Searches for direct CPV in charm at LHCb

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ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Introduction

- In the Standard Model (SM), charge-parity violation (*CPV*) in the quark sector comes only from the phase in the CKM matrix
- Order of magnitudes too small to explain our matter dominated universe

$\rightarrow$ Look for New Physics (NP) processes that enhance *CPV*

- Direct *CPV* (or *CPV* in the decay)
  - Difference of decay rate between two *CP* conjugated states

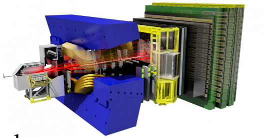
$$\left|A(D^0 \rightarrow f)\right|^2 \neq \left|A(\bar{D}^0 \rightarrow \bar{f})\right|^2$$

Introduction

Why look for *CPV* in charm ?

- Prediction of *CPV* in charm from the SM are small
  - $\rightarrow$ Lots of room for NP enhancement
- Only way to probe for *CPV* in the up-type sector
  - $\rightarrow$ Complementary to other searches in B or K

Why look for *CPV* in charm at LHCb ?



- Largest sample of charm decays
  - Large $c\bar{c}$ cross-section:

$$\sigma(pp \rightarrow c\bar{c}X) = (2369 \pm 3 \pm 152 \pm 118)\,\mu\text{b}\,,$$

at 13 TeV and for $p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$, $2.0 < y < 4.5$ [JHEP 03 (2016) 159]

  - $\rightarrow$ Large charm yields ($\mathcal{O}(100\,\mathrm{M})$ $D^0 \rightarrow K^-\pi^+$ tagged decays)
- Good momentum resolution ($0.5 - 1\%$)
- Good tracking efficiency (over 95%)
- Excellent vertex resolution (IP resolution $(15 + 29/p_{\mathrm{T}})\,\mu\text{m}$)

Experimental observable

The experimental observable is not directly A_{CP}, but A_{raw} :

$$A_{\mathrm{raw}} = A_{CP} + A_P + A_D + A_{\mathrm{tag}}$$

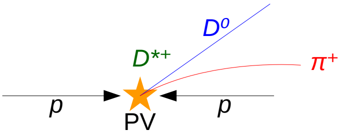
- The production asymmetry A_P : In *pp* collisions there is an initial anti-quark deficit
- The detection asymmetry A_D : Mesons and anti-mesons have different behaviours in matter
- The tagging asymmetry A_{tag} : The tagging particle also has different behaviour in matter according to its charge
- The *CP* asymmetry A_{CP} : What we want to measure

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

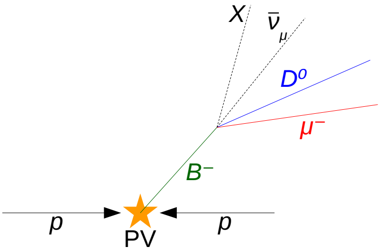
Production and tagging asymmetries

At LHCb, we use 2 independent tagging methods :

Prompt
$D^{*+} \to D^0 \pi^+$

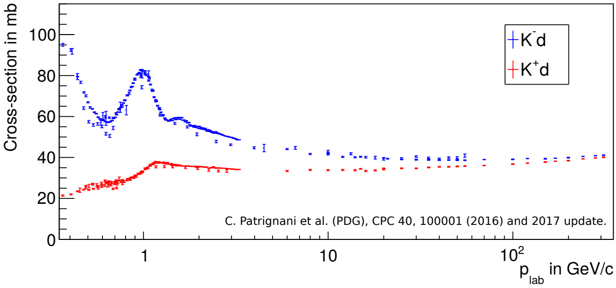


Semileptonic
$B^- \to D^0 \mu^- \overline{\nu}_\mu X$



Detection asymmetry

- Detection asymmetry reduced by flipping magnet polarity regularly
- Residual detection asymmetry due to intrinsic different cross-section between the two charges of a particle when interacting with the detector's material



Experimental trick

- Difficult to measure the detector asymmetries
- One solution is to analyse 2 similar decays
  - They need to have the same tagging channel
  - e.g. $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  - Cancel the detector asymmetries by subtracting the two raw asymmetries

$$
\begin{aligned}
\Delta A_{CP} &= A_{\mathrm{raw}}(D^0 \to K^+K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+\pi^-) \\
&= A_{CP}(D^0 \to K^+K^-) + A_P(D^{*+}) + A_D(K^+K^-) + A_{\mathrm{tag}}(\pi^+) \\
&\quad - A_{CP}(D^0 \to \pi^+\pi^-) - A_P(D^{*+}) - A_D(\pi^+\pi^-) - A_{\mathrm{tag}}(\pi^+) \\
&= A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)
\end{aligned}
$$

Experimental status

- Most precise measurements to date
  - Based on Run 1 data
  - Updated analyses with Run 2 data under way

$$A_{CP}(D^0 \to K^+K^-) = (0.4 \pm 1.2 \pm 1.0) \times 10^{-3}$$ [Phys. Lett. B 767 (2017), 177-187]

$$A_{CP}(D^0 \to \pi^+\pi^-) = (0.7 \pm 1.4 \pm 1.1) \times 10^{-3}$$ [Phys. Lett. B 767 (2017), 177-187]

$$\Delta A_{CP}(D^0 \to h^+h^-) = (1.0 \pm 0.8 \pm 0.3) \times 10^{-3}$$ [Phys. Rev. Lett. 116, 191601 (2016)]

→ In the following slides, I will present a highlight of the latest results

A measurement of the *CP* asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$

[JHEP 03 (2018) 182]

ΔA_{CP} in Λ_c^+ decays

[JHEP 03 (2018) 182]

- Dataset : 3.0 fb^{-1}, Run 1
- Production mode : $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$
- Raw asymmetry :

$$A_{\text{raw}}(f) = A_{CP}(f) + A_P(\Lambda_b^0) + A_{\text{tag}}(\mu) + A_D(f)$$

where f = pK^+K^-, $p\pi^+\pi^-$

- Removing experimental asymmetries by taking the difference between the two final states

$$\begin{aligned} \Delta A_{CP} &= A_{\text{raw}}(pK^+K^-) - A_{\text{raw}}(p\pi^+\pi^-) \\ &= A_{CP}(pK^+K^-) - A_{CP}(p\pi^+\pi^-) \end{aligned}$$

  - Assuming the kinematics is the same for the two final states

ΔA_{CP} in Λ_c^+ decays

[JHEP 03 (2018) 182]

- The kinematics of the two final states are not the same

$\rightarrow$ Reweight the kinematics of $p\pi^+\pi^-$ to pK^+K^-

  - Reweight with decision trees with gradient boosting (GBDT)
  - Reweight for Λ_c^+ transverse momentum and pseudorapidity and p transverse momentum
  - limited by statistics of pK^+K^- final state

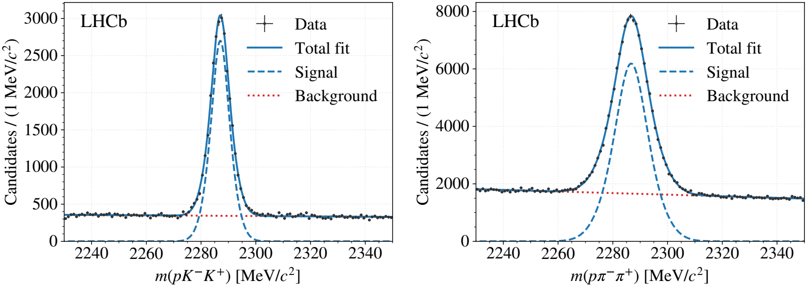
- Quote a weighted asymmetry:

$$\Delta A_{CP}^{\mathrm{wgt}} = A_{\mathrm{raw}}(pK^+K^-) - A_{\mathrm{raw}}^{\mathrm{wgt}}(p\pi^+\pi^-)$$

  - Weight function published in order to compare with theoretical predictions

Yields

$N_{\rm sig} = 25190 \pm 200$ $\qquad$ $N_{\rm sig} = 161390 \pm 584$



Results

$$\Delta A_{CP}^{\rm wgt} = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$$

- First measurement of *CPV* parameters in 3-body Λ_c^+ decays.
- No *CPV* observed

Measurement of *CP* asymmetries in $D^{\pm} \to \eta' \pi^{\pm}$ and $D_s^{\pm} \to \eta' \pi^{\pm}$ decays

[Phys. Lett. B 771 (2017) 21-30]

A_{CP} in $D^{\pm}_{(s)} \to \eta' \pi^{\pm}$ decays

[Phys. Lett. B 771 (2017) 21-30]

- Dataset : 3.0 fb^{-1}, Run 1
- Observable:

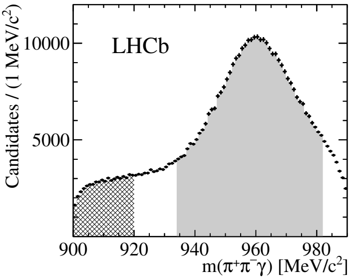
$$A_{\text{raw}} = A_{CP} + A_P(D^{\pm}_{(s)}) + A_D(\eta' \pi^{\pm})$$

  - Production and detection asymmetries estimated from control channels
  - Since the charge of the *D* meson specifies the flavour, no tagging needed

$\rightarrow$ No tagging asymmetry

A_{CP} in $D^{\pm}_{(s)} \to \eta' \pi^{\pm}$ decays

- First analysis of $D^{\pm}_{(s)} \to \eta' \pi^{\pm}$ decays at a hadron collider
- Decay of the η' : $\eta' \to \pi^+ \pi^- \gamma$
- Challenging to reconstruct the η' because of the neutral photon



A_{CP} in $D_{(s)}^{\pm} \to \eta' \pi^{\pm}$ decays [Phys. Lett. B 771 (2017) 21-30]

- Control channels:
  - For $D^{\pm} \to \eta'\pi^{\pm}$: $D^{\pm} \to K_S^0\pi^{\pm}$, $K_S^0 \to \pi^+\pi^-$
  - For $D_s^{\pm} \to \eta'\pi^{\pm}$: $D_s^{\pm} \to \phi\pi^{\pm}$, $\phi \to K^+K^-$

- Construct difference of *CP* asymmetries

$$\begin{aligned}
\Delta A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) &\equiv A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) - A_{CP}(D^{\pm} \to K_S^0\pi^{\pm}) \\
&= A_{\text{raw}}(D^{\pm} \to \eta'\pi^{\pm}) - A_{\text{raw}}(D^{\pm} \to K_S^0\pi^{\pm}) + A(\overline{K}^0 - K^0) \\
\Delta A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) &\equiv A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) - A_{CP}(D_s^{\pm} \to \phi\pi^{\pm}) \\
&= A_{\text{raw}}(D_s^{\pm} \to \eta'\pi^{\pm}) - A_{\text{raw}}(D_s^{\pm} \to \phi\pi^{\pm})
\end{aligned}$$

- Extract the *CP* asymmetries

$$A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) \approx \Delta A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) + A_{CP}(D^{\pm} \to K_S^0\pi^{\pm})$$
$$A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) \approx \Delta A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) + A_{CP}(D_s^{\pm} \to \phi\pi^{\pm})$$

Results

$N_{\text{sig}}(D^{\pm} \to \eta'\pi^{\pm}) = (62.7 \pm 0.4) \times 10^3$
$N_{\text{sig}}(D_s^{\pm} \to \eta'\pi^{\pm}) = (152.2 \pm 0.5) \times 10^3$

- Measure the two ΔA_{CP}

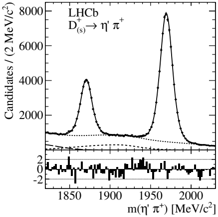
$$\Delta A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) = (-5.8 \pm 7.2 \pm 5.3) \times 10^{-3}$$
$$\Delta A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) = (-4.4 \pm 3.6 \pm 2.2) \times 10^{-3}$$

- Extract the two A_{CP} with input from the control channels

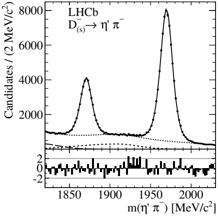
$$A_{CP}(D^{\pm} \to \eta'\pi^{\pm}) = (-6.1 \pm 7.2 \pm 5.3 \pm 1.2) \times 10^{-3}$$
$$A_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) = (-8.4 \pm \underbrace{3.6}_{\text{stat}} \pm \underbrace{2.2}_{\text{syst}} \pm \underbrace{2.7}_{\text{control channel}}) \times 10^{-3}$$

- Compatible with no *CPV*

$D^{+}_{(s)}$



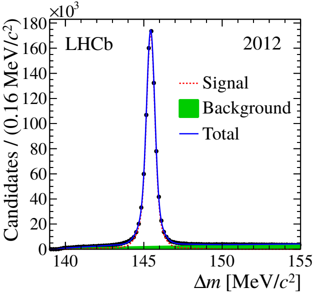
$D^{-}_{(s)}$



Search for CP violation in the phase space of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays

[Phys. Lett. B 769 (2017) 345-356]

- Dataset : $3.0\,\text{fb}^{-1}$, Run 1
- Production mode : $D^{*+} \to D^0\pi^+$
- $N_{\text{sig}} = (1008 \pm 1) \times 10^3$



Parametrisation of the phase space

- Ordering of the particles:
  - For the D^0: $\pi_1\pi_2\pi_3\pi_4 = \pi^+\pi^-\pi^+\pi^-$, where largest $m(\pi^+\pi^-) = m(\pi_3\pi_4)$
  - For the $\bar{D}^0$: *CP* is applied $\pi_1\pi_2\pi_3\pi_4 = \pi^-\pi^+\pi^-\pi^+$
- 5D phase space:
  - $m(\pi_1\pi_2), m(\pi_1\pi_4), m(\pi_2\pi_3), m(\pi_1\pi_2\pi_3), m(\pi_1\pi_2\pi_4)$

The energy test [J. Stat. Comput. Simul. 75 (2005) 109]

- Sensitive to local *CPV* in the phase space
- Model independent unbinnned method
- Define a metric to compute the distance between 2 points in the phase space
- Define a test statistic, T

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}$$

- Build the "no *CPV* " hypothesis as a set of random permutations of the data
- Compare the value in data to the "no *CPV* " hypothesis

This is the first application of the energy test to a 4-body decay

2 tests are performed

- P-even test: D^0 vs $\bar{D}^0$ (*i.e.* I+II vs III+IV)

Definition of the triple-product:

$$\text{For the } D^0: \quad C_T = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$

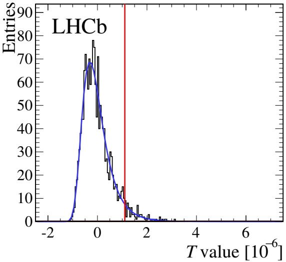
$$\text{For the } \bar{D}^0: \quad CP(C_T) = -C(C_T) = -\bar{C}_T$$

- P-odd test: $C_T>0$ vs $C_T<0$ (*i.e.* I+IV vs II+III)

I D^0 $C_T > 0$	$\bar{D}^0$ III $-\bar{C}_T > 0$
II D^0 $C_T < 0$	$\bar{D}^0$ IV $-\bar{C}_T < 0$

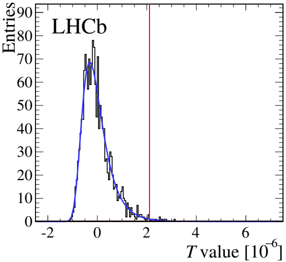
Results

P-even test



p-value $= (4.6 \pm 0.5)\%$

P-odd test

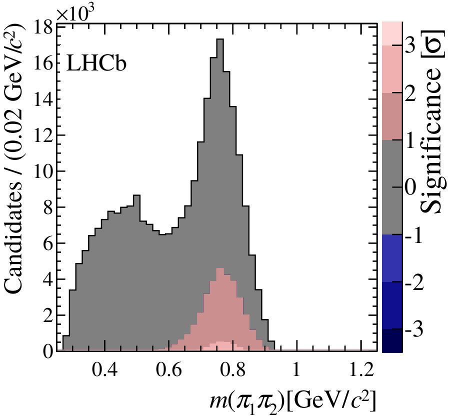


p-value $= (0.6 \pm 0.2)\%$

P-odd test corresponds to a significance of CPV of 2.7σ.

Results

Local asymmetry exceeding 2σ seen in the region of the $\rho(770)^0$



Measurement of the time-integrated *CP* asymmetry in $D^0 \to K_S^0 K_S^0$ decays

Preliminary

[LHCb-PAPER-2018-012]

A_{CP} in $D^0 \to K^0_S K^0_S$ decays

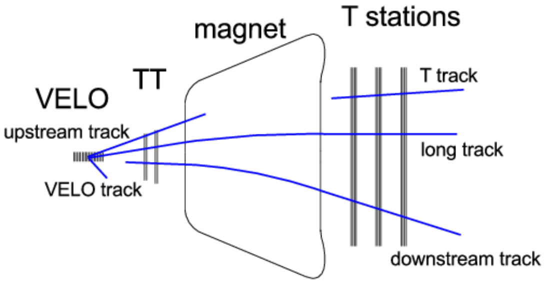
- Dataset : 2.0 fb^{-1}, 2015-2016
- Production mode : $D^{*+} \to D^0 \pi^+$
- Raw asymmetry :

$$A_{\mathrm{raw}}(K^0_S K^0_S) = A_{CP}(K^0_S K^0_S) + A_P(D^{*+}) + A_{\mathrm{tag}}(\pi^+)$$

- No detection asymmetries from the daughters of the D^0 since they are symmetric
- Removing production and tagging asymmetries by using a control channel $D^0 \to K^+ K^-$:

$$\begin{aligned} \Delta A_{CP} &= A_{\mathrm{raw}}(K^0_S K^0_S) - A_{\mathrm{raw}}(K^+ K^-) \\ &= A_{CP}(K^0_S K^0_S) - A_{CP}(K^+ K^-) \end{aligned}$$

Various possible tracks in LHCb:



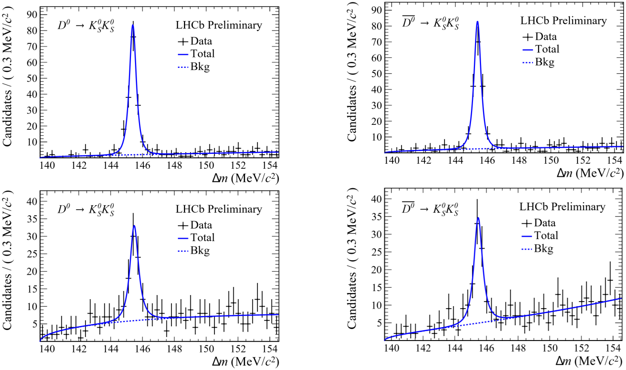
For this analysis:

- LL: the two K_S^0 decay in the VELO and have long tracks
- LD: one K_S^0 has a long track and one decays downstream of the VELO (downstream track)

$D^0 \to K^0_S K^0_S$ $\qquad$ $\bar{D}^0 \to K^0_S K^0_S$

$N^{LL}_{sig} = 759 \pm 32$ LL

$N^{LD}_{sig} = 308 \pm 26$ LD



Results

- $A_{CP} = (4.2 \pm 3.4 \pm 1.0)\%$
- Compatible with Run 1 result: $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$
- Average : $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

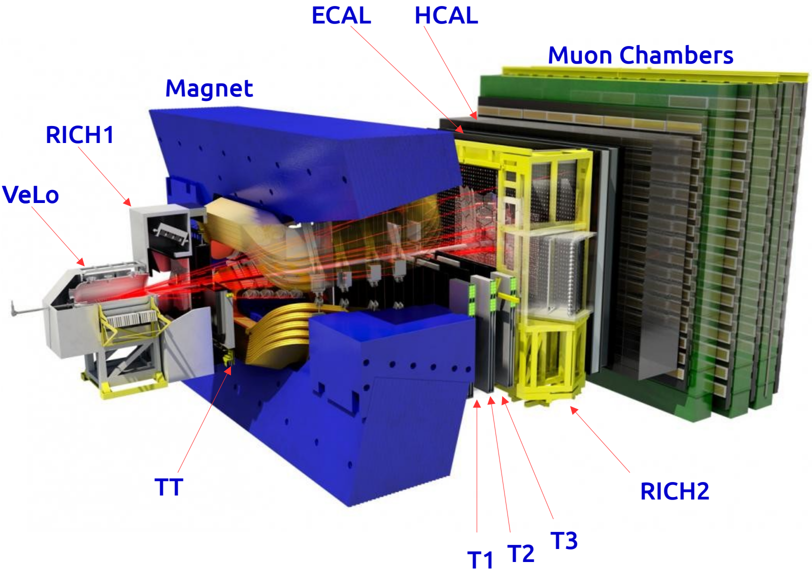
$\to$ Catching up with the Belle result

Conclusion

- This was a highlight of 4 recent analyses from LHCb
  - Angelo Carbone will also present a new result on direct *CPV* in $D^0 \to K^+\pi^-$ decays later today
- No *CPV* has been observed in charm yet
- Reaching the precision of the theory predictions $(10^{-3} - 10^{-4})$
  - New estimate of direct *CPV* in charm : $\mathcal{O}(10^{-4})$ [Khodjamirian and Petrov, PLB 774 (2017), 235-242]
- More promising results with Run 2 are coming
  - Already collected 3.7 fb^{-1} between 2015 and 2017
  - Expect to have a total dataset (Run 1 + Run 2) of $\sim$ 9.0 fb^{-1} at the end of this year
- Working hard towards the upgrade for even better results

BACKUP

The LHCb detector



Details on energy test

- The metric used to define the distance is:

$$d_{ij}^2 = (m_{12}^{2,j} - m_{12}^{2,i})^2 + (m_{14}^{2,j} - m_{14}^{2,i})^2 + (m_{23}^{2,j} - m_{23}^{2,i})^2 + (m_{123}^{2,j} - m_{123}^{2,i})^2 + (m_{124}^{2,j} - m_{124}^{2,i})^2$$

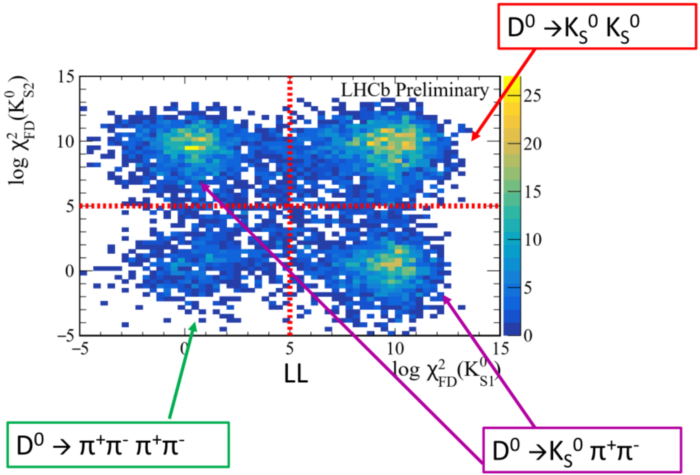
- The test statistic T is defined to compare the distances:

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}},$$

- first two terms : average weighted distance between events in 1 sample of n ($\bar{n}$) events
- third term : average weighted distance between events in both samples
- ψ function : Gaussian with tuneable width

$$\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}$$

Removing specific backgrounds:



A_{CP} in $D^0 \to K^0_S K^0_S$ decays

Removing specific backgrounds: