

# Recent results from LHCb

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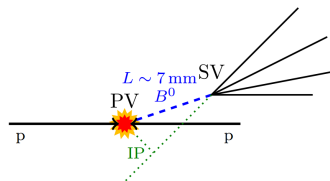
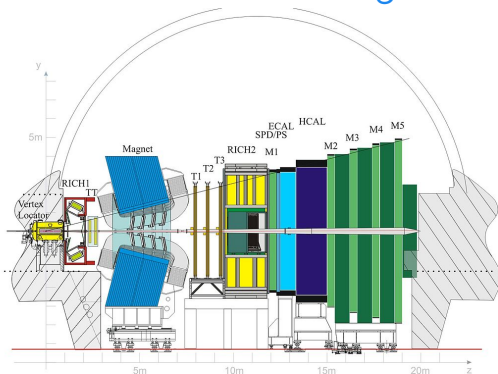


Barcelona,  
April 18, 2016

# Outline

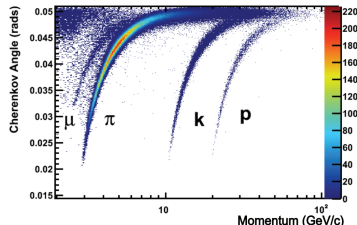
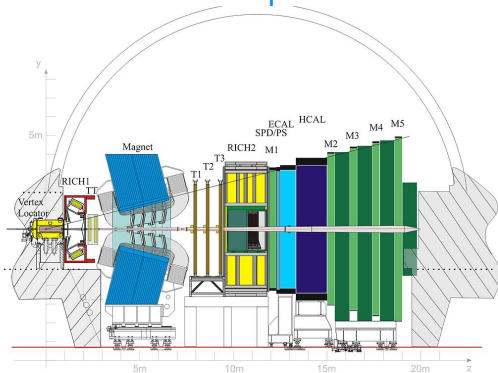
1. LHCb detector.
2. Angular analysis of  $B_d^0 \rightarrow K^* \mu\mu$ .
3. Other LHCb EWP measurements.
4. Glimpse into the future.

# LHCb detector - tracking



- Excellent Impact Parameter (IP) resolution ( $20 \mu\text{m}$ ).  
⇒ Identify secondary vertices from heavy flavour decays
- Proper time resolution  $\sim 40 \text{ fs}$ .  
⇒ Good separation of primary and secondary vertices.
- Excellent momentum ( $\delta p/p \sim 0.4 - 0.6\%$ ) and inv. mass resolution.  
⇒ Low combinatorial background.

# LHCb detector - particle identification



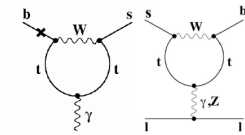
- Excellent Muon identification  $\epsilon_{\mu \rightarrow \mu} \sim 97\%$ ,  $\epsilon_{\pi \rightarrow \mu} \sim 1 - 3\%$
- Good  $K - \pi$  separation via RICH detectors,  $\epsilon_{K \rightarrow K} \sim 95\%$ ,  
 $\epsilon_{\pi \rightarrow K} \sim 5\%$ .  
⇒ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds. Muons:  
 $p_T > 1.76 \text{ GeV}$  at L0,  $p_T > 1.0 \text{ GeV}$  at HLT1,  
 $B \rightarrow J/\psi X$ : Trigger  $\sim 90\%$  efficient.

# Analysis of Rare decays

Analysis of FCNC in a model-independent approach, effective Hamiltonian:

$$b \rightarrow s\gamma(*) : \mathcal{H}_{\Delta F=1}^{\text{SM}} \propto \sum_{i=1}^{10} V_{ts}^* V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) (\bar{\ell}\gamma_\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) (\bar{\ell}\gamma_\mu \gamma_5 \ell), \dots$



- **SM** Wilson coefficients up to NNLO + e.m. corrections at  $\mu_{ref} = 4.8$  GeV [Misiak et al.]:

$$\mathcal{C}_7^{\text{SM}} = -0.29, \mathcal{C}_9^{\text{SM}} = 4.1, \mathcal{C}_{10}^{\text{SM}} = -4.3$$

- **NP** changes short distance  $\mathcal{C}_i - \mathcal{C}_i^{\text{SM}} = \mathcal{C}_i^{\text{NP}}$  and induce new operators, like

$\mathcal{O}'_{7,9,10} = \mathcal{O}_{7,9,10} (P_L \leftrightarrow P_R) \dots$  also scalars, pseudo-scalar, tensor operators...

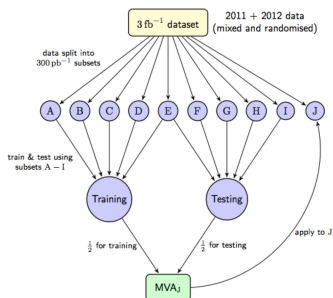
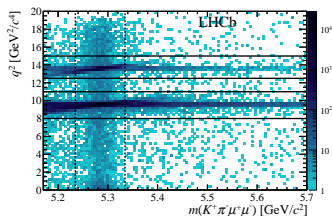
# Analysis of Rare decays



# LHCb measurement of $B_d^0 \rightarrow K^* \mu \mu$

# Multivariate selection

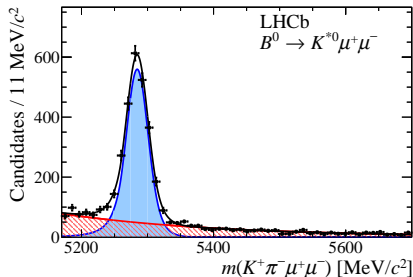
- JHEP 1602 (2016) 104
- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to reject background.
- Reject the regions of  $J/\psi$  and  $\psi(2S)$ .
- Specific vetos for backgrounds:  $\Lambda_b \rightarrow pK\mu\mu$ ,  $B_s^0 \rightarrow \phi\mu\mu$ , etc.
- Using k-Fold technique and signal proxy  $B \rightarrow J/\psi K^*$  for training the BDT.
- Improved selection allowed for finer binning than the  $1\text{fb}^{-1}$  analysis.





# Mass modelling

- ⇒ The signal is modelled by a sum of two Crystal-Ball functions with common mean.
- ⇒ The background is a single exponential.
- ⇒ The base parameters are obtained from the proxy channel:  $B_d^0 \rightarrow J/\psi(\mu\mu)K^*$ .
- ⇒ All the parameters are fixed in the signal pdf.
- ⇒ Scaling factors for resolution are determined from MC.
- ⇒ In fitting the rare mode only the signal, background yield and the slope of the exponential is left floating.
- ⇒ We found  $624 \pm 30$  candidates in the most interesting  $[1.1, 6.0] \text{ GeV}^2/c^4$  region and  $2398 \pm 57$  in the full range  $[1.1, 19.] \text{ GeV}^2/c^4$ .



⇒ The S-wave fraction is extracted using LASS model.

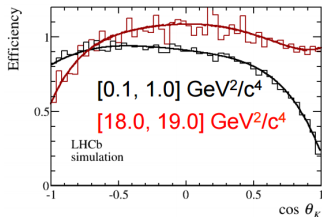
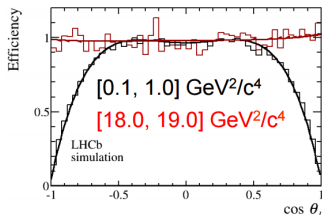
# Detector acceptance

- Detector distorts our angular distribution.
- We need to model this effect.
- 4D function is used:

$$\epsilon(\cos \theta_l, \cos \theta_k, \phi, q^2) = \sum_{ijkl} P_i(\cos \theta_l) P_j(\cos \theta_k) P_k(\phi) P_l(q^2),$$

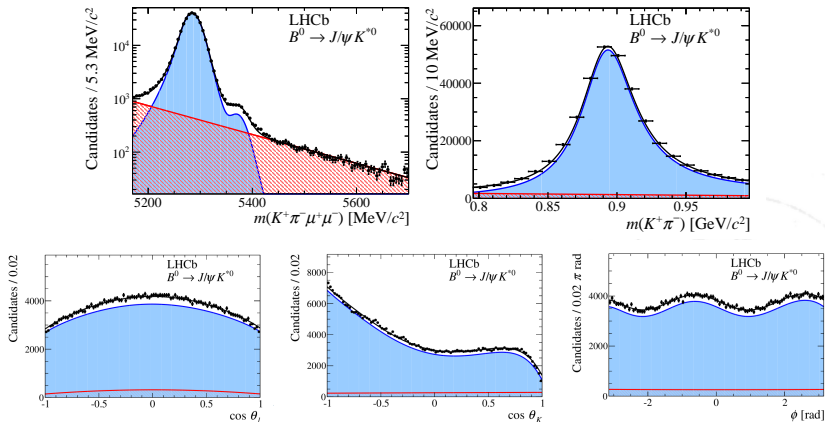
where  $P_i$  is the Legendre polynomial of order  $i$ .

- We use up to 4<sup>th</sup>, 5<sup>th</sup>, 6<sup>th</sup>, 5<sup>th</sup> order for the  $\cos \theta_l, \cos \theta_k, \phi, q^2$ .
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space and reweighing the  $q^2$  distribution to make it flat.



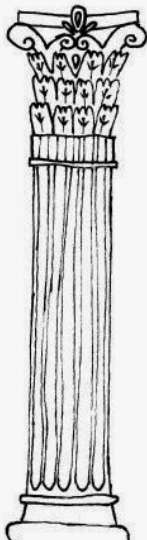
# Control channel

- We tested our unfolding procedure on  $B \rightarrow J/\psi K^*$ .
- The result is in perfect agreement with other experiments and our different analysis of this decay.

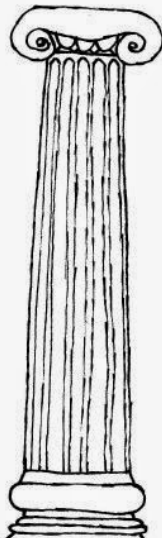


# The columns of New Physics

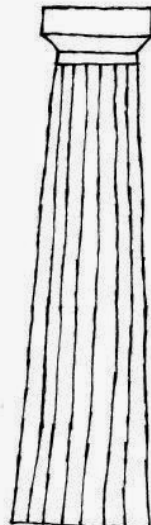
Amplitudes



Maximum likelihood fit



Method of Moments



# The columns of New Physics

## 1. Maximum likelihood fit:

- The most standard way of obtaining the parameters.
- Can have problem with low statistics.

## 2. Method of moments:

- Less precise than the likelihood estimator (10 – 15% larger uncertainties).
- Does not suffer from the problems of likelihood fit.

## 3. Amplitude fit:

- Incorporates all the physical symmetries inside the amplitudes! The most precise estimator.
- Has theoretical assumptions inside!

# Maximum likelihood fit - Results

⇒ In the maximum likelihood fit one could weight the events accordingly to the  $\frac{1}{\epsilon(\cos \theta_l, \cos \theta_k, \phi, q^2)}$

⇒ Better alternative is to put the efficiency into the maximum likelihood fit itself:

$$\mathcal{L} = \prod_{i=1}^N \epsilon_i(\Omega_i, q_i^2) \mathcal{P}(\Omega_i, q_i^2) / \int \epsilon(\Omega, q^2) \mathcal{P}(\Omega, q^2) d\Omega dq^2$$

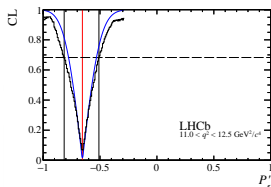
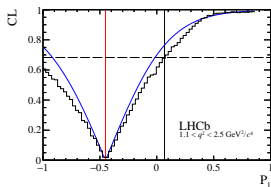
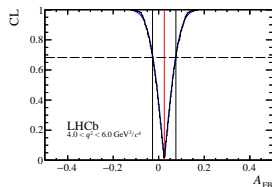
⇒ Only the relative weights matters!

⇒ The Procedure was commissioned with TOY MC study.

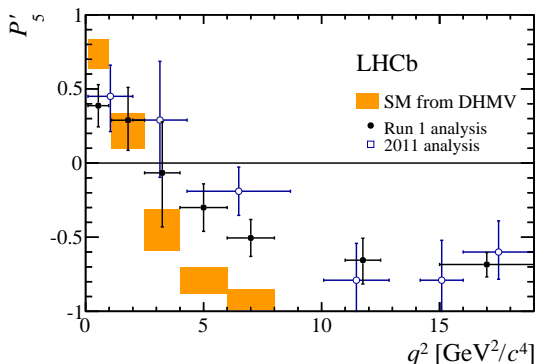
⇒ Use Feldmann-Cousins to determine the uncertainties.

⇒ Angular background component is modelled with 2<sup>nd</sup> order Chebyshev polynomials, which was tested on the side-bands.

⇒ S-wave component treated as nuisance parameter.

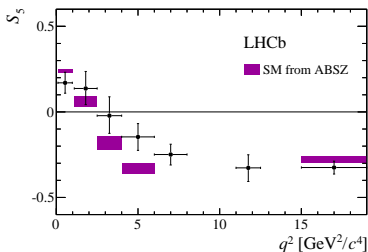
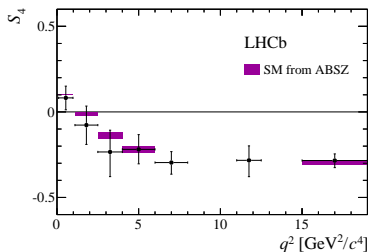
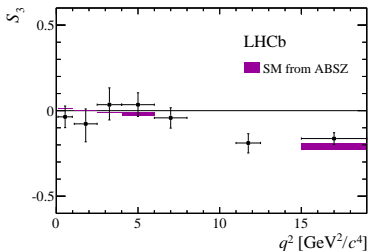
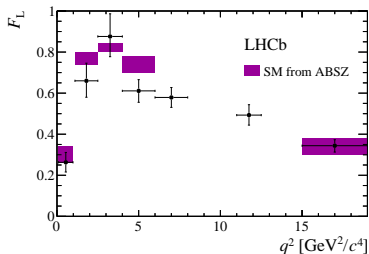


# Maximum likelihood fit - Results



- Tension with  $3 \text{ fb}^{-1}$  gets confirmed!
- two bins both deviate by  $2.8 \sigma$  from SM prediction.
- Result compatible with previous result; [Phys.Rev.Lett. 111 \(2013\) 191801](#)
- SM: [JHEP12\(2014\)125](#)

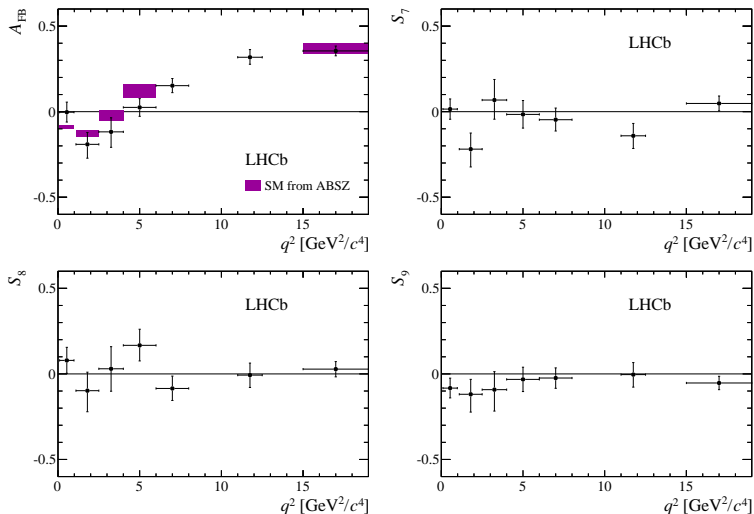
# Maximum likelihood fit - Results



⇒ SM: [Eur.Phys.J. C75 \(2015\) no.8, 382](#)



# Maximum likelihood fit - Results



⇒ SM: [Eur.Phys.J. C75 \(2015\) no.8, 382](#)

# Method of moments

⇒ See [Phys.Rev.D91\(2015\)114012](#), F.Beaujean , M.Chrzaszcz, N.Serra, D. van Dyk for details.

⇒ The idea behind Method of Moments is simple: Use orthogonality of spherical harmonics,  $f_j(\vec{\Omega})$  to solve for coefficients within a  $q^2$  bin:

$$\int f_i(\vec{\Omega}) f_j(\vec{\Omega}) = \delta_{ij}$$

$$M_i = \int \left( \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \right) \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} f_i(\vec{\Omega}) d\Omega$$

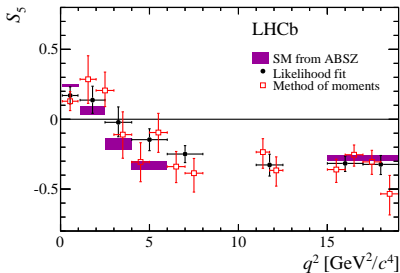
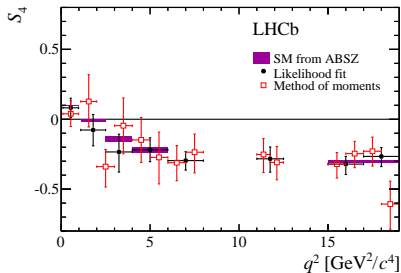
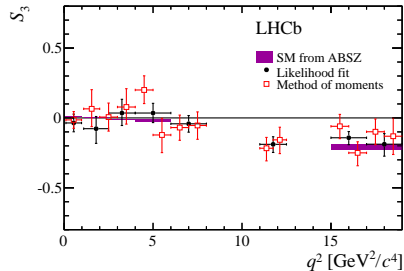
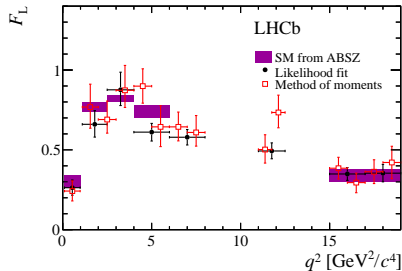
⇒ Don't have true angular distribution but we "sample" it with our data.

⇒ Therefore:  $\int \rightarrow \sum$  and  $M_i \rightarrow \hat{M}_i$

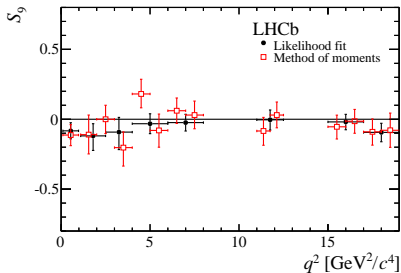
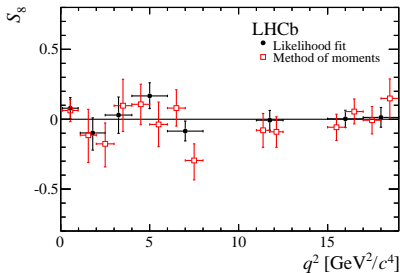
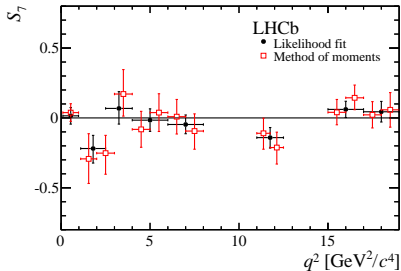
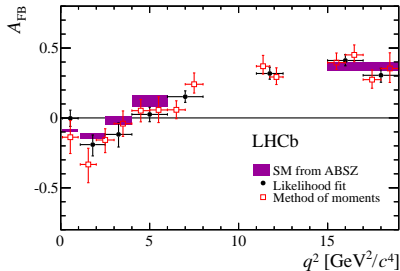
$$\hat{M}_i = \frac{1}{\sum_e \omega_e} \sum_e \omega_e f_i(\vec{\Omega}_e)$$

⇒ The weight  $\omega$  accounts for the efficiency. Again the normalization of weights does not matter.

# Method of moments - results

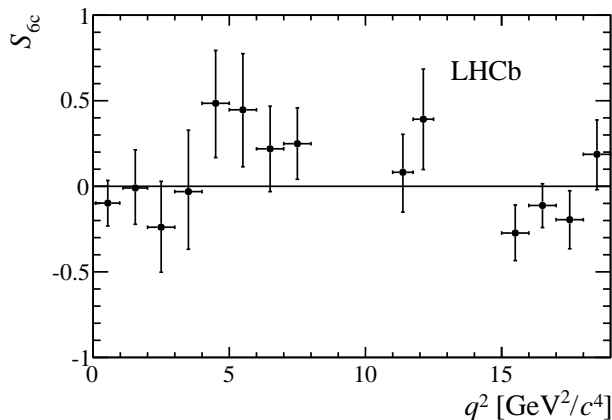


# Method of moments - results



# Method of moments - results

⇒ Method of Moments allowed us to measure for the first time a new observable:



⇒ LHCb also measured the CP asymmetries with Method of Moments and the likelihood fit that are consistent with SM

# Amplitudes method

⇒ Fit for amplitudes as (continuous) functions of  $q^2$  in the region:  $q^2 \in [1.1.6.0] \text{ GeV}^2/c^4$ .

⇒ Needs some Ansatz:

$$A(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$$

⇒ The assumption is tested extensively with toys.

⇒ Set of 3 complex parameters  $\alpha, \beta, \gamma$  per vector amplitude:

- $L, R, 0, \parallel, \perp, \Re, \Im \rightarrow 3 \times 2 \times 3 \times 2 = 36$  DoF.
- Scalar amplitudes: +4 DoF.
- Symmetries of the amplitudes reduces the total budget to: 28.

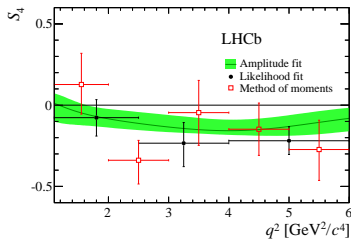
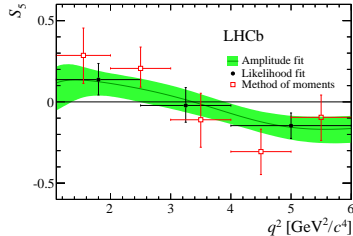
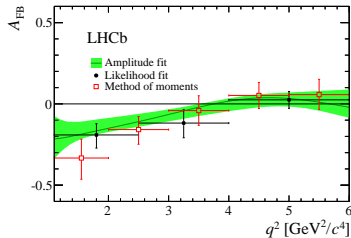
⇒ The technique is described in [JHEP06\(2015\)084](#), U. Egede, M. Patel, K.A. Petridis.

⇒ Allows to build the observables as continuous functions of  $q^2$ :

- At current point the method is limited by statistics.
- In the future the power of this method will increase.

⇒ Allows to measure the zero-crossing points for free and with smaller errors than previous methods.

# Amplitudes - results



Zero crossing points:

$$q_0(S_4) < 2.65 \quad \text{at } 95\% \text{ CL}$$

$$q_0(S_5) \in [2.49, 3.95] \quad \text{at } 68\% \text{ CL}$$

$$q_0(A_{FB}) \in [3.40, 4.87] \quad \text{at } 68\% \text{ CL}$$

# Compatibility with SM

⇒ Use EOS software package to test compatibility with SM.

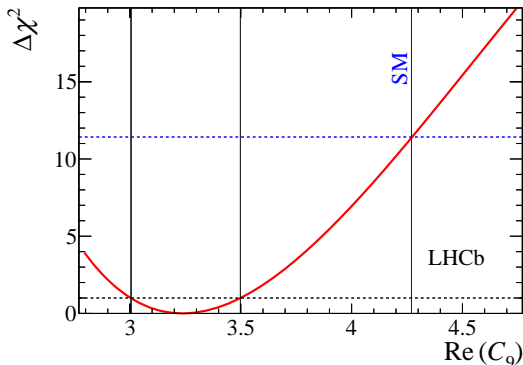
⇒ Perform the  $\chi^2$  fit to the measured:

$$F_L, A_{FB}, S_{3,\dots,9}.$$

⇒ Float a vector coupling:  $\Re(C_9)$ .

⇒ Best fit is found to be  $3.4 \sigma$  away from the SM.

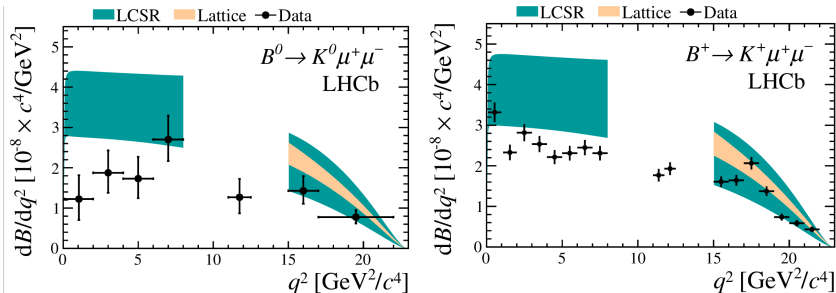
$$\Delta\mathcal{R}(C_9) \equiv \mathcal{R}(C_9)^{\text{fit}} - \mathcal{R}(C_9)^{\text{SM}} = -1.03$$



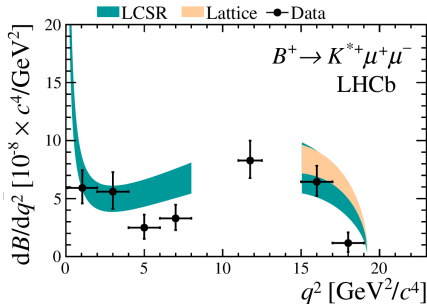


# Other related LHCb measurements.

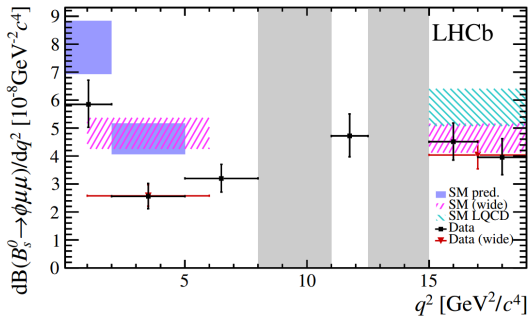
# Branching fraction measurements of $B \rightarrow K^{*\pm} \mu\mu$



- Despite large theoretical errors the results are consistently smaller than SM prediction.
- [JHEP 07 \(2012\) 133](#)

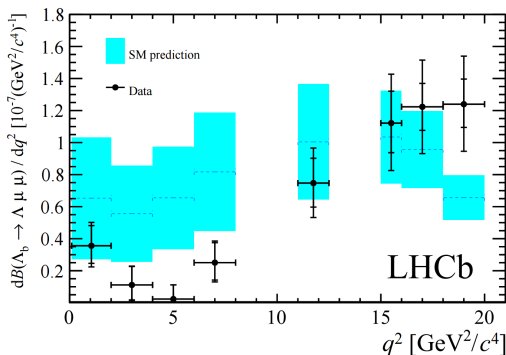


# Branching fraction measurements of $B_s^0 \rightarrow \phi\mu\mu$



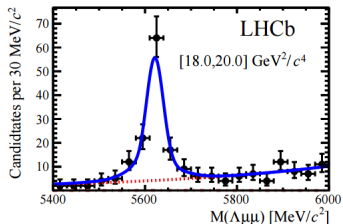
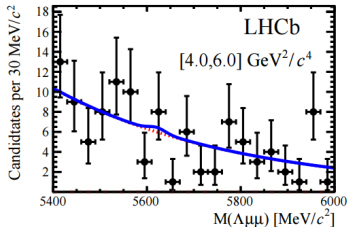
- Recent LHCb measurement [JHEP09 \(2015\) 179](#).
- Suppressed by  $\frac{f_s}{f_d}$ .
- Cleaner because of narrow  $\phi$  resonance.
- $3.3 \sigma$  deviation in SM in the  $1 - 6 \text{ GeV}^2$  bin.

# Branching fraction measurements of $\Lambda_b \rightarrow \Lambda \mu \mu$



- Last years LHCb measurement [[JHEP 06 \(2015\) 115](#)].
- In total  $\sim 300$  candidates in data set.
- Decay not present in the low  $q^2$ .

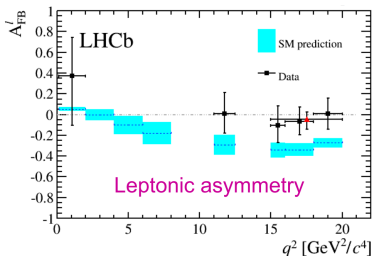
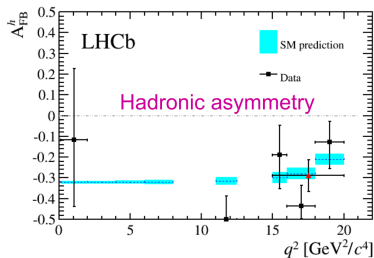
# Branching fraction measurements of $\Lambda_b \rightarrow \Lambda \mu \mu$



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# Angular analysis of $\Lambda_b \rightarrow \Lambda \mu \mu$

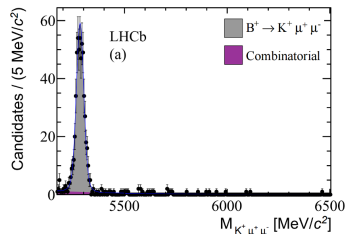
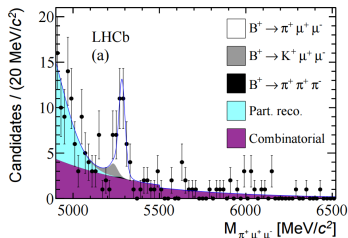
- For the bins in which we have  $> 3 \sigma$  significance the forward backward asymmetry for the hadronic and leptonic system.



- $A_{FB}^H$  is in good agreement with SM.
- $A_{FB}^\ell$  always in above SM prediction.

# First observation of $B_d^0 \rightarrow \pi\mu\mu$

- LHCb for the first time observed a CKM suppressed decay of  $B \rightarrow \pi^\pm \mu\mu$
- We observed  $25 \pm 6$  events in  $1 \text{ fb}^{-1}$  data set.
- Need to separate a large peaking component:  $B \rightarrow K^\pm \mu\mu$  from our signal window.
- In the future we can expect more aggressive physics program with this and similar channels  $\mapsto$  see Kostas talk!



# Lepton universality test

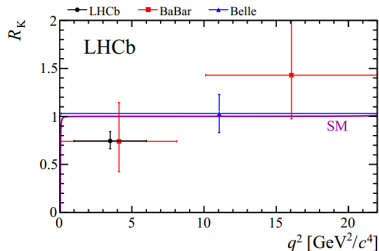
- Does the NP couple equally to all flavours?

$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}) .$$

- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct for bremsstrahlung.
- Take double ratio with  $B^+ \rightarrow J/\psi K^+$  to cancel systematics.

- In  $3\text{fb}^{-1}$ , LHCb measures  $R_K = 0.745_{-0.074}^{+0.090}(\text{stat.})_{-0.036}^{+0.036}(\text{syst.})$

- Consistent with SM at  $2.6\sigma$ .
- See more details in Rafaels and Martinos talks!

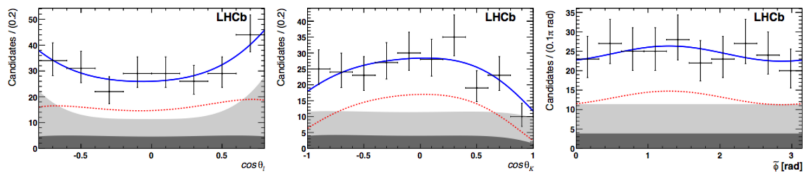


- Phys. Rev. Lett. 113, 151601 (2014)



# Angular analysis of $B^0 \rightarrow K^* e e$

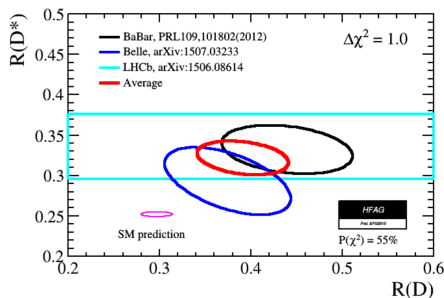
- With the full data set ( $3\text{fb}^{-1}$ ) we performed angular analysis in  $0.0004 < q^2 < 1 \text{ GeV}^2$ .
- [JHEP04\(2015\)064](#)



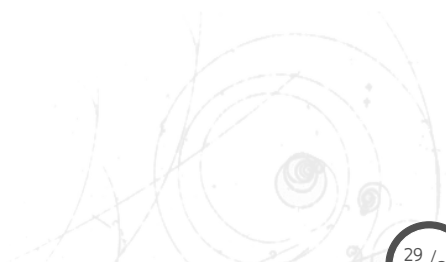
- Results in full agreement with the SM.
- Similar strength on  $C_7$  Wilson coefficient as from  $b \rightarrow s\gamma$  decays.

## There is more!

- There is one other LUV decay recently measured by LHCb.
- $R(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu)}{\mathcal{B}(B \rightarrow D^* \mu \nu)}$
- Clean SM prediction:  $R(D^*) = 0.252(3)$ , PRD 85 094025 (2012)
- LHCb result:  $R(D^*) = 0.336 \pm 0.027 \pm 0.030$ , HFAG average:  
 $R(D^*) = 0.322 \pm 0.022$
- $3.9 \sigma$  discrepancy wrt. SM.



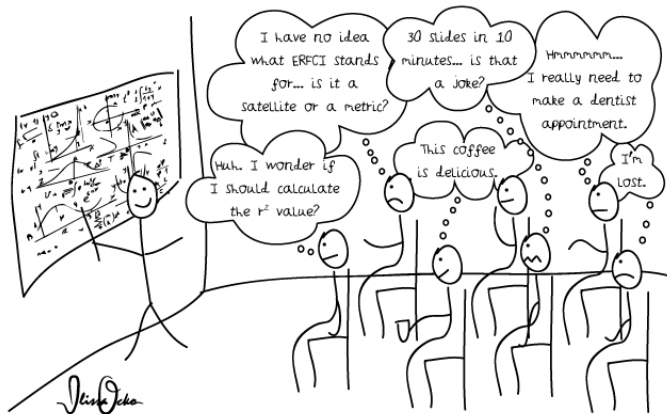
# Steps in the near future



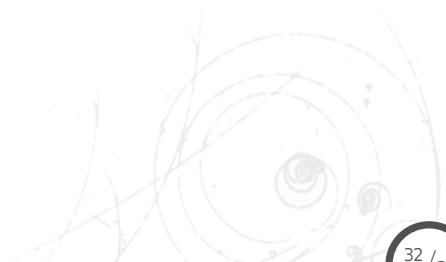
# Conclusions

- LHCb is and still will provide the most precise measurements of EWP!
- Many analysis in the pipe line!
- Even more ideas to what to do with existing and further data.

# Thank you for the attention!

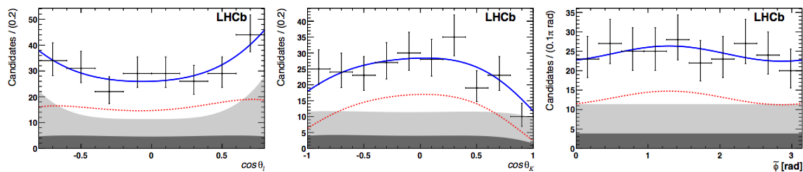


# Backup



# Angular analysis of $B^0 \rightarrow K^* e e$

- With the full data set ( $3\text{fb}^{-1}$ ) we performed angular analysis in  $0.0004 < q^2 < 1 \text{ GeV}^2$ .
- [JHEP04\(2015\)064](#)



- Results in full agreement with the SM.
- Similar strength on  $C_7$  Wilson coefficient as from  $b \rightarrow s\gamma$  decays.

## Angular analysis of $B^0 \rightarrow K^* e e$

- With the full data set ( $3\text{fb}^{-1}$ ) we performed angular analysis in  $0.0004 < q^2 < 1 \text{ GeV}^2$ .
- Electrons channels are extremely challenging experimentally:
  - Bremsstrahlung.
  - Trigger efficiencies.
- Determine the angular observables:  $F_L$ ,  $A_T^{(2)}$ ,  $A_T^{\text{Re}}$ ,  $A_T^{\text{Im}}$ :

$$F_L = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}$$

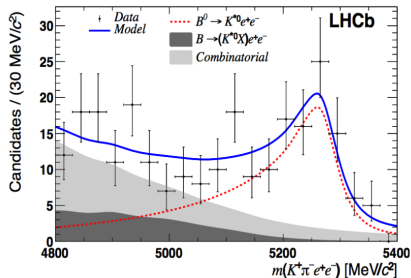
$$A_T^{(2)} = \frac{|A_{\perp}|^2 - |A_{||}|^2}{|A_{\perp}|^2 + |A_{||}|^2}$$

$$A_T^{\text{Re}} = \frac{2\mathcal{R}e(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2}$$

$$A_T^{\text{Im}} = \frac{2\mathcal{I}m(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2},$$



# Angular analysis of $B^0 \rightarrow K^* e e$



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