Direct CP violation in charmless $B^{\pm}$ three-body decays: where Flavour Physics meets Hadron Physics

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CP violation in the *B* system - generalities

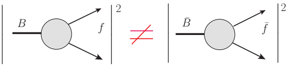
The Standard Model (SM), one of the pilars of the contemporary Physics, is challenged by three observations:

- neutrino oscillations;
- the existence of dark matter;
- the baryon asymmetry in the Universe (BAU).

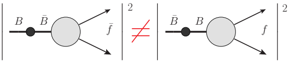
All measurements of *CP* violation (*CP*V) in heavy meson decays are consistent with the SM predictions. However, the amount of *CP*V in the SM is orders of magnitude smaller than that required to explain BAU: there must be other sources of *CP*V.

The study of *CP*V is a portal to new Physics.

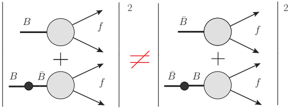
Three possible manifestations of *CP*V in decays of flavoured mesons:



*CP*V in the decay, possible for both B^+ and B^0



*CP*V in the mixing, only for B^0



*CP*V in the interference between mixing and decay

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 leading to the same final state:

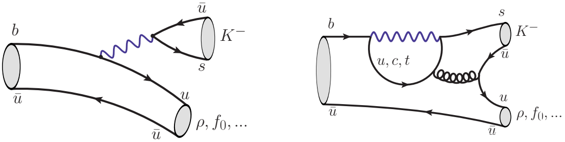
$$A = a_1 + a_2\, e^{(\delta+\gamma)}, \quad \overline{A} = a_1 + a_2\, e^{(\delta-\gamma)}$$

$$\mathcal{A}_{CP}^{\mathrm{dir}} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = \frac{2a_1 a_2 \sin\gamma \sin\delta}{a_1^2 + a_2^2 + 2a_1 a_2 \cos\gamma \cos\delta}.$$

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

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

$B^- \to K^- \rho^0 (f_0)$



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.

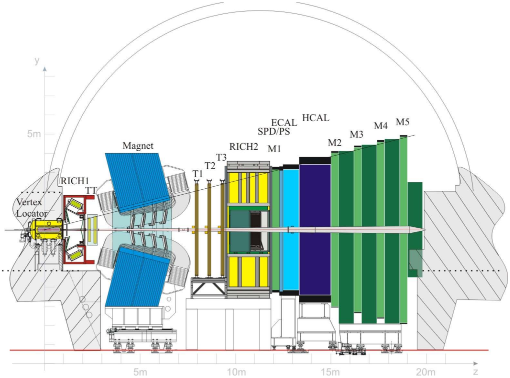
What makes three-body decays particularly interesting:

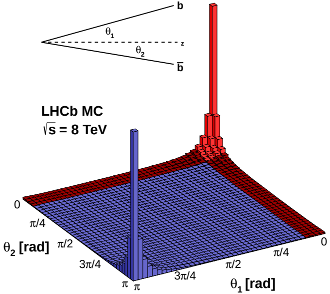
all final states have a rich resonant structure. The interference between resonances plus FSI at hadron level provide additional sources of strong phase difference. Large effects in regions of the Dalitz plot may arise.

In this presentation:

- $B^{\pm} \to K^{\pm}h^{+}h^{-},\ B^{\pm} \to \pi^{\pm}h^{+}h^{-} \quad h = \pi,\ K$
  Phys.Rev. **D**90, 112004 (2014), arXiv::1408.5373
- $B^{\pm} \to p\bar{p}h^{\pm}, \quad h = \pi,\ K$
  Phys.Rev.Lett. **113**, 141801 (2014), arXiv:1407.5907

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





$\sim$30% of $b\bar{b}$ pairs are produced within the LHCb acceptance.

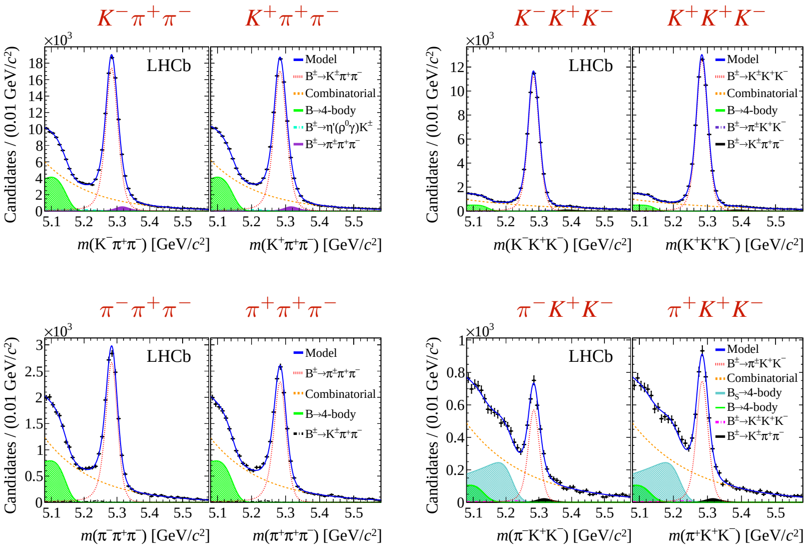
- decay time resolution of $\sim$45 fs;
- 95% tracking efficiency;
- $\delta p/p$: 0.4 - 0.6% (5-100 GeV/c);

Run I:

- 1 fb^{-1} at $\sqrt{s} = 7$ TeV
- 2 fb^{-1} at $\sqrt{s} = 8$ TeV

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

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



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:

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

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

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

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

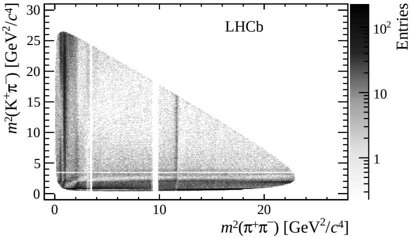
Global asymmetries $\Longrightarrow$ typically small, not the most sensitive observable:

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

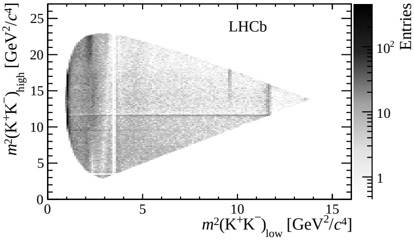
Errors are statistical, systematic and the uncertainty on $\mathcal{A}_{CP}(B^{\pm} \to J/\psi K^{\pm})$.

The Dalitz plots

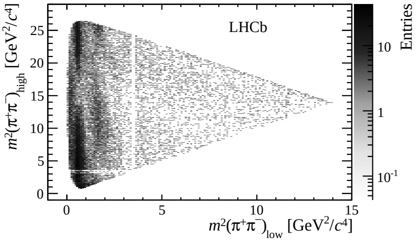
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$



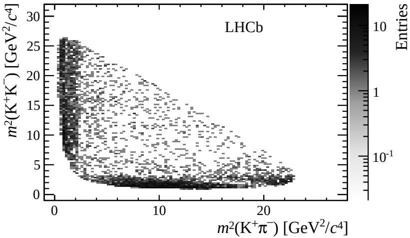
$B^{\pm} \to K^{\pm}K^{+}K^{-}$



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



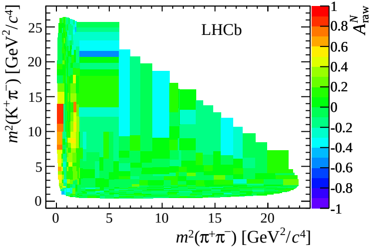
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

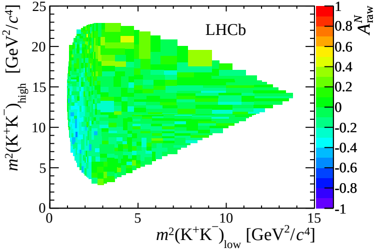


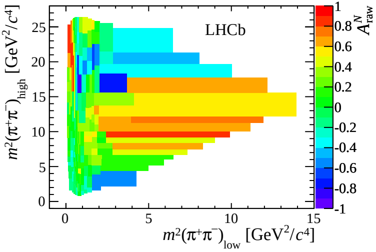
A dense, rich resonance structure, plus a large nonresonant component.
(plots are not corrected for acceptance and include background)

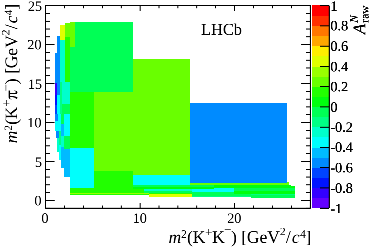
Distribution of charge asymmetries in the Dalitz plot

- 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.



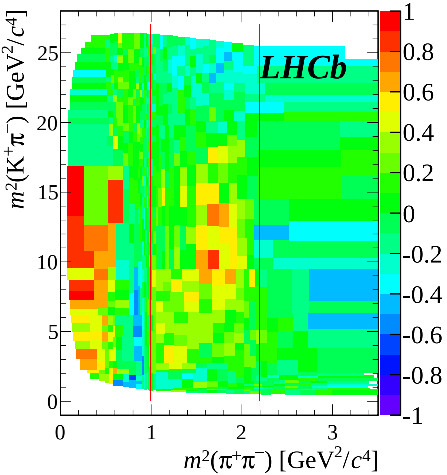




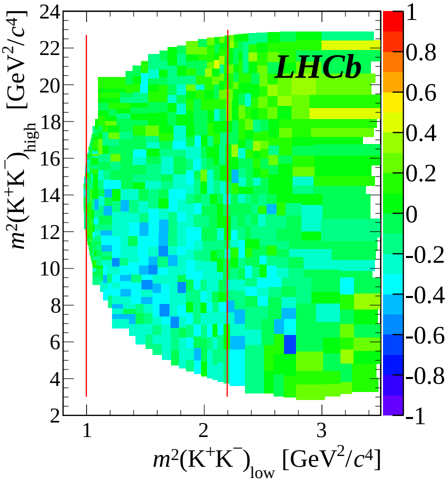


$B^\pm \to K^\pm h^+ h^-$ charge asymmetries: a zoom at low $\pi^+\pi^-/K^+K^-$ mass

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



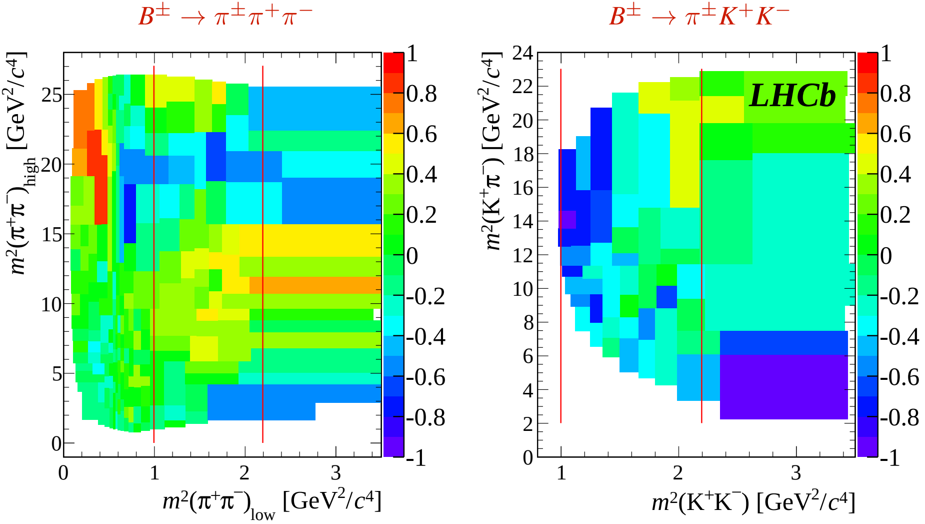
$B^\pm \to K^\pm K^+ K^-$



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

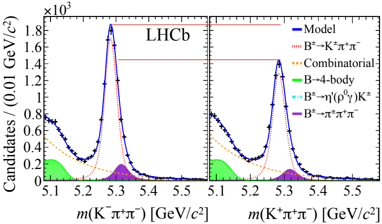
Strong phase difference would come from $\pi\pi \leftrightarrows KK$ rescattering.

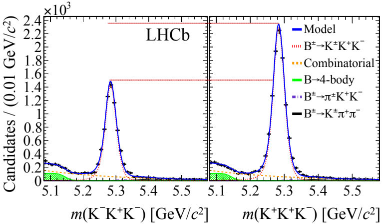
$B^\pm \to \pi^\pm h^+ h^-$ charge asymmetries: a zoom at low $\pi^+\pi^-/K^+K^-$ mass

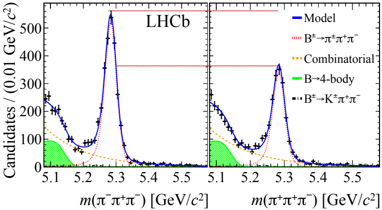


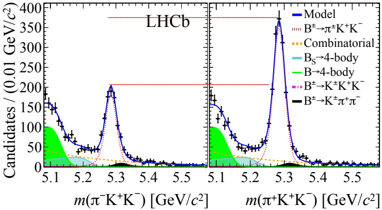
Similar effect in $B^\pm \to \pi^\pm h^+ h^-$ (more evident in $B^\pm \to \pi^\pm K^+ K^-$).

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

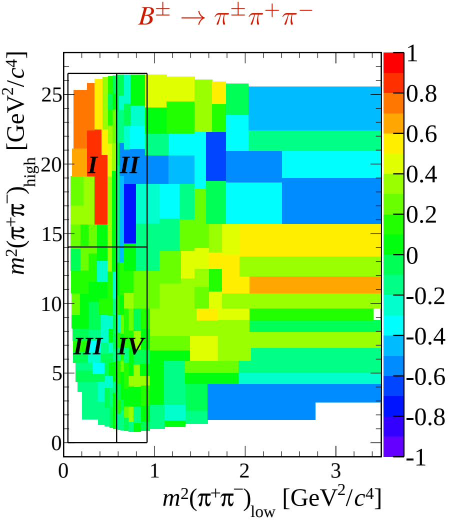




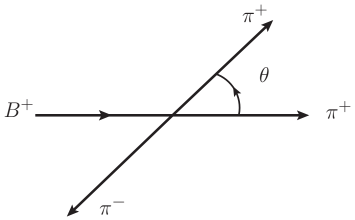


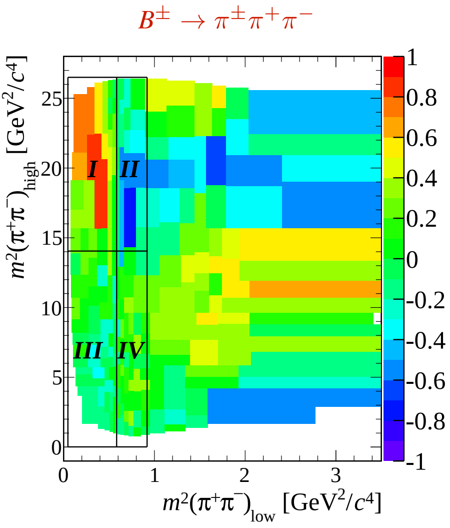


Decay	N_s	A_{CP}
$B^\pm \to K^\pm\pi^+\pi^-$	15562 ± 165	$+0.121 \pm 0.022$
$B^\pm \to K^\pm K^+K^-$	16992 ± 142	-0.211 ± 0.014
$B^\pm \to \pi^\pm\pi^+\pi^-$	4329 ± 76	$+0.172 \pm 0.027$
$B^\pm \to \pi^\pm K^+K^-$	2500 ± 57	-0.328 ± 0.041



- resonance peaks appear when events are projected into $m^2(\pi^+\pi^-)_{\text{low}}$ axis;
- angular distributions, when resonances have spin, appear in $m^2(\pi^+\pi^-)_{\text{high}}$
- sectors I and II correspond to $\cos\theta < 0$, while sectors III and IV to $\cos\theta > 0$;
- the line dividing sectors I and III from II and IV are at $m^2(\pi^+\pi^-)_{\text{low}} = m^2_{\rho^0}$





A simple isobar model:

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

$$A_\rho = \frac{F_D F_\rho}{s_{\rm low} - m_\rho^2 + i m_\rho \Gamma} |\mathbf{p}||\mathbf{q}| \cos\theta$$

$$= f_\rho (s_{\rm low} - m_\rho^2 - i m_\rho \Gamma) \cos\theta$$

$A_{\rm NR}$ = a complex constant

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

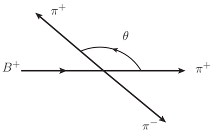
$$\mathcal{A}_{CP}(s_{\rm low}, s_{\rm high}) \propto |\mathcal{M}_-|^2 - |\mathcal{M}_+|^2,$$

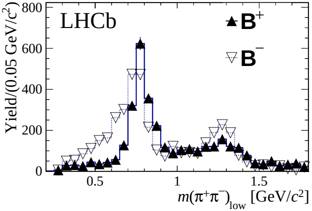
$$\mathcal{A}_{CP} \propto (c_-^{\rho\,2} - c_+^{\rho\,2})|A_\rho|^2 + (c_-^{\rm NR\,2} - c_+^{\rm NR\,2}) + \cos\theta\,(s_{\rm low} - m_\rho^2)\, 2{\rm Re}(c_-^\rho c_-^{\rm NR} - c_+^\rho c_+^{\rm NR}) f_\rho + \ldots$$

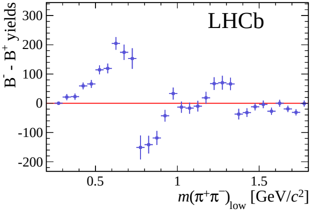
$B^\pm \to \pi^\pm\pi^+\pi^-$ — charge asymmetries from S- and P-wave interference

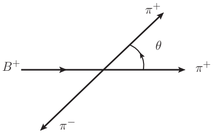
The distribution of the difference between B^+ and B^- yields is compatible with an S- and P-wave interference term, linear in $\cos\theta$.

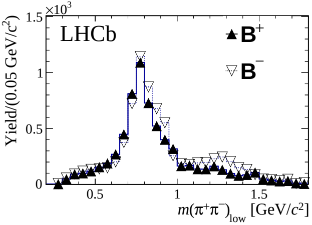
$$\mathcal{A}_{CP} \propto (c_-^{\rho\,2} - c_+^{\rho\,2})|A_\rho|^2 + (c_-^{\mathrm{NR}\,2} - c_+^{\mathrm{NR}\,2}) + \cos\theta\,(s_{\mathrm{low}} - m_\rho^2)\, 2\mathrm{Re}(c_-^\rho c_-^{\mathrm{NR}} - c_+^\rho c_+^{\mathrm{NR}}) f_\rho + \ldots$$

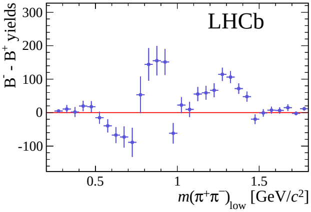


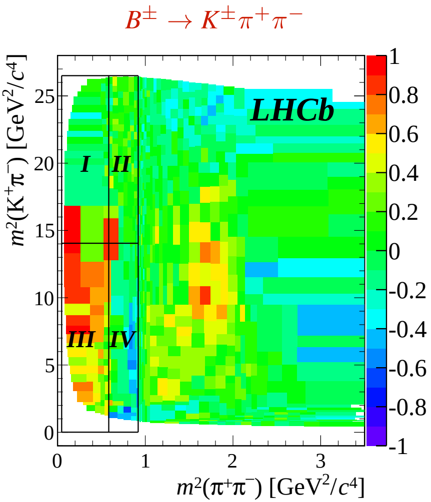












A simple isobar model:

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

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

$$= f_\rho \, (s_{\pi\pi} - m_\rho^2 - i m_\rho \Gamma_\rho) \, \cos\theta$$

$$A_{f_0} = \frac{1}{s_{\pi\pi} - m_{f_0}^2 + i m_{f_0} \Gamma_{f_0}}$$

$$= f_{f_0} (s_{\pi\pi} - m_{f_0}^2 - i m_{f_0} \Gamma_{f_0})$$

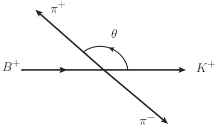
$$\mathcal{M}_{\pm}(s_{\pi\pi}, s_{K\pi}) = c_{\pm}^{\rho} A_\rho + c_{\pm}^{f_0} A_{f_0}$$

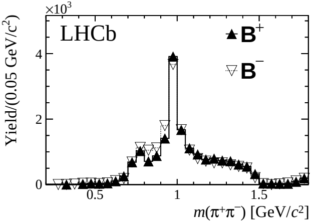
$$\mathcal{A}_{CP} \propto (c_-^{\rho 2} - c_+^{\rho 2})|A_\rho|^2 + (c_-^{f_0 2} - c_+^{f_0 2})|A_{f_0}|^2 + \cos\theta \, (s - m_\rho^2)(s - m_{f_0}^2) \times$$
$$f_\rho f_{f_0} 2\, \mathrm{Re}(c_-^{\rho} c_-^{f_0} - c_+^{\rho} c_+^{f_0}) + \ldots$$

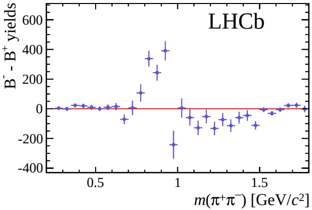
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ — charge asymmetries from S- and P-wave interference

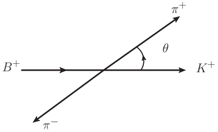
For low $K\pi$ mass ($\cos\theta > 0$), the distribution of the difference between B^{+} and B^{-} yields follows what is expected from S- and P-wave interference.

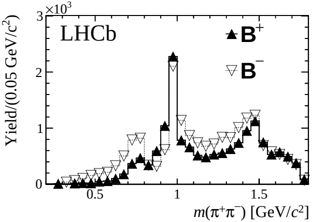
Different patterns for $\cos\theta > 0$ and $\cos\theta < 0$.
Amplitude analysis needed.

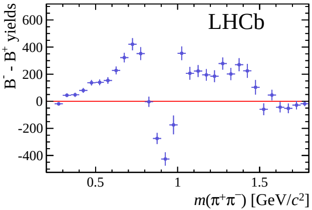






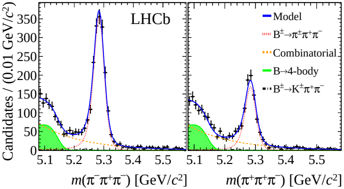




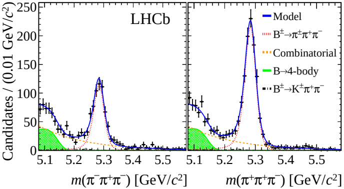


Charge asymmetries from S- and P-wave interference

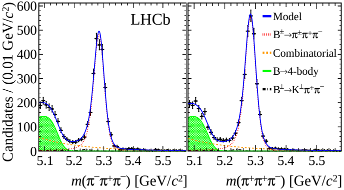
$B^\pm \to \pi^\pm\pi^+\pi^-$ – sector I



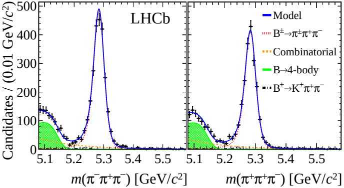
$B^\pm \to \pi^\pm\pi^+\pi^-$ – sector II



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



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



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

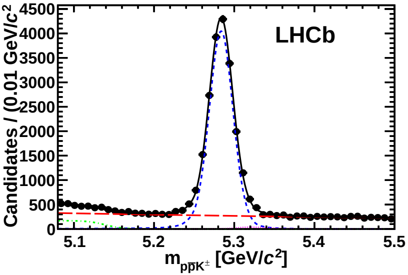
sector	N_s	A_{CP}
I	2629 ± 59	$+0.302 \pm 0.030$
II	1653 ± 46	-0.244 ± 0.039
III	5204 ± 79	-0.076 ± 0.021
IV	4476 ± 72	$+0.055 \pm 0.025$

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

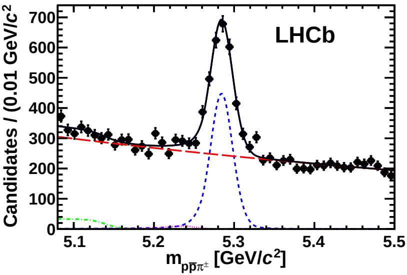
sector	N_s	A_{CP}
I	2909 ± 80	-0.052 ± 0.057
II	6136 ± 99	$+0.140 \pm 0.038$
III	2856 ± 86	$+0.598 \pm 0.087$
IV	2107 ± 55	-0.208 ± 0.060

$B^{\pm} \to p\bar{p}h^{\pm}$ — signals and yields from Run I

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



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



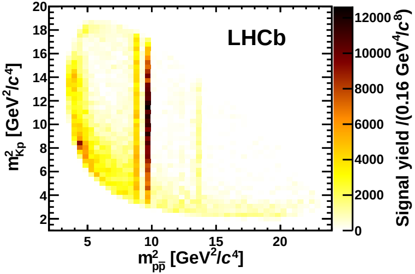
Signals include charmonium decaying to $p\bar{p}$.

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

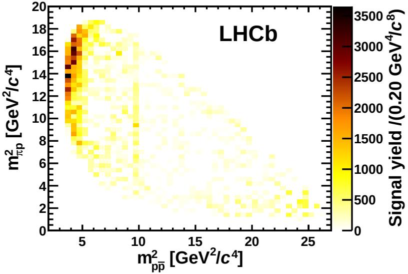
mode	yield
$J/\psi[p\bar{p}]\ K^{+}$	4260 ± 67
$\eta_c[p\bar{p}]\ K^{+}$	2182 ± 64
$\psi(2S)[p\bar{p}]\ K^{+}$	368 ± 20
$\overline{\Lambda}(1520)p$	128 ± 20
$p\bar{p}K^{+}$ $(m_{p\bar{p}} < 2.85$ GeV$/c^2)$	8510 ± 104
total	18721 ± 142
$J/\psi[p\bar{p}]\ \pi^{+}$	122 ± 12
$p\bar{p}\pi^{+}$ $(m_{p\bar{p}}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

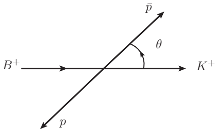
$B^{\pm} \to p\bar{p}h^{\pm}$ — Dalitz plots

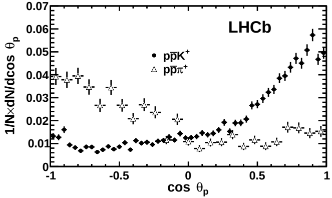
$B^{\pm} \to p\bar{p}K^{\pm}$



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





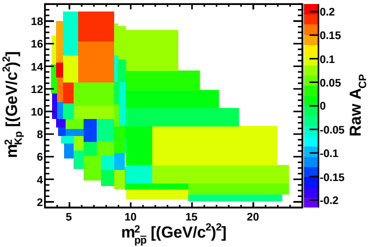


Enhancement near $p\bar{p}$ threshold at low $pK^{\pm}$ and high $p\pi^{\pm}$ mass.

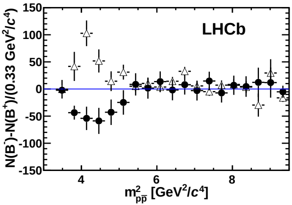
Forward-backward asymmetry has opposite sign in each final state.

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

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



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



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

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

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

mode	$\mathcal{A}_{CP}$
$\eta_c[p\bar{p}]K^+$	$+0.040 \pm 0.034$
$\psi(2S)[p\bar{p}]K^+$	$+0.092 \pm 0.058$
$p\bar{p}K^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$	$+0.021 \pm 0.020$
$p\bar{p}K^+$, $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$, $m^2_{pK} < 10\ \mathrm{GeV}^2/c^4$	-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

Theoretical issues on the modelling of decay amplitudes

The full amplitude analysis is the next step, necessary to understand the mechanisms generating such a large, localized *CP* asymmetries.

However, there are many questions to be answered:

- How to model the large nonresonant components?
- How to include rescattering effects connecting two different final states?
- How to include thee-body FSI?
- Can we safely assume the ratio tree/penguin to be constant across the Dalitz plot? Are the 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!

Summary

Decays of $B^{\pm}$ mesons into light hadrons are an excellent laboratory for direct *CP*V studies.

Three-body decays have a higher sensitivity to *CP*V than two-body decays:

a rich pattern of large (up to 80%), localized *CP* asymmetries is observed; this pattern may be due to the different sources of strong phase difference, namely the interference between resonances, FSI at the hadron level.

The full Dalitz plot analysis is the next step.

More to come from LHC Run II: 5 fb^{-1} expected.

Backup

$\pi\pi \to KK$

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

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(Received 28 August 1978; revised manuscript received 14 July 1980)

We have carried out an amplitude analysis of the K^-K^+ system produced in the reactions $\pi^-p \to K^-K^+n$ and $\pi^+n \to K^-K^+p$ 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 $\pi\pi \to \bar{K}K$ 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.

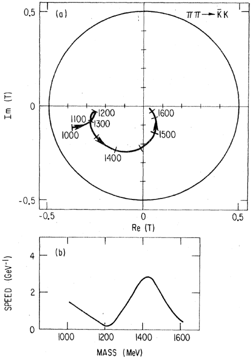
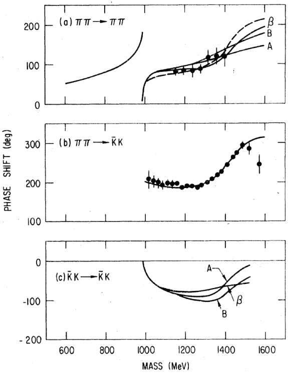


FIG. 28. (a) Argand-plot representation of $T(\pi\pi \to \bar{K}K)$, and (b) speed $|dT(\pi\pi \to \bar{K}K)/dM|$.



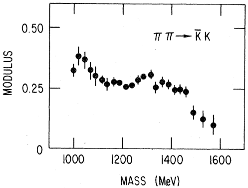
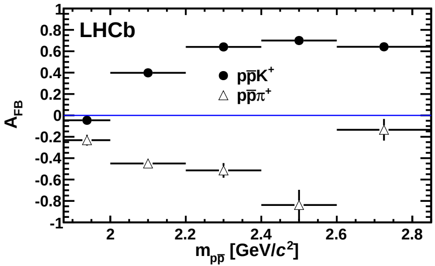


FIG. 27. Modulus of the $\pi\pi \to \bar{K}K$ scattering amplitude $|T(\pi\pi \quad \bar{K}K)|$ from solution I(b).



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:

$$\mathcal{B}(B^+ \to p\bar{p}\pi^+,\, m_{p\bar{p}} < 2.85 \mathrm{GeV}/c^2) = (1.07 \pm 0.11(\mathrm{stat}) \pm 0.03(\mathrm{syst}) \pm 0.11(\mathrm{BF})) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \overline{\Lambda}(1520)p) = (3.15 \pm 0.48(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \pm 0.26(\mathrm{BF})) \times 10^{-7}$$