

# Recent results on angular analysis of decay $B \rightarrow K^* \mu\mu$ at LHCb

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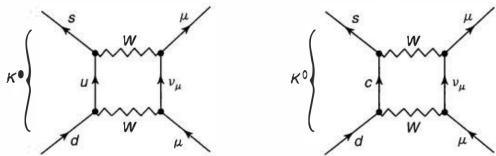
University of Padova  
March 22, 2016

# Outline

1. Why flavour is important.
2. LHCb detector.
3.  $b \rightarrow sll$  theory in a nutshell.
4. LHCb measurements of  $B_d^0 \rightarrow K^* \mu\mu$ 
  - Maximum likelihood fit.
  - Method of moments.
  - Amplitudes fit.
5. Other related LHCb measurements.
6. Global fit to  $b \rightarrow sll$  measurements.
7. Disclaimers about some theory predictions.
8. Conclusions.

# Why Flavour is important?

# A lesson from history - GIM mechanism



- Cabibbo angle was successful in explaining dozens of decay rates in the 1960s.
- There was, however, one that was not observed by experiments:  $K^0 \rightarrow \mu^- \mu^+$ .
- Glashow, Iliopoulos, Maiani (GIM) mechanism was proposed in the 1970 to fix this problem. The mechanism required the existence of the 4<sup>th</sup> quark.
- At that point most of the people were skeptical about that. Fortunately in 1974 the discovery of the  $J/\psi$  meson silenced the skeptics.

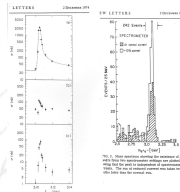
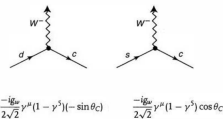
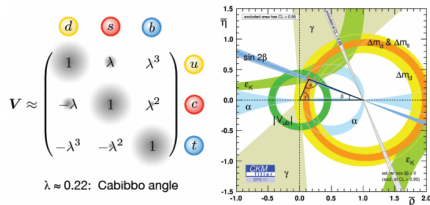
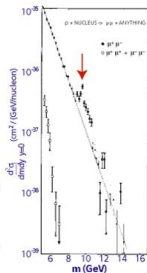


Fig. 1. Cross section versus energy for the reaction  $e^+e^- \rightarrow \text{hadrons}$ . The  $J/\psi$  peak is clearly visible at 3.1 GeV. The  $J/\psi$  peak is also visible in the cross section for  $e^+e^- \rightarrow J/\psi$ . The  $J/\psi$  peak is also visible in the cross section for  $e^+e^- \rightarrow J/\psi$ . The  $J/\psi$  peak is also visible in the cross section for  $e^+e^- \rightarrow J/\psi$ .

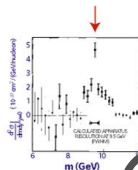
# A lesson from history - CKM matrix



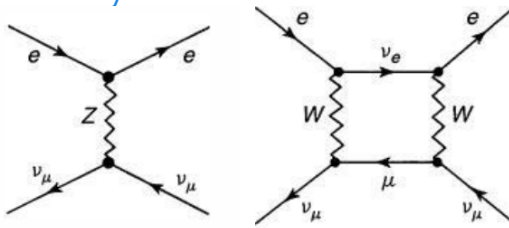
- Similarly CP violation was discovered in 1960s in the neutral kaons decays.
- $2 \times 2$  Cabbibo matrix could not allow for any CP violation.
- For the CP violation to be possible one needs at least a  $3 \times 3$  unitary matrix  $\rightarrow$  Cabibbo-Kobayashi-Maskawa matrix (1973).
- It predicts existence of  $b$  (1977) and  $t$  (1995) quarks.



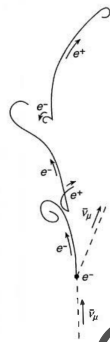
Results published in  
Physical Review Letters  
August 1, 1977



# A lesson from history - Weak neutral current

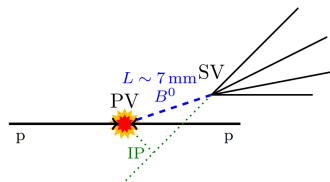
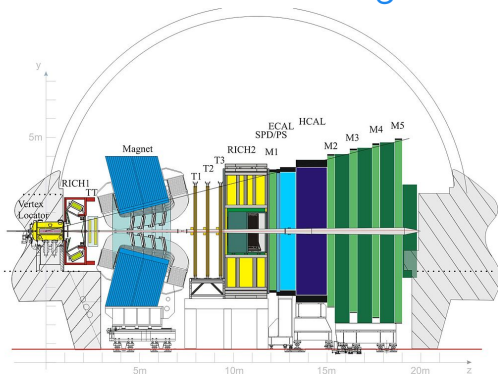


- Weak neutral currents were first, introduced in 1958 by Buldman.
- Later on they were naturally incorporated into unification of weak and electromagnetic interactions.
- 't Hooft proved that the GWS models was renormalizable.
- Everything was there on theory side, only missing piece was the experiment, till 1973.



# LHCb detector

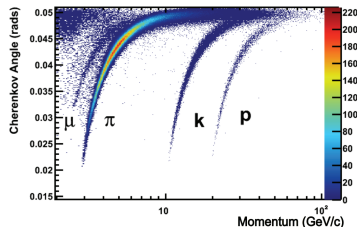
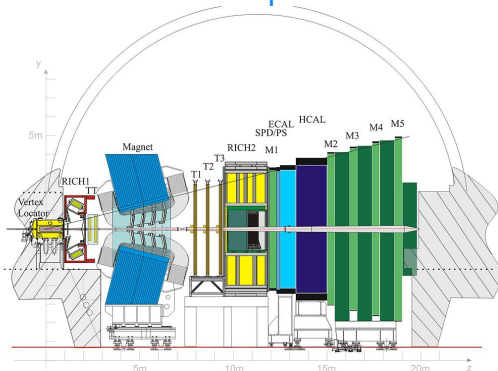
# LHCb detector - tracking



- 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

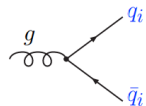
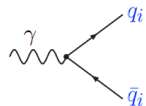
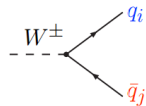
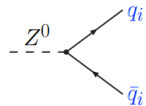
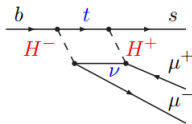
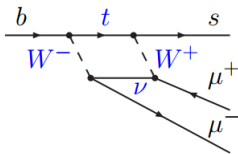


- Excellent Muon identification  $\epsilon_{\mu \rightarrow \mu} \sim 97\%$ ,  $\epsilon_{\pi \rightarrow \mu} \sim 1 - 3\%$
- Good  $K - \pi$  separation via RICH detectors,  $\epsilon_{K \rightarrow K} \sim 95\%$ ,  
 $\epsilon_{\pi \rightarrow K} \sim 5\%$ .  
⇒ Reject peaking backgrounds.
- High 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  $\sim 90\%$ .

$b \rightarrow sll$  theory in a nutshell.

# Why rare decays?

- In SM allows only the charged interactions to change flavour.
  - Other interactions are flavour conserving.
- One can escape this constrain and produce  $b \rightarrow s$  and  $b \rightarrow d$  at loop level.
  - This kind of processes are suppressed in SM  $\rightarrow$  Rare decays.
  - New Physics can enter in the loops.



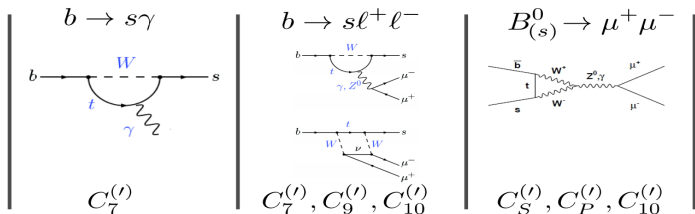
# Tools in rare $B^0$ decays

- Operator Product Expansion and Effective Field Theory

$$H_{eff} = -\frac{4G_f}{\sqrt{2}} VV'^* \sum_i \left[ \underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\text{right-handed}} \right],$$

- i=1,2 Tree
- i=3-6,8 Gluon penguin
- i=7 Photon penguin
- i=9,10 EW penguin
- i=S Scalar penguin
- i=P Pseudoscalar penguin

where  $C_i$  are the Wilson coefficients and  $O_i$  are the corresponding effective operators.

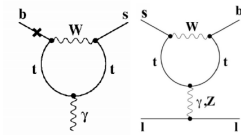


# Analysis of Rare decays

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.]:

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

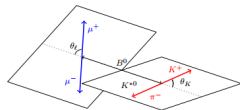
- **NP** changes short distance  $\mathcal{C}_i - \mathcal{C}_i^{\text{SM}} = \mathcal{C}_i^{\text{NP}}$  and induce new operators, like

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

# $B^0 \rightarrow K^* \mu^- \mu^+$ kinematics

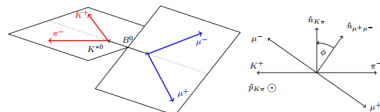
$\Rightarrow$  The kinematics of  $B^0 \rightarrow K^* \mu^- \mu^+$  decay is described by three angles  $\theta_l$ ,  $\theta_k$ ,  $\phi$  and invariant mass of the dimuon system ( $q^2$ ).

$\Rightarrow \cos \theta_k$ : the angle between the direction of the kaon in the  $K^*$  ( $\overline{K}^*$ ) rest frame and the direction of the  $K^*$  ( $\overline{K}^*$ ) in the  $B^0$  ( $\overline{B}^0$ ) rest frame.



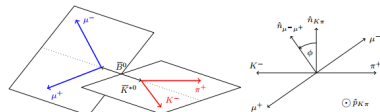
(a)  $\theta_k$  and  $\theta_l$  definitions for the  $B^0$  decay

$\Rightarrow \cos \theta_l$ : the angle between the direction of the  $\mu^-$  ( $\mu^+$ ) in the dimuon rest frame and the direction of the dimuon in the  $B^0$  ( $\overline{B}^0$ ) rest frame.



(b)  $\phi$  definition for the  $B^0$  decay

$\Rightarrow \phi$ : the angle between the plane containing the  $\mu^-$  and  $\mu^+$  and the plane containing the kaon and pion from the  $K^*$ .



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

## $B^0 \rightarrow K^* \mu^- \mu^+$ kinematics

⇒ The kinematics of  $B^0 \rightarrow K^* \mu^- \mu^+$  decay is described by three angles  $\theta_l$ ,  $\theta_k$ ,  $\phi$  and invariant mass of the dimuon system ( $q^2$ ).

$$\begin{aligned} \frac{d^4\Gamma}{dq^2 d\cos\theta_K d\cos\theta_l d\phi} = & \frac{9}{32\pi} \left[ J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_l \right. \\ & + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + J_5 \sin 2\theta_K \sin \theta_l \cos \phi \\ & + (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos \theta_l + J_7 \sin 2\theta_K \sin \theta_l \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin \phi \\ & \left. + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \right], \end{aligned}$$

⇒ This is the most general expression of this kind of decay.

# Transversity amplitudes

⇒ One can link the angular observables to transversity amplitudes

$$J_{1s} = \frac{(2 + \beta_\ell^2)}{4} \left[ |A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2 \right] + \frac{4m_\ell^2}{q^2} \operatorname{Re} \left( A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*} \right),$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2} \left[ |A_t|^2 + 2\operatorname{Re}(A_0^L A_0^{R*}) \right] + \beta_\ell^2 |A_S|^2,$$

$$J_{2s} = \frac{\beta_\ell^2}{4} \left[ |A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2 \right], \quad J_{2c} = -\beta_\ell^2 \left[ |A_0^L|^2 + |A_0^R|^2 \right],$$

$$J_3 = \frac{1}{2} \beta_\ell^2 \left[ |A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2 \right], \quad J_4 = \frac{1}{\sqrt{2}} \beta_\ell^2 \left[ \operatorname{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*}) \right],$$

$$J_5 = \sqrt{2} \beta_\ell \left[ \operatorname{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}) - \frac{m_\ell}{\sqrt{q^2}} \operatorname{Re}(A_\parallel^L A_S^* + A_\parallel^{R*} A_S) \right],$$

$$J_{6s} = 2\beta_\ell \left[ \operatorname{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*}) \right], \quad J_{6c} = 4\beta_\ell \frac{m_\ell}{\sqrt{q^2}} \operatorname{Re}(A_0^L A_S^* + A_0^{R*} A_S),$$

$$J_7 = \sqrt{2} \beta_\ell \left[ \operatorname{Im}(A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*}) + \frac{m_\ell}{\sqrt{q^2}} \operatorname{Im}(A_\perp^L A_S^* - A_\perp^{R*} A_S) \right],$$

$$J_8 = \frac{1}{\sqrt{2}} \beta_\ell^2 \left[ \operatorname{Im}(A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*}) \right], \quad J_9 = \beta_\ell^2 \left[ \operatorname{Im}(A_\parallel^{L*} A_\perp^L + A_\parallel^{R*} A_\perp^R) \right],$$



## Link to effective operators

⇒ So here is where the magic happens. At leading order the amplitudes can be written as:

$$A_{\perp}^{L,R} = \sqrt{2}Nm_B(1 - \hat{s}) \left[ (C_9^{\text{eff}} + C_9^{\text{eff}'}) \mp (C_{10} + C'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}'}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2}Nm_B(1 - \hat{s}) \left[ (C_9^{\text{eff}} - C_9^{\text{eff}'}) \mp (C_{10} - C'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_{\perp}(E_{K^*})$$

$$A_0^{L,R} = -\frac{Nm_B(1 - \hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (C_9^{\text{eff}} - C_9^{\text{eff}'}) \mp (C_{10} - C'_{10}) + 2\hat{m}_b(C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_{\parallel}(E_{K^*}),$$

where  $\hat{s} = q^2/m_B^2$ ,  $\hat{m}_i = m_i/m_B$ . The  $\xi_{\parallel,\perp}$  are the form factors.

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$$A_0^{L,R} = -\frac{Nm_B(1 - \hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (C_9^{\text{eff}} - C_9^{\text{eff}'}) \mp (C_{10} - C'_{10}) + 2\hat{m}_b(C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_{\parallel}(E_{K^*}),$$

where  $\hat{s} = q^2/m_B^2$ ,  $\hat{m}_i = m_i/m_B$ . The  $\xi_{\parallel,\perp}$  are the form factors.

⇒ Now we can construct observables that cancel the  $\xi$  form factors at leading order:

$$P'_5 = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

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

# LHCbs $B^0 \rightarrow K^* \mu^- \mu^+$ , Selection

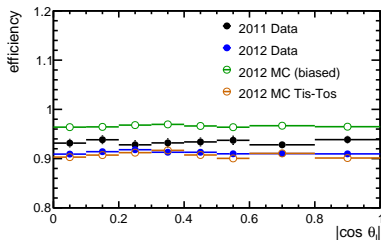
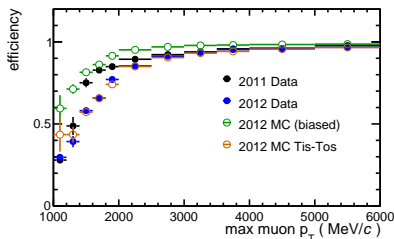
⇒ Trigger

- Muon trigger.
- Topological trigger.

⇒ Good modelling with MC.

⇒ Selection:

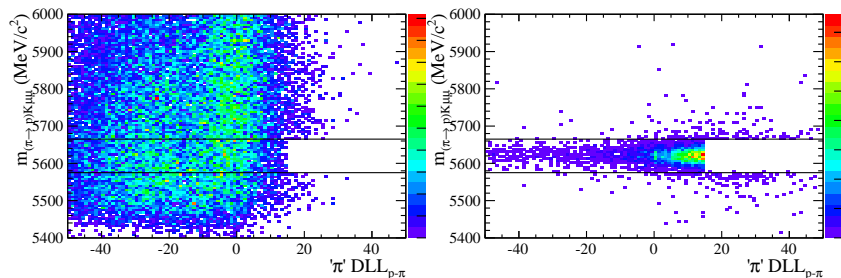
- As loose as possible.
- Based on the  $B^0$  vertex quality, impact parameters, loose Particle identification for the hadrons.
- The variables were chosen in a way we are sure they are correctly modelled in MC.



# Peaking backgrounds

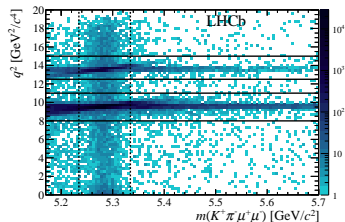
- ⇒ A number of peaking backgrounds that can mistaken as your signal.
- ⇒ There where a specially designed vetoes to fight each of them.

Channel	after preselection, before vetoes		after vetoes and selection	
	Estimated events	% signal	Estimated events	% signal
$\Lambda_b \rightarrow \Lambda^*(1520)^0 \mu\mu$	$(1.0 \pm 0.5) \times 10^3$	$19 \pm 8$	$51 \pm 25$	$1.0 \pm 0.4$
$\Lambda_b \rightarrow p K \mu\mu$	$(1.0 \pm 0.5) \times 10^2$	$1.9 \pm 0.8$	$5.7 \pm 2.8$	$0.11 \pm 0.05$
$B_d^0 \rightarrow K^+ \mu\mu$	$28 \pm 7$	$0.55 \pm 0.06$	$1.6 \pm 0.5$	$0.031 \pm 0.006$
$B_s^0 \rightarrow \phi \mu\mu$	$(3.2 \pm 1.3) \times 10^2$	$6.2 \pm 2.1$	$17 \pm 7$	$0.33 \pm 0.12$
signal swaps	$(3.6 \pm 0.9) \times 10^2$	$6.9 \pm 0.6$	$33 \pm 9$	$0.64 \pm 0.06$
$B_d^0 \rightarrow K^* J/\psi$ swaps	$(1.3 \pm 0.4) \times 10^2$	$2.6 \pm 0.4$	$2.7 \pm 2.8$	$0.05 \pm 0.05$

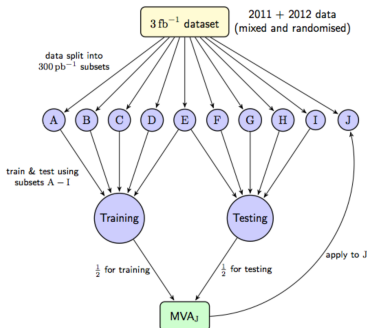
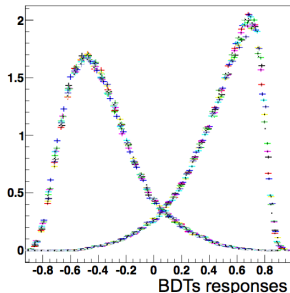


# Multivariate simulation

- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to discriminate signal and background.
- BDT with k-Folding technique.
- Completely data drive.

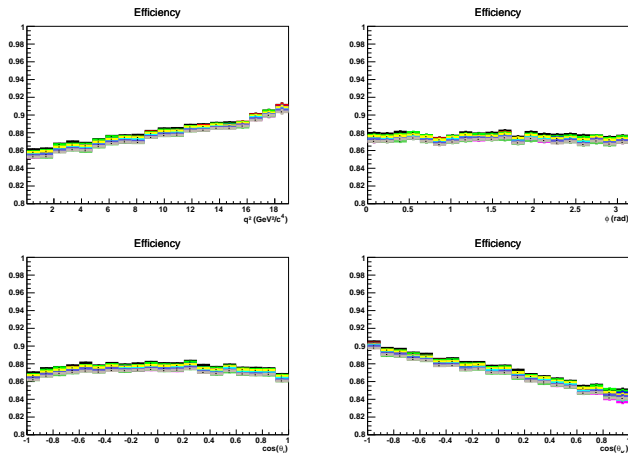


MVA\_baseline\_S



# Multivariate simulation, efficiency

⇒ BDT was also checked in order not to bias our angular distribution:



⇒ The BDT has small impact on our angular observables. We will correct for this effects later on.

# Mass modelling

⇒ The signal is modelled by a sum of two Crystal-Ball function with common mean.

⇒ The background is a single exponent

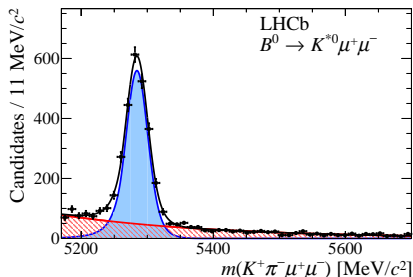
⇒ The base parameters is performed in the proxy channel:

$$B_d^0 \rightarrow J/\psi(\mu\mu)K^*$$

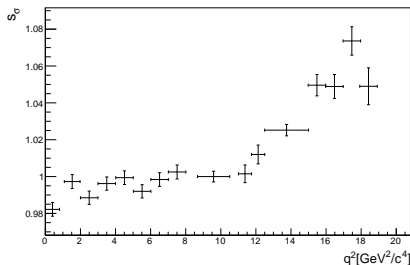
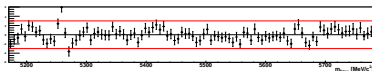
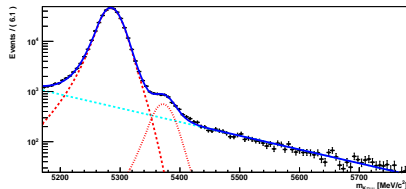
⇒ All the parameters are fixed in the signal pdf.

⇒ 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 got  $624 \pm 30$  candidates in the most interesting  $[1.1, 6.0] \text{ GeV}^2/c^4$  region and  $2398 \pm 57$  in the full range  $[1.1, 19.] \text{ GeV}^2/c^4$ .

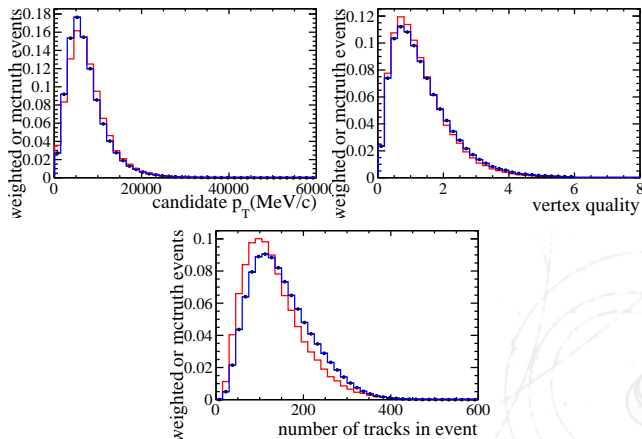


⇒ The S-wave fraction is extracted using a LASS model.



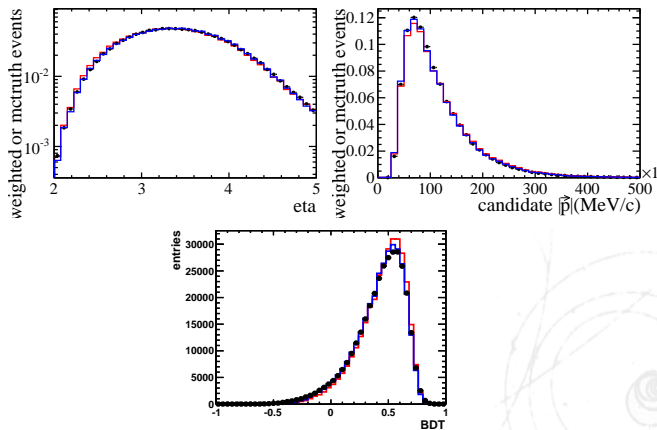
# Monte Carlo corrections

- ⇒ No Monte Carlo simulation is perfect! One needs to correct for remaining differences.
- ⇒ We reweighted our  $B_d^0 \rightarrow K^* \mu \mu$  Monte Carlo accordingly to differences between the  $B_d^0 \rightarrow K^* J/\psi$  in data (Splot) and Monte Carlo.



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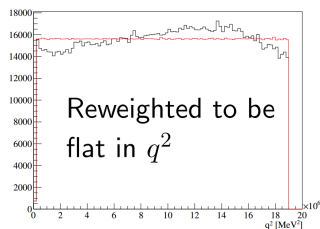
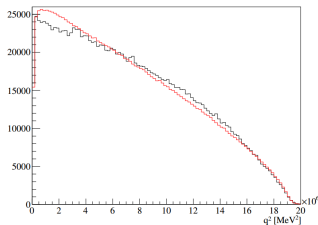
# Detector acceptance

- 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  $4^{th}$ ,  $5^{th}$ ,  $6^{th}$ ,  $5^{th}$  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.
- To make this work the  $q^2$  distribution needs to be reweighed to be flat.



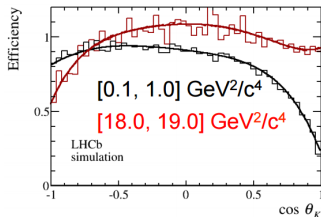
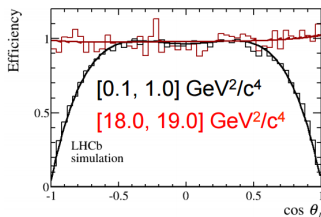
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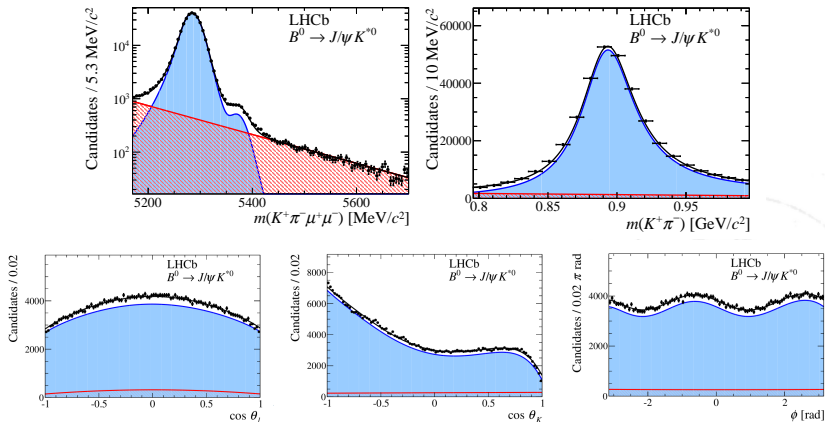
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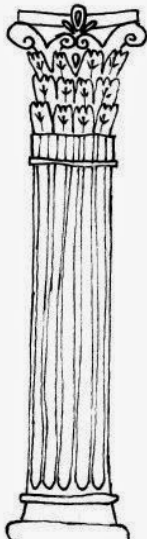
# Control channel

- 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.

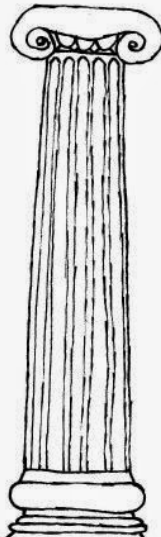


# The columns of New Physics

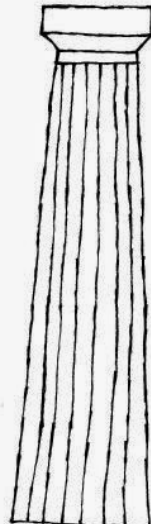
Amplitudes



Maximum likelihood fit



Method of Moments



# The columns of New Physics

## 1. Maximum likelihood fit:

- The most standard way of obtaining the parameters.
- Suffers from convergence problems, under coverages, etc. in 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:

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

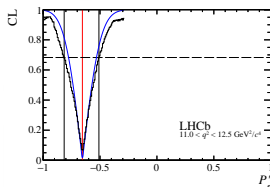
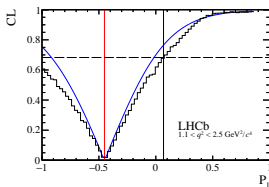
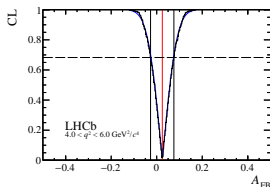
⇒ Only the relative weights matters!

⇒ The Procedure was commissioned with TOY MC study.

⇒ Use Feldmann-Cousins to determine the uncertainties.

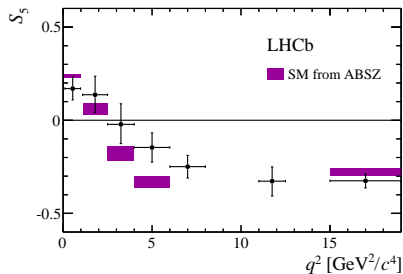
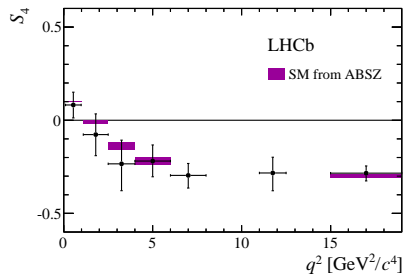
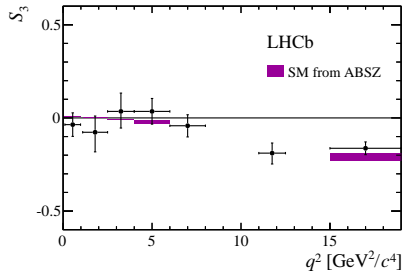
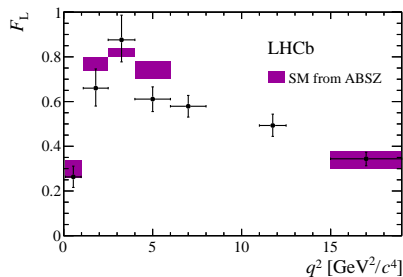
⇒ Angular background component is modelled with 2<sup>nd</sup> order Chebyshev polynomials, which was tested on the side-bands.

⇒ S-wave component treated as nuisance parameter.

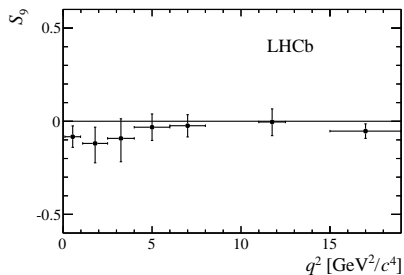
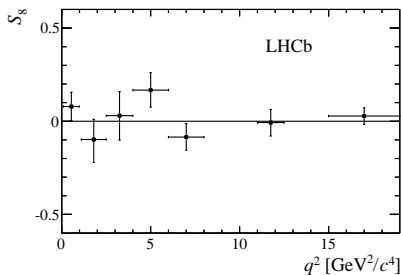
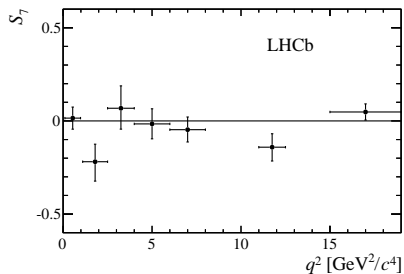
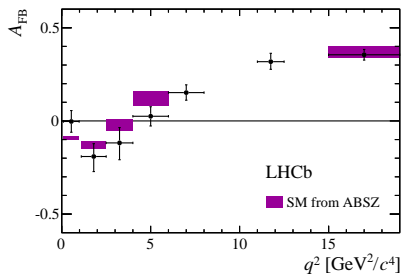




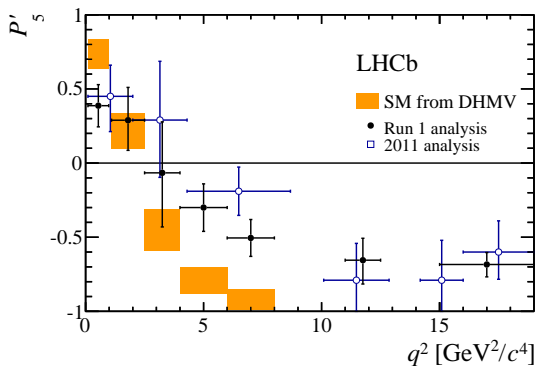
# Maximum likelihood fit - Results



# Maximum likelihood fit - Results



# Maximum likelihood fit - Results



- Tension with  $3 \text{ fb}^{-1}$  gets confirmed!
- The two bins deviate both in  $2.8 \sigma$  from SM prediction.
- Result compatible with previous result.

# 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:

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

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

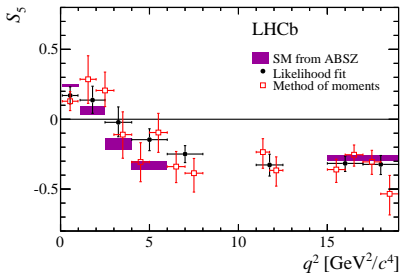
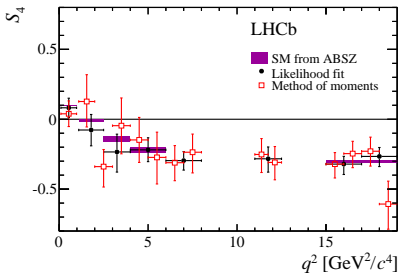
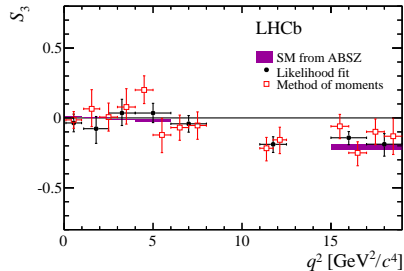
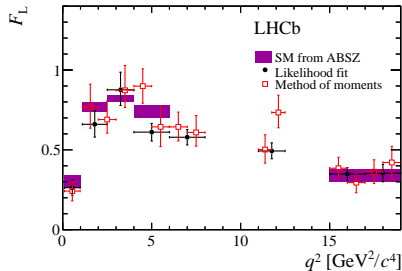
⇒ Don't have true angular distribution but we "sample" it with our data.

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

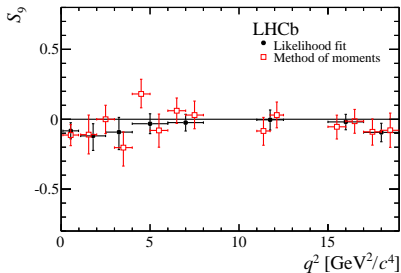
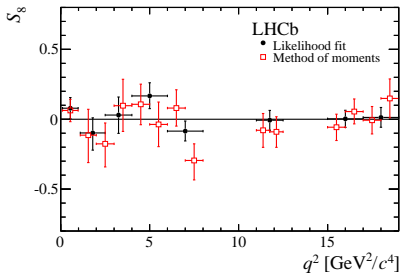
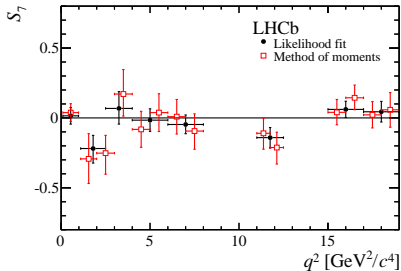
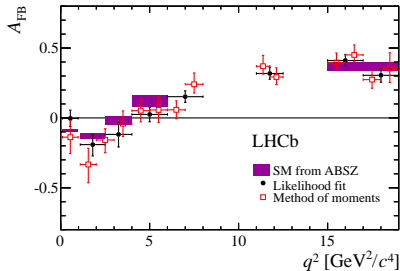
$$\hat{M}_i = \frac{1}{\sum_e \omega_e} \sum_e \omega_e f_i(\vec{\Omega}_e)$$

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

# Method of moments - results

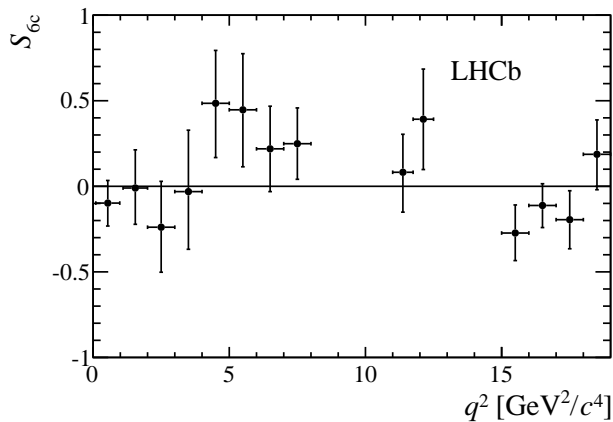


# Method of moments - results



# Method of moments - results

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



# 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 test 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](#).

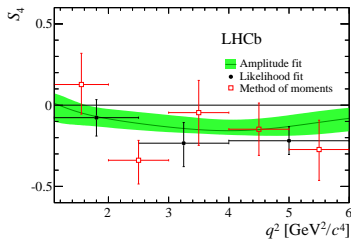
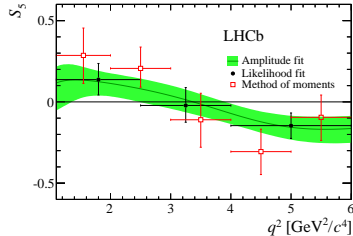
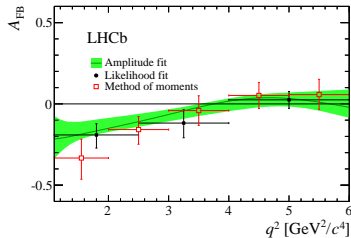
⇒ Allows to build the observables as continuous functions of  $q^2$ :

- 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.

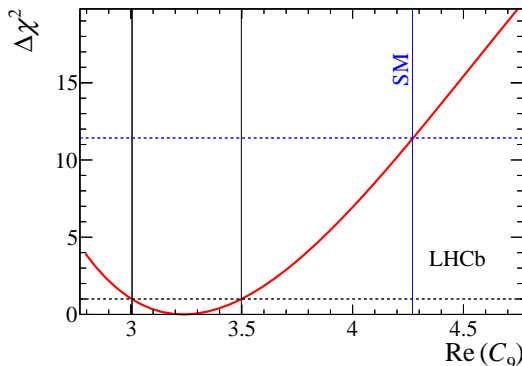
⇒ Perform the  $\chi^2$  fit to the measured:

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

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

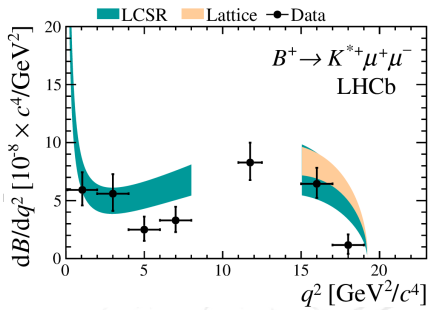
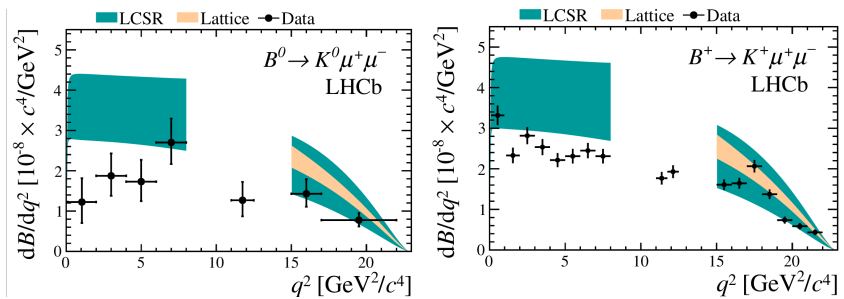
⇒ Best fit is found to be  $3.4 \sigma$  away from the SM.

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



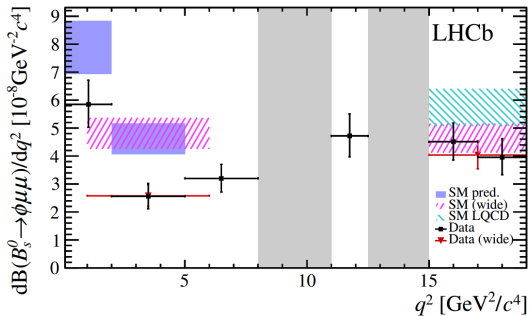
# Other related LHCb measurements.

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



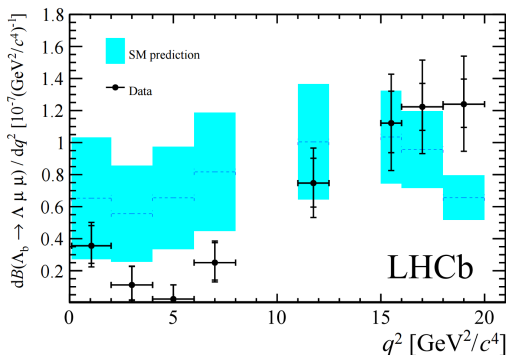
- Despite large theoretical errors the results are consistently smaller than SM prediction.

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



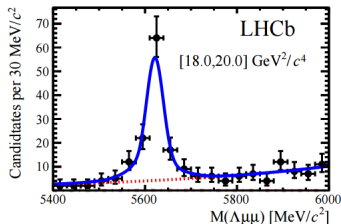
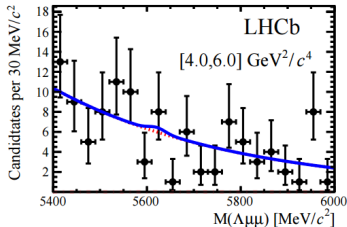
- Recent LHCb measurement [JHEPP09 (2015) 179].
- Suppressed by  $\frac{f_s}{f_d}$ .
- Cleaner because of narrow  $\phi$  resonance.
- $3.3 \sigma$  deviation in SM in the  $1 - 6 \text{ GeV}^2$  bin.

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



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

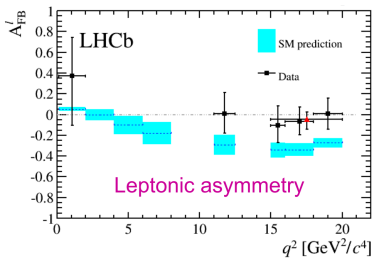
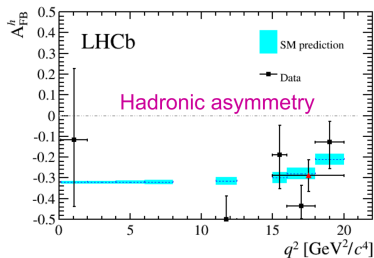
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# Angular analysis of $\Lambda_b \rightarrow \Lambda \mu \mu$

- 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.



# Lepton universality test

- If  $Z'$  is responsible for the  $P'_5$  anomaly, does it couple equally to all flavours?

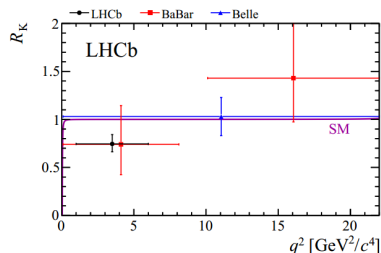
$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}) .$$

- 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

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

- Consistent with SM at  $2.6\sigma$ .



- 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  $0.0004 < q^2 < 1 \text{ GeV}^2$ .
- Electrons channels are extremely challenging experimentally:
  - Bremsstrahlung.
  - Trigger efficiencies.
- Determine the angular observables:  $F_L$ ,  $A_T^{(2)}$ ,  $A_T^{\text{Re}}$ ,  $A_T^{\text{Im}}$ :

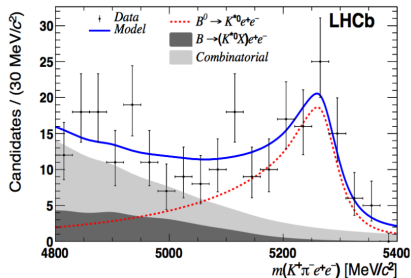
$$F_L = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}$$

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

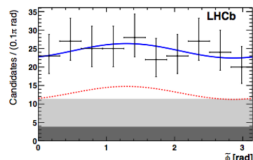
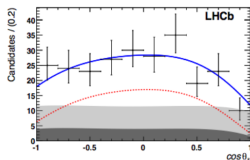
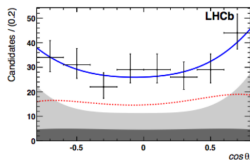
$$A_T^{\text{Re}} = \frac{2\mathcal{R}e(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2}$$

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

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



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



# Global fit to $b \rightarrow sll$ measurements

# Link the observables

⇒ Fit prepare by S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, arXiv::1510.04239

- Inclusive

- $B \rightarrow X_s \gamma$  ( $BR$ ) .....  $c_7^{(\prime)}$
- $B \rightarrow X_s \ell^+ \ell^-$  ( $dBR/dq^2$ ) .....  $c_7^{(\prime)}, c_9^{(\prime)}, c_{10}^{(\prime)}$

- Exclusive leptonic

- $B_s \rightarrow \ell^+ \ell^-$  ( $BR$ ) .....  $c_{10}^{(\prime)}$

- Exclusive radiative/semileptonic

- $B \rightarrow K^* \gamma$  ( $BR, S, A_I$ ) .....  $c_7^{(\prime)}$
- $B \rightarrow K \ell^+ \ell^-$  ( $dBR/dq^2$ ) .....  $c_7^{(\prime)}, c_9^{(\prime)}, c_{10}^{(\prime)}$
- **$B \rightarrow K^* \ell^+ \ell^-$**  ( $dBR/dq^2$ , **Optimized Angular Obs.**) ..  $c_7^{(\prime)}, c_9^{(\prime)}, c_{10}^{(\prime)}$
- $B_s \rightarrow \phi \ell^+ \ell^-$  ( $dBR/dq^2$ , Angular Observables) .....  $c_7^{(\prime)}, c_9^{(\prime)}, c_{10}^{(\prime)}$
- $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$  (None so far)
- etc.

# Statistic details

⇒ Frequentist approach:

$$\chi^2(C_i) = [O_{\text{exp}} - O_{\text{th}}(C_i)]_j [Cov^{-1}]_{jk} [O_{\text{exp}} - O_{\text{th}}(C_i)]_k$$

- $\mathbf{Cov} = \mathbf{Cov}^{\text{exp}} + \mathbf{Cov}^{\text{th}}$ . We have  $Cov^{\text{exp}}$  for the first time
- Calculate  $Cov^{\text{th}}$ : correlated multigaussian scan over all nuisance parameters
- $Cov^{\text{th}}$  depends on  $C_i$ : Must check this dependence

For the Fit:

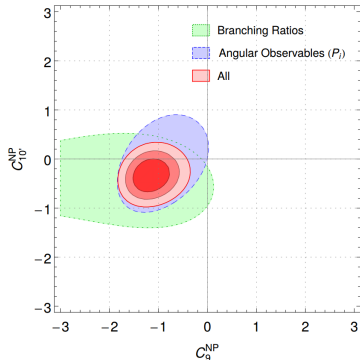
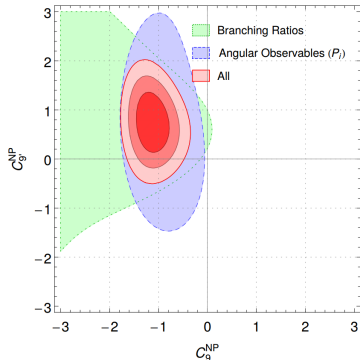
- Minimise  $\chi^2 \rightarrow \chi_{\text{min}}^2 = \chi^2(C_i^0)$  (Best Fit Point =  $C_i^0$ )
- Confidence level regions:  $\chi^2(C_i) - \chi_{\text{min}}^2 < \Delta\chi_{\sigma,n}$

⇒ The results from 1D scans:

Coefficient $C_i^{\text{NP}} = C_i - C_i^{\text{SM}}$	Best fit	$1\sigma$	$3\sigma$	$\text{Pull}_{\text{SM}}$
$C_9^{\text{NP}}$	-1.09	[-1.29, -0.87]	[-1.67, -0.39]	4.5 ←
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.68	[-0.85, -0.50]	[-1.22, -0.18]	4.2 ←
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$	-1.06	[-1.25, -0.86]	[-1.60, -0.40]	4.8 ← (no $R_K$ )

# Theory implications

- The data can be explained by modifying the  $C_9$  Wilson coefficient.
- Overall there is around  $4.5 \sigma$  discrepancy wrt. SM.



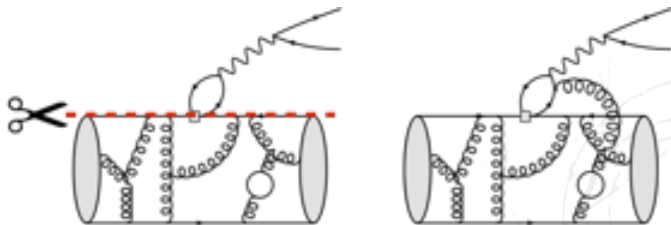
Coefficient	Best Fit Point	Pull <sub>SM</sub>
$(\mathcal{C}_7^{\text{NP}}, \mathcal{C}_9^{\text{NP}})$	$(-0.00, -1.07)$	<b>4.1</b>
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}})$	$(-1.08, 0.33)$	<b>4.3</b>
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{7'}^{\text{NP}})$	$(-1.09, 0.02)$	<b>4.2</b>
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{9'}^{\text{NP}})$	$(-1.12, 0.77)$	<b>4.5</b>
$(\mathcal{C}_9^{\text{NP}}, \mathcal{C}_{10'}^{\text{NP}})$	$(-1.17, -0.35)$	<b>4.5</b>
$(\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}})$	$(-1.15, 0.34)$	<b>4.7</b>
$(\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}})$	$(-1.06, 0.06)$	<b>4.4</b>
$(\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}}, \mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}})$	$(-0.64, -0.21)$	3.9
$(\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}, \mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}})$	$(-0.72, 0.29)$	3.8

- $\mathcal{C}_9^{\text{NP}}$  always play a dominant role
- All 2D scenarios above  $4\sigma$  are quite indistinguishable. We have done a systematic work to check what are the most relevant Wilson Coefficients to explain all deviations, by allowing progressively different WC to get NP contributions and compare the pulls.



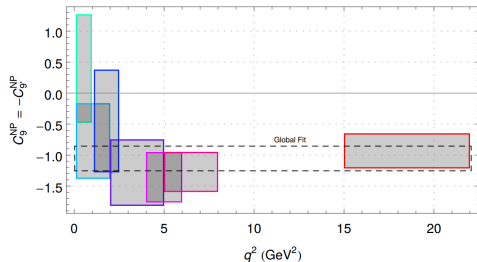
## If not NP?

- We are not there yet!
- There might be something not taken into account in the theory.
- Resonances ( $J/\psi$ ,  $\psi(2S)$ ) tails can mimic NP effects.
- There might be some non factorizable QCD corrections.  
” However, the central value of this effect would have to be significantly larger than expected on the basis of existing estimates” D.Straub, 1503.06199 .



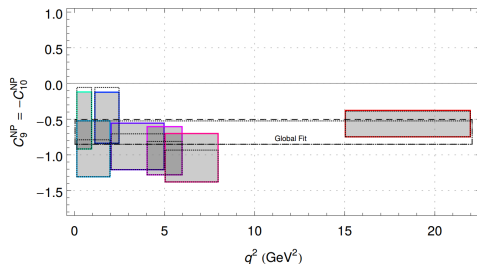
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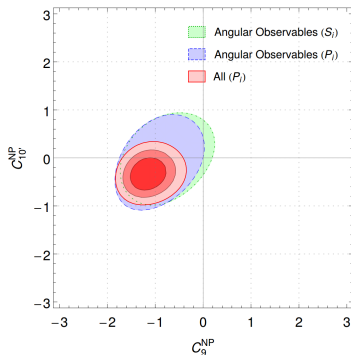
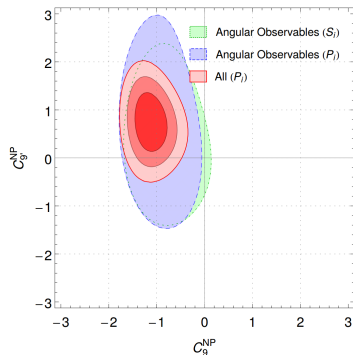
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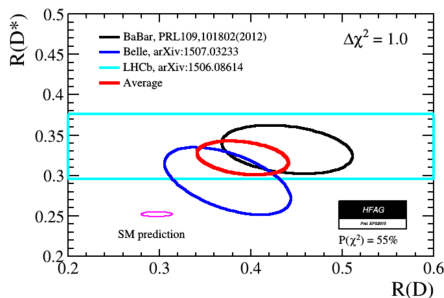
# If not NP?

- How about our clean  $P_i$  observables?
- The QCD cancel as mentioned only at leading order.
- Comparison to normal observables with the optimised ones.



## 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.



# Disclaimers about some theory predictions

# Disclaimer, credit to J.Matias!

⇒ [arXiv:1512.07157](https://arxiv.org/abs/1512.07157), Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli

- Introduce a fully arbitrary parametrization for non-factorizable power correction:

$$H_\lambda \rightarrow H_\lambda + h_\lambda \text{ where } h_\lambda = h_\lambda^{(0)} + h_\lambda^{(1)} q^2 + h_\lambda^{(2)} q^4 \quad \text{and} \quad h_\lambda^{(0)} \rightarrow C_7^{NP}, h_\lambda^{(1)} \rightarrow C_9^{NP}$$

with  $(\lambda = 0, \pm)$

(copied from JC'14).

**Complications:** complete lack of theory input/output ⇒ **no predictivity** with 18 free parameters (any shape). Specific problems...

- One has to go back and look at the symmetries of the amplitudes. They imply the Matias-Serra relations:

$$P_2^{rel} = \frac{1}{2} \left[ P_4' P_5' + \delta_a + \frac{1}{\beta} \sqrt{(-1 + P_1 + P_4'^2)(-1 - P_1 + \beta^2 P_5'^2) + \delta_b} \right]$$

where  $\delta_a$  and  $\delta_b$  are function of product of tiny  $P_6', P_8', P_3$ .

⇒ *This is true independently of any crazy non-factorizable, factorizable, or New Physics (with no weak phases) that is included inside the  $H_\lambda$  (or  $A_{\perp, \parallel, 0}$ )*

# Disclaimer, credit to J.Matias!

⇒ Using theory predictions (DHMV'15, JHEP 1412 (2014) 125) for bin [4,6] one has:

$$\langle P_1 \rangle = 0.03 \quad \langle P_4' \rangle = +0.82 \quad \langle P_5' \rangle = -0.82 \quad \langle P_2 \rangle = -0.18$$

⇒ consistency relation ⇒  $\langle P_2 \rangle^{rel} = -0.17$  ( $\Delta = 0.01$  from binning). Perfect agreement!

⇒ The previous relation can be rewritten in terms of  $A_{FB} = f(F_L, S_i)$ :

		$CFFMPSV_{\text{predictions}}$	$CFFMPSV_{\text{full fit}}$	SM-DHMV
[4, 6]	$\langle A_{FB} \rangle^{rel}$	<b><math>-0.14 \pm 0.04</math></b>	<b><math>-0.16 \pm 0.03</math></b>	$+0.05 \pm 0.19$
	$\langle A_{FB} \rangle$	<b><math>+0.05 \pm 0.04 \Rightarrow 3.7\sigma</math></b>	<b><math>+0.04 \pm 0.03 \Rightarrow 4.8\sigma</math></b>	$+0.08 \pm 0.11 \Rightarrow 0.1\sigma$
[6, 8]	$\langle A_{FB} \rangle^{rel}$	$-0.27 \pm 0.08$	$-0.15 \pm 0.05$	$+0.17 \pm 0.18$
	$\langle A_{FB} \rangle$	$+0.12 \pm 0.08 \Rightarrow 3.6\sigma$	$+0.13 \pm 0.03 \Rightarrow 4.9\sigma$	$+0.21 \pm 0.21 \Rightarrow 0.1\sigma$

- "No deviation is present once all the theoretical uncertainties are taken into account".



⇒ arXiv::1603.04355

## Signal of right-handed currents using $B \rightarrow K^* \ell^+ \ell^-$ observables at the kinematic endpoint.

Anirban Karan,<sup>1</sup> Rusa Mandal,<sup>1</sup> Abinash Kumar Nayak,<sup>1</sup> Rahul Sinha,<sup>1</sup> and Thomas E. Browder<sup>2</sup>

<sup>1</sup>*The Institute of Mathematical Sciences, Taramani, Chennai 600113, India*

<sup>2</sup>*Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*

(Dated: March 15, 2016)

The decay mode  $B \rightarrow K^* \ell^+ \ell^-$  is one of the most promising modes to probe physics beyond the standard model (SM), since the angular distribution of the decay products enable measurement of several constraining observables. LHCb has recently measured these observables using 2 fb<sup>-1</sup> of data as a binned function of  $q^2$ , the dilepton invariant mass squared. We show that LHCb data implies a  $5\sigma$  overall signal for new physics and provides unambiguous evidence for right-handed currents, which are absent in the SM. These conclusions are derived in the maximum  $q^2$  limit and are free from hadronic corrections. Our approach differs from other approaches that probe new physics at low  $q^2$  as it does not require estimates of hadronic parameters but relies instead on heavy quark symmetries that are reliable at the maximum  $q^2$  kinematic endpoint.

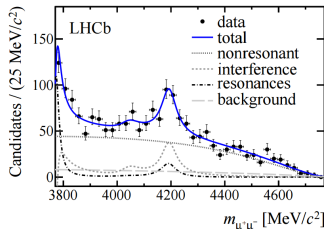
# Disclaimer

⇒ arXiv::1603.04355

- ⇒ "The relation in Eq. (24) between form factors is expected to be satisfied in the large  $q^2$  region. Eq. (24) is naturally satisfied if it is valid at each order in the Taylor expansion of the form factors"
- ⇒ They need the Eq. 24 to be valid with at least leading order at the Taylor expansion.
- ⇒ But this is not guaranteed as a resonant contribution can violate this expression.

The large  $q^2$  region where the  $K^*$  has low-recoil energy has also been studied [3, 12] in a modified heavy quark effective theory framework. In the limit  $q^2 \rightarrow q_{\max}^2$  the hadronic form factors satisfy the conditions

$$\frac{\tilde{G}_{\parallel}}{\tilde{F}_{\parallel}} = \frac{\tilde{G}_{\perp}}{\tilde{F}_{\perp}} = \frac{\tilde{G}_0}{\tilde{F}_0} = -\kappa \frac{2m_b m_B C_7}{q^2}, \quad (24)$$



# Conclusions

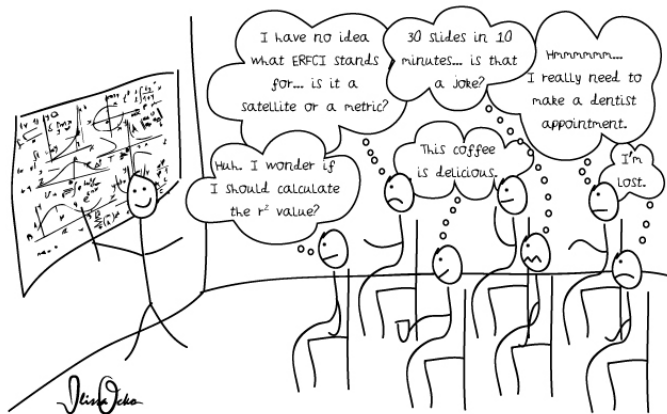
- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

# Conclusions

- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
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- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

“... when you have eliminated all the Standard Model explanations, whatever remains, however improbable, must be New Physics.”  
prof. Joaquim Matias

# Thank you for the attention!



# Backup