Measurement of the CP violation parameter A_Γ with $D^0 \to \pi^-\pi^+\pi^+\pi^-$ decays

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IOP HEPP & APP 2019, Imperial College

Introduction

- CP Violation and mixing in neutral mesons
- CP Violation in the charm sector
- A_Γ
  - Measuring A_Γ
- A_Γ in $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$

CP Violation and mixing in neutral mesons

- CP violation is necessary to explain the matter anti-matter asymmetry of the universe.

1. **CPV in decay:** $|\bar{A}_{\bar{f}} / A_f| \neq 1$
2. **CPV in mixing** : $|q/p| \neq 1$
3. **CPV in interference between decay and mixing**:

$$\phi = \arg(\frac{q\bar{A}_{\bar{f}}}{pA_f}) \neq 0$$

$$\begin{tikzcd}
\overline{D^0} \arrow[rr, "\bar{A}_{\bar{f}}"] \arrow[dr, "q/p"'] & & f \\
& D^0 \arrow[ur, "A_f"'] &
\end{tikzcd}$$

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- Violation of flavour quantum numbers by the weak interaction
  => **mass eigenstates** of neutral mesons are linear combinations of **flavour eigenstates**

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$$

mass eigenstates

flavour eigenstates

Mixing parameters

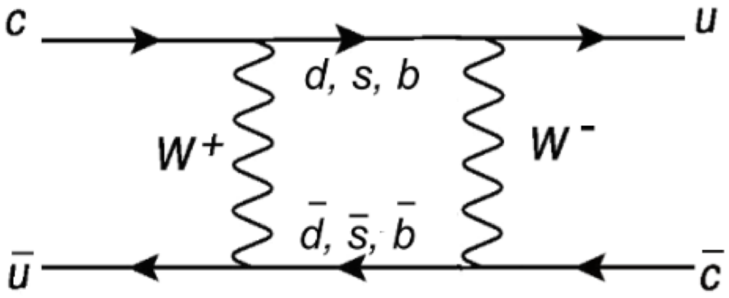
$$x \equiv \frac{m_1 - m_2}{\Gamma}\ ,\ y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma}\ ,\ \phi = \arg\left(\frac{q}{p}\frac{\overline{A_f}}{A_f}\right)$$

Mixing observables

$$\Delta m = m_1 - m_2\ ,\ \Gamma = (\Gamma_1 + \Gamma_2)/2$$
$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

CP Violation in Charm

- **First observation of CPV in charm decays reported by LHCb at the Rencontres de Moriond QCD conference, March 2019.** [arXiv:1903.08726]



- **CPV has not yet been observed in D^0 mixing**
- Charm quarks are the **only up-type quark** that manifests **flavour oscillation**.
  - First single experiment observation of $D^0 - \overline{D^0}$ oscillations reported by LHCb in 2012 [*Phys. Rev. Lett.* 110 (2013) 101802]
  - New physics may be hidden in the loops

- SM predictions of CPV in charm are very small $\sim 10^{-3}$
  - Challenging: large yields and control of systematic uncertainties necessary to obtain required precision.
  - Large production cross-section of charm hadrons at LHC.

- Current experimental sensitivity approaching interesting region where theoretical CPV predictions sit.

A_Γ

- $\boldsymbol{A_\Gamma}$ **measures the time-dependent CPV** for a D^0 decaying to a CP eigenstate final state f.
  - SM expectations: $A_\Gamma < O(10^{-4})$

- Singly cabibbo suppressed decays like $\boldsymbol{D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-}$ are especially sensitive to new physics.
  - Good probe due to high statistics and low systematic uncertainty

- This analysis will be the first measurement of A_Γ in a four-body decay mode.
  - Multi body decays allow for CP asymmetries to be measured across the phase space of the decay.

A_Γ

Due to slow mixing rate of charm mesons ($x, y \sim 10^{-2}$) the **time dependent CP asymmetry** can be approximated at first order as the sum of two terms:

$$A_{CP}(t) = \frac{\Gamma\left(D^0(t) \to f\right) - \Gamma\left(\overline{D^0}(t) \to f\right)}{\Gamma\left(D^0(t) \to f\right) + \Gamma\left(\overline{D^0}(t) \to f\right)} \approx A_{CP}^{dir}(f) + A_{CP}^{ind}(f)\frac{t}{\tau_D}$$

$$A_{CP}^{ind}(f) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\ \phi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi \right]$$

CPV in mixing: $\left|\frac{q}{p}\right| \neq 1$

CPV in interference: $\phi \neq 0, \pi$

A_Γ

- $\boldsymbol{A_\Gamma}$ is defined as the asymmetry between D^0 and $\overline{D^0}$ **effective lifetimes**.

In the limit of small CP violation in the decay:

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}\left(\overline{D^0} \to f\right)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}\left(\overline{D^0} \to f\right)} \approx \boxed{-A_{CP}^{ind}(f)} \qquad \frac{1}{\hat{\Gamma}} = \hat{\tau} = \frac{\int t\Gamma(t)dt}{\int \Gamma(t)dt}$$

Thus $\boldsymbol{A_\Gamma \neq 0}$ indicates indirect CPV in the charm sector, sensitive to both mixing and interference.

A_Γ

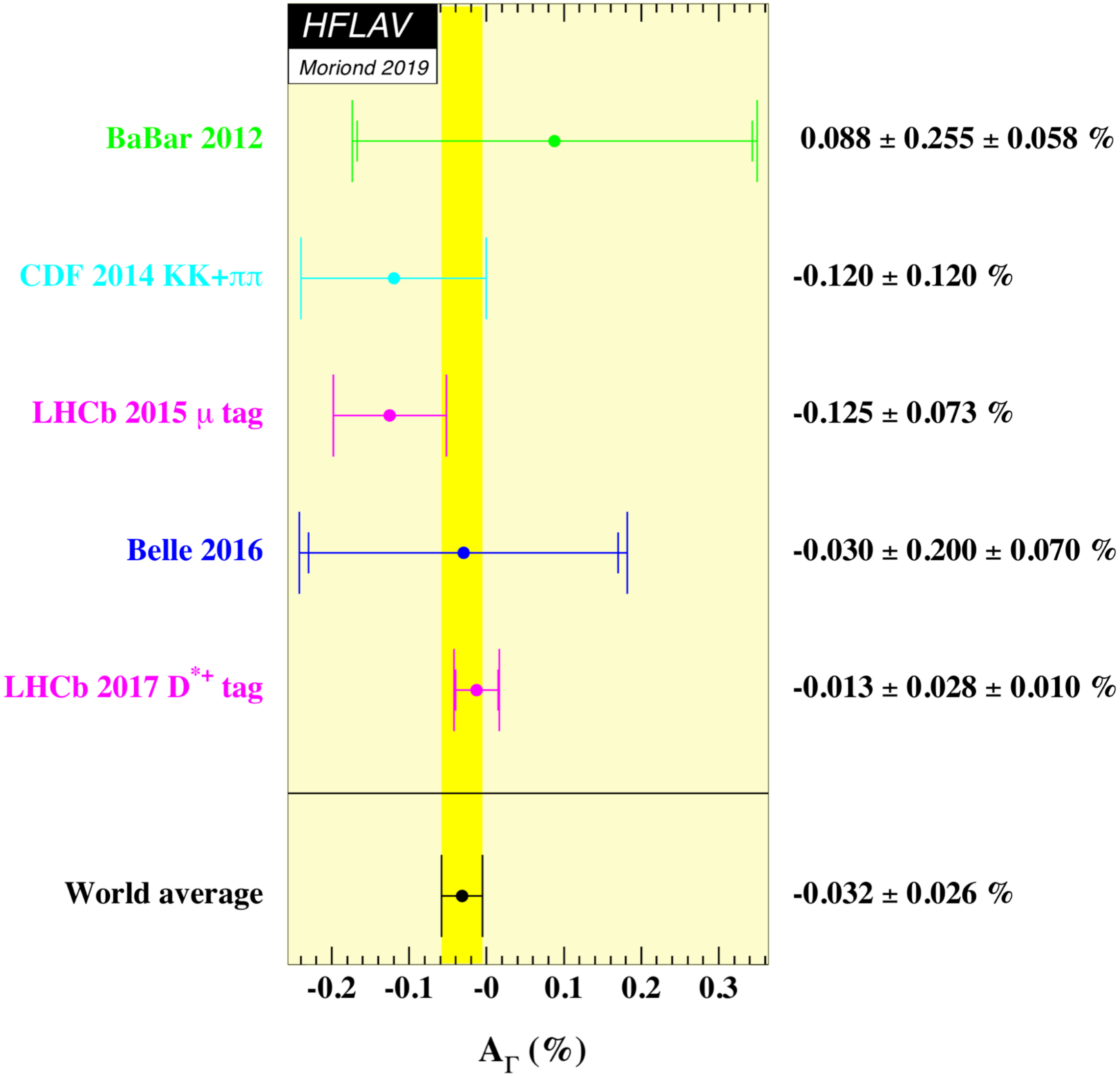
- A_Γ is considered universal for all decays with CP-even final states, in approximation.

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$ is a final state with **mixed** CP content
  - Measured A_Γ picks up a factor of $(2F_+ - 1)$ with respect to pure CP-even or odd final states.
  - F_+ = CP-even content of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ (*Phys. Rev.* **D 91** (2015) 094032)

- $F_+^{4\pi} = (0.769 \pm 0.021 \pm 0.010\ )$
  - CLEO measured result (JHEP01 (2018) 144)
  - A_Γ is determined by multiplying the measured asymmetry by 1.859

Current Experimental Status

- World best measurements of the parameter A_Γ with $\mathrm{D}^0 \rightarrow K^+K^-$ and $\mathrm{D}^0 \rightarrow \pi^+\pi^-$ decays.
- Average is compatible with zero within 3×10^{-4}, dominated by LHCb two-body run 1 measurement.



Plot obtained from HFLAV April 2019

Measuring A_{Γ}

- Measuring the **effective lifetimes** requires precise knowledge of their time-dependent reconstruction efficiency.
- This is **challenging** to achieve at hadron colliders given the decay-time-related requirements of the trigger used.
- Instead measure the **raw asymmetry** between the number of reconstructed D^0 and $\overline{D^0}$ mesons.

$$A_{Raw}(t) = \frac{dN(D^0,t) - dN(\overline{D^0},t)}{dN(D^0,t) + dN(\overline{D^0},t)} \approx A_{CP}(t) + A_D(t) + A_P$$

$$A_{CP}^{dir} - A_{\Gamma}\frac{t}{\tau_{D^0}}$$

A_{Γ} extracted as –ve the slope

Detector induced charge asymmetry. Possible time dependence mimicking fake slope

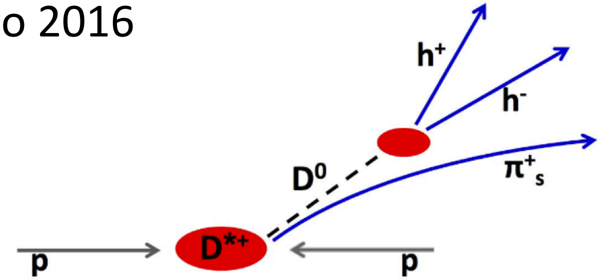
Time-independent production asymmetry

- $A_D(t)$ depends on time due to correlations between the D0 decay time and the π_s momentum used to infer the D0 flavour.
- Bias to A_{Γ} as a result cannot be neglected.

Method first utilised in 2-body A_{Γ} analysis (Phys. Rev. Lett. 118, 261803 (2017))

Analysis Overview

- Use 9 fb^{-1} of data collected at LHCb between 2011 and 2018
  - Today presenting preliminary results from 2011 to 2016



- Need to determine whether decaying D meson is produced as D^0 or $\overline{D^0}$ to perform CPV measurement
  - Strong decays $D^{*+} \to D^0\pi_s^+$
    $D^{*-} \to \overline{D}^0\pi_s^-$

- High statistics $D^0 \to K^-\pi^+\pi^+\pi^-$ control channel used to validate procedure.
  - $A_\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)$ should be zero in the absence of any detector effects.

- $A_\Gamma(D^0 \to \pi^-\pi^+\pi^+\pi^-)$ blinded – artificial gradient + intercept added to asymmetry.

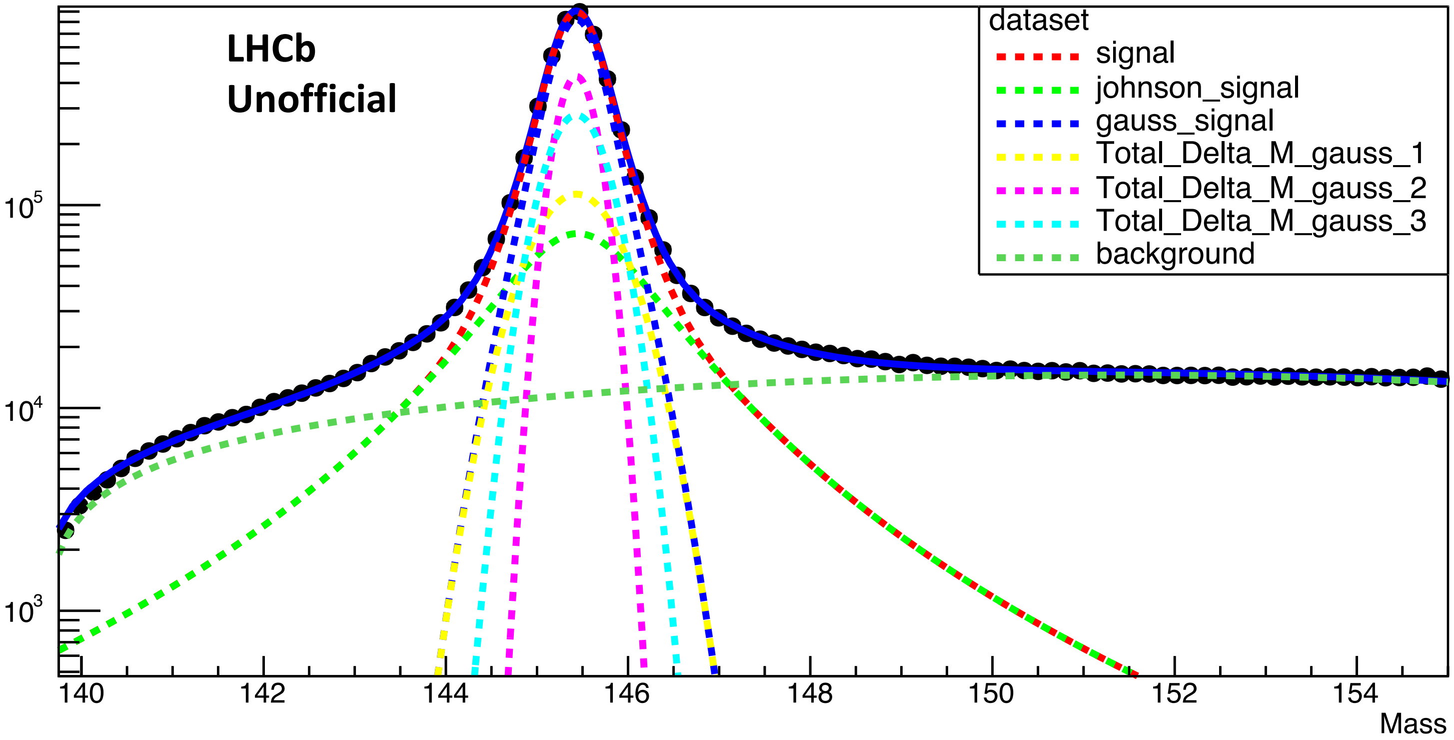
- Samples are split by year and magnet polarity.

- Each sample is split into 30 approximately equally populated decay time bins to 6.0 ps. A_{Raw} measured in each time bin.
- A_Γ is measured through a linear fit to $A_{Raw}(t)$

Fit Model

- Signal: Johnson SU-distribution in Δm [$m(D^{*}) - m(D)$] + 3 gaussians
- Random pion background:
  - $\Delta m : f(\Delta m) = \left(\sqrt{\Delta m \ - \Delta m_{\pi}}\right)[1 + \alpha(\Delta m - m_{\pi}) + \beta(\Delta m \ - \Delta m_{\pi})^{2}]$

$K^{-}\pi^{+}\pi^{+}\pi^{-}$ 2015 MagDown



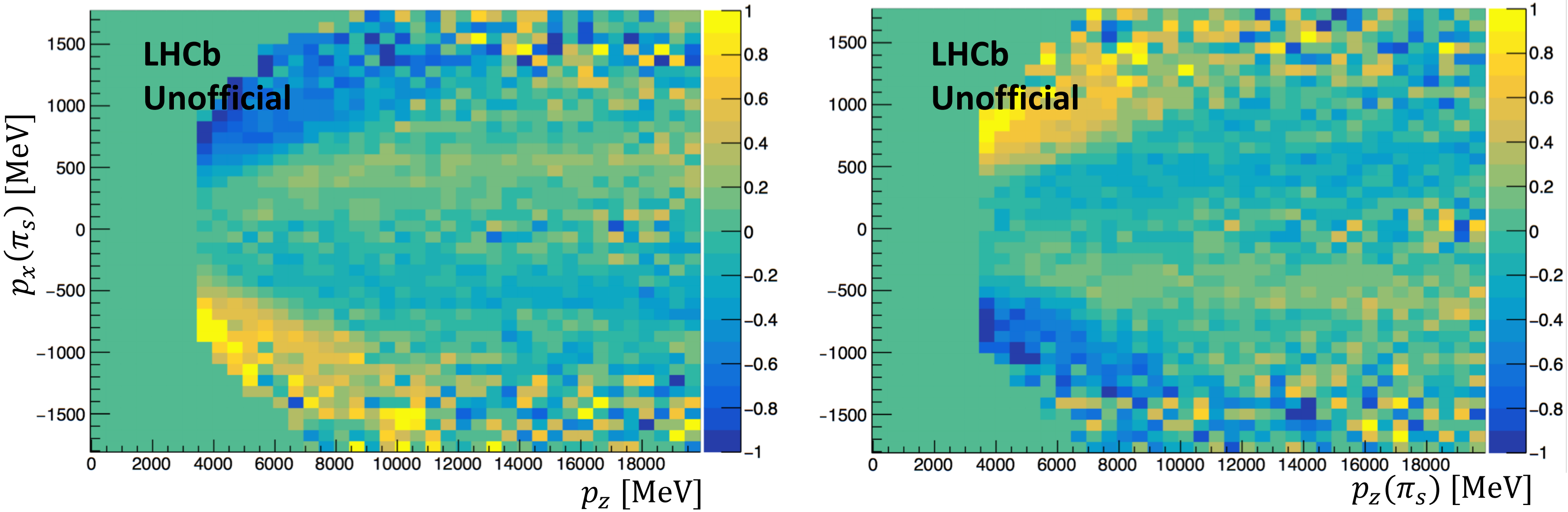
Momentum charge asymmetries

$$A_{Raw}(t) = \frac{dN(D^0,t) - dN(\overline{D^0},t)}{dN(D^0,t) + dN(\overline{D^0},t)} \approx A_{CP}^{direct} - A_\Gamma \frac{t}{\tau_{D^0}} + A_D(t) + A_P$$

LHCb detector acceptance not CP-symmetric over the whole space

In reconstruction and selection of the π_s charge asymmetries are present and strongly depend on the π_s momentum.

Averaging between magnet up and magnet down polarities does not necessarily eliminate this problem with the degree of precision needed due to variation of run conditions over time.



Raw asymmetry of soft pion charges in p_x against p_z for 2012 MagUp(left) and MagDown (right)

Reweighting

To restore the CP symmetry a correction is applied in time-integrated $(C, q_{\pi_s}\theta_x, \theta_y)$ distribution, where C is proportional to track curvature in the magnetic field, q_{π_s} is the charge of the soft pion, and θ_x θ_y are the pion emission angles in the bending and vertical planes, respectively.

$$C = \frac{1}{\sqrt{p_x^2 + p_z^2}}$$

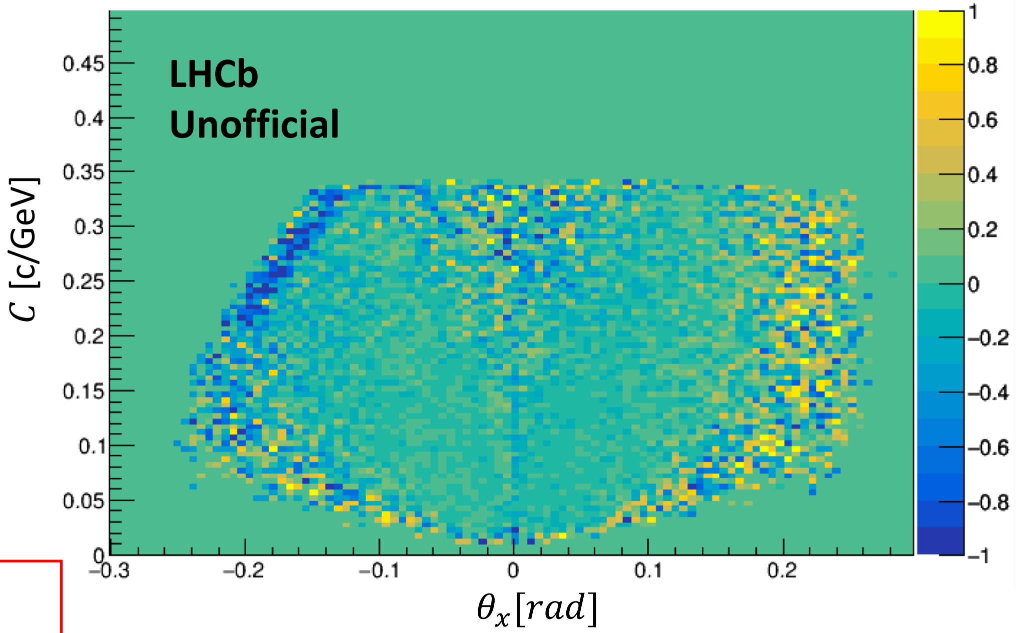
$$\theta_x = \arctan\left(\frac{p_x}{p_z}\right)$$

$$\theta_y = \arctan\left(\frac{p_y}{p_z}\right)$$

Reweigh the 3D momentum distributions of p+ and pi- to make them equal

$$\mathrm{N}^+(C, \theta_x, \theta_y) = N^-(C, -\theta_x, \theta_y)$$

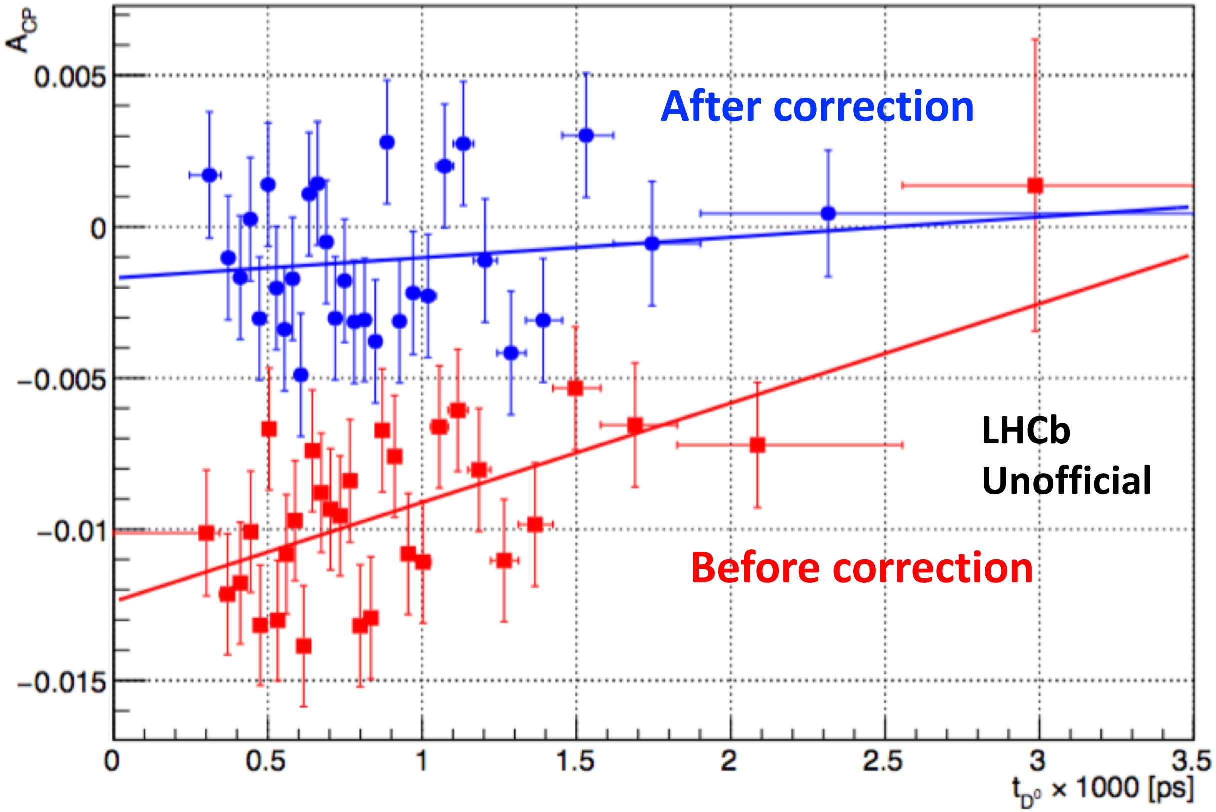
$$\sqrt{\omega_{i,j,k}} = \sqrt{\frac{\Sigma_\alpha n^{\alpha+}_{i,-j,k}}{\Sigma_\alpha n^{\alpha-}_{i,-,k}}} \quad \text{and} \quad \sqrt{\nu_{i,j,k}} = \sqrt{\frac{\Sigma_\alpha n^{\alpha-}_{i,-j,k}}{\Sigma_\alpha n^{\alpha+}_{i,-,k}}}$$



Time-integrated raw asymmetry in $(C, q_{\pi_s}\theta_x)$ of 2011 MagUp

Reweighting

A_Γ is inconsistent with zero before weighting, and consistent after weighting.



After reweighting both the intercept and slope become consistent with zero demonstrating CP symmetry has been restored

Magdown 2012

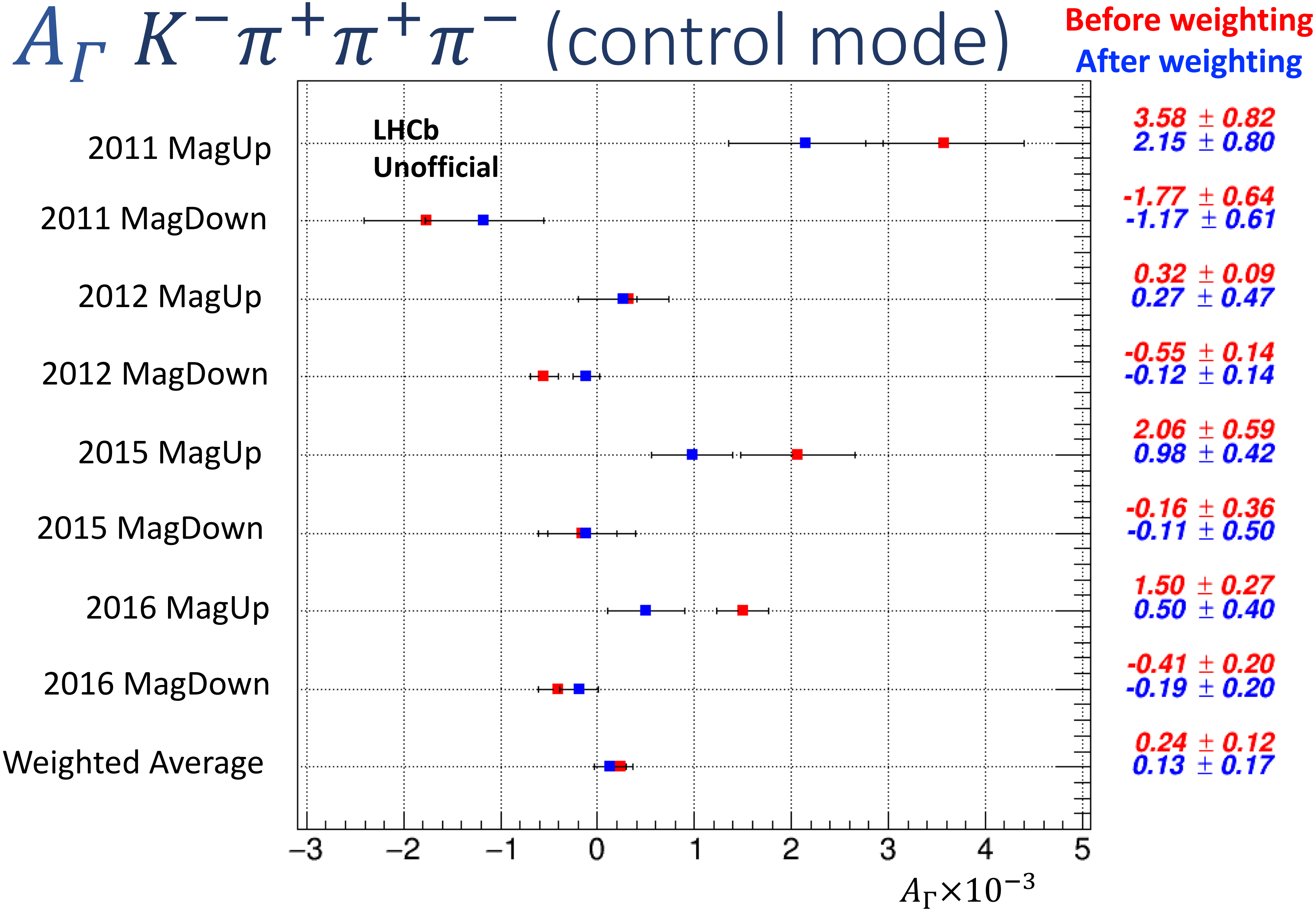
Before:

$$A_\Gamma^{K3\pi} = -(0.55 \pm 0.14) \times 10^{-3}$$

After:

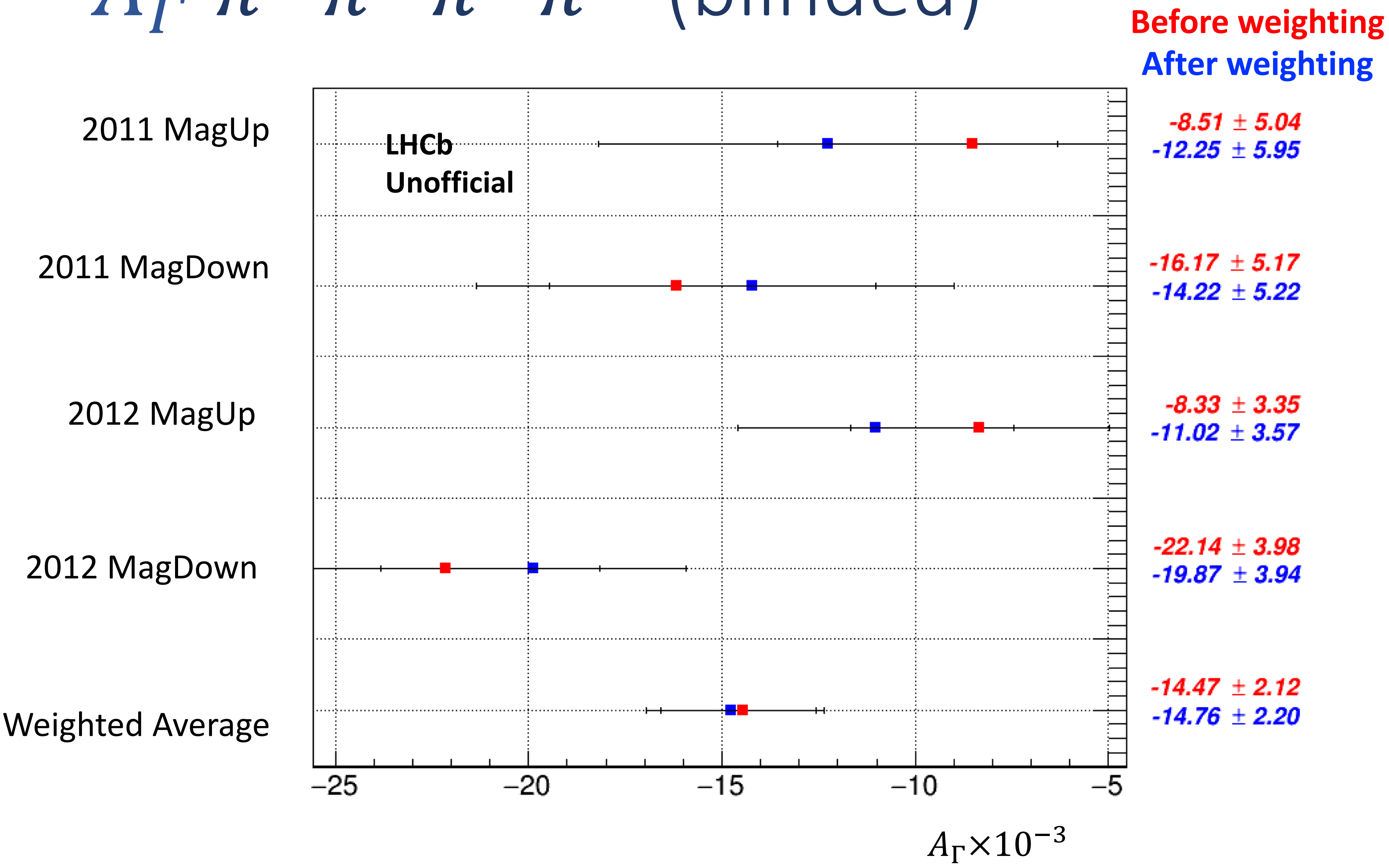
$$A_\Gamma^{K3\pi} = -(0.12 \pm 0.14) \times 10^{-3}$$

$A_{\Gamma}\ K^{-}\pi^{+}\pi^{+}\pi^{-}$ (control mode)



$A_{\Gamma}\ \pi^{-}\pi^{+}\pi^{+}\pi^{-}$ (blinded)

Scale factor applied



Systematics

Possible sources of systematic uncertainty to be considered:

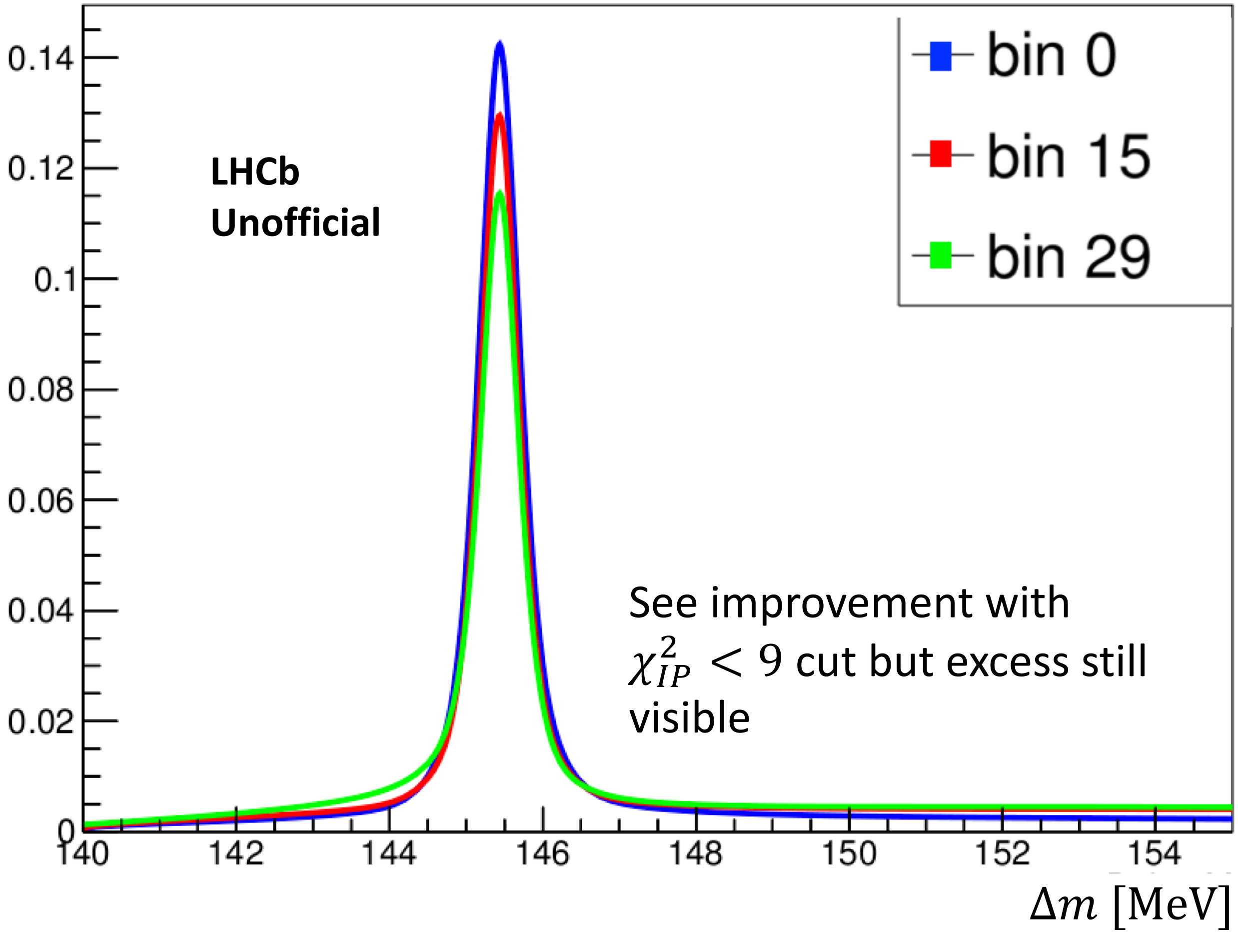
- Contribution of secondaries
  - D* not from primary vertex of an interaction
  - Suppressed by cut on χ_{IP}^2 but some may still be present
- Fitting procedure
- Reweighting procedure
- Uncertainty on F_+
  - Should translate to uncertainty of relative size on A_Γ
- Efficiency as function of phase space

Conclusion

- A_Γ is a sensitive probe of CP violation in the charm sector.
- Preliminary results of A_Γ $(\pi^-\pi^+\pi^+\pi^-)$ presented.
- Expected uncertainty of ~10^{-3}on A_Γ with full dataset.

Backup

DTF and Δm



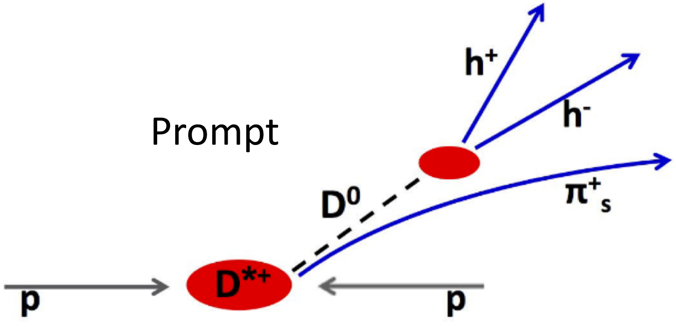
$D^0 \to K^-\pi^+\pi^+\pi^-$ 2015 MagUp

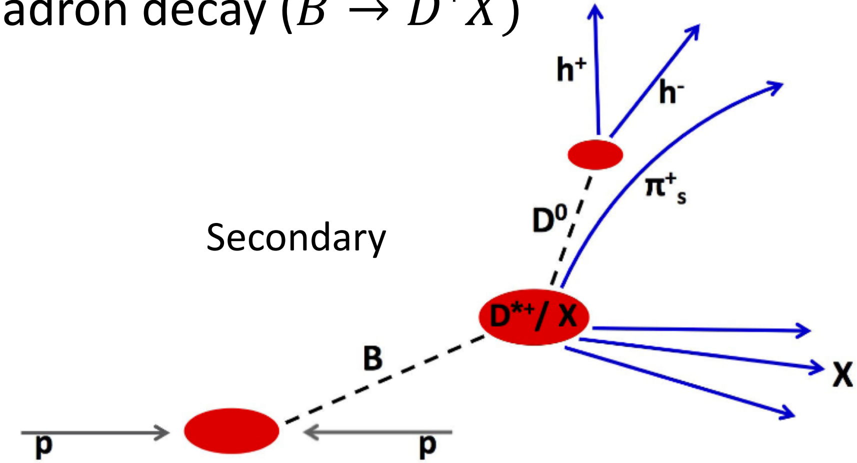
See improvement with $\chi^2_{IP} < 9$ cut but excess still visible

- Decay Tree Fitter
  - Forces D^{*+} DV to coincide with the PV
  - Produces a time-dependent artificial tail in Δm due to secondary decays
  - Excess is largest in highest decay time bin
  - DTF is not used in this analysis

Secondary decays

- Source of background
- $D^{*+} \rightarrow D^0\pi^+$ decays have two components:
  - Prompt: D^*coming from the primary vertex of an interaction
  - Secondary: D^*coming from a B hadron decay ($B \rightarrow D^*X$)





- Secondaries contribute to A_raw(t) because the fraction of secondary decays depends strongly on reconstructed decay time.
- Systematic uncertainty must be applied if not accounted for.