Rare Decays and Search for BSM Physics at LHCb

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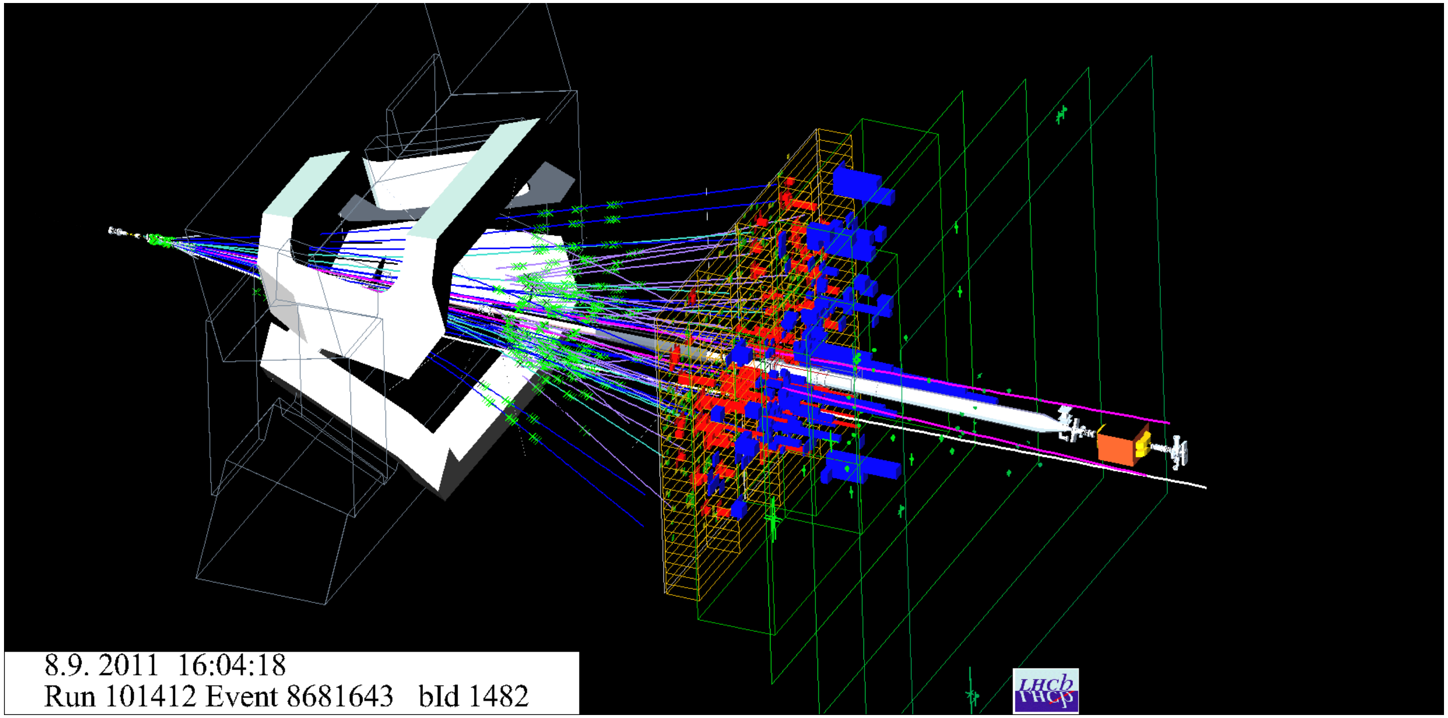
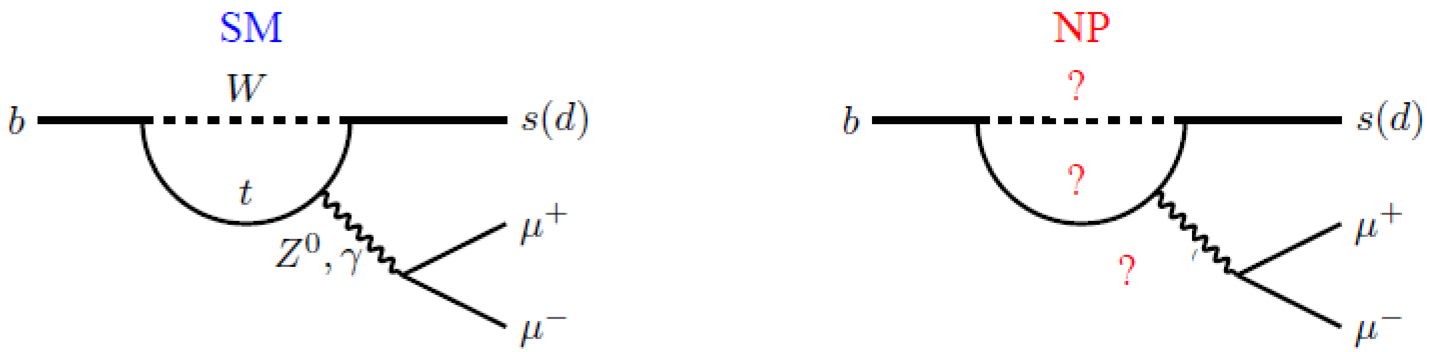


LISHEP 2015

Why rare decays ?

- Up to now, no sign of New Physics (NP) from direct searches... but indirect NP effects can also appear in heavy flavour rare decays.

- Flavour changing neutral currents are forbidden at the tree level in the SM, they can only proceed through loop diagrams.



- NP virtual particles can enter the loop and modify observables such as branching ratios, CP asymmetries, angular distributions,…

- Complementary to ATLAS/CMS searches, flavour can probe a very high scale!

Which rare decays ?

- Different type of decays give access to different observables sensitive to different new physics contributions

- The correlations between the observables allows to identify the type of new physics involved $\Rightarrow$ important to measure all possible observables

- The usual suspects:
  - $B \rightarrow \ell\ell$★: branching fraction
  - $b \rightarrow s\,\ell\ell$: branching fraction as function of q^2 ($=m_{\ell\ell}^2$), angular observables
    - Ex: $B_d \rightarrow K^{*0}\mu^+\mu^-$ $B_d \rightarrow K^{*0}e^+e^-$, $B_s \rightarrow \phi\mu^+\mu^-$, $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$
  - Test of lepton universality
  - Search for lepton flavour violating decays
  - Rare charm decays
  - …

★ℓ = muon or electron, tau much more difficult experimentally

How to interpret SM deviation ?

- b → s ℓℓ decays can theoretically be described by effective hamiltonian

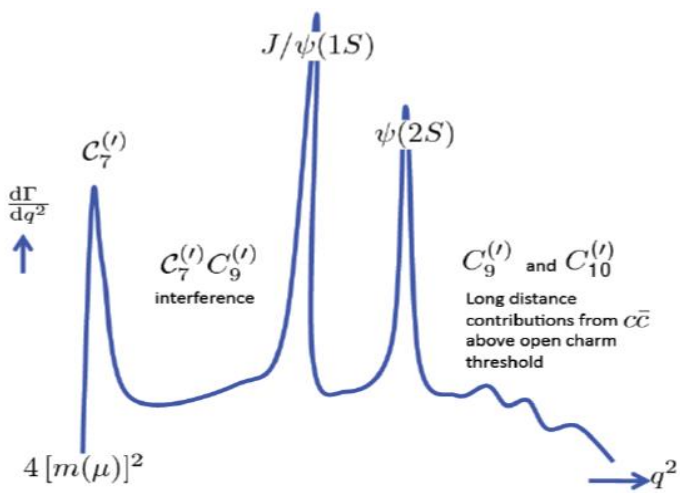
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

left-handed part ($C_i \mathcal{O}_i$)

right-handed part suppressed in SM ($C_i' \mathcal{O}_i'$)

i=1,2 Tree
i=3-6,8 gluon penguin
i=7 photon penguin
i=9,10 electroweak penguin
i= S,P Scalar, Pseudo scalar penguin

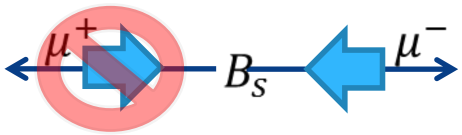
- Operators O_i depends on hadronic form factors, which usually dominate theoretical uncertainties
- Wilson coefficient C_i describe short distance effects, they are sensitive to NP



- B → K* ℓℓ : C_7 C_9 C_{10}
- B → ℓℓ : C_{10} C_S C_P
- B → X_s γ : C_7

Interest of $B_{s/d}\to\mu^+\mu^-$

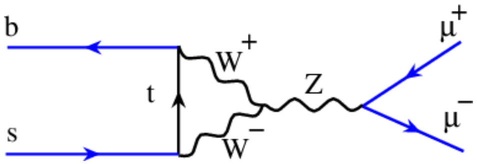
- Flavour changing neutral current and helicity suppressed decays

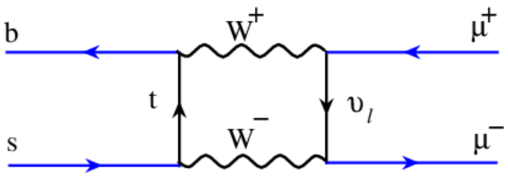


- Precise SM prediction:

  (PRL 112 (2014) 101801)

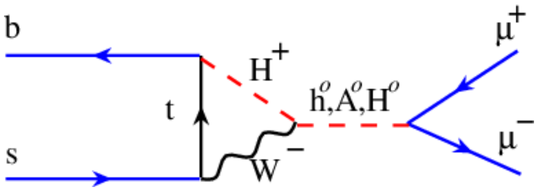
  - $BR(B_s\to\mu^+\mu^-) = (3.66\pm0.23) \times10^{-9}$
  - $BR(B_d\to \mu^+\mu^-) = (1.06\pm0.09) \times10^{-10}$





- Possible new particles in the loops

Ex:2HDM



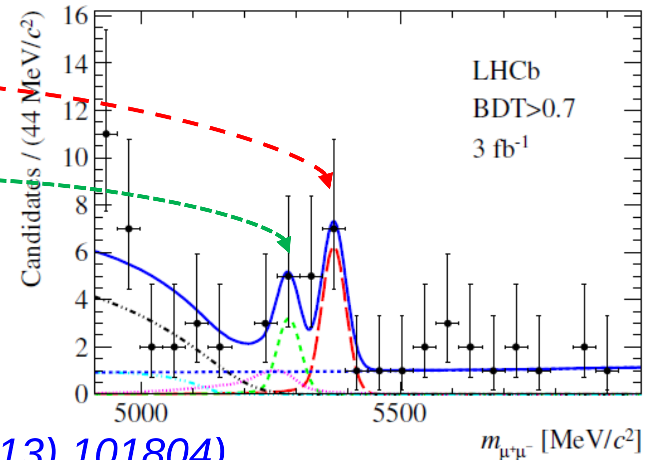
Very good place to look for physics beyond SM, intensively searched for over 30 years!

$B_{s/d} \rightarrow \mu^+\mu^-$

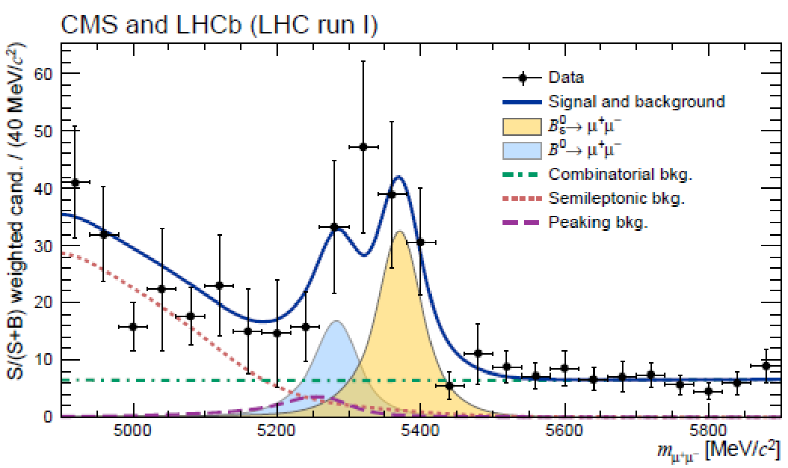
LHCb, 3fb[-1] *(PRL 111 (2013) 101805)* :

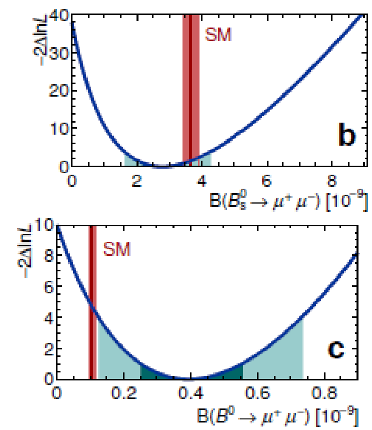
$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$



- CMS obtained similar results with 25 fb[-1] *(PRL 111 (2013) 101804)*
- Combination *(Nature 522 (2015) 68)* :



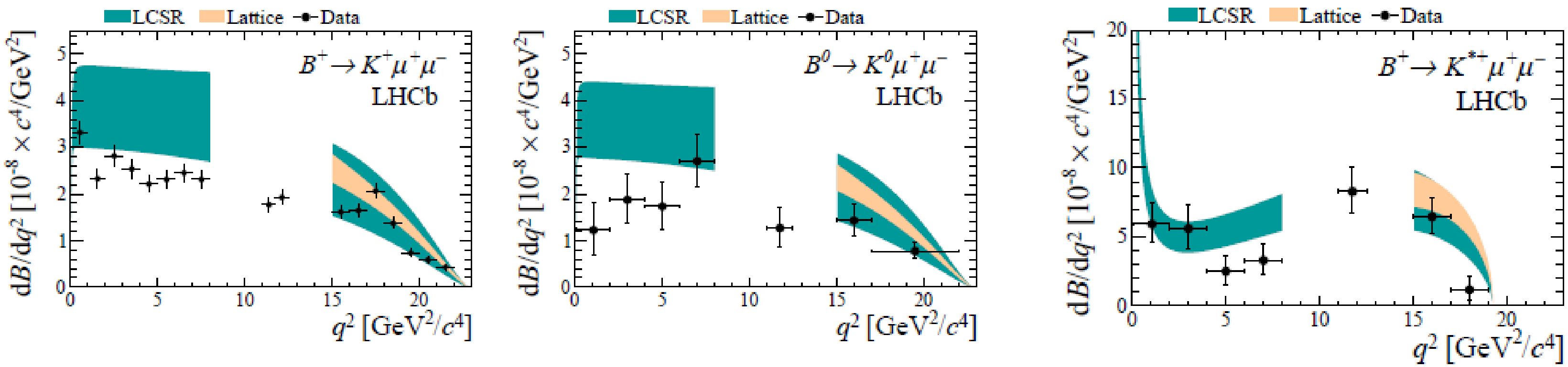


First observation (at 6.2 σ) for B_s and first evidence (at 3.2 σ) for B^0

Results compatible with SM predictions at 1.2 σ for B_s and 2.2 σ for B_d but deviations from SM are still possible!

b → sμμ branching fractions vs q^2

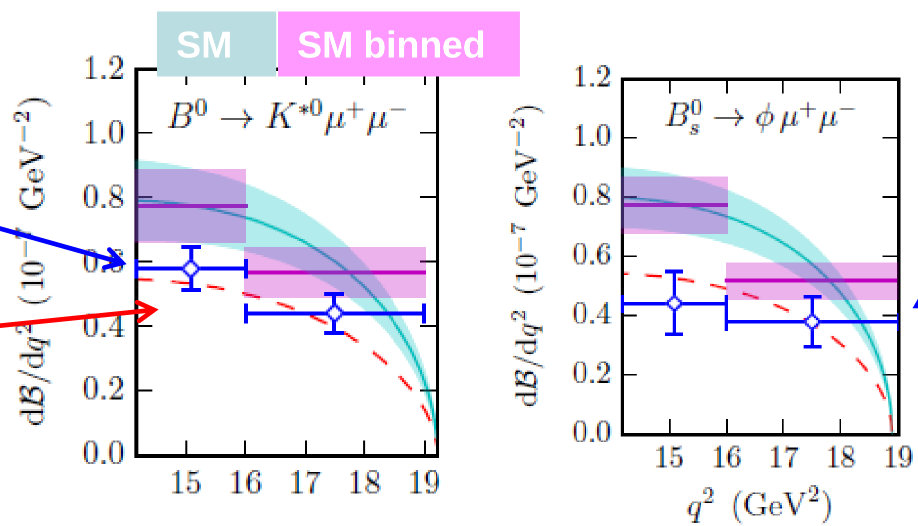
- BR measurement of $B^+ \to K^+ \mu\mu$, $B^0 \to K^0 \mu\mu$ and $B^+ \to K^{*+} \mu\mu$ *(JHEP 06 (2014) 133)*



- Experimental average of $B^0 \to K^{*0} \mu\mu$ and $B_s \to \phi\mu\mu$ at high q^2 : Horgan et al *(PRL 112, 212003)*

Average from LHCb, CDF, CMS, ATLAS

$C_9 = C_9^{SM} - 1.5$

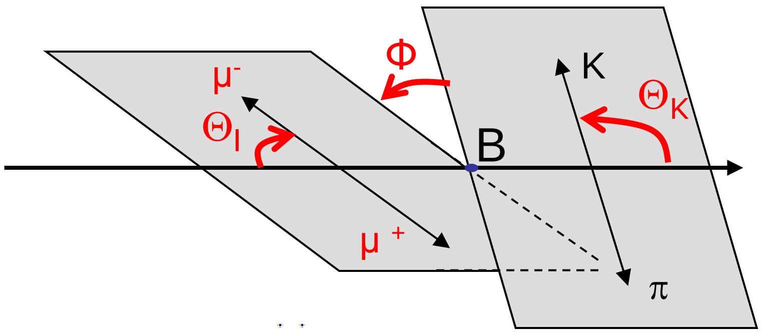


Average from LHCb, CDF

⇒ Branching fractions tend to lie below SM predictions

Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

- Decay described by 3 angles and di-muon invariant mass squared q^2
- A_{FB}, F_L and S_i are determined in bins of q^2 and depends on Wilson coefficients C_7, C_9, C_{10} and hadronic form factors

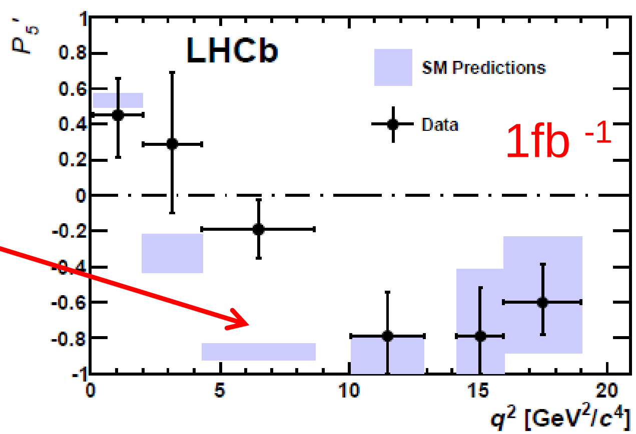


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos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

The previous analysis on 1 fb^{-1} revealed a local discrepancy at 3.7 σ for P'_5 (“cleaner” observable)

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

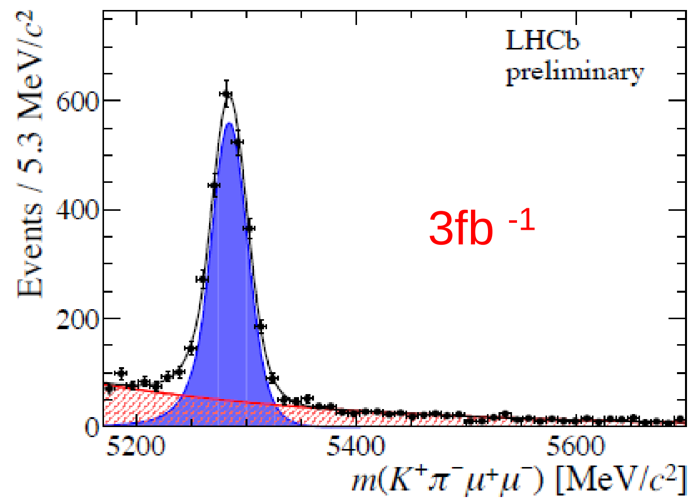
PRL 111 (2013) 191801

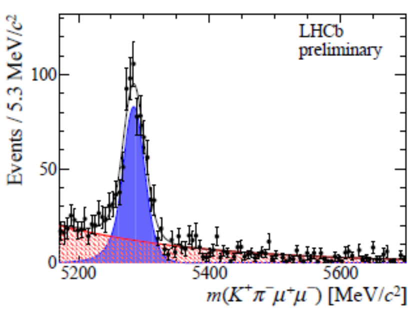


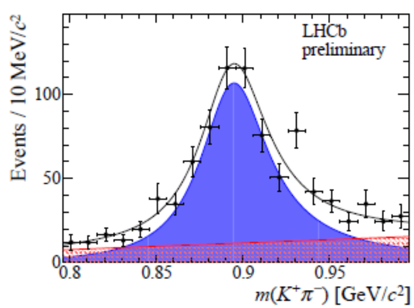
Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

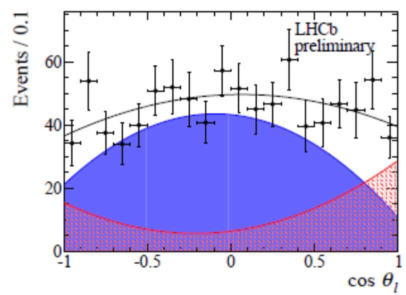
LHCb-CONF-2015-002

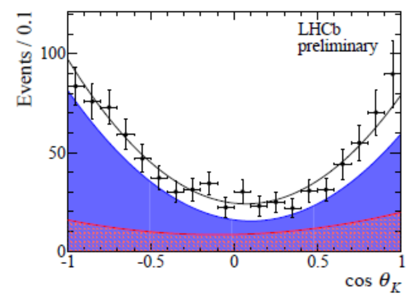
- Analysis updated with the $3fb^{-1}$ recorded during Run 1 : 2398 ± 57 signal events
- Angular observables extracted from likelihood fit in decay angles and $m_{K\pi\mu\mu}$ in q^2 bins
- Kπ S wave contribution taken into account by fitting simultaneously the Kπ mass
- Example in the bin $1.1<q^2< 6.0$ GeV^2:

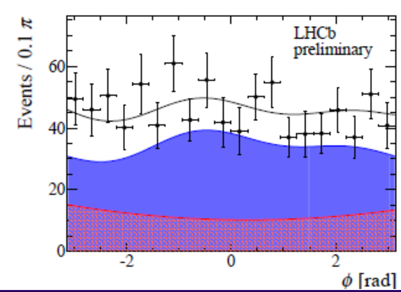




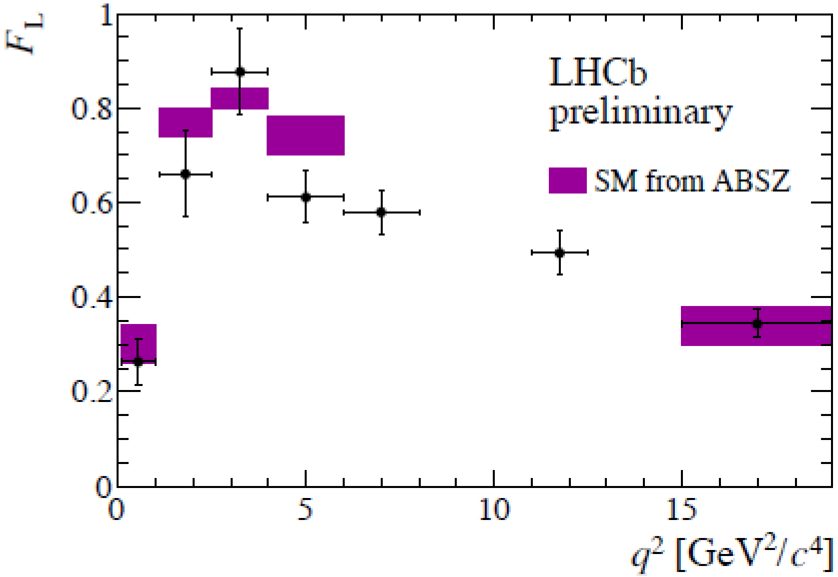


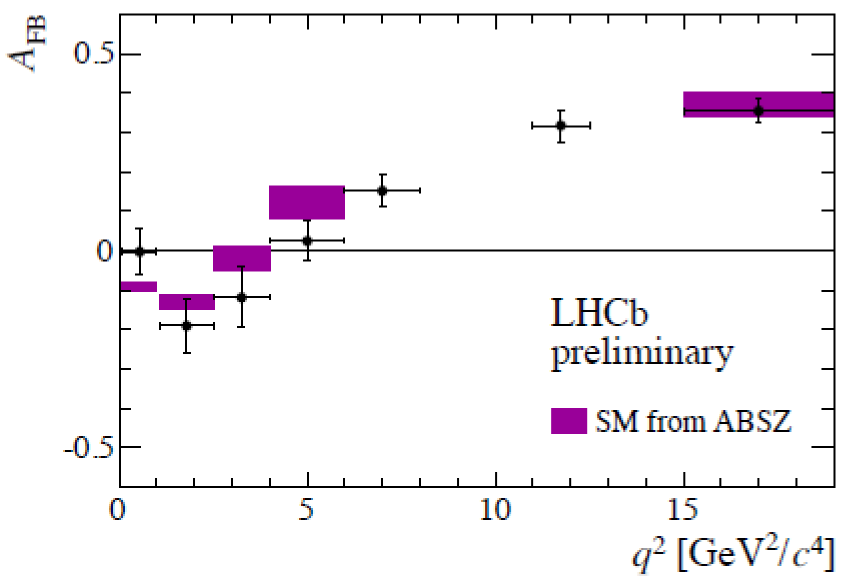






Angular observables of $B_d \rightarrow K^{*0}\mu^+\mu^-$



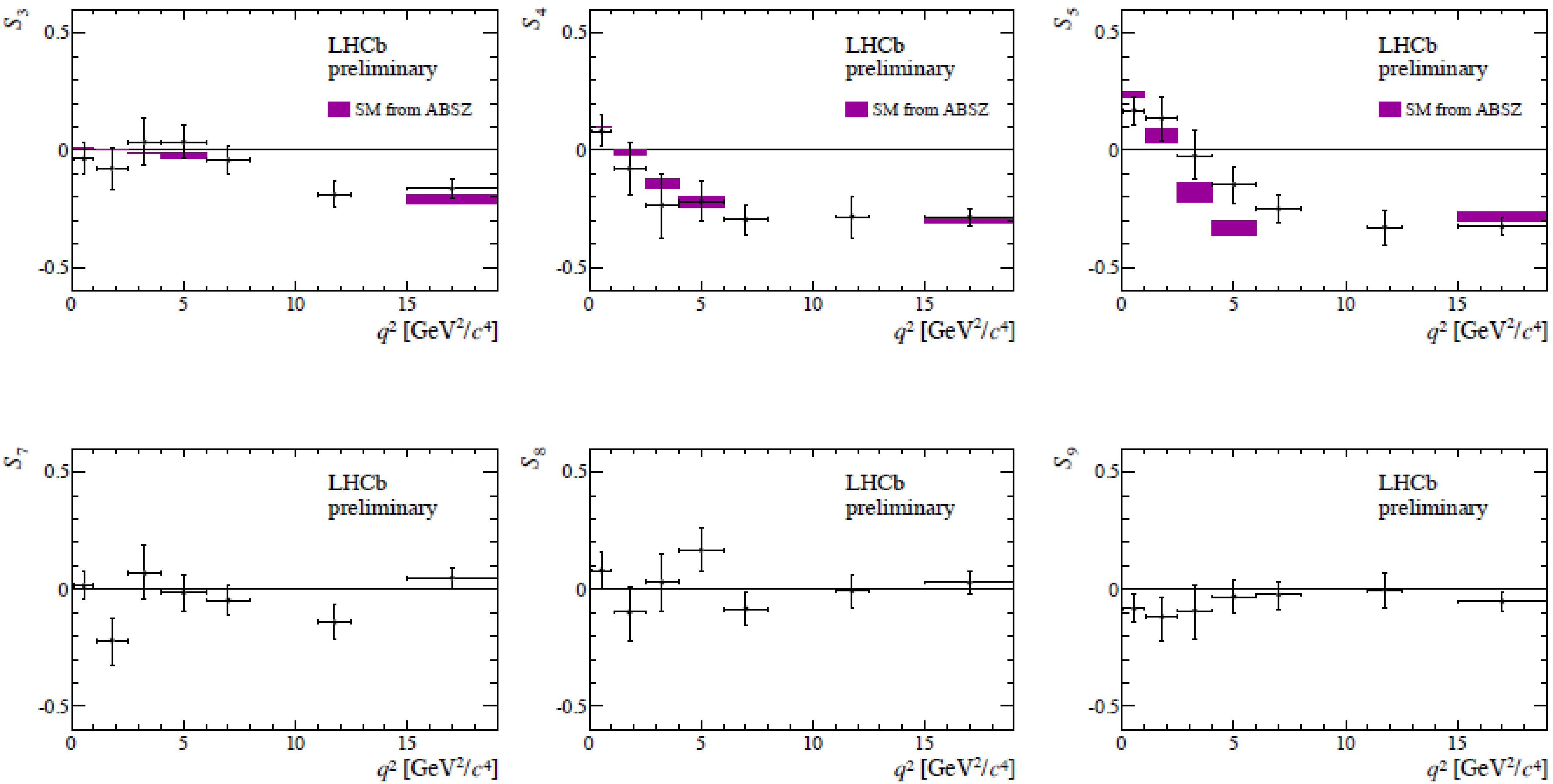


Theory prediction from arXiv:1503.6634, arXiv:1411.3161

- A_{FB} systematically below SM prediction
- Zero crossing point evaluated as in previous analysis *(PRL 111 (2013) 191801)* and consistent with SM (~4.0GeV^2) :

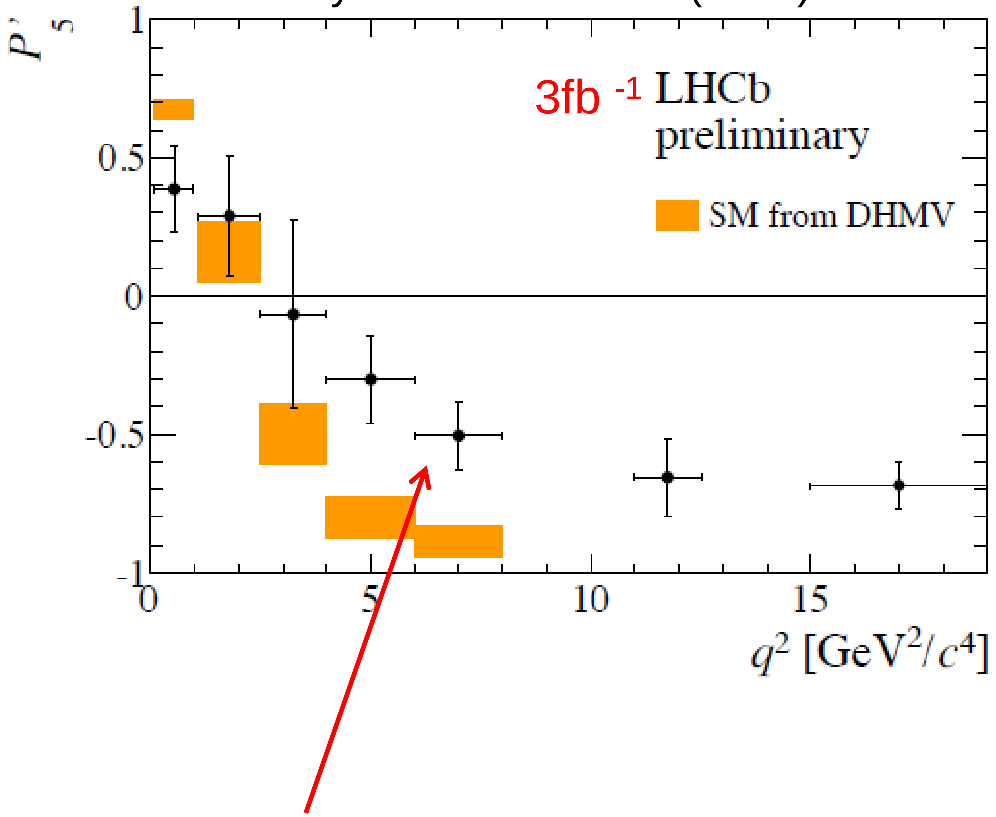
$$q_{ZCP}^2 = 3.7^{+0.8}_{-1.1} \text{GeV}^2$$

Angular observables of $B_d \to K^{*0}\mu^+\mu^-$



Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

Theory from JHEP 1412 (2014) 125

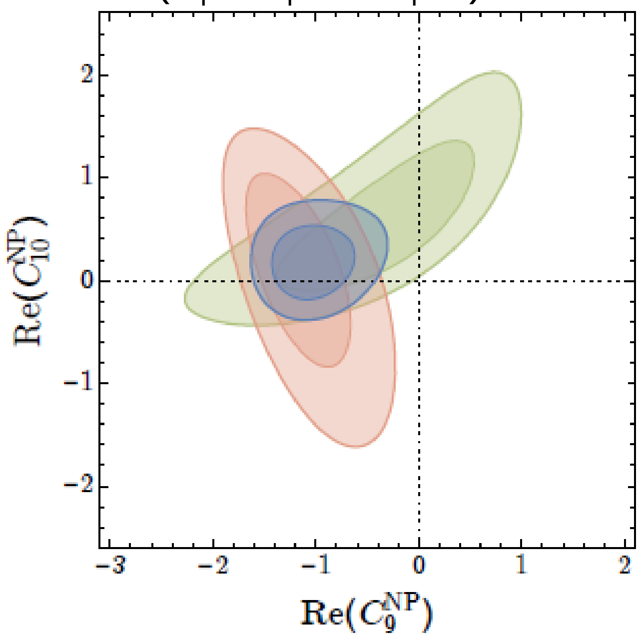


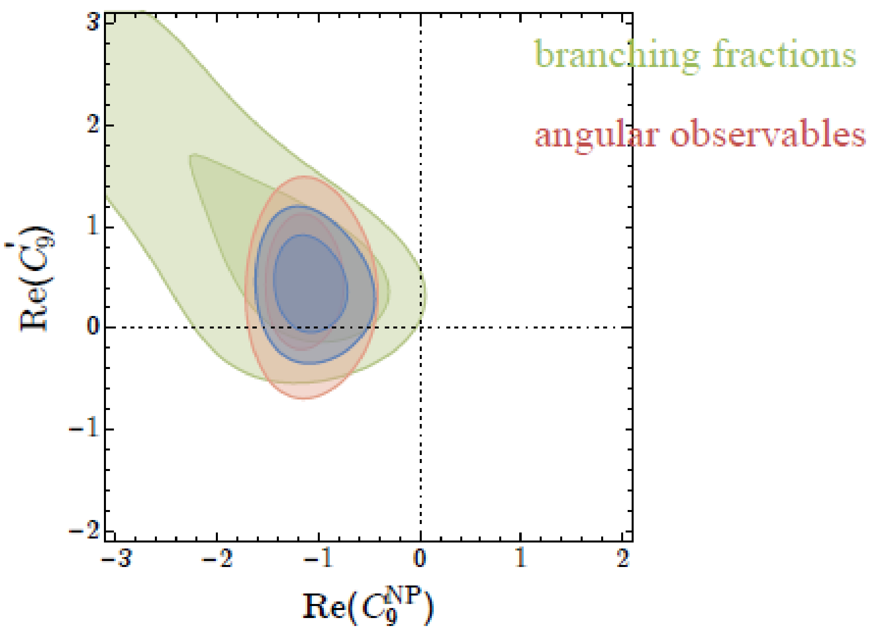
Discrepancy in P'_5 still there at 3.7 σ level doing a naïve combination of the two bins (2.9 σ each)

Theoretical interpretation

Global model-independent fit of the Wilson coefficients using 88 measurements from ATLAS, CMS, LHCb (Altmannshofer, Straub, arXiv:1503.06199)

($C_i = C_i^{SM} + C_i^{NP}$)

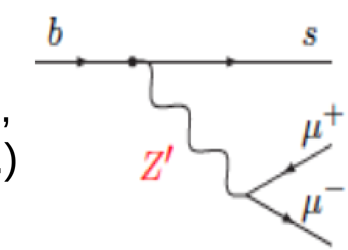




The fit prefers C_9^{NP}~-1.1 by 3.7 σ

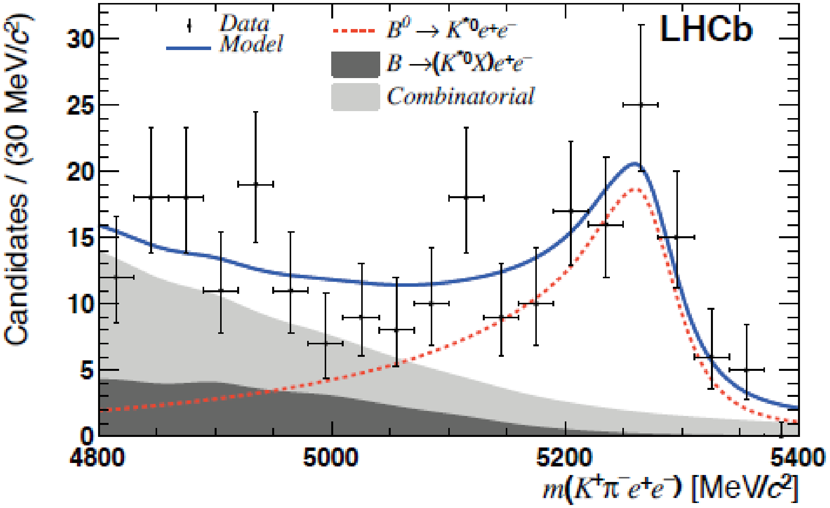
Could be due to a Z' (Gauld et al., JHEP 1401 (2014) 069, Buras et al., JHEP 1402 (2014) 112, Altmannshofer et al. PRD 89 (2014) 095033,...)

or not well understood hadronic effect..



Angular analysis of $B_d \to K^{*0}e^+e^-$

JHEP 1504 (2015) 064



- Angular analysis of $B_d \to K^{*0}e^+e^-$ at small q^2 values is sensitive to photon polarization, which is predominantly left-handed in the SM
- Measurement of F_L , $A_T^{(2)}$ $A_T^{(Im)}$ $A_T^{(Re)}$ in the q^2 region [0.004,1.0] GeV^2, using 124 signal candidates

$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2} \qquad A_T^{\rm Im}(q^2 \to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

Result:

obs.	result
F_L	$+0.16 \pm 0.06 \pm 0.03$
$A_T^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$
$A_T^{\rm Re}$	$+0.10 \pm 0.18 \pm 0.05$
$A_T^{\rm Im}$	$+0.14 \pm 0.22 \pm 0.05$

Jaeger et al. JHEP 05 (2013) 043

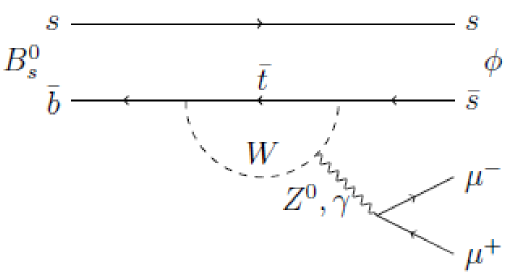
obs.	SM prediction
F_L	$+0.10^{+0.11}_{-0.05}$
$A_T^{(2)}$	$+0.03^{+0.05}_{-0.04}$
$A_T^{\rm Re}$	$-0.15^{+0.04}_{-0.03}$
$A_T^{\rm Im}$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

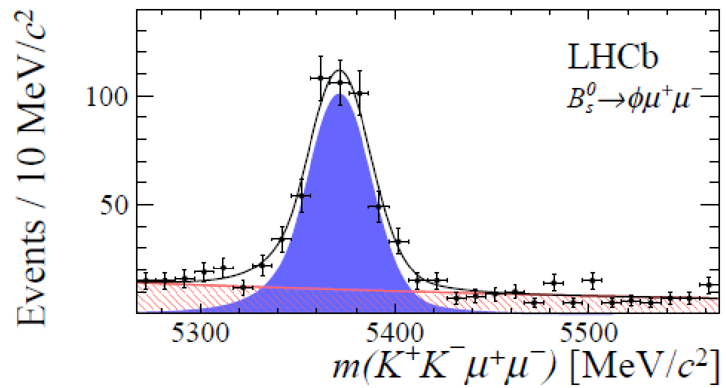
Results consistent with SM, sensitivity to, C'_7 comparable to time-dependent analysis of $B \to K_s \pi^0 \gamma$ by B factories (PRD 78 071102, PRD 74 111104)

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

arXiv:1506.08777

- Very similar to $B_d \to K^{*0}\mu^+\mu^-$, but not self-tagged

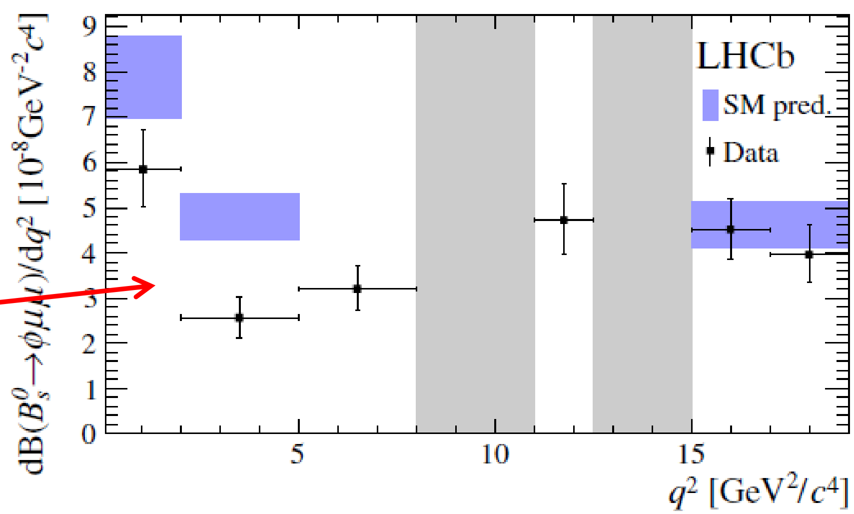




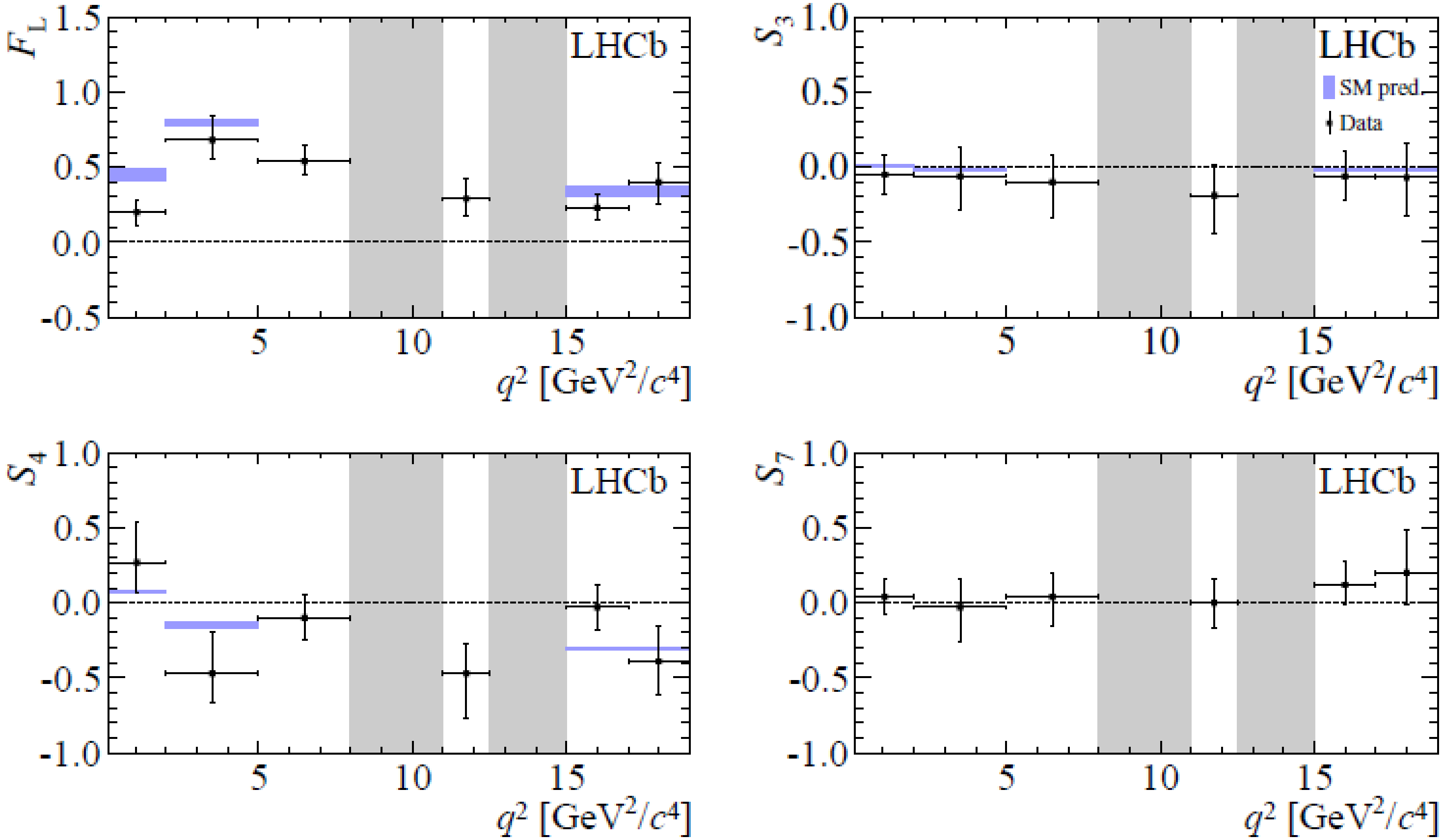
- Update with full Run1 data : 432 ± 24 signal events

- Full angular analysis performed

Branching fraction also shows tension with SM prediction at low q^2

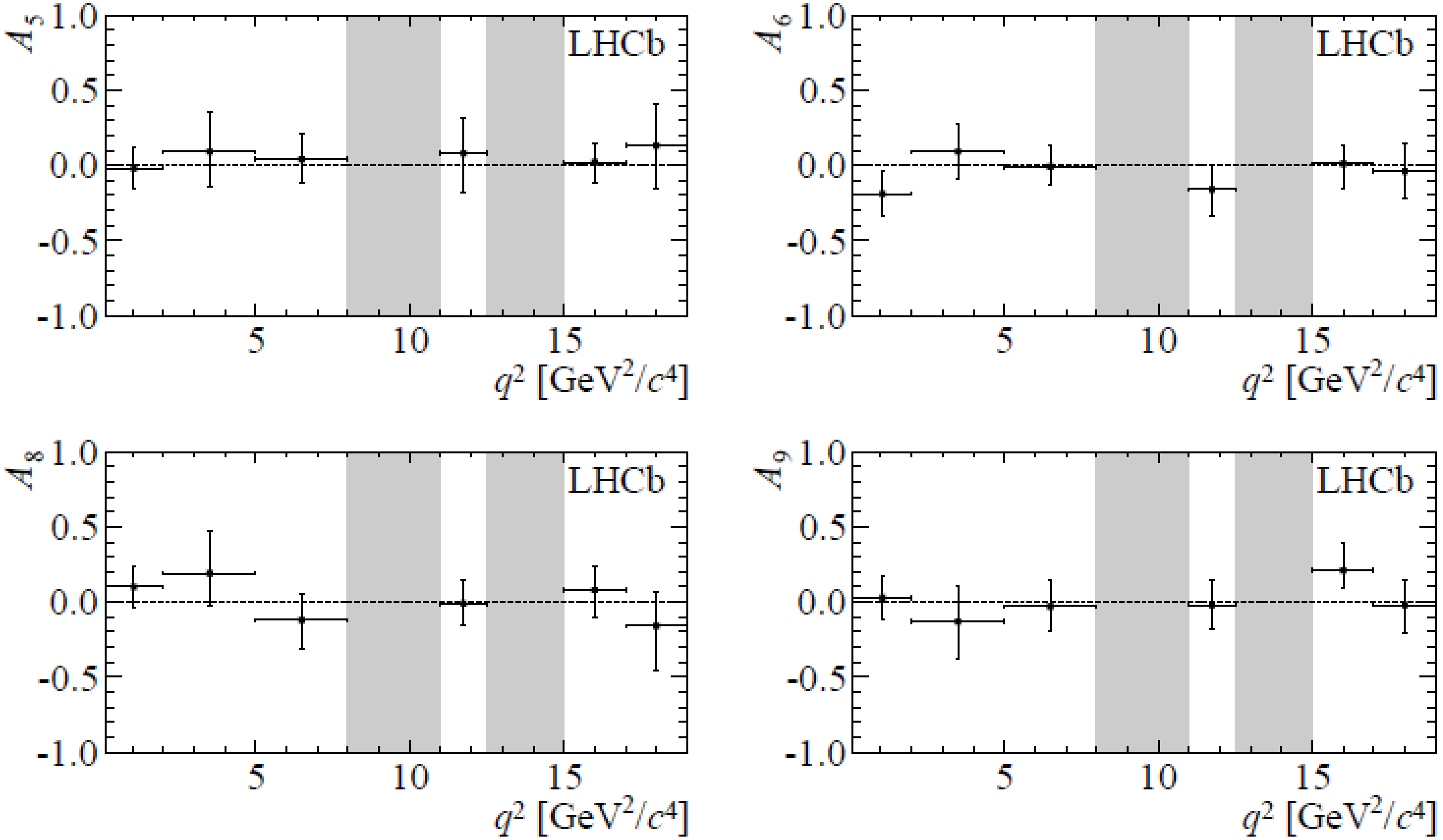


$B_s \rightarrow \phi\mu^+\mu^-$



All angular observables consistent with SM predictions

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

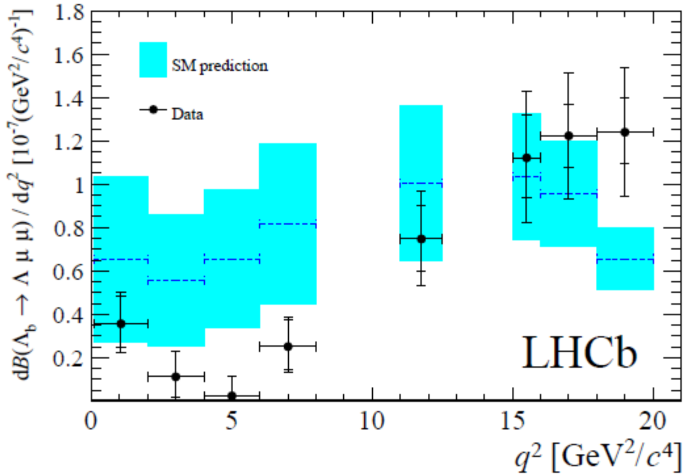


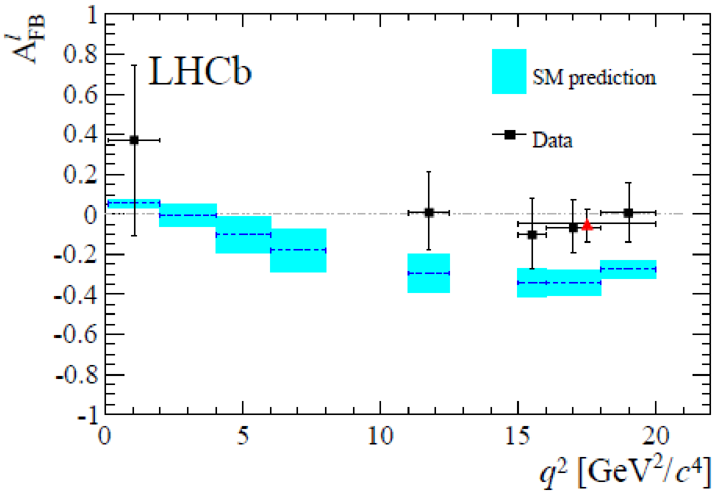
All angular observables consistent with SM predictions

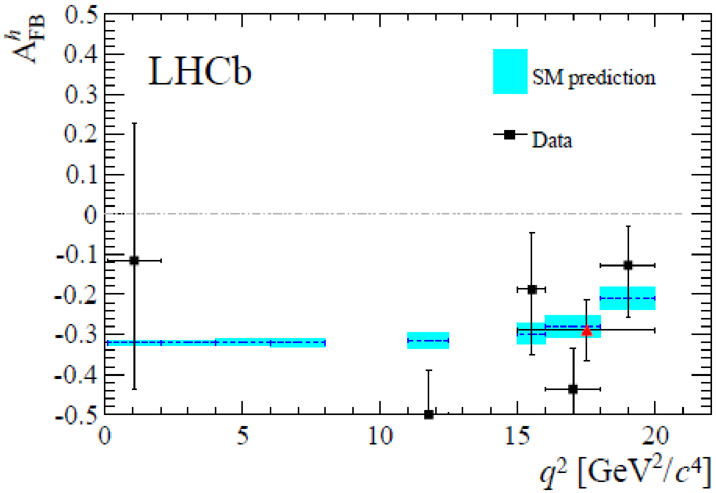
$\Lambda_b \to \Lambda \mu^+\mu^-$

JHEP 06 (2015) 115

- Baryonic system provides sensitivity to additional observables
- Measurement of the BR in 8 q^2 bins
- Rate still too low to perform a full angular analysis but forward-backward asymmetries are measured fitting one dimensional angular distributions





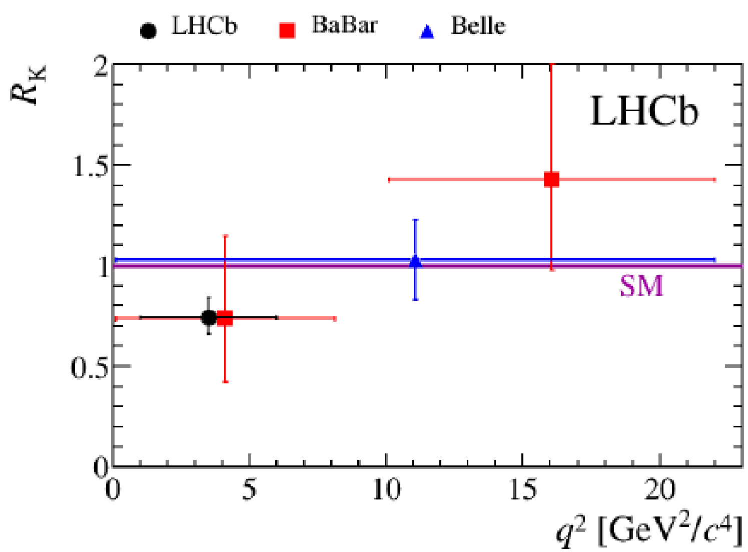


Similar tension with SM prediction for branching fraction at low q^2

Test of lepton universality: R_K

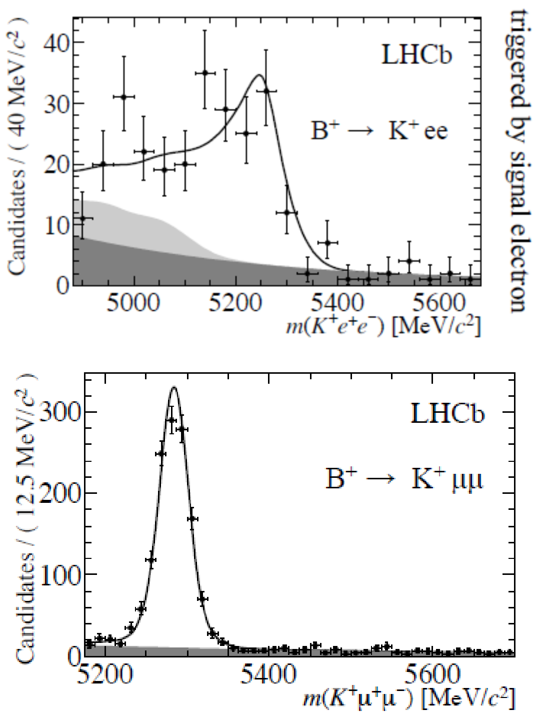
$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$$

- In SM R_K is predicted to be 1
- LHCb measurement in $1<q^2< 6.0\ \mathrm{GeV}^2/c^4$



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

PRL 113 (2014) 151601



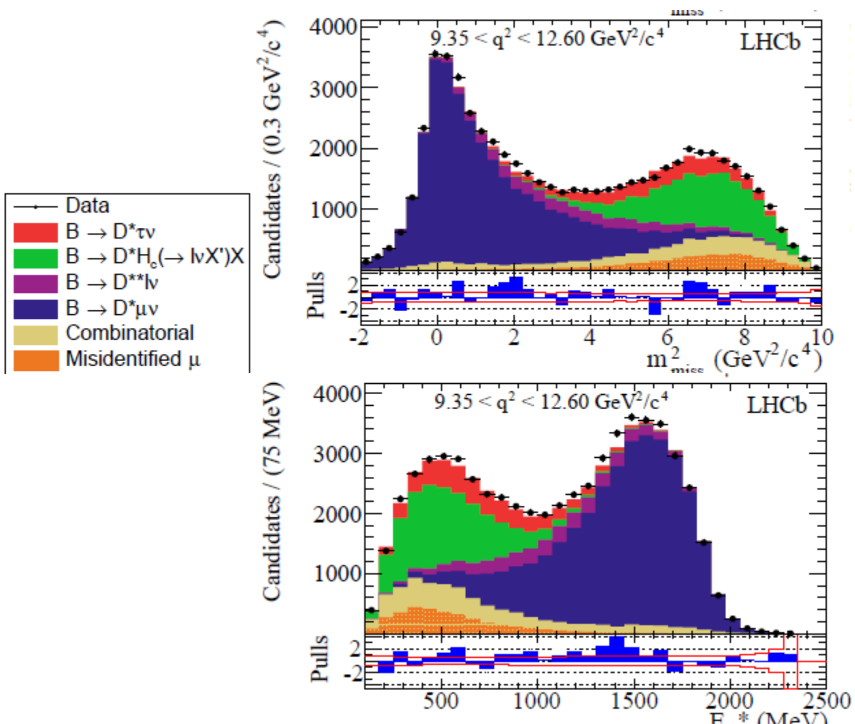
- 2.6 σ from SM
- electron mode is in agreement with SM ⇒ deficit of muon mode again

Test of lepton universality: R(D*)

$$R(D) = \frac{B(B^0 \to D^+\tau^-\nu)}{B(B^0 \to D^+\mu^-\nu)} \qquad R(D^*) = \frac{B(B^0 \to D^{*+}\tau^-\nu)}{B(B^0 \to D^{*+}\mu^-\nu)}$$

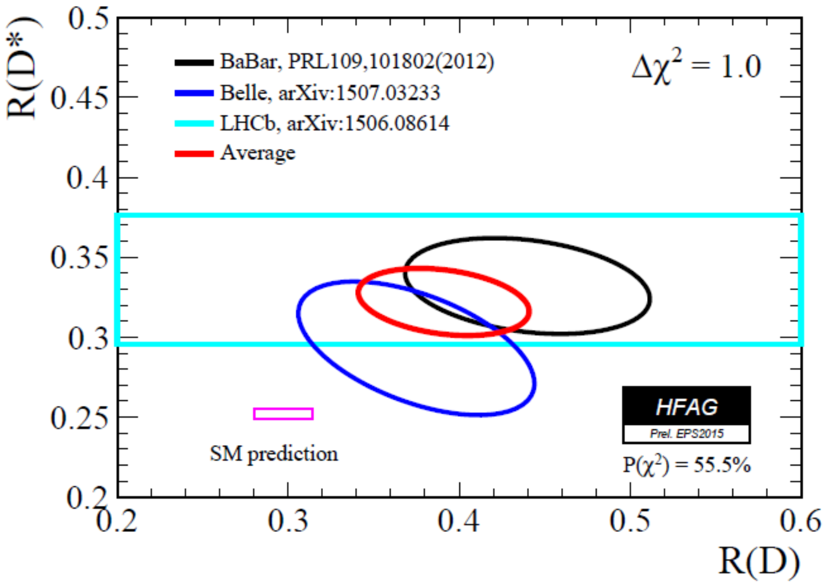
- Some tension found in the past by Babar and Belle
- LHCb perform the first measurement of R(D*) at a hadronic collider, using $\tau \to \mu\nu\nu$
- Separate signal from background fitting M_{miss}^2, q^2, and E_μ

arXiv:1506.08614



R(D*) measured value is 2.1 σ higher than SM prediction, confirming the tension.

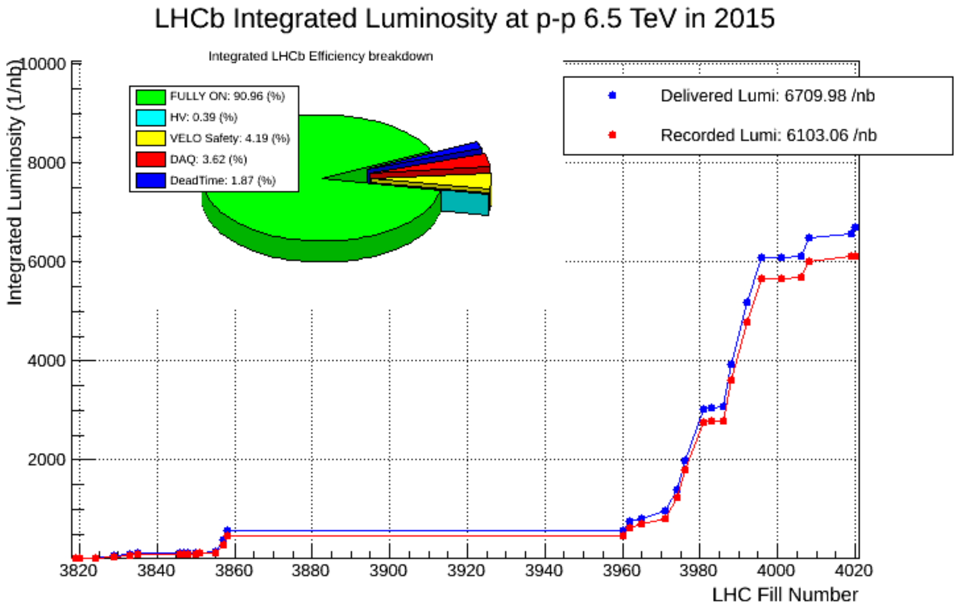
Average is 3.9σ away from SM



Summary

- LHCb obtained a lot of interesting results from Run 1 data
  - Mainly using muonic decays but electrons and taus are coming!
  - Not shown here: LFV $\tau \to \mu\mu\mu$, radiative $B \to X_s \gamma$, LNV $B^- \to \pi^+ \mu^- \mu^-$ …
- Rare decays show several hints of beyond SM effects:
  - global analysis shows that a lower value of C_9 is prefered over SM at 3.7 σ
  - P_5' in $B_d \to K^{*0} \mu^+ \mu^-$
  - $B_s \to \phi \mu^+ \mu^-$
  - $\Lambda_b \to \Lambda \mu^+ \mu^-$
  - R_K , R(D*)

Run 2 data will help understanding them!



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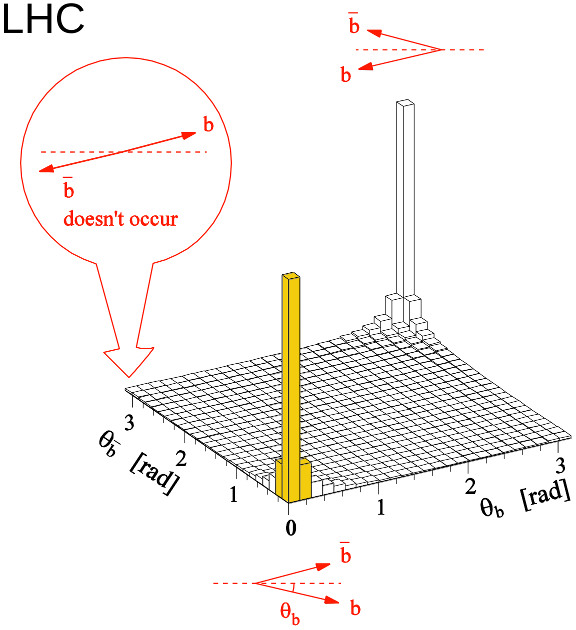
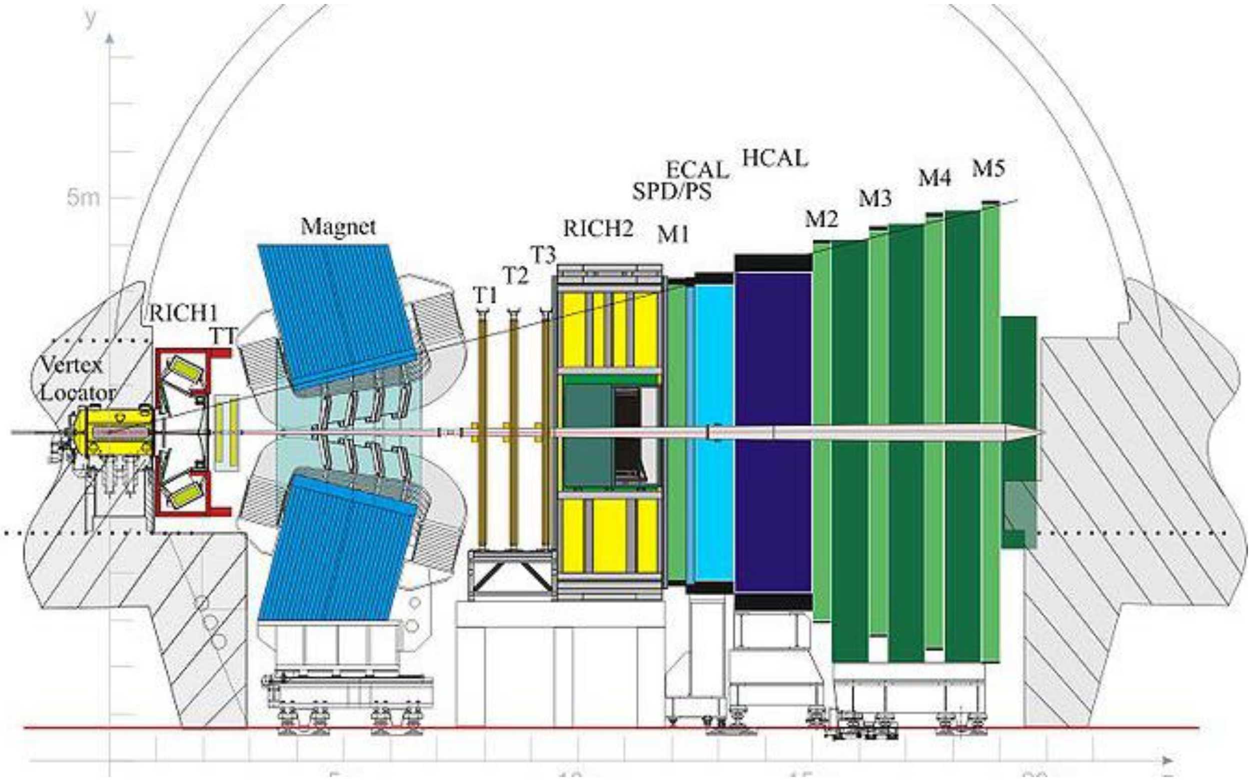
LHCb

- Forward spectrometer optimised for heavy flavour physics at the LHC
  - Large acceptance 2<η<5
  - Low trigger thresholds
  - Precise vertexing
  - Efficient particle identification
  - Large boost (B mesons flight ~1cm)





Integrated luminosity:
1 fb^{-1} @ 7TeV (2011)
2 fb^{-1} @ 8TeV (2012)

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

- Differential decay rate:

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_{j(s,c)} I_{j(s,c)}(q^2) f_j(\vec{\Omega}) \quad \text{and}$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_{j(s,c)} \bar{I}_{j(s,c)}(q^2) f_j(\vec{\Omega}) \quad ,$$

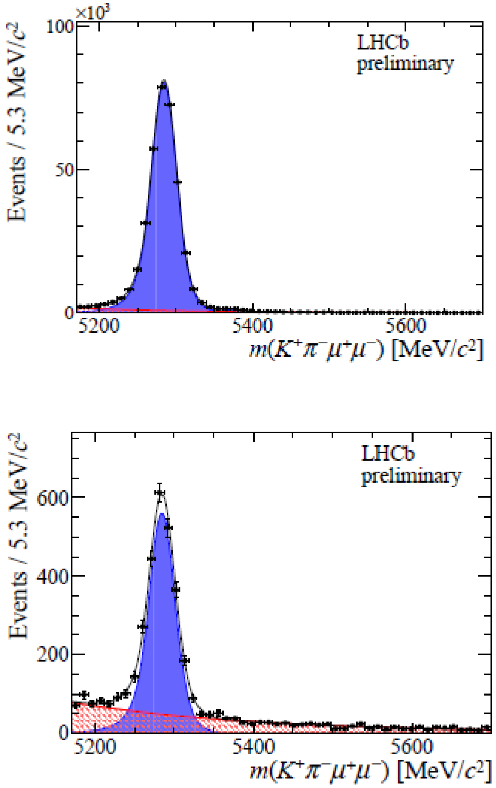
- CP average observables:

$$S_j = \left(I_{j(s,c)} + \bar{I}_{j(s,c)}\right) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

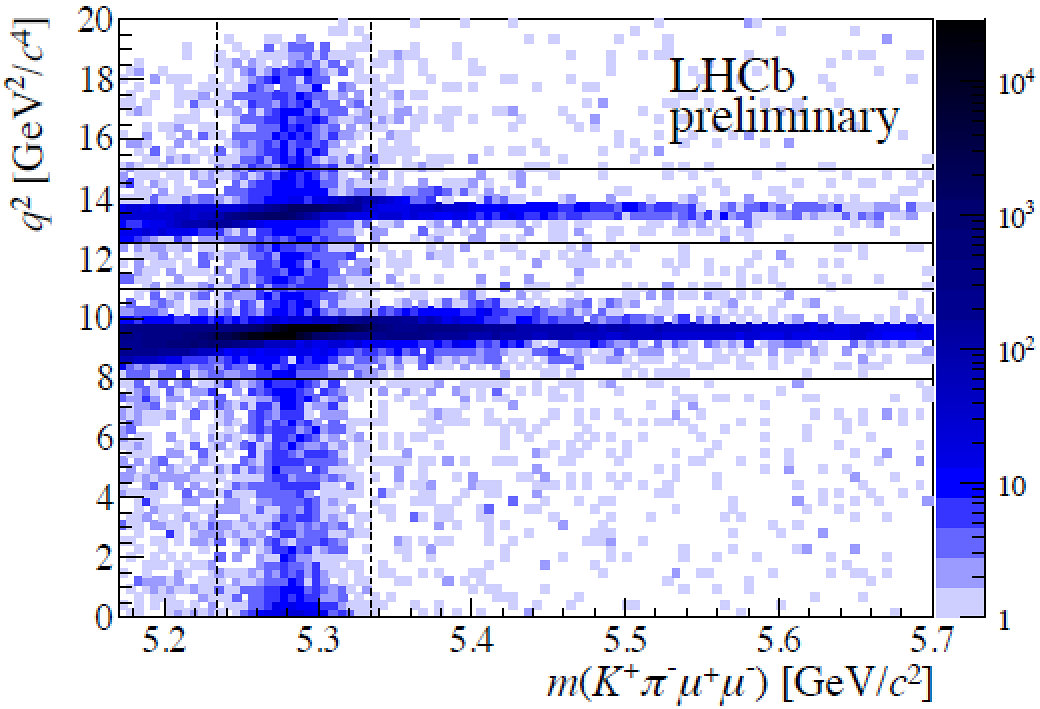
- S wave:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = (1-F_\mathrm{S})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} + \frac{3}{16\pi}F_\mathrm{S}\sin^2\theta_\ell + \text{S-P interference}$$

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



LHCb
preliminary
Events / 5.3 MeV/c²
m(K⁺π⁻μ⁺μ⁻) [MeV/c²]

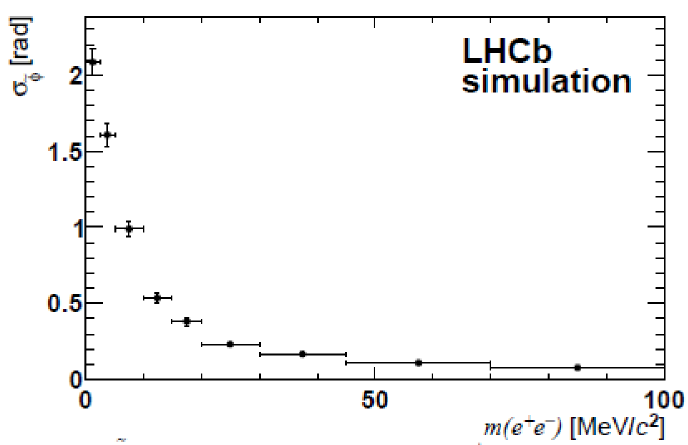


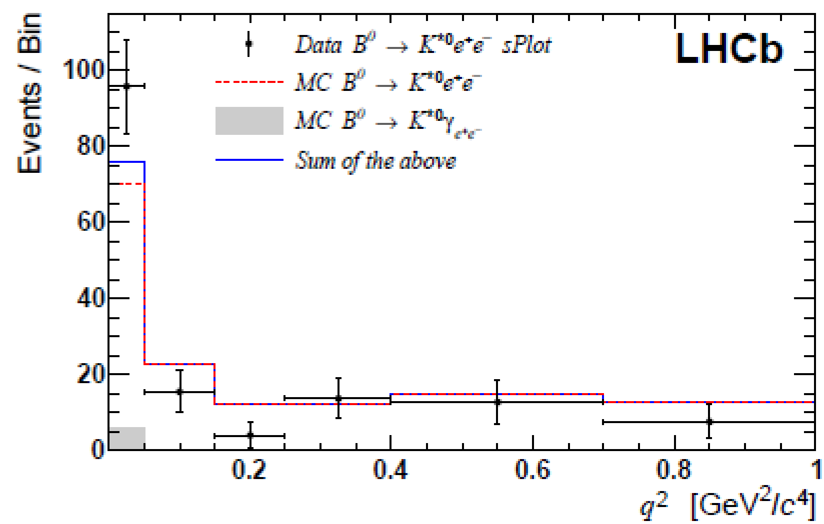
LHCb
preliminary
q² [GeV²/c⁴]
m(K⁺π⁻μ⁺μ⁻) [GeV/c²]

Simplify the decay rate expression folding phi angle : $\tilde{\phi} = \phi + \pi$ if $\phi < 0$,

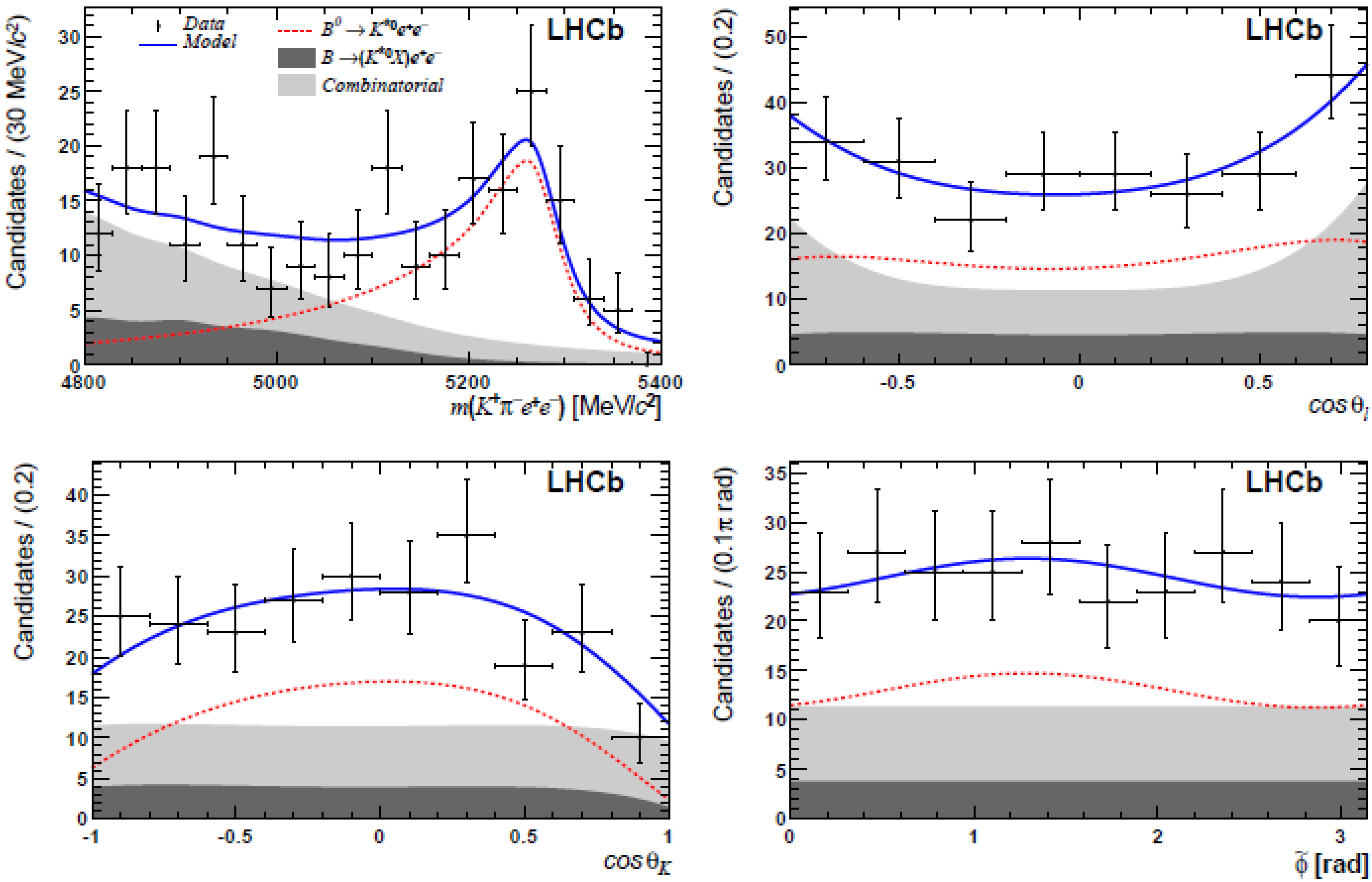
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Bigg[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \left(\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K - F_\mathrm{L}\cos^2\theta_K\right)\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + (1-F_\mathrm{L})A_\mathrm{T}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{\mathrm{Im}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Bigg].$$

Remove low q2 events because of poor phi resolution due to multipole scattering





$B_d \to K^{*0} e^+ e^-$

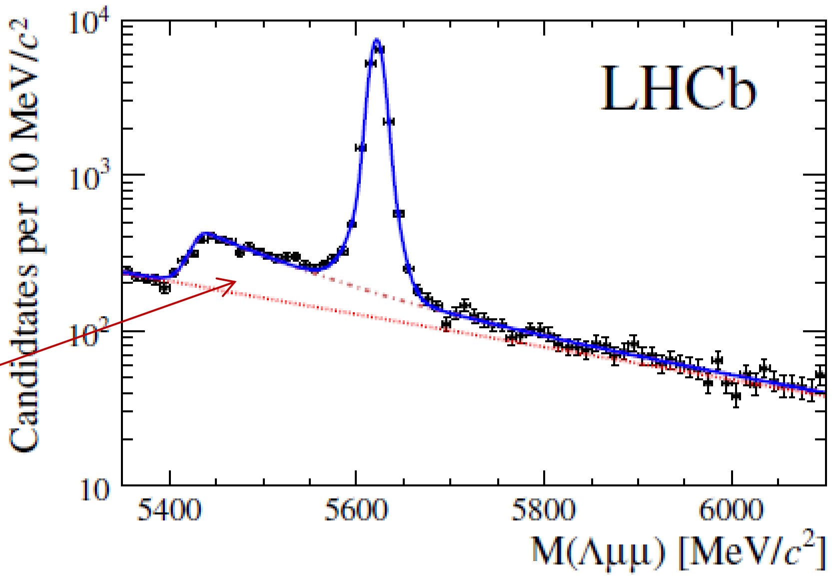


LHCb
Data
Model
$B^0 \to K^{*0}e^+e^-$
$B \to (K^{*0}X)e^+e^-$
Combinatorial
Candidates / (30 MeV/c^2)
$m(K^+\pi^-e^+e^-)$ [MeV/c^2]
Candidates / (0.2)
$\cos\theta_l$
$\cos\theta_K$
Candidates / (0.1π rad)
$\tilde{\phi}$ [rad]

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

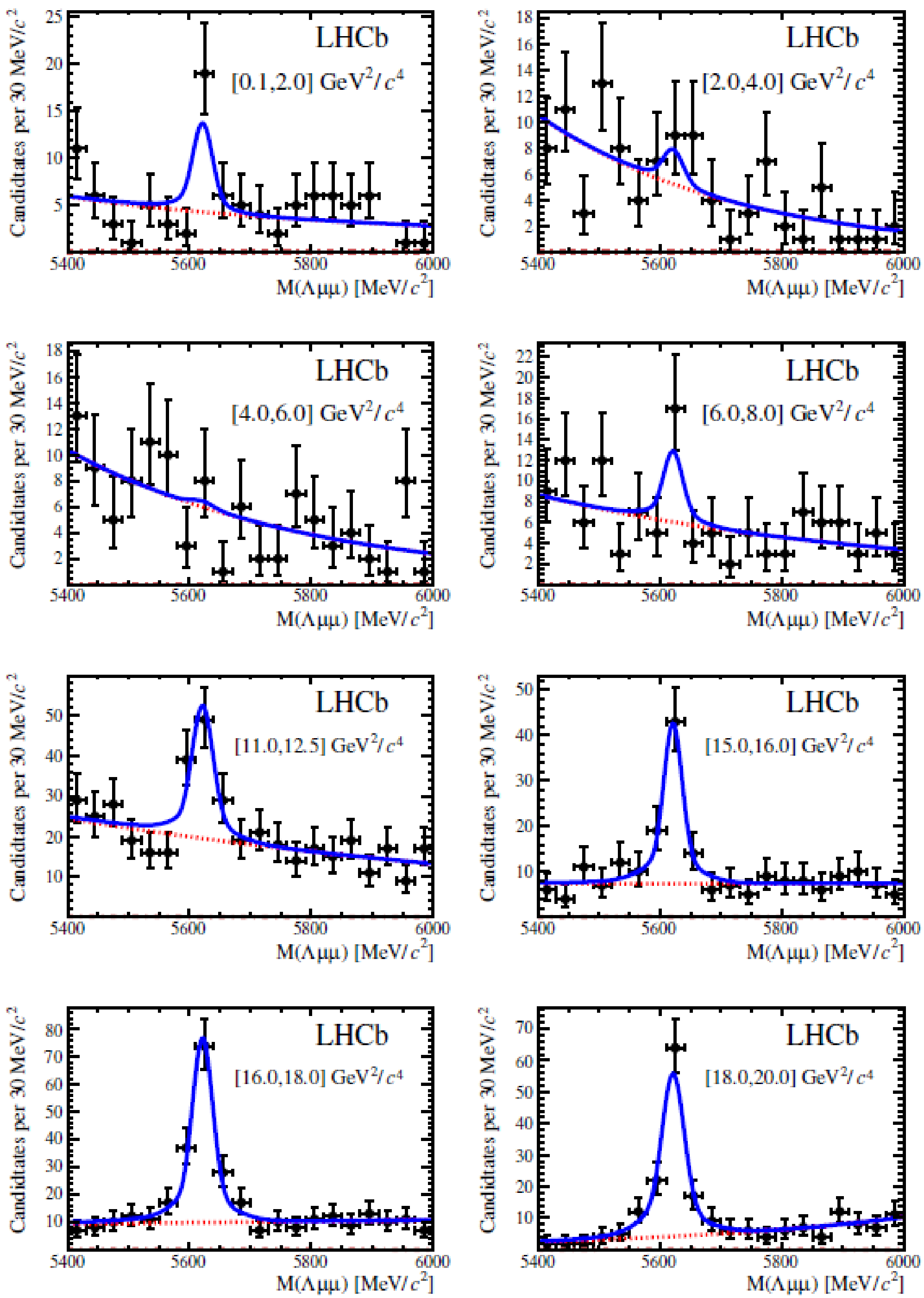
Normalization channel: $\Lambda_b \to J/\Psi\Lambda$

Peaking background $\Lambda_b \to J/\Psi K_s$



Signal yield $\Lambda_b \to \Lambda\, \mu^+\mu^-$

q^2 interval [GeV$^2/c^4$]	Total signal yield	Significance
0.1–2.0	16.0 ± 5.3	4.4
2.0–4.0	4.8 ± 4.7	1.2
4.0–6.0	0.9 ± 2.3	0.5
6.0–8.0	11.4 ± 5.3	2.7
11.0–12.5	60 ± 12	6.5
15.0–16.0	57 ± 9	8.7
16.0–18.0	118 ± 13	13
18.0–20.0	100 ± 11	14
1.1–6.0	9.4 ± 6.3	1.7
15.0–20.0	276 ± 20	21


LHCb
[0.1,2.0] GeV²/c⁴
[2.0,4.0] GeV²/c⁴
[4.0,6.0] GeV²/c⁴
[6.0,8.0] GeV²/c⁴
[11.0,12.5] GeV²/c⁴
[15.0,16.0] GeV²/c⁴
[16.0,18.0] GeV²/c⁴
[18.0,20.0] GeV²/c⁴
Candidates per 30 MeV/c²
M(Λμμ) [MeV/c²]