Measurement of CP violation in charmless two-body B decays at LHCb

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on behalf of the LHCb collaboration

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Outline

- Importance of charmless two-body B decays
- First evidence for the two body charmless baryonic decay $B^0 \to p\bar{p}$ NEW
- Branching fractions and CP asymmetries in $B^{\pm} \to K_S h^{\pm}$ decays ($h = \pi$, K) NEW
- Direct CP asymmetries in $B^0_{(s)} \to K^+\pi^-$ decays
  - First observation of CP violation in B^0_s decays
- Time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ NEW

Importance of charmless two-body B decays

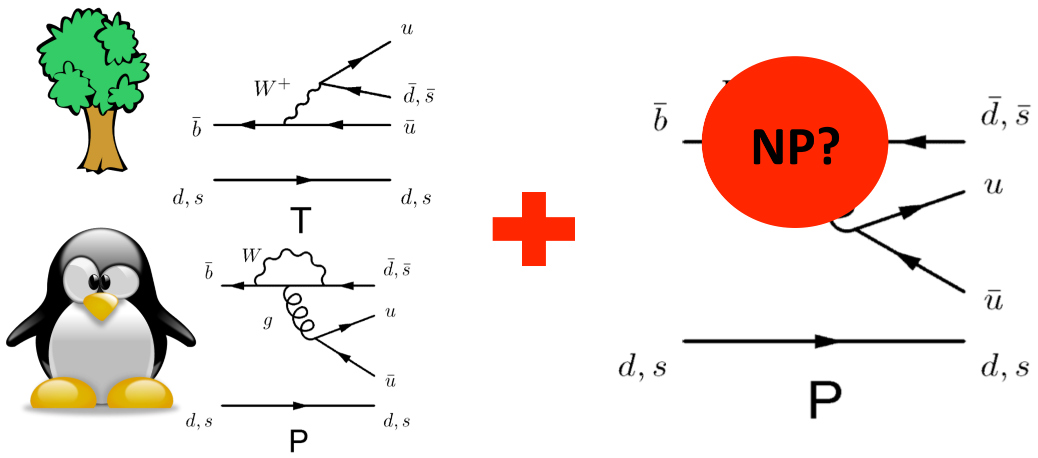
- Charmless two-body B decays provide valuable information for:
  - improving knowledge of CKM matrix
    - UT angles and the B_s mixing phase
  - validating theoretical tools to deal with QCD contributions
    - QCD factorization, pQCD, SCET, …
  - constraining New Physics
    - CP-violation observables and branching fractions can differ from Standard Model predictions

Direct CP asymmetries

$$A_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}}$$

Time-dependent CP asymmetries

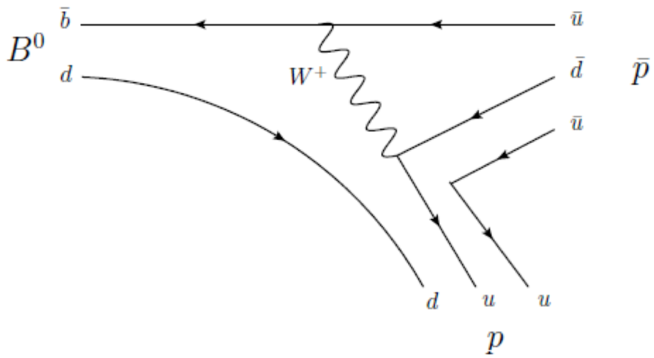
$$A(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



- As penguin topologies are generally sizeable, effects from New Physics in loops may be sizeable as well
- Theoretical interpretation is however not straightforward, because of unknown hadronic parameters in the amplitudes

First evidence for the baryonic decay $B^0_{(s)} \to p\bar{p}$

NEW



- Still unobserved decays
  - Any measurement of BR < 10^{-7} will rule out all the current theoretical predictions
    - Phys. Rev. D43 (1991) 1599
    - Phys. Rev, D66 (2002) 014020
    - Ann.Rev.Nucl.Part.Sci. 59 (2009) 215

- Analysis strategy
  - Relative branching ratio measurement

yields

efficiencies

$$\mathcal{B}(B^0_{(s)} \to p\bar{p}) = \frac{N(B^0_{(s)} \to p\bar{p})}{N(B^0 \to K^+\pi^-)} \cdot \frac{\epsilon_{B^0 \to K^+\pi^-}}{\epsilon_{B^0_{(s)} \to p\bar{p}}} \cdot f_d/f_{d(s)} \cdot \mathcal{B}(B^0 \to K^+\pi^-)$$

Hadronization fractions

  - Event selection based on multivariate algorithm
    - Boosted Decision Tree, optimized in order to achieve the best significance on signal yields
  - Determination of efficiencies
    - Mainly determined from Monte Carlo and cross-checked with calibration samples from data

} Main systematic uncertainties

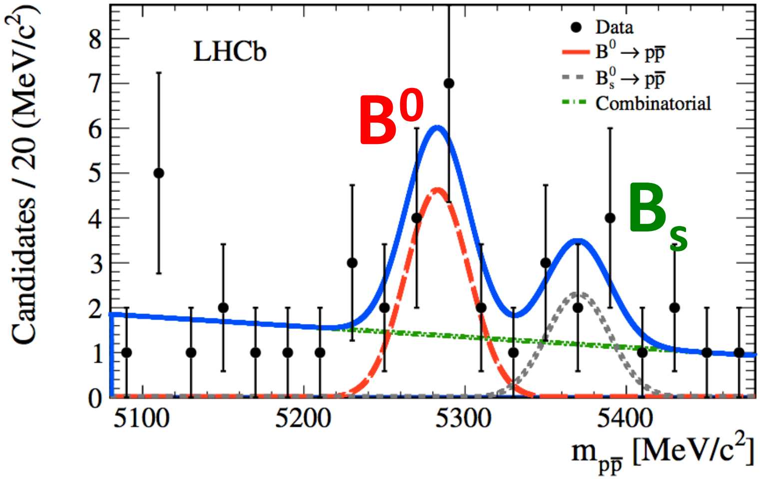
First evidence for the baryonic decay $B^0_{(s)} \to p\bar{p}$

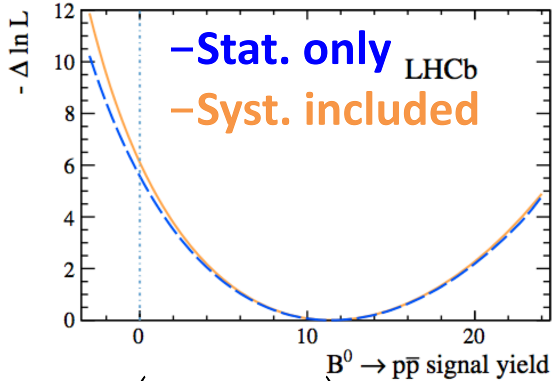
NEW

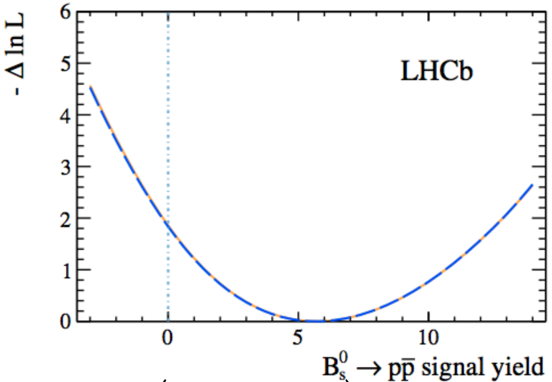
Preliminary
LHCB-PAPER-2013-038

$\mathcal{L} = 0.9/\text{fb}$ @ $\sqrt{s} = 7$ TeV

Profile likelihood







$$N\left(B^0 \to p\bar{p}\right) = 11.4^{+4.3}_{-4.1}$$

$$N\left(B^0_s \to p\bar{p}\right) = 5.7^{+3.5}_{-3.2}$$

The Feldman-Cousins frequentist method has been used to determine the confidence intervals

Using Wilks' theorem:

- Likelihood ratio with respect to no-signal hypothesis
- 3.3σ significance for B^0 (including systematics)
- 1.9σ significance for B_s (including systematics)

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.47\,^{+0.62}_{-0.51}\,^{+0.35}_{-0.14}) \times 10^{-8} \quad \text{at} \quad 68.27\% \quad \text{CL}$$

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.47\,^{+1.09}_{-0.81}\,^{+0.69}_{-0.18}) \times 10^{-8} \quad \text{at} \quad 90\% \quad \text{CL}$$

First evidence at more than 3σ

$$\mathcal{B}(B^0_s \to p\bar{p}) = (2.84\,^{+2.03}_{-1.68}\,^{+0.85}_{-0.18}) \times 10^{-8} \quad \text{at} \quad 68.27\% \quad \text{CL}$$

$$\mathcal{B}(B^0_s \to p\bar{p}) = (2.84\,^{+3.57}_{-2.12}\,^{+2.00}_{-0.21}) \times 10^{-8} \quad \text{at} \quad 90\% \quad \text{CL}$$

Branching fraction and CP asymmetry measurements of the $B^\pm \to K_S\pi^\pm$ and $B^\pm \to K_S K^\pm$ decays

NEW

- Current experimental status
  - No evidence of CP violation

Measurement	BaBar in units of 10^{-6}	Belle in units of 10^{-6}
$\mathcal{B}(B^\pm \to K^0\pi^\pm)$	$23.9 \pm 1.1 \pm 1.0$	$23.97 \pm 0.53 \pm 0.71$
$\mathcal{B}(B^\pm \to \overline{K}^0 K^\pm)$	$1.61 \pm 0.44 \pm 0.09$	$1.11 \pm 0.19 \pm 0.05$
$\mathcal{A}^{CP}(B^\pm \to K^0\pi^\pm)$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$
$\mathcal{A}^{CP}(B^\pm \to \overline{K}^0 K^\pm)$	$+0.10 \pm 0.26 \pm 0.03$	$+0.014 \pm 0.168 \pm 0.002$

- Event selection
  - Based on multivariate algorithm (BDT)
  - Different optimization for $K_S\pi$ and K_SK final states
- Fits to the invariant mass spectra in order to extract signal yields and raw asymmetries

$$A_{raw} = \frac{N(B^- \to K_s^0 h^-) - N(B^+ \to K_s^0 h^+)}{N(B^- \to K_s^0 h^-) + N(B^+ \to K_s^0 h^+)}$$

- Relative branching ratio determination
  - Selection efficiencies from Monte Carlo
  - PID efficiencies from calibration samples of $D^* \to D^0(K\pi)\pi$ decays

Yields ratio

$$\frac{\mathcal{BR}(B^- \to K_s^0 K^-)}{\mathcal{BR}(B^- \to K_s^0 \pi^-)} = \frac{N(B^- \to K_s^0 K^-)}{N(B^- \to K_s^0 \pi^-)} \frac{\varepsilon(B^- \to K_s^0 \pi^-)}{\varepsilon(B^- \to K_s^0 K^-)}$$

Efficiency ratio

- Correction to the raw asymmetries
  - CP violation in K_S → small
  - K_S regeneration from K_L interaction with the detector → negligible in LHCb acceptance
  - Detection and production asymmetries determined from $B^\pm \to J/\psi K^\pm$ decays

$$A_{CP} = A_{raw} - A_{\text{Det.+Prod.}} - A_{K_S^0}$$

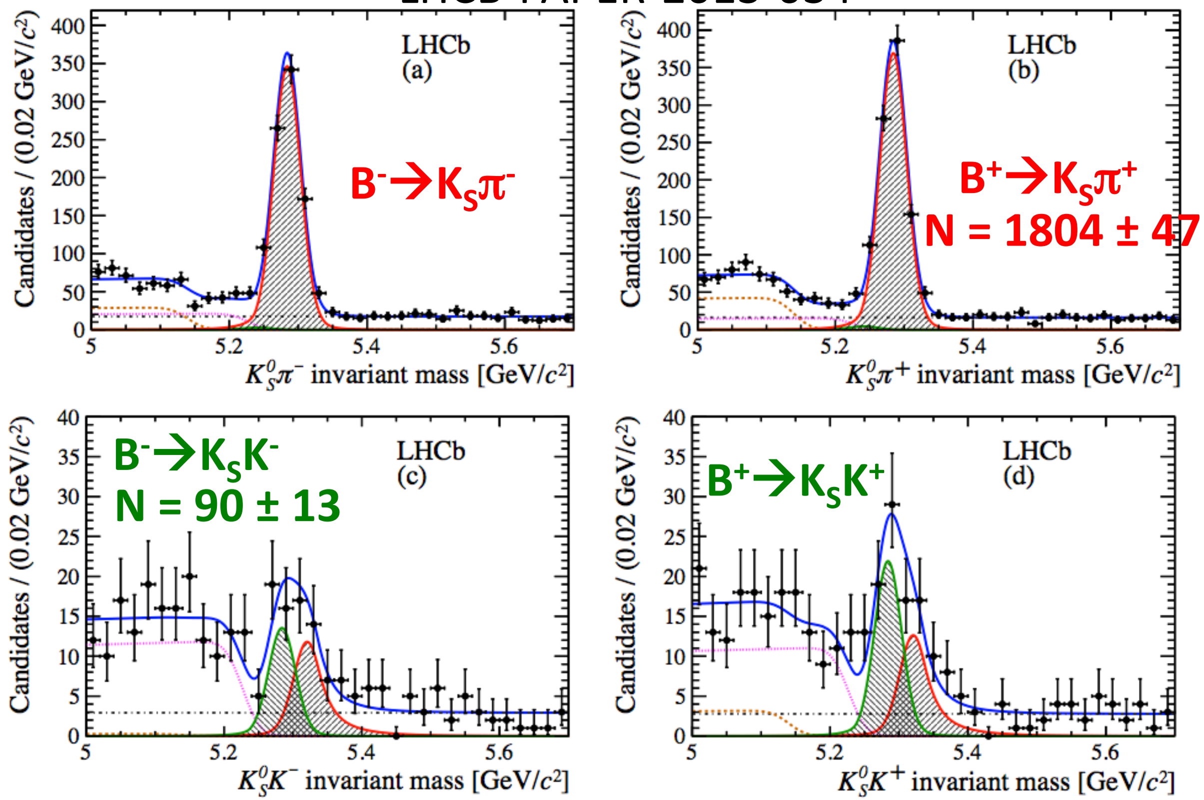
$$A_{raw}(B^+ \to J/\psi K^+) = A_{CP} + A_{\text{Det.+Prod.}}$$

Branching fraction and CP asymmetry measurements of the $B^{\pm} \to K_S \pi^{\pm}$ and $B^{\pm} \to K_S K^{\pm}$ decays

NEW

Preliminary

LHCB-PAPER-2013-034



$\mathcal{L}$ = (1/fb @ √s = 7 TeV) + (2/fb @ √s = 8 TeV)

- No evidence of CP violation in either decay
- Main systematics
  - Invariant mass fit model for the relative branching ratio
  - Detection and production asymmetries for CPV measurement

$$\frac{\mathcal{B}\left(B^{+} \to K_{\mathrm{S}}^{0} K^{+}\right)}{\mathcal{B}\left(B^{+} \to K_{\mathrm{S}}^{0} \pi^{+}\right)} = 0.064 \pm 0.009\ (\mathrm{stat.}) \pm 0.004\ (\mathrm{syst.})$$

$$\begin{aligned} \mathcal{A}^{CP}\left(B^{+} \to K_{\mathrm{S}}^{0} \pi^{+}\right) &= -0.024 \pm 0.025\ (\mathrm{stat.}) \pm 0.010\ (\mathrm{syst.}) \\ \mathcal{A}^{CP}\left(B^{+} \to K_{\mathrm{S}}^{0} K^{+}\right) &= -0.21 \pm 0.14\ (\mathrm{stat.}) \pm 0.01\ (\mathrm{syst.}) \end{aligned}$$

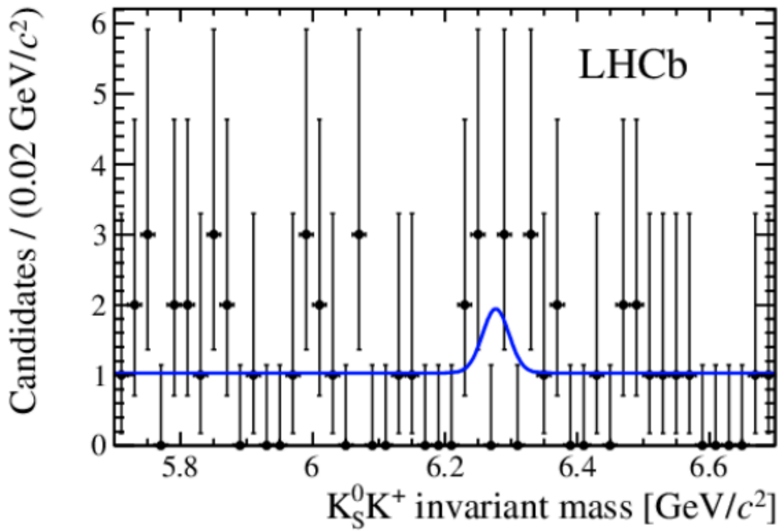
Results are compatible and competitive with B-Factories

Search for the $B_c^\pm \to K_S K^\pm$ decay

NEW

Preliminary
LHCB-PAPER-2013-034

$\mathcal{L}$ = 1/fb @ √s = 7 TeV

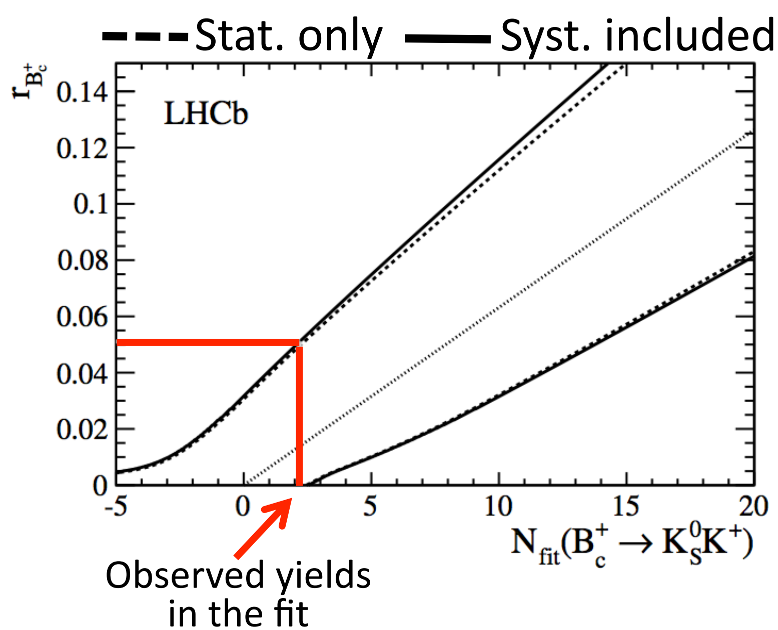


- Same strategy as for $B^\pm$ analysis
  - Dedicated optimization of BDT
  - Relative BR with respect to $B^\pm \to K_S \pi^\pm$
  - Main systematic uncertainty coming from the determination of selection efficiency
    - Performed by means of Monte Carlo

- Feldman-Cousin's method has been used to estimate confidence intervals

$$r_{B_c^+} = \frac{f_c}{f_u} \cdot \frac{\mathcal{B}\left(B_c^+ \to K_S^0 K^+\right)}{\mathcal{B}\left(B^+ \to K_S^0 \pi^+\right)} < 5.1 \times 10^{-2} \text{ at } 90\% \text{ C.L.}$$

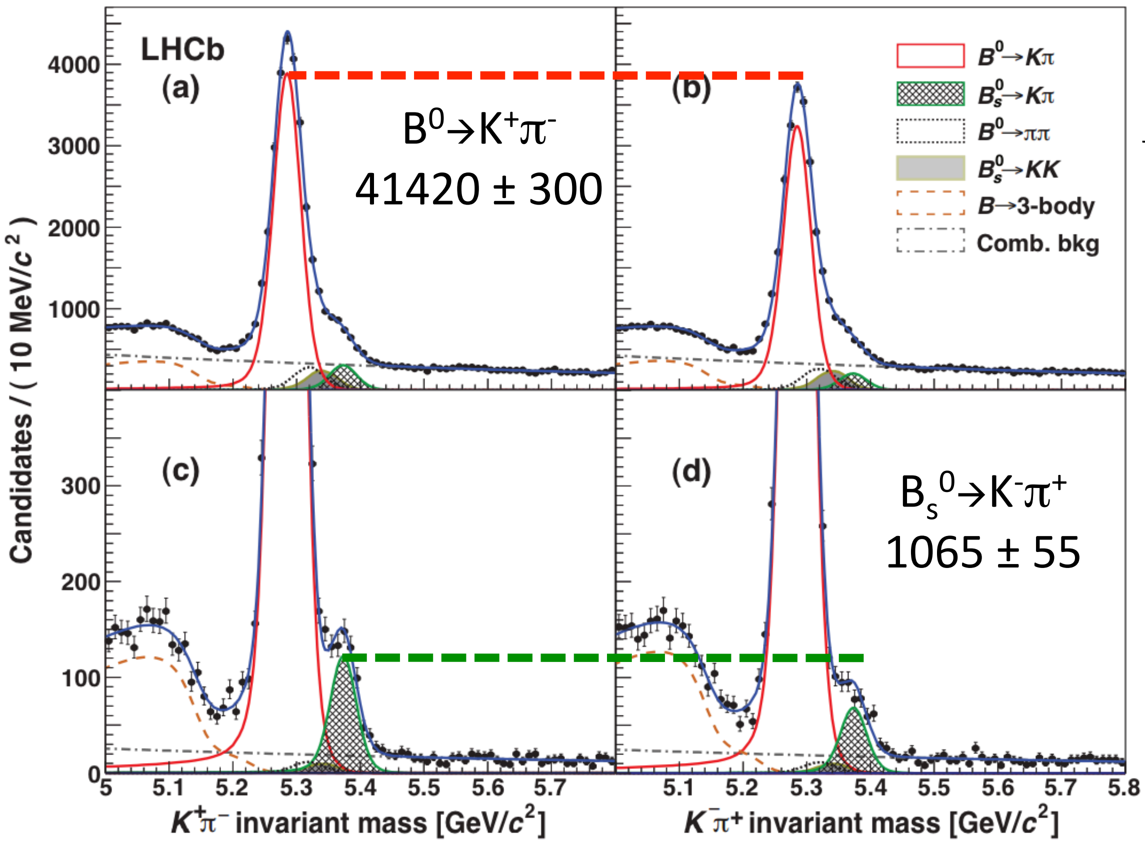
First upper limit on a charmless and bottomless B_c-meson decays



Direct CP asymmetries in $B^0_{(s)} \to K\pi$ decays

Phys. Rev. Lett. 110 (2013) 221601

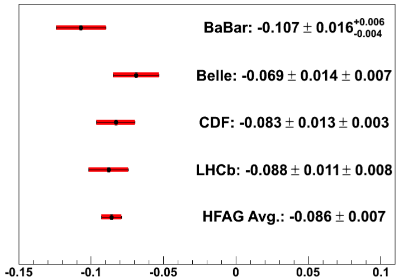
$\mathcal{L}$ = (1/fb @ √s = 7 TeV)



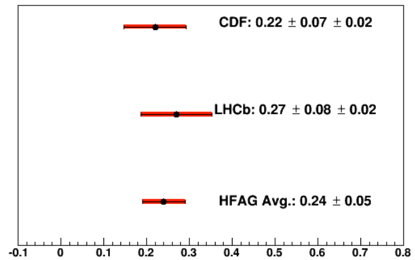
$$A_{\text{raw}}\left(B^0 \to K^+\pi^-\right) = -0.091 \pm 0.006$$

$$A_{\text{raw}}\left(B_s^0 \to K^-\pi^+\right) = 0.28 \pm 0.04$$

Precedent results



$A_{CP}(B^0 \to K\pi)$



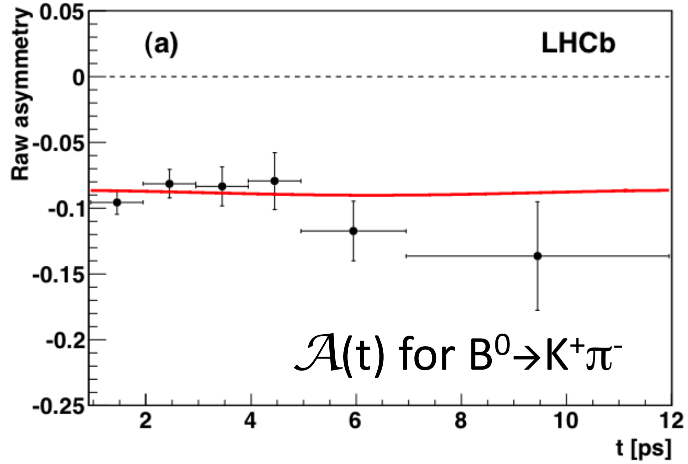
$A_{CP}(B_s \to \pi K)$

- Event selection is cut-based:
  - Different optimization for $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$
- Control of PID efficiencies
  - Determine the amount of cross-feed backgrounds under the peak
  - Calibrated from $D^{*+} \to D^0(K^-\pi^+)\pi^+$
- Invariant mass fits in order to extract raw asymmetries
- Correction to the raw asymmetries
  - Detection asymmetry
  - Production asymmetry

Direct CP asymmetries in $B^0_{(s)} \to K\pi$ decays

- $K^+\pi^-/K^-\pi^+$ detection asymmetry is studied by means of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $D^{*+} \to D^0(K^+K^-)\pi^+$ and untagged $D^0 \to K^-\pi^+$ decays
- Production asymmetries are extracted directly from the $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ samples
  - Production asymmetry determined from fits to untagged decay time spectra
    - No evidence of non-zero production asymmetry
- Main systematic uncertainties come from the determination of instrumental corrections to the raw asymmetries

$$\mathcal{A}(t) \approx A_{CP} + A_{\rm D} + A_{\rm P}\cos\left(\Delta m_{d(s)} t\right)$$



Phys. Rev. Lett. 110 (2013) 221601

$$A_{CP}\left(B^0 \to K\pi\right) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst}),$$

Most precise measurement of this quantity to date, 10.5σ from zero

$$A_{CP}\left(B^0_s \to K\pi\right) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}).$$

First observation of CP violation in B_s decays, with significance of 6.5σ

- Test using U-Spin

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

- Using LHCb results for branching ratios [JHEP 10 (2012) 037]

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

Time-dependent CPV in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

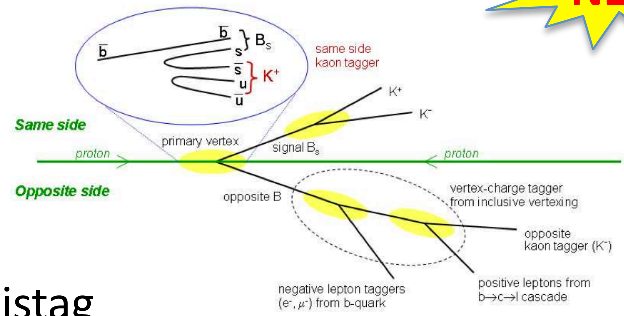
NEW

- Event selection is based on BDT algorithm
  - Different optimizations for $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
- Determination of B initial flavour is crucial:
  - In this analysis used only "Opposite Side" taggers
  - A neural network determines an event-by-event mistag probability
  - Samples divided into categories of predicted mistag
  - Simultaneous invariant mass and decay time fit with $B \to K\pi$ decays
    - Calibration of flavour tagging response: $\varepsilon D^2 \approx 2.4\%$
    - Determination of B^0 and B_s production asymmetries

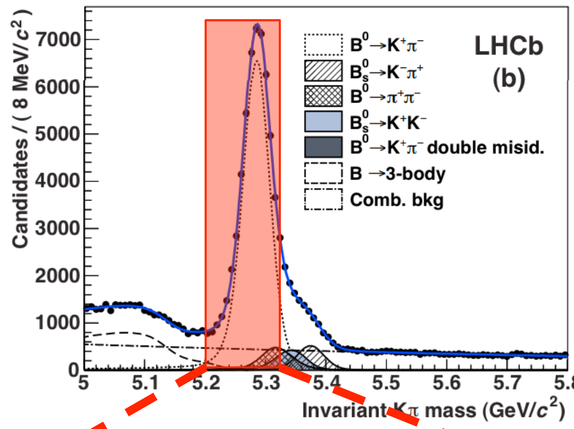
$$A_P(B^0) = (0.6 \pm 0.9)\% \qquad A_P(B_s) = (7 \pm 5)\%$$

- Decay time resolution
  - Non-negligible dilution of the oscillation amplitude for the $B_s \to K^+K^-$ decay
  - Studied from prompt charmonium and bottomonium decays to di-muons

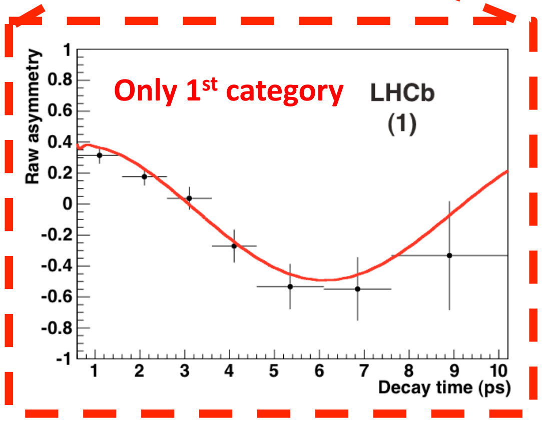
$$\sigma_t = 50 \pm 5\,\text{fs}$$



$\mathcal{L}$ = (1/fb @ √s = 7 TeV)



Preliminary
LHCB-PAPER-2013-040



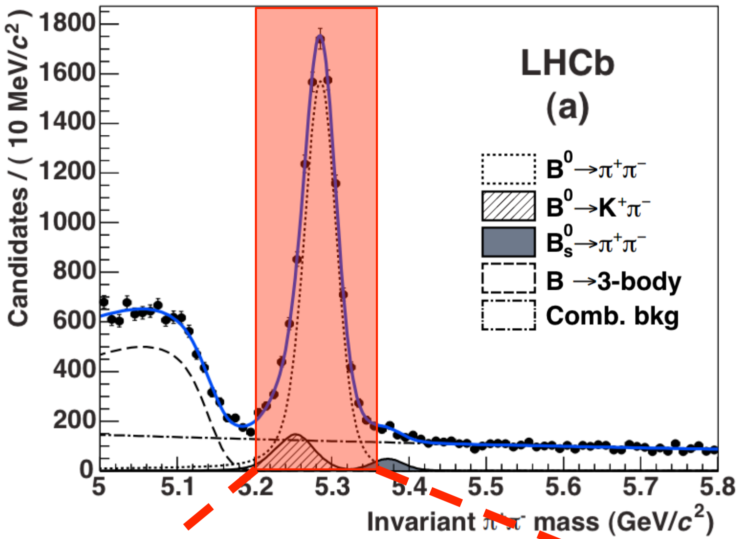
Time-dependent CPV in $B^0 \to \pi^+\pi^-$

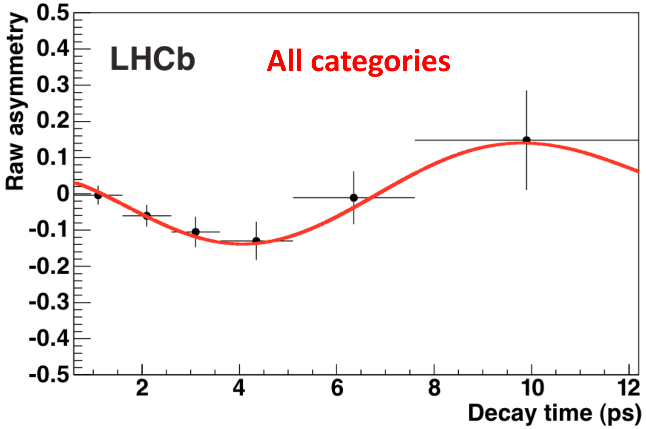
NEW

Preliminary

LHCB-PAPER-2013-040

$\mathcal{L}$ = (1/fb @ √s = 7 TeV)





$$\mathcal{A}(t) = -C_f \cos(\Delta m_d t) + S_f \cos(\Delta m_d t)$$

C → direct CP violation

S → mixing-induced CP violation

$$C_{\pi\pi} = -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst}),$$
$$S_{\pi\pi} = -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst}),$$
$$\rho(C_{\pi\pi},\ S_{\pi\pi}) = 0.38.$$

Results are compatible with previous measurements from BaBar and Belle

The significance for ($C_{\pi\pi}$, $S_{\pi\pi}$) to differ from (0, 0) is 5.6σ

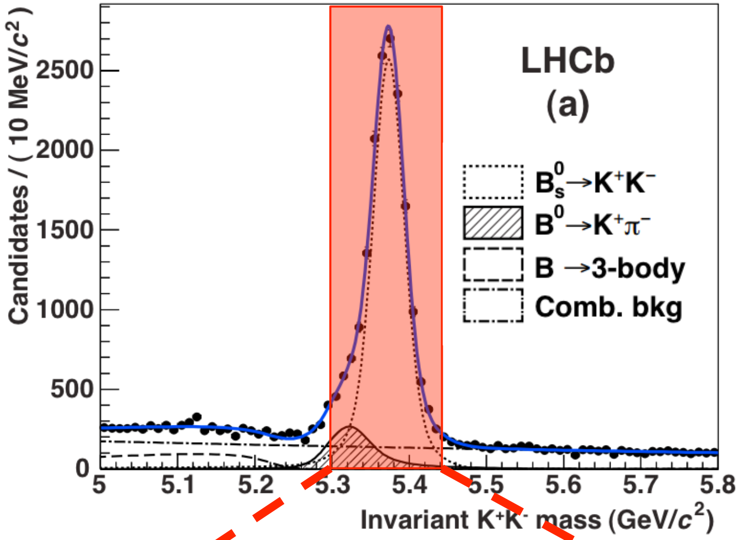
Time-dependent CPV in $B_s^0 \to K^+K^-$

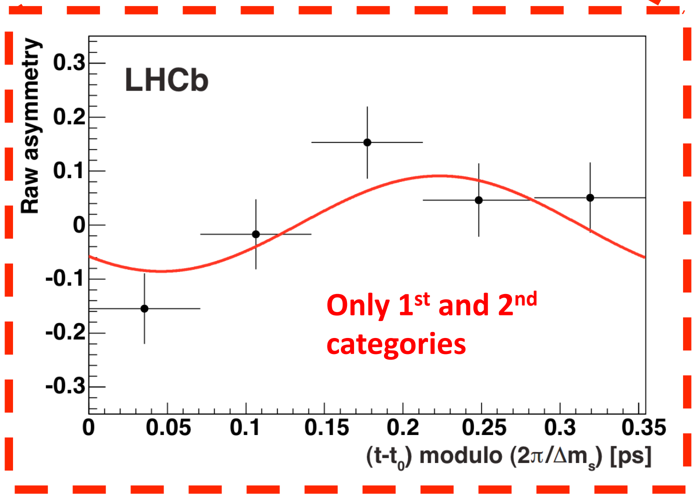
NEW

Preliminary

LHCB-PAPER-2013-040

$\mathcal{L}$ = (1/fb @ √s = 7 TeV)





$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_s t) + S_f \cos(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)}$$

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$\rho(C_{KK}, S_{KK}) = 0.02.$$

The significance for (C_{KK}, S_{KK}) to differ from (0, 0) is 2.7σ

Conclusions (I)

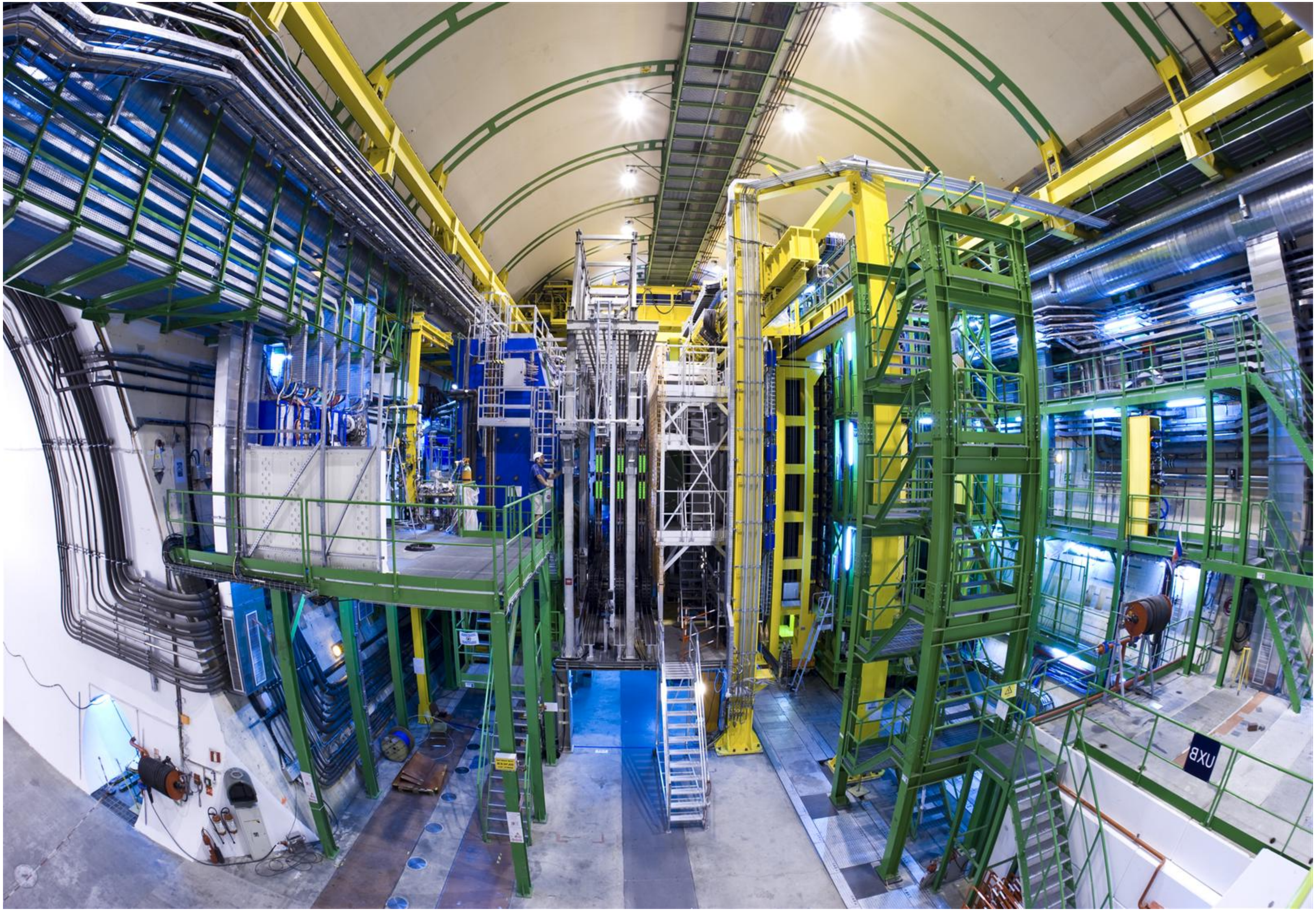
- LHCb has recently obtained several results regarding charmless two-body B decays
- Search for baryonic decays of B^0 and B_s mesons using 0.9 fb^{-1} @ $\sqrt{s}$ = 7 TeV NEW
  - Limits on branching ratios of $B^0 \rightarrow p\bar{p}$ and $B_s \rightarrow p\bar{p}$
  - First evidence of $B^0 \rightarrow p\bar{p}$ with 3.3σ significance
- Measurement of branching ratios and CP asymmetries in $B^\pm \rightarrow K_S h^\pm$ decays using 1 fb^{-1} @ $\sqrt{s}$ = 7 TeV + 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV
  - Results are compatible and competitive with B-factories NEW
  - No evidence of CPV in either decay
  - Upper limit on the BR of $B_c^\pm \rightarrow K_S K^\pm$ decay (using 1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)

Conclusions (II)

- Measurement of direct CP asymmetries in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ decays using 1 fb^{-1}@ √s = 7 TeV
  - World's best measurement of $A_{CP}(B^0 \to K^+\pi^-)$ with 10.5σ significance
  - First observation of CP violation in B_s decays with 6.5σ significance
- Measurement of time-dependent CP asymmetries of $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ using 1 fb^{-1}@ √s = 7 TeV **NEW**
  – No striking evidence of differences with respect to SM, but measurements performed with a fraction of the available luminosity
    - Room for improvements adding other 2 fb^{-1} @ √s = 8 TeV and same side taggers

Backup

The LHCb detector



The LHCb detector