

Anomalies in Flavour Physics

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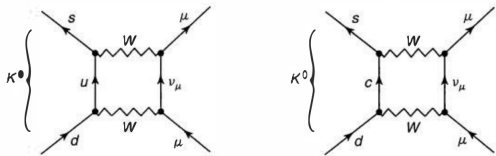
University of
Zurich ^{UZH}

Imperial College
October 16, 2015

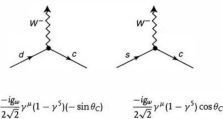
Outline

1. Why flavour is important.
2. $b \rightarrow sll$ theory in a nutshell.
3. LHCb measurements of $b \rightarrow sll$.
4. Global fit to $b \rightarrow sll$ measurements.
5. Conclusions.

A lesson from history - GIM mechanism



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



$$\frac{-ig_W}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5) (-\sin \theta_C)$$

$$\frac{-ig_W}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5) \cos \theta_C$$

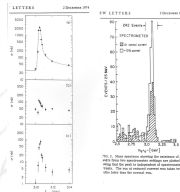
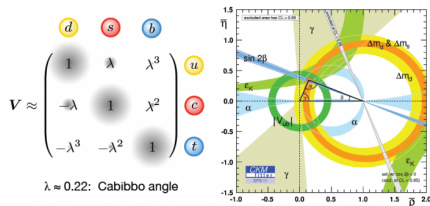
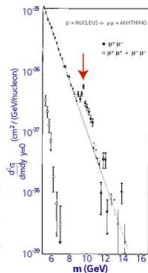


Fig. 1. Cross section versus energy for the decay $J/\psi \rightarrow \mu^+ \mu^-$. The solid line is the theoretical prediction for the decay of a charmonium state into muon pairs. The dashed line is the experimental data. The peak at 3.1 GeV is the J/ψ meson. The width of the peak is the natural width of the J/ψ meson.

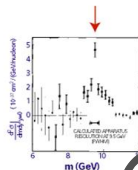
A lesson from history - CKM matrix



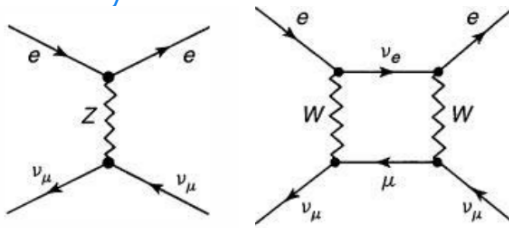
- Similarly CP violation was discovered in 1960s in the neutral kaons decays.
- 2×2 Cabbibo matrix could not allow for any CP violation.
- For the CP violation to be possible one needs at least a 3×3 unitary matrix \rightarrow Cabibbo-Kobayashi-Maskawa matrix (1973).
- It predicts existence of b (1977)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



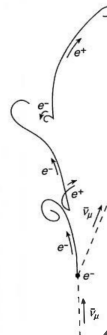
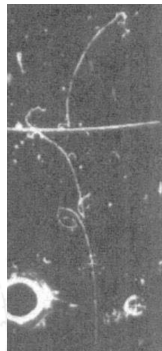
Results published in
Physical Review Letters
August 1, 1977



A lesson from history - Weak neutral current



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



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:**

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

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

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

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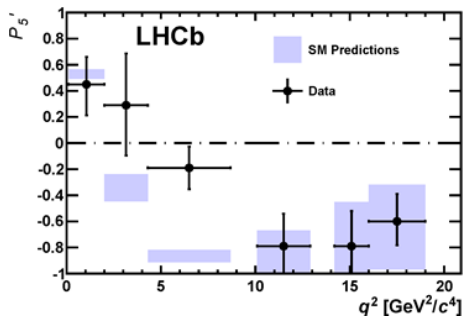
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> 2 σ deviations from SM

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

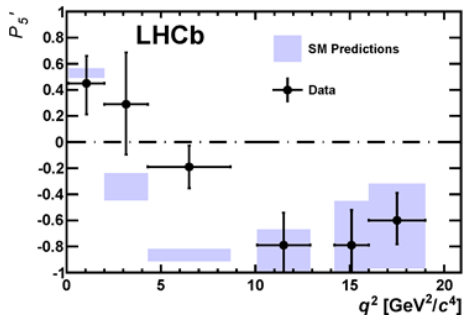
August 2013:



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

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

August 2013:



- LHCb observed a deviation in $4.3 - 8.68 \text{ GeV}^2$ using 1 fb^{-1} of data.
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Now let's move back and see the theory behind the $B^0 \rightarrow K^* \mu^- \mu^+$ and P'_5 .

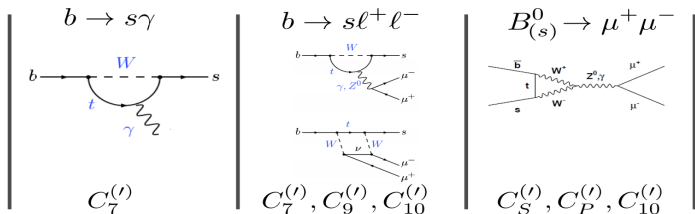
Tools in rare B^0 decays

- Operator Product Expansion and Effective Field Theory

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

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

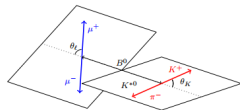
where C_i are the Wilson coefficients and O_i are the corresponding effective operators.



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

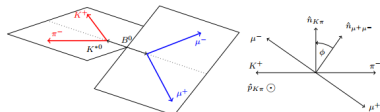
\Rightarrow The kinematics of $B^0 \rightarrow K^* \mu^- \mu^+$ decay is described by three angles θ_l , θ_k , ϕ and invariant mass of the dimuon system (q^2).

$\Rightarrow \cos \theta_k$: 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.



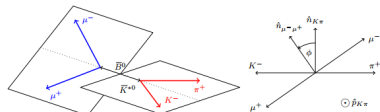
(a) θ_k and θ_l definitions for the B^0 decay

$\Rightarrow \cos \theta_l$: 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.



(b) ϕ definition for the B^0 decay

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



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

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

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

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

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

Transversity amplitudes

⇒ One can link the angular observables to transversity amplitudes

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

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

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

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

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

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

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

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

Link to effective operators

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

$$\begin{aligned}A_{\perp}^{L,R} &= \sqrt{2}Nm_B(1-\hat{s}) \left[(C_9^{\text{eff}} + C_9^{\text{eff}'}) \mp (C_{10} + C'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}'}) \right] \xi_{\perp}(E_{K^*}) \\A_{\parallel}^{L,R} &= -\sqrt{2}Nm_B(1-\hat{s}) \left[(C_9^{\text{eff}} - C_9^{\text{eff}'}) \mp (C_{10} - C'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_{\perp}(E_{K^*}) \\A_0^{L,R} &= -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(C_9^{\text{eff}} - C_9^{\text{eff}'}) \mp (C_{10} - C'_{10}) + 2\hat{m}_b(C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_{\parallel}(E_{K^*}), \quad (3)\end{aligned}$$

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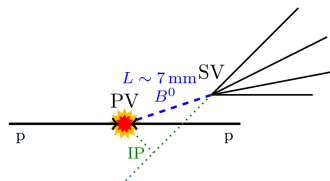
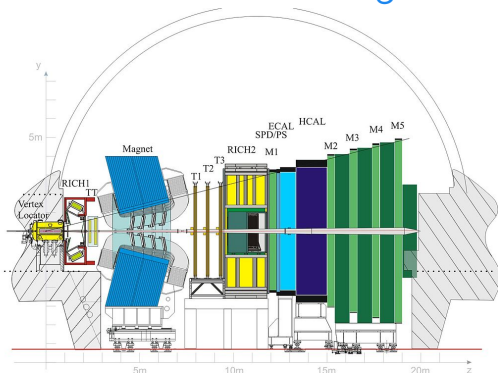
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where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

⇒ Now we can construct observables that cancel the ξ form factors at leading order:

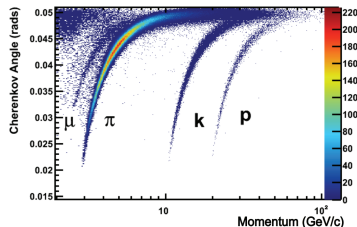
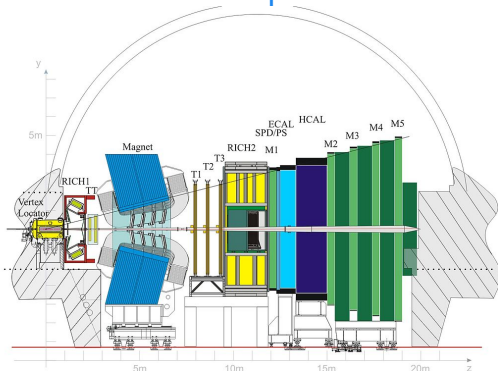
$$P'_5 = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}} \quad (4)$$

LHCb detector - tracking



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

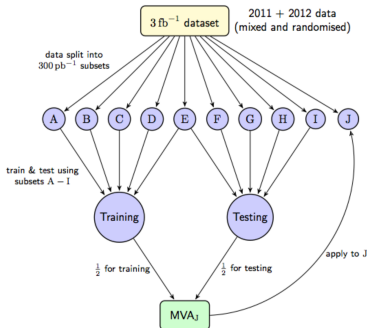
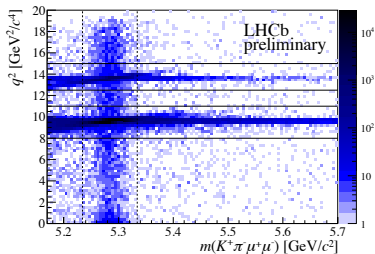
LHCb detector - particle identification



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

LHCb update of the $B^0 \rightarrow K^* \mu^- \mu^+$, 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: $\Lambda_b \rightarrow pK\mu\mu$, $B_s^0 \rightarrow \phi\mu\mu$, 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 1fb^{-1} analysis.

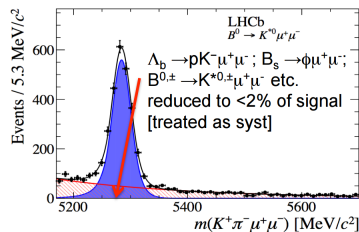


LHCb update of the $B^0 \rightarrow K^* \mu^- \mu^+$, Selection

- 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.



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

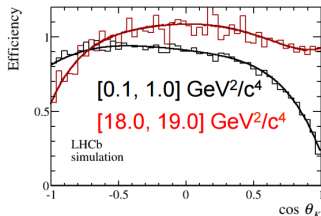
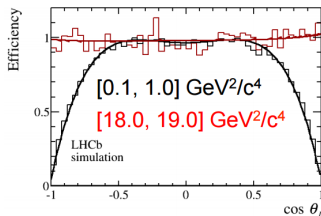
Detector acceptance

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

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

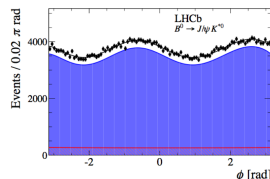
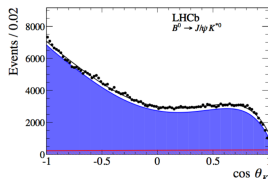
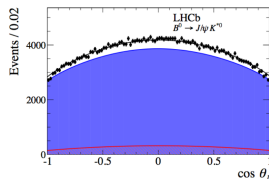
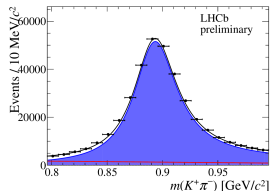
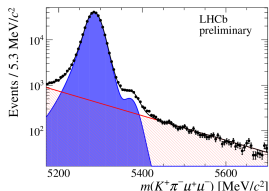
where P_i is the Legendre polynomial of order i .

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

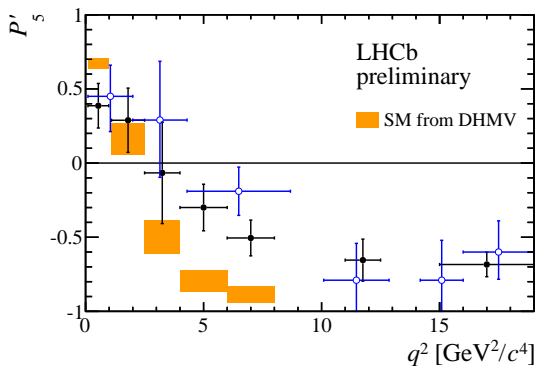


Control channel

- 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.

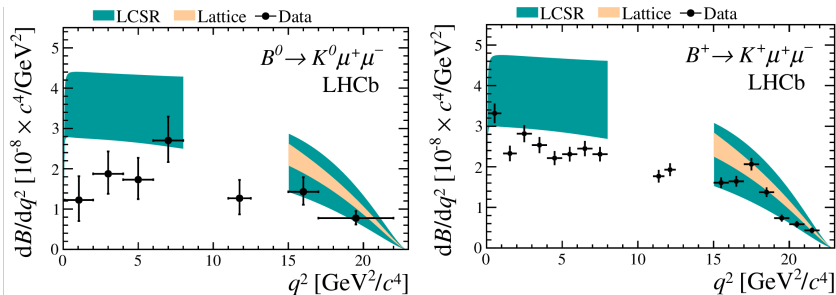


Results in $B \rightarrow K^* \mu \mu$

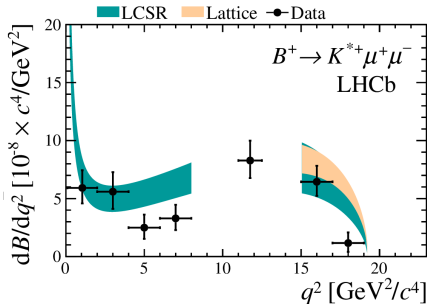


- Tension with 3 fb^{-1} gets confirmed!
- The two bins deviate both in 2.8σ from SM prediction.
- Result compatible with previous result.

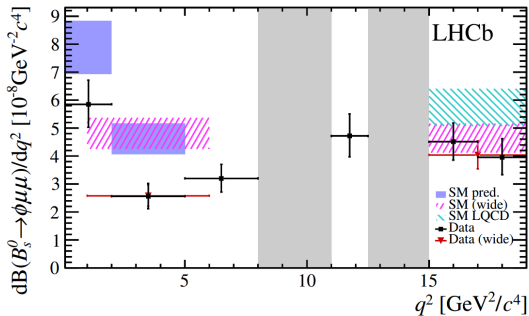
Branching fraction measurements of $B \rightarrow K^{*\pm} \mu \mu$



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

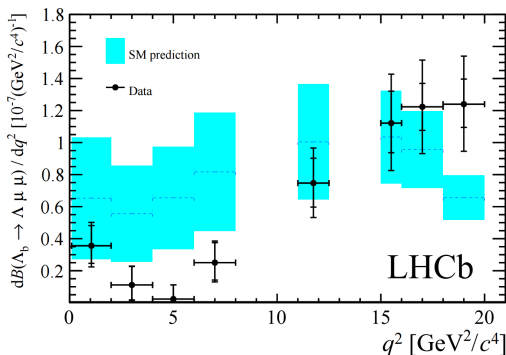


Branching fraction measurements of $B_s^0 \rightarrow \phi\mu\mu$



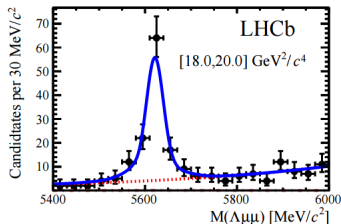
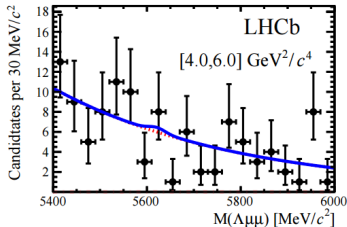
- Recent LHCb measurement [JHEPP09 (2015) 179].
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow ϕ resonance.
- 3.3σ deviation in SM in the $1 - 6 \text{ GeV}^2$ bin.

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



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

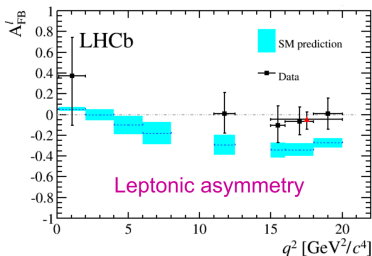
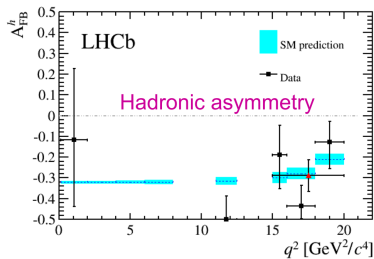
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Angular analysis of $\Lambda_b \rightarrow \Lambda \mu \mu$

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



- A_{FB}^H is in good agreement with SM.
- A_{FB}^ℓ always in above SM prediction.

Lepton universality test

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

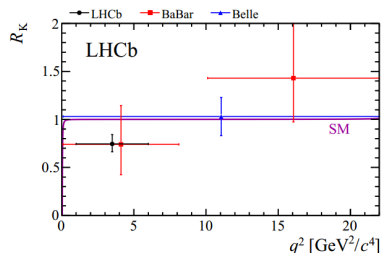
$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (dB[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}) .$$

- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct for bremsstrahlung.
- Take double ratio with $B^+ \rightarrow J/\psi K^+$ to cancel systematics.

- In 3fb^{-1} , LHCb measures

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

- Consistent with SM at 2.6σ .



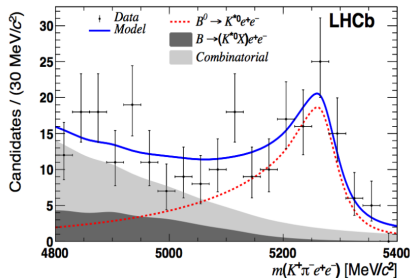
- Phys. Rev. Lett. 113, 151601 (2014)

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

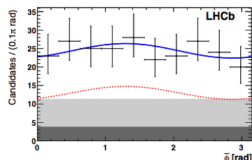
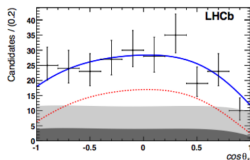
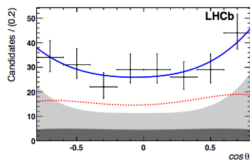
- With the full data set (3fb^{-1}) we performed angular analysis in $0.0004 < q^2 < 1 \text{ GeV}^2$.
- Electrons channels are extremely challenging experimentally:
 - Bremsstrahlung.
 - Trigger efficiencies.
- Determine the angular observables: F_L , $A_T^{(2)}$, A_T^{Re} , A_T^{Im} :

$$\begin{aligned} F_L &= \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2} \\ A_T^{(2)} &= \frac{|A_{\perp}|^2 - |A_{||}|^2}{|A_{\perp}|^2 + |A_{||}|^2} \\ A_T^{\text{Re}} &= \frac{2\mathcal{R}e(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2} \\ A_T^{\text{Im}} &= \frac{2\mathcal{I}m(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2 + |A_{\perp}|^2}, \end{aligned} \tag{5}$$

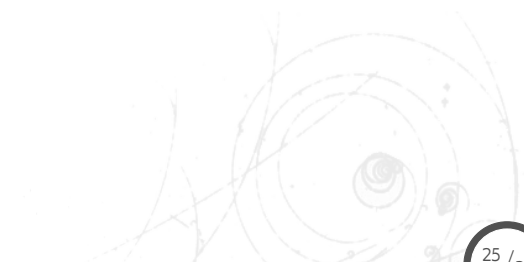
Angular analysis of $B^0 \rightarrow K^* e e$



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



Theory implications

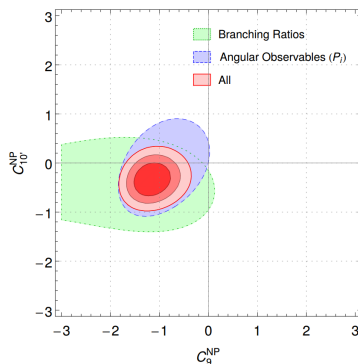
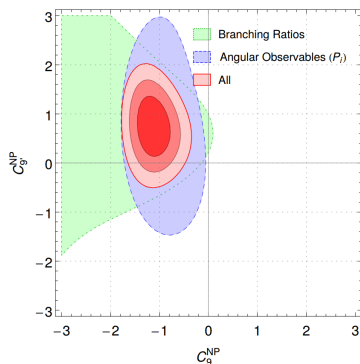


Theory implications

- A preliminary fit prepared by S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, presented at [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
 - $PB_{(s)} \rightarrow K^*(\phi)\mu\mu$, Horgan et al 2013
 - $B \rightarrow Kee$, $B \rightarrow K^*ee$ and R_k .
- Overall there is around 4.5σ discrepancy wrt. SM.

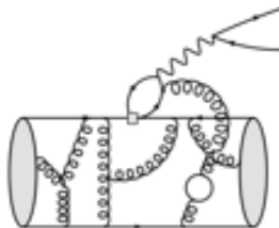
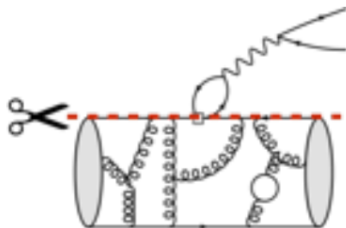
Theory implications

- A preliminary fit prepared by S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, presented at [1510.04239](#)
- The data can be explained by modifying the C_9 Wilson coefficient.
- Overall there is around 4.5σ discrepancy wrt. SM.



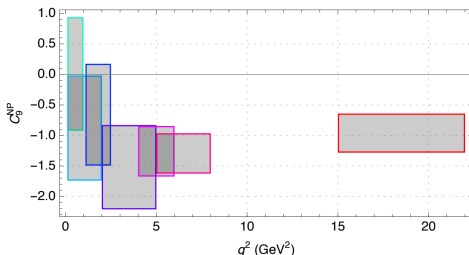
If not NP?

- We are not there yet!
- There might be something not taken into account in the theory.
- Resonances (J/ψ , $\psi(2S)$) tails can mimic NP effects.
- There might be some no factorizable QCD corrections.
" However, the central value of this effect would have to be significantly larger than expected on the basis of existing estimates" D.Straub, 1503.06199 .



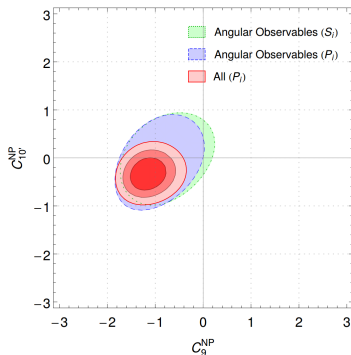
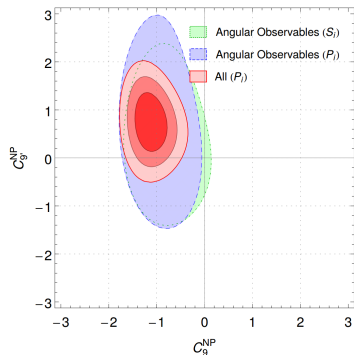
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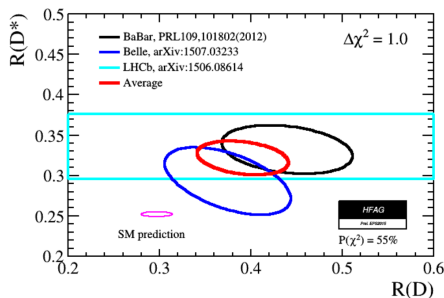
If not NP?

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



There is more!

- There is one other LUV decay recently measured by LHCb.
- $R(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu)}{\mathcal{B}(B \rightarrow D^* \mu \nu)}$
- Clean SM prediction: $R(D^*) = 0.252(3)$, PRD 85 094025 (2012)
- LHCb result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$, HFAG average:
 $R(D^*) = 0.322 \pm 0.022$
- 3.9σ 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!

