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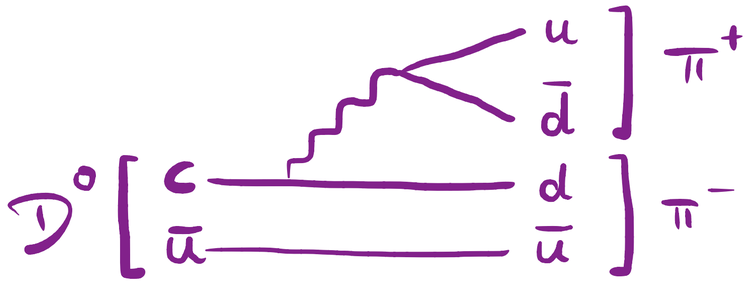
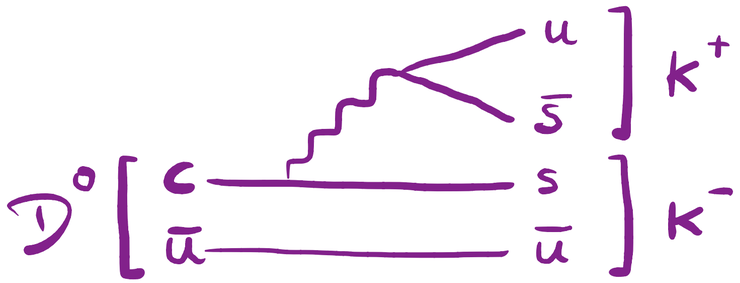
Direct CP violation searches in multi-body D decays at LHCb

$D^0 \to \pi^+\pi^-\pi^0$
& $D^0 \to K_S K^\pm \pi^\mp$ NEW!

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

$D^0 \to PP$

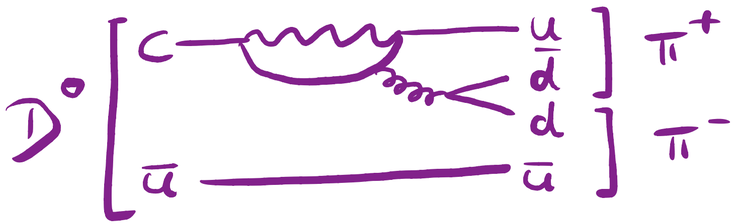


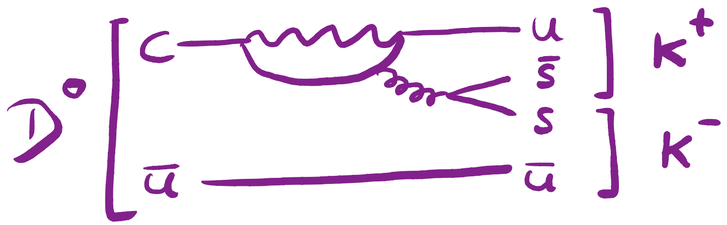


ΔA_{CP}

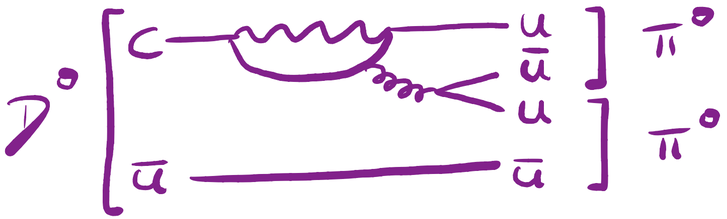
$A_{CP}(\pi\pi)$ ⟷ $A_{CP}(KK)$

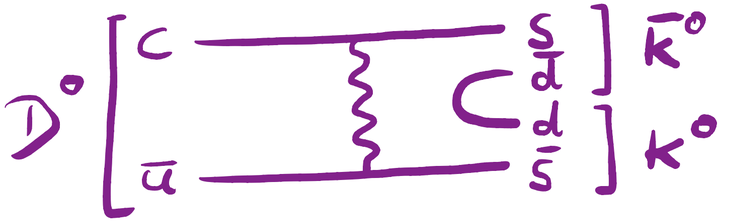
U-spin





Isospin





Brod, Kagan Zupan (2011),
Hiller Jung Schacht (2013),
Nierste, Schacht (2015)

Large ACP?

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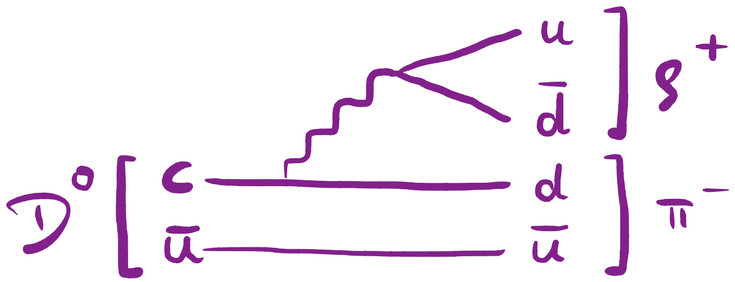
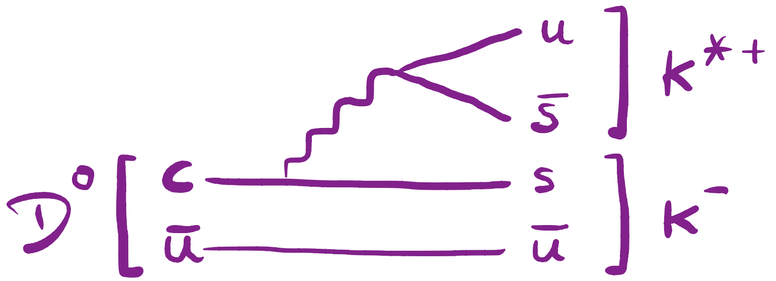
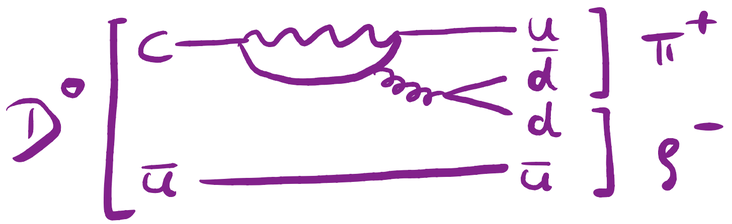
Adding spin

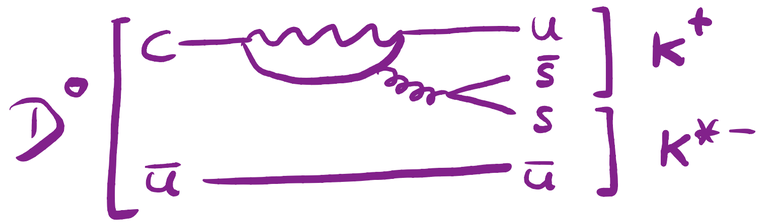
Keeping weak structure

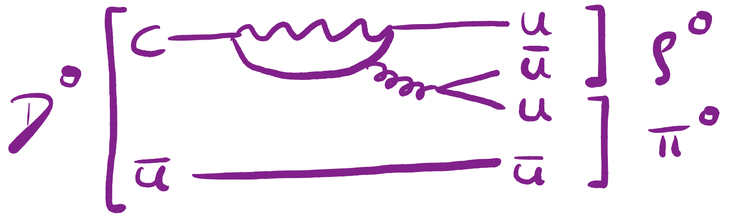
$D^0 \to VP$


D⁰
c
ū
u
d̄
d
ū
ρ⁺
π⁻


D⁰
c
ū
u
s̄
s
ū
K*⁺
K⁻


D⁰
c
ū
u
d̄
d
ū
π⁺
ρ⁻


D⁰
c
ū
u
s̄
s
ū
K⁺
K*⁻


D⁰
c
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ū
ρ⁰
π⁰


D⁰
c
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s
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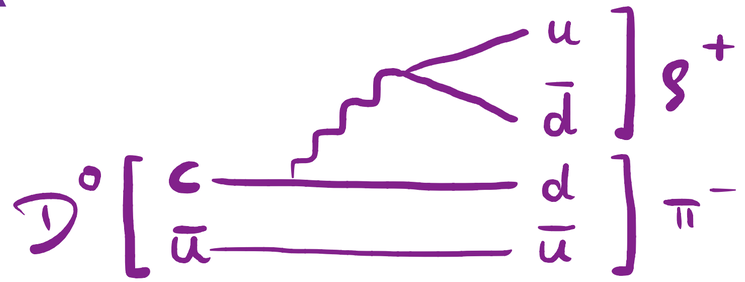
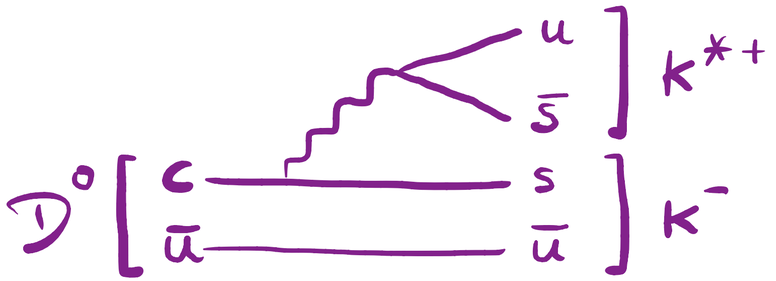
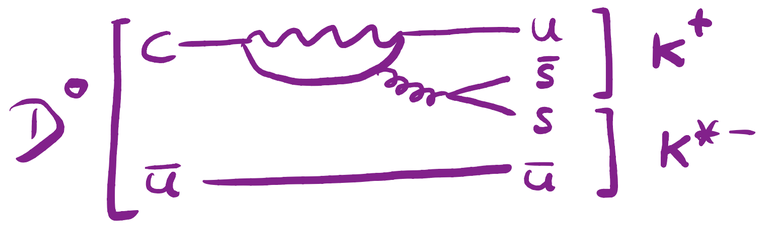
K̄⁰
K*⁰

$D^0 \to VP$





Final state: $\pi^+\pi^-\pi^0$



Final state: $K_S K^\pm \pi^\mp$

Grossman, Kagan, Zupan (2012)
Sum rules

Nierste, Schacht (2017)
Also interesting

arXiv:2306.12746
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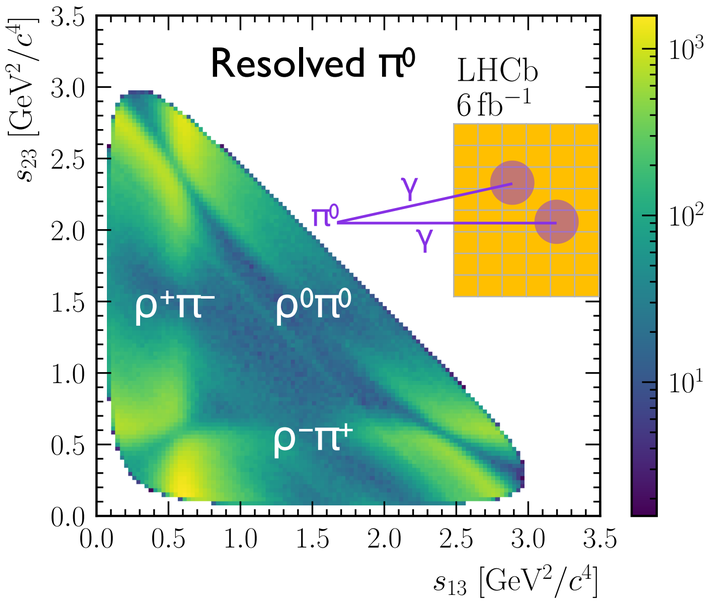
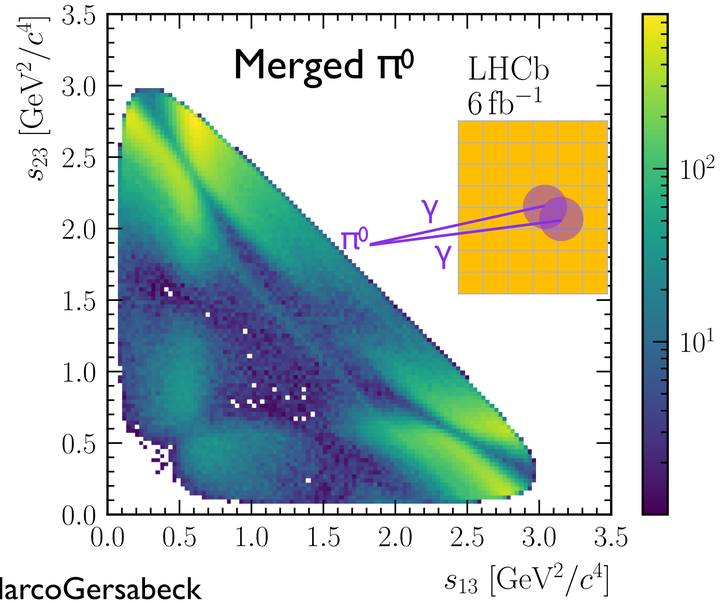
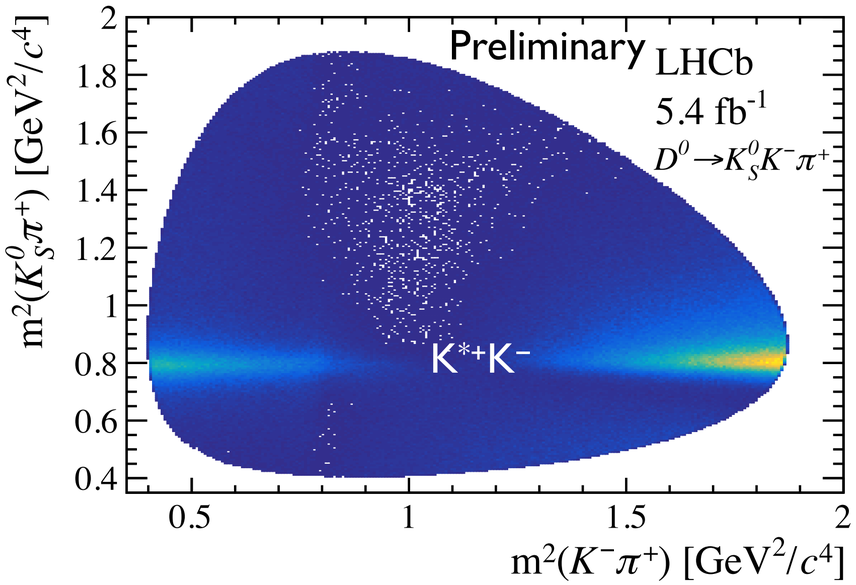
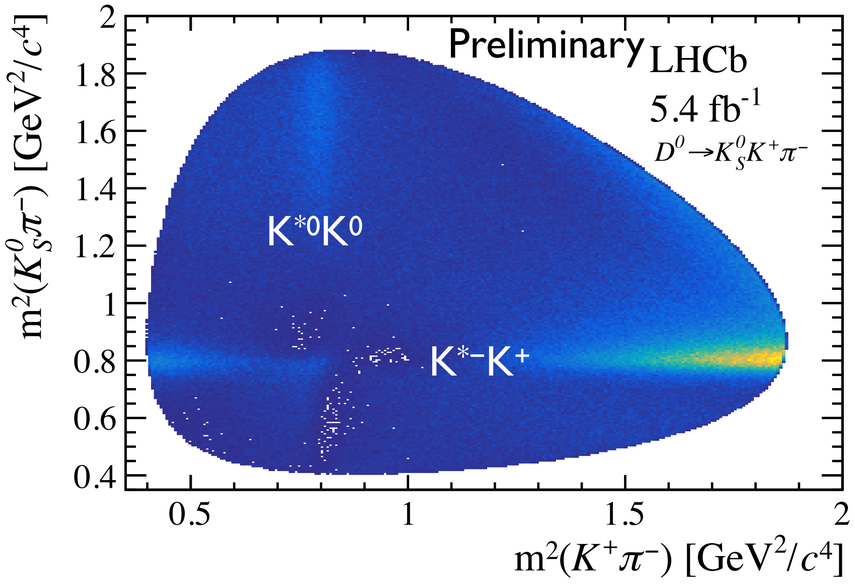
Multi-body intereference





- Three-body pseudo-scalar final-state phase space can be described with two variables
  - ➡ Dalitz plot
- Dalitz plots give access to interfering amplitudes with rapidly varying strong phases
  - ➡ Fertile ground for local CP asymmetries





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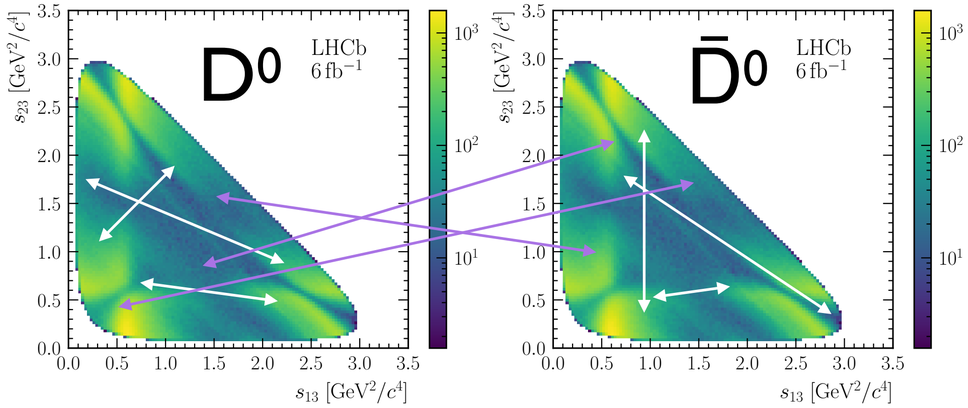
Energy test

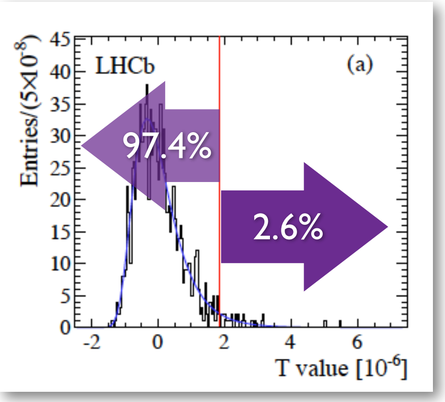


- Model-independent unbinned two-sample test to discover localised asymmetries
- Compares weighted distances in phase spaces among all pairs of events
  - ➡ Grouped in D^0-D^0, $\bar{D}^0$-$\bar{D}^0$, D^0-$\bar{D}^0$
- Weighting function decreases with distance
  - ➡ Emphasising localised effects
- Weighted distances are averaged with opposite sign for D^0-$\bar{D}^0$ cross term
  - ➡ Resulting statistic, T, approximately 0 if D^0 & $\bar{D}^0$ from same underlying distribution
  - ➡ Asymmetry leads to T > 0
- T-value distribution for CP symmetry hypothesis from repeated random assignment of D^0-$\bar{D}^0$ flavour tag
  - ➡ p-value obtained as fraction of distribution greater than measured T

$$d_{ij}^2 = [(\Delta s_{12})_{ij}^2 + (\Delta s_{13})_{ij}^2 + (\Delta s_{23})_{ij}^2]$$

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

$$T \equiv \frac{1}{2n(n-1)} \sum_{i,j\neq i}^{n} \psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)} \sum_{i,j\neq i}^{\overline{n}} \psi_{ij} - \frac{1}{n\overline{n}} \sum_{i,j}^{n,\overline{n}} \psi_{ij}$$



Previous analysis: p-value = 2.6%

Method: Aslan, Zech, 2004, Wiliams, 2011, Parkes et al. 2017, Barter, Burr, Parkes, 2018, Zech 2018

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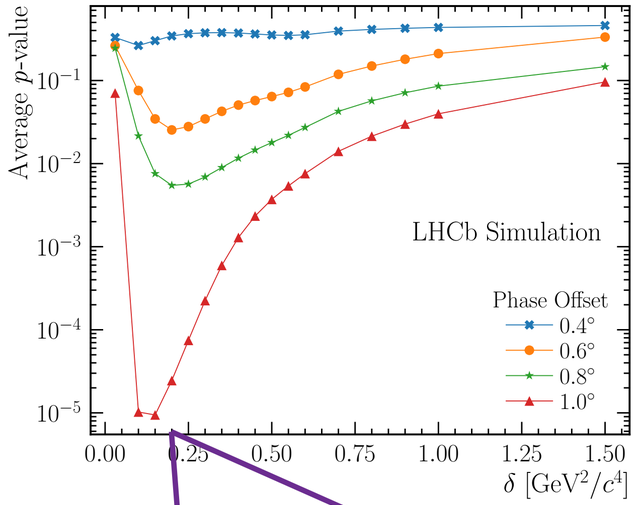
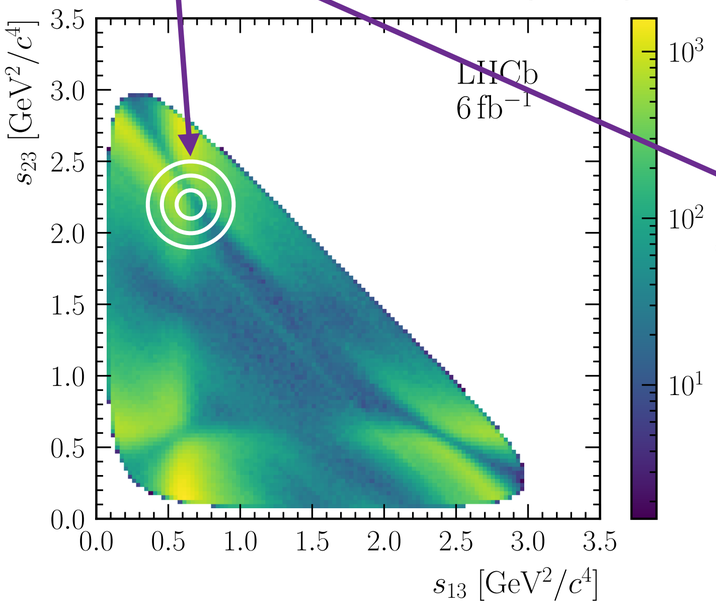
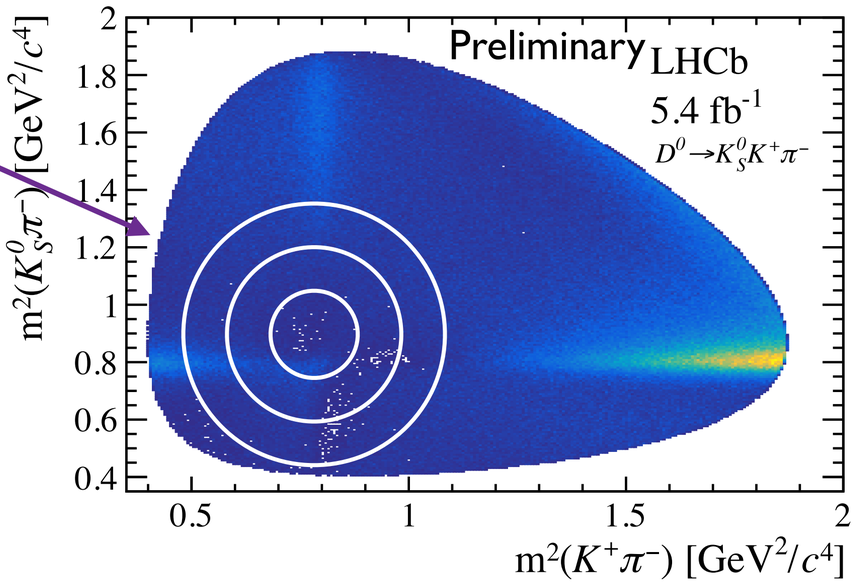
Sensitivity

- Energy test is a discovery tool
  - ➡ Single result is a p-value for agreement with CP symmetry hypothesis
    - Does not yield limits for specific models
- Sensitivity tests can test effect of models
  - ➡ Can identify scenarios that should lead to observations
    - Non-observation can then use these as limits





- Chose δ = 0.2 GeV²/c⁴ for both analyses
- Expect evidence for CPV due to
  - ➡ 0.9° phase shift in ρ(770)⁺π⁻
  - ➡ 2° phase shift or 2% amplitude difference in K*(892)±K∓



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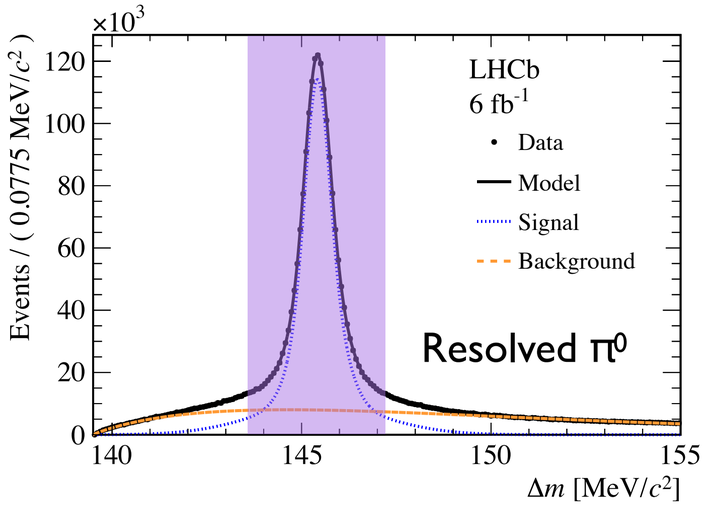
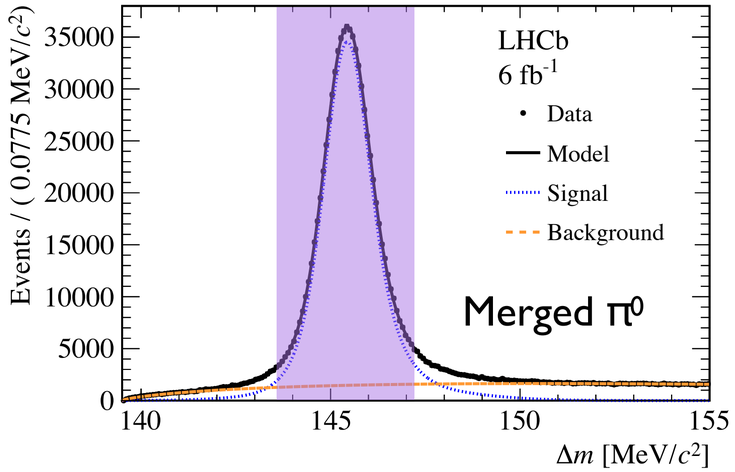
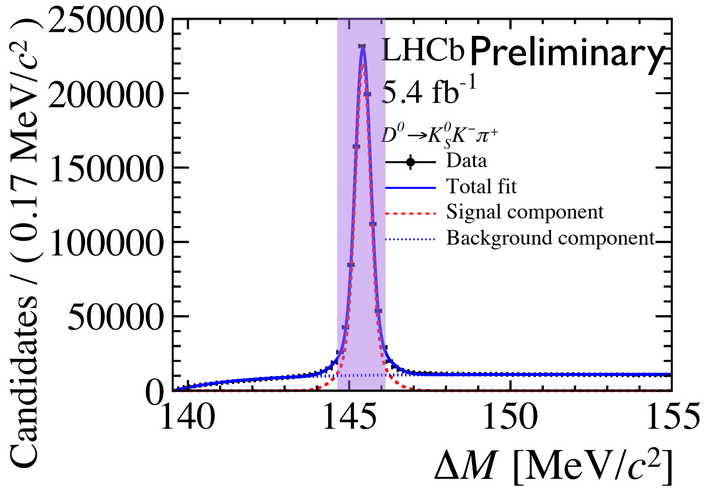
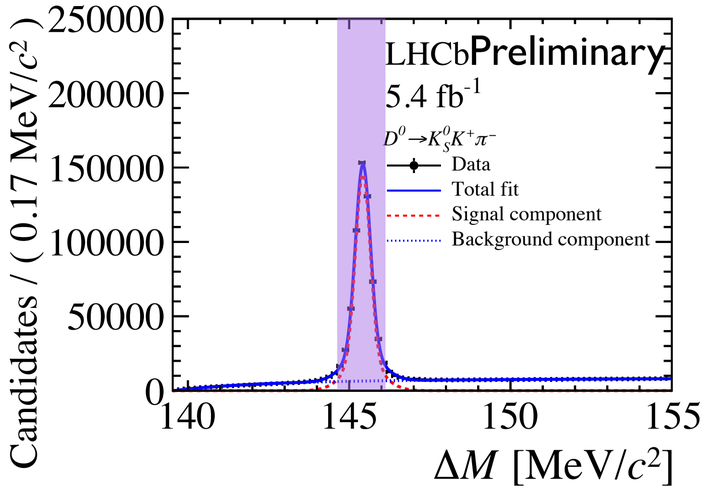
Data





- All samples flavour-tagged by reconstructing $D^{*+} \to D^0\pi^+$ decays
- Purity above 90% (~80% for resolved π^0)
- All signal candidates in mass window passed to energy test
  - ➡ Resolved and merged π^0 samples are combined
  - ➡ Fit just indicative to assess background level





2.47M signal candidates (Run 1: 0.67M)

1.57M signal candidates in both final states

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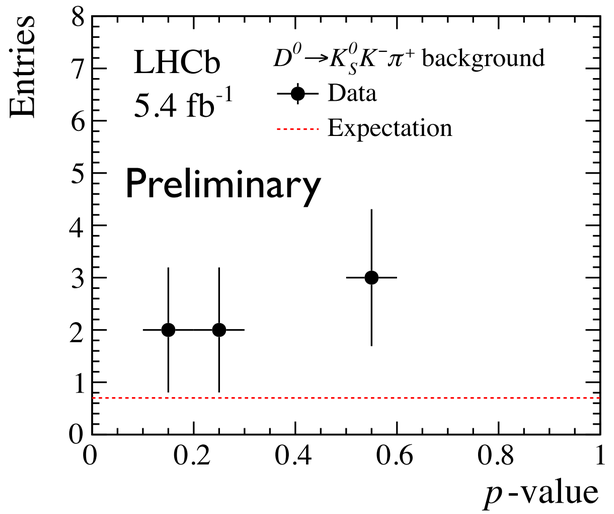
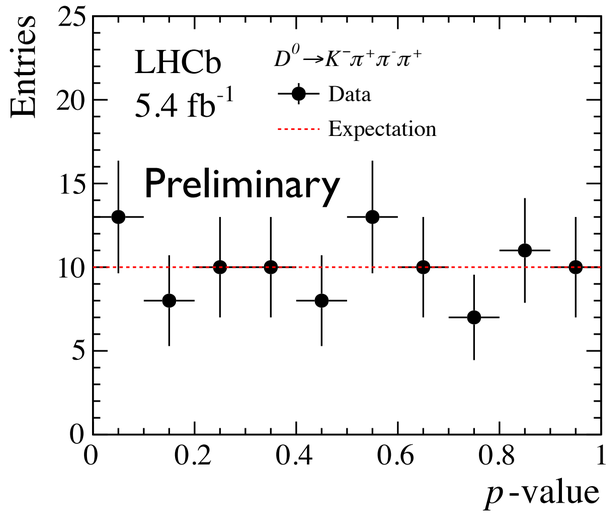
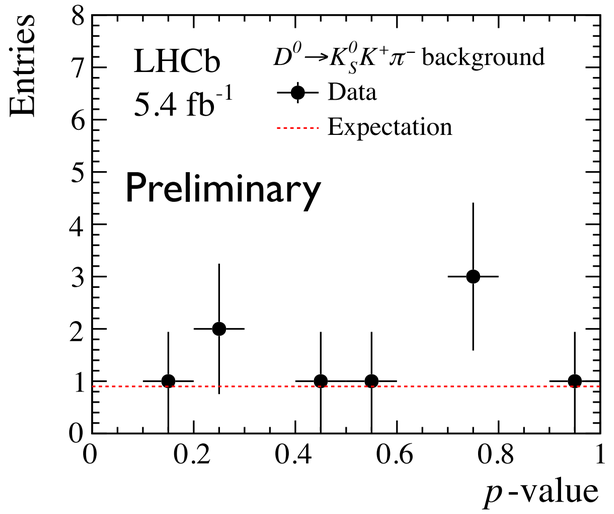
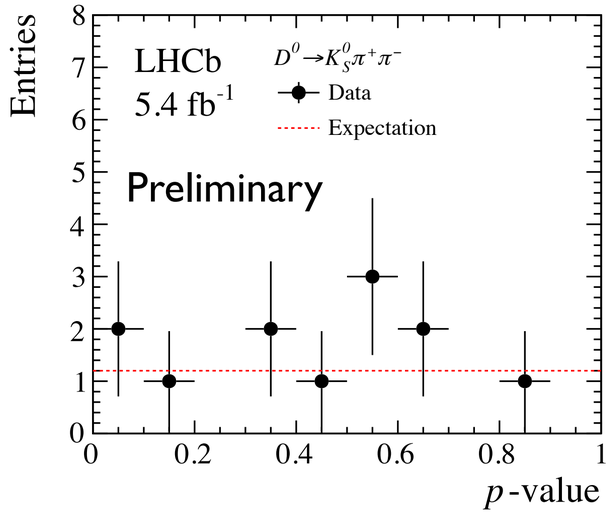
Nuisances

- All selected data analysed in energy test without efficiency correction or background subtraction
- Sources of asymmetry other than signal CP violation:
  - ➡ Background asymmetry (CP or other)
    - Symmetric background also affects (dilutes) sensitivity
  - ➡ Production or detection asymmetry
    - Needs to lead to localised effects in phase space
- Cross-checks
  - ➡ Measure control samples
    - Background dominated mass side bands
    - Control modes with related final states: $K^-\pi^+\pi^0$, $K_S\pi^+\pi^-$, $K^-\pi^+\pi^+\pi^-$
  - ➡ Pseudo-experiments with injected asymmetries
  - ➡ Sub-sample consistency checks (year, dipole polarity, trigger selection)









Results

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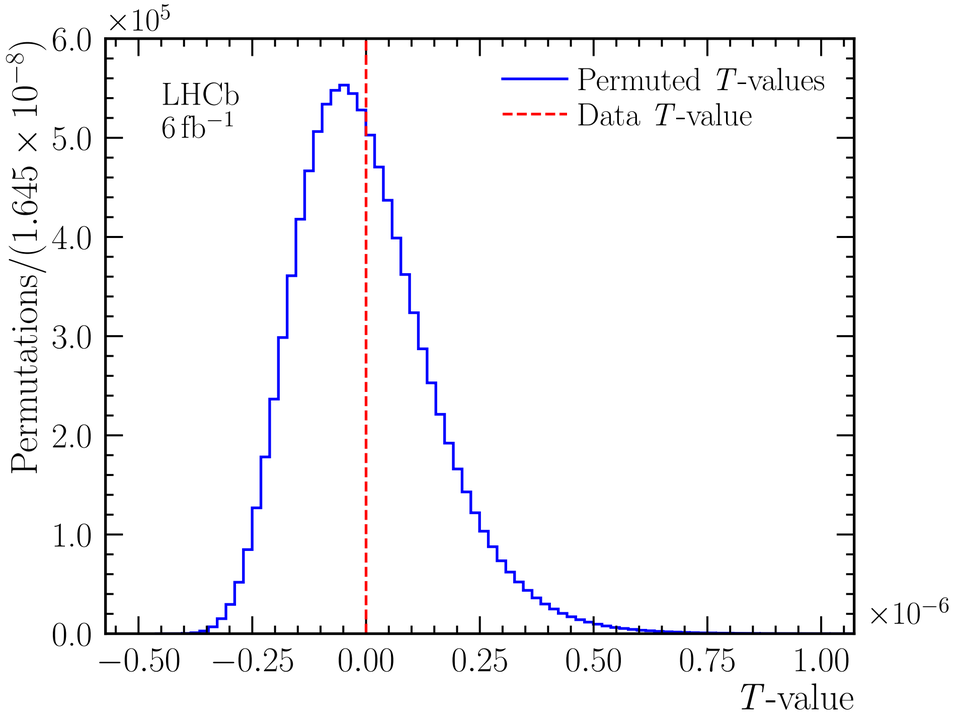
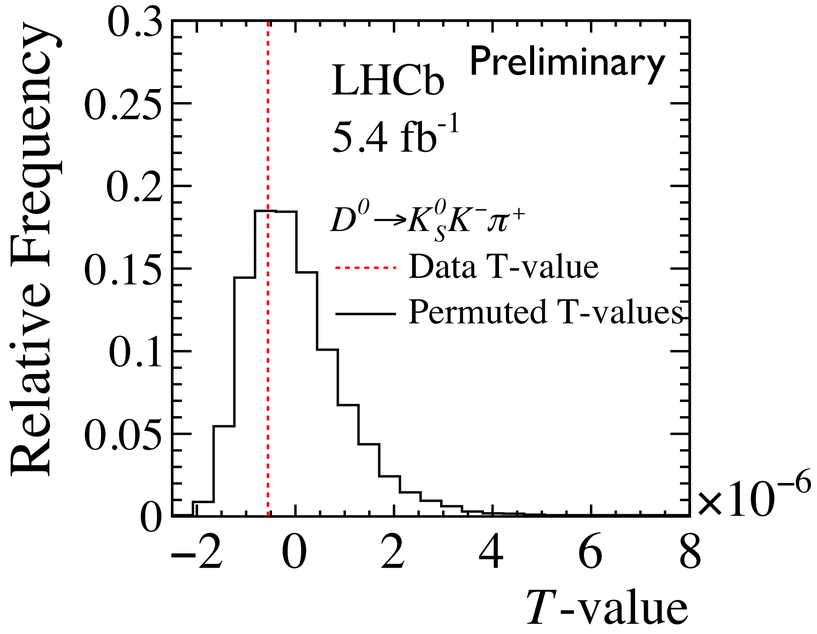
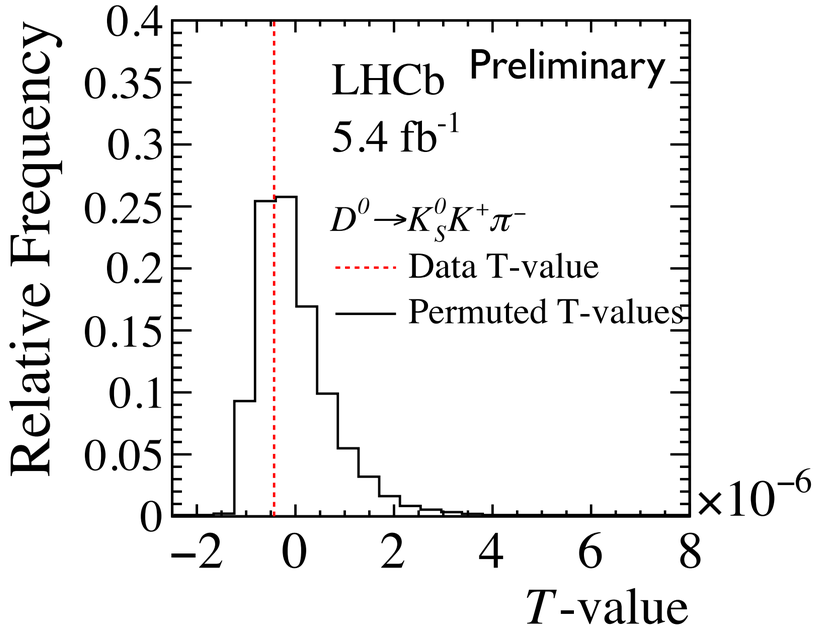
- p-values for agreement with CP symmetry
  - ➡ $D^0 \to \pi^+\pi^-\pi^0$: 62%
  - ➡ $D^0 \to K_S K^-\pi^+$: 70%
  - ➡ $D^0 \to K_S K^+\pi^-$: 66%

NEW
Preliminary







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Conclusions

- LHCb conducted two model-independent searches for CP violation in three-body D^0 decays
- Energy-test results for $D^0 \to K_S K^- \pi^+$, $D^0 \to K_S K^+ \pi^-$, NEW and $D^0 \to \pi^+ \pi^- \pi^0$ decays shows agreement with CP symmetry
- No indication of CP violation in modes related to two-body discovery channels

➡ Sensitivity is still above observed two-body levels

➡ Looking forward to analyses of other channels and Run 3 data!

Including $D_{(s)}^+ \to K^- K^+ K^+$, JHEP 07 (2023) 067
See also Plenary talk by Evelina Gersabeck