Anomalies in Flavour Physics

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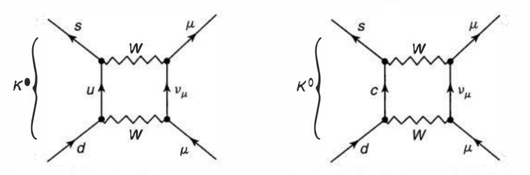
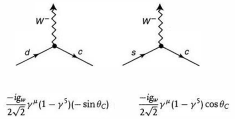
Outline

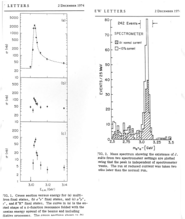
1. History of Flavour Physics discoveries.
2.
3.

A lesson from history - GIM mechanism

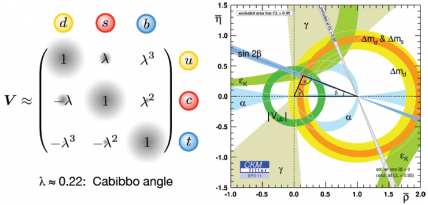


- Cabibbo angle was successful at explaining dozens of decay rates in the 1960s.
- There was one how ever that was not observed by experiments: $K^0 \rightarrow \mu^-\mu^+$.
- Glashow, Iliopoulos, Maiani (GIM) mechanism was proposed in the 1970 to fix this problem. The mechanism required the existence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

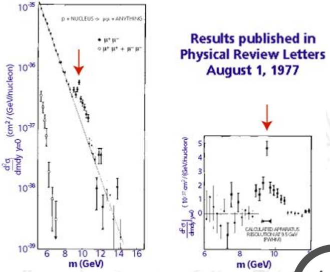




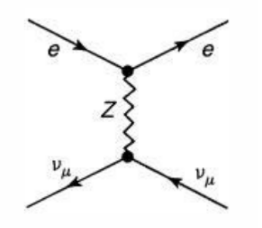
A lesson from history - CKM matrix

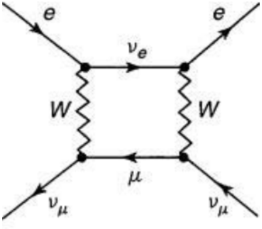


- Similarly CP violation was discovered in 1960s in the neutral kaons decays.
- 2×2 Cabbibo matrix could not allow for any CP violation.
- For the CP violation to be possible one needs atleast 3×3 unitary matrix $\looparrowright$ Cabibbo-Kobayashi-Maskawa matrix (1973).
- It predicts existence of b (1977)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

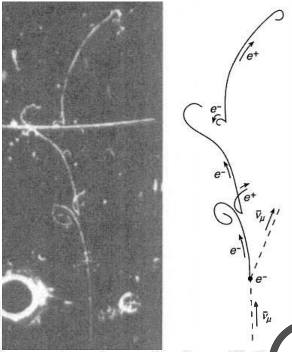


A lesson from history - Weak neutral current



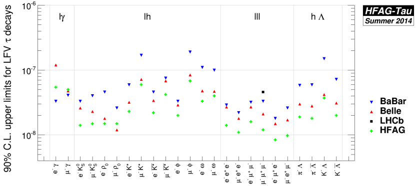


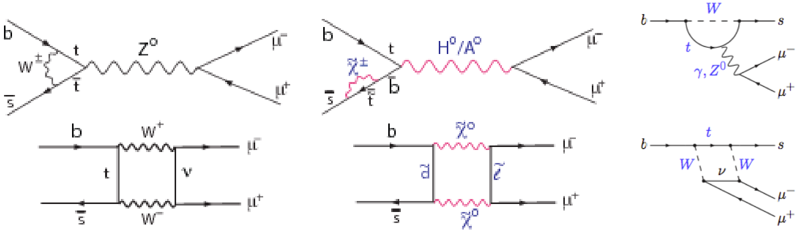
- First the weak neutral currents were introduced in 1958 by Buldman.
- Later on they were naturally build in unification of weak and electromagnetic interactions.
- 't Hooft proved that the GWS models was renormalizable.
- Everything was there in theory side, only missing piece was the experiment, till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



Modern challenges: loops come in to the game

- Standard Model contributions suppressed or absent:
  - Flavour Changing Neutral Currents.
  - CP violation
  - Lepton Flavour/Number or Lepton Universality violation.
- In general can probe physics beyond GPD reach.





Recent measurements

⇛ Branching fractions:

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

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

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

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

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

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

⇛ CP asymmetry:

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

⇛ Isospin asymmetry:

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

⇛ Lepton Universality:

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

⇛ Angular:

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

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

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

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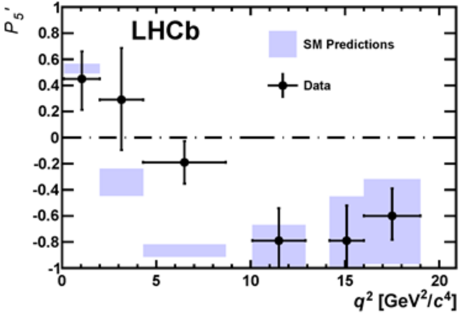
$> 2\ \sigma$ deviations from SM

$B^0 \to K^* \mu^- \mu^+$, where it all begun

August 2013:



- LHCb observed a deviation in $4.3 - 8.68\ \mathrm{GeV}^2$ using $1\ \mathrm{fb}^{-1}$ of data.
- It turned out that the discrepancy occurred in an observable that was not constrained.

$B^0 \to K^* \mu^- \mu^+$, where it all begun

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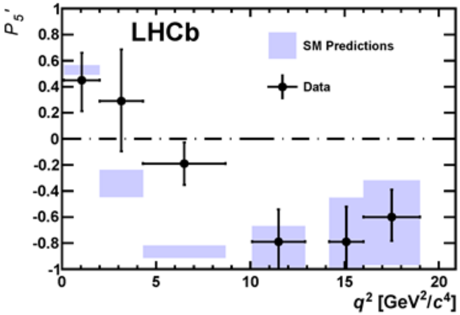

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Now let's move back and see the theory behind the $B^0 \to K^* \mu^- \mu^+$ and P_5'.

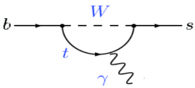
- **Operator Product Expansion and Effective Field Theory**

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

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

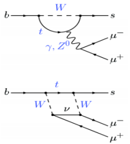
where C_i are the Wilson coefficients and O_i are the corresponding effective operators.

$b \to s\gamma$



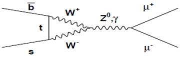
$C_7^{(\prime)}$

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



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

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



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

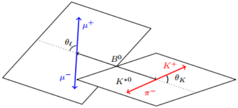
$B^0 \to K^* \mu^- \mu^+$ kinematics

⇛ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decays is described in three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

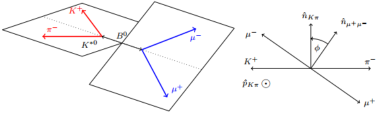
⇛ $\cos\theta_k$: the angle between the direction of the kaon in the K^* ($\overline{K^*}$) rest frame and the direction of the K^* ($\overline{K^*}$) in the B^0 ($\overline{B}^0$) rest frame.

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

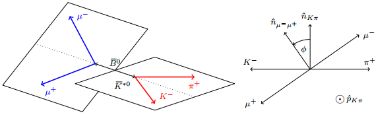
⇛ ϕ: the angle between the plane containing the μ^- and μ^+ and the plane containing the kaon and pion from the K^*.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



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

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

⇛ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decays is described in three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

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

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

Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

$$\begin{aligned}
J_{1s} &= \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2+|A_\parallel^L|^2+|A_\perp^R|^2+|A_\parallel^R|^2\right]+\frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R\,*}+A_\parallel^L A_\parallel^{R\,*}\right)\,,\\
J_{1c} &= |A_0^L|^2+|A_0^R|^2+\frac{4m_\ell^2}{q^2}\left[|A_t|^2+2\mathrm{Re}(A_0^L A_0^{R\,*})\right]+\beta_\ell^2\,|A_S|^2\,,\\
J_{2s} &= \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2+|A_\parallel^L|^2+|A_\perp^R|^2+|A_\parallel^R|^2\right], \qquad J_{2c}=-\beta_\ell^2\left[|A_0^L|^2+|A_0^R|^2\right],\\
J_3 &= \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2-|A_\parallel^L|^2+|A_\perp^R|^2-|A_\parallel^R|^2\right], \qquad J_4=\frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L\,*}+A_0^R A_\parallel^{R\,*})\right],\\
J_5 &= \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L\,*}-A_0^R A_\perp^{R\,*})-\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^*+A_\parallel^{R\,*}A_S)\right],\\
J_{6s} &= 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L\,*}-A_\parallel^R A_\perp^{R\,*})\right], \qquad J_{6c}=4\beta_\ell\,\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^*+A_0^{R\,*}A_S)\,,\\
J_7 &= \sqrt{2}\beta_\ell\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\parallel^{\mathrm{L}\,*}-\mathrm{A}_0^\mathrm{R}\mathrm{A}_\parallel^{\mathrm{R}\,*})+\frac{\mathrm{m}_\ell}{\sqrt{\mathrm{q}^2}}\mathrm{Im}(\mathrm{A}_\perp^\mathrm{L}\mathrm{A}_\mathrm{S}^*-\mathrm{A}_\perp^{\mathrm{R}\,*}\mathrm{A}_\mathrm{S}))\right],\\
J_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\perp^{\mathrm{L}\,*}+\mathrm{A}_0^\mathrm{R}\mathrm{A}_\perp^{\mathrm{R}\,*})\right], \qquad J_9=\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_\parallel^{\mathrm{L}\,*}\mathrm{A}_\perp^\mathrm{L}+\mathrm{A}_\parallel^{\mathrm{R}\,*}\mathrm{A}_\perp^\mathrm{R})\right], \qquad (2)
\end{aligned}$$

Link to effective operators

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

$$
\begin{aligned}
A_{\perp}^{L,R} &= \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}) \\
A_{\parallel}^{L,R} &= -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}) \\
A_{0}^{L,R} &= -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}),
\end{aligned} \tag{3}
$$

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

Link to effective operators

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

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

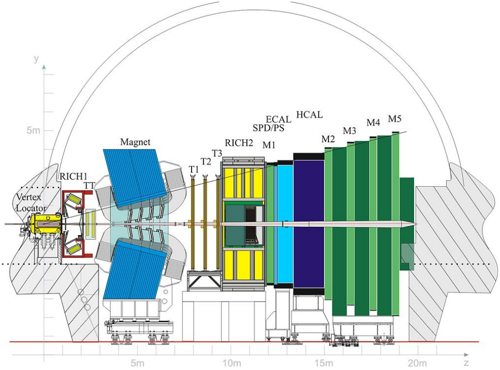
$$A_{0}^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9^{\rm eff\prime})\mp(\mathcal{C}_{10}-\mathcal{C}_{10}^{\prime})+2\hat{m}_b(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\parallel}(E_{K^*}), \quad (3)$$

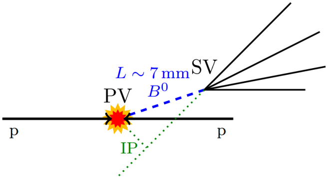
where $\hat{s}=q^2/m_B^2$, $\hat{m}_i=m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

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

$$P_5^{\prime} = \frac{J_5+\bar{J}_5}{2\sqrt{-(J_2^c+\bar{J}_2^c)(J_2^s+\bar{J}_2^s)}} \quad (4)$$

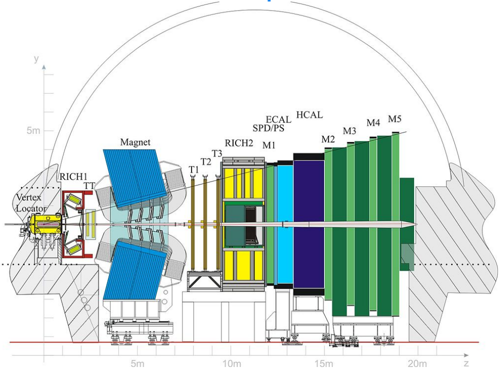
LHCb detector - tracking

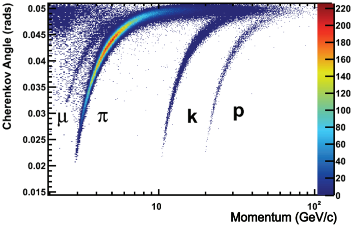




- Excellent Impact Parameter (IP) resolution ($20\ \mu$m).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass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

LHCb detector - particle identification

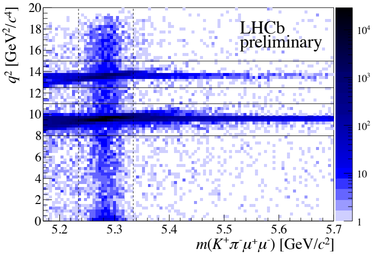


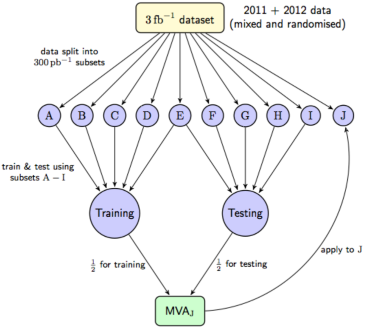


- Excellent Muon identification $\epsilon_{\mu\rightarrow\mu} \sim 97\%$, $\epsilon_{\pi\rightarrow\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\rightarrow K} \sim 95\%$, $\epsilon_{\pi\rightarrow K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies,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

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

- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to discriminate signal and background.
- Reject the regions of J/ψ 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 $1\mathrm{fb}^{-1}$ analysis.

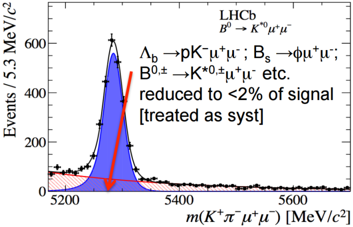




LHCb update of the $B^0 \to K^* \mu^- \mu^+$, Selection

- 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.



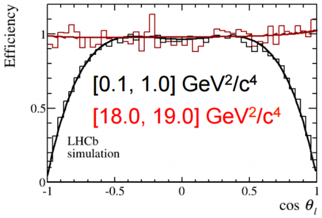
- In total we found 2398 ± 57 candidates in the $0.1 - 19\ \mathrm{GeV}^2$ q^2 region.
- 624 ± 30 candidates in the theoretically the most interesting $1.1 - 6.0\ \mathrm{GeV}^2$ region.

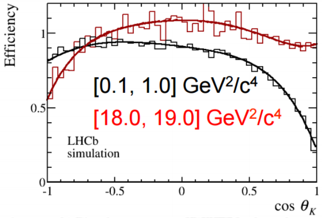
Detector acceptance

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

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

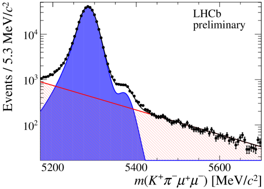
  where P_i is the Legendre polynomial of order i.
- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.

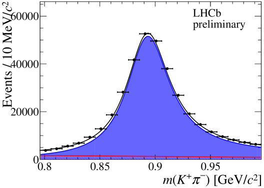


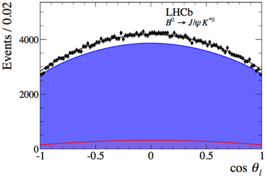


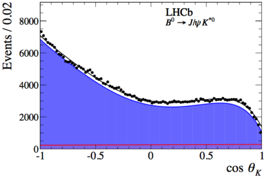
Control channel

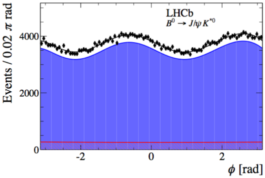
- We tested our unfolding procedure on $B \to J/\psi K^{*}$.
- The result is in perfect agreement with other experiments and our different analysis of this decay.



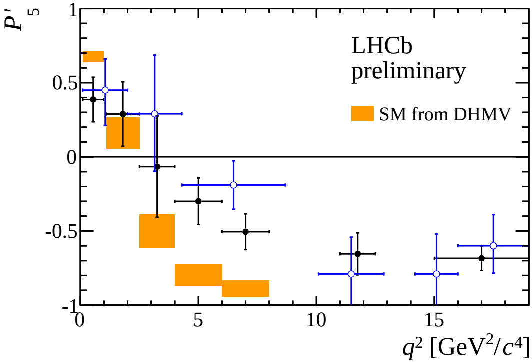






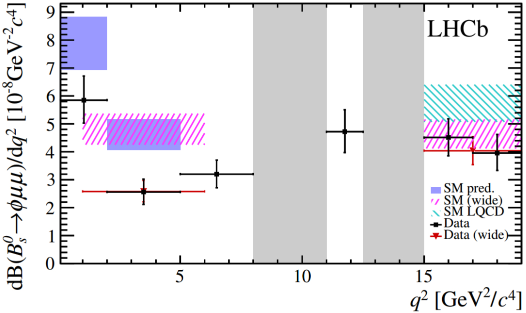


Results in $BtoK^{*}\mu\mu$



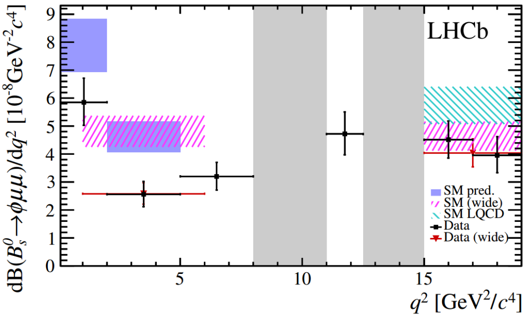
- Tension with $3~\mathrm{fb}^{-1}$ gets confirmed!
- The two bins deviate both in $2.8~\sigma$ form SM prediction.
- Result compatible with previous result.

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



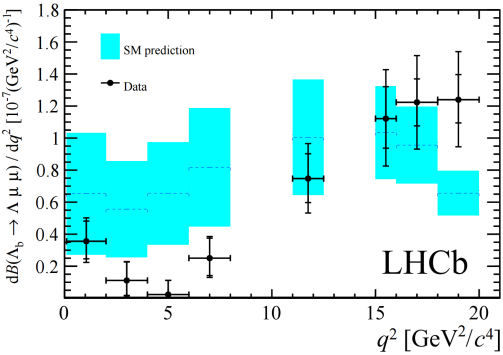
- Recent LHCb measurement [JHEPP09 (2015) 179].
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow ϕ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.

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 ϕ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.

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



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

Backup