Measurements of direct CP violation in multi-body charm decays at LHCb

Marco Gersabeck (The University of Manchester)
on behalf of the LHCb collaboration

CKM 2016, Mumbai, 29/11/2016

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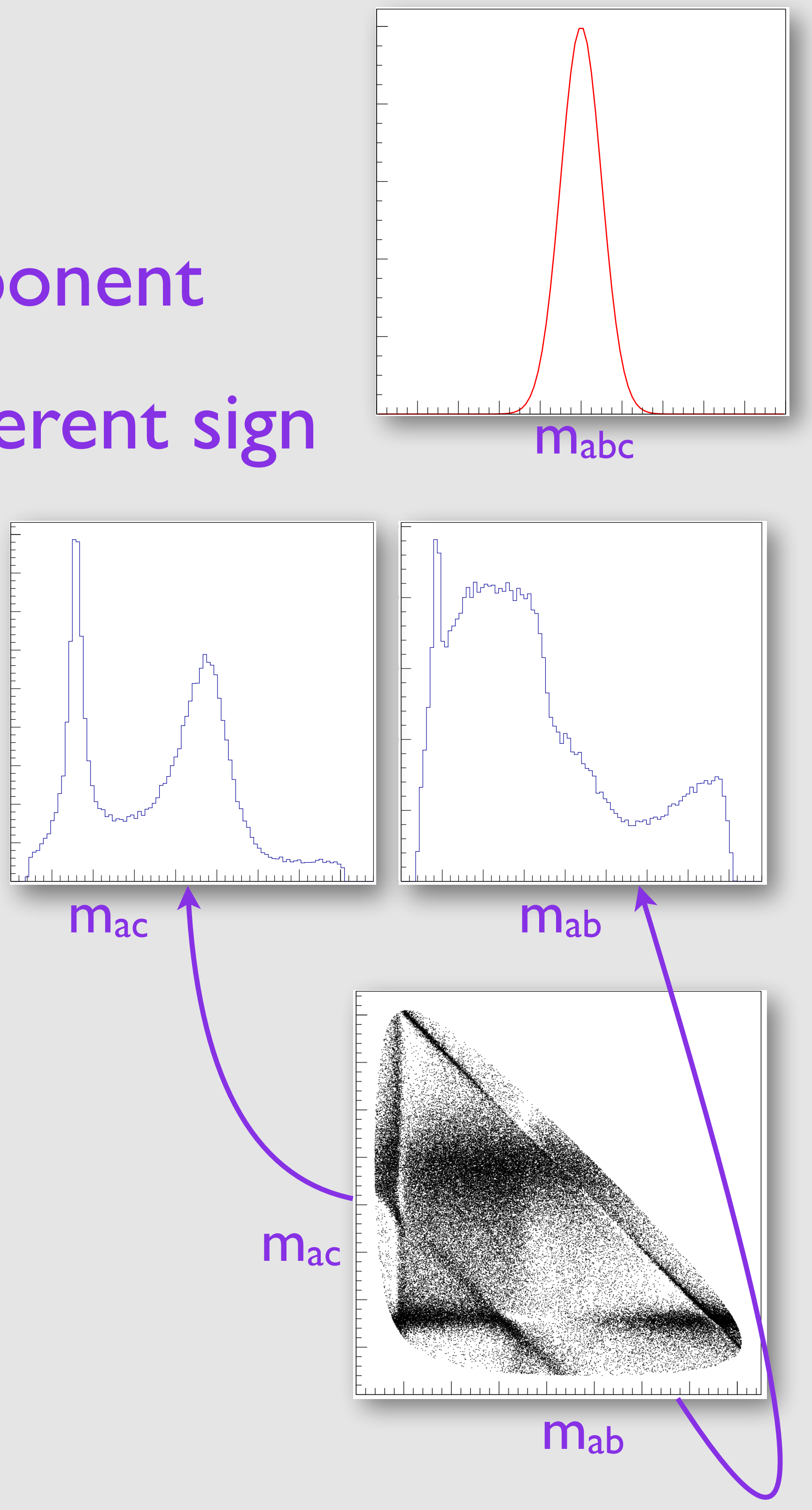
Multi-body asymmetries

- Phase-space integrated
  - ➡ Tests for asymmetry in dominant component
  - ➡ May wash out local asymmetries of different sign
- In selected regions of phase space
  - ➡ Can be applied to test asymmetry of locally dominant resonance
- Generic search for local asymmetries
  - ➡ Fully exploits resonance structure
  - ➡ Different approaches



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Searches for local asymmetries

- Model-dependent
  - ➡ Fit an amplitude model to D and $\bar{D}$ separately and look for discrepancies
    - See Jonas' talk
- Model-independent
  - ➡ P-even CPV
    - Various methods, binned vs unbinned
  - ➡ P-odd CPV
    - Local triple product asymmetries

Measured asymmetries

- Measure $A_{raw}(D\to f) = \dfrac{N(D\to f) - N(\bar{D}\to \bar{f})}{N(D\to f) + N(\bar{D}\to \bar{f})}$
- Get to first order

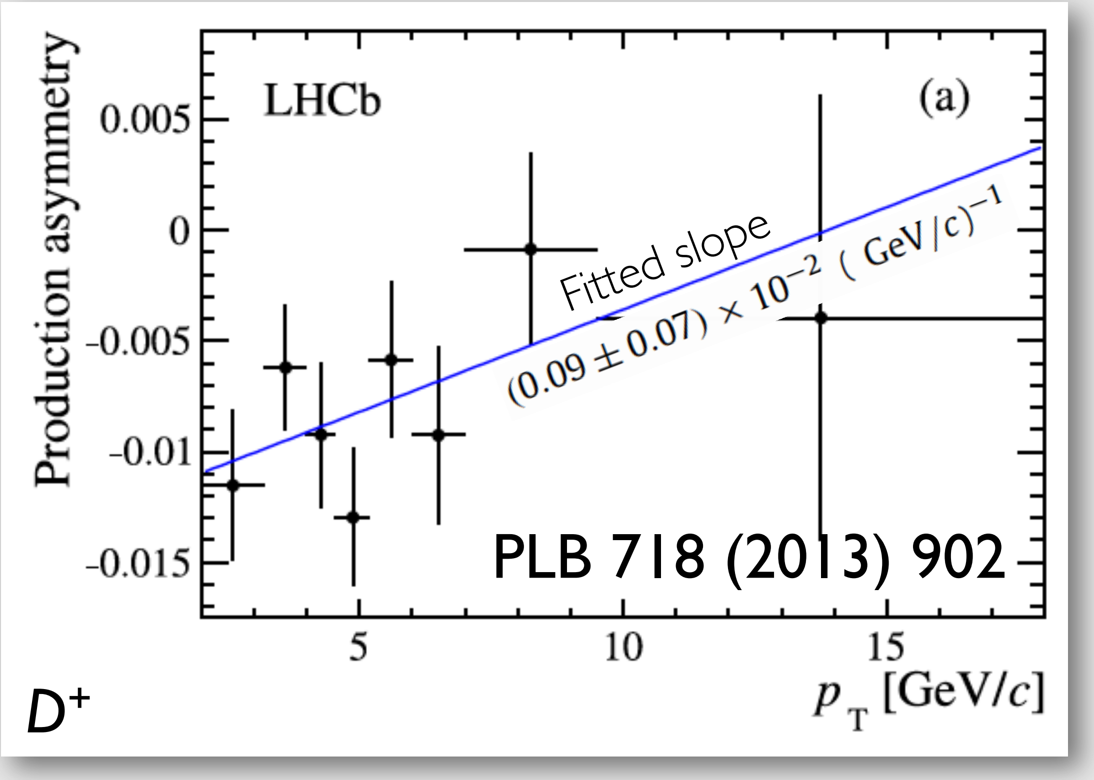
$$A_{raw}(D\to f) = A_{CP}(D\to f) + A_{prod}(D) + A_{det}(f) + A_{det}(tag)$$

particle tagging D and $\bar{D}$

- Need to constrain
  - ➡ Production asymmetry
  - ➡ Detection asymmetry (final state and flavour tag)
- General idea
  - ➡ Use similar Cabibbo-allowed processes and assume $A_{CP}(D\to f) = 0$ or use external input where available
- Nuisance asymmetries can generate local asymmetries e.g. if dependent on kinematics

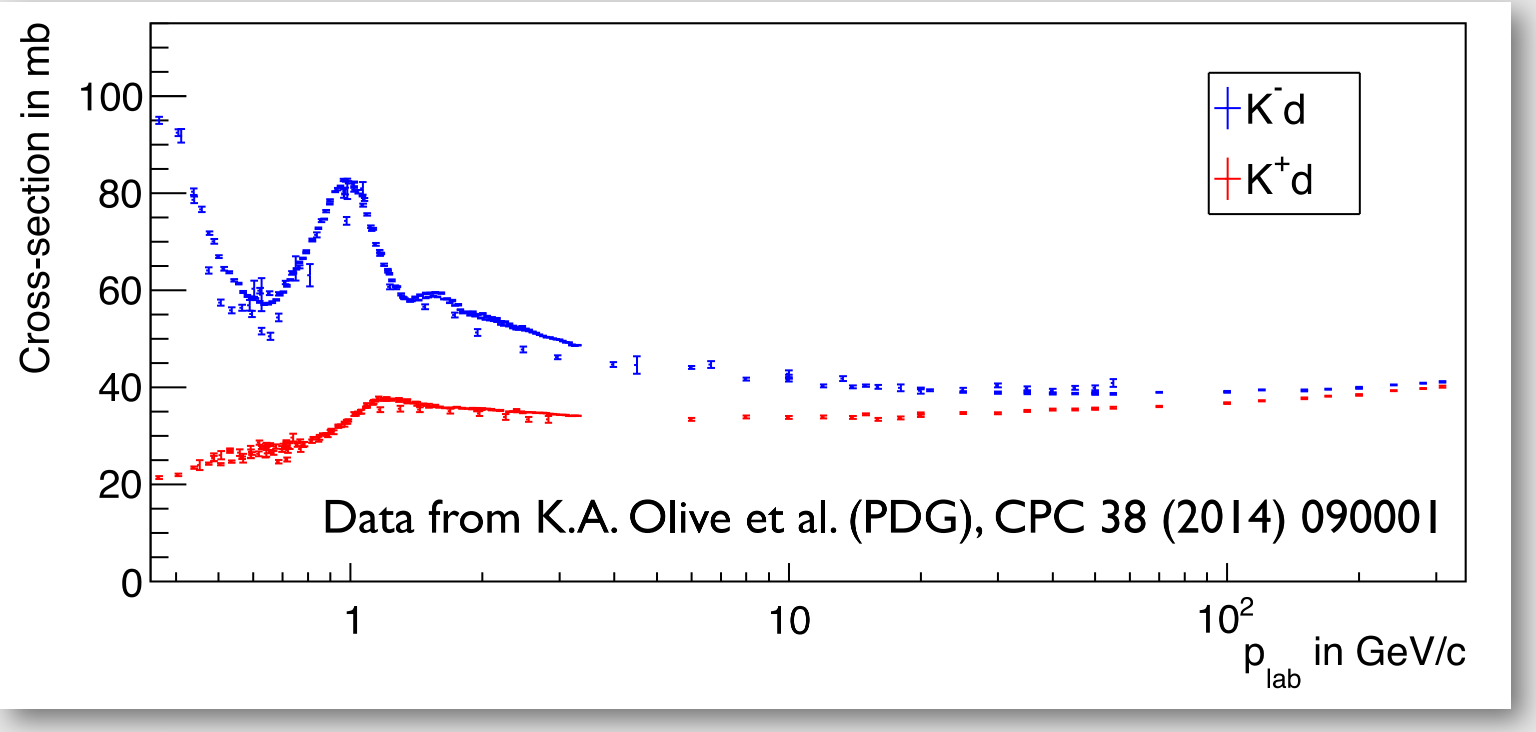
Production asymmetries

- Particular to pp collider
  - ➡ "Replaces" forward-backward asymmetry at e^+e^- and $p\bar{p}$
- Valence quarks favour the production of matter baryons
  - ➡ Favours antimatter mesons
- Production asymmetry can depend on kinematics
  - ➡ Accounted through binning / re-weighting

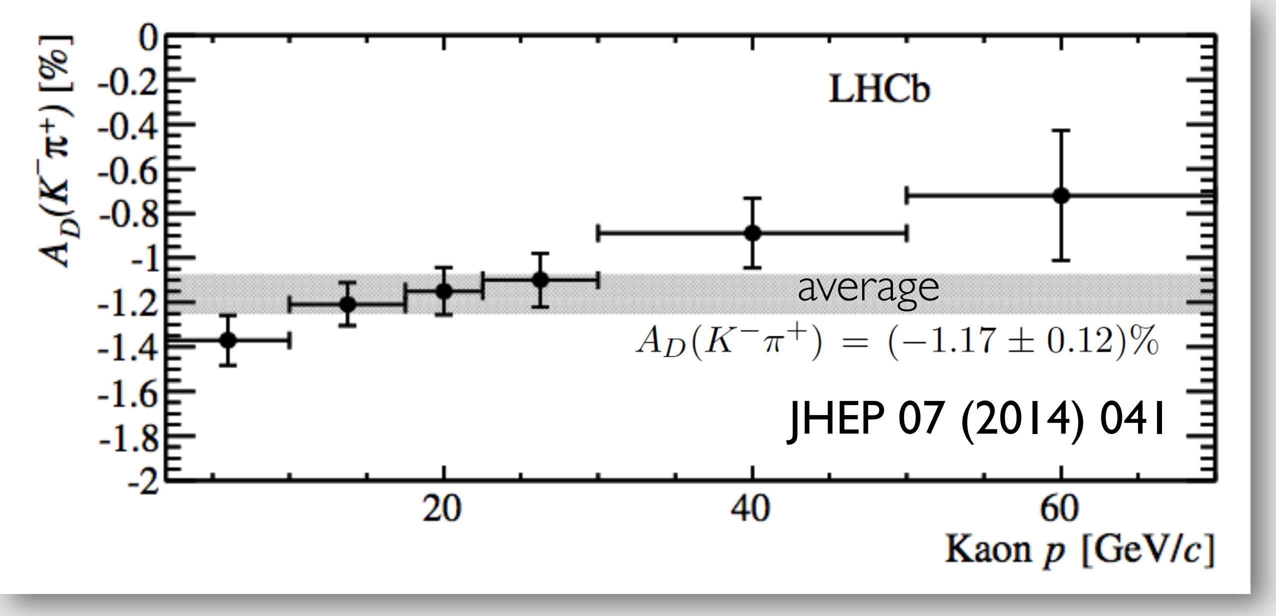


Detection asymmetries

- Material interaction can be asymmetric
  - ➡ Strange quark can produce hyperons



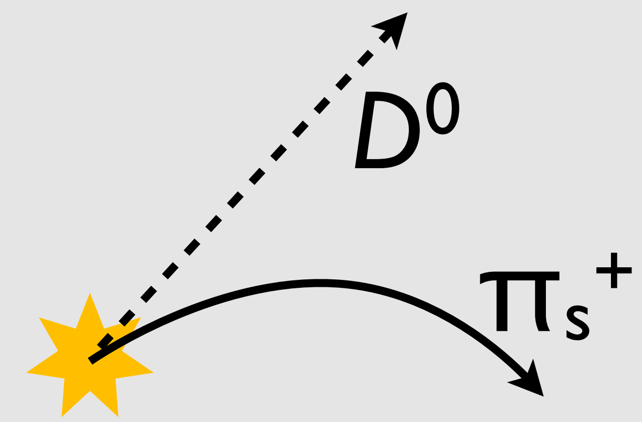
- Detector can be asymmetric
  - ➡ Causes asymmetry through different bending of positive and negative tracks

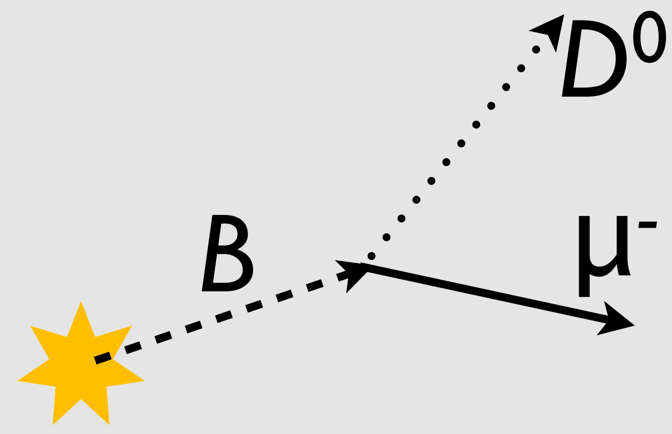


➡ Regularly revert dipole polarity

Flavour tagging

- Prompt D*-tagged
  - ➡ Larger yields
  - ➡ Background from D-from-B
- Muon-tagged
  - ➡ Smaller yields (somewhat)
  - ➡ Larger level of combinatorial background
  - ➡ Independent systematic uncertainties
- Doubly-tagged
  - ➡ The best of both worlds
  - ➡ Smallest samples





Results

In selected regions of phase-space

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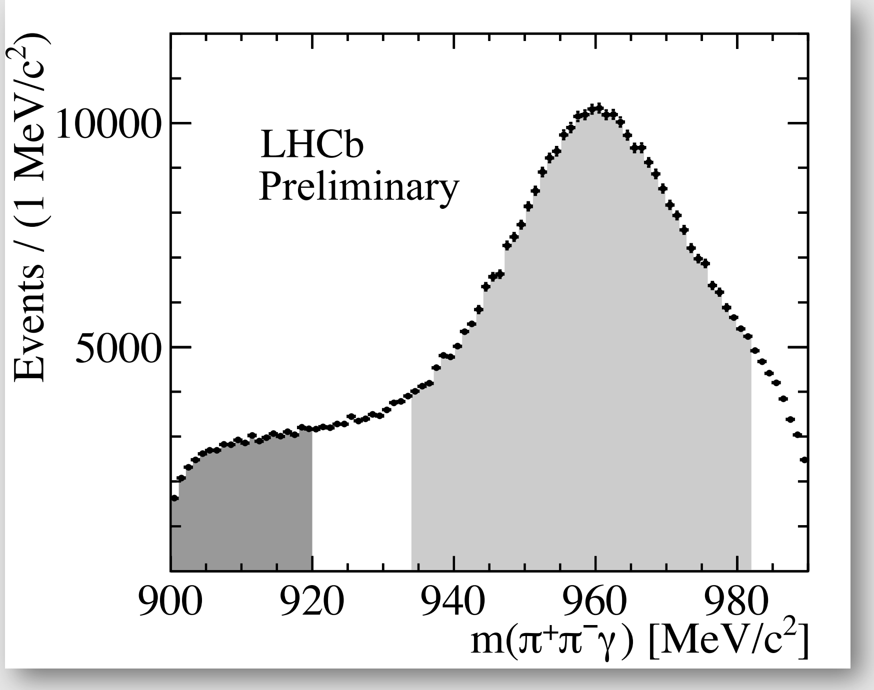
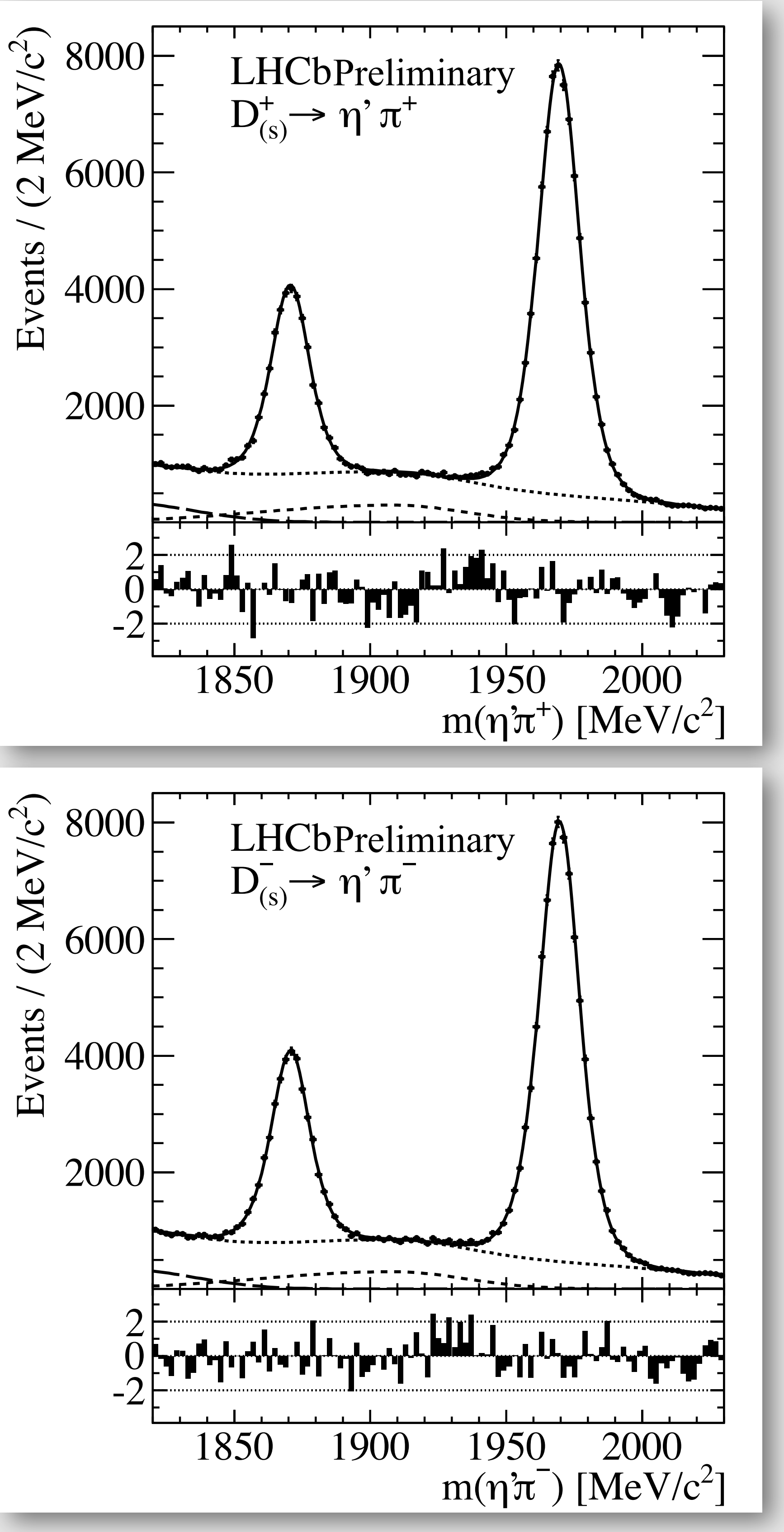
$D_{(s)}^{\pm} \rightarrow \eta' \pi^{\pm}$

- From $\pi^{\pm}\pi^{+}\pi^{-}\gamma$ candidates select those with $m(\pi^{+}\pi^{-}\gamma)$ near the η' mass and with $m(\pi^{\pm}\eta')$ near the $D_{(s)}$ mass





- Remove production/detection asymmetries through differences to

➡ $D^{\pm} \rightarrow K_S \pi^{\pm}$ and $D_s^{\pm} \rightarrow \phi \pi^{\pm}$

- Splitting in different trigger samples to check for trigger-induced asymmetries

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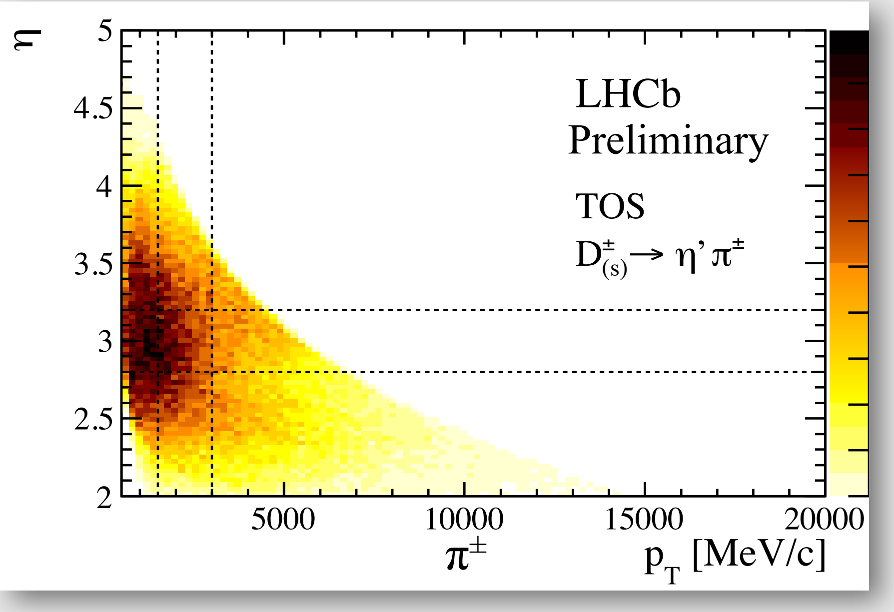
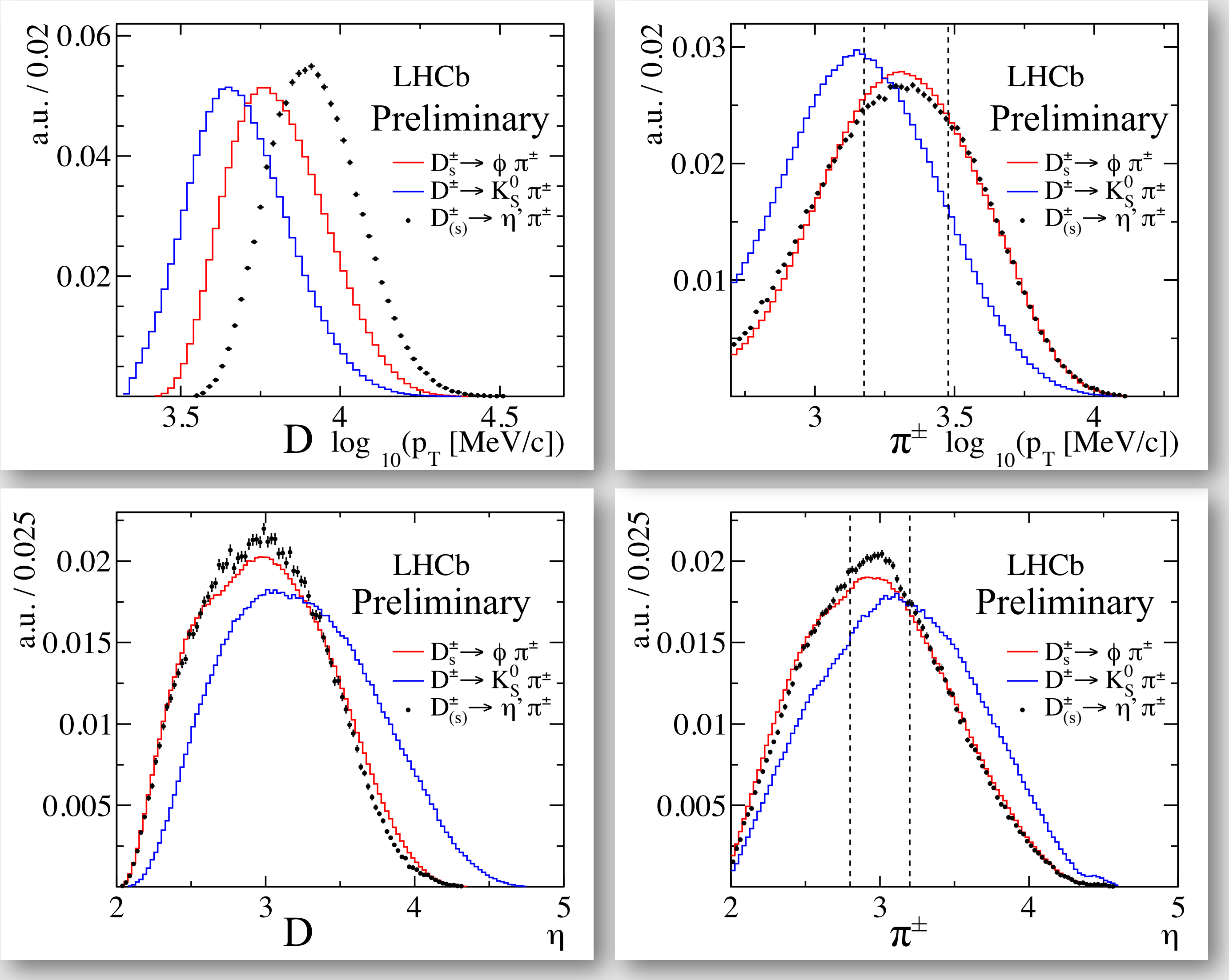
$D_{(s)}^{\pm} \to \eta' \pi^{\pm}$

- Split in 3×3 bins of D and bachelor pion kinematics
  - ➡ Ensure better cancellation of nuisance asymmetries





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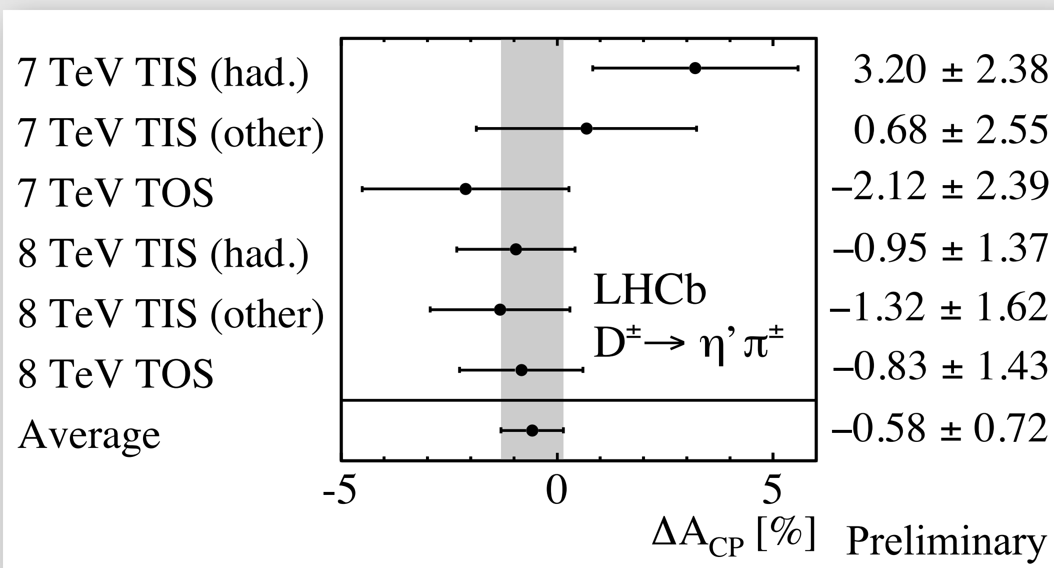
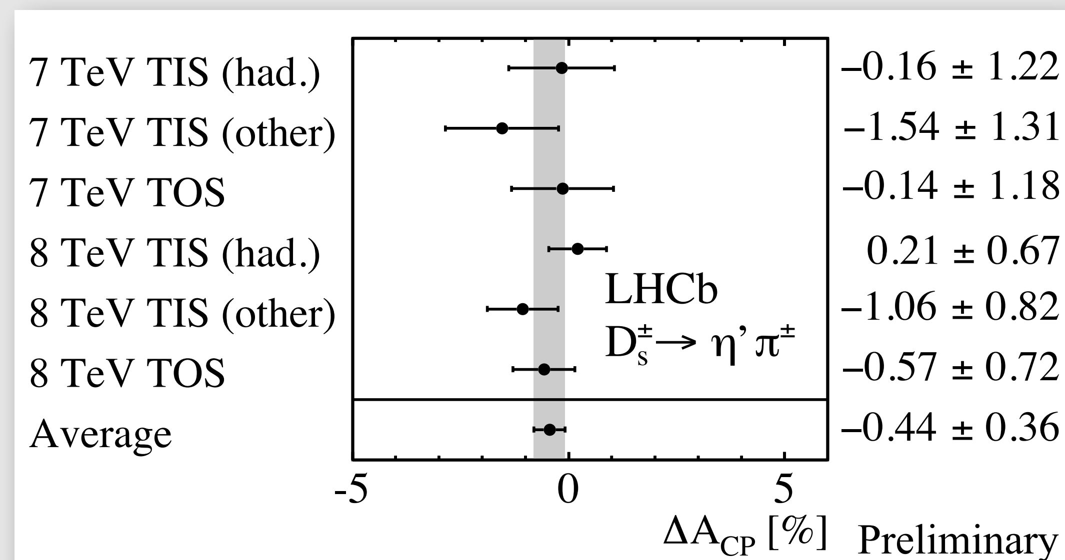
$D_{(s)}^{\pm} \rightarrow \eta' \pi^{\pm}$

Source	$\delta[\Delta \mathcal{A}_{CP}(D^{\pm})]$	$\delta[\Delta \mathcal{A}_{CP}(D_s^{\pm})]$
Non-prompt charm	0.03	0.03
Trigger	0.09	0.09
Background model	0.50	0.19
Fit procedure	0.16	0.09
Sideband subtraction	0.03	0.02
K^0 asymmetry	0.08	–
$D_{(s)}^{\pm}$ production asymmetry	0.07	0.02
Total	0.55	0.24





- Final result subtracting CF asymmetries from existing (Belle and D0) measurements

Belle, PRL 109 (2012) 021601
D0, PRL 112 (2014) 111804

$$\mathcal{A}_{CP}(D^{\pm} \rightarrow \eta' \pi^{\pm}) = (-0.52 \pm 0.72 \pm 0.55 \pm 0.12)\%$$
$$\mathcal{A}_{CP}(D_s^{\pm} \rightarrow \eta' \pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%$$

Preliminary

Results

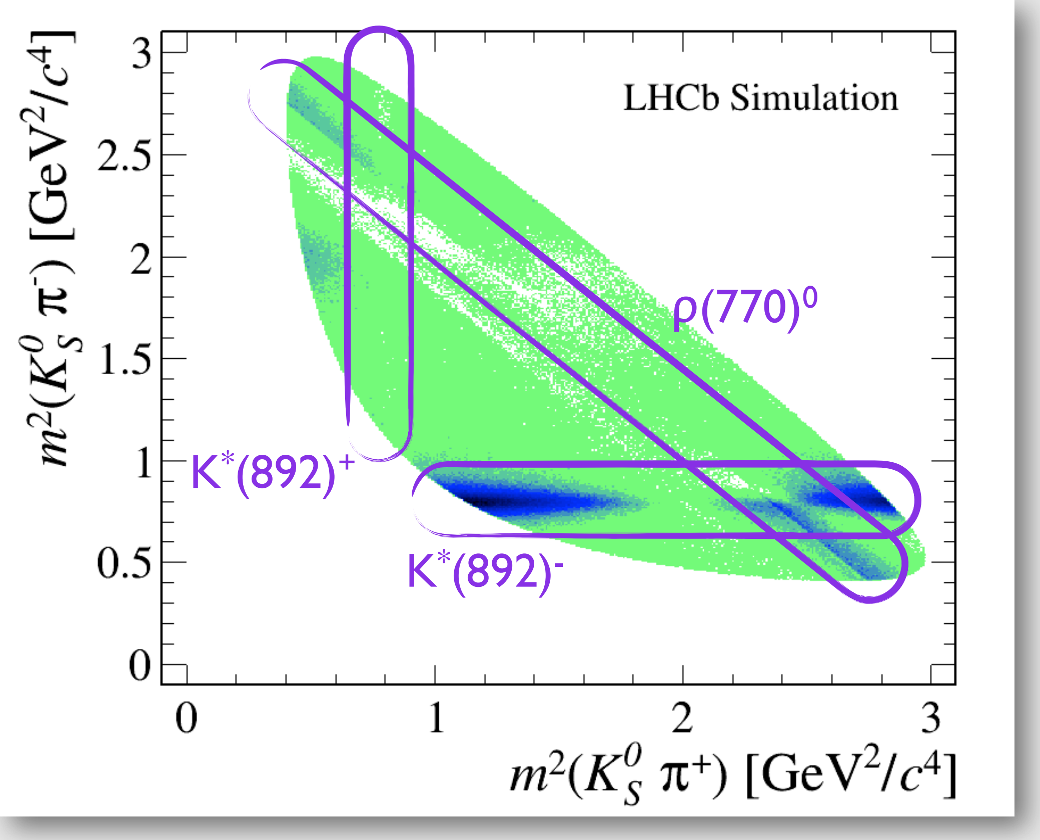
Local asymmetries

On Dalitz plots

- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases
  - ➡ Superb playground for CP violation
- Look for local asymmetries
  - ➡ Model-independent: Look for asymmetries in regions of phase space by "counting"
  - ➡ Model-dependent: Fit all contributions to phase-space and look for differences in fit parameters

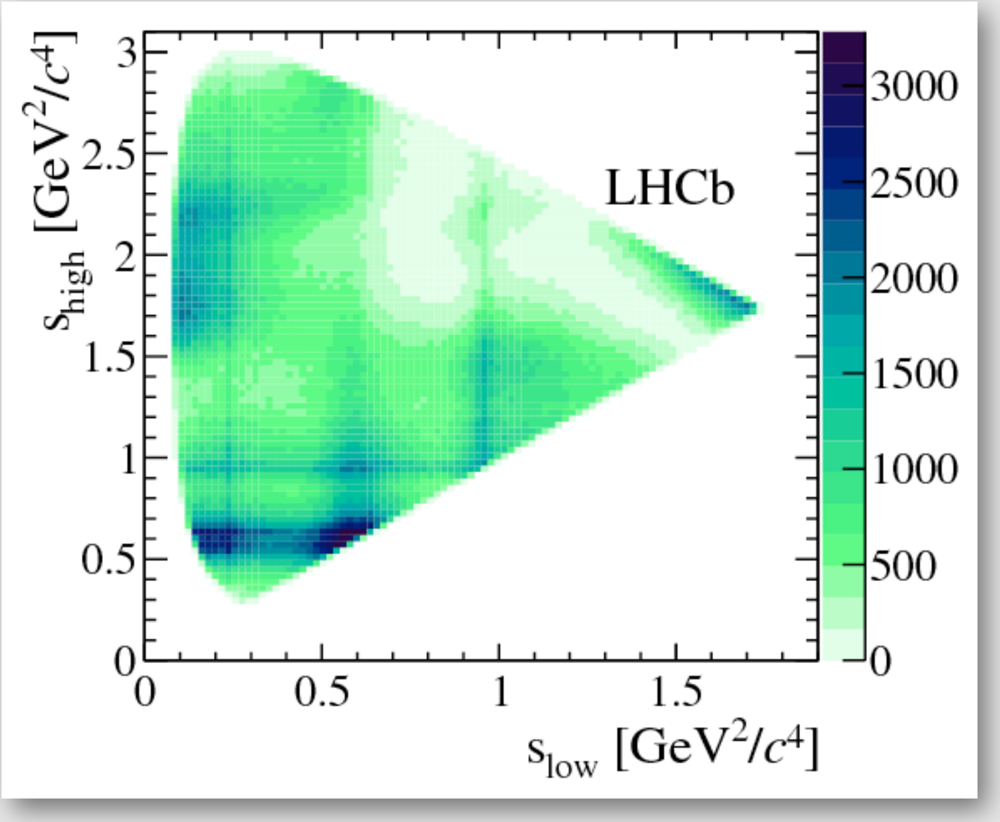
Discovery tools

Detailed understanding



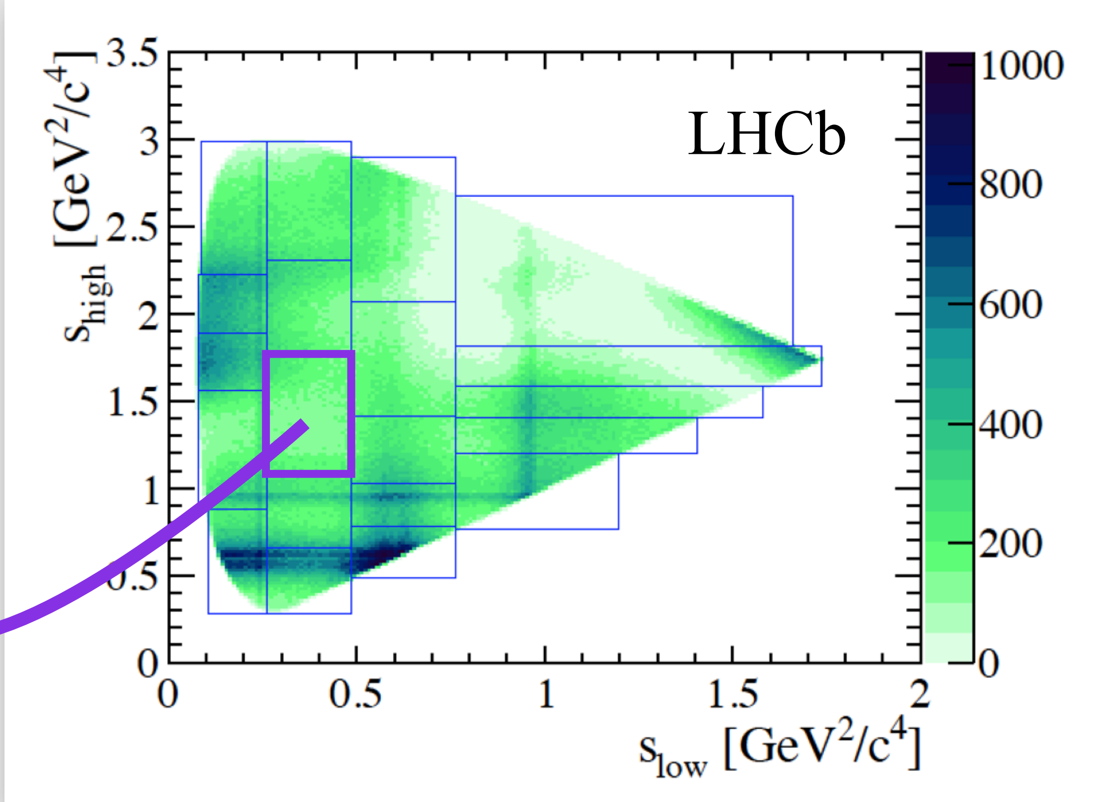
Courtesy of S. Reichert

$D^+ \rightarrow 3\pi$



- Model-independent searches for CP violation
  - ➡ Over 3M D^+ & D^- decays in 1 fb^{-1}
  - ➡ Search for asymmetry significances in bins of phase space
  - ➡ Search for local asymmetries through un-binned comparison with nearest neighbours

Binned method



$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

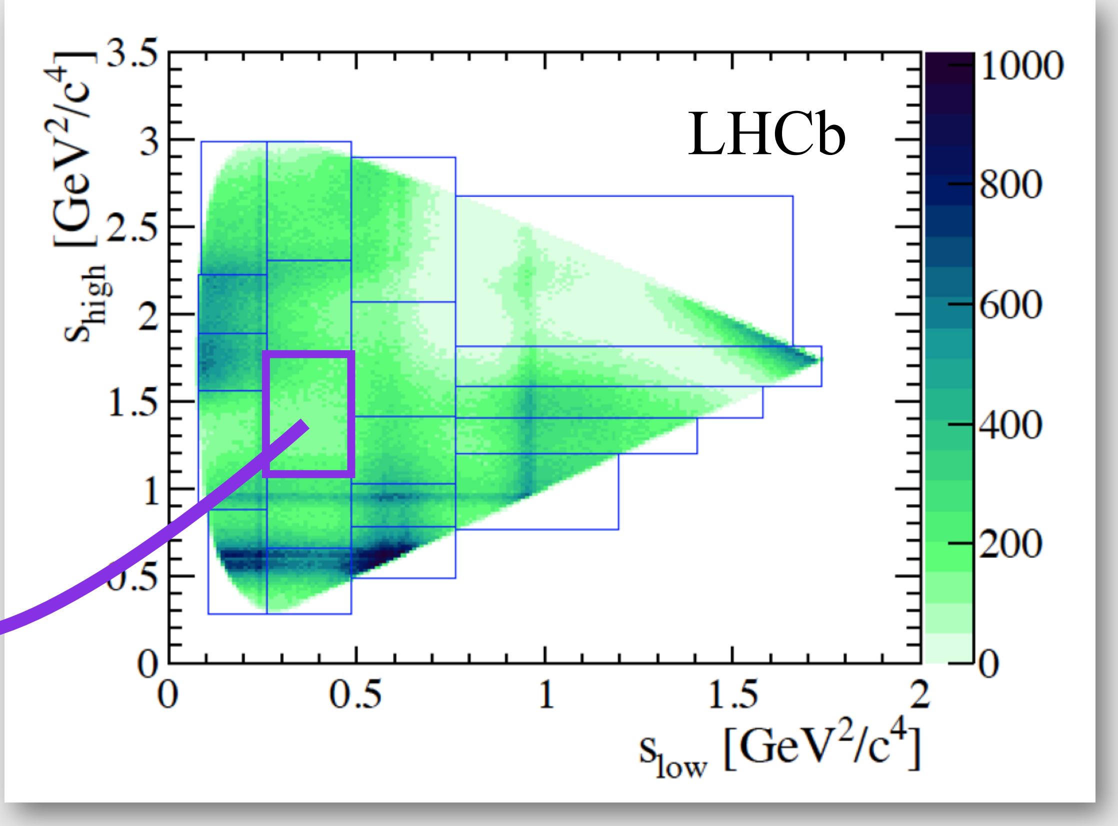
$$\alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}$$

removes sensitivity to global asymmetries

$$\chi^2 = \sum (\mathcal{S}^i_{CP})^2$$

p-values for no-CPV hypothesis > 50% for different binnings

Binned method



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removes sensitivity to global asymmetries

$$\chi^2 = \sum (\mathcal{S}_{CP}^{i})^2$$

Similar results also obtained with un-binned kNN method*

p-values for no-CPV hypothesis > 50% for different binnings

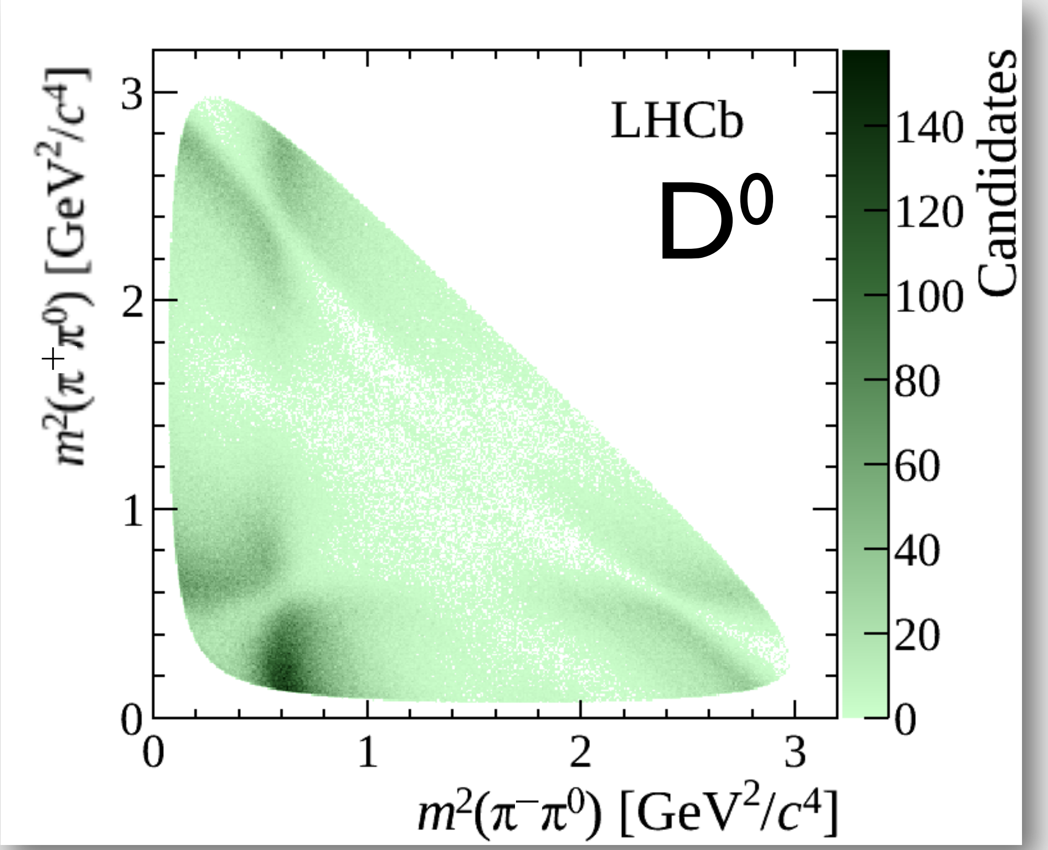
*reduced sensitivity due to inclusion of few neighbours

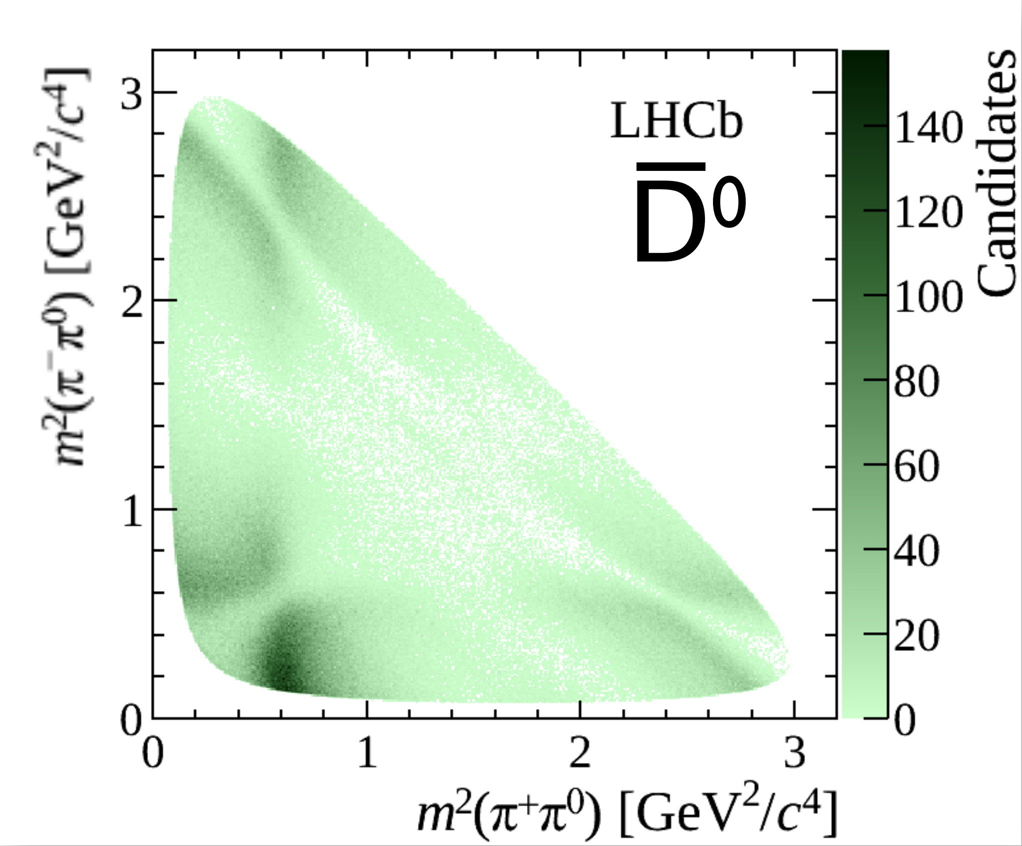
PLB 740 (2015) 158

Why not unbinned?

- Need to compare each event with every other
  - ➡ Computationally challenging for O(1M) events
  - ➡ Use GPUs to exploit massive parallelisation
  - ➡ Applied to $D^0 \to \pi^+\pi^-\pi^0$ decays
- Energy test (M. Williams, PRD 84 (2011) 054015)
  - ➡ Test statistic (T) comparing pairwise weighted distances (ψ_{ij}) in phase space
  - ➡ Compare
    $D^0 \leftrightarrow D^0$
    $\bar{D}^0 \leftrightarrow \bar{D}^0$
    $D^0 \leftrightarrow \bar{D}^0$
  - ➡ Expect T~0 (no CPV) or T>0 (CPV)

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





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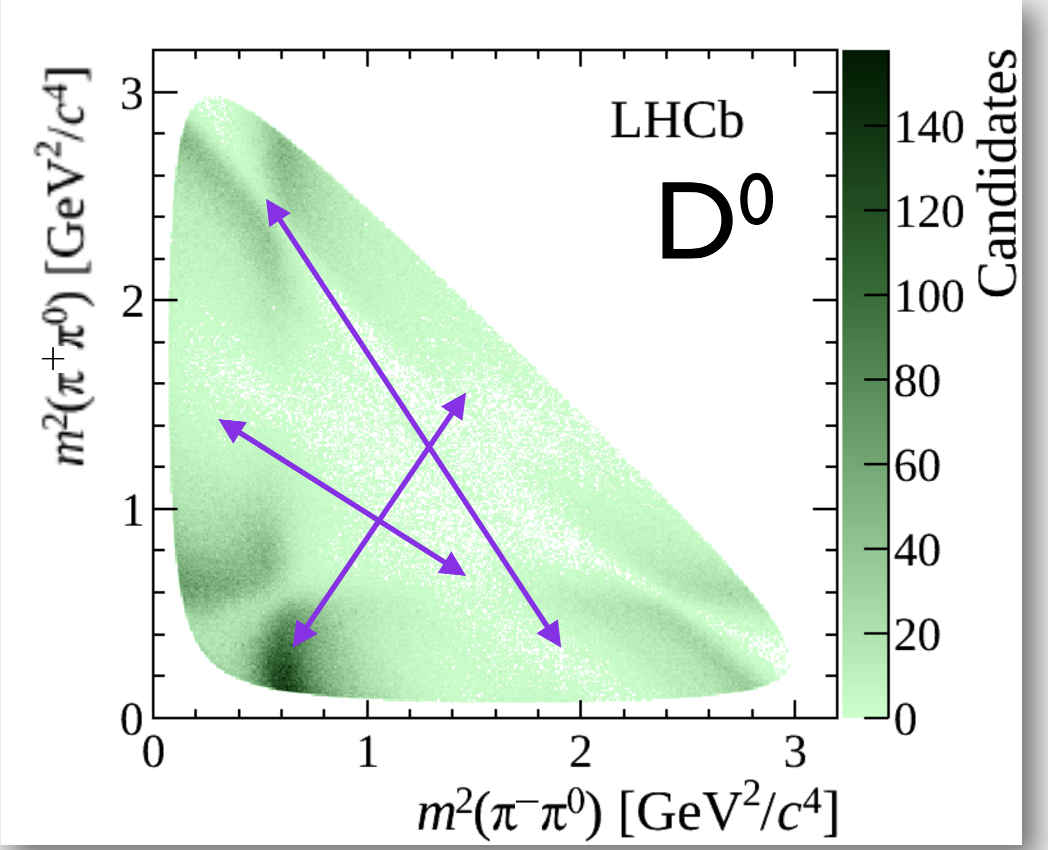

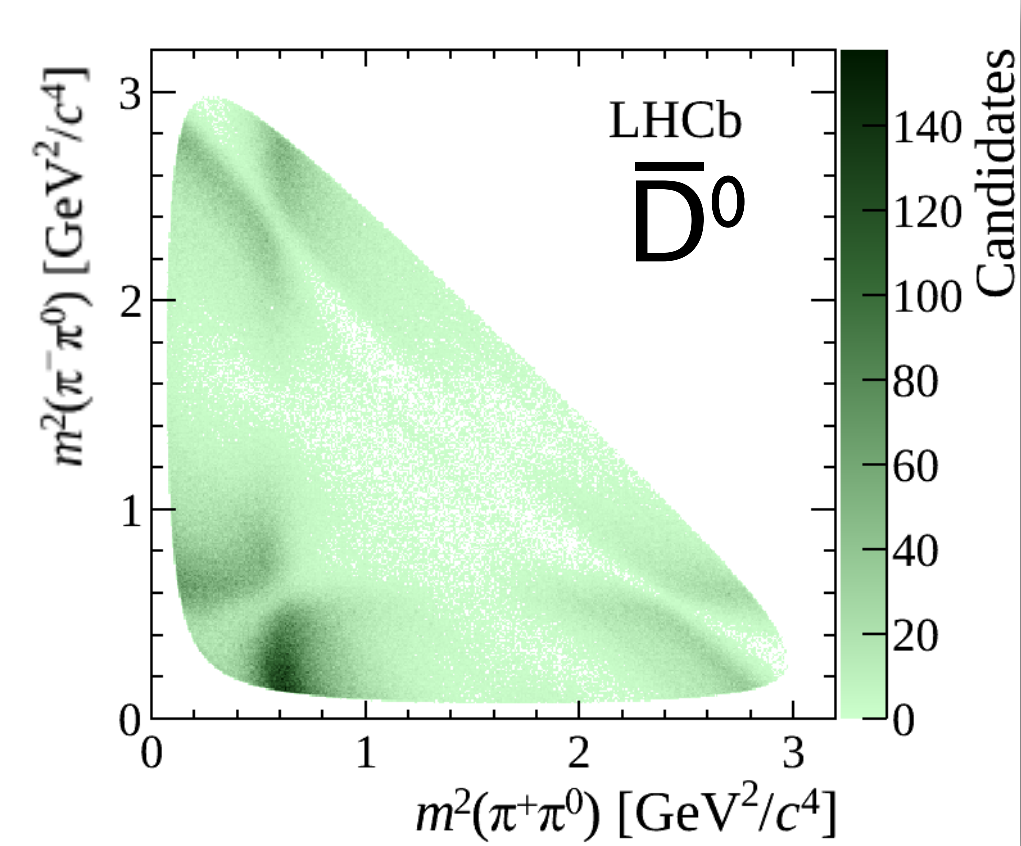

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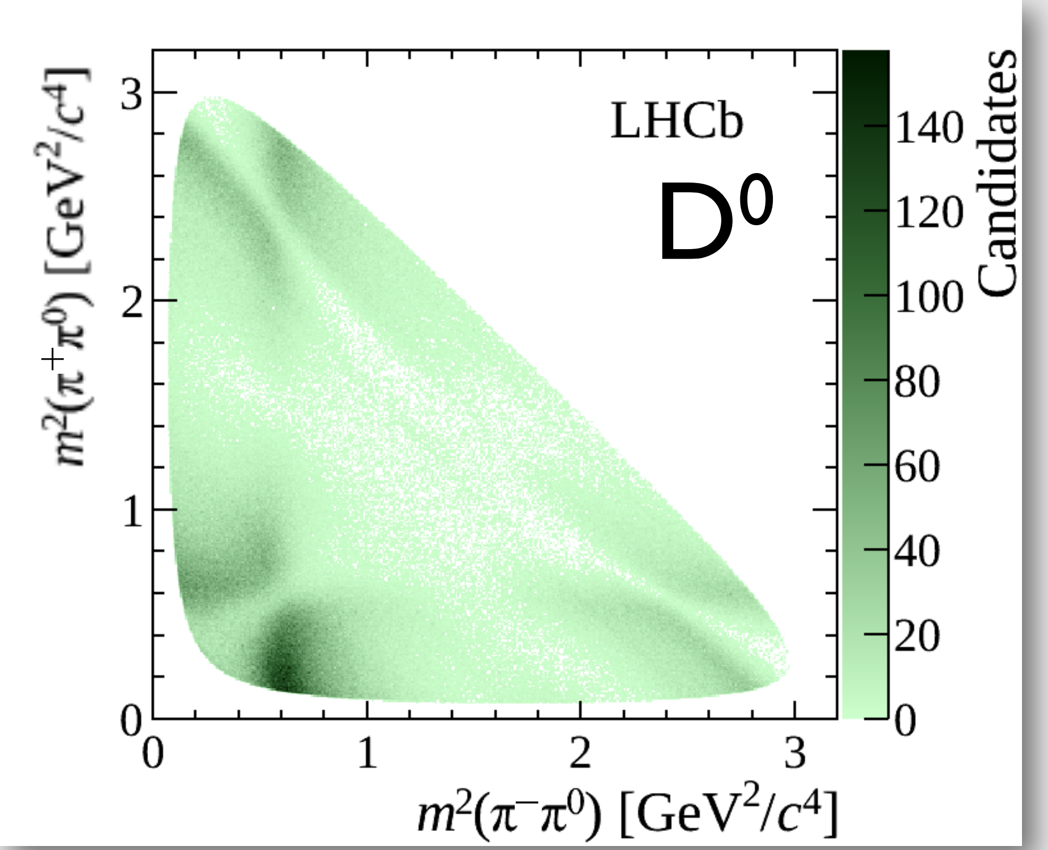

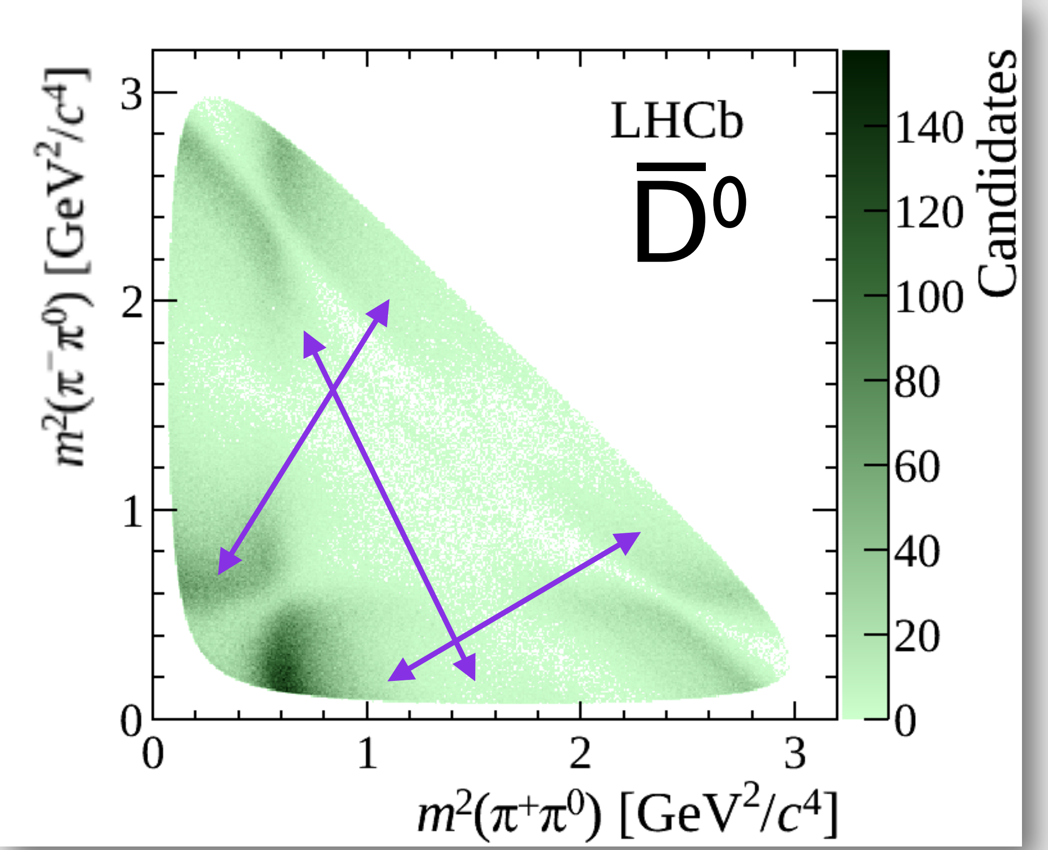

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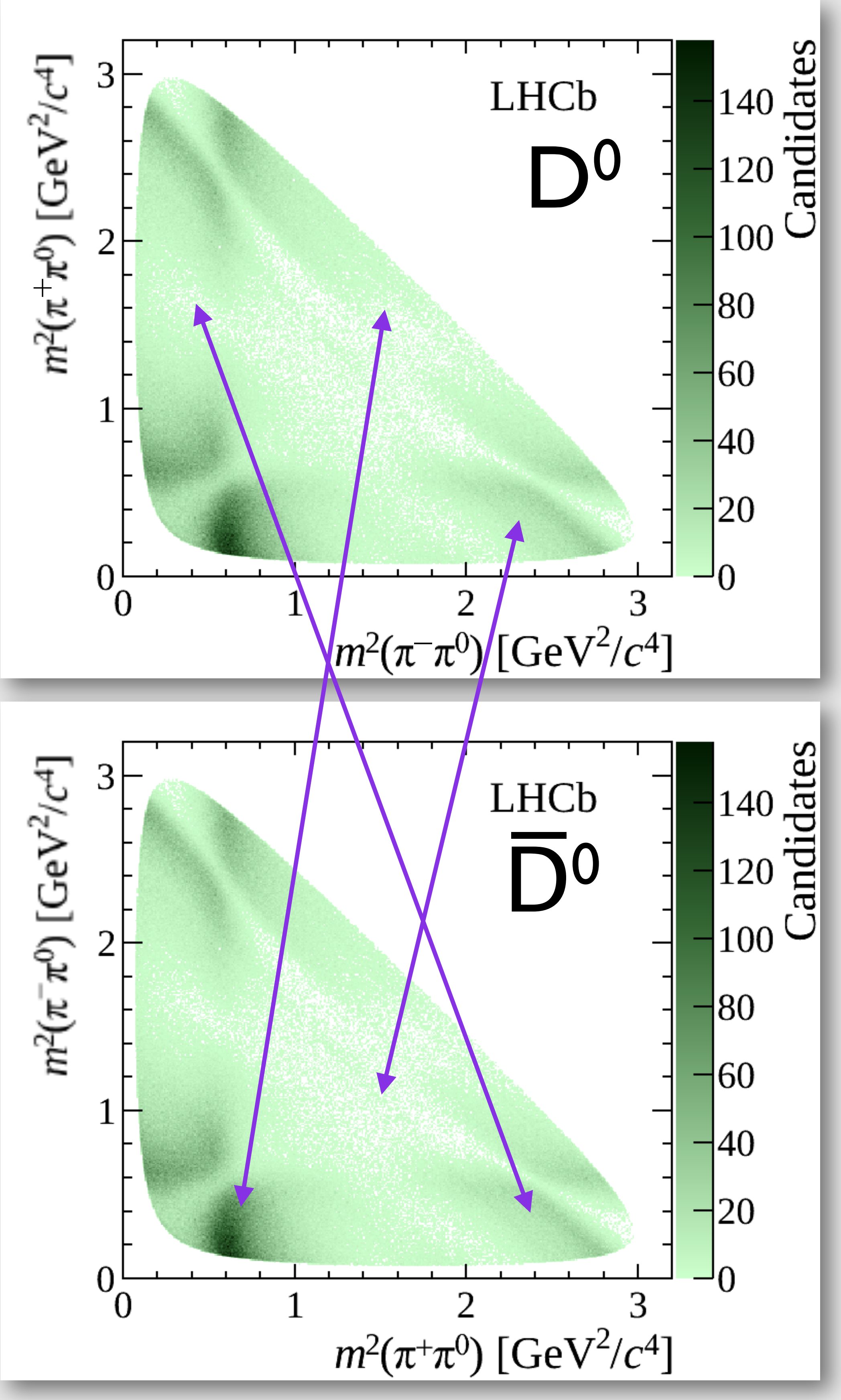
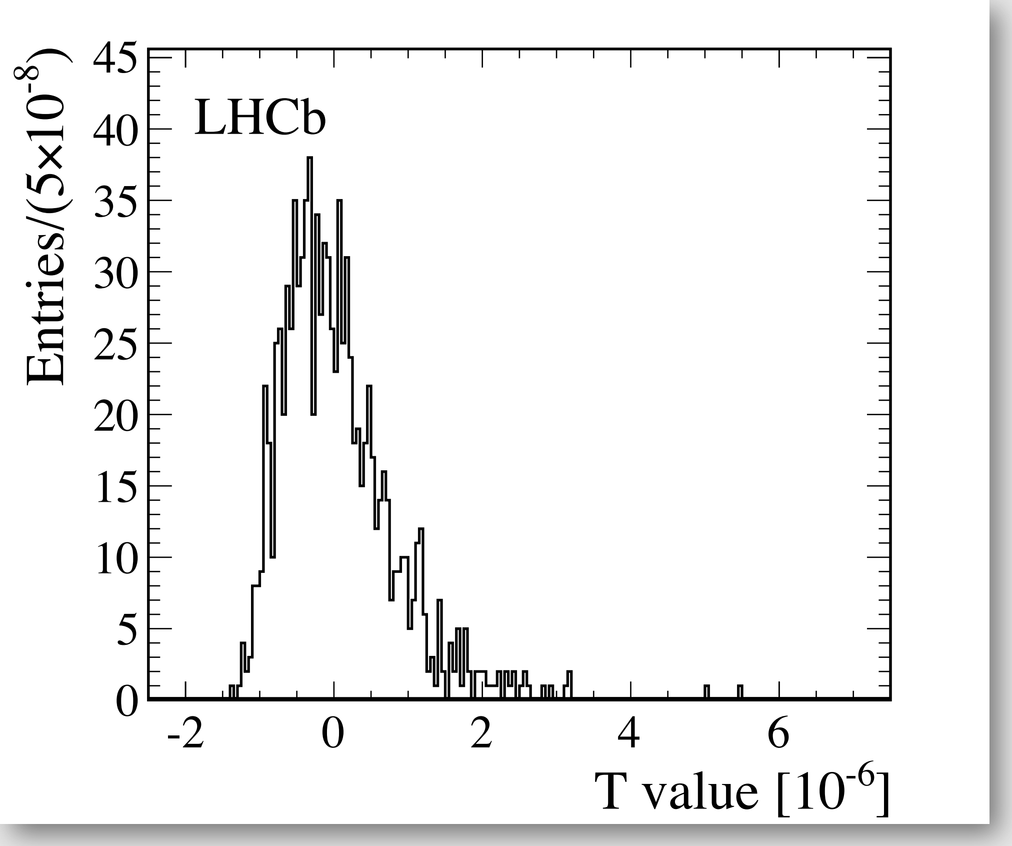


CP symmetry hypothesis

- Need to know T-value distribution for CP-symmetric case
  - ➡ Randomly assign flavour tag to each event
  - ➡ Calculate T value
  - ➡ Repeat many times
- Assign p-value as fraction of permutation T values greater than T value measured on normally tagged sample
  - ➡ Use Generalised Extreme Value function to extrapolate for T values exceeding distribution



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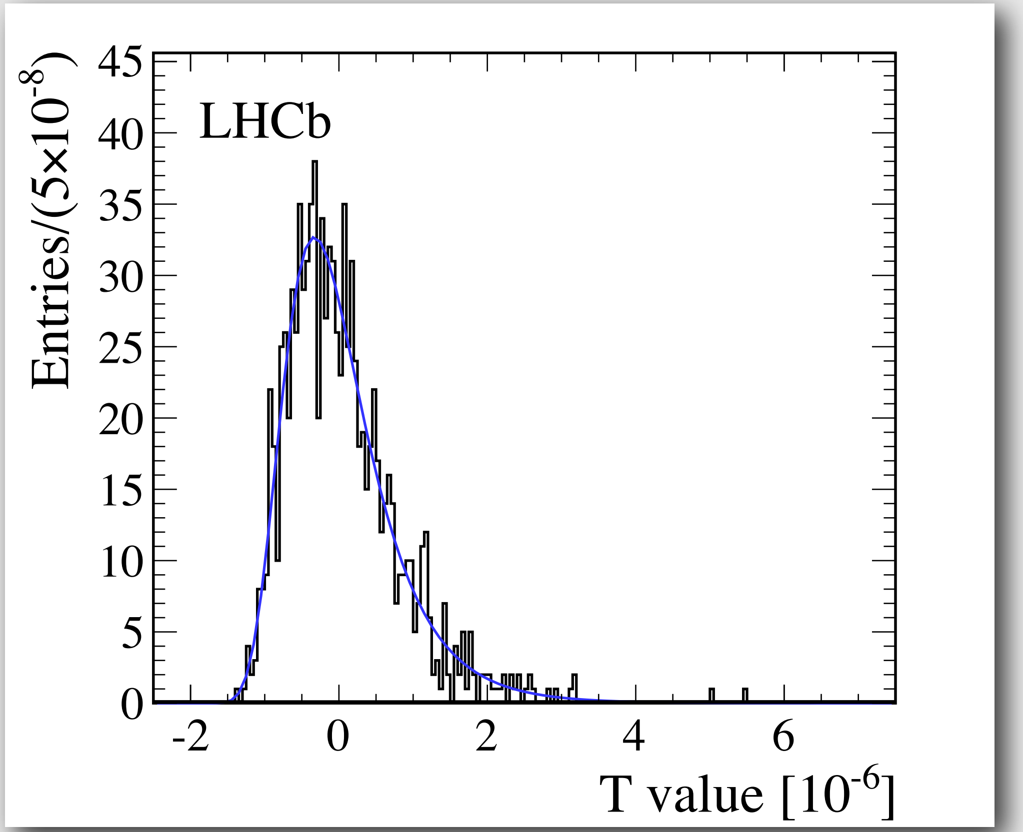


Visualising asymmetries

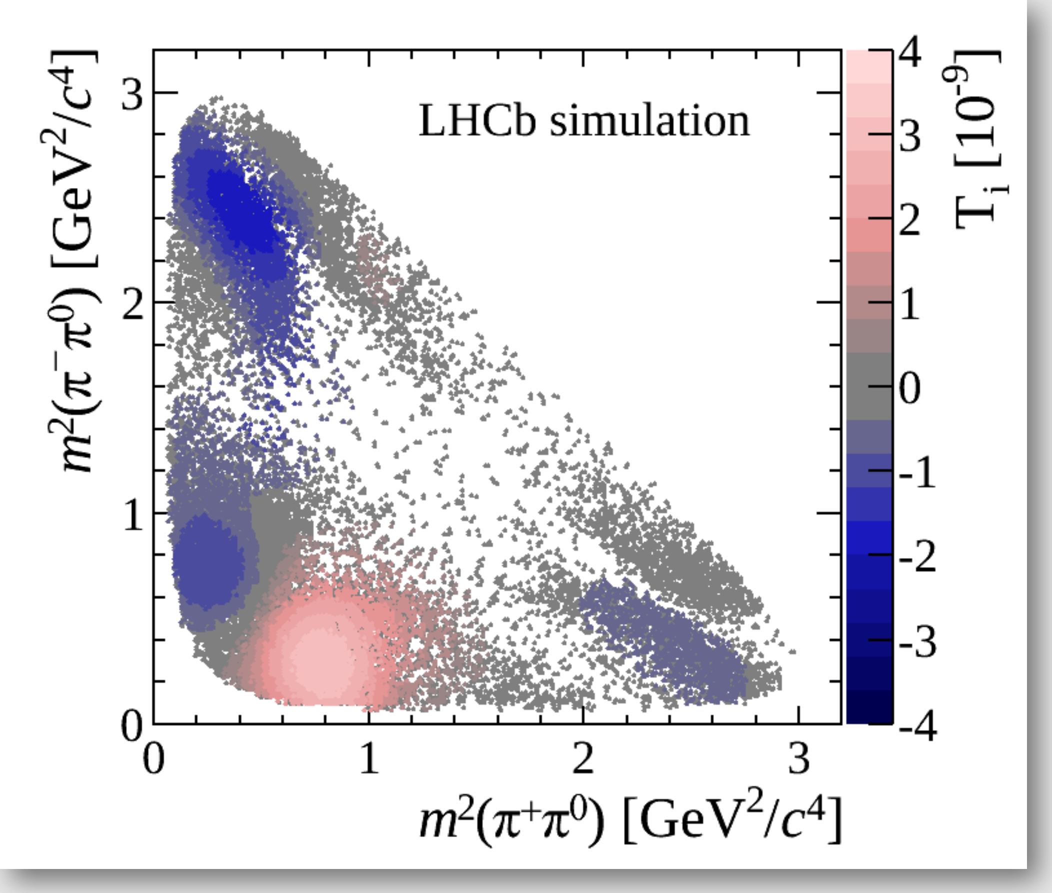
$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}},$$

- Split T value calculation into contributions from each event

➡ $T=\sum_i T_i + \sum_i \overline{T}_i$

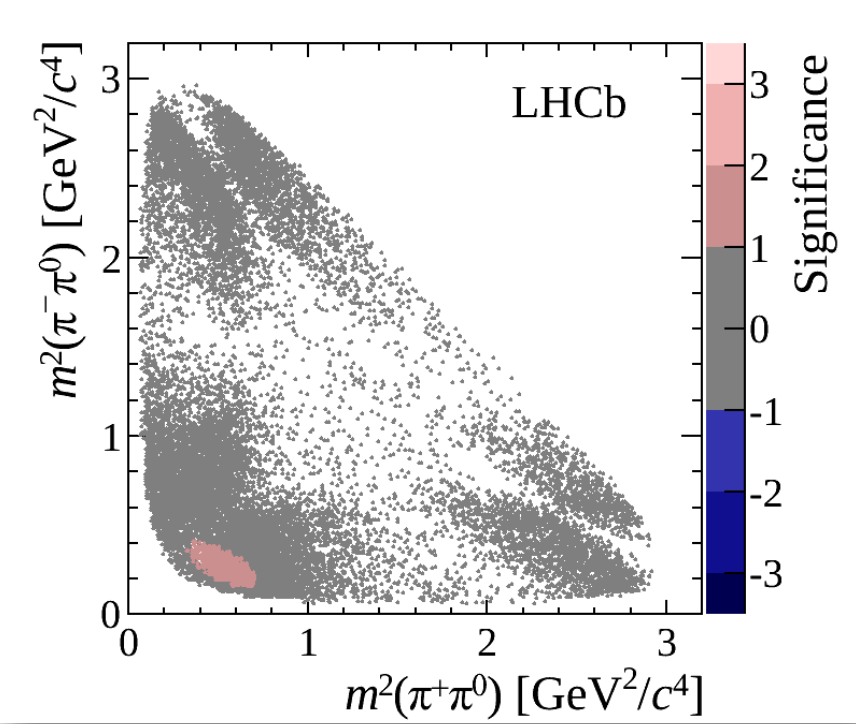
- Compare each T_i ($\overline{T}_i$) to the permutation T_i ($\overline{T}_i$) values

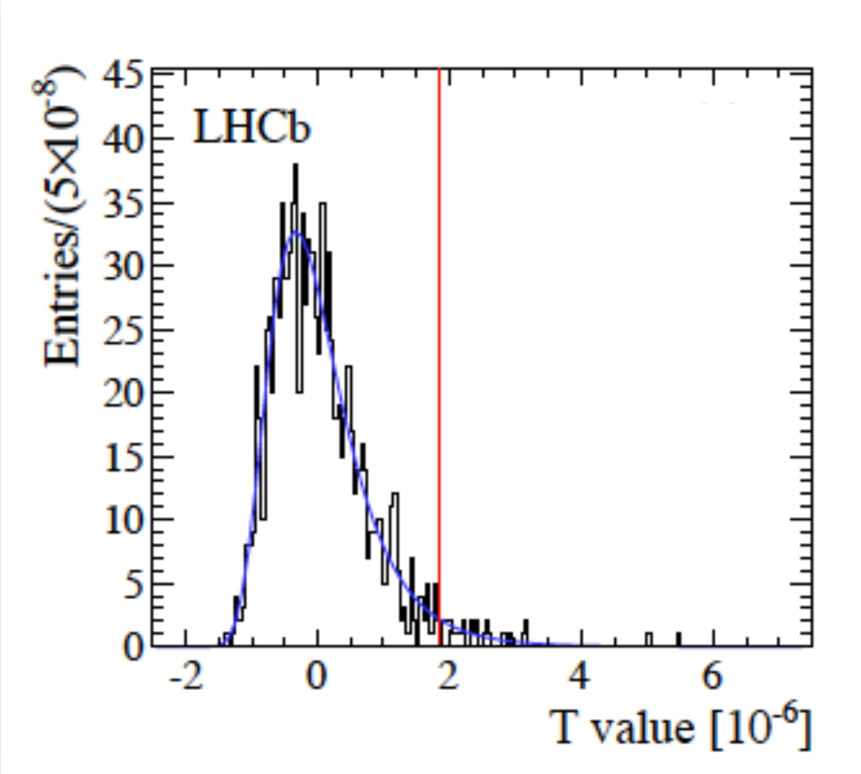
➡ Can assign local asymmetry significances



Results

- 8×larger sample than BaBar PRD 78 (2008) 051102
  - ➡ 420k resolved π^0, 250k merged π^0
  - ➡ Similar or better sensitivity
- Result based on 1000 permutations
  - ➡ P-value as fraction above nominal T value
  - ➡ (2.6±0.5)%





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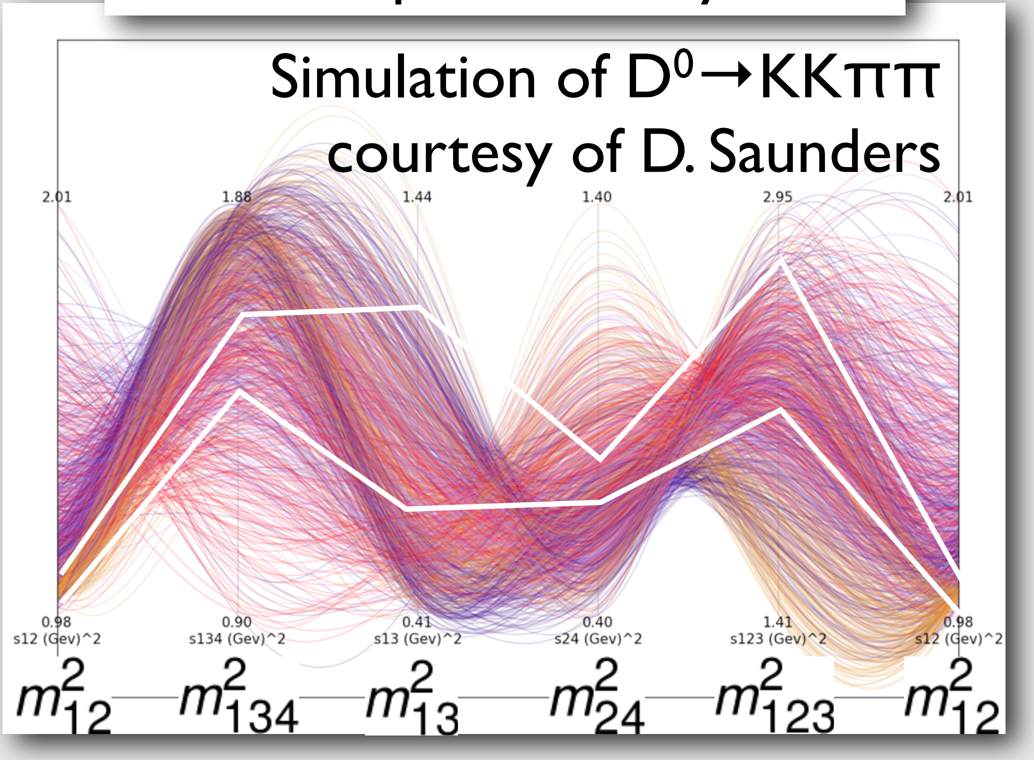
3→4 body

- Phase space is 5-dimensional
- Have to choose among six 2-body and four 3-body invariant masses
  - ➡ Additional degree of freedom
    - Sign of triple product distinguishing P-even and P-odd contributions
- Visualisation is slightly more challenging
  - ➡ Bins are 5D hypercubes

Parallel axes: 5D "Dalitz" plot
Events represented by lines



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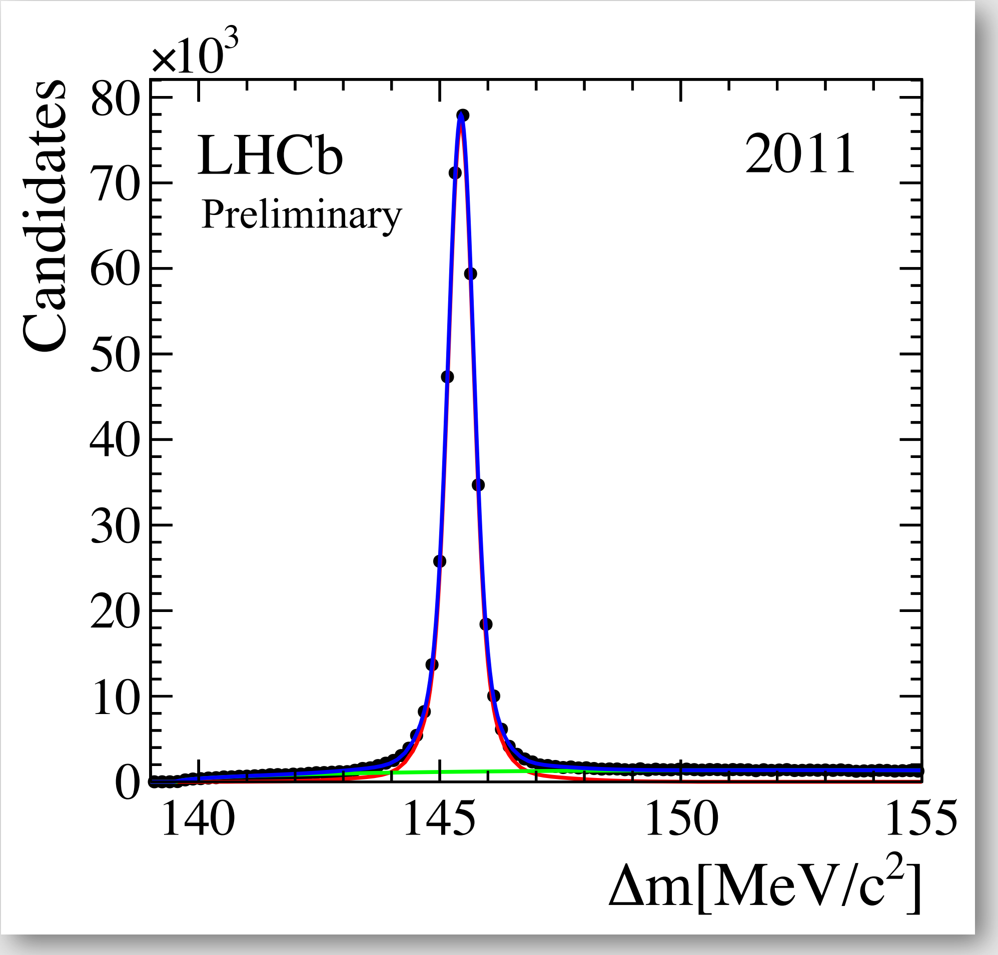
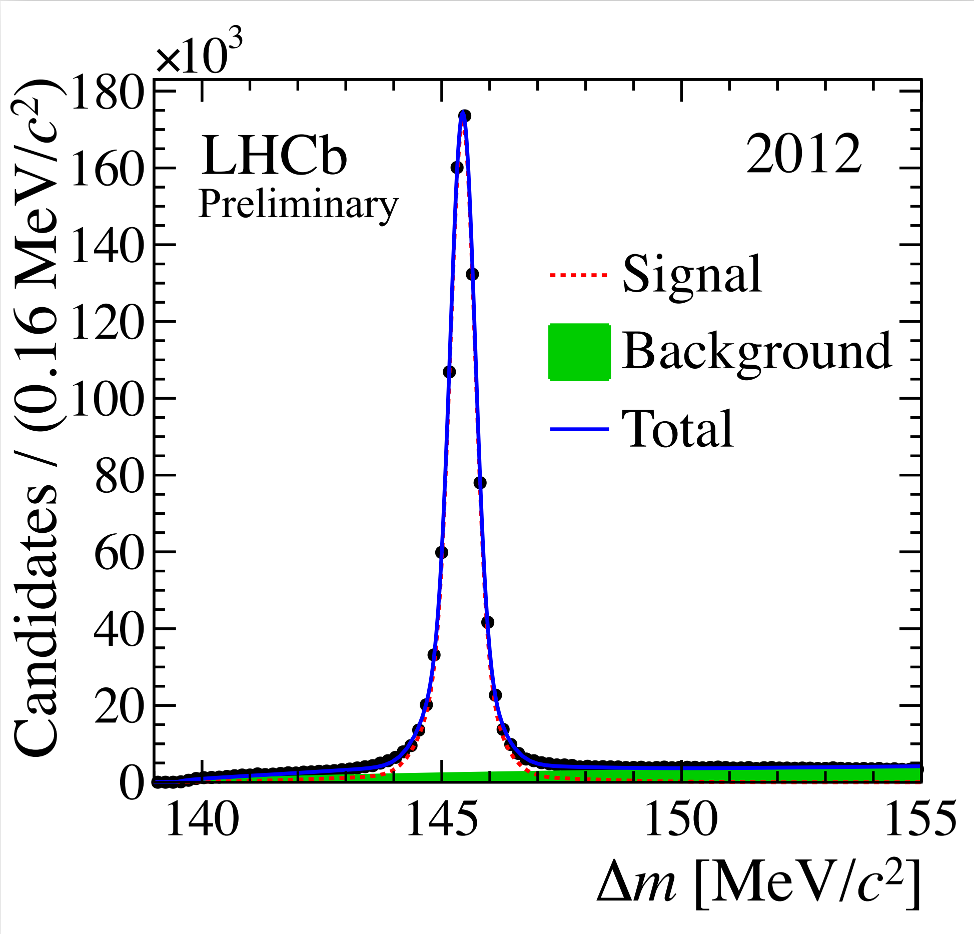
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

- D^*-tagged, 3 fb^{-1}
- 940,000 signal candidates with ~96% purity
- D-from-B background suppressed





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Spanning 5 dimensions

- Choice of co-ordinates
  - ➡ Positive particles have even numbers
  - ➡ Ignore two same-sign pion pairs
  - ➡ Identify the highest two-body invariant mass as m_{34}
    - Most activity is in lower invariant mass regions
  - ➡ Remove m_{34}, m_{134}, m_{234}
  - ➡ Retain m_{12}, m_{14}, m_{23}, m_{123}, m_{124}
- Split by sign of triple product $C_T = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$

$$[\mathrm{I}]\ D^0(C_T > 0), \quad [\mathrm{II}]\ D^0(C_T < 0), \quad [\mathrm{III}]\ \overline{D}^0(-\overline{C}_T > 0), \quad [\mathrm{IV}]\ \overline{D}^0(-\overline{C}_T < 0).$$

- Test for asymmetries in
  - ➡ P-even CPV: I+II vs III+IV and P-odd CPV: I+IV vs II+III

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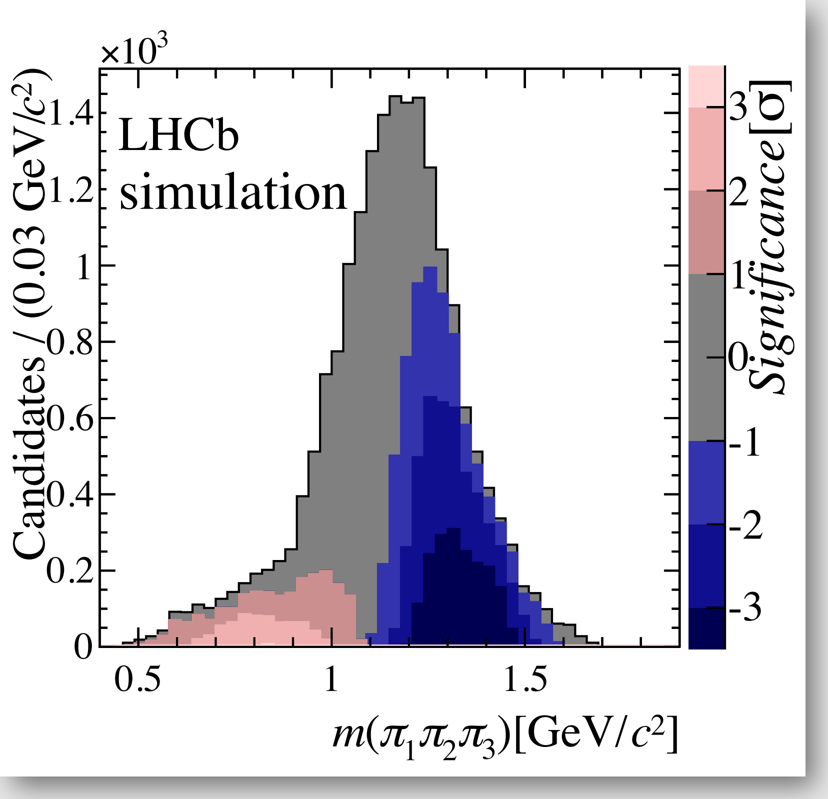
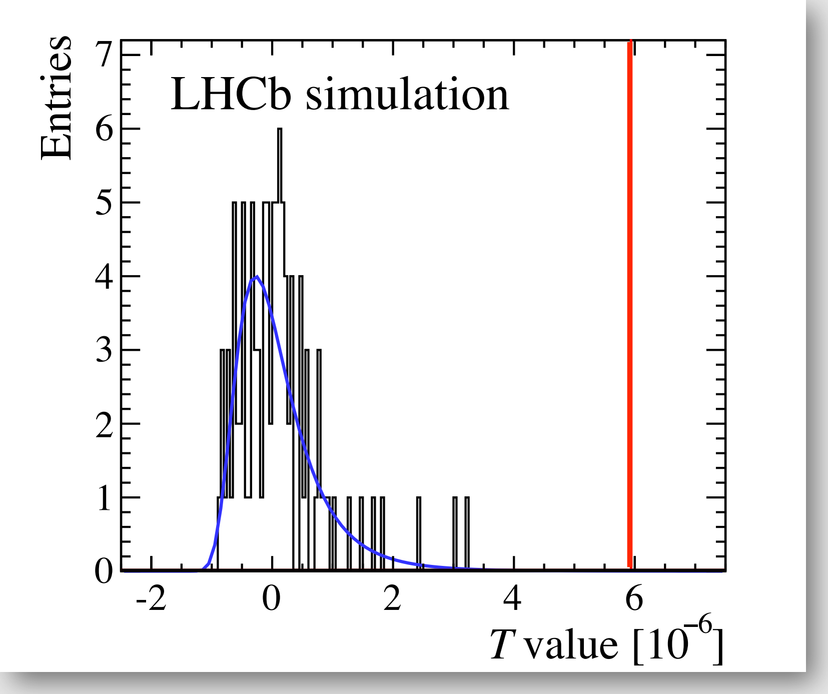
Sensitivity studies

- Simulating pseudo-experiments with a range of CP violation scenarios
  - ➡ Based on new model based on CLEO-c data P. d'Argent et al., 1611.09253
  - ➡ Amplitude and phase shifts in
    - ‣ $\rho\rho_{\text{P-wave}}$, $\rho\rho_{\text{D-wave}}$, $a_1\pi$



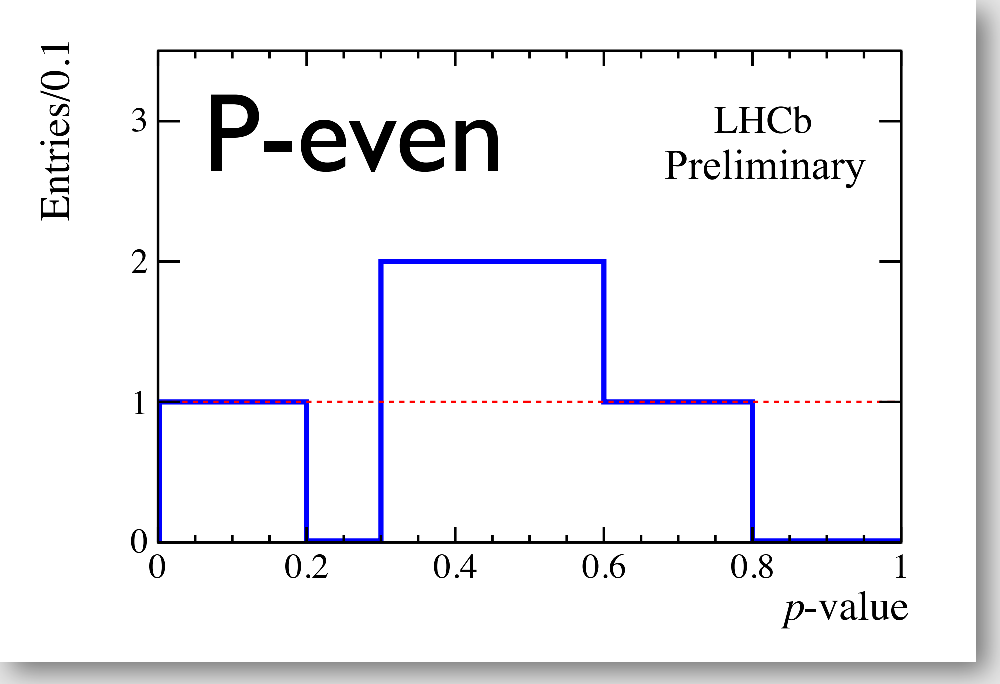
Example: a_1 phase shift

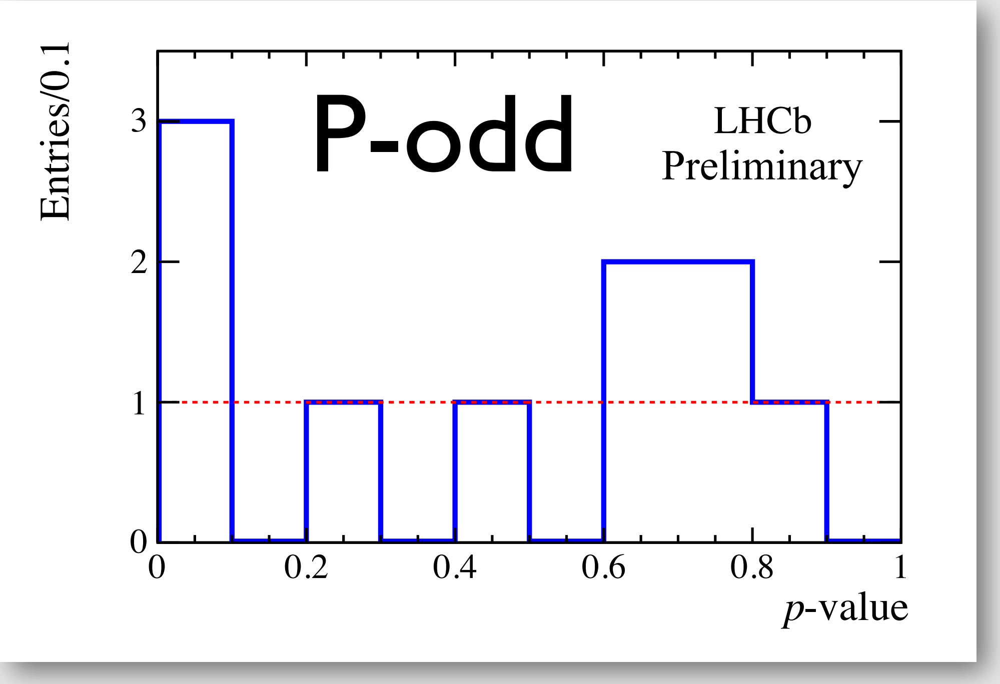
	R (partial wave) $(\Delta A, \Delta\phi)$	p-value (fit)
P-even	$a_1 \to \rho^0\pi$ (S) $(5\%, 0°)$	$2.6^{+3.4}_{-1.7} \times 10^{-4}$
	$a_1 \to \rho^0\pi$ (S) $(0\%, 3°)$	$1.2^{+3.6}_{-1.2} \times 10^{-6}$
	$\rho^0\rho^0$ (D) $(5\%, 0°)$	$3.8^{+2.9}_{-1.9} \times 10^{-3}$
	$\rho^0\rho^0$ (D) $(0\%, 4°)$	$9.6^{+24}_{-7.2} \times 10^{-6}$
	$\rho^0\rho^0$ (P) $(4\%, 0°)$	$3.0^{+1.2}_{-0.9} \times 10^{-3}$
P-odd	$\rho^0\rho^0$ (P) $(0\%, 3°)$	$9.8^{+4.4}_{-3.8} \times 10^{-4}$



Control mode

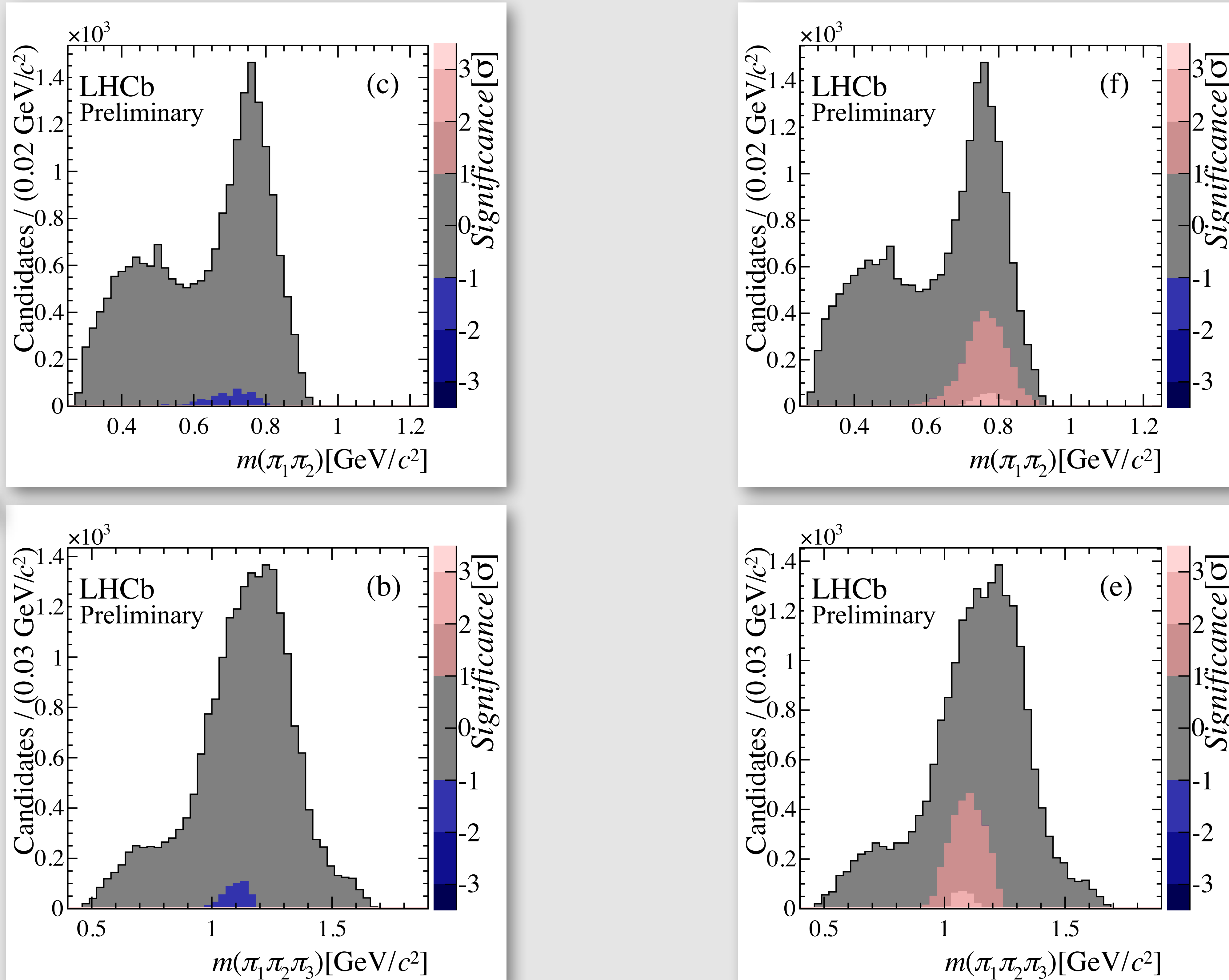
- Use Cabibbo-favoured $D^0 \to K^- \pi^+ \pi^- \pi^+$ as control mode
  - ➡ Split in 10 samples of similar size to signal mode
  - ➡ Analyse with P-even and P-odd test
  - ➡ Tests sensitivity to variation of (detection) asymmetries across phase-space





Visual results

P-even



P-odd

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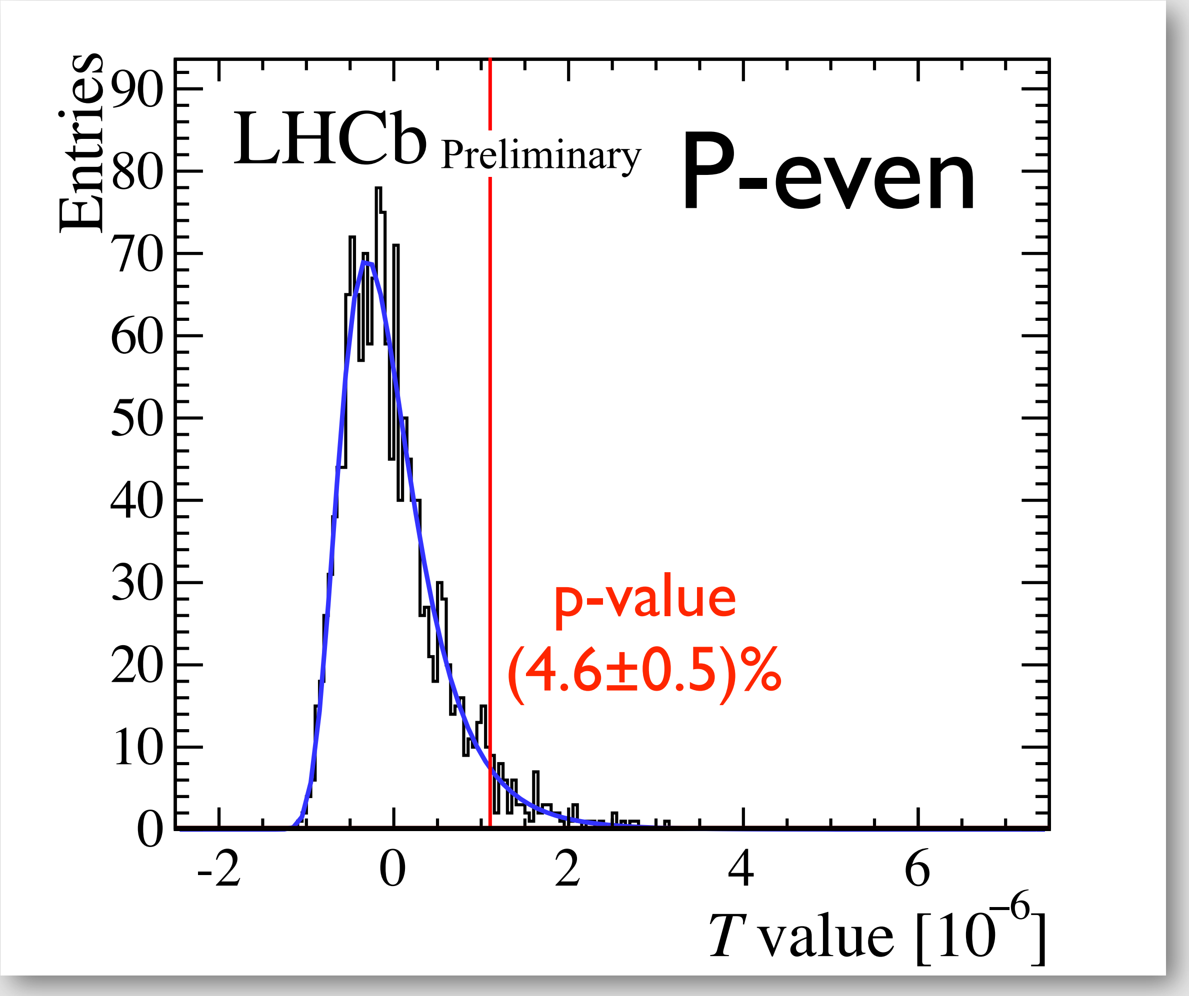
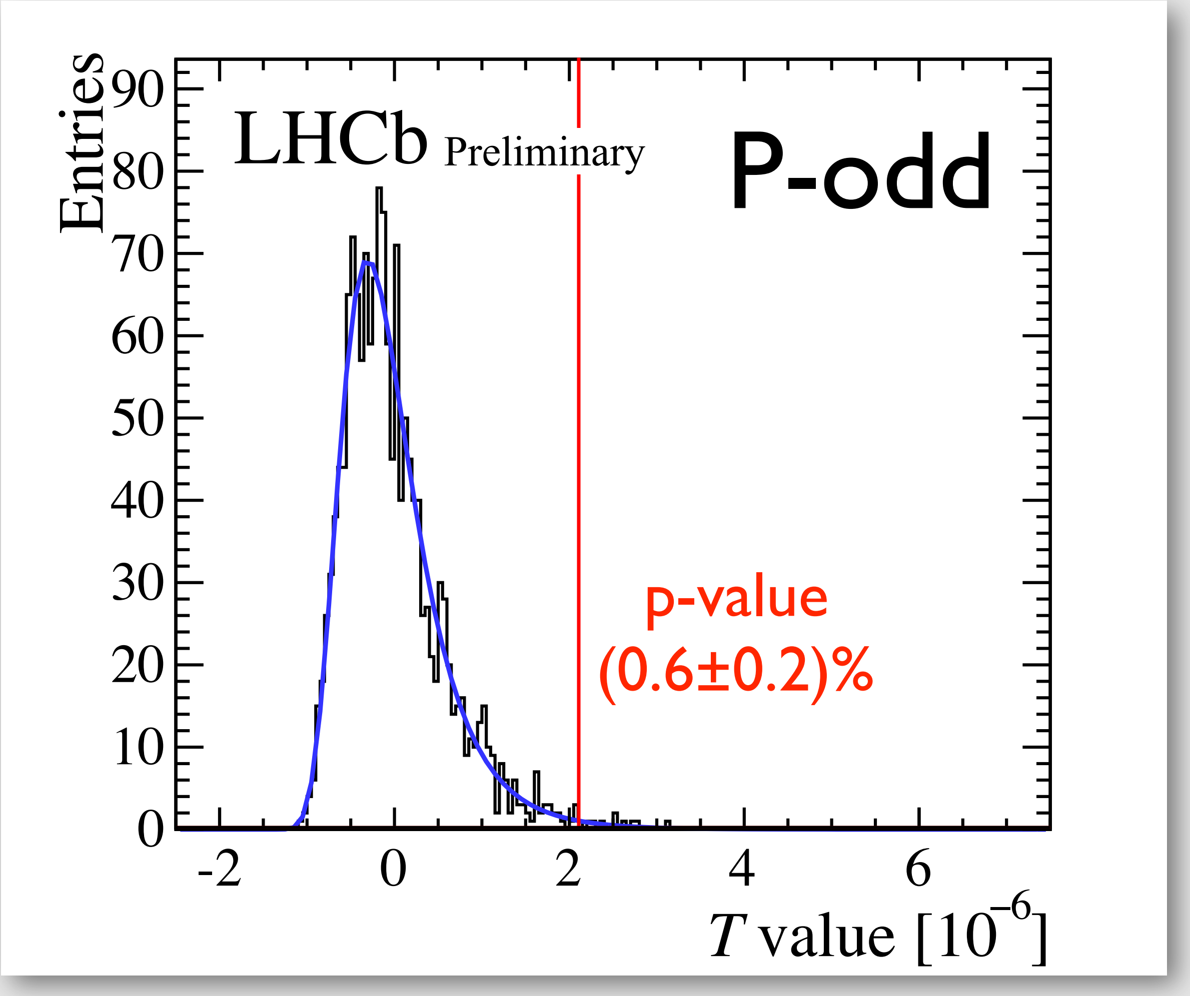
Numerical results

- Nearly 2000 permutations to get no-CPV T values
- Both tests allow assigning p-value from counting
  - ➡ Do not rely on GEV fit
- Small p-value, particularly for P-odd CP violation





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More multi-bodies

- Most of the 3 and 4-body meson decays unexplored or based on small samples
  - ➡ Several updates in the making
    - Will exploit a range of methods
- Huge potential in baryon sector
  - ➡ Need to control proton detection asymmetry

Conclusions

- Multi-body final states offer many ways for CP violation to act
- A multitude of methods exists focusing on different physics aspects

- Preliminary results on η’π decays LHCb-PAPER-2016-041

$$\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) = (-0.52 \pm 0.72 \pm 0.55 \pm 0.12)\%$$
$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%$$

- Energy test applied to $D^0 \to \pi^+\pi^-\pi^+\pi^-$ for the first time with sensitivity to P-even and P-odd CPV LHCb-PAPER-2016-044
  - ➡ p-values for 2000 permutations: 4.6% and 0.6%, respectively

- Many more analyses to come
  - ➡ Have already 2 fb^{-1} at 13 TeV