# Quark flavour anomalies of the SM

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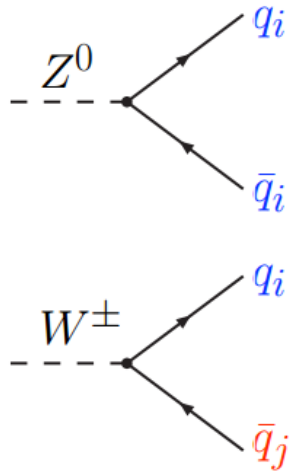
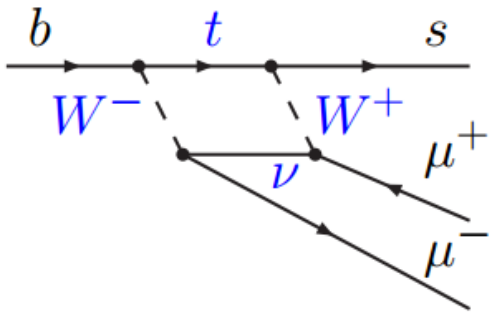
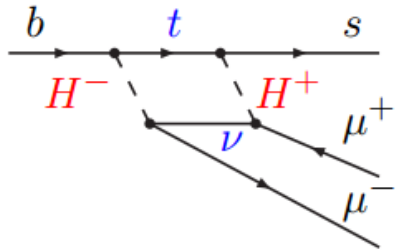
# Why electroweak penguin decays?

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





# Tools

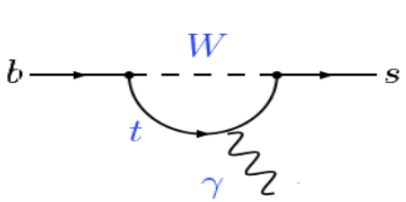
- **Operator Product Expansion and Effective Field Theory**

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

| | |
|---|---|
| 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 penguin |

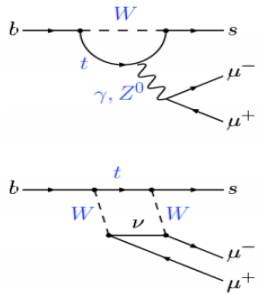
where $C_i$ are the Wilson coefficients and $O_i$ are the corresponding effective operators.

$b \to s\gamma$



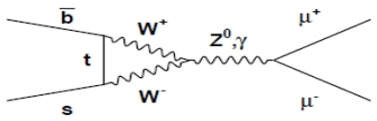

$C_7^{(\prime)}$

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




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

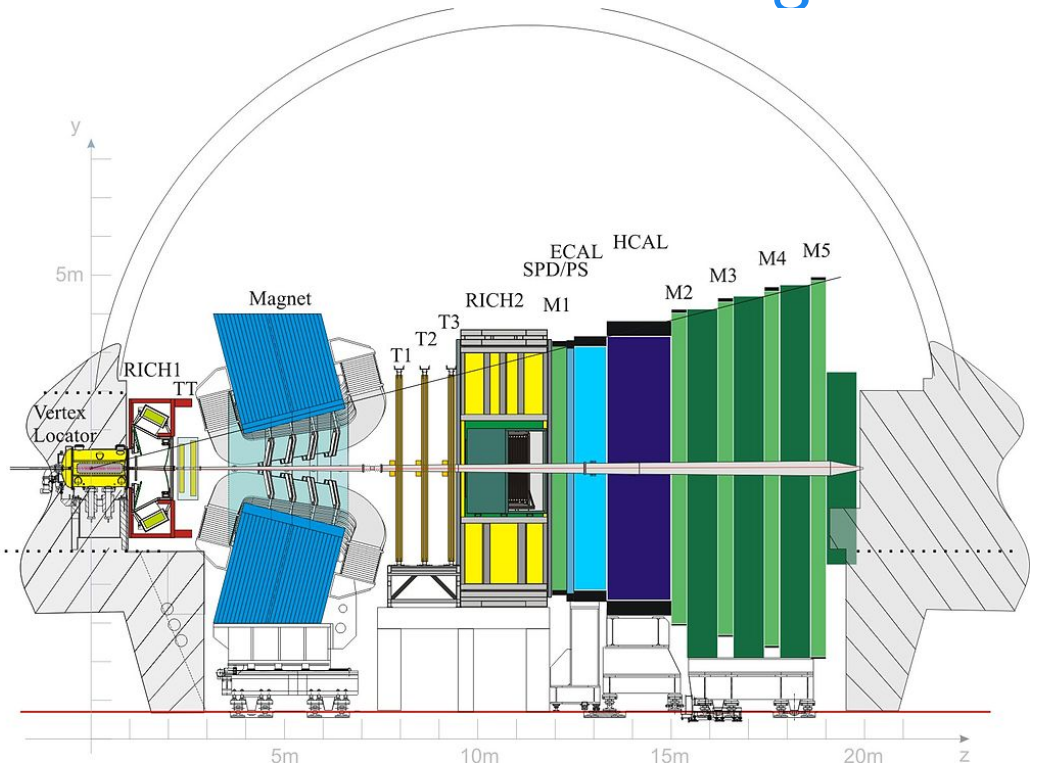
$B^0_{(s)} \to \mu^+\mu^-$

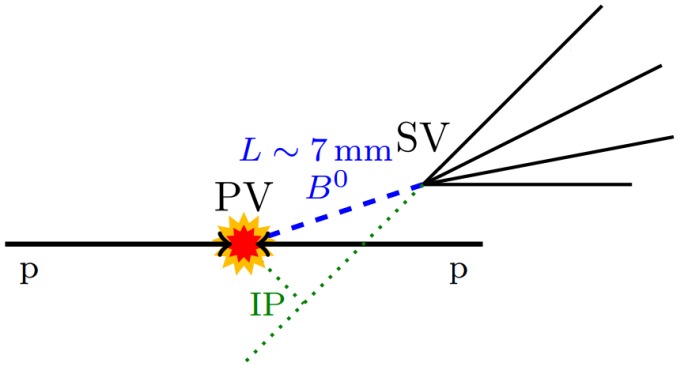



$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

# LHCb detector - tracking

*Int. J. Mod. Phys. A30 (2015) 1530022*




- Excellent Impact Parameter (IP) resolution ($20\ \mu\mathrm{m}$).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40 - 50$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.5 - 1.0\%$) and inv. mass resolution.
  $\Rightarrow$ Low combinatorial background.

# LHCb detector - PID

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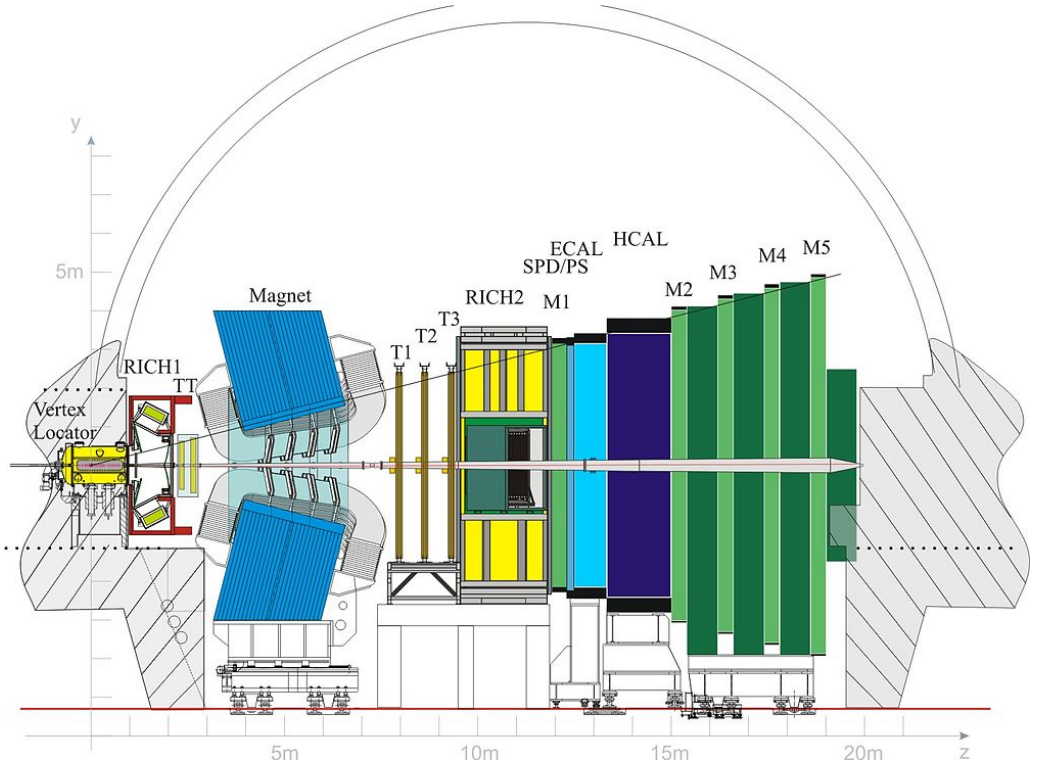


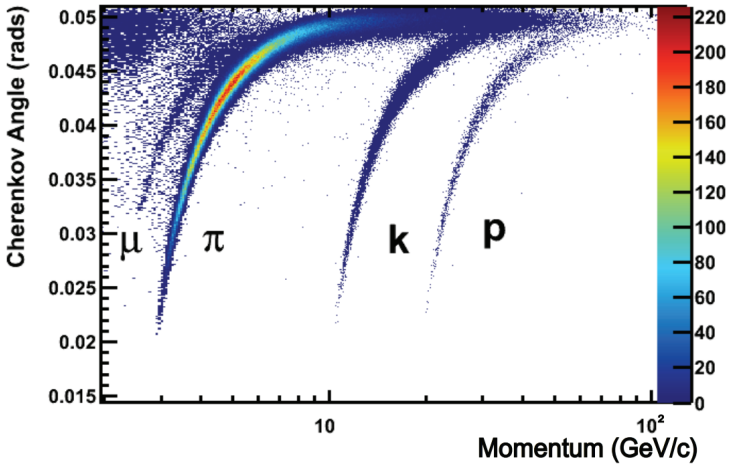


- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds.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

# Recent measurements of $b \to s\ell\ell$

## $\Rrightarrow$ Branching fractions:

$B \to K\mu^-\mu^+$ 1606.04731

$B_s^0 \to \phi\mu^-\mu^+$ JHEP 09 (2015) 179

$B^\pm \to \pi^\pm\mu^-\mu^+$ JHEP 12 (2012) 125

$\Lambda_b \to \Lambda\mu^-\mu^+$ JHEP 06 (2015) 115

$B \to \mu^-\mu^+$ Nature 15

## $\Rrightarrow$ CP asymmetry:

$B^\pm \to \pi^\pm\mu^-\mu^+$ JHEP 10 (2015) 034

## $\Rrightarrow$ Isospin asymmetry:

$B \to K\mu^-\mu^+$ JHEP 06 (2014) 133

## $\Rrightarrow$ Lepton Universality:

$B^\pm \to K^\pm\ell\bar{\ell}$ PRL 113, (2014)

## $\Rrightarrow$ Angular:

$B^0 \to K^*\ell\bar{\ell}$ JHEP 02 (2016) 104

$B^{0,\pm} \to K^{*,\pm}\ell\bar{\ell}$ PRD 86 032012

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$> 2\ \sigma$ deviations from the SM

⇛ This talk is not possible to cover all flavour anomalies.

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

⇛ 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 ($q^2$).

⇛ The angular distribution can be written as:

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

⇛ This equation is valid in the SM for massless leptons!

# Link to effective operators

$\Rightarrow$ The observables $S_i$ are bilinear combinations of transversity amplitudes: $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_0^{L,R}$.

$\Rightarrow$ 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 soft 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 soft form factors.

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

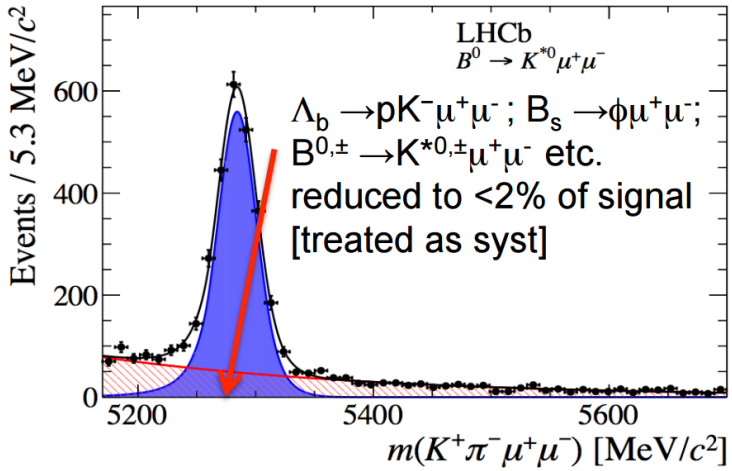
$$P_5' = \frac{S_5 + \bar{S}_5}{2\sqrt{F_L(1-F_L)}}$$

# $B^0 \to K^*\mu^-\mu^+$, 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:
  - Beside the $K^*$ resonance there might might a tail from other higher mass states.
  - We modelled it in the analysis.
  - Reduced the systematic compared to previous analysis.




- In total we found $2398 \pm 57$ candidates in the $(0.1, 19)\ \mathrm{GeV}^2/\mathrm{c}^4$ $q^2$ region.
- $624 \pm 30$ candidates in the theoretically the most interesting $(1.1 - 6.0)\ \mathrm{GeV}^2/\mathrm{c}^4$ region.

# Detector acceptance

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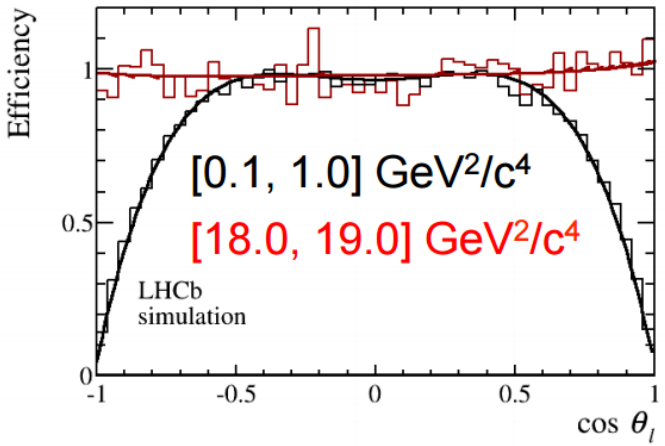
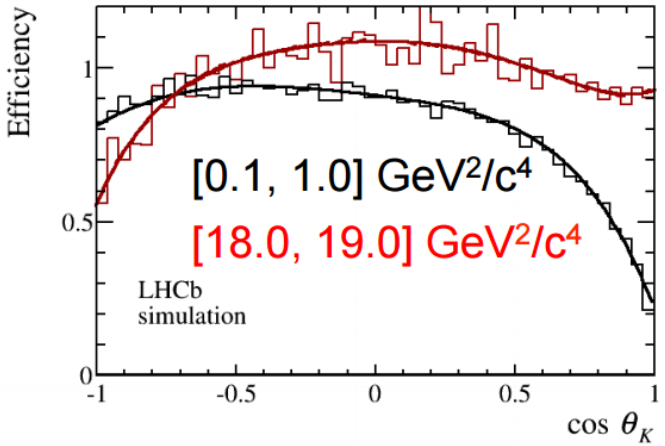
- Detector distorts our angular distribution.
- We need to model this effect.
- Full 4D function is used:

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

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 $\cos\theta_l, \cos\theta_k, \phi, q^2$.
- $600$ terms in total!

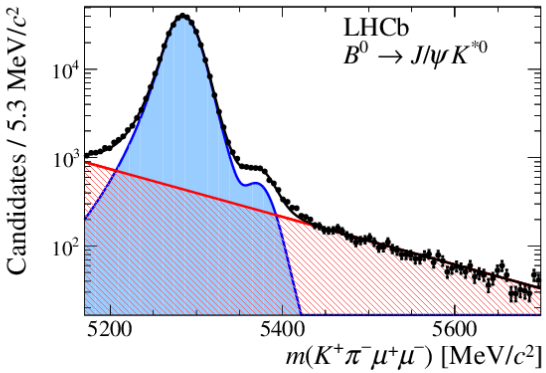


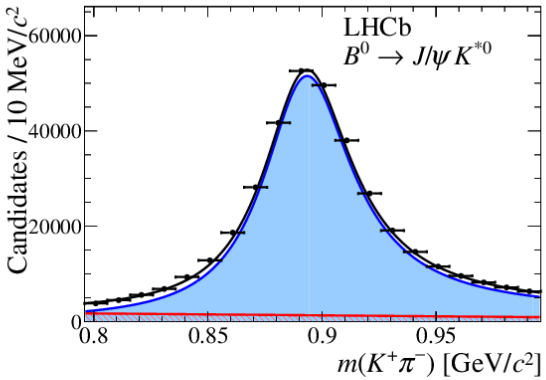



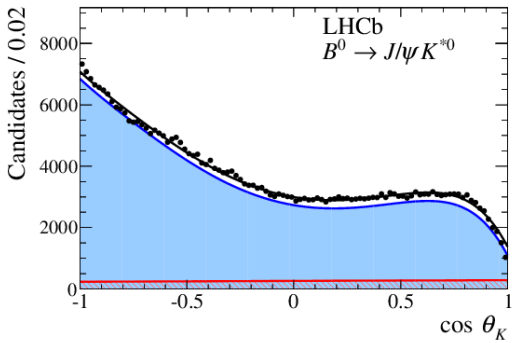
# Control channel

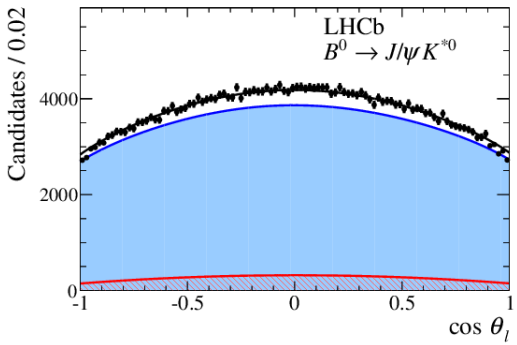


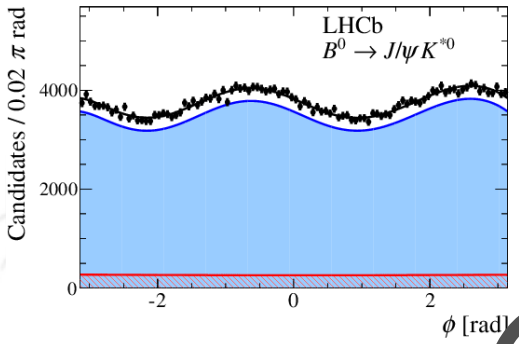
- We tested our unfolding procedure on $B \to J/\psi K^*$.
- The result is in perfect agreement with other experiments and our different analysis of this decay.



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

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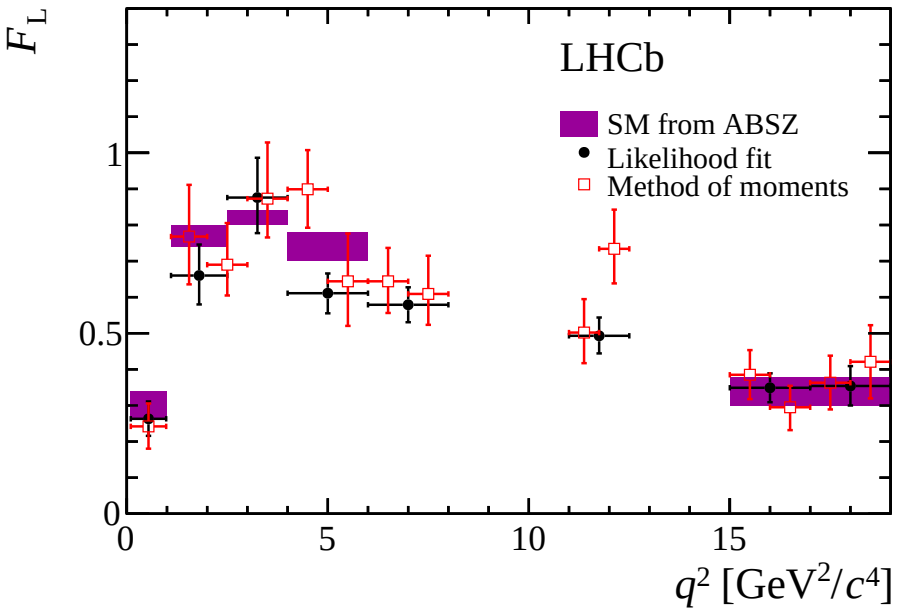


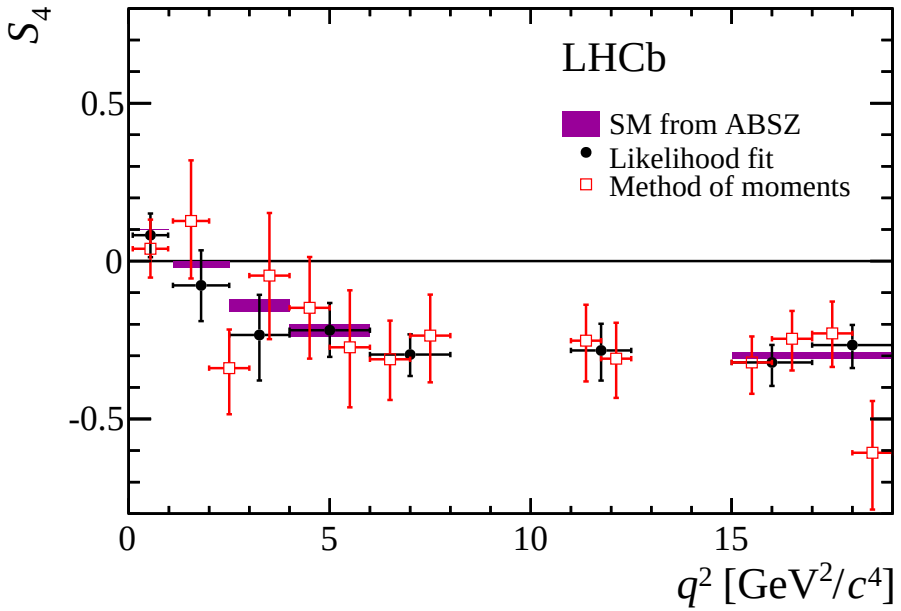


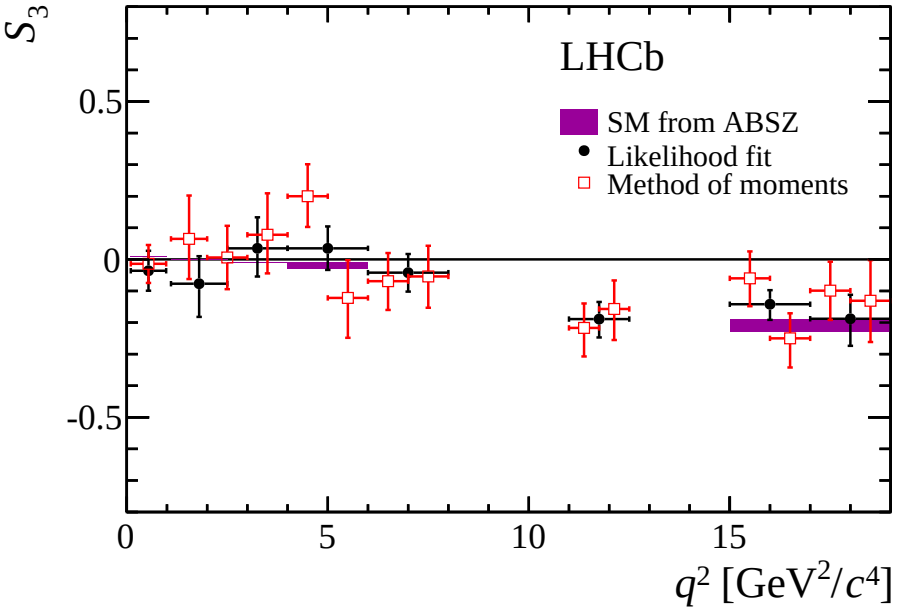


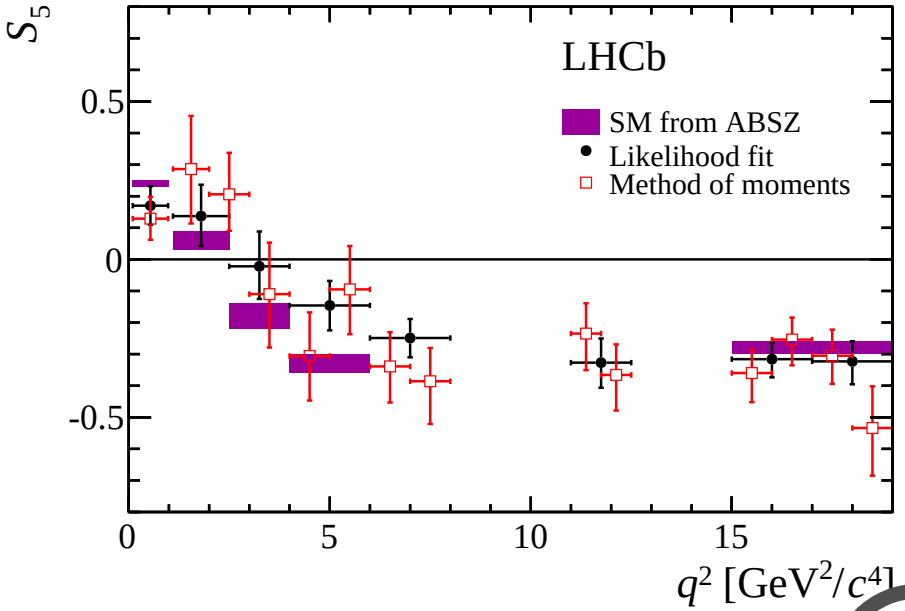

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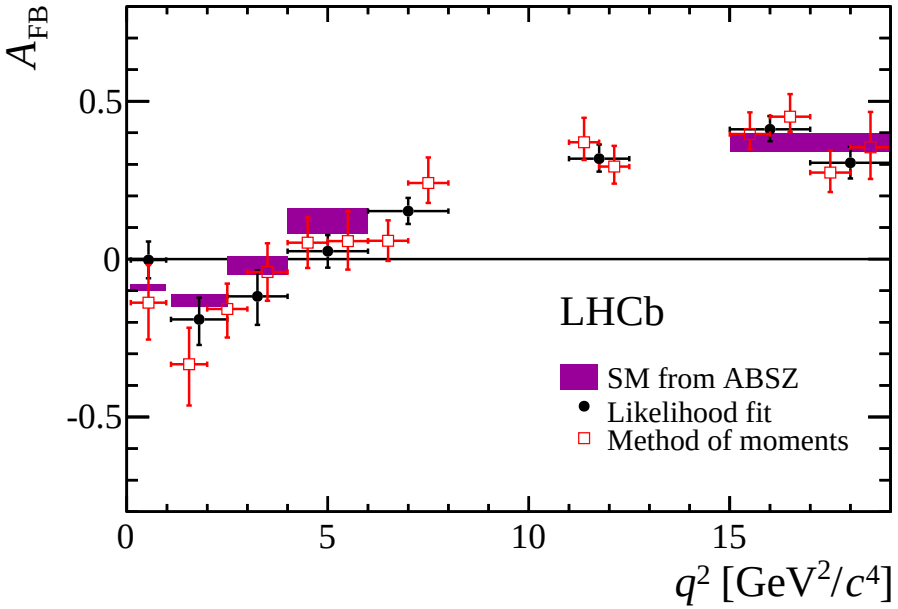


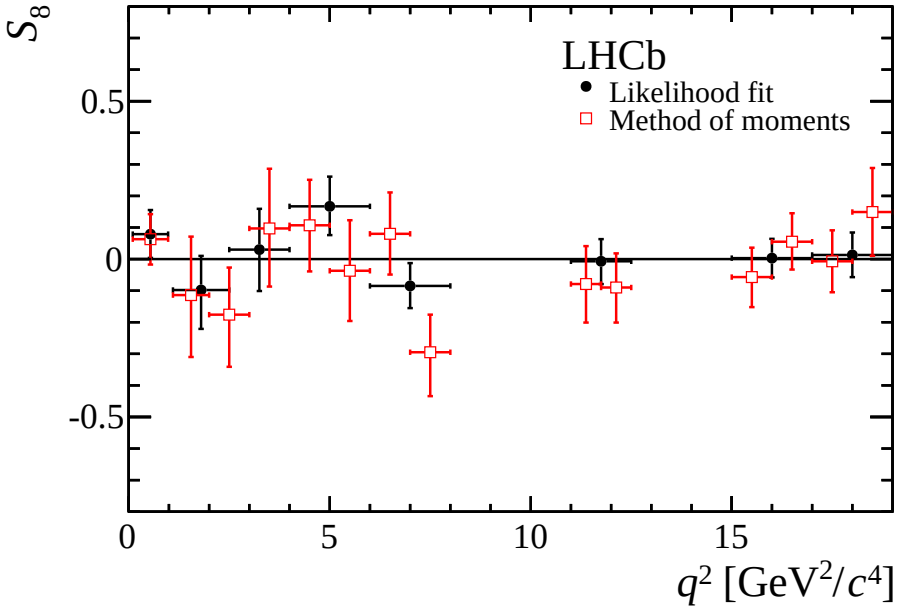


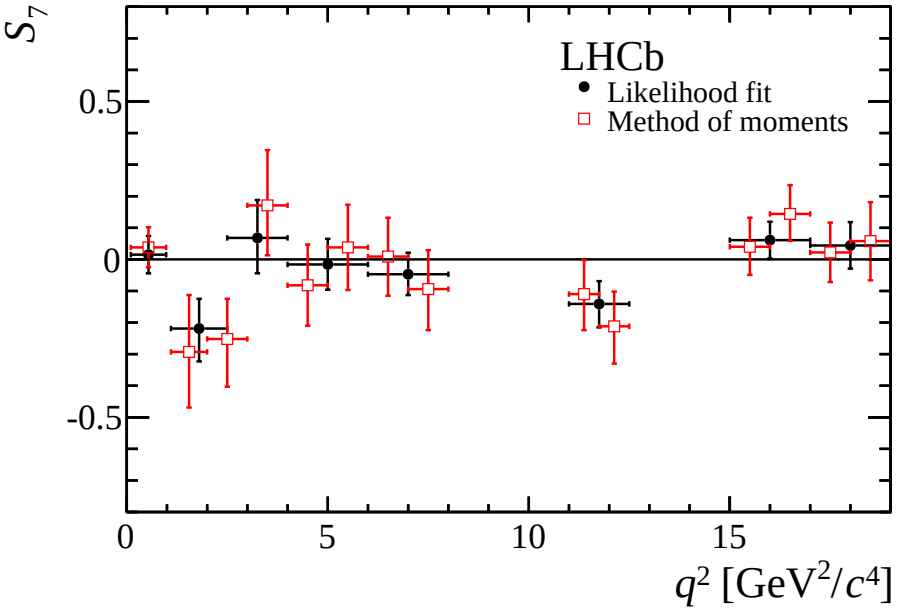


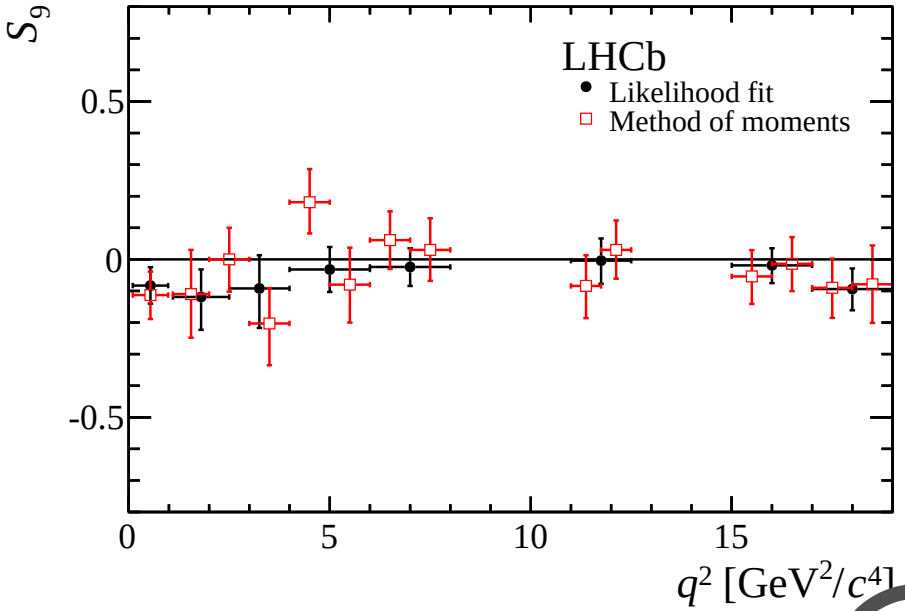

# Results in $B \to K^* \mu\mu$

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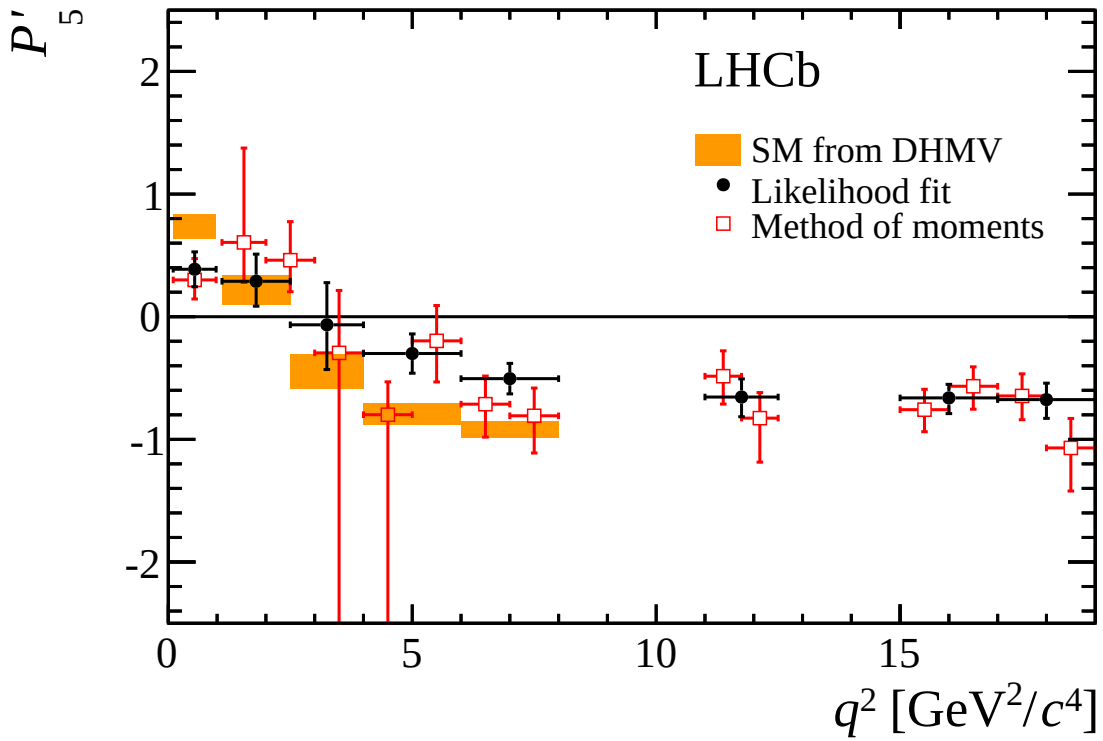
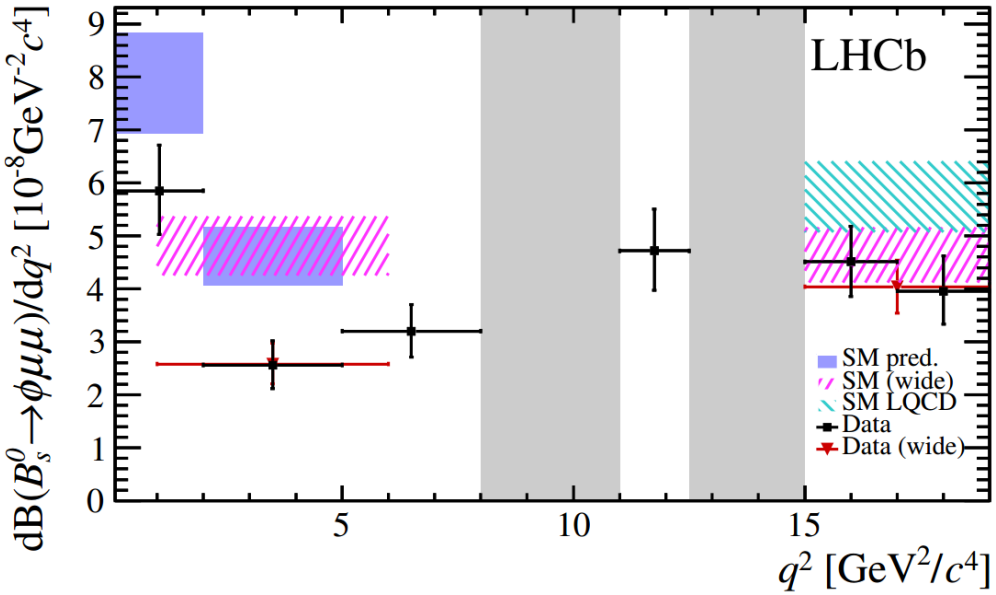
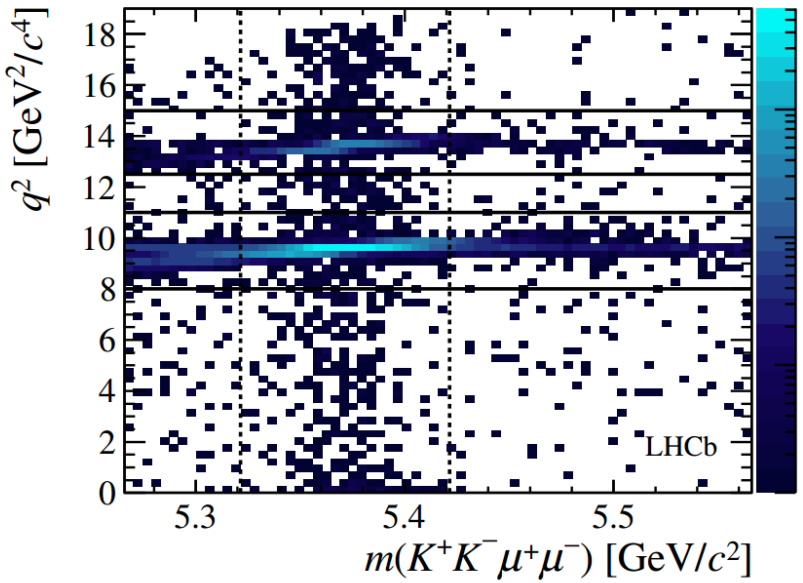



- Tension gets confirmed!
- The two bins deviate by $2.8$ and $3.0$ $\sigma$ from the SM prediction.
- Result compatible with previous result.

# BF measurements of $B_s^0 \to \phi\mu\mu$

*JHEP09 (2015) 179*

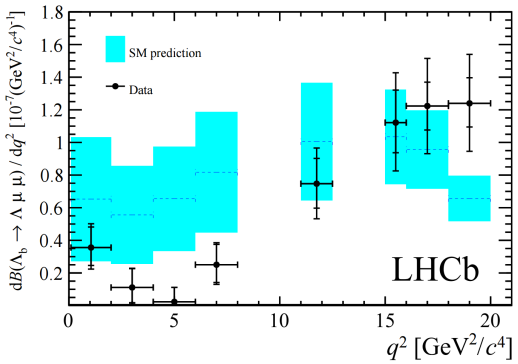


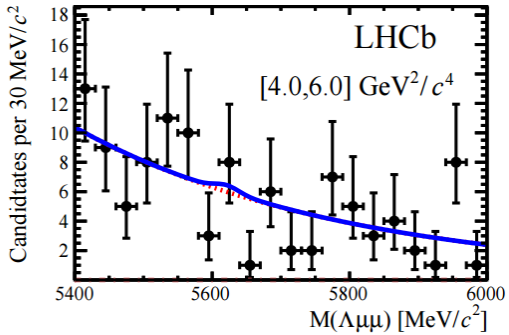



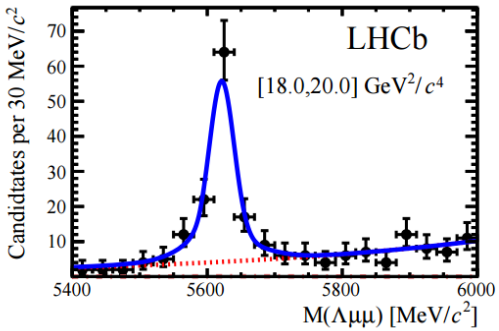

- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow $\phi$ resonance.
- $3.3\ \sigma$ deviation in the SM in the $1 - 6\mathrm{GeV}^2/\mathrm{c}^4$ bin.
- Angular part in agreement with the SM ($S_5$ is not accessible).

# Measurements of $\Lambda_b \to \Lambda\mu\mu$

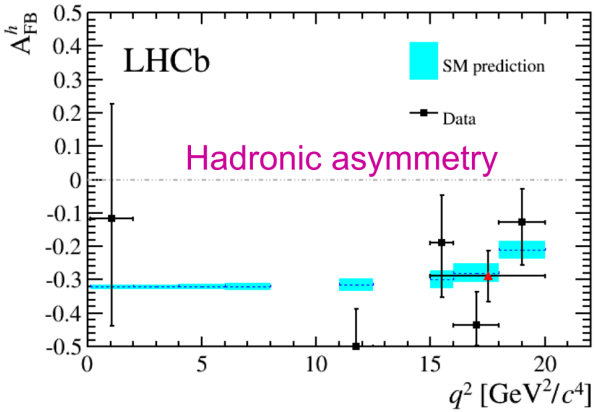
JHEP 06 (2015) 115

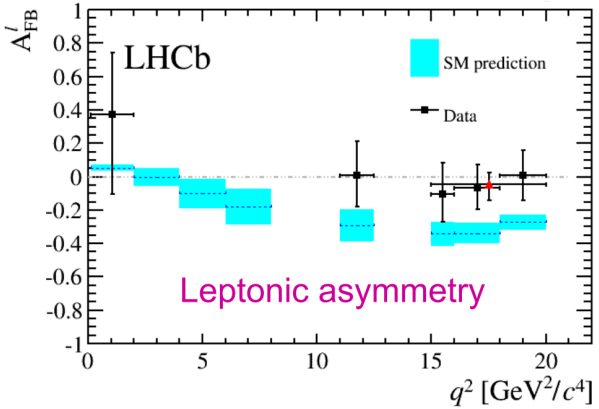



- In total $\sim 300$ candidates in data set.
- Decay not present in the low $q^2$.
- For the bins in which we have $> 3\ \sigma$ significance the forward backward asymmetry is measured for the hadronic and leptonic system.



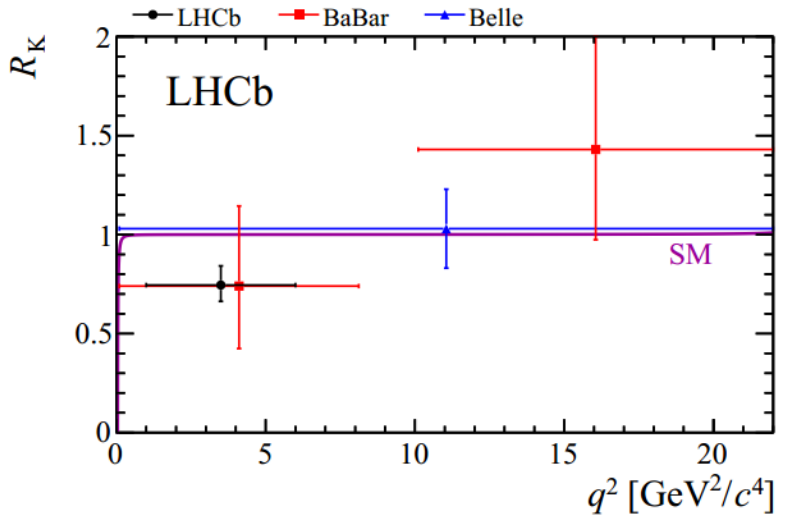



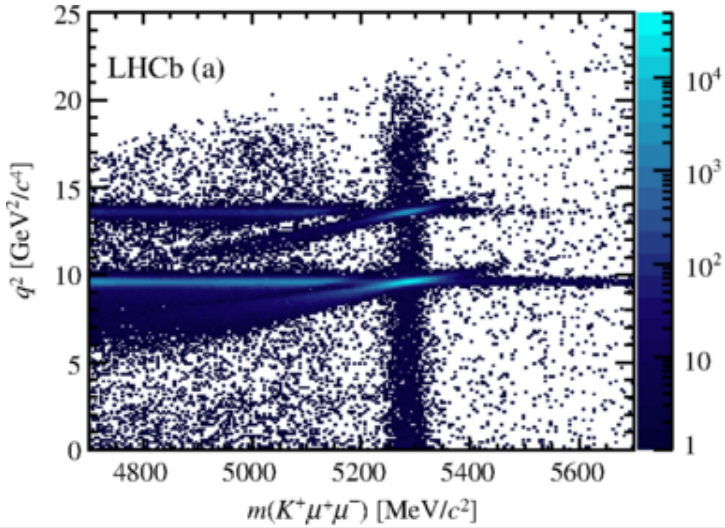
# Lepton universality test

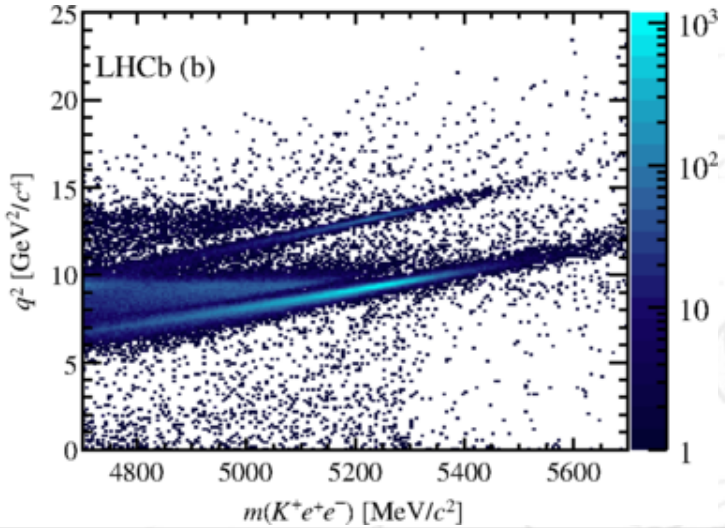
*Phys. Rev. Lett. 113, 151601 (2014)*

- 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 $3\text{fb}^{-1}$, LHCb measures
  $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with the SM at $2.6\sigma$.

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



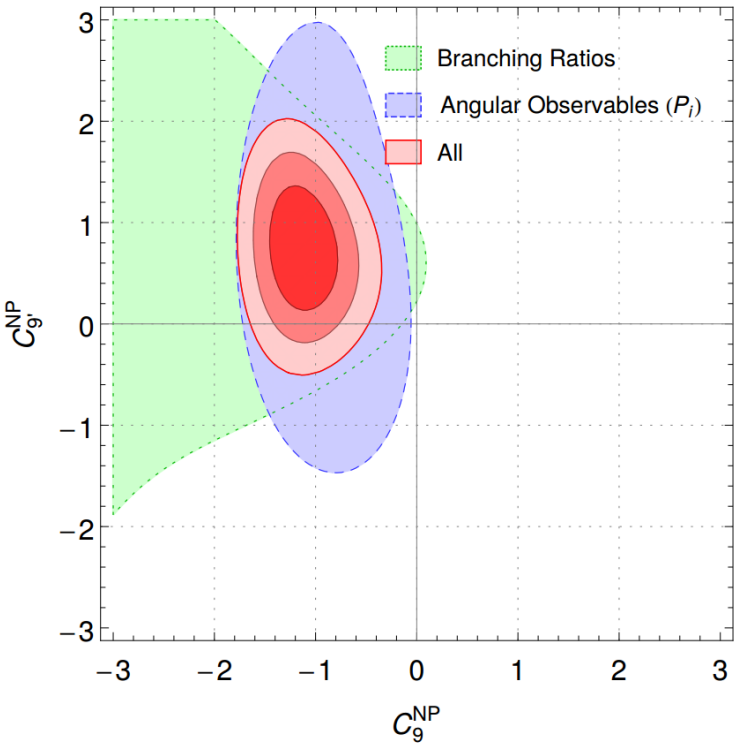



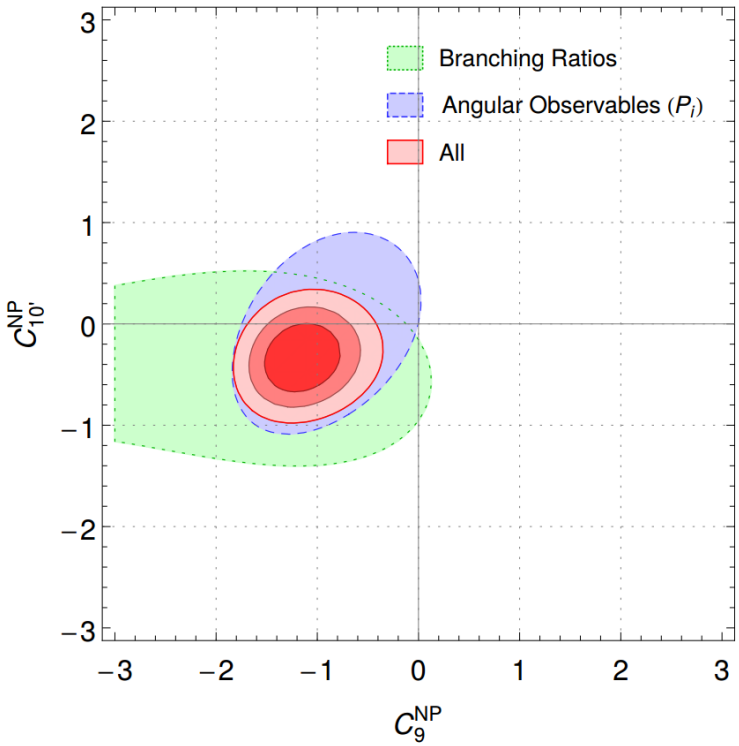



# Theory implications

JHEP 06 (2016) 092

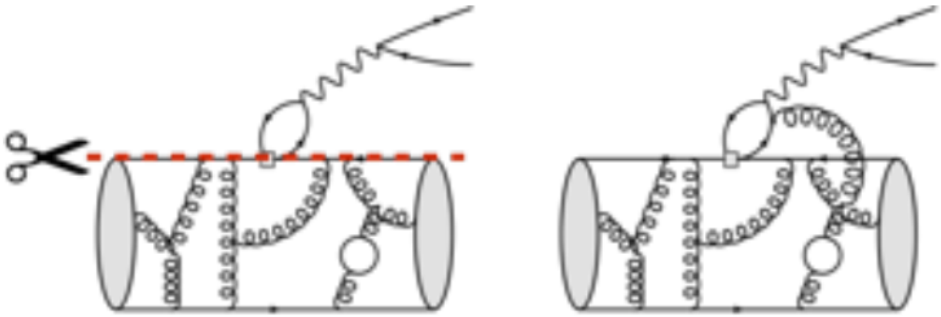
- A fit prepared by `S. Descotes-Genon, L. Hofer, J. Matias, J. Virto`.
- The data can be explained by modifying the $C_9$ Wilson coefficient.
- Overall there is $> 4\ \sigma$ discrepancy wrt. the SM prediction.



# 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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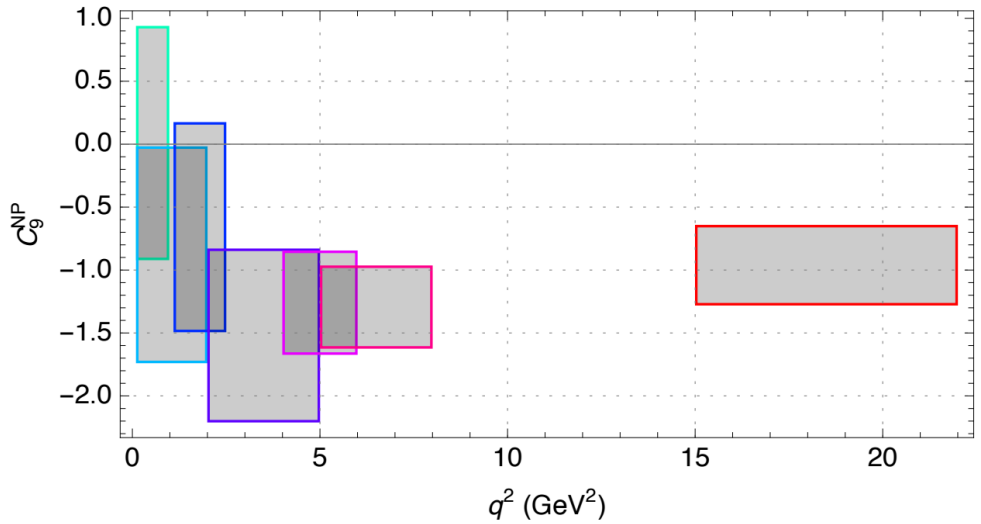

# Grab it While it's Hot!

- ⇛ Yesterday(18.04) we shown a new preliminary result: CERN Seminar
- ⇛ We measured the ratio:

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}$$

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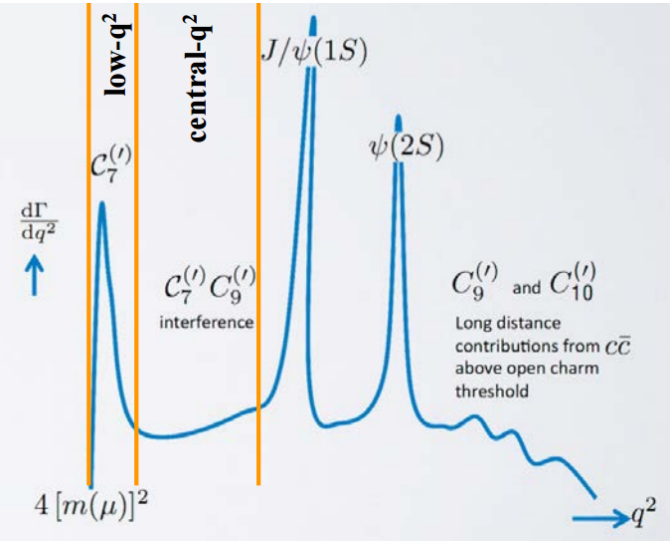
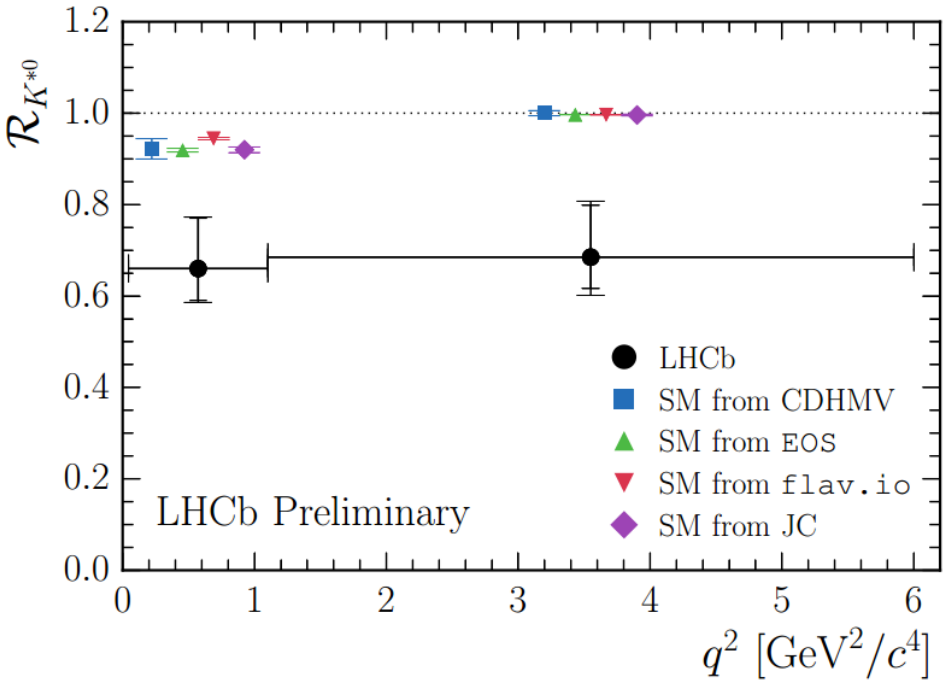
$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}$$

⇛ Measurement performed in two $q^2$ bins.

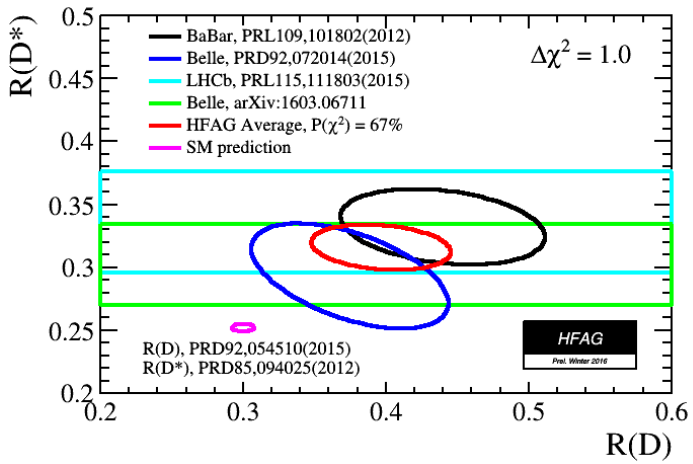
⇛ Normalized in double ratio to $B \to K^* J/\psi$.



# There is more!

- There is one other Lepton Universality Violation 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: $R(D^*) = 0.322 \pm 0.022$
- $4.0\ \sigma$ 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.
- More data will shade a light on the matter.
- Time will tell if this is QCD+fluctuations or new Physics:

# Conclusions

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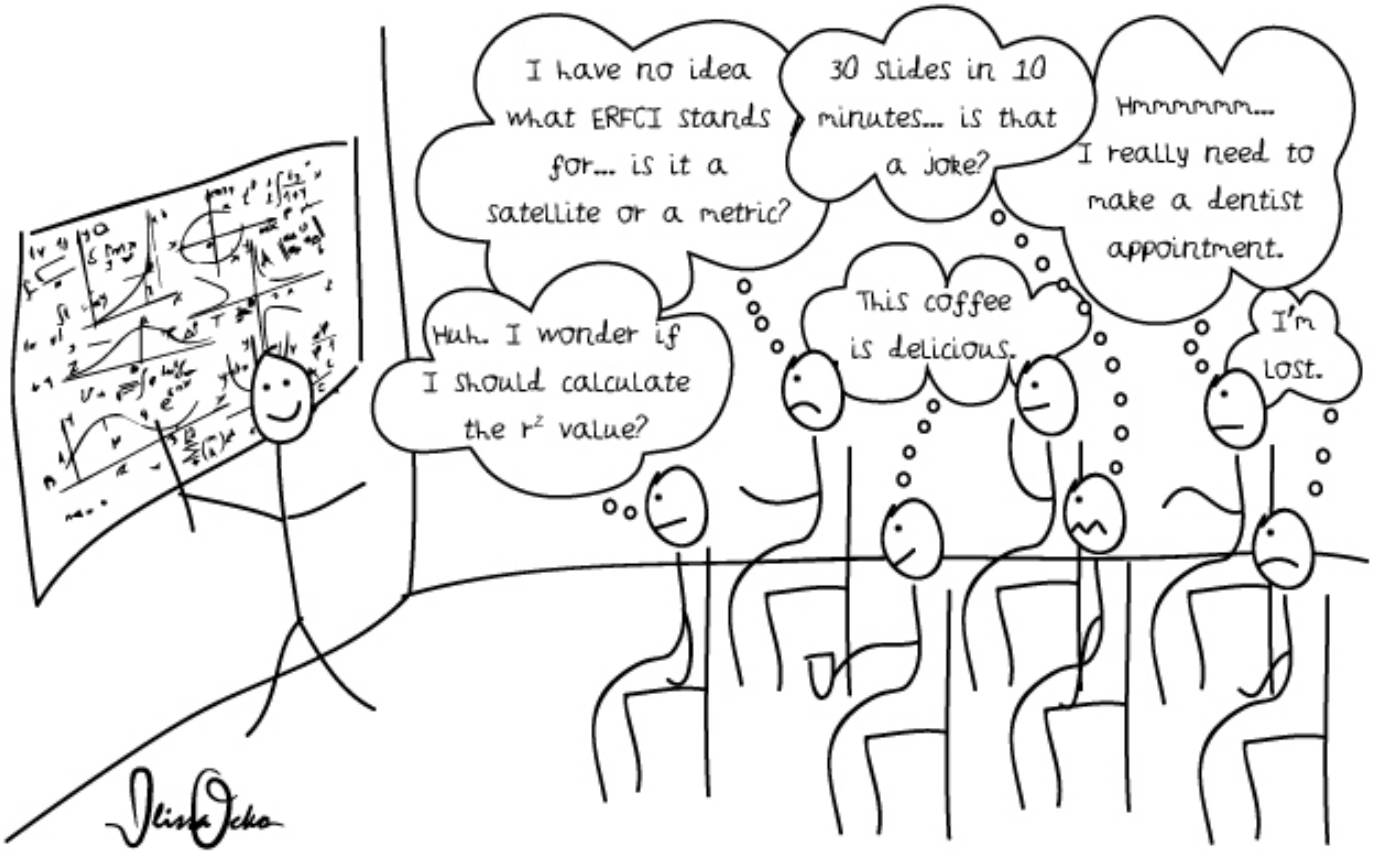
"... when you have eliminated all the
Standard Model explanations, whatever remains,
however improbable, must be New Physics."
Prof. Joaquim Matias

# Thank you for the attention!



# Backup

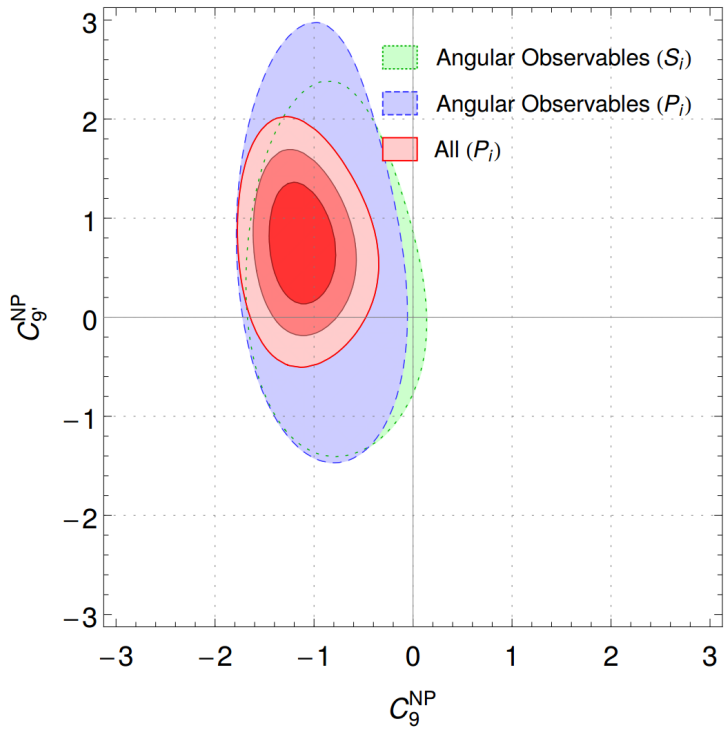
# Theory implications

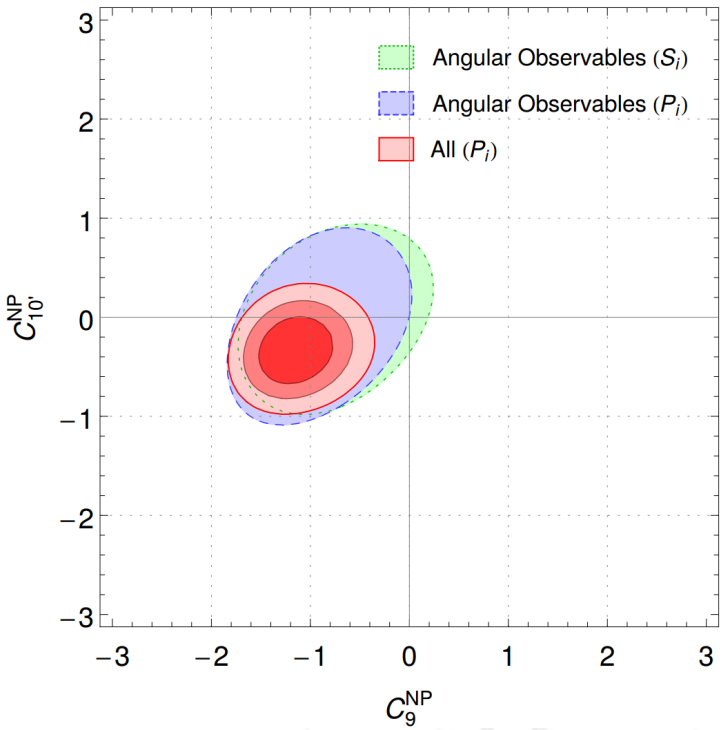
| Coefficient | Best fit | $1\sigma$ | $3\sigma$ | $\text{Pull}_{\text{SM}}$ | p-value (%) |
|---|---|---|---|---|---|
| $\mathcal{C}_7^{\text{NP}}$ | $-0.02$ | $[-0.04, -0.00]$ | $[-0.07, 0.04]$ | 1.1 | 16.0 |
| $\mathcal{C}_9^{\text{NP}}$ | $-1.11$ | $[-1.32, -0.89]$ | $[-1.71, -0.40]$ | **4.5** | 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.



# Transversity amplitudes

$\Rightarrow$ 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

$\Rightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as (soft form factors):

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

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

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\parallel(E_{K^*}),$$

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

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

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

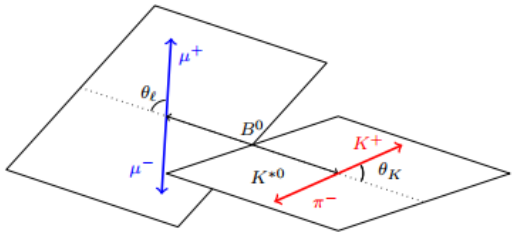
# $B^0 \to K^* \mu^- \mu^+$ kinematics

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

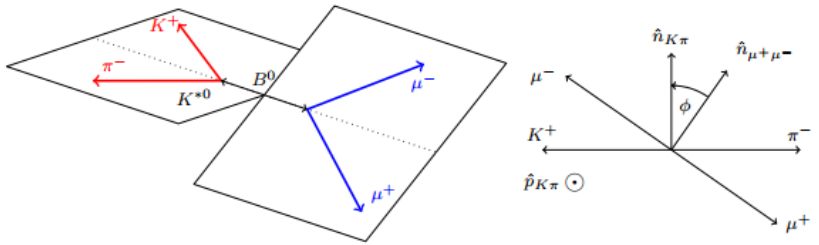
$\Rightarrow$ $\cos\theta_k$: the angle between the direction of the kaon in the $K^*$ ($\overline{K}^*$) rest frame and the direction of the $K^*$ ($\overline{K}^*$) in the $B^0$ ($\bar{B}^0$) rest frame.

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

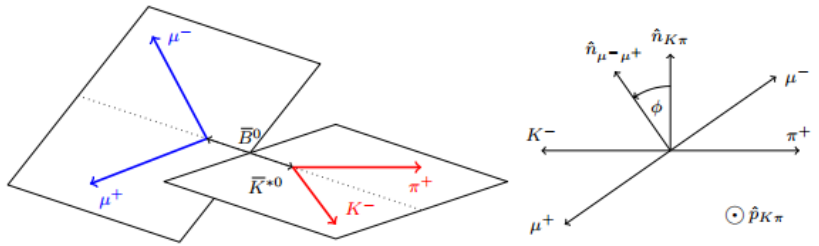
$\Rightarrow$ $\phi$: the angle between the plane containing the $\mu^-$ and $\mu^+$ and the plane containing the kaon and pion from the $K^*$.




(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:

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

# Link to effective operators

$\Rightarrow$ The observables $J_i$ are bilinear combinations of transversity amplitudes: $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_0^{L,R}$.

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

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

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

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[ (\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\parallel(E_{K^*}),$$

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

$\Rightarrow$ Now we can construct observables that cancel the $\xi$ soft 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 $B \to K^* \mu\mu$

$\Rrightarrow$ We have 12 angular coefficients ($S_i$).
$\Rrightarrow$ There exist 4 symmetry transformations that leave the angular distributions unchanged:

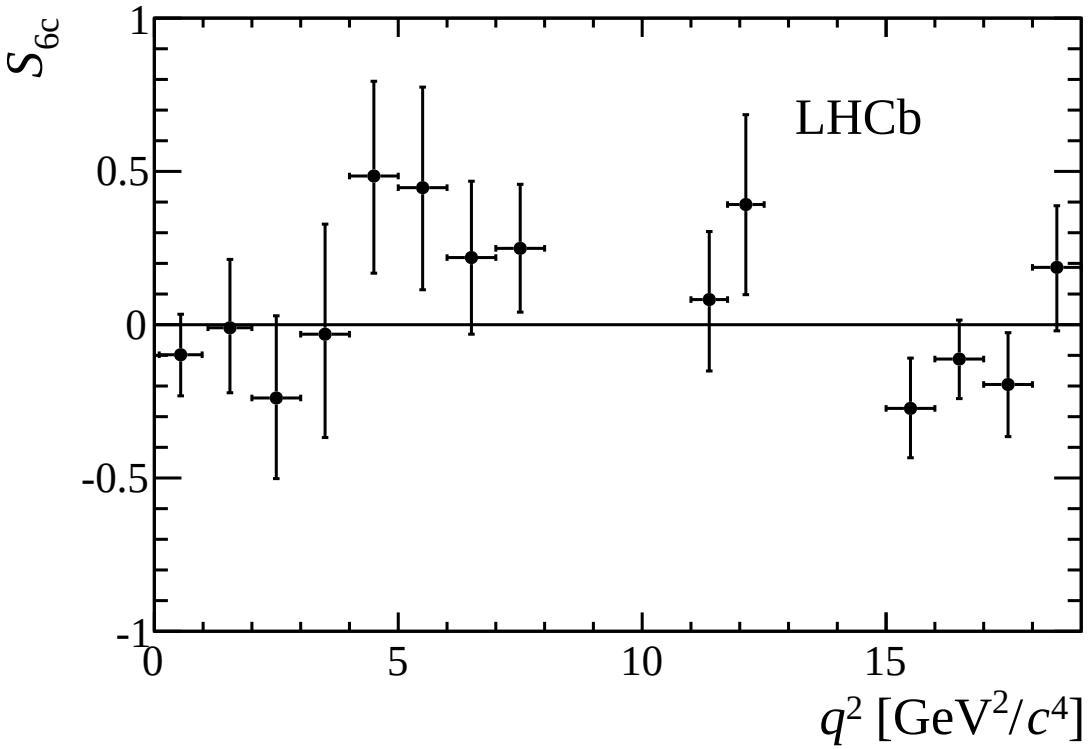
$$n_\parallel = \begin{pmatrix} A_\parallel^L \\ A_\parallel^{R*} \end{pmatrix}, \quad n_\perp = \begin{pmatrix} A_\perp^L \\ -A_\perp^{R*} \end{pmatrix}, \quad n_0 = \begin{pmatrix} A_0^L \\ A_0^{R*} \end{pmatrix}.$$

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

$\Rrightarrow$ Using this symmetries one can show that there are 8 independent observables. The pdf can be written as:

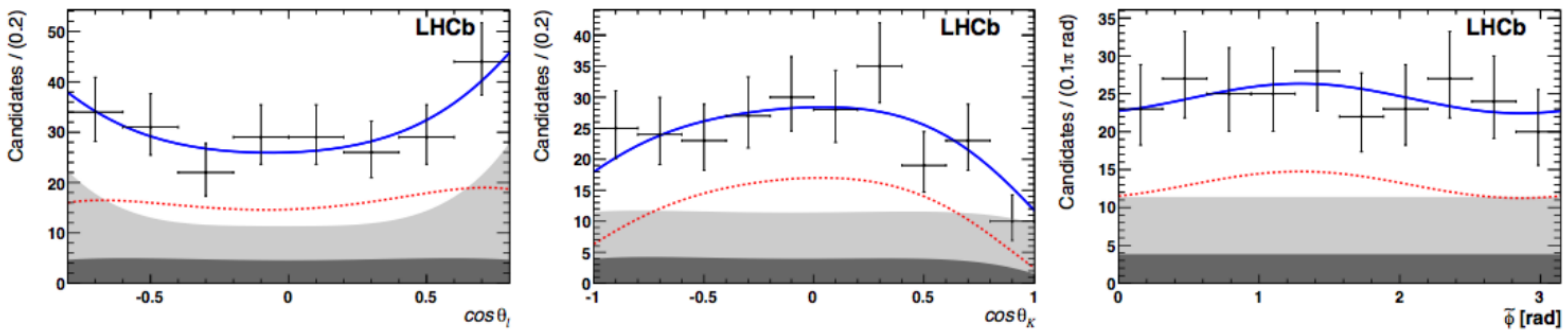
$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l \, \mathrm{d}\cos\theta_k \, \mathrm{d}\phi}\bigg|_{\mathrm{P}} = \frac{9}{32\pi} \Big[ & \tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k \\ & + F_{\mathrm{L}}\cos^2\theta_k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

- Thanks to Method of Moments there was the possibility to measure a new observable $S_{6c}$.




- Measurement is consistent with the SM prediction.

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

*JHEP 04 (2015) 064*

- With the full data set ($3\,\mathrm{fb}^{-1}$) we performed angular analysis in $0.0004 < q^2 < 1\ \mathrm{GeV}^2/\mathrm{c}^4$.
- Electrons channels are extremely challenging experimentally:
  - Bremsstrahlung.
  - Trigger efficiencies.
- Determine the angular observables: $F_\mathrm{L}$, $A_\mathrm{T}^{(2)}$, $A_\mathrm{T}^\mathrm{Re}$, $A_\mathrm{T}^\mathrm{Im}$:
- Results in full agreement with the SM.
- Similar strength on $C_7$ Wilson coefficient as from $b \to s\gamma$ decays.