CP Violation in Charmless Multibody B Decays at LHCb

XLI International Conference on High Energy Physics - ICHEP22

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Date: 2022/07/07

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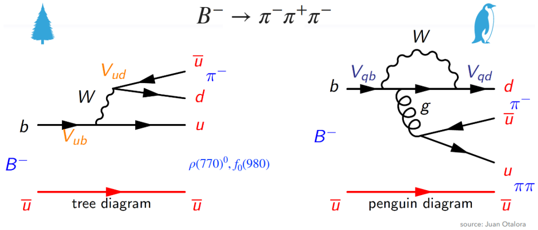
Overview

1. Theory Overview
2. Search for $\not{CP}$ in $B^0 \to p\overline{p}K^+\pi^-$ decays
3. Measurement of $\not{CP}$ in $B^\pm \to h^\pm h^+ h^-$ decays
4. Conclusions

Theory Overview

Direct $\not{CP}$ in the CKM Matrix

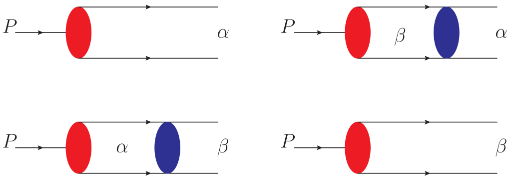
- Interference between two different amplitudes that contributes to the same final state and with different weak and strong phases.
  - The weak phase changes sign under charge conjugation while the strong phase remains the same under the same operation.
- Example: strong phase from a penguin diagram.



$$|\langle f|T|i\rangle|^2 - |\langle \bar{f}|T|\bar{i}\rangle|^2 = -4A_1A_2 sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

Strong Phase from a Hadronic Rescattering

- In a simplified formulation: P particle decays in a family of only two final states alpha and beta:



- Weak phase is the same but strong phase now from the S-Matrix.

$$S_{matrix} = \begin{pmatrix} e^{2i\delta_\alpha} & t_{\alpha\beta} e^{i(\delta_\alpha+\delta_\beta)} \\ t_{\alpha\beta} e^{i(\delta_\alpha+\delta_\beta)} & e^{2i\delta_\beta} \end{pmatrix} \Rightarrow \begin{array}{l} \langle\alpha| T |P\rangle = e^{i\delta_\alpha}[T_\alpha + i t_{\alpha\beta} T_\beta] \\ \langle\beta| T |P\rangle = e^{i\delta_\beta}[T_\beta + i t_{\alpha\beta} T_\alpha] \end{array}$$

Search for ~~CP~~ in $B^0 \to p\overline{p}K^+\pi^-$ decays

- Promising process to observe $\not{CP}$ in B decays to final state with half-spin particles. Eur. Phys. J. C (2020) 80:565
  - Prequel: First evidence of $\not{CP}$ in the $B^\pm \to p\overline{p}K^\pm$ decay. Phys. Rev. Lett. 113 (2014) 141801
- Search for $\not{P}$ and $\not{CP}$ using triple-product observables.
  - $\hat{T}$-odd observables:

$$C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p) \qquad \overline{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\overline{p}})$$

  - Asymmetries:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0} \qquad \bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

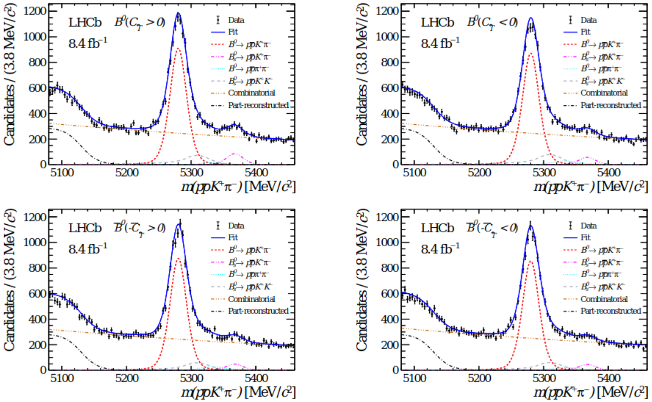
  - P and CP observables:

$$a_P^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}}) \qquad a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$$

Search for $\not{CP}$ in $B^0 \to p\overline{p}K^+\pi^-$ decays

LHCb collaboration arXiv:2205.08973[hep-ex]

- Results for phase-space integrated asymmetries:



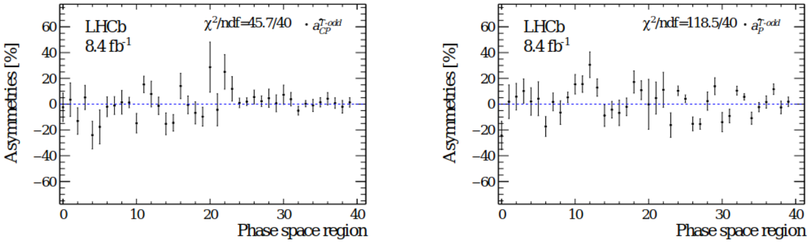
$$a_P^{\hat{T}-odd} = (1.49 \pm 0.85 \pm 0.08)\%$$

$$a_{CP}^{\hat{T}-odd} = (0.51 \pm 0.85 \pm 0.08)\%$$

Search for $\not{CP}$ in $B^0 \to p\bar{p}K^+\pi^-$ decays

LHCb collaboration arXiv:2205.08973[hep-ex]

- Results for phase-space regions asymmetries:



- CP conservation at 1σ.
- P violation at 6σ in the region of low $p\bar{p}$ mass and near the $K^*(892)^0$ resonance.
  - Full amplitude analysis needed to associate the $\not{P}$ to any resonance amplitude.

Measurement of C̸P̸ in $B^{\pm} \longrightarrow h^{\pm}h^{+}h^{-}$ decays

Overview of $\not{C}\not{P}$ in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

- Previous Results:
    - Evidence of Integrated $\not{C}\not{P}$ and high localised $\not{C}\not{P}$ across the phase space. Phys. Rev. D90, (2014) 112004
    - Amplitude analysis of $B^{\pm} \to K^{\pm}\pi^{+}K^{-}$: $\not{C}\not{P}$ connected to $\pi\pi \leftrightarrow KK$ rescattering amplitude. Phys. Rev. Lett. 123, (2019) 231802
        - Largest $\not{C}\not{P}$ measurement associated to a single amplitude: $A_{CP} = (66.4 \pm 4.0)\%$.
    - Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: $\not{C}\not{P}$ in S-wave, S- and P-wave interference and in D-wave.
      Phys. Rev. D101, (2020) 012006; Phys. Rev. Lett. 124, (2020) 031801
- Analysis using Run2 data only (5.9 fb^{-1}):
    - Inspect all 4 hadronic channels for $\not{C}\not{P}$ measurements:
        - In integrated phase-space;
        - In regions of the phase-space;
        - Using a model-independent method to inpect regions with an isolated pseudoscalar-vector resonances ($B \to PV$).
    - Test for U-spin symmetry predictions.

Overview of $\not{C}\not{P}$ in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

- The observable for the analysis is defined as:

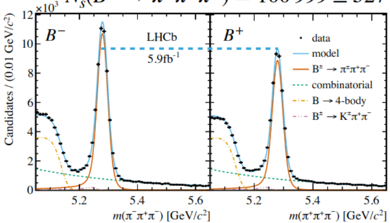
$$A_{CP} = \frac{A_{RAW}^{COR} - A_P}{1 - A_{RAW}^{COR} A_P}$$

- A_{RAW}^{COR} is the raw asymmetry corrected by the acceptance and detector asymmetry.
- A_P is the production asymmetry extracted from the control channel $B^{\pm} \to J/\psi K^{\pm}$.

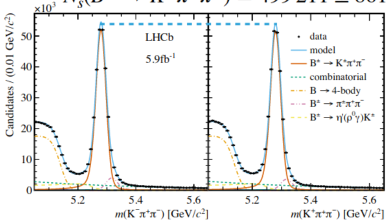
Integrated $\not{C}\not{P}$ Measurement

LHCb collaboration arXiv:2206.07622v1[hep-ex]

$N_s(B^\pm \to \pi^\pm\pi^+\pi^-) = 100\,999 \pm 527$



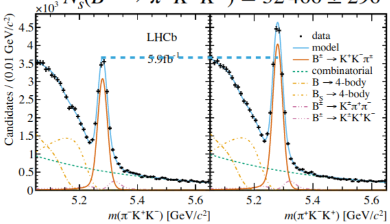
$N_s(B^\pm \to K^\pm\pi^+\pi^-) = 499\,211 \pm 861$



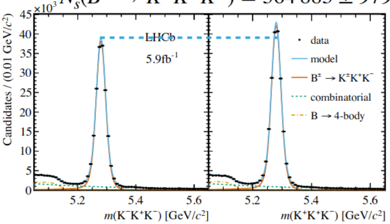
$A_{CP} = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ (14.1σ)

$A_{CP} = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$ (2.4σ)

$N_s(B^\pm \to \pi^\pm K^+K^-) = 32\,466 \pm 296$



$N_s(B^\pm \to K^\pm K^+K^-) = 364\,883 \pm 979$

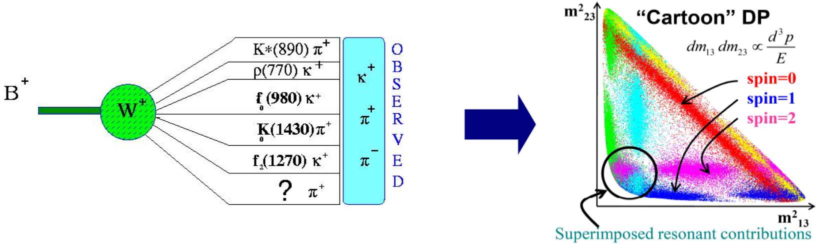


$A_{CP} = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$ (13.6σ)

$A_{CP} = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$ (8.5σ)

$\not{CP}$ regions of the phase-space

- Dalitz plot allows the study of B decays and its intermediate states.
  - 2-D phase space defined by $m_{ij}^2 = (E_i + E_j)^2 - (p_i + p_j)^2$.

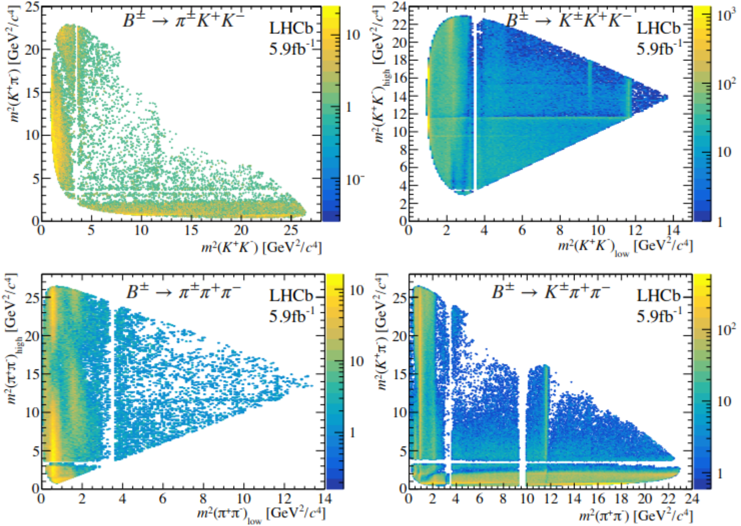


- Interference between intermediate states with different weak and strong phases generates $\not{CP}$.

$\not{CP}$ regions of the phase-space

LHCb collaboration arXiv:2206.07622v1[hep-ex]

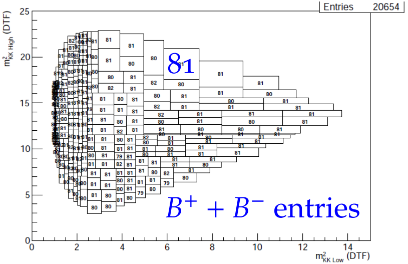
Distribution of events over the phase space

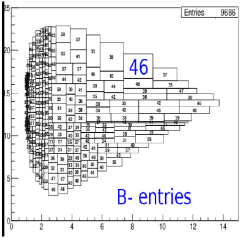


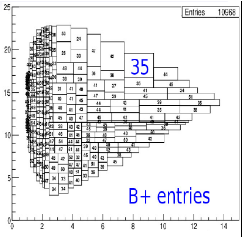
Background subtracted

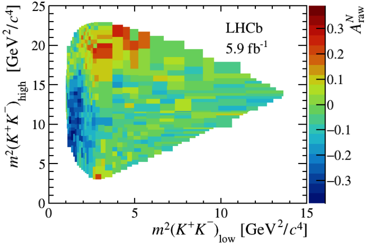
Phase-space inspection

◎ Evaluate the asymmetries in each bin of the phase-space:



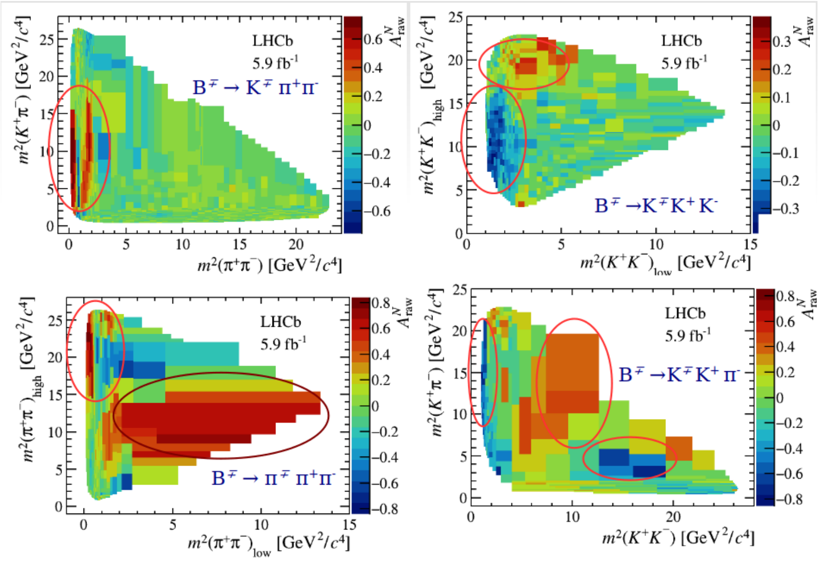






$\not{C}\not{P}$ in regions of phase-space

LHCb collaboration arXiv:2206.07622v1[hep-ex]

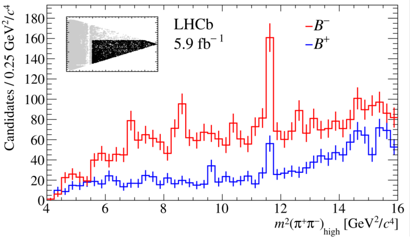


CP in region with charmonium

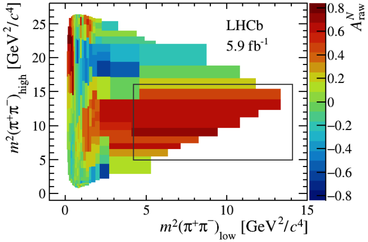
LHCb collaboration arXiv:2206.07622v1[hep-ex]

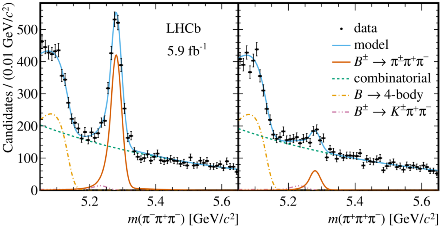
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays:

- Surprisingly large CP observed.
  - No direct CP expected in $\chi_{c0}(1P)$ in Standard Model.
  - Interference with a non-resonant decay amplitude.
    Phys. Rev. Lett. 74 (1995) 4984
  - Double-charm rescattering.
    Phys. Lett. B806 (2020) 135490



$$A_{CP} = (74.5 \pm 2.7_{stat} \pm 1.8_{syst} \pm 0.3_{J/\psi K})\%$$





U-spin symmetry test

LHCb collaboration arXiv:2206.07622v1[hep-ex]

- U-spin simmetry implies that $d \leftrightarrow s$ in the contribution diagrams. Hence:
  Phys. Lett. B564 (2003) 90

$$\Delta\Gamma(B^\pm \to \pi^\pm\pi^+\pi^-) = -\Delta\Gamma(B^\pm \to K^\pm K^+ K^-)$$
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- Using the same U-spin arguments, one can also predicts:

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$$\Delta\Gamma(B^\pm \to K^\pm\pi^+\pi^-) = -\Delta\Gamma(B^\pm \to \pi^\pm\pi^+\pi^-)$$

- The LHCb results are:

$$\frac{A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-)\mathcal{B}(B^\pm \to \pi^\pm\pi^+\pi^-)}{A_{CP}(B^\pm \to K^\pm K^+ K^-)\mathcal{B}(B^\pm \to K^\pm K^+ K^-)} = -1.06 \pm 0.08$$
$$\frac{A_{CP}(B^\pm \to \pi^\pm K^+ K^-)\mathcal{B}(B^\pm \to \pi^\pm K^+ K^-)}{A_{CP}(B^\pm \to K^\pm\pi^+\pi^-)\mathcal{B}(B^\pm \to K^\pm\pi^+\pi^-)} = -0.92 \pm 0.18\,.$$

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  Phys. Lett. B806 (2020) 135490; Phys. Lett. B728 (2014) 579

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$$\Delta\Gamma(B^\pm \to K^\pm\pi^+\pi^-) = -\Delta\Gamma(B^\pm \to \pi^\pm\pi^+\pi^-)$$

- The LHCb results are:

$$\frac{A_{CP}(B^\pm \to \pi^\pm K^+ K^-)\mathcal{B}(B^\pm \to \pi^\pm K^+ K^-)}{A_{CP}(B^\pm \to K^\pm K^+ K^-)\mathcal{B}(B^\pm \to K^\pm K^+ K^-)} = 0.47 \pm 0.04$$

$$\frac{A_{CP}(B^\pm \to K^\pm\pi^+\pi^-)\mathcal{B}(B^\pm \to K^\pm\pi^+\pi^-)}{A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-)\mathcal{B}(B^\pm \to \pi^\pm\pi^+\pi^-)} = 0.48 \pm 0.09\,.$$

LHCb collaboration arXiv:2206.02038v1[hep-ex]

- Model-independent method that explores the angular distribution characteristic of these decays. Phys. Rev. D94 (2016) 054028
  - Few $B^\pm \to h^\pm(V \to h^+h^-)$ measurements in the literature and huge theoretical interest.
- For isolated vector ressonances, asymmetry is $\propto$ to square modulus of amplitude difference

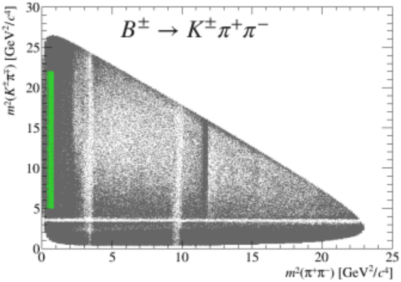
$$|\mathcal{M}_\pm|^2 = \underbrace{p_0^\pm}_{\textit{Direct scalar } A_{CP}} + \underbrace{p_1^\pm \cos\theta(m_V^2, s_\perp)}_{\textit{Scalar and Vector interf.}} + \underbrace{p_2^\pm \cos^2\theta(m_V^2, s_\perp)}_{\textit{Direct vector } A_{CP}}$$

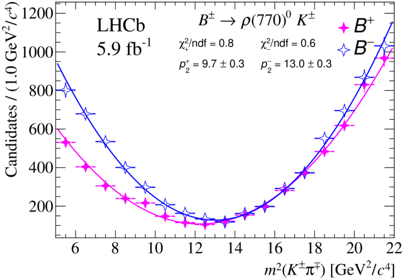
- $p_2^\pm$ can be obtained from a simple quadratic fit and hence:

$$A_{CP}^V = \frac{|\mathcal{M}_-|^2 - |\mathcal{M}_+|^2}{|\mathcal{M}_-|^2 + |\mathcal{M}_+|^2} = \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

~~CP~~ in BPV: $\rho(770)^0 - \omega(782)$ mixing region

LHCb collaboration arXiv:2206.02038v1[hep-ex]





$$A_{CP} = (15.0 \pm 1.9_{stat} \pm 1.1_{syst} \pm 0.3_{J/\psi K})\% \qquad 6.8\sigma$$

- Amplitude analysis results for the $\rho(770)^0$ component:

$$A_{CP} = (44 \pm 10 \pm 4^{+5}_{-13})\%$$

BaBar collaboration: Phys. Rev. D78 (2008) 012004

$$A_{CP} = (30 \pm 11 \pm 2^{+11}_{-4})\%$$

Belle collaboration: Phys. Rev. Lett. 96 (2006) 251803

Conclusions

Conclusions

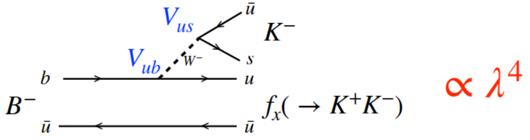
- LHCb collaboration has published some interesting results related to $\not{CP}$ in multibody charmless B decays.
- No $\not{CP}$ observed in $B^0 \longrightarrow p\bar{p}K^+\pi^-$ decays and $\not{P}$ observed at 6σ around the low $p\bar{p}$ mass and $K^*(892)^0$ resonance.
  - A full amplitude analysis is needed to relate the observed $\not{P}$ to an specific resonance amplitude.
- Large $\not{CP}$ is observed in the $B^\pm \longrightarrow h^\pm h^+ h^-$ decays:
  - Large integrated $\not{CP}$ in $B^\pm \longrightarrow \pi^\pm\pi^+\pi^-$, $B^\pm \longrightarrow K^\pm\pi^+K^-$ and $B^\pm \longrightarrow K^\pm K^+ K^-$ decays.
  - Even larger localized $\not{CP}$ in all 4 decay channels.
    - $(74.5 \pm 2.7)\%$ asymmetry in the $\chi_{c0}(1P)$ resonance region in $B^\pm \longrightarrow \pi^\pm\pi^+\pi^-$ decays.
    - $(15.0 \pm 1.9)\%$ asymmetry in the $\rho - \omega$ mixing region in the $B^\pm \longrightarrow K^\pm\pi^+\pi^-$ decays.
  - Results are consistent with U-spin symmetry.

BACKUP

- The CKM Matrix introduces the $\not{CP}$ possibility through the weak phase (Wolfenstein parametrization):

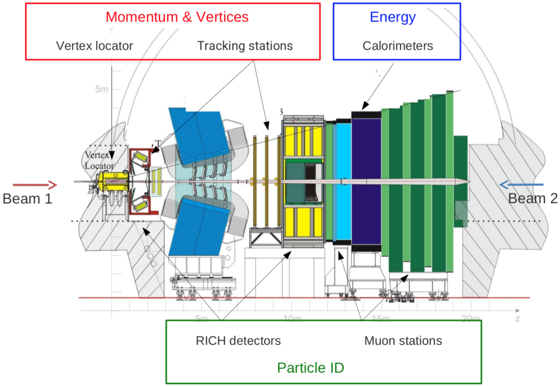
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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



LHCb Experiment

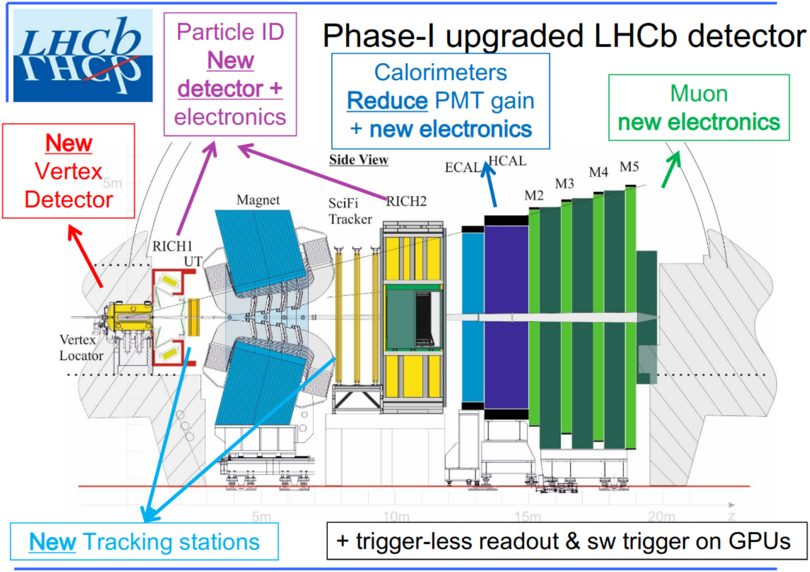
forward arm spectrometer for precision measurements ($2<\eta<5$)



- good vertex and impact parameter resolution ($\sigma(IP) = 15 \pm 29/p_T$ μm)
- excellent momentum resolution ($\sigma(m_B) \sim 25$ MeV/c^2 for 2-body decays)
- excellent particle ID (μ ID 97% for ($\pi \to \mu$) misID of 1-3%)
- stable running conditions constant μ
- trigger on small p_T and low mass objects
- real time analysis alignment and calibration fully automated

- 9 fb^{-1} recorded over Run1 and Run2 $p-p$ colisions.
  - Run1 with 7 and 8 TeV and Run2 with 13 TeV.
- $p-Pb$, $Pb-Pb$ and $p-gas$ (fixed target) runs.
- LHCb trully is a multi-purpose forward detector.

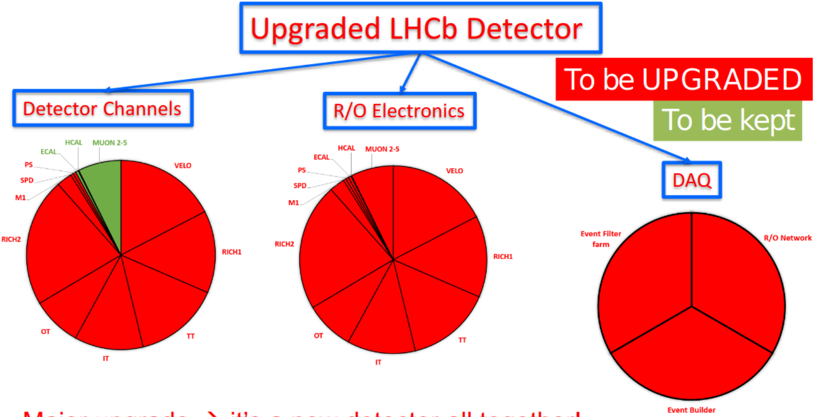
LHCb Detector for Run3



LHCb Detector for Run3

Phase-I Upgrade for Run 3

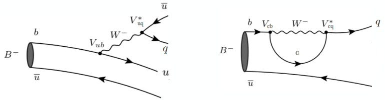
CERN-LHCC-2012-007



Major upgrade → it's a new detector all together!

U-spin symmetry test

- Main diagram contribution for all channels:



$$
\begin{aligned}
A(B^+ \to K^+\pi^+\pi^-) &= V^*_{ub}V_{us}\mathcal{U}_{s_1} + V^*_{cb}V_{cs}\mathcal{C}_{s_1}\,,\\
A(B^+ \to \pi^+K^+K^-) &= V^*_{ub}V_{ud}\mathcal{U}_{d_2} + V^*_{cb}V_{cd}\mathcal{C}_{d_2}\,,\\
A(B^+ \to \pi^+\pi^+\pi^-) &= V^*_{ub}V_{ud}\mathcal{U}_{d_3} + V^*_{cb}V_{cd}\mathcal{C}_{d_3}\,,\\
A(B^+ \to K^+K^+K^-) &= V^*_{ub}V_{us}\mathcal{U}_{s_4} + V^*_{cb}V_{cs}\mathcal{C}_{s_4}\,,
\end{aligned}
$$

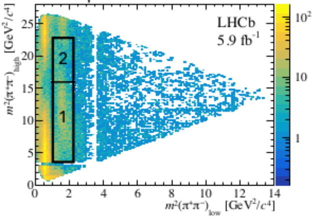
$$\Delta\Gamma_{CP}(h_1^\pm h_2^\pm h_3^\mp) = \Gamma(B^- \to h_1^- h_2^+ h_3^-) - \Gamma(B^+ \to h_1^+ h_2^- h_3^+)\,.$$

- $V^*_{ij}V_{kl}$ are the CMK elements. The $\mathcal{U}$ stands for the tree contribution and C for the penguin.

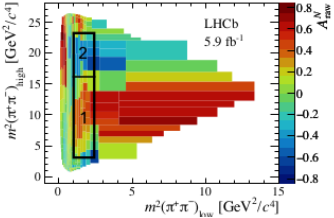
$$\Delta\Gamma_{CP} = \Gamma(B^-) - \Gamma(B^+) = A_{CP}(B^\mp)BR(B^\mp)/\tau B^\mp$$

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

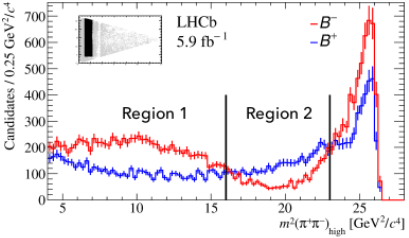
Phase space distribution of events



A_{CP} in bins of phase space



Hadronic rescattering $\pi\pi \leftrightarrow KK$
$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$



Region 1
$A_{CP} = (+30.3 \pm 0.9_{\rm stat} \pm 0.4_{\rm syst} \pm 0.3_{J/\psi K})\,\%$

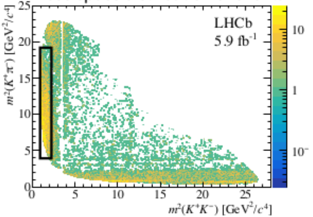
Region 2
$A_{CP} = (-28.4 \pm 1.7_{\rm stat} \pm 0.7_{\rm syst} \pm 0.3_{J/\psi K})\,\%$

Weak phase doesn't change over the phase space
$\rightarrow$ A_{CP} sign changing caused by strong phases

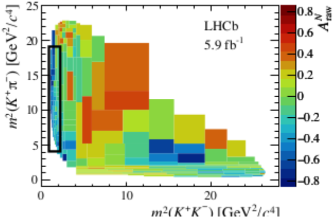
$\not{C}\not{P}$ in regions of the phase-space

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

Phase space distribution of events

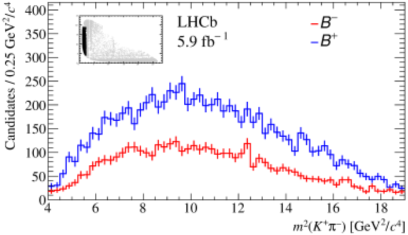


A_{CP} in bins of phase space



Hadronic rescattering $\pi\pi \leftrightarrow KK$

$1 < m^2(K^+K^-) < 2.25$



$A_{CP} = (-35.8 \pm 1.0_{\text{stat}} \pm 1.4_{\text{syst}} \pm 0.3_{J/\psi K})\,\%$

$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ amplitude analysis with run1:

A_{CP}(rescattering) = $(-66.4 \pm 3.8 \pm 1.9)\,\%$

Relative size contribution = $(16.4 \pm 0.8 \pm 1.0)\,\%$

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