Energy test and its application in CPV searches in multi-body charm decays at LHCb

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

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Why CPV in charm interesting?

Why charm?

- CP violation found in K and B sectors, not in charm
- Charm is the only up-type sector that could search for CP violation

Why CPV not found in charm?

- Small CKM contribution
- CPV is expected to be small in charm sector

Why we search CPV in charm?

- May enhance this amplitude through the introduction of new process and particles
- CPV in charm is clean probe for New Physics

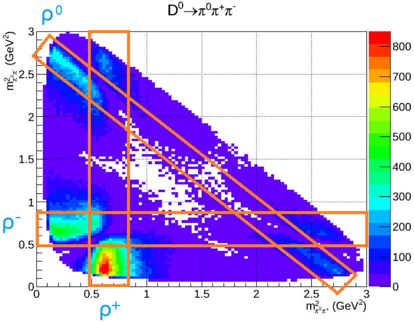
Why multi-body decays?

Multibody charm decays

- Allow to access a wide range of decays within the same final state that may have different contribution processes

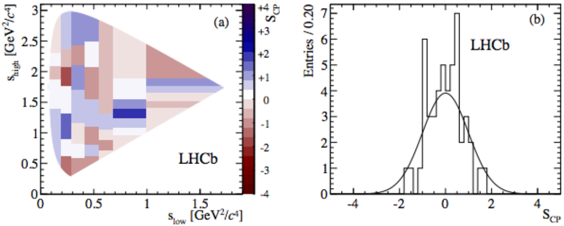
Phase space - Dalitz plot

- Plot that could display decay intermediate states
- Could be used to localize the source of CP violation



Techniques applied on LHCb data in CPV searches

- Amplitude analysis:
- S_{CP} (Binned χ^2 method):
  - Define $S_{CP}^i = \dfrac{N_i(X) - \alpha N_i(\bar{X})}{\sqrt{\sigma_i^2(X) + \alpha\sigma_i^2(\bar{X})}}$, where $\alpha = \dfrac{\Sigma_i N_i(D)}{\Sigma_i N_i(\bar{D})}$
  - Kind of LHCb 'standard' method in CPV searches

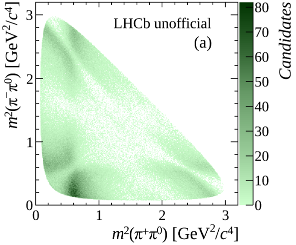


- Energy test ← What I will talk about today!

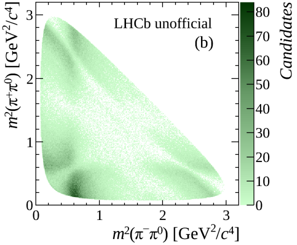
The energy test

A model independent unbinned method: Energy test

- Looking for asymmetries in phase space
- Compare CP conjugated X and $\bar{X}$ decays statistically



(a) $D^0 \rightarrow \pi^- \pi^+ \pi^0$



(b) $\bar{D}^0 \rightarrow \pi^+ \pi^- \pi^0$

Energy test

- Test statistic:

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

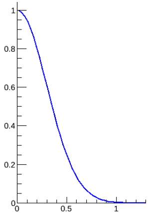
with metric function $\psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$, d_{ij} is the distance between event i and j in phase space, metric parameter σ determine the width of metric function

No CP violation:

- all averaged distances in phase space equal $\rightarrow T \simeq 0$

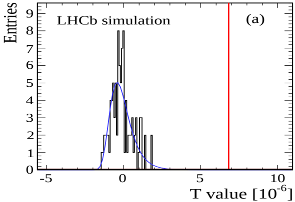
CP asymmetry:

- averaged distances between X and $\bar{X}$ sets larger
- averaged ψ between X and $\bar{X}$ 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 X or $\bar{X}$
- 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, p-value $\simeq 0.3\%$ corresponds to 3σ



Energy test with GPU

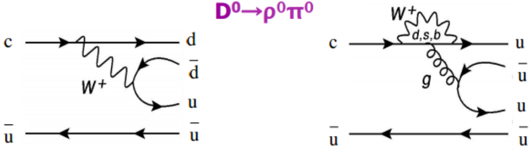
- Energy test consider distances between every two event, which will lead to $\sim$(Number of events)$^2/2$ calculations $\rightarrow$ prohibitively long calculation time on CPU for large datasets
- Parallel architecture of GPU makes it possible to dramatically reduce computation time for datasets with 10^4 to 10^6 events on GPU
- Applied with CUDA computing platform of NVIDIA GPUs
- Implemented with Thrust, a C++ template library for CUDA

$D^0 \to \pi^-\pi^+\pi^0$ with the energy test

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

Singly Cabibbo suppressed decay: Tree + Penguin

- Phase space dominated by interfering $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ resonances



First CP violation search at LHCb with π^0

First time use full LHCb π^0 reconstruction:

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

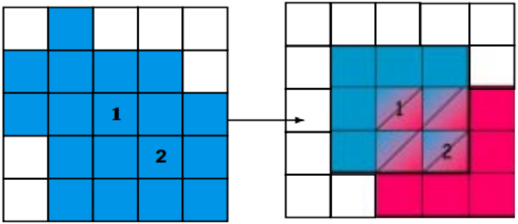
Previous studies:

BaBar: PRD78, 051102 (2008) Belle: PLB662, 102-110 (2008)

CPV effects of several percent excluded

π^0 reconstruction in *ECAL*

- π^0 end up with two separated photon clusters within *ECAL* granularity
  $\to$ resolved π^0
- π^0 end up with one merged photon cluster within *ECAL* granularity
  $\to$ merged π^0

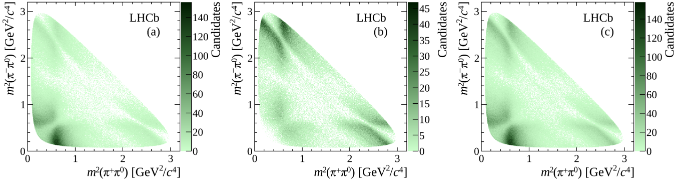


Single cluster **2 interleaved subclusters**

Resolved and merged π^0

- resolved π^0 $\to$ large photon separation angle $\to$ π^0 has low momentum $\to$ bottom left corner on $m^2_{\pi^-\pi^0}$ vs $m^2_{\pi^+\pi^0}$ Dalitz plot
- merged π^0 $\to$ small photon separation angle$\to$ π^0 has high momentum $\to$ band from top left to bottom right on $m^2_{\pi^-\pi^0}$ vs $m^2_{\pi^+\pi^0}$ Dalitz plot

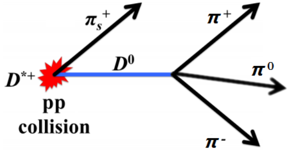
PLB740, 158-167(2015)



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

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

Prompt: $D^{*+} \to D^0\pi_s^+$
Flavour tagged by slow pion (π_s^+)
$\Delta M = M(D^{*+}) - M(D^0)$



2012 data, integrated luminosity 2fb^{-1}, yields 8 times larger than BaBar
Selected candidates:
(a) Resolved π^0s (left), 416×10^3 candidates, purity 82%
(b) Merged π^0s (right), 247×10^3 candidates, purity 91%

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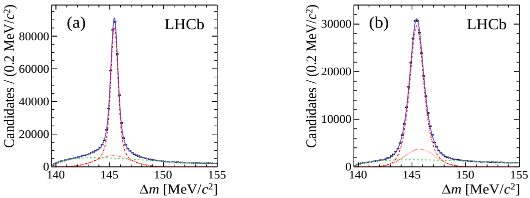

Visualisation

- 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 $\to$ Show regions in Dalitz plot which contribute the most

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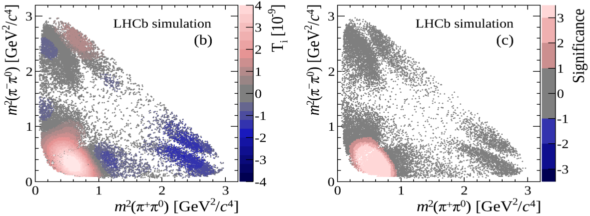
Monte Carlo sample: 2% CP violation in the amplitude of the ρ^+ resonance



Sensitivity

- Metric parameter $\sigma = 0.3 GeV^2/c^4$
- 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

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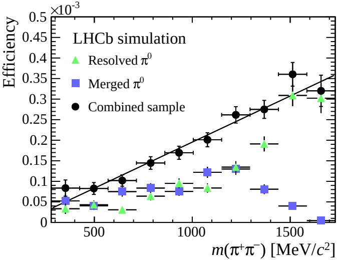

Table 1: Overview of sensitivities to various *CP* violation scenarios. ΔA and $\Delta\phi$ denote, respectively, change in amplitude and phase of the resonance R.

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

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

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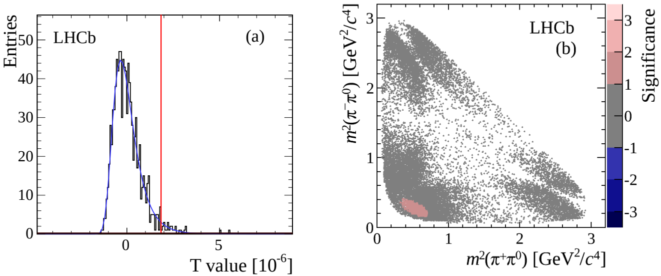


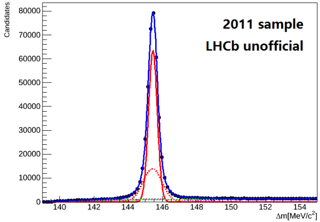
$D^0 \to \pi^+\pi^-\pi^+\pi^-$ with the energy test

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

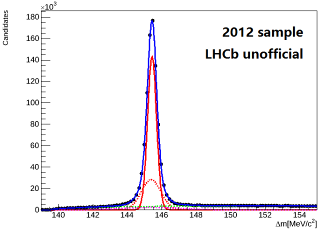
- Singly Cabbibo suppressed decay with penguin contribution
- 4 body charm decay
- Dominate resonant modes are $D^0 \to a_1(1260)^+\pi^-$ and $D^0 \to \rho^0\rho^0$
- Previously studied by LHCb with 2011 data and using S_{CP} method (paper)

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

Prompt: $D^{*+} \to D^0\pi_s^+$
2011: 317,828 candidates with purity 97.4%
2012: 716,150 candidates with purity 96.5%



2011 data



2012 data

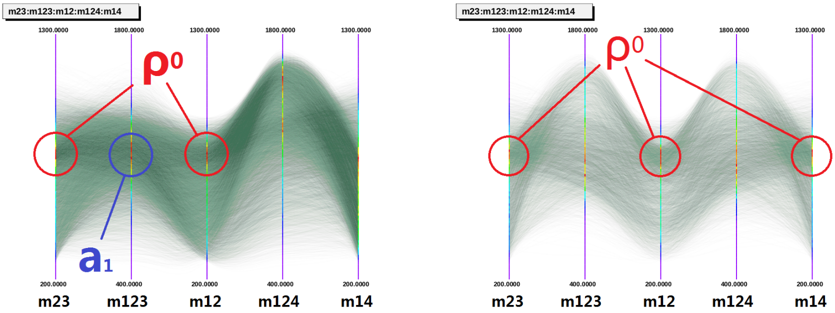
Coordinates for 4π energy test

- Four-body decay have 5 degrees of freedom
- 6 two-body invariant masses, 4 of them are physically meaningful
- 4 three-body invariant masses

- Fix the charge order of the four pions: 1234$=+-+-$
- $m^2(\pi^+\pi^-)$: s12 s14 s23 s34 are all possible combinations
- $m^2(\pi^+\pi^-\pi^+)$: s123 s134
- $m^2(\pi^+\pi^-\pi^-)$: s124 s234
- Find the largest $m^2(\pi^+\pi^-)$, and let it be s34, the order is fully determined
- The dominating resonances are not with very high mass, so reject highest two-body mass combinations s34 and three-body combinations including it: s134, s234
- 5 combinations left: s12 s14 s23 s123 s124

Visualisation

Parallel coordinates is used as the tool to visualise 5 dimensional phase space



Left: $D^0 \to (a_1^+ \to \rho^0\pi^+)\pi^-$. Right: $D^0 \to \rho^0\rho^0$.
Also usual scatter plots can be used for visualistation, e.g. s12 vs s124, s12 vs s14, etc.

Sensitivity studies

- Apply energy test on CP asymmetric MC samples
- Amplitude/phase change on a_1 and $\rho\rho$ resonances for either D^0 or $\overline{(}D^0)$
- p-value less than 3×10^{-3} (3σ), considered to be sensitive

$p-$values:

- 1M events per sample
- $\sigma = 0.5(GeV/c^2)^2$

Asymmetries	T_0 value	$p-$value (fit)
a_1 Δphase 2°, ΔAmp 0	8.96×10^{-6}	2.2×10^{-4}
a_1 Δphase 0, ΔAmp 2%	4.37×10^{-6}	3.0×10^{-3}
$\rho\rho(S)$ Δphase 5°, ΔAmp 0	5.11×10^{-6}	1.7×10^{-3}

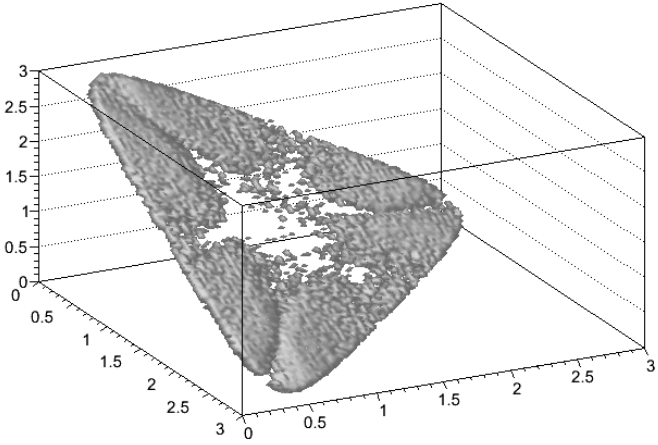
Data is still blinded, More studies is still ongoing...

Summaries

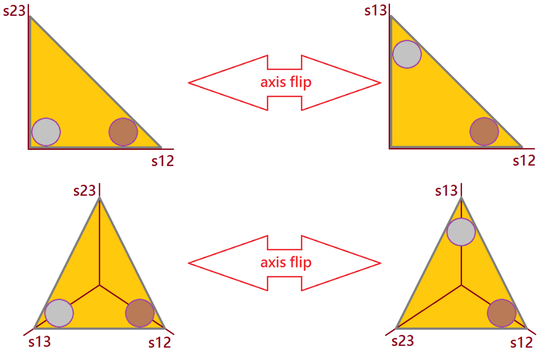
- First application of energy test in CPV searches
- Method implemented with GPU
- World's best sensitivity in $D^0 \to \pi^- \pi^+ \pi^0$ channel with no CPV found
- First CPV search in LHCb with π^0
- $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$ analyses with energy test in good shape

Backup

3D Dalitz phase space



3D Dalitz phase space



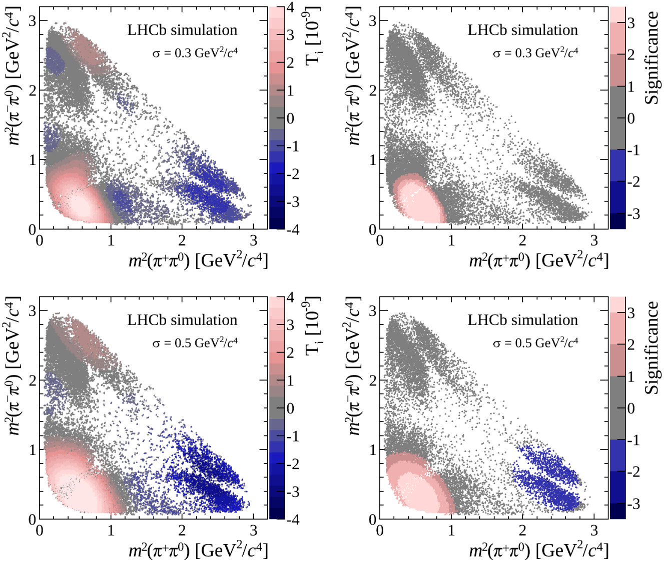
Distances between two regions in 3D Dalitz phase space remains unchanged under axis flip, which ensure a unique T-value

p-values

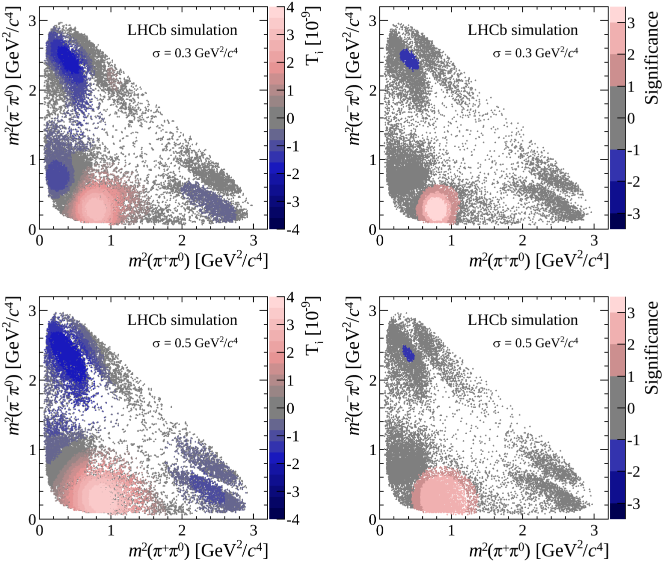
Small p-values extracted form a generalised extreme value (GEV) function fit

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

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



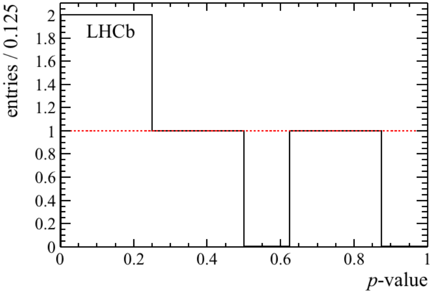
Matric parameter σ: $\Delta\phi(\rho^+(770)) = 1^\circ$



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

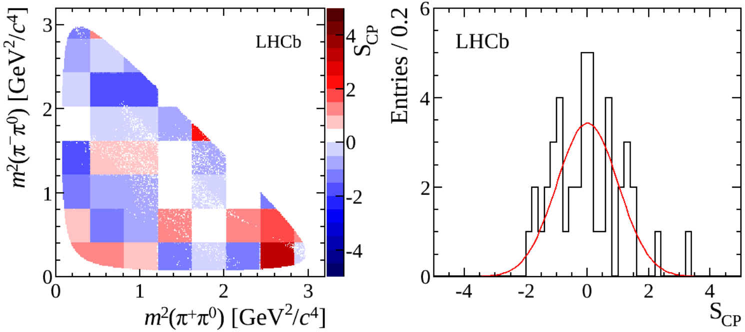
Cross check with $D^0 \to \pi^-\pi^+\pi^0$ backgrounds, to avoid asymmetries from background that may bias result

- 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



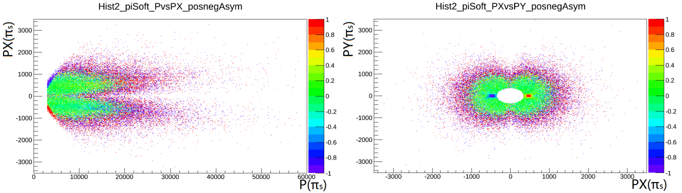
Consistent with energy test result

Detector asymmetries

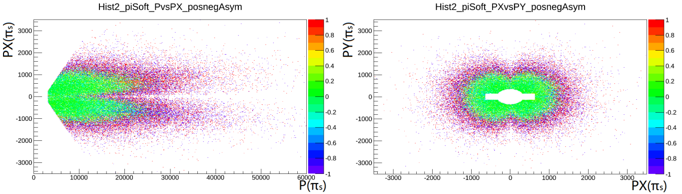
Same fiducial cuts as in 2011 $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decay analysis

```
piSoft_P > 3200 && ( abs(piSoft_PX)<0.317*(piSoft_PZ - 2400))
abs(piSoft_PX) > 640 || abs(piSoft_PX) < 240
  || piSoft_PY > 150 || piSoft_PY < -150
```

Before fiducial cuts

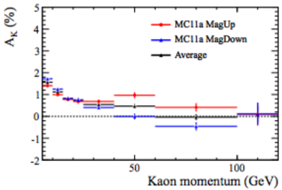


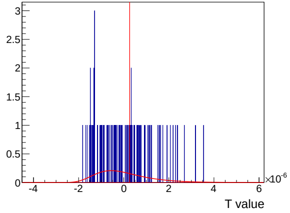
After fiducial cuts



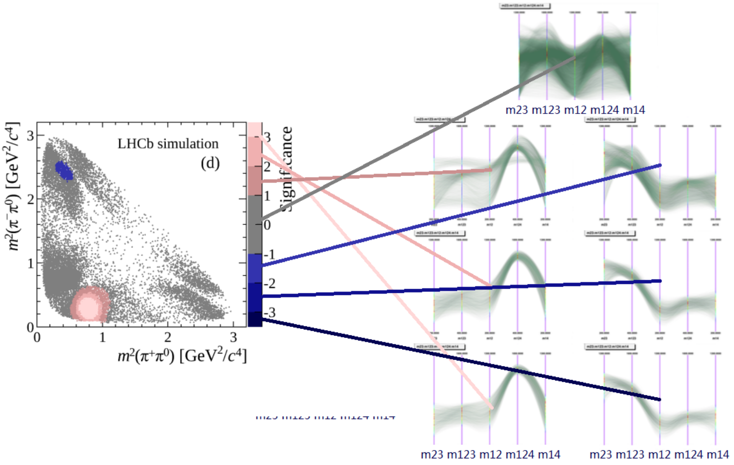
Detection asymmetries

- Start with three-body decays
- Introduce Kaon detection asymmetry as function of momentum in $D^+ \to K^-\pi^+\pi^+$ decay MC samples (LHCb-INT-2012-027)
- Pion detection asymmetry is much less than Kaon
- Not sensitive to Kaon detection asymmetry





Visualisation of significant events



Example: : 2% amplitude asymmetric change in a_1.