31th March 2023

Measurements of *CP* asymmetries in charm decays in the charmingly-beauty experiment – LHCb

Part 1:

The first evidence for *CP* asymmetry in a specific charm meson decay

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Part 2:

New approach for searching for *CP* asymmetry in charm baryons

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Menu

Part 1

- **Introduction**
  - Why do we study flavour physics?
  - Neutral mesons mixing and known *CP* asymmetries values
  - Reconstruction of charm particles in the LHCb detector
- **The examples of the LHCb measurements**
  - The first evidence of nonzero *CP* asymmetry in a specific charm meson decay

Part 2

  - *CP* violation measurements in three-body charm baryons
    - Selection criteria of $\Xi_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+$
    - Mass distributions and statistics
    - The binned and unbinned results in control decays
    - Energy Test method
    - Kernel Density Estimation technique
- **Summary**

Why do we study flavour physics at hadronic machines?

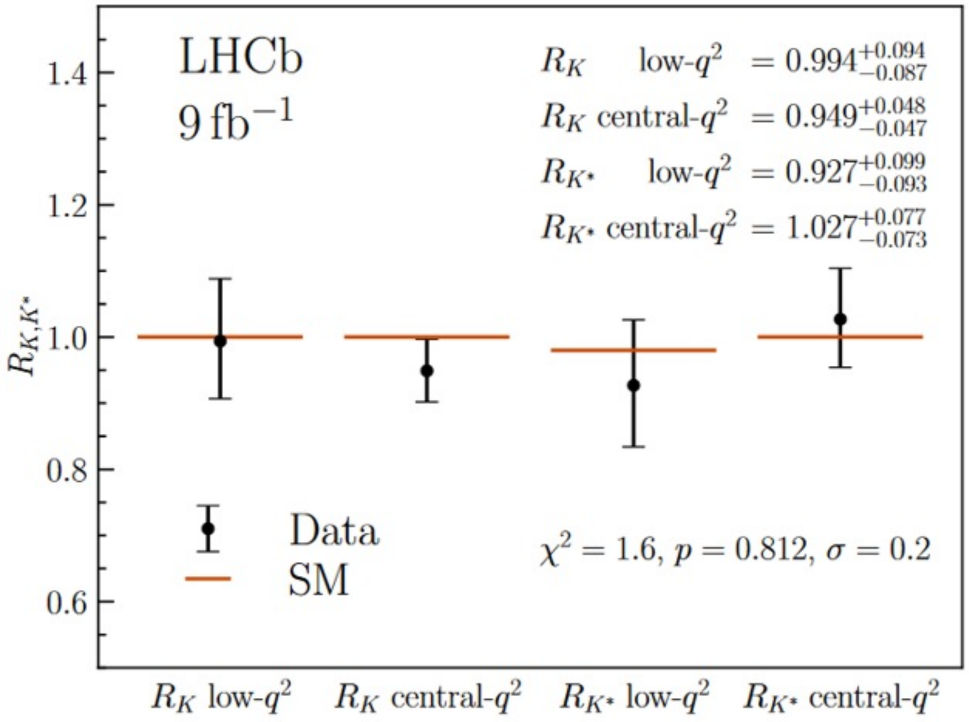
- The Standard Model is a theory which describes "well" existed data, but there are many phenomena which are not understood:
  - Why are there three fermion generations? Only three?
  - Hierarchy in Yukawa couplings?
  - *CP* violation in quark sector is too small to explain the matter-antimatter asymmetry in the universe. Are there other sources of *CP* violation?
  - April '22: the measured *W* mass is different from the SM calculations! (CDF collaboration)

Why do we study flavour physics at hadronic machines?

arXiv:2212.09153

- December '22:
  The lepton universality story

  The LHCb measures agreement with the Standard Model curbing earlier enthusiasm

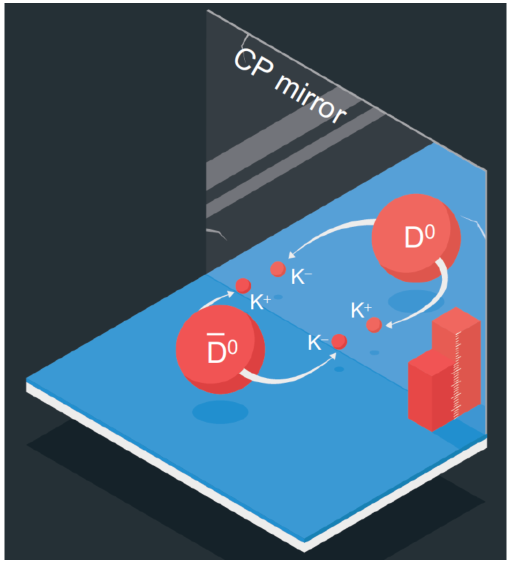


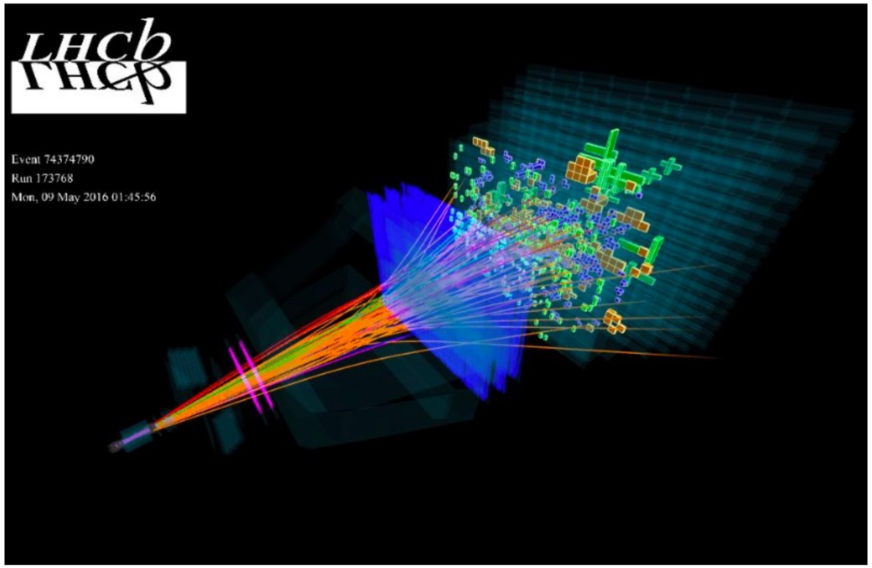
- Is there physics beyond the Standard Model?

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\displaystyle\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{dq^2} dq^2}{\displaystyle\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{dq^2} dq^2}$$

Why do we study flavour physics at hadronic machines?

- Flavour physics provides a unique window into new physics through indirect searches (potentially sensitive to higher energy scales than direct searches)
    - ➢ finding disagreement (in the LHCb) will be indirect indication of new phenomena existence





- Measurements of *CP* asymmetries in charm sector are very promising for searches for new physics signals

Neutral mesons mixing (oscillation)

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

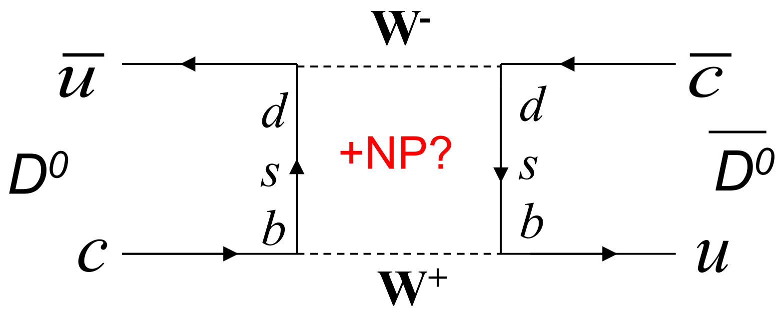
$$i\frac{d}{dt}\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix}$$

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

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

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

experiment

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

theory

$$m \equiv (m_1 + m_2)/2$$
$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

experiment theory

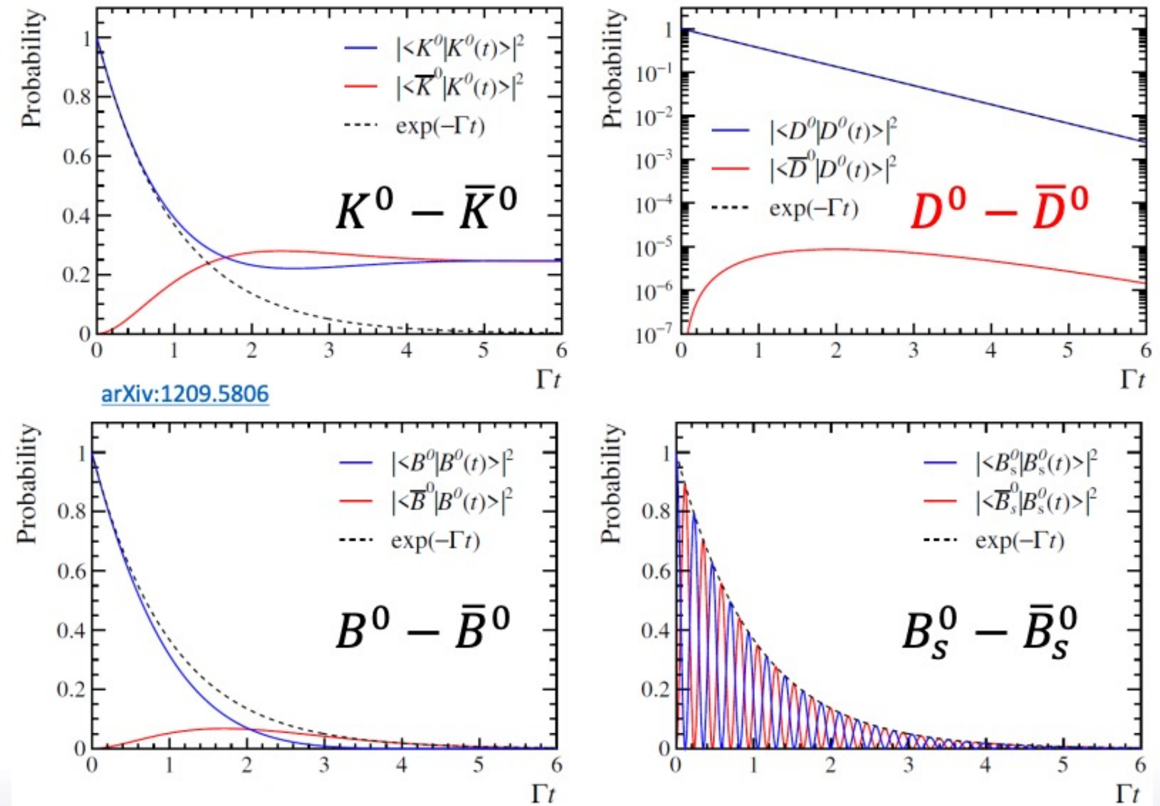
$$\Delta m = M_H - M_L = 2|M_{12}|(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...)$$
$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|cos\phi(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...)$$

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

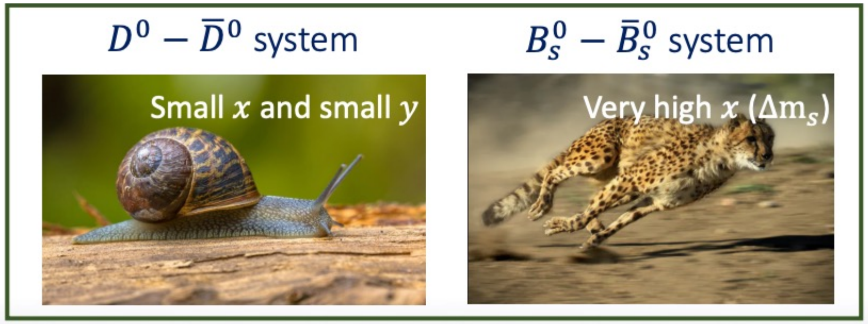
If $\phi \neq 0$ or $|p/q| \neq 1$ then *CP* violation occurs

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

Neutral meson mixing: very different systems!



$$Prob(D^0 \to \bar{D}^0, t) = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

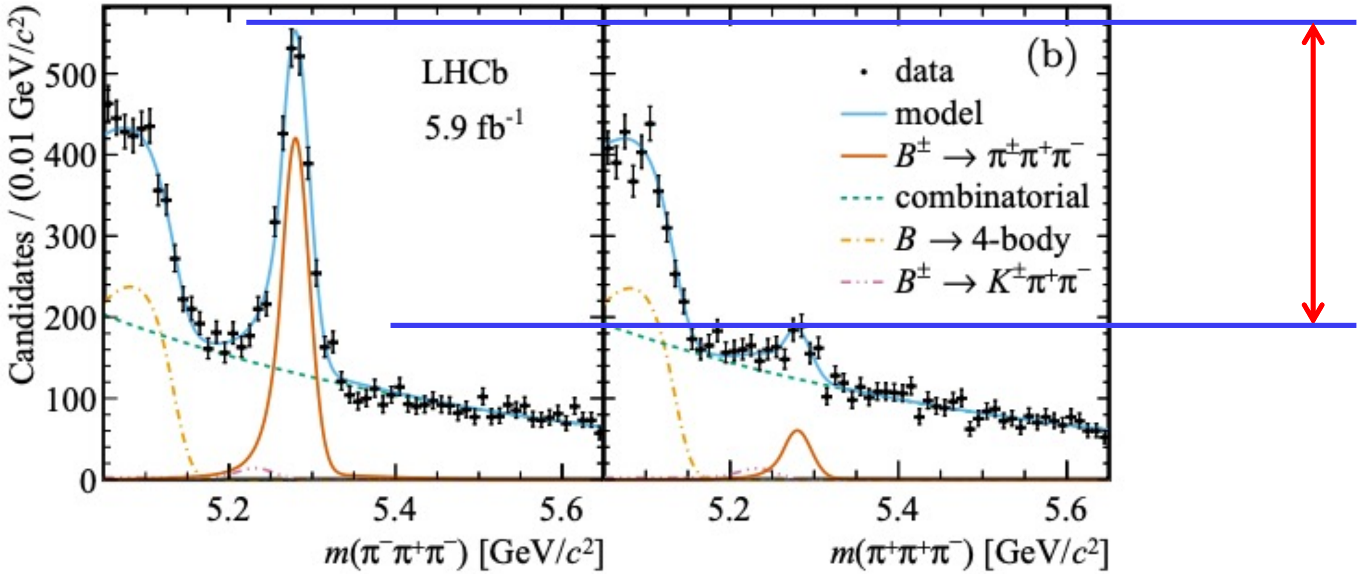


Experimental knowledge of x and y (HFLAV, PDG)

System	x	y
$K^0 - \bar{K}^0$	-0.946 ± 0.004	0.99650 ± 0.00001
$D^0 - \bar{D}^0$	$(4.09^{+0.48}_{-0.49})\times10^{-3}$	$(6.15^{+0.56}_{-0.55})\times10^{-3}$
$B^0 - \bar{B}^0$	-0.769 ± 0.004	$(0.1 \pm 0.1)\times10^{-2}$
$B_s^0 - \bar{B}_s^0$	26.89 ± 0.07	$(12.9 \pm 0.6)\times10^{-2}$

CP asymmetry values are also significantly different in beauty and charm systems

- Local *CP* violation is ~75% in $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ (LHCb-PAPER-2021-049)
  The largest *CP* asymmetry ever observed!



CP violation is clearly seen

- In charm sector:
  - in the SM, the expected *CP* violation is very small $\lesssim 10^{-4} - 10^{-3}$
  - the LHCb measurement (PRL 122 (2019) 211803)

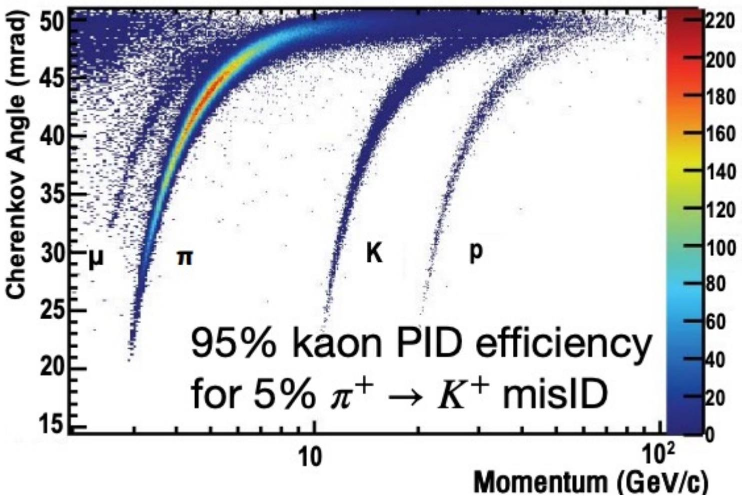
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-1.54 \pm 0.29) \cdot 10^{-3}$$

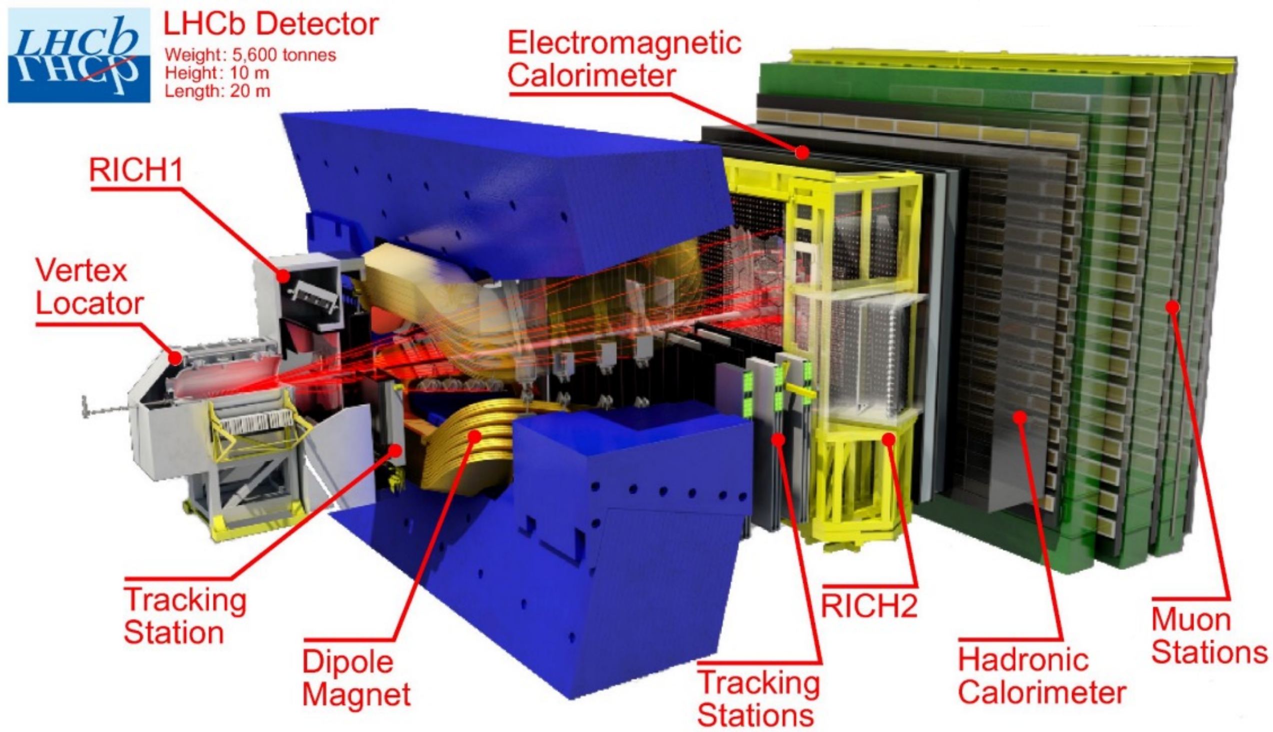
  - new physics contributions can enhance *CP* violation up to 10^{-2}

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

The LHCb detector in Run 1 and Run 2 (2011-2018)

JINST 3 S08005





Detector in the forward region ($2 < \eta < 5$):

- excellent particle identification for for π and K (misidentification < 5%)
- very good momentum resolution (0.4 - 1.0%)
- excellent IP resolution (11+23.6/p_T μm) and very good decay time resolution (~45fs)

Factory of beauty and charm particles

In the LHCb acceptance:

$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\ \mu b \quad (\sqrt{s} = 7\ \mathrm{TeV})$ Run 1 (2011-2012): 3/fb

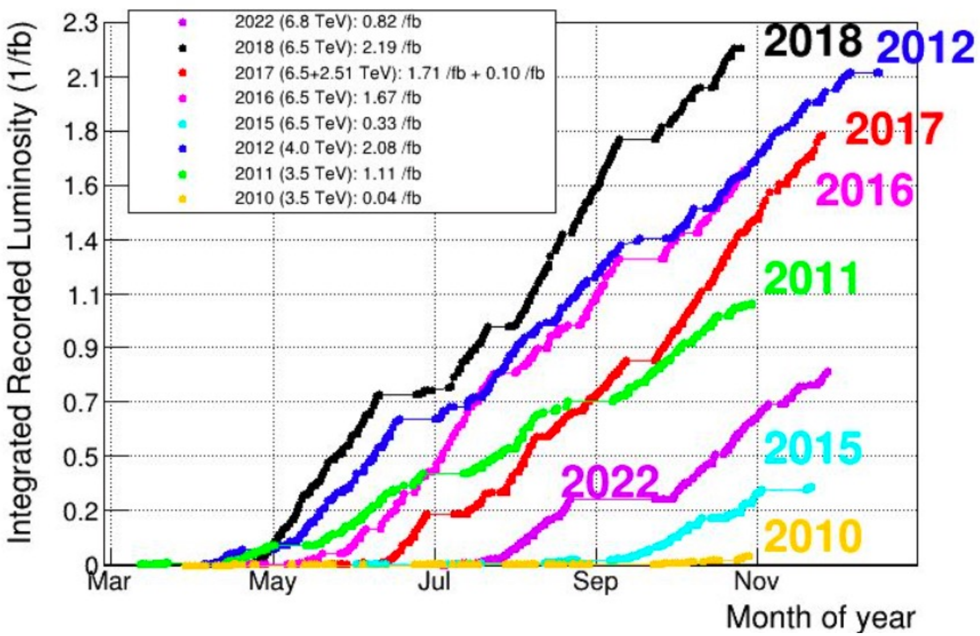
Phys.Lett.B694 (2010) 209-216

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

Nucl.Phys.B871 (2013) 1

$\sigma(c\bar{c}) = 2369 \pm 3 \pm 152\ \mu b \quad (\sqrt{s} = 13\ \mathrm{TeV})$ Run 2 (2015-2018): 6/fb

JHEP 05 (2017) 074

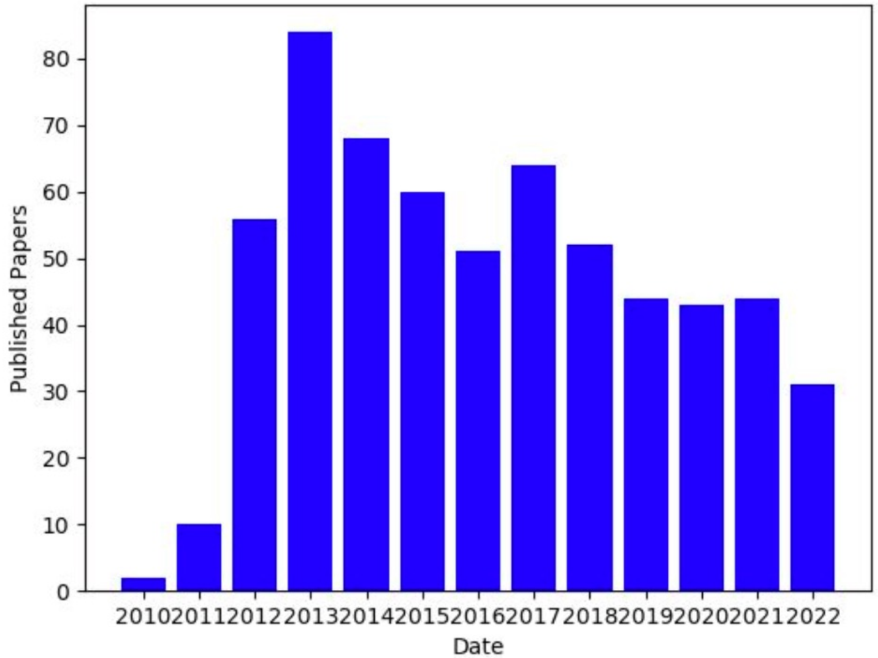


For each 1/fb:
~28k $B^0_s \to J/\psi(\mu\mu)\,\phi(K^+K^-)$
~2M $D^{*\pm} \to D^0(\to K^-K^+)\,\pi^\pm$

Not just a flavour physics experiment

More than 600 papers!

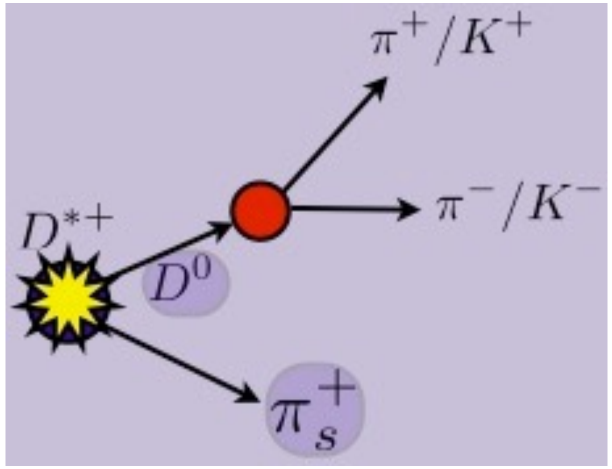
- Mixing and *CP* violation in B decays
- Rare B/D/K decays
- Charm decays
- Semileptonic B decays
- Spectroscopy and exotic hadrons
- Hadron production
- Heavy ion physics, fixed target with SMOG
- Electroweak physics, QCD
- Exotics (dark matter, long-lived particles)



Measuring asymmetry between matter and antimatter

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

prompt D^0



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

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

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

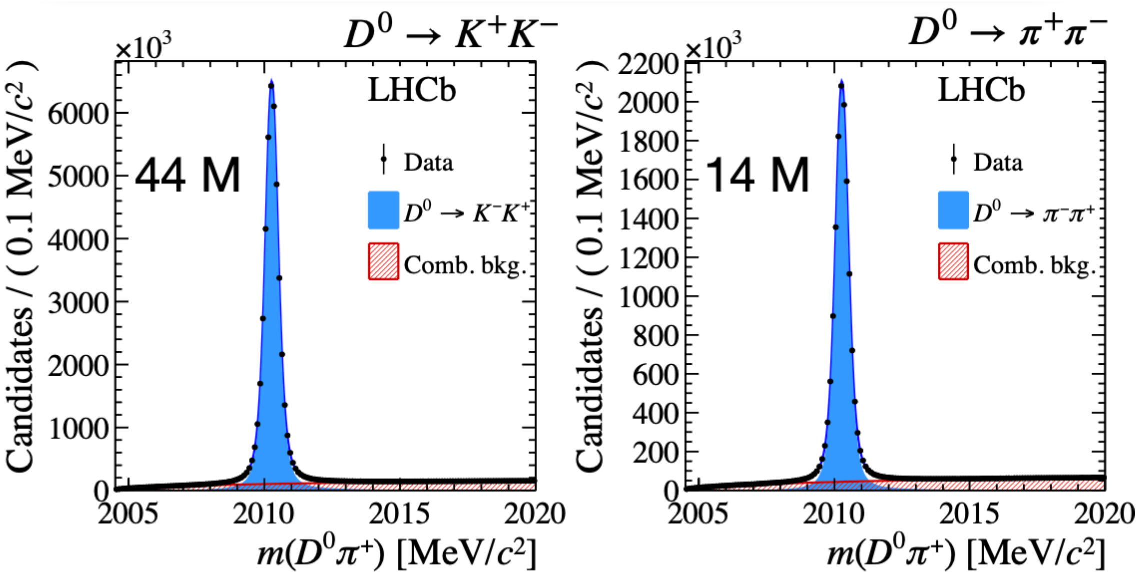
- The A_P is independent of the final state and this term cancels in the first order if we subtract raw asymmetries

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

PRL 122 (2019) 211803

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

[JHEP 1106 (2011) 089]



- 2015-2018, 5.7/fb
- Observable is mainly sensitive to direct *CP* asymmetry
- Indirect *CP* asymmetry is smaller than 10%

ΔA_{CP} – bittersweet result

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

PRL 122 (2019) 211803

Two possibilities:

- $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have the same magnitude but different sign (unlikely today)
- Asymmetries are significantly different:
  $A_{CP}(K^+K^-)$ is a few times smaller then $A_{CP}(\pi^+\pi^-)$

  for example,
  "*CP* violation in D decays to two pseudoscalars: A SM-based calculation"
  E. Solomonidi, BEACH 2022 Conference in Cracow

- Nonetheless, to properly determine and investigate the source of potential *CP* violation, one has to examine the single asymmetry

Measurement of *CP* asymmetry in $D^0 \to K^- K^+$

LHCb-PAPER-2022-024, arXiv:2209.03179

- Measuring time integrated asymmetry of single mode is much harder

$$A(K^-K^+) \approx A_{CP}(K^-K^+) + A_{\rm P}(D^{*+}) + A_{\rm D}(\pi^+_{\rm tag})$$

- $A_{\rm P}$ and $A_{\rm D}$ are determined using control samples with negligible *CP* asymmetry

$$\begin{aligned}
A(K^-\pi^+) &\approx A_{\rm P}(D^{*+}) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+) + A_{\rm D}(\pi^+_{\rm tag}),\\
A(K^-\pi^+\pi^+) &\approx A_{\rm P}(D^+) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+_1) + A_{\rm D}(\pi^+_2),\\
A(\overline{K}{}^0\pi^+) &\approx A_{\rm P}(D^+) + A(\overline{K}{}^0) + A_{\rm D}(\pi^+),\\
A(\phi\pi^+) &\approx A_{\rm P}(D^+_s) + A_{\rm D}(\pi^+),\\
A(\overline{K}{}^0K^+) &\approx A_{\rm P}(D^+_s) + A(\overline{K}{}^0) + A_{\rm D}(K^+).
\end{aligned}$$

LHCb-PAPER-2022-024, arXiv:2209.03179

Data from Run 2:

37M of $D^0 \to K^-K^+$ decays

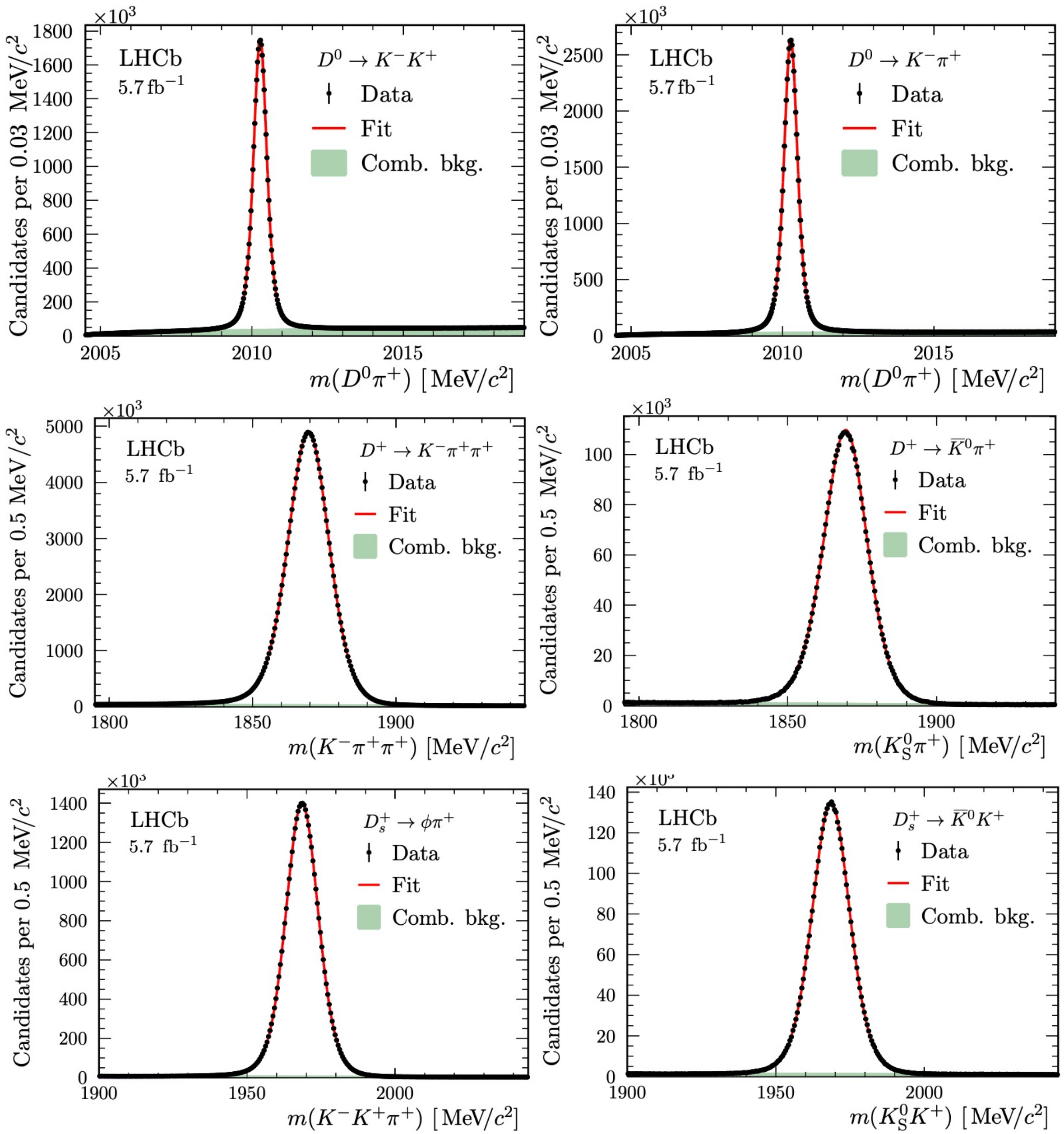
58M of $D^0 \to K^-\pi^+$ decays

188M of $D^+ \to K^-\pi^+\pi^+$ decays

6M of $D^+ \to K^0\pi^+$ decays

43M of $D^+_s \to \phi\pi^+$ decays

5M of $D^+ \to K^0K^+$ decays



LHCb-PAPER-2022-024, arXiv:2209.03179

The measured CP asymmetry (Run 2 only):

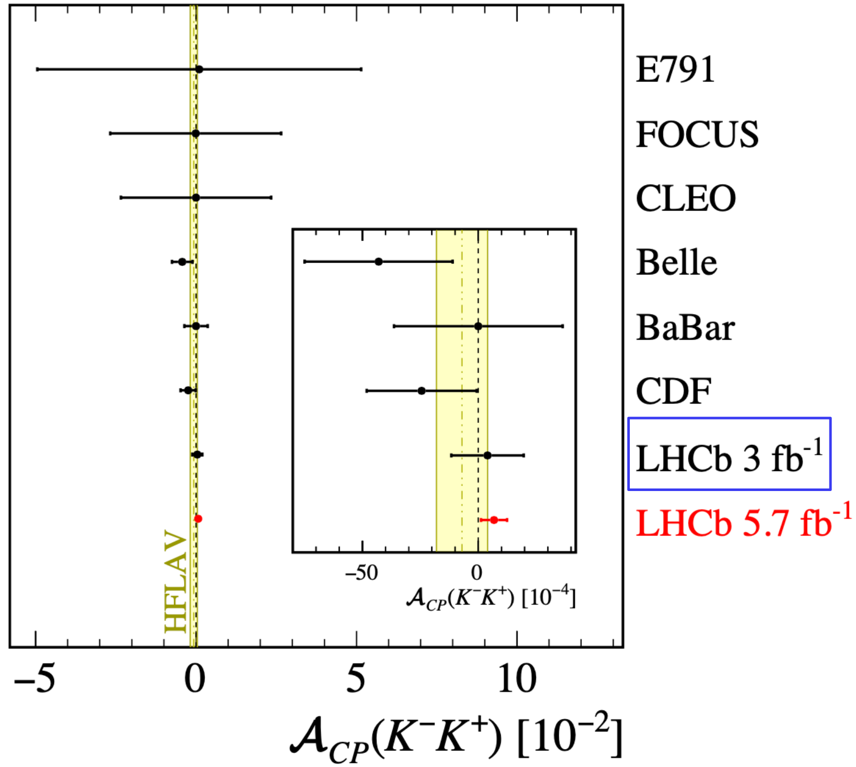
$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

The value is consistent with zero but can be subtracted from ΔA_{CP}

Assuming that *CP* is conserved in mixing and in the interference between decay and mixing ΔY

$$\mathcal{A}_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

$$\Delta Y_{K^-K^+} = \Delta Y_{\pi^-\pi^+} = \Delta Y$$



Direct *CP* asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$

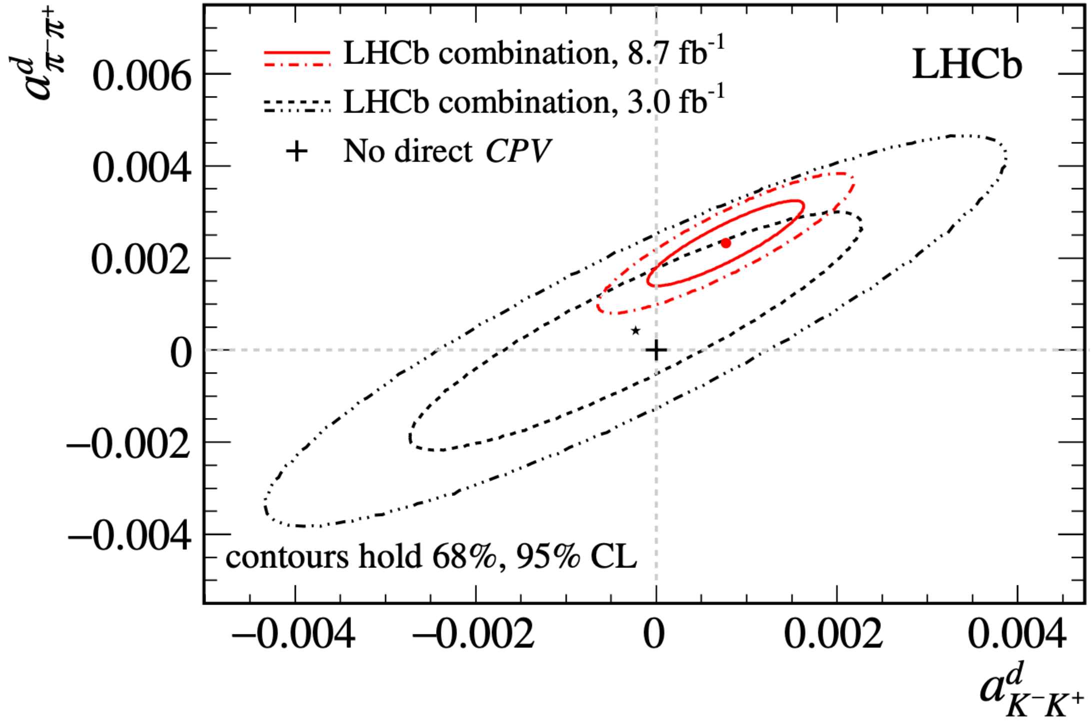
LHCb-PAPER-2022-024, arXiv:2209.03179

Combining Run 1 and Run 2 data:

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

the uncertainties include systematic and statistical contributions



The direct *CP* asymmetries deviate from zero by 1.4 and 3.8 standard deviations for $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$

This is the first evidence for direct *CP* violation in a specific charm decay

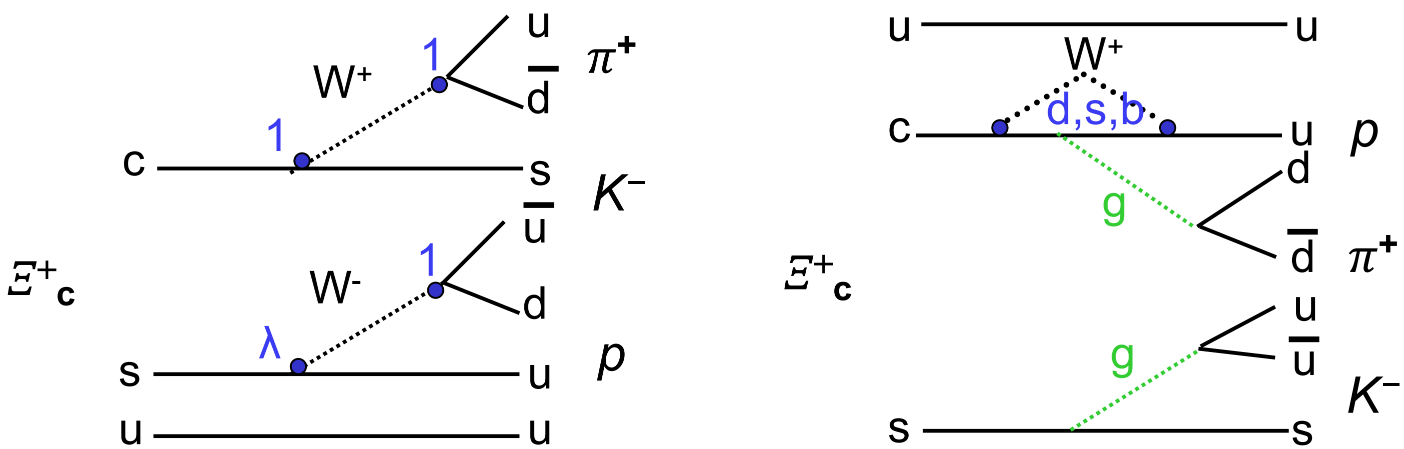
Results departure from U-spin symmetry ($a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$) of 2.7σ

The first searches for *CPV* in $\Xi_c^+ \to pK^-\pi^+$

The $\Xi^+_c \to pK^-\pi^+$ decays are singly Cabibbo-suppressed decays = place of *CP* violation in the Standard Model

- Data collected in Run 1, $\sqrt{s}$ = 7 TeV and 8 TeV, L = 3 fb^{-1} [Eur. Phys. J. C80 (2020) 986],

λ = 0.22

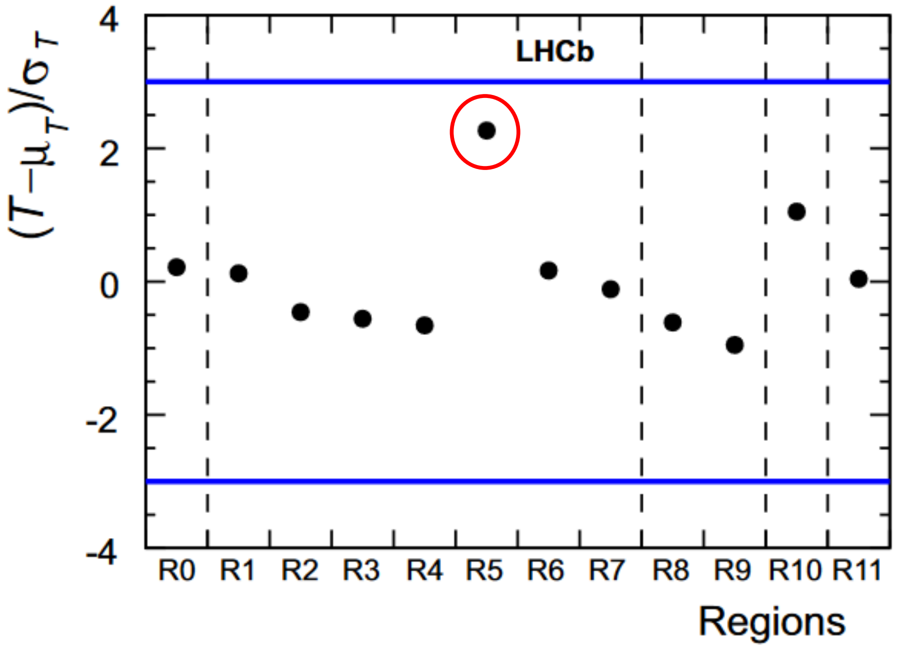


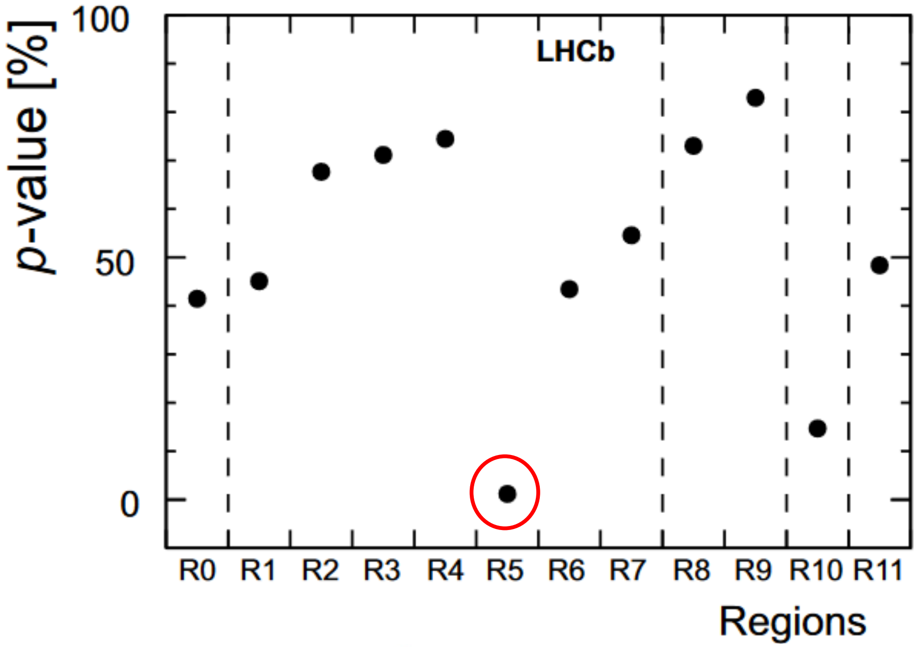
- If tree and penguin processes interfere with different phases for Ξ_c^+ and Ξ_c^- then *CP* symmetry is broken
- Penguin diagram opens possibilities for new particles exchange

The k-nearest neighbour method

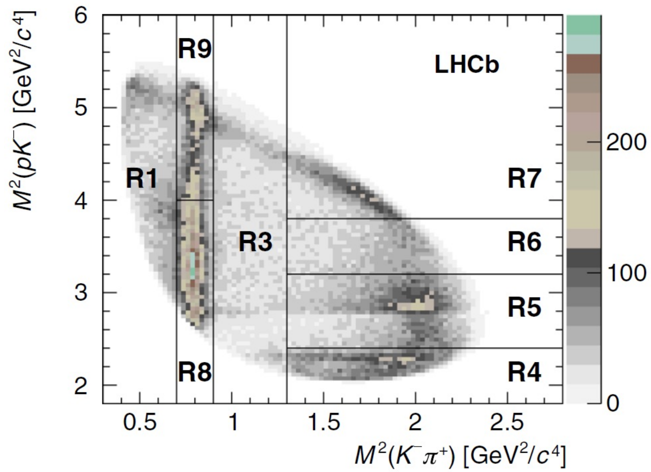
$$T = \frac{1}{n_k(n_+ + n_-)} \Sigma_{i=1}^{n_+ + n_-} \Sigma_{k=1}^{n_k} I(i,k)$$

Eur. Phys. J. C80 (2020) 986





- Results are consistent with *CP* symmetry,
- **Local effect in one region corresponds to 2.7σ,**
- **It is worth to continue analysis with Run 2 data.**

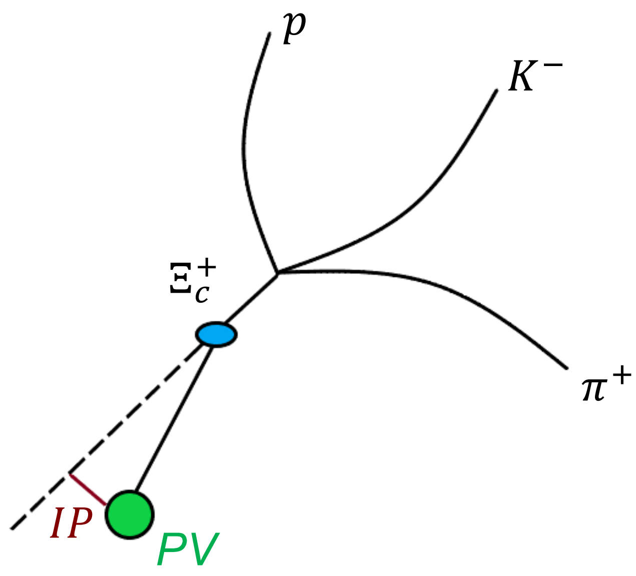


Proton/Kaon/Pion

- PID
- ProbNN
- IPχ^2
- TRACK_GhostProb
- momentum

Charm baryon

- Vertex $\chi^2/ndof$
- IPχ^2
- p_T
- DIRA
- FDχ^2
- Pseudorapidity η
- Lifetime τ



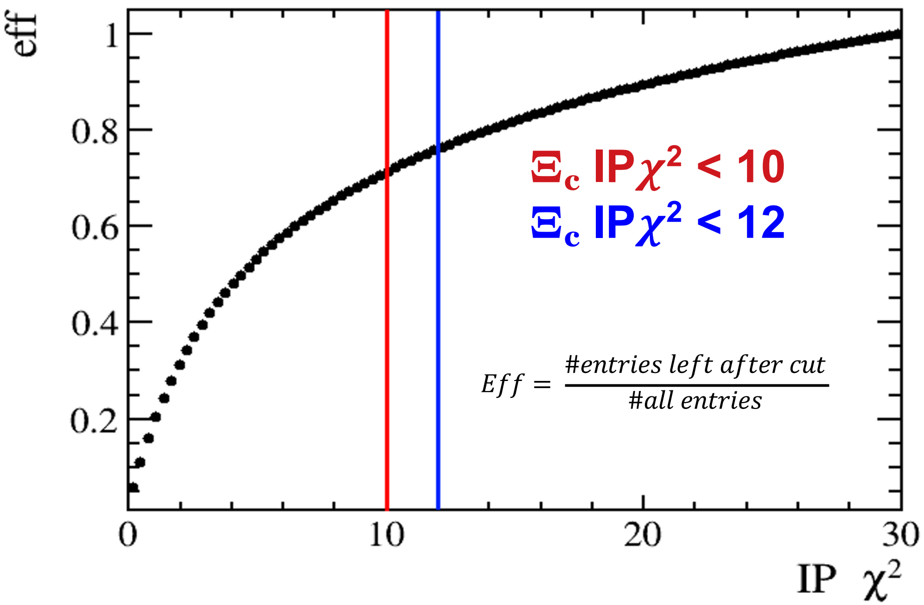
Goal is to maxmize signal reducing background.

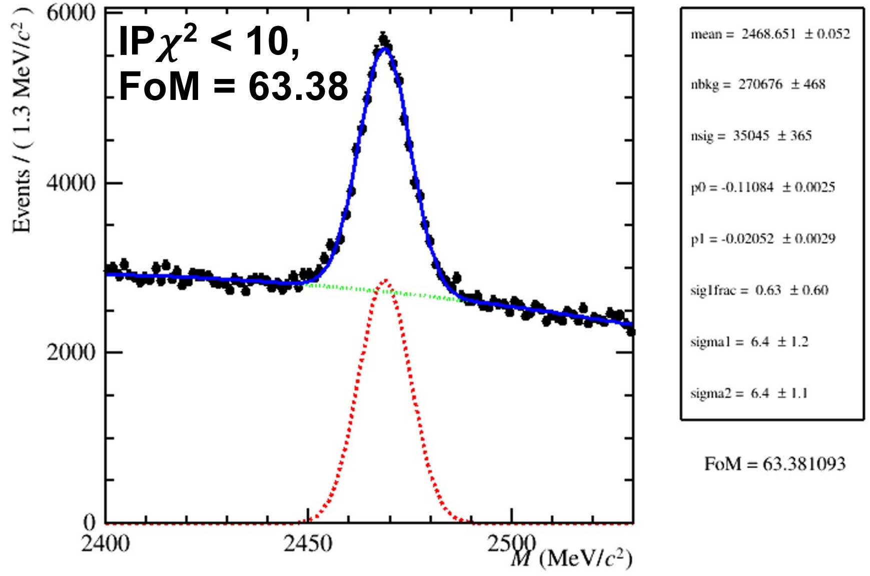
Figure of Merit: $$FoM = \frac{S}{\sqrt{S+B}}$$

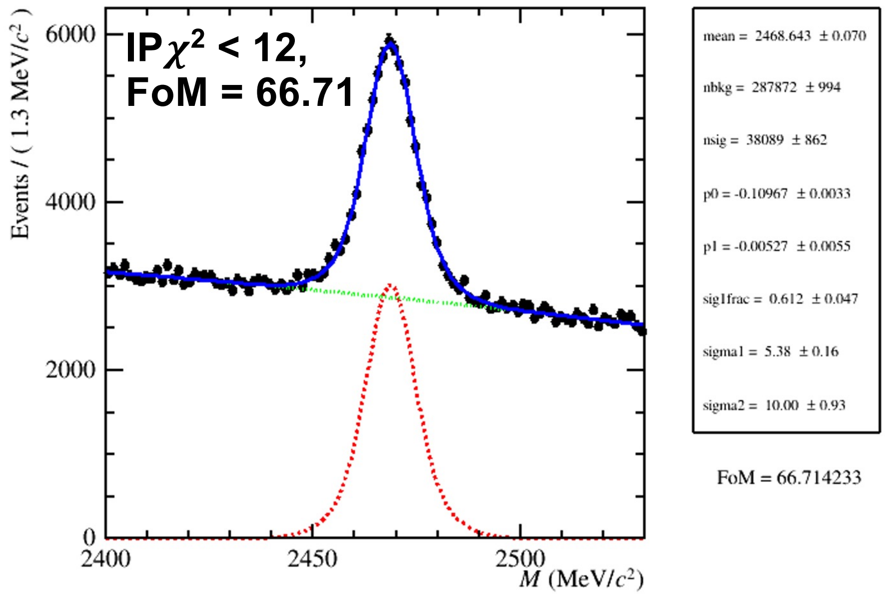
S – no. signal candidates, *B* – no. Background candidates

Selection process - Ξ_c IPχ^2

An example







cut	8	10	12	15
S	37k	35k	38k	38k
B	244k	270k	288k	313k
FoM	69	63	67	64

Eff ~ 78%

Selection proces – final cuts

Finally, the following cuts were chosen:

Proton/Kaon/Pion

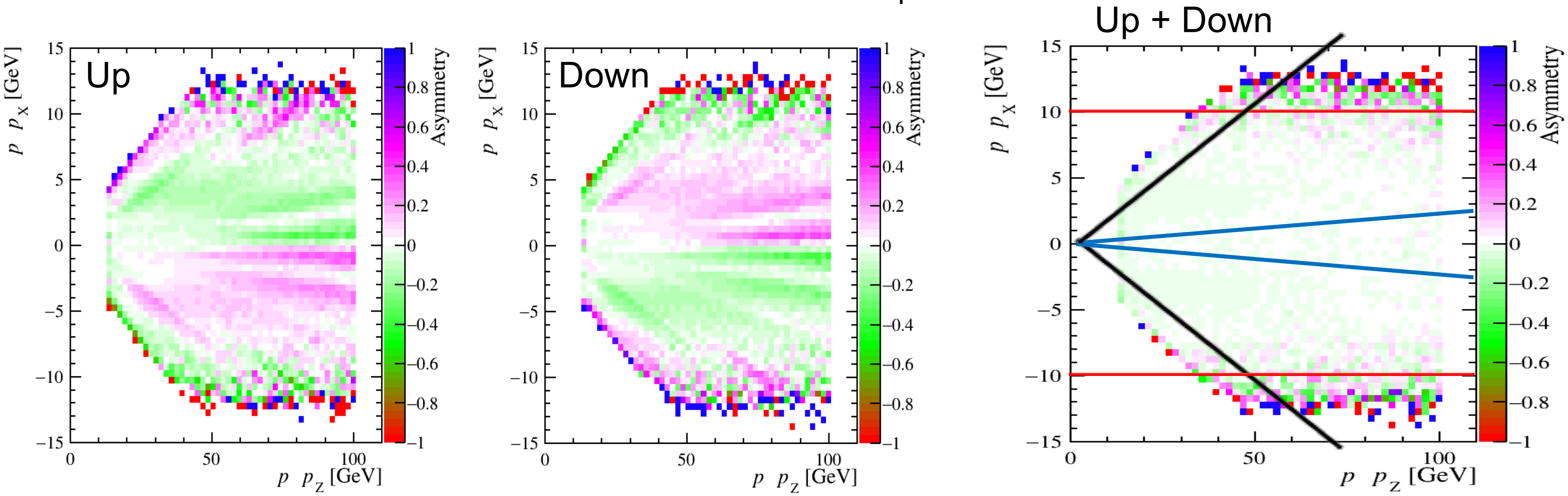
- PID >10/>-10/<12
- ProbNN >0.5/>0.1/>0.1
- IPχ^2 >9
- TRACK_GhostProb <0.4
- momentum
  - proton: 15<P<100 GeV
  - kaon: 3<P<150 GeV
  - pion: 3<P<150 GeV

Charm baryon

- Vertex $\chi^2/ndof$ <8
- IPχ^2 <12
- p_T 4< p_T <16 GeV
- DIRA >0.99995
- FDχ^2 <2000
- Pseudorapidity η (2;4,5)
- Lifetime τ $(0.0005, 0.0015)\ ns$

Fiducial cuts

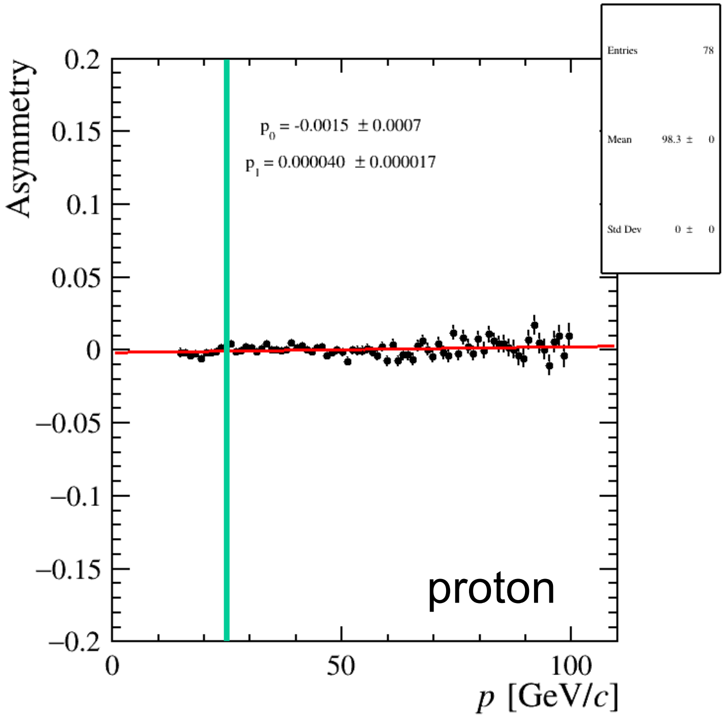
$$Asymmetry = \frac{N_+ - N_-}{N_+ + N_-}$$

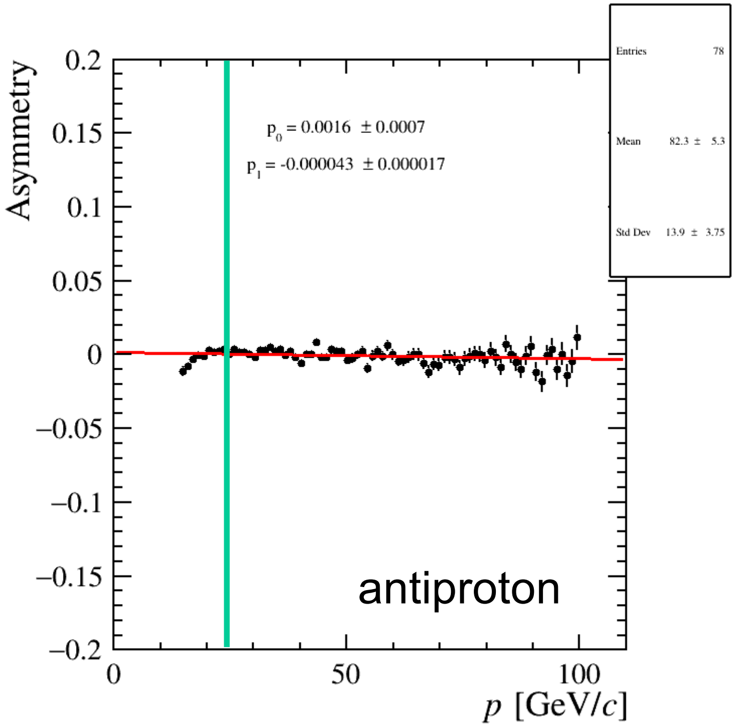


- Geometry of the detector can be not uniform
- After adding MagUp and MagDown data samples the detector effects will remain
- Large detector asymmetries are expected in the external regions and close to the beam axis

- Due to different cross section for interacting with the material of the detector particles and antiparticles can be reconstructed disparately which leads to **reconstruction asymmetry**

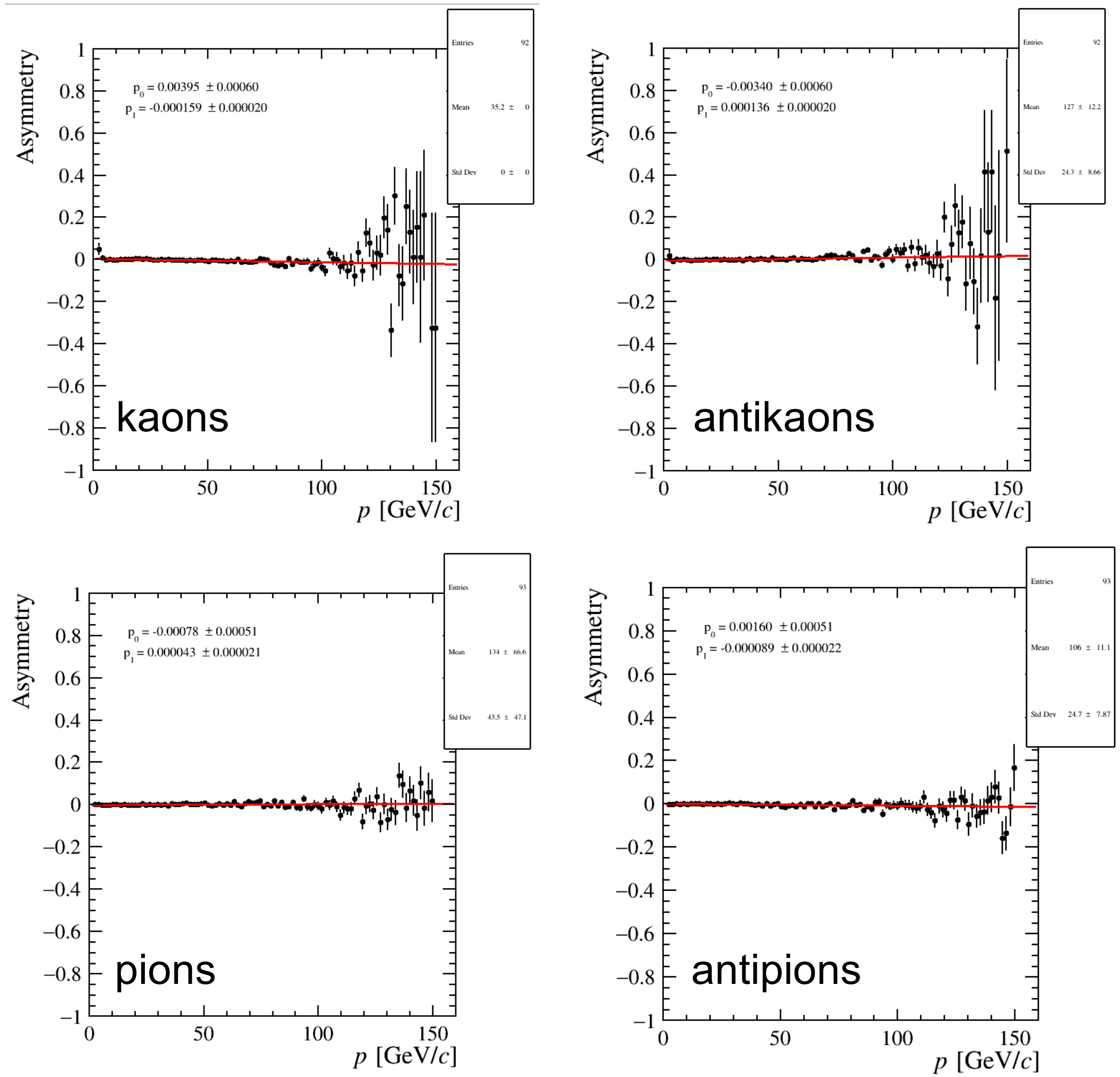
$$Asymmetry = \frac{N_U - N_D}{N_U + N_D}$$





Protons and antiprotons with p < 25 GeV are rejected

Reconstruction effects for kaons and pions



Kaons are rejected if:
p < 15 GeV
Pions are rejected if:
p < 15 GeV

The largest reconstruction effects are for protons

The Run 2 final statistics

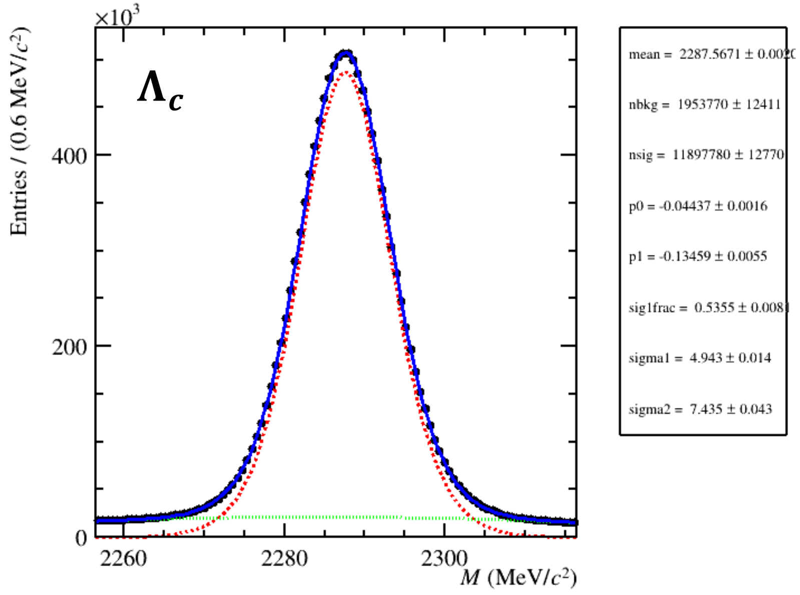
	Ξ_c (Mass Peak +/-20 MeV)	Λ_c
2016	**554090**	**4133105**
2017	**584235**	**4644854**
2018	**648538**	**5073606**
Run 2	**1786863**	**13851565**

- **~ 1.09 mln Ξ_c candidates (only signal, from fit)**

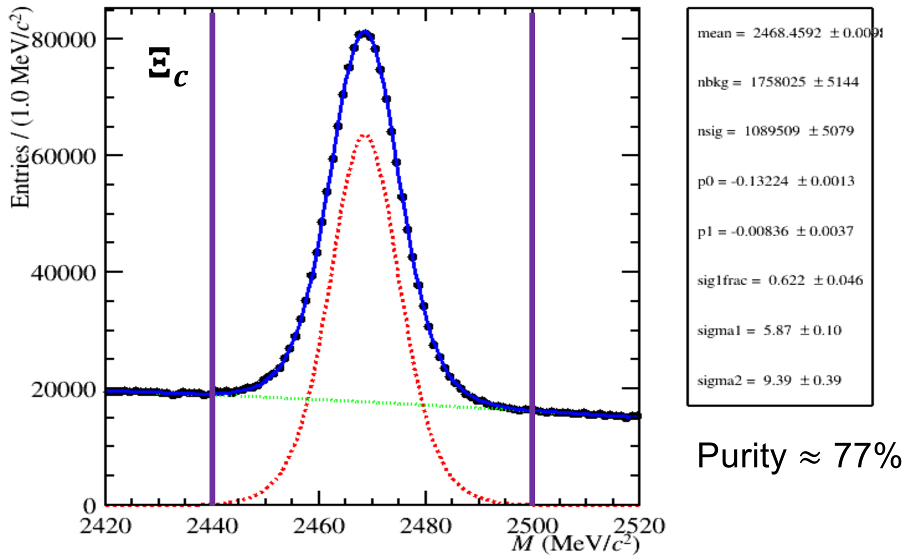
  (> 5 times more than in Run 1 !)

- **~ 14 mln Λ_c candidates**

Control decays



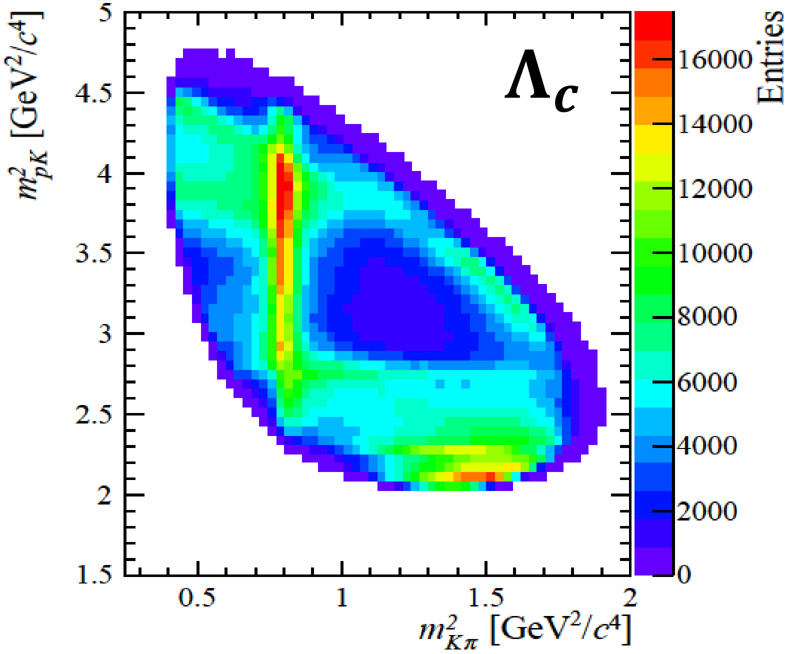
Signal decays, blind



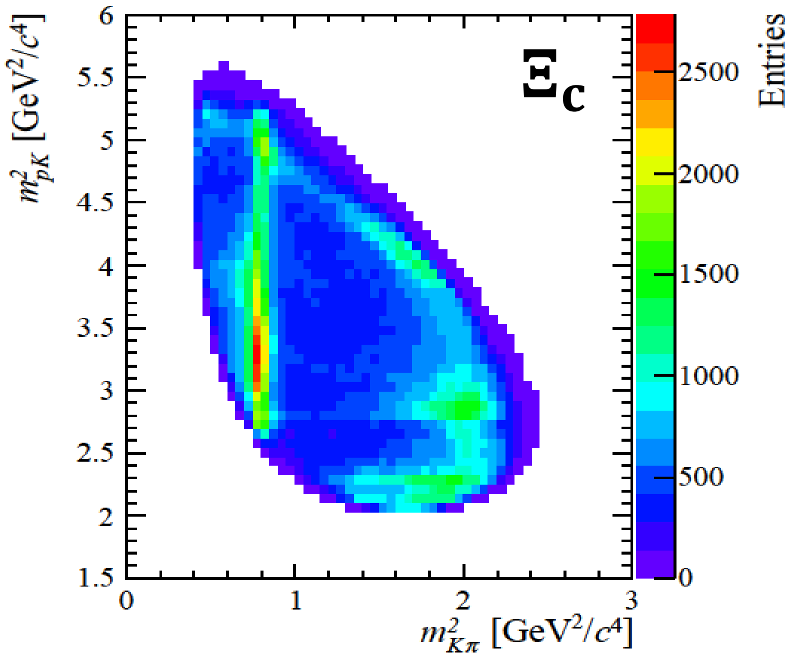
Purity ≈ 77%

2018 data

control decays



signal decays



The intermediate resonances are different for control decays and signal decays.

The S_{CP} method

The method is based on dividing the phase space into n bins. For each bin, significance of the difference between number of particles (N+) and antiparticles (N-) is computed, using the following expression:

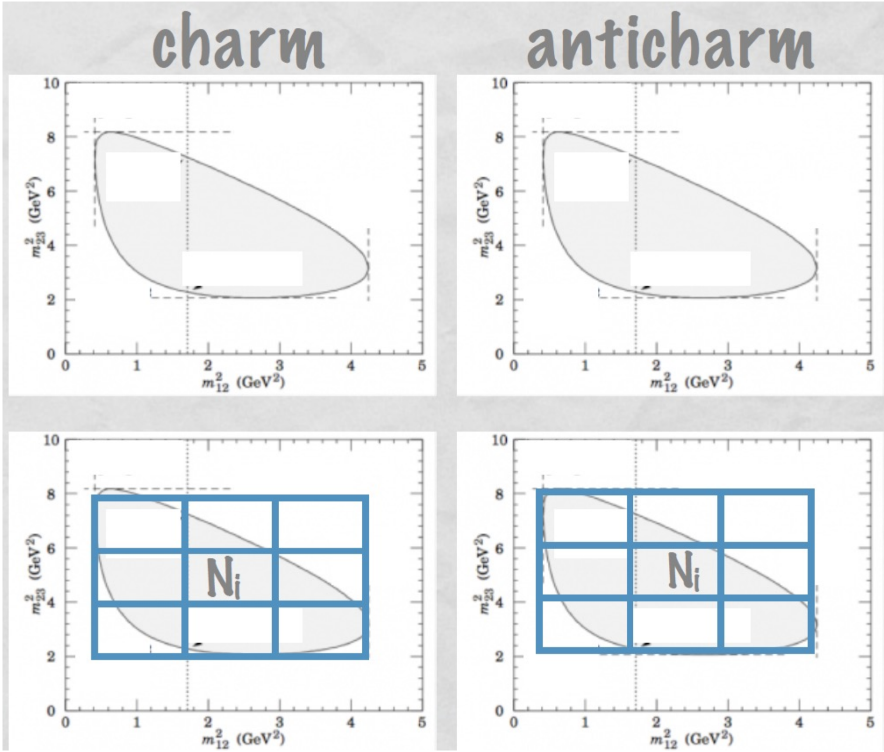
$$S_{CP}^{i} = \frac{N_i^{+} - \alpha N_i^{-}}{\sqrt{\alpha(N_i^{+} + N_i^{-})}}$$

where α = N+/N- accounts for global asymmetries

$\chi^2/ndf = \sum_i S_{CP}^{i} /(nbins-1)$

No CPV: $S_{CP} \sim N(0,1)$

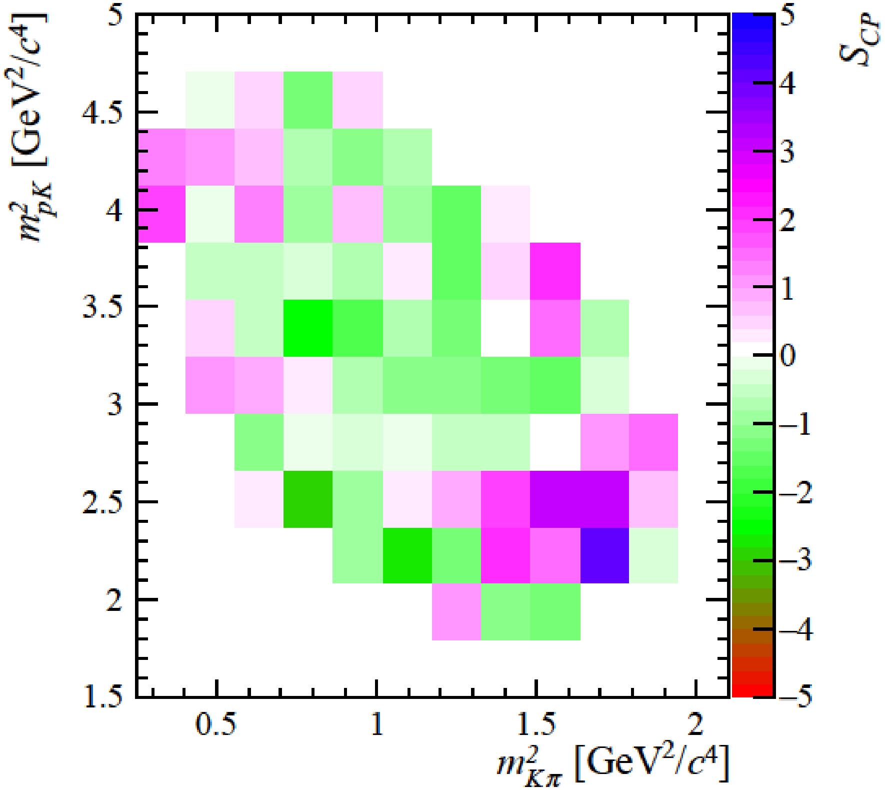
CPV: p-value ≪ 1 ($5\sigma \sim 6 \times 10^{-7}$)

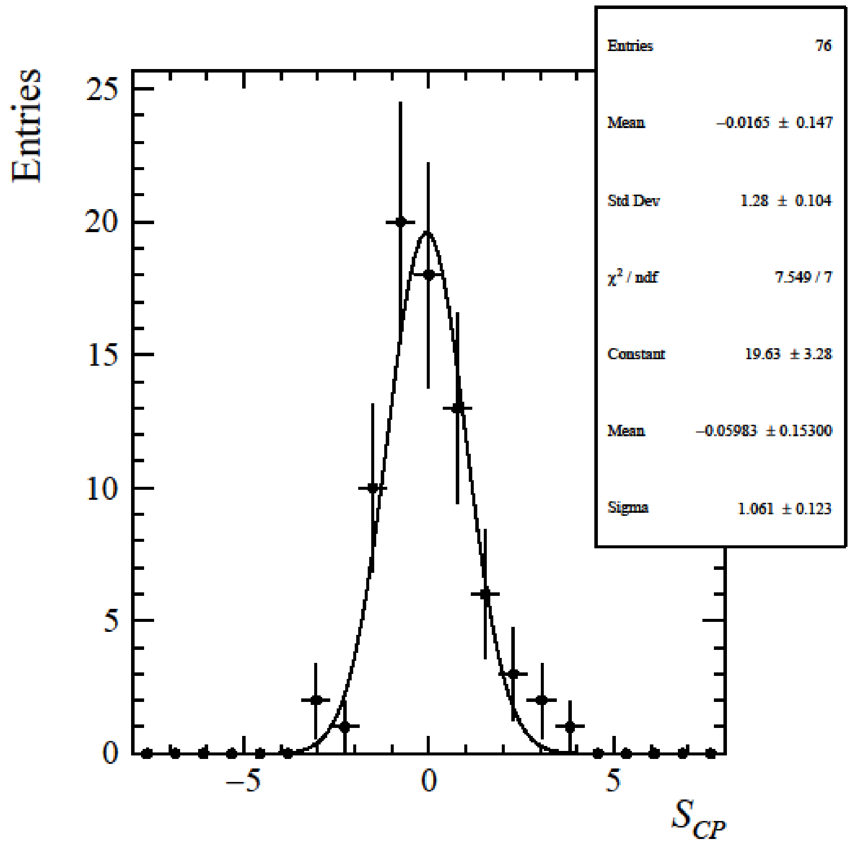


The binned results in the control decays $\Lambda_c \to pK^-\pi^+$

There are 76 bins in Dalitz plot

mean = -0.0165 ± 0.147
sigma = 1.28 ± 0.104



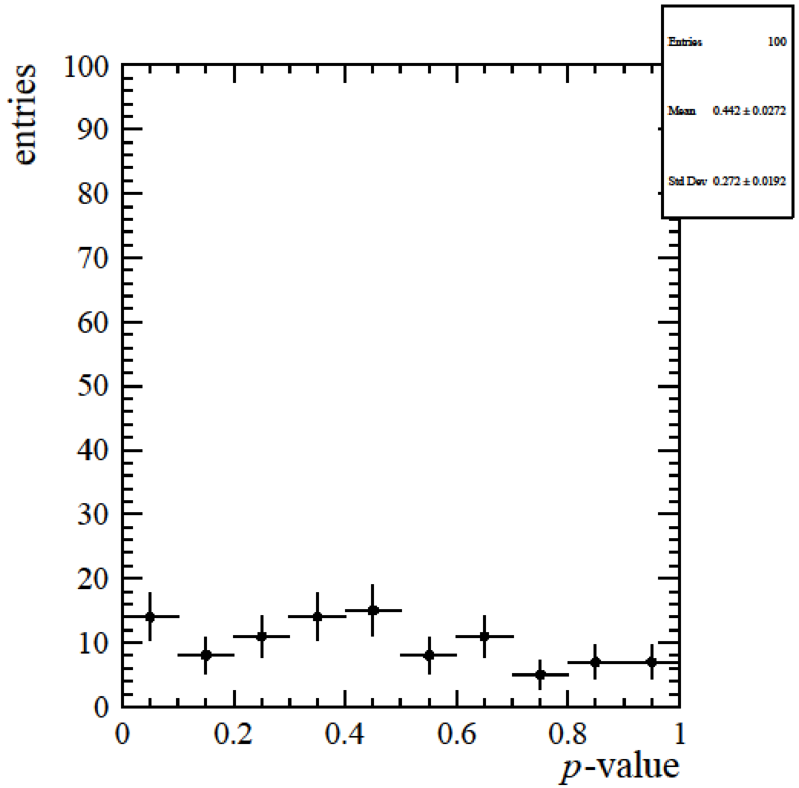


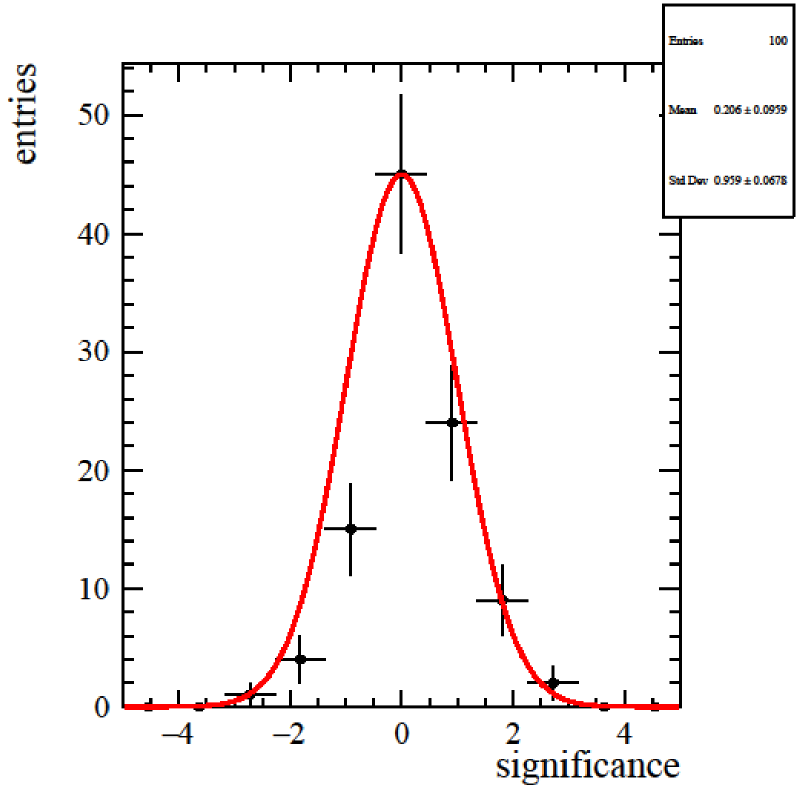
No fake signal of *CPV* in control decays

Results in subsamples in control decays

The whole sample is divided into 100 subsamples

mean = 0.206 ± 0.096
sigma = 0.959 ± 0.068





The p-value distribution is flat as expected - no fake signal of *CPV*

The Energy Test (ET)

- Defined as the analogue of the problem known in physics: the potential energy of the field of charges (with continous density distribution)
- Energy is minimum when two distribution are identical (total charge = 0)
- Can be used to compare two PDFs, denoted as f_a and f_p:

$$\phi = \frac{1}{2}\int\int (f_p(\vec{x})f_p(\vec{x}') + f_a(\vec{x})f_a(\vec{x}') - 2f_p(\vec{x})f_a(\vec{x}'))K(\vec{x},\vec{x}')d\vec{x}d\vec{x}'$$

where K is integral kernel. It is a metric that defines distance in the multivariate space.
Usually we use Gaussian distance function:

$$K(\vec{x},\vec{x}') = \exp(-\frac{(\vec{x}-\vec{x}')^2}{2\delta})$$

where δ governs the width of the Gaussian

The Energy Test (ET)

- ET can be estimated without the need for any knowledge about the forms of f_a or f_p:

$$T = \phi = \frac{1}{n(n-1)} \sum_{i,j>i}^{n} K(|\vec{x}_i - \vec{x}_j|) + \frac{1}{m(m-1)} \sum_{i,j>i}^{m} K(|\vec{x}_i{}' - \vec{x}_j{}'|) - \frac{1}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} K(|\vec{x}_i - \vec{x}_j{}'|)$$

Null hypothesis H_0: $f_p = f_a$:

- ϕ value for overall samples = nominal ϕ value
- We need control set of ϕ values (permuted ϕ values) for which the null hypothesis holds:
  - We calculate ϕ values for symmetric samples:
  - Mix the data together and randomly assign events to two new samples
- Next step is to calculate p-value:

$$p = \frac{\text{number of permuted } T \text{ values greater than nominal } T}{\text{total number of permuted } T \text{ values}}$$

- If $f_p = f_a$ then p-value is uniformly distributed on [0,1]
- If $f_p \neq f_a$ then p-value → 0

The ET results in control Λ_c decays

Λ_c control samples:

10k permutations

	2016	2017	2018	Run 2
T-value	$6.62839 \cdot 10^{-7}$	$8.1397 \cdot 10^{-8}$	$1.67794 \cdot 10^{-7}$	$2.99603 \cdot 10^{-7}$
p-value	0.0137	0.2385	0.129	0.0021

No fake signal of CPV

The ET results in toy samples: no *CPV*

max-perm = 50
- n-perm = 1000, p-value = 0.808
- n-perm = 5000, p-value = 0.766
- n-perm = 10000, p-value = 0.766

max-perm = 100
- n-perm = 1000, p-value = 0.767
- n-perm = 5000, p-value = 0.784
- n-perm = 10000, p-value = 0.775

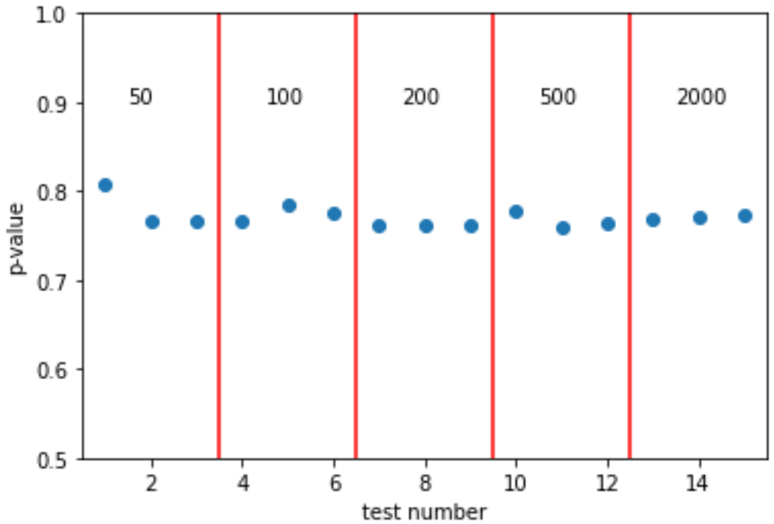
max-perm = 200
- n-perm = 1000, p-value = 0.762
- n-perm = 5000, p-value = 0.762
- n-perm = 10000, p-value = 0.762

Sample with 200k entries

No fake signal of *CPV*

max-perm = 500
- n-perm = 1000, p-value = 0.778
- n-perm = 5000, p-value = 0.76
- n-perm = 10000, p-value = 0.765

max-perm = 2000
- n-perm = 1000, p-value = 0.769
- n-perm = 5000, p-value = 0.7714
- n-perm = 10000, p-value = 0.7724



The ET results in 5% toy sample

Sample with 200k entries

***CPV*: 5% difference in amplitudes of K^* resonance**

5 mln permutations

p-value = $9.2987 \cdot 10^{-7}$

***CPV* is confirmed**

Power of the method:

- **ET is sensitive to *CPV* if it is 5% in K^* and 200k events (1/5 of Run 2 statistics)**

Kernel Density Estimation (KDE)

Kernel Density Estimation is a non-parametric method:

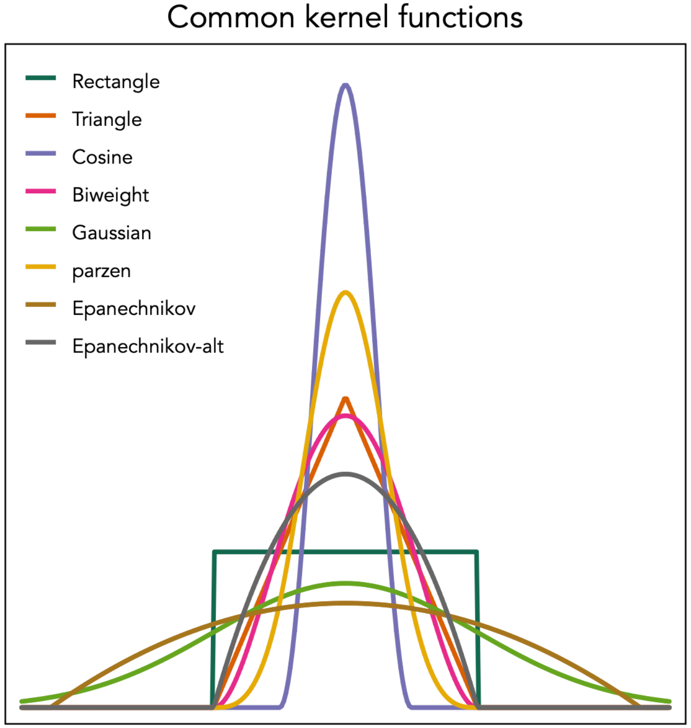
$$f(\hat{x}) = \frac{1}{n}\sum_{i=1}^{n} \omega(x - x_i, h)$$

where: $\omega(t,h) = \frac{1}{h}K(\frac{t}{h})$ is weighting function.

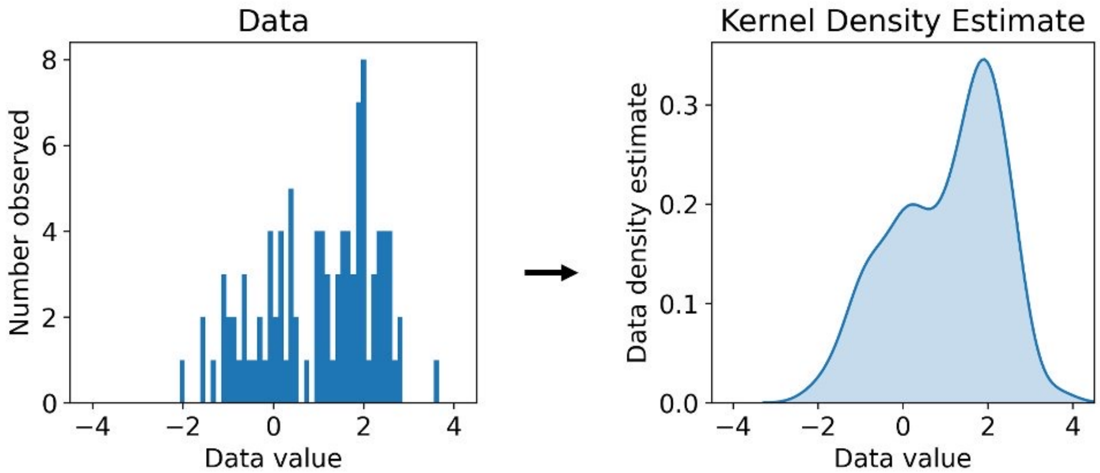
K is the kernel function, *h* – bandwidth parameter

In this analysis I use triangle kernel:

$$\omega(t,h) = \begin{cases} \frac{1}{h}\left(1 - \frac{|t|}{h}\right) & for\ |t| < h \\ 0 & otherwise \end{cases}$$



KDE example:



Bandwidth optimization

- Significant impact in KDE performance
- Globally determined bandwidth:

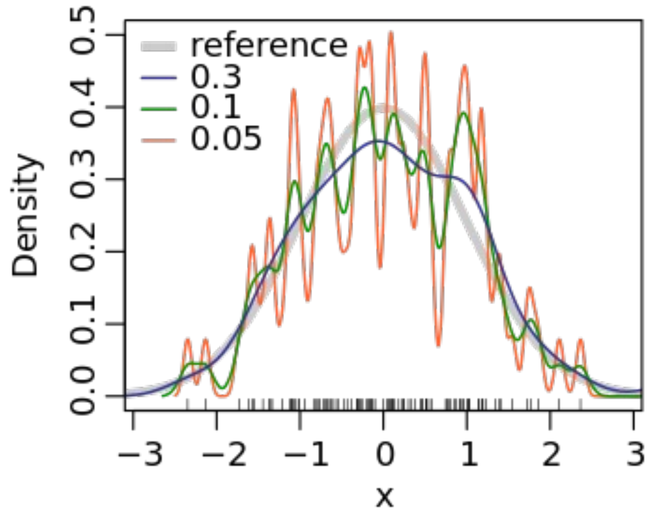
$$h = k\,\hat{S} N^{-0.2}$$

where k – correction parameter (1.06),
$\hat{S}$ - standard deviation of the sample,
N – sample size

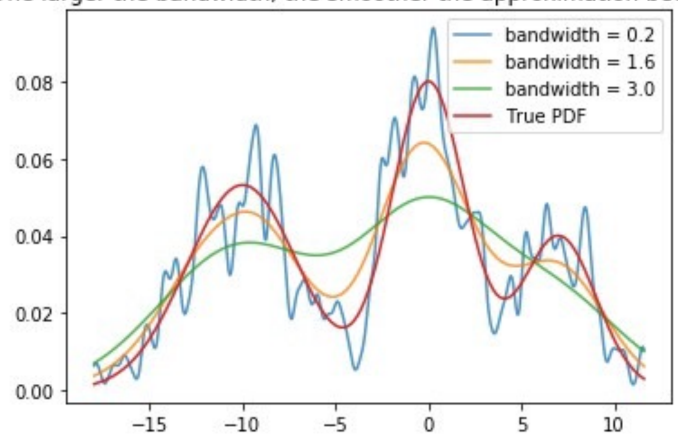
- Adaptive bandwidth parameter hopt:

$$\boldsymbol{h^{i}_{opt}} = \frac{\boldsymbol{h}}{\sqrt{\boldsymbol{f(x_i)}}}$$

- Whole proces can be repeated multiple times

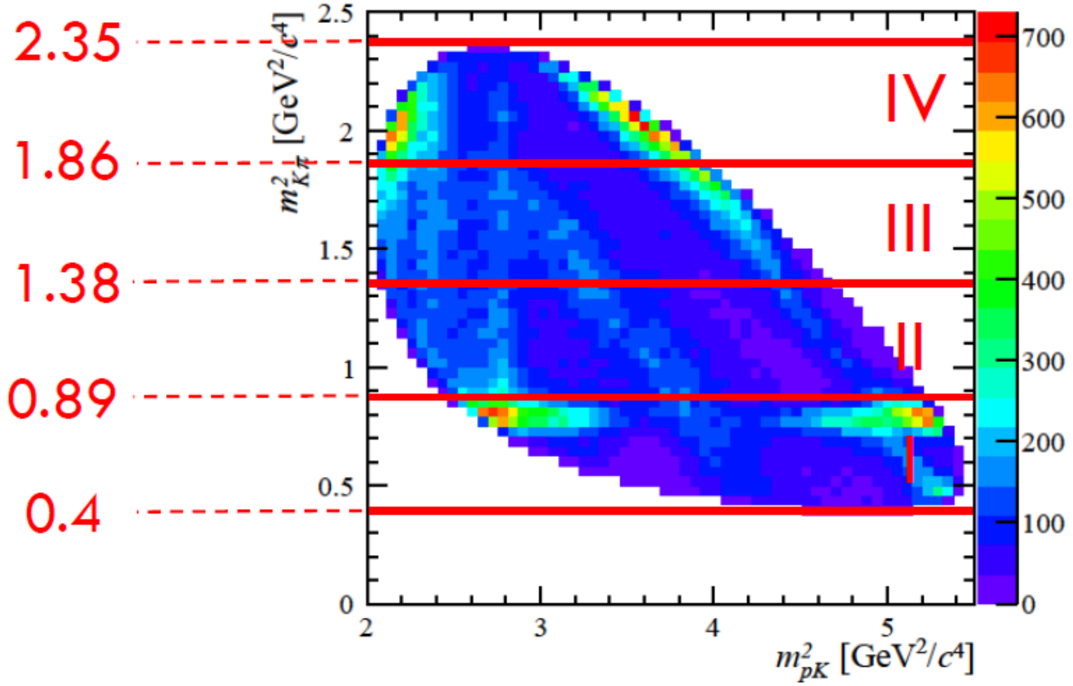


Effect of various bandwidth values
The larger the bandwidth, the smoother the approximation becomes

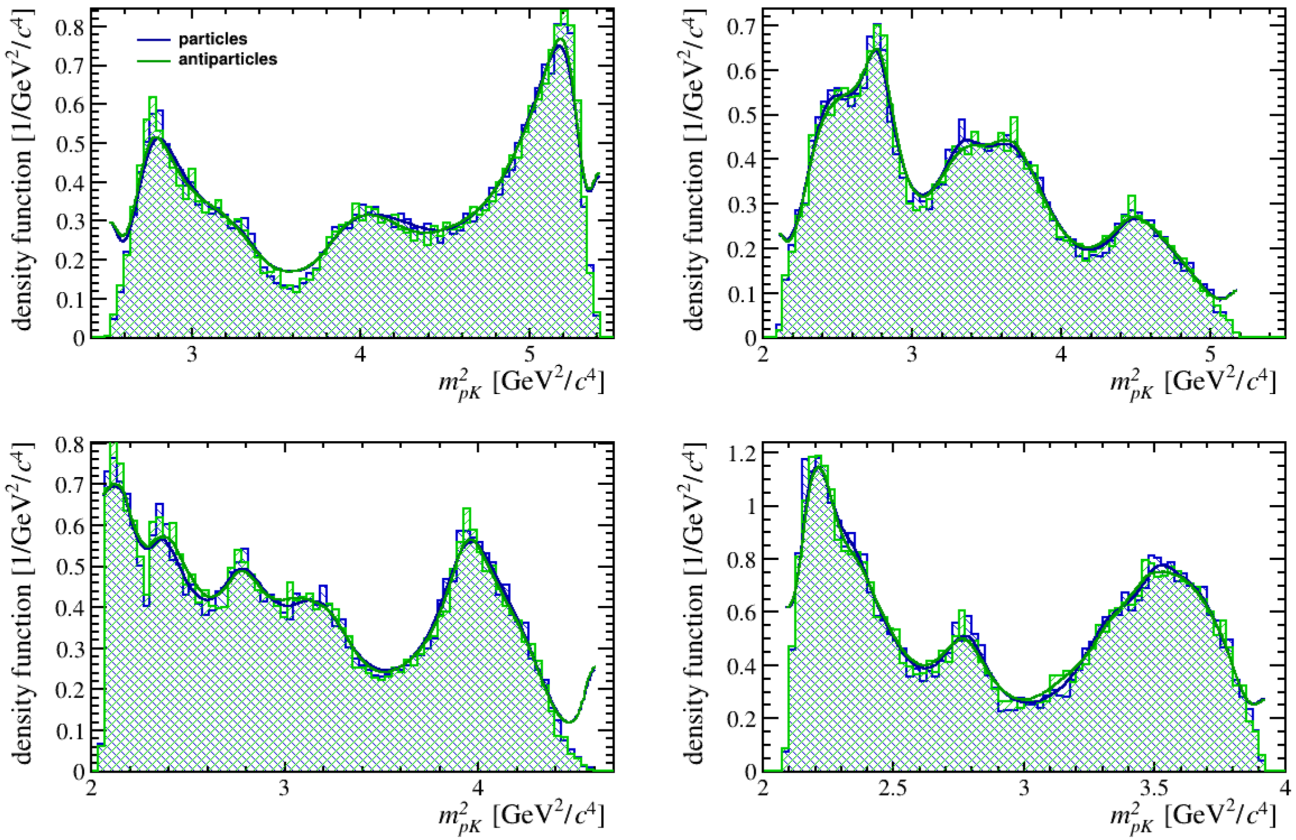


KDE 1D scenario

- Toy sample with no *CPV*
- 200k entries in each sample (100k particles and 100k antiparticles),
- The Dalitz plots are split into four kinematic regions, each of which is subsequently projected onto the horizontal axis.

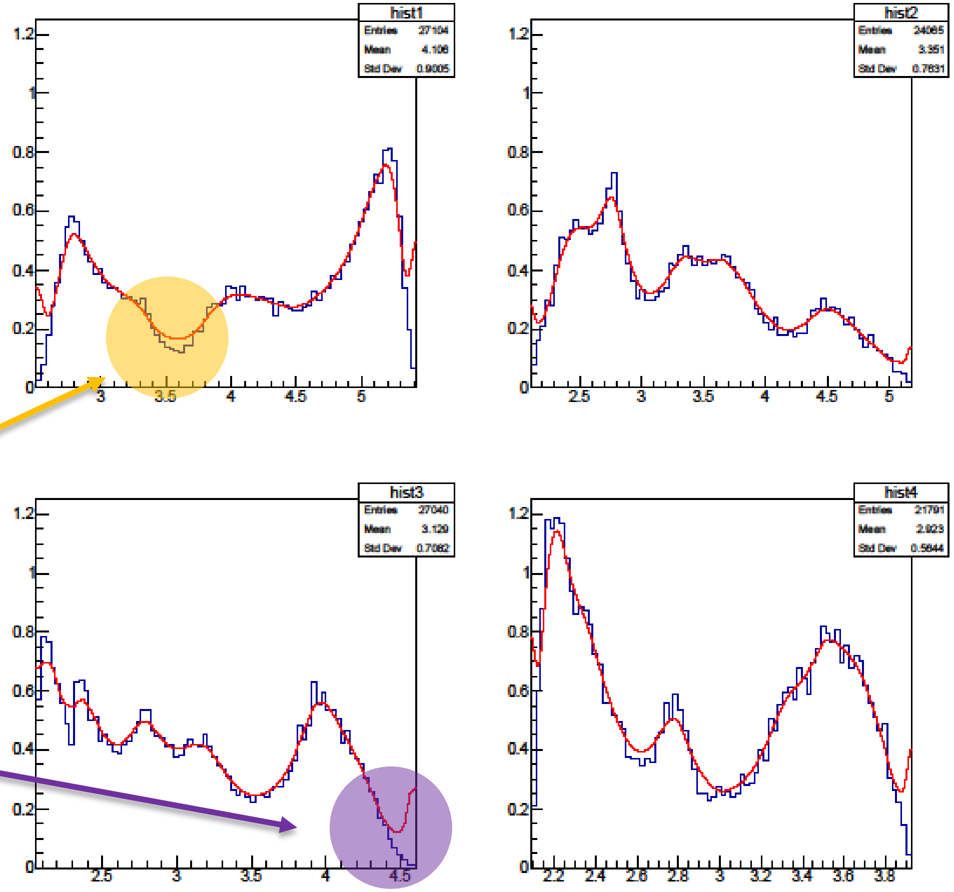


- There are no visible differences between particle and antiparticle density functions – as expected



Smoothing parameter optimization

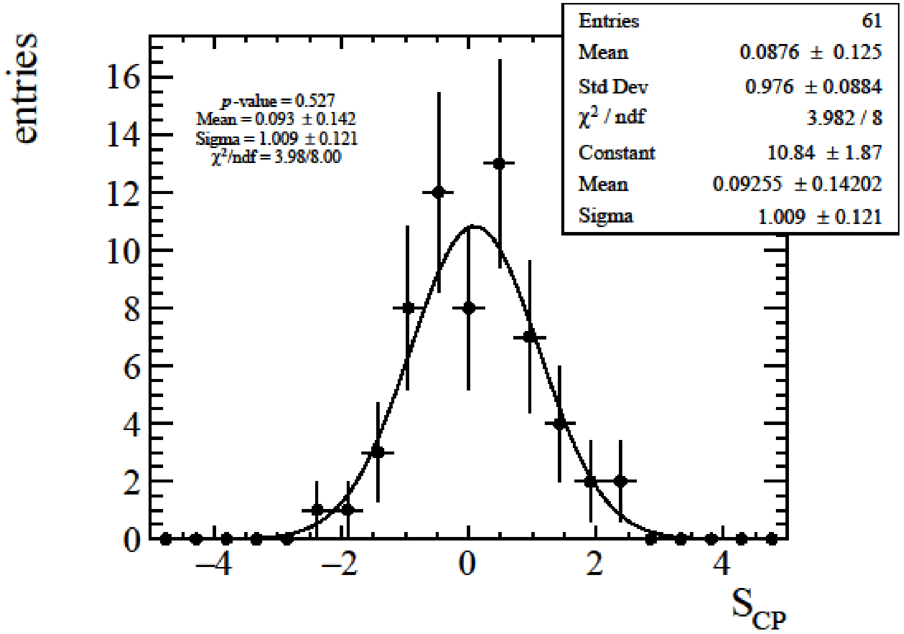
- only particle PDF and histogram are drawn,
- very first estimation,
- poor optimization,
- large gaps between PDFs and histograms,
- problem with boundaries.



KDE 2D scenario in toy sample with no *CPV*

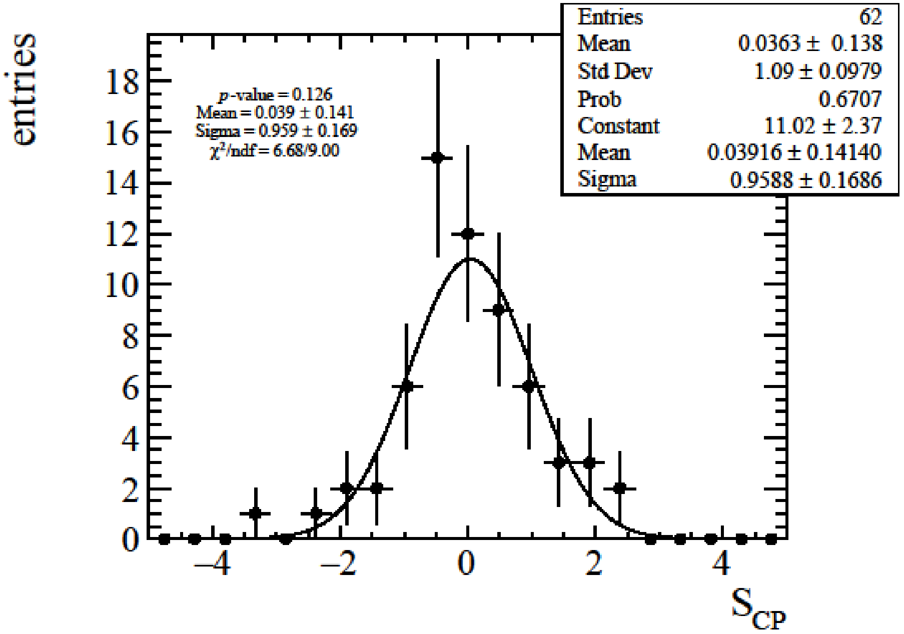
KDE is used to improve the sensitivity of the S_{CP} method

Before KDE:



p-value = 0.527
Mean = 0.093 ± 0.142
Sigma = 1.009 ± 0.121

After KDE:

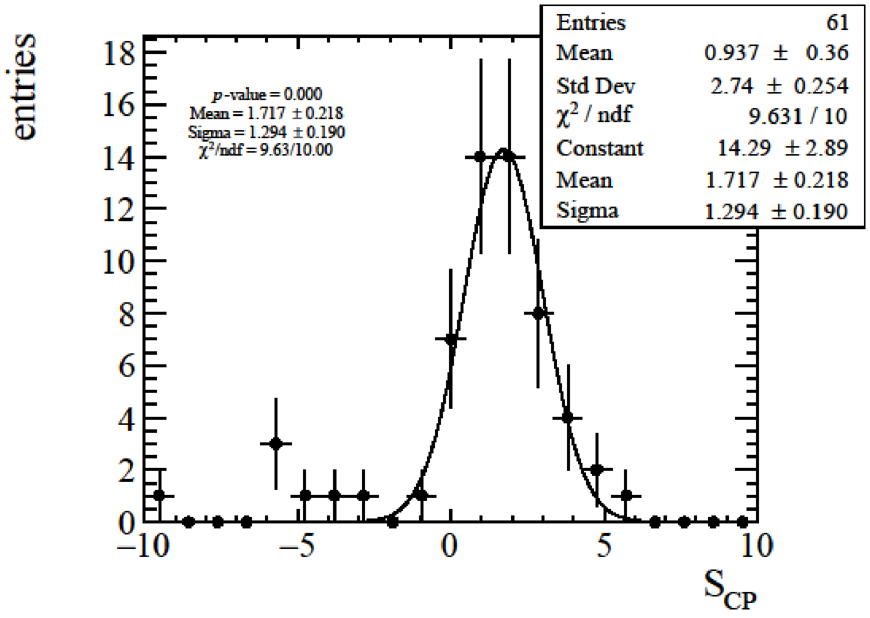


p-value = 0.126
Mean = 0.039 ± 0.141
Sigma = 0.959 ± 0.169

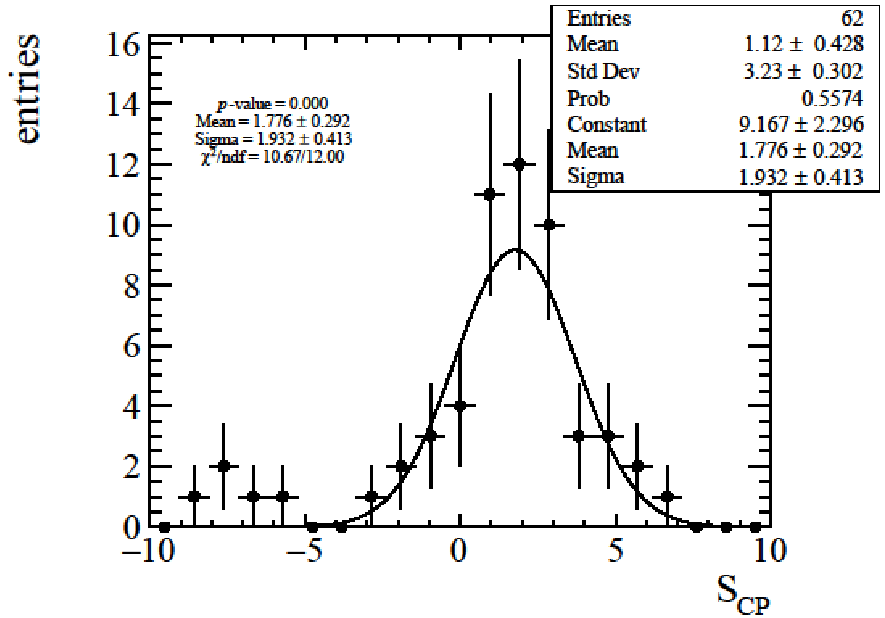
The S_{CP} results after KDE implementation look reasonable

KDE 2D scenario in toy sample with 20% *CPV*

Before KDE:



After KDE:



p-value = 0.0
Mean = 1.717 ± 0.218
Sigma = 1.294 ± 0.190

p-value = 0.0
Mean = 1.776 ± 0.292
Sigma = 1.932 ± 0.413

The CPV is confirmed as it should be

Summary

- The first evidence for direct *CP* violation in a specific charm hadron decay

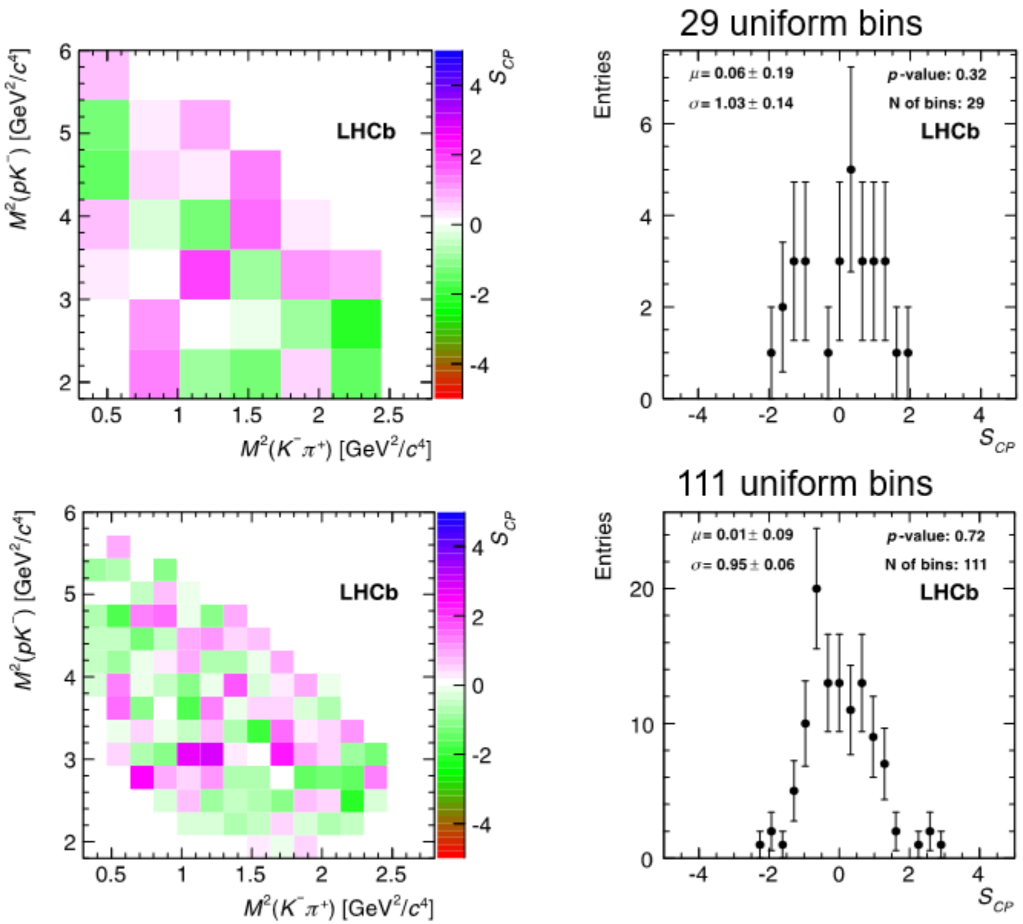
$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

- So far, in any baryon decays the measured *CP*-violating asymmetries are compatible with the hypothesis of *CP* symmetry

- New measurements of *CP* asymmetries in $\Xi_c^+ \to pK^-\pi^+$ decays are expected using binned S_{CP} and unbinned Energy Test methods improved with Kernel Density Estimation technique

  ✓ The methods are tested in control $\Lambda_c^+ \to pK^-\pi^+$ decays as well as in toy samples
  ✓ The methods do not generate fake signal of *CP* violation and confirms its existence if exists


BACK UP!



- p-values > 32%
- S_{CP} agree with N(0,1)
- Results are consistent with CP symmetry

The kNN method

The kNN tests whether baryons and antibaryons share the same parent distribution function.

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

Under the null hypothesis $T \sim N(\mu_T, \sigma_T)$:

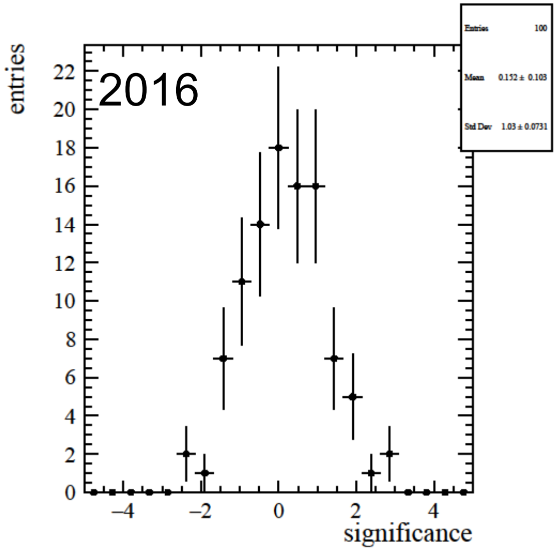
$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

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

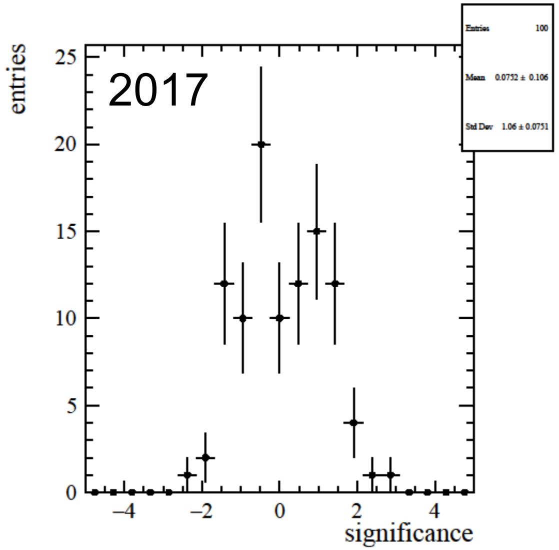
[J. Am. Stat. Assoc. 81, 799 (1986)]

Binned results in control decays $\Lambda_c \to pK^-\pi^+$

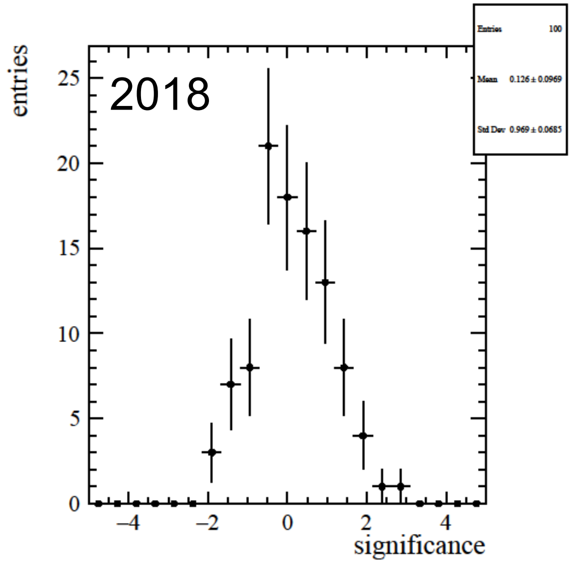
The S_{CP} method is performed individually for each year of data taking



Mean = 0.15 ± 0.10
Sigma = 1.03 ± 0.07



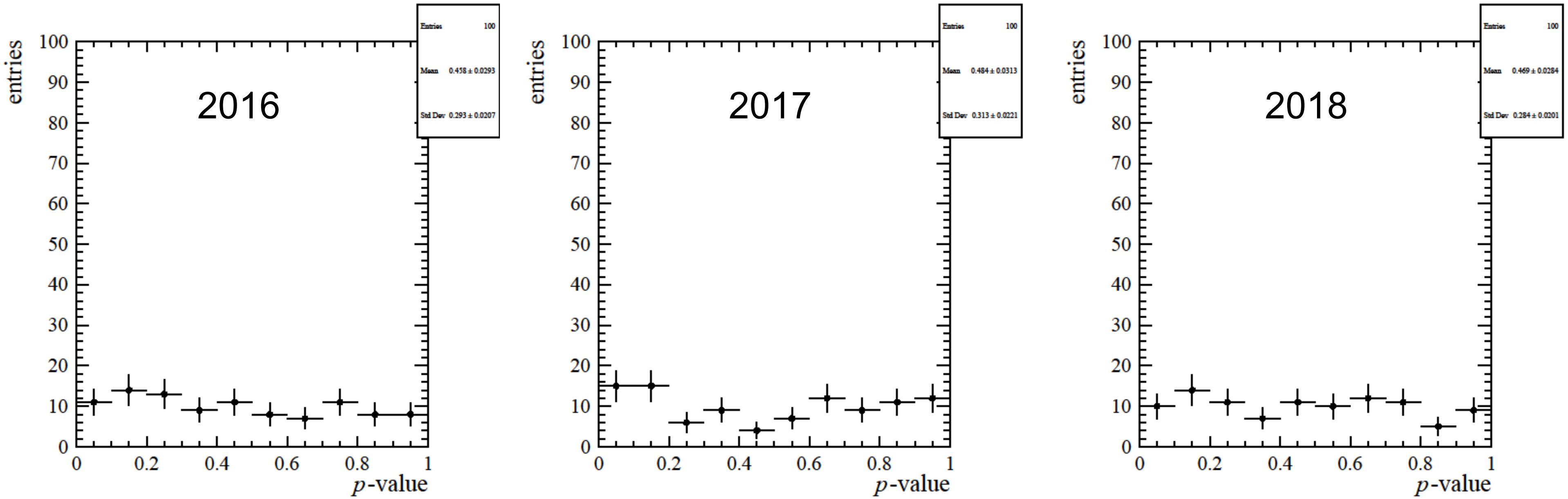
Mean = 0.08 ± 0.11
Sigma = 1.06 ± 0.08



Mean = 0.13 ± 0.10
Sigma = 0.969 ± 0.069

Means agree with 0, sigmas agree with 1
Conclusion: No fake signal of CPV.

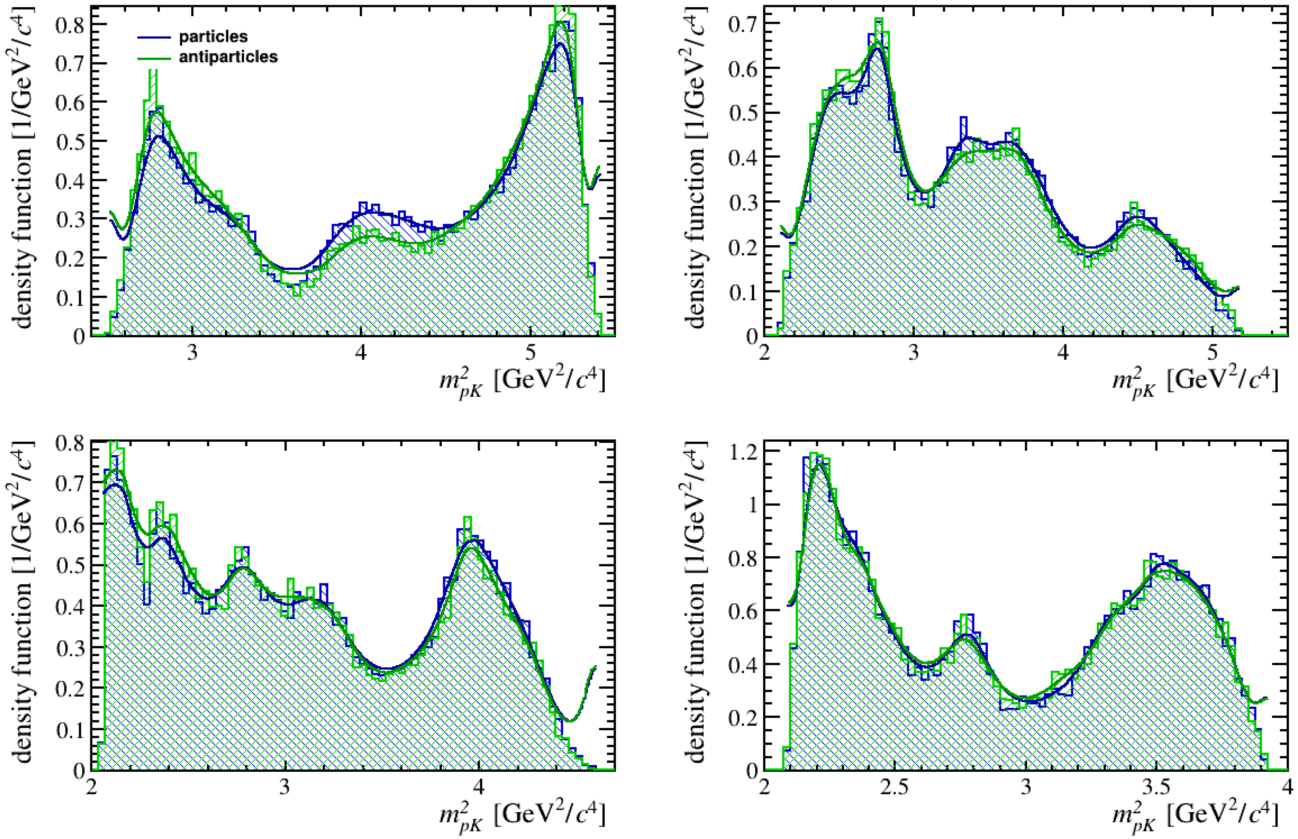
100 random subsamples for each year of data taking.



Flat distributions => Conclusion: No fake signal of CPV.

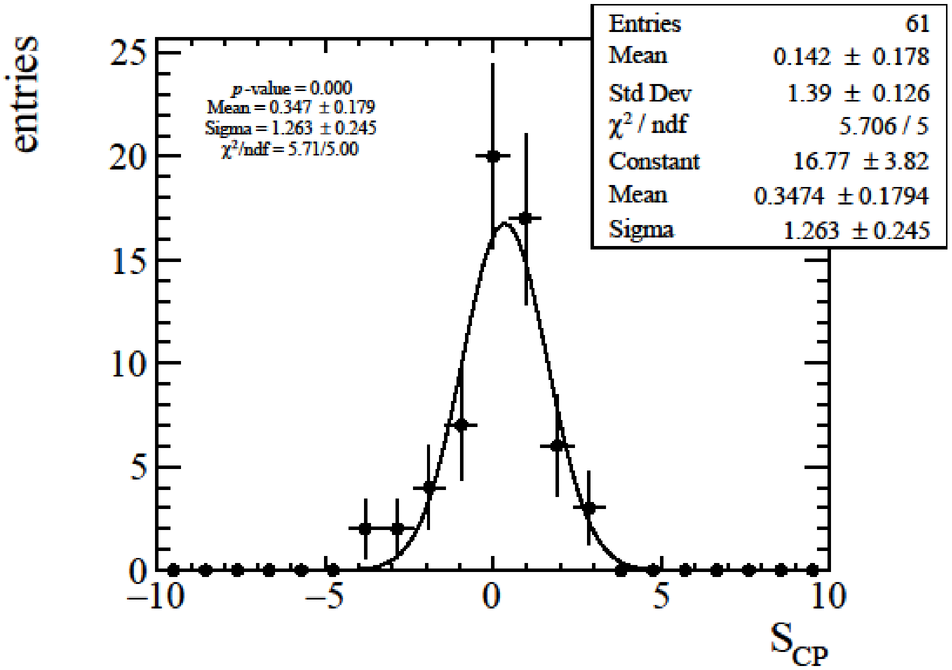
KDE results: 20% CP sample

- Difference between particles and antiparticles is clearly visible,
- KDE works properly,
- Next steps: Compute p-value and optimize bandwidth,



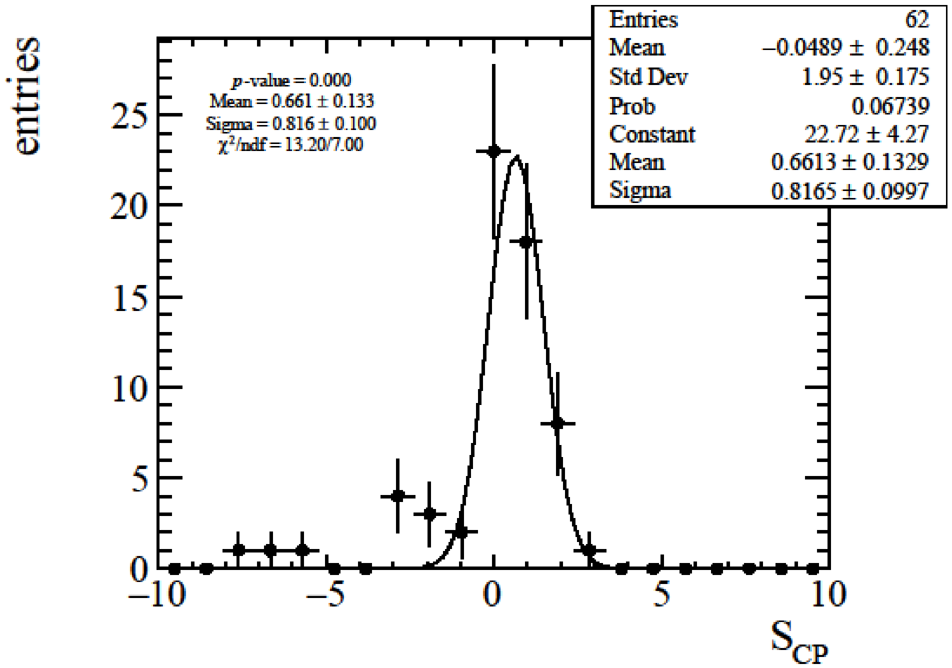
KDE 2D scenario in toy sample with 5% *CPV*

Before KDE:



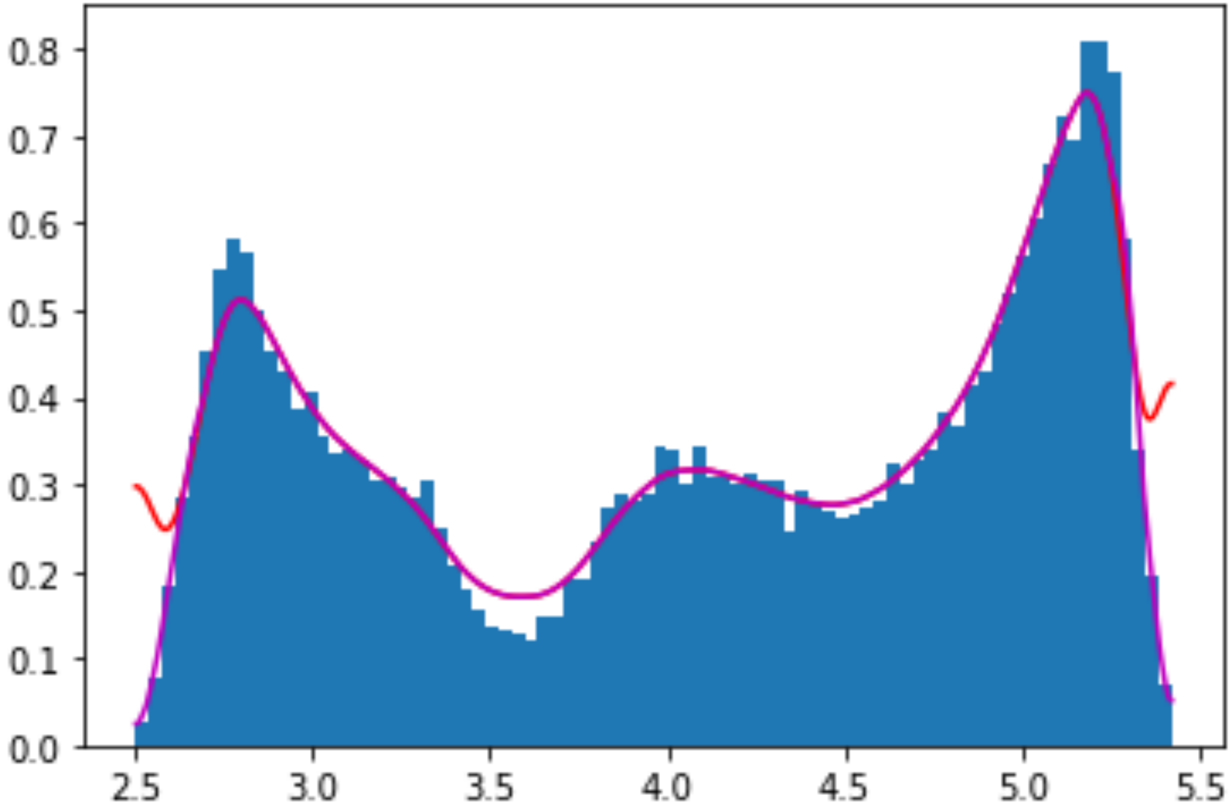
p-value = 9.77645e-06
Mean = 0.347 ± 0.179
Sigma = 1.263 ± 0.245

After KDE:



p-value = 2.07183e-22
Mean = 0.661 ± 0.133
Sigma = 0.816 ± 0.100

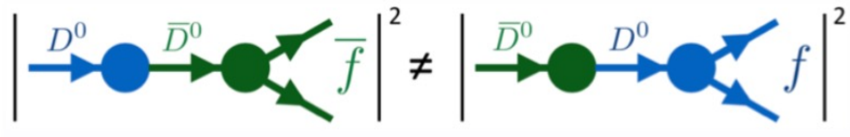
KDE – 1D after boundary correction



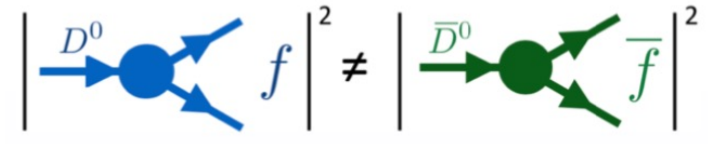
Three ways of *CP* violation in the Standard Model

P^0 = K^0, B^0, B^0_s, D^0
$P^\pm$ = $K^\pm$, $B^\pm$, $B^\pm_s$, $D^\pm$, $\Lambda^\pm_b$, $\Lambda^\pm_c$, $\Xi^\pm_c$ …

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



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



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

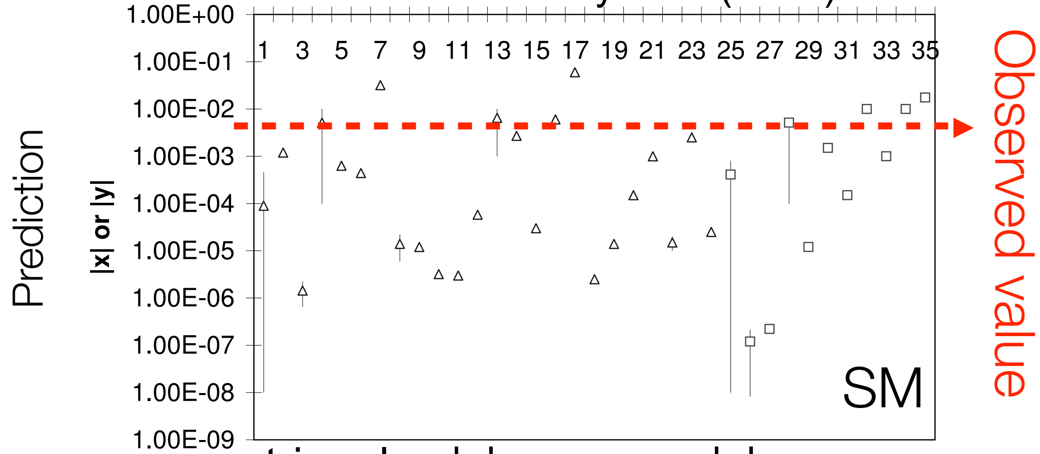
Mixing and decay processes can be mediated via loop diagrams.
New physics is likely to enter in loops where new particles can be exchanged.

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}

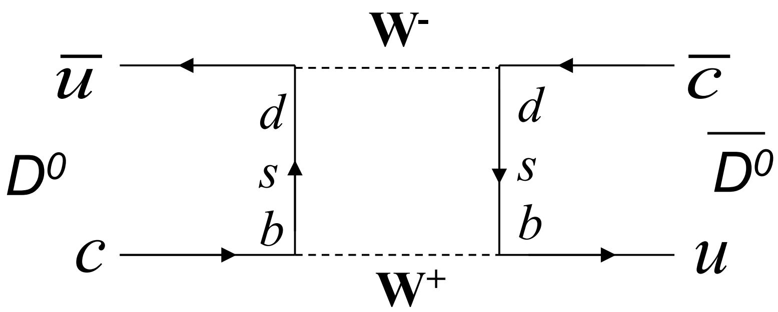
Int.J.Mod.Phys.A21(2006)5381 ;
Ann.Rev.Nucl.Part.Sci.58(2008)249

Int.J.Mod.Phys.A21(2006)5686

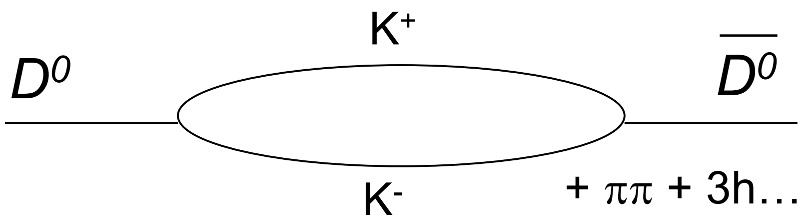


triangles |x| ; squares |y|

x ~ y < 1%



Mixing via box diagram, short range



+ rescat-tering (new issue)

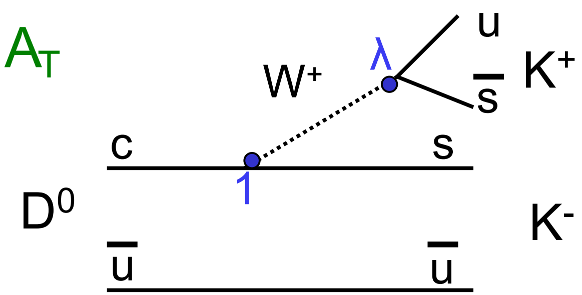
Mixing via hadronic intermediate states, long range (difficult to calculate)

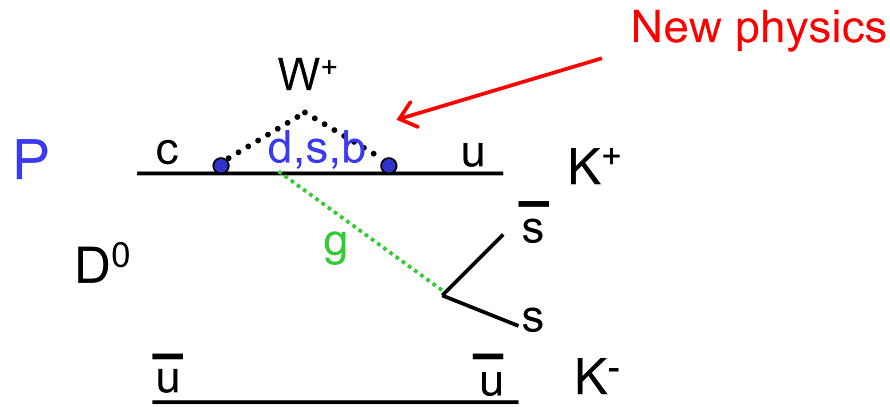
Perfect place for new physics searching (small background from the SM)
Since *CP* violation, *x* and *y* are very small, we need very precise detector to measure observables with extremely high accuracy → LHCb at LHC

Singly Cabibbo−suppressed decay (SCS):

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

$\lambda = 0.22$





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

$\sim\lambda$ $\quad\sim\lambda$ $\quad\sim\lambda$ $\quad\sim\lambda^6$

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

$=A_T$ $\quad=P$ — weak phases — strong phases !!!

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