# Recent results from LHCb

## A brief selection

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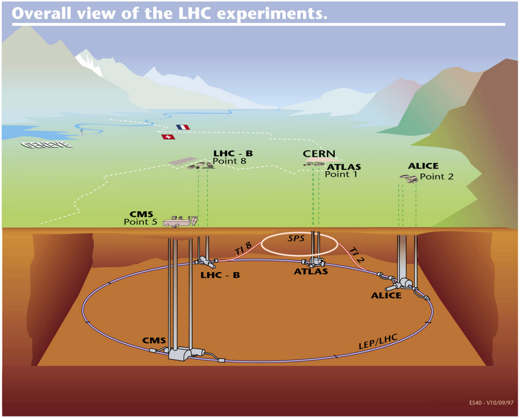
on behalf of the LHCb collaboration

University of Glasgow Particle Physics

Fourth workshop on flavour symmetries and consequences in accelerators and cosmology (FLASY 2014)
17-21 June 2014, University of Sussex, Brighton, UK

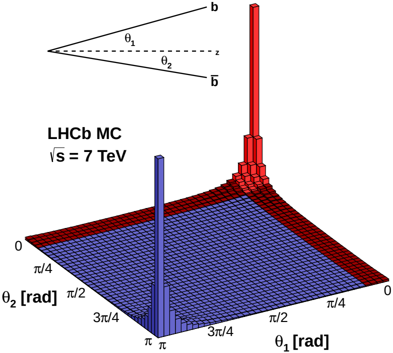
# LARGE HADRON COLLIDER

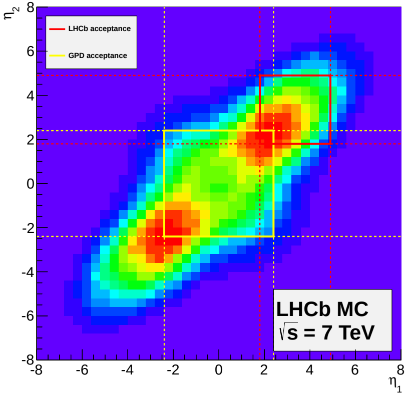


# Forward acceptance

Forward acceptance $2 < \eta < 5$.

Takes advantage of the predominant forward production of heavy flavored hadrons.

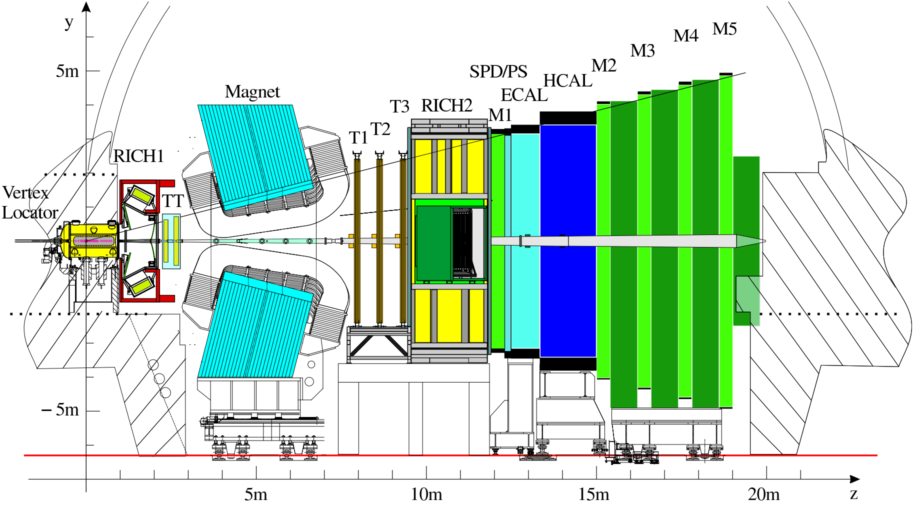



Pseudorapidity range unique among the LHC detectors.

Complementary to the GPDs.

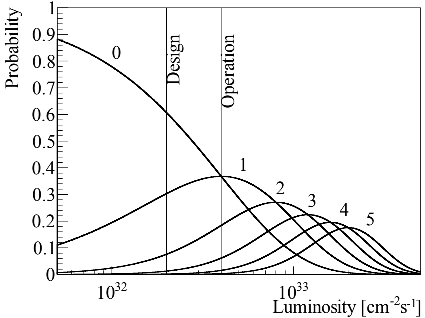
# LHCb detector



# LHCb beyond design

Exceeding design specifications to maximize physics reach

| | Design | 2012 |
|---|---|---|
| Instantaneous luminosity, $\mathcal{L}_{\text{inst}}$ ( $\text{cm}^{-2}\,\text{s}^{-1}$) | $2 \times 10^{32}$ | $4 \times 10^{32}$ |
| Mean visible *p*-*p* interactions/crossing, $\mu$ | 0.4 | 1.6 |
| HLT output rate to tape ( kHz) | 2 | 5 |




High rate heavy flavor production into LHCb acceptance:

$\sigma_{pp}^{\text{vis}} = 58.8 \pm 0.2\,\text{mb}$
[JINST 7 (2012) P01010]

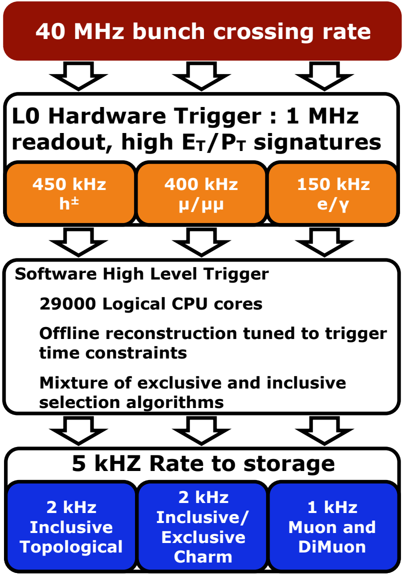
$\sigma_{b\bar{b},\text{acc}} = 75.3 \pm 14.1\,\mu\text{b}$
[PLB 694 209-216]

$\Rightarrow$ 30 kHz of $b\bar{b}$ production.

$\sigma_{c\bar{c},\text{acc}} = 1419 \pm 134\,\mu\text{b}$
[Nucl.Phys.B 871, 1-20]

$\Rightarrow$ 600 kHz of $c\bar{c}$ production.

# TRIGGER STRUCTURE




Architecture and performance documented in JINST 8 (2013) P04022.

Input includes 15 MHz of non-empty bunch crossings.

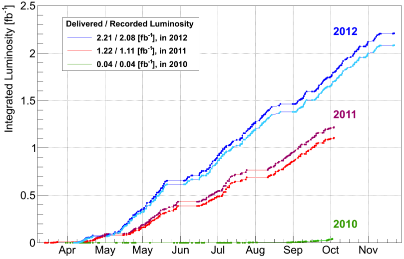
L0 hardware trigger includes three main collections of channels

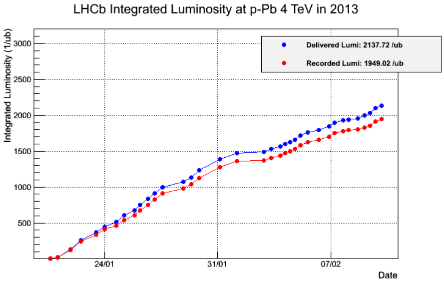
- Hadron calorimeter triggers,
- Muon detector triggers,
- Electromagnetic calorimeter triggers.

HLT software trigger divided into two sequential stages

- HLT1: high-$p_T$ displaced tracks,
  - 70 kHz retention.
- HLT2: full event reconstruction

# LHCb data collection 2010-2013




Data collection with *pp* collisions:

2010 38 pb$^{-1}$ $\sqrt{s} = 7\,\text{TeV}$,
2011 1.1 fb$^{-1}$ $\sqrt{s} = 7\,\text{TeV}$,
2012 2.0 fb$^{-1}$ $\sqrt{s} = 8\,\text{TeV}$.

Data collection with *p*Pb collisions:

2013 1.9 nb$^{-1}$ $\sqrt{s_{NN}} = 5\,\text{TeV}$.

# LHCb physics program I

LHCb is designed for high precision searches for indirect evidence of New Physics beyond the Standard Model in

- Heavy meson mixing, *e.g.*,
  - $\phi_s$ in $B_s^0$ mixing,
  - $A_\Gamma$ in $D^0$-$\bar{D}^0$ mixing.
- *CP* violation, *e.g.*,
  - $\gamma(\phi_3)$ in $B$ decays,
  - Direct *CP* violation in $B$ and $D$ decays.
- Rare transitions of of $b$ (and $c$) hadrons, *e.g.*,
  - Branching fractions of rare decays like $B_{(s)} \to \mu^+\mu^-$,
  - $A_{\mathrm{FB}}$ and angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and related modes.

In these tasks, LHCb is performing admirably.

# LHCb physics program II

However, it is also an ideal laboratory for a much broader physics program, including

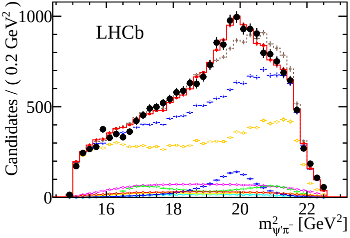
- Spectroscopy and the discovery of new states,
- Precision mass and lifetime measurements,
- Production measurements and precision tests of QCD,
- Precision branching fraction and decay amplitude measurements, including newly observed decay modes,
- Studies of proton–ion collisions at forward rapidities.

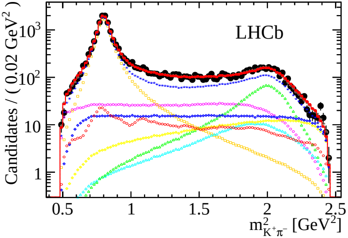
Almost 200 papers submitted to journals

- This talk includes just a small selection of recent results

# $Z(4430)^-$ in $B^0 \to \psi'\pi^- K^+$

PRL 112 222002 (2014)




Four-dimensional amplitude analysis of $B^0 \to \psi'(\mu^+\mu^-)\pi^- K^+$

- $m^2(K^+\pi^-)$, $m^2(\psi'\pi^-)$,
- $\psi'$ helicity angle $\cos\theta_{\psi'}$,
- and decay plane angle $\phi$.

$25176 \pm 174$ $B^0 \to \psi'(\mu^+\mu^-)\pi^- K^+$ decays

- An order of magnitude more than previous analyses.

$Z(4430)^-$ established at $13.9\sigma$ with properties

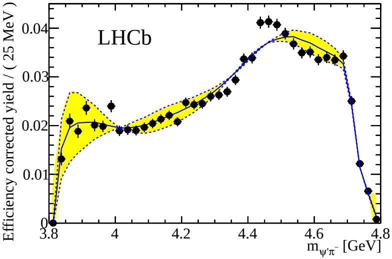
- $m(Z) = 4475 \pm 7^{+15}_{-25}$ MeV,
- $\Gamma(Z) = 172 \pm 13^{+37}_{-34}$ MeV,
- $f_Z = (5.9 \pm 0.9^{1.5}_{3.3})\%$,
- $J^P = 1^+$, with other assignments ruled out at $> 9\sigma$.

# $Z(4430)^-$ IN $B^0 \to \psi' \pi^- K^+$

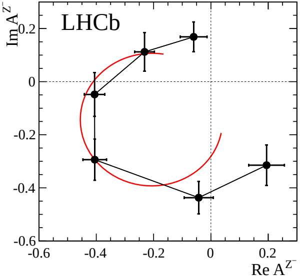
PRL 112 222002 (2014)

Model-independent analysis:

- Method of BaBar, PRD 79 112001 (200
- Legendre moments of $K^*$ helicity angle distribution in slices of $m(K^+\pi^-)$
- Reflect $J \leq 2$ moments into the $m(\psi'\pi^-)$ distribution.




$K^*$ reflections unable describe the data.




Replace Breit-Wigner amplitude model for $Z(4430)^-$ with six independent complex amplitudes in bins of $m(\psi'\pi^-)$ in the peak region,

- Tests phase variation with mass,
- Argand diagram shows rapid variation of phase at peak of magnitude,

Consistent with resonance.

# $A_{CP}$ IN $D^0 \to h^- h^+$ DECAYS

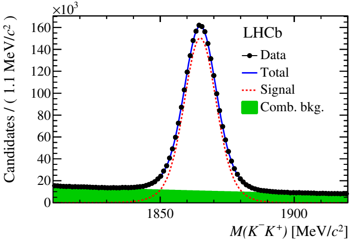
LHCb-PAPER-2014-013, ACCEPTED BY JHEP

Samples of $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ produced in $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$

- Charge of muon tags initial flavor of $D^0$.

Observed asymmetries a combination of *CP* asymmetry and confounding detection and production asymmetries…

$$A_{\rm raw} = A_{CP} + A_{\rm D}(\mu^-) + A_{\rm P}(\bar{B})$$




$\sim$2 million $D^0 \to K^- K^+$ decays

Full 3 fb$^{-1}$ Run 1 sample

…that cancel in the difference

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$$

Further, $A_{CP}(K^-K^+)$ can be extracted directly

- $\bar{B} \to D^0(K^-\pi^+)\mu^-\bar{\nu}_\mu X$ decays to cancel $A_{\rm D}(\mu^-) + A_{\rm P}(\bar{B})$,
- Samples of promptly produced $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ to measure the $K^-\pi^+$ detection asymmetry in the $D^0 \to K^-\pi^+$ sample

$$A_{CP}(K^-K^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(K^-\pi^+) + A_{\rm D}(K^-\pi^+)$$

# $A_{CP}$ IN $D^0 \to h^- h^+$ DECAYS

LHCb-PAPER-2014-013, ACCEPTED BY JHEP

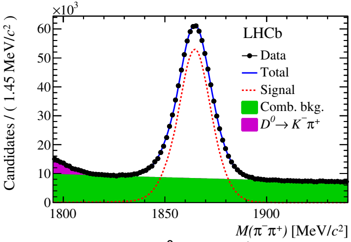
$A_{CP}$ has contributions from direct and indirect $CP$ violation.

Indirect contribution dependent on mean $D^0$ decay time of sample.

$$A_{CP} \approx a_{CP}^{\text{dir}} - A_\Gamma \frac{\langle t \rangle}{\tau}$$

$\frac{\langle t \rangle}{\tau}$ similar for $K^- K^+$ and $\pi^- \pi^+$ samples

$\Rightarrow \Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}}$




$\sim$0.8 million $D^0 \to \pi^- \pi^+$ decays

Full 3 fb$^{-1}$ Run 1 sample

The most precise measurements of time-integrated CP asymmetries in $D^0 \to h^- h^+$ decays from a single experiment to date:

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\,\%$$

$$A_{CP}(K^- K^+) = (-0.06 \pm 0.15 \pm 0.10)\,\%$$

$$A_{CP}(\pi^- \pi^+) = (-0.20 \pm 0.19 \pm 0.10)\,\%$$

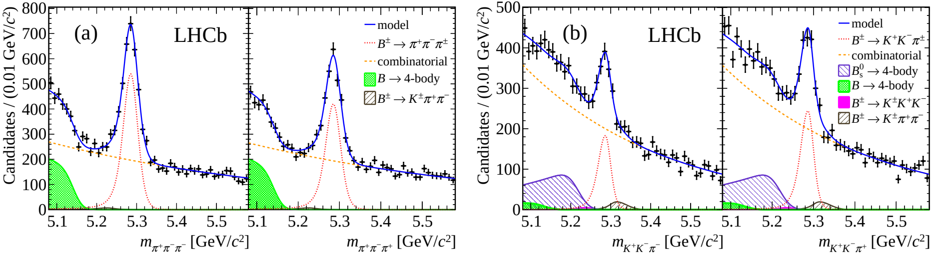
# INCLUSIVE CPV IN $B^\pm \to K^+K^-\pi^\pm$ AND $B^\pm \to \pi^+\pi^-\pi^\pm$

PRL 112 011801 (2014)

First evidence of inclusive $C\!P$ asymmetry in these modes:

$$A_{C\!P}(K^+K^-\pi^\pm) = -0.141 \pm 0.040(\text{stat}) \pm 0.018(\text{syst}) \pm 0.007\,(A_{C\!P}(J/\psi K^\pm))\ (3.2\sigma)$$
$$A_{C\!P}(\pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021(\text{stat}) \pm 0.009(\text{syst}) \pm 0.007\,A_{C\!P}(J/\psi K^\pm)\ (4.9\sigma)$$

(First evidence of $C\!P$ asymmetry in 3-body charmless $B$ decays in an earlier analysis of $B^\pm \to K^+K^-K^\pm$, PRL 111 (2013) 101801)




$4904 \pm 148$ $B^\pm \to \pi^+\pi^-\pi^\pm$, 1 fb$^{-1}$ LHCb data

$1870 \pm 133$ $B^\pm \to K^+K^-\pi^\pm$, 1 fb$^{-1}$ LHCb data

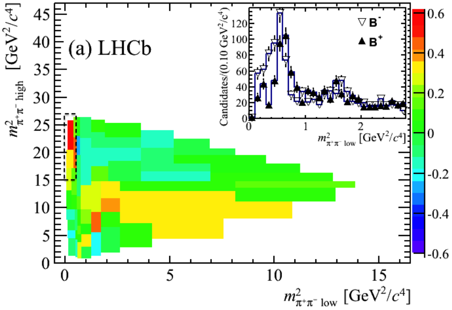
Observed asymmetry a combination of $C\!P$ asymmetry and confounding detection and production asymmetries

$$A_{\text{raw}} = A_{C\!P} + A_{\text{D}}(\pi^\pm) + A_{\text{P}}(B^\pm)$$

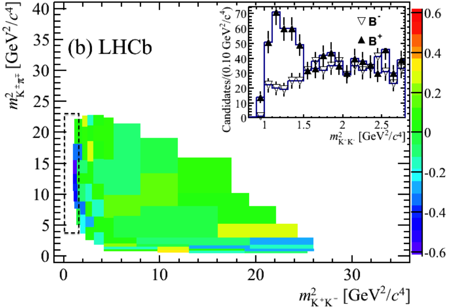
- $A_{\text{D}}(\pi^\pm)$ previously measured
- $A_{\text{P}}(B^\pm)$ from $B^\pm \to J/\psi K^\pm$

# LOCAL CPV IN $B^{\pm} \to K^+K^-\pi^{\pm}$ AND $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$

PRL 112 011801 (2014)




$B^{\pm} \to \pi^+\pi^-\pi^{\pm}$: large asymmetry in $m^2_{\pi^+\pi^-\,\mathrm{high}} > 15\ \mathrm{GeV}^2/c^4$ and $m^2_{\pi^+\pi^-\,\mathrm{low}} < 0.4\ \mathrm{GeV}^2/c^4$.



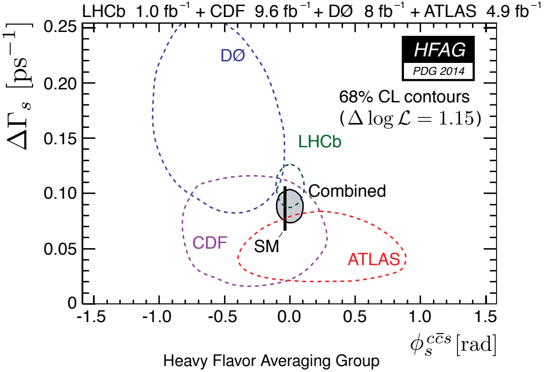

$B^{\pm} \to K^+K^-\pi^{\pm}$: large asymmetry in $m^2_{K^+K^-} < 1.5\ \mathrm{GeV}^2/c^4$.

Regions of large asymmetry not clearly associated to resonances.

$$A^{\mathrm{reg}}_{CP}(K^+K^-\pi^{\pm}) = -0.648 \pm 0.040(\mathrm{stat}) \pm 0.013(\mathrm{syst}) \pm 0.007\,(A_{CP}(J/\psi\,K^{\pm}))$$

$$A^{\mathrm{reg}}_{CP}(\pi^+\pi^-\pi^{\pm}) = 0.584 \pm 0.082(\mathrm{stat}) \pm 0.027(\mathrm{syst}) \pm 0.007\,(A_{CP}(J/\psi\,K^{\pm}))$$

# $\phi_s$ AVERAGE WITH LHCb 1 fb$^{-1}$ results



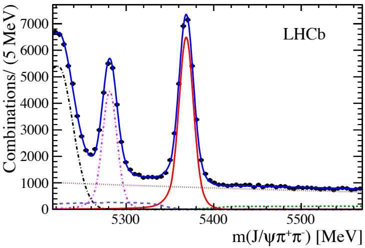

The *CP*-violating phase, $\phi_s$, characterizing the interference between $B_s^0$ mixing and decay in $b \to c\bar{c}s$ transitions.

- Sensitive to NP in mixing diagrams and penguin decay diagrams.
- SM: $\phi_s^{\rm SM} = -2 \arg \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = -0.0363^{+0.0016}_{-0.0015}$ rad [Charles *et al.*, PRD 84 033005 (2011)]

World average with LHCb 1 fb$^{-1}$: $\phi_s = 0.00 \pm 0.07$ rad

# $\phi_s$ IN $B_s^0 \to J/\psi\,\pi^+\pi^-$

LHCb-PAPER-2014-019, SUBMITTED TO PLB




New measurement of $\phi_s$ in $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays

$27100 \pm 200$ $B_s^0 \to J/\psi\,\pi^+\pi^-$ candidates with 79.6% purity in the full Run 1 3 $\text{fb}^{-1}$.

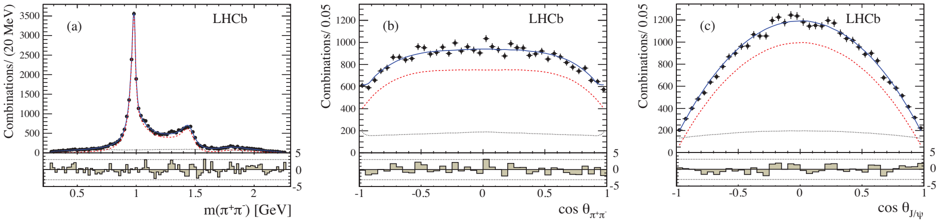
(Update to $\phi_s$ in $B_s^0 \to J/\psi\,K^+K^-$ with 3 $\text{fb}^{-1}$ is in preparation.)

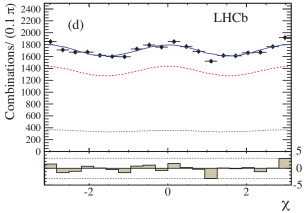
Time-dependent flavor-tagged amplitude fit that determines the *CP* content of the final state

- Independent variables: $J/\psi\,\pi^+\pi^-$ mass, $\pi^+\pi^-$ mass, three angles in the helicity basis, and decay time.
- Resonant components as in LHCb, LHCB-PAPER-2014-012
- Same-side and opposite-side flavor tagging
- Decay time acceptance measured in $B^0 \to J/\psi\,K^{*0}$.

# $\phi_s$ IN $B_s^0 \to J/\psi\,\pi^+\pi^-$

## LHCb-PAPER-2014-019, SUBMITTED TO PLB




Allowing for direct *CP* violation that is common for all amplitudes:

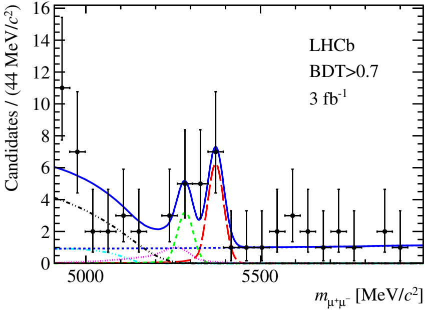
$$\phi_s = 70 \pm 68 \pm 8\,\text{mrad}$$
$$|\lambda| = 0.89 \pm 0.05 \pm 0.01$$

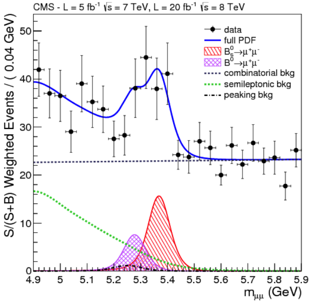
Consistent with Standard Model prediction:

$$\phi_s^{\text{SM}} = -36.3^{+1.6}_{-1.5}\,\text{mrad}$$ [Charles *et al.*, PRD 84 033005 (2011)]

# $B_s^0 \to \mu^+\mu^-$ in LHC Run 1

Evidence for $B_s^0 \to \mu^+\mu^-$ in LHCb and CMS




LHCb: $4.0\sigma$ significance in $3\,\text{fb}^{-1}$ [PRL 111, 101805 (2013)]

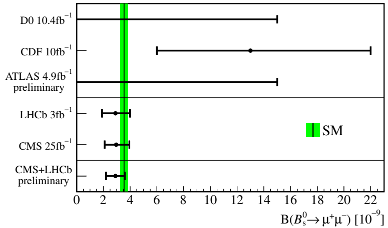
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0}\right) \times 10^{-9}$$

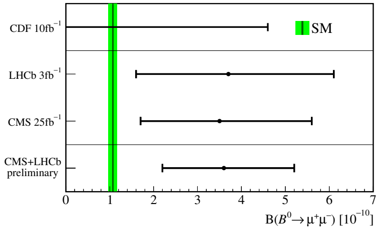
CMS: $4.3\sigma$ significance in $25\,\text{fb}^{-1}$ [PRL 111, 101804 (2013)]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}$$

# $B_s^0 \to \mu^+\mu^-$ COMBINED RESULT

## CMS-PAS-BPH-13-007, LHCb-CONF-2013-012




Naive combination of LHCb and CMS Run I measurements:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$$

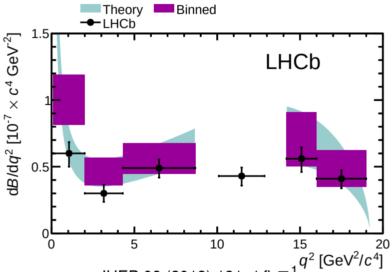
Consistent with SM predictions [Bobeth *et al.* PRL 112, 101801 (2014)]

$$\mathcal{B}^{\mathrm{SM}}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

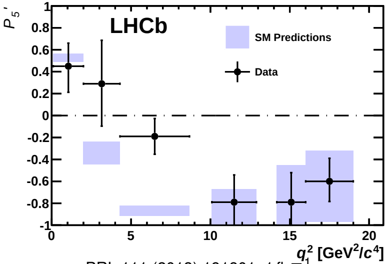
Preliminary conclusions (thorough treatment in progress):

- $B_s^0 \to \mu^+\mu^-$ observed at $> 5\sigma$ significance!
- No statistically significant evidence for $B^0 \to \mu^+\mu^-$.

# ANALYSIS OF $B^0 \to K^{*0} \mu^+ \mu^-$




JHEP 08 (2013) 131, 1 fb$^{-1}$




PRL 111 (2013) 191801, 1 fb$^{-1}$

Differential branching fraction, $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$, and angular analysis [JHEP 08 (2013) 131]

- Four observables after angular folding
  - $A_{\mathrm{FB}}$: dimuon F-B asymmetry,
  - $F_L$: fractional $K^{*0}$ polarization,
  - $S_3$: asymmetry related to the virtual photon polarization,
  - $A_9$: a CP asymmetry.

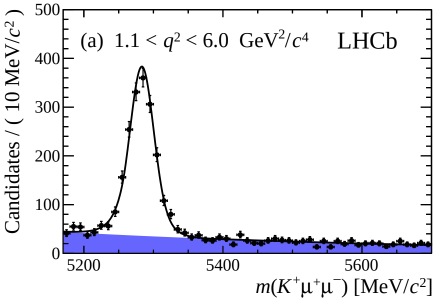
Form-factor independent angular analysis [PRL 111 (2013) 191801]

- Observables with canceling form-factor uncertainties,
- $3.7\sigma$ discrepancy in $P_5'$.

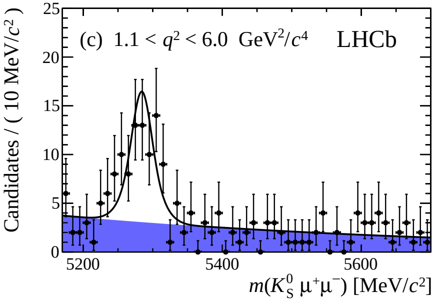
Isospin asymmetry with $B^+ \to K^{*+} \mu^+ \mu^-$ [LHCB-PAPER-2014-006]

# Angular analysis of $B \to K \mu^+ \mu^-$

LHCb-PAPER-2014-007, submitted to JHEP




$4746 \pm 81$ $B^+ \to K^+ \mu^+ \mu^-$ in 3 fb$^{-1}$




$176 \pm 17$ $B^0 \to K^0_S \mu^+ \mu^-$ in 3 fb$^{-1}$

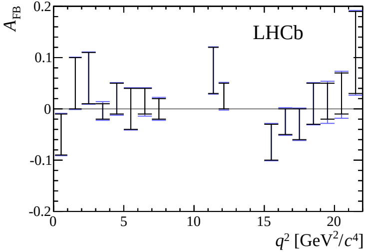
Angular analysis of $B^+ \to K^+ \mu^+ \mu^-$ and $B^0 \to K^0_s \mu^+ \mu^-$ in bins of $q^2$ to measure

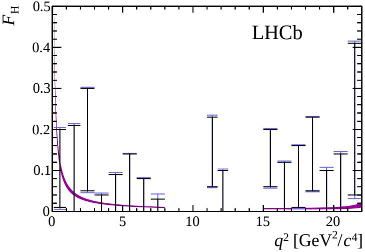
- $A_{\mathrm{FB}}$: forward-backward asymmetry ($B^+ \to K^+ \mu^+ \mu^-$ only)
  - Approximately 0 in SM
- $F_H$: fractional contribution of (pseudo)scalar and tensor amplitudes to the decay width
  - Small in SM

# Angular analysis of $B \to K\mu^+\mu^-$

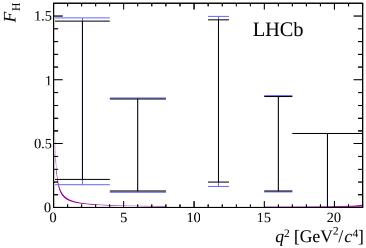
LHCb-PAPER-2014-007, submitted to JHEP

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




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




Consistent with SM predictions in every $q^2$ bin.

Constrains contributions from (pseudo)scalar and tensor amplitudes.

Figures show SM predictions from Bobeth *et al.*, JHEP 01 (2012) 107

# SUMMARY

Exploitation of the full LHC Run 1 data set of $3\,\text{fb}^{-1}$ at LHCb is underway and yielding some of the most precise measurements in the *b* and *c* sector.

- Only a fraction of our results were presented today,
- Many more measurements in progress.

No deviations from the SM yet observed.

LHC Run 2 projected to add $8\,\text{fb}^{-1}$, allowing LHCb to find or rule-out large sources of flavour symmetry breaking at the TeV scale.

An upgraded LHCb detector to operate during LHC Runs 3 and 4 is approved and in development,

- Up to $50\,\text{fb}^{-1}$
- Essential to match SM theory errors in many key measurements.