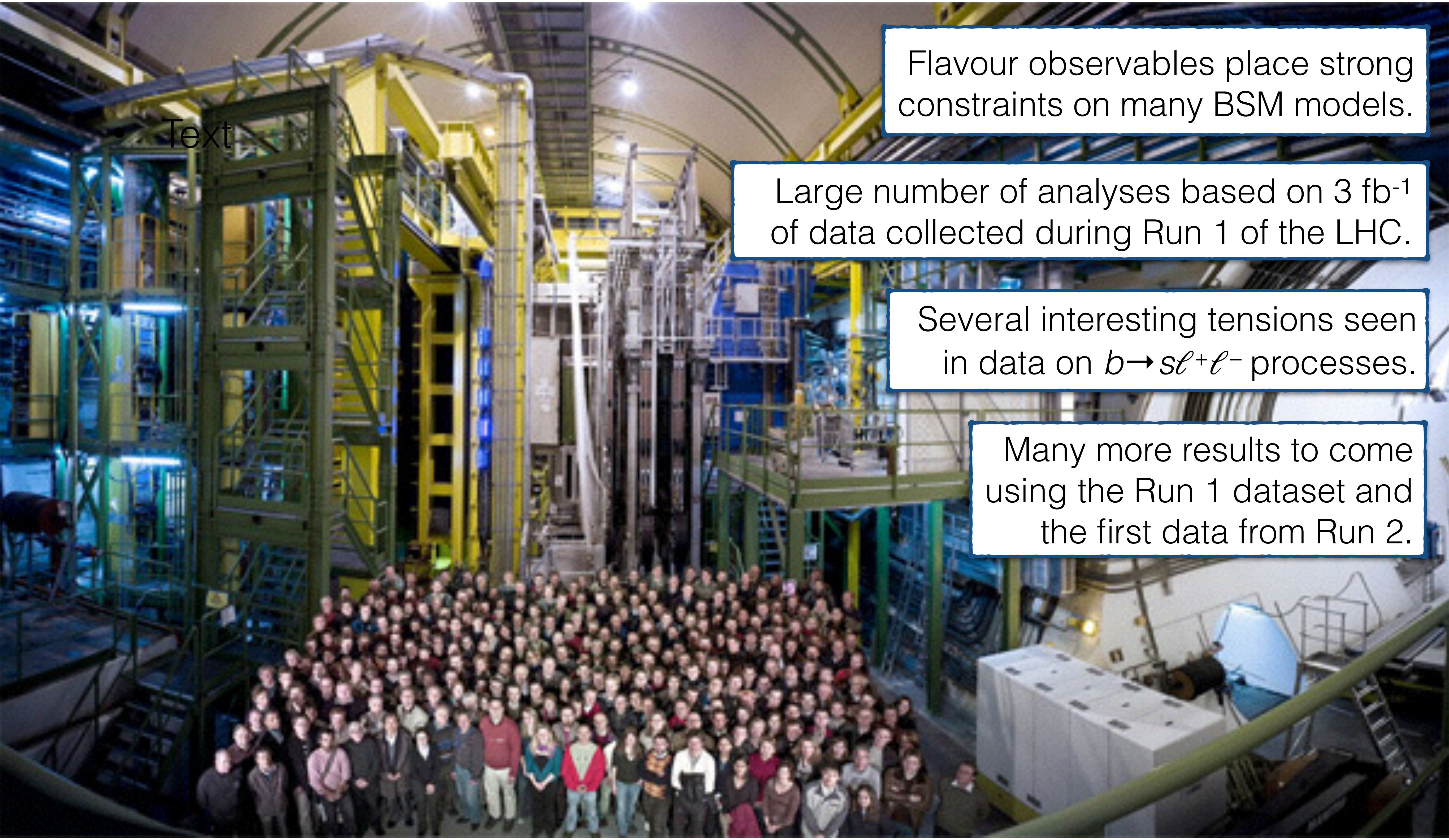
No evidence for any signal.
Set limit using the CLs method:

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

[LHCb, PLB 754 (2016) 167]



Summary



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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

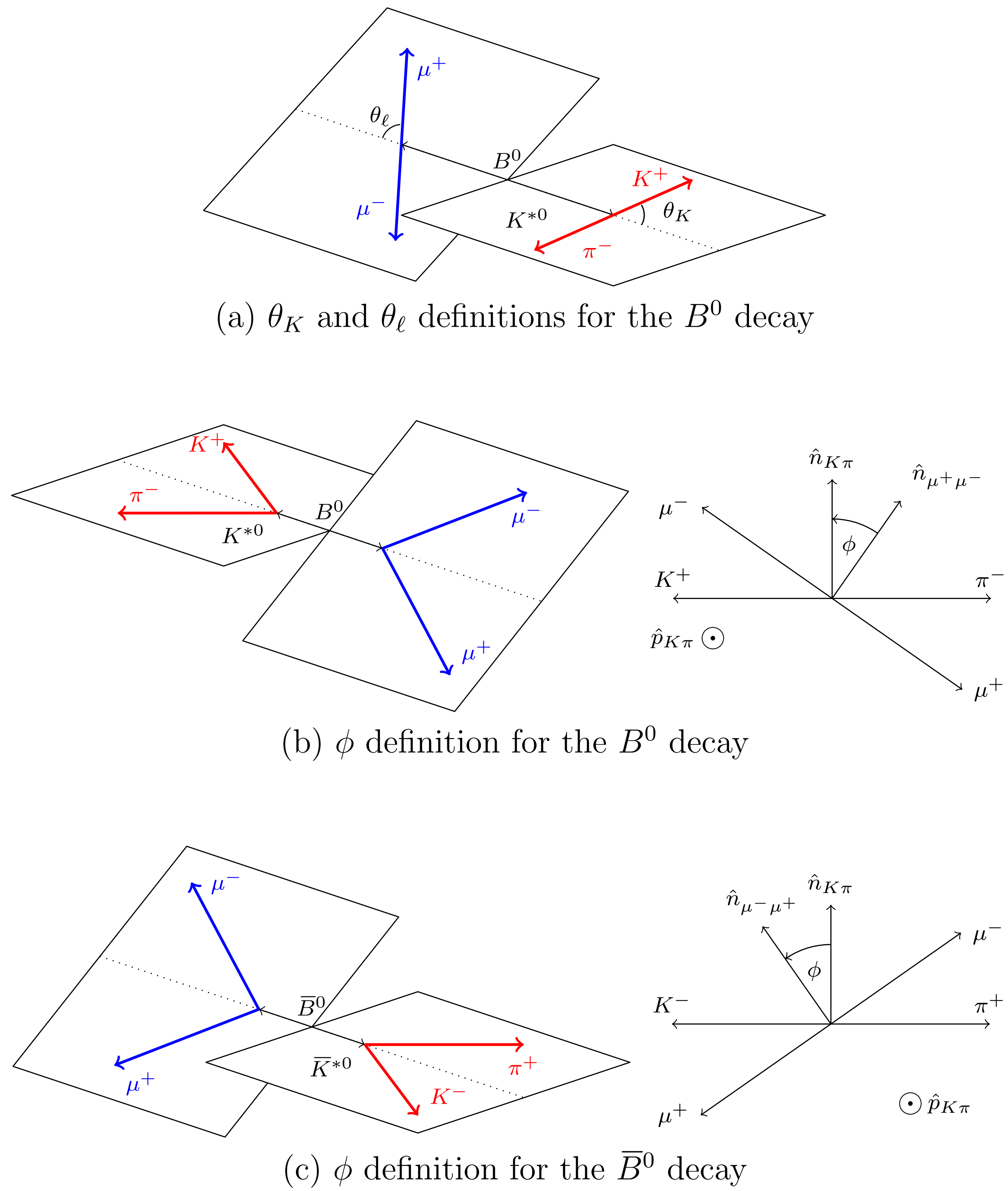
Backup

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

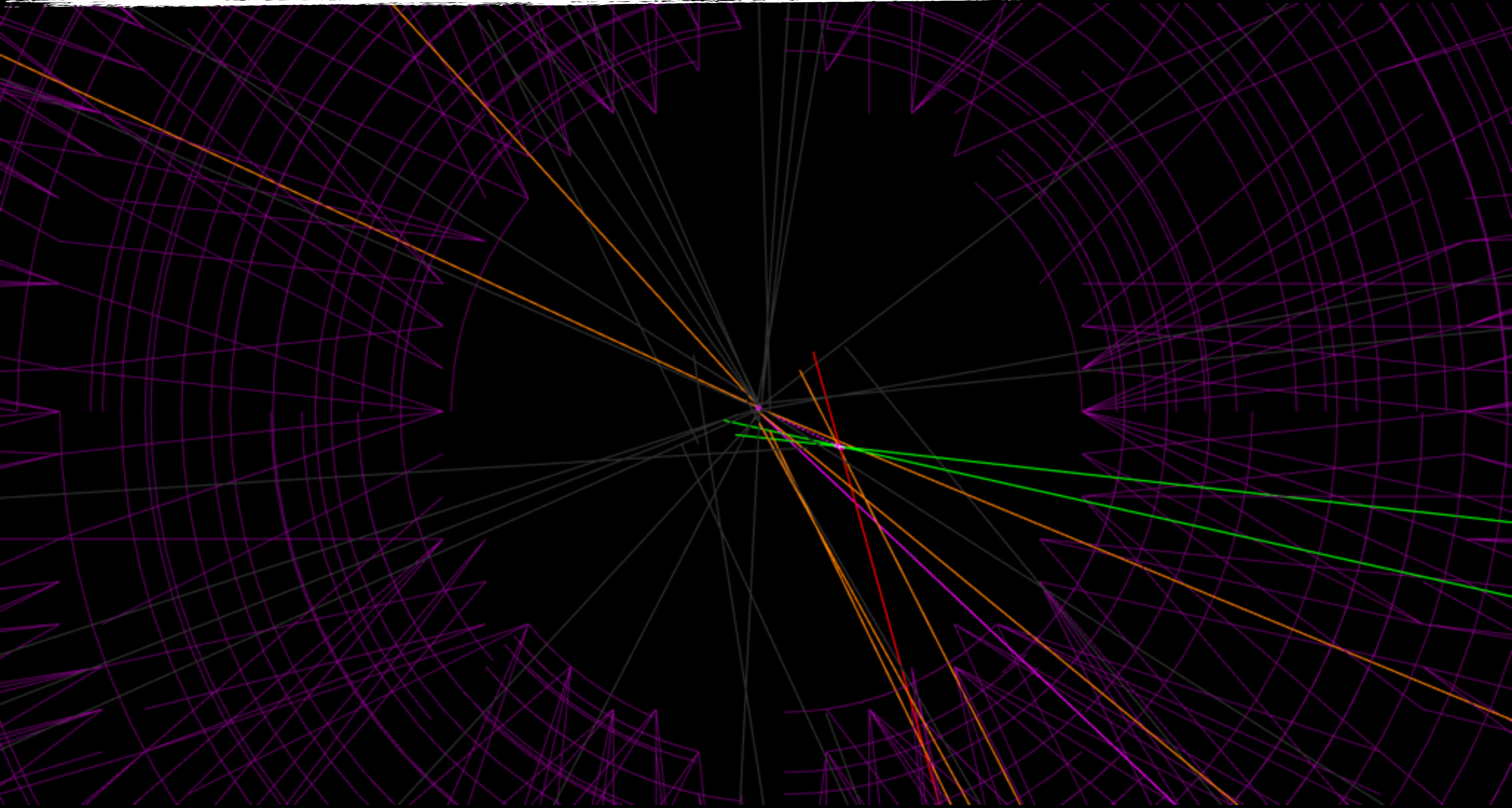
- Four-body final state.
  - ➡ Angular distribution provides many observables that are sensitive to NP.

  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.



Candidate selection

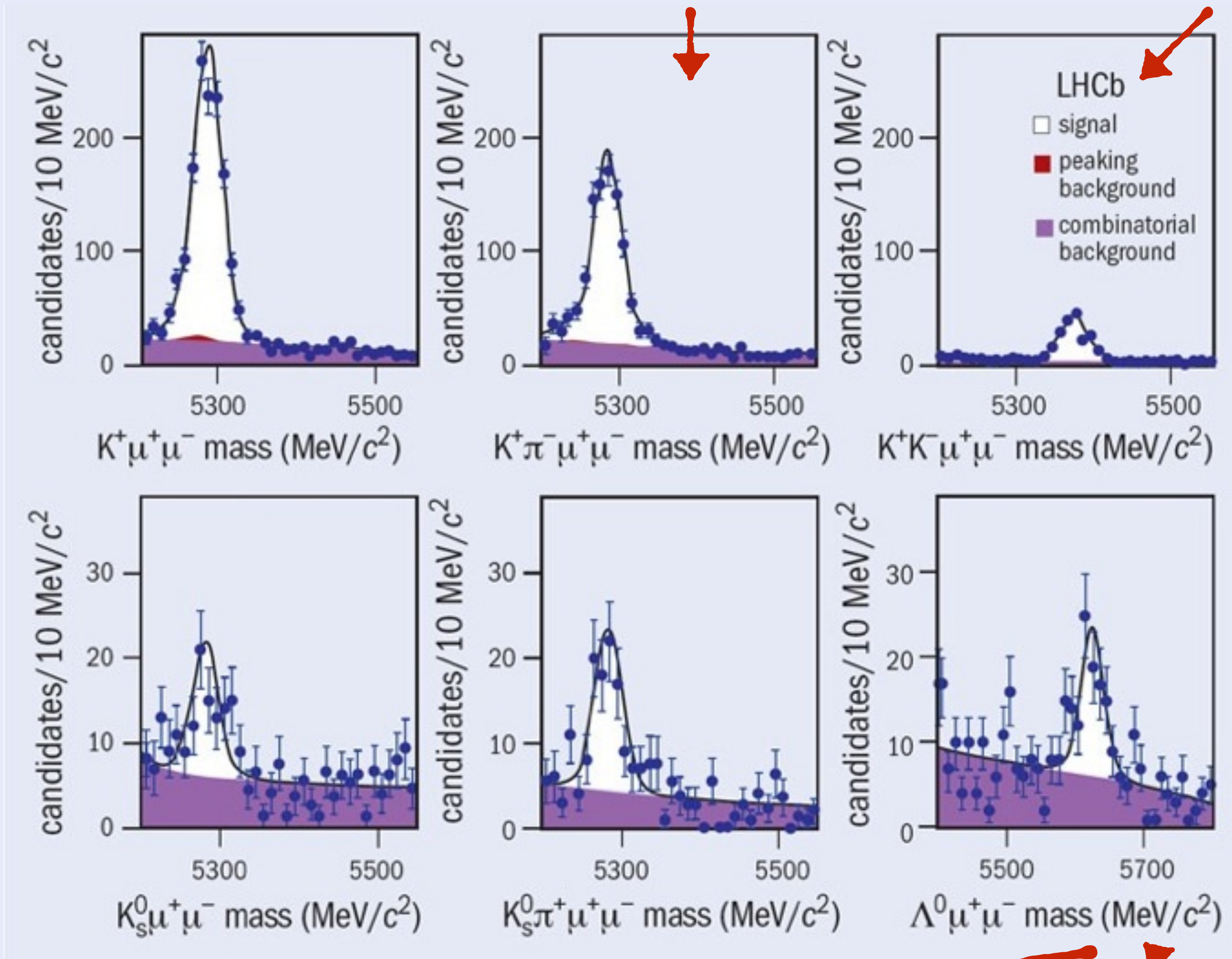


exploit the B lifetime to select candidates (~1cm decay length)

Signals in LHCb 1 fb^{-1} dataset

additional track

suppressed by f_s/f_d



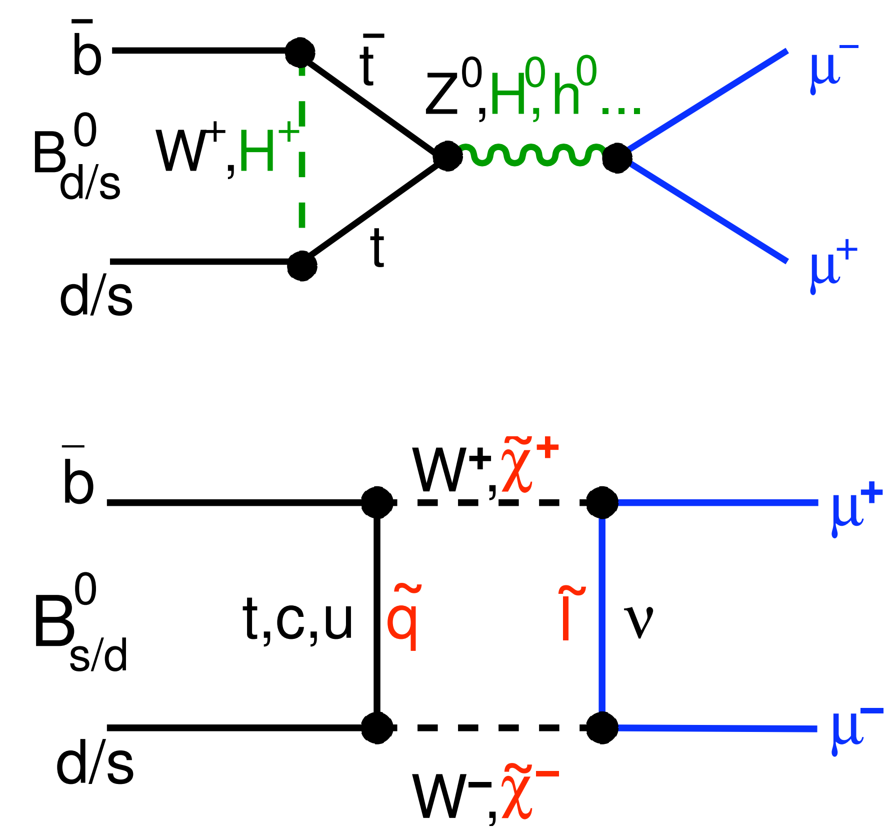
long-lived K_S^0 or Λ^0

suppressed by f_Λ/f_d

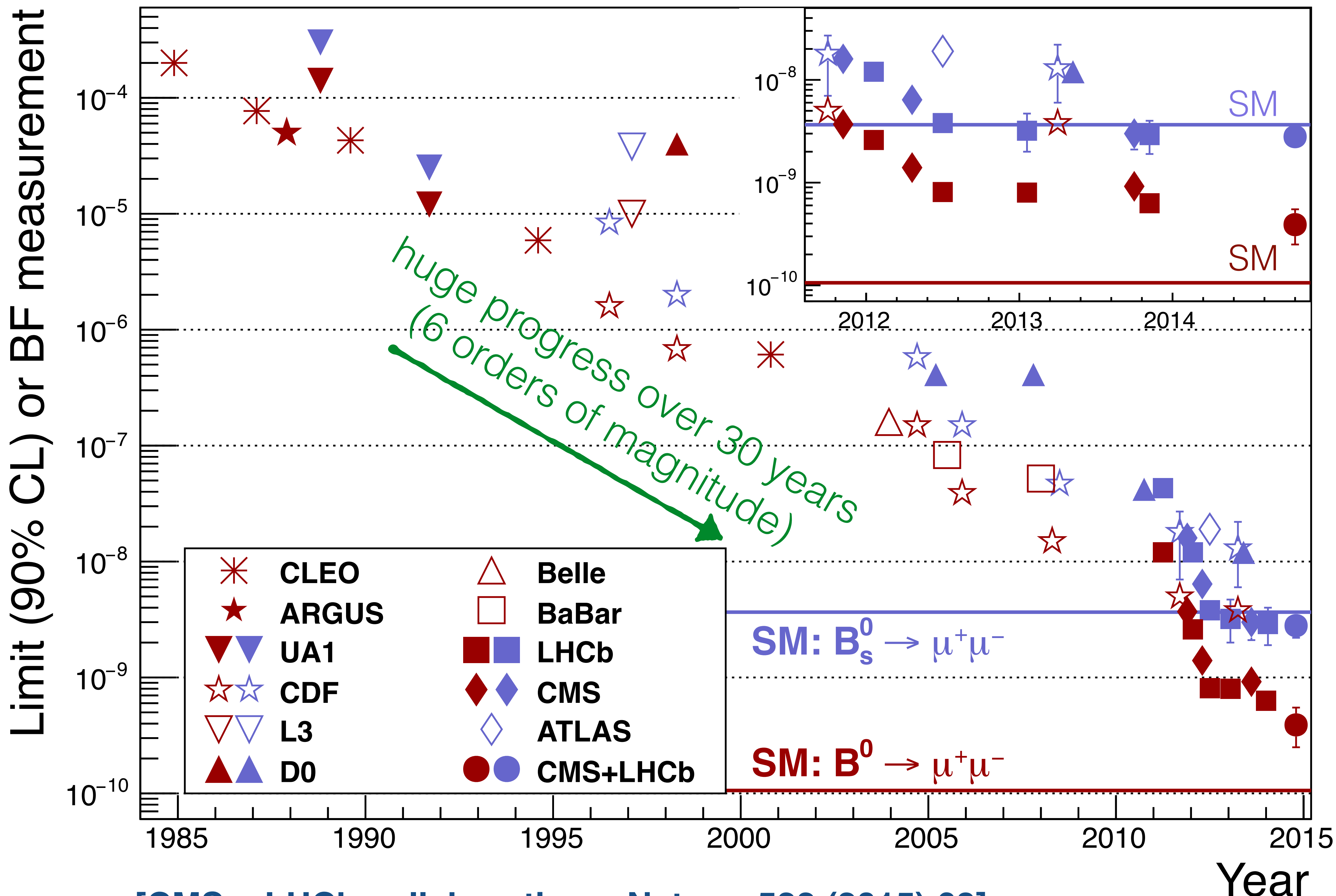
[from CERN courier, May 2013]

Leptonic decays

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



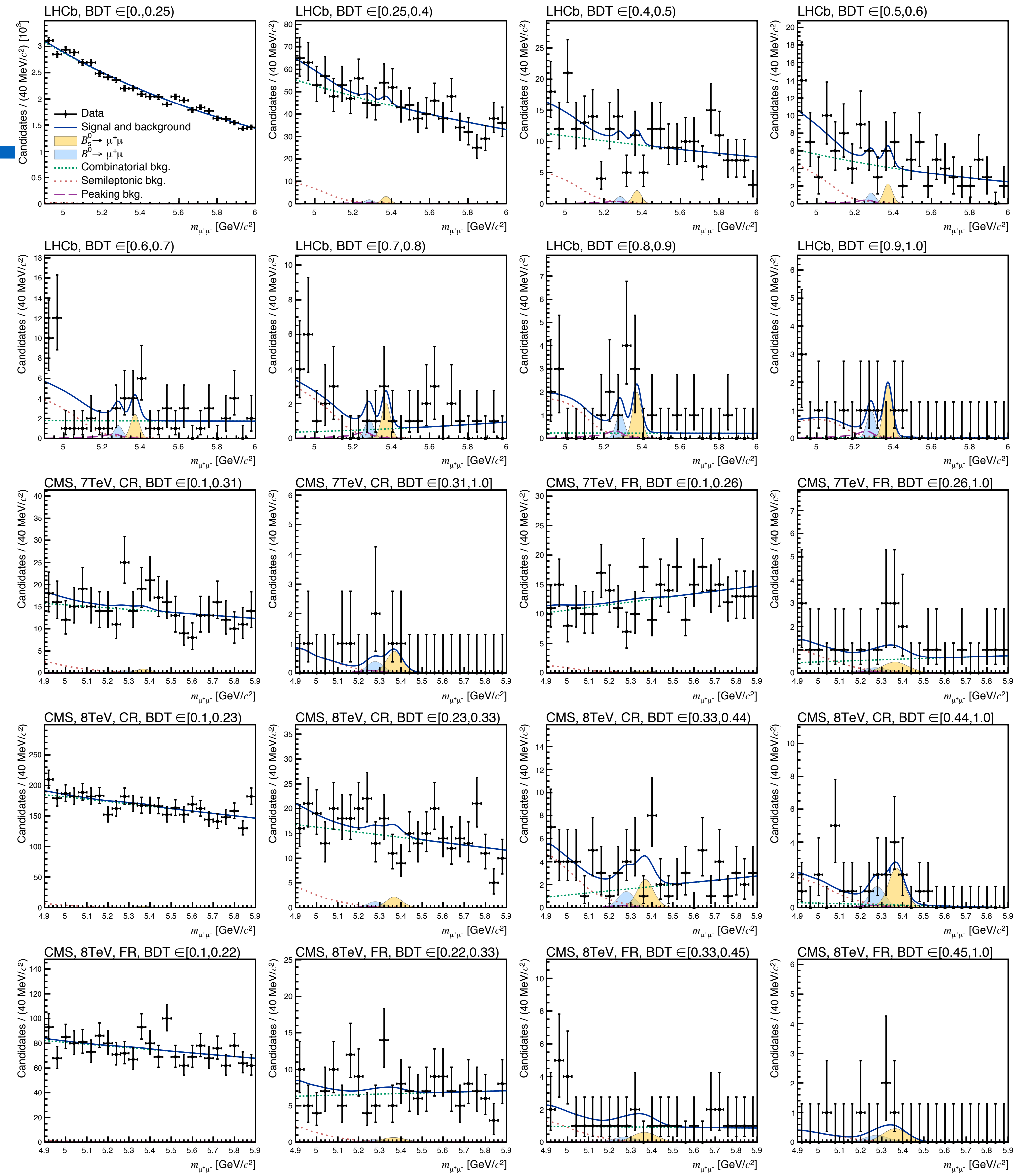
$B_{(s,d)} \to \mu^+\mu^-$ history



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

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

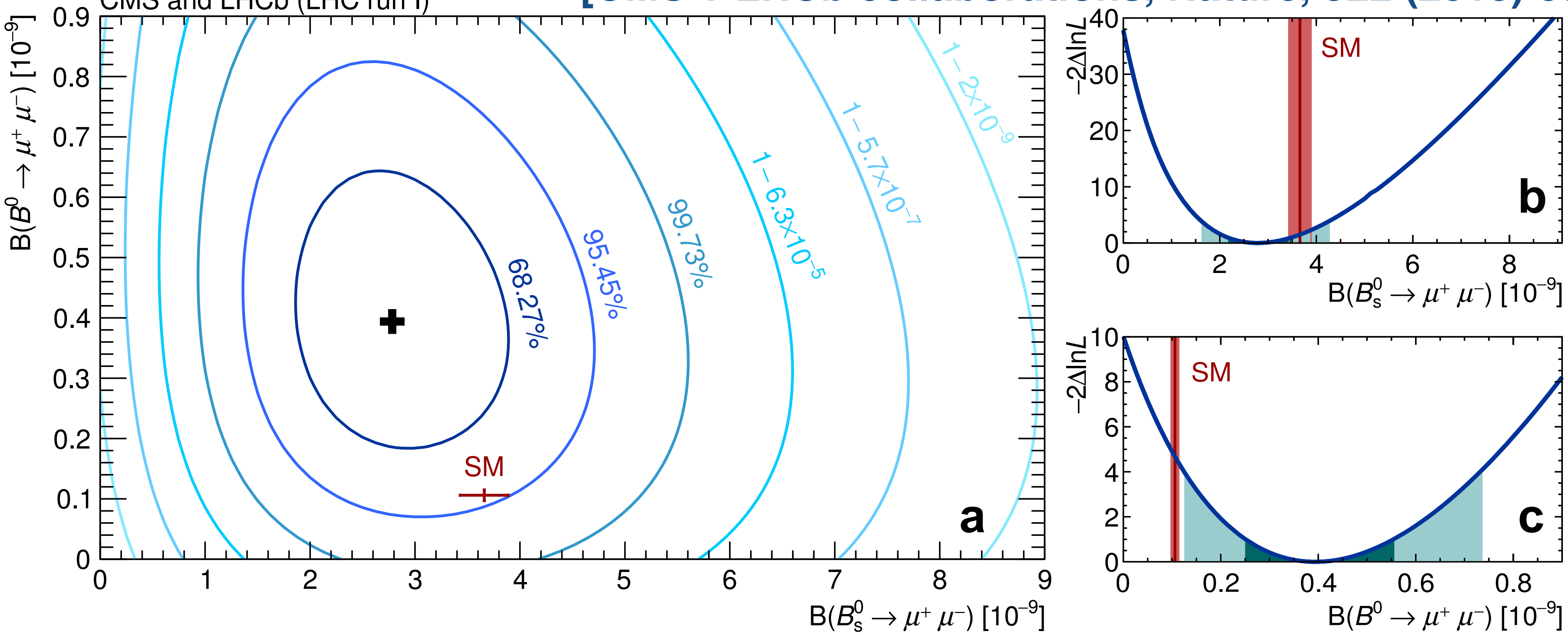
- CMS + LHCb have performed a simultaneous analysis of the datasets from the two experiments.
  - ➡ Binned in MVA response.
  - ➡ CMS data also split by barrel/end cap.
- Nuisance parameters (backgrounds, f_s/f_d) shared between the experiments.



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

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

[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.

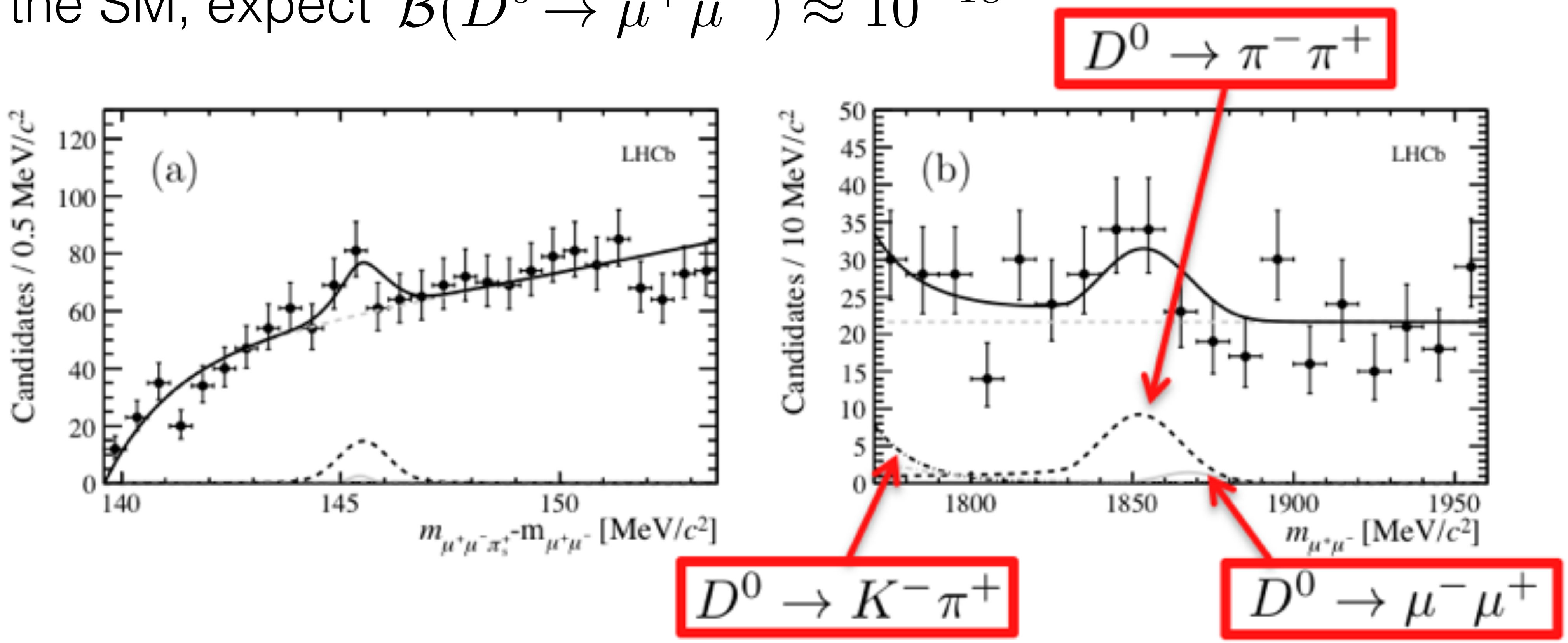
➡ Compatible with SM predictions at 1.2σ (Bs) and 2.2σ (B^0).

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

$D^0 \to \mu^+\mu^-$

- Effective GIM suppression, expect short distance contribution in the SM, expect $\mathcal{B}(D^0 \to \mu^+\mu^-) \approx 10^{-18}$

[LHCb, PLB 725 (2013) 15-24]



- Exploit small Δm in $D^{*+} \to D\pi^+$ to suppress combinatorial background. Precision is limited by $\pi \to \mu$ mis-id.

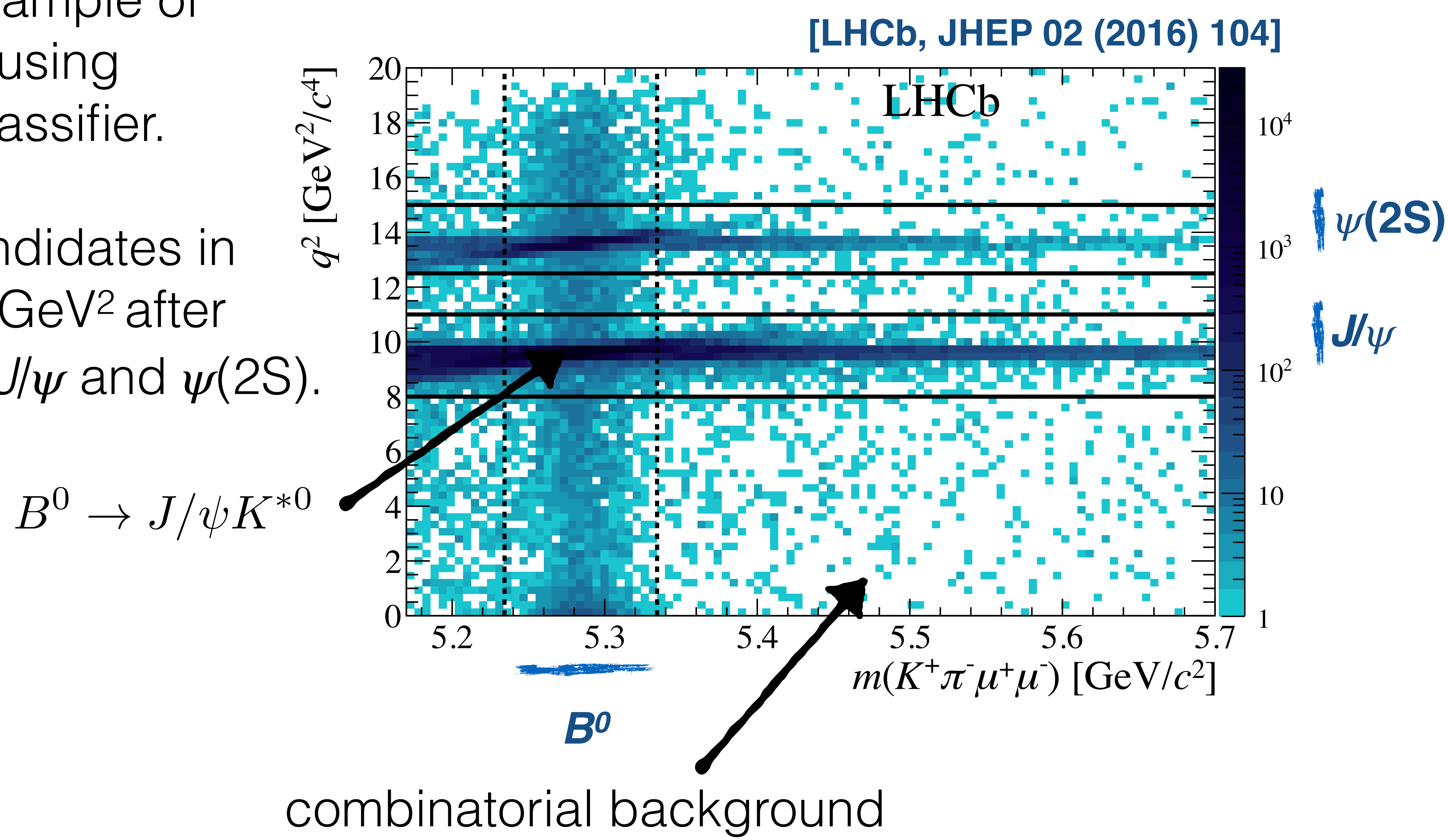
- LHCb sets world best branching fraction limit of:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.8 \times 10^{-9} \text{ at } 95\% \text{ C.L.}$$

Reconstructed candidates

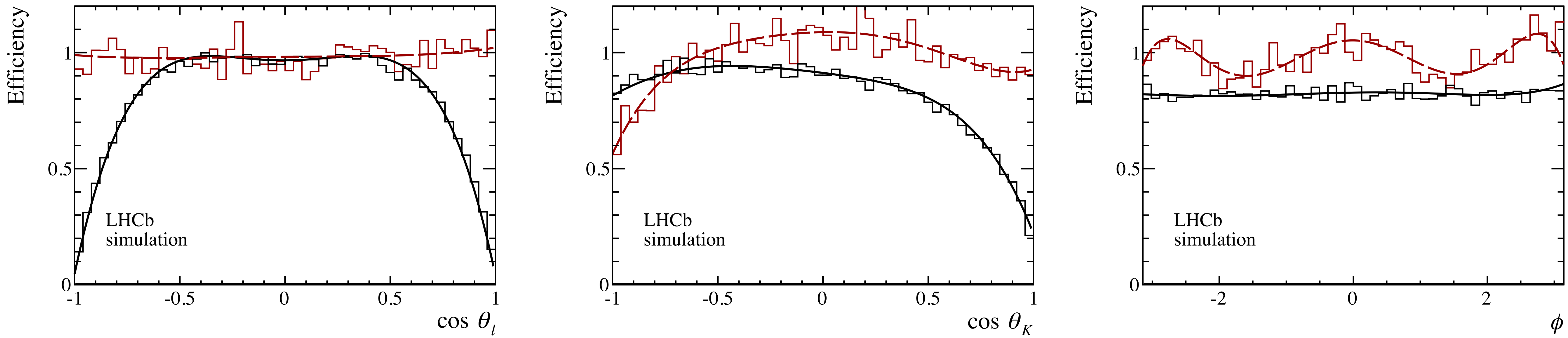
Select clean sample of signal events using multivariate classifier.

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



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:

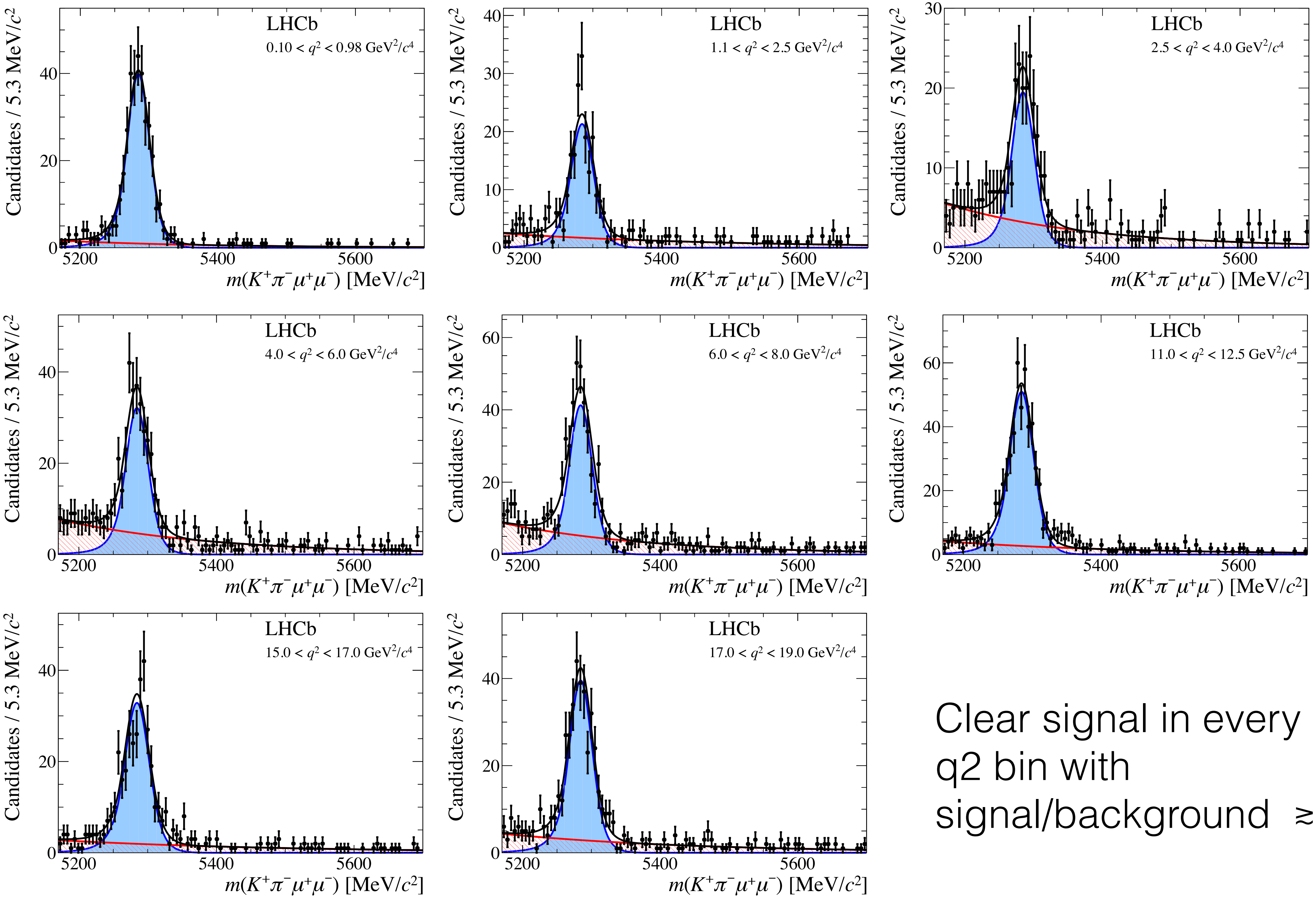
$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) \times L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

Legendre polynomial of degree *n*.

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

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

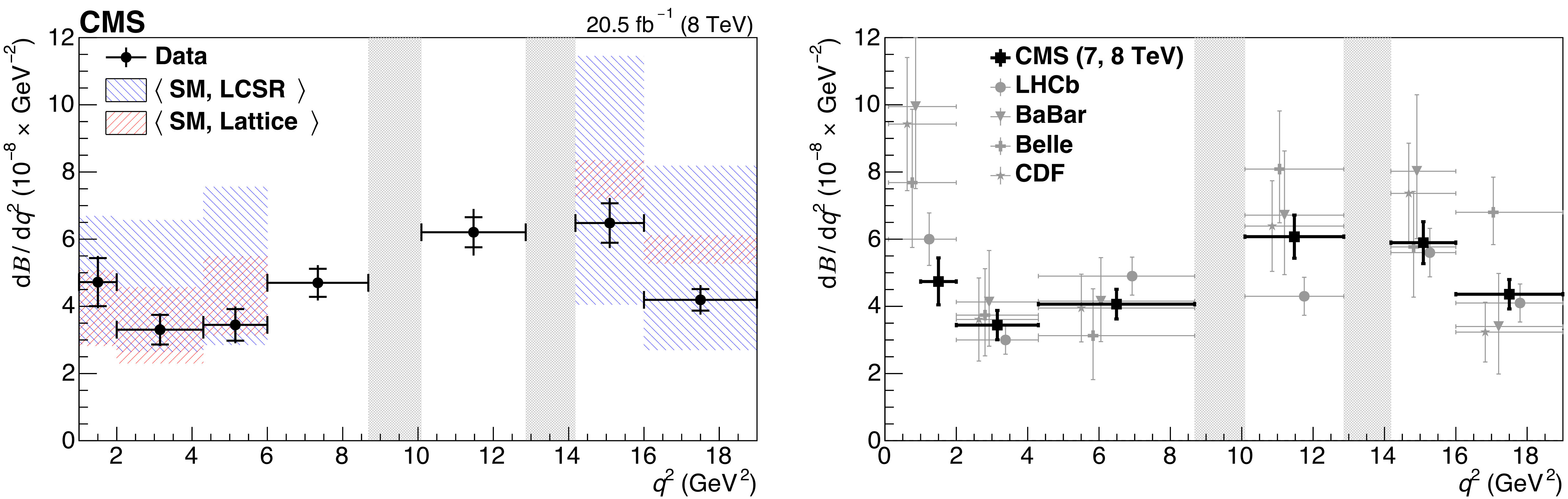
[LHCb, JHEP 02 (2016) 104]



Clear signal in every q2 bin with signal/background ≳ 3

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

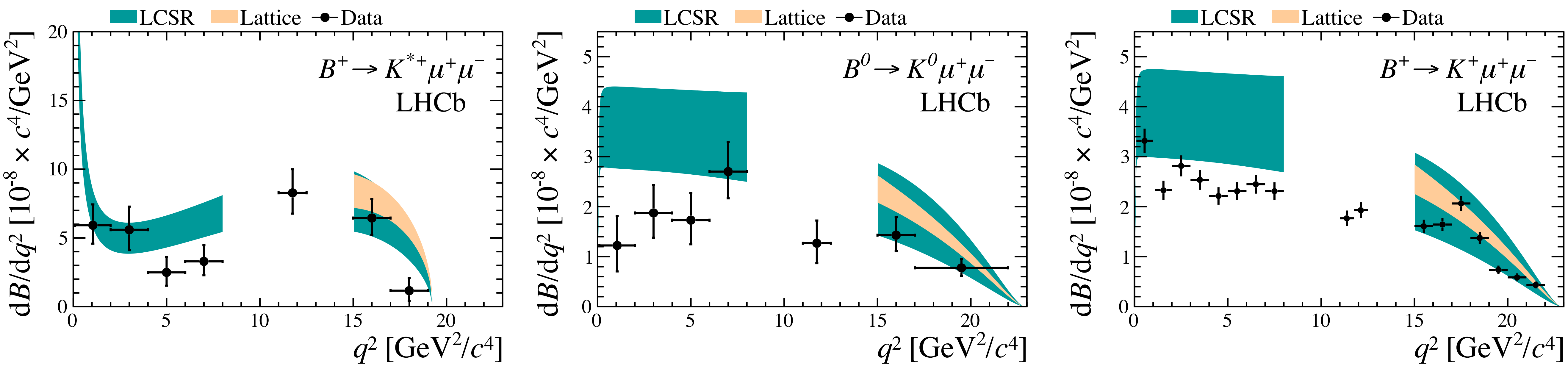
[CMS-BPH-13-010, arXiv:1507.08126]



- Branching fraction measurements from different experiments are compatible.

Branching fractions

[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).

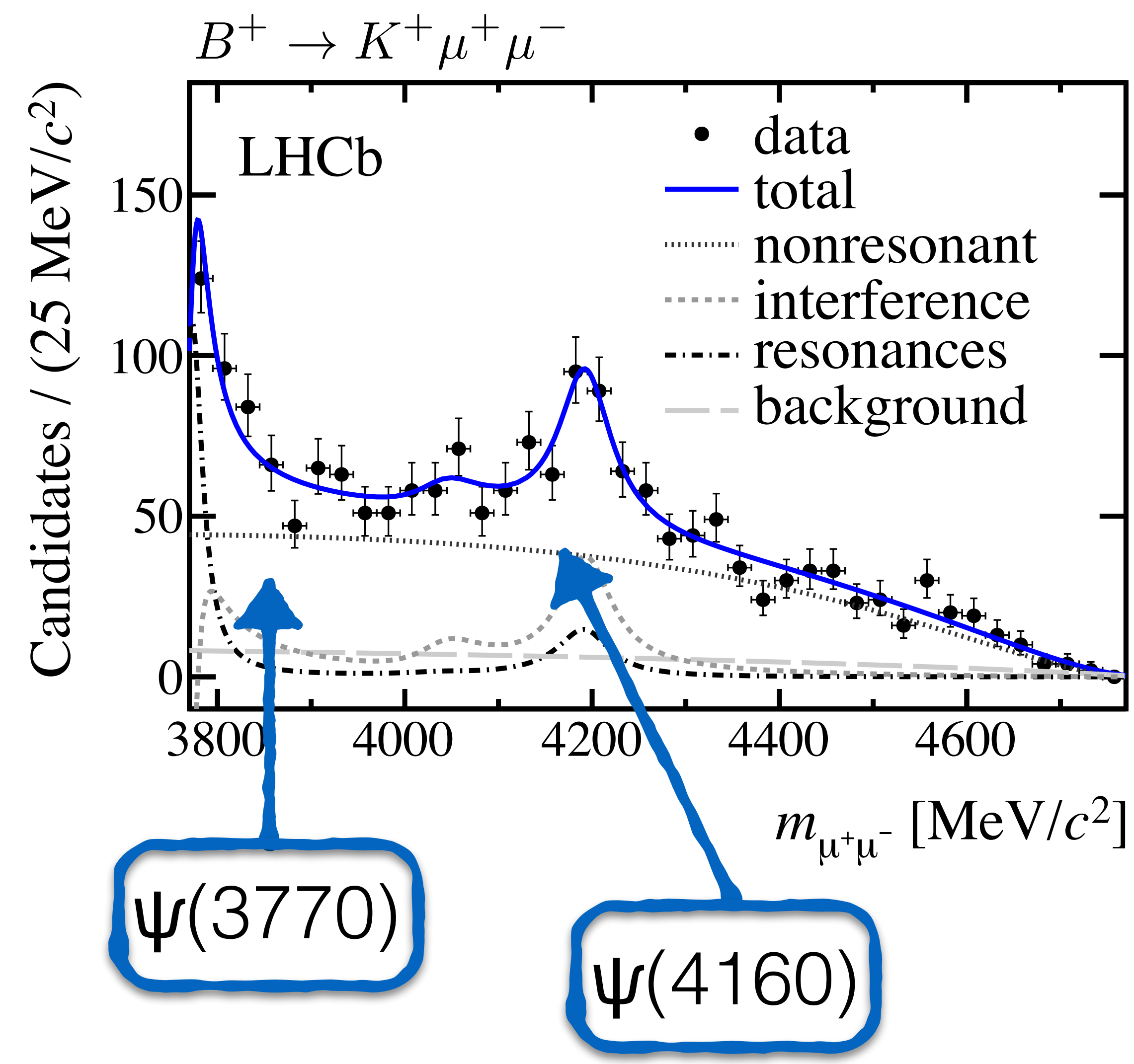
Resonance structure

- 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

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

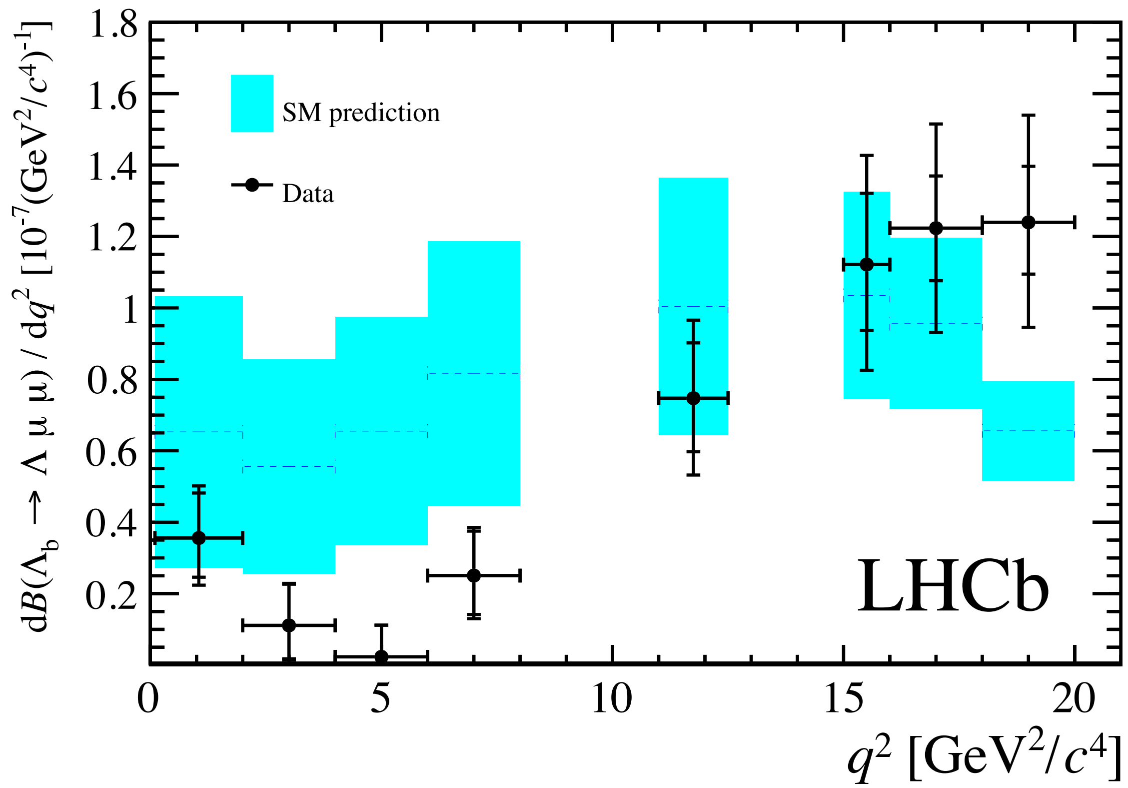
for narrow states this needs to be convoluted by our experimental resolution



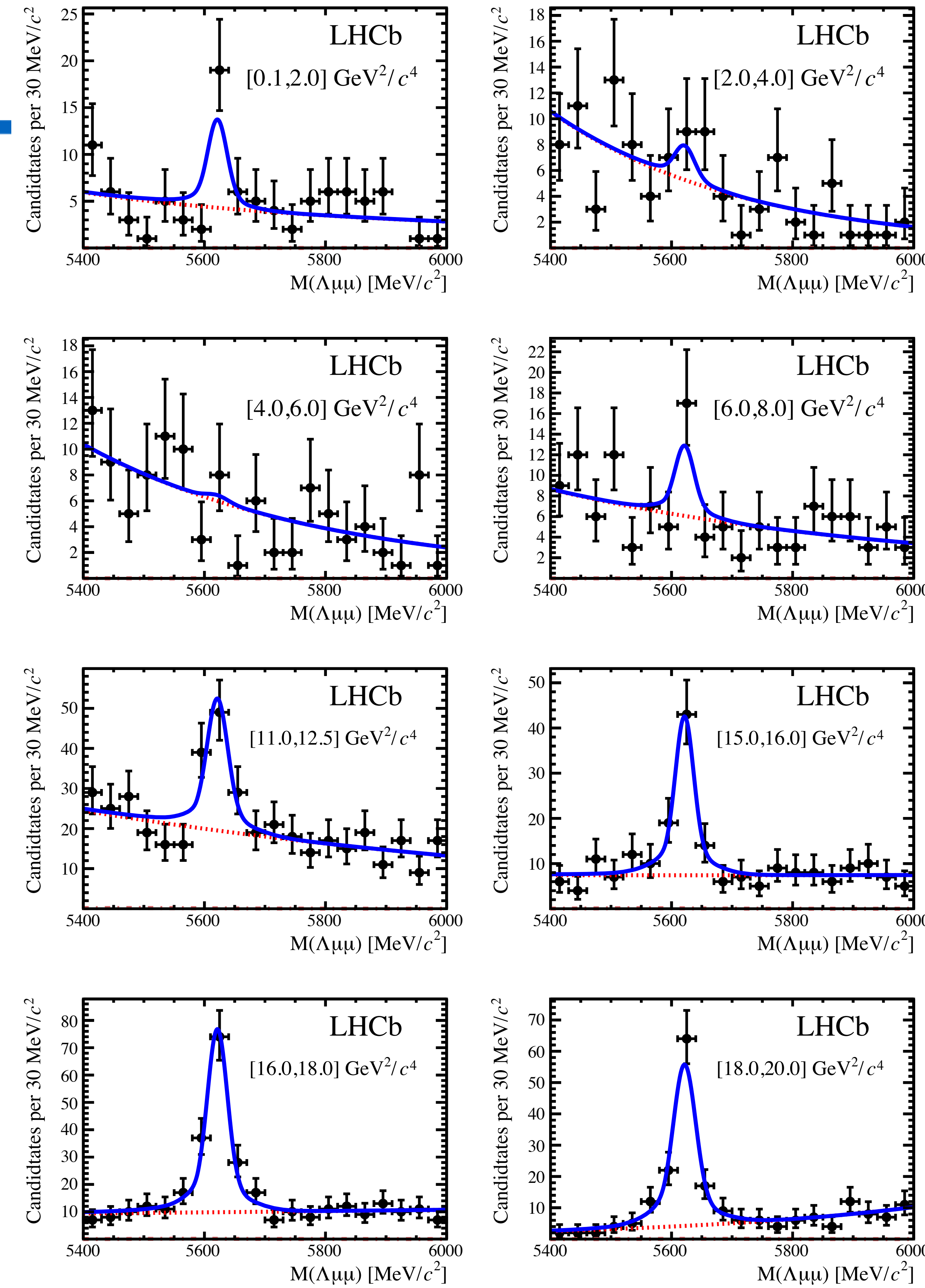
[LHCb, PRL 111 (2013) 112003]

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)?

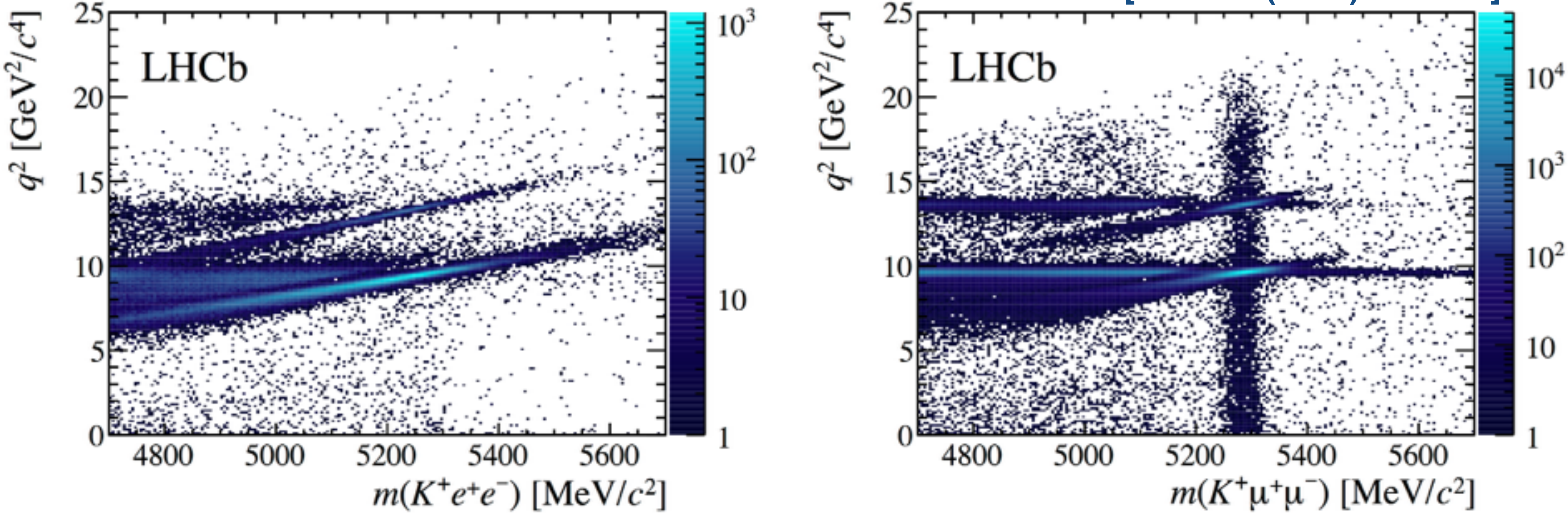


[LHCb, JHEP 06 (2015) 115]

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

Electron reconstruction in R_K

LHCb [PRL113 (2014) 151601]



- Two big experimental differences between electrons/muons:
    - ➡ Bremsstrahlung/FSR from the electrons (recover clusters with $E_T > 75$ MeV/c^2)
    - ➡ Typically require higher trigger thresholds for electrons and have a lower tracking efficiency (due to material interactions).

R_K result

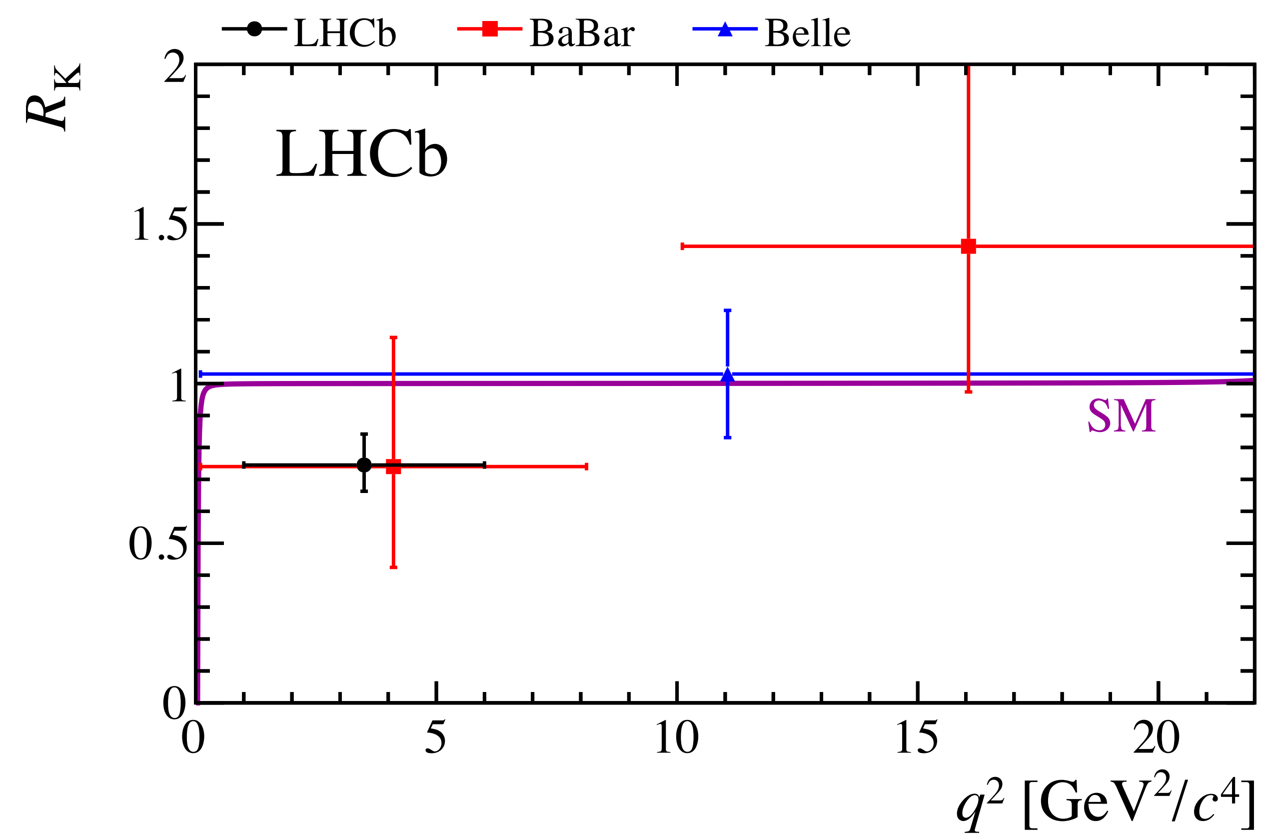
- In the run 1 dataset, LHCb determines:

$$R_{\rm K} = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}$$

in the range $1 < q^2 < 6$ GeV^2, 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/out of the window using MC



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

$R_K < 1$ implies a deficit of muons w.r.t. electrons.

Rare $b \to s$ decays

- Can write a Hamiltonian for in terms of an effective theory as:

Wilson coefficient (integrating out scales above μ)

Local operator with different Lorentz structure

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

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

local operator

NP scale

- κ can have all/some/none of the suppression of the SM,

e.g. MFV inherits SM CKM suppression.

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"

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

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 (the dilpeton system can also be produced by emitting a photon from a hadronic transition).

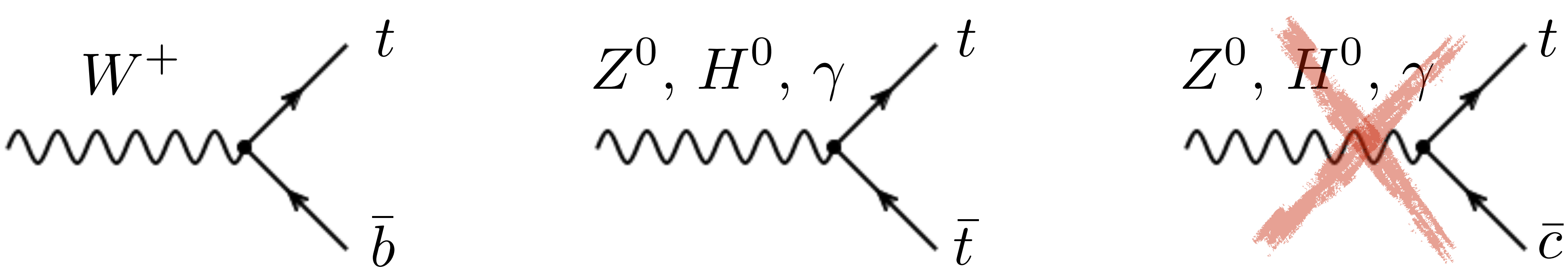
Flavour in the SM

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

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

- $\mathcal{L}_{\mathrm{Higgs}}$ 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,

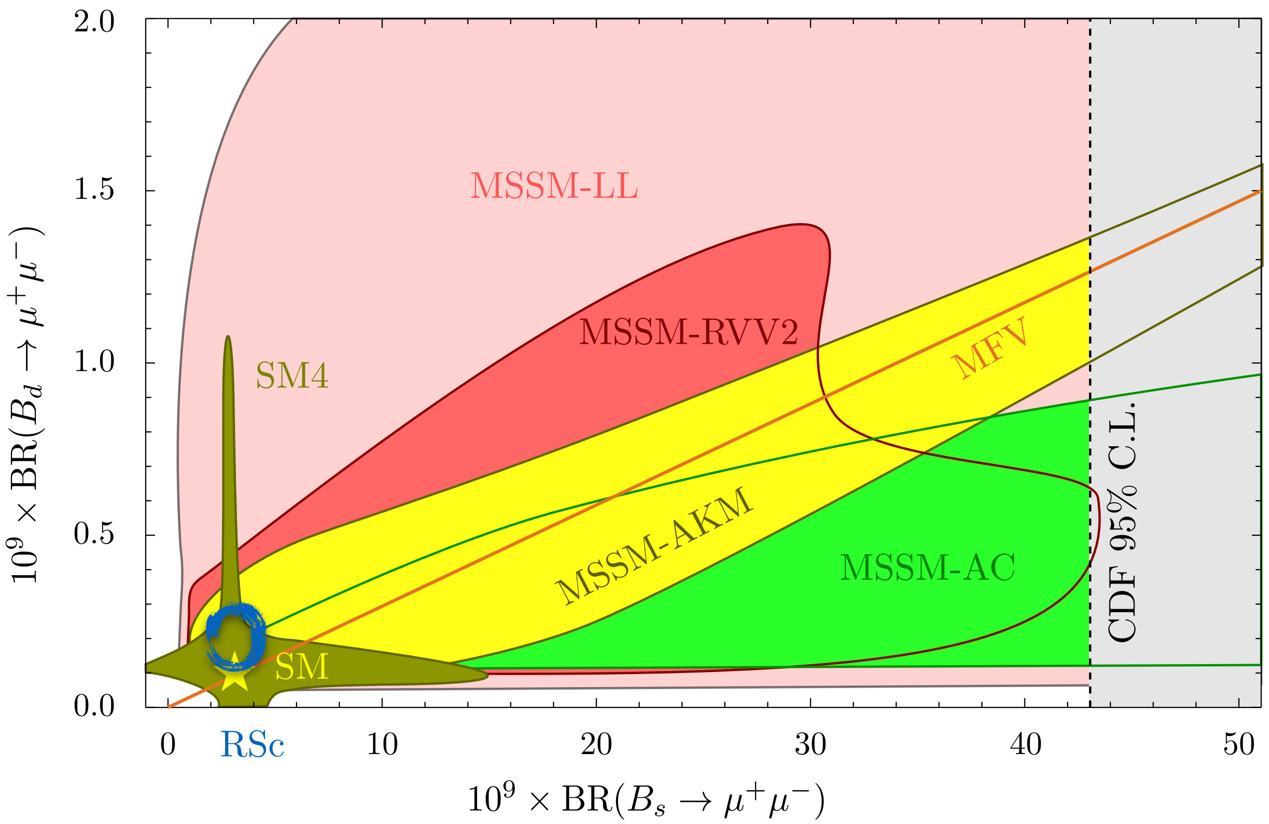


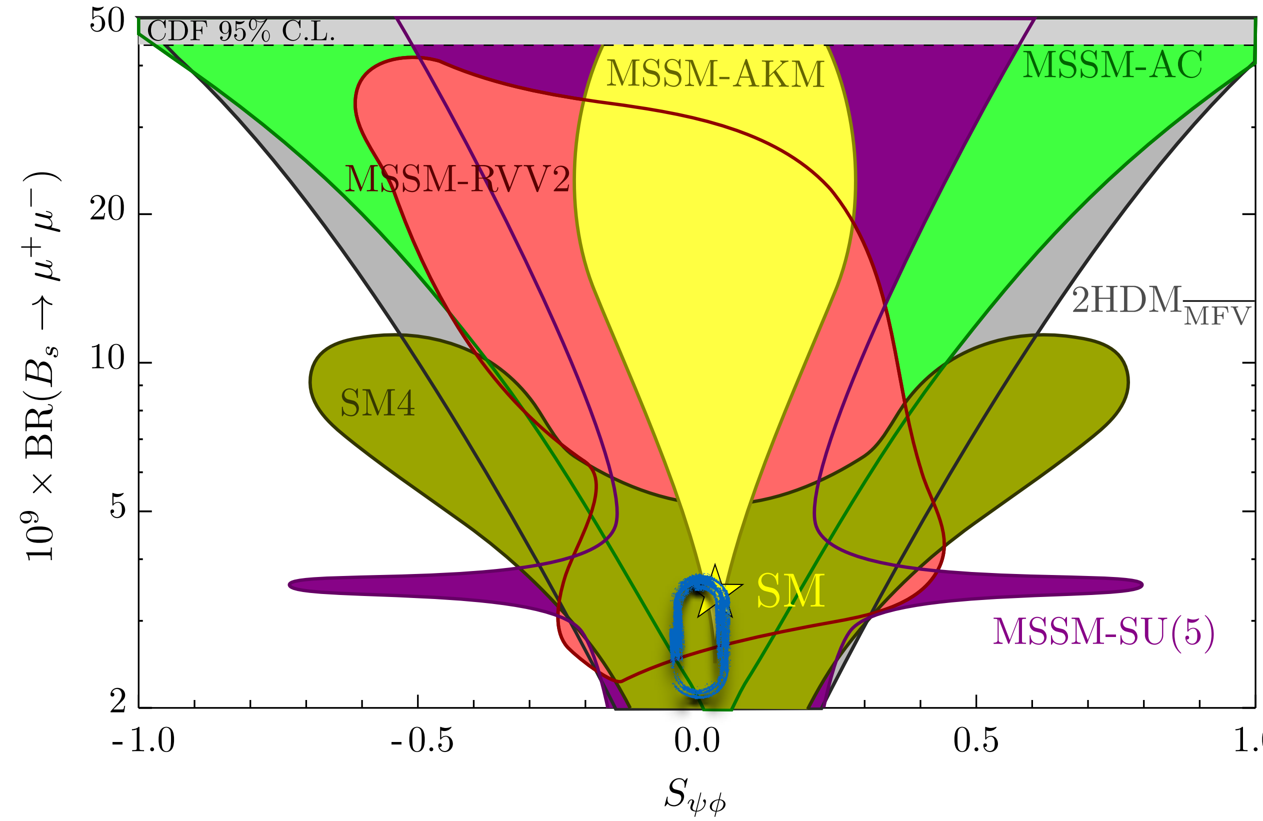
  ➡ Quark flavour-violating interactions governed by the CKM.

  ➡ No tree level FCNCs in the SM.

Flavour constraints

[Straub, arXiv:1107.0266]





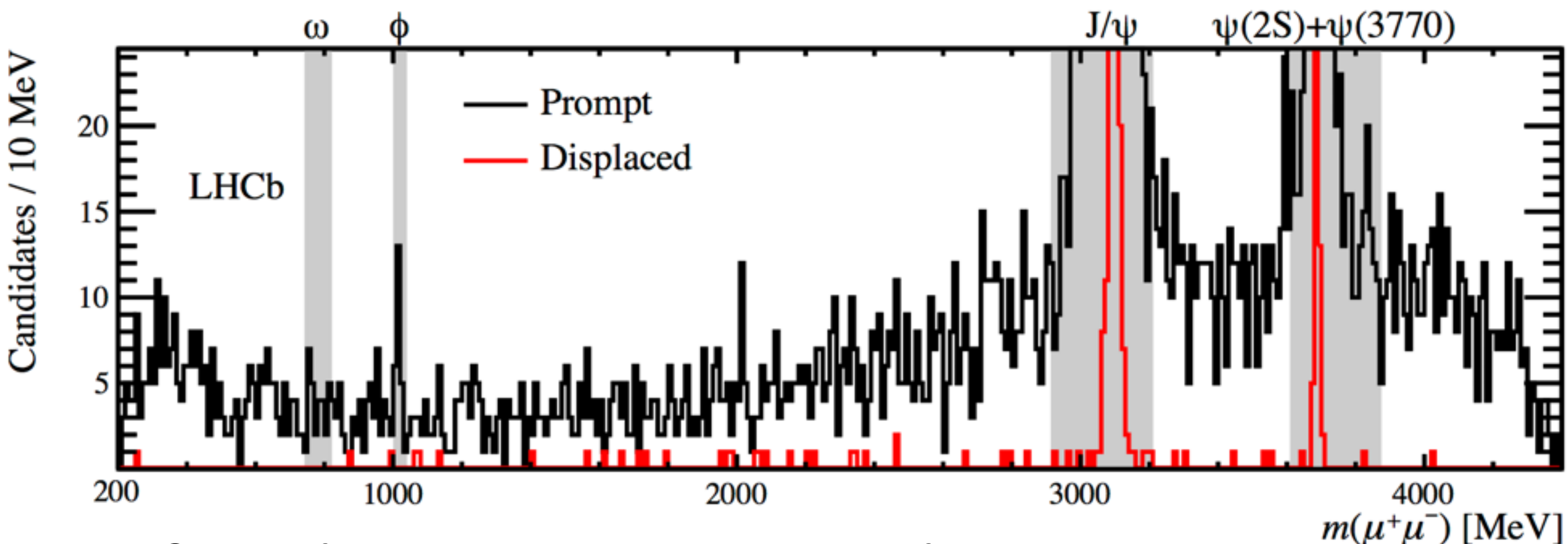
constraints prior to LHC, constraints at the end of Run 1

- 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.

Displaced dimuon

[LHCb, LHCb-PAPER-2015-036]

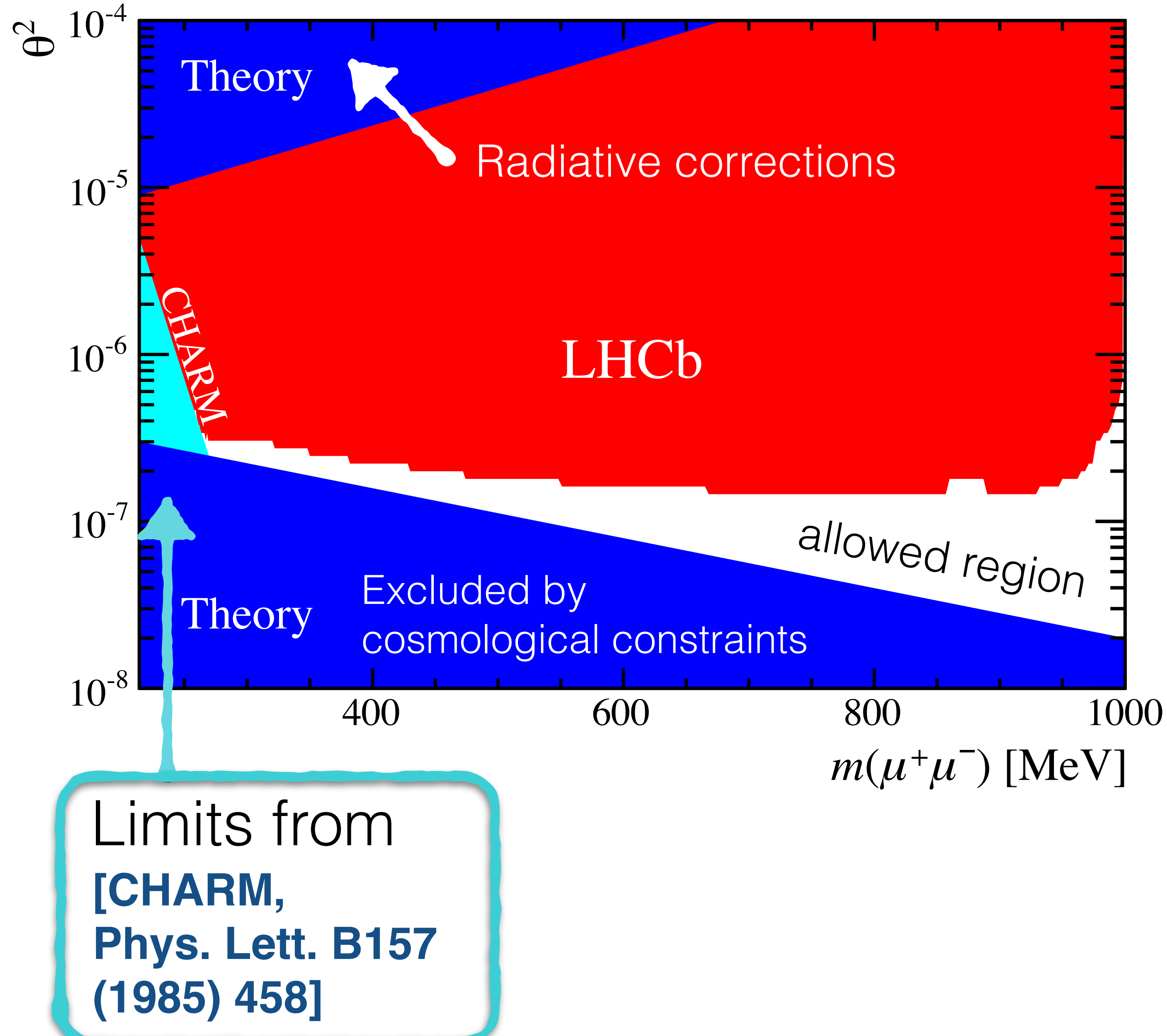


- Search for peak in dimuon spectrum, for either prompt and displaced (> $3\sigma_t$) dimuon pairs.
  - ➡ Data consistent with background only hypothesis. Largest local excess at 253 MeV.
- Sensitive in LHCb to lifetimes up-to 1 ns, but best sensitivity for lifetimes less than 10 ps.

Example: Inflaton

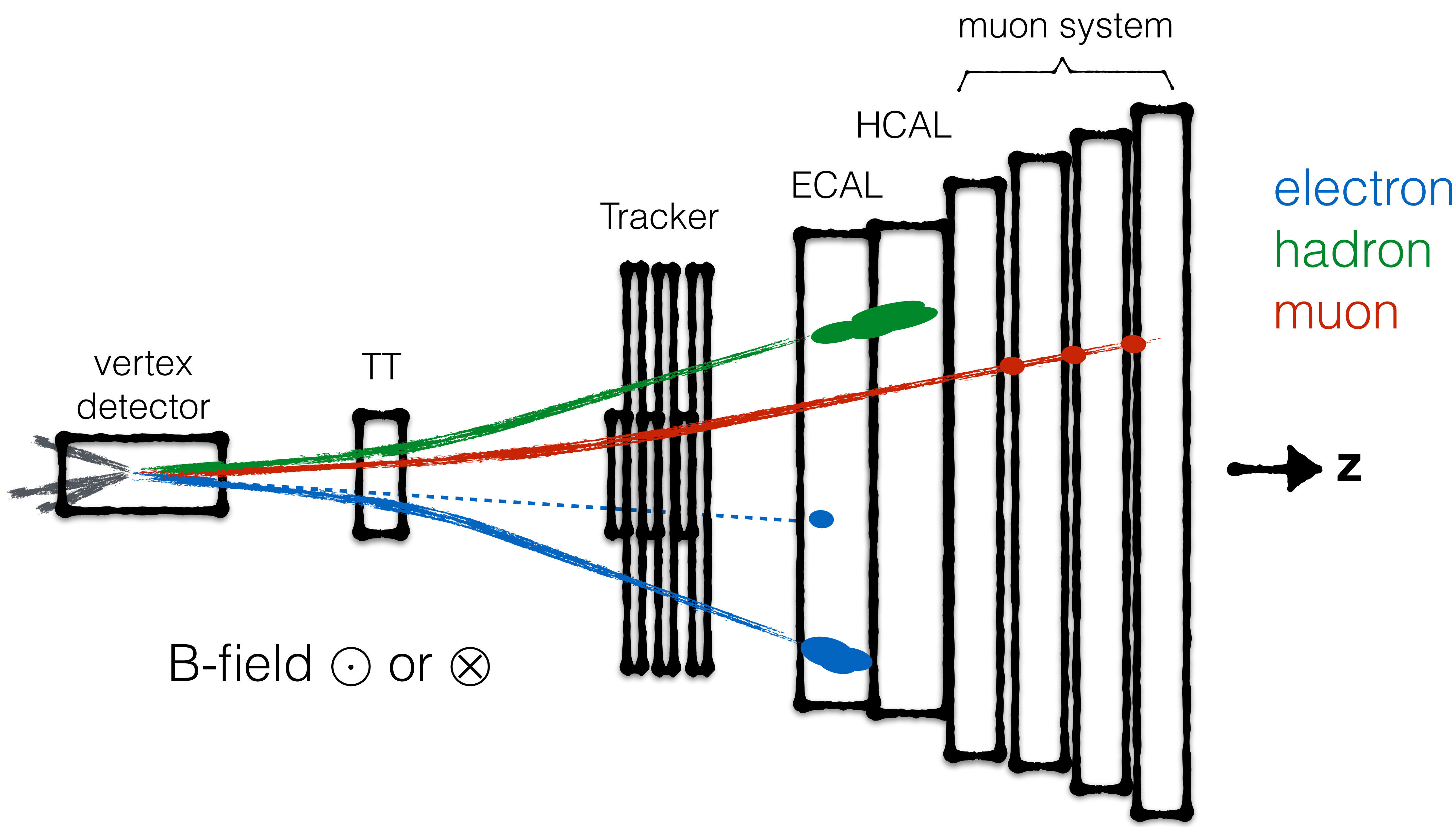
- Concrete model with Inflaton field mixing with Higgs, with mixing angle θ.
  - ➡ Introduce 3 sterile neutrinos to explain origin of neutrino mass, BAU and provide a DM candidate.
    [Shaposhnikov, and Tkachev, Phys. Lett. B 639 (2006) 414, Bezrukov and Gorbunov, Phys. Lett. B736 (2014) 494]
- Can exclude large part of the parameter space.

From [LHCb, LHCb-PAPER-2015-036]



Particle reconstruction

(in the LHCb detector)



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