Charmless 3-body decays of b-hadrons

Thomas Latham
(on behalf of the LHCb collaboration)

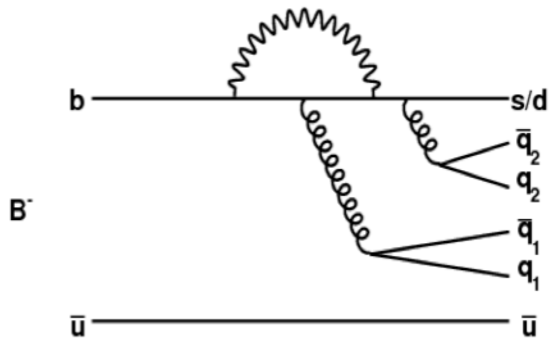
15th August 2013
DPF 2013 - University of California, Santa Cruz

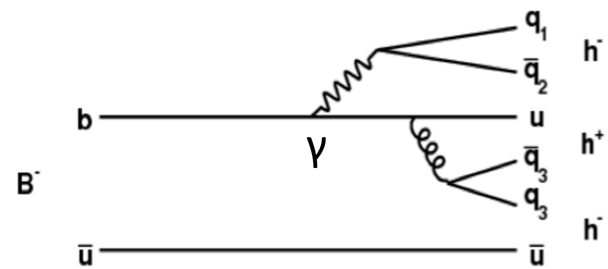
THE UNIVERSITY OF WARWICK

Overview

- Introduction
- Experimental results
  - $B^+ \longrightarrow h^+ h^+ h^-$
  - $B^+ \longrightarrow p \bar{p} h^+$
  - $B^0 \longrightarrow h^+ h^- \pi^0$
  - $B_{(s)}{}^0 \longrightarrow K_S h^+ h^-$
- Conclusion

Why charmless decays?

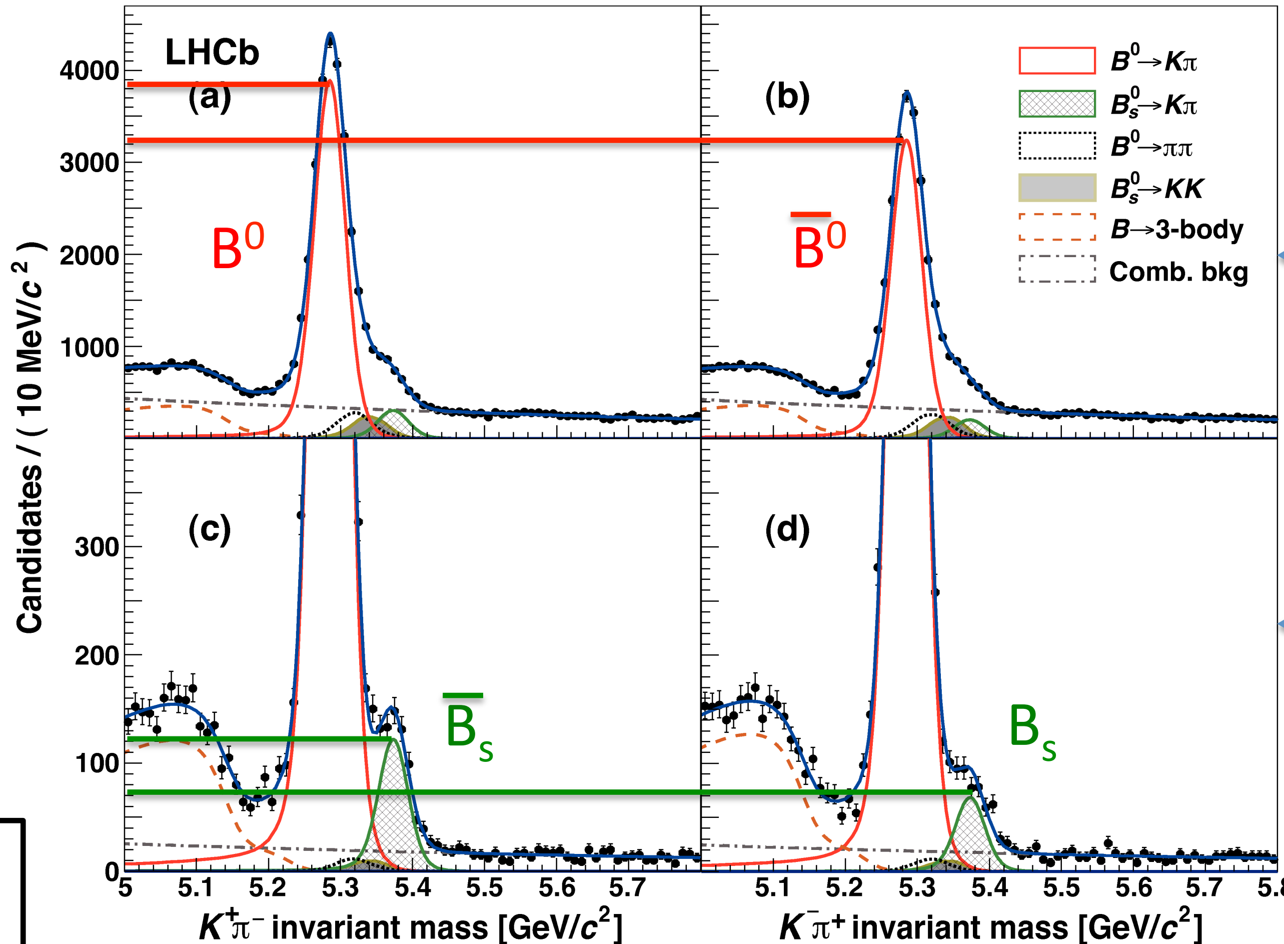




- Contributions from both loop (penguin) and tree decay diagrams
- These diagrams have a relative weak phase (= γ in SM)
- Interference can therefore give rise to direct CP violation
- In neutral B decays can make time-dependent measurements, allowing measurements of mixing-induced CP asymmetries
- These can be compared with measurements from, e.g. $B^0 \longrightarrow J/\psi$ KS or $B_s \longrightarrow J/\psi\ \phi$ to search for signs of new physics

Phys. Rev. Lett. 110, 221601 (2013)

$B^0 \longrightarrow K^+\pi^-$ and $B_s \longrightarrow K^-\pi^+$



Fits to samples that use different selection criteria

$1.0\ \text{fb}^{-1}$
2011 data

Phys. Rev. Lett. 110, 221601 (2013)

B^0 -> $K^+\pi^-$ and B_s -> $K^-\pi^+$

- First observation (6.5σ) of CP violation in B_s system:

$$A_{CP}\left(B_s \to K^-\pi^+\right) = \frac{\Gamma\left(\bar{B}_s \to K^+\pi^-\right) - \Gamma\left(B_s \to K^-\pi^+\right)}{\Gamma\left(\bar{B}_s \to K^+\pi^-\right) + \Gamma\left(B_s \to K^-\pi^+\right)} = 0.27 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.})$$

- Also world's best single measurement of:

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

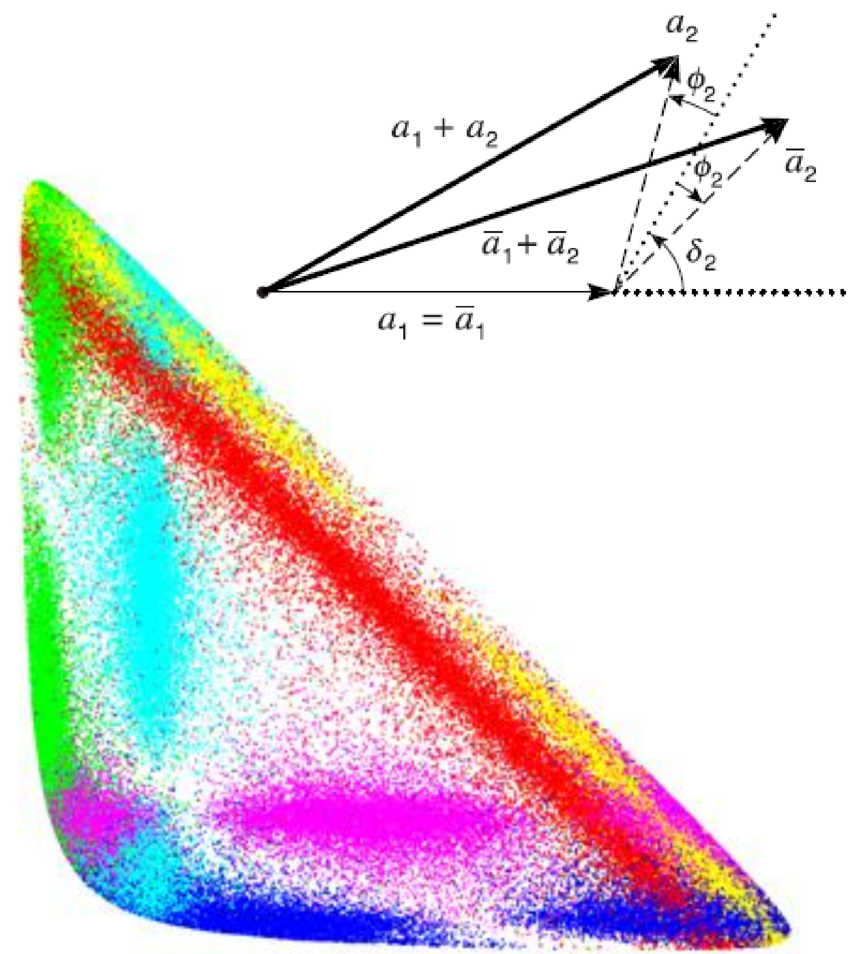
- Results consistent with world averages and previous LHCb measurements
- Also appear consistent with the Standard Model (Δ=0):

$$\Delta = \frac{A_{CP}\left(B^0 \to K^+\pi^-\right)}{A_{CP}\left(B_s^0 \to K^-\pi^+\right)} + \frac{BF\left(B_s^0 \to K^-\pi^+\right)}{BF\left(B^0 \to K^+\pi^-\right)}\frac{\tau_d}{\tau_s} = -0.02 \pm 0.05 \pm 0.04$$

PLB 492, 297 (2000)

Why 3-body decays?

- Source of strong phase differences in 2-body decays not well understood
- Interferences between intermediate states in 3-body decays allows the measurement of relative phases as well as magnitudes
- Provides additional information to better constrain theoretical models
- Can also help to resolve trigonometric ambiguities in weak phase measurements



Toy MC Dalitz plot (DP)

$B^+ \longrightarrow h^+ h^+ h^-$ decays

Introduction

- Searches for direct CP violation in $B^+ \longrightarrow h^+ h^+ h^-$ decays are motivated by
  - Evidence for large CPV in $B^+ \longrightarrow \rho^0 K^+$ from both Belle and BaBar
    [Phys. Rev. Lett. 96, 251803 (2006); Phys. Rev. D 78, 012004 (2008)]
  - Recent evidence of CPV in $B^+ \longrightarrow \phi K^+$ from BaBar
    [Phys. Rev. D 85, 112010 (2012)] (see talk tomorrow morning by J. Albert)
  - Large A_{CP} measurements in $B^0 \longrightarrow K^+\pi^-$ and $B_s \longrightarrow K^-\pi^+$
- The three-body environment will allow a clearer understanding of the strong phases via amplitude analysis
- First step is to establish the level of CPV and its variation over the phase space, represented by the Dalitz plot

arXiv:1306.1246 [hep-ex]
Accepted by Phys. Rev. Lett.

CPV in $B^+ \longrightarrow K^+ h^+ h^-$

- Analysis uses 1 fb^{-1} data from 2011 (~ ⅓ of total LHCb data sample)
- Measure raw asymmetry from simultaneous mass fit to B^+ and B^- candidate samples, defining

$$A_{\text{raw}} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$

- Must be corrected for production and detection asymmetries:

$$A_{CP} = A_{raw} - A_D(K^\pm) - A_P(B^\pm)$$

- Use the decay $B^+ \longrightarrow J/\psi\ (\mu^+\mu^-)\ K^+$ to determine this:

$$A_D(K^\pm) + A_P(B^\pm) = A_{raw}(J/\psi K^+) - A_{CP}(J/\psi K^+)$$

- Where:

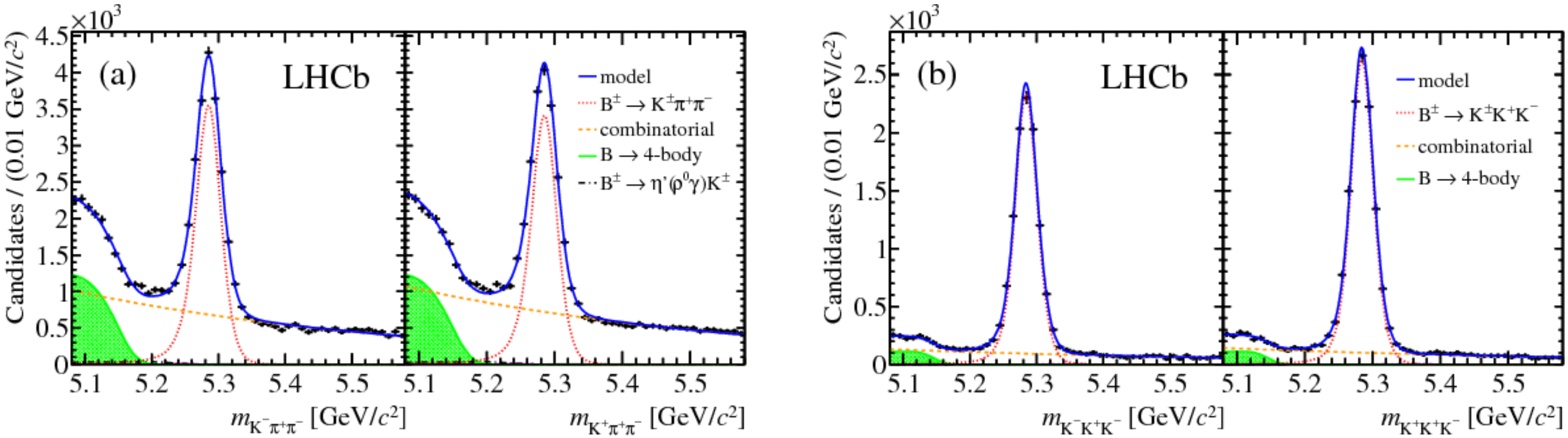
$$A_{CP}(J/\psi K^+) = (0.1 \pm 0.7)\%$$

PRD 86, 010001 (2012)

arXiv:1306.1246 [hep-ex]
Accepted by Phys. Rev. Lett.

CPV in $B^+ \longrightarrow K^+ h^+ h^-$

$B^- \longrightarrow K^- \pi^+ \pi^-$ $B^+ \longrightarrow K^+ \pi^+ \pi^-$ $B^- \longrightarrow K^- K^+ K^-$ $B^+ \longrightarrow K^+ K^+ K^-$



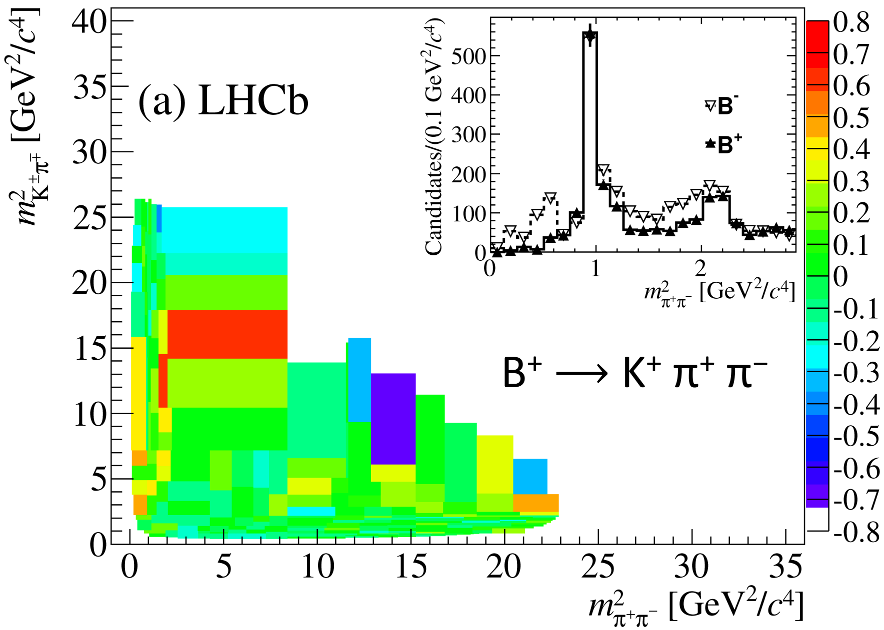
- $A_{CP}(B^+ \longrightarrow K^+ \pi^+ \pi^-) = 0.032 \pm 0.008$ (stat.) ± 0.004 (syst.) ± 0.007 ($J/\psi K^+$)
- Significance of CPV = 2.8σ

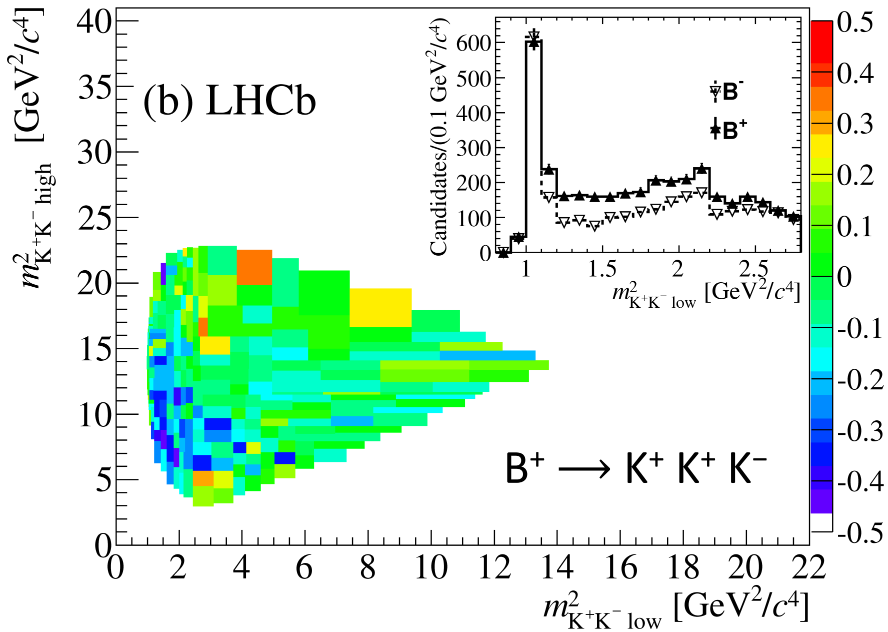
- $A_{CP}(B^+ \longrightarrow K^+ K^+ K^-) = -0.043 \pm 0.009$ (stat.) ± 0.003 (syst.) ± 0.007 ($J/\psi K^+$)
- Significance of CPV = 3.7σ

- The third uncertainty is due to the $J/\psi K^+$ CP asymmetry measurement

arXiv:1306.1246 [hep-ex]
Accepted by Phys. Rev. Lett.

CPV in $B^+ \longrightarrow K^+ h^+ h^-$

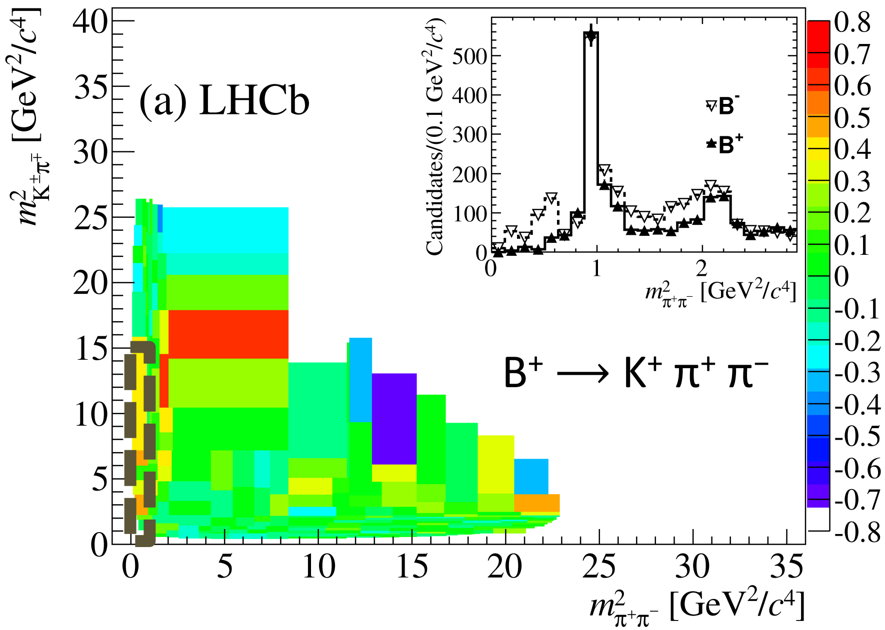


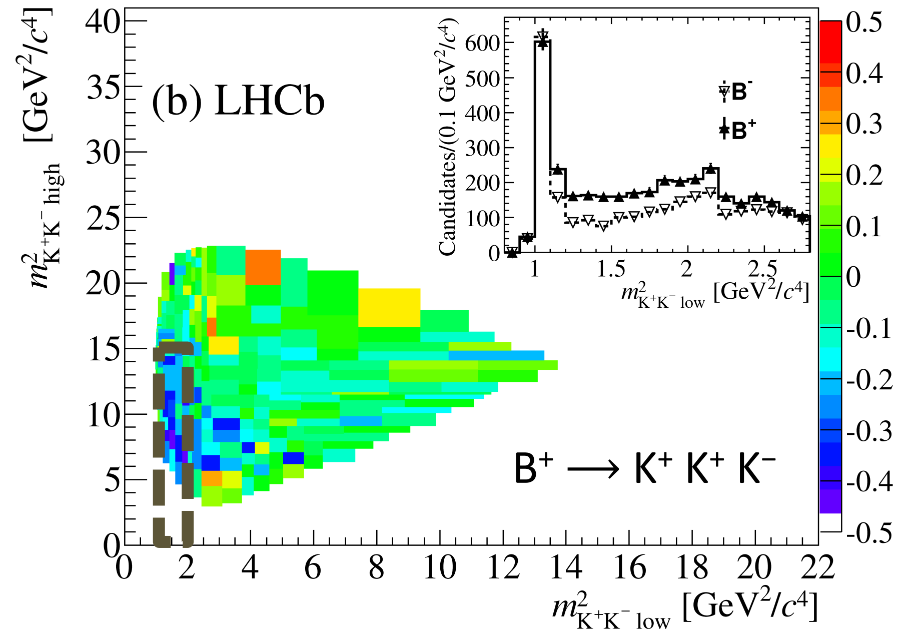


- Study variation of A_{raw} over Dalitz plot
- Some areas of phase space have very large asymmetries, e.g. region around ρ^0 resonance in $B^+ \longrightarrow K^+ \pi^+ \pi^-$ but also regions not clearly associated with a resonance, particularly in $B^+ \longrightarrow K^+ K^+ K^-$

arXiv:1306.1246 [hep-ex]
Accepted by Phys. Rev. Lett.

CPV in $B^+ \longrightarrow K^+ h^+ h^-$





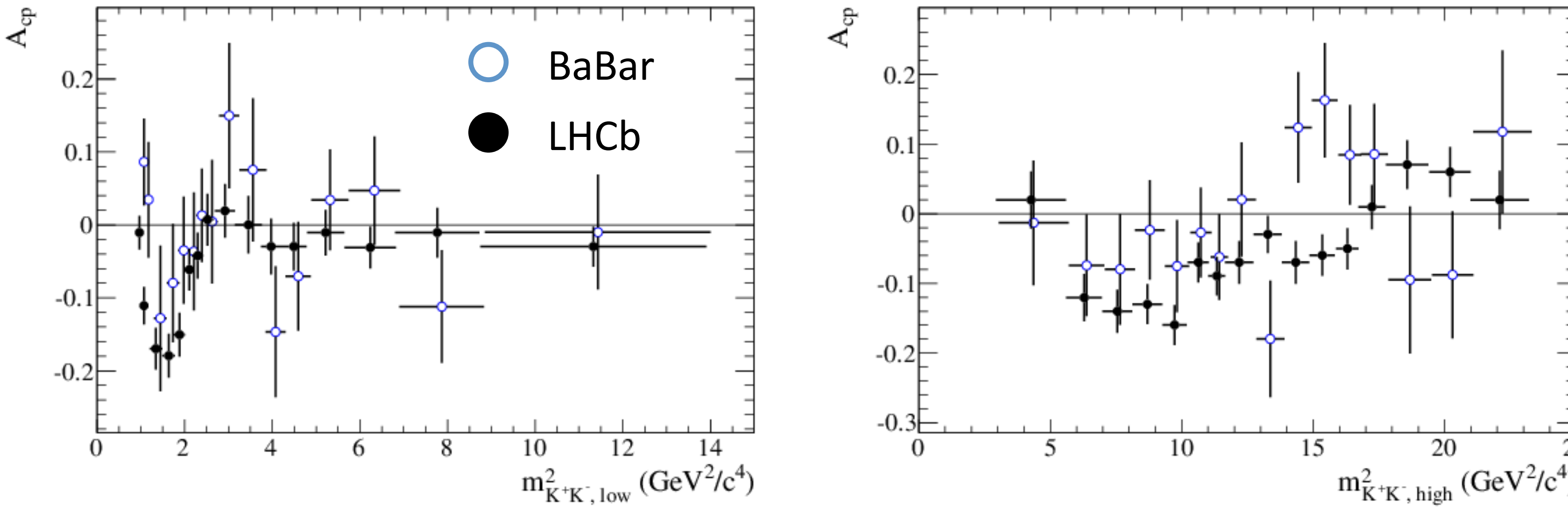
$A_{CP}(\text{local}) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007$

$A_{CP}(\text{local}) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007$

- Study variation of A_{raw} over Dalitz plot
- Some areas of phase space have very large asymmetries, e.g. region around ρ^0 resonance in $B^+ \longrightarrow K^+ \pi^+ \pi^-$ but also regions not clearly associated with a resonance, particularly in $B^+ \longrightarrow K^+ K^+ K^-$

arXiv:1305.4218 [hep-ex]
& LHCb-CONF-2012-018

Comparison between experiments

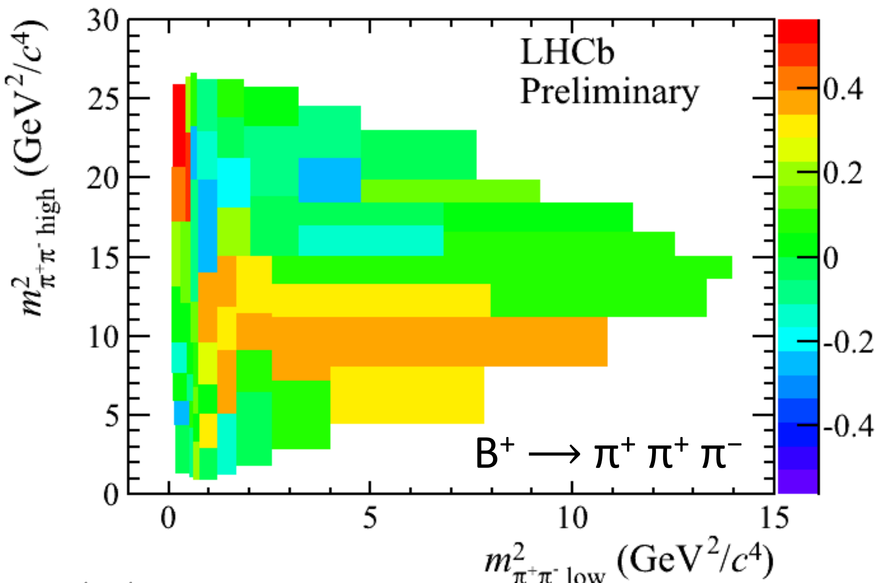


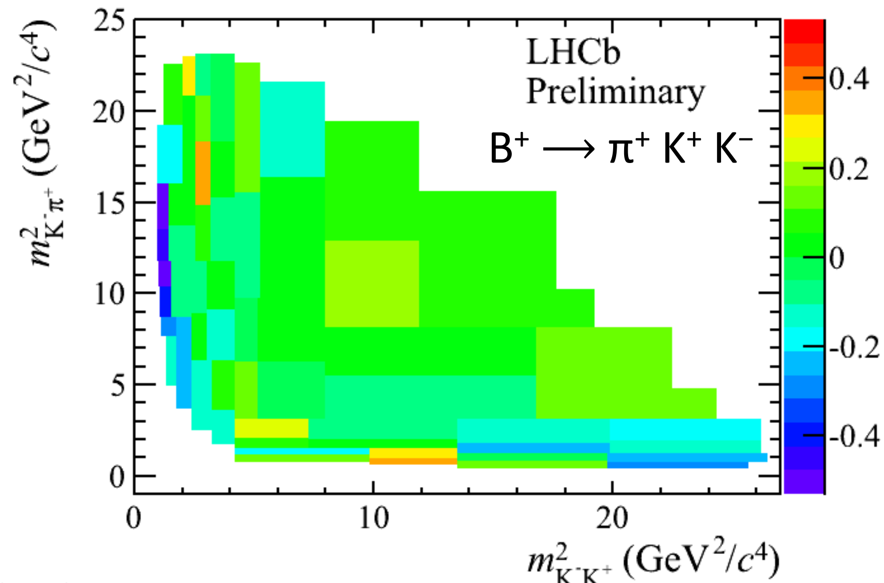
- Distributions of $A_{CP}(B^+ \longrightarrow K^+ K^+ K^-)$ as function of K^+K^- invariant mass
- Show very similar shapes
- Slight offset (left) 0.045 ± 0.021, (right) 0.053 ± 0.021
- However, NB that LHCb numbers are A_{raw} not A_{CP}, so discrepancy is reduced (< 2σ) once this is accounted for
- See talk tomorrow morning by J. Albert for more details

LHCb-CONF-2012-028

CPV in $B^+ \longrightarrow \pi^+ h^+ h^-$

- Similar patterns seen in $B^+ \longrightarrow \pi^+ h^+ h^-$ decays
- Large localised asymmetries, not necessarily associated with a resonance
- Again, asymmetries have opposite sign between the two modes
- Possible that $\pi\pi \leftrightarrow KK$ rescattering is playing a role in generating the strong phase difference
- Amplitude analyses of these modes crucial to understand these effects in more detail





$B^+ \longrightarrow p\,\bar{p}\,h^+$ decays

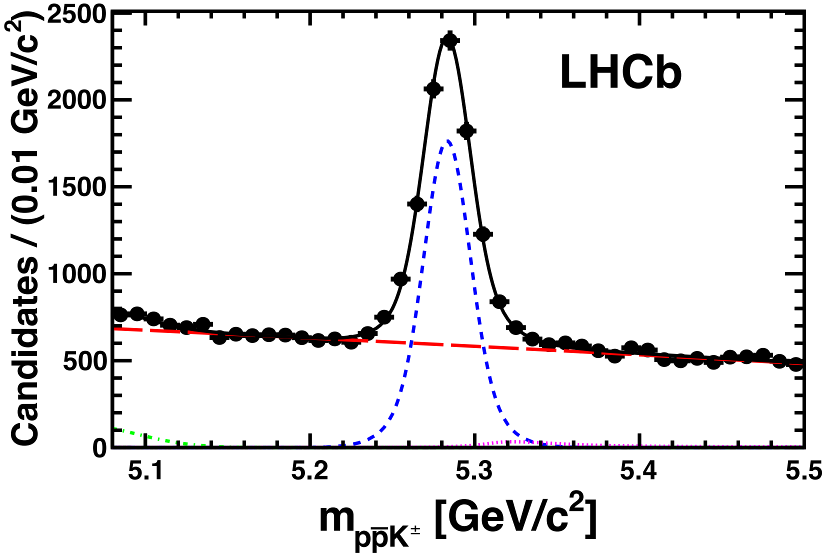
arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

Introduction

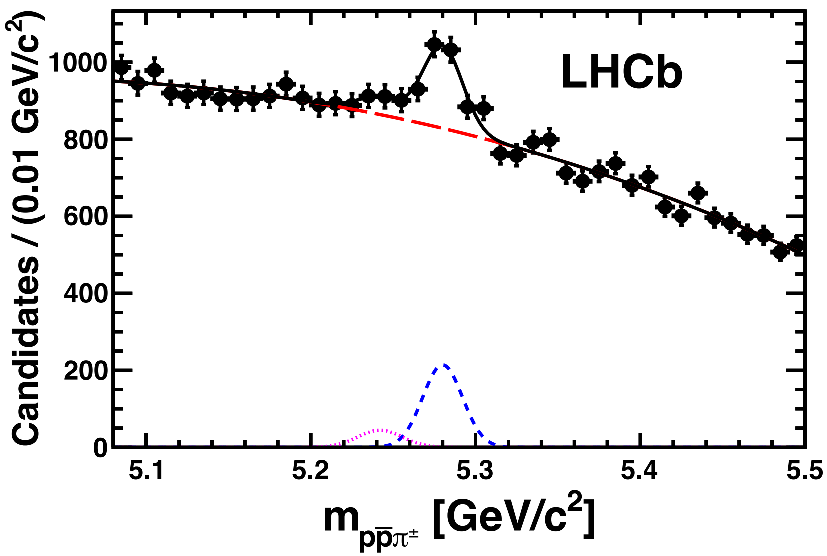
- Motivated by:
  - Large CPV seen in $B^+ \longrightarrow h^+ h^+ h^-$ decays
    - Is rescattering playing a significant role in those modes?
    - Since $h^+h^- \leftrightarrow p\bar{p}$ expected to be smaller than $\pi^+\pi^- \leftrightarrow K^+K^-$, would therefore expect smaller CPV here
  - Threshold enhancements seen in many B decays to a baryon anti-baryon pair plus meson(s) – want to better understand the dynamics of such decays
  - Interesting also to study charmonium contributions, see previous LHCb analysis [Eur. Phys. J. C73, 2462 (2013)]
- Measure decay dynamics and A_{CP} in regions of the phase space
- Analysis uses 1.0 fb^{-1} of 2011 data

arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

Signal Yields



$N(p\bar{p}K^{+}) = 7029 \pm 139$



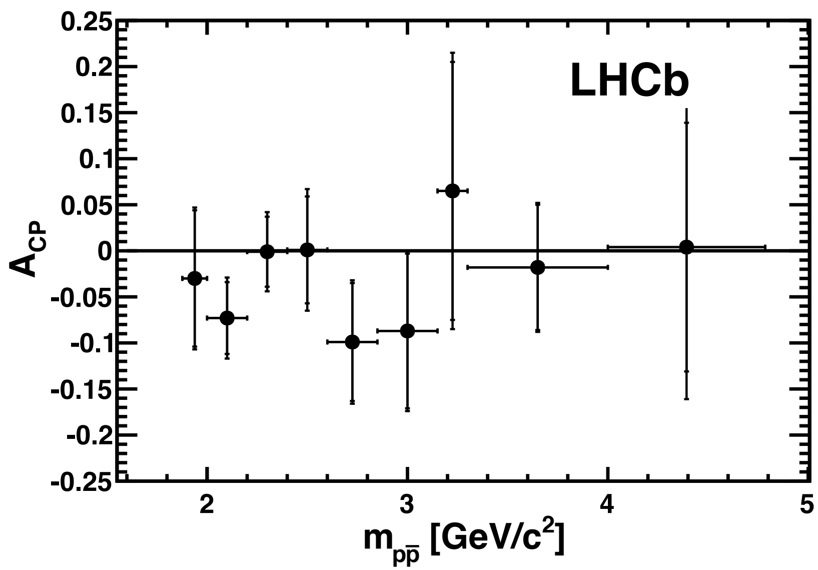
$N(p\bar{p}\pi^{+}) = 656 \pm 70$

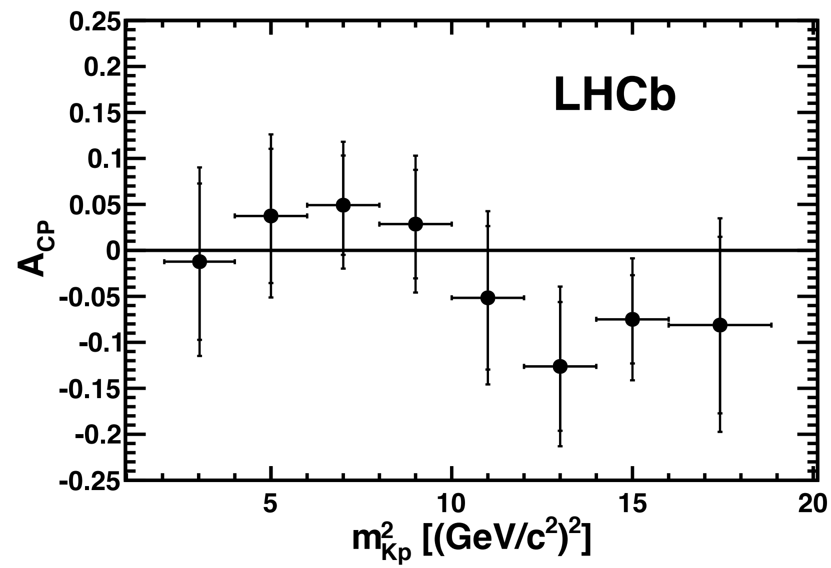
- Perform fits to B-candidate invariant mass distribution
- Model includes components for signal, cross-feed, combinatorial and partially-reconstructed backgrounds
- As expected, smaller yield for the pion mode, also with larger background

arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

CP Asymmetries

- Perform simultaneous fits to B^+ and B^- samples, globally and in bins of the $p\bar{p}$ and Kp invariant masses
- No significant asymmetry seen in any phase space region

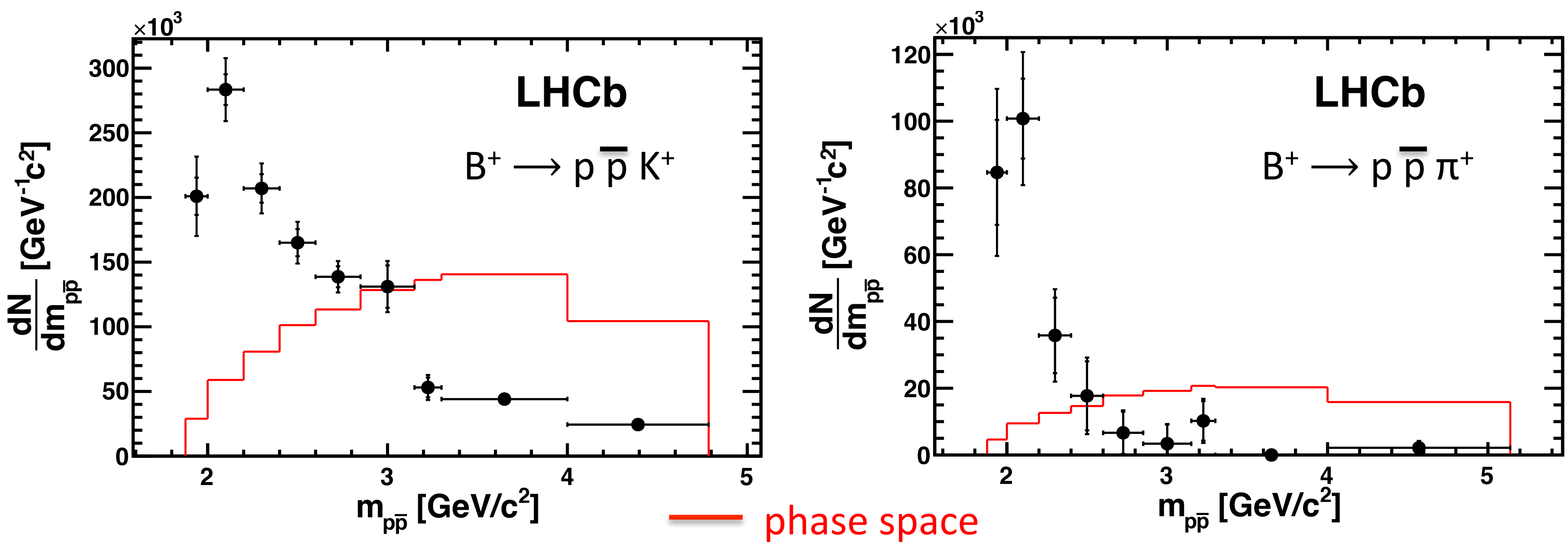




arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

Decay Dynamics

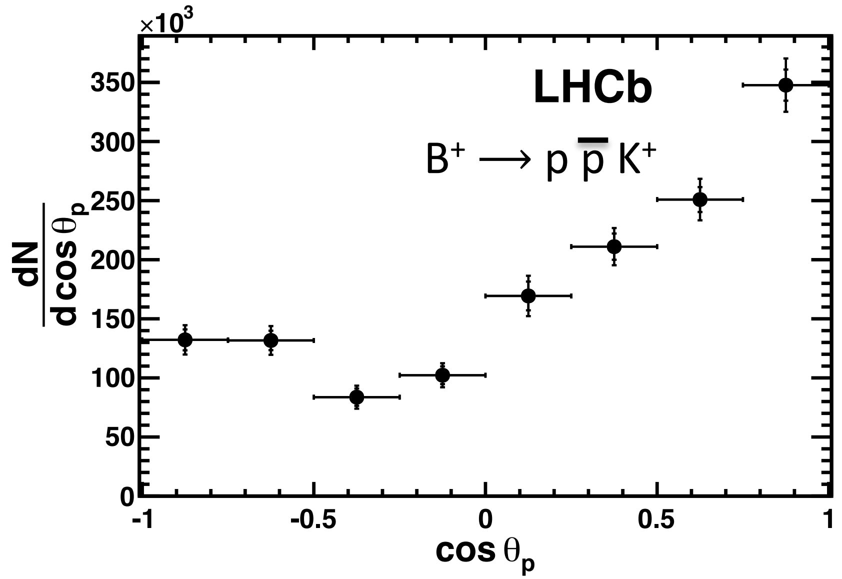
- Differential production spectra show clear enhancements towards threshold in the proton-antiproton invariant mass
- The enhancement is more extreme for $p\bar{p}\pi$

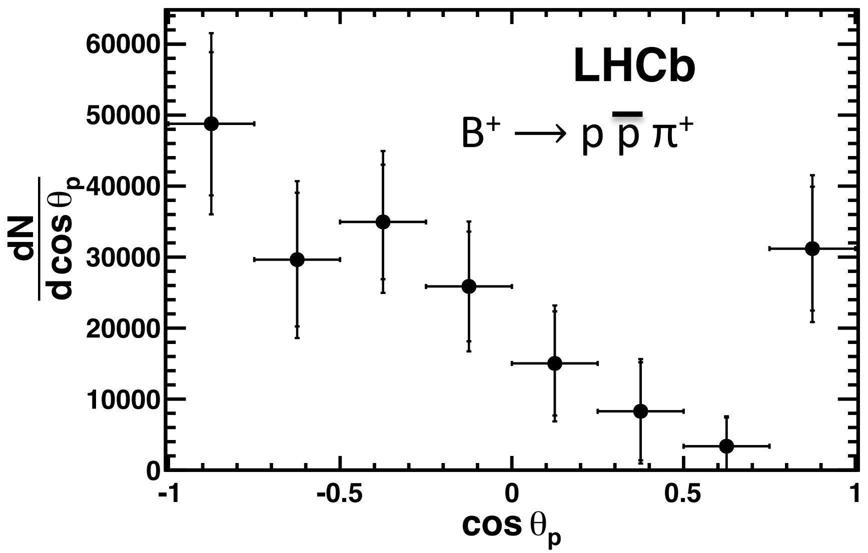


arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

Decay Dynamics

- Differential production spectra also calculated as a function of the angle between the meson and the opposite-sign baryon in the $p\bar{p}$ rest frame
- Striking opposite behaviour for the two decay modes:





A_{FB} = 0.370 ± 0.018 (stat.) ± 0.016 (syst.)

A_{FB} = −0.392 ± 0.117 (stat.) ± 0.015 (syst.)

$B^+ \longrightarrow \bar{\Lambda}(1520)\,p$

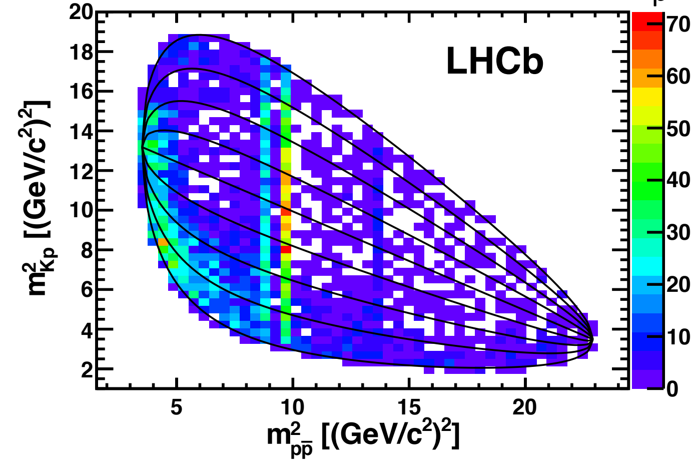
arXiv:1307.6165 [hep-ex]
Submitted to Phys. Rev. D

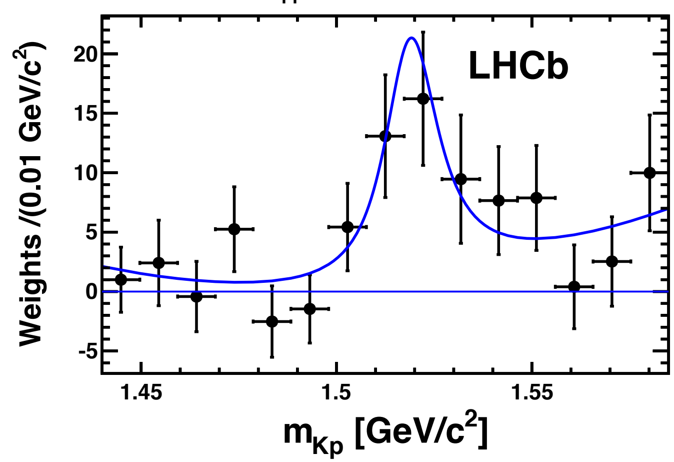
- Background subtracted plots are created using the sPlot technique

NIM A555, 356 (2005)

- Low $p\bar{p}$ invariant mass enhancement and charmonium bands clearly visible
- Can also see some enhancement at low Kp invariant mass
- Lower plot shows this projection
- 2D fit to m_{Kp} and m_B performed to extract yield of resonance contribution
- Significance of 5.1σ
- Branching fraction measured to be

Black lines = lines of constant θ_p



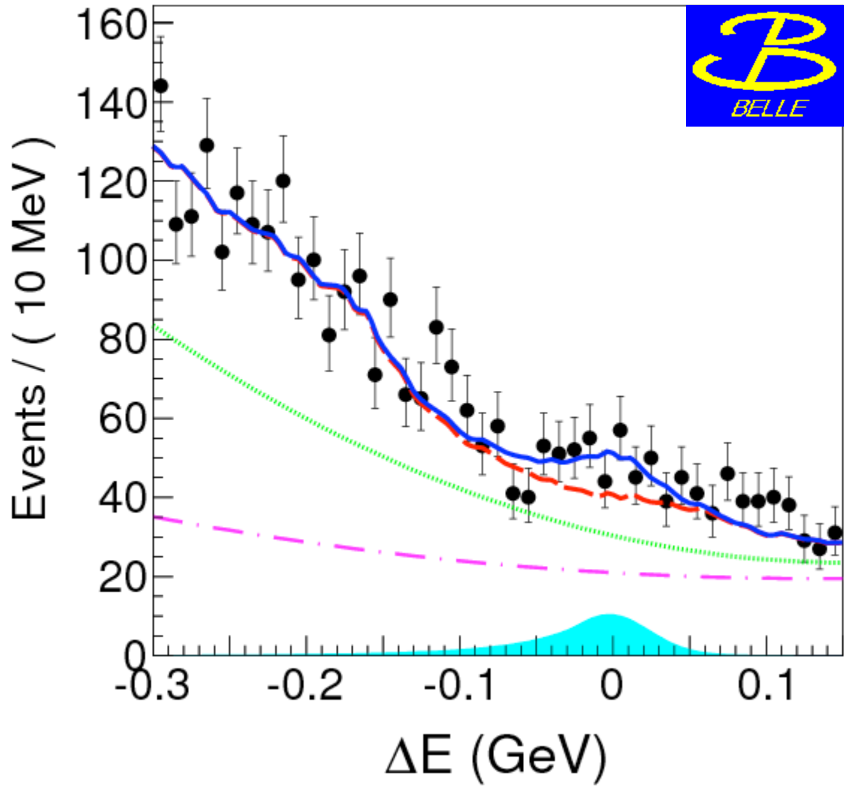


$$BF(B^+ \to \bar{\Lambda}(1520)p) = \left(3.9\ ^{+1.0}_{-0.9}\ (\text{stat.}) \pm 0.1\ (\text{syst.}) \pm 0.3\ (\text{BF})\right) \times 10^{-7}$$

$B^0 \longrightarrow h^+ h^- \pi^0$ decays

Evidence for $B^0 \longrightarrow K^+ K^- \pi^0$

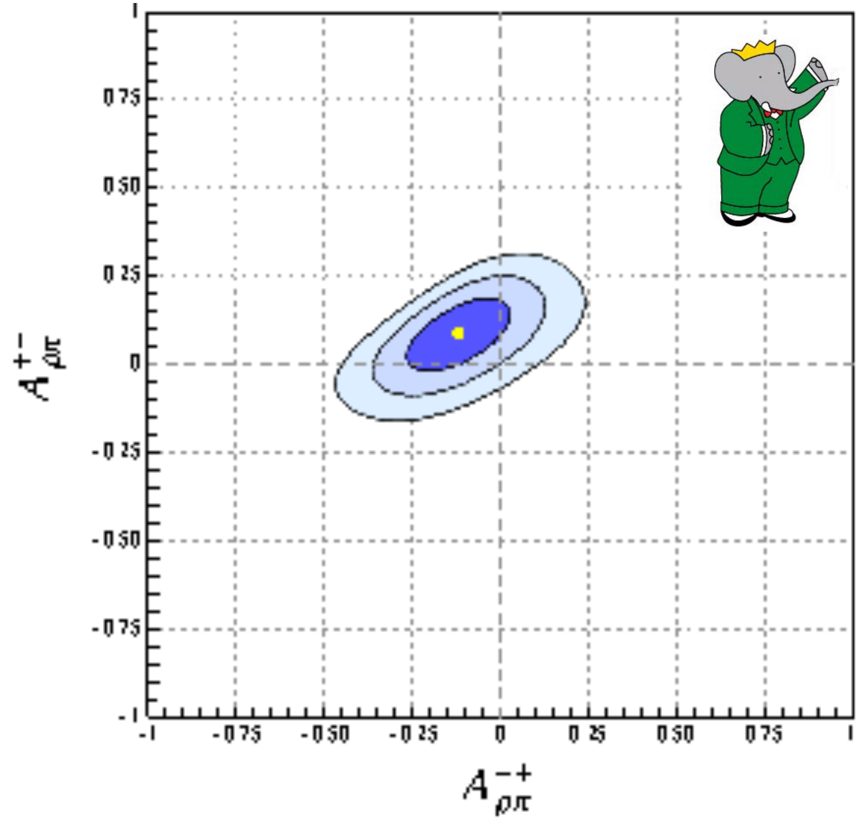
- Analysis uses data sample of 772 million $B\bar{B}$ pairs
- 299 ± 83 signal events
- Significance of 3.5σ
- $BF(B^0 \longrightarrow K^+ K^- \pi^0)$ = $(2.17 \pm 0.60 \pm 0.24) \times 10^{-6}$
- See talk this afternoon by Y. Kwon for more details



Phys. Rev. D 88, 012003 (2013)

$B^0 \longrightarrow \pi^+ \pi^- \pi^0$

- Time-dependent Dalitz-plot analysis
- Aim to measure CKM angle α using Snyder-Quinn method [Phys. Rev. D 48, 2139 (1993)]
- Scan for α found not to be robust with current statistics
- However, extraction of direct CPV parameters is robust
- Consistency with no direct CP violation: $\Delta\chi^2 = 6.42$
- See talk this afternoon by T. Miyashita for more details



$$A^{+-}_{\rho\pi} \equiv \frac{\Gamma(\bar{B}^0 \to \rho^-\pi^+) - \Gamma(B^0 \to \rho^+\pi^-)}{\Gamma(\bar{B}^0 \to \rho^-\pi^+) + \Gamma(B^0 \to \rho^+\pi^-)}$$

$$A^{-+}_{\rho\pi} \equiv \frac{\Gamma(\bar{B}^0 \to \rho^+\pi^-) - \Gamma(B^0 \to \rho^-\pi^+)}{\Gamma(\bar{B}^0 \to \rho^+\pi^-) + \Gamma(B^0 \to \rho^-\pi^+)}$$

$B_{(s)}^0 \longrightarrow K_S h^+ h^-$ decays

Introduction

- Time-dependent flavour-tagged DP analyses sensitive to mixing-induced CP-violating phases
  - e.g. recent BaBar measurement:

    $\beta_{eff}(\phi K_S) = (21 \pm 6 \pm 2)^\circ$

    in the decay $B^0 \longrightarrow K_S K^+ K^-$

    [Phys. Rev. D 85, 112010 (2012)]
  - See talk tomorrow morning by J. Albert for more details of this and other 3K DP analyses

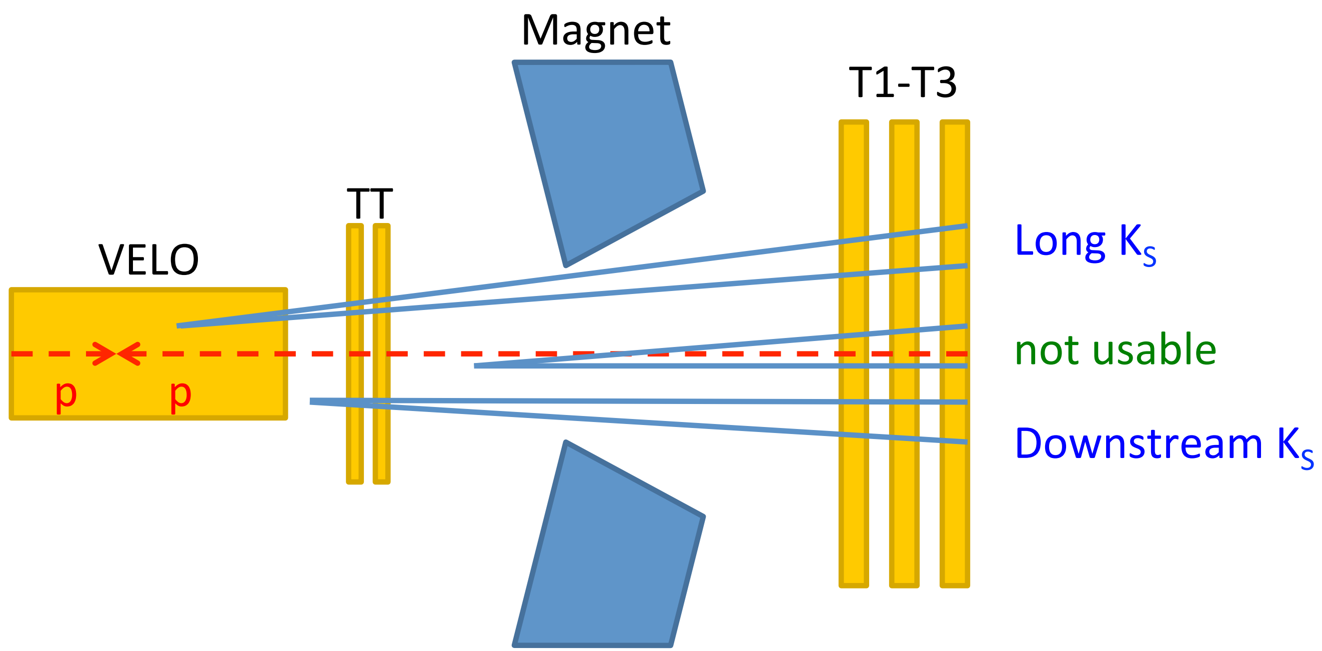
Decay	Observed?	Favoured?
$B^0 \longrightarrow K_S \pi^+ \pi^-$	✓	✓
$B^0 \longrightarrow K_S K^\pm \pi^\mp$	✓	✗
$B^0 \longrightarrow K_S K^+ K^-$	✓	✓
$B_s \longrightarrow K_S \pi^+ \pi^-$	✗	✗
$B_s \longrightarrow K_S K^\pm \pi^\mp$	✗	✓
$B_s \longrightarrow K_S K^+ K^-$	✗	✗

- Such an analysis not possible with current LHCb statistics
- First step is to search for the three previously unseen B_s decays

arXiv:1307.7648 [hep-ex]
Submitted to JHEP

Analysis Method

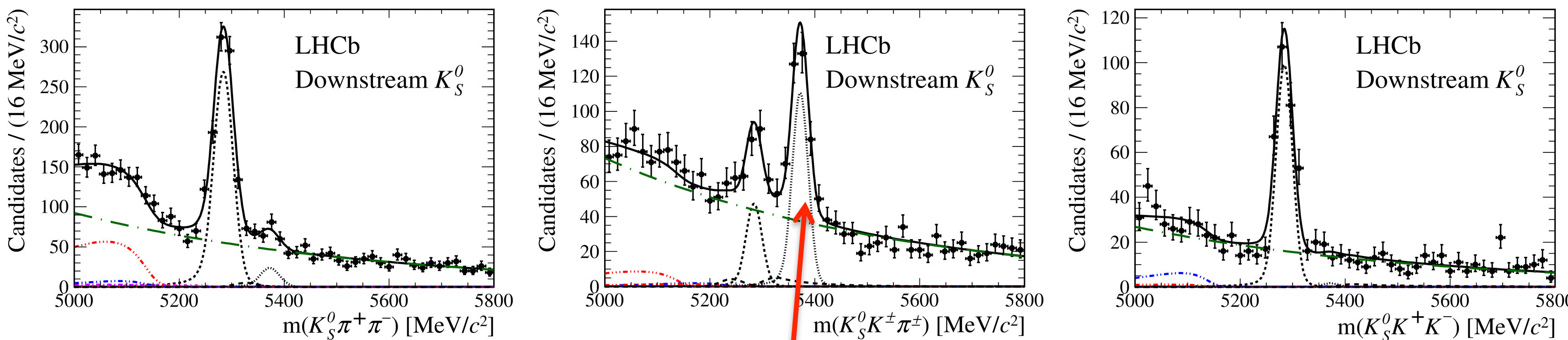
- Analysis uses 1.0 fb^{-1} of 2011 data
- Selection optimised separately for favoured and suppressed decays
- K_S decays to $\pi^+ \pi^-$ divided into two categories:
  - Long: pion tracks have hits in the vertex detector (VELO)
  - Downstream: pion tracks have no VELO hits



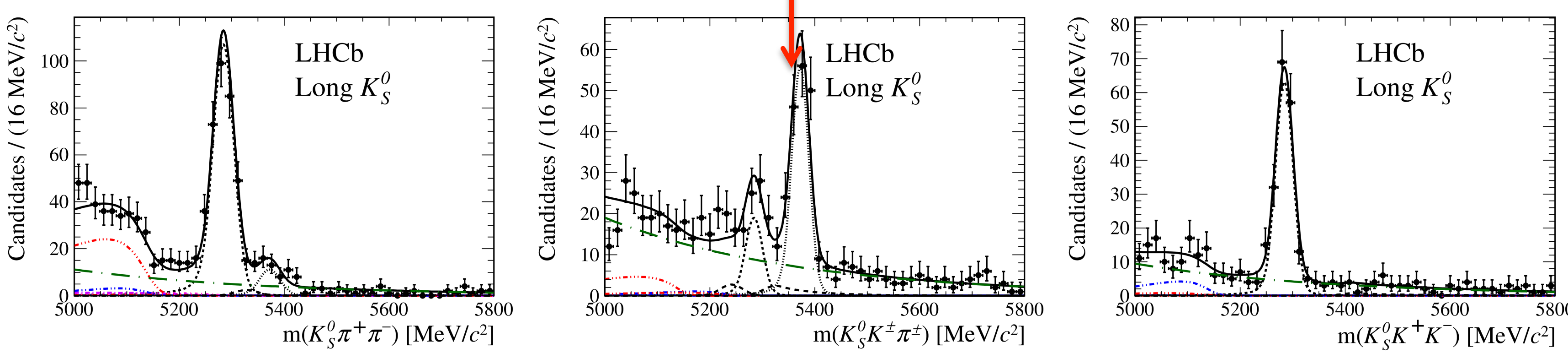
arXiv:1307.7648 [hep-ex]
Submitted to JHEP

Favoured-mode selection

$B^0 \longrightarrow K_S \pi^+ \pi^-$ | $B_s \longrightarrow K_S K^\pm \pi^\mp$ | $B^0 \longrightarrow K_S K^+ K^-$

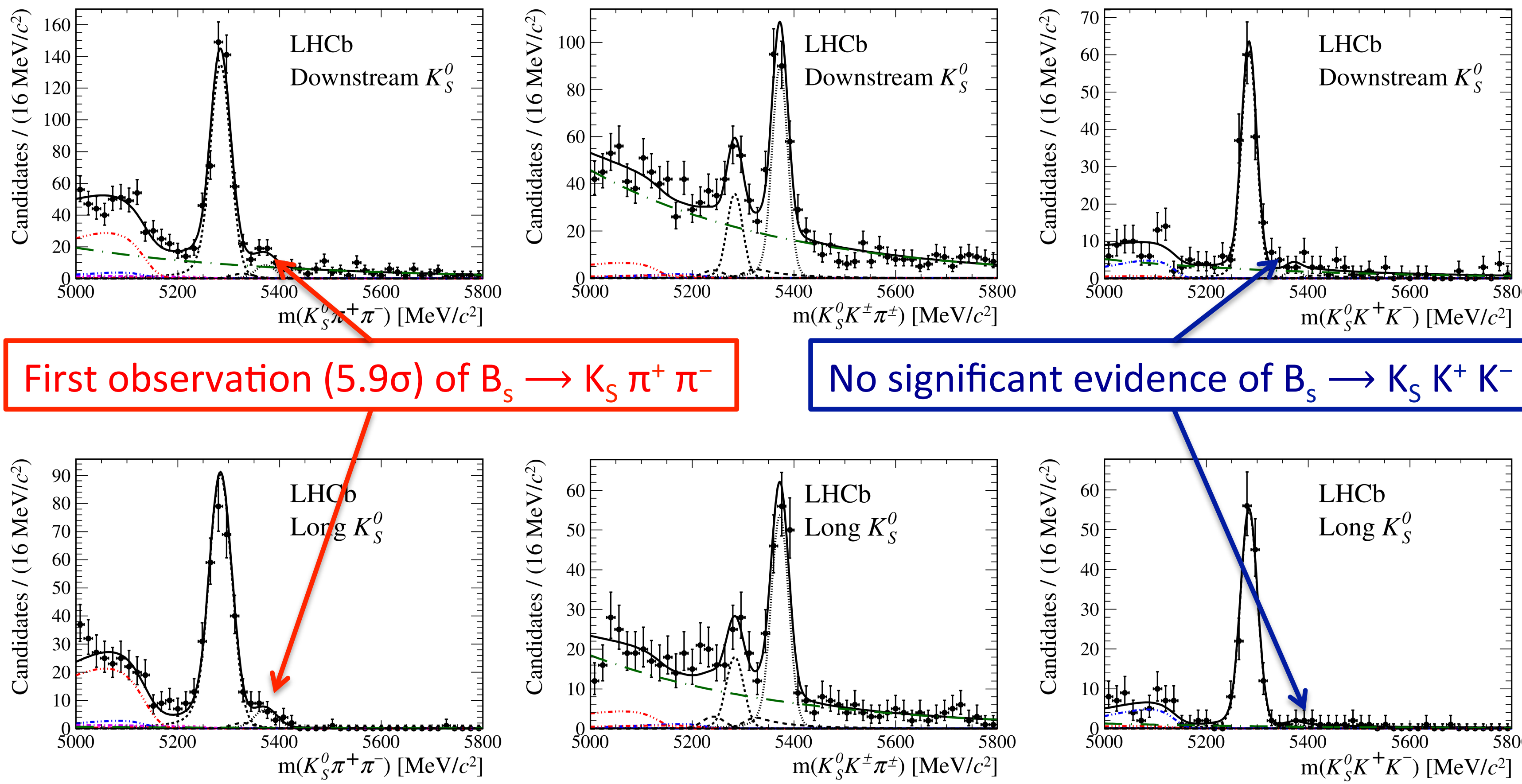


Unambiguous first observation of $B_s \longrightarrow K_S K^\pm \pi^\mp$



Suppressed-mode selection

$B_s \longrightarrow K_S \pi^+ \pi^-$ | $B^0 \longrightarrow K_S K^\pm \pi^\mp$ | $B_s \longrightarrow K_S K^+ K^-$



First observation (5.9σ) of $B_s \longrightarrow K_S \pi^+ \pi^-$

No significant evidence of $B_s \longrightarrow K_S K^+ K^-$

arXiv:1307.7648 [hep-ex]
Submitted to JHEP

Branching fractions

- Branching fractions measured with respect to the decay $B^0 \longrightarrow K_S\, \pi^+\, \pi^-$
  - World average value BF = $(2.48 \pm 0.10) \times 10^{-5}$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 0.128 \pm 0.017\,(\text{stat.}) \pm 0.009\,(\text{syst.})\,,$$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 0.385 \pm 0.031\,(\text{stat.}) \pm 0.023\,(\text{syst.})\,,$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 0.29 \pm 0.06\,(\text{stat.}) \pm 0.03\,(\text{syst.}) \pm 0.02\,(f_s/f_d)\,,$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 1.48 \pm 0.12\,(\text{stat.}) \pm 0.08\,(\text{syst.}) \pm 0.12\,(f_s/f_d)\,,$$

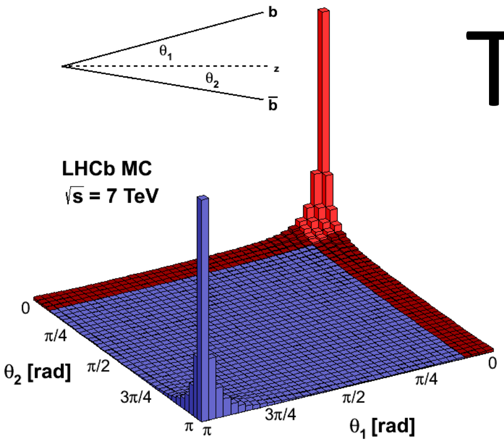
$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} \in [0.004; 0.068] \text{ at } 90\% \text{ CL}\,.$$

Summary

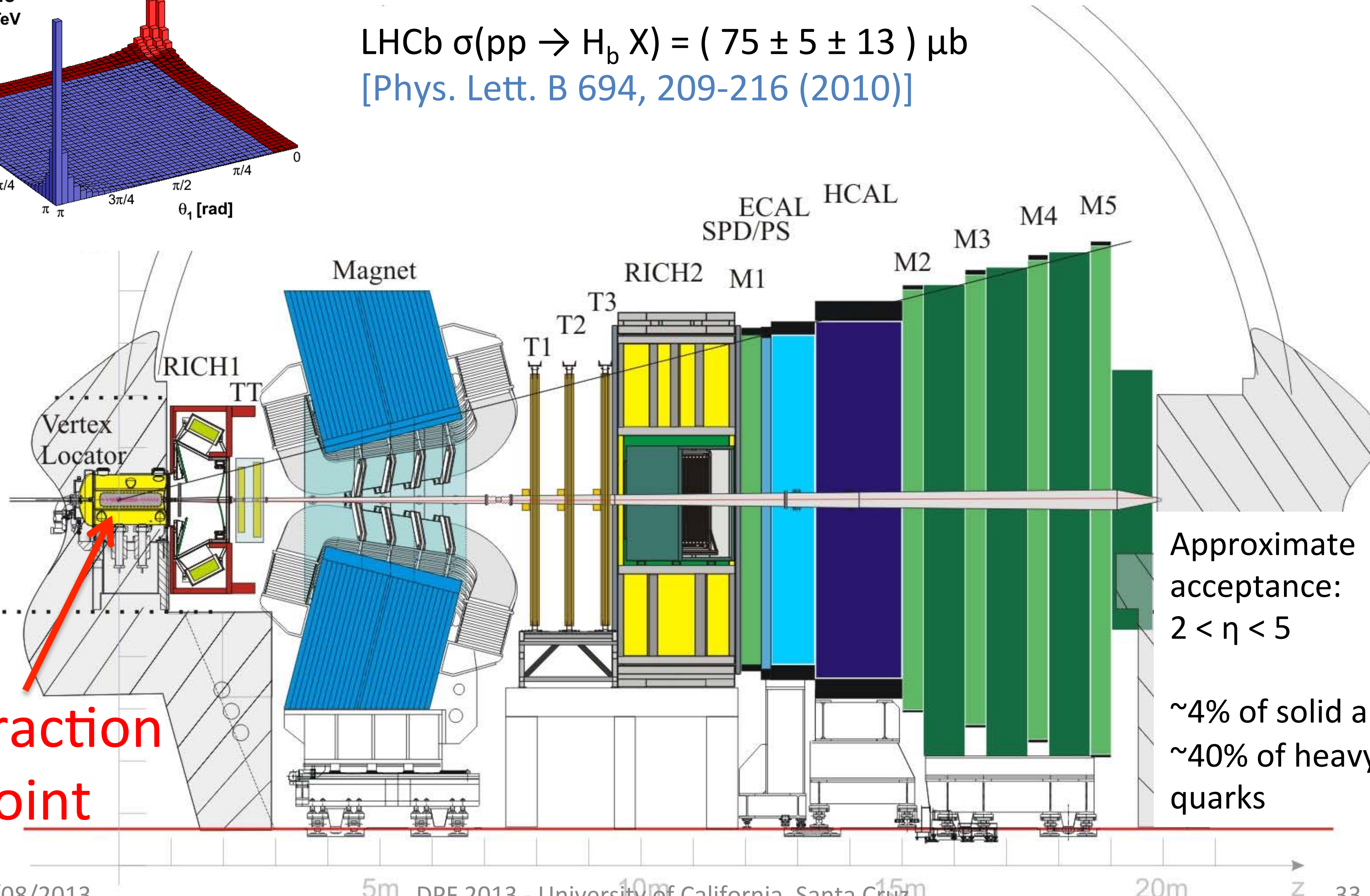
- A wealth of charmless 3-body decay modes under study
  - Exciting new direct CP violation results in $B^+ \longrightarrow h^+h^+h^-$
  - Interesting puzzles in $B^+ \longrightarrow p\bar{p}h^+$ decay dynamics
  - First evidence of $B^0 \longrightarrow K^+K^-\pi^0$
  - Improved measurements of mixing-induced and direct CP violation in $B^0 \longrightarrow \phi K_S$ and $B^0 \longrightarrow \rho\pi$
  - First observations of B_s decays to $K_S\pi\pi$ and $K_SK\pi$
- Many exciting results to come
  - B-factories updating results to final dataset and studying new modes
  - LHCb embarking on amplitude analyses using the combined 2011 + 2012 ($1\ fb^{-1} + 2\ fb^{-1}$) dataset
  - Decays of b-baryons (e.g. Λ_b & Ξ_b) also being studied
- Watch this space!

Backup Slides

The LHCb detector



LHCb $\sigma(pp \rightarrow H_b X)$ = (75 ± 5 ± 13) μb
[Phys. Lett. B 694, 209-216 (2010)]

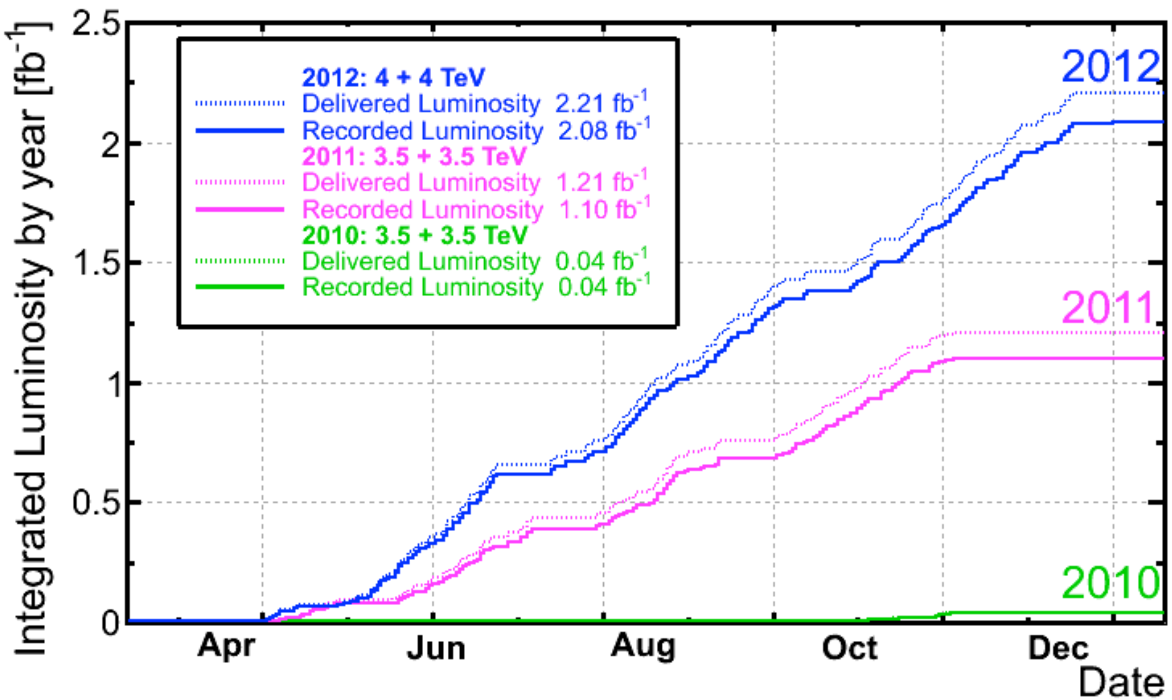


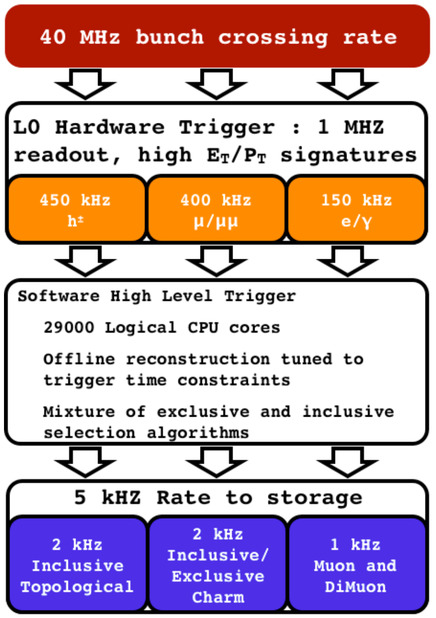
Interaction Point

Approximate acceptance:
$2 < \eta < 5$

~4% of solid angle
~40% of heavy quarks

Data Sample





- Trigger Efficiencies:
  - ~30% efficient for multibody hadronic
  - ~90% efficient for dimuons