# Anomalies in Flavour physics

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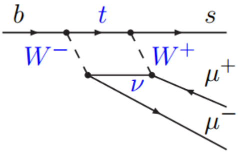
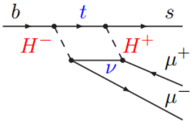
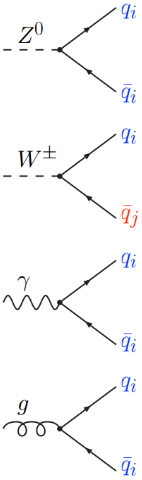
# Why rare decays?

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

# Tools

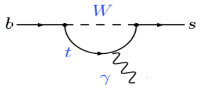
- **Operator Product Expansion and Effective Field Theory**

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

| | |
|---|---|
| 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 |

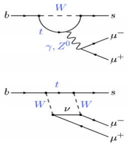
where $C_i$ are the Wilson coefficients and $O_i$ are the corresponding effective operators.

$b \to s\gamma$



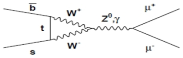

$C_7^{(\prime)}$

$b \to s\ell^+\ell^-$



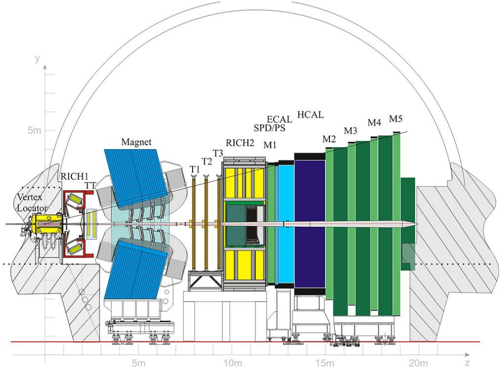

$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

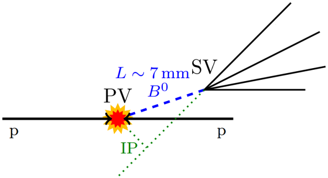
$B^0_{(s)} \to \mu^+\mu^-$




$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

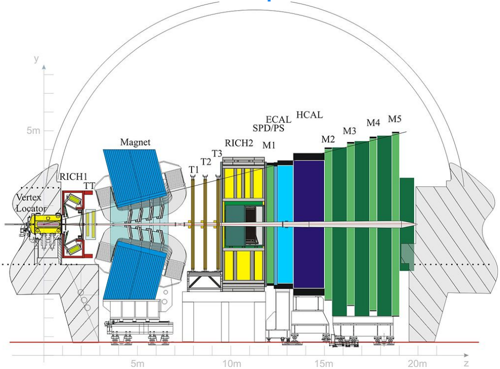
# LHCb detector - tracking

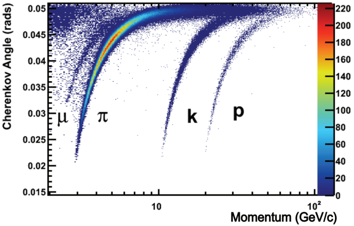



- Excellent Impact Parameter (IP) resolution ($20\ \mu$m).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass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

# LHCb detector - particle identification




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

# Recent measurements

⇛ Branching fractions:

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

$B^0 \to K^*\mu^-\mu^+$ CMS, Jul 15

$B_s^0 \to \phi\mu^-\mu^+$ LHCb, Jun 15

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

$\Lambda_b \to \Lambda\mu^-\mu^+$ LHCb, Mar 15

$B \to \mu^-\mu^+$ CMS+LHCb, Jun 15

⇛ CP asymmetry:

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

⇛ Isospin asymmetry:

$B \to K\mu^-\mu^+$ LHCb, Mar 14

⇛ Lepton Universality:

$B^\pm \to K^\pm\ell\bar{\ell}$ LHCb, Jun 14

⇛ Angular:

$B^0 \to K^*\ell\bar{\ell}$ LHCb, Jan 15

$B^\pm \to K^{*,\pm}\ell\bar{\ell}$ BaBar, Aug 15

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**$> 2\ \sigma$ deviations from SM**

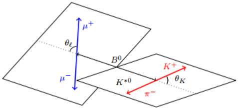
# $B^0 \to K^* \mu^- \mu^+$ kinematics

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

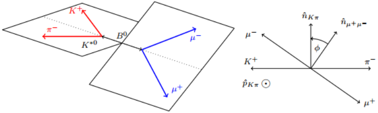
⇛ $\cos\theta_k$: the angle between the direction of the kaon in the $K^*$ ($\overline{K^*}$) rest frame and the direction of the $K^*$ ($\overline{K^*}$) in the $B^0$ ($\overline{B}^0$) rest frame.

⇛ $\cos\theta_l$: 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.

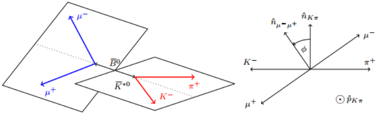
⇛ $\phi$: the angle between the plane containing the $\mu^-$ and $\mu^+$ and the plane containing the kaon and pion from the $K^*$.



(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay



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



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

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

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

⇛ 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

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

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

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

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

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

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

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

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

# Link to effective operators

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

$$A_{\perp}^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[ (\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[ (\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{0}^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

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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$$A_{0}^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

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

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

$$P_5^{\prime} = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

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

⇛ We have 12 angular coefficients ($S_i$).
⇛ There exists 4 symmetry transformations that leave the angular distributions non changed:

$$n_{\|} = \begin{pmatrix} A_{\|}^{L} \\ A_{\|}^{R*} \end{pmatrix}, \quad n_{\perp} = \begin{pmatrix} A_{\perp}^{L} \\ -A_{\perp}^{R*} \end{pmatrix}, \quad n_{0} = \begin{pmatrix} A_{0}^{L} \\ A_{0}^{R*} \end{pmatrix}.$$

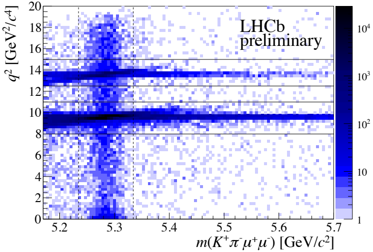
$$n_i^{'} = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i \,.$$

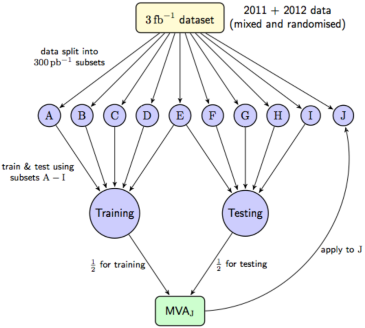
⇛ Using this symmetries one can show that there are 8 independent observables. The pdf can be wrote as:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l \,\mathrm{d}\cos\theta_k \,\mathrm{d}\phi}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k \\ + F_{\mathrm{L}}\cos^2\theta_k + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos 2\theta_l \\ - F_{\mathrm{L}}\cos^2\theta_k\cos 2\theta_l + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi \\ + S_4\sin 2\theta_k\sin 2\theta_l\cos\phi + S_5\sin 2\theta_k\sin\theta_l\cos\phi \\ + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_k\cos\theta_l + S_7\sin 2\theta_k\sin\theta_l\sin\phi \\ + S_8\sin 2\theta_k\sin 2\theta_l\sin\phi + S_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big].$$

# LHCb update of the $B^0 \to K^* \mu^- \mu^+$, 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: $\Lambda_b \to pK\mu\mu$, $B_s^0 \to \phi\mu\mu$, etc.
- Using k-Fold technique and signal proxy $B \to J/\psi K^*$ for training the BDT.
- Improved selection allowed for finer binning than the $1\text{fb}^{-1}$ analysis.

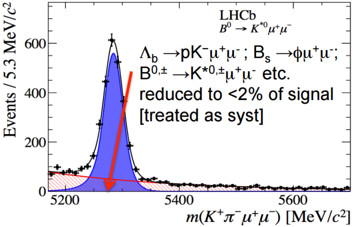


# LHCb update of the $B^0 \to K^*\mu^-\mu^+$, Selection

- Signal modelled by a sum of two Crystal-Ball functions.
- Shape is defined using $B \to J/\psi K^*$ 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 $(0.1, 19)$ GeV$^2$ $q^2$ region.
- $624 \pm 30$ candidates in the theoretically the most interesting $(1.1 - 6.0)$ GeV$^2$ region.

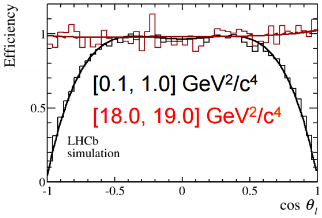
# Detector acceptance

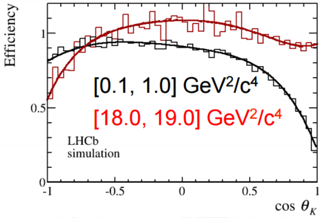
- Detector distorts our angular distribution.
- We need to model this effect.
- 4D function is used:

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

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

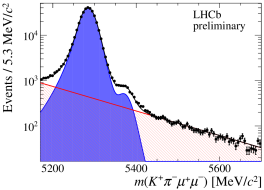
- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.

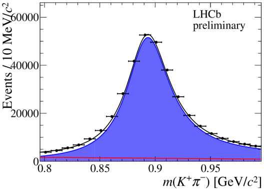


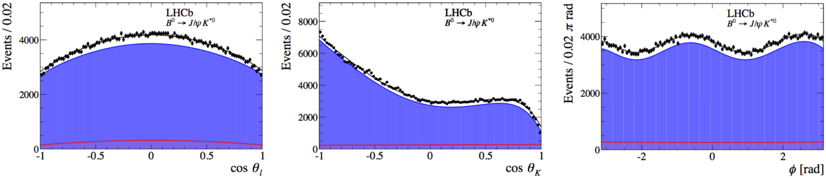



# Control channel

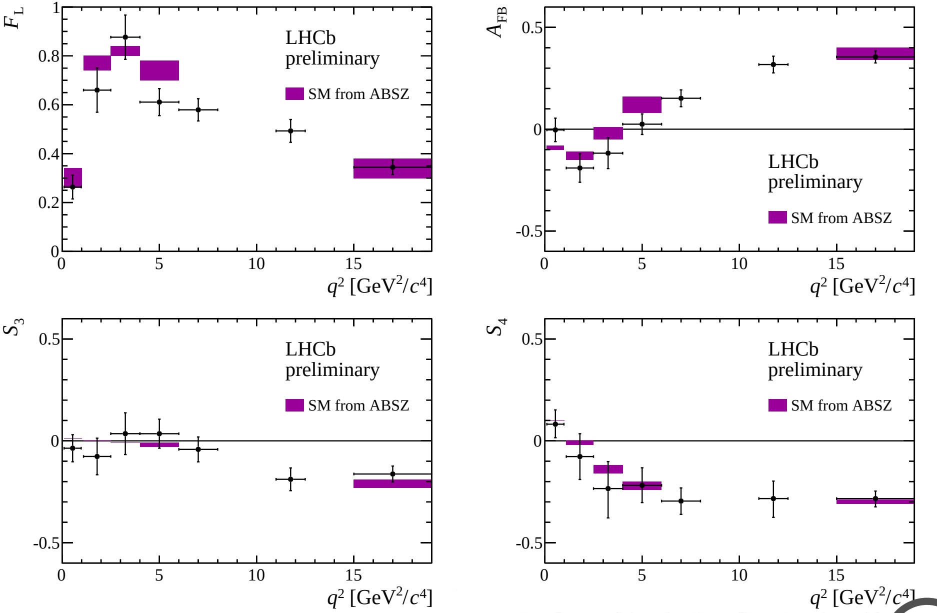
- We tested our unfolding procedure on $B \to J/\psi K^*$.
- The result is in perfect agreement with other experiments and our different analysis of this decay.



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



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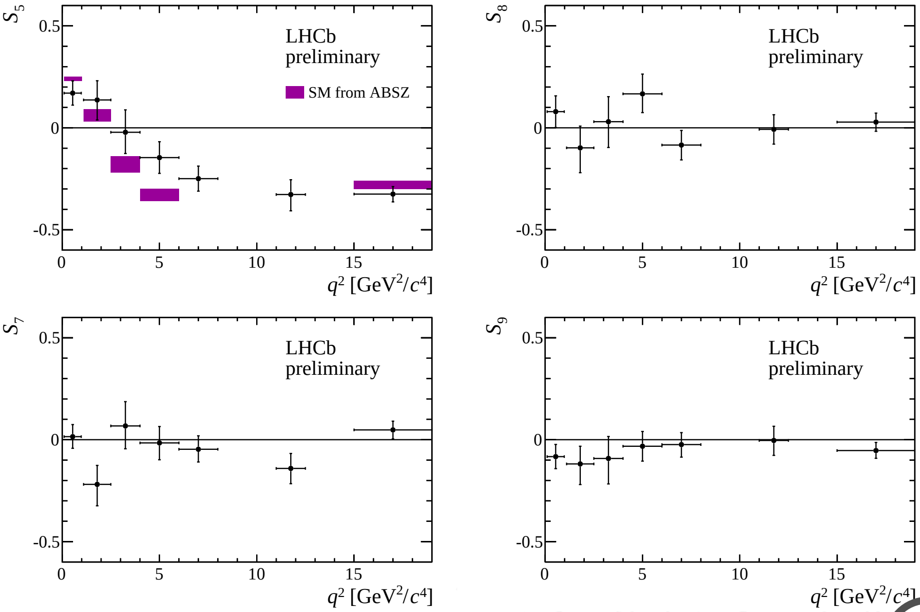
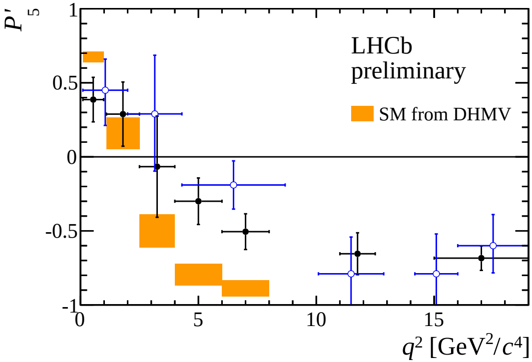
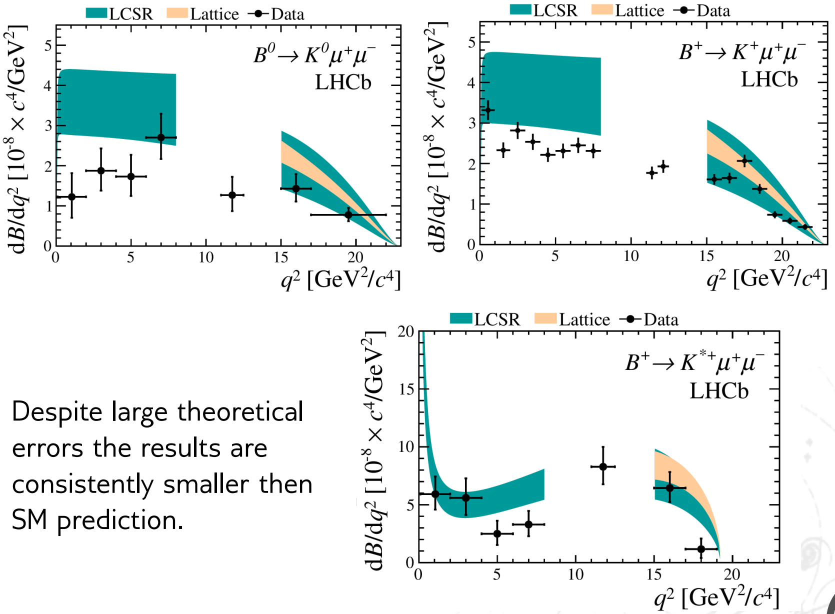


# Results in $B \to K^* \mu\mu$



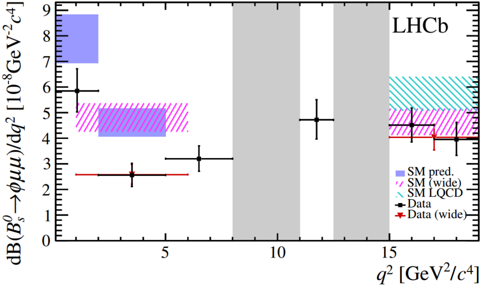

- Tension with $3\ \mathrm{fb}^{-1}$ gets confirmed!
- The two bins deviate both in $2.8\ \sigma$ from SM prediction.
- Result compatible with previous result.

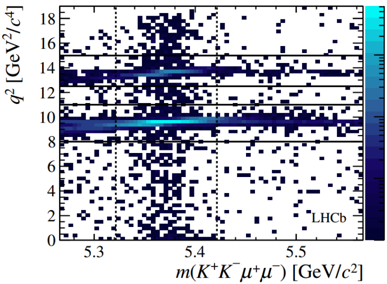
# Branching fraction measurements of $B \to K^{*\pm}\mu\mu$




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

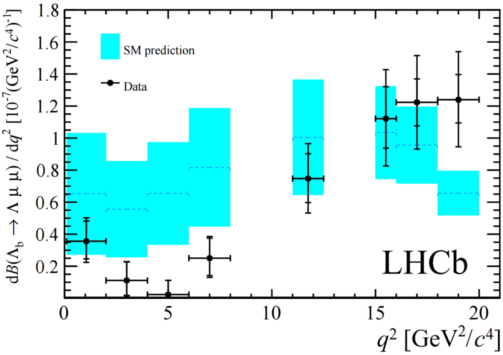
# Branching fraction measurements of $B_s^0 \to \phi\mu\mu$



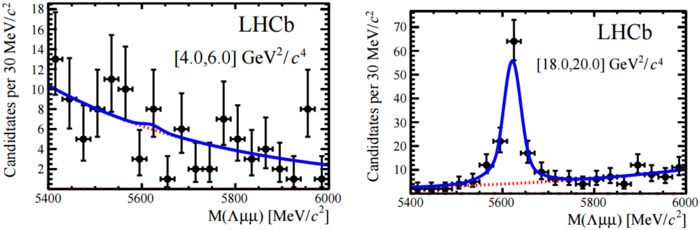

- Recent LHCb measurement, JHEPP09 (2015) 179.
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow $\phi$ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.
- Angular part in agreement with SM ($S_5$ is not accessible).

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




- 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 $\Lambda_b \to \Lambda\mu\mu$

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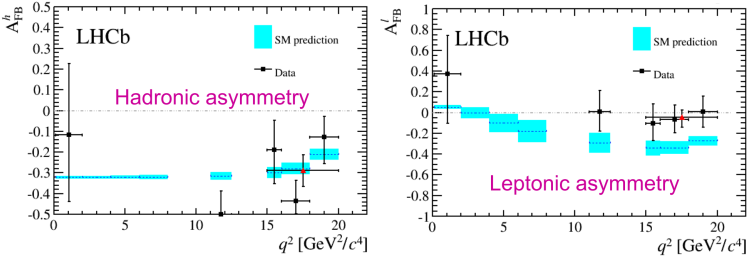
- In total $\sim 300$ candidates in data set.
- Decay not present in the low $q^2$.

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

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



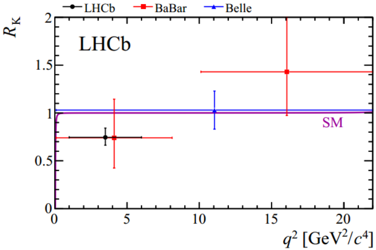

- $A^H_{FB}$ is in good agreement with SM.
- $A^\ell_{FB}$ always in above SM prediction.

# Lepton universality test

- If $Z'$ is responsible for the $P_5'$ anomaly, does it couple equally to all flavours?

$$R_{\rm K} = \frac{\int_{q^2=1\,{\rm GeV}^2/c^4}^{q^2=6\,{\rm GeV}^2/c^4} ({\rm d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/{\rm d}q^2){\rm d}q^2}{\int_{q^2=1\,{\rm GeV}^2/c^4}^{q^2=6\,{\rm GeV}^2/c^4} ({\rm d}\mathcal{B}[B^+ \to K^+e^+e^-]/{\rm d}q^2){\rm d}q^2} = 1 \pm \mathcal{O}(10^{-3})\ .$$

- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct for bremsstrahlung.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- In $3{\rm fb}^{-1}$, LHCb measures $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with SM at $2.6\sigma$.



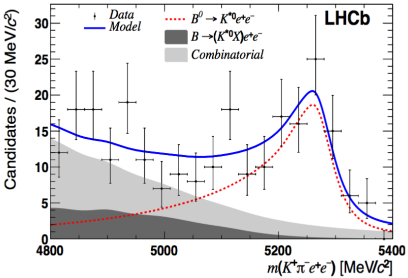

- Phys. Rev. Lett. 113, 151601 (2014).

# Angular analysis of $B^0 \to K^*ee$

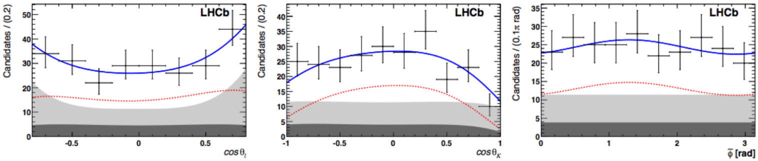
- With the full data set ($3\text{fb}^{-1}$) we performed angular analysis in $0.0004 < q^2 < 1~\text{GeV}^2$, JHEP 04 (2015) 064.
- Electrons channels are extremely challenging experimentally:
  - Bremsstrahlung.
  - Trigger efficiencies.
- Determine the angular observables: $F_{\rm L}$, $A_{\rm T}^{(2)}$,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

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

# Angular analysis of $B^0 \to K^* ee$




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

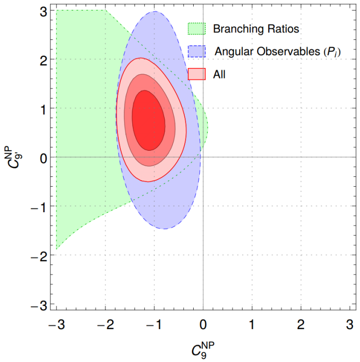


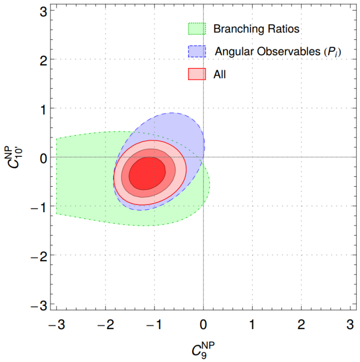
# Theory implications

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

# Theory implications

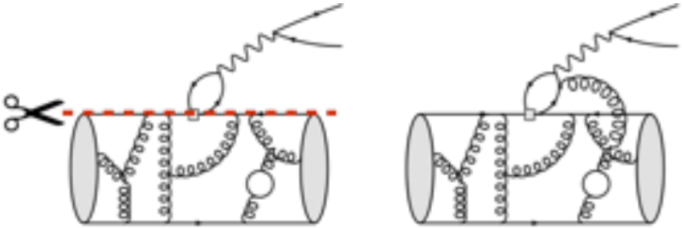
- A preliminary fit prepared by `S. Descotes-Genon, L. Hofer, J. Matias, J. Virto`, presented in arXiv::1510.04239
- The data can be explained by modifying the $C_9$ Wilson coefficient.
- Overall there is around $> 4.\ \sigma$ discrepancy wrt. SM.



# 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 .



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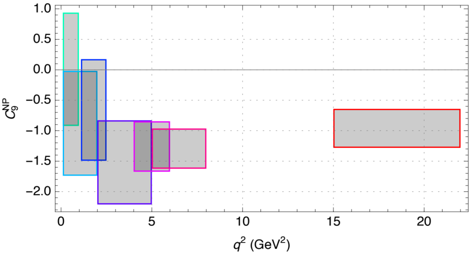
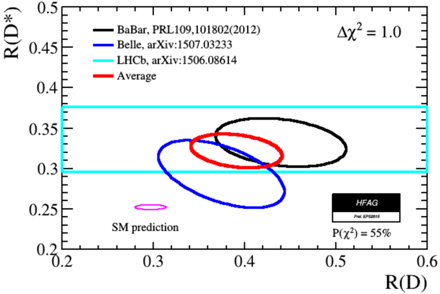


# There is more!

- There is one other LUV decay recently measured by LHCb.
- $R(D^*) = \dfrac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^* \mu\nu)}$
- 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

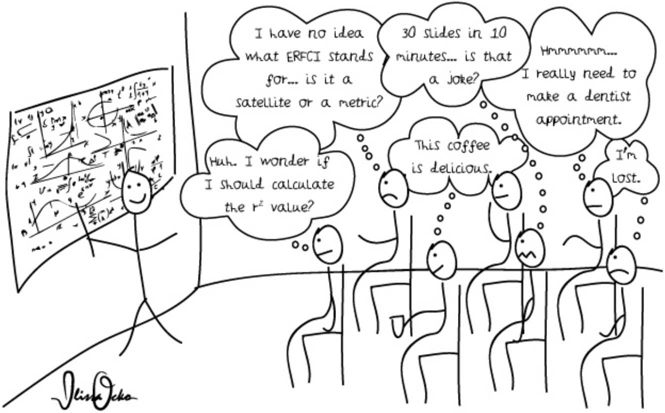
- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

# 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!



# Backup

# Theory implications

| Coefficient | Best fit | $1\sigma$ | $3\sigma$ | $\text{Pull}_{\text{SM}}$ | p-value (%) |
|---|---|---|---|---|---|
| $\mathcal{C}_7^{\text{NP}}$ | $-0.02$ | $[-0.04, -0.00]$ | $[-0.07, 0.04]$ | 1.1 | 16.0 |
| $\mathcal{C}_9^{\text{NP}}$ | $-1.11$ | $[-1.32, -0.89]$ | $[-1.71, -0.40]$ | **4.5** | 62.0 |
| $\mathcal{C}_{10}^{\text{NP}}$ | 0.58 | $[0.34, 0.84]$ | $[-0.11, 1.41]$ | 2.5 | 25.0 |
| $\mathcal{C}_{7'}^{\text{NP}}$ | 0.02 | $[-0.01, 0.04]$ | $[-0.05, 0.09]$ | 0.7 | 15.0 |
| $\mathcal{C}_{9'}^{\text{NP}}$ | 0.49 | $[0.21, 0.77]$ | $[-0.33, 1.35]$ | 1.8 | 19.0 |
| $\mathcal{C}_{10'}^{\text{NP}}$ | $-0.27$ | $[-0.46, -0.08]$ | $[-0.84, 0.28]$ | 1.4 | 17.0 |
| $\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$ | $-0.21$ | $[-0.40, 0.00]$ | $[-0.74, 0.55]$ | 1.0 | 16.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$ | $-0.69$ | $[-0.88, -0.51]$ | $[-1.27, -0.18]$ | **4.1** | 55.0 |
| $\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$ | $-0.09$ | $[-0.35, 0.17]$ | $[-0.88, 0.66]$ | 0.3 | 14.0 |
| $\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | 0.20 | $[0.08, 0.32]$ | $[-0.15, 0.56]$ | 1.7 | 19.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$ | $-1.09$ | $[-1.28, -0.88]$ | $[-1.62, -0.42]$ | **4.8** | 72.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | $-0.68$ | $[-0.49, -0.49]$ | $[-1.36, -0.15]$ | 3.9 | 50.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | $-0.17$ | $[-0.29, -0.06]$ | $[-0.54, 0.18]$ | 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.