Overview of recent experimental results in flavour physics

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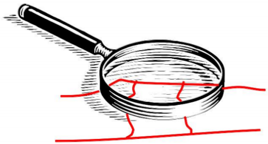
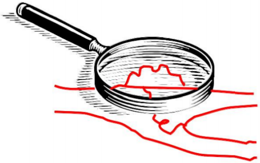
Flavour Physics, WHAT, WHY HOW?

⇛ WHAT: Quarks and leptons exists in 6 ”flavors” (u,c,t,d,s,b) and (e,μ, τ, ν_e, ν_μ, ν_τ).

⇛ WHY:

- Flavour is the heart of SM. It involves 22 from 28 free parameters, like masses mixing and CP violation.
- Flavor physics loop processes (box and penguins) are sensitive to energy scales well beyond the ones of the accelerators, thanks to virtual contributions.





→ Indirect search for New Physics

⇛ HOW:

- Compare precise theoretical predictions with precise experimental measurements.
- LHCb, Belle, BaBar, ATLAS, CMS, NA62, BESIII, neutrinos experiments,...

Introduction to flavor physics

⇛ Masses and mixing of quarks have a common origin in the SM: The Yukawa interactions with the Higgs:

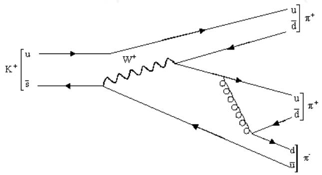
$$\mathcal{L}_{\text{Yukawa}} = -Y^d_{ij}\bar{Q}'_{Li}\phi d'_{Rj} - Y^u_{ij}\bar{Q}'_{Ri}\phi u'_{Rj}$$

⇛ The masses are generated using SSB by diagonalizing Y. The CKM matrix relats the mass eigenstates with the flavour eigenstates:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}' = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}^{\text{phys}}$$

⇛ The charge current interactions between quarks are proportional to the CKM matrix elements:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{u}\gamma^{\mu}(1-\gamma^5)V_{CKM}d + ...$$



CP violation

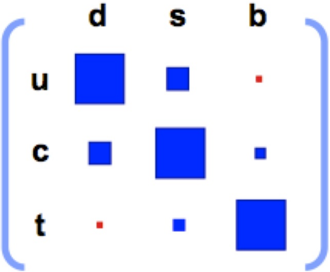
⇛ The 3×3 CKM has build inside the CP violation:

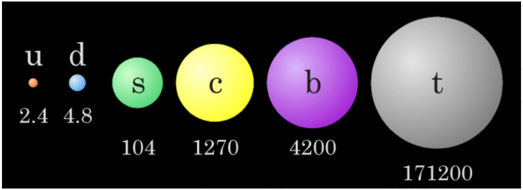
$$V_{ij} \neq V_{ij}^* \quad \Rightarrow \quad (CP)\mathcal{L}_{CC} \neq \mathcal{L}^\dagger$$

⇛ In the Wolfenstein parametrization the CKM matrix reads:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

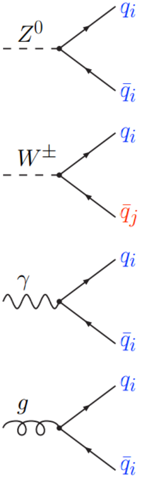
⇛ Strong hierarchy:

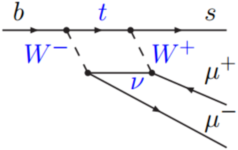


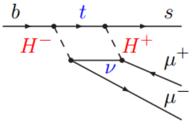


Why rare decays?

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







Searching for New Physics

⇛ The fundamental questions:

- Why 3 generations? Why such hierarchy structure?
- Stability of the Higgs vacum? Dark Matter?
- Baryon asymmetry of the universe? CP in SM is to small!

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⇛ Two ways to answer them:

- Direct searches: try to produce directly new real particles ”on-shell”, but we don't know their mass or lifetime and we are limited by the center-of-mass energy of accelerator.
- Indirect searches: study the effect of “off-shell” (virtual) particles within quantum loop. Compare precise theoretical predictions with precise experimental measurements. Not limited by the center-of-mass energy of accelerator. It happened in the past:
  - CP violation in the Kaon system: existence of b and t quarks.
  - Lack of observation of $K^0_S \to \mu\mu$: existence of c quark.
  - Neutral weak currents: existence of Z boson.
- Very powerful tool!

Selected physics results:

- Rare Decays
  - $B_s^0/B_d^0 \to \mu\mu$
  - $B_d^0 \to K^*\mu\mu$, $B_s^0 \to \phi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$.
- Tests of lepton universalities:
  - $R_k = \mathcal{B}(B^+ \to K^+\mu\mu)/\mathcal{B}(B^+ \to K^+ee)$
  - $R(D),\ R(D^*)$
- $(g-2)_\mu$
- CP violation:
  - γ angle.
  - CP violation in B_d^0 and B_s^0.
  - CP violation in charm.
  - CP violation in kaons.
  - V_{ub}.

Heavy flavor experiments

Rare decays

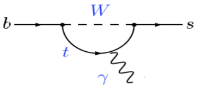
- **Operator Product Expansion and Effective Field Theory**

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

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

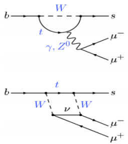
where C_i are the Wilson coefficients and O_i are the corresponding effective operators.

$b \to s\gamma$



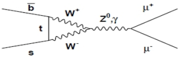
$C_7^{(\prime)}$

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



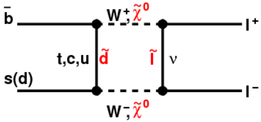
$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

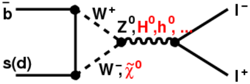
$B^0_{(s)} \to \mu^+\mu^-$



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

$B^0 \to \mu^+\mu^-$

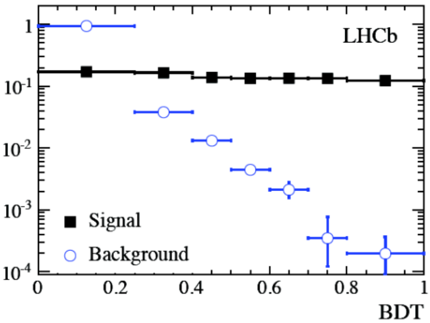


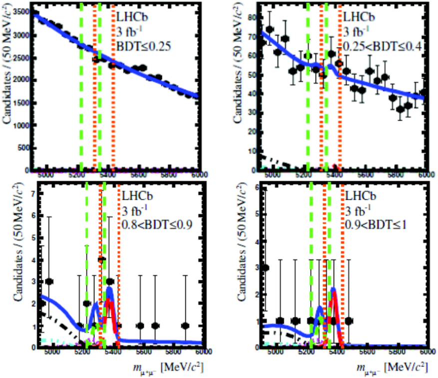


- Clean theoretical prediction, GIM and helicity suppressed in the SM:
  - $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^-\mu^+) = (1.06 \pm 0.09) \times 10^{-10}$
- Sensitive to contributions from scalar and pesudoscalar couplings.
- Probing: MSSM, higgs sector, etc.
- In MSSM: $\mathcal{B}(B_s^0 \to \mu^-\mu^+) \sim \mathrm{tg}^6\,\beta / m_A^4$

PRL 111 (2013) 101805

- Background rejection power is a key feature of rare decays $\to$ use multivariate classifiers (BDT) and strong PID.

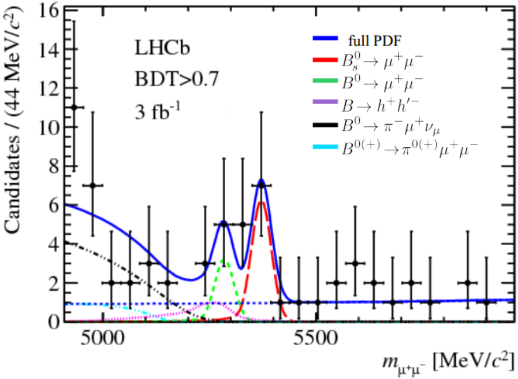




- Normalize the BF to $B^+ \to J/\psi(\mu\mu)K^+$ and $B^0 \to K\pi$.

$B^0 \to \mu^+\mu^-$ Results

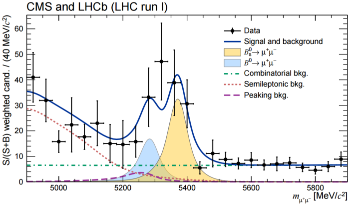
- Nov. 2012:
  - First evidence 3.5σ for $B^0 \to \mu^+\mu^-$. with $2.1\ \mathrm{fb}^{-1}$.
- Summer 2013:
  - Full data sample: $3\ \mathrm{fb}^{-1}$.

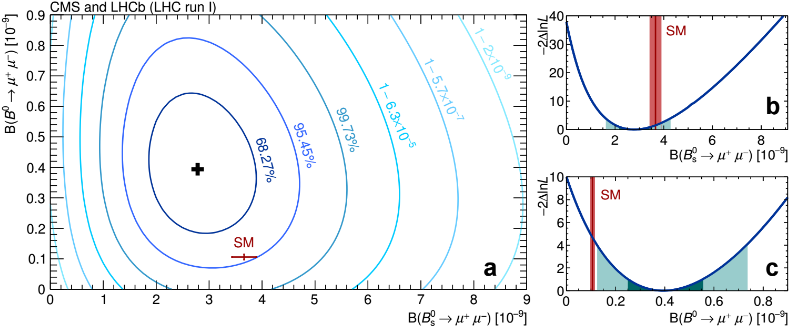


- Measured BF:
  $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.9^{+1.1}_{-1.0}(stat.)^{+0.3}_{-0.1}(syst.)) \times 10^{-9}$
- 4.0σ significance!
- $\mathcal{B}(B^0 \to \mu^-\mu^+) < 7 \times 10^{-10}$ at 95% CL
- CMS result: PRL 111 (2013) 101805

LHCb+CMS Combination

$$\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^-\mu^+) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$



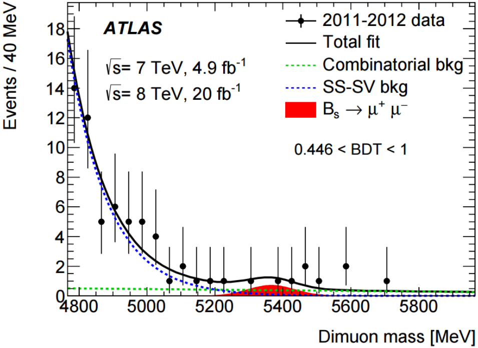


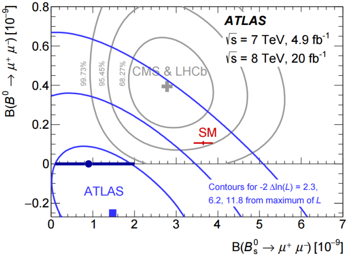
$2.3\,\sigma$ compatibility with SM!

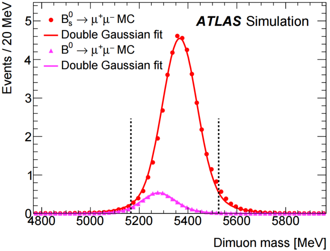
ATLAS enters the game

arXiv:1604.04263

- $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^-\mu^+) < 4.2 \times 10^{-10}$ at 95 CL







⇛ The decay of $B_d^0 \to K^*\mu\mu$ has number of angular observables that are sensitive to different Wilson coefficients: $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$.

⇛ The complete angular expression is given by:

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

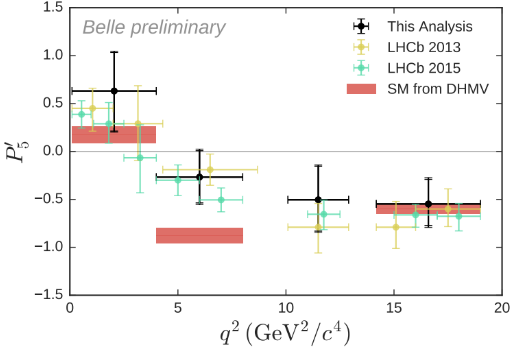
⇛ Furthermore, one can construct a form factor free observables:

$$P_5' = \frac{S_5}{F_L(1-F_L)}$$

⇛ Analysis performed with 3 methods:

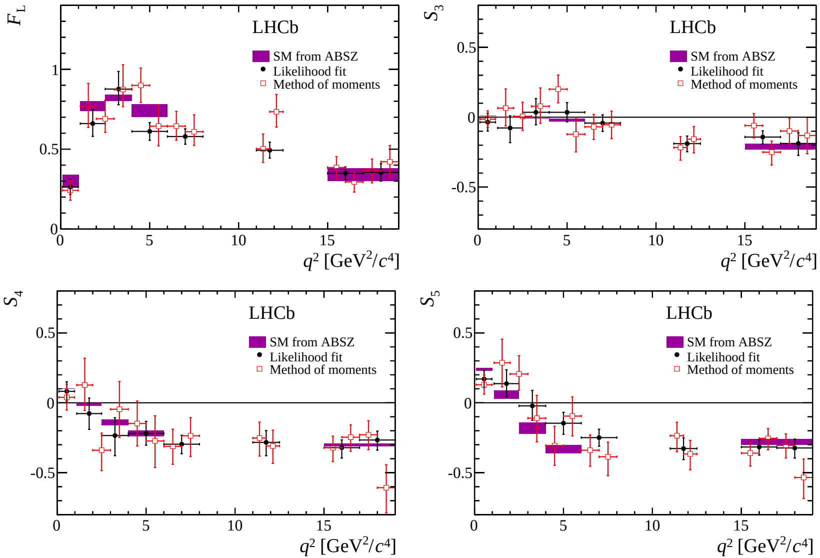
- Likelihood fit.
- Method of moments.
- Amplitudes fit.

$B_d^0 \to K^* \mu\mu$ results

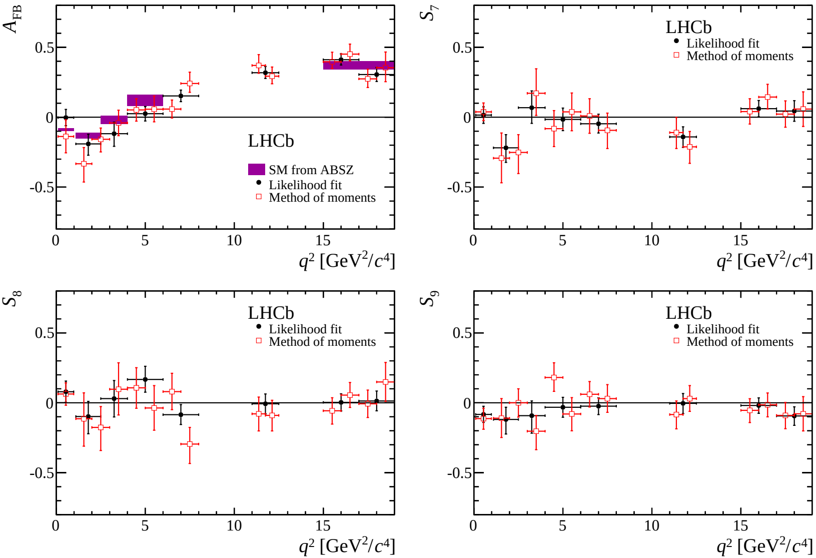


- Tension with $3\ \mathrm{fb}^{-1}$ gets confirmed!
- two bins both deviate by $2.8\ \sigma$ from SM prediction.
- Result compatible with previous results and Belle!
- SM: JHEP12(2014)125

$B_d^0 \to K^* \mu\mu$ results

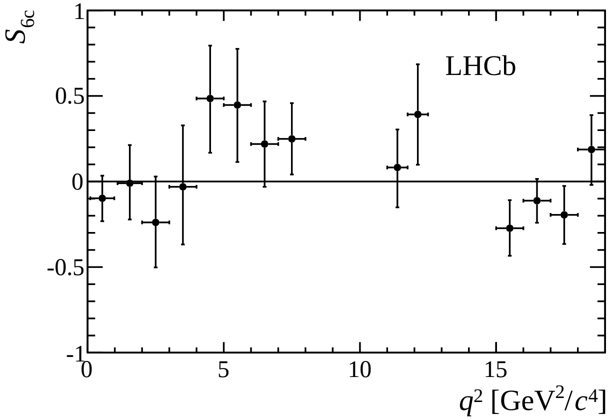


$B_d^0 \to K^*\mu\mu$ results



$B_d^0 \to K^* \mu\mu$ 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

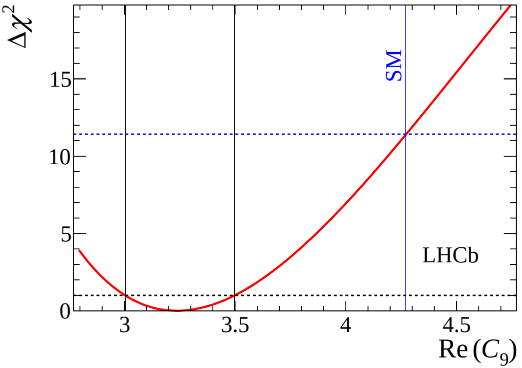
Compatibility with SM

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

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

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

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



BF of $B \to K^{*\pm}\mu\mu$

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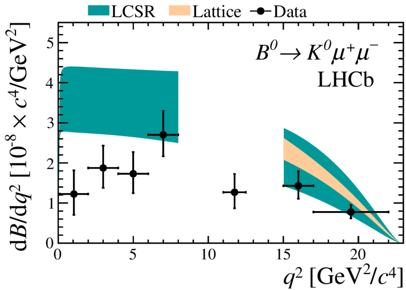
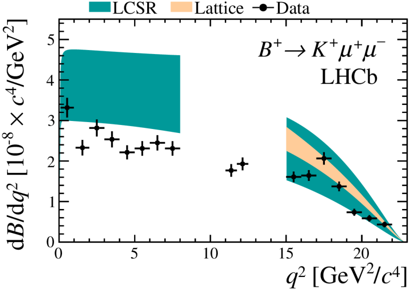
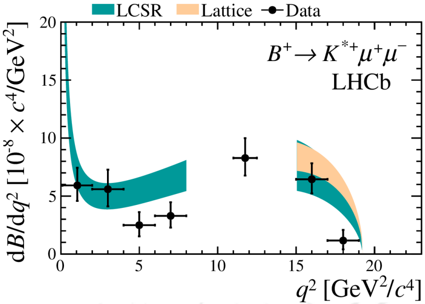
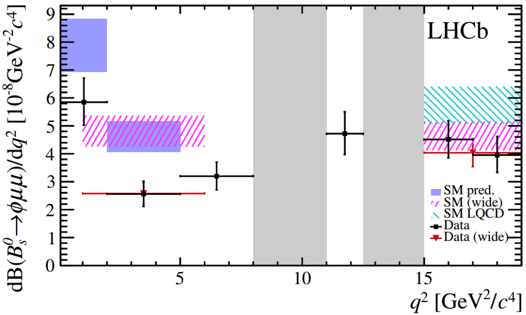




- Despite large theoretical errors the results are consistently smaller than SM prediction.

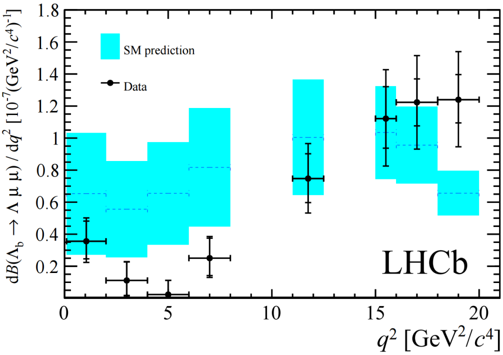


BF of $B_s^0 \to \phi\mu\mu$



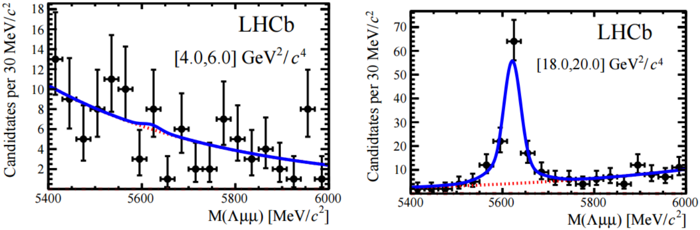
- Last years LHCb measurement.
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow ϕ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.

BF of $\Lambda_b \to \Lambda\mu\mu$



- Last years LHCb measurement.
- In total ~ 300 candidates in data set.
- Decay not present in the low q^2.

BF of $\Lambda_b \to \Lambda\mu\mu$



- Last years LHCb measurement.
- In total ~ 300 candidates in data set.
- Decay not present in the low q^2.

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

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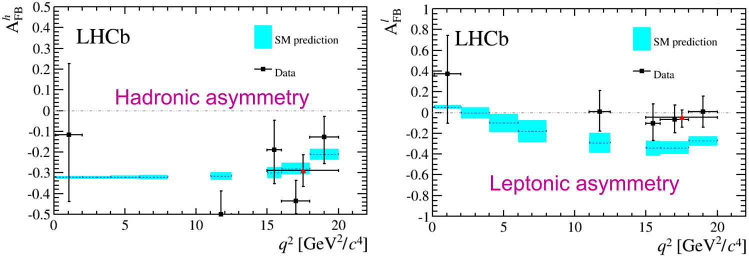
- For the bins in which we have $> 3\ \sigma$ significance the forward backward asymmetry for the hadronic and leptonic system.



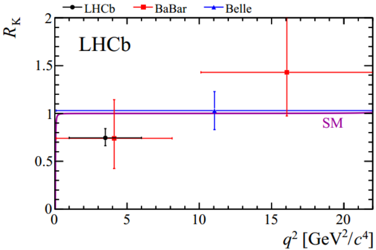
- A^H_{FB} is in good agreement with SM.
- A^ℓ_{FB} always in above SM prediction.

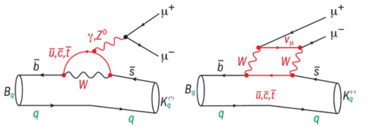
Lepton Universality tests

- Does the NP couple equally to all flavours?

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

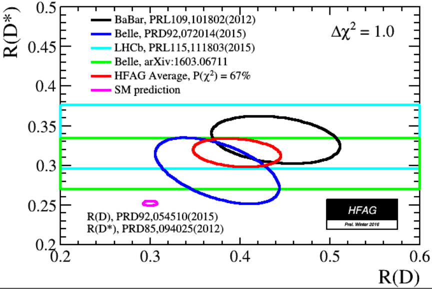
- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct for bremsstrahlung.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- In $3\mathrm{fb}^{-1}$, LHCb measures: $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with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





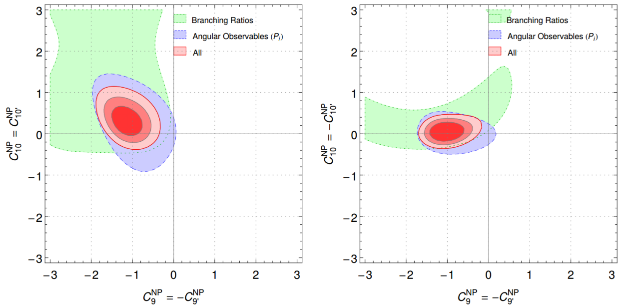
More Lepton universality tests

- 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: $R(D^*) = 0.322 \pm 0.022$
- $4.0\ \sigma$ discrepancy wrt. SM.



Explanation of anomalies

⇛ Thanks to S. Descotes-Genon, L.Hofer, J.Matias, J.Virto we have a global fit to the anomalies.

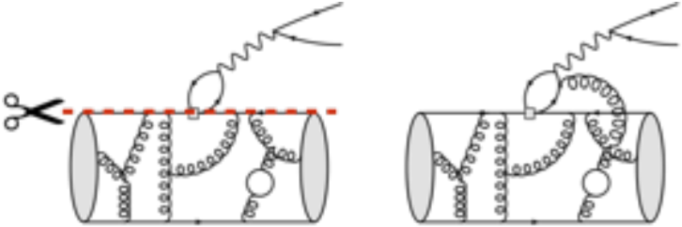


⇛ The fit prefer a modification of C_9 Wilson coefficient with a value of $C_9^{NP} = -1$, with a significance over 4σ.

⇛ Many theories link might accommodate the observed deviations.

Explanation of anomalies

- 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 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, 1503.06199` .

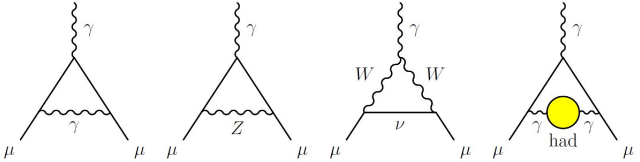


$$(g-2)_\mu$$

Muon anomalous magnetic moment $(g-2)_\mu$

⇛ Dirac equations predict a muon magnetic moment $\overrightarrow{M} = g_\mu \frac{e}{2m_\mu} \overrightarrow{S}$ with a gyromagnetic ratio $g_\mu = 2$. Experimentally $g_\mu > 2$.

⇛ This anomaly a_μ arises from calculable quantum fluctuations:



⇛ SM value $a_\mu^{\rm SM} = (116591803 \pm 49) \times 10^{-11}$ [PDG 2014]

⇛ Experiment: $a_\mu^{\rm E821} = (116592091 \pm 63) \times 10^{-11}$ [PDG 2014]

⇛ Difference: $a_\mu^{\rm E821} - a_\mu^{\rm SM} = (288 \pm 80) \times 10^{-11} \Leftrightarrow 3.6\ \sigma$!

⇛ Underestimated uncertainties? SUSY? NP?

⇛ Fermilabs E989 should futher reduce the experimental error to $\pm 16 \times 10^{-11}$.

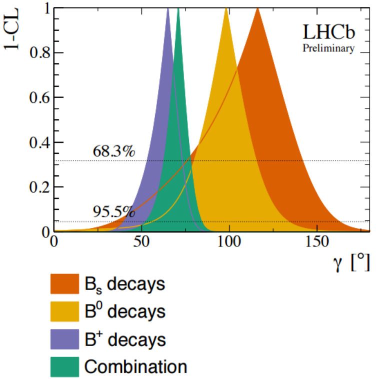
γ angle

⇛ $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \approx \arg(-\frac{V_{ub}^*}{V_{cb}^*})$ is the last well known CKM angles.

⇛ Can be determined by:

- Tree level processes, nearly insensitive to NP. Act as reference. Negligible theoretical uncertainty, using $B \to DK$.
- Loop processes, sensitive to NP.

⇛ Comparing the two can reveal NP!



⇛ The LHCb combinations leads to: $\gamma = 70.9^{+7.1}_{-8.5}$.

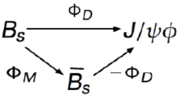
⇛ Improved by 2^{deg} compared to our previous result!

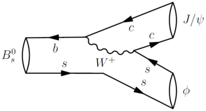
⇛ Other B-factories have 2 times larger errors:

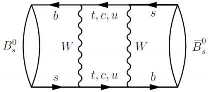
- BaBar: $\gamma = (70 \pm 18)^{\text{deg}}$
- Belle: $\gamma = (73^{+18}_{-15})^{\text{deg}}$

Mixing induced CPV in B_s^0

⇛ Interference between B_s^0 decaying to $J/\psi\phi$ either directly or by oscillations gives rise to CP violation phase: $\phi_s^{J/\psi\phi}$







⇛ In the Sm $\phi_s \approx -2\beta + s = -(0.0376^{+0.0007}_{-0.0008})$ rad, where $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$

⇛ At the leading order the same phase is expected $B_s^0 \to D_s D_s$ and $B \to J/\psi\pi\pi$.

⇛ NP can enter in the B_s^0 mixing!

⇛ Measured by simultaneous fit to B_s^0 and $\bar{B}_s^0$ decay rates:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta_\mu\, d\varphi_h\, d\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, M(B_s^0), |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \ldots)$$

Backup

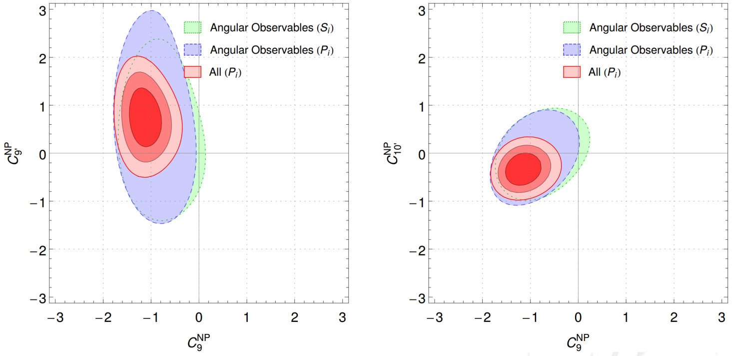
Theory implications

Coefficient	Best fit	1σ	3σ	Pull_{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

⇛ One can link the angular observables to transversity amplitudes

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

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

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

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

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

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

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\parallel^{\mathrm{L}*}-\mathrm{A}_0^\mathrm{R}\mathrm{A}_\parallel^{\mathrm{R}*})+\frac{\mathrm{m}_\ell}{\sqrt{\mathrm{q}^2}}\mathrm{Im}(\mathrm{A}_\perp^\mathrm{L}\mathrm{A}_\mathrm{S}^*-\mathrm{A}_\perp^{\mathrm{R}*}\mathrm{A}_\mathrm{S}))\right],$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\perp^{\mathrm{L}*}+\mathrm{A}_0^\mathrm{R}\mathrm{A}_\perp^{\mathrm{R}*})\right], \qquad J_9=\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_\parallel^{\mathrm{L}*}\mathrm{A}_\perp^\mathrm{L}+\mathrm{A}_\parallel^{\mathrm{R}*}\mathrm{A}_\perp^\mathrm{R})\right],$$

Link to effective operators

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

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

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

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

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

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

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

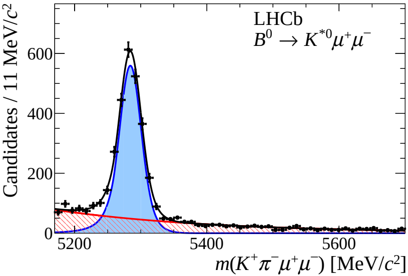
where $\hat{s}=q^2/m_B^2$, $\hat{m}_i=m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

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

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

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 $[1.1, 19.]\ \mathrm{GeV}^2/\mathrm{c}^4$.



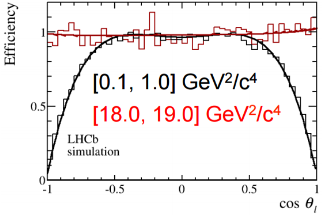
⇛ The S-wave fraction is extracted using a LASS model.

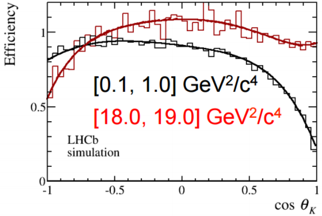
Detector acceptance

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

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

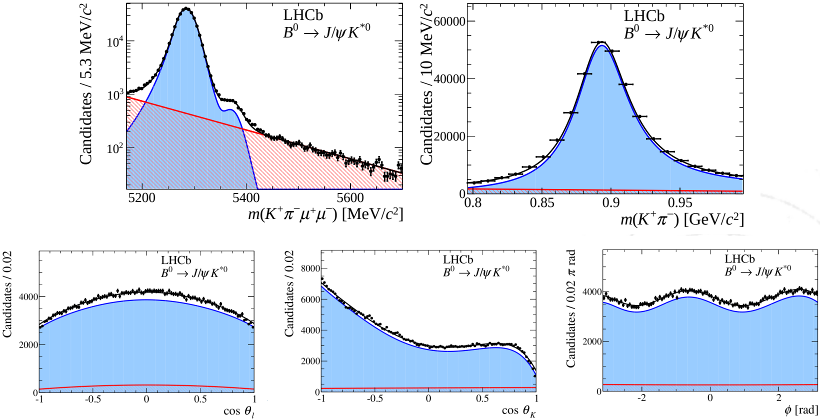
  where P_i is the Legendre polynomial of order i.
- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space and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



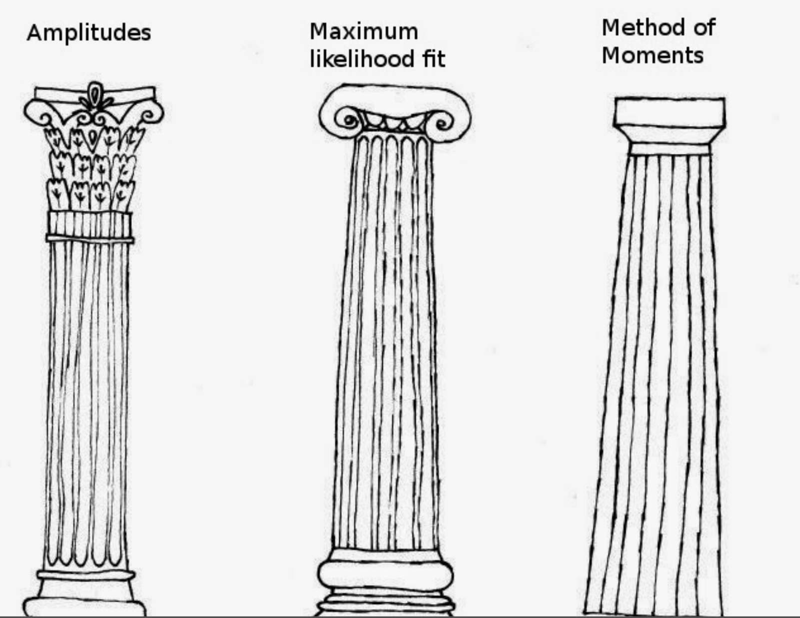


Control channel

- 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



$B_d^0 \to K^* \mu\mu$ 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:

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

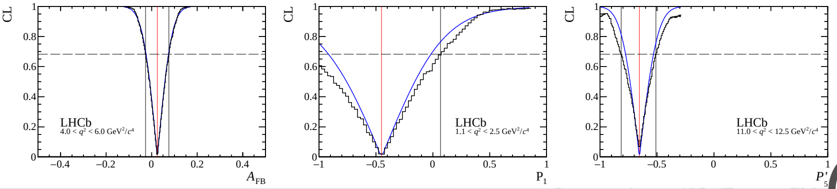
⇛ Only the relative weights matters!

⇛ The Procedure was commissioned with TOY MC study.

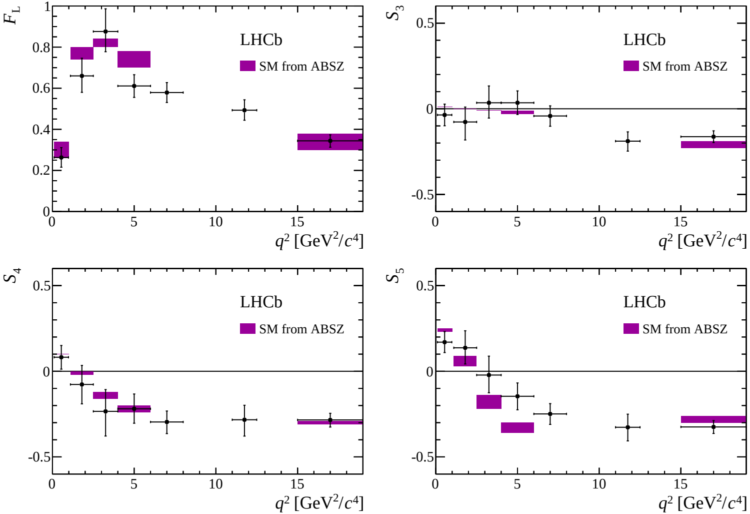
⇛ Use Feldmann-Cousins to determine the uncertainties.

⇛ 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.

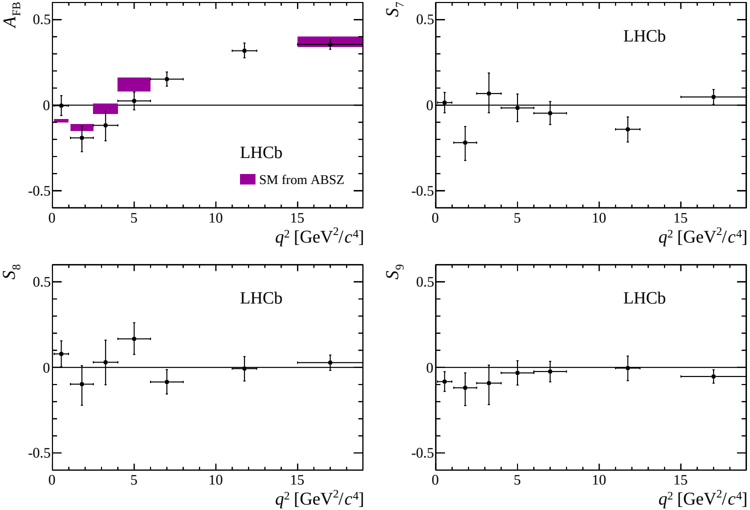


Maximum likelihood fit - Results



⇛ 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

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

$\Rrightarrow$ 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:

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

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

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

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

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

$\Rrightarrow$ The weight ω accounts for the efficiency. Again the normalization of weights does not matter.

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:

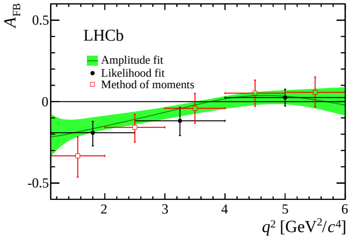
- $L,~R,~0,~\|,~\perp,~\Re,~\Im \rightarrowtail~~3 \times 2 \times 3 \times 2 = 36$ DoF.
- Scalar amplitudes: $+4$ DoF.
- Symmetries of the amplitudes reduces the total budget to: 28.

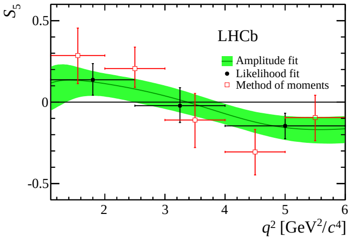
⇛ The technique is described in JHEP06(2015)084, U. Egede, M. Patel, K.A. Petridis.
⇛ Allows to build the observables as continuous functions of q^2:

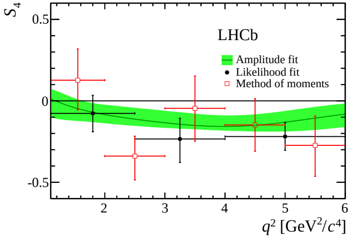
- At current point the method is limited by statistics.
- In the future the power of this method will increase.

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

Amplitudes - results







Zero crossing points:

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