A first search for CP violation in $\Xi_c^+ \rightarrow pK^-\pi^+$ decays

Artur Ukleja on behalf of the LHCb collaboration

arXiv: 2006.03145
doi: 10.1140/epjc/s10052-020-8365-0
Eur. Phys. J. C80 (2020) 986

Eur. Phys. J. C (2020) 80:986
https://doi.org/10.1140/epjc/s10052-020-8365-0

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Search for *CP* violation in $\Xi_c^+ \rightarrow pK^-\pi^+$ decays using model-independent techniques

LHCb Collaboration*
CH-1211, Geneva 23, Switzerland

Received: 8 June 2020 / Accepted: 8 August 2020

Abstract A first search for *CP* violation in the Cabibbo-suppressed $\Xi_c^+ \rightarrow pK^-\pi^+$ decay is performed using both a binned and an unbinned model-independent technique in the Dalitz plot. The studies are based on a sample of proton-proton collision data, corresponding to an integrated luminosity of 3.0 fb^{-1}, and collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV. The data are consistent with the hypothesis of no *CP* violation.

1 Introduction

The non-invariance of fundamental interactions under the combination of charge conjugation and parity transformation, known as *CP* violation (*CPV*), is a key requirement for the generation of the baryon–antibaryon asymmetry in the body decays offer access to more observables that are sensitive to *CP*-violating effects. For a three-body baryon decay the kinematics can be characterised by three Euler angles and two squared invariant masses, which form a Dalitz plot [19]. The Euler angles are redundant if all initial spin states are integrated over. Interference effects in the Dalitz plot probe *CP* asymmetries in both the magnitudes and phases of amplitudes. In three-body decays there can be large local *CP* asymmetries in the Dalitz plot, even when no significant global *CPV* exists. A recent example has been measured in the decay $B^+ \rightarrow \pi^+\pi^-\pi^+$ [20].

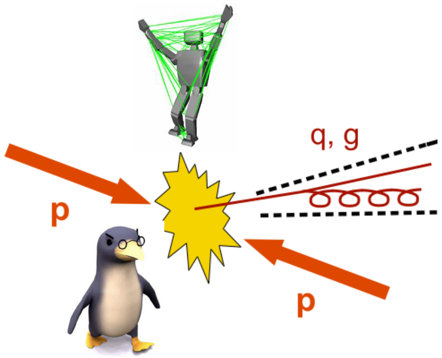
In the SM, *CPV* asymmetries in the charm sector are expected at the order of 10^{-3} or less [21] for singly Cabibbo-suppressed (SCS) decays. New physics (NP) contributions can enhance *CP*-violating effects up to 10^{-2} [22–30]. Searches for *CPV* in Ξ_c^+ baryon decays[1] provide a test of the

Why are we interested in flavour physics?

- The Standard Model (SM) is a theory which describes well existed data, but there are many phenomena which are not understood:
  - known value of CPV in the SM is too small to explain the observed size of matter domination over antimatter in universe
  - expected CPV in charm sector is small $\lesssim 10^{-3}$ (much smaller than in the beauty sector)

- The main goal of particle physics is to search for physics beyond the SM

There are two ways of searches for New Physics:



- direct searches for produced new objects (Atlas and CMS)

- indirect searches via testing the SM in precise measurements of known processes, finding disagreement will be indirect indication of new phenomena existence (BaBar, Belle, LHCb,…)

CP violation

Violation of charg-space parity **CPV** means that the laws of physics change if

- we replace a particle with an antiparticle (C)

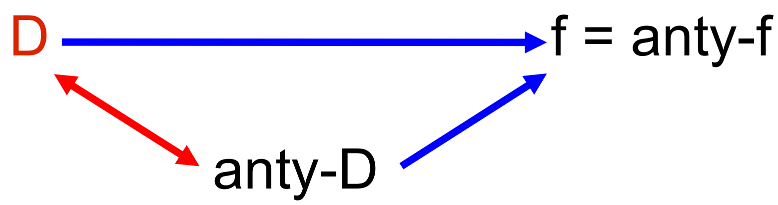
  and

- we change the directions of all coordinates $(x,y,z) \rightarrow (-x,-y,-z)$ (P)

  (the observed process is not a mirror image of the initial ones)

There are three ways of CPV:

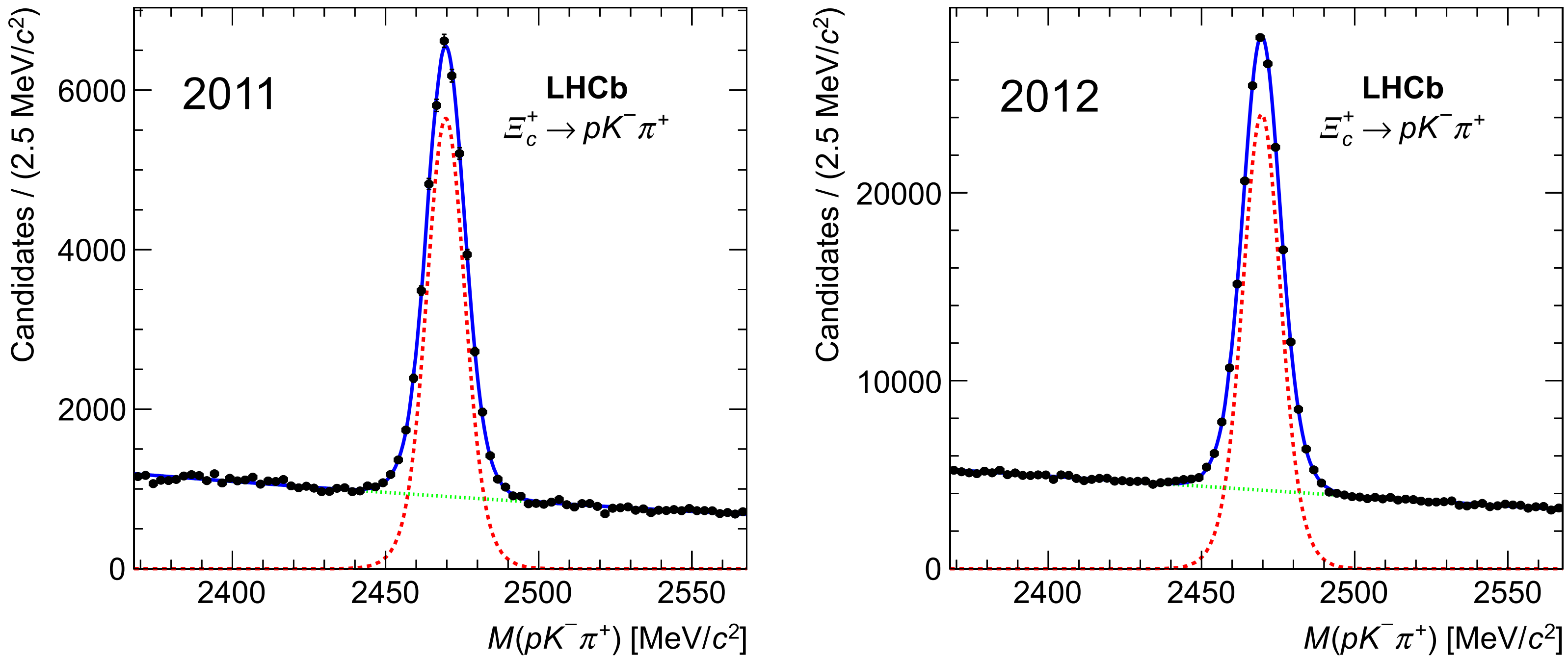
1. in mixing ($D^0 \rightarrow$ anty-$D^0 \neq$ anty-$D^0 \rightarrow D^0$)
2. direct (in decay amplitudes)
3. interference between direct decays and decays with mixing



- In the Standard Model, CPV is described by the CKM matrix
- So far, CPV is confirmed in K, B, B_s, D, but not in baryons (beauty and charm)
- Searches in $\Xi^+_c \rightarrow pK^-\pi^+$: only direct CPV

Statistics $\Xi^{+}_{c} \to pK^{-}\pi^{+}$

Eur. Phys. J. C80 (2020) 986



Ξ_c	2011	2012
magnet down	22701 ± 216	78688 ± 446
magnet up	15007 ± 181	77930 ± 484
Total	36410 ± 297	157420 ± 658

Ξ_c: 193 830 candidates

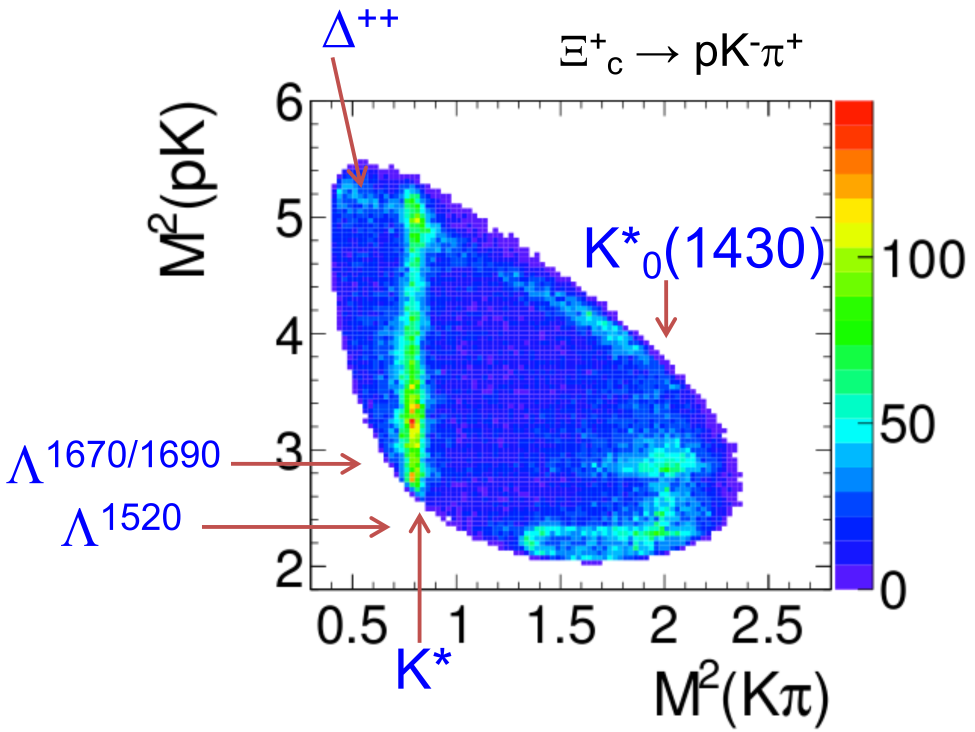
CP violation in Dalitz plot

- Decay products form many resonance states visible in Dalitz plot
  ⇒ strong phases vary from region to region

$$A_{CP} \propto sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

weak phases strong phases

Eur. Phys. J. C80 (2020) 986

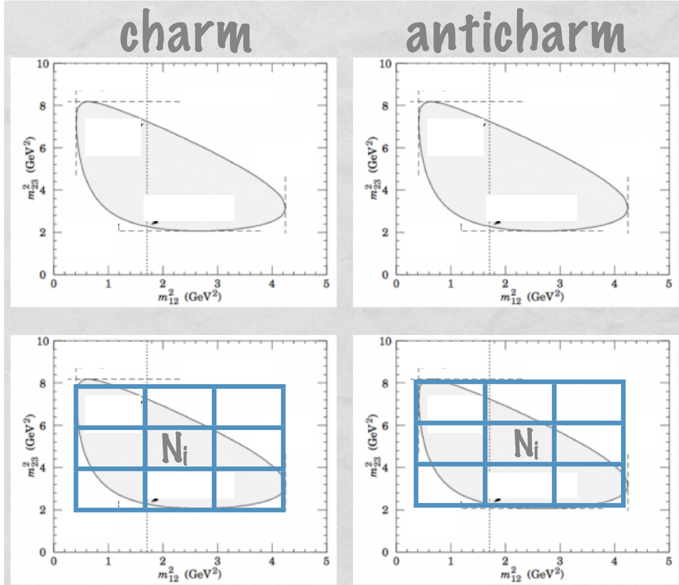


- The charge asymmetry can be measured locally in the regions of Dalitz plots
- No clear indications where CPV would appear
- To find asymmetries the Dalitz plots for Ξ^+_c and Ξ^-_c are compared locally (searches are based on techniques that are model-independent)

The binned S_{CP} method

- In each bin a significance of a difference between Ξ^+_c and Ξ^-_c is calculated

$$S^i_{CP} \equiv \frac{N^i_+ - \alpha N^i_-}{\sqrt{\alpha(N^i_+ + N^i_-)}} \qquad \alpha = \frac{N^+}{N^-}$$



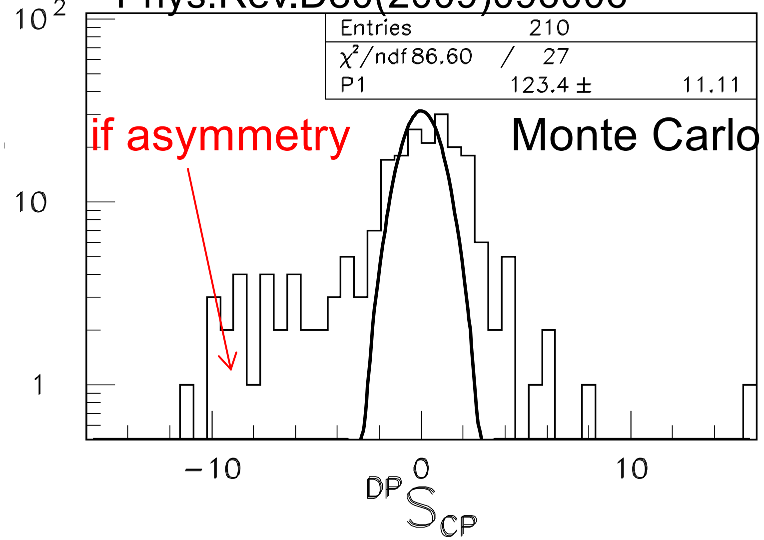
- To cancel global asymmetries (production asymmetry, etc.) the Dalitz plots are normalized

- If no CPV (only statistical fluctuations) then S_{CP} is Gauss distributed (μ=0, σ=1)

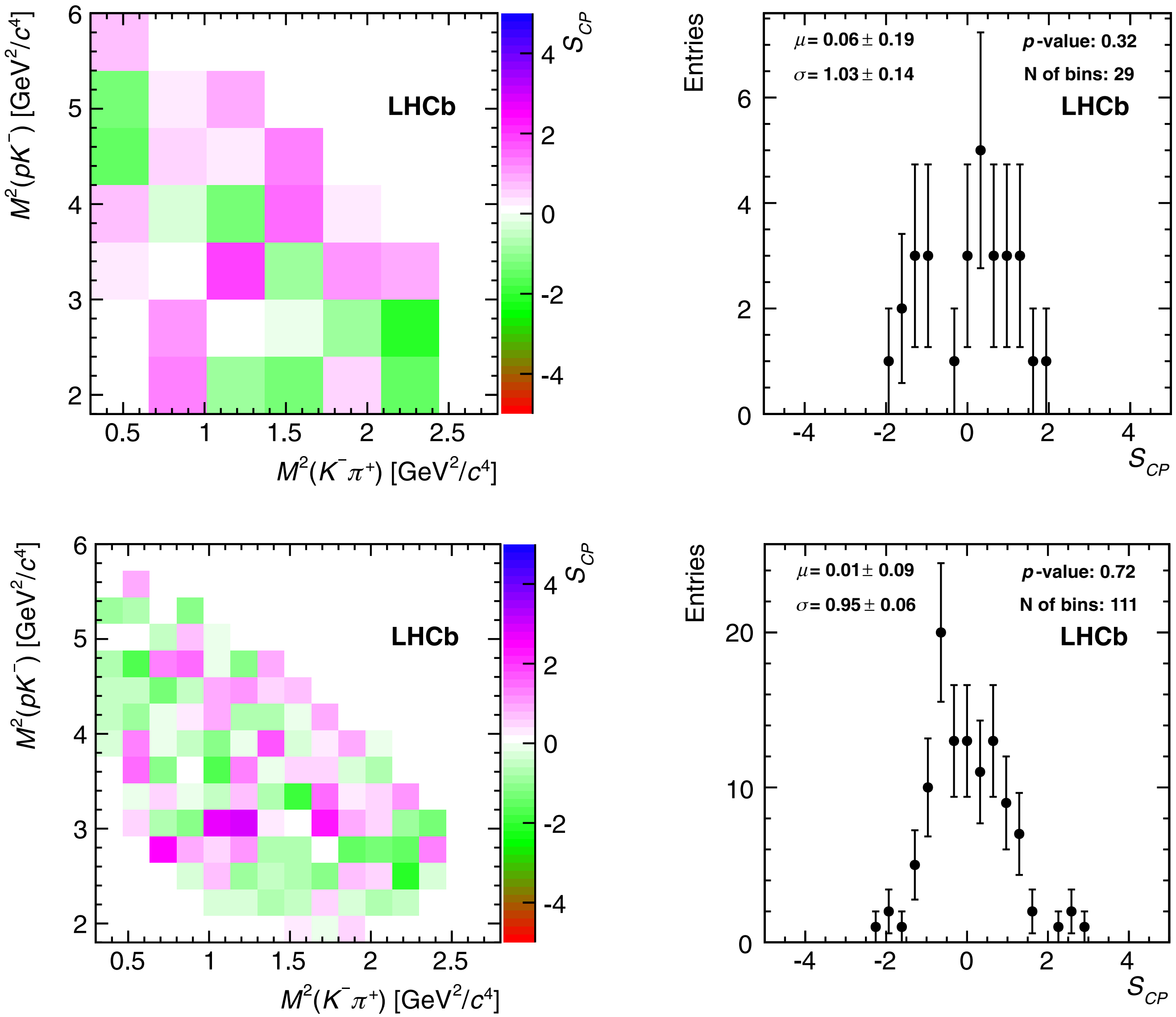
- The $\chi^2 = \Sigma {S^i_{CP}}^2$ test is calculated to obtain p-value for the null hypothesis to test if Ξ^+_c and Ξ^-_c distributions are statistically compatible

p-value ≪ 1 in case of CPV

Bediaga et al.
Phys.Rev.D80(2009)096006



Results using binned S_{CP} method

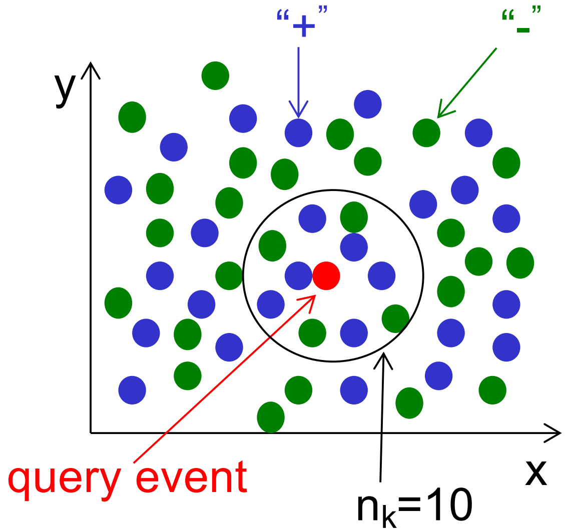


Eur. Phys. J. C80 (2020) 986

- Uniform and adaptive binning schemes with different bin numbers are tested
- S_{CP} distributions agree with the normal Gaussian function
- The p-values are greater than 32%
- Results are consistent with no observation of CP asymmetry.

The unbinned k-nearest neighbour method

Idea and analysis done by the Warsaw Group



- To compare "+" and "-" a test statistic T is defined, which is based on the counting particles with the same sign to each event for a given number of the nearest neighbour events

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

I(i,k) = 1 if i^{th} event and its k^{th} nearest neighbour have the same charge ("+"—"+" , "-"—"-")

I(i,k) = 0 if pair has opposite charge ("+"—"–")

- T is the mean fraction of like pairs in the pooled sample of the two datasets

- The expected distribution can be calculated using mean μ_T and variance σ_T

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

$$\lim_{n, n_k, D \to \infty} \sigma_T^2 = \frac{1}{n n_k}\left(\frac{n_+ n_-}{n^2} + 4\frac{n_+^2 n_-^2}{n^4}\right)$$

The kNN method

- The kNN method allows to find differences between two samples if they come from:

  ✧ normalization: if $n_+ \neq n_-$ then $\mu_T \neq \mu_{TR} = (n-2) / 2(n-1)$

  ➢ Production asymmetry can be manifested by different normalization

  ✧ shape: if $f_+ \neq f_-$ then $T \neq \mu_T$

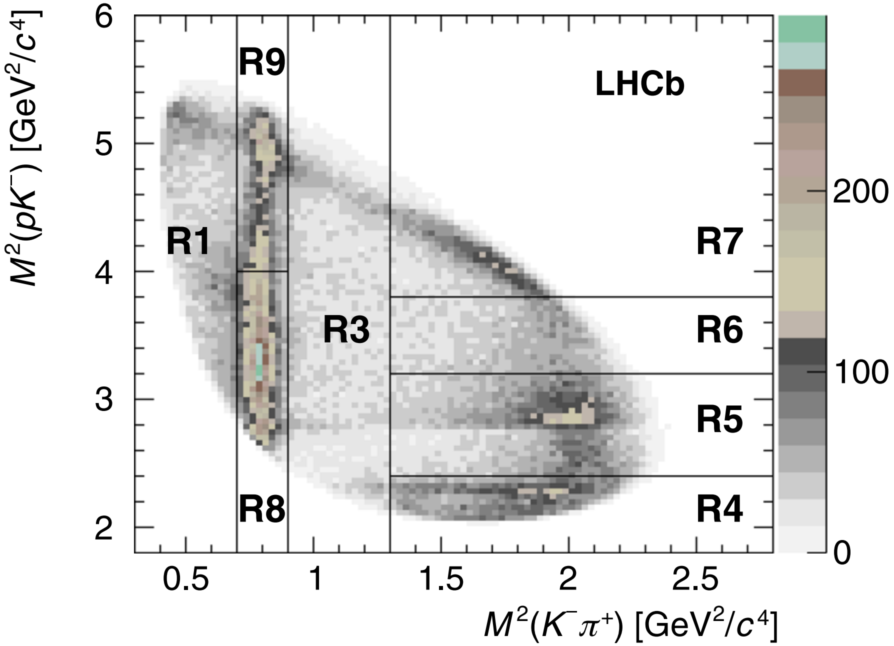
$\Longrightarrow$ the two numbers of standard deviations and corresponding p-values are calculated

p-value $\ll$ 1 in case of CPV

Dalitz plot division

To increase the power of the kNN method, the Dalitz plot is divided into regions

Eur. Phys. J. C80 (2020) 986



Dalitz plot division:

X= $M^2(K\pi)$;   Y=$M^2(pK)$

R1: X<0.7

R2: X≥0.7 & X<0.9   (R2=R8+R9)

R3: X≥0.9 & X<1.3

R4: X≥1.3 & Y<2.4

R5: X≥1.3 & Y≥2.4 & Y<3.2

R6: X≥1.3 & Y≥3.2 & Y<3.8

R7: X≥1.3 & Y≥3.8

R8: X≥0.7 & X<0.9 & Y<4

R9: X≥0.7 & X<0.9 & Y≥4

R10: X≥1.3 & Y<3.2   (R10=R4+R5)

R11: X≥1.3   (R11=R4+R5+R6+R7)

Resonances:

K^*, $K^*_0(1410)$, $K^*_0(1430)$, $K^*_2(1430)$,

Λ^{1520}, Λ^{1600}, Λ^{1890}, $\Lambda^{1670/1690/1710}$, $\Lambda^{1800/1820/1830}$,

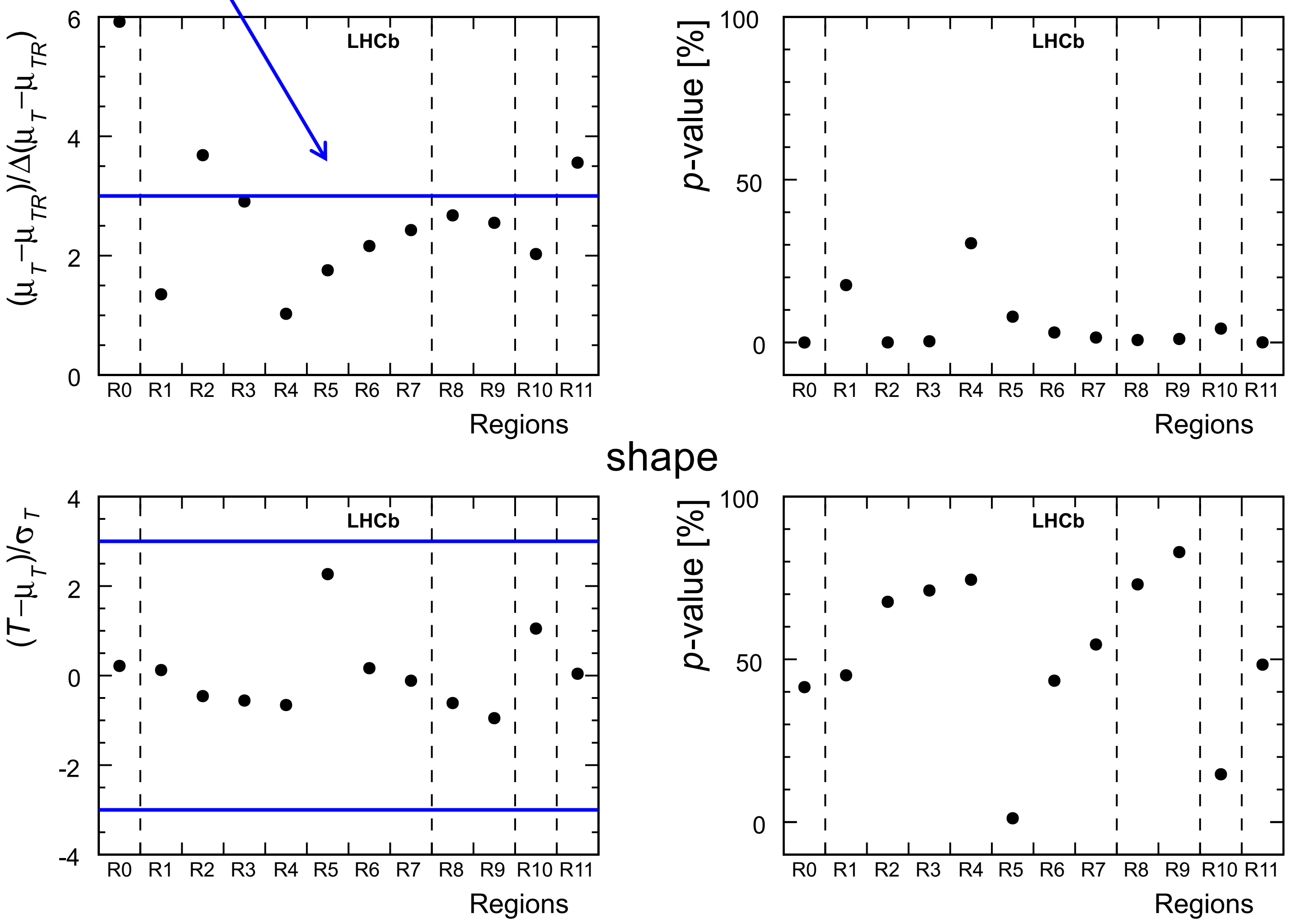
Δ^{++}, Δ^{1232}, $\Delta^{1600/1620}$, Δ^{1700}

Results using kNN method

Eur. Phys. J. C80 (2020) 986

production asymmetry

normalization



For the first time the Ξ^+_c production asymmetry of Ξ^+_c is estimated at LHC: A_{prod}~1.5 %

One p-value corresponds to 2.7σ of agreement

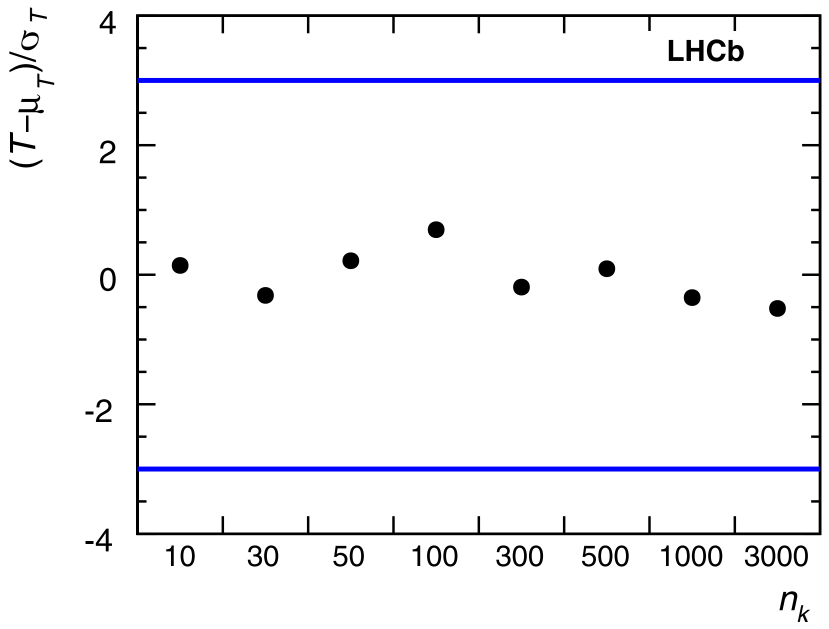
- Nonzero asymmetry in normalization part is an effect of nonzero production asymmetry
- No observation of CPV using the kNN method

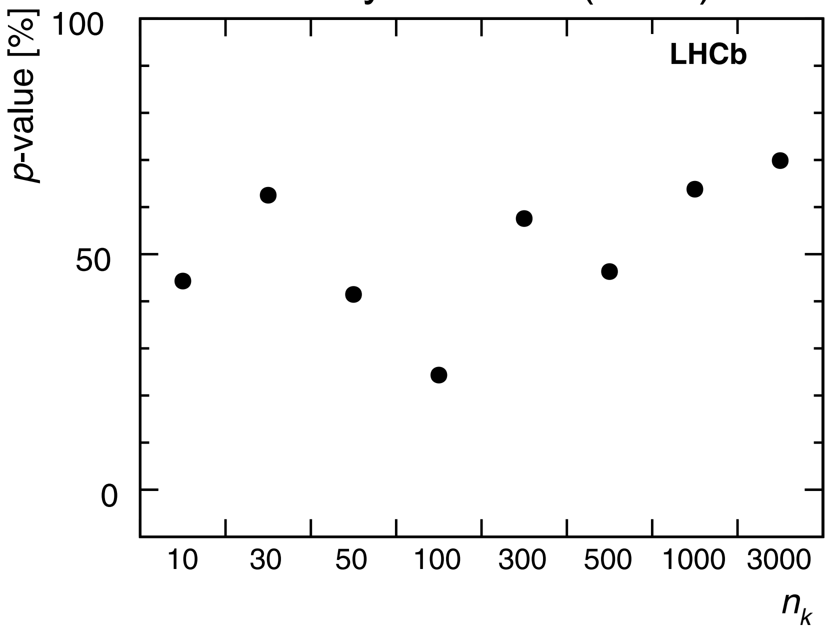
The n_k dependence

The n_k dependence (whole Dalitz plot, R0)

Note: points are correlated

Eur. Phys. J. C80 (2020) 986





- All points vary from -3σ to +3σ (for n_k from 10 to 3000)
- The results are consistent with no observation of CPV

Significance of the measurements

- The first searches for CPV in Ξ^{+}_{c} decays.
- Model-independent searches.
- For the first time the Ξ^{+}_{c} production asymmetry of Ξ^{+}_{c} is estimated at LHC: A_{prod}~1.5 %
- A unique search method for CPV in HEP – the k-nearest neighbour method.
- Monte Carlo studies give hope for the effectiveness of the kNN method. The sensitivity is not worse than the other methods, and sometimes it can be even better.
- The analysis is being continued with the collaboration of AGH LHCb Group. In Run 2 the yield of Ξ^{+}_{c} is four times larger than in Run 1. The other methods are going to be used: Energy Test, Kernel Density Estimator.

Summary

- The work would not be possible without the enormous support of the Warsaw LHCb Group
- Thanks to everyone who supported me and gave me helpful advices

Eur. Phys. J. C (2020) 80:986
https://doi.org/10.1140/epjc/s10052-020-8365-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Check for updates

Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ decays using model-independent techniques

LHCb Collaboration*
CH-1211, Geneva 23, Switzerland

Received: 8 June 2020 / Accepted: 8 August 2020

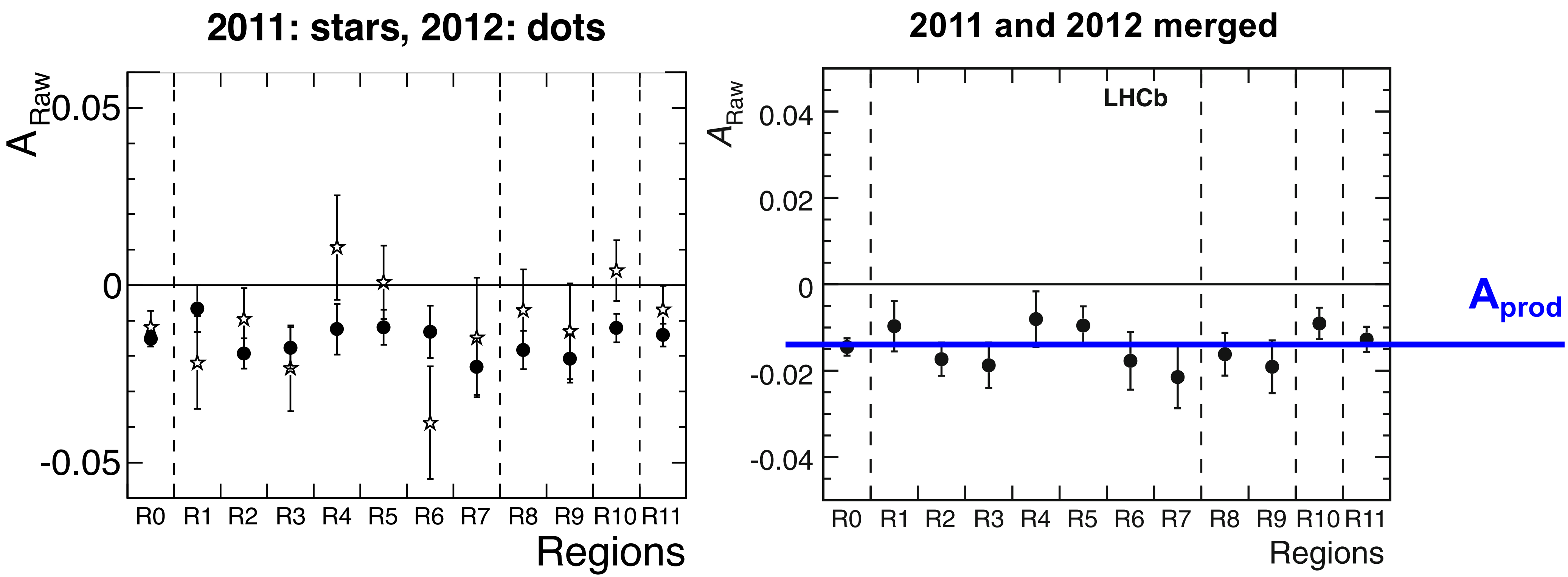
Abstract A first search for CP violation in the Cabibbo-suppressed $\Xi_c^+ \to pK^-\pi^+$ decay is performed using both a binned and an unbinned model-independent technique in the Dalitz plot. The studies are based on a sample of proton-proton collision data, corresponding to an integrated luminosity of 3.0 fb^{-1}, and collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV. The data are consistent with the hypothesis of no CP violation.

1 Introduction

The non-invariance of fundamental interactions under the combination of charge conjugation and parity transformation, known as CP violation (CPV), is a key requirement for the generation of the baryon–antibaryon asymmetry in the body decays offer access to more observables that are sensitive to CP-violating effects. For a three-body baryon decay the kinematics can be characterised by three Euler angles and two squared invariant masses, which form a Dalitz plot [19]. The Euler angles are redundant if all initial spin states are integrated over. Interference effects in the Dalitz plot probe CP asymmetries in both the magnitudes and phases of amplitudes. In three-body decays there can be large local CP asymmetries in the Dalitz plot, even when no significant global CPV exists. A recent example has been measured in the decay $B^+ \to \pi^+\pi^-\pi^+$ [20].

In the SM, CPV asymmetries in the charm sector are expected at the order of 10^{-3} or less [21] for singly Cabibbo-suppressed (SCS) decays. New physics (NP) contributions can enhance CP-violating effects up to 10^{-2} [22–30]. Searches for CPV in Ξ_c^+ baryon decays[1] provide a test of the

Back up



$$A_{RAW} = \frac{N_- - N_+}{N_+ + N_-}$$

R2=R8+R9

Within errors, the raw asymmetry in all regions is quite similar (negative ~ -1.5%). It has a characteristic behavior for the expected production asymmetry

- It was checked that the constant value of A_{RAW} in regions of the Dalitz plot is maintained in bins of η and p_T