Measurements of time-integrated CP and other asymmetries

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

CHARM 2015,
Detroit, 19 May 2015

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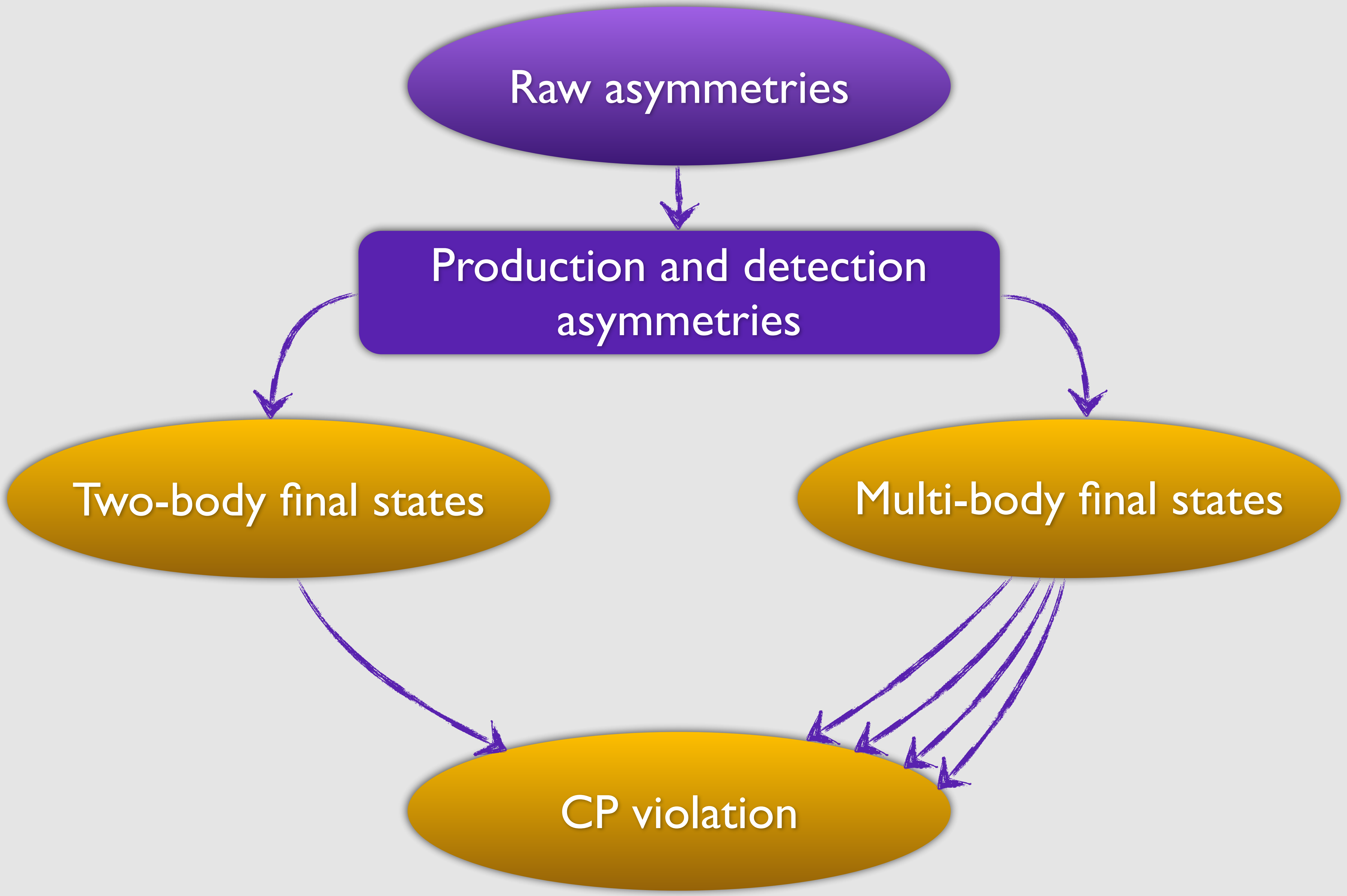
Outline



Raw asymmetries
Production and detection asymmetries
Two-body final states
Multi-body final states
CP violation

Measured asymmetries

- Measure $A_{raw}(D \rightarrow f) = \dfrac{N(D \rightarrow f) - N(\overline{D} \rightarrow \overline{f})}{N(D \rightarrow f) + N(\overline{D} \rightarrow \overline{f})}$

- Get to first order

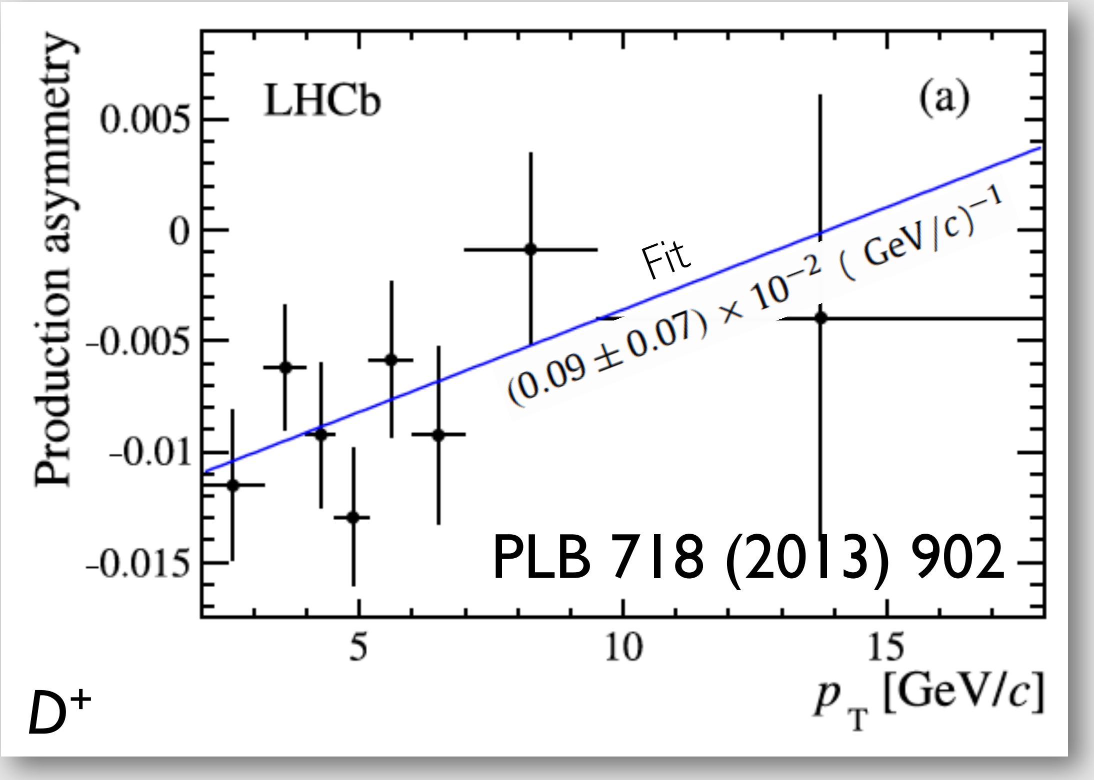
particle tagging
D and $\overline{D}$

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

- Need to constrain
  - ➡ Production asymmetry
  - ➡ Detection asymmetry (final state and flavour tag)
- General idea
  - ➡ Use similar Cabibbo-allowed processes and assume $A_{CP}(D \rightarrow f) = 0$

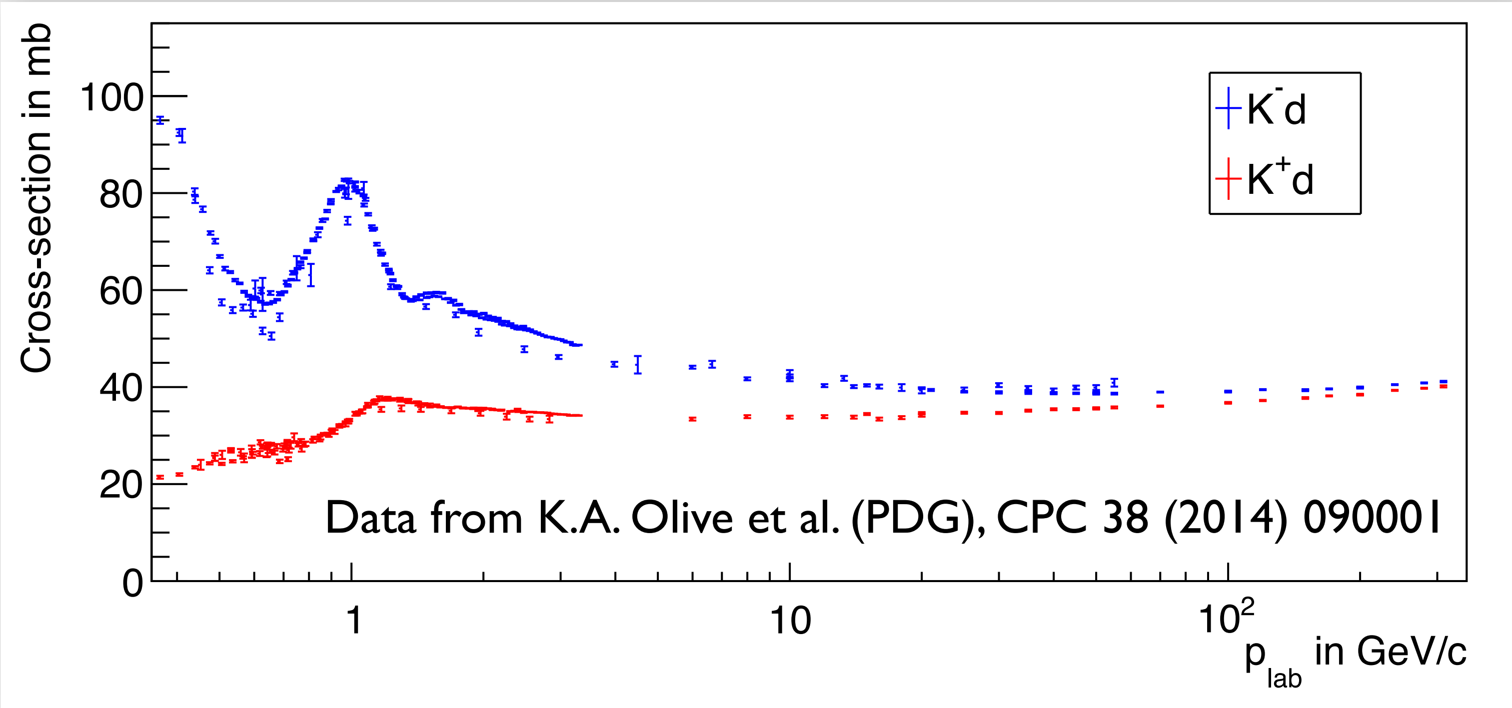
Production asymmetries

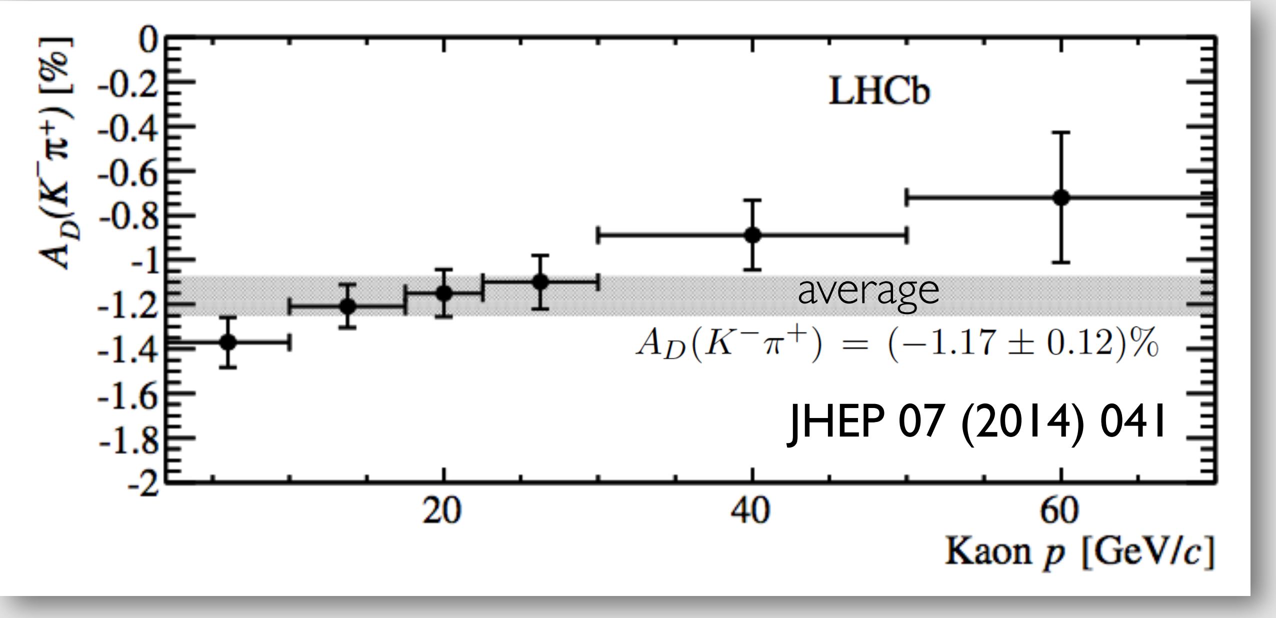
- Particular to pp collider
  - ➡ "Replaces" forward-backward asymmetry at e^+e^- and $p\bar{p}$
- Valence quarks favour the production of matter baryons
  - ➡ Favours antimatter mesons
- Production asymmetry can depend on kinematics
  - ➡ Accounted through binning / re-weighting



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

Results

Two-body decays

First example

- Measurement

$$\mathcal{A}_{\text{meas}}^{D_{(s)}^{\pm}\to K_{\rm S}^{0}h^{\pm}} = \frac{N_{\text{sig}}^{D_{(s)}^{+}\to K_{\rm S}^{0}h^{+}} - N_{\text{sig}}^{D_{(s)}^{-}\to K_{\rm S}^{0}h^{-}}}{N_{\text{sig}}^{D_{(s)}^{+}\to K_{\rm S}^{0}h^{+}} + N_{\text{sig}}^{D_{(s)}^{-}\to K_{\rm S}^{0}h^{-}}},$$

$$\mathcal{A}_{\text{meas}}^{D_{(s)}^{\pm}\to K_{\rm S}^{0}h^{\pm}} \approx \mathcal{A}_{CP}^{D_{(s)}^{\pm}\to K_{\rm S}^{0}h^{\pm}} + \mathcal{A}_{\text{prod}}^{D_{(s)}^{\pm}} + \mathcal{A}_{\text{det}}^{h^{\pm}} + \mathcal{A}_{K^0/\overline{K}^0},$$

- Extract CP asymmetries using control modes

$$\mathcal{A}_{CP}^{D_s^{\pm}\to K_{\rm S}^{0}\pi^{\pm}} = \mathcal{A}_{\text{meas}}^{D_s^{\pm}\to K_{\rm S}^{0}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{D_s^{\pm}\to \phi\pi^{\pm}} - \mathcal{A}_{K^0}.$$

$$\mathcal{A}_{CP}^{D^{\pm}\to K_{\rm S}^{0}K^{\pm}} = \left[\mathcal{A}_{\text{meas}}^{D^{\pm}\to K_{\rm S}^{0}K^{\pm}} - \mathcal{A}_{\text{meas}}^{D_s^{\pm}\to K_{\rm S}^{0}K^{\pm}}\right] - \left[\mathcal{A}_{\text{meas}}^{D^{\pm}\to K_{\rm S}^{0}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{D_s^{\pm}\to \phi\pi^{\pm}}\right] - \mathcal{A}_{K^0}$$

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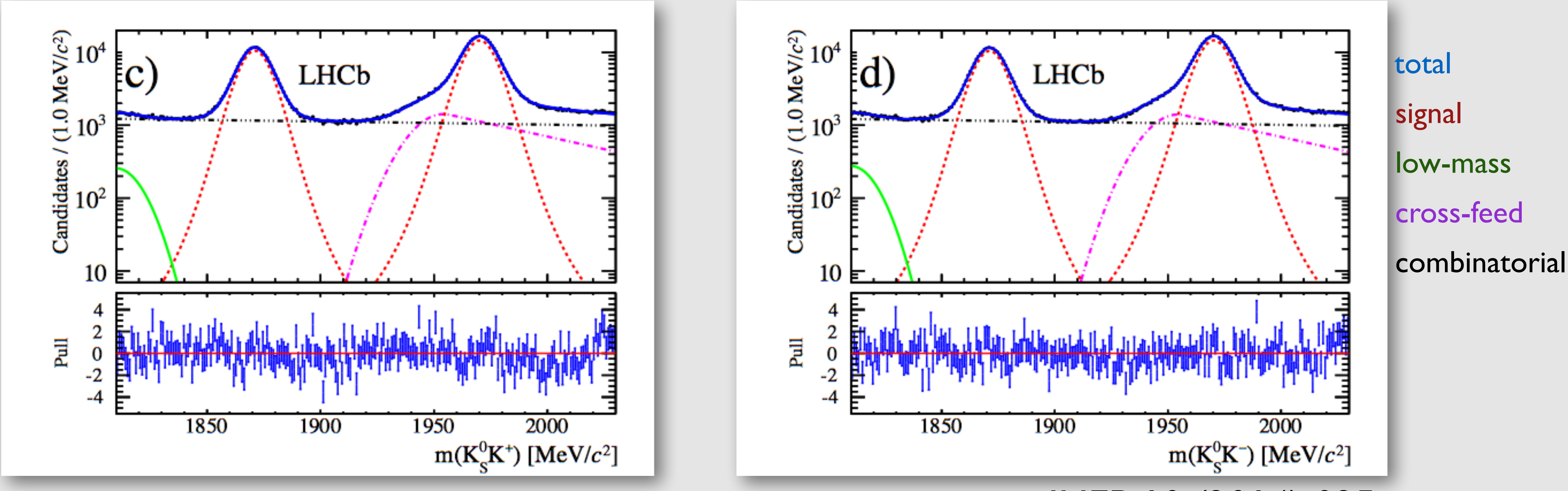
Results for Ksh

- Charged D two-body modes are challenging due to neutral particles involved
- Measurement based on 3 fb^{-1}
- Uses weighted control mode kinematics and average of dipole magnet polarities
- All approximately zero

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%$$
$$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%,$$



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The Δa_{CP} saga*

- What is Δa_{CP}?

$$\Delta a_{CP} \equiv a_{CP}(K^- K^+) - a_{CP}(\pi^- \pi^+) = a_{\text{raw}}(K^- K^+) - a_{\text{raw}}(\pi^- \pi^+).$$

- Interplay of direct and indirect CP violation

$$\Delta a_{CP} = \Delta a_{CP}^{\text{dir}} \left(1 + y_{CP} \frac{\overline{\langle t \rangle}}{\tau}\right) + \overline{A}_\Gamma \frac{\Delta \langle t \rangle}{\tau},$$

- Individual asymmetries are expected to have opposite sign due to CKM structure

$$A(\overline{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}\left(V_{cs}V_{us}^* - V_{cd}V_{ud}^*\right)(T \pm \delta S) - V_{cb}V_{ub}^*\left(P \mp \tfrac{1}{2}\delta P\right),$$

*after A. Lenz @ CHARM 2013, arXiv:1311.6447

EPJC 73 (2013) 2373

Latest results

- D*-tagged (1 fb^{-1}, preliminary)

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\%\,.$$

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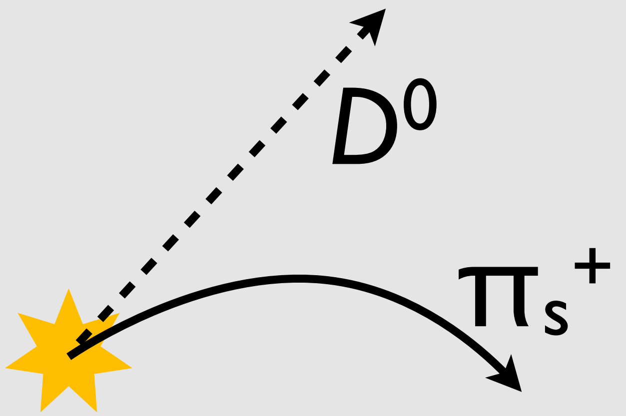

- muon-tagged (3 fb^{-1})

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%\,,$$

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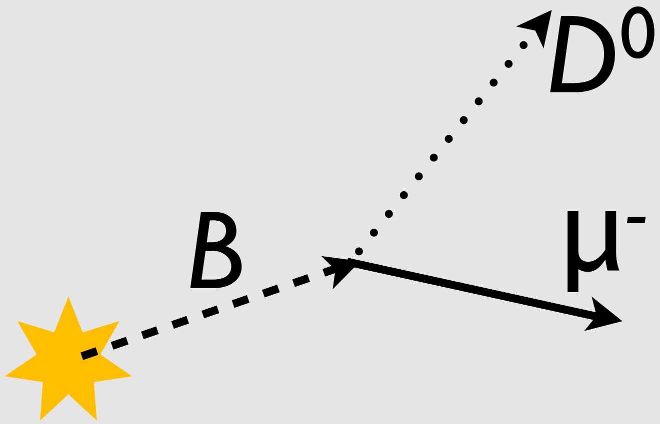

Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure want

average

$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

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Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure want

D from B

average
$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure want

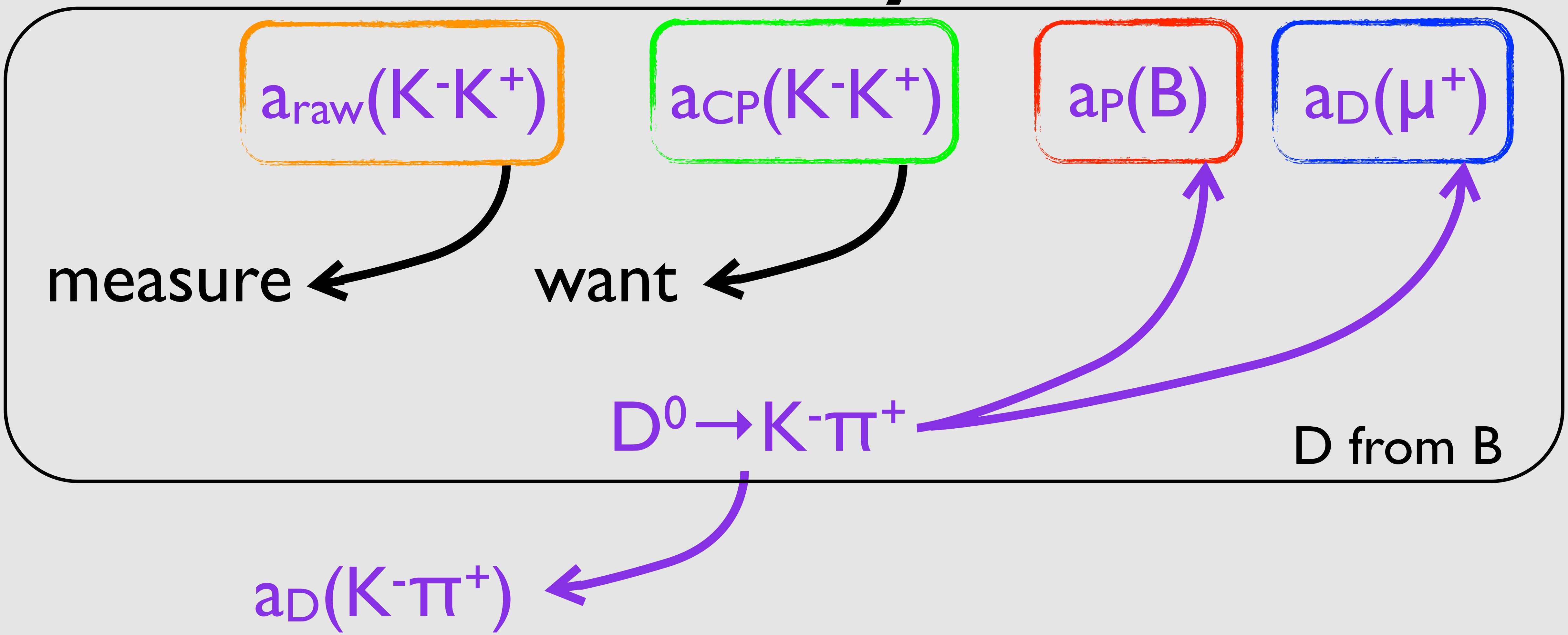
$D^0 \to K^-\pi^+$

D from B

average

$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

Individual asymmetries



average

$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

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Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure

want

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

D from B

$a_D(K^-\pi^+)$

average
$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

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

Prompt D

Individual asymmetries

$a_{raw}(K^-K^+)$

$a_{CP}(K^-K^+)$

$a_P(B)$

$a_D(\mu^+)$

measure

want

$D^0 \rightarrow K^-\pi^+$

D from B

$a_D(K^-\pi^+)$

average

$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

$D^+ \rightarrow K^-\pi^+\pi^+$

Prompt D

$a_P(D^+)$, $a_D(\pi^+)$

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Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure

want

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

D from B

$a_D(K^-\pi^+)$

average

$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

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

Prompt D

$a_P(D^+)$, $a_D(\pi^+)$

$D^+ \to K_S\pi^+$

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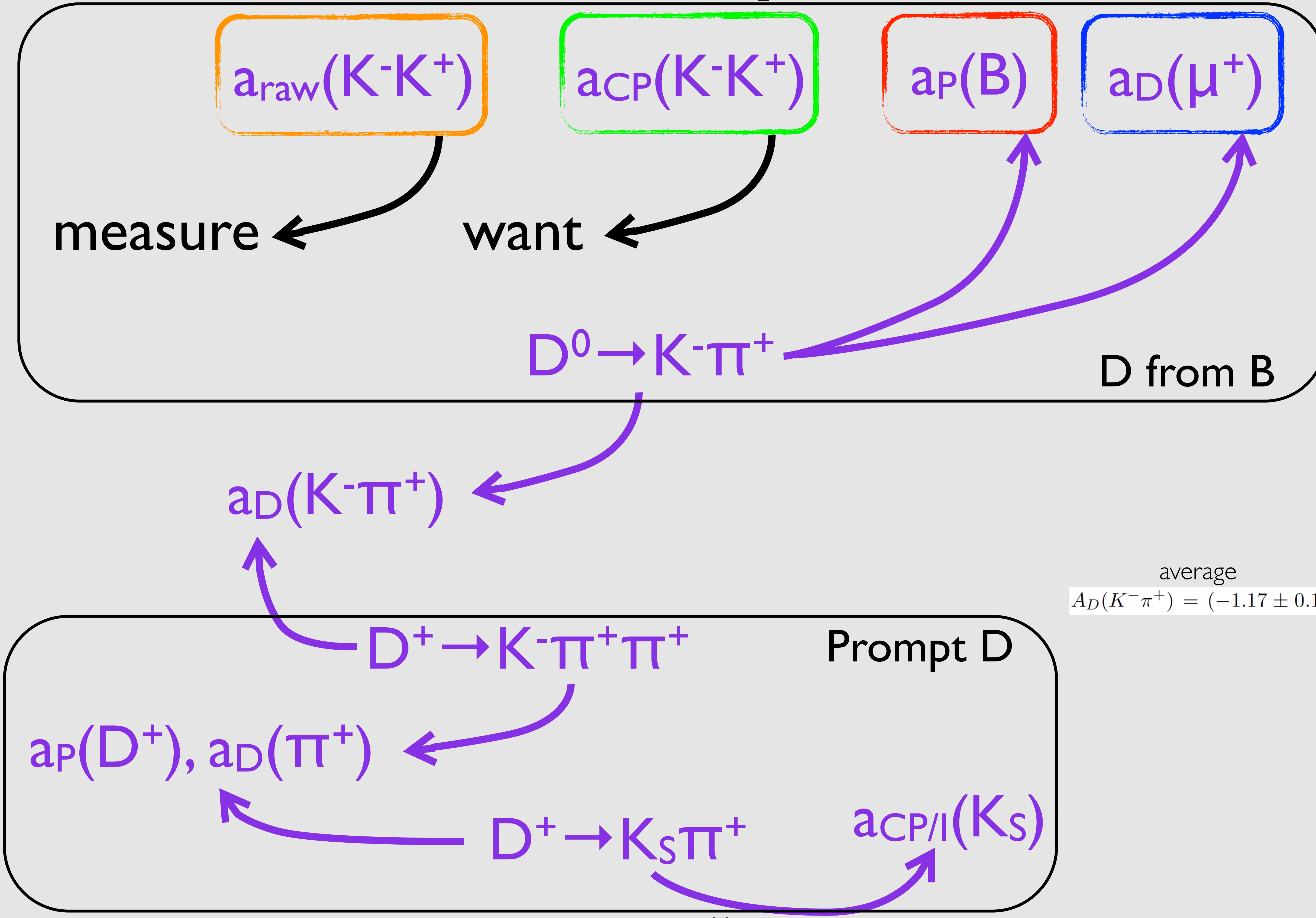
Individual asymmetries



average
$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

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Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure

want

$D^0 \rightarrow K^-\pi^+$

$a_D(K^-\pi^+)$

assume no CPV in Cabibbo-favoured final states

average
$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

$D^+ \rightarrow K^-\pi^+\pi^+$

$a_P(D^+)$, $a_D(\pi^+)$

$D^+ \rightarrow K_S\pi^+$

$a_{CP/I}(K_S)$

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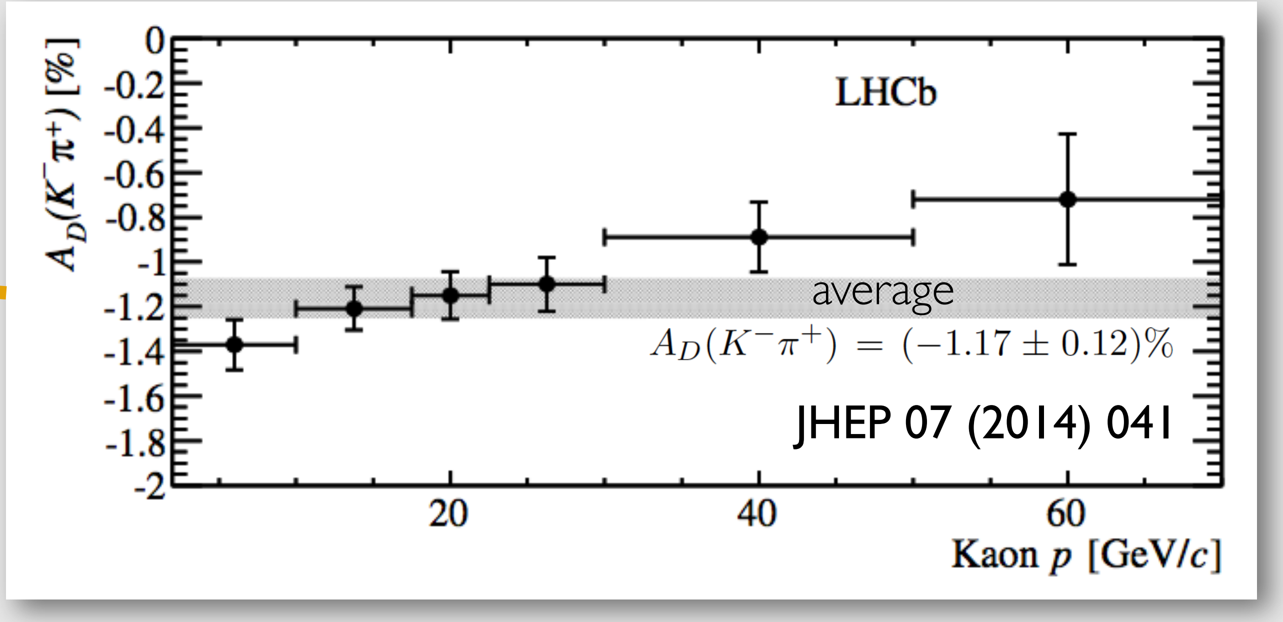
Individual asymmetries

$a_{raw}(K^-K^+)$ $a_{CP}(K^-K^+)$ $a_P(B)$ $a_D(\mu^+)$

measure want

$D^0 \rightarrow K^-\pi^+$

$a_D(K^-\pi^+)$



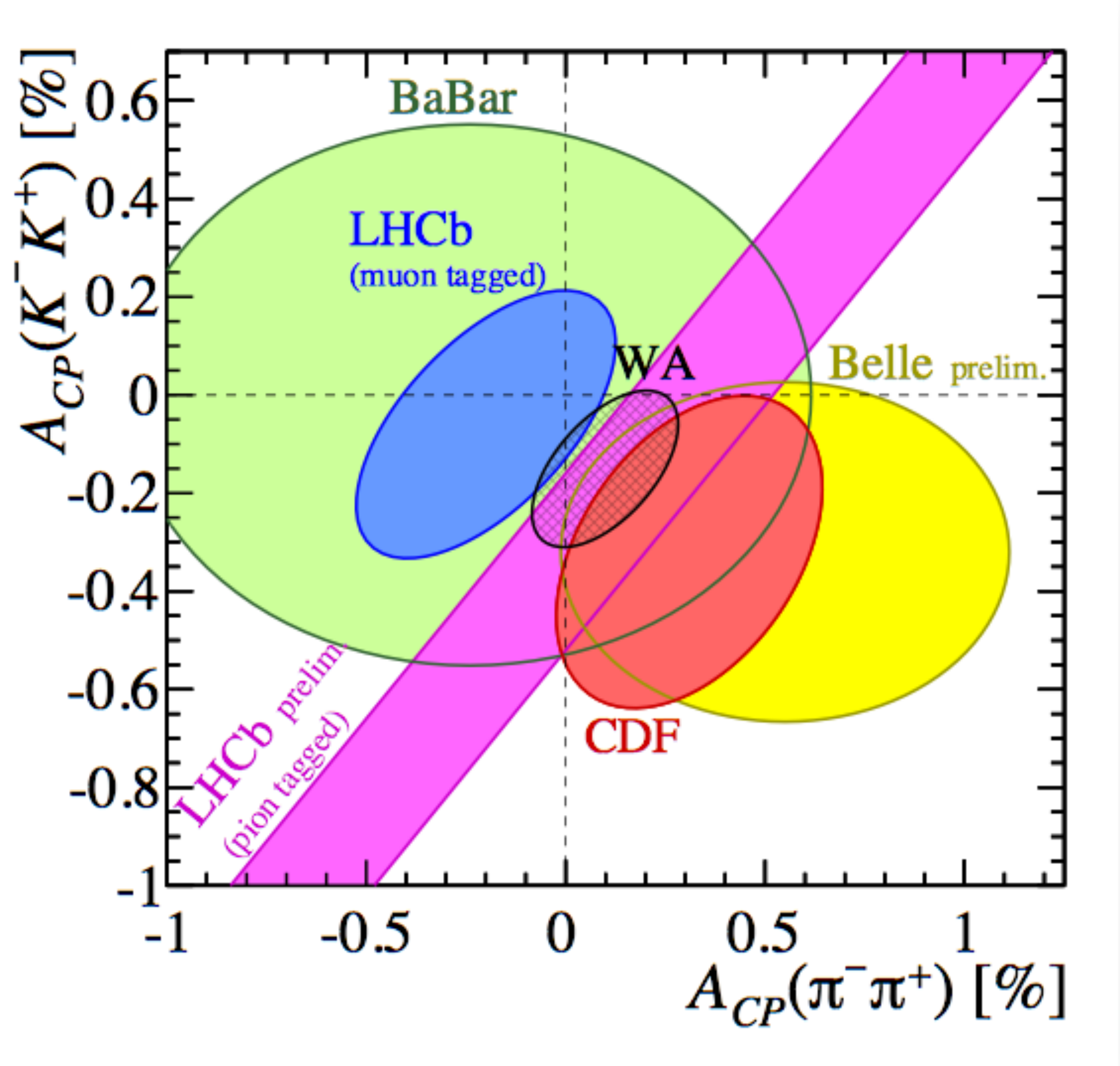
$D^+ \rightarrow K^-\pi^+\pi^+$

$a_P(D^+)$, $a_D(\pi^+)$

$D^+ \rightarrow K_S\pi^+$ $a_{CP/I}(K_S)$

(Δ)a_{CP} results

- Ignoring contribution from indirect CPV



$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%\,,$$

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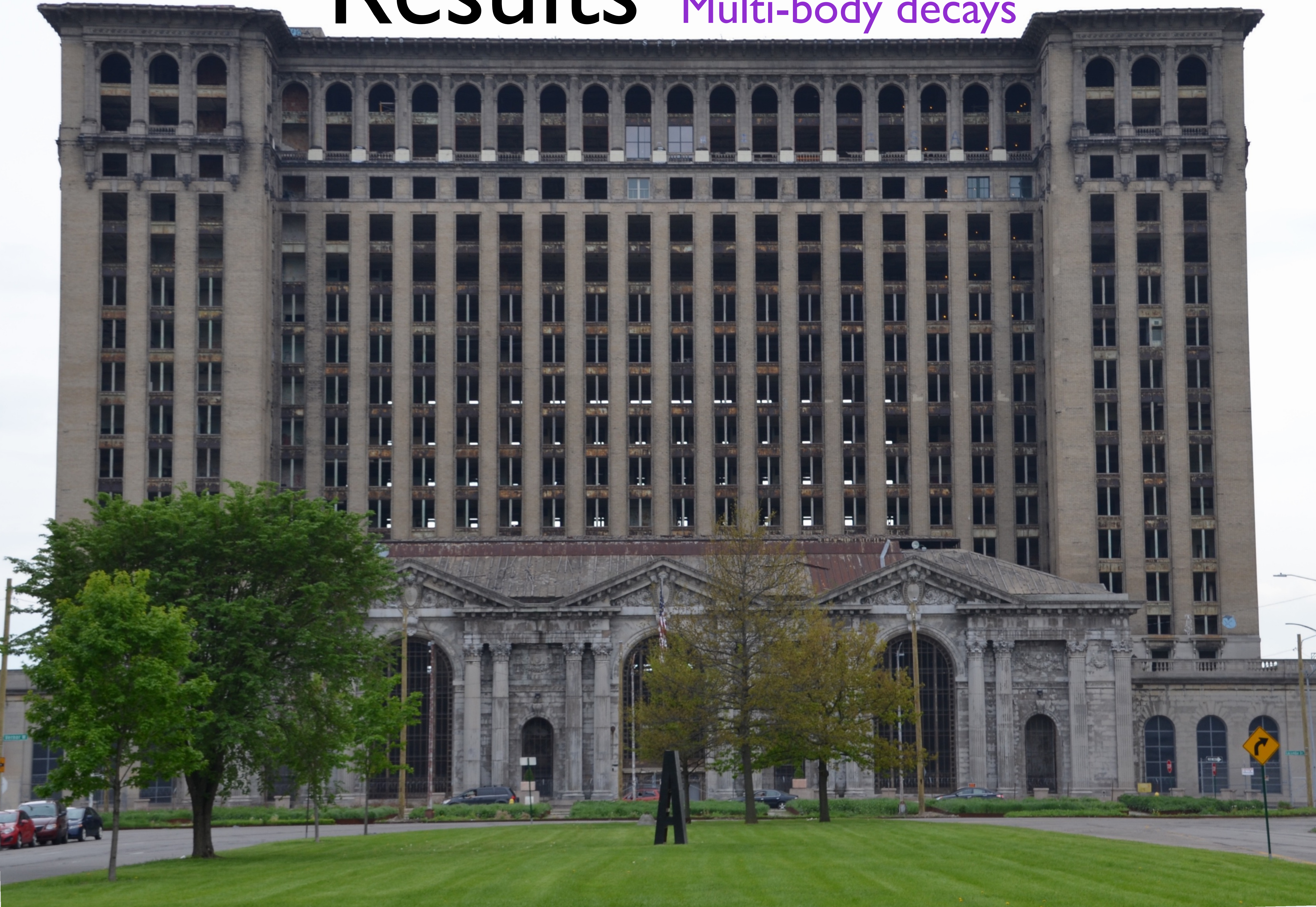
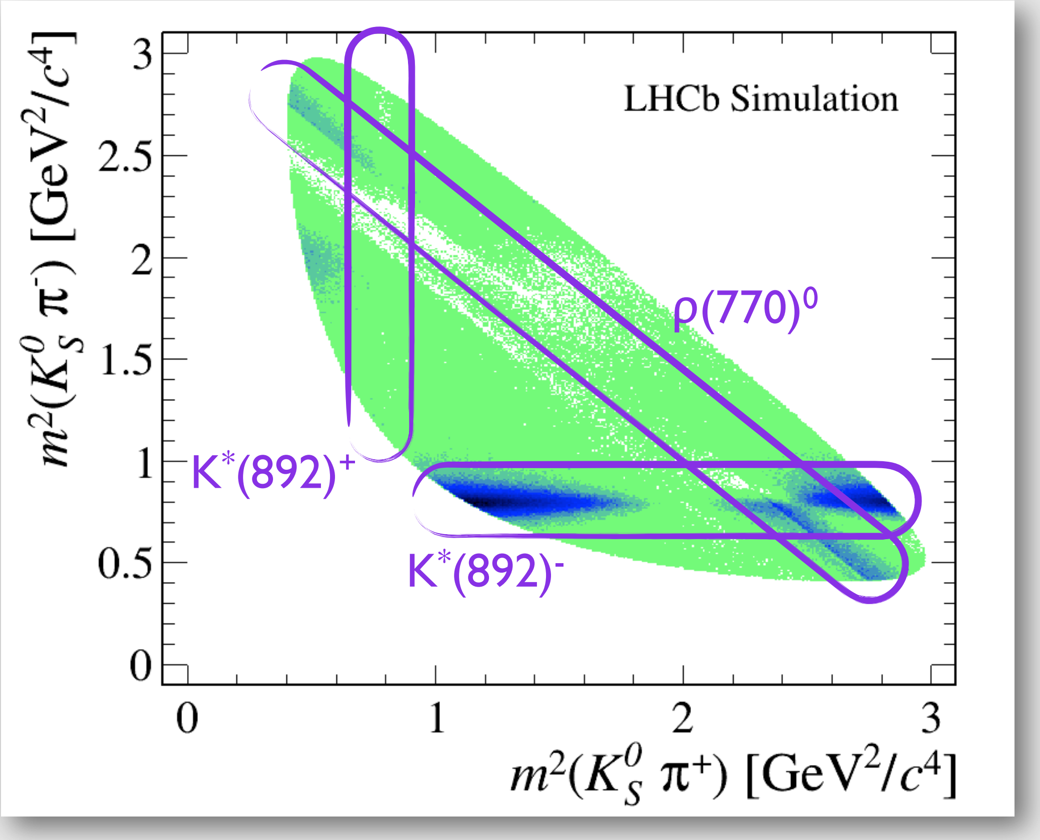
Results

Multi-body decays



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-dependent:
    Fit all contributions to phase-space and look for differences in fit parameters
  - ➡ Model-independent:
    Look for asymmetries in regions of phase space by "counting"



Courtesy of S. Reichert

$D^+ \to 3\pi$

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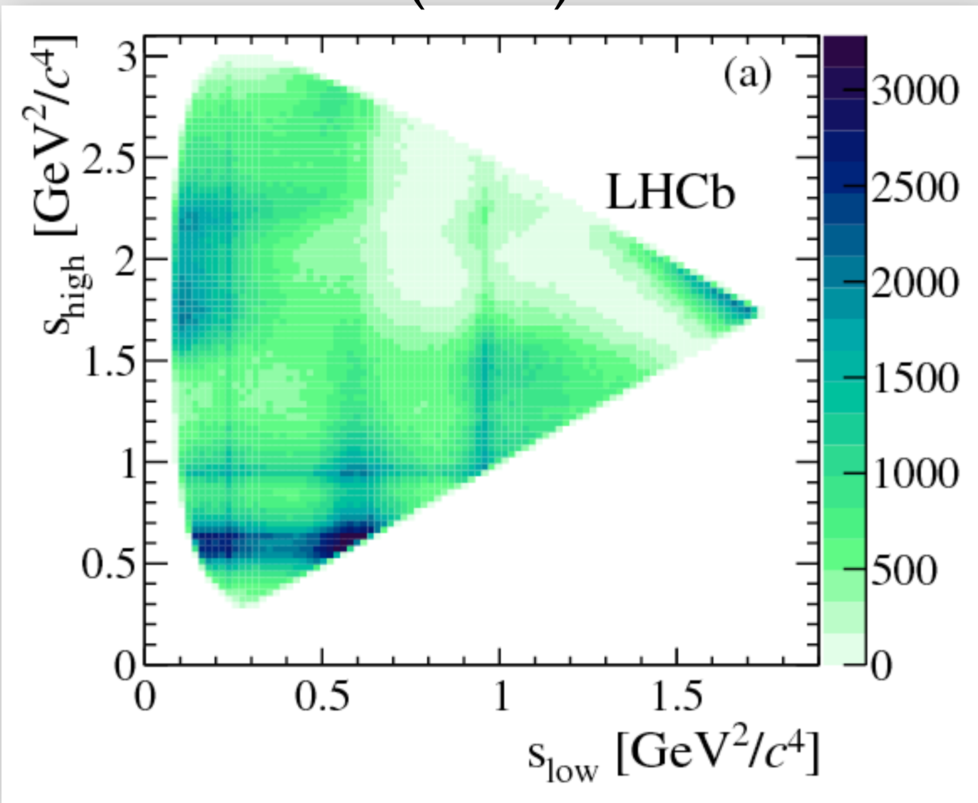

- Model-independent searches for CP violation
  - ➡ Over 3M D^+ & D^- decays in 1 fb^{-1}
  - ➡ Search for asymmetry significances in bins of phase space
  - ➡ Search for local asymmetries through un-binned comparison with nearest neighbours

Binned method

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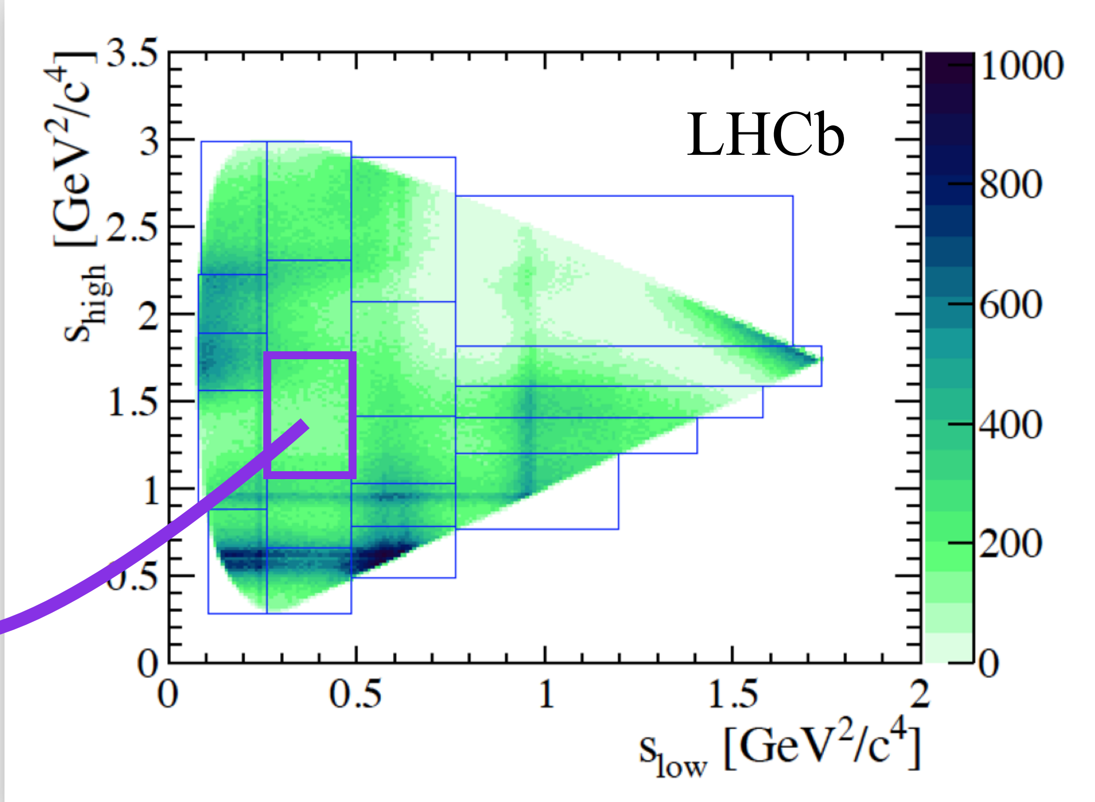

$$\mathcal{S}_{CP}^{i} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

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

removes sensitivity to global asymmetries

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

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

Binned method

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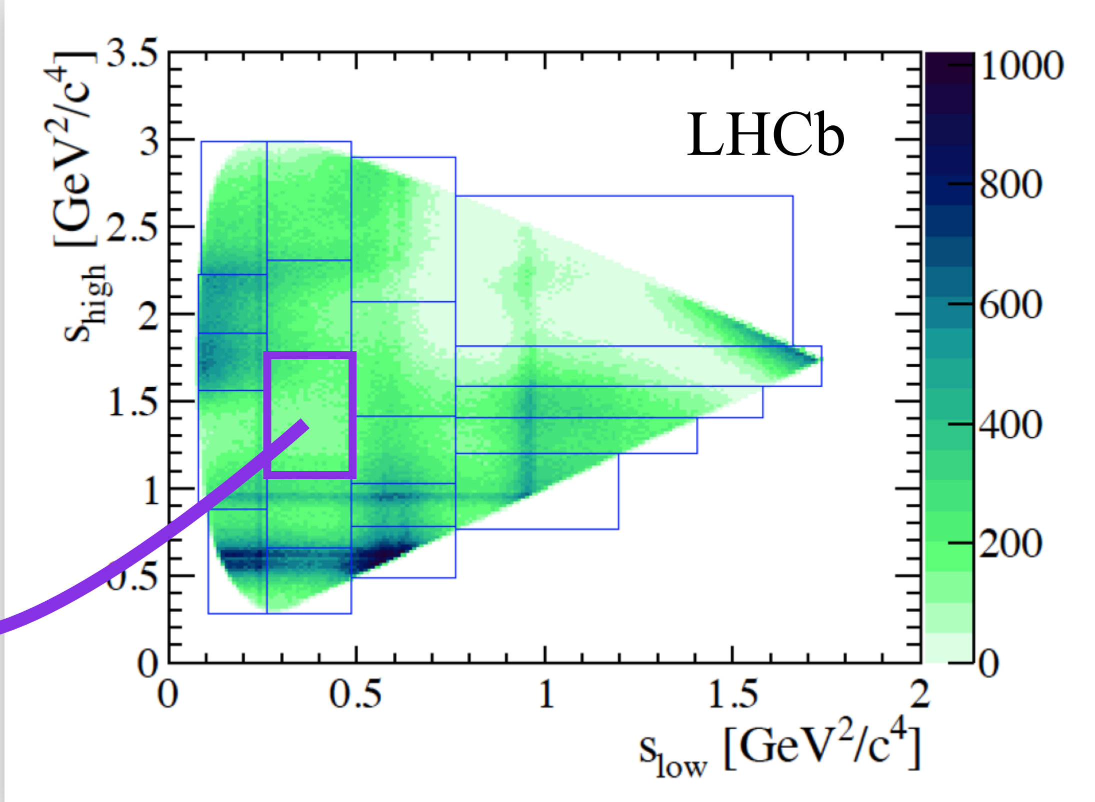


$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

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

removes sensitivity to global asymmetries

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

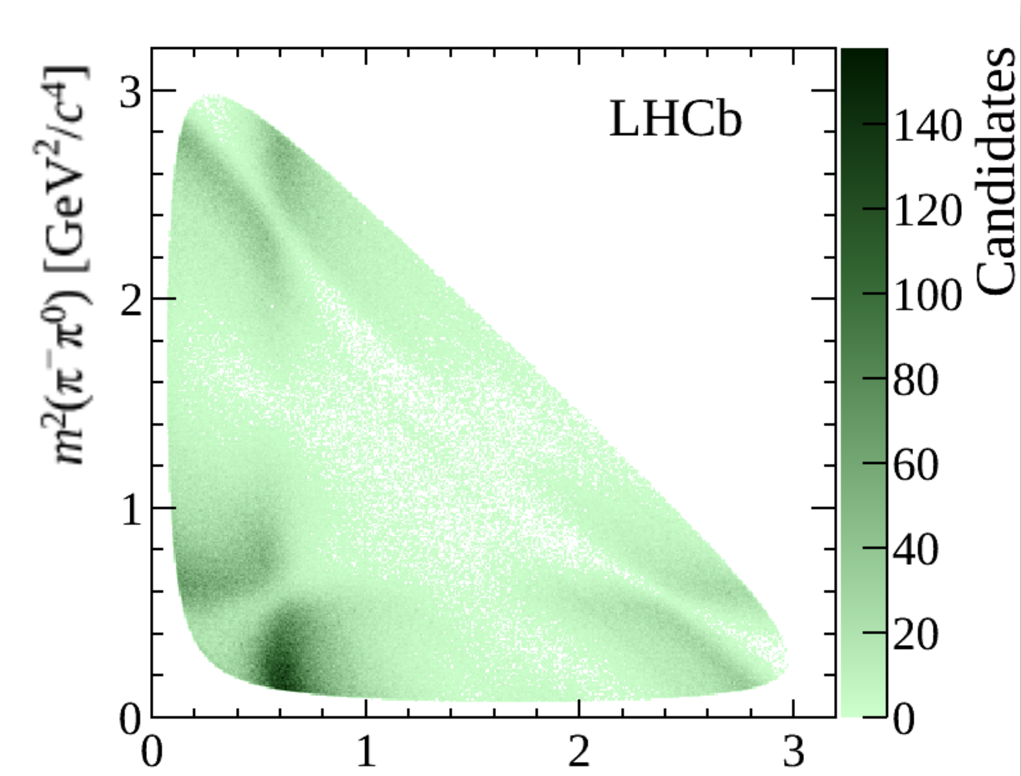
Similar results also obtained with un-binned kNN method*

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

*reduced sensitivity due to inclusion of few neighbours

Why not un-binned?

- 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 in phase space
  - ➡ Compare
    $D^0 \leftrightarrow D^0$
    $\overline{D}^0 \leftrightarrow \overline{D}^0$
    $D^0 \leftrightarrow \overline{D}^0$
  - ➡ Expect T~0 (no CPV) or T>0 (CPV)



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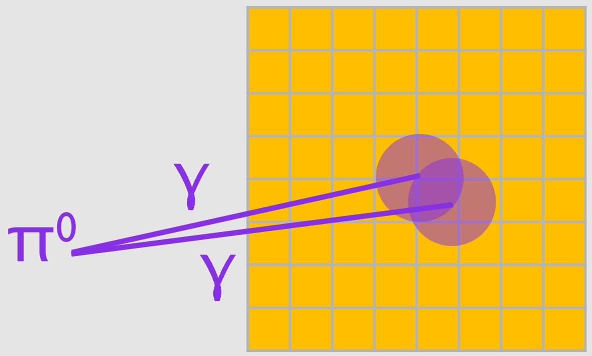
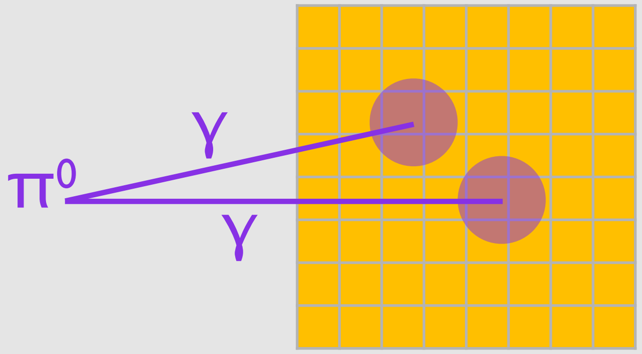
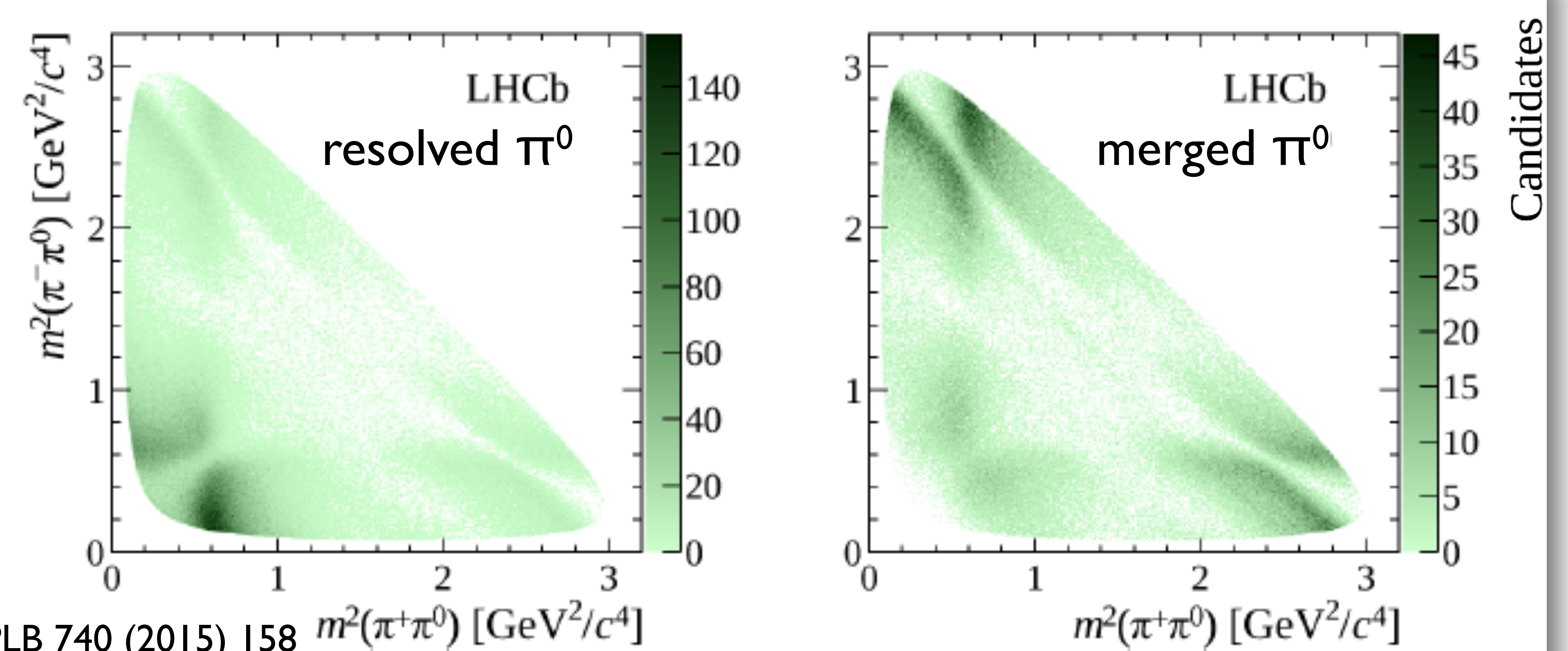
All π^0s

- Reconstructing merged and resolved π^0s
- Merged photon clusters
  - ➡ High energy, small opening angle, small $m(\pi^+\pi^-)$
- Resolved photon clusters (includes conversions)
  - ➡ Small energy, large opening angle, large $m(\pi^+\pi^-)$
- Complementary phase-space coverage







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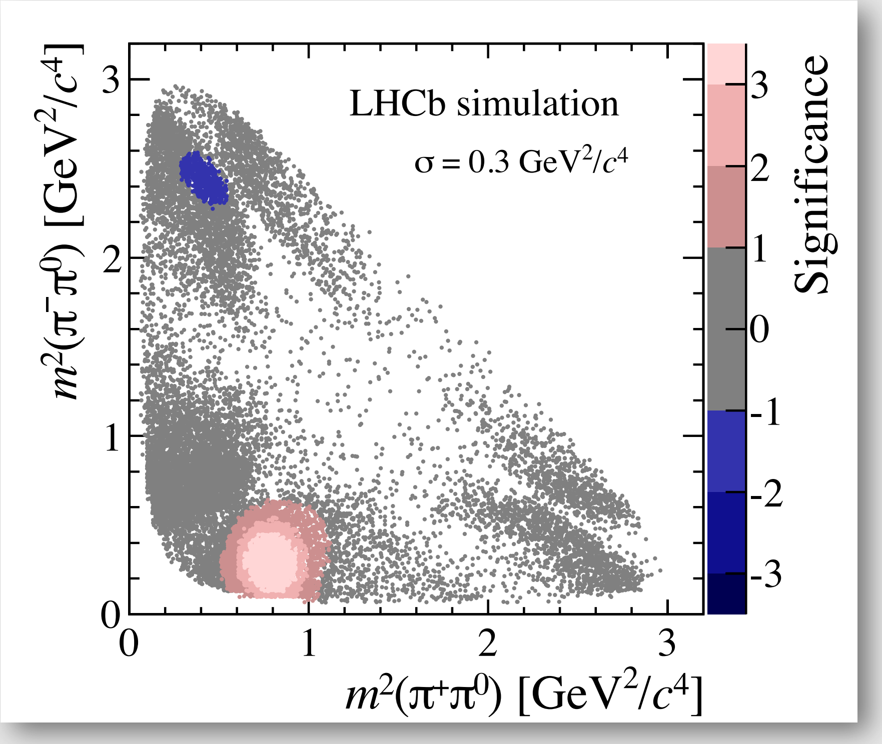
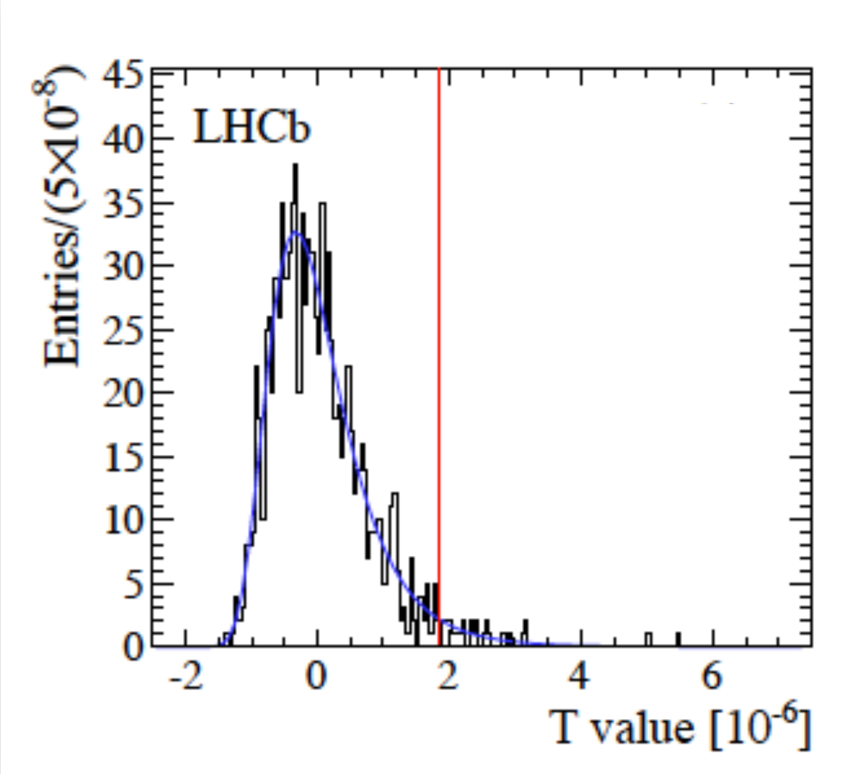
Results

- 8×larger sample than BaBar PRD 78 (2008) 051102
  - ➡ 420k resolved π^0, 250k merged π^0
  - ➡ Similar or better sensitivity
- Using permutations with randomly assigned flavour tags to obtain no-CPV sample
  - ➡ Reference T distribution
- Result based on 1000 permutations
  - ➡ P-value as fraction above nominal T value
  - ➡ (2.6±0.5)%





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CP violation in decay

- Range of new measurements with increasing precision in several decay modes
    - ➡ 2-body (K_Sh, hh)
    - ➡ Multi-body (model-independent, including π^0)
- Route forward:
    - ➡ Measurements in related modes (two-body, resonances) to identify potential sources of CP violation
    - ➡ Model-independent measurements are discovery strategies
    - ➡ Need model-dependent measurements for quantitative interpretation
- Future expectations
    - ➡ See Chris's talk on Friday