

# Electroweak penguin measurements



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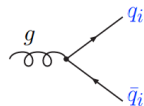
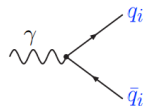
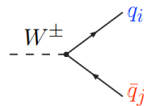
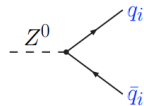
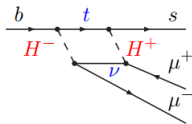
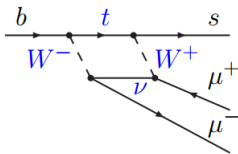


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# Why rare decays?

- 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.

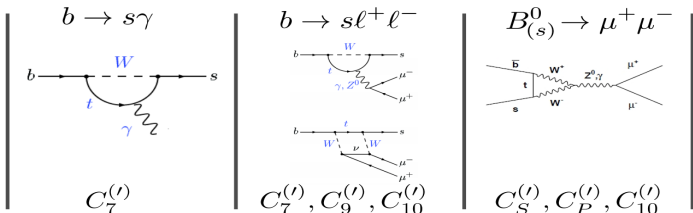


- Operator Product Expansion and Effective Field Theory

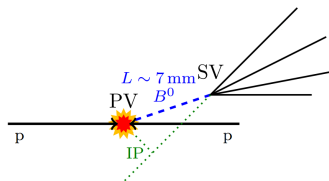
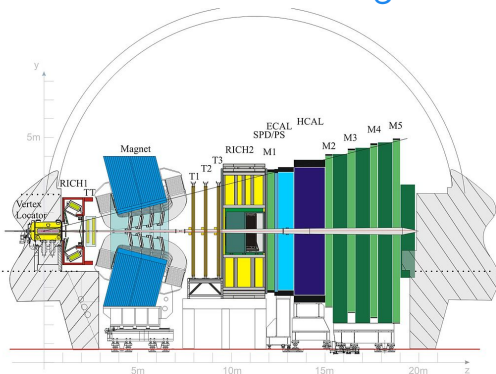
$$H_{eff} = -\frac{4G_f}{\sqrt{2}} VV'^* \sum_i \left[ \underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\text{right-handed}} \right],$$

- 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 pen

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

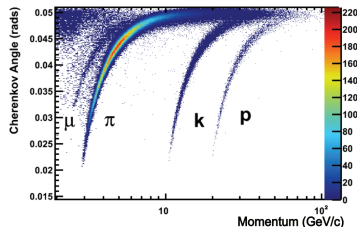
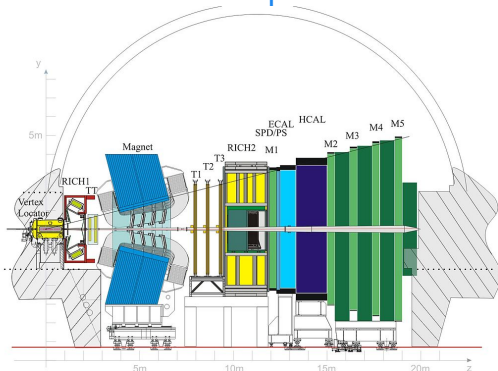


# LHCb detector - tracking



- 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,  $\epsilon_{K \rightarrow K} \sim 95\%$ ,  
 $\epsilon_{\pi \rightarrow K} \sim 5\%$ .  
 $\Rightarrow$  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  $\sim 90\%$ .

# Recent measurements

⇒ **Branching fractions:**

$$B^{0,\pm} \rightarrow K^{0,\pm} \mu^- \mu^+ \quad \text{LHCb, Mar 14}$$

$$B^0 \rightarrow K^* \mu^- \mu^+ \quad \text{CMS, Jul 15}$$

$$B_s^0 \rightarrow \phi \mu^- \mu^+ \quad \text{LHCb, Jun 15}$$

$$B^\pm \rightarrow \pi^\pm \mu^- \mu^+ \quad \text{LHCb, Sep 15}$$

$$\Lambda_b \rightarrow \Lambda \mu^- \mu^+ \quad \text{LHCb, Mar 15}$$

$$B \rightarrow \mu^- \mu^+ \quad \text{CMS+LHCb, Jun 15}$$

⇒ **CP asymmetry:**

$$B^\pm \rightarrow \pi^\pm \mu^- \mu^+ \quad \text{LHCb, Sep 15}$$

⇒ **Isospin asymmetry:**

$$B \rightarrow K \mu^- \mu^+ \quad \text{LHCb, Mar 14}$$

⇒ **Lepton Universality:**

$$B^\pm \rightarrow K^\pm \ell \bar{\ell} \quad \text{LHCb, Jun 14}$$

⇒ **Angular:**

$$B^0 \rightarrow K^* \ell \bar{\ell} \quad \text{LHCb, Jan 15}$$

$$B^\pm \rightarrow K^{*,\pm} \ell \bar{\ell} \quad \text{BaBar, Aug 15}$$

$$B_s^0 \rightarrow \phi \ell \bar{\ell} \quad \text{LHCb, Jun 15}$$

$$\Lambda_b \rightarrow \Lambda \mu^- \mu^+ \quad \text{LHCb, Mar 15}$$

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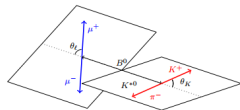
$$\Lambda_b \rightarrow \Lambda \mu^- \mu^+ \quad \text{LHCb, Mar 15}$$

> 2  $\sigma$  deviations from SM

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

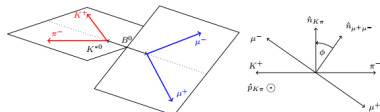
$\Rightarrow$  The kinematics of  $B^0 \rightarrow K^* \mu^- \mu^+$  decay is described by three angles  $\theta_l$ ,  $\theta_k$ ,  $\phi$  and invariant mass of the dimuon system ( $q^2$ ).

$\Rightarrow \cos \theta_k$ : 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.



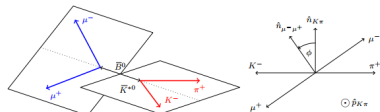
(a)  $\theta_k$  and  $\theta_l$  definitions for the  $B^0$  decay

$\Rightarrow \cos \theta_l$ : 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

$\Rightarrow$  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 ( $q^2$ ).

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

$\Rightarrow$  This is the most general expression of this kind of decay.

$\Rightarrow$  The  $CP$  averaged angular observables are defined:

$$S_i = \frac{J_i + \bar{J}_i}{(d\Gamma + d\bar{\Gamma})/dq^2}$$

# 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:

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

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

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

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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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:

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

# Symmetries in $B \rightarrow K^* \mu \mu$

⇒ We have 12 angular coefficients ( $S_i$ ).

⇒ There exists 4 symmetry transformations that leave the angular distributions non changed:

$$n_{\parallel} = \begin{pmatrix} A_{\parallel}^L \\ A_{R^*}^L \end{pmatrix}, \quad n_{\perp} = \begin{pmatrix} A_{\perp}^L \\ -A_{\perp}^{R^*} \end{pmatrix}, \quad n_0 = \begin{pmatrix} A_0^L \\ A_0^{R^*} \end{pmatrix}.$$

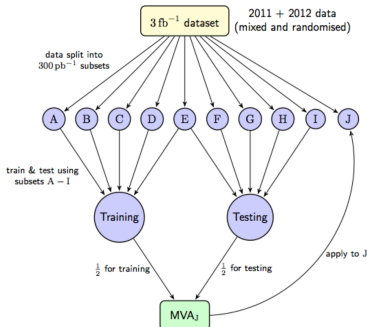
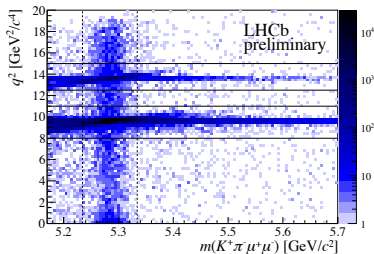
$$n'_i = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i.$$

⇒ Using this symmetries one can show that there are 8 independent observables. The pdf can be wrote as:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d(\Gamma + \bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\phi} \Big|_{\mathbb{P}} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_k \right. \\ \left. + F_L \cos^2 \theta_k + \frac{1}{4}(1 - F_L) \sin^2 \theta_k \cos 2\theta_l \right. \\ \left. - F_L \cos^2 \theta_k \cos 2\theta_l + S_3 \sin^2 \theta_k \sin^2 \theta_l \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_k \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_k \sin \theta_l \cos \phi \right. \\ \left. + \frac{4}{3} A_{\text{FB}} \sin^2 \theta_k \cos \theta_l + S_7 \sin 2\theta_k \sin \theta_l \sin \phi \right. \\ \left. + S_8 \sin 2\theta_k \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_k \sin^2 \theta_l \sin 2\phi \right].$$

# LHCb update of the $B^0 \rightarrow K^* \mu^- \mu^+$ , Selection

- LHCb-CONF-2015-002
- 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:  $\Lambda_b \rightarrow p K \mu \mu$ ,  $B_s^0 \rightarrow \phi \mu \mu$ , 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.

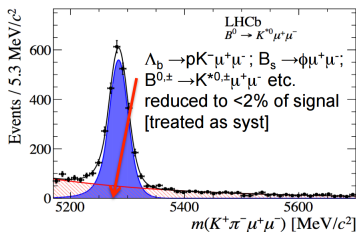


# LHCb update of the $B^0 \rightarrow K^* \mu^- \mu^+$ , Selection

- Signal modelled by a sum of two Crystal-Ball functions.
- Shape is defined using  $B \rightarrow J/\psi K^*$  and corrected for  $q^2$  dependency.
- Combinatorial background modelled by exponent.

- $K\pi$  system:

- Rel. Breit Wigner for P-wave
- LASS model for the S-wave.
- Linear model for background.
- Reduced the systematic compared to previous analysis.



- In total we found  $2398 \pm 57$  candidates in the  $(0.1, 19)$   $\text{GeV}^2$   $q^2$  region.
- $624 \pm 30$  candidates in the theoretically the most interesting  $(1.1 - 6.0)$   $\text{GeV}^2$  region.

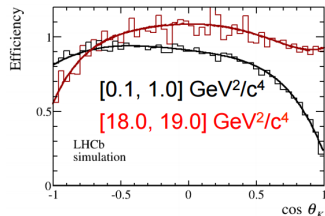
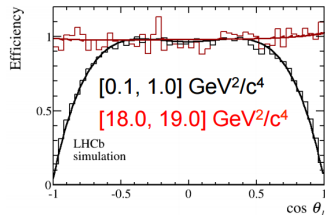
# Detector acceptance

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

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

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

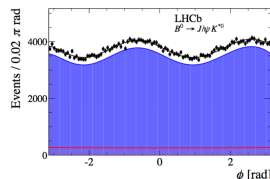
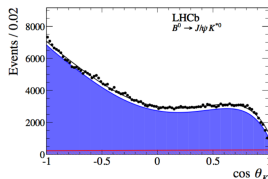
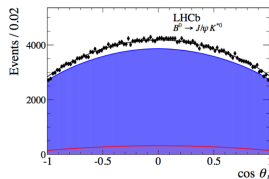
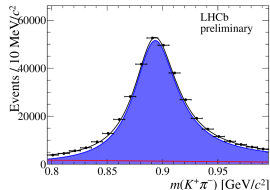
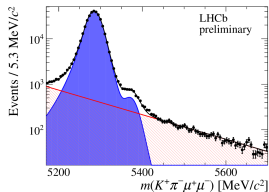
- We use up to 4<sup>th</sup>, 5<sup>th</sup>, 6<sup>th</sup>, 5<sup>th</sup> order for the  $\cos \theta_l, \cos \theta_k, \phi, q^2$ .



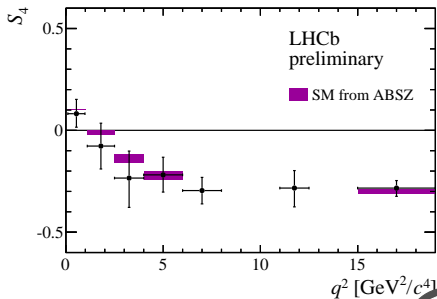
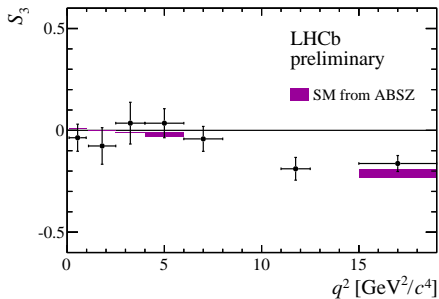
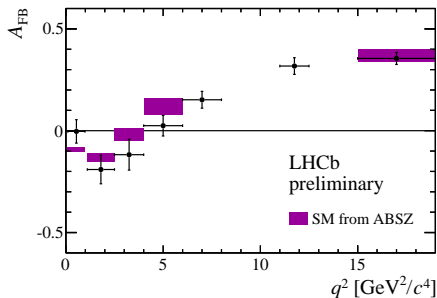
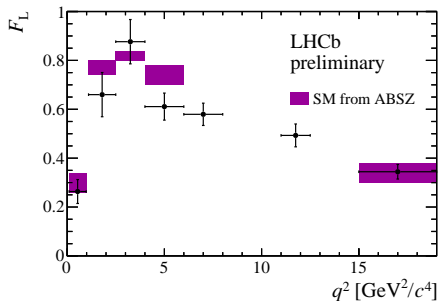


# Control channel

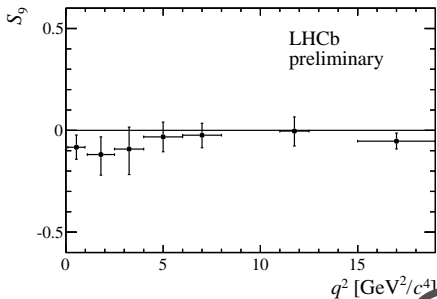
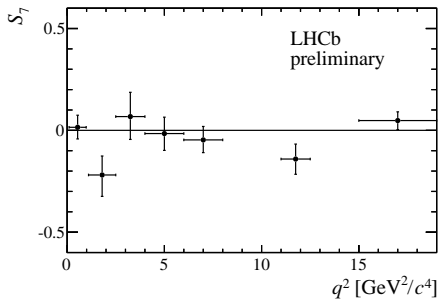
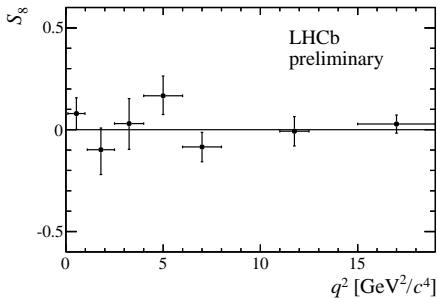
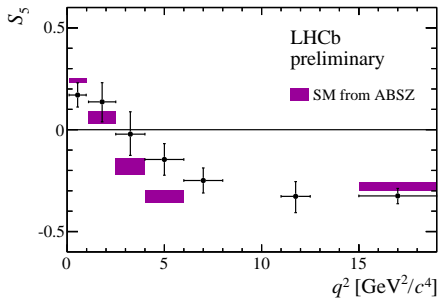
- We tested our unfolding procedure on  $B \rightarrow J/\psi K^*$ .
- The result is in perfect agreement with other experiments and our different analysis of this decay.



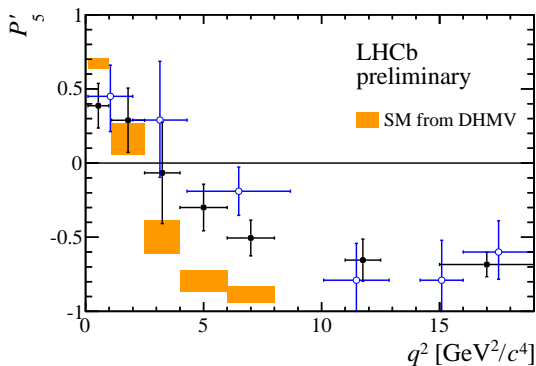
# $B^0 \rightarrow K^* \mu \mu$ results



# $B^0 \rightarrow K^* \mu \mu$ results

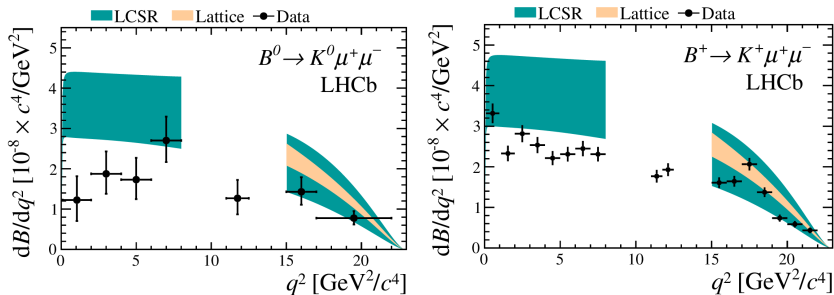


# Results in $B \rightarrow K^* \mu \mu$

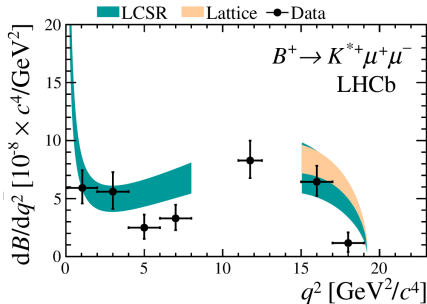


- Tension with  $3 \text{ fb}^{-1}$  gets confirmed!
- The two bins deviate both in  $2.8 \sigma$  from SM prediction.
- Result compatible with previous result.

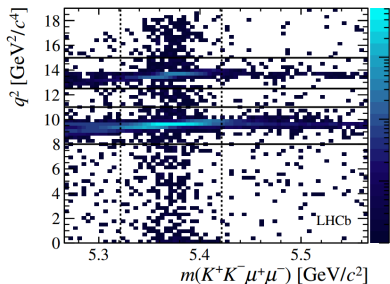
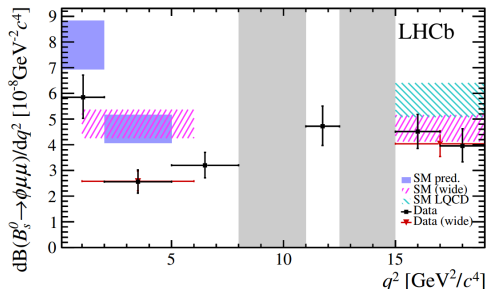
# Branching fraction measurements of $B \rightarrow K^{*\pm} \mu\mu$



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

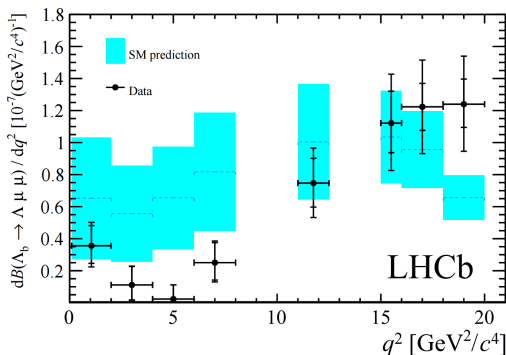


# Branching fraction measurements of $B_s^0 \rightarrow \phi\mu\mu$



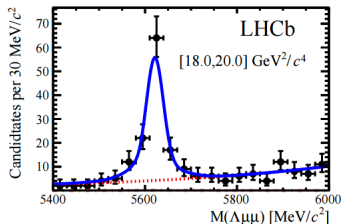
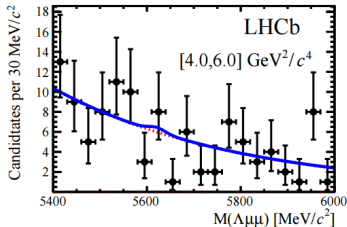
- Recent LHCb measurement, [JHEPP09 \(2015\) 179](#).
- Suppressed by  $\frac{f_s}{f_d}$ .
- Cleaner because of narrow  $\phi$  resonance.
- $3.3 \sigma$  deviation in SM in the  $1 - 6\text{GeV}^2$  bin.
- Angular part in agreement with SM ( $S_5$  is not accessible).

# 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  $q^2$ .

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

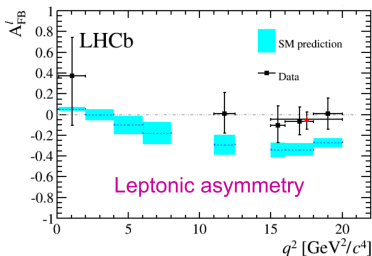
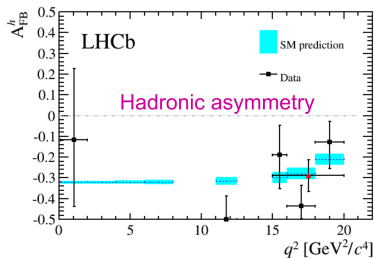


- This years LHCb measurement [JHEP 06 \(2015\) 115](#).
- In total  $\sim 300$  candidates in data set.
- Decay not present in the low  $q^2$ .



# 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

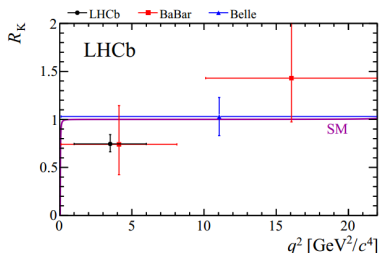
- If  $Z'$  is responsible for the  $P'_5$  anomaly, does it couple equally to all flavours?

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

- 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.

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

- Consistent with SM at  $2.6\sigma$ .



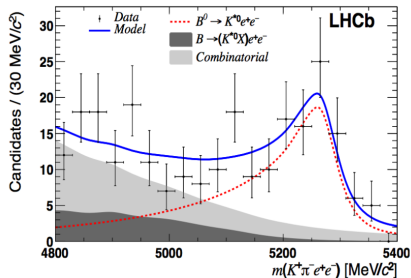
- [Phys. Rev. Lett. 113, 151601 \(2014\)](#).

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

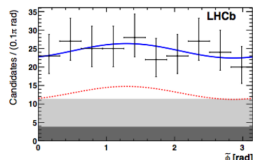
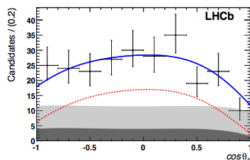
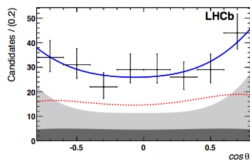
- With the full data set ( $3\text{fb}^{-1}$ ) we performed angular analysis in  $0.0004 < q^2 < 1 \text{ GeV}^2$ , [JHEP 04 \(2015\) 064](#).
- Electrons channels are extremely challenging experimentally:
  - Bremsstrahlung.
  - Trigger efficiencies.
- Determine the angular observables:  $F_L$ ,  $A_T^{(2)}$ ,  $A_T^{\text{Re}}$ ,  $A_T^{\text{Im}}$ :

$$\begin{aligned} F_L &= \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2} \\ A_T^{(2)} &= \frac{|A_{\perp}|^2 - |A_{||}|^2}{|A_{\perp}|^2 + |A_{||}|^2} \\ A_T^{\text{Re}} &= \frac{2\mathcal{R}e(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2} \\ A_T^{\text{Im}} &= \frac{2\mathcal{I}m(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2}, \end{aligned} \tag{1}$$

# 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.

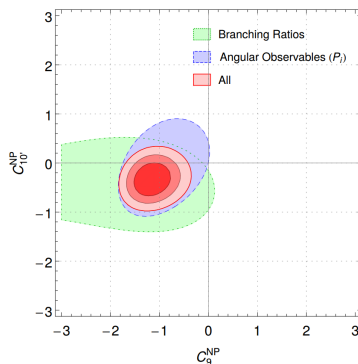
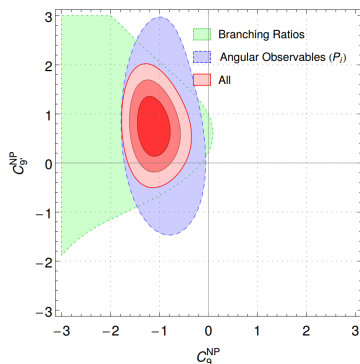


# Theory implications

- A preliminary fit prepared by S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, presented in [arXiv::1510.04239](https://arxiv.org/abs/1510.04239)
- Took into the fit:
  - $\mathcal{B}(B \rightarrow X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$ , Misiak et. al. 2015.
  - $\mathcal{B}(B \rightarrow \mu\mu)$ , theory: Bobeth et al 2013, experiment: LHCb+CMS average (2015)
  - $\mathcal{B}(B \rightarrow X_s \mu\mu)$ , Huber et al 2015
  - $\mathcal{B}(B \rightarrow K \mu\mu)$ , Bouchard et al 2013, 2015
  - $B_{(s)} \rightarrow K^*(\phi) \mu\mu$ , Horgan et al 2013
  - $B \rightarrow Kee$ ,  $B \rightarrow K^* ee$  and  $R_k$ .

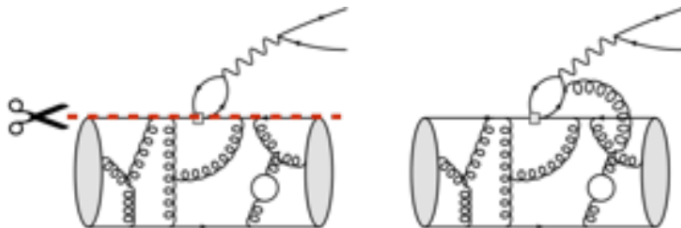
# Theory implications

- A preliminary fit prepared by S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, presented in [arXiv::1510.04239](https://arxiv.org/abs/1510.04239)
- The data can be explained by modifying the  $C_9$  Wilson coefficient.
- Overall there is around  $> 4. \sigma$  discrepancy wrt. SM.



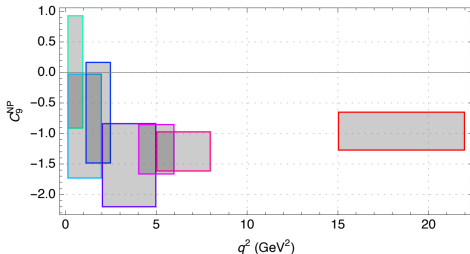
## If not NP?

- 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, [arXiv::1503.06199](https://arxiv.org/abs/1503.06199) .



## If not NP?

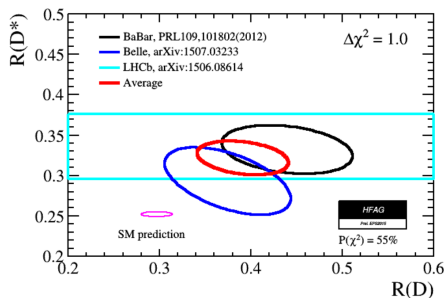
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## There is more!

- 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.



# Conclusions

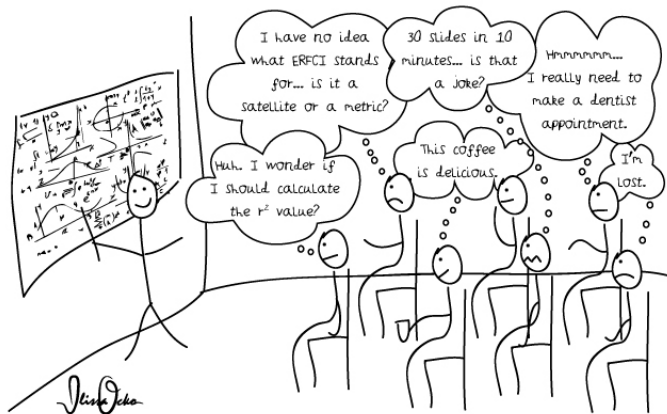
- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

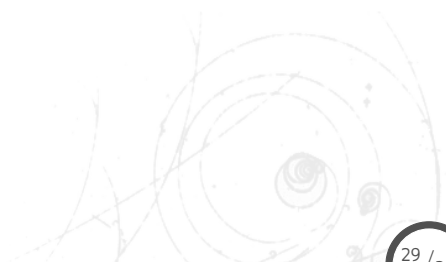
# Conclusions

- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- 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:

“... 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!





# Theory implications

Coefficient	Best fit	$1\sigma$	$3\sigma$	Pull <sub>SM</sub>	p-value (%)
$C_7^{\text{NP}}$	-0.02	[-0.04, -0.00]	[-0.07, 0.04]	1.1	16.0
$C_9^{\text{NP}}$	-1.11	[-1.32, -0.89]	[-1.71, -0.40]	<b>4.5</b>	62.0
$C_{10}^{\text{NP}}$	0.58	[0.34, 0.84]	[-0.11, 1.41]	2.5	25.0
$C_{7'}^{\text{NP}}$	0.02	[-0.01, 0.04]	[-0.05, 0.09]	0.7	15.0
$C_{9'}^{\text{NP}}$	0.49	[0.21, 0.77]	[-0.33, 1.35]	1.8	19.0
$C_{10'}^{\text{NP}}$	-0.27	[-0.46, -0.08]	[-0.84, 0.28]	1.4	17.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.21	[-0.40, 0.00]	[-0.74, 0.55]	1.0	16.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.69	[-0.88, -0.51]	[-1.27, -0.18]	<b>4.1</b>	55.0
$C_{9'}^{\text{NP}} = C_{10'}^{\text{NP}}$	-0.09	[-0.35, 0.17]	[-0.88, 0.66]	0.3	14.0
$C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$	0.20	[0.08, 0.32]	[-0.15, 0.56]	1.7	19.0
$C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$	-1.09	[-1.28, -0.88]	[-1.62, -0.42]	<b>4.8</b>	72.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ $= -C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$	-0.68	[-0.49, -0.49]	[-1.36, -0.15]	3.9	50.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ $= C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$	-0.17	[-0.29, -0.06]	[-0.54, 0.18]	1.5	18.0

Table 2: *Best-fit points, confidence intervals, pulls for the SM hypothesis and p-values for different one-dimensional NP scenarios.*

## 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.

