# Overview of LHCb results

Marcin Chrząszcz
mchrzasz@cern.ch

on behalf of the LHCb collaboration,
Universität Zürich,
Institute of Nuclear Physics, Polish Academy of Science

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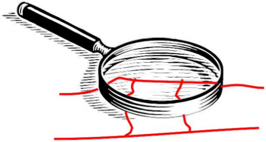
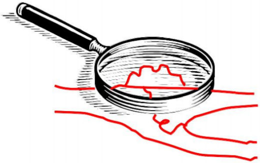
# Flavour Physics, WHAT, WHY HOW?

⇛ WHAT: Quarks and leptons exists in 6 ”flavours” (u,c,t,d,s,b) and (e,$\mu$, $\tau$, $\nu_e$, $\nu_\mu$, $\nu_\tau$).

⇛ WHY:

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





$\rightarrow$ Indirect search for New Physics

⇛ HOW:

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

# Searching for New Physics

⇛ The fundamental questions:

- Why 3 generations? Why such a hierarchy structure?
- Stability of the Higgs vacum? Dark Matter?
- Baryon asymmetry of the universe? CP in SM is too 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 $K_S^0 \to \mu\mu$: 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:
  - $R_k = \mathcal{B}(B^+ \to K^+\mu\mu)/\mathcal{B}(B^+ \to K^+ee)$
  - $R(D),\ R(D^*)$
- CP violation:
  - CP violation in $B_d^0$ and $B_s^0$
  - CP violation in charm
  - $V_{ub}$

# Rare decays

# Tools

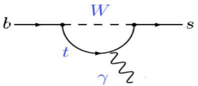
- **Operator Product Expansion and Effective Field Theory**

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

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

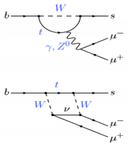
where $C_i$ are the Wilson coefficients and $O_i$ are the corresponding effective operators.

$b \to s\gamma$



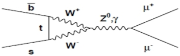

$C_7^{(\prime)}$

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




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

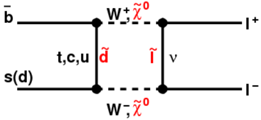
$B^0_{(s)} \to \mu^+\mu^-$

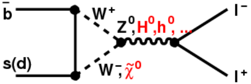



$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

# $B_{d,s} \to \mu^+\mu^-$

- Clean theoretical prediction, GIM and helicity suppressed in the SM:
  - $\mathcal{B}(B^0_s \to \mu^-\mu^+) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^-\mu^+) = (1.06 \pm 0.09) \times 10^{-10}$
- Sensitive to contributions from scalar and pesudoscalar couplings.
- Probing: MSSM, higgs sector, etc.
- In MSSM: $\mathcal{B}(B^0_s \to \mu^-\mu^+) \sim \mathrm{tg}^6\,\beta/m^4_A$
- Theory errors dominated by the form factors! Will go down in the future.

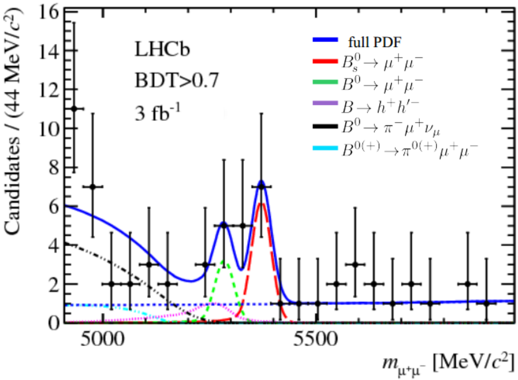



# $B^0 \to \mu^+\mu^-$ Results



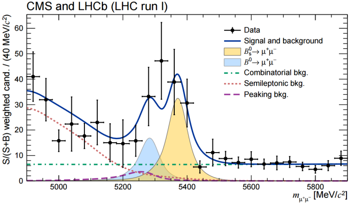
- Nov. 2012:
  - First evidence $3.5\sigma$ for $B^0 \to \mu^+\mu^-$. with $2.1\ \mathrm{fb}^{-1}$.
- Summer 2013:
  - Full data sample: $3\ \mathrm{fb}^{-1}$.



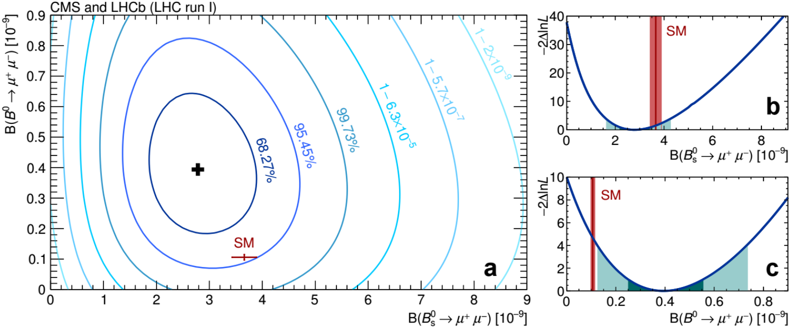

- Measured BF:
  $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.9^{+1.1}_{-1.0}(stat.)^{+0.3}_{-0.1}(syst.)) \times 10^{-9}$
- $4.0\sigma$ significance!
- $\mathcal{B}(B^0 \to \mu^-\mu^+) < 7 \times 10^{-10}$ at $95\%$ CL
- CMS result: PRL 111 (2013) 101805

# LHCb+CMS Combination

*Nature 522 (2015) 68*




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




$2.3\,\sigma$ compatibility with SM!

$\Rrightarrow$

⇛ 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:

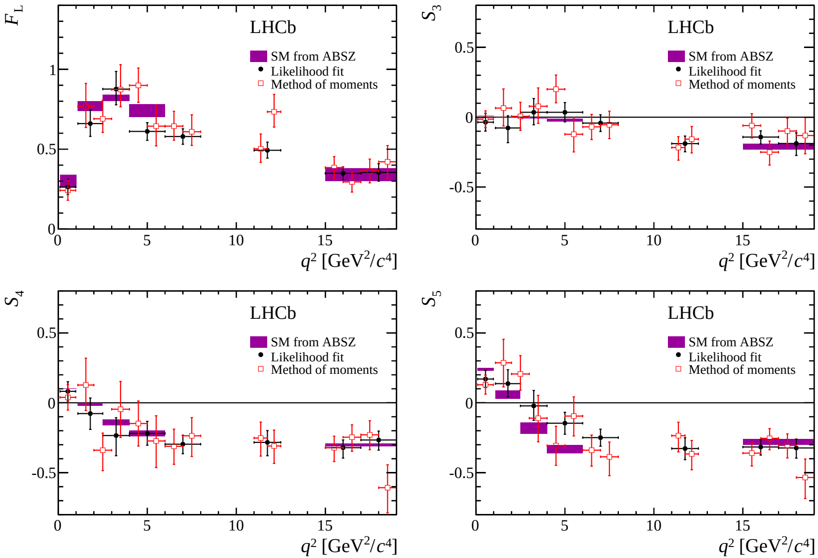
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell\right.$$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

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

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

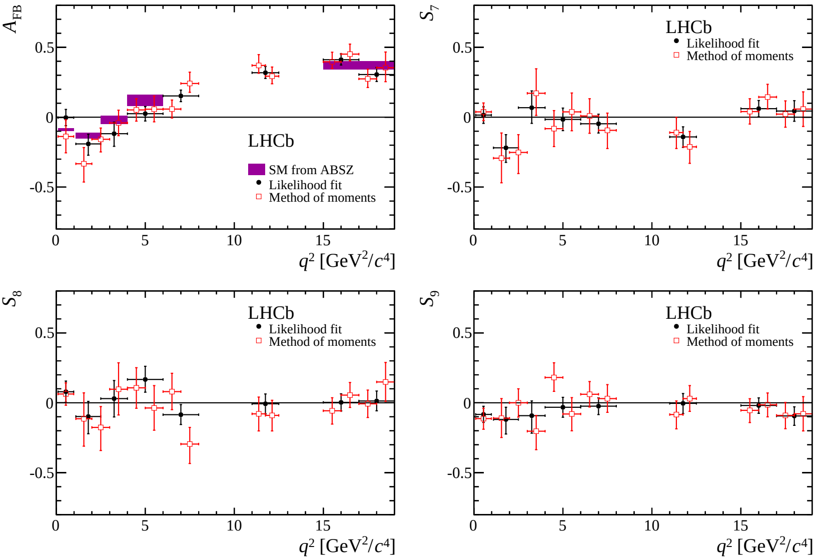
# $B_d^0 \to K^* \mu\mu$ results





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

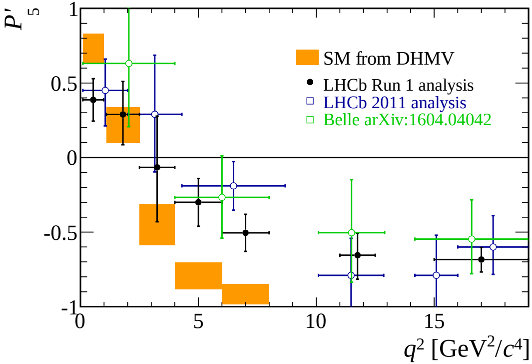
*JHEP 02 (2016) 104*




$\Rrightarrow$ $S_7$, $S_8$, $S_9$ are zero in the SM!

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

arxiv:1604.04042




- 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

# Compatibility with SM

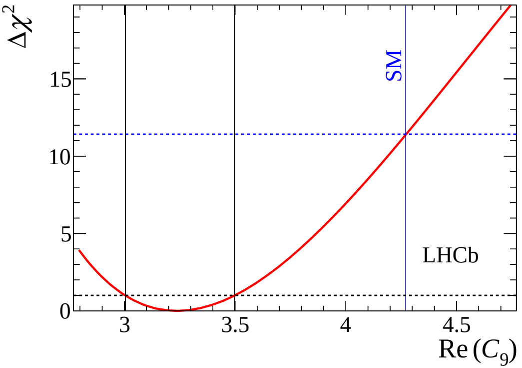


$\Rightarrow$ Use EOS software package to test compatibility with SM.
$\Rightarrow$ Perform the $\chi^2$ fit to the measured:

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

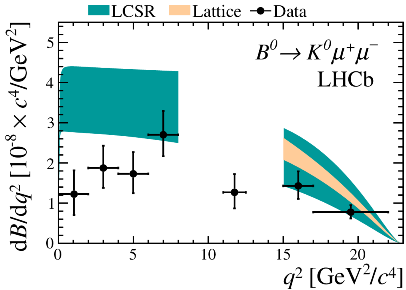
$\Rightarrow$ Float a vector coupling: $\Re(C_9)$.
$\Rightarrow$ Best fit is found to be $3.4\ \sigma$ away from the SM.

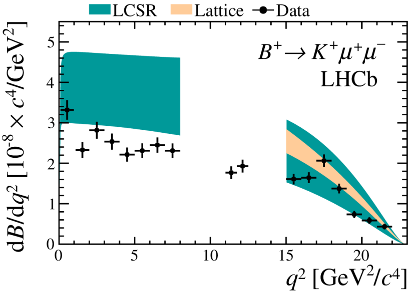
$$\Delta\Re(C_9) \equiv \Re(C_9)^{\rm fit} - \Re(C_9)^{\rm SM} = -1.03$$



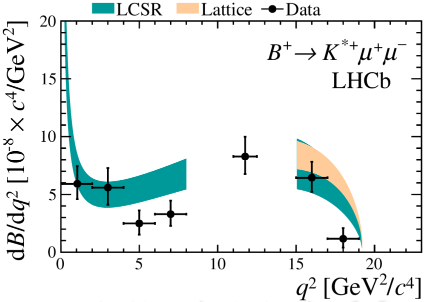
# BF of $B \to K^{*\pm}\mu\mu$

JHEP 07 (2012) 133



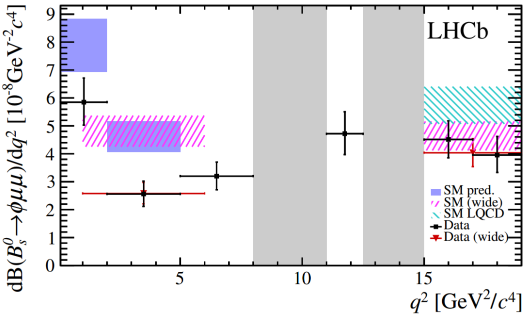




- Despite large theoretical errors the results are consistently smaller than SM prediction.



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

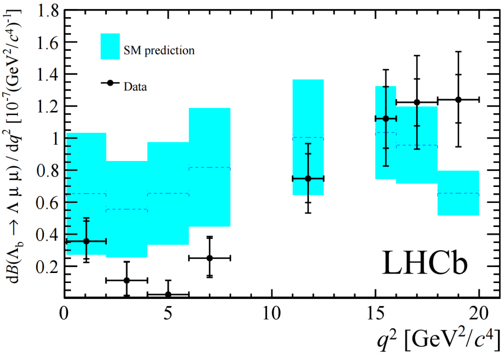





- Last years LHCb measurement.
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow $\phi$ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.

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

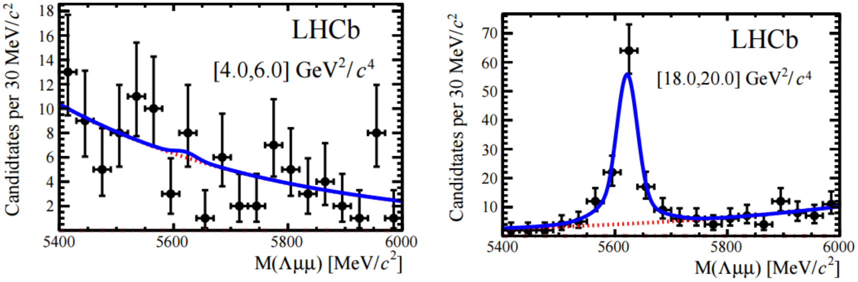





- Last years LHCb measurement.
- In total $\sim 300$ candidates in data set.
- Decay not present in the low $q^2$.

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

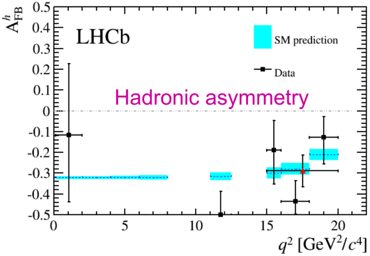


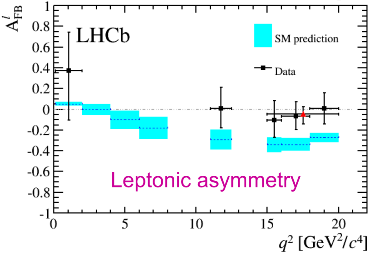



- Last years LHCb measurement.
- In total $\sim 300$ candidates in data set.
- Decay not present in the low $q^2$.

# 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.
- $A^{\ell}_{FB}$ always above SM prediction.

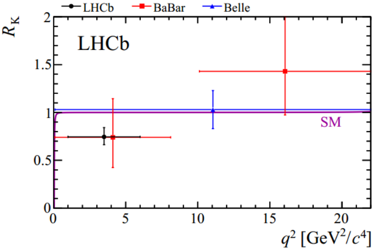
# Lepton Universality tests

# Lepton universality test

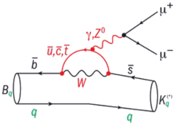
*Phys. Rev. Lett. 113, 151601 (2014)*

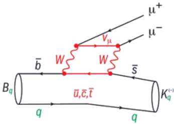
- Does the NP couple equally to all flavours?

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



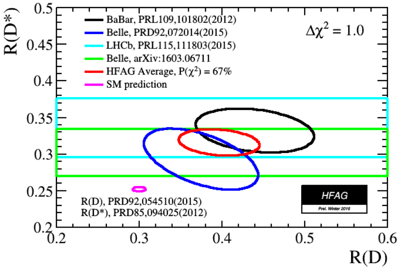

- Challenging electron analysis.
- Migration of events modelled by MC.
- Correct for Bremsstrahlung.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- In $3{\rm fb}^{-1}$, LHCb measures: $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with SM at $2.6\sigma$.



# More Lepton universality tests

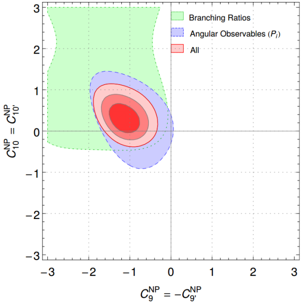
- There is one other LUV decay recently measured by LHCb.
- $R(D^*) = \dfrac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)}$
- Clean SM prediction: $R(D^*) = 0.252(3)$, PRD 85 094025 (2012)
- LHCb result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- HFAG average: $R(D^*) = 0.322 \pm 0.022$
- $4.0\ \sigma$ discrepancy wrt. SM.

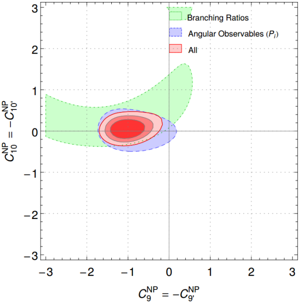


# Explanation of anomalies

arXiv:1510.04239

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

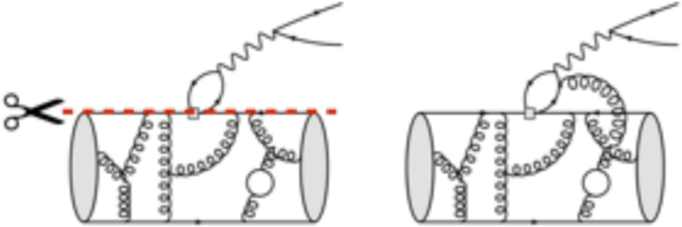



⇛ The fit prefer a modification of $C_9$ Wilson coefficient with a value of $C_9^{NP} = -1$, with a significance over $4\sigma$.

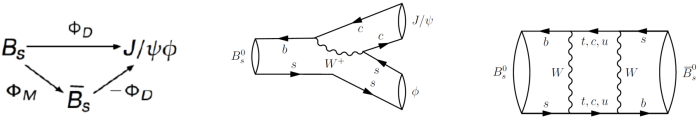
# Explanation of anomalies

- We are not there yet!
- There might be something not taken into account in the theory.
- Resonances ($J/\psi$, $\psi(2S)$) tails can mimic NP effects.
- There might be some non factorizable QCD corrections.
  " However, the central value of this effect would have to be significantly larger than expected on the basis of existing estimates" `D.Straub, 1503.06199` .



# Mixing induced CPV in $B_s^0$

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




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

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

$\Rrightarrow$ NP can enter in the $B_s^0$ mixing!

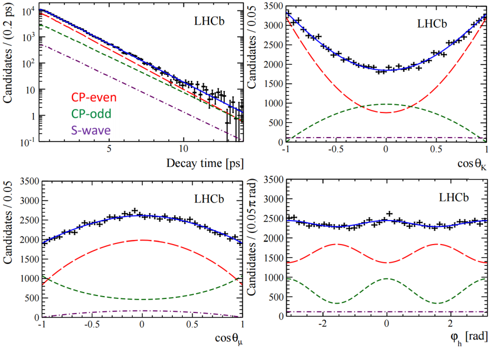
$\Rrightarrow$ Measured by simultaneous fit to $B_s^0$ and $\bar{B}_s^0$ decay rates:

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

# Mixing induced CPV in $B_s^0$

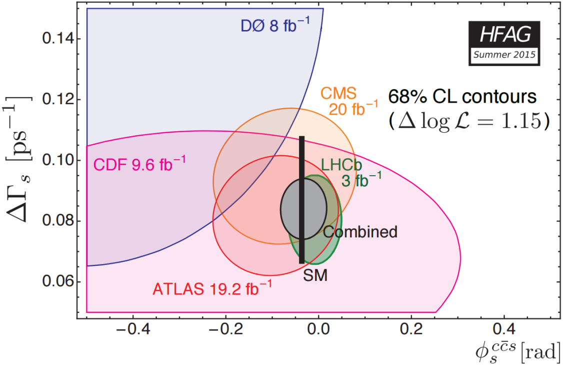
*PRL 114, 041801 (2015)*

⇛ Unbinned maximum likelihood fit (time, mass, angles, initial flavour):




- $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad.
- $\Gamma_s = (\Gamma_L + \Gamma_H)/2 = 0.6603 \pm 0.0027 \pm 0.0015\ \mathrm{ps}^{-1}$
- $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$
- Combined with $B_s^0 \to J/\psi\pi\pi$: $\phi_s = -0.010 \pm 0.039$ rad.

# Mixing induced CPV in $B_s^0$

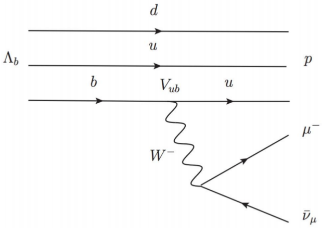



- ⇛ LHCb is dominating the world average!
- ⇛ $\phi_s^{\rm HFAG} = -0.034 \pm 0.033$.
- ⇛ Compatible with SM, but there is still plenty room for NP!
- ⇛ Penguin pollution constrained from $B^0 \to J/\psi\rho$ and $B_s^0 \to J/\psi\bar{K}^*$

$\Rrightarrow$ Since a long time the smallest of the CKM matrix elements $V_{ub}$ has been determined in two ways:

- inclusively: $b \to u\ell\nu$, $|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$
- exclusively: $B \to \pi\ell\nu$, $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
- $3\ \sigma$ tensions!

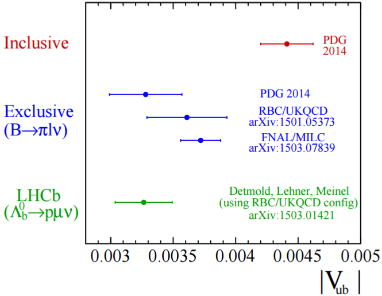
$\Rrightarrow$ LHCb perspectively enters the game with baryons decay: $\Lambda_b \to p\mu\nu$.

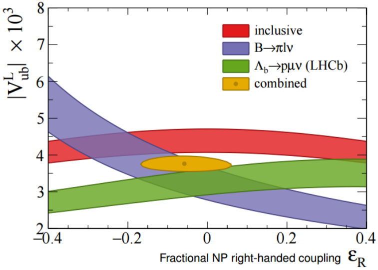



$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF}$$

where $R_{FF}$ is a ratio of form factors, that can be calculated using lattice QCD [arxiv:1503.01421].

$\Rightarrow |V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06(V_{cb})) \times 10^{-3}$

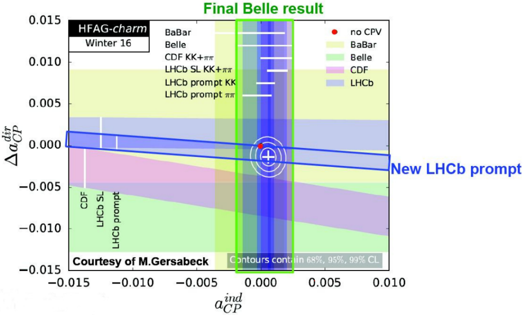



- LHCbs measurement makes the discrepancy larger and is spot on the exclusive B-factories results.
- Disfavor NP models with significant right handed current
- Debatable world averages, depending on the input used (theory, BR of control mode, ...)

⇛ The $A_{CP}$ asymmetry is defined as:

$$A_{CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}, \quad f = K^+K^-, \pi^+\pi^-$$




⇛ New world average:

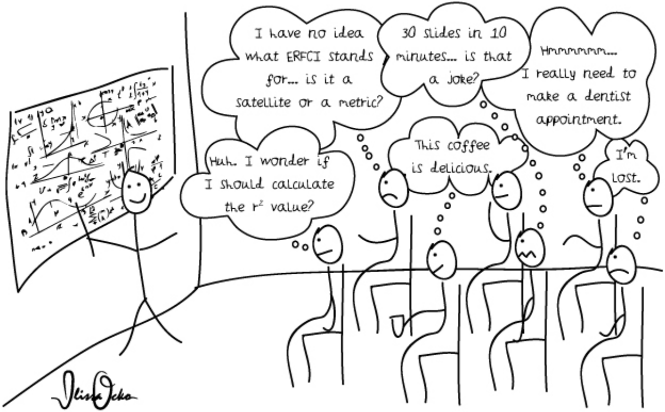
$$a_{CP}^{\text{ind}} = (0.056 \pm 0.040)\%$$
$$a_{CP}^{\text{dir}} = (-0.137 \pm 0.070)\%$$

⇛ Results consistent with no CPV at $6.5$ % CL.

# Conclusions

$\Rrightarrow$ Flavour physics is still playing an important role for hunting new physics!
$\Rrightarrow$ Anomalies in the electroweak penguin and lepton universality combine to over $4\sigma$ significance discrepancy for NP.
$\Rrightarrow$ The dominant anomaly was recently confirmed by Belle experiment!
$\Rrightarrow$ Most precise measurements of CP violations in $B_s^0$ system.
$\Rrightarrow$ First $V_{ub}$ determination from baryon decays!
$\Rrightarrow$ Stay tuned as there are plenty of more results in the pipe line!

# Thank you for the attention!



# Backup

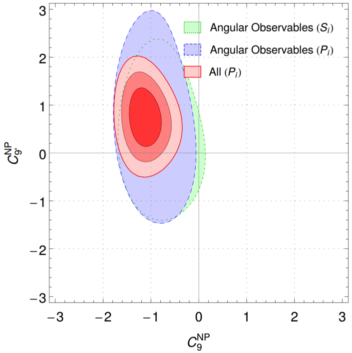
# Theory implications

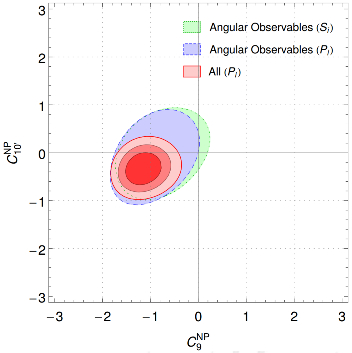
| Coefficient | Best fit | $1\sigma$ | $3\sigma$ | $\text{Pull}_{\text{SM}}$ | p-value (%) |
|---|---|---|---|---|---|
| $\mathcal{C}_7^{\text{NP}}$ | $-0.02$ | $[-0.04, -0.00]$ | $[-0.07, 0.04]$ | 1.1 | 16.0 |
| $\mathcal{C}_9^{\text{NP}}$ | $-1.11$ | $[-1.32, -0.89]$ | $[-1.71, -0.40]$ | **4.5** | 62.0 |
| $\mathcal{C}_{10}^{\text{NP}}$ | 0.58 | $[0.34, 0.84]$ | $[-0.11, 1.41]$ | 2.5 | 25.0 |
| $\mathcal{C}_{7'}^{\text{NP}}$ | 0.02 | $[-0.01, 0.04]$ | $[-0.05, 0.09]$ | 0.7 | 15.0 |
| $\mathcal{C}_{9'}^{\text{NP}}$ | 0.49 | $[0.21, 0.77]$ | $[-0.33, 1.35]$ | 1.8 | 19.0 |
| $\mathcal{C}_{10'}^{\text{NP}}$ | $-0.27$ | $[-0.46, -0.08]$ | $[-0.84, 0.28]$ | 1.4 | 17.0 |
| $\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$ | $-0.21$ | $[-0.40, 0.00]$ | $[-0.74, 0.55]$ | 1.0 | 16.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$ | $-0.69$ | $[-0.88, -0.51]$ | $[-1.27, -0.18]$ | **4.1** | 55.0 |
| $\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$ | $-0.09$ | $[-0.35, 0.17]$ | $[-0.88, 0.66]$ | 0.3 | 14.0 |
| $\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | 0.20 | $[0.08, 0.32]$ | $[-0.15, 0.56]$ | 1.7 | 19.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$ | $-1.09$ | $[-1.28, -0.88]$ | $[-1.62, -0.42]$ | **4.8** | 72.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | $-0.68$ | $[-0.49, -0.49]$ | $[-1.36, -0.15]$ | 3.9 | 50.0 |
| $\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$ | $-0.17$ | $[-0.29, -0.06]$ | $[-0.54, 0.18]$ | 1.5 | 18.0 |

Table 2: *Best-fit points, confidence intervals, pulls for the SM hypothesis and p-values for different one-dimensional NP scenarios.*

# If not NP?

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



# Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

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

# Link to effective operators

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

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

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

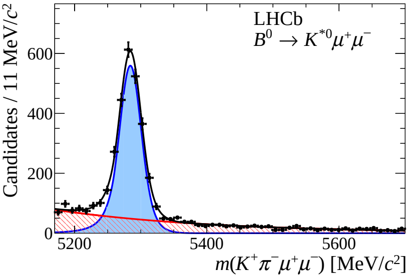
where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

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

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

# 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 $624 \pm 30$ candidates in the most interesting $[1.1, 6.0]$ $\mathrm{GeV}^2/\mathrm{c}^4$ region and $2398 \pm 57$ in the full range $[1.1, 19.]$ $\mathrm{GeV}^2/\mathrm{c}^4$.



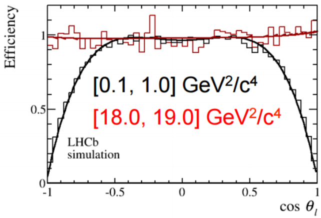

⇛ The S-wave fraction is extracted using a LASS model.

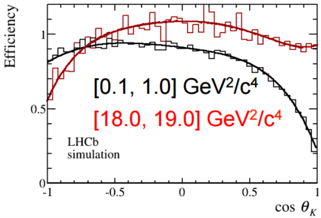
# Detector acceptance

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

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

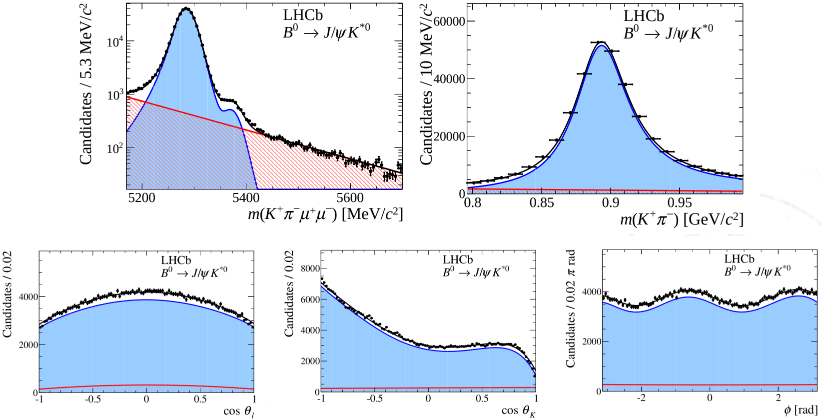
  where $P_i$ is the Legendre polynomial of order $i$.
- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space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



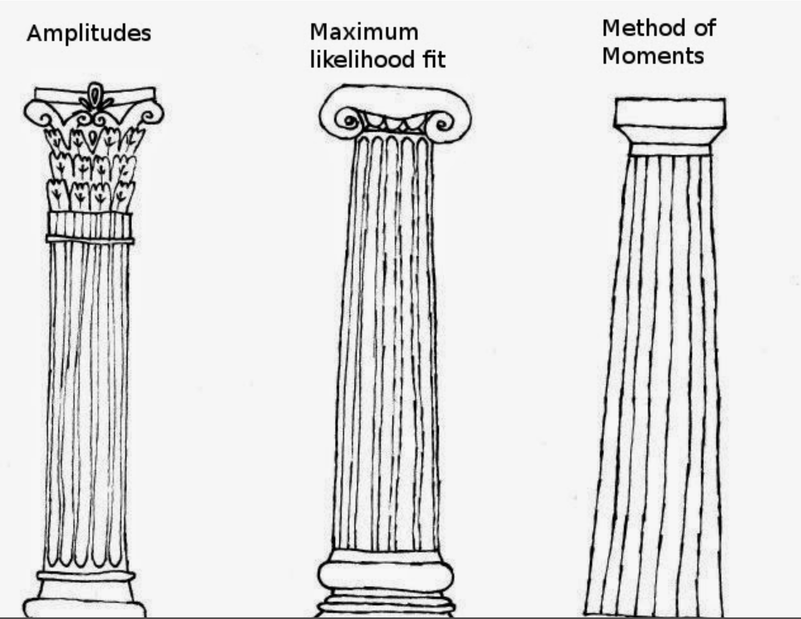



# Control channel

- 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



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

$\Rrightarrow$ Better alternative is to put the efficiency into the maximum likelihood fit itself:

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

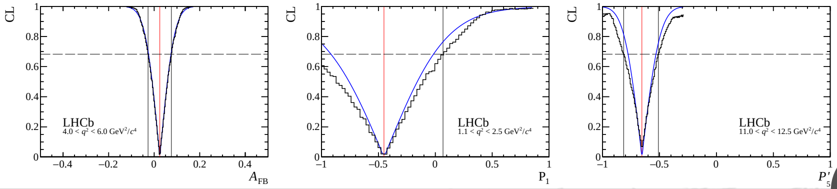
$\Rrightarrow$ Only the relative weights matters!

$\Rrightarrow$ The Procedure was commissioned with TOY MC study.

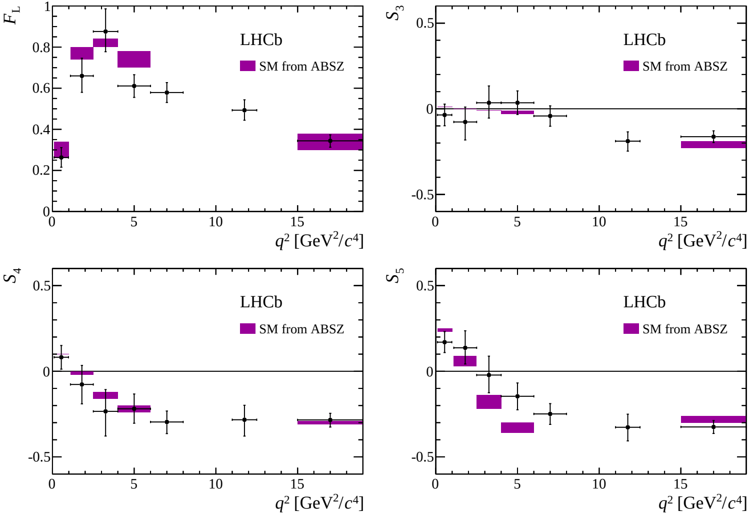
$\Rrightarrow$ Use Feldmann-Cousins to determine the uncertainties.

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

$\Rrightarrow$ S-wave component treated as nuisance parameter.

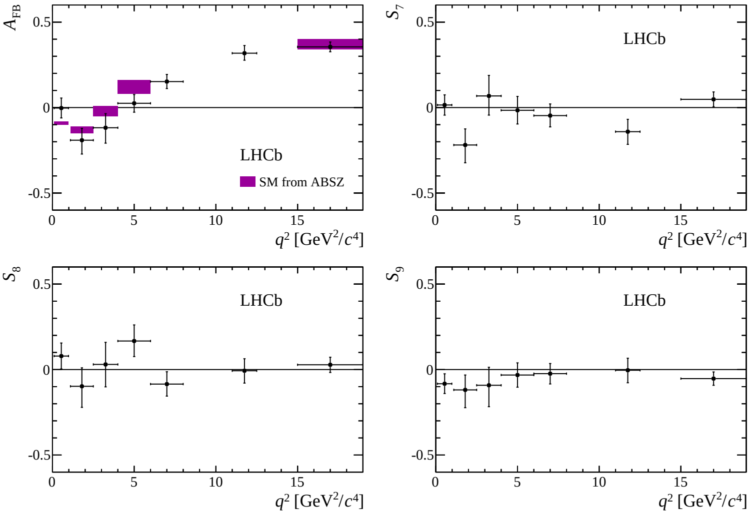


# Maximum likelihood fit - Results




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

# Maximum likelihood fit - Results




$\Rightarrow$ 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: $\int \to \sum$ and $M_i \to \widehat{M}_i$

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

$\Rrightarrow$ The weight $\omega$ 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: $q^2 \in [1.1.6.0]\ \mathrm{GeV}^2/c^4$.
⇛ 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 $\alpha, \beta, \gamma$ per vector amplitude:

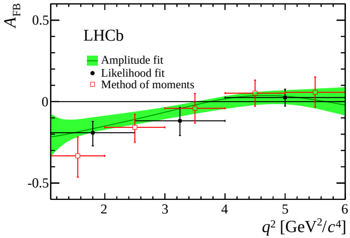
- $L$, $R$, $0$, $\parallel$, $\perp$, $\Re$, $\Im$ $\rightarrowtail$ $3 \times 2 \times 3 \times 2 = 36$ DoF.
- Scalar amplitudes: $+4$ DoF.
- Symmetries of the amplitudes reduces the total budget to: $28$.

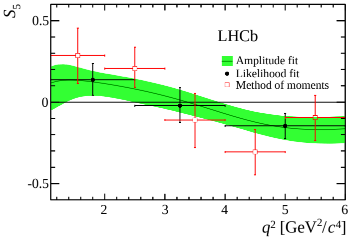
⇛ The technique is described in JHEP06(2015)084, U. Egede, M. Patel, K.A. Petridis.
⇛ Allows to build the observables as continuous functions of $q^2$:

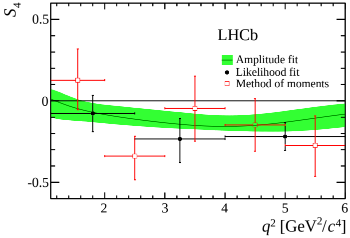
- At current point the method is limited by statistics.
- In the future the power of this method will increase.

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

# Amplitudes - results



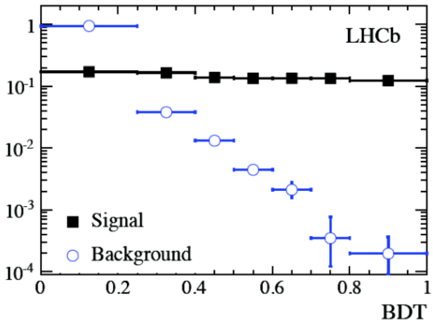



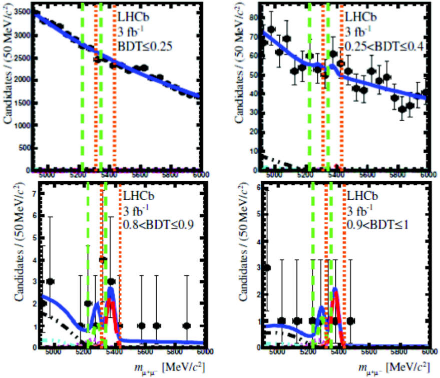




Zero crossing points:

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

- 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 $B^0 \to K\pi$.

# Tetra&Petraquarks

$\Rrightarrow$ Idea of this multi quark states started in the $1960$s:

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
*California Institute of Technology, Pasadena, California*

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

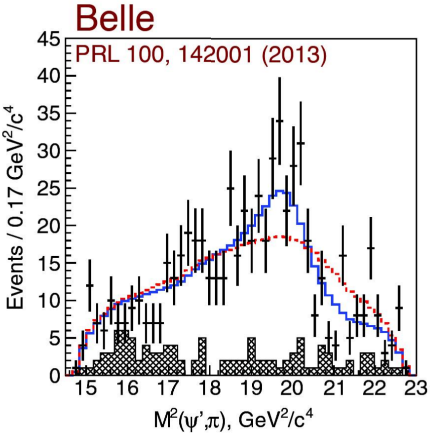
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles $d^-$, $s^-$, $u^0$ and $b^0$ exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(qqq)$, $(qqqq\bar{q})$ etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$ etc. It is assuming that the lowest

$\Rrightarrow$ Searches for years and many "discoveries" not confirmed

# $Z(4430)^-$

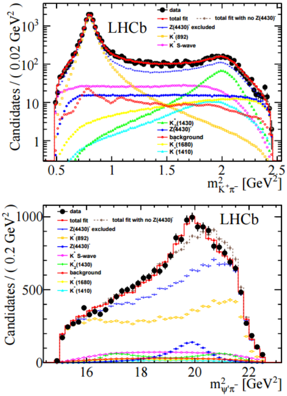
$\Rrightarrow$ $Z(4430)^-$ special "tetraquark candidate",because charged: cannot be a $c\bar{c}$ state!
$\Rrightarrow$ Belle discovered it in $B^0 \to \Upsilon(2S)K\pi$, with evidence of $J^P = 1^+$ [PRD 88 (2013) 074026].
$\Rrightarrow$ Using method of moments, Babar claimed they do not need the $Z(4430)^-$ to described their data [PRD 79 (2009) 112001].
$\Rrightarrow$ LHCb reproduced BaBar moments analysis with the full Run1 sample ($3\ \mathrm{fb}^{-1}$) and clearly something mote was needed to describe the data [PRL 112, 222002 (2014)].

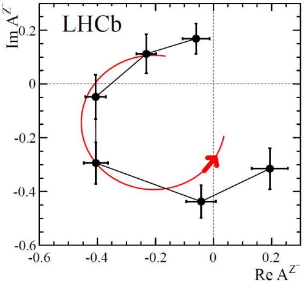


⇛ LHCb unbinned amplitude analysis of $B^0 \to \psi(2S) K^+ \pi^-$,
$m = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV/c^2}$, $\Gamma = 172 \pm 13^{37}_{34}\ \mathrm{MeV/c^2}$

⇛ $J^P$ is confirmed to be $1^+$ and Argand plot shows the typical pattern for resonances.

⇛ Minimal quark content $c\bar{c}d\bar{u}$.




Fitted values of the $Z$ amplitude in six $m^2_{\psi'\pi^-}$ bins.

Red is expectation from BW

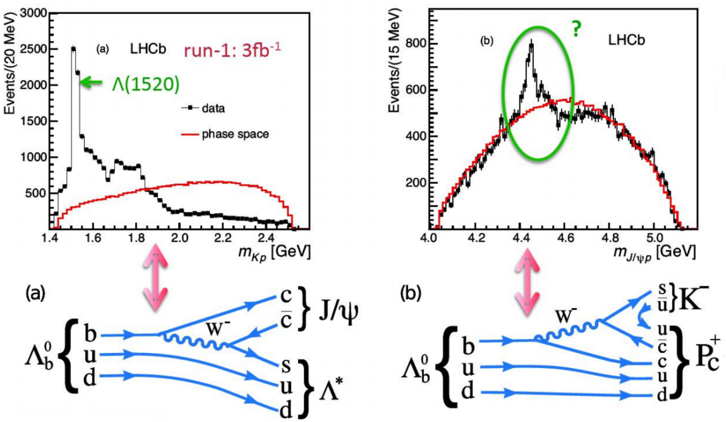
# Pentaquarks in $\Lambda_b \to J/\psi p K$

[LHCb, PRL 115 (2015) 072001]

⇛ $\Lambda_b \to J/\psi p K$ was studied initially for a precise $\Lambda_b$ lifetime .

⇛ Close look at the Dalitz: $m(Kp) - m(J/\psi p)$

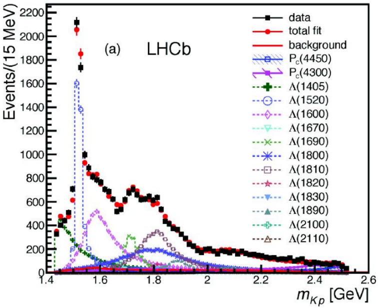
- $m(Kp)$ has a rich structure of excited $\Lambda$ states.
- $m(J/\psi p)$ has something inside!

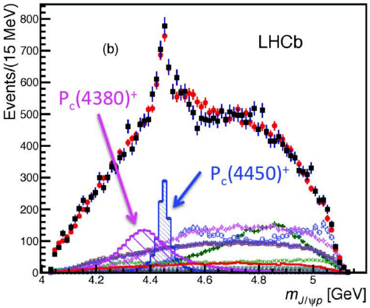


# Pentaquarks in $\Lambda_b \to J/\psi p K$

$\Rightarrow$ Super complex fit needed to describe the data: $5$ decay angles, $14$ possible $\Lambda^*$ resonances for $m(K\pi)$ and two brand new pentaquarks for $m(J/\psi p)$:

- $P_c(4380)^+$: $4380 \pm 8 \pm 29$ MeV/c$^2$, $\Gamma = 205 \pm 18 \pm 86$ MeV/c$^2$, $J^P = \frac{3}{2}^-$
- $P_c(4450)^+$: $4449, 8 \pm 1.7 \pm 2.5$ MeV/c$^2$, $\Gamma = 39 \pm 5 \pm 19$ MeV/c$^2$, $J^P = \frac{5}{2}^+$



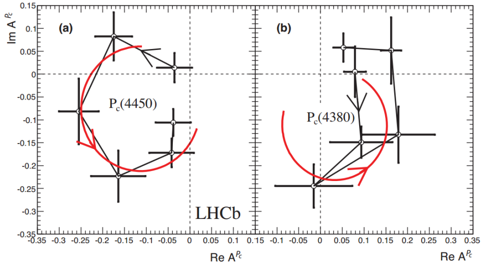



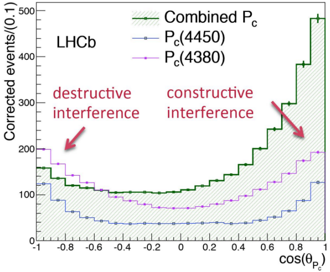
# Pentaquarks in $\Lambda_b \to J/\psi p K$

[LHCb, PRL 115 (2015) 072001]

- Angrad plots show the phase motion for the resonances.
- The $P_c(4380)$ has one point off by a $2\sigma$.

- The interference patterns confirm the opposite parities.




$\Rrightarrow$ The significance was evaluated with a TOY MC:

- $P_c(4380)^+ \;:\; 9\sigma$
- $P_c(4450)^+ \;:\; 12\sigma$

$\Rrightarrow$ The states are consistent with $c\bar{c}uud$.