Recent results from LHCb

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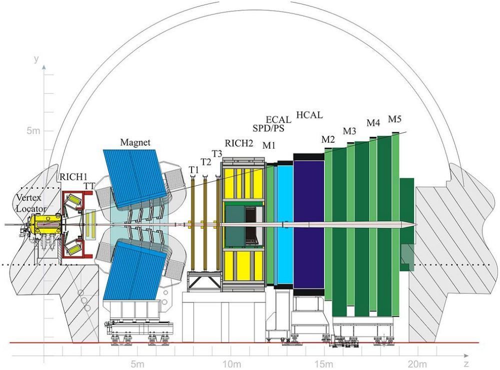
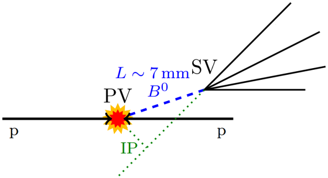
Outline

1. LHCb detector.
2. Angular analysis of $B_d^0 \to K^* \mu\mu$.
3. Other LHCb EWP measurements.
4. Glimpse into the future.

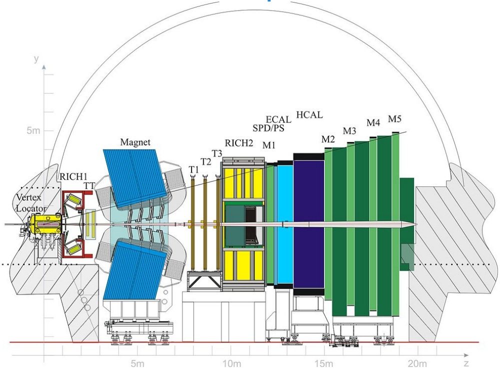
LHCb detector - tracking

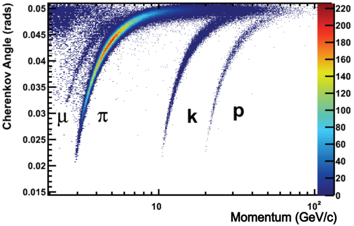




- Excellent Impact Parameter (IP) resolution ($20\ \mu\mathrm{m}$).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and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

LHCb detector - particle identification



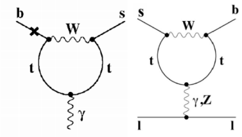


- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds.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

Analysis of Rare decays

Analysis of FCNC in a model-independent approach, effective Hamiltonian:

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$



- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma^{\mu\nu} P_R b\right) F_{\mu\nu}$
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma_\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma_\mu \gamma_5 \ell)$, ...

• **SM** Wilson coefficients up to NNLO + e.m. corrections at $\mu_{ref} = 4.8$ GeV [Misiak et al.]:

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

• **NP** changes short distance $\mathcal{C}_i - \mathcal{C}_i^{\rm SM} = \mathcal{C}_i^{\rm NP}$ and induce new operators, like

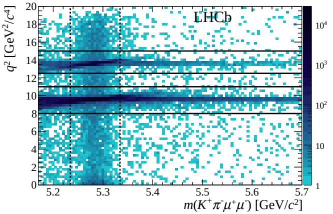
$\mathcal{O}'_{7,9,10} = \mathcal{O}_{7,9,10}\ (P_L \leftrightarrow P_R)$ ... also scalars, pseudoescalar, tensor operators...

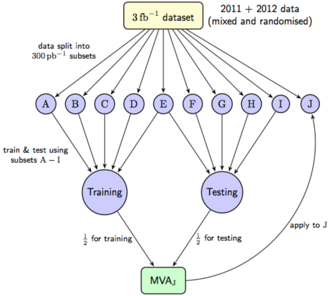
Analysis of Rare decays

LHCb measurement of $B_d^0 \to K^* \mu\mu$

Multivariate selection

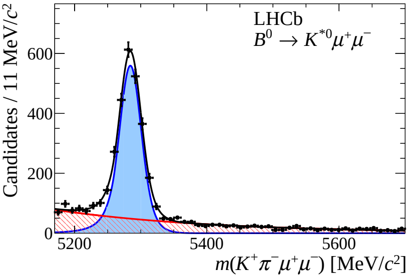
- JHEP 1602 (2016) 104
- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to reject background.
- Reject the regions of J/ψ and $\psi(2S)$.
- Specific vetos for backgrounds: $\Lambda_b \to pK\mu\mu$, $B_s^0 \to \phi\mu\mu$, etc.
- Using k-Fold technique and signal proxy $B \to J/\psi K^*$ for training the BDT.
- Improved selection allowed for finer binning than the $1\mathrm{fb}^{-1}$ analysis.





Mass modelling

⇛ The signal is modelled by a sum of two Crystal-Ball functions with common mean.
⇛ The background is a single exponential.
⇛ The base parameters are obtained from the proxy channel: $B_d^0 \to J/\psi(\mu\mu)K^*$.
⇛ All the parameters are fixed in the signal pdf.
⇛ Scaling factors for resolution are determined from MC.
⇛ In fitting the rare mode only the signal, background yield and the slope of the exponential is left floating.
⇛ We found 624 ± 30 candidates in the most interesting $[1.1, 6.0]\ \mathrm{GeV}^2/\mathrm{c}^4$ region and 2398 ± 57 in the full range $[1.1, 19.]\ \mathrm{GeV}^2/\mathrm{c}^4$.



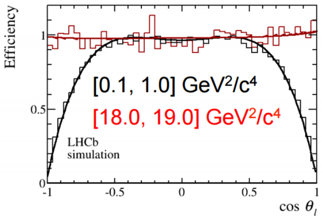
⇛ The S-wave fraction is extracted using a LASS model.

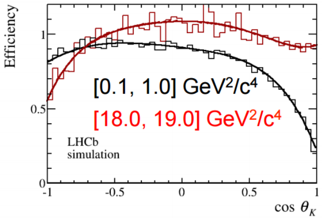
Detector acceptance

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

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

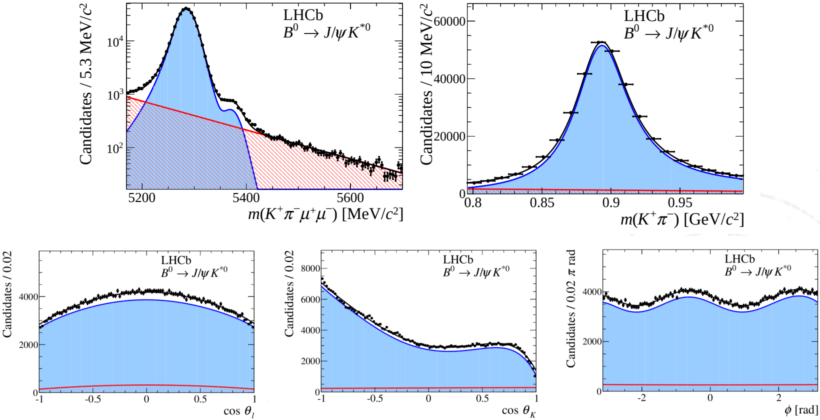
  where P_i is the Legendre polynomial of order i.
- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space and reweighing the q^2 distribution to make is flat.



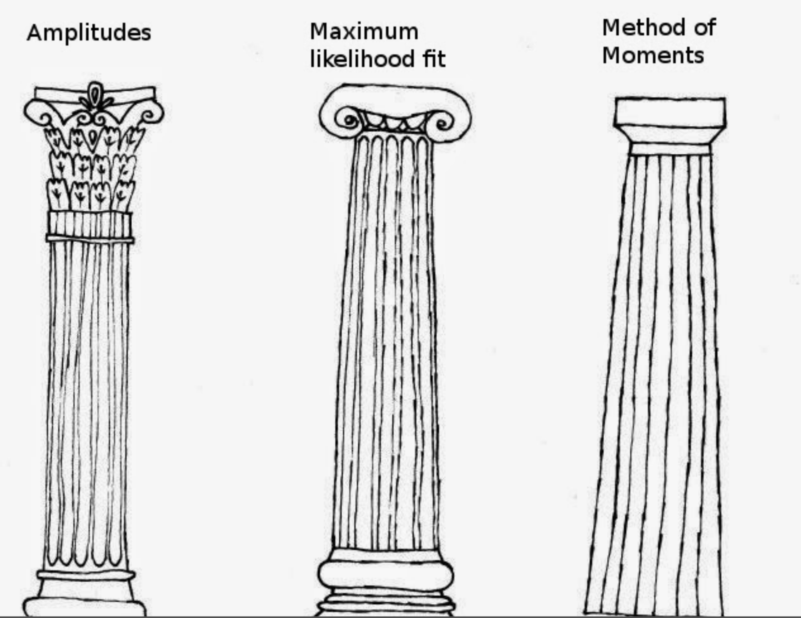


Control channel

- 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.



The columns of New Physics



The columns of New Physics

1. Maximum likelihood fit:
   - The most standard way of obtaining the parameters.
   - Can have problem with low statistics.
2. Method of moments:
   - Less precise then the likelihood estimator ($10-15\%$ larger uncertainties).
   - Does not suffer from the problems of likelihood fit.
3. Amplitude fit:
   - Incorporates all the physical symmetries inside the amplitudes! The most precise estimator.
   - Has theoretical assumptions inside!

Maximum likelihood fit - Results

⇛ In the maximum likelihood fit one could weight the events accordingly to the $\frac{1}{\varepsilon(\cos\theta_l, \cos\theta_k, \phi, q^2)}$

⇛ Better alternative is to put the efficiency into the maximum likelihood fit itself:

$$\mathcal{L} = \prod_{i=1}^{N} \epsilon_i(\Omega_i, q_i^2)\mathcal{P}(\Omega_i, q_i^2) / \int \epsilon(\Omega, q^2)\mathcal{P}(\Omega, q^2) d\Omega dq^2$$

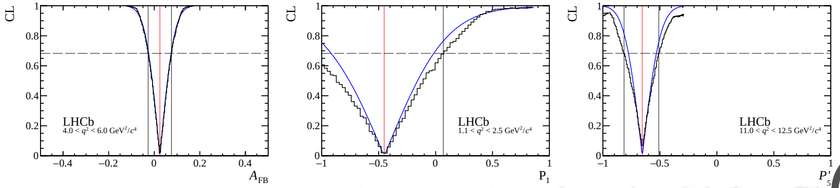
⇛ Only the relative weights matters!

⇛ The Procedure was commissioned with TOY MC study.

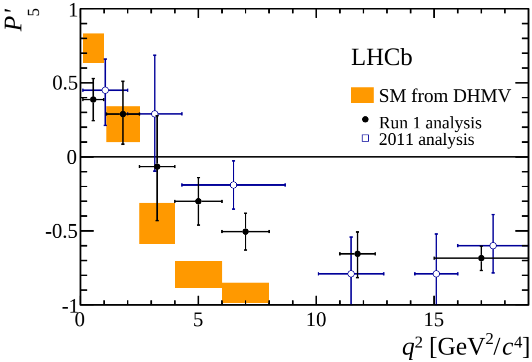
⇛ Use Feldmann-Cousins to determine the uncertainties.

⇛ Angular background component is modelled with 2^{nd} order Chebyshev polynomials, which was tested on the side-bands.

⇛ S-wave component treated as nuisance parameter.

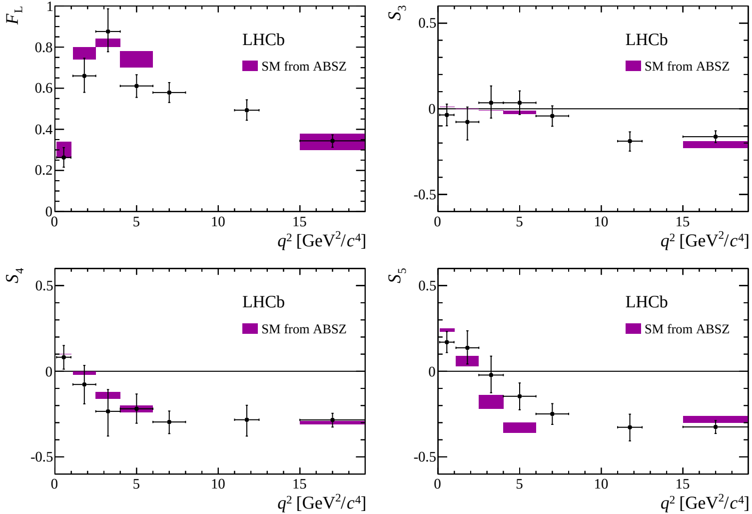


Maximum likelihood fit - Results



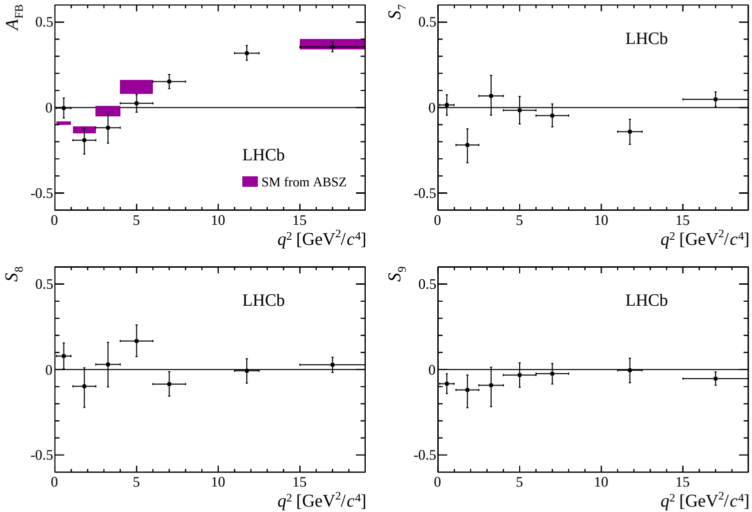
- Tension with $3\ \mathrm{fb}^{-1}$ gets confirmed!
- two bins both deviate by $2.8\ \sigma$ from SM prediction.
- Result compatible with previous result; Phys.Rev.Lett. 111 (2013) 191801
- SM: JHEP12(2014)125

Maximum likelihood fit - Results



⇛ SM: Eur.Phys.J. C75 (2015) no.8, 382

Maximum likelihood fit - Results



⇛ SM: Eur.Phys.J. C75 (2015) no.8, 382

Method of moments

⇛ See Phys.Rev.D91(2015)114012, F.Beaujean , M.Chrzaszcz, N.Serra, D. van Dyk for details.

⇛ The idea behind Method of Moments is simple: Use orthogonality of spherical harmonics, $f_j(\overrightarrow{\Omega})$ to solve for coefficients within a q^2 bin:

$$\int f_i(\overrightarrow{\Omega}) f_j(\overrightarrow{\Omega}) = \delta_{ij}$$

$$M_i = \int \left(\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \right) \frac{d^3(\Gamma + \bar{\Gamma})}{d\overrightarrow{\Omega}} f_i(\overrightarrow{\Omega}) d\Omega$$

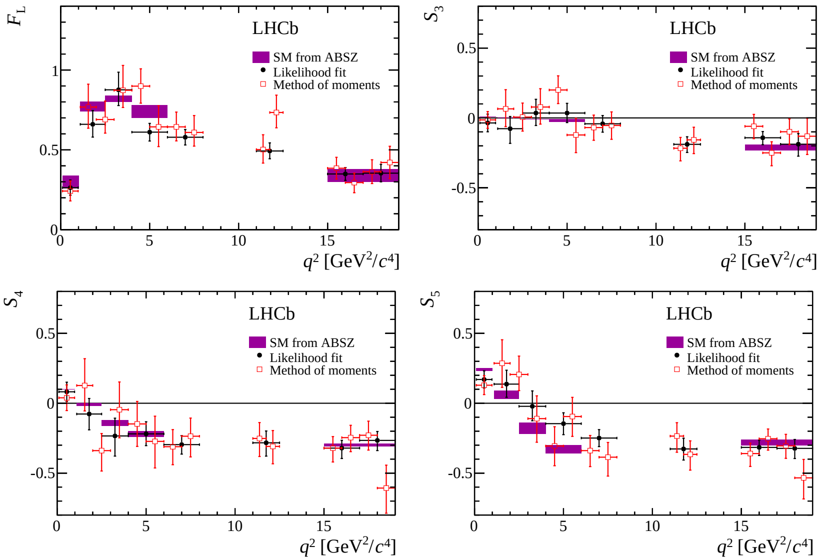
⇛ Don't have true angular distribution but we "sample" it with our data.

⇛ Therefore: $\int \rightarrow \sum$ and $M_i \rightarrow \widehat{M}_i$

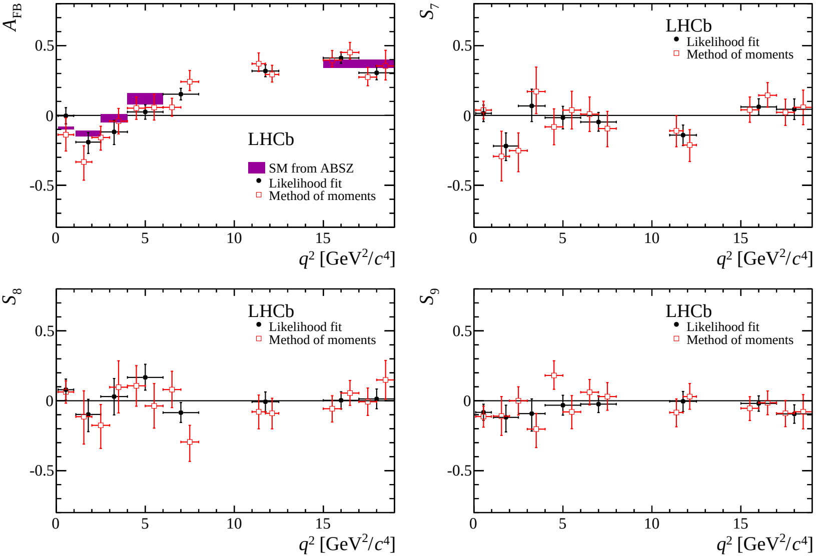
$$\hat{M}_i = \frac{1}{\sum_e \omega_e} \sum_e \omega_e f_i(\overrightarrow{\Omega}_e)$$

⇛ The weight ω accounts for the efficiency. Again the normalization of weights does not matter.

Method of moments - results

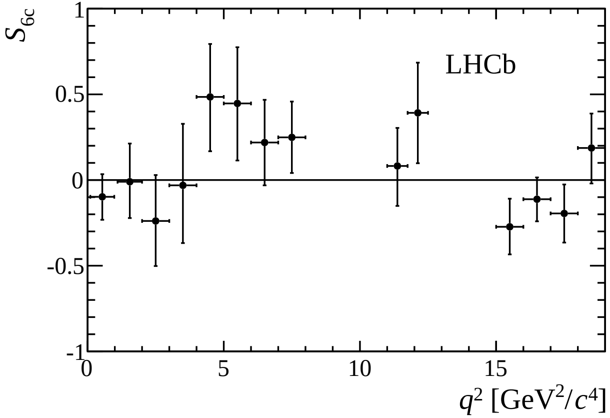


Method of moments - results



Method of moments - results

⇛ Method of Moments allowed us to measure for the first time a new observable:



⇛ LHCb also measured the CP asymmetries with Method of Moments and the likelihood fit that are consistent with SM

Amplitudes method

⇛ Fit for amplitudes as (continuous) functions of q^2 in the region: $q^2 \in [1.1.6.0]$ $\mathrm{GeV}^2/\mathrm{c}^4$.
⇛ Needs some Ansatz:

$$A(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$$

⇛ The assumption is tested extensively with toys.
⇛ Set of 3 complex parameters α, β, γ per vector amplitude:

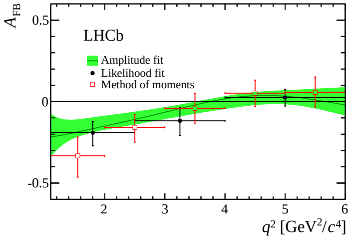
- $L, R, 0, \|, \perp, \Re, \Im \rightarrowtail \; 3 \times 2 \times 3 \times 2 = 36$ DoF.
- Scalar amplitudes: $+4$ DoF.
- Symmetries of the amplitudes reduces the total budget to: 28.

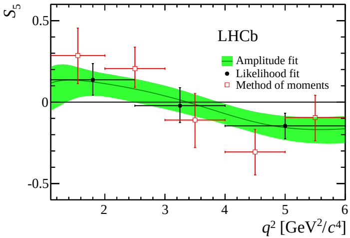
⇛ The technique is described in JHEP06(2015)084, U. Egede, M. Patel, K.A. Petridis.
⇛ Allows to build the observables as continuous functions of q^2:

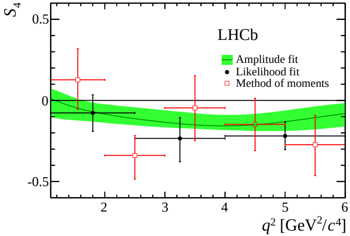
- At current point the method is limited by statistics.
- In the future the power of this method will increase.

⇛ Allows to measure the zero-crossing points for free and with smaller errors than previous methods.

Amplitudes - results







Zero crossing points:

$$q_0(S_4) < 2.65 \quad \text{at } 95\%\ CL$$
$$q_0(S_5) \in [2.49, 3.95] \quad \text{at } 68\%\ CL$$
$$q_0(A_{FB}) \in [3.40, 4.87] \quad \text{at } 68\%\ CL$$

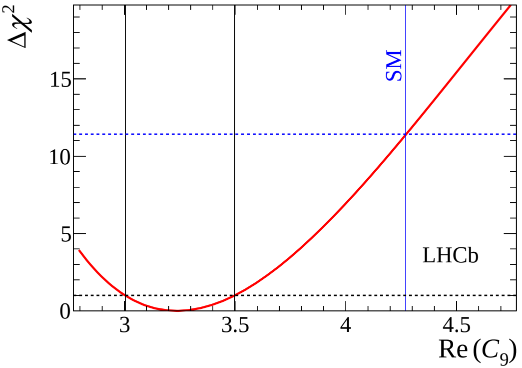
Compatibility with SM

$\Rightarrow$ Use EOS software package to test compatibility with SM.
$\Rightarrow$ Perform the χ^2 fit to the measured:

$$F_L, A_{FB}, S_{3,...,9}.$$

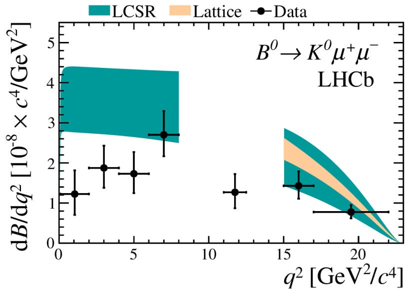
$\Rightarrow$ Float a vector coupling: $\Re(C_9)$.
$\Rightarrow$ Best fit is found to be $3.4\ \sigma$ away from the SM.

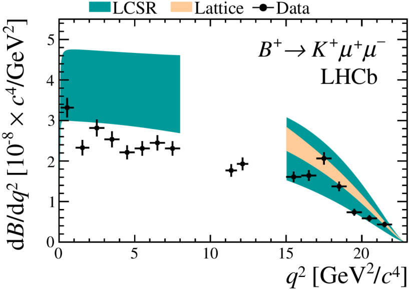
$$\Delta\Re(C_9) \equiv \Re(C_9)^{\text{fit}} - \Re(C_9)^{\text{SM}} = -1.03$$



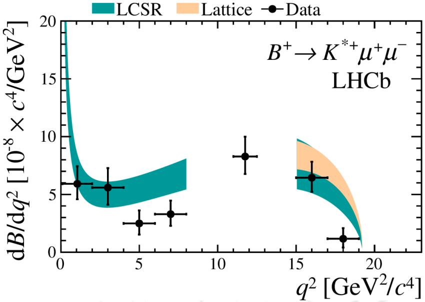
Other related LHCb measurements.

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

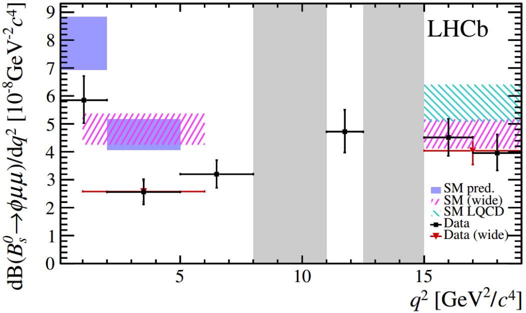




- Despite large theoretical errors the results are consistently smaller than SM prediction.
- JHEP 07 (2012) 133

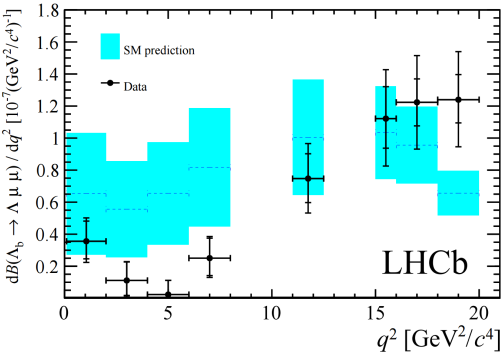


Branching fraction measurements of $B_s^0 \to \phi\mu\mu$



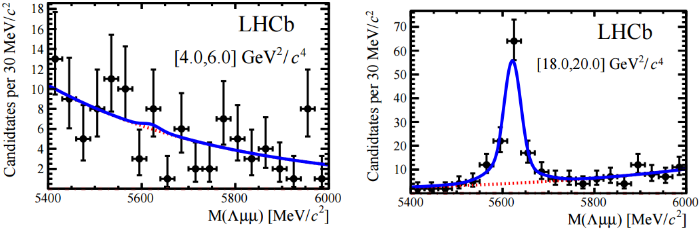
- Recent LHCb measurement JHEP09 (2015) 179.
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow ϕ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.

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



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

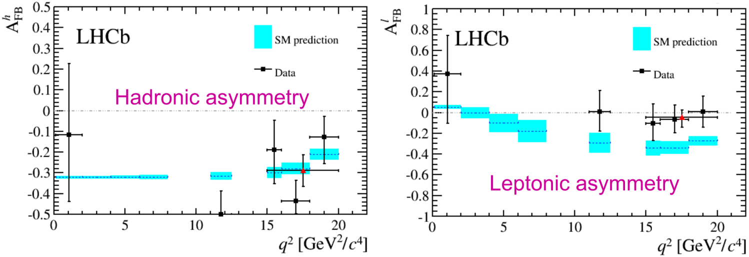
Branching fraction measurements of $\Lambda_b \to \Lambda\mu\mu$



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

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

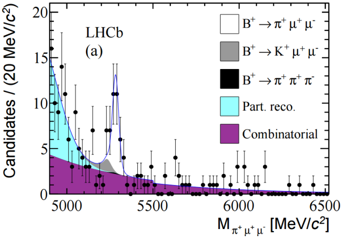
- For the bins in which we have $> 3\ \sigma$ significance the forward backward asymmetry for the hadronic and leptonic system.

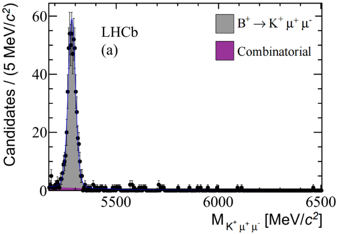


- A^H_{FB} is in good agreement with SM.
- A^ℓ_{FB} always in above SM prediction.

First observation of $B_d^0 \to \pi\mu\mu$

- LHCb for the first time observed a CKM suppressed decay of $B \to \pi^{\pm}\mu\mu$
- We observed 25 ± 6 events in $1\ \text{fb}^{-1}$ data set.
- Need to separate a large peaking component: $B \to K^{\pm}\mu\mu$ form our signal window.
- In the future we can expect more aggressive physics program with this and similar channels $\mapsto$ see Kostas talk!

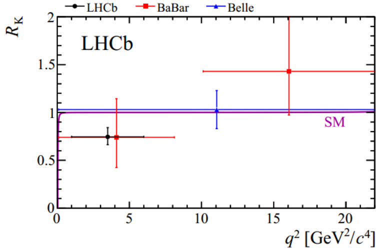




Lepton universality test

- Does the NP couple equally to all flavours?

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

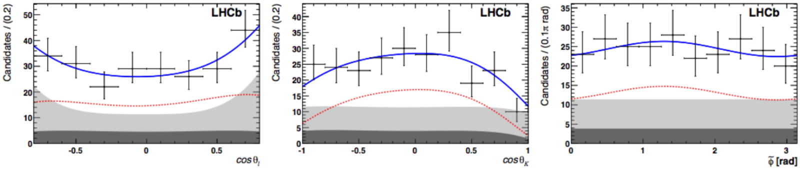


- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct for bremsstrahlung.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- In $3{\rm fb}^{-1}$, LHCb measures $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with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

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

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

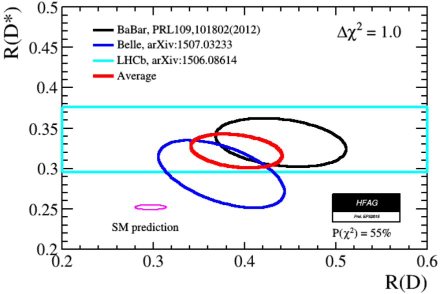
- With the full data set (3fb^{-1}) we performed angular analysis in $0.0004 < q^2 < 1\ \text{GeV}^2$.
- JHEP04(2015)064



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

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.

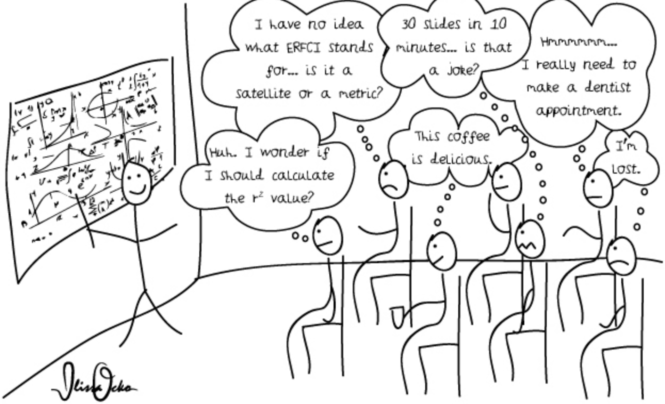


Steps in the near future

Conclusions

- LHCb is and still will provide the most precise measurements of EWP!
- Many analysis in the pipe line!
- Even more ideas to what to do with existing and further data.

Thank you for the attention!



Backup

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

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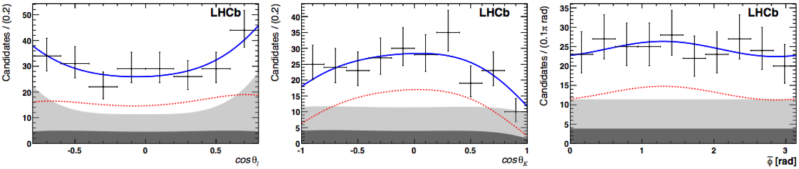

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Angular analysis of $B^0 \to K^*ee$

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

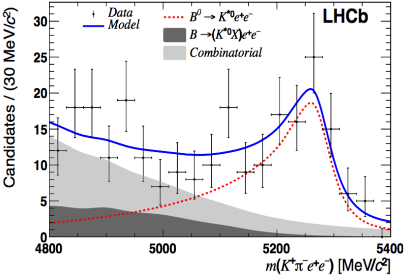
$$F_{\mathrm{L}} = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}$$

$$A_{\mathrm{T}}^{(2)} = \frac{|A_{\perp}|^2 - |A_{||}|^2}{|A_{\perp}|^2 + |A_{||}|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Re}} = \frac{2\mathcal{R}e(A_{||L}A^*_{\perp L} + A_{||R}A^*_{\perp R})}{|A_{||}|^2 + |A_{\perp}|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Im}} = \frac{2\mathcal{I}m(A_{||L}A^*_{\perp L} + A_{||R}A^*_{\perp R})}{|A_{||}|^2 + |A_{\perp}|^2},$$

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.