Charge-Parity asymmetry in $B^{\pm}$ mesons decays to three-body charmless final states at LHCb experiment.

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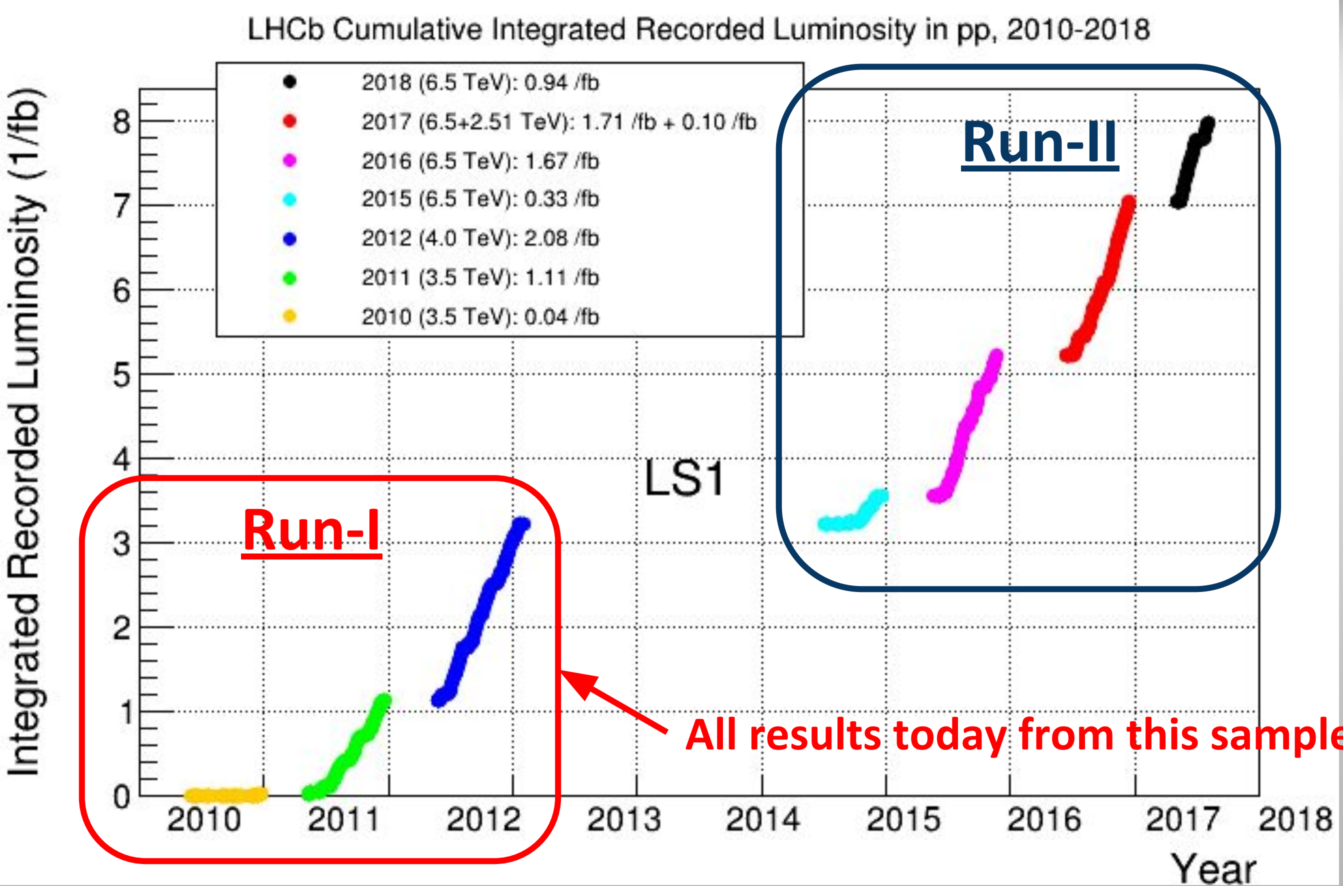
Data samples



All results today from this sample.

Motivation

- Charge-Parity asymmetry (A_{CP}), or CP violation, is one of the necessary ingredients for the observed difference between matter and antimatter in the universe.
  - 1^{st} observed 1964 in Kaons systems
  - Later was also observed in mesons B in 2001 by BaBar and BELLE experiments.

- In the Standard Model of particle physics, A_{CP} appears by the nature of the complex mixing matrix among quarks.

- The hadronic B decays sector is an attractive place for the study of A_{CP}.

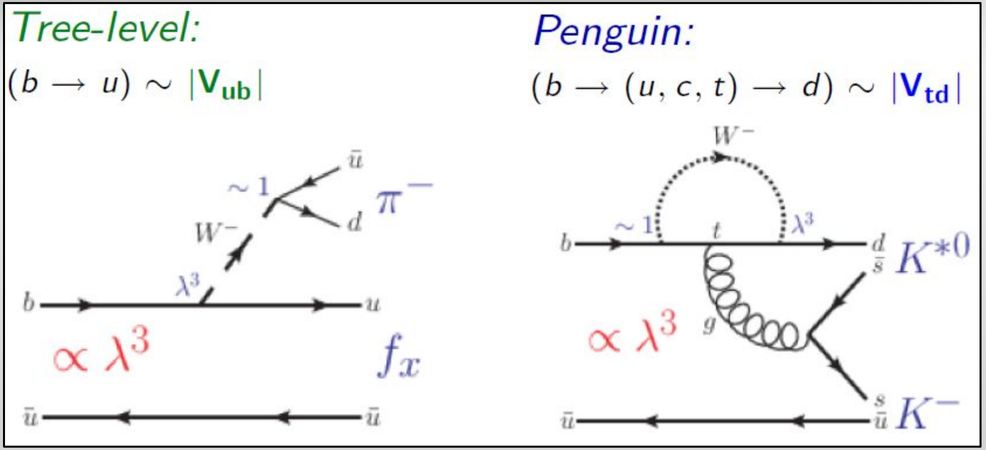
- Charged three-body B decays, with pions and kaons in their final states, are particularly interesting:

$$B^+ \rightarrow \pi^+ \pi^- \pi^+ \quad , \quad B^+ \rightarrow K^+ K^- \pi^+ \quad , \quad B^+ \rightarrow \pi^+ K^- \pi^+ \quad , \quad B^+ \rightarrow K^+ K^- K^+$$

A_{CP} in charged charmless $B^+ \rightarrow h^+ h^- h^+$ decays

At quark level 2 interfering amplitudes.
Tree & Penguin, with different phases.

The interference of these resonant states with different weak and strong phases can produce large CP effects.



Feynman diagrams for B+ $\rightarrow \pi$+ K- K+

The **resonance signatures** can be **inspected** in the so-called **Dalitz plot**.
Due to difference of the magnitude of the amplitude A of a particle decaying into a certain final state and that of its antiparticle.

$|A|^2 \neq |\bar{A}|^2 \Rightarrow$ Differences in the number of events observed for B+ and B -

(The observable to which we can access.)

Dalitz plot - Phase space for 3-body spinless decays

Dalitz plot is the representation of the phase space of a decay.

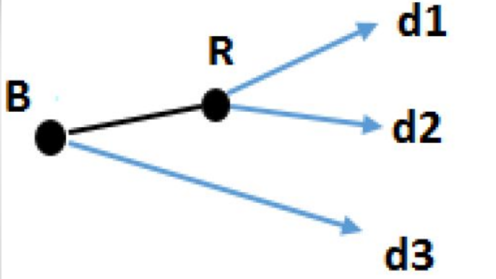
It can be defined in terms of two out of three following invariants:

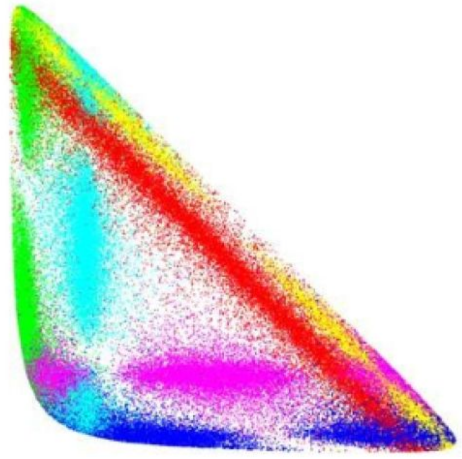
$$m_{12}^2 = (p_1 + p_2)^2$$
$$m_{13}^2 = (p_1 + p_3)^2$$
$$m_{23}^2 = (p_2 + p_3)^2$$

The event distribution in Dalitz plot is proportional to the square of the decay amplitude.

$$d\Gamma = \frac{|A|^2 \, dm_{ij}^2 \, dm_{jk}^2}{(2\pi)^3 \, 32 \, M^3}$$

Being so, any **non-uniform distribution** of points in the **Dalitz plot** directly **reflects the dynamics** in the decay.



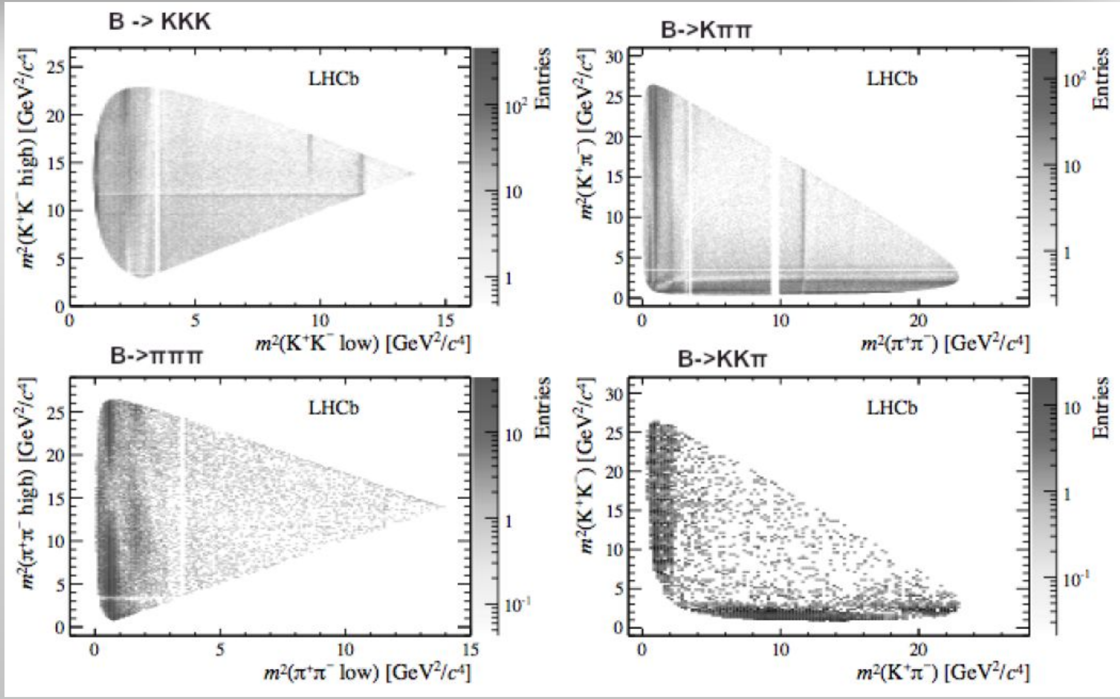


Measurements of A_{CP} in the three-body phase space

Objectives:

- Inclusive A_{CP} measurement in phase space of the $B \rightarrow hhh$ decays.

- A_{CP} measurements by regions of the phase space.



A_{CP} measurements strategy:

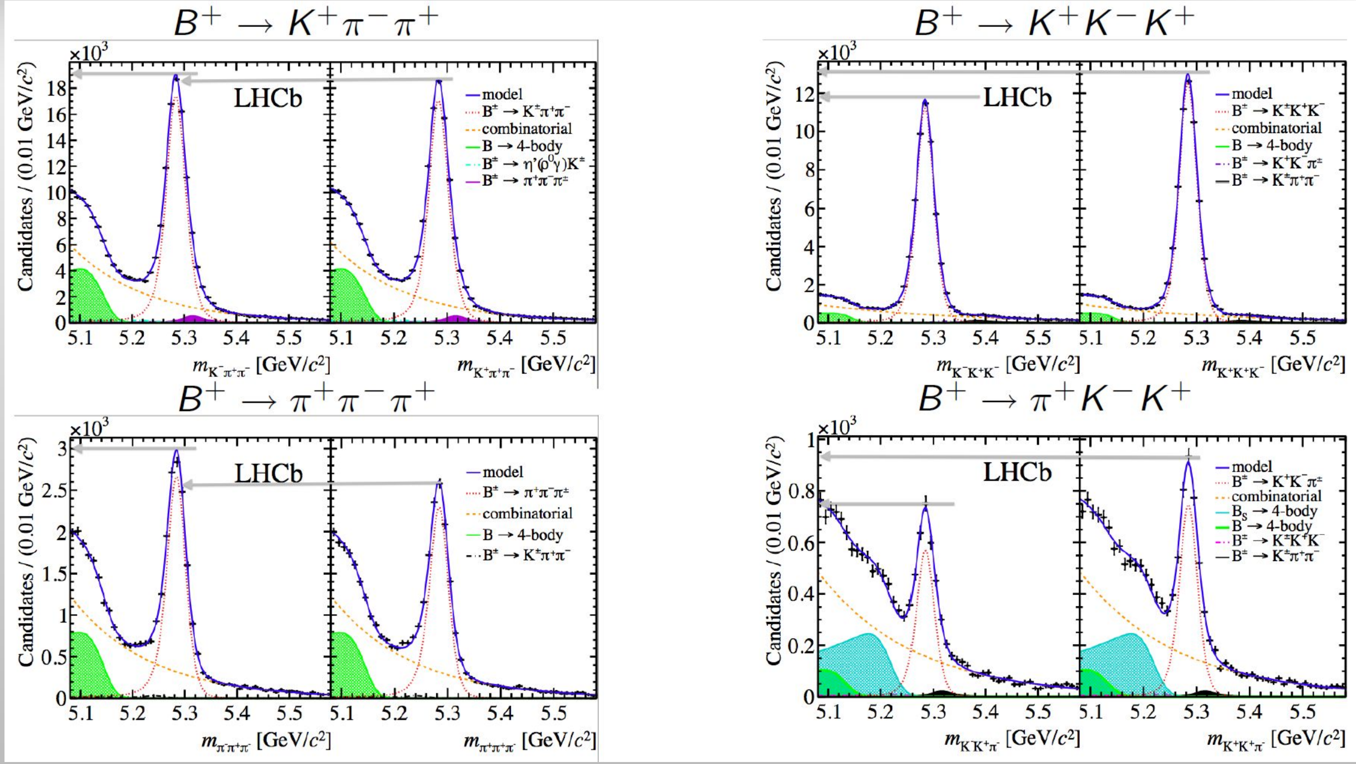
- Perform the mass fit and obtention of the raw asymmetry (A_{raw}).
- A_{raw} correction due to acceptance, detection and production effects.
- Obtention of the A_{CP} integrated in the phase space and the A_{CP} in regions of the phase space.

Integrated A_{CP} in the three-body phase space

Raw asymmetry (A_{raw}) measurement from the mass fit:

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

where N_{B-} and N_{B+} are the number of B- and B+ events, respectively, in the final state.



Integrated A_{CP} in the three-body phase space

- Then we need to perform corrections to the A_{raw} due to:
  - The detector acceptance:
    - The detector geometry.
    - The sub-detector efficiencies.
    - Effects introduced from all selection stages: Production of acceptance maps.
  - Production asymmetry
  - Detection asymmetry

- A_{CP} measurements for the $B^+ \to h^+ h^- h^+$ channels:

$$A_{CP}(B^\pm \to K^\pm \pi^- \pi^+) = +0.025 \pm 0.004(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.007(J/\Psi\ K)\ ,\ \text{significance: } 2.8\sigma$$

$$A_{CP}(B^\pm \to K^\pm K^- K^+) = -0.036 \pm 0.004(\text{stat.}) \pm 0.002(\text{syst.}) \pm 0.007(J/\Psi\ K)\ ,\ \text{significance: } 4.3\sigma$$

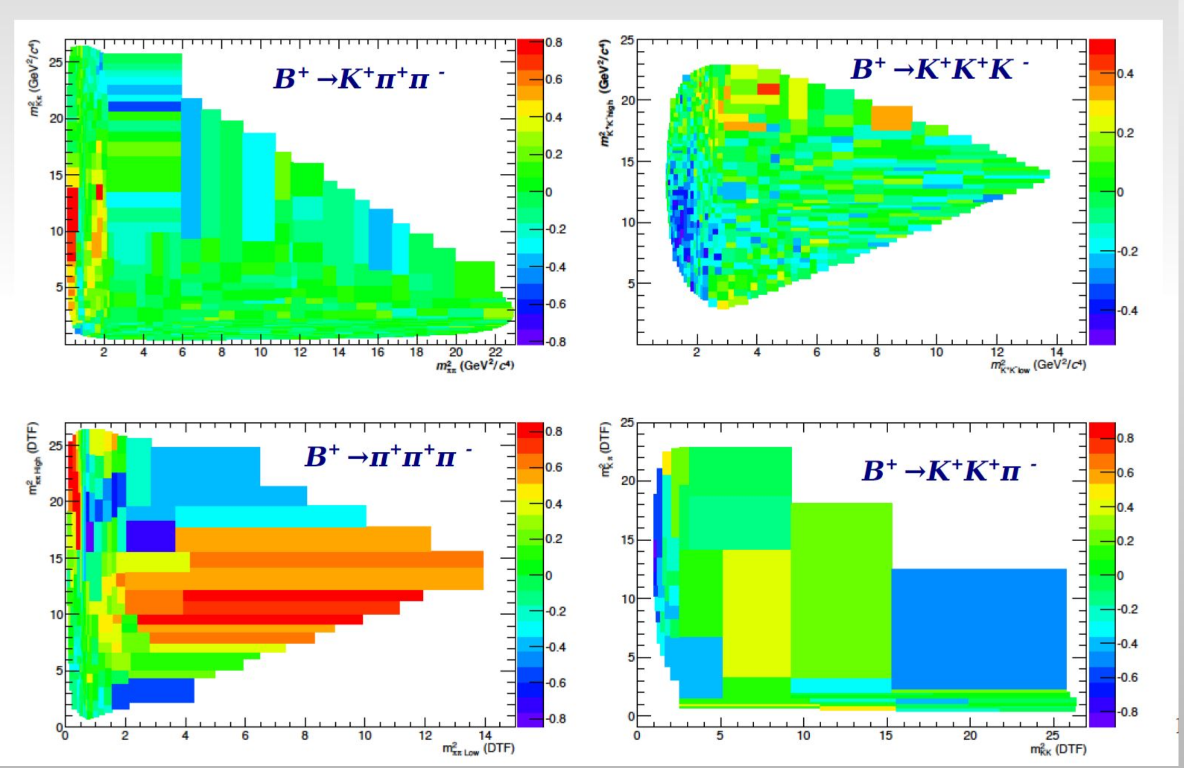
$$A_{CP}(B^\pm \to \pi^\pm \pi^- \pi^+) = +0.058 \pm 0.008(\text{stat.}) \pm 0.009(\text{syst.}) \pm 0.007(J/\Psi\ K)\ ,\ \text{significance: } 4.2\sigma$$

$$A_{CP}(B^\pm \to \pi^\pm K^- K^+) = +0.123 \pm 0.017(\text{stat.}) \pm 0.012(\text{syst.}) \pm 0.007(J/\Psi\ K)\ ,\ \text{significance: } 5.6\sigma$$

A_{CP} in the phase space

Asymmetry distribution in bins of Dalitz plots (A_{raw}^{N}) - Mirandizing method (Phys.Rev.D 86,036005 (2012)).

- $N^{\pm}$ is the number of events per bin.
- A_{raw}^{N} is calculated with background subtracted and acceptance corrected.



Asymmetries in regions of the phase space are evident.

Some regions have a excess of B^+ events (**cold colors**) and other regions a excess of B- events (**hot colors**).

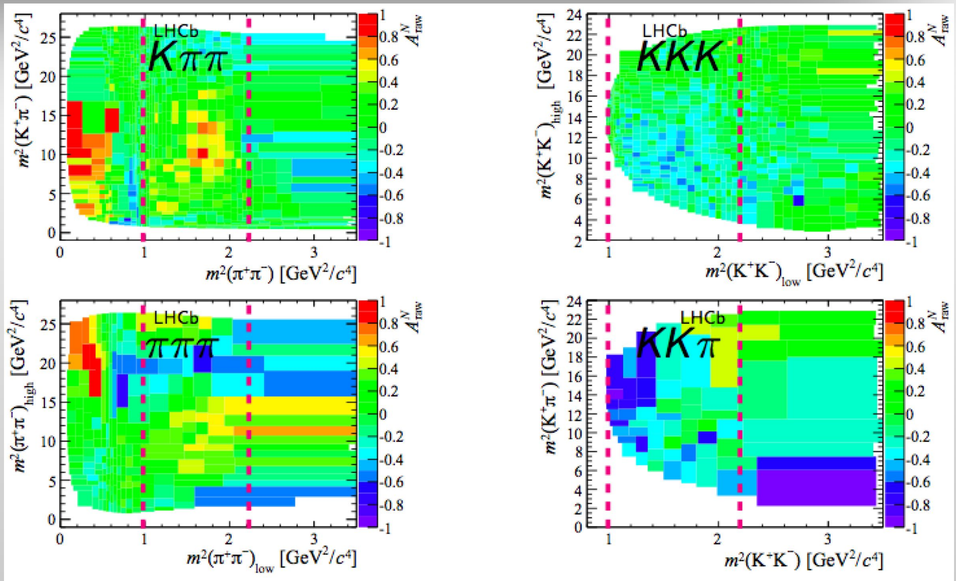
A_{CP} in the phase space (zoom at the low mass region)

Notice: Asymmetry in this low mass region has opposite sign for:

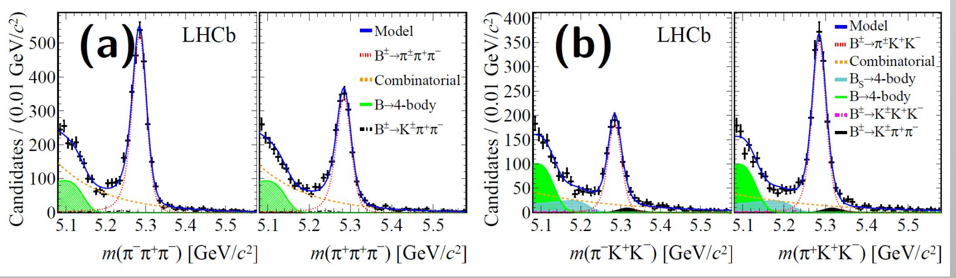
$B^{\pm} \to K^{\pm} \pi^{-} \pi^{+}$ and $B^{\pm} \to K^{\pm} K^{-} K^{+}$

and for

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



This region precisely correspond to the expected rescattering region $\pi\pi$ <--> KK (1-1.5 GeV/c^2).



Large asymmetries found in this particular region for the four channels:

$A_{CP}(B^{\pm}\to\pi^{\pm}\pi^{-}\pi^{+})$ = **+0.172** ±0.021 ±0.015 ±0.007

$A_{CP}(B^{\pm}\to\pi^{\pm}K^{-}K^{+})$ = **-0.328** ±0.028 ±0.029 ±0.007

Amplitude analysis

In order to understand the origin of these asymmetries and the rich structures present in the Dalitz plot it is necessary to perform an Amplitude Analysis.

We are interested in determining their decay amplitudes, their relative contributions and how they are interfering, to understand the possible CP violation sources.

Model dependent analysis - not obvious approach.
⇒ Workshop organized at CBPF for discussion between experimentalist and theoretician:
LHCb workshop on multi-body decays of B and D mesons (Jul 27, 2015)

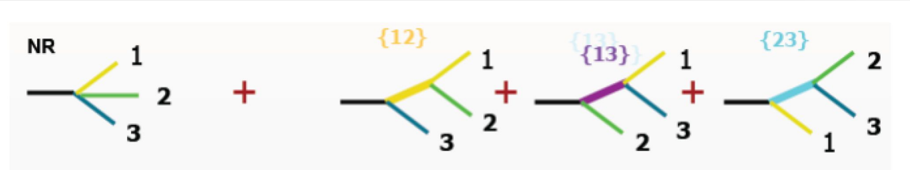
Two analysis currently in review by the LHCb collaboration:

- $B^{\pm} \longrightarrow \pi^{\pm} K^{-} K^{+}$ amplitude analysis using Run-I data.
- $B^{\pm} \longrightarrow \pi^{\pm} \pi^{-} \pi^{+}$ amplitude analysis using Run-I data.

$B^{\pm} \longrightarrow \pi^{\pm} K^{-} K^{+}$ amplitude analysis

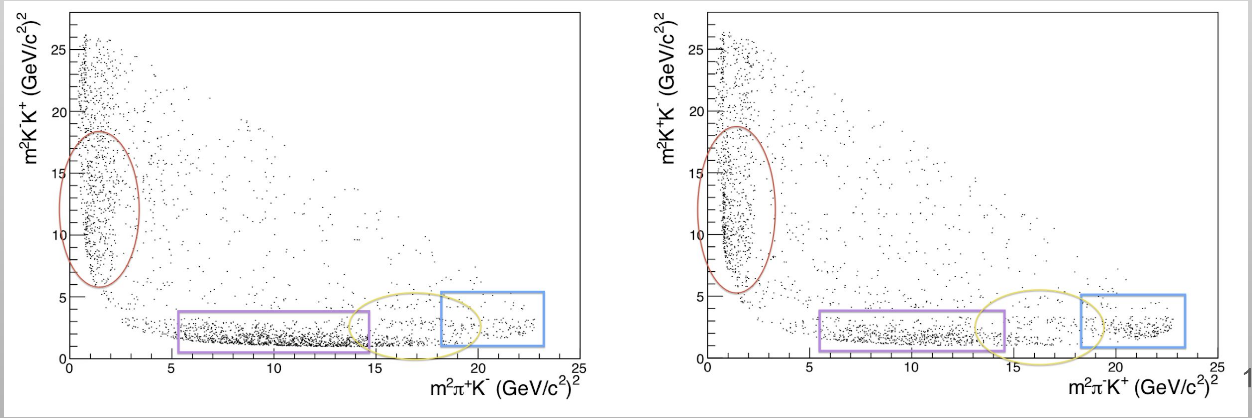
The Isobar Model: The total decay amplitude is expressed as a coherent sum of the partial contributing amplitudes:

$$A(s_{12}, s_{23}, \vec{\alpha}) = \sum_{i=1}^{N} c_i M_{R_i}(s_{12}, s_{23}, \vec{\alpha})$$



-c_i is the complex coefficient for a given resonance decay mode.
-Since the density of points is proportional to $|A|^2$, it will be possible to extract the amplitude and phases of each resonant states, their contributions and their asymmetry.

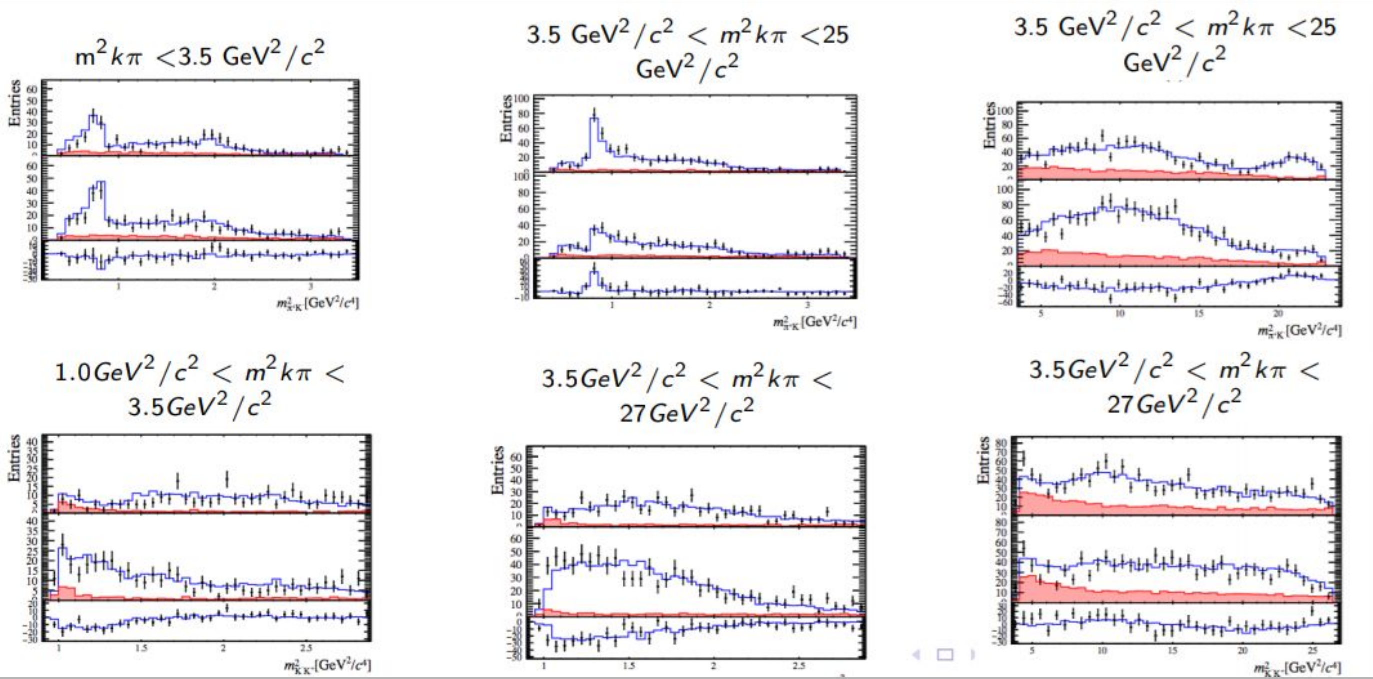
Fit event by event in the Dalitz plot, for B+ and B- separately.

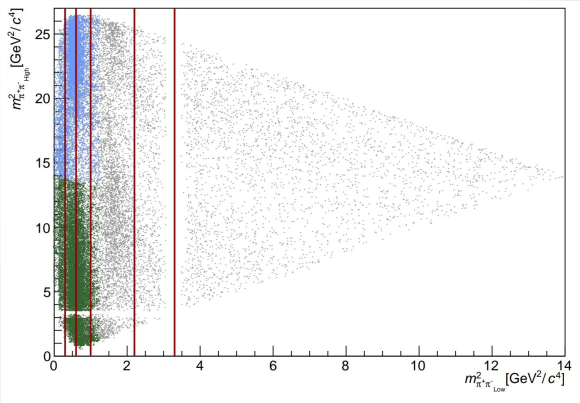


$B^{\pm} \to \pi^{\pm} K^{-} K^{+}$ amplitude analysis

- Amplitude analysis performed for the 1st time for this decay.

[NLL -9570] Component	Fit fraction (%) B^+	B^-	A_{CP} (%)
$K^{*0}(892)$	5.7 ± 0.8	9.7 ± 1.0	11.2 ± 8.5
$K_0^{*0}(1430)$	3.5 ± 0.8	5.8 ± 1.2	10.0 ± 14.8
TobiasNR_Kpi	31.5 ± 2.0	35.0 ± 2.6	-10.1 ± 5.2
$\rho^0(1450)$	29.7 ± 1.5	32.5 ± 1.8	-10.9 ± 4.3
$f_2(1270)$	4.7 ± 0.9	11.4 ± 1.3	27.7 ± 10.0
Rescattering	23.4 ± 1.1	6.3 ± 0.8	-66.8 ± 3.8
$\phi(1020)$	0.2 ± 0.2	0.4 ± 0.2	14.3 ± 42.9
Fit Fraction Sum	99.3	95.8	





$B^{\pm} \longrightarrow \pi^{\pm}\,\pi^{-}\,\pi^{+}$ amplitude analysis

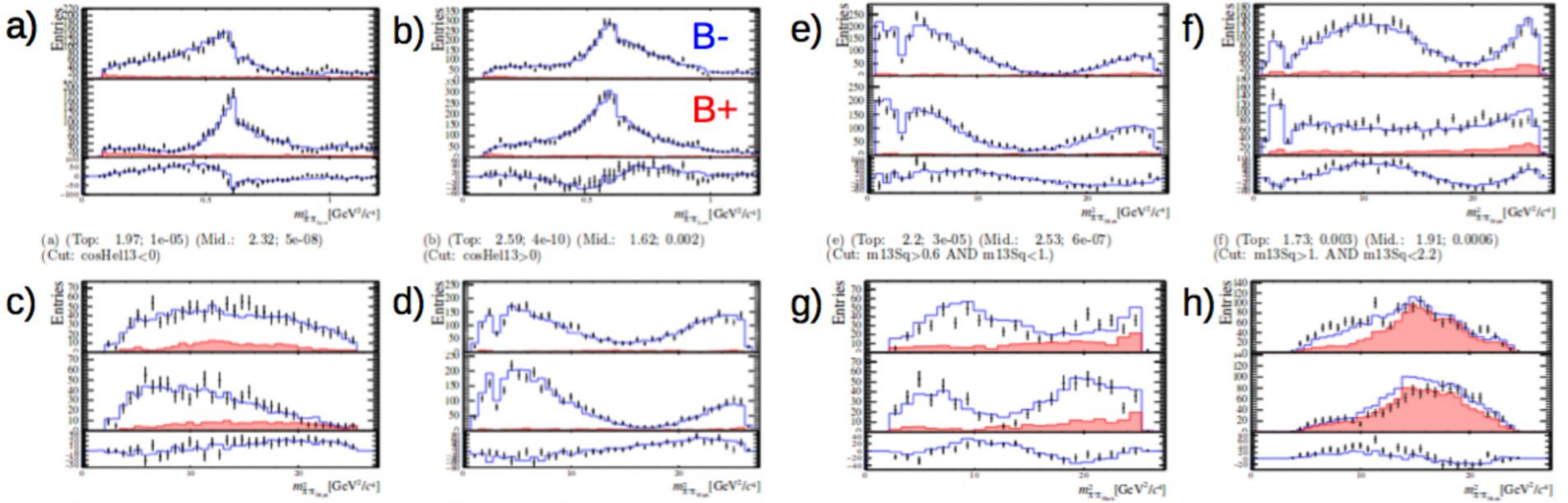
Amplitude analysis performed with three different approaches regarding the S-wave:

⇒ Isobar Model formalism ⇒ K-Matrix formalism

⇒ QIM (Quasi-Independent-Model)

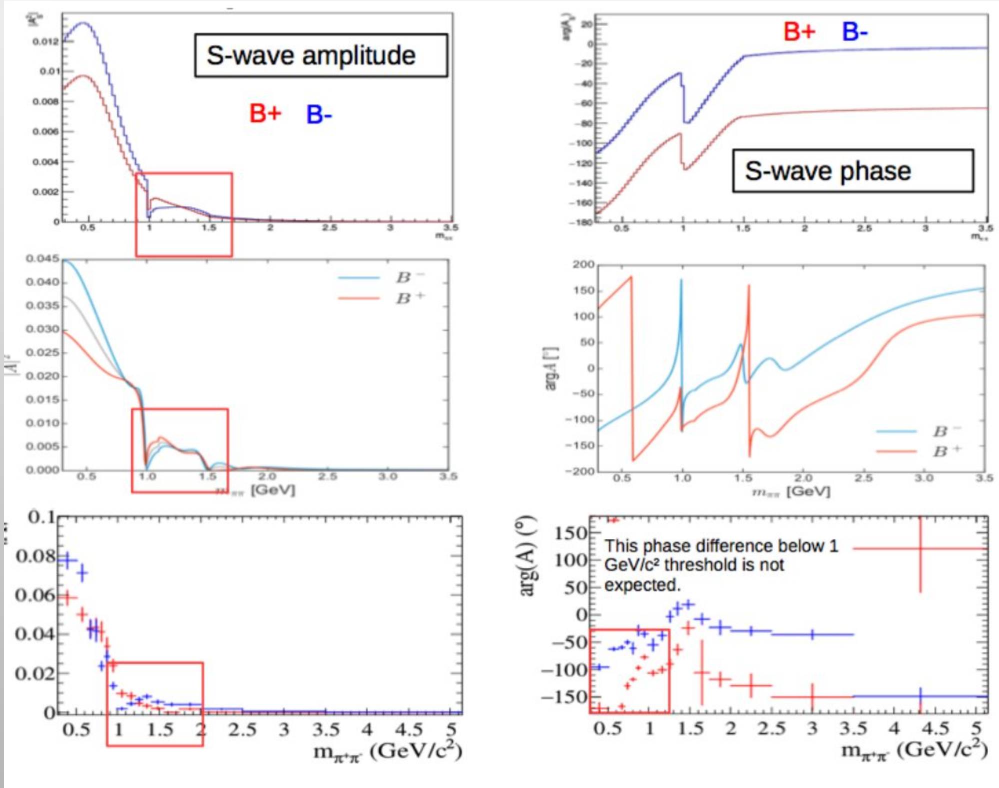
Non S-wave part is similar between the approaches.

From the Isobar model approach.



$B^{\pm} \longrightarrow \pi^{\pm}\,\pi^{-}\,\pi^{+}$ amplitude analysis

Comparison between the 3 approaches, S-wave:



Model 1 results					
Model	Contrib	FF(%)	δ^-[deg]	δ^+[deg]	A_{CP} (%)
Isobar Model	$(\rho-\omega)_{mix}$	56.2 ± 0.8	0 ± 0	0 ± 0	0.0 ± 0.0
	$f_2(1270)$	11.0 ± 1.0	65 ± 3	16 ± 4	41.6 ± 5.8
	$f_2(X)$	1.0 ± 0.2	-7 ± 7	-78 ± 17	68.5 ± 15.6
	$\rho(1450)$	5.3 ± 0.5	148 ± 4	128 ± 4	-21.8 ± 6.5
	$\rho_3(1690)$	0.7 ± 0.3	-31 ± 12	-26 ± 6	-66.8 ± 12.4
Isobar s-wave fit 10720	-	24.3 ± 0.8	-	-	-
K-matrix	$\rho(770)^0$	54.1 ± 0.8	0 ± 0	0 ± 0	1.5 ± 1.6
	$f_2(1270)$	11.6 ± 1.5	73 ± 5	16 ± 5	32.9 ± 6.2
	$f_2(X)$	1.0 ± 0.5	-4 ± 17	-99 ± 18	25.9 ± 23.4
	$\rho(1450)$	7.1 ± 5.2	-170 ± 6	146 ± 5	-19.7 ± 7.7
	$\rho_3(1690)$	1.3 ± 0.14	-19 ± 13	4 ± 9	-75.2 ± 8.0
K-matrix s-wave	-	28.1 ± 0.8	-	-	19.7 ± 21.6
QMI	"$\rho(770)^0$"	55.1 ± 0.9	0 ± 0	0 ± 0	3.2 ± 1.9
	"$\omega(782)^0$"	0.6 ± 0.1	-3 ± 7	-25 ± 6	-12.3 ± 15.0
	$f_2(1270)$	13.4 ± 0.8	76 ± 3	20 ± 5	37.4 ± 6.6
	$f_2(X)$	0.6 ± 0.2	-32 ± 13	-93 ± 21	43.0 ± 27.9
	$\rho(1450)$	6.9 ± 0.6	-176 ± 6	147 ± 7	-18.5 ± 8.3
	$\rho_3(1690)$	1.0 ± 0.1	13 ± 22	2 ± 10	-91.5 ± 6.0
QMI s-wave	-	26.4 ± 0.8	-	-	15.1 ± 3.1

⇒ There is an asymmetry in the S-wave from all three approaches that flips its sign around 1 GeV/c².

⇒ Run-II data will offer a better insight on this.

Summary

Published:

- Phys. Rev. Lett. 111, 101801 (2013) - Editor suggestion,
  Measurement of CP violation in the phase space of $B^\pm \longrightarrow K^\pm \pi^- \pi^+$ and $B^\pm \longrightarrow K^\pm K^- K^+$
- Phys. Rev. Lett. 112, 011801 (2014),
  Measurement of CP violation in the phase space of $B^\pm \longrightarrow \pi^\pm K^- K^+$ and $B^\pm \longrightarrow \pi^\pm \pi^- \pi^+$
- Phys. Rev. D90, 112004 (2014),
  Measurements of CP violation in the three-body phase space of charmless B± decays

Ongoing:

- $B^\pm \longrightarrow \pi^\pm \pi^- \pi^+$ amplitude analysis using Run-I data $\Leftarrow$ in collaboration review
- $B^\pm \longrightarrow \pi^\pm K^- K^+$ amplitude analysis using Run-I data $\Leftarrow$ in collaboration review
- $B^\pm \longrightarrow K^\pm K^- K^+$ amplitude analysis using Run-I data
- Measurements of CP violation in the three-body phase space (with data acquired until 2016)

With the statistics available for the analysis (Run-I + Run-II) we estimate an increase in a factor 2 with respect to the published papers.

Many issues remain open.

Impact of the analysis

- “Measurements of CP Violation in the three-body phase space of charmless $B^{\pm}$ decays”
Phys.Rev. D90 112004 (2014), 63 citations, Spires database

Had a lot of repercutions within the LHCb collaboration:

- Publications in the CERN Courier magazine (the laboratory magazine)

- In edition commemorative of the 50 years of the discovery of CP-Violation of the CERN Courier magazine, our results were presented with especial mention:

  “LHCb has also discovery very large and rather puzzling - CP-violation effects in decays of B mesons to three particles (pions or kaons), which need to be understood with further experimental and theoretical investigation.” (http://cerncourier.com/ows/article/cern/57858)

- Master Class using our data.