Observation of *CP* violation in charm decays

Tracking Meeting

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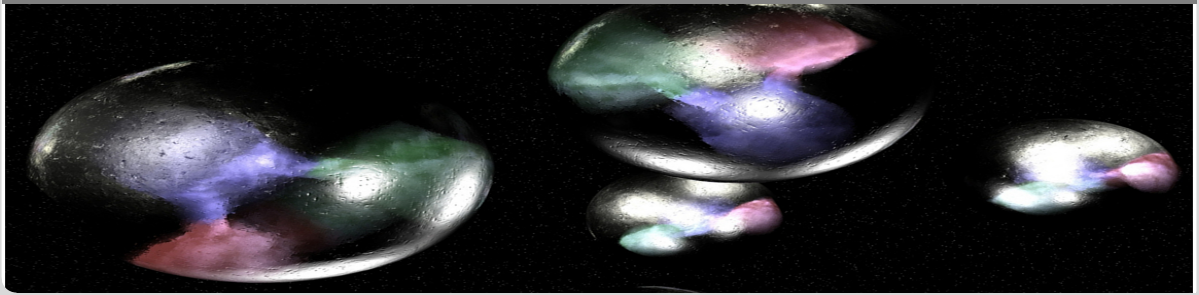
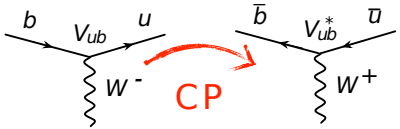


CP violation in the Standard Model

- *CP*-violation (CPV): breaking of the invariance with respect to the combined transformation **charge conjugation (*C*)** and **parity inversion (*P*)**
- Sakharov: theoretical requirement for **baryon-asymmetry** of the universe
- arises in SM from a non-vanishing complex phase for a **quark mixing** matrix with 3 (V_{CKM}) or more generations
- **suppressed for charm** $\mathcal{O}(A_{CP}) = 10^{-4} - 10^{-3}$



$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\phi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\phi} & -\lambda^2 & 1 \end{pmatrix} \end{array}$$

$(\lambda \approx 0.22)$

Reminder: Different types of CPV

CPV in decay (direct):

$$\Gamma(M \to f) \neq \Gamma(\bar{M} \to \bar{f})$$

CPV from mixing (indirect)

$$\Gamma(M^0 \to \bar{M}^0) \neq \Gamma(\bar{M}^0 \to M^0)$$

CPV from interference of mixing and decay

$$\Gamma(M^0 \to f_{CP}) \neq \Gamma(\bar{M}^0 \to f_{CP})$$

Motivation: Why bother?

CPV discoveries so far

1956 Wu: Discovery of parity violation

1964 Cronin, Fitch: CPV in K decays (mixing)

1973 Kobayashi, Mask's: CKM matrix

1999 NA31/48, KTeV: Direct CPV in K decays

2001 BaBar and Belle: CPV in $B^0 \to J/\psi K^0_S$
$\Rightarrow$ CPV well-established

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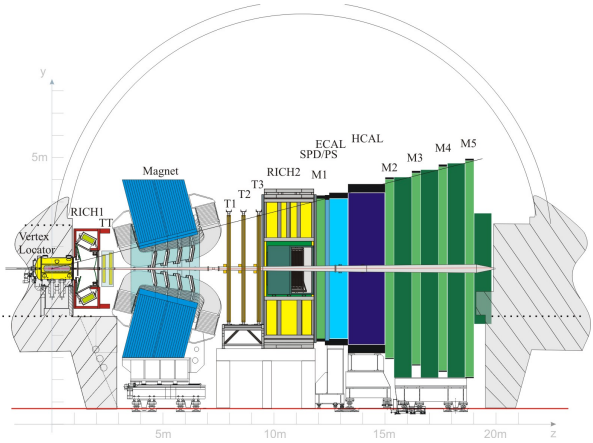
Motivation for charm studies

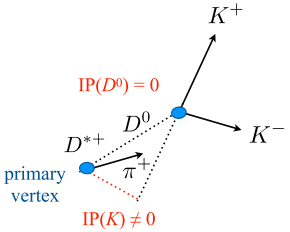
- CPV **too low in SM** to explain baryon-asymmetry
  $\to$ NP contributions?
- small SM CPV in charm $\to$ **sensitive to NP**
- CPV with **up-type quarks**
- theory challenge: low-energy QCD

The LHCb Experiment

- “single-arm forward spectrometer”
- *pp* @ 13 TeV: large cross-section for B and D-meson production
- large boosts $\rightarrow$ displaced vertices
- good PID capabilities
- analysis used 5.9 fb^{-1}
- triggers: 1 hardware, 2 software (“turbo stream” online reco)

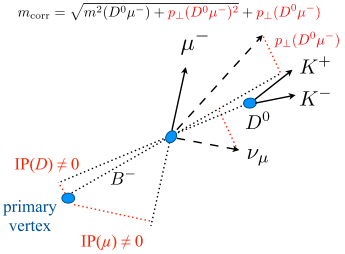


Tagged $D^0 \to K^+K^-/\pi^+\pi^-$ decays at LHCb



π tagged

- prompt decays $D^{*+} \to \pi^+ D^0 (\to h^+h^-)$
- kaons/pions from D^0 form displaced vertex
- pion charge determines flavor, forms D^{*+}vertex at primary vertex



μ tagged

- semileptonic B decays $B^- \to \mu\overline{\nu}_\mu D^0 (\to h^+h^-)$
- muon paired with D^0 at displaced vertex tags flavor
- m_{corr} is the D^0 μ^- mass corrected for the missing neutrino p_T

Measuring charge asymmetry

- CP asymmetry (time-integrated)

$$A_{CP}(\mathrm{D}^0 \to h^+h^-) = \frac{\Gamma(\mathrm{D}^0 \to h^+h^-) - \Gamma(\overline{\mathrm{D}}^0 \to h^+h^-)}{\Gamma(\mathrm{D}^0 \to h^+h^-) + \Gamma(\overline{\mathrm{D}}^0 \to h^+h^-)}$$

- Raw measured asymmetry

$$\begin{aligned} A_{\mathrm{raw}}(\mathrm{D}^0 \to h^+h^-) &= \frac{N(\mathrm{D}^0 \to h^+h^-) - N(\overline{\mathrm{D}}^0 \to h^+h^-)}{N(\mathrm{D}^0 \to h^+h^-) + N(\overline{\mathrm{D}}^0 \to h^+h^-)} \\ &\approx A_{CP}(\mathrm{D}^0 \to h^+h^-) + A_D(\pi/\mu) + A_P(\mathrm{D}^*/\mathrm{B}^-) \end{aligned}$$

  - A_D detection asymmetries: charge-dependent reconstruction efficiencies for pions/muons
  - A_P production asymmetries: from hadronization asymmetries of D^* and b in pp-collisions

What is measured: ΔA_{CP}

- detection and production asymmetries **cancel in difference**

$$\begin{aligned} \Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &\approx A_{\mathrm{raw}}(K^+K^-) - A_{\mathrm{raw}}(\pi^+\pi^-) \end{aligned}$$

- Interpretation: Approx. the CP asymmetry in first order via

$$A_{CP}(f) \approx a^{\mathrm{dir}}_{CP}(f) - \frac{\langle t(f) \rangle}{\tau(D^0)} A_\Gamma(f) \Rightarrow \Delta A_{CP} \approx \Delta a^{\mathrm{dir}}_{CP} - \frac{\Delta \langle t \rangle}{\tau(D^0)} A_\Gamma$$

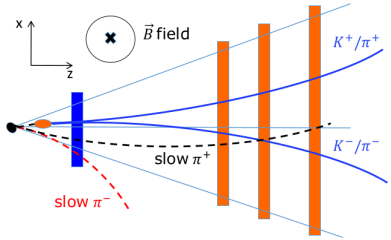
$\Delta a^{\mathrm{dir}}_{CP}$: difference in **direct CP asymmetry**

$\frac{\Delta \langle t \rangle}{\tau(D^0)}$: ≈ 0.1, diff. in mean reconstructed $D^0 \to h^+h^-$ decay times normalized to D^0 lifetime

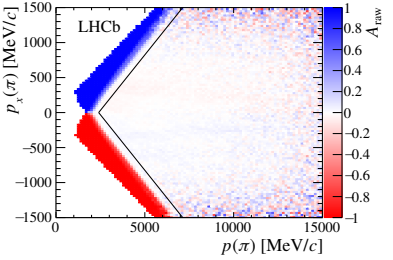
A_Γ: asymmetry of $D^0/\overline{D}^0 \to h^+h^-$ effective decay widths, $\mathcal{O}(10^{-4})$ in SM

Event selection: Fiducial requirements

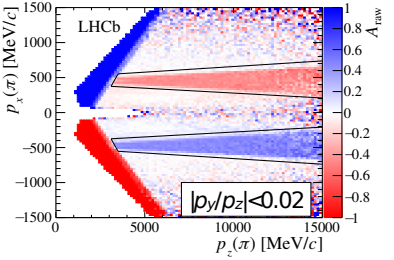
- exclude kinematic regions, where tagging pions of only a specific charge curve out of the acceptance
- high $A_D \Rightarrow$ raw asymmetry close to 100%



soft pions **leave outer acceptance**

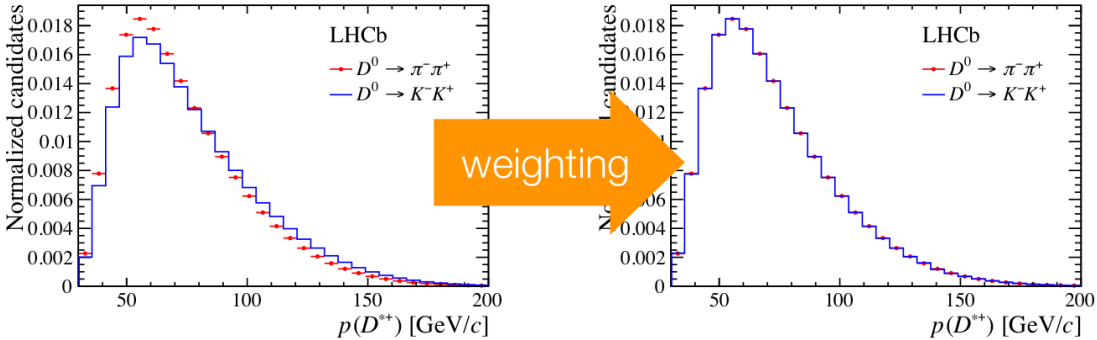


soft pions enter **beam-pipe**



Reweighting of kinematic distributions

- A_D and A_P depend on kinematics
- might not cancel well if kin. distributions of $D^0 \to f$ differ for $f = K^+K^-$ and $f = \pi^+\pi^-$
- $\Rightarrow$ **event-by-event reweighting** of K^+K^- sample in p_T, η, ϕ of D^{*+}/ D^0
- result: effect on ΔA_{CP} below 10^{-4}

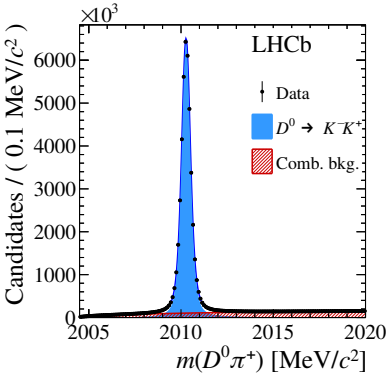


A_{raw} measurement: Fit of mass distributions

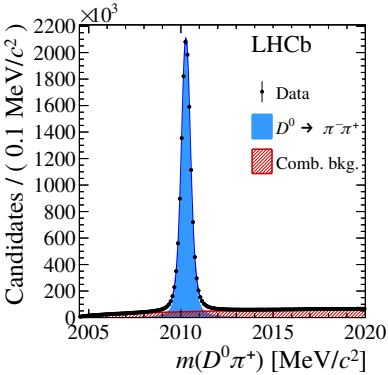
- extract A_{raw} signal by simultaneous least-squares fits of **binned mass distributions**
- advantage: distributions the same for $\mathrm{K}^+\,\mathrm{K}^-$ and $\pi^+\,\pi^-$
- **π tagged**
  - simultaneous fit of $m(\mathrm{D}^0\pi^+)$ and $m(\overline{\mathrm{D}}^0\pi^-)$
  - A_{raw} parameter shared
  - signal mass model: sum of 3 gaussians and Johnson S_U function (“asymm. gaussian”)
  - background: empirical function of two free parameters
- **μ tagged**
  - simultaneous fit of $m(\mathrm{D}^0)$ and $m(\overline{\mathrm{D}}^0)$
  - A_{raw} parameter shared
  - signal mass model: sum of 2 gaussians convolved with truncated power law for FSR
  - background: exponential function
  - feed-down from $\mathrm{K}^+\,\pi^-$ modeled as tail of additional gaussian

Fit results: π tagged

$K^+ K^-$ final states

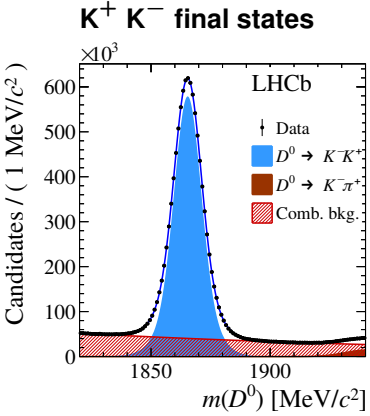


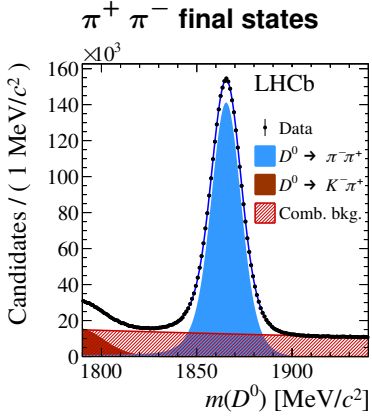
$\pi^+ \pi^-$ final states



- 44 and 14 million $K^+ K^-$ and $\pi^+ \pi^-$ events, respectively

Fit: μ tagged





- 9 and 3 million $K^+ K^-$ and $\pi^+ \pi^-$ events, respectively

Systematic uncertainties

- **π-tagged systematics** dominated by
  - fit model
    (from from fitting alternative models to toy-MC)
  - misreconstructed background peaking in $m(\mathrm{D}^0\pi^+)$ and not in $m(\mathrm{D}^0)$
    (from yield and asymmetries of backgrounds on $m(\mathrm{D}^0)$ distributions)
- **μ-tagged systematics** dominated by
  - mistag: wrong muon
    from $\mathrm{K}^-\ \pi^+$ control sample
  - B reconstruction efficiency as function of decay time between $\mathrm{K}^+\ \mathrm{K}^-$ and $\pi^+\ \pi^-$, might worsen cancellation of A_P

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Results

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2(\text{stat.}) \pm 0.9(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8(\text{stat.}) \pm 5(\text{syst.})] \times 10^{-4}$$

Combined

$$\Delta A_{CP} = (-15.4 \pm 2.9)) \times 10^{-4}$$

- 5.3σ significance for deviation from 0
- first observation of *CP* violation in charm

Results II and outlook

With A_Γ and $\Delta < t >$ from LHCb averages and world average D^0 lifetime:

$$\Delta a_{CP}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4} \Rightarrow \text{mostly direct CPV}$$

- results at upper limit but compatible with SM
- further measurements and theoretical improvements necessary

Thanks for listening