Search for CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays at LHCb

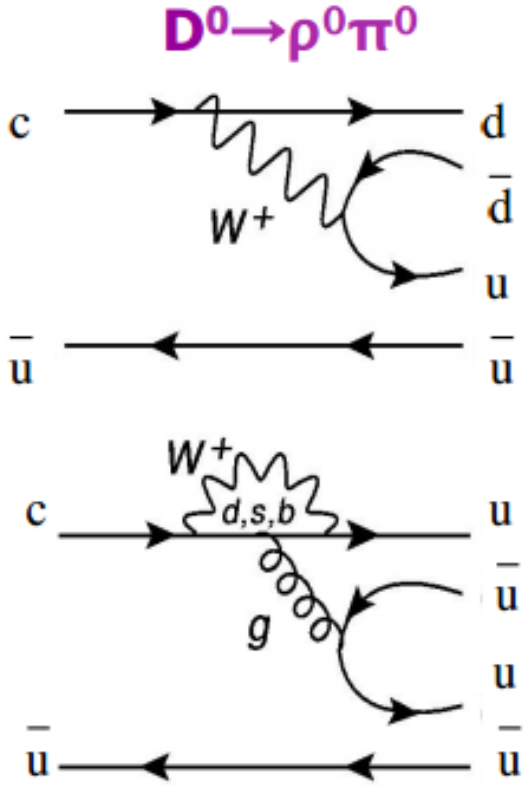
Shanzhen Chen[1], on behalf of the LHCb collaboration
[1]The University of Manchester

Flavorful Ways to New Physics
Freudenstadt
28-31 October 2014

Introduction to $D^0 \to \pi^-\pi^+\pi^0$

Singly Cabibbo suppressed decay:
Tree + Penguin

- CP asymmetry $< 10^{-3} \sim 10^{-2}$ within SM
- New Physics can increase CPV
- Phase space dominated by three interfering $\rho\pi$ resonances

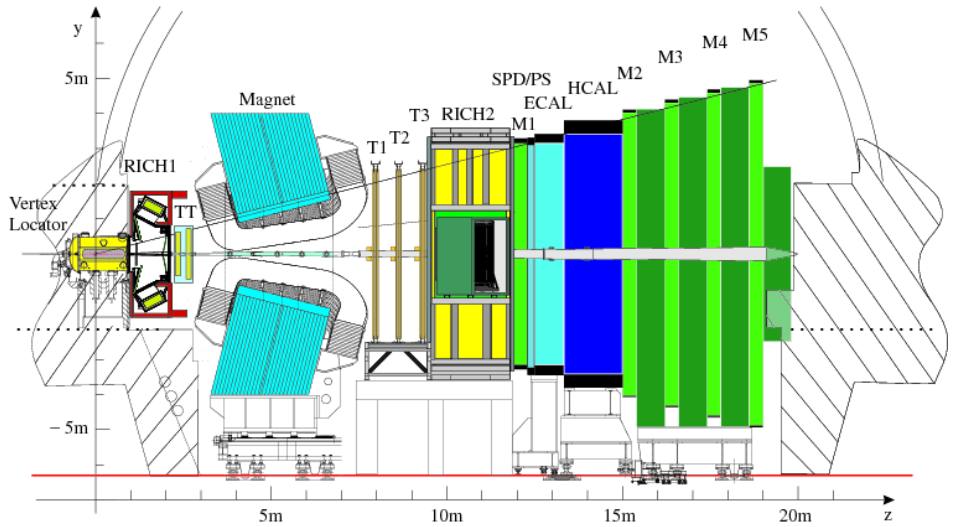


First time use full LHCb π^0 reconstruction:

- Two separated photon clusters (resolved π^0)
- Two overlapping photon clusters (merged π^0)

Previous studies:
BaBar: PRD78, 051102 (2008) Belle: PLB662, 102-110 (2008)
CPV effects of several % excluded

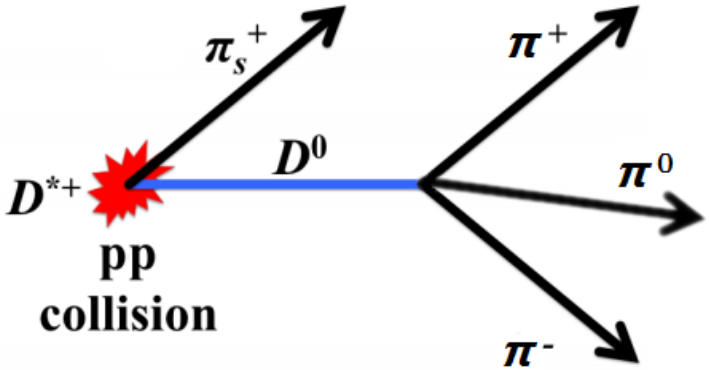
The LHCb Detector



- Single-arm forward spectrometer with acceptance $2 < \eta < 5$, designed for precision measurement of decays involving b and c quarks
- Vertex Locator (VELO) provides fine tracking about the interaction point, achieving impact parameter (IP) resolutions of $20\mu m$ for tracks with $p_T > 1GeV$
- Electromagnetic calorimeter ($ECAL$) and hadronic calorimeter ($HCAL$) measure the energy of electrons, photons, and hadrons

$D^0 \to \pi^-\pi^+\pi^0$ data

Prompt: $D^{*+} \to D^0\pi_s^+$, flavor tagged by slow pion (π_s^+)

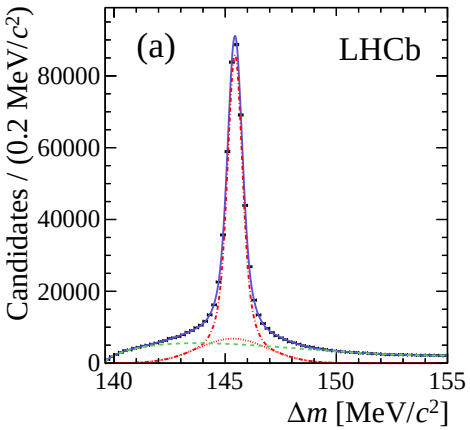


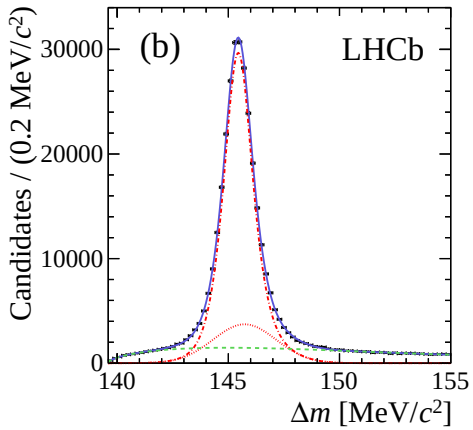
2012 data, integrated luminosity 2fb^{-1}

Selected candidates:

(a) Resolved π^0s, 416×10^3 candidates, purity 82%

(b) Merged π^0s, 247×10^3 candidates, purity 91%



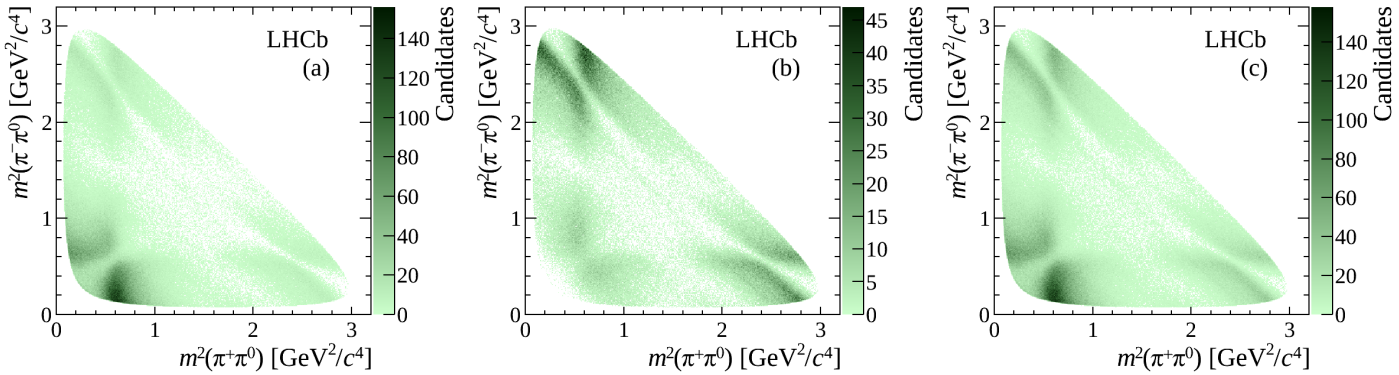


arXiv:1410.4170

Resolved and merged π^0

- π^0 has low momentum $\to$ two separated photon clusters in *ECAL* $\to$ resolved π^0
- π^0 has high momentum $\to$ one merged photon cluster in *ECAL* $\to$ merged π^0

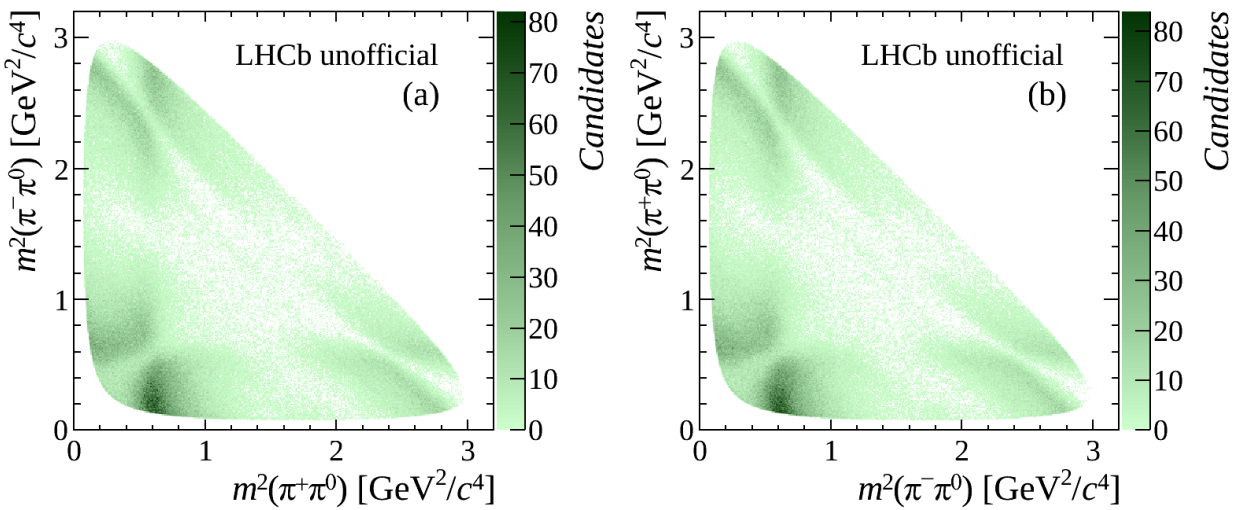
arXiv:1410.4170



(a) Resolved π^0 (b) Merged π^0 (c) Combined sample

A model independent unbinned method: Energy test

- Looking for asymmetries on Dalitz plot
- Compare D^0 and $\bar{D}^0$ decays statistically



Dalitz plot for (a) D^0 candidates and (b) $\bar{D}^0$ candidates.

Energy test

- Test statistic:

$$T = \underbrace{\frac{1}{n(n-1)}\sum_{i,j>i}^{n}\psi(d_{ij})}_{\text{average } \psi \text{ of } D^0 \text{ set}} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)}\sum_{i,j>i}^{\bar{n}}\psi(d_{ij})}_{\text{average } \psi \text{ of } \bar{D^0} \text{ set}} - \underbrace{\frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi(d_{ij})}_{\text{average } \psi \text{ of } D^0 \text{ to } \bar{D^0}}$$

with $\psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$, $d_{ij} = \mid (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i}) \mid$

- Default metric parameter: $\sigma = 0.3 GeV^2/c^4$

No CP violation:

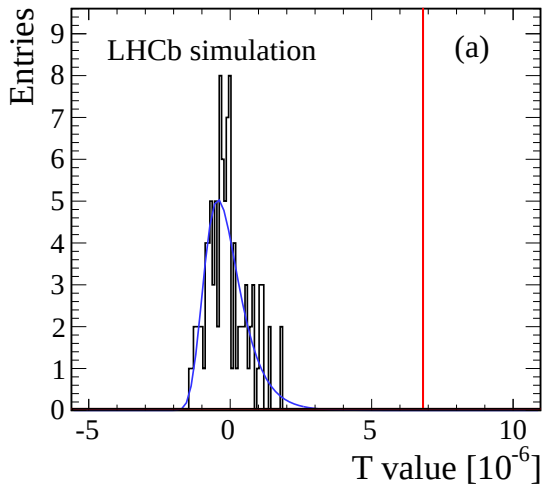
- all averaged distances equal $\rightarrow$ $T \simeq 0$

CP asymmetry:

- averaged distances between D^0 and $\bar{D^0}$ sets larger
- averaged ψ between D^0 and $\bar{D^0}$ sets smaller
- $T > 0$

Principle of measurement

- Use T value to test if data consistent with no-CPV hypothesis
- No-CPV samples from permutation of data: randomly assign D^0 or $\bar{D}^0$
- Compare T value from data with T values from no-CPV samples (T_{perm})
- p-value: fraction of permutations with T_{perm} above T
- p-value from counting or fitting T_{perm} with generalized extreme value (GEV) function (if p-value very small)
- CP asymmetry $\rightarrow$ small p-value



arXiv:1410.4170

Energy test: sensitive, simple, feasible

Sensitive:

- More sensitive than binned method (S_{CP})

  M.Williams PRD84, 054015(2011)
- More sensitive than kNN method

  B.Aslan, G.Zech NIM A357, 626-636 (2005)

Simple:

- Investigate CPV in decay distributions, global asymmetries can be ignored
- Efficiency and/or background can be ignored if similar for D^0 and $\bar{D}^0$

Feasible:

- CPU consuming but feasible on GPU

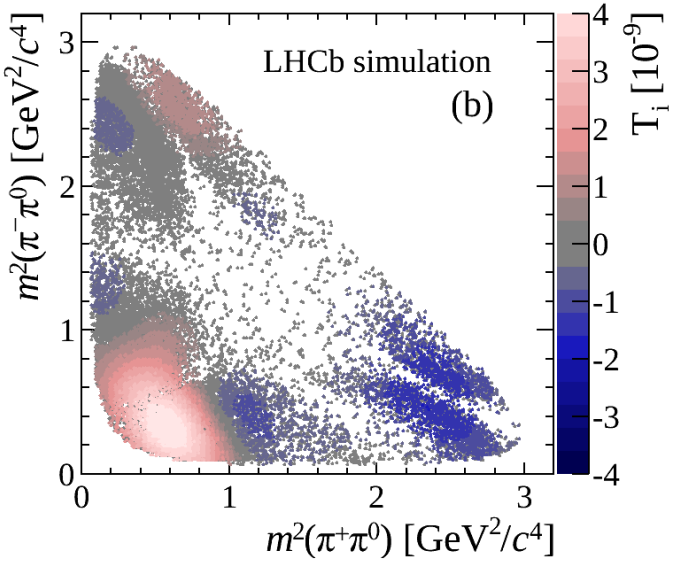
Visualisation

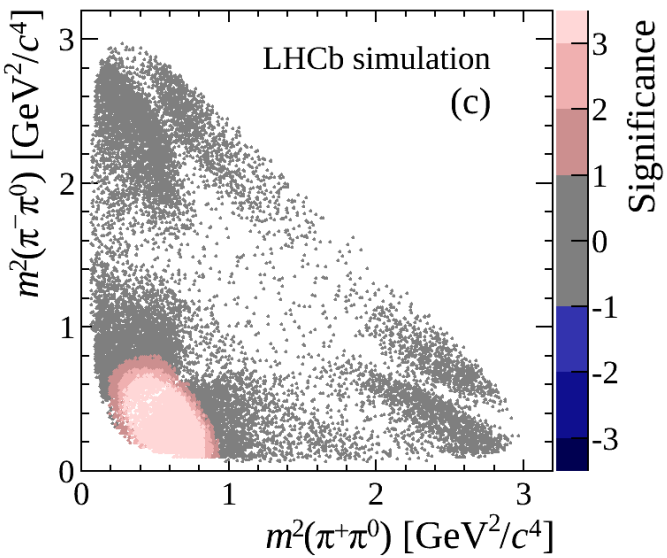
- Plot contribution of each event to total T-value

$$T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^{n} \psi(d_{ij}) - \frac{1}{2n\bar{n}} \sum_{j}^{\bar{n}} \psi(d_{ij})$$

- Use T_i^{max} and T_i^{min} distributions from permutations to set significance levels
- Plot T_i values in terms of these significance levels $\rightarrow$ Show regions in Dalitz plot which contribute the most

arXiv:1410.4170





Sensitivity

arXiv:1410.4170

- Selection efficiency obtained using full LHCb phase space MC
- Sensitivity studies use toy MC samples made in same data size to model signal decays
- Background events modelled according to sideband distributions
- Better sensitivities than BaBar for most of CPV scenarios

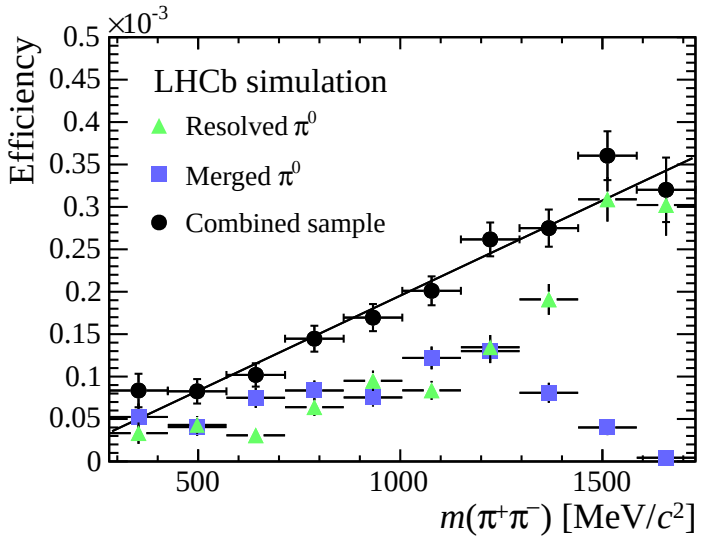


Table 1: Overview of sensitivities to various CP violation scenarios. ΔA and $\Delta\phi$ denote, respectively, change in amplitude and phase of the resonance R.

R (ΔA, $\Delta\phi$)	p-value (fit)	Upper limit
ρ^0 (4%, 0°)	$3.3^{+1.1}_{-3.3} \times 10^{-4}$	4.6×10^{-4}
ρ^0 (0%, 3°)	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ (2%, 0°)	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ (0%, 1°)	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- (2%, 0°)	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- (0%, 1.5°)	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

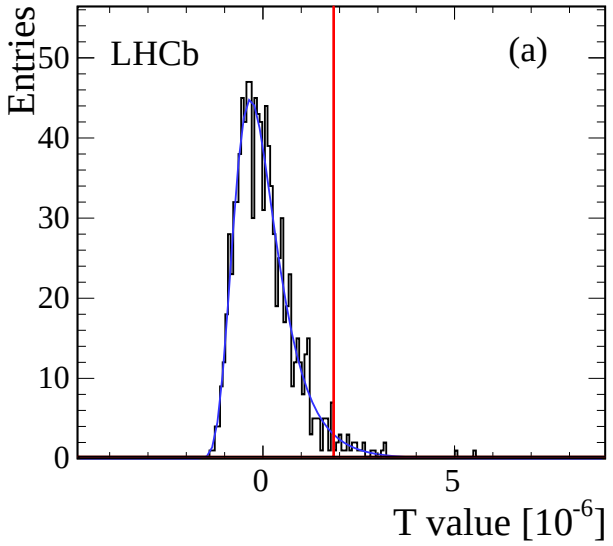
Results

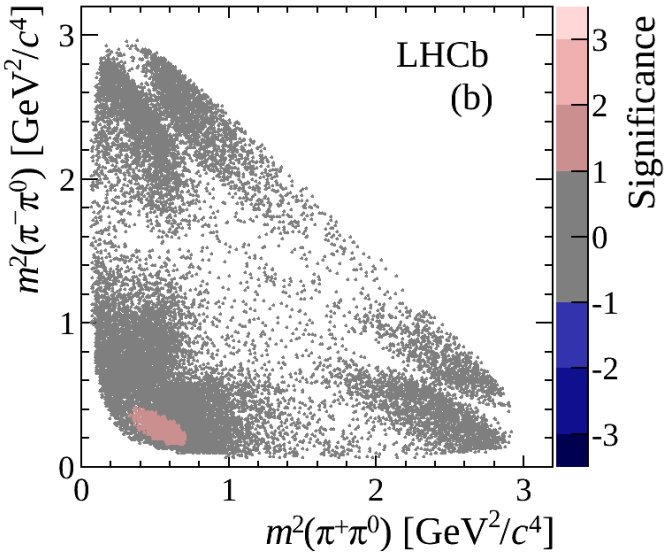
arXiv:1410.4170

- With 1000 permutations
- For no-CPV hypothesis: p-value $= (2.6 \pm 0.5)\%$
  Result consistent with no CPV hypothesis
- Other metric parameters:

Table 2: Results for various metric parameter values. The p-values are obtained with the counting method.

σ [GeV$^2/c^4$]	p-value
0.2	$(4.6 \pm 0.6) \times 10^{-2}$
0.3	$(2.6 \pm 0.5) \times 10^{-2}$
0.4	$(1.7 \pm 0.4) \times 10^{-2}$
0.5	$(2.1 \pm 0.5) \times 10^{-2}$



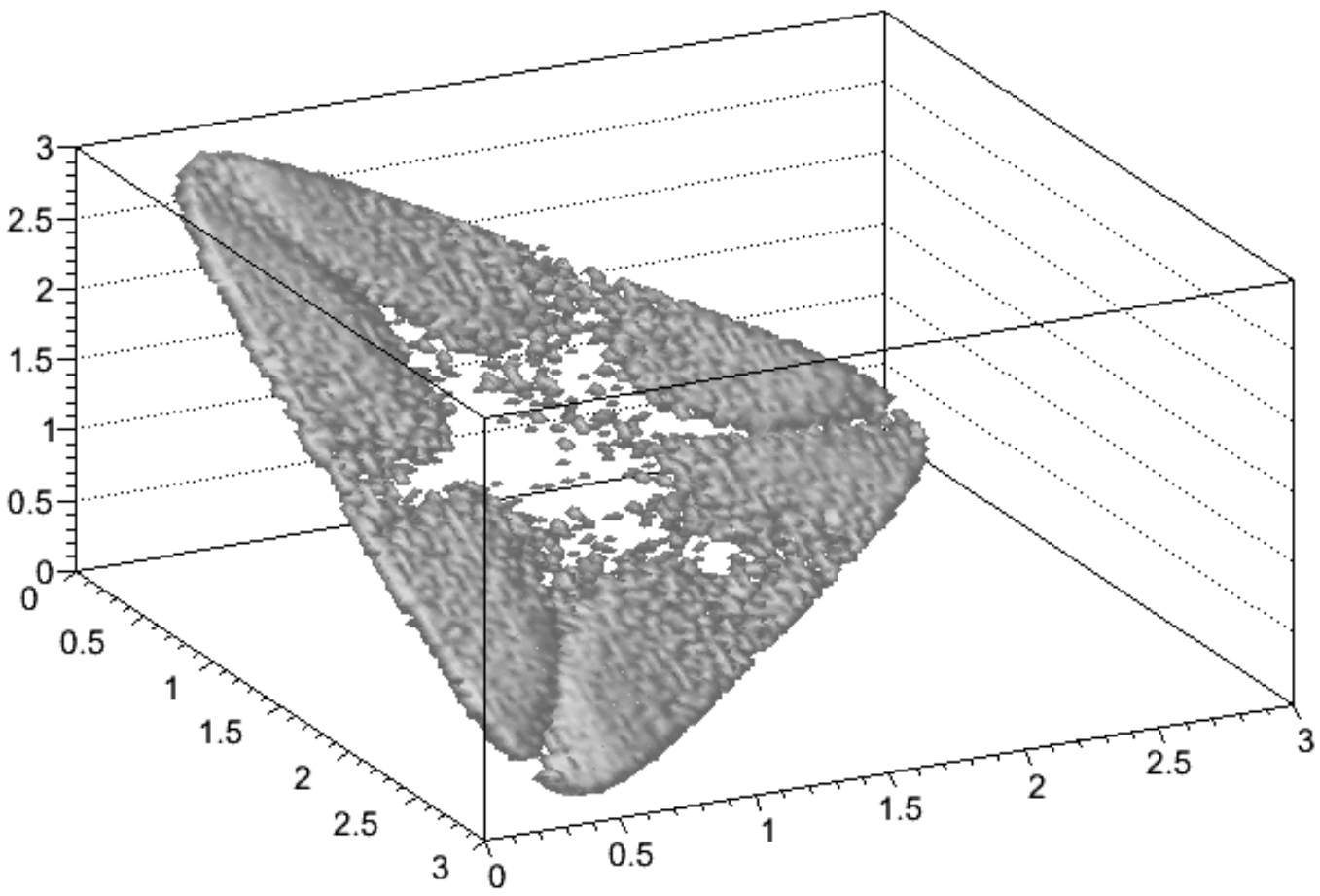


Conclusions

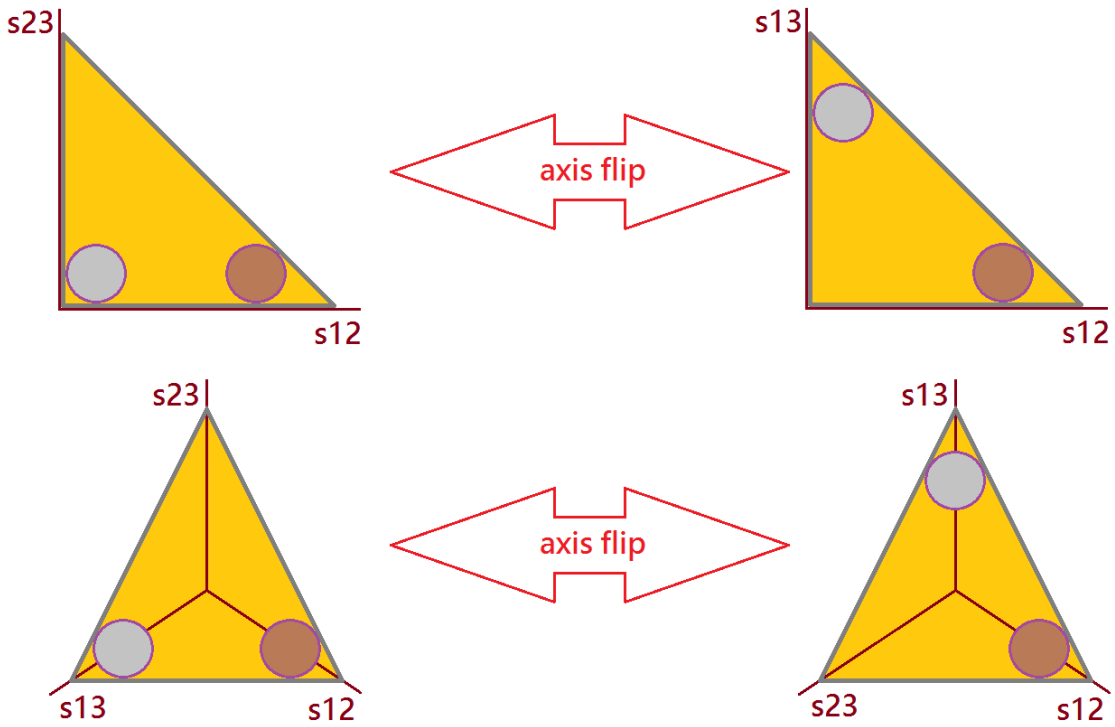
- First CPV measurement using both merged and resolved π^0s at LHCb
- Using 2012 LHCb data, integrated luminosity 2fb^{-1}
- 663×10^3 selected candidates, with purity $82\%(\text{resolved}) \sim 91\%(\text{merged})$
- First application of energy test in CPV search
- Method implemented with GPU
- World's best sensitivity in $D^0 \to \pi^-\pi^+\pi^0$ channel
- p-value $= (2.6 \pm 0.5)\%$, result consistent with no CPV

Backup

3D Dalitz phase space



3D Dalitz phase space



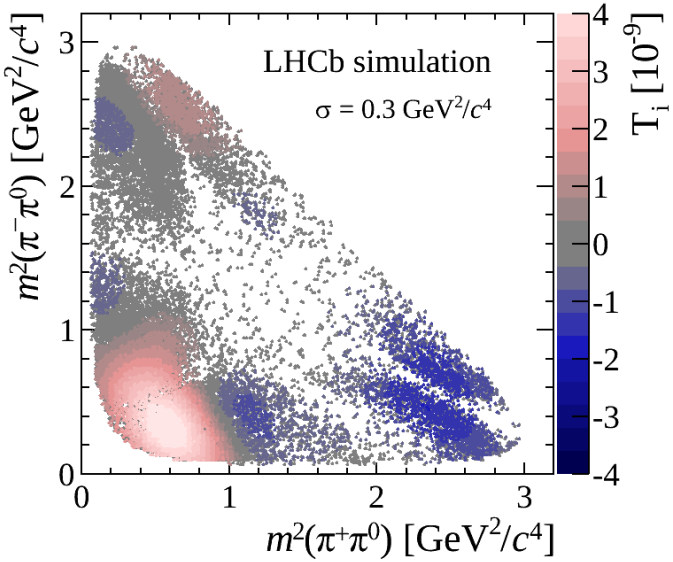
Distances between two regions in 3D Dalitz phase space remains unchanged under axis flip, which ensure a unique T-value

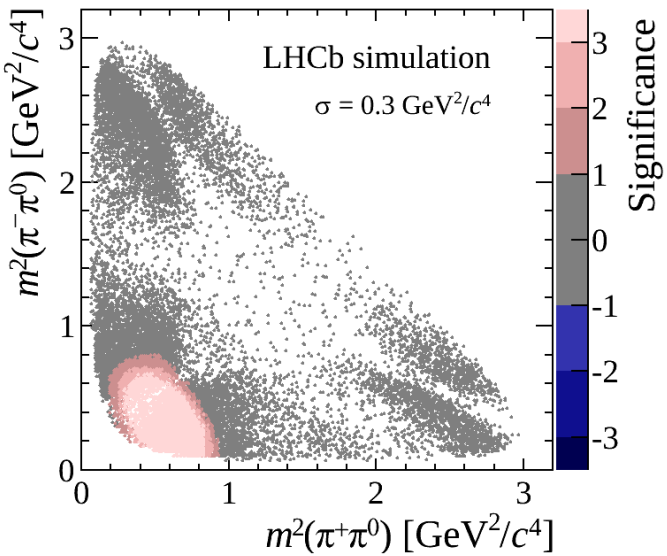
p-values

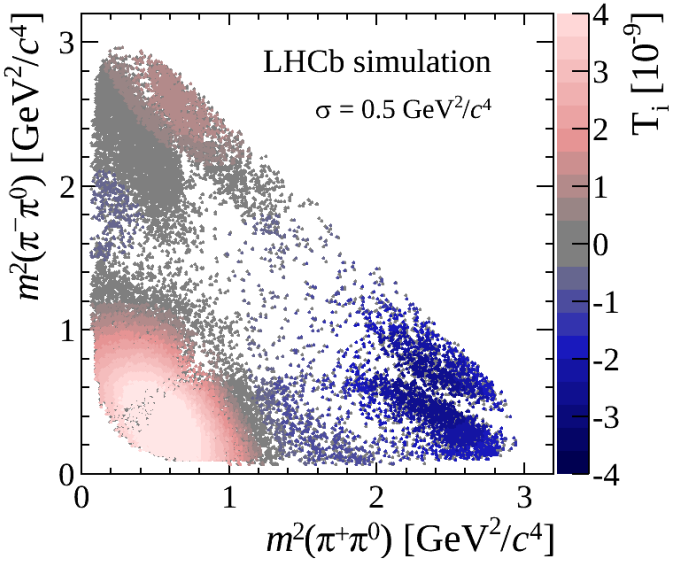
Small p-values extracted form a generalised extreme value (GEV) function fit

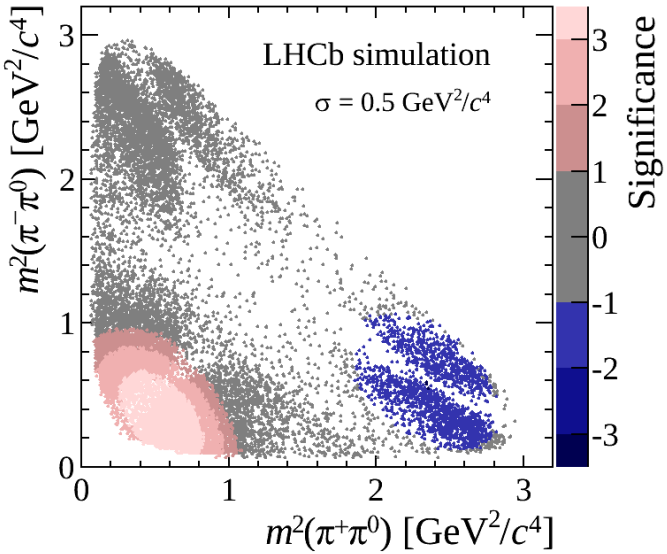
$$f(T;\mu,\sigma,\xi) = N\left[1+\xi\left(\frac{T-\mu}{\sigma}\right)\right]^{(-1/\xi)-1}\exp\left\{-\left[1+\xi\left(\frac{T-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

Matric parameter σ: $\Delta A(\rho^+(770)) = 2\%$

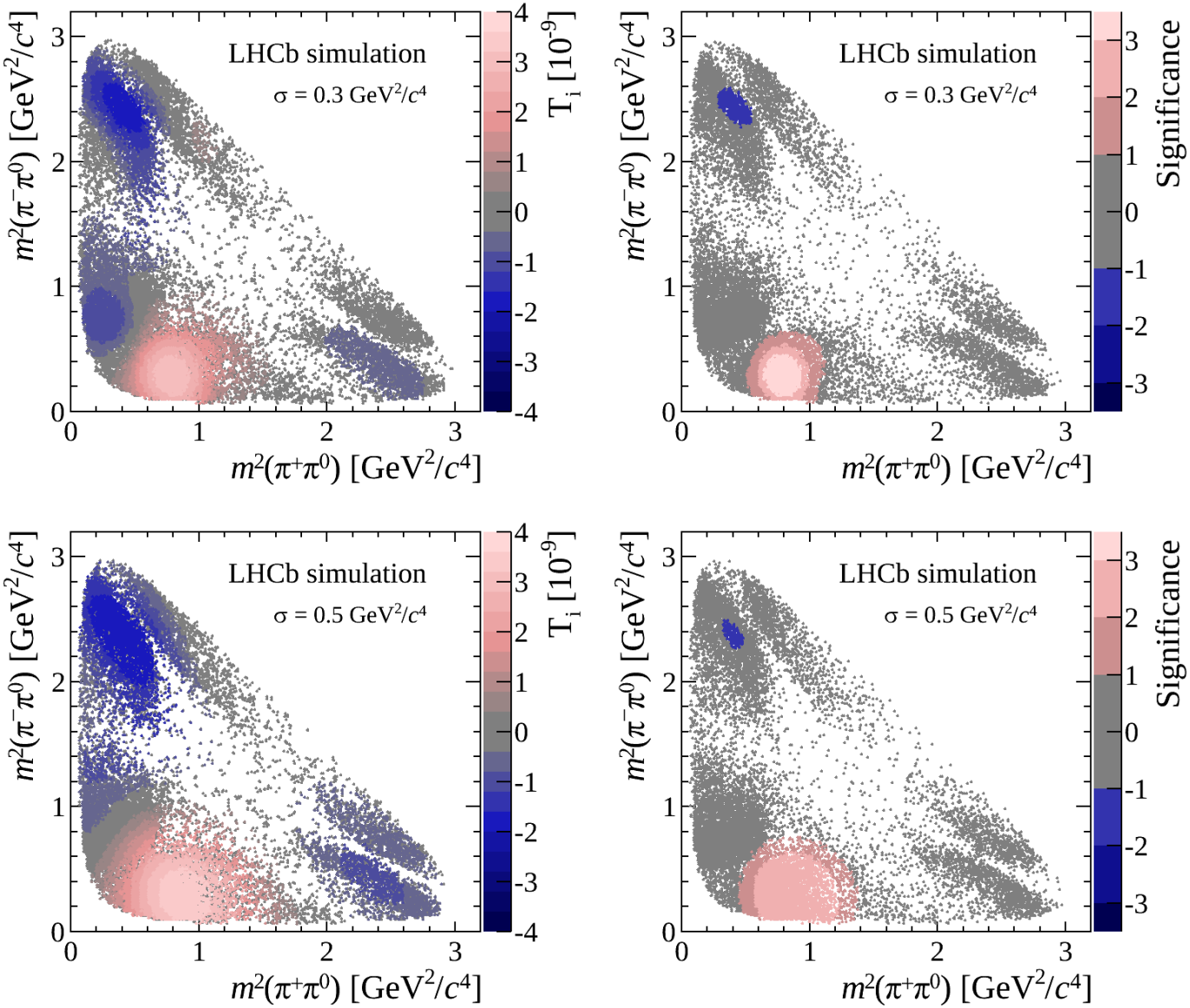








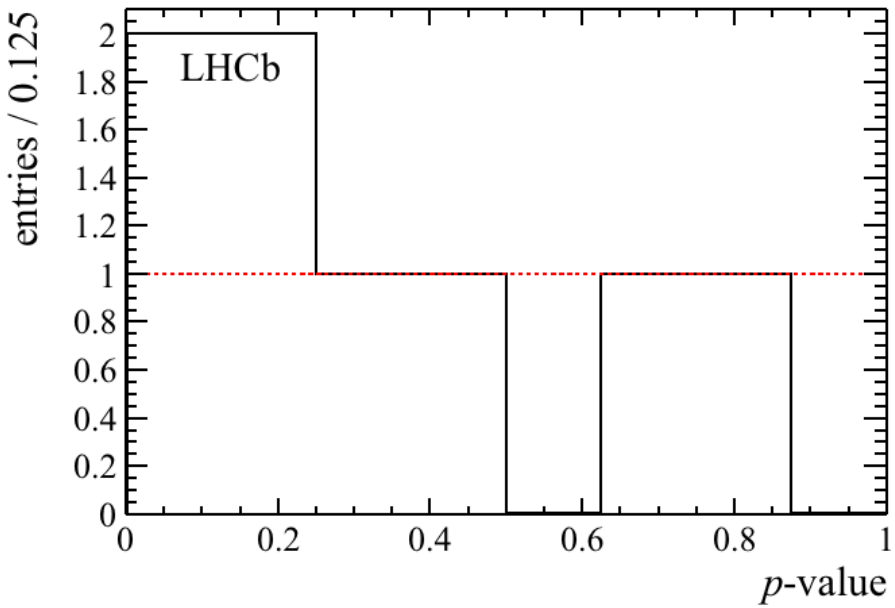
Matric parameter σ: $\Delta\phi(\rho^+(770)) = 1^\circ$



Cross checks 1: detection asymmetries

Cross check with Cabibbo-favoured $D^0 \to K^-\pi^+\pi^0$ channel, to avoid detection asymmetries that may bias result

- Split into 8 sub-samples
- Split by polarity



No indication of detector related asymmetries

Cross checks 2: asymmetries from background

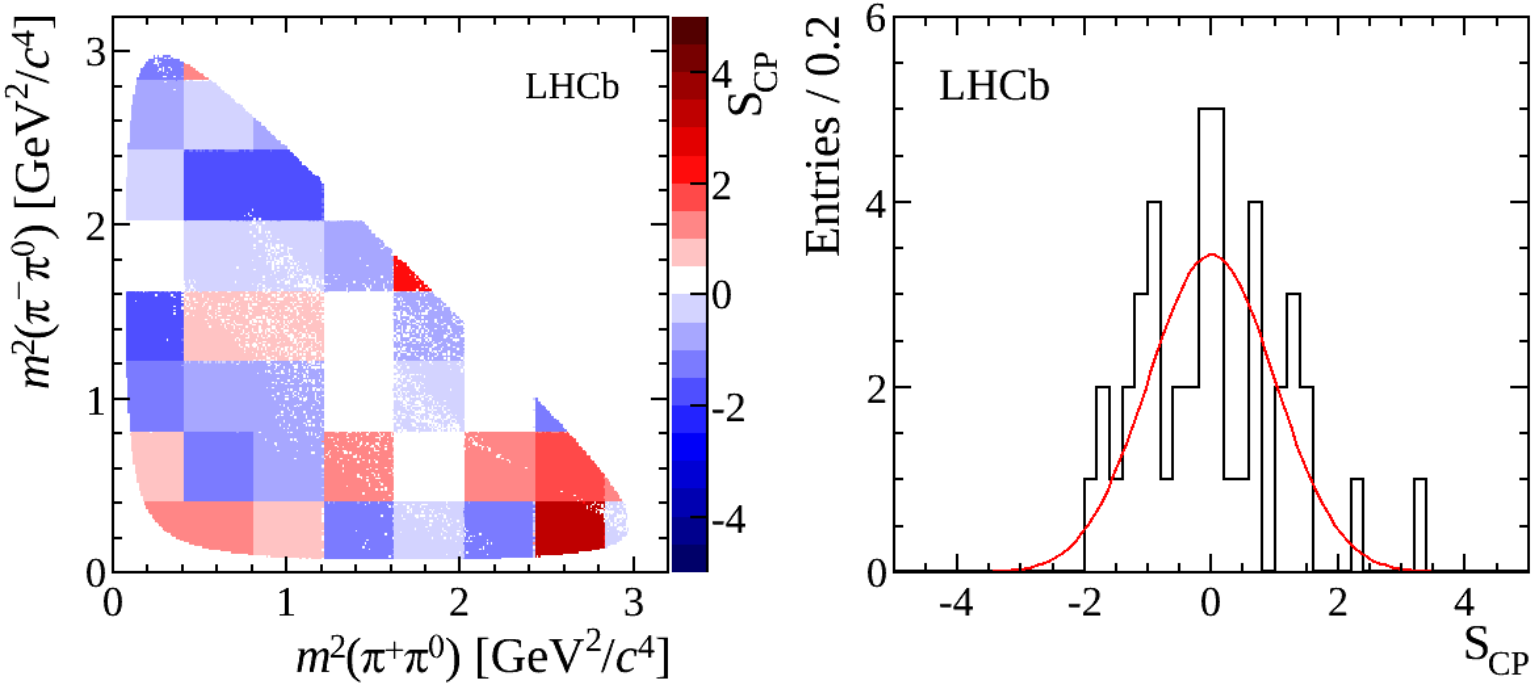
Cross check with $D^0 \to \pi^-\pi^+\pi^0$ backgrounds, to avoid asymmetries from background that may bias result

- Apply energy test to the upper sideband of Δm
- Generating toys for D^0 and $\bar{D}^0$ sidebands

No indication of background related asymmetries

Cross checks 3: binned method

Cross check with S_{CP} method



Consistent with energy test result