B Physics at LHCb

Melissa Cruz Torres[1,2] on behalf of the LHCb collaboration

[1] *Universidad Nacional Autónoma de Honduras (UNAH), Honduras*
[2] *Centro Brasileiro de Pesquisas Físicas (CBPF), Brazil*

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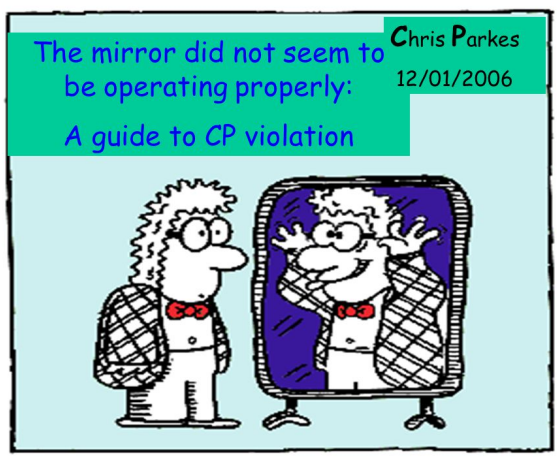
Introduction

LHCb: Large Hadron Collider - beauty

Its main purpose the study the *CP* violation phenomena and rare decays in hadron with b and c quarks.

- B and D hadrons are produced in the forward (or backward) direction.
- The LHCb detector is a single-arm forward spectrometer

Matter and antimatter do not behave in the same way in nature $\rightarrow$ weak interactions are not invariant under **C**, **P** and **CP** transformations.



CP-violation has been observed in

- K (strange): First observed in 1965
- B (beauty): 2000
  - Particularly in the Beauty sector it has been reported in $B^{\pm}, B^0, B_s^0$ mesons decays
  - $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ baryon decays LHCb, Nature Physics 13 (2017) 391 $\rightarrow$ still this evidence has not been confirmed with larger data sample (arXiv:1912.10741).
- D (charm) sector: 2019 $\rightarrow$ a lot to explore!

Introduction

The amount of matter and antimatter asymmetry in the universe cannot all be explained within the Standard Model, **we search for new sources of CPV!**

CP violation naturally arises in the Standard Model through the mixing matrix among the families of quarks, the CKM matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix},$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4),$$

where $\lambda = \sin\theta_c$, ρ and η are real parameters.

- *CP* violation manifests from the complex nature of V_{CKM}. The mixing matrix from quarks (V_{CKM}) is different from that of antiquarks ($V_{CKM}^{\dagger}$)

CP violation mechanism

- **Direct *CP* violation**: $|A|^2 \neq |\bar{A}|^2 \Rightarrow$ the observables to which we can access (differences in number of events of particle and antiparticles).
  The only mechanism for charged decays (e.g $B^{\pm}$ and b-baryons)
  - $\mathcal{A}_{CP}(B \to f) = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \Sigma_{ij} |A_i||A_j| sin(\delta_i - \delta_j) sin(\phi_i - \phi_j)$
  - Three conditions

At least two interfering amplitudes to same final state

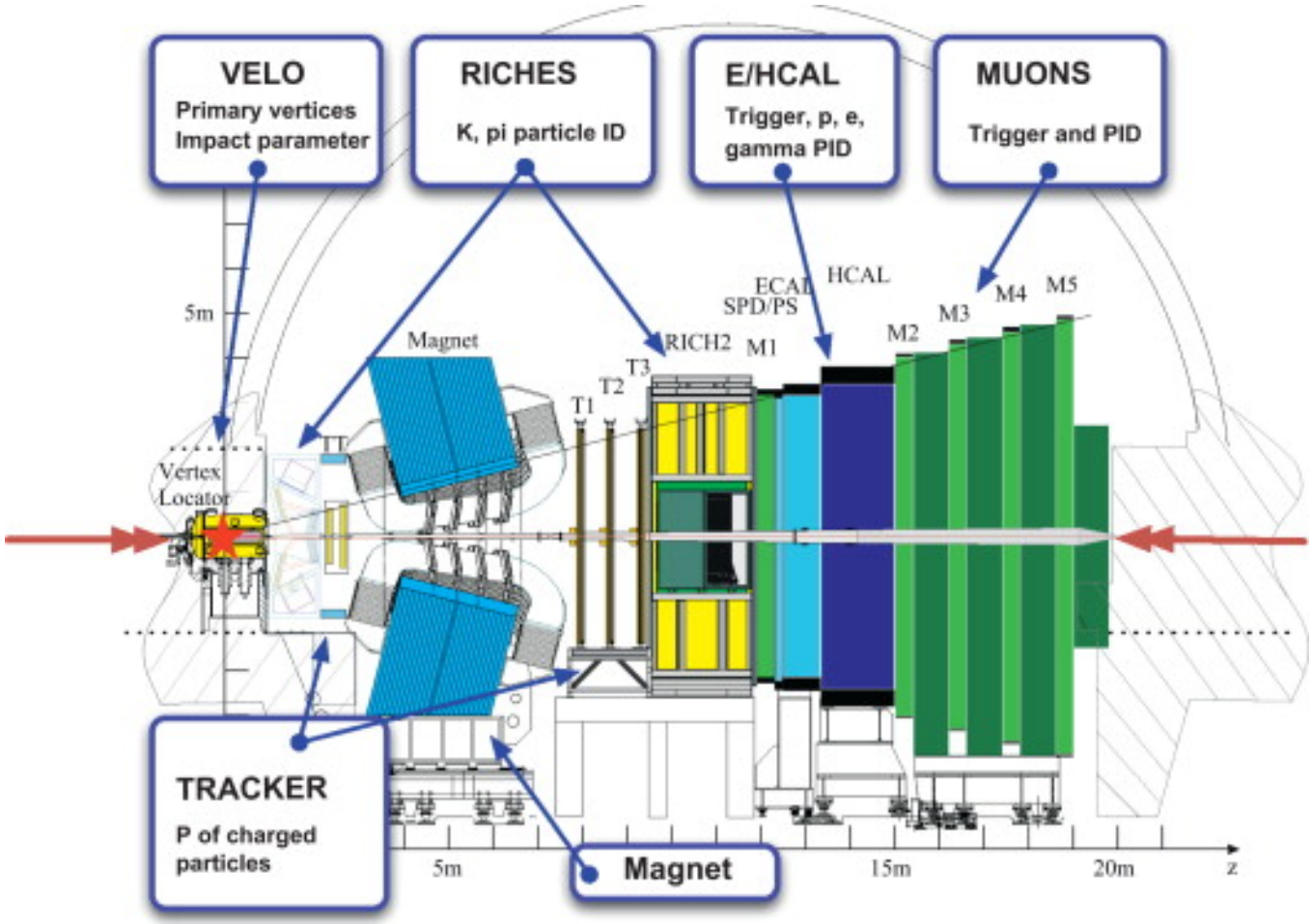
Weak phase difference
$\phi_i - \phi_j \neq 0$
explained by the CKM matrix

Strong phase difference
$\delta_i - \delta_j \neq 0$
short distance effects Breit-Wigner phase and complex coupling
long distance effects - FSI (final state interactions).

- *CP*-violation by mixing: related to the difference in the rate oscillation between particle and antiparticle.
- CP-violation through the interference between a decay amplitude and mixing.

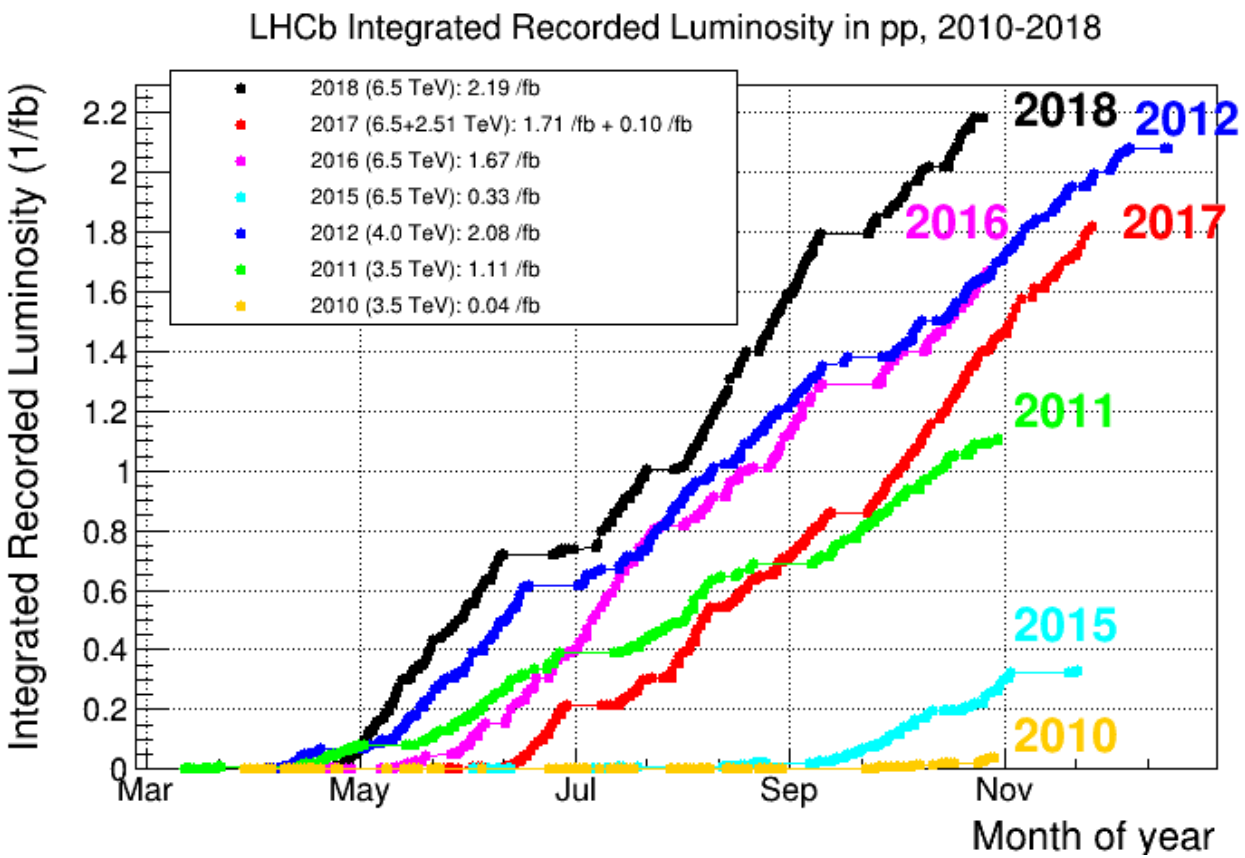
The LHCb detector

- It's a single-arm forward spectrometer designed for the study of B and D mesons.
- It covers a pseudo-rapidity range of $1.5 < \eta < 5.0$ [Int. J. Mod. Phys. A 30, 1530022 (2015)]



LHCb data sample

- Run I data: $\mathcal{L}$=3.0 fb^{-1} from pp collisions at 7 TeV (2011) and 8 TeV (2012) in the center-of-mass-energy.
- Run II data: 6.0 fb^{-1} from pp collisions at 13 TeV 2015- 2018.



Event Selection

- **Online**: *Selection thanks to the trigger system.*

L0-trigger selection (hardware)

Select objects related to:

1. Hadrons (L0Hadron)
2. Photons (L0Photon)
3. Electron (L0Electron)
4. Muon (L0Muons)

- The L0 trigger uses the information provided by the calorimeters and muon chambers.

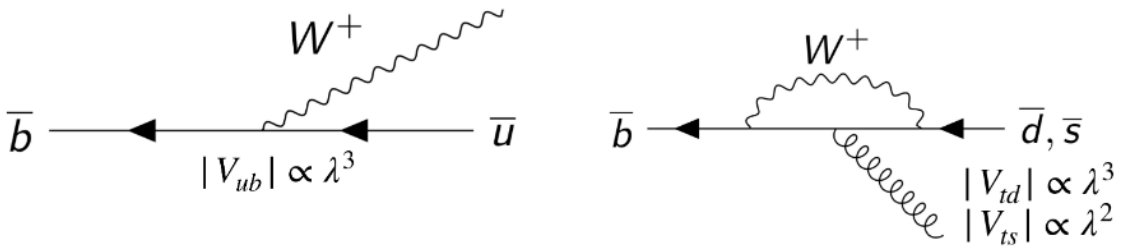
- **High-Level trigger (software)**: Is based in algorithms that perform partial (HLT1) and full reconstruction of all tracks (HLT2).

- **Offline**: *Refined selection for the obtention of the candidates.*

Charmless B-decays

**B-hadron decays without charm or charmonium contributions in their final states.*

Decays that involve transitions of the type $b \to u(s)$ or $b \to d$



Charmless B-decays offer a rich environment for CP violation studies

- Dominant tree-level and Penguin Diagrams contribute in the same order of magnitude
- Sensitive ground for *CP* violation studies.

Charmless B decays

- Multi-body decays dominated by rich resonant structures
  - CP violation signatures localized in regions of the phase space have been found.
  - Allows better understanding of B-hadrons dynamics
- Interesting to search for new source of CP violation.

Broad program at LHCb with Run I/Run II data

e.g

- Dalitz plot analysis
- Time-dependent/independent CPV analysis
- Searches for unobserved decays of B mesons and baryons

Outline

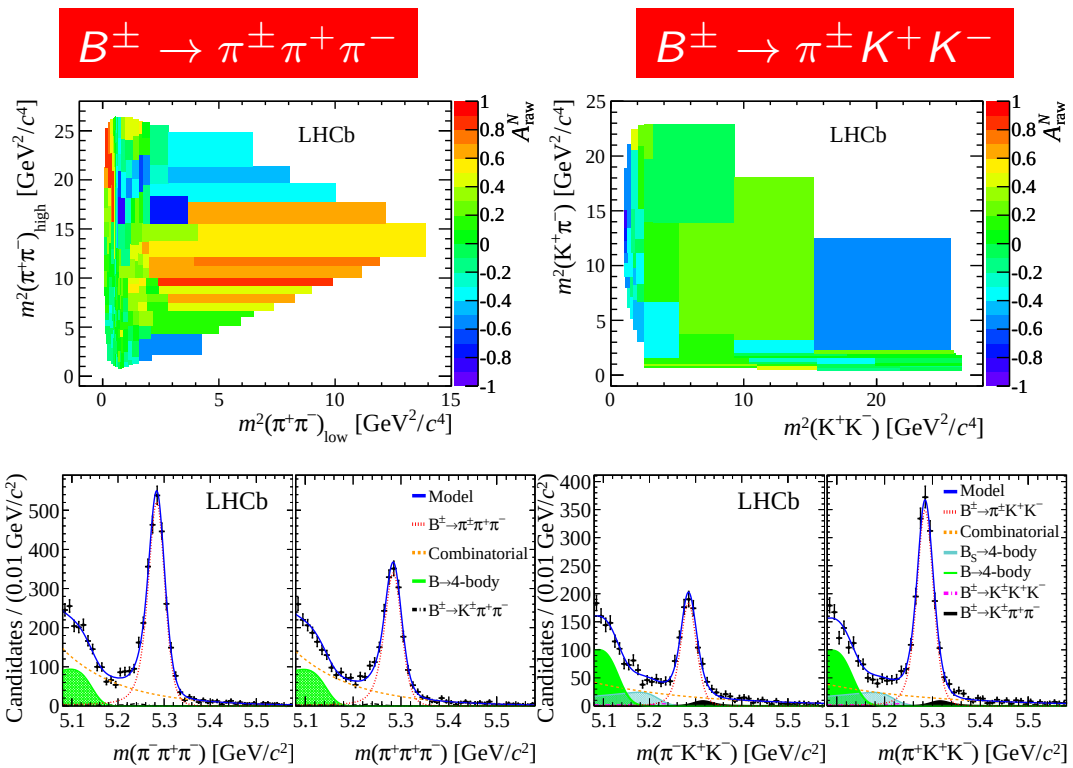
- **Amplitudes Analysis $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$**
  - $\mathcal{L} = 3$ fb^{-1}, Run I data 2011 + 2012, Phys. Rev. Lett. 123 (2019) 231802
- **Amplitudes Analysis $B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$**
  - $\mathcal{L} = 3$ fb^{-1}, Run I data 2011 + 2012, Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D 101 (2020) 012006
- **Measurements of the relative branching fractions of $B^{+} \to h^{+} h^{'+} h^{''-}$ decays**
  - $\mathcal{L} = 3$ fb^{-1}, Run I data 2011 + 2012, arXiv:2010.11802

The three-body $B^+ \to h^+h'^+h'^-$ decays: Motivation

$h^{(\prime)(\prime)}$ stand for pions or kaons: $B^+ \to \pi^+\pi^+\pi^-$, $B^+ \to K^+K^+K^-$, $B^+ \to \pi^+K^+\pi^-$, $B^+ \to \pi^+K^+K^-$

- Interesting decays that have revealed important *CP* violation effects

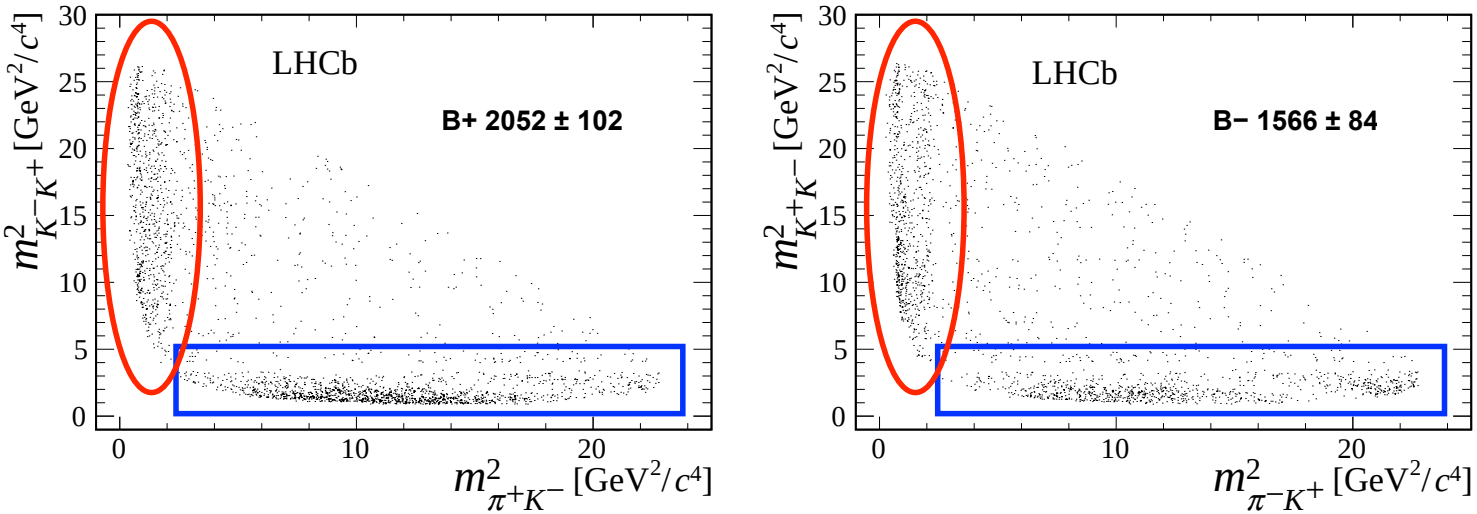
- Large integrated *CP* asymmetries and *CP* signatures in localized regions of the phase space. Model-independent analysis with Run I data by LHCb [PRD 90 (2014) 112004]



- **The study of the underlying dynamics was needed.**

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

$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ phase space separated by B^{+} and B^{-} [Phys. Rev. Lett. 123 (2019) 231802]



Dalitz plot analysis performed using the Isobar model formalism:

$$\mathcal{A}(m^2_{\pi^+K^-}, m^2_{K^+K^-}) = \sum_{i=1}^{N} c_i \mathcal{M}_{Ri}(m^2_{\pi^+K^-}, m^2_{K^+K^-})$$

where $c_i = a_i e^{i\alpha}$ is the isobar coefficient

is the amplitude for the intermediate state i.

From fit to Dalitz plot, we extract:

$$A_{CP} = (|\bar{c}_i|^2 - |c_i|^2)/(|\bar{c}_i|^2 + |c_i|^2)$$

$$\mathrm{FF}_i = \frac{\int (|c_i \mathcal{M}_i|^2 + |\bar{c}_i \overline{\mathcal{M}}_i|^2) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{\pi^+K^-}}{\int (|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{\pi^+K^-}}.$$

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

First Amplitude Analysis for this decay [Phys. Rev. Lett. 123 (2019) 231802]

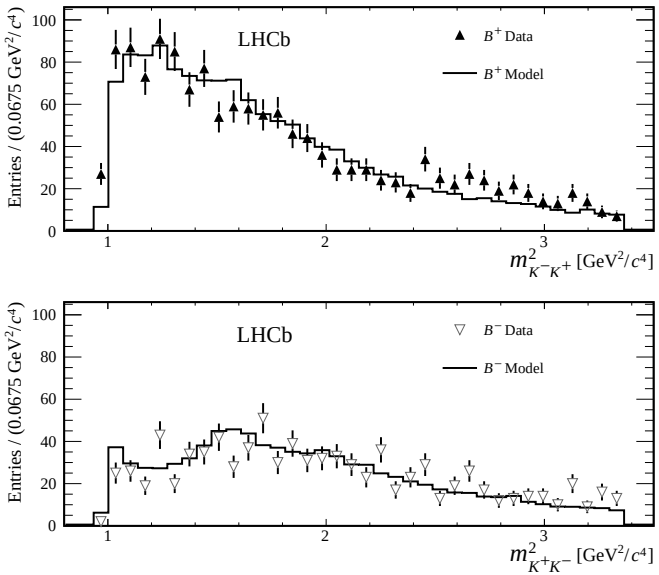
Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

Single pole form factor:
Phenomenological description of the partonic interaction $(1 + \frac{m^2_{\pi K}}{\Lambda^2})^{-1}$
Phys.Rev.D92.054010,2015

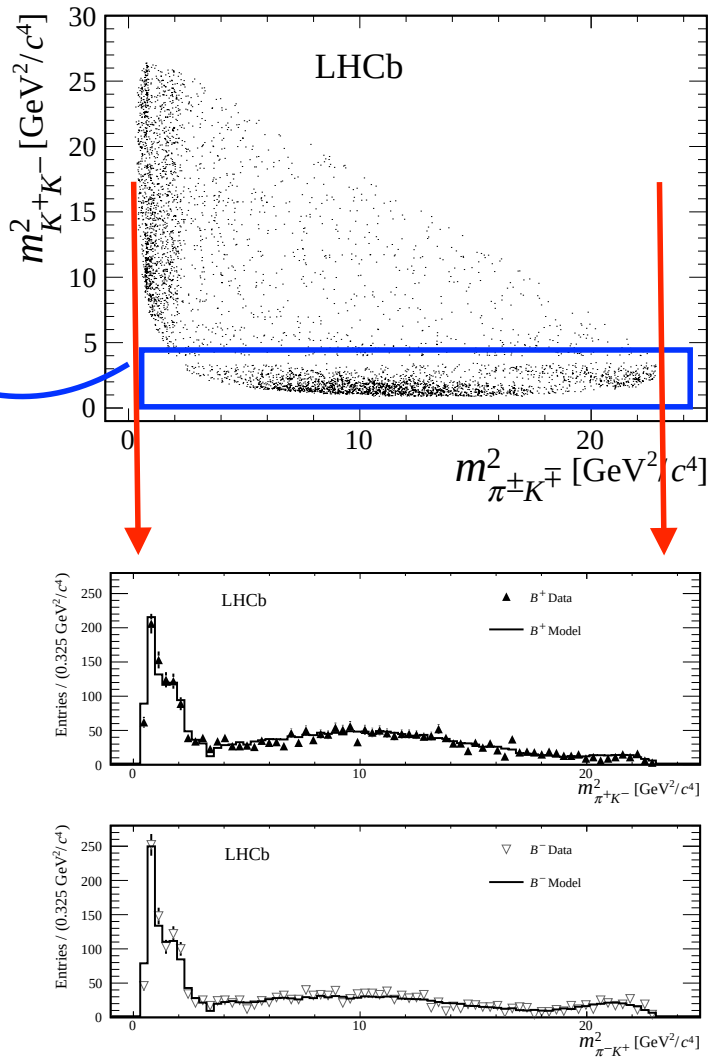
Dedicated rescattering amplitude:
Defined in the region
$0.95 < m_{KK} < 1.42$ GeV/c^2,
$\Rightarrow \sqrt{1-\eta^2} e^{2i\delta}$, where η and δ are taken from [PhysRev. D71, 074016(2005)]

- **Large *CP* asymmetry associated with the rescattering region $\sim$ -66 %.**
  - This represents the largest asymmetry found for a single amplitude
  - Positive *CP* asymmetry found in this region for its coupled channel $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$
- **Asymmetries in the $K\pi$ system consistent with zero.**
- **Large contribution found for the non-resonant and $B^{\pm} \to \rho^0(1450)\pi^{\pm}$ components, $\sim$ 30%.**

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



[Phys. Rev. Lett. 123 (2019) 231802]

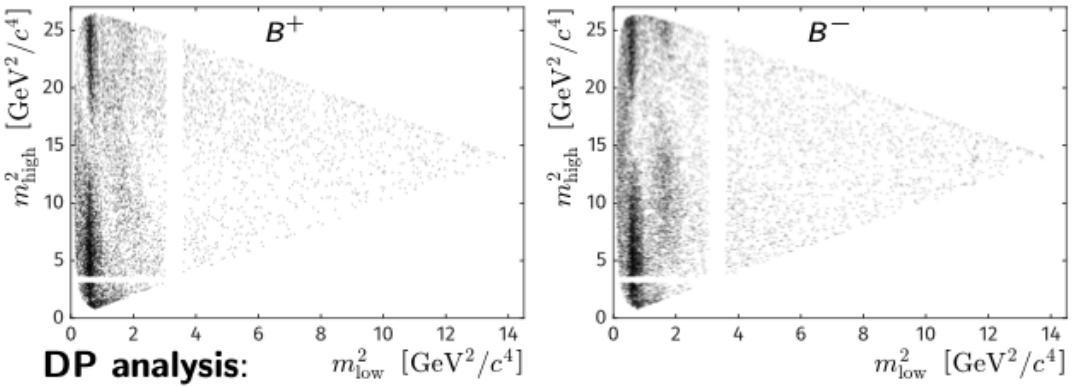


Overall a good data parametrization is obtained

Amplitude Analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Phys. Rev. Lett. 124 (2020) 031801
Phys. Rev. D 101 (2020) 012006

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ separated by B^{+} and B^{-}, total signal yield: 20 594 $\pm$ 1569



DP analysis:

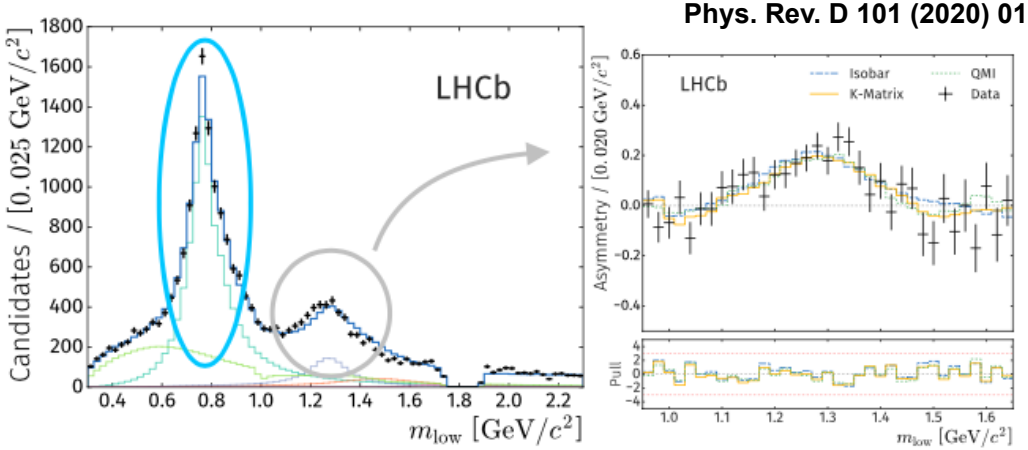
Visible asymmetries in the $\rho(770)$ and $f_2(1270)$ region

Isobar description for the non S-wave amplitudes.
$\pi\pi$ S-wave: high level of complexity, many resonances and open channels.
Three different complementary approaches were followed.

- **Isobar Model**: Pole parametrisation for $f_0(500)$ and a $\pi\pi \leftrightarrow KK$ rescattering amplitude for the region $0.95 < m_{\pi\pi} < 1.42$ GeV$/c^2$ (PhysRev. D71, 074016(2005))
- **K-Matrix model**: Take into account all open channels $\to$ rescattering coupling to 5 initial states: $\pi\pi, KK, 4\pi, \eta\eta, \eta\eta'$.
- **Quasi-model-independent**: Fit magnitude and phase in regions of the DP.

Amplitude Analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Phys. Rev. Lett. 124 (2020) 031801
Phys. Rev. D 101 (2020) 012006

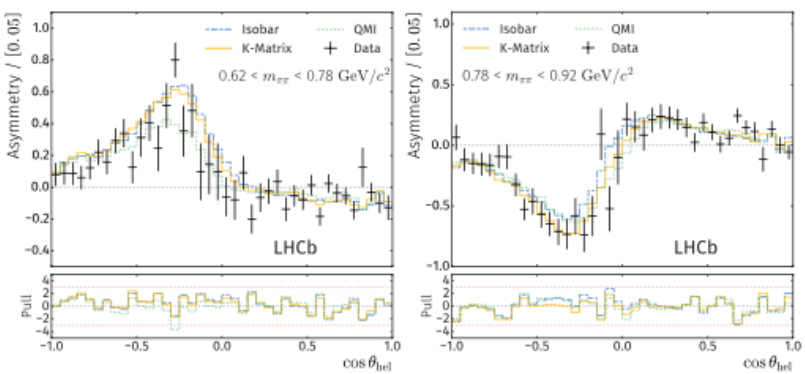


Sizable *CP* asymmetry associated with the $f_2(1270)$ resonance.

Significance of CP violation found to be $\sim 15\sigma$.

- *CP* asymmetry changes sign in the $\rho(770)$ region.

Clearly seen when splitting data according to the sign of $\text{Cos}\theta_{hel}$:

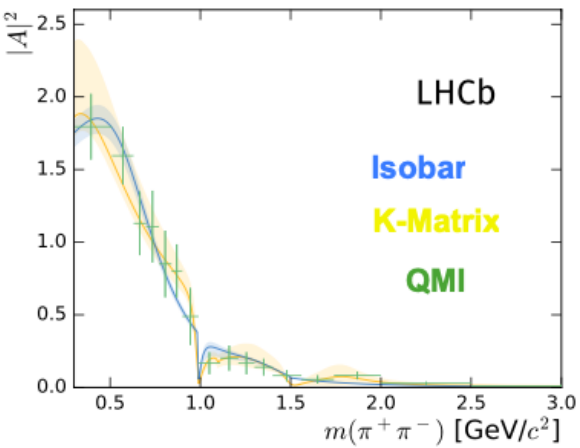


- Characteristic pattern due to the interference of spin-0 - spin-1 objects.
- Interference between spin-1 $\rho(770)$ and spin-0 S-wave.
- *CP* asymmetry vanishing over integration in the $\text{Cos}\theta_{hel}$.

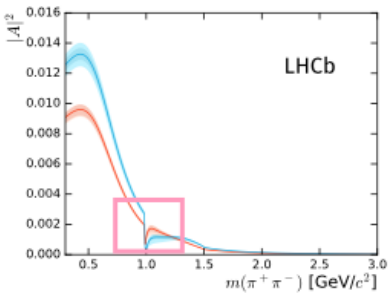
Amplitude Analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Phys. Rev. Lett. 124 (2020) 031801
Phys. Rev. D 101 (2020) 012006

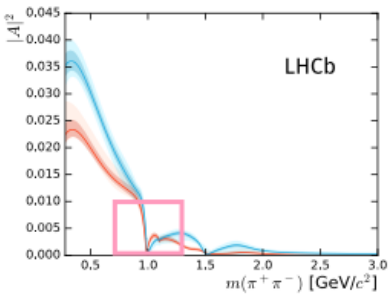
- Good agreement between the three approaches in the description of the S-wave squared magnitude.



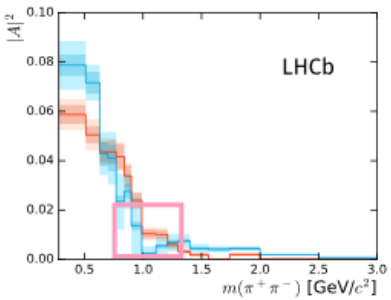
- Projection separated by B^+ and B^-:
  - Agreement reinforced.
  - Direct CP violation effects at low $m_{\pi\pi}$ values.
  - Asymmetry flips its sign around 1 GeV/c^2.



Isobar Model



K-Matrix



Quasi-model-Independent

Measurements of the relative branching fraction of $B^+ \to h^+h'^+h'^-$ decays

Motivation

- From amplitude analysis, the fit fractions for contributing resonances are extracted.
  - To convert to quasi-two-body branching fractions, precise knowledge of the three-body branching fractions is needed.
- Current knowledge of the $B^+ \to h^+h'^+h'^-$ BFs (with precisions of 4% to 9%) is not sufficient given the sensitivity of the Dalitz plot analyses.

Mode	PDG average branching fraction (10^{-6})
$B^+ \to K^+K^+K^-$	34.0 ± 1.4
$B^+ \to \pi^+K^+K^-$	5.2 ± 0.4
$B^+ \to K^+\pi^+\pi^-$	51.0 ± 2.9
$B^+ \to \pi^+\pi^+\pi^-$	15.2 ± 1.4

[PDG]

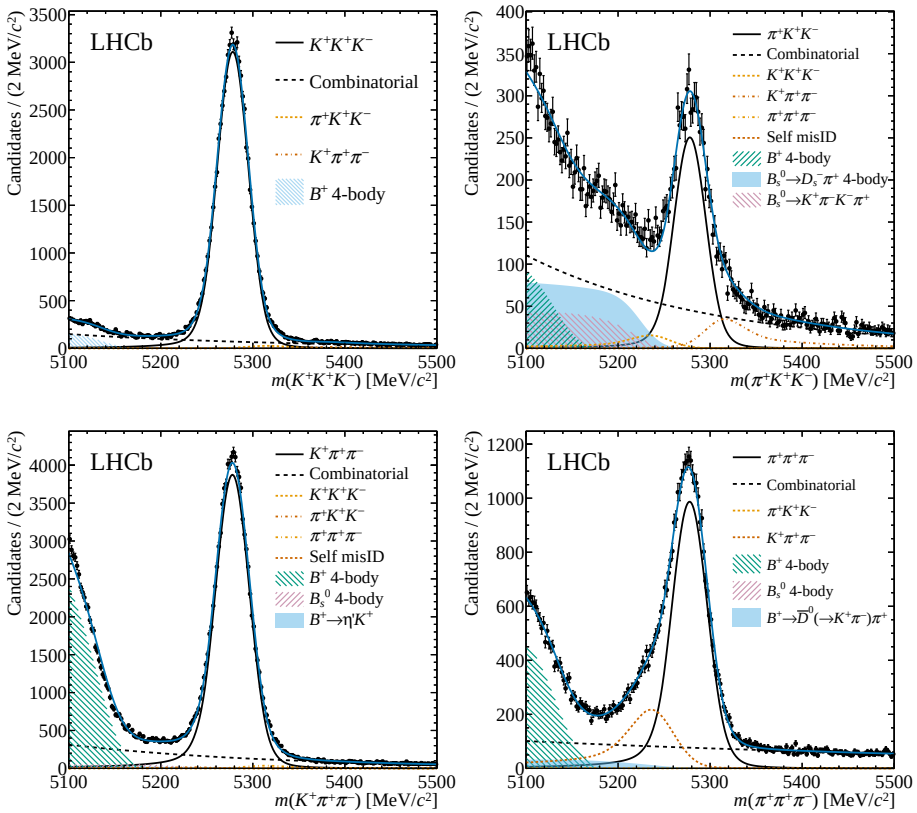
In this analysis the relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays is obtained.

Measurements of the relative branching fraction of $B^+ \to h^+ h'^+ h'^-$ decays

• Using Run I data sample (2011 + 2012), • Pre-selection based on the topology of the decays channels. • Refined offline selection to reduce background.

Extraction of the signal and background yields from a simultaneous fit to all channels,

[LHCb-PAPER-2020-031, arXiv:2010.11802]



Mass fit results:

Decay	Fit yield
$B^+ \to K^+K^+K^-$	69 310 ± 280
$B^+ \to \pi^+K^+K^-$	5 760 ± 140
$B^+ \to K^+\pi^+\pi^-$	94 950 ± 430
$B^+ \to \pi^+\pi^+\pi^-$	25 480 ± 200

Branching Fractions determination requires corrections due to:

• Efficiency variation across the phase space - obtained from simulated Data Sample.

• Signal distribution in the 3-body phase space.

▷ Extracted using the sPlot technique.

Measurements of the relative branching fraction of $B^+ \to h^+h'^+h''^-$ decays

Results [LHCb-PAPER-2020-031, arXiv:2010.11802]

$$\frac{\mathcal{B}(B^+ \to h^+h'^+h''^-)}{\mathcal{B}(B^+ \to K^+K^+K^-)} = \frac{\mathcal{N}^{corr}_{hhh}}{\mathcal{N}^{corr}_{KKK}}, \mathcal{N} \text{ is the signal yield - efficiency corrected.}$$

$\mathcal{B}$ ratio	Value
$\mathcal{B}(B^+ \to \pi^+K^+K^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$0.151 \pm 0.004 \pm 0.008$
$\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$1.703 \pm 0.011 \pm 0.022$
$\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$0.488 \pm 0.005 \pm 0.009$

- The relative branching fractions are presented here.
- Large systematic uncertainties
  ▷ dominant from background modelling.

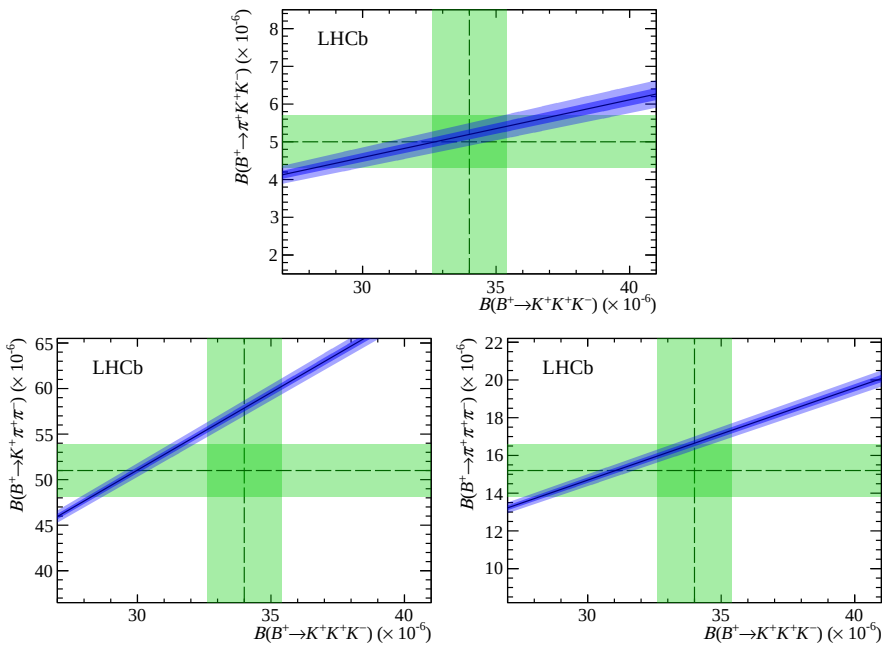
Results applied to quasi-two-body BFs extracted from $B^+ \to \pi^+\pi^+\pi^-$ amplitude analysis

$B(B^+ \to \rho^0(770)\pi^+)$ improves from 16% to 6%.

Current WA value [arXiv:1612.07233]:
$\mathcal{B}(B^+ \to \rho^0(770)\pi^+) = (8.3^{+1.2}_{-1.3}) \times 10^{-6}$

Improved measurement:
$\mathcal{B}(B^+ \to \rho^0(770)\pi^+) = (9.5 \pm 0.6) \times 10^{-6}$

Comparison with the current world averages



- **All measurements in good agreement**
- **Furthermore, significant improvement in the precision of all measured ratios is obtained.**

Summary

- **A lot of work ongoing in the LHCb experiment, with a very broad program in the search for CP-asymmetries in b- and c-hadrons.**

- Amplitude analysis for the decay channel $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ performed for the first time [Phys. Rev. Lett. 123 (2019) 231802].
  - Largest asymmetry found for a single amplitude ($\sim$ -66%).
- Amplitude analysis for the decay channel $B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$ [Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D 101 (2020) 012006].
  - First observation of CPV in a decay involving a tensor state.
  - First observation of CPV due to interference between two quasi-two body decays.
- Measurement of the relative branching fractions of $B^{+} \to h^{+} h^{'+} h^{'-}$ decays [LHCb-PAPER-2020-031, arXiv:2010.11802].
  - All measurements in good agreement with their WA, furthermore, significant improvement in the precision of all ratios is obtained.

- **A lot of analysis in progress with the addition of Run II data, exciting results ahead!**

Thank you for your attention

Backup

Measurements of the relative branching fraction of $B^+ \to h^+h'^+h''^-$ decays

Table 7: Measured relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays, where the first uncertainty is statistical and the second is systematic.

$\mathcal{B}$ ratio	Value
$\mathcal{B}(B^+ \to \pi^+K^+K^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$0.151 \pm 0.004 \pm 0.008$
$\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$1.703 \pm 0.011 \pm 0.022$
$\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-)$	$0.488 \pm 0.005 \pm 0.009$
$\mathcal{B}(B^+ \to K^+K^+K^-)/\mathcal{B}(B^+ \to \pi^+K^+K^-)$	$6.61 \pm 0.17 \pm 0.33$
$\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to \pi^+K^+K^-)$	$11.27 \pm 0.29 \pm 0.54$
$\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)/\mathcal{B}(B^+ \to \pi^+K^+K^-)$	$3.23 \pm 0.09 \pm 0.19$
$\mathcal{B}(B^+ \to K^+K^+K^-)/\mathcal{B}(B^+ \to K^+\pi^+\pi^-)$	$0.587 \pm 0.004 \pm 0.008$
$\mathcal{B}(B^+ \to \pi^+K^+K^-)/\mathcal{B}(B^+ \to K^+\pi^+\pi^-)$	$0.0888 \pm 0.0023 \pm 0.0047$
$\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+\pi^+\pi^-)$	$0.2867 \pm 0.0029 \pm 0.0045$
$\mathcal{B}(B^+ \to K^+K^+K^-)/\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)$	$2.048 \pm 0.020 \pm 0.040$
$\mathcal{B}(B^+ \to \pi^+K^+K^-)/\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)$	$0.310 \pm 0.008 \pm 0.020$
$\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)$	$3.488 \pm 0.035 \pm 0.053$

Amplitude Analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Comparison of the three approaches for the description of the S-wave squared magnitude (left) and phase motion (right)

- Isobar model approach (top)
- K-matrix approach (middle)
- QMI approach (bottom)