Search for local CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays using the Energy Test method

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Overview

Motivation - The Charm Sector

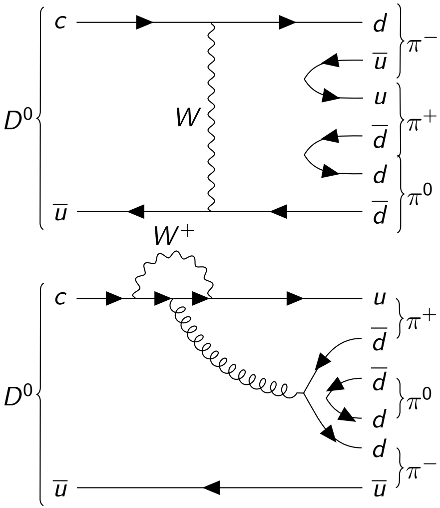
- CP violation (CPV) only recently discovered in charm when compared with the beauty and strange sectors
  - So far, only detected in $D^0 \rightarrow h^+ h^-$ decays
  - *Phys. Rev. Lett. 122 (2019) 211803*
- CPV has been measured and predicted by the SM to be of order $(10^{-4}) - (10^{-3})$
- Important to expand the search for CPV to other charm decays

Motivation

- Higher sensitivity possible by searching for local CPV in multibody decays
- Large interference contributions as the strong phase varies across phase space
- $D^0 \to \pi^-\pi^+\pi^0$ is a promising channel for CPV detection.
  1. Main contribution is due to singly Cabibbo suppressed (SCS) decay.
  2. Standard Model expectation:

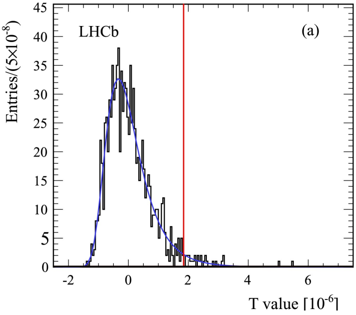
     CPV: $O(10^{-3})$

     Phys.Rev.D.75.036008
  3. May be enhanced by new physics.



Motivation - Experimental Status

- Energy Test using LHCb Run 1 data ($\mathcal{L}_{int} = 2fb^{-1}$) with a signal Yield $\sim$ 570k
  - p $= (2.6 \pm 0.5)\%$
    Phys. Lett. B 740 (2015) 158
- Binned χ^2 method used by BaBar with a signal yield $\sim$ 82k
  - $\mathcal{A}_{CP} = (0.31 \pm 0.41)\%$
    Phys. Rev. D 78 (2008) 051102
- Global asymmetry: $\mathcal{A}_{CP} = (0.3 \pm 0.4)\%$ **PDG**



Energy Test Method

- Model-independent, unbinned statistical test sensitive to local CPV
- Test statistic for a distance function ψ_{ij}:

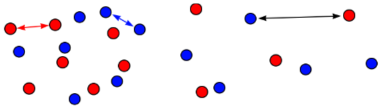
$$T = \underbrace{\sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)}}_{\text{All } D^0 \text{ Candidates}} + \underbrace{\sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)}}_{\text{All } \bar{D}^0 \text{ Candidates}} - \underbrace{\sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}}_{\text{Opposite Flavour Pairs}}$$

- Distance function scales described by Gaussian with parameter δ:

$$\psi_{ij} = e^{\frac{-d_{ij}^2}{2\delta^2}}$$

- Distance computed from Dalitz plane
- T value converted to p-value under null hypothesis of CP symmetry, using data-driven approach (see next slide)

Parkes. C et al, *2017 J. Phys. 44 085001*

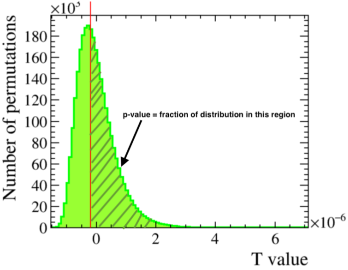


$$d_{ij}^2 = (m_{12}^{2,j} - m_{12}^{2,i})^2 + (m_{23}^{2,j} - m_{23}^{2,i})^2 + (m_{13}^{2,j} - m_{13}^{2,i})^2$$

T Value and Scaling Method

- Calculate T-value distribution for null hypothesis by resampling (permutating) data, with random flavour assignments
- P-value defined by counting number of permutations with larger T-value than real data
- Permutations are CP symmetric by construction
- Large nominal T value ⇒ asymmetry between samples.

Example of permuted T value distribution



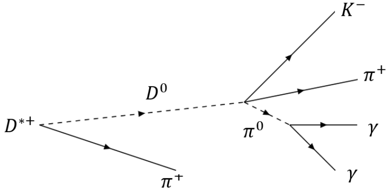
Selection Overview

- Analyse data from LHCb Run 2 (2015-2018) ($\mathcal{L}_{int} = 5.9 fb^{-1}$)
- Use prompt $D^{*+} \rightarrow D^0 \pi_s^+$ where the soft pion, π_s, tags the flavour of D^0
- $\pi^0 (\rightarrow \gamma + \gamma)$ can be reconstructed in two ways based on the diphoton angle:
  1. Merged pion: diphoton energy deposit in same ECAL cluster.
  2. Resolved pion: diphoton energy deposited in different cluster.
- Selection strategy is to use a loose pre-selection followed by an MVA

Event reconstruction

Decay Topology

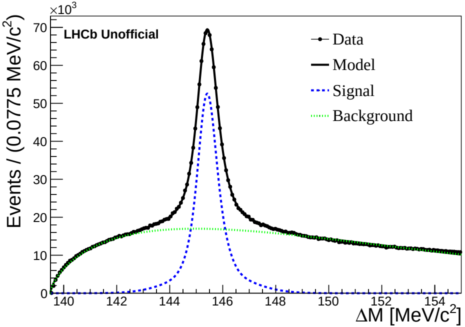
- Phase space computed by requiring:
  1. D^* originates from the primary vertex.
  2. D^0 mass is constrained to the PDG value.



- **Offline Selection**
  - Require candidates to pass hardware (L0) and software trigger requirements (HLT1 & HLT2)
  - $|m_{\pi^0}$-134.9770$| < 28$ MeV (Merged π^0s only)
  - $|m_{D^0}$-1864.83$| < 60$ MeV
  - Require D^0 decay products be displaced from PV

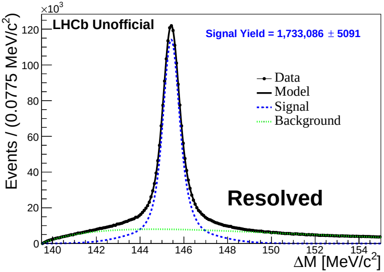
MVA Strategy

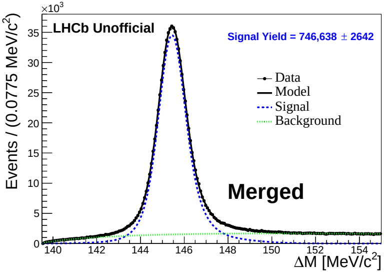
- MVA trained on real sPlotted data with k-folding (k=2) separately for merged and resolved samples
- BDT cut chosen to optimise signal significance ($\frac{S}{\sqrt{S+B}}$)
- BDT input variables exploit final state kinematics, decay topology, and vertex quality



Δm fit of resolved sample after applying offline selections

ΔM Fits





- Post-MVA fits to Resolved (left) and Merged (right) samples.
- Yield is 4 times larger than Run1 analysis
- Resolved: Purity after (before) the cut is $\sim$ 83% (50%) between 143.6$< \Delta M <$147.2 MeV
- Merged - Purity is 91%, no MVA cut applied

Sensitivity Studies

- Energy Test has a single tunable parameter, δ, optimised using toy simulation
- Generate toys in a number of different CPV scenarios and scan over a range of δ values to find the minimum p-value
- Generate signal phase space using Laura assuming D^0 and $\overline{D^0}$ have identical amplitude models. *Comput. Phys. Commun., 231 (2018) 0010-4655*
- Create realistic toys by incorporating efficiency and background effects into generated phase space

Sensitivity Studies - Amplitude Model

- Amplitude model taken from BaBar analysis of $B^{\pm} \to D^0(\to \pi^-\pi^+\pi^0)K^{\pm}$ Phys. Rev. Letters, 99 (2007) 251801

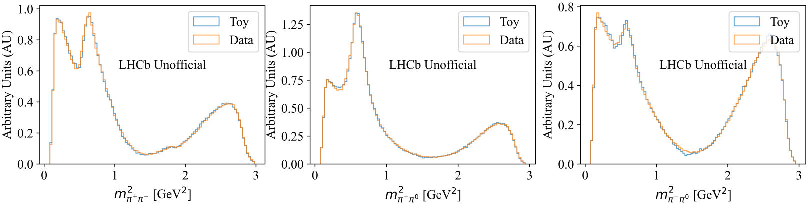
Resonance	Amplitude a_n	Phase ϕ_n ($^\circ$)	Fit Fraction f_n (%)
$\rho(770)^+$	0.823	0	67.8
$\rho(770)^0$	0.512	16.2	26.2
$\rho(770)^-$	0.588	-2.0	34.6
$\rho(1450)^+$	0.033	-146	0.11
$\rho(1450)^0$	0.055	10	0.30
$\rho(1450)^-$	0.134	16	1.79
$\rho(1700)^+$	0.202	-146	0.11
$\rho(1700)^0$	0.055	10	0.30
$\rho(1700)^-$	0.134	16	1.79
$f_0(400)$	0.091	8	0.82
$f_0(980)$	0.050	-59	0.25
$f_0(1370)$	0.061	156	0.37
$f_0(1500)$	0.062	12	0.39
$f_0(1710)$	0.056	51	0.71
$f_2(1270)$	0.115	-171	1.32
non resonant	0.092	-11	0.84

Realistic Toys

- T-value will be affected by resolution effects, efficiency and background candidates in the signal. This may shift the optimal value of δ
- Model detector resolution and efficiency in a data driven manner, using multivariate BDT reweighter
- Model background in data-driven manner, again with BDT reweighter

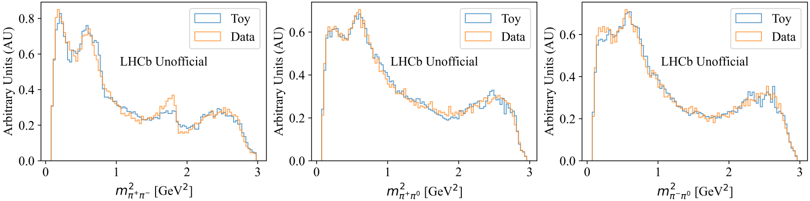
Detector Efficiency Model

- Train a BDT to re-weight Generator-level toy to match phase space of signal window in Δm, ignoring flavour
- Accept-reject candidates from a generator-level toy to produce a toy with detector efficiency incorporated
- Train on sPlotted signal between $|\Delta m - 145.4| < 1.8$ MeV
- 10M generator level candidates used in training and testing



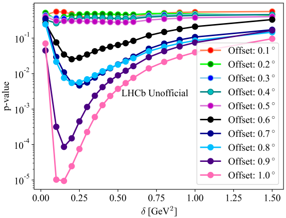
Background Model

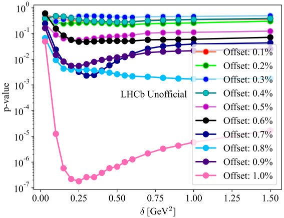
- Train a BDT to re-weight uniformly distributed phase space to match phase space of signal channel sidebands
- Accept-reject candidates from uniformly distributed phase space to produce toy background
- Train on sPlotted background candidates with $\Delta m < 142 || \Delta m > 150$ MeV



Realistic Toys - δ Scan

- Find optimal δ by inserting phase/amplitude asymmetries in dominant/sub-dominant resonance and generating ensembles of toys
- Each point consists of the mean p-value for a set of 5 unique toys
- Each p-value is calculated with 10M permutations
- Asymmetries inserted into $\rho(770)^{\pm}$

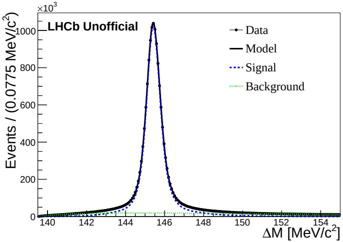


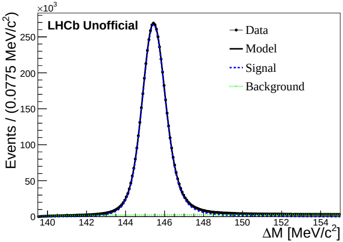


p-values for phase (left) and magnitude asymmetries (right) in $\rho(770)^{+}$

Control Channel

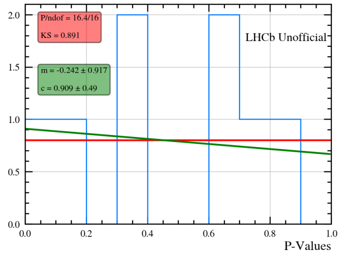
- Use Control mode to check influence of systematic effects introduced by detection and production asymmetries
- Use the Cabibbo Favoured $D^0 \to K^-\pi^+\pi^0$ as control channel
- Selection aligned between control and signal modes (other than PID on kaon)
- Yield approximately 8 times that of signal channel





Control Channel - Signal Region

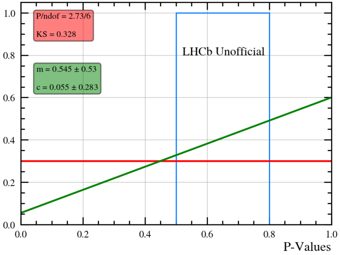
- Run Energy Test over the D^0 region, 143.6$<\Delta M<$147.2 MeV
- Split into 8 independent sub-samples, each with the same yield as the signal sample
- Plot p-values from the 8 tests
- **Flat p-value distribution** indicates consistency with CP symmetry hypothesis



P-Value distribution for the combined resolved and merged sample in the control channel in Run2 for δ=0.2

Control Channel - Sidebands

- Locally varying background asymmetries can bias the measurement
- Apply Energy Test on the sidebands to check the contributions from the background
- Sideband Definition: $(\Delta m > 150\,\text{MeV} \,||\, 139.5 < \Delta m < 142\,\text{MeV})$
- Split into 3 independent sub-samples,
- Each sub-sample has the same yield as the background in the signal region of the signal sample



P-value distribution for Control Channel sidebands using δ=0.2

Summary Next Steps

- The energy test is a sensitive method to search for local CPV within multibody phase space
- $D^0 \to \pi^+\pi^-\pi^0$ a promising channel and builds on LHCb Run 1 analysis
- Possibility of observing CPV with 4x the statistics compared with Run 1 measurement
- Analysis under internal LHCb review, awaiting approval to unblind.

Signal Channel Sidebands

- Apply Energy Test on the signal-channel sidebands to check for possible contributions from the background in the signal channel
- Combining Resolved and Merged channels with δ=0.2 yields p = **0.09**

Training the Classifier

Topological and Other Variables

- **log_FITCHI2:** The log of the χ^2 probability calculated for the DTF fit obtained by imposing the PV constraint on the D^* and D^0 mass constraint.
- **log_D_IPCHI2_OWNPV:** - The logarithm of the χ^2_{IP} of the primary vertex of the D^0 given as a function of difference of χ^2 in the present and absence of the D^0.
- **acos_D_DIRA_OWNPV:** - arccos of the angle between the D^0 momentum vector and the displacement vector joining the production and decay vertices.
- **log_pi0_CL** - logarithm of the π^0 confidence level
- **D_CosTheta:** - cosine of the angle between D^0 momentum in D^* rest frame and D^* momentum in the lab frame
- **D_FDCHI2_OWNPV:** - χ^2 of D^0 flight distance measured with respect to its PV
- **pi0_CosTheta:** - cosine of the angle between π^0 momentum in D^0 rest frame and D^0 momentum in lab frame
- **Kstr_CosTheta:** - cosine of the angle between the $\pi^+\pi^-$ resonance momentum in D^0 rest frame and D^0 momentum in lab frame

Training the Classifier

Kinematic Variables

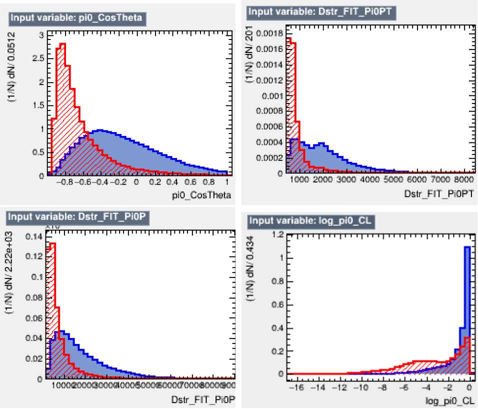
- **Dstr_FIT_Pi0PT:**- p_T of π^0
- **Dstr_FIT_Pi0P:** - p of π^0
- **Dstr_FIT_PT:** - p_T of D^0
- **Dstr_FIT_PT:** - p_T of $D^{*\pm}$
- **H_PT_SUM:** The scalar sum of the transverse momenta of π^- and π^+.

Variables in *red* have been added since the last WG Presentation

Training the Classifier - Resolved

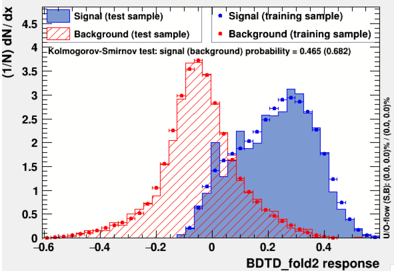
TMVA Rank	Variable
1	Dstr_FIT_Pi0PT
2	pi0_CosTheta
3	Kstr_CosTheta
4	Dstr_FIT_Pi0P
5	log_pi0_CL
6	Dstr_FIT_DPT
7	Dstr_FIT_PT
8	acos_D_DIRA_OWNPV
9	log_FITCHI2_Prob
10	D_FDCHI2_OWNPV
11	log_D_IPCHI2_OWNPV
12	D_CosTheta
13	H_PT_SUM

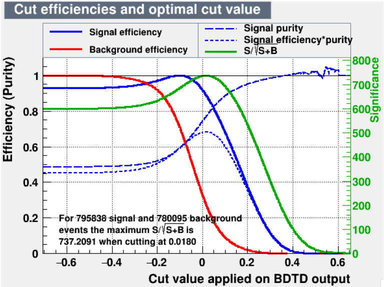
Rank of BDT variables



Training the Classifier - Resolved

- Decent separation with a range of optimal cut values

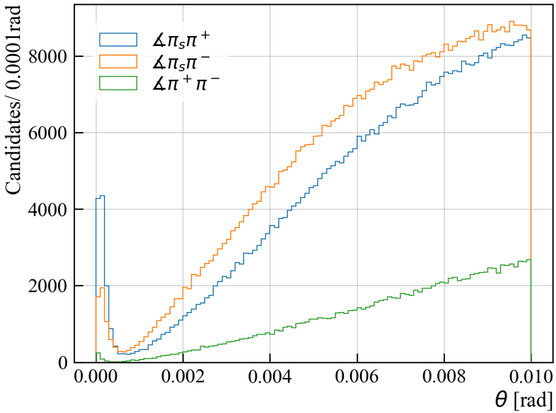




Cut applied at >0.05 to increase purity while staying in the highest significance region

Clone Removal

- Use angle between pairs of tracks of charged particles
- Impose a cut > 0.0005rad



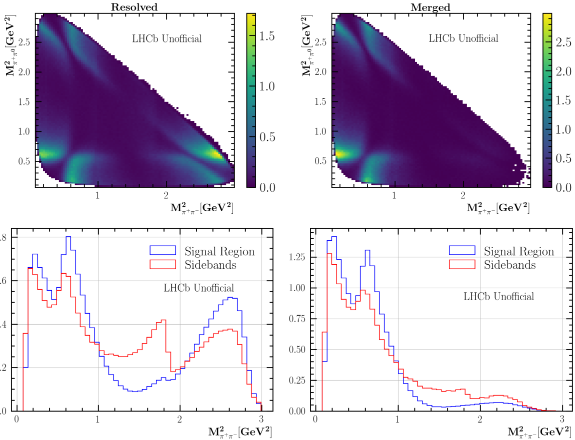
Event Selection - Stripping

Particle	Quantity	Cut
π^+ or π^-	p_T χ^2 w.r.t best PV	> 1700 M/c > 36
$\pi^\pm$ pair	DOCA χ^2 $m_{\pi\pi}$ vertex χ^2/DoF χ^2 w.r.t best PV	< 15 < 1850 M/c < 3 > 100
π^0 π^0 (resolved only)	p_T $\lvert m_{\gamma\gamma} - 135\text{ MeV}\rvert$	> 500 M/c < 15 MeV
D^0	vertex χ^2/DoF p_T $\lvert m_{\pi^-\pi^+\pi^0} - 1864.84\text{ MeV}\rvert$ $\lvert m_{D^0} - 1864.84\text{ MeV}\rvert$	< 20 > 1400 M/c < 160 MeV < 150 MeV
π_s	p_T ghost probability PIDe min χ^2_{IP}	> 300 M/c < 0.35 < 5 < 9
D^{*+}	$m_{D^{+-}} - m_{D^0}$ vertex χ^2/DoF DOCA χ^2 $m_{\pi^-\pi^+\pi^0\pi_s} - m_{\pi^-\pi^+\pi^0}$	< 180 MeV < 9 < 20 < 185 MeV

*

Dalitz Projections

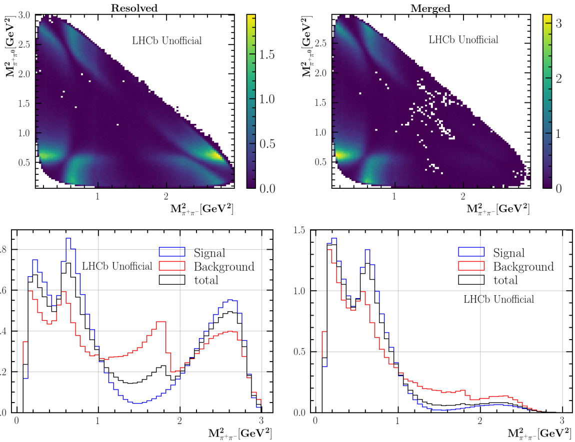
- Dalitz coordinates flipped for $\overline{D}^0$ sample to match D^0 distribution (in case of CP symmetry)



Resolved (left) and Merged (right)

Dalitz Projections

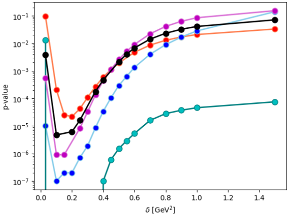
- Same plots, but sWeighting to subtract background (full ΔM range)



Resolved (left) and Merged (right)

Generator Level Toys - δ Scan

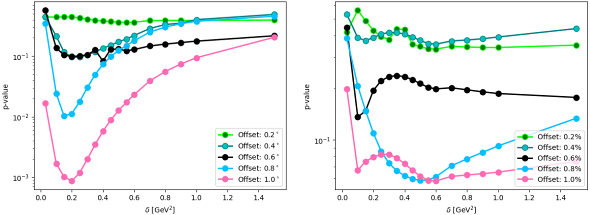
- Look at p-value as a function of δ by taking the mean p-value from a set of 5 independent toys for each asymmetry and delta value.



Distribution of p-values as a function of δ for a set of toys with 1° phase asymmetry in dominant resonance

Generator Level Toys - δ Scan

- Plots below are for asymmetries inserted into sub-dominant resonance
- Based on the δ scans, a preliminary optimal value of $\delta = 0.2$ is chosen



p-values for phase asymmetries (left) and magnitude asymmetries (right)