Direct CP violation in charmless $B^{\pm}$ three-body decays

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on behalf of the LHCb collaboration.

Implications of LHCb measurements and future prospects

16/9/14

Charmless $B^{\pm}$ decays: an excellent laboratory for direct *CP*V studies.

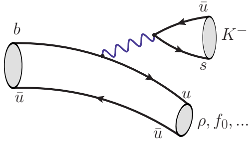
Direct *CP*V arises from the interference of amplitudes with different weak and strong phases:

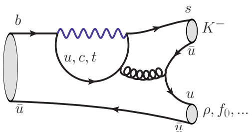
$$A = a_1 + a_2\, e^{(\delta+\gamma)}, \quad \overline{A} = a_1 + a_2\, e^{(\delta-\gamma)}$$

$$\mathcal{A}_{CP}^{\rm dir} = \frac{2a_1 a_2 \sin\gamma \sin\delta}{a_1^2 + a_2^2 + 2a_1 a_2 \cos\gamma \cos\delta}.$$

This is realized in the context of the Bander-Silverman-Soni (BSS) mechanism:

(PRL **43**, 242 (1979))





Rescattering at the quark level in the loop diagram originates a strong phase, provided the gluon is timelike. Same mechanism for all hadronic final states.

What makes three-body decays particularly interesting:

all final states have a rich resonant structure. The interference between resonances and FSI at hadron level provide additional sources of strong phase difference. Large effects in regions of the Dalitz plot may arise.

In this presentation:

- $B^{\pm} \to K^{\pm}h^{+}h^{-}, \; B^{\pm} \to \pi^{\pm}h^{+}h^{-} \quad h = \pi, \; K$
  LHCB-PAPER-2014-044, arXiv::1408.5373

- $B^{\pm} \to p\bar{p}h^{\pm}, \quad h = \pi, \; K$
  LHCB-PAPER-2014-034, arXiv:1407.5907

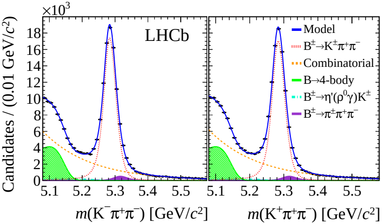
All results correspond to full Run I data set (3 fb^{-1})

The $B^\pm \to K^\pm h^+ h^-$, $\pi^\pm h^+ h^-$ signals from Run I

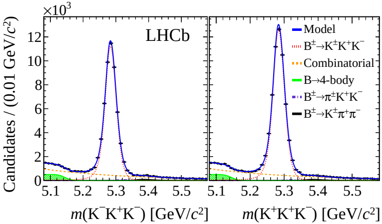
$b \to s\bar{u}u$

penguin dominated

$K^-\pi^+\pi^-$ $K^+\pi^+\pi^-$



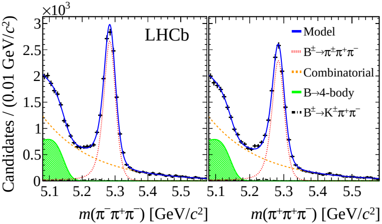
$K^-K^+K^-$ $K^+K^+K^-$



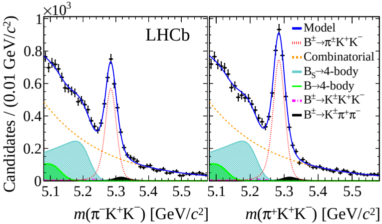
$b \to d\bar{u}u$

tree dominated

$\pi^-\pi^+\pi^-$ $\pi^+\pi^+\pi^-$



$\pi^-K^+K^-$ $\pi^+K^+K^-$



Total yields (stat errors)				
	181069 ± 404	$B^\pm \to K^\pm\pi^+\pi^-$	109240 ± 354	$B^\pm \to K^\pm K^+ K^-$
	24907 ± 222	$B^\pm \to \pi^\pm\pi^+\pi^-$	6161 ± 172	$B^\pm \to \pi^\pm K^+ K^-$

Phase space integrated CP asymmetries

Global (phase space integrated) asymmetry is computed from observed signal yields:

$$A_{\text{obs}} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}, \qquad N_{B^\pm} = \text{acceptance corrected yields}$$

CP asymmetry: obtained correcting A_{obs} for the $B^\pm$ production asymmetry and asymmetry in the detection of unpaired hadron $(B^\pm \to K^\pm h^+ h^-, B^\pm \to \pi^\pm h^+ h^-)$

$$\mathcal{A}_{CP} = A_{\text{obs}} - A^B_{\text{prod}} - A^h_{\text{det}} ,$$

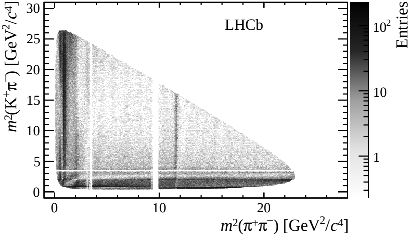
$A^B_{\text{prod}}, A^K_{\text{det}}$ from $B^\pm \to J/\psi[\mu^+\mu^-]\,K^\pm$, A^π_{det} from $D^{*+} \to D^0[K^-\pi^-\pi^+\pi^+]\,\pi^+$.

Global asymmetries $\Longrightarrow$ typically small, not the most sensitive observable:

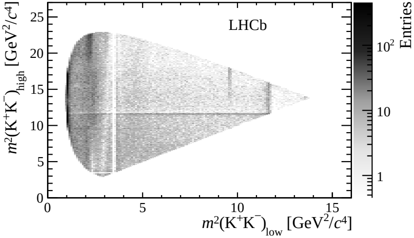
$$\mathcal{A}_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +\,0.025 \pm 0.004 \pm 0.004 \pm 0.007 \quad (2.8\sigma)$$
$$\mathcal{A}_{CP}(B^\pm \to K^\pm K^+ K^-) = -\,0.036 \pm 0.004 \pm 0.002 \pm 0.007 \quad (4.3\sigma)$$
$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +\,0.058 \pm 0.008 \pm 0.009 \pm 0.007 \quad (4.2\sigma)$$
$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm K^+ K^-) = -\,0.123 \pm 0.017 \pm 0.012 \pm 0.007 \quad (5.6\sigma)$$

Errors are statistical, systematic and the uncertainty on $\mathcal{A}_{CP}(B^\pm \to J/\psi K^\pm)$.

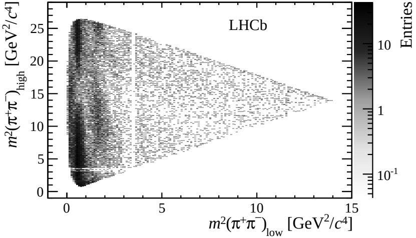
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$



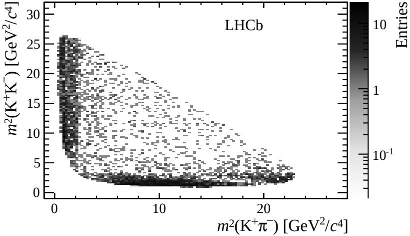
$B^{\pm} \to K^{\pm}K^{+}K^{-}$



$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



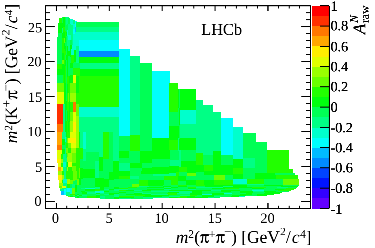
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

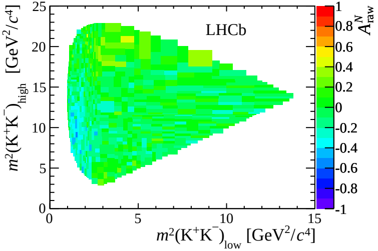


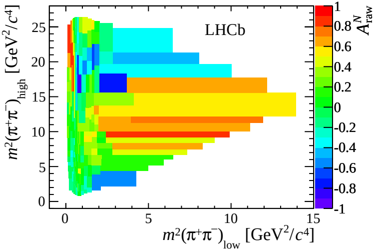
A dense, rich resonance structure, but with a large nonresonant component.

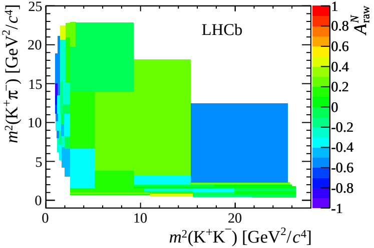
Distribution of charge asymmetries in the Dalitz plot

- rich pattern in the $\pi\pi$ system, mainly at low mass; very little activity in the $K\pi$ system.
- different mechanisms in action, possibly related to different sources of strong phase. A full amplitude analysis is needed.

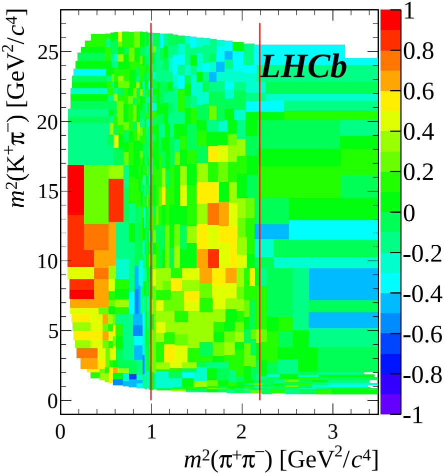




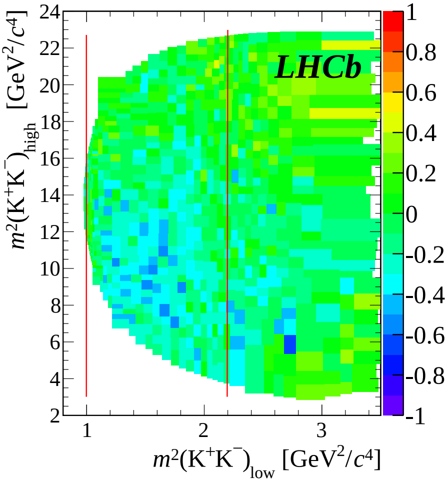




$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$



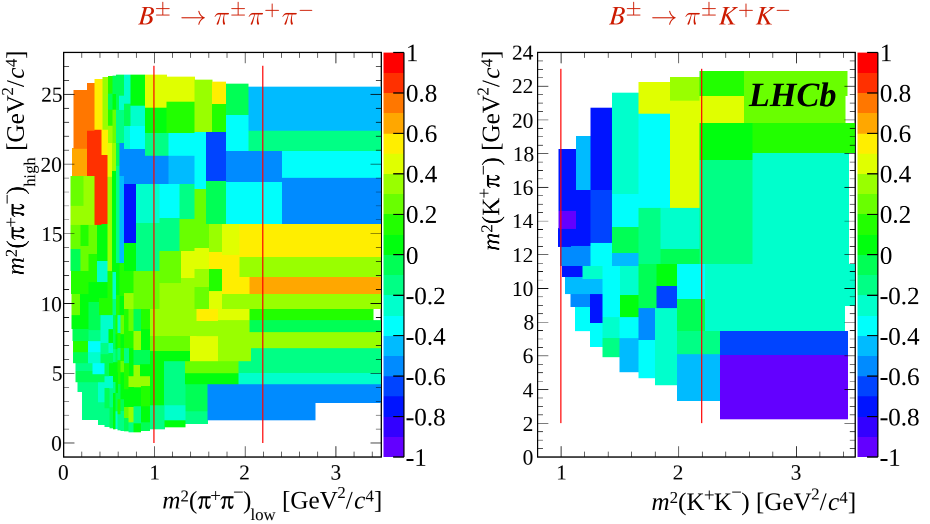
$B^{\pm} \to K^{\pm}K^{+}K^{-}$



$\pi^{+}\pi^{-} \leftrightarrows K^{+}K^{-}$ rescattering? *CPT* symmetry imposes a constraint on particle/antiparticle partial widths: $\sum \Gamma_i(B \to f_i) = \sum \Gamma_i(\overline{B} \to \bar{f}_i)$.

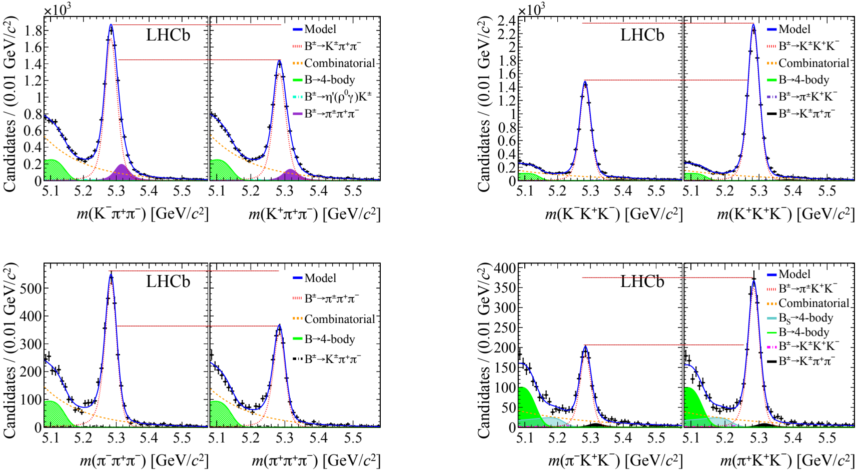
Strong phase difference would come from $\pi\pi \leftrightarrows KK$ rescattering.

$B^{\pm} \to \pi^{\pm} h^{+} h^{-}$ charge asymmetries: a zoom at low $\pi^{+}\pi^{-}/K^{+}K^{-}$ mass

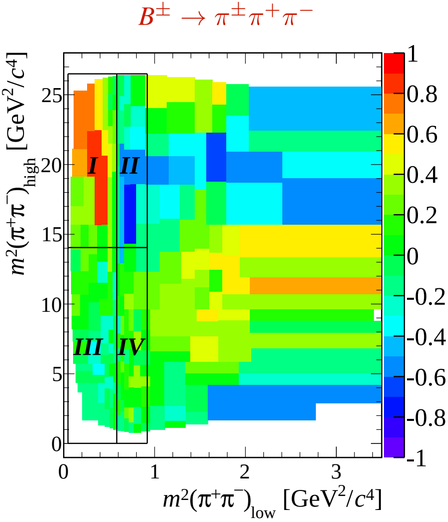


Similar effect in $B^{\pm} \to \pi^{\pm} h^{+} h^{-}$ (more evident in $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$).

Charge asymmetries in the "rescattering" region $(1 < m^2_{h^+h^-} < 2.2\ \mathrm{GeV}^2/c^4)$



Decay	N_s	A_{CP}
$B^\pm \to K^\pm\pi^+\pi^-$	15562 ± 165	$+0.121 \pm 0.022$
$B^\pm \to K^\pm K^+K^-$	16992 ± 142	-0.211 ± 0.014
$B^\pm \to \pi^\pm\pi^+\pi^-$	4329 ± 76	$+0.172 \pm 0.027$
$B^\pm \to \pi^\pm K^+K^-$	2500 ± 57	-0.328 ± 0.041



A simple isobar model:

$\rho^0(770)\pi^+$ plus a NR component

$$A_\rho = \frac{F_D F_\rho |\mathbf{p}||\mathbf{q}| \cos\theta}{s - m_0^2 + i m_0 \Gamma}$$

$$= \frac{F_D F_\rho |\mathbf{p}||\mathbf{q}|}{(s - m_0^2)^2 + m_0^2 \Gamma^2} (s - m_0^2 - i m_0 \Gamma) \cos\theta$$

$$= f_\rho (s - m_0^2 - i m_0 \Gamma) \cos\theta$$

$$\mathcal{M}_\pm = c_\pm^\rho A_\rho(s_{\rm low}) + c_\pm^{\rm NR} A_{\rm NR}(s_{\rm low}, s_{\rm high})$$

$$\mathcal{A}_{CP} \propto |\mathcal{M}_-|^2 - |\mathcal{M}_+|^2,$$

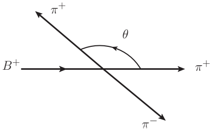
$$\mathcal{A}_{CP} \propto ({c_-^\rho}^2 - {c_+^\rho}^2)|A_\rho|^2 + ({c_-^{\rm NR}}^2 - {c_+^{\rm NR}}^2)|A_{\rm NR}|^2 + f_\rho\, A_{\rm NR} \times$$

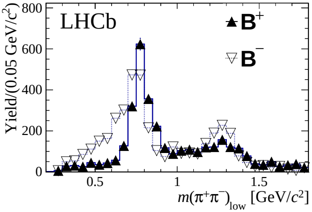
$$[\cos\theta\, (s_{\rm low} - m_0^2) 2\, {\rm Re}(c_-^\rho c_-^{\rm NR} - c_+^\rho c_+^{\rm NR}) + \cos\theta\, m_0 \Gamma\, 2\, {\rm Im}(c_-^\rho c_-^{\rm NR} - c_+^\rho c_+^{\rm NR})]$$

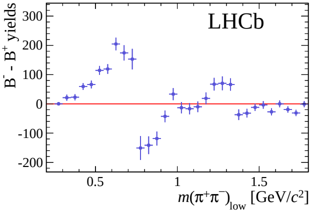
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ — charge asymmetries from S- and P-wave interference

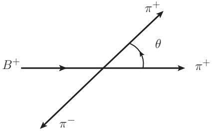
The distribution of the difference between B^+ and B^- yields is compatible with an S- and P-wave interference term, linear in $\cos\theta$.

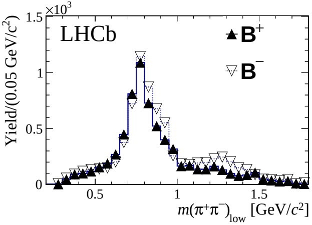
Effect is more pronounced at high $\pi^+\pi^-$ masses $(\cos\theta < 0)$.

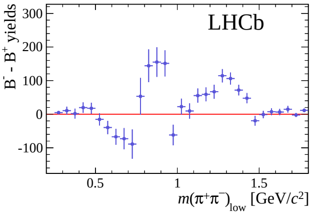


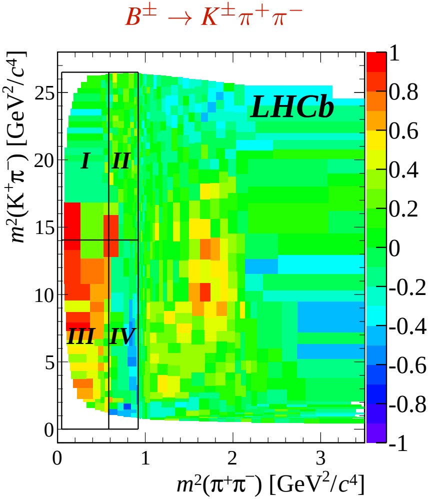












A simple isobar model:

$\rho^0(770)K^\pm + f_0(980)K^\pm$

$$A_\rho = \frac{F_D F_\rho |\mathbf{p}||\mathbf{q}| \cos\theta}{s - m_0^2 + i m_0 \Gamma} = \frac{F_D F_\rho |\mathbf{p}||\mathbf{q}|}{(s-m_\rho^2)^2 + m_\rho^2\Gamma_\rho^2}(s - m_\rho^2 - i m_\rho \Gamma_\rho)\cos\theta = f_\rho\,(s - m_\rho^2 - i m_\rho\Gamma_\rho)\,\cos\theta$$

$$A_{f_0} = \frac{1}{s - m_{f_0}^2 + i m_{f_0}\Gamma_{f_0}} = f_{f_0}(s - m_{f_0}^2 - i m_{f_0}\Gamma_{f_0})$$

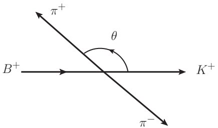
$$\mathcal{M}_\pm = c_\pm^\rho A_\rho + c_\pm^{f_0} A_{f_0}$$

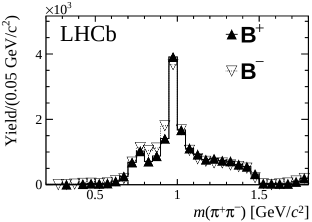
$$\mathcal{A}_{CP} \propto (c_-^{\rho 2} - c_+^{\rho 2})|A_\rho|^2 + (c_-^{f_0 2} - c_+^{f_0 2})|A_{f_0}|^2 + f_\rho f_{f_0} \times$$
$$[\cos\theta\,(s - m_\rho^2)(s - m_{f_0}^2) 2\,\mathrm{Re}(c_-^\rho c_-^{f_0} - c_+^\rho c_+^{f_0}) + \cos\theta\, m_\rho\Gamma_\rho m_{f_0}\Gamma_{f_0} 2\mathrm{Im}(c_-^\rho c_-^{f_0} - c_+^\rho c_+^{f_0})]$$

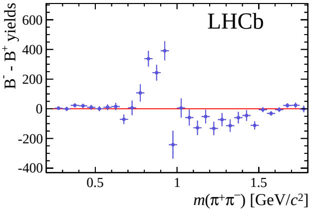
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ — charge asymmetries from S- and P-wave interference

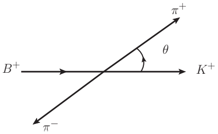
For low $K\pi$ mass ($\cos\theta > 0$), the distribution of the difference between B^{+} and B^{-} yields follows what is expected from S- and P-wave interference.

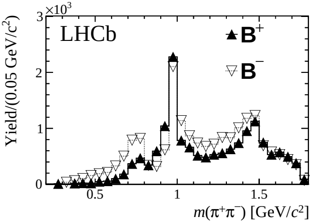
Different patterns for $\cos\theta > 0$ and $\cos\theta < 0$.
Amplitude analysis needed.

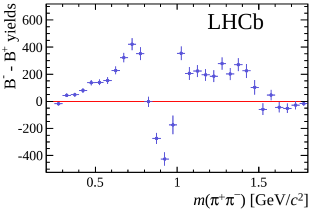






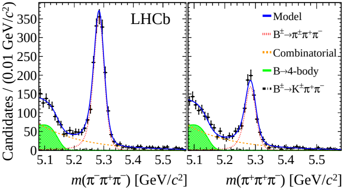




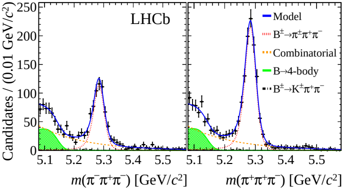


Charge asymmetries from S- and P-wave interference

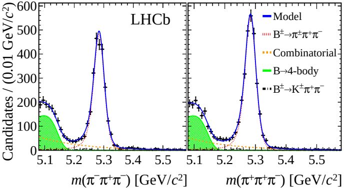
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ – sector I



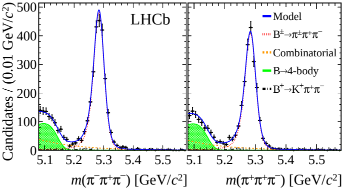
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ – sector II



$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ – sector III



$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ – sector IV



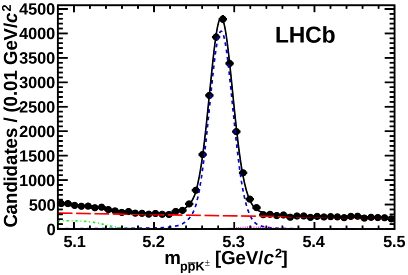
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

sector	N_s	A_{CP}
I	2909 ± 80	-0.052 ± 0.057
II	6136 ± 99	$+0.140 \pm 0.038$
III	2856 ± 86	$+0.598 \pm 0.087$
IV	2107 ± 55	-0.208 ± 0.060

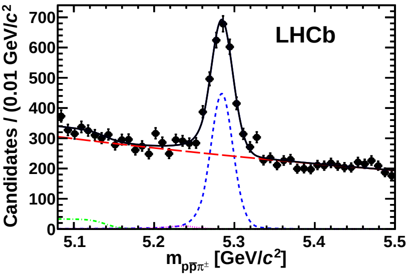
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

sector	N_s	A_{CP}
I	2629 ± 59	$+0.302 \pm 0.030$
II	1653 ± 46	-0.244 ± 0.039
III	5204 ± 79	-0.076 ± 0.021
IV	4476 ± 72	$+0.055 \pm 0.025$

$B^{\pm} \to p\bar{p}K^{\pm}$



$B^{\pm} \to p\bar{p}\pi^{\pm}$

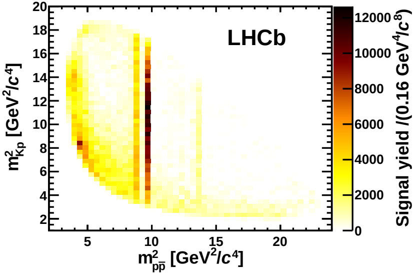


Yields extracted from two-dimensional fits to the invariant mass distributions of $p\bar{p}h^{\pm}$ and $p\bar{p}$ or $\bar{p}K^{+}$.

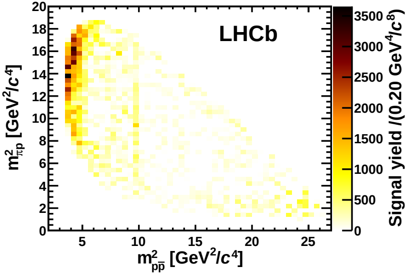
mode	yield
$J/\psi\ K^{+}$	4260 ± 67
$\eta_c K^{+}$	2182 ± 64
$\psi(2S)K^{+}$	368 ± 20
$\overline{\Lambda}(1520)p$	128 ± 20
$p\bar{p}K^{+}$ ($m_{p\bar{p}} < 2.85$ GeV/c^2)	8510 ± 104
total	18721 ± 142
$J/\psi\ \pi^{+}$	122 ± 12
$p\bar{p}\pi^{+}$ ($m_{p\bar{p}} < 2.85$ GeV/c^2)	1632 ± 64
total	1988 ± 74

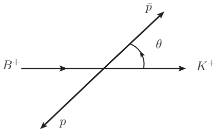
$B^{\pm} \to p\bar{p}h^{\pm}$ — Dalitz plots

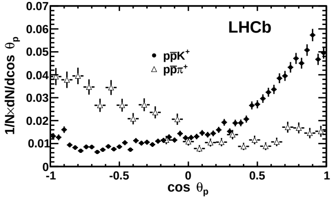
$B^{\pm} \to p\bar{p}K^{\pm}$



$B^{\pm} \to p\bar{p}\pi^{\pm}$





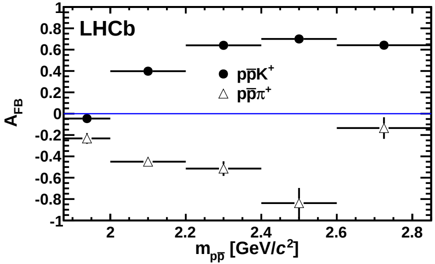


Enhancement near $p\bar{p}$ threshold at low $pK^{\pm}$ and high $p\pi^{\pm}$ mass.

Forward-backward asymmetry has opposite sign in each final state.

Charmonium is much more prominent in $B^{\pm} \to p\bar{p}K^{\pm}$.

Forward-backward asymmetry and updated BR measurement



For $m_{p\bar{p}} < 2.85$ GeV/c^2:

$$A_{\rm FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

$$A_{\rm FB} = +0.495 \pm 0.014 \quad (p\bar{p}K^{\pm})$$

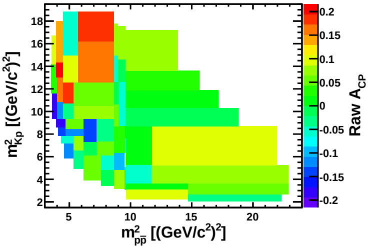
$$A_{\rm FB} = -0.495 \pm 0.034 \quad (p\bar{p}\pi^{\pm})$$

Updated branching fractions:

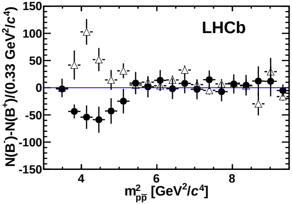
$$\mathcal{B}(B^+ \to p\bar{p}\pi^+,\, m_{p\bar{p}} < 2.85 \mathrm{GeV}/c^2) = (1.07 \pm 0.11(\mathrm{stat}) \pm 0.03(\mathrm{syst}) \pm 0.11(\mathrm{BF})) \times 10^{-6}$$

$$\mathcal{B}(B^+ \to \overline{\Lambda}(1520)p) = (3.15 \pm 0.48(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \pm 0.26(\mathrm{BF})) \times 10^{-7}$$

$B^\pm \to p\bar{p}K^\pm$ — CP asymmetries across the Dalitz plot



black circles: $m^2_{pK} < 10\ \mathrm{GeV}^2/c^4$;
open triangles: $m^2_{pK} > 10\ \mathrm{GeV}^2/c^4$.



$$A_{\rm obs} = \frac{N(B^- \to p\bar{p}K^-) - N(B^+ \to p\bar{p}K^+)}{N(B^- \to p\bar{p}K^-) + N(B^+ \to p\bar{p}K^+)},$$

$N =$ acceptance corrected yields.

$$\mathcal{A}_{CP} = A_{\rm obs} - A^B_{\rm prod} - A^K_{\rm det}\ ,$$

$A^B_{\rm prod}$, $A^K_{\rm det}$ from $B^\pm \to J/\psi\, K^\pm$.

mode	$\mathcal{A}_{CP}$
$\eta_c K^+$	$+0.040 \pm 0.034$
$\psi(2S)K^+$	$+0.092 \pm 0.058$
$p\bar{p}K^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$	$+0.021 \pm 0.020$
$p\bar{p}K^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$, $m^2_{pK} < 10\ \mathrm{GeV}^2/c^4$	-0.036 ± 0.023
$p\bar{p}K^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$, $m^2_{pK} > 10\ \mathrm{GeV}^2/c^4$	$+0.096 \pm 0.024$
$p\bar{p}\pi^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$)	-0.041 ± 0.039

Summary

Charmless three-body decays of $B^{\pm}$ mesons are an excellent laboratory for direct *CP*V studies. Different sources of strong phase difference lead to a rich pattern of large, localized *CP* asymmetries. Amplitude analysis is the necessary next step.

Amplitude analysis of $B^{\pm} \to K^{\pm}h^{+}h^{-}$, $\pi^{\pm}h^{+}h^{-}$, $p\bar{p}h^{\pm}$ is quite challenging:

- How to model the large nonresonant component?
- How to include rescattering effects in the decay amplitude?
- How to include thee-body FSI?
- Can we safely assume the ratio tree/penguin to be constant across the Dalitz plot? Are coefficients of the isobar model independent of position?
- How to parametrize the enhancement at low $p\bar{p}$ mass?

Input from theory is extremely necessary!

A workshop on these subjects will happen in Rio de Janeiro, July 28-30, 2015

Backup

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Amplitude analysis of the K^-K^+ system produced in the reactions $\pi^-p \rightarrow K^-K^+n$ and $\pi^+n \rightarrow K^-K^+p$ at 6 GeV/c

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We have carried out an amplitude analysis of the K^-K^+ system produced in the reactions $\pi^-p \rightarrow K^-K^+n$ and $\pi^+n \rightarrow K^-K^+p$ using data from a high-statistics experiment performed with the Argonne effective-mass spectrometer. Combining the results from the two reactions allows us to analyze the $\bar{K}K$ production amplitudes in terms of their isospin-zero and -one components. We use phenomenological arguments based on t dependence and on the expected properties of the P and D waves to resolve ambiguities. Our favored solution exhibits an enhancement around 1300 MeV in the isospin-zero S wave produced by π exchange. In this solution the Argand plot for the $\pi\pi \rightarrow \bar{K}K$ S wave changes rapidly above 1300 MeV, consistent with a resonance at 1425 ± 15 MeV with width 160 ± 30 MeV. We show that our solution is consistent with the features of neutral and charged $\bar{K}K$ systems found in other experiments.

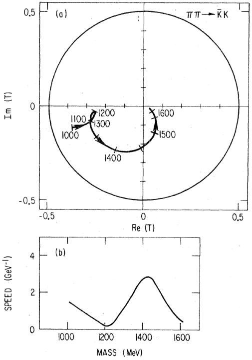
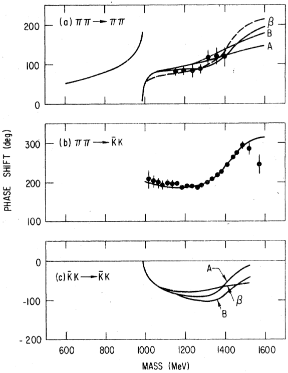


FIG. 28. (a) Argand-plot representation of $T(\pi\pi \rightarrow \bar{K}K)$, and (b) speed $|dT(\pi\pi \rightarrow \bar{K}K)/dM|$.



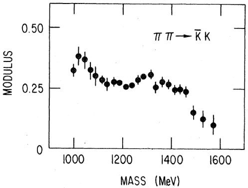


FIG. 27. Modulus of the $\pi\pi \rightarrow \bar{K}K$ scattering amplitude $|T(\pi\pi \quad \bar{K}K)|$ from solution I(b).