Particle and Astroparticle Physics Division Seminar

The charm of the charming *CP* violation effects in the LHCb experiment

Cracow, 26th April 2022

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Menu

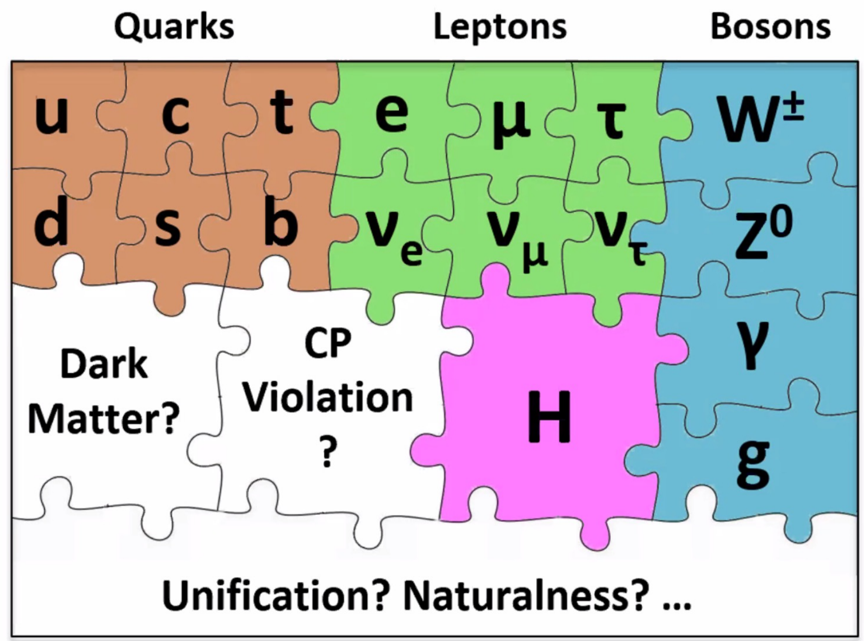
- **Introduction**
  - ✧ Why are we interested in flavour physics?
  - ✧ Known sources of *CP* violation in the Standard Model
  - ✧ Reconstruction of charm particles in the LHCb detector

- **The examples of the LHCb measurements**
  - ✧ The first observation of *CP* violation in $D^0 \to K^- K^+, \pi^- \pi^+$ mesons (2019)
  - ✧ The first observation of the mass difference between neutral charm mesons
  - ✧ The first search for *CP* violation in $\Xi^+_c \to pK^- \pi^+$ baryons
  - ✧ The first estimation of production asymmetry of Ξ^+_c

- **Summary and the nearest future**

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 *CP* violation (CPV) in the SM is too small to explain the observed size of matter domination over antimatter in the universe
  - ➢ 7 April ’22: the measured *W* mass is different from the SM calculations! (CDF collaboration)

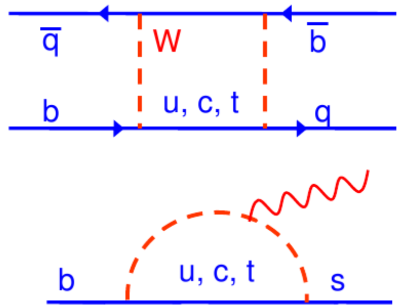
- The main goal of particle physics is to search for physics beyond the SM

Why are we interested in flavour physics?

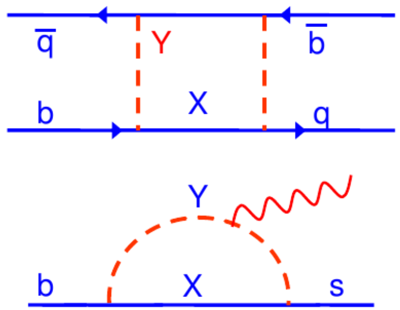
- The LHCb does indirect searches for new physics via testing the Standard Model in very precise measurements of known processes
  - ➢ finding disagreement will be indirect indication of new phenomena existence

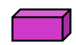
- The new particles can appear in the loops

Standard Model



New physics



box diagrams 

penguin diagrams 

- In particular, *CP* violation in charm sector is very promising
  Why? → This seminar!

Neutral mesons mixing (oscillation)

- Neutral mesons can change (oscillate) into their own antiparticles, as the mass eigenstates are linear combinations of the flavour eigenstates

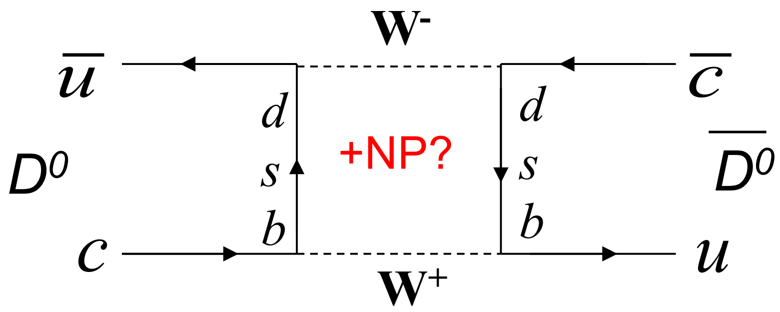
$$i\frac{d}{dt}\begin{pmatrix}|D^0\rangle\\|\overline{D}^0\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0\rangle\\|\overline{D}^0\rangle\end{pmatrix}$$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Mass eigenstates are different from flavour eigenstates

- The flavour-changing neutral currents do not occur at tree level in the SM

- They allow for hypothetical particles of arbitrarily high mass to contribute significantly to the process



- This can affect the mixing of mesons and antimesons such that measurements of these processes can probe physics beyond the SM

Neutral mesons mixing

Two parameters describe mixing: mass difference *x* and decay with difference *y*

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

In theory: $x \approx y$

experiment theory

$$\Delta m = M_H - M_L = 2|M_{12}|(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|cos\phi(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...)$$

x, *y* – the dimensionless parameters

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

weak phase (*CP*-violating phase): $\phi \equiv arg(-M_{12}/\Gamma_{12})$

theory

$$m \equiv (m_1 + m_2)/2$$

$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

If $\phi \neq 0$ or $|p/q| \neq 1$ then *CP* violation occurs

So far, the current world averages:

$x = (3.7 \pm 1.2) \cdot 10^{-3}$ (≈ 0 !)

$y = (6.8^{+0.6}_{-0.7}) \cdot 10^{-3}$ ($\not\approx 0$)

$|q/p| = 0.951^{+0.053}_{-0.042}$ (≈ 1)

$\phi = -0.092^{+0.085}_{-0.079}$ (≈ 0)

HFAG, arXiv: 1909.12524

x (Δm), *y* ($\Delta\Gamma$), ϕ – measured experimentally

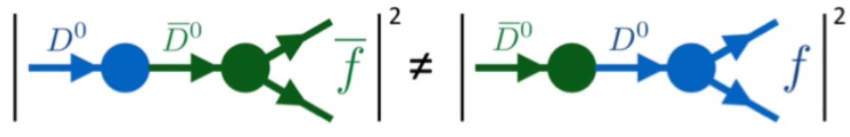
The data remain marginally compatible with $x \approx 0$, and are consistent with *CP* symmetry

Three ways of *CP* violation in the Standard Model

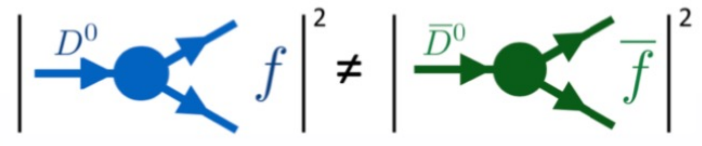
$P^0 = K^0, B^0, B^0_s, D^0$

$P^\pm = K^\pm, B^\pm, B^\pm_s, D^\pm, \Lambda^\pm_b, \Lambda^\pm_c, \Xi^\pm_c \ldots$

1. In the mixing (only neutral particles)
   $P^0 \rightarrow$ anti-P^0 $\neq$ anti-$P^0 \rightarrow P^0$



2. In the amplitudes of direct decays
   (neutral and charge particles)
   $P^\pm \rightarrow f$ $\neq$ anti-$P^\pm \rightarrow$ anti-f



3. In the interference between
   direct decays and decays via
   mixing (only neutral particles)

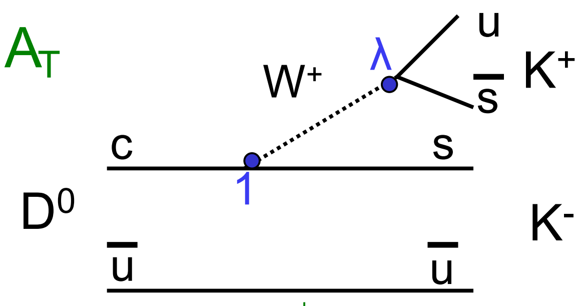
Mixing and decay processes can be mediated via loop diagrams.
New physics is likely to enter in loops where new particles can be exchanged.

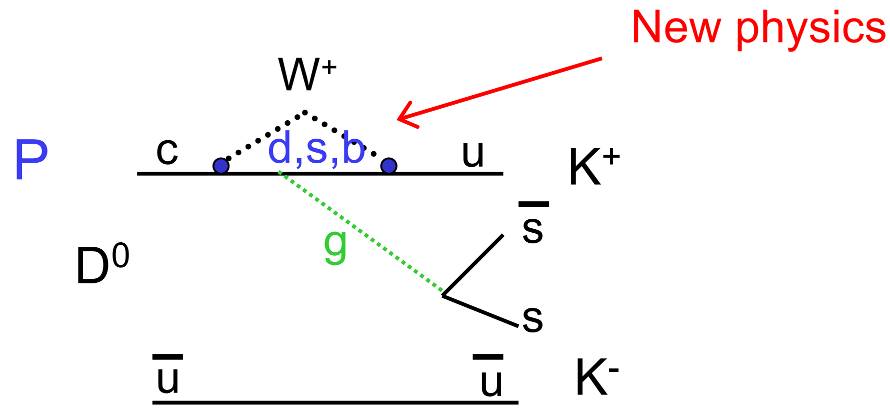
CP violation in direct decays

Singly Cabibbo−suppressed decay (SCS):

- a place for *CP* violation in the Standard Model (only)
- both: tree and penguin diagrams

$\lambda = 0.22$





$$A = \underbrace{V_{us}V^*_{cs}}_{\sim\lambda} A_T + \underbrace{V_{ud}V^*_{cd}}_{\sim\lambda} P_d + \underbrace{V_{us}V^*_{cs}}_{\sim\lambda} P_s + \underbrace{V_{ub}V^*_{cb}}_{\sim\lambda^6} P_b$$

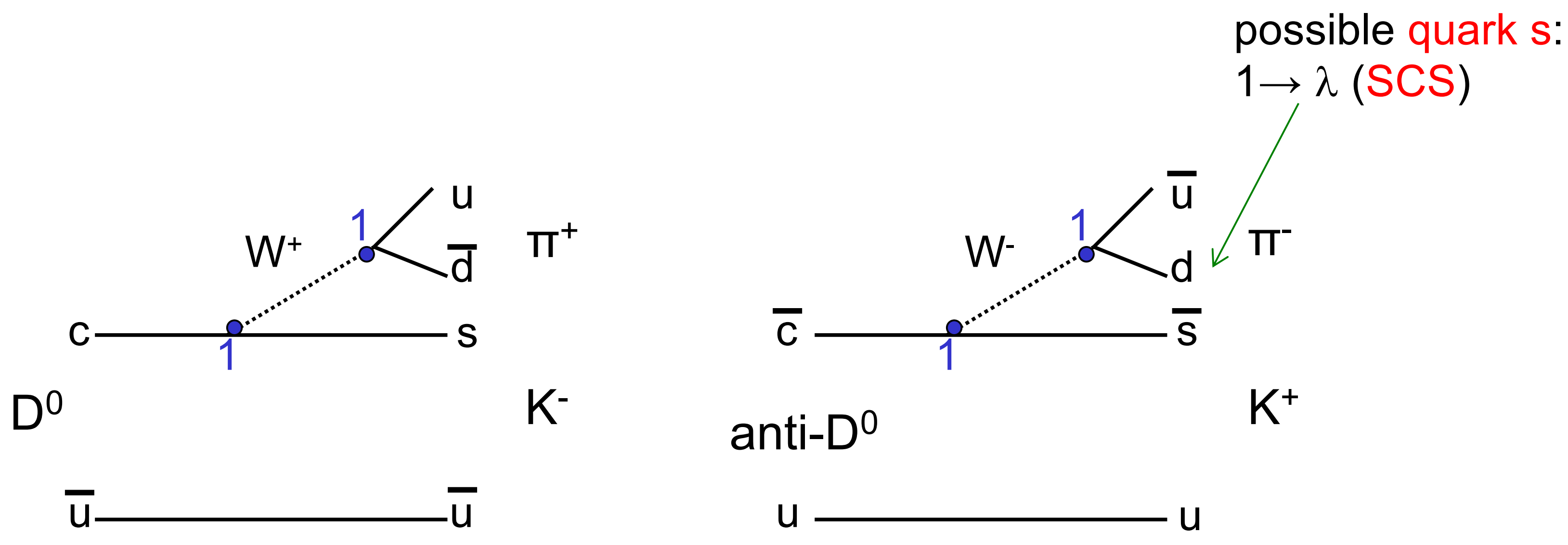
$$Asym_{CP} \sim |A_1||A_2| sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

$=A_T$ $=P$ weak phases strong phases !!!

To observe *CP* violation, at least two amplitudes must interfering with different weak phases AND DIFFERENT STRONG PHASES

Cabibbo−favoured decay (CF)

- no penguin contribution and no *CP* violation in the Standard Model
- used to check the detector effects (control decays)



In contrast to CF and SCS, there are doubly Cabibbo−suppressed decays (DCS)

- no tree diagrams, only penguin with loops
- no *CP* violation in the Standard Model
- any signal of *CP* violation means new physics existence

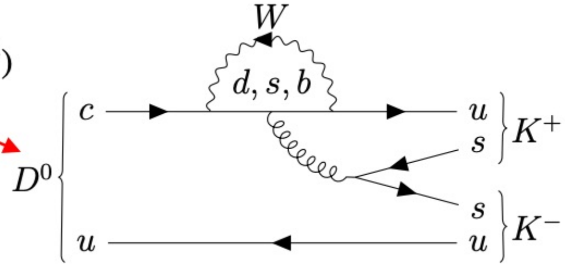
Re-scattering contribution

In the Standard Model, *CP* violation is expected to be detectable only in singly Cabibbo-supressed decays

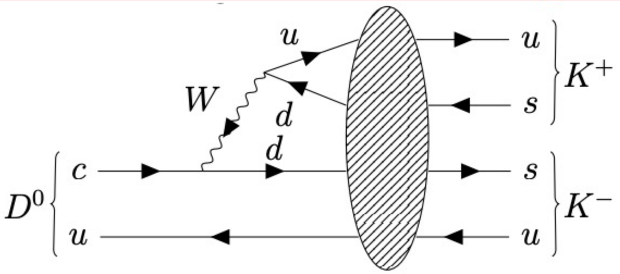
d s b

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \; -iA\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

u c t

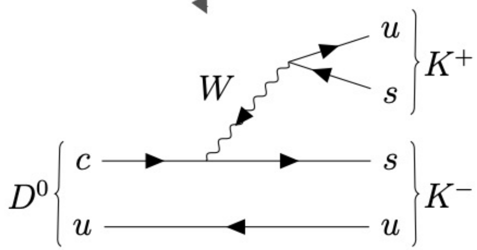


QCD penguin



Re-scattering: d anti-d → s anti-s

It may be more important than we thought previously



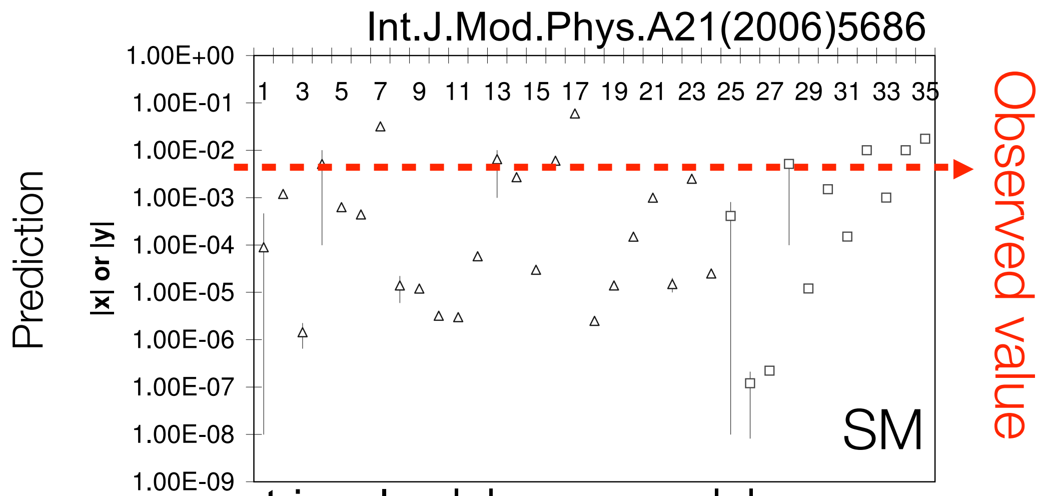
Tree

Re-scattering following a tree level amplitude and *CP* violation follows from tiny nonunitary of 2 x 2 CKM submatrix

The Standard Model predictions for charm

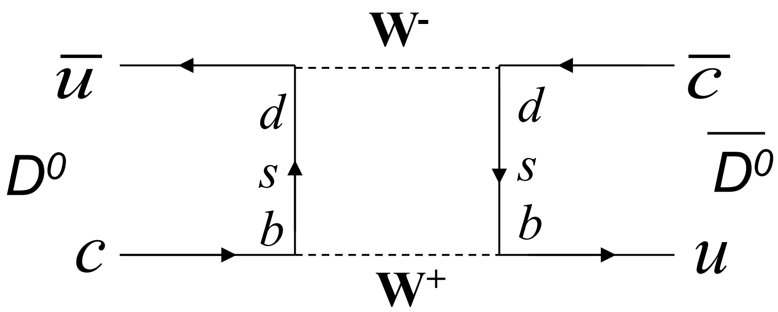
- Predicted CPV in charm sector is very small $\lesssim 10^{-4} - 10^{-3}$ (much smaller than in the beauty sector)
- The SM predictions vary widely
- New physics contributions can enhance CPV up to 10^{-2}

Int.J.Mod.Phys.A21(2006)5381 ; Ann.Rev.Nucl.Part.Sci.58(2008)249

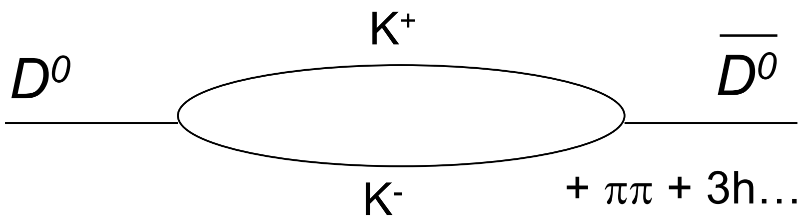


triangles |x| ; squares |y|

$x \sim y < 1\%$



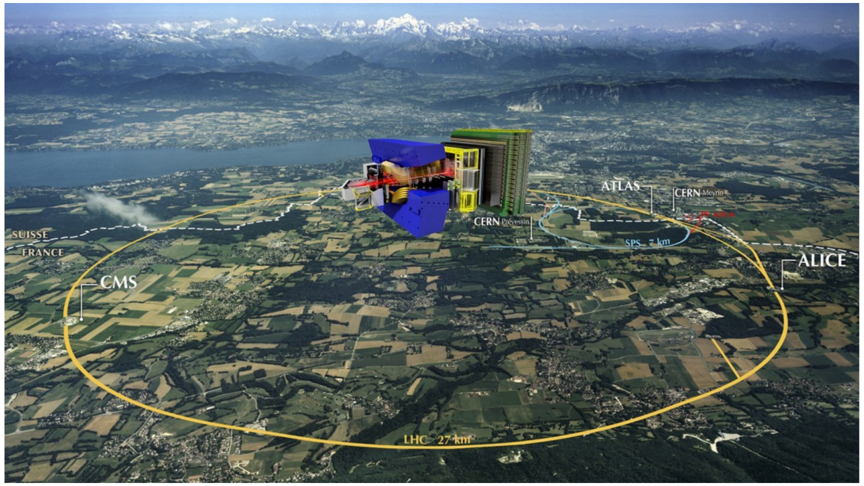
Mixing via box diagram, short range

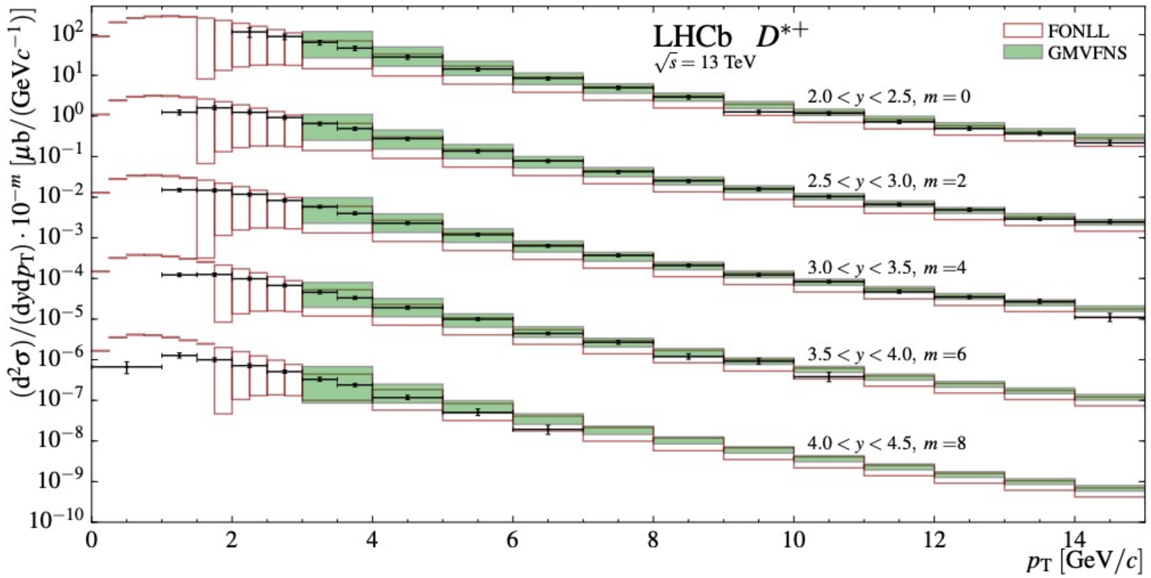


+ rescattering (new issue)

Mixing via hadronic intermediate states, long range (difficult to calculate)

Perfect place for new physics searching (small background from the SM)
Since *CP* violation, *x* and *y* are very small, we need very precise detector to measure observables with extremely high accuracy → LHCb at LHC





In the LHCb acceptance:

$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\ \mu b \quad (\sqrt{s} = 7\ \text{TeV})$ Run 1 (2011-2012)

Phys.Lett.B694 (2010) 209-216

$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116\ \mu b \sim 20 \times \sigma(b\bar{b}) \quad (\sqrt{s} = 7\ \text{TeV})$ Run 1 (2011-2012)

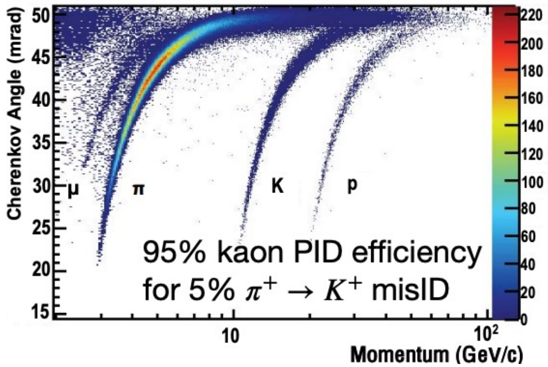
Nucl.Phys.B871 (2013) 1

$\sigma(c\bar{c}) = 2369 \pm 3 \pm 152\ \mu b \quad (\sqrt{s} = 13\ \text{TeV})$ Run 2 (2015-2018)

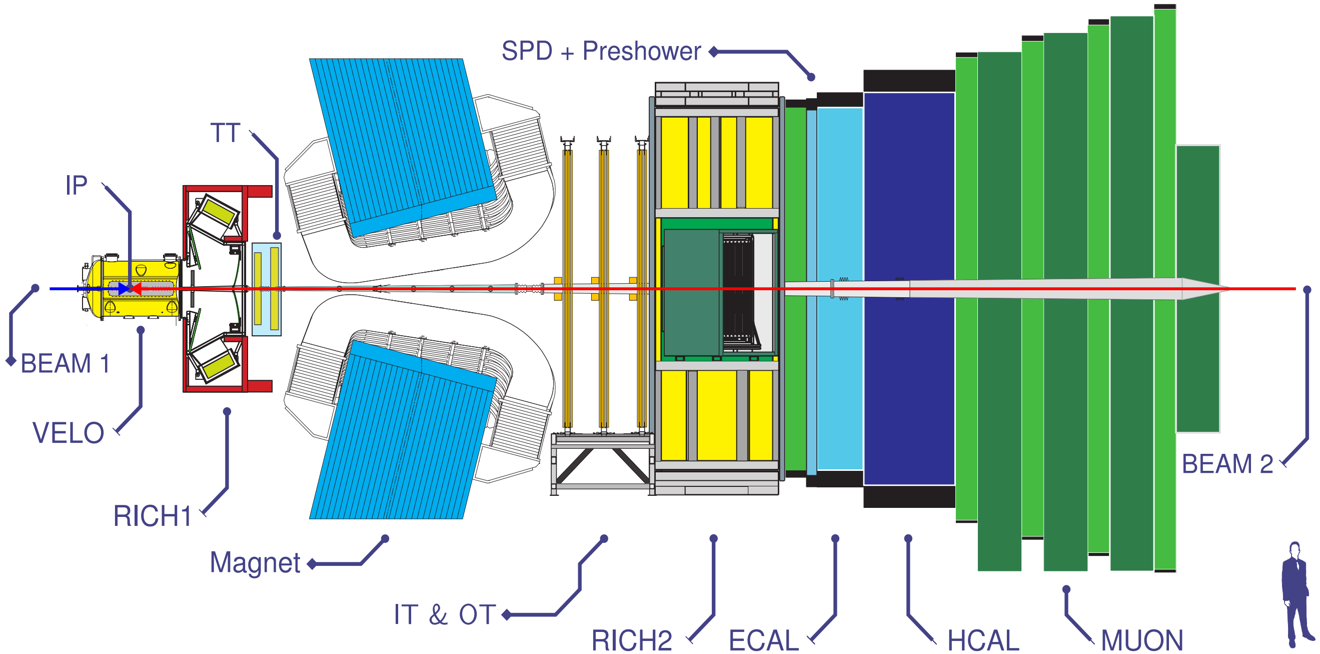
JHEP 05 (2017) 074

- LHC produces the largest number of *c* – anti-*c* pairs in the world
- Mostly boosted at large η ($2 < \eta < 5$)

LHCb: charm-ing and beauti-ful experiment at LHC



The single-arm forward spectrometer
(a new concept for HEP experiments)
Status at the end of 2018



Run 1 (2011-2012): 3/fb
Run 2 (2015-2018): 6/fb

For each 1/fb:
~28k $B^0_s \to J/\psi(\mu\mu)\ \phi(K^+K^-)$
~2M $D^{*\pm} \to D^0(\to K^-K^+)\pi^\pm$

- VELO – precision primary and secondary vertex measurements,
  resolution of IP: 11+23.6/p_T μm, decay τ resolution ~ 45 fs: 0.1 $\tau(D^0)$
- Excellent tracking resolution: $\Delta p/p$ = 0.4% at 5 GeV to 0.6% at 100 GeV
- RICH – very good particle identification for π and K, misidentification < 5%

Measuring *CP* asymmetry

- The $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are used to measure the time integrated *CP* violation
- The measured raw asymmetry A_{raw} may be written as a sum of components that are physics and detector effects:

$$A_{raw}(f) = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}$$

$$A_{raw}(f) \approx A_{CP}(f) + A_{D}(f) + A_{P}(D)$$

CP asymmetry what we want to measure

The detector asymmetries of particle reconstructions

The production asymmetry (different numbers of *D* and anti-*D* at the production vertex)

The A_{raw}, A_D and A_P are order ~2% or smaller but A_{CP} is smaller than 10^{-3}

The first observation of *CP* violation in charm

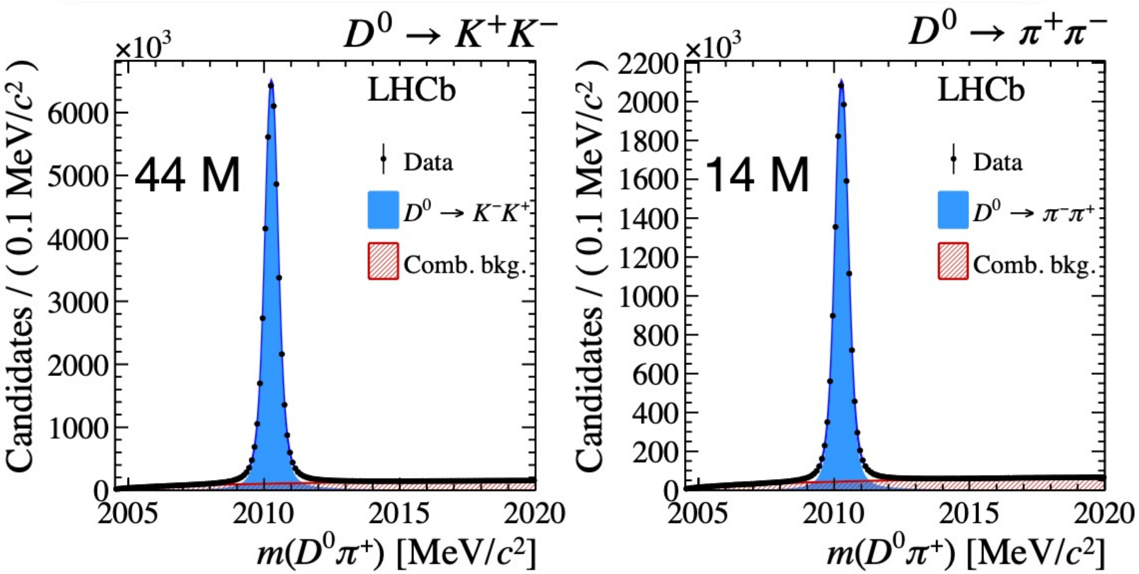
- The detector asymmetries for K^-K^+ and $\pi^-\pi^+$ cancel since the final states are charge symmetric
- The A_P is independent of the final state and this term cancels in the first order if we subtract raw asymmetries

$$A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) =$$
$$= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \equiv \Delta A_{CP} = (-1.54 \pm 0.29) \cdot 10^{-3}$$ (5.3σ)

PRL 122 (2019) 211803

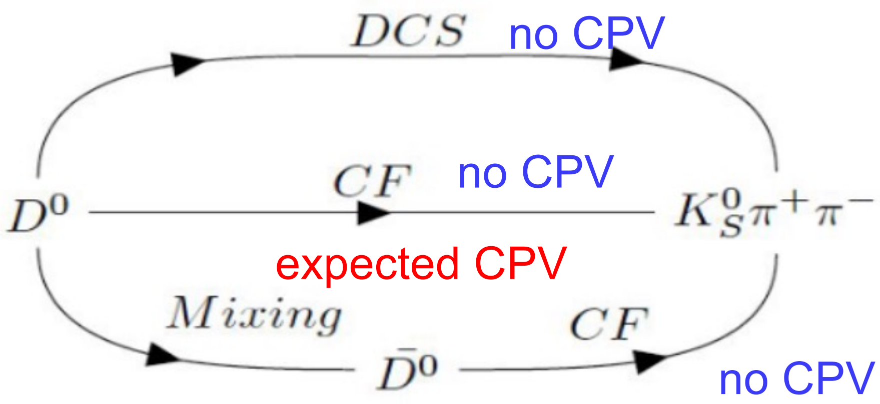
$$\Delta A_{CP} = [a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

[JHEP 1106 (2011) 089]



- 2015-2018, 5.7/fb
- Direct (majority) and indirect *CP* asymmetries contribute
- Indirect CP asymmetry is smaller than 10%

Prompt $D^{*+} \rightarrow D^0 (\rightarrow K^0_s \pi^+ \pi^-) \pi^+$

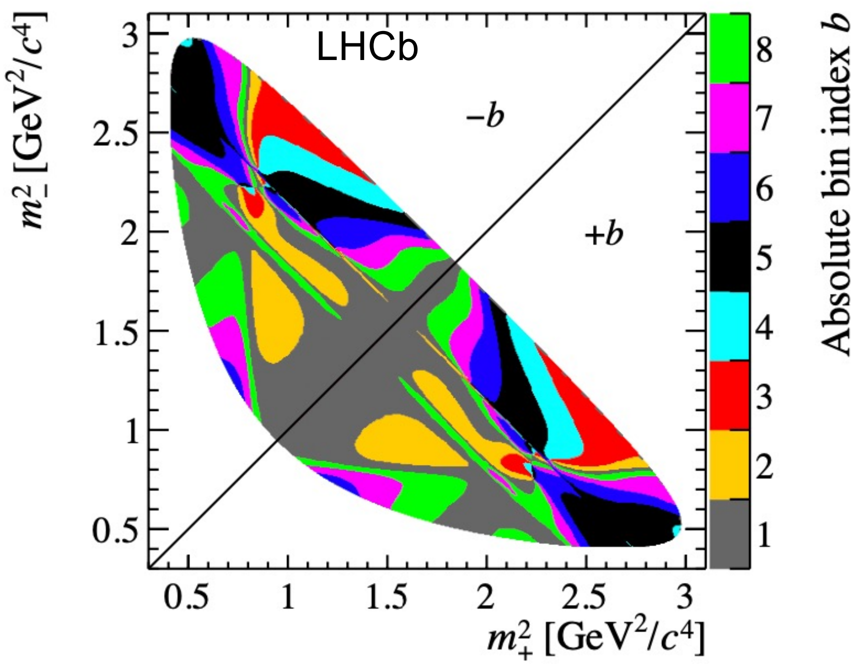


- In the Standard Model:
  - *CP* is negligible in CF and DCS
  - *CP* is expected in the interference between mixing and decay

- The dynamics of the decay are expressed as a function of two squared invariant masses following the Dalitz-plot formalism

The bin-flip method

Phys. Rev. Lett. 127 (2021) 111801

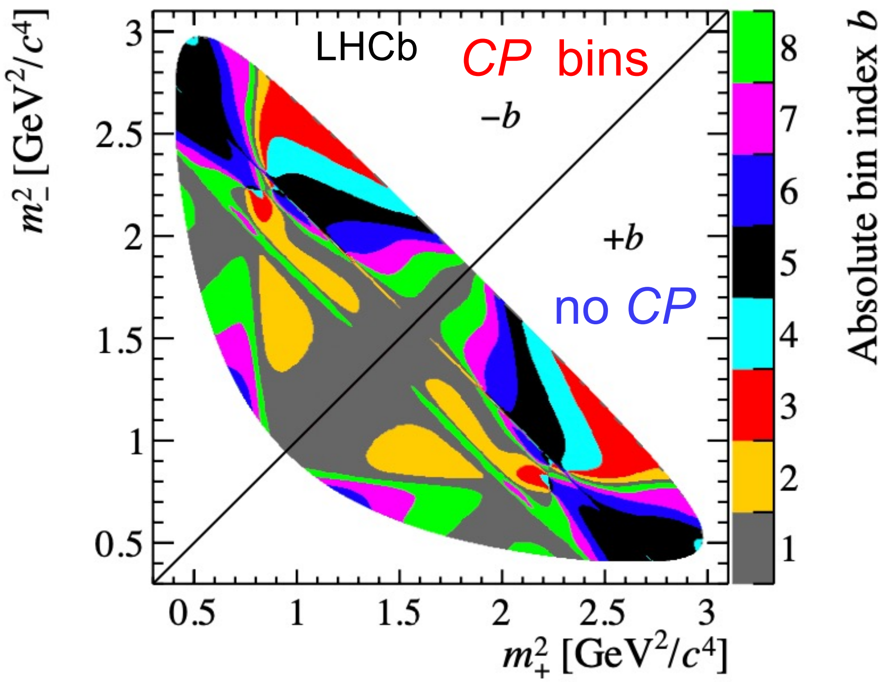


$$m^2_{\pm}(K^0_s\pi^{\pm}) \text{ for } D^0$$
$$m^2_{\mp}(K^0_s\pi^{\mp}) \text{ for } \bar{D}^0$$

The bin-flip method

- A model-independent approach
- Data are partitioned into 8 disjoint bins (formed symmetrically), which are defined to preserve nearly constant strong phase differences between D^0 and anti-D^0 amplitudes within each bin (external inputs from CLEO and BES III)
- Region with $m^2_+ > m^2_-$ are dominated by CF D^0 decays (marked $+b$), no CP
- In the opposite region (marked $-b$), the relative contribution from decays following an oscillation is enhanced, expected CP

Phys. Rev. Lett. 127 (2021) 111801

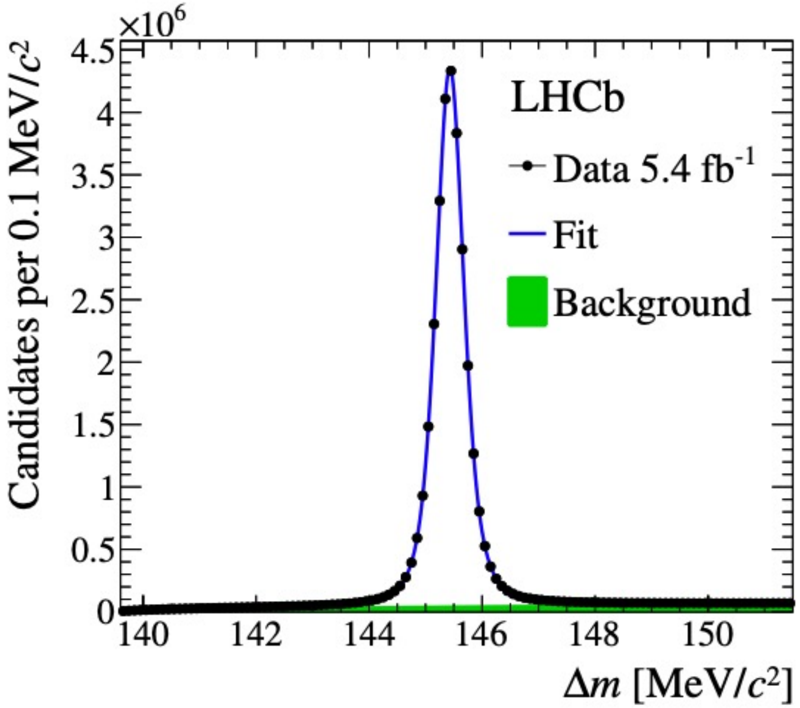


To find signal of CP violation, the ratio (R) of the number of decays in each negative Dalitz-plot bin ($-b$) to its positive counterpart ($+b$) is measured in the time dependence, separately for D^0 and anti-D^0

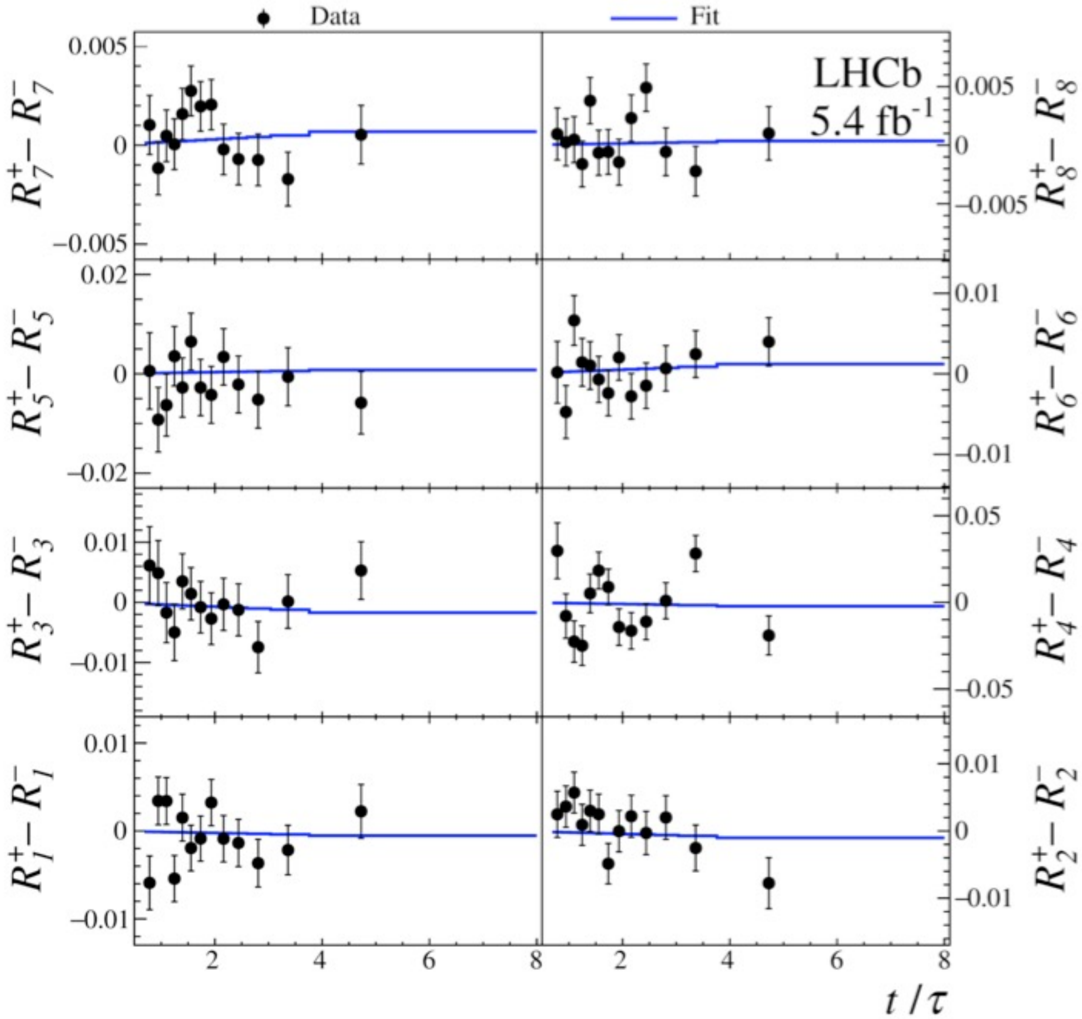
Prompt $D^{*+} \to D^0\ (\to K^0_s \pi^+ \pi^-)\ \pi^+$

Phys. Rev. Lett. 127 (2021) 111801

30.6 M candidates



Differences of D^0 (R^+) and anti-D^0 (R^-) ratios



The resolutions are smaller than the bin sizes:

- for squared-mass ~0.006 GeV^2
- for decay-time ~60 fs

Fit ratios (R) to obtain: x, y, $|q/p|$, ϕ

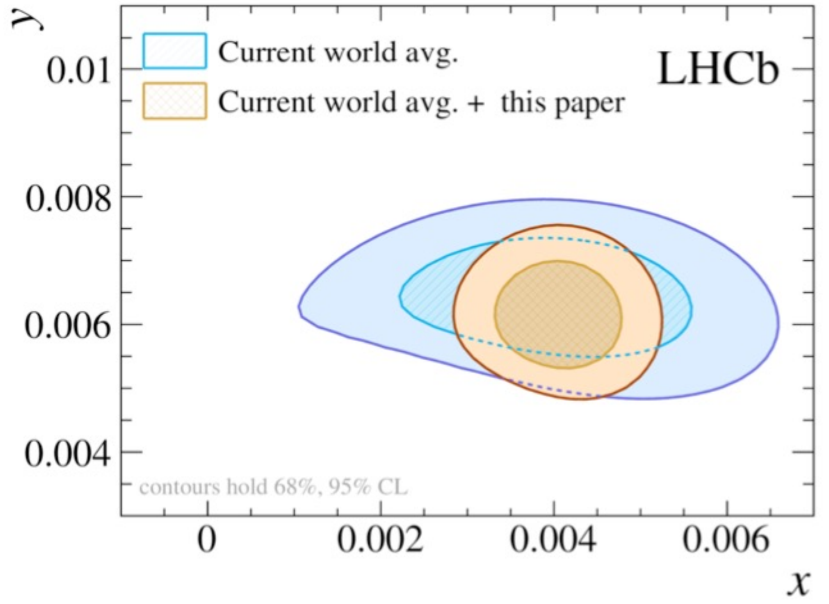
The first observation of the mass difference in charm

Phys. Rev. Lett. 127 (2021) 111801

Obtained from fit to the measured ratios

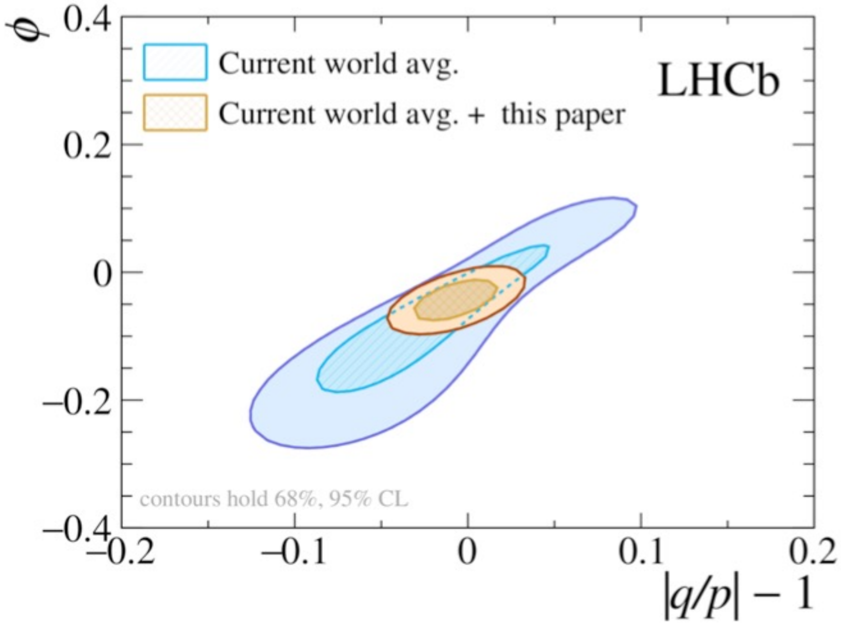
$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$



- The first observation of nonzero x (>7σ)
- The uncertainty on y is worse wrt. previous measurements, but x is measured more precisely (the bin-flip method is optimized for the measurement of mass difference)
- Data are consistent with *CP* symmetry
- Is there discrepancy between x and y ?

To be continued….

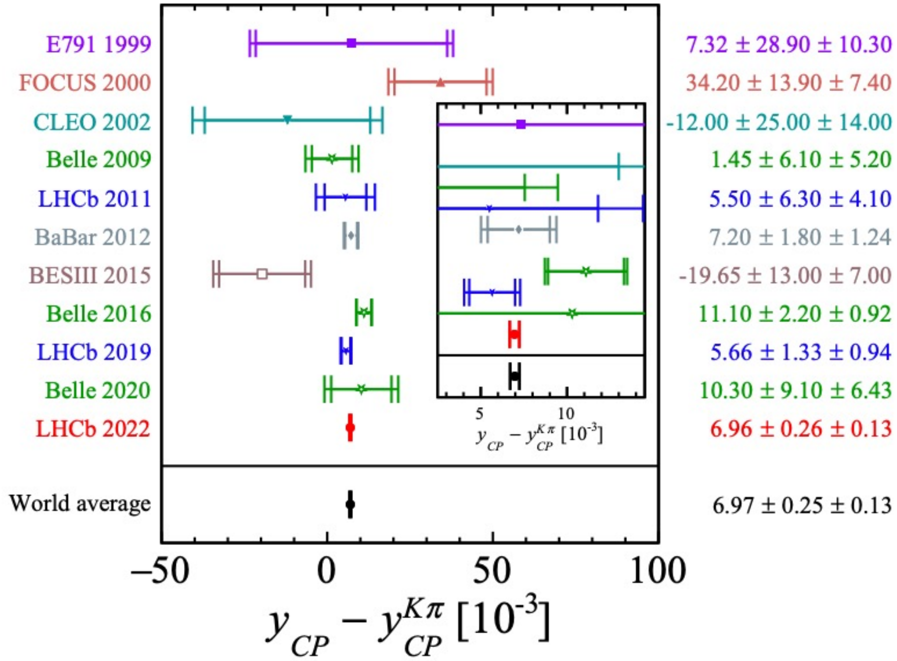


Presented at Moriond 2022
arXiv:2202.09106 (LHCb-PAPER-2021-041)

y can be probed using $D^0 \to K^-\pi^+$
and $D^0 \to f$ with $f \to K^-K^+, \pi^-\pi^+$
via observable $y^f_{CP} - y^{K\pi}_{CP}$:

$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y^f_{CP} - y^{K\pi}_{CP} \approx y(1+\sqrt{R_D})$$

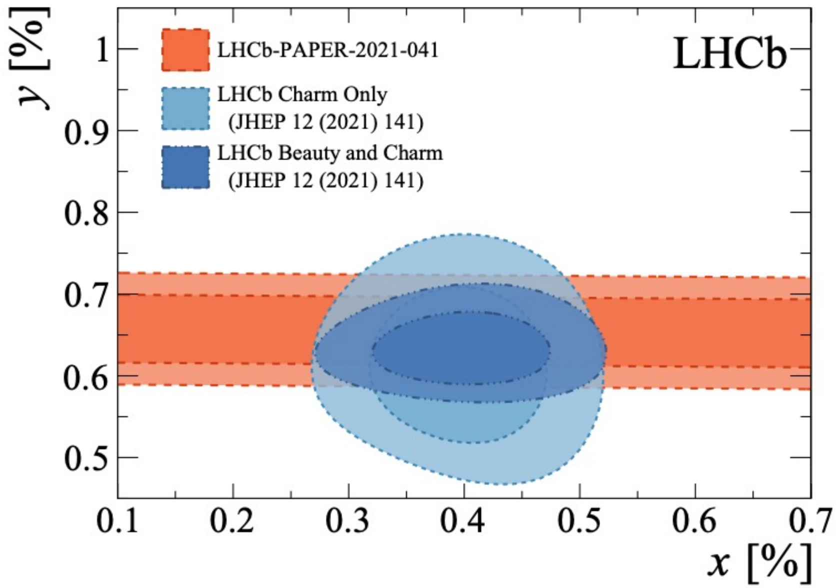
$$R_D = \frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}$$



Calculated y parameter:

$$y = (6.46^{+0.24}_{-0.25}) \times 10^{-3}$$

Improvement by more than a factor 2!



Charm oscillation parameter y is measured with statistical uncertainty of 0.25×10^{-3}

A search for physics beyond the Standard Model

Eur.Phys.J. C80 (2020) 986

AGH University of Science and Technology Press
Cracow, 2021
ISBN: 978-83-66727-27-4

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

THE EUROPEAN PHYSICAL JOURNAL C

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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

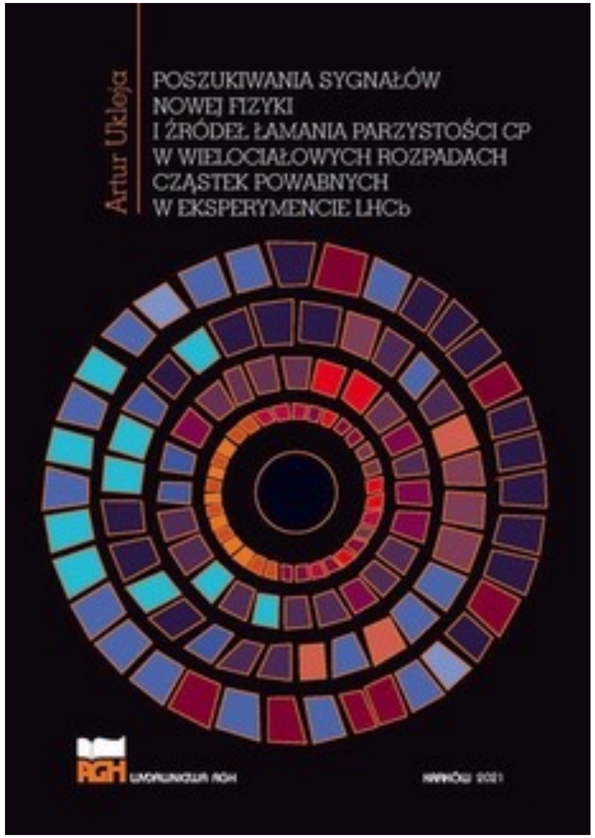
Received: 8 June 2020 / Accepted: 8 August 2020

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 $3.0\,\text{fb}^{-1}$, 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].

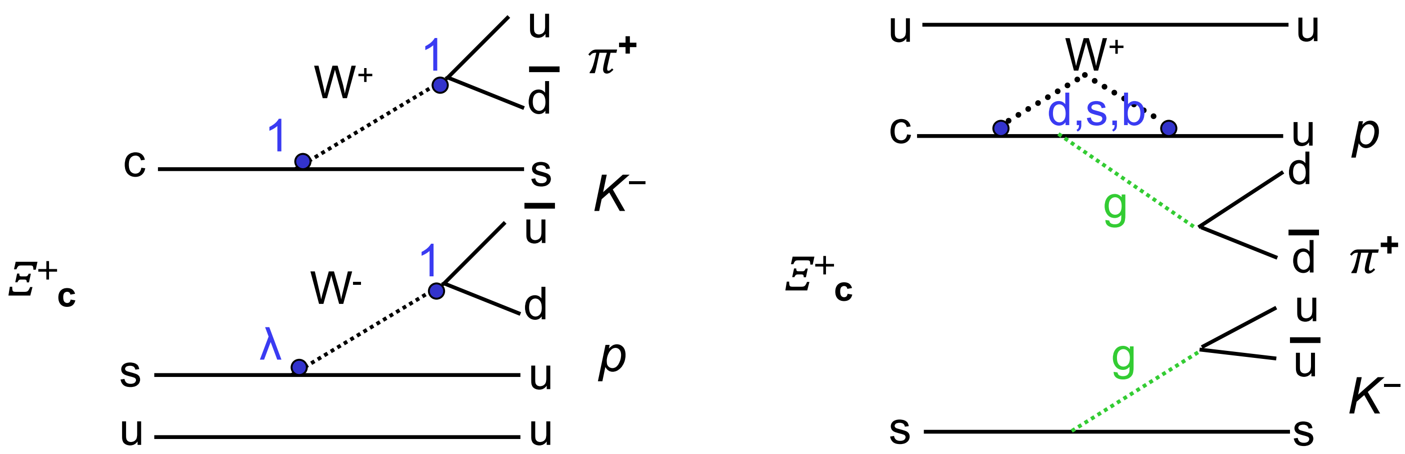
In the SM, *CPV* asymmetries in the charm sector are expected at the order of 10^{-3} or less [21] for singly Cabibbo-suppressed (SCS) decays. New physics (NP) contributions can enhance *CP*-violating effects up to 10^{-2} [22–30]. Searches for *CPV* in Ξ_c^+ baryon decays[1] provide a test of the



Mechanism of *CP* violation in $\Xi^{+}_{c} \rightarrow pK^{-}\pi^{+}$ decays

The $\Xi^{+}_{c} \rightarrow pK^{-}\pi^{+}$ decays are singly Cabibbo-suppressed decays = place of *CP* violation in the Standard Model

λ = 0.22



- If tree and penguin processes interfere with different phases for Ξ^{+}_{c} and Ξ^{-}_{c} then *CP* symmetry is broken
- Penguin diagram opens possibilities for new particles exchanging

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

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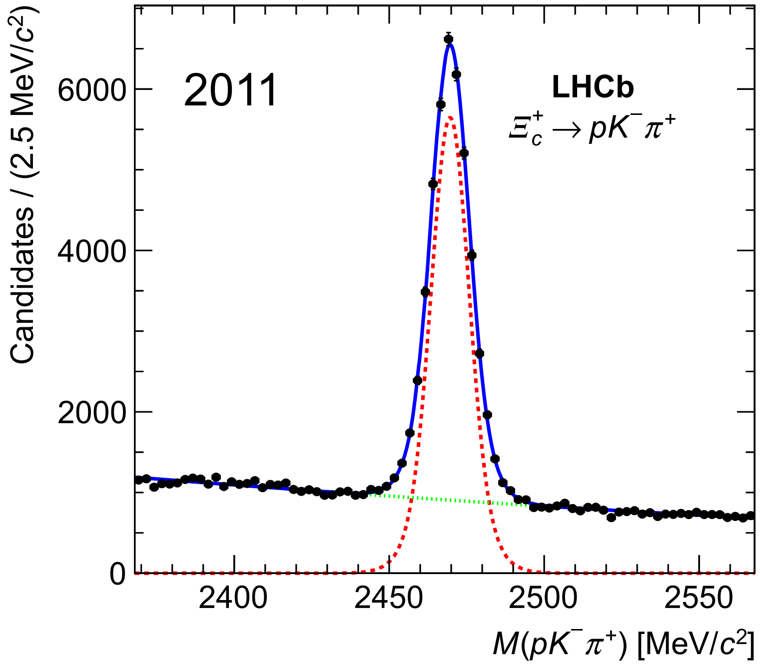

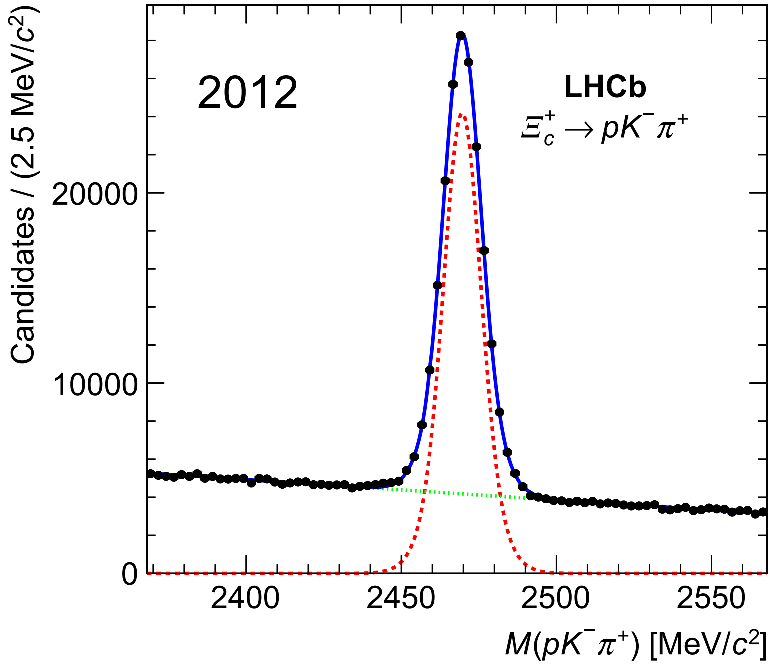

Ξ_c	2011	2012
Magnet Down	22701 ± 216	78688 ± 446
Magnet Up	15007 ± 181	77930 ± 484
Total	36410 ± 297	157420 ± 658

In full Run 1, there are ~ 0.2M prompt $\Xi^{\pm}_{c}$ candidates

Purity ~80%

Methodology of *CP* violation search

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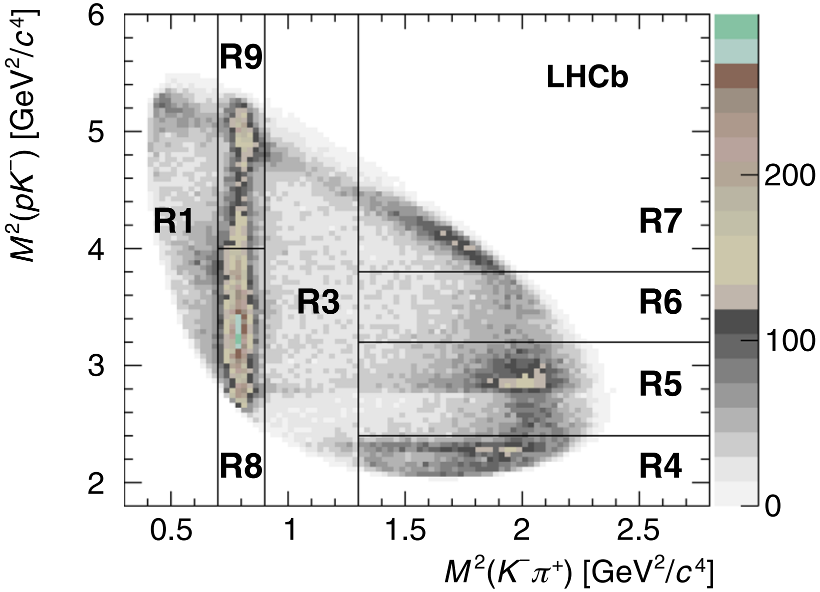
- The decay products form many resonance states visible in the Dalitz plot
- The charge asymmetry (*CP* violation effects) changes from region to region
- *CP* asymmetry can be wash out if we measure it in the full phase space
- No clear indications where *CP* violation would appear
- To find *CP* asymmetries, the Dalitz plots for Ξ^+_c and Ξ^-_c are compared locally using model independent techniques

$\Xi^+_c \to pK^-\pi^+$



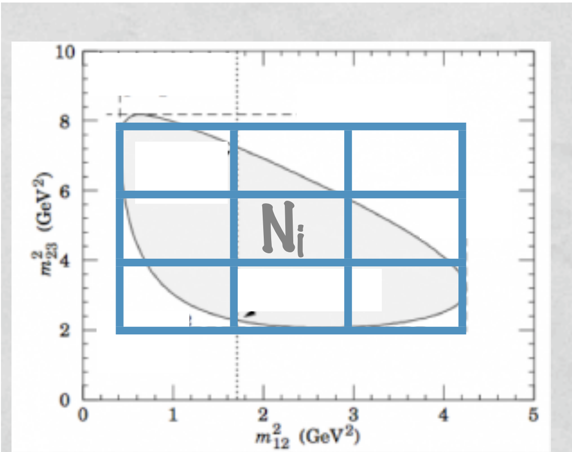
Resonances:
K^*, $K^*_0(1410)$, $K^*_0(1430)$, $K^*_2(1430)$,
Λ^{1520}, Λ^{1600}, Λ^{1890}, $\Lambda^{1670/1690/1710}$,
$\Lambda^{1800/1820/1830}$, Δ^{++}, Δ^{1232}, $\Delta^{1600/1620}$, Δ^{1700}

The binned S_{CP} method

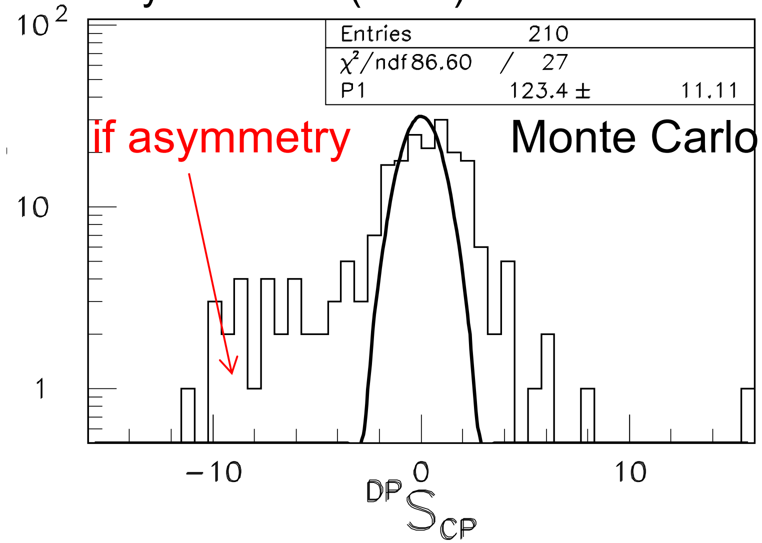
- In each bin a significance of a difference between Ξ^+_c and Ξ^-_c is calculated

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

- To cancel global asymmetries, the Dalitz plots are normalized



Phys.Rev.D80(2009)096006



- If no *CP* violation (only statistical fluctuations) then S_{CP} is Gaussian (μ=0, σ=1)

- The $\chi^2 = \Sigma\,(S^i_{CP})^2$ test is used to obtain *p*-value for the null hypothesis (no *CP* violation): *p*-value $\ll 1$ in case of *CP* violation (*p*-value $< 3\cdot10^{-7}$ for 5σ)

The control test of the binned S_{CP} method

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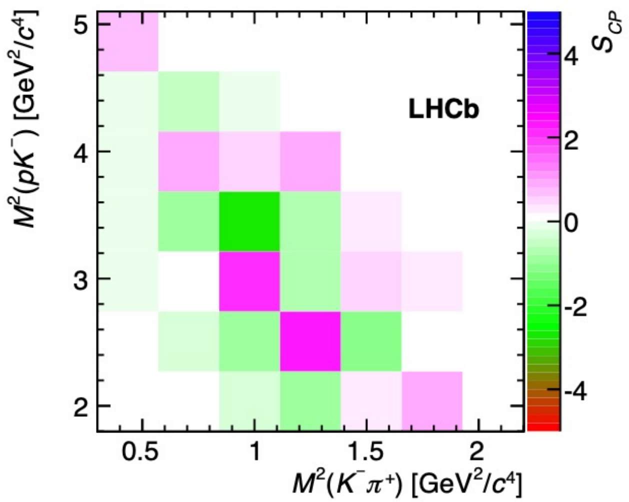
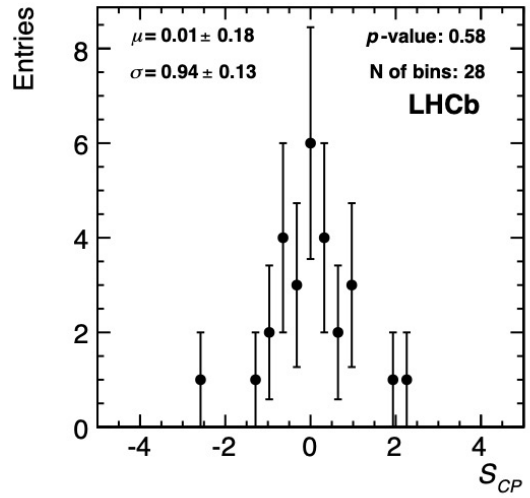
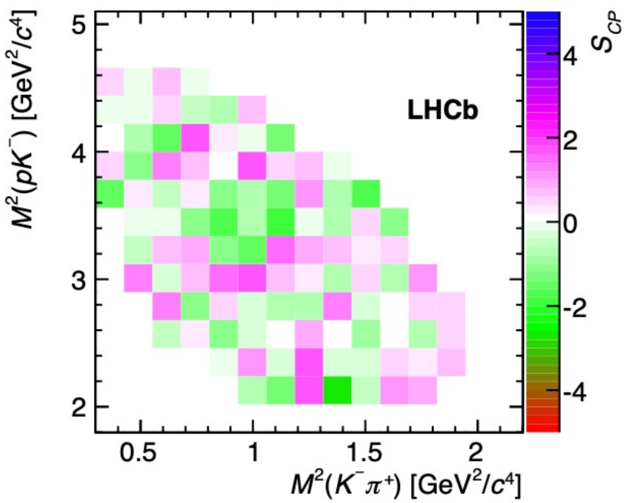
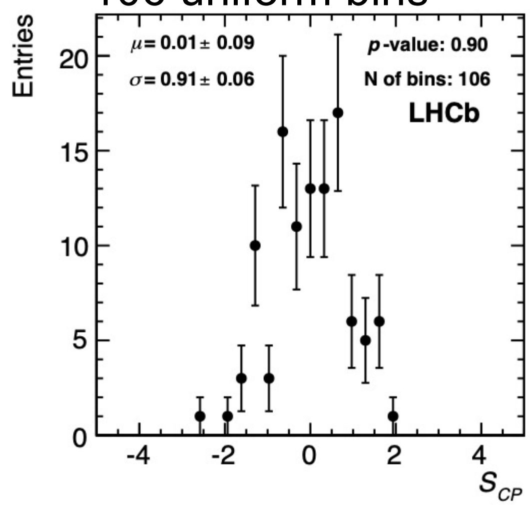


28 uniform bins





106 uniform bins



2M $\Lambda^+_c \to pK^-\pi^+$
Purity ~98%
No CPV in the SM

- The two binning schemes are tested: with smaller and larger (about 4 times) number of uniform bins
- The fake signals of *CP* asymmetries are no seen, i.e. *p*-values are larger than 58% and the distributions are consistent with Gaussian

CP violation searches using the binned S_{CP} method

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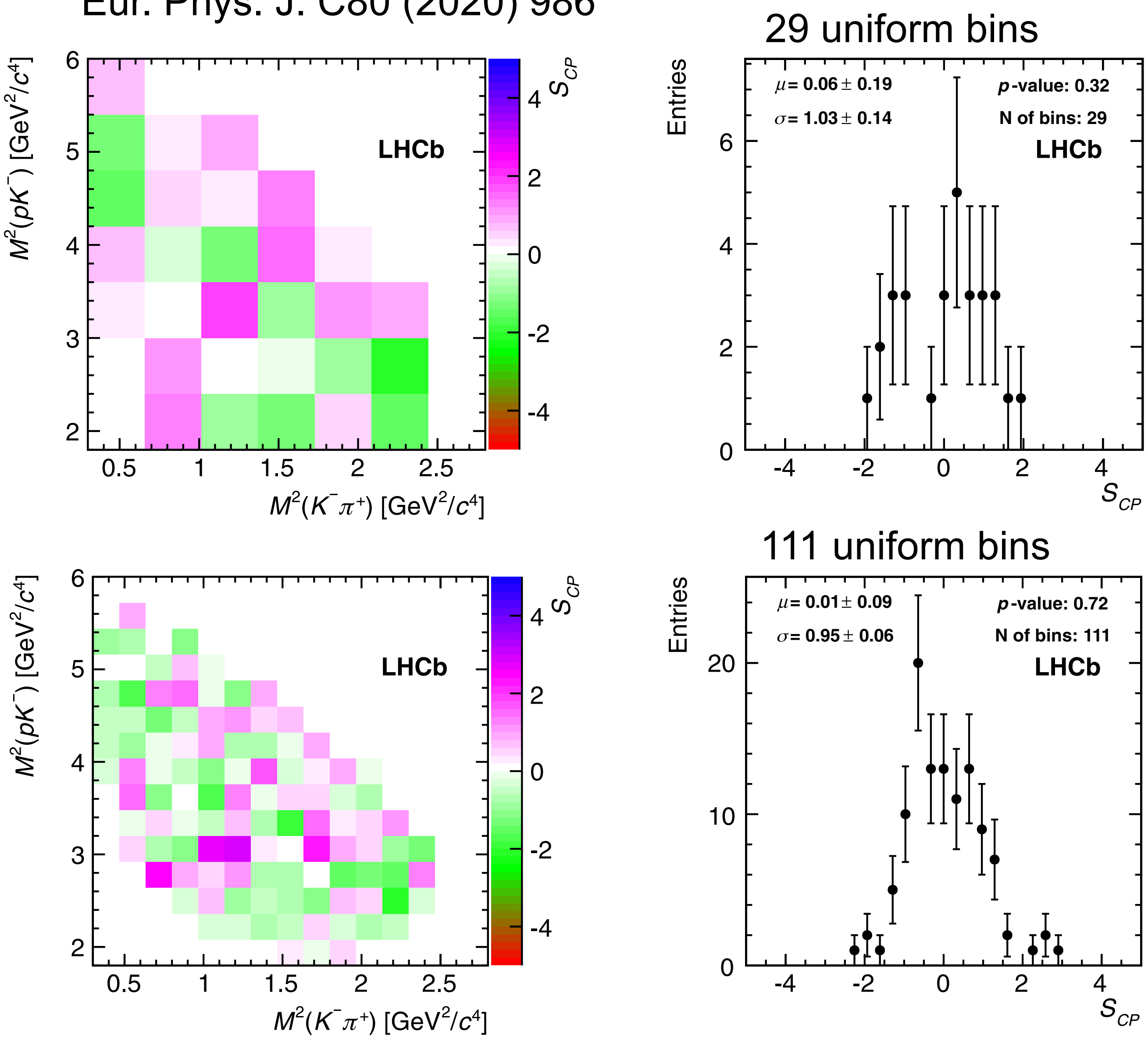
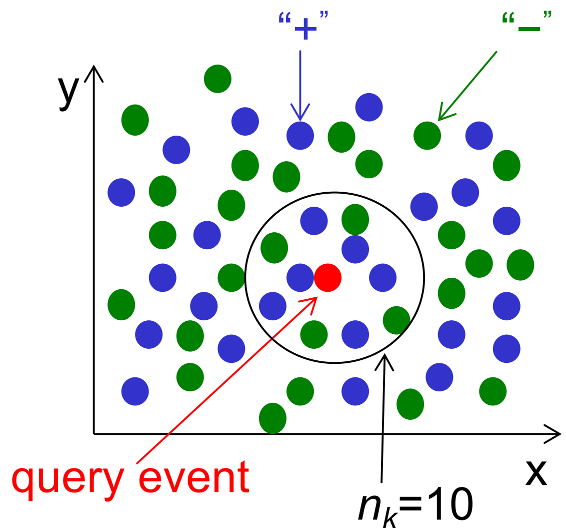


0.2M $\Xi^+_c \to pK^-\pi^+$
Place for CPV in the SM

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

The unbinned k nearest neighbour method

- 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 (n_k)



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

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

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

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

- If $n_+ = n_-$ then $\mu_T \approx 1/2$ ($=\mu_{TR}$) (mean value) and $\sigma_T^2 = \frac{1}{n n_k}(0.25 + 0.25)$

The k nearest neighbour method

- The k nearest neighbour method allows to find differences between two samples if they come from:

  ✧ normalization: 1^0: if $n_+ = n_-$ then $\mu_T = \mu_{TR}$; 2^0: if $n_+ \neq n_-$ then $\mu_T \neq \mu_{TR}$

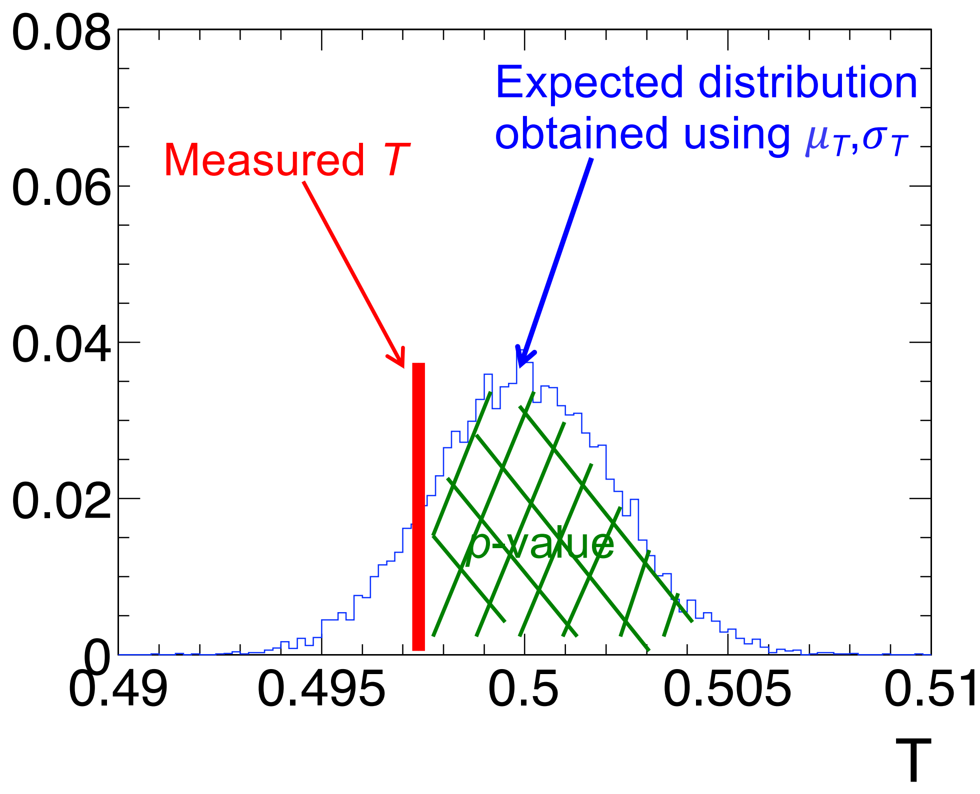
  ✧ shape: if $f_+ \neq f_-$ then $T \neq \mu_T$

  $\Longrightarrow$ there are two *p*-values

- The production asymmetry can be manifested by different normalization

- For shape, the *p*-value is the area under the expected curve from measured T to 1

- *p*-value $\ll 1$ in case of *CP* violation



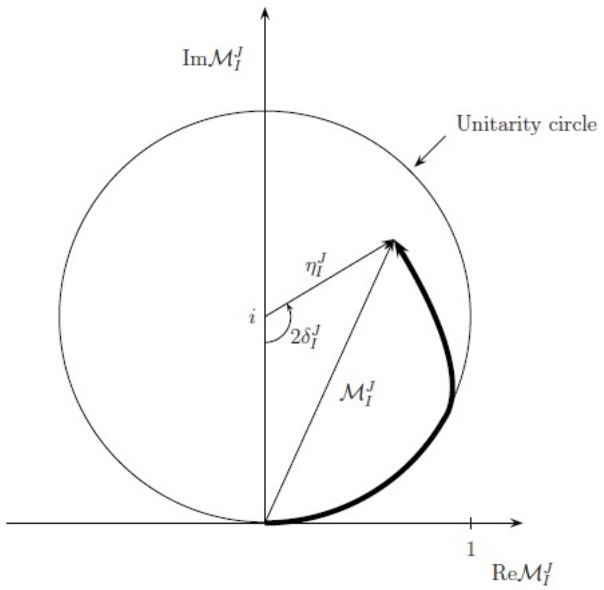
The sensitivity of the measurements due to strong phase

- The non-zero strong phase difference is **necessary** to observe *CP* violation

$$Asym_{CP} \sim |A_1||A_2| sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

weak phases strong phases

- A strong phase δ varies with changing of a resonance mass (Argand diagram)



The amplitude is represented as a point in the complex plane in the interior or on the boundary of the unitarity circle

$$\mathcal{M}_I^J = \frac{\Gamma}{(m_R^2 - s) - i\Gamma/2},$$

Γ – decay rate
m_R – resonance mass
s – total energy squared in CMS

The strong phase is given by: $$\tan\delta = \frac{\Gamma/2}{m_R^2 - s}.$$

If s changes around m^2_R then δ changes rapidly from 0 to π

- To increase the sensitivity of the k nearest neighbour method, the Dalitz plot is divided into regions defined around resonances

The Dalitz plot division

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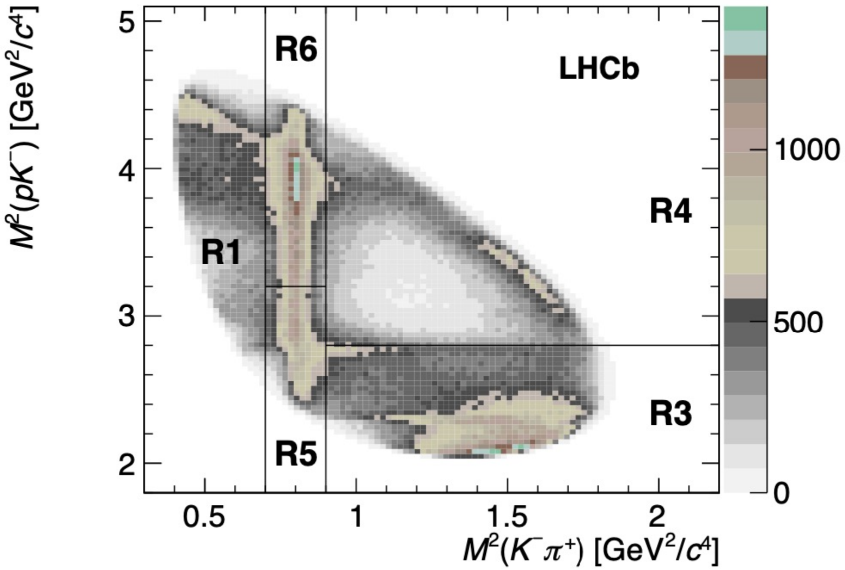
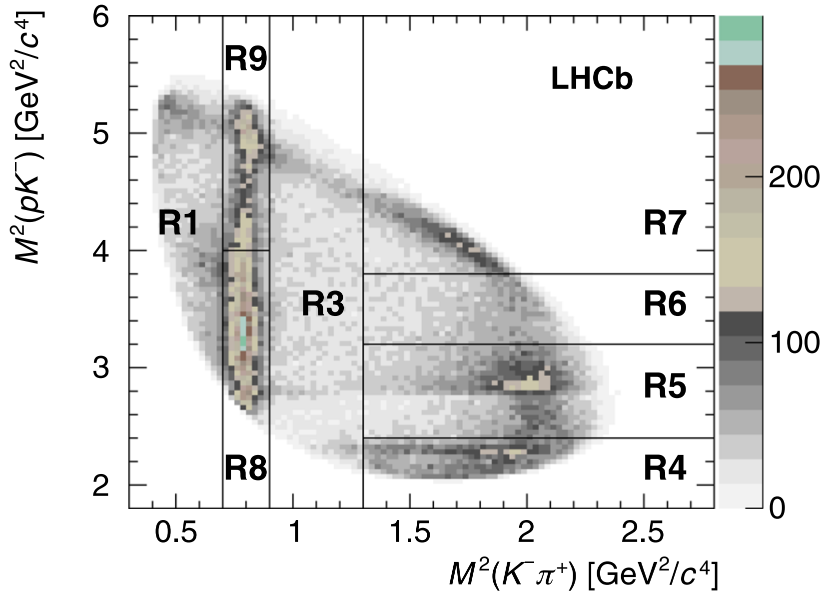
$\Lambda^+_c \to pK^-\pi^+$
no *CP* violation in the SM



6 regions
R2=R5+R6

$\Xi^+_c \to pK^-\pi^+$
place for *CP* violation in the SM



11 regions
R2=R8+R9 ; R10=R4+R5 ;
R11=R4+R5+R6+R7

R0 – whole Dalitz plot

The total asymmetry in the control $\Lambda^{+}_{c} \to pK^{-}\pi^{+}$ decays

- The total asymmetry is a mixture of few asymmetries: production, detectors, ~~CP~~

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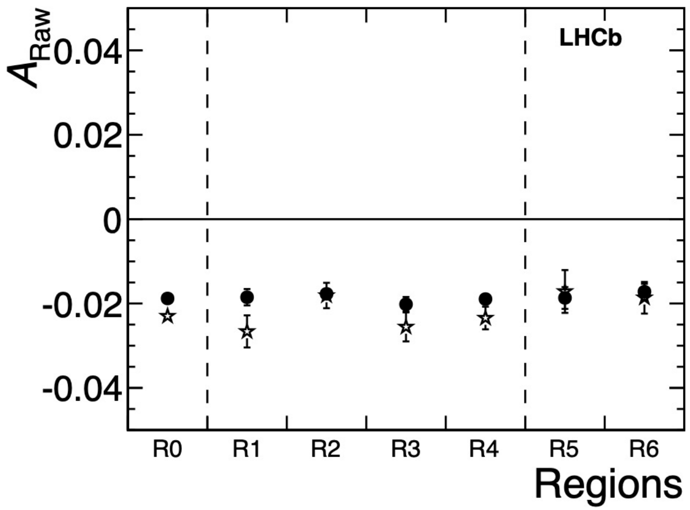
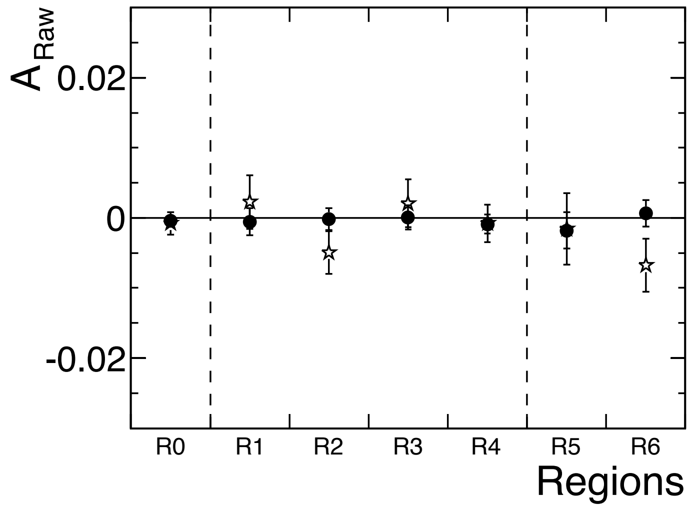
$$A_{RAW} = \frac{N_{-} - N_{+}}{N_{+} + N_{-}}$$

2011: stars, 2012: dots



The sign of Λ^{+}_{c} is random



- The total asymmetry in all regions is quite similar, about −2% (characteristic behaviour for the expected production asymmetry)
- If sign of Λ^{+}_{c} is random then total asymmetry in all regions is zero and the detector effects are smaller than the errors (<0.0004 in R0)

The total asymmetry in $\Xi^+_c \to pK^-\pi^+$ (place for *CP* violation)

- The total asymmetry is a mixture of few asymmetries: production, detectors, *CP*

- The measured total asymmetry in all regions is quite similar, about −1.5% (behaviour is characteristic for the production asymmetry)
- The detector asymmetries are smaller than 10^{-4}
- Due to the strong phase variation, *CP* asymmetry should vary from region to region (not constant value)
- Is −1.5% the production asymmetry of Ξ^+_c?

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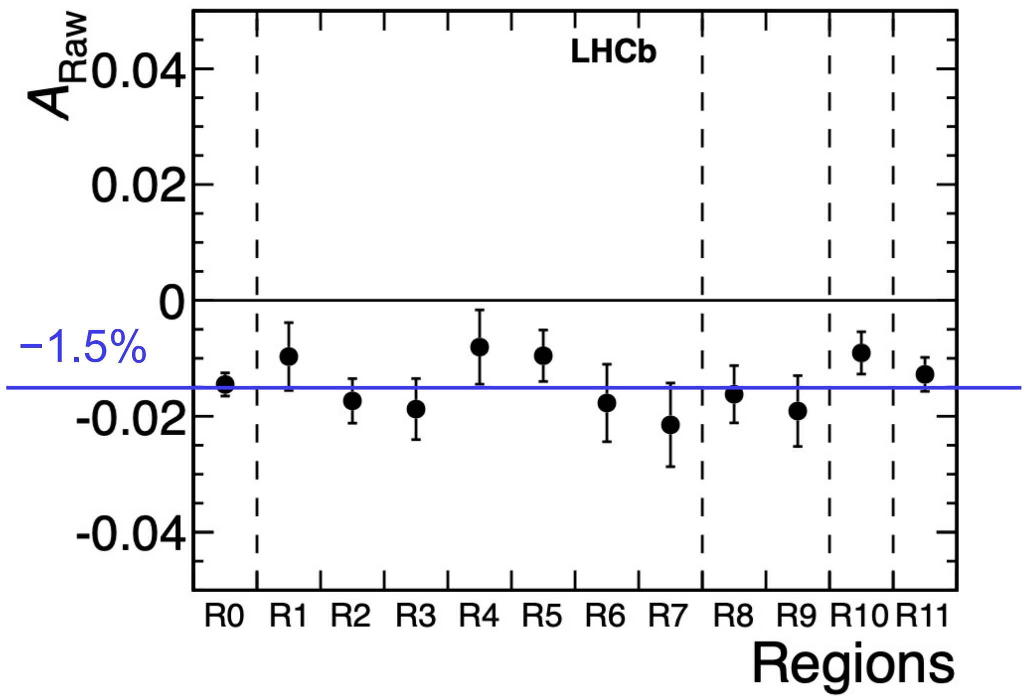

The k nearest neighbour results in the control $\Lambda^+_c \to pK^-\pi^+$ decays

Consequence of nonzero production asymmetry

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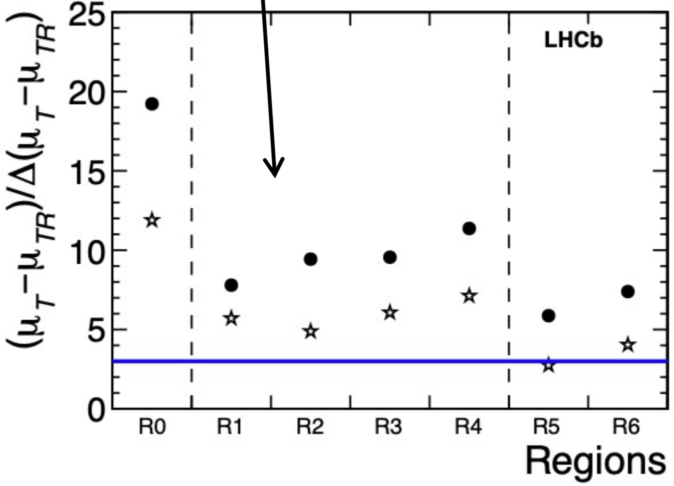
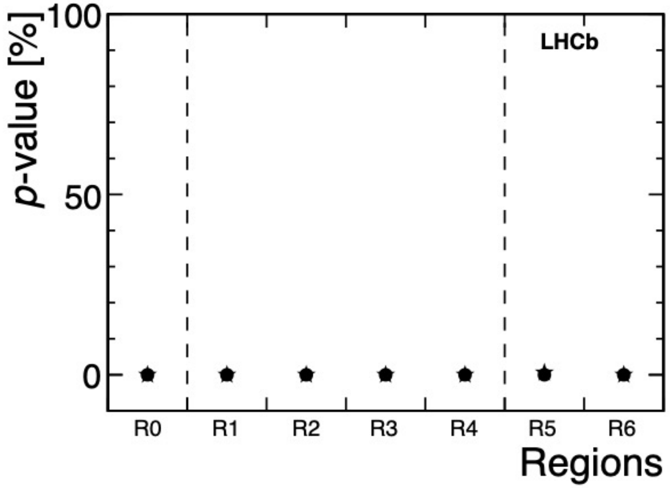
normalization



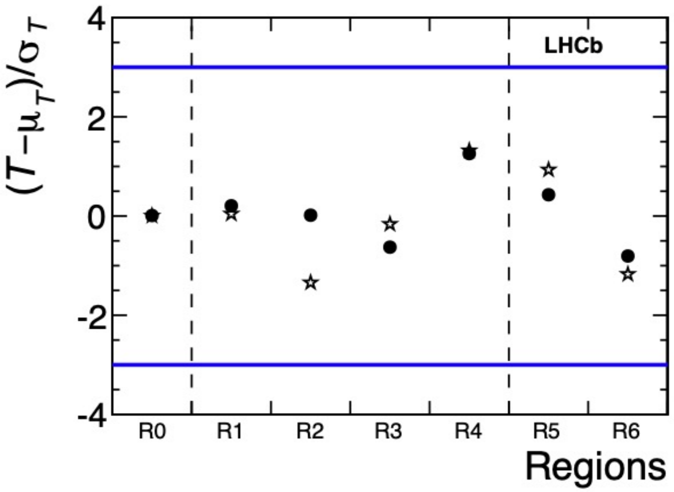


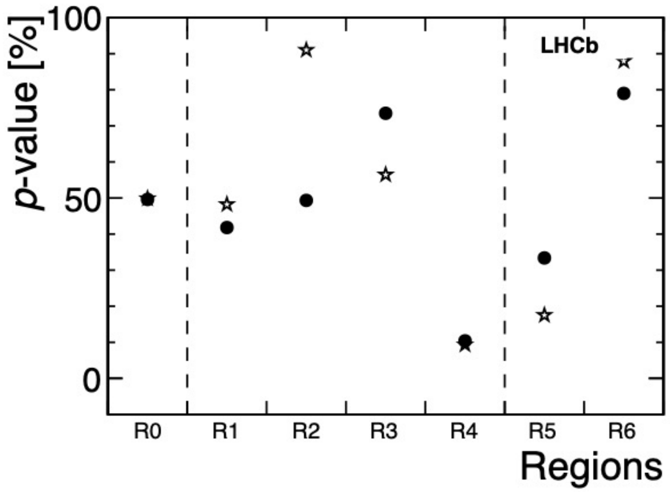
2011: starts, 2012: dots

$n_k = 50$

No *CP* violation in the Standard Model

shape





The production asymmetry is visible in the normalization part

No fake signal of *CP* violation in the shape part

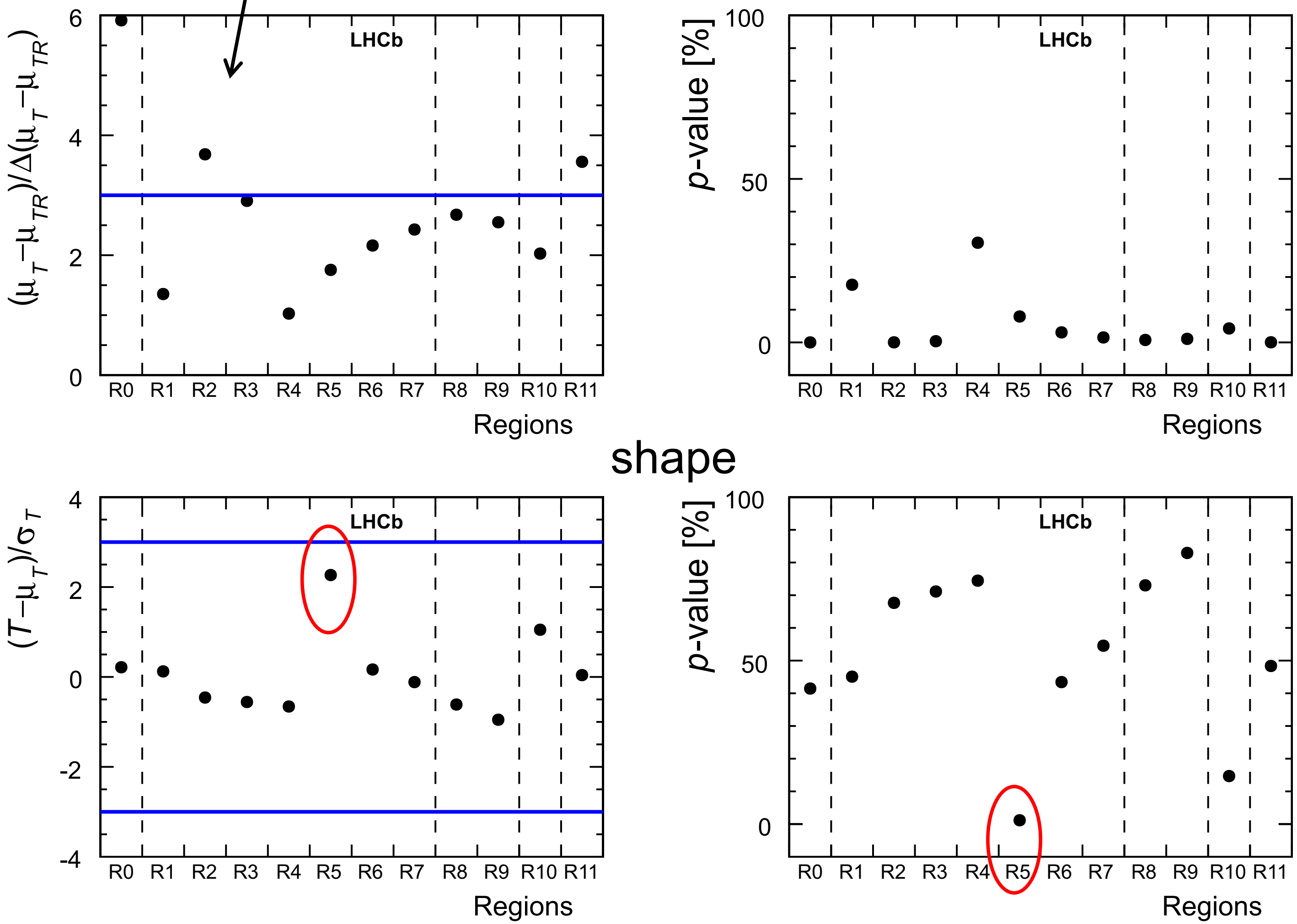
CP asymmetry in $\Xi^{+}_{c} \to pK^{-}\pi^{+}$ (place for *CP* violation)

Consequence of nonzero production asymmetry

Eur. Phys. J. C80 (2020) 986

normalization

The kNN results with $n_k = 50$



Place for *CP* violation in the Standard Model

The production asymmetry in the normalization part is seen

No observation of *CP* violation but one *p*-value corresponds to 2.7σ

−1.5% is the first estimation of the production asymmetry of Ξ^{+}_{c} at LHC

Summary

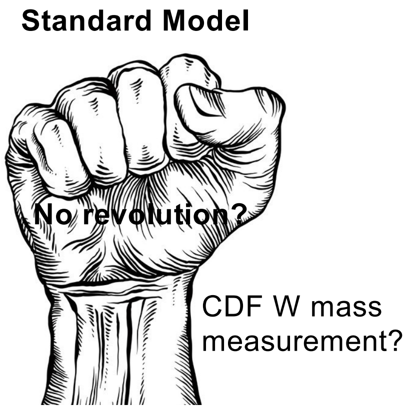
- Charm is the dark horse of flavour physics

- *CP* violation in charm sector is confirmed only in the difference of asymmetries

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-1.54 \pm 0.29) \cdot 10^{-3}$$

(inconclusive whether it confirms to the Standard Model or not)

- Is there discrepancy between mixing parameters *x* and *y* ?
- Is there possible to measure *CP* violation is any single charm decay ?
- Is there *CP* violation in any baryon decays ?
- Is there new physics ?



The nearest future

- We need better understand *CP*-violating mechanisms by measuring it in other channels (and perhaps find other *CP* violation sources)
  - also in B decays where unexpectedly in $B \to hhh$ huge value of *CP* violation is measured in regions not associated to the resonances
  - local *CP* violation is ~75% in $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ (LHCb-PAPER-2021-049) The largest CPV ever observed!

- The LHCb upgrade (started in 2019) has just almost finished
- Soon we start collecting data (Run 3)
- The goal is to reach ~50/fb (sensitivity comparable or better than theoretical uncertainties)

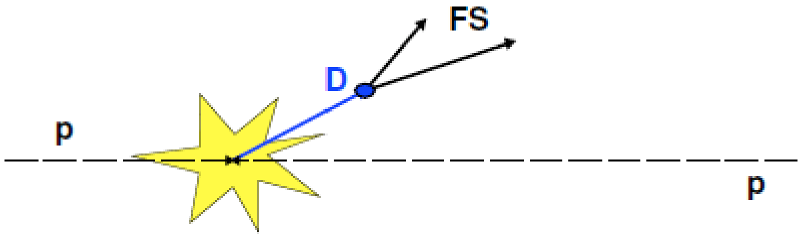

BACK UP!

Charm particle production in the LHCb

Two production types:

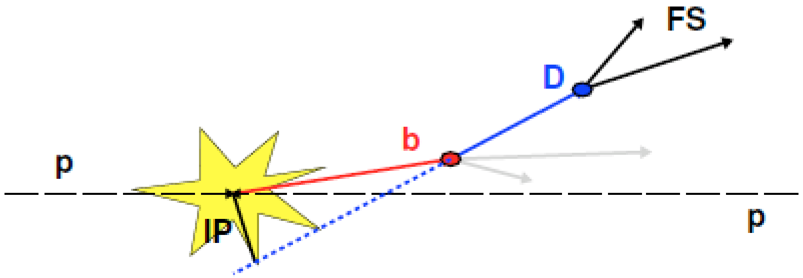
1. prompt – produced directly in the primary vertex

IP ~ 0



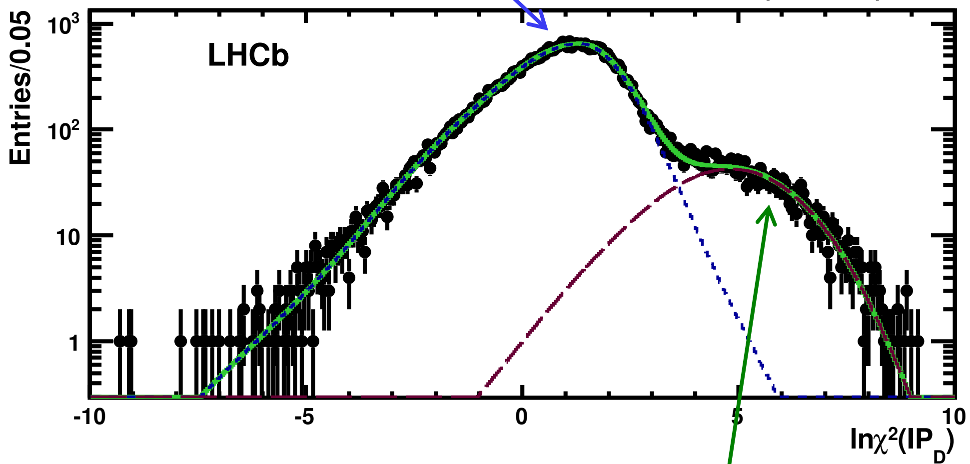
2. secondary – produced in B, Λ_b ,… decays $B \rightarrow DX$, $\Lambda_b \rightarrow \Xi_c X$,…

IP > 0



prompt

JHEP04(2012)129



secondary

IP – impact parameter wrt. the primary vertex

The D^0 flavour tagging

Flavour cannot be inferred from the final state if this is shared by D^0 and anti-D^0

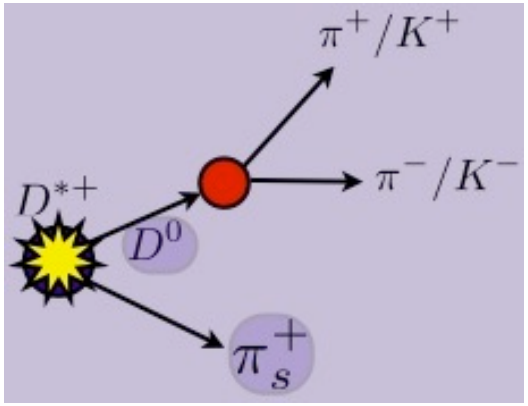
The LHCb uses two methods to identify D^0 flavour at the production state

1. pion-tagged method
   the sign of slow pion from D^* decays is used to tag the initial D^0 flavour

   $D^{*+} \rightarrow D^0 \pi^+_s$

   $D^{*-} \rightarrow$ anti-$D^0 \pi^-_s$

prompt D^0

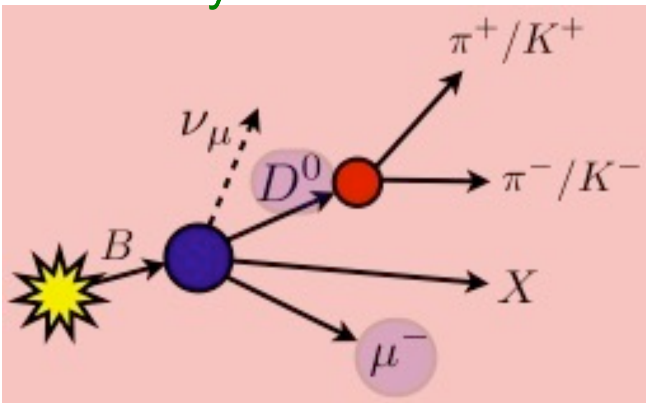


2. muon-tagged method (yield ~1/6)
   the sign of muon from semileptonic B decays is used to tag D^0 flavour

   $B^- \rightarrow D^0 \mu^- \nu_\mu X$

   $B^+ \rightarrow$ anti-$D^0 \mu^+ \nu_\mu X$

secondary D^0

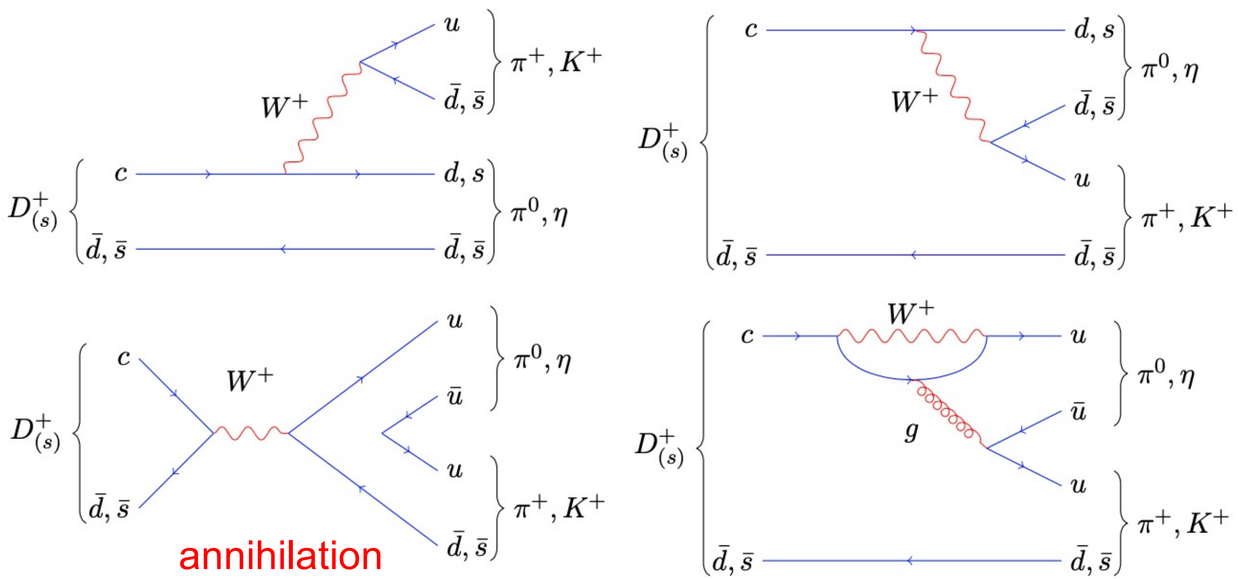


Time integrated *CP* violation in $D^+_{(s)} \to h^+h^0$

There are seven charged D^+ meson decays that allow to test of direct *CP* violation in the amplitude decays

$D^+_{(s)} \to h^+\pi^0$, $h^+\eta$, where h is K or π and the π^0 and η are reconstructed using the $\gamma\gamma$ (the more common) or $e^+e^-\gamma$ (one photon converts to an e^+e^- pair)

The measurements are made relative to the control modes $D^+_{(s)} \to K^0_s h^+$ to cancel the production and detection asymmetries

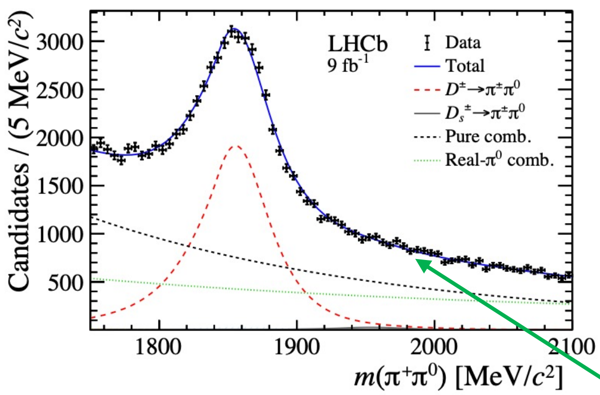


The SCS $D^+ \to \pi^+\pi^0$ is interest:

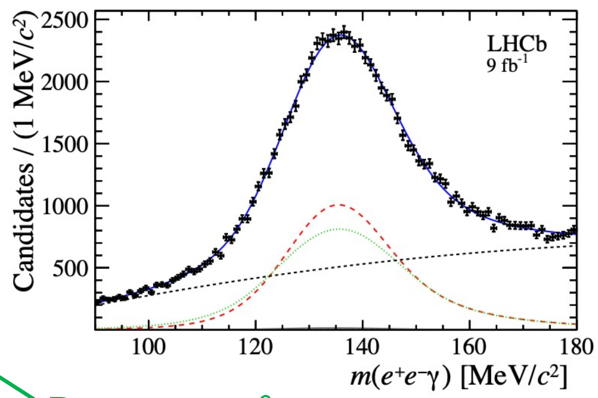
- the *CP* asymmetry in the SM is expected to be zero as a result of isospin constraints
- proceeds via an annihilation decay and is highly suppressed
- would be an indication of physics beyond the SM

JHEP 06 (2021) 019

$D^+ \rightarrow \pi^+ \pi^0$

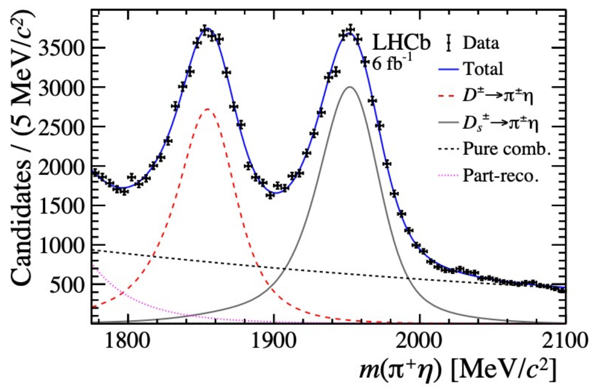


$\pi^0 \rightarrow e^+e^-\gamma$

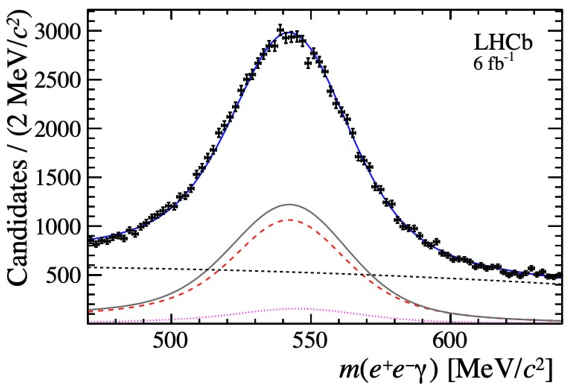


$D^+_s \rightarrow \pi^+ \pi^0$

$D^+_{(s)} \rightarrow \pi^+ \eta$



$\eta \rightarrow e^+e^-\gamma$



The $D^+ \rightarrow \pi^+ \pi^0$ decay:

- would be an indication of physics beyond the SM
- ~25k candidates

Mode	Yield 2011	Yield 2012	Yield Run 2
$D^+ \rightarrow \pi^+\pi^0$	740 ± 60	$2\,240 \pm 120$	$25\,750 \pm 430$
$D_s^+ \rightarrow \pi^+\pi^0$	20 ± 30	-50 ± 50	450 ± 120
$D^+ \rightarrow K^+\pi^0$	10 ± 13	90 ± 30	$2\,440 \pm 110$
$D_s^+ \rightarrow K^+\pi^0$	54 ± 13	150 ± 30	$2\,580 \pm 90$
$D^+ \rightarrow \pi^+\eta$	-	-	$32\,760 \pm 380$
$D_s^+ \rightarrow \pi^+\eta$	-	-	$37\,950 \pm 340$
$D^+ \rightarrow K^+\eta$	-	-	880 ± 70
$D_s^+ \rightarrow K^+\eta$	-	-	$2\,520 \pm 70$

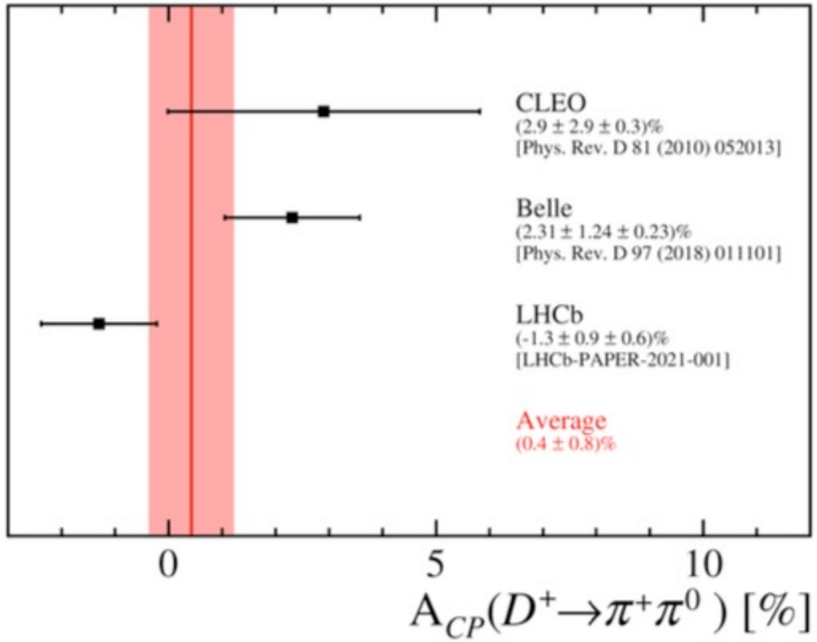
The *CP* asymmetry is not calculated in the $D^+_s \rightarrow \pi^+ \pi^0$ decays due to non sufficient statistics

Time integrated CP violation in $D^+_{(s)} \to h^+h^0$

LHCb results, JHEP 06 (2021) 019

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$

Results in $D^+ \to \pi^+ \pi^0$



- These results are consistent with no CP violation and mostly constitute the most precise measurements of A_{CP} in these decay modes to date

- Recently Belle also reported precise measurements (Phys. Rev. D103 (2021) 112005)

$$A_{CP}(D_s^+ \to K^+\pi^0) = 0.064 \pm 0.044 \pm 0.011$$
$$A_{CP}(D_s^+ \to K^+\eta) = 0.021 \pm 0.021 \pm 0.004$$
$$A_{CP}(D_s^+ \to \pi^+\eta) = 0.002 \pm 0.003 \pm 0.003$$

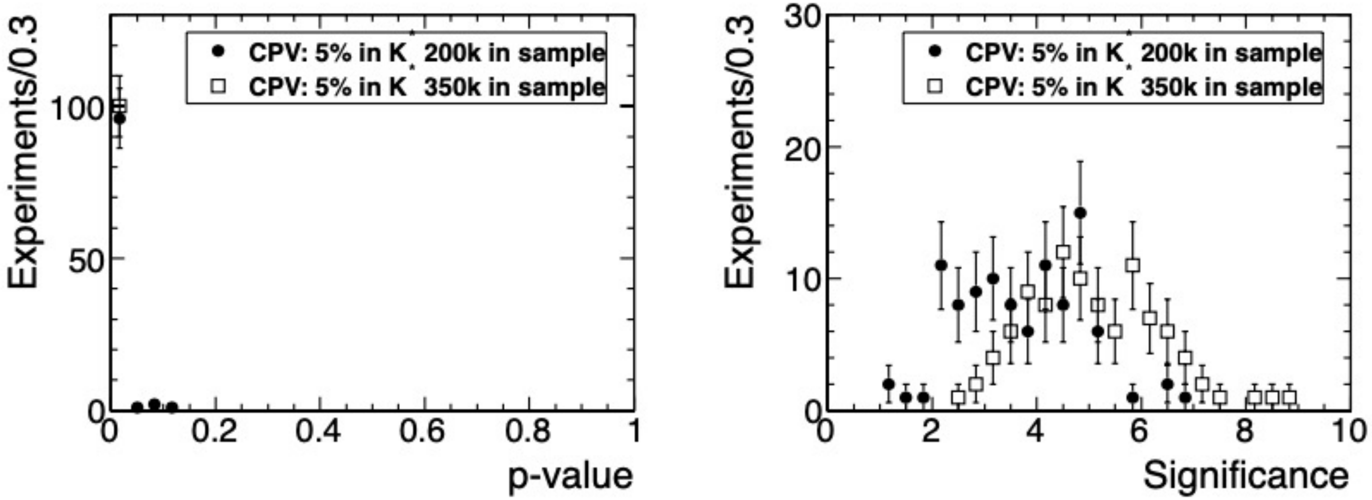
In agreement with LHCb

The toy Monte Carlo data were used to check the power of the both methods

For the same Ξ^+_c statistics (0.2M) as collected in the experiment:

- ✧ the S_{CP} method is sensitive to *CP* asymmetry if is larger or equal to 5% in amplitudes of K^* or 10% in Δ^{1232} resonances
- ✧ the k nearest neighbour method is sensitive to *CP* asymmetry if is larger or equal to 5% in amplitudes of K^* or 5% in Δ^{1232} resonances

100 Monte Carlo samples



- In Run 2, there are five times more the $\Xi^+_c \rightarrow pK^-\pi^+$ decays
- Hope to see the first signal of *CP* violation in baryon decays

The n_k dependence

The n_k is the parameter which can change the results. It is similar to different bin numbers in the S_{CP} binned method

The results are in whole Dalitz plot (R0) and the points are correlated

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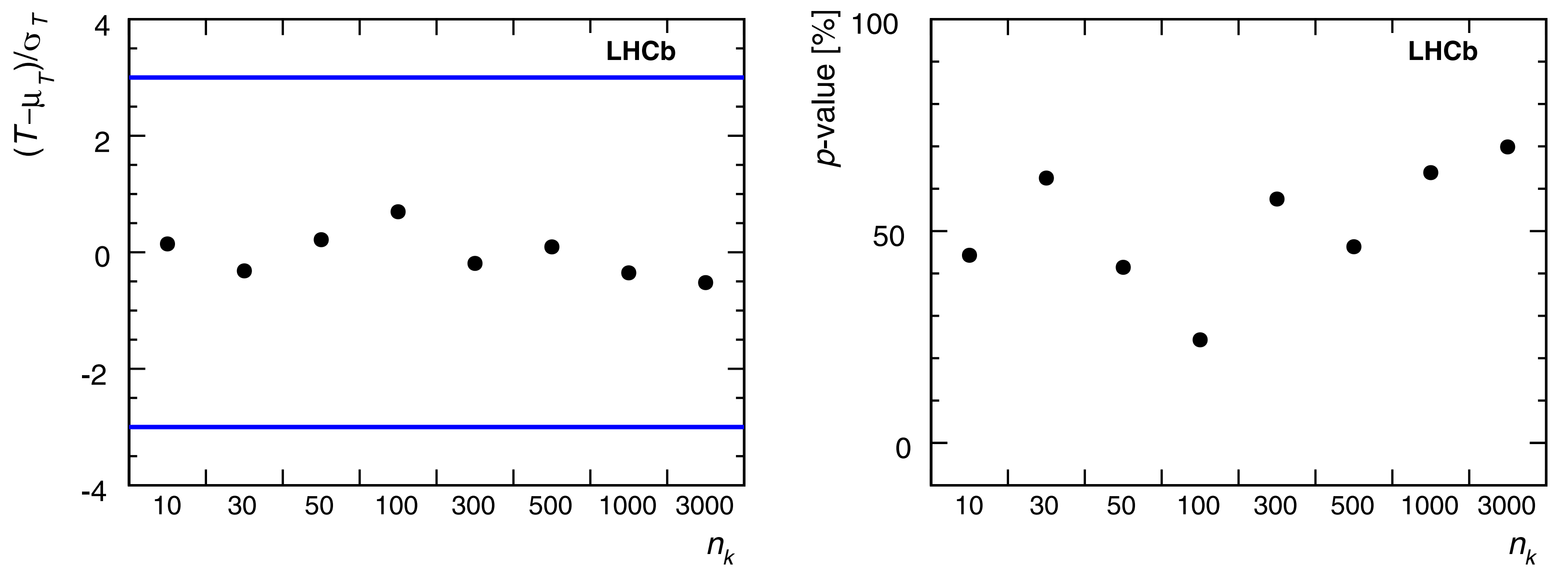

- All points vary from -3σ to $+3\sigma$ (for n_k from 10 to 3000)
- The results are consistent with no observation of *CP* violation
- Since the results are promising, the searches are continued using new data

To increase the power of the k-nearest neighbour method, the Dalitz plot is divided into regions

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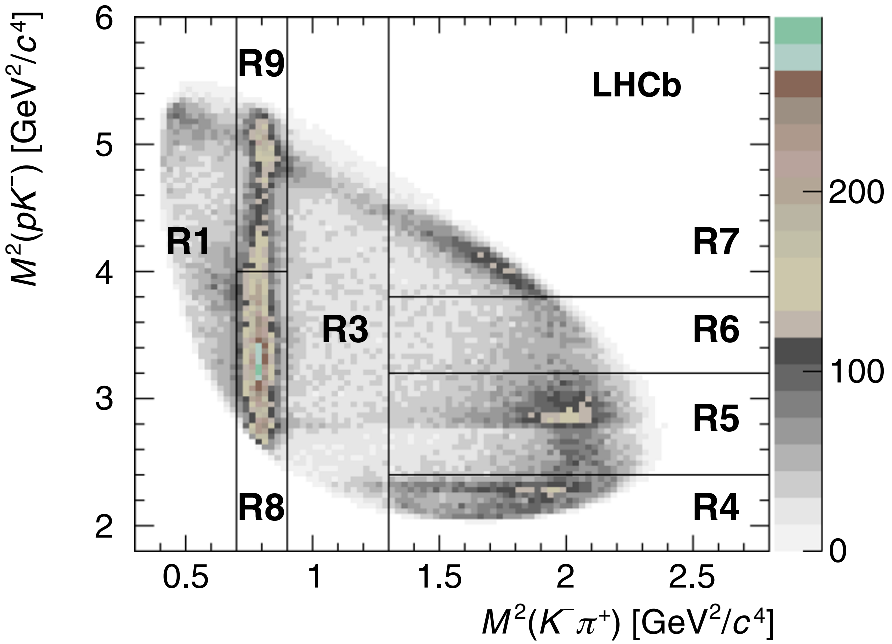

Dalitz plot division:

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}

The CP violation search procedure and cross-checks

- The CPV searches were performed in "blinding" way
- All stages of search techniques were developed using only control decays as well as generated data while region with possible signal of CPV in $\Xi^{\pm}_{c}$ decays was not accessible
- The hidden region of a potential signal of CPV was shared after obtaining approval of the LHCb collaboration (on this stage search procedure was frozen without possibility of changes)
- Control channel and mass sidebands do not show localized asymmetries
  - ✧ no asymmetry observed in control $\Lambda^{+}_{c} \rightarrow p K^{-}\pi^{+}$ decays
  - ✧ no asymmetry observed in sidebands of $\Xi^{+}_{c} \rightarrow p K^{-}\pi^{+}$ decays
- The toy MC data were used to check the power of method for Ξ^{+}_{c} statistics collected in the experiment:
  - ✧ the S_{CP} sees CPV if is larger than 5% in K* or larger than 10% in Δ^{1232}

Statistics of $\Lambda^+_c \to pK^-\pi^+$

- Decays where CPV is not expected in the SM (control decays)
- Used to check possible detector effects and for simulation fake signal of CPV

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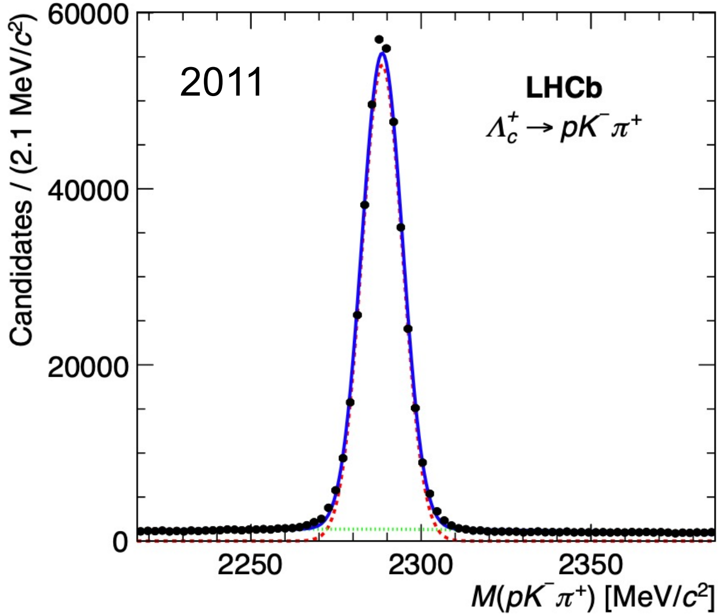
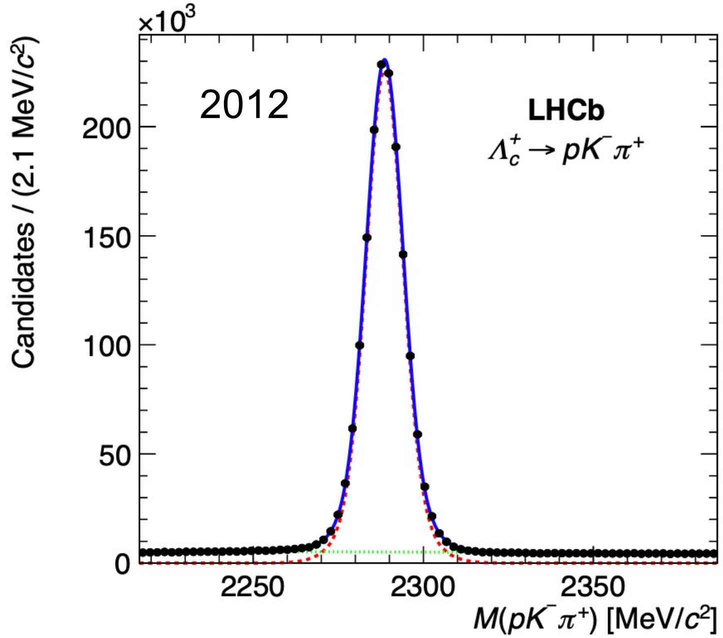


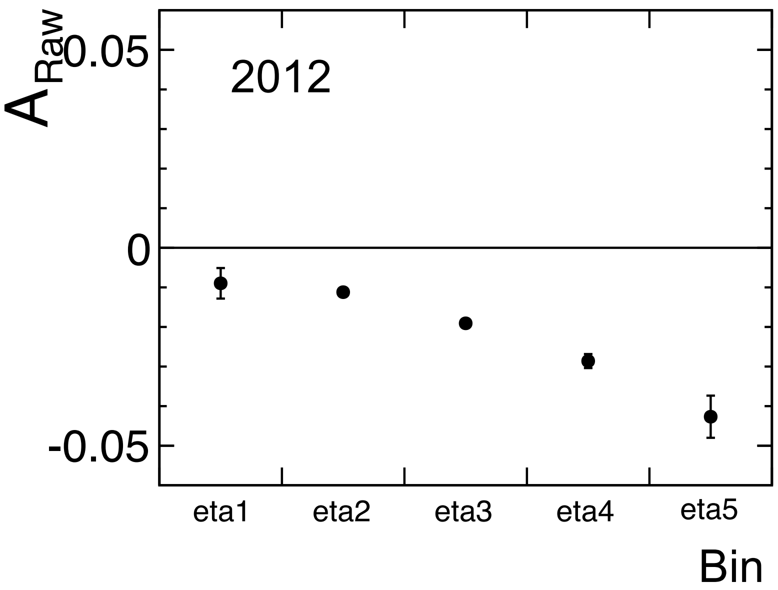


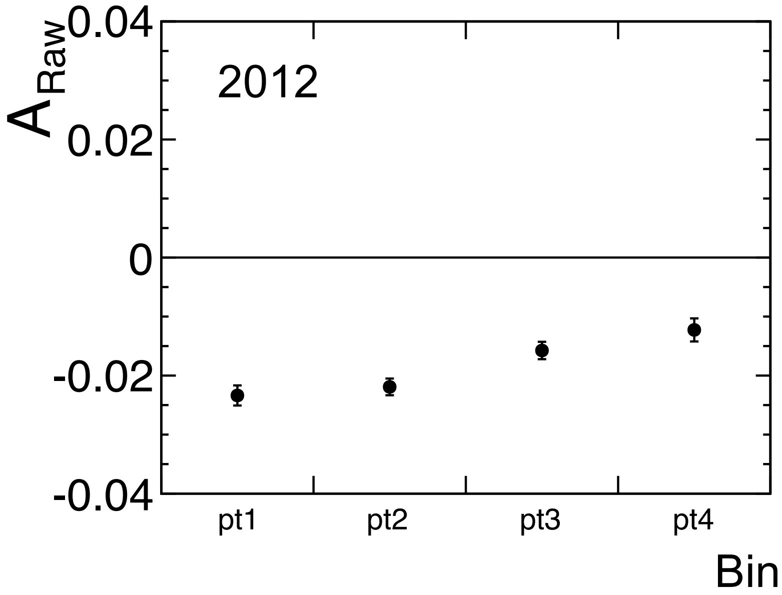
Λ_c	2011	2012
Magnet Down	237788 ± 554	770699 ± 1014
Magnet Up	159996 ± 464	755710 ± 1014
Total	376341 ± 617	1534502 ± 1436

In full Run 1 there are ~ 2M $\Lambda^{\pm}_c$ candidates

Purity ~98%

Dependence of raw asymmetry in CF $\Lambda^+_c \to pK^-\pi^+$ on η and p_T



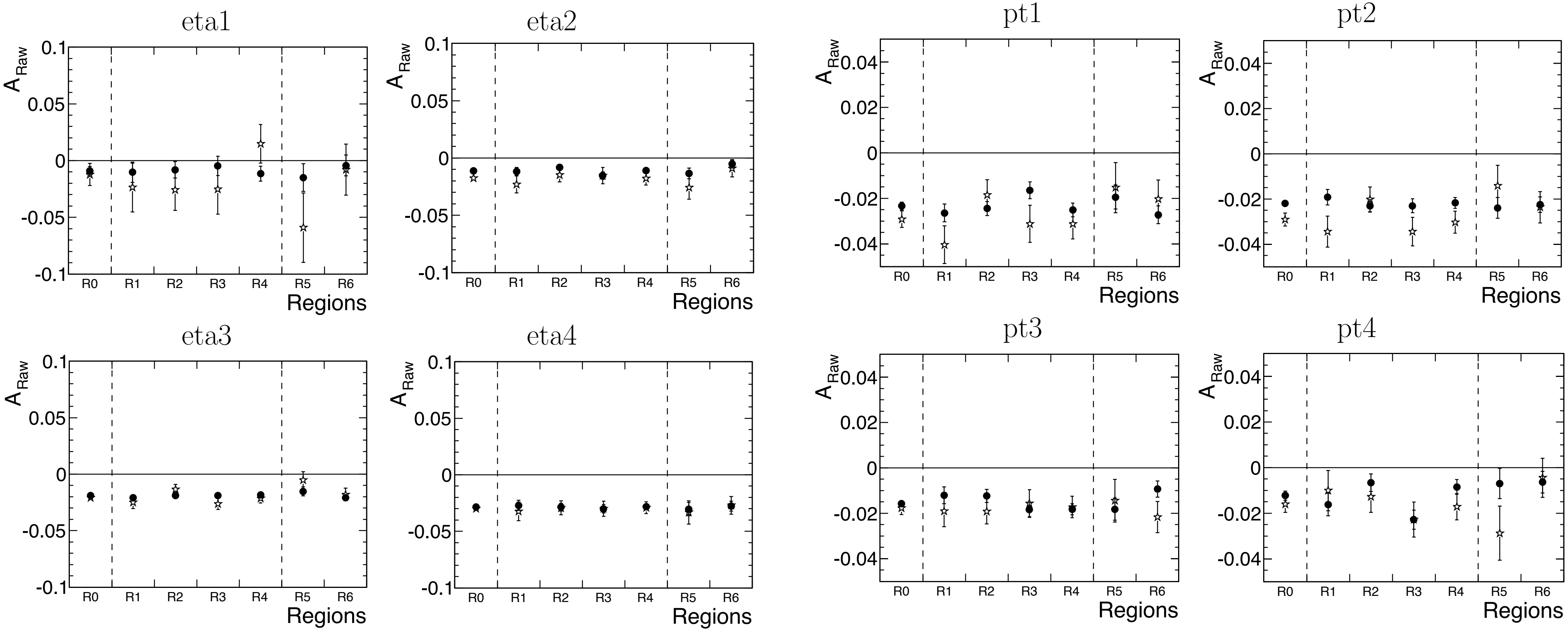


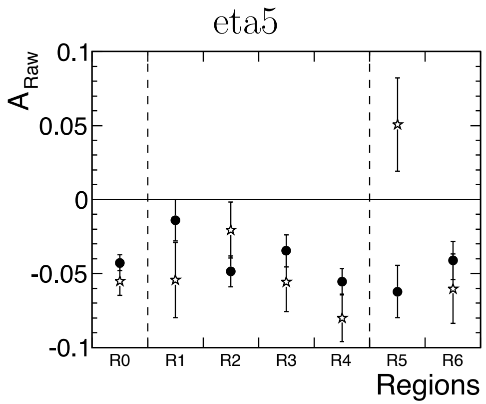
- eta1: $\eta < 2.5$,
- eta2: $2.5 \leq \eta < 3$,
- eta3: $3 \leq \eta < 3.5$,
- eta4: $3.5 \leq \eta < 4$,
- eta5: $\eta \geq 4$.

- pt1: $p_T < 5$ GeV,
- pt2: $5 \leq p_T < 6.5$ GeV,
- pt3: $6.5 \leq p_T < 9$ GeV,
- pt4: $p_T \geq 9$ GeV.

The A_{RAW} depends on η and p_T

The raw asymmetry in CF $\Lambda^+_c \to pK^-\pi^+$ in bins η and p_T





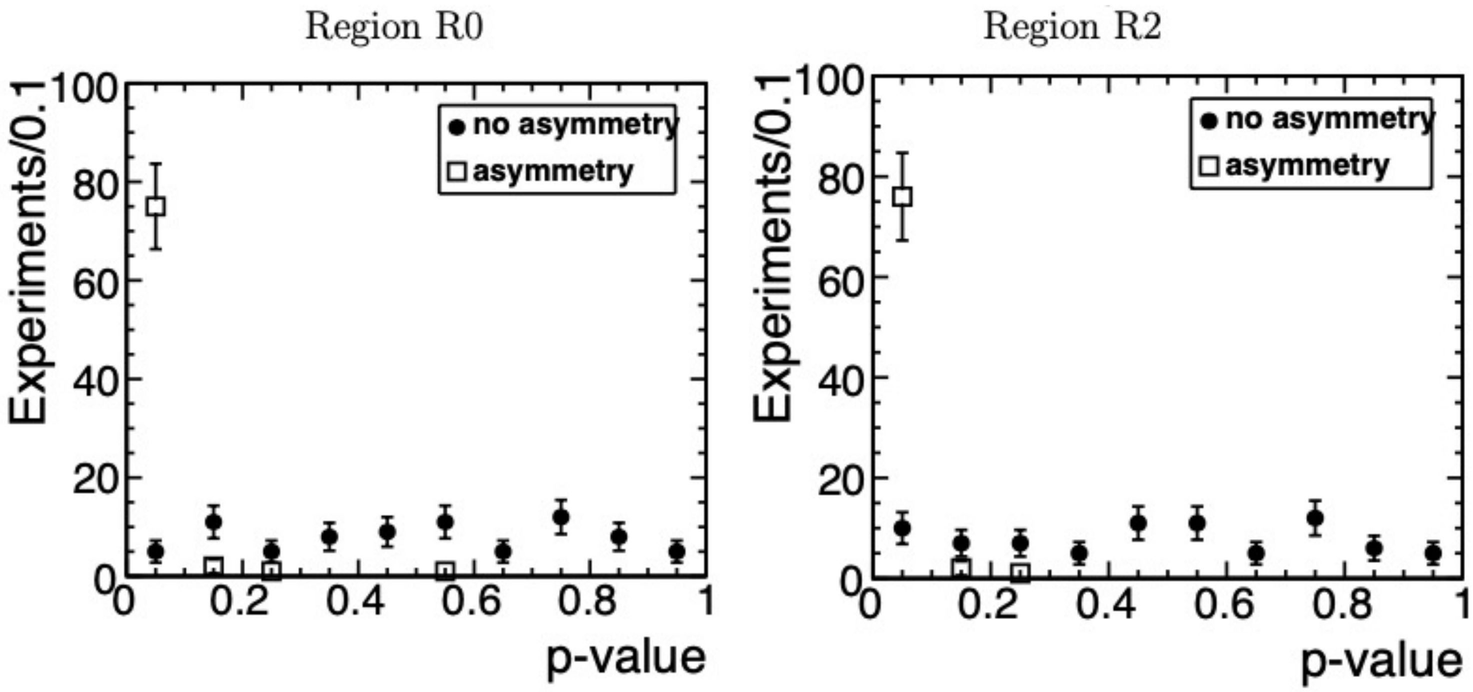
2011: stars, 2012: dots

The constant value of A_{RAW} in regions of the Dalitz plot is maintained in bins of η and p_T

The k nearest neighbour results in the control $\Lambda^+_c \to pK^-\pi^+$ decays

The $\Lambda^+_c \to pK^-\pi^+$ data are dived into 79 subsamples with 20k events in each

The results are in shape part



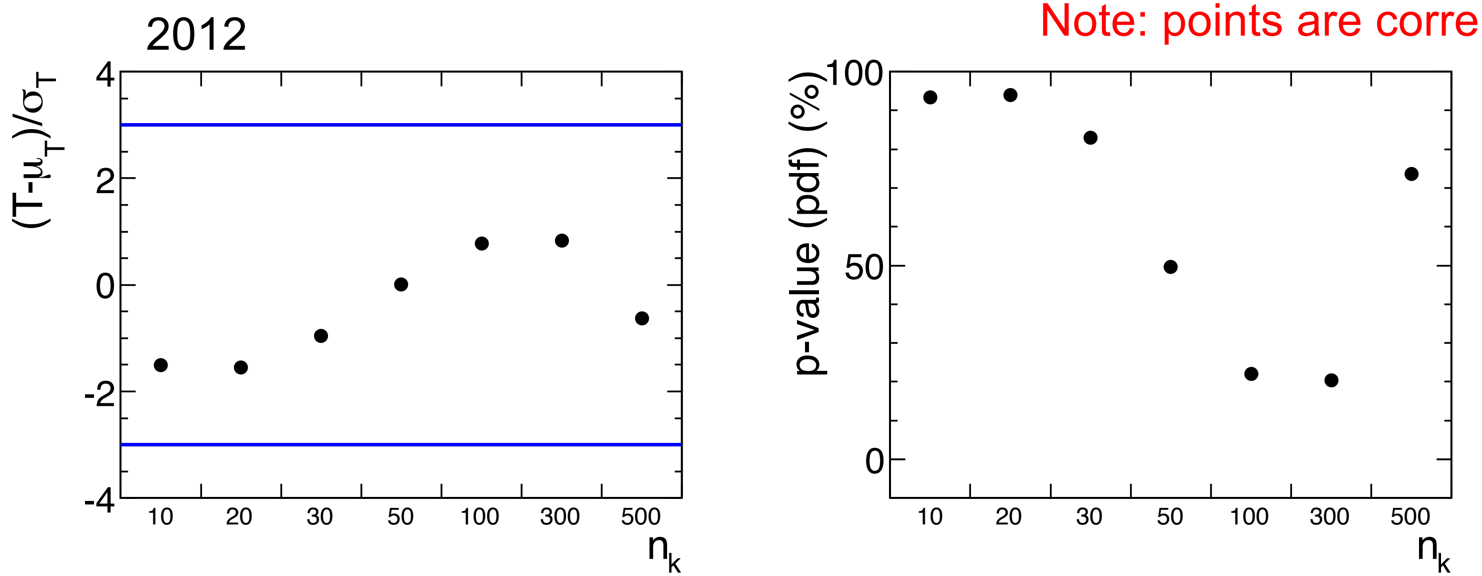
- The artificial *CP* asymmetry is implemented in *K** resonance amplitudes (region R2) as 10% and clearly seen as a deviation from flat distribution
- Since the *p*-value distribution is flat, the method does not generate fake signals of *CP* violation in data

The n_k dependence

μ_T (normalization part) does not depend on the n_k

The results in the whole Dalitz plot (region R0)

Note: points are correlated



Even for large value of n_k, there is no asymmetry larger than 3σ.

Tests checking in the toy MC data of $\Xi^{+}_{c} \rightarrow pK^{-}\pi^{+}$

The toy Monte Carlo for $\Xi_c^+ \to pK^-\pi^+$

- The toy MC data are generated with 200000 events (similar to the data)
- The model was built using the resonances which are seen in data

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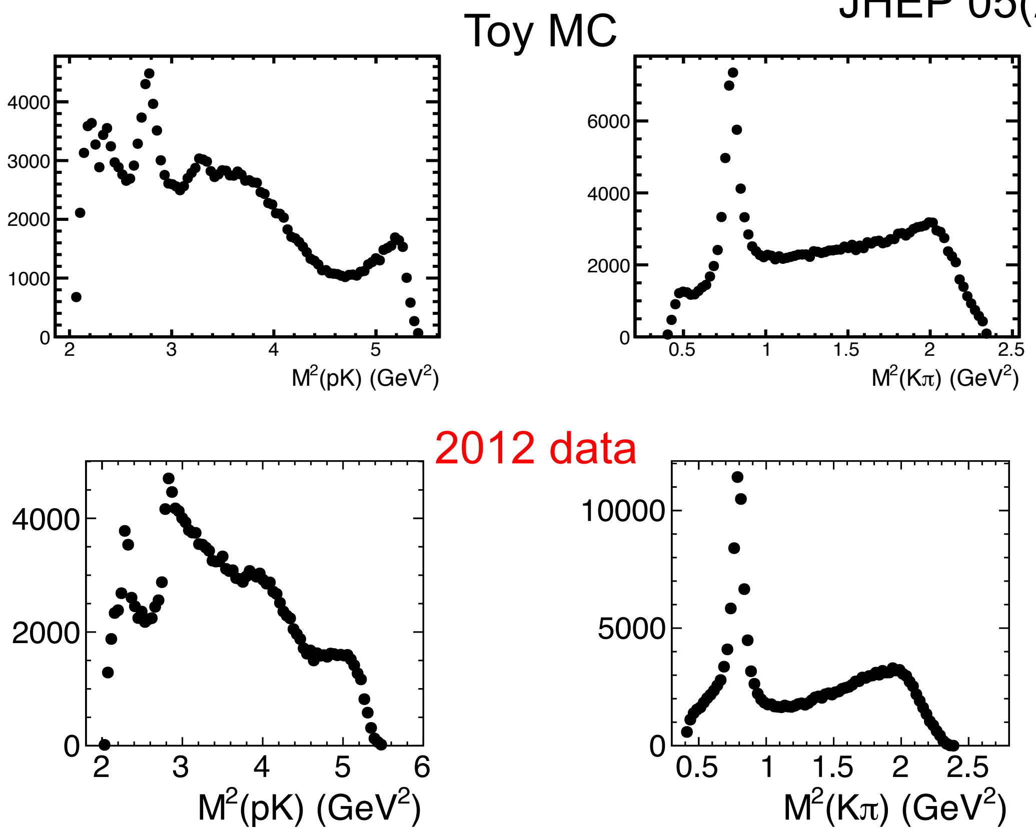
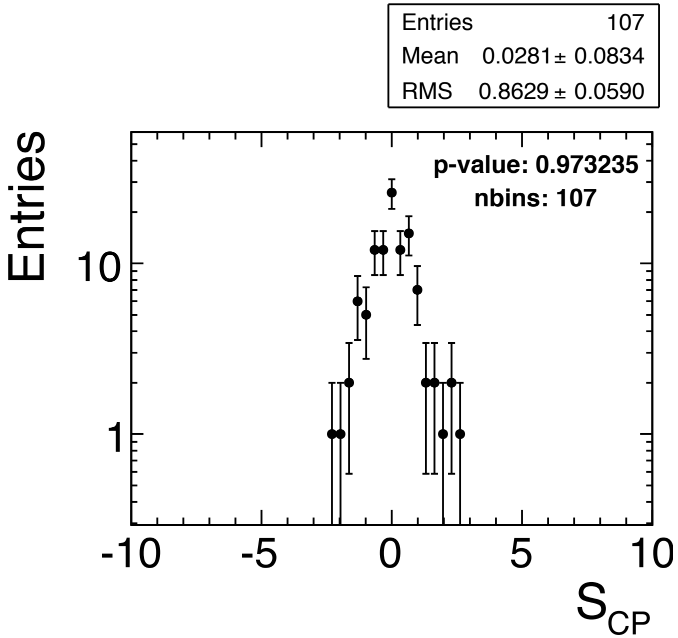


resonance	amplitude
$\Delta(1232)$	0.200999
$\Delta(1600)$	0.023790
$\Delta(1620)$	0.163071
$\Delta(1700)$	0.034367
$K_2^*(1430)$	0.096963
K^*	0.202016
$K^*(1410)$	0.000766
$K^*(1430)$	0.202707
$\Lambda(1520)$	0.003633
$\Lambda(1600)$	0.013376
$\Lambda(1670)$	0.049216
$\Lambda(1690)$	0.016265
$\Lambda(1710)$	0.011306
$\Lambda(1800)$	0.005983
$\Lambda(1810)$	0.003354
$\Lambda(1820)$	0.007696
$\Lambda(1830)$	0.006324
$\Lambda(1890)$	0.008913
Sum	1.050745

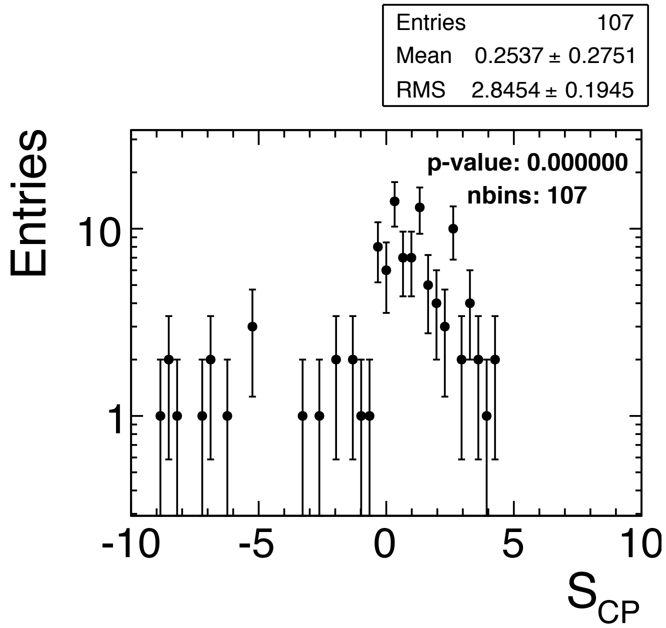
The essential resonances are mostly reproduced in the model

Sensitivity of the S_{CP} method

CP asymmetry is not introduced



CP asymmetry is introduced as **20%** difference in K* amplitudes

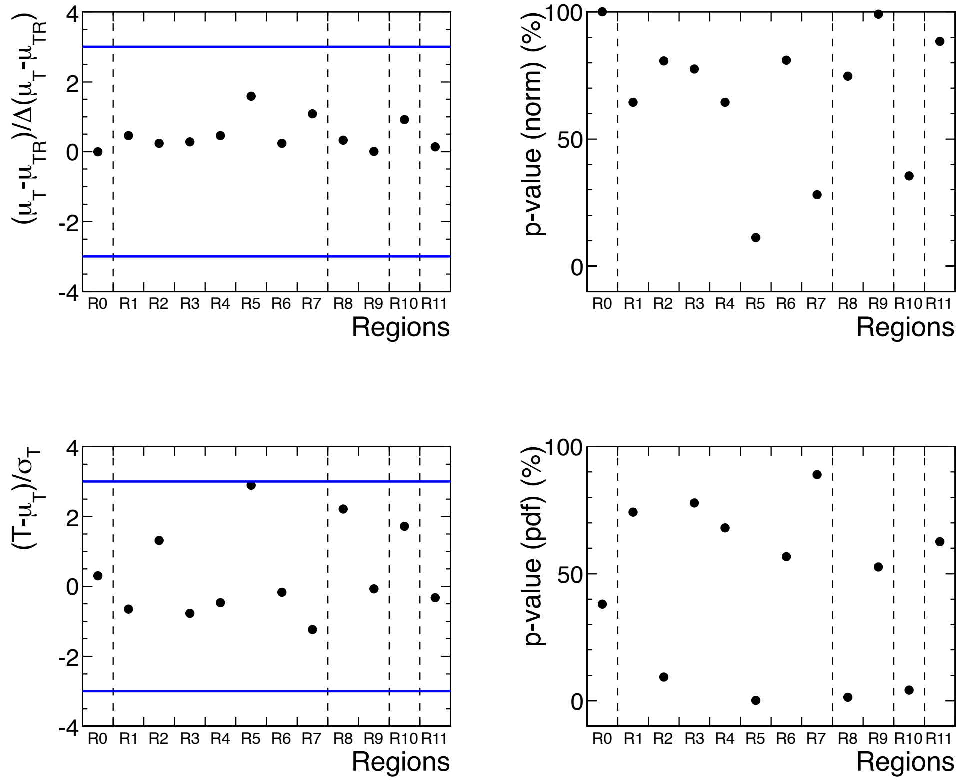


- Different bin numbers and sizes are tested
- The S_{CP} method does not generate fake asymmetry
- The S_{CP} method sees asymmetry if it is larger or equal than 5% in amplitudes of K* or 10% in amplitudes of Δ^{1232}

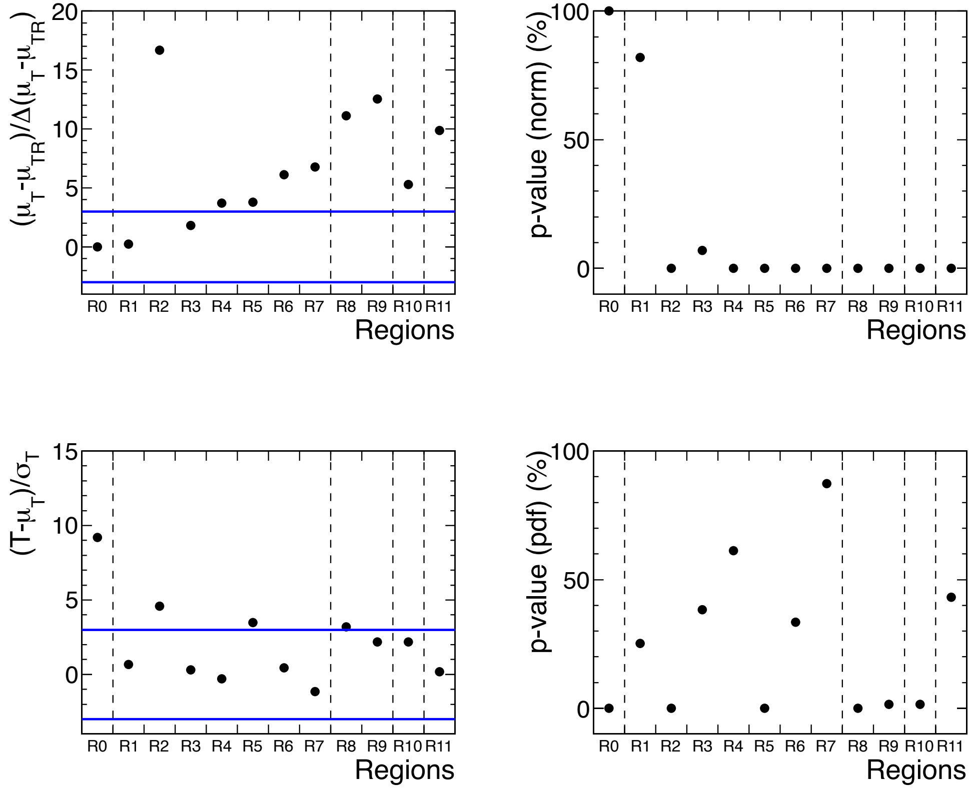
The sensitivity of the kNN method

n_k=50

CP asymmetry is not introduced



CP asymmetry is introduced as **20%** difference in K* amplitudes

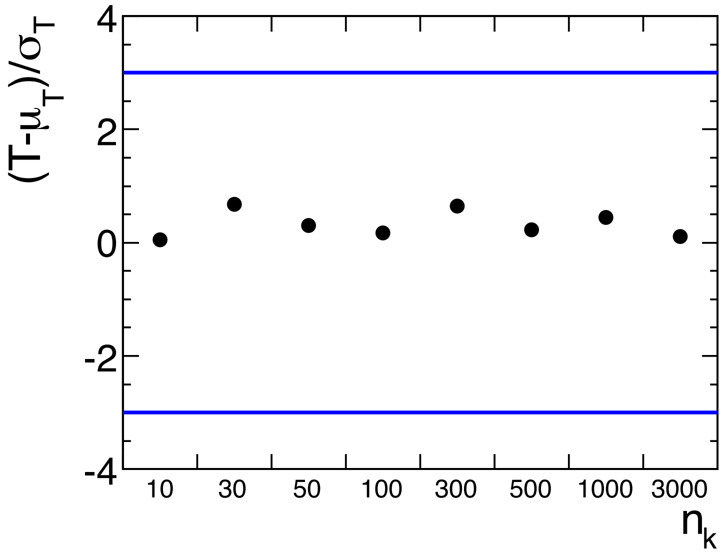


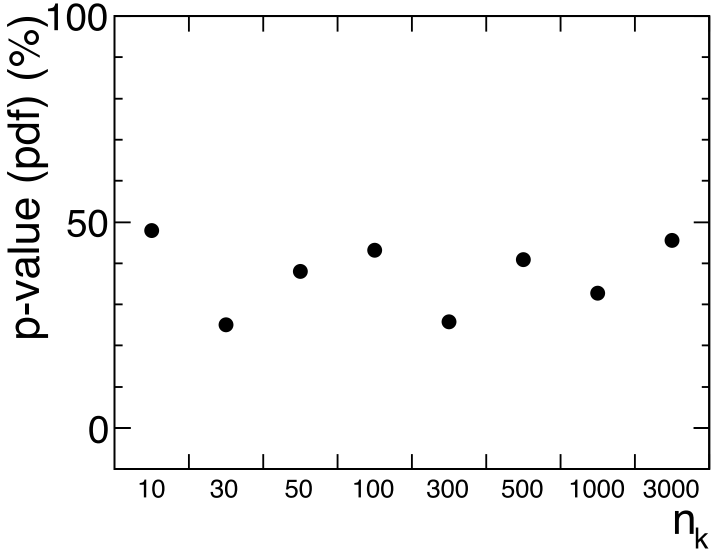
- Different bin numbers and sizes are tested
- The kNN method does not generate fake asymmetry
- The kNN method sees asymmetry if it is larger or equal than 5% in amplitudes of K* or 5% in amplitudes of Δ^{1232} (the S_{CP} starts to see from 10%)

The n_k dependence (R0 region)

CP asymmetry is not introduced

Note: points are correlated





- All points vary from -3σ to +3σ (for n_k from 10 to 3000)
- The n_k corresponds to the size of bin in the binned method. The n_k=3000 for a given statistics can be compared with 33 bins
- The method does not generate signal of CP asymmetry if it does not exist