Searches for CP violation in charm at LHCb

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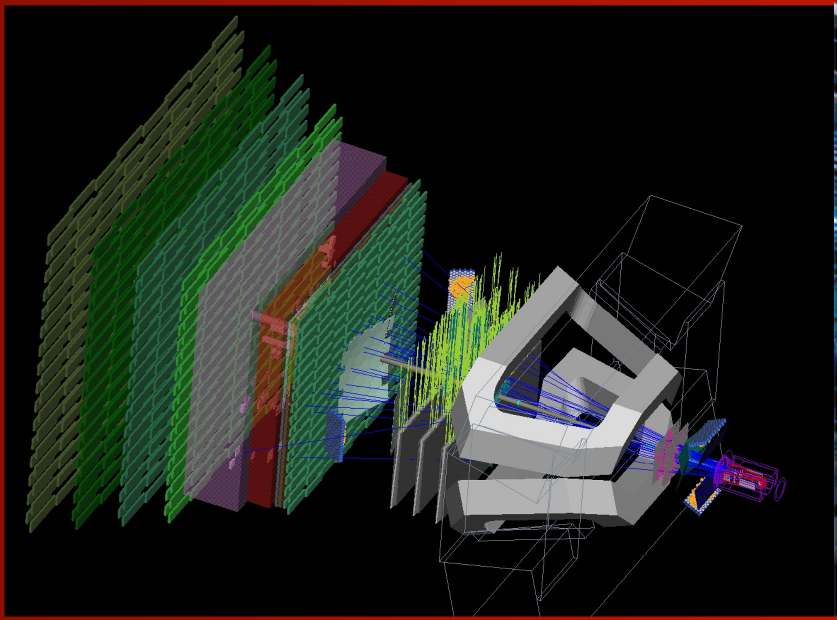
on behalf of the LHCb collaboration



LHCb Charm CP Violation (CPV) talks (at Charm)

Measurements of time-integrated CP and other asymmetries

Marco Gersabeck
19 May

Measurements of mixing and indirect CP violation

Stefanie Reichert
20 May

Measurements of T-odd observables

Maurizio Martinelli
20 May

Searches for CPV in charm

now

Also relevant to CPV in Charm at LHCb

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Searches for CPV in charm

now

The Future of Charm Physics at LHCb

CPV, and more

Chris Parkes
22 May

Outline

- Introduction
- The LHCb Detector
- Flavor tagging neutral D mesons at LHCb
- Searches for Direct CP Violation
- Searches for Indirect CP Violation
- Conclusion

Charm at LHCb?

- We are most certainly a B physics experiment. However…
- The same properties that optimize LHCb for B physics also make LHCb **an excellent charm physics experiment**.

- The charm cross section is ~20 times larger than the b cross section.
  - **$\sigma(c\bar{c})_{LHCb} = 1419 \pm 133\ \mu b$ (Nucl. Phys. B 871 (2013), 1)** @ $\sqrt{s} = 7$ TeV
  - **$\sigma(b\bar{b})_{LHCb} = 75.3 \pm 14.1\ \mu b$ (Phys. Lett. B 694 (2010), 209)**
- ~5 trillion $c\bar{c}$ were produced during LHC Run 1, in our acceptance!

- LHCb can make precision measurements in charm
  with high sensitivity to New Physics hiding in quantum loops…
  - We have the world's best sensitivity to **CP violation** in charm.

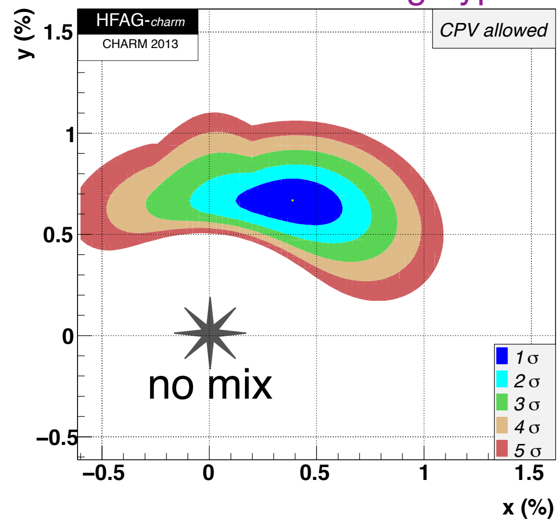
- Boosted quarks, high rapidities: ideal for studying time-dependent effects

Knowledge of the Neutral Charm System in 2013

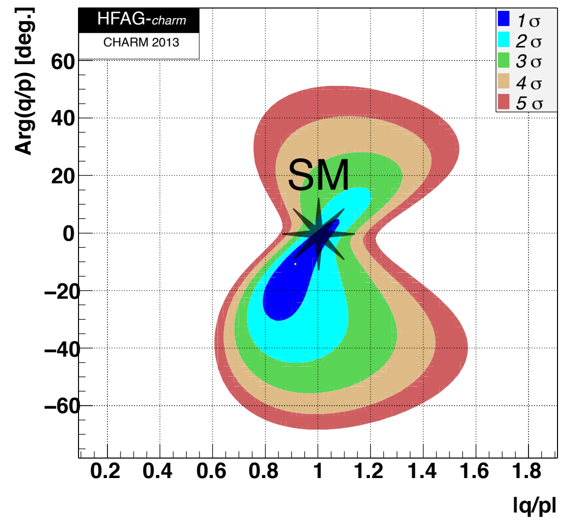
- D^0, the only mixing meson with up-type quarks.
- Neutral D mass eigenstates: $D_{1,2} = p|D\rangle \pm q|\bar{D}\rangle$
  $\phi = \arg(q/p)$
  - $x = \dfrac{m_2 - m_1}{\Gamma}$ ~mixing frequency
  - $y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$ ~lifetime difference
- CP violation if $|q/p| \neq 1$ or CPV phase $\phi \neq 0$
- $x = (0.39 \pm 0.17)\%$, $y = (0.67 \pm 0.08)\%$
- $|q/p| = 0.91 \pm 0.11$, $\phi = -10.8^\circ \pm 12.3^\circ$

Averages by HFAG (Charm 2013)
The errors on x, |p/q|, and ϕ are asymmetric, I show the larger error.

Inconsistent w/no-mixing hypothesis



Consistent with no CPV



Where do we look for CPV in charm?

- No CPV weak phase in charm flavor transitions.

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

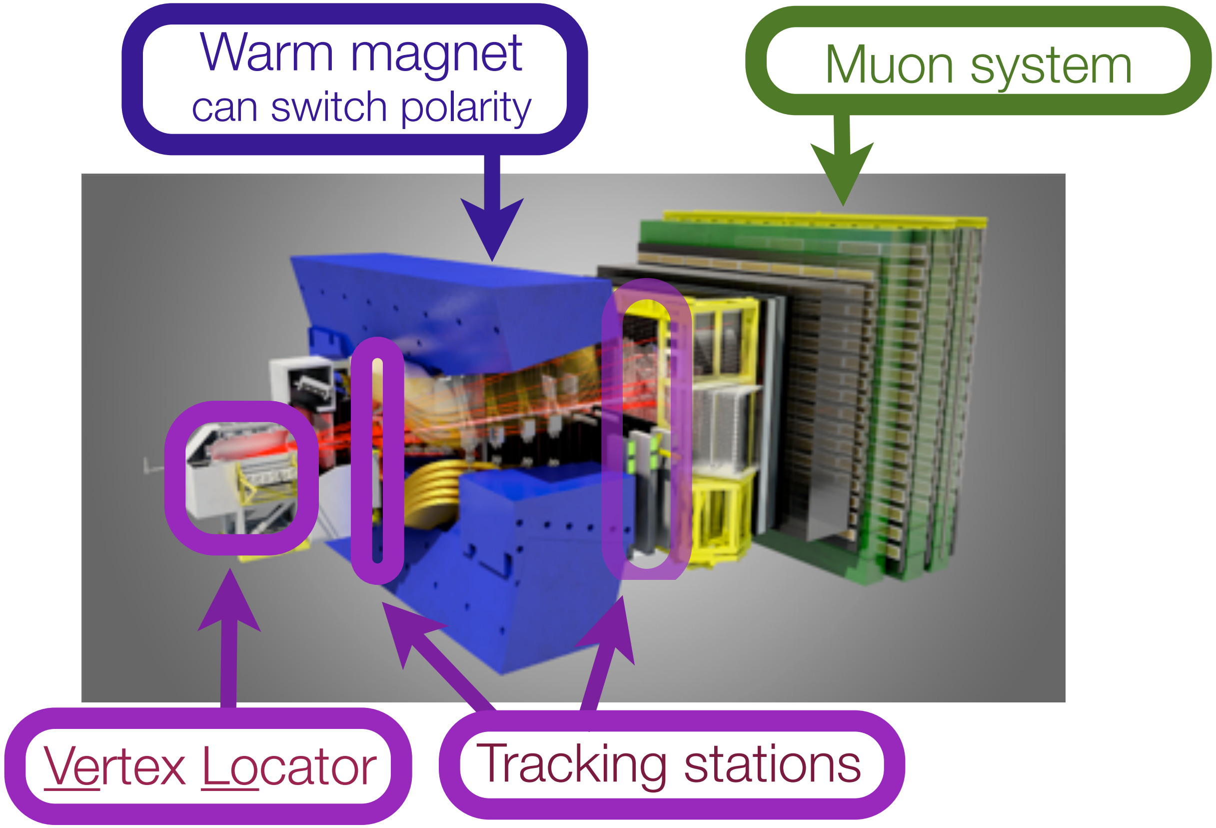
- V_{ub} and it's associated weak phase may enter via quantum loop.
  - In Cabibbo-favored (CF) decays the amplitudes of these diagrams are dominated by the tree process.
  - In singly Cabibbo-suppressed (SCS) decays, loop diagrams can contribute.

- Standard Model (SM): x, y at most 1%, small CPV
  - O(1%) CPV could mean potential new physics in the loops

- Indirect (mixing-induced) CPV searches look at SCS decays, but can also exploit interference between CF decay (after mixing) and DCS decay.

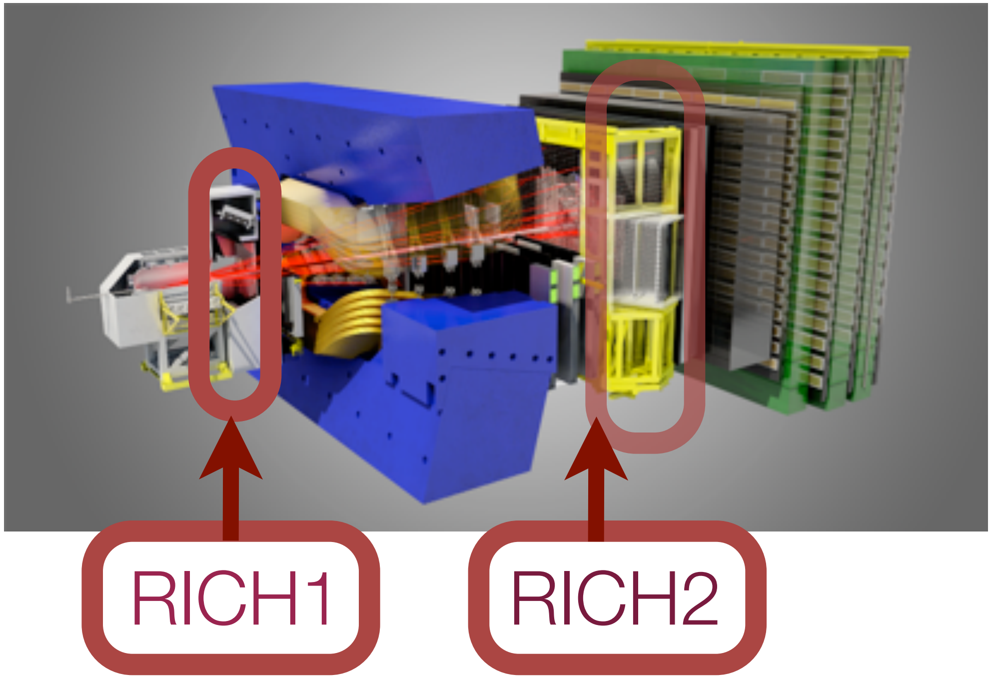
LHCb Experiment: Tracking

- Accurate decay time resolution from our vertex locator (VELO)
- High muon reconstruction efficiency from muon stations
- Good momentum resolution from tracking stations, $\Delta p/p$ = 0.35% — 0.55%



LHCb Experiment: Charged kaon/pion separation

- K/π separation provided by Ring Imaging Cherenkov (**RICH**) detectors



- The ability to identify particles at LHCb is critical to many of our analyses.

Charm Trigger and LHCb recorded luminosty

- We have an excellent **Trigger** for charm decays
- Charm trigger uses 33% (2011) - 40% (2012) of our trigger bandwidth
- Ability to trigger on tracks with lower p_T

- **1.0 fb^{-1} at 7 TeV** collected by LHCb in **2011**
- **2 fb^{-1} at 8 TeV** collected by LHCb in **2012**, higher cross section for charm
- Instantaneous luminosity delivered to LHCb fixed at $\mathscr{L} = 4 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$

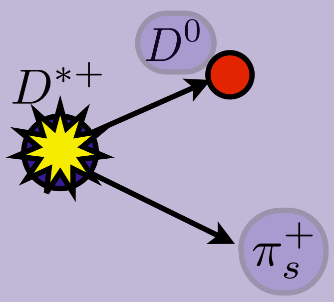
Run	√s in TeV	L in fb^{-1}	L_{eq}	ΣL_{eq}
1 (2011)	7	1	1	**1**
1 (2012)	8	2	2.3	**3.3**

Flavor tagging neutral D mesons at LHCb

- LHCb uses two methods to tag the flavor of neutral D mesons

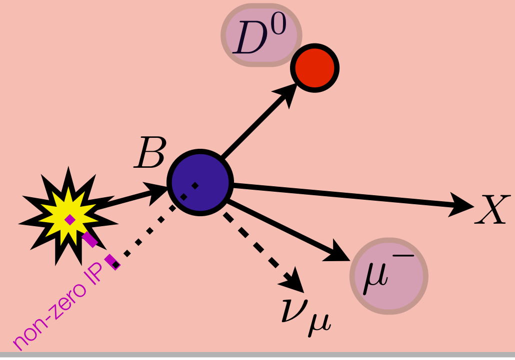
D* decays (Prompt)

Use slow pion from D* decays to tag D flavor: $D^{*+} \to D^0 \pi_s^+$ or $D^{*-} \to \bar{D}^0 \pi_s^-$



Semileptonic (SL) B decay (Secondary)

Use muon charge to tag D flavor: $B \to \bar{D}^0 \mu^+ \nu_\mu X$ or $B \to D^0 \mu^- \nu_\mu X$



Search for direct CPV in charm

- CPV in $D_{(s)}^{+} \rightarrow K_S^0\, h^+$
- ΔA_{CP} in $D^0 \rightarrow h^+h^-$
- Time-integrated CPV in $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays
- CPV via triple product asymmetries in $D^0 \rightarrow K^+K^-\pi^+\pi^-$
- Search for CP violation in $D^+ \rightarrow \pi^+\pi^+\pi^-$ Dalitz plot
  - (discussed in Marco’s Talk)

Search for direct CPV in Charm

A_{CP} is a time-integrated CP asymmetry defined as:

$$A_{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

SM predictions do not rule out a few 10^{-3} in charm

NP could enhance up to $\mathcal{O}(10^{-2})$ in charm Phys.Rev. D75 (2007) 036008

Analysis techniques

- Magnetic field frequently flipped.
    - Using both 'magnet up' and 'magnet down' data cancels many asymmetries

- Kinematic areas with large detection asymmetries can be removed

- Take raw asymmetries and use cancellation techniques to extract CP decay asymmetries.

CPV in $D_{(s)}^+ \to K_S^0 h^+$

- Search for direct CP asymmetry in the **SCS** decays

$$\mathcal{A}_{CP}^{D_{(s)}^{\pm} \to K_S^0 h^{\pm}}$$

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

CPV in $D_{(s)}^+ \to K_S^0 h^+$

- Search for direct CP asymmetry in the **SCS** decays
- Measured asymmetries are affected by other asymmetries

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

measure

want

Production asymmetry

f's detection asymmetry

Correction due to CPV in kaon system

CPV in $D_{(s)}^+ \to K_S^0 h^+$

- Search for direct CP asymmetry in the **SCS** decays
- Measured asymmetries are affected by other asymmetries

$$\mathcal{A}_{\rm meas}^{D^\pm_{(s)}\to K^0_S h^\pm} \approx \mathcal{A}_{CP}^{D^\pm_{(s)}\to K^0_S h^\pm} + \mathcal{A}_{\rm prod}^{D^\pm_{(s)}} + \mathcal{A}_{\rm det}^{h^\pm} + \mathcal{A}_{K^0/\overline{K}^0}$$

measure	want	Production asymmetry	f's detection asymmetry	Correction due to CPV in kaon system

- Combine with **CF** decays where CPV is not expected. Take asymmetries to isolate CP asymmetries e.g.

$$\mathcal{A}_{CP}^{D^\pm_s\to K^0_S \pi^\pm} = \mathcal{A}_{\rm meas}^{D^\pm_s\to K^0_S \pi^\pm} - \mathcal{A}_{\rm meas}^{D^\pm_s\to \phi\pi^\pm} - \mathcal{A}_{K^0}$$

$\mathcal{A}_{K^0} = (+0.07 \pm 0.02)\%$
calculation described in JHEP 07 (2014) 041

CPV in $D_{(s)}^{+} \to K_S^0 h^+$

JHEP 1410 (2014) 25
$3.0 fb^{-1}$

see Marco's talk

- Search for direct CP asymmetry in the **SCS** decays
- Measured asymmetries are affected by other asymmetries

$$\mathcal{A}_{\text{meas}}^{D^{\pm}_{(s)}\to K^0_S h^{\pm}} \approx \mathcal{A}_{CP}^{D^{\pm}_{(s)}\to K^0_S h^{\pm}} + \mathcal{A}_{\text{prod}}^{D^{\pm}_{(s)}} + \mathcal{A}_{\text{det}}^{h^{\pm}} + \mathcal{A}_{K^0/\overline{K}^0}$$

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$\mathcal{A}_{K^0} = (+0.07 \pm 0.02)\%$
calculation described in JHEP 07 (2014) 041

- Results:

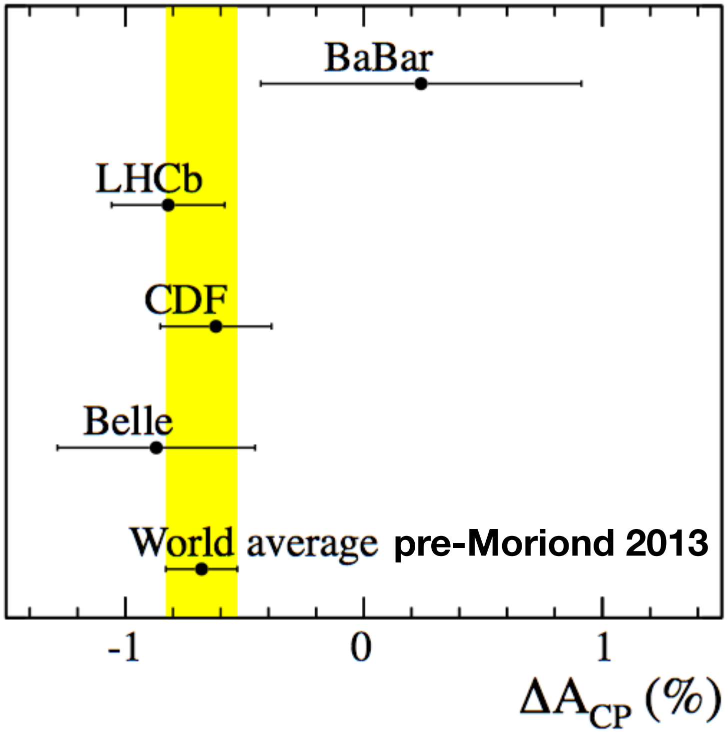
$$\mathcal{A}_{CP}^{D^{\pm}\to K^0_S K^{\pm}} = (+0.03 \pm 0.17 \pm 0.14)\%$$
$$\mathcal{A}_{CP}^{D^{\pm}_s\to K^0_S \pi^{\pm}} = (+0.38 \pm 0.46 \pm 0.17)\%$$

- Can also get a sum of both **SCS** asymmetries using **CF** $D_{(s)}^{+} \to K_S h^+$

$$\mathcal{A}_{CP}^{D^{\pm}\to K^0_S K^{\pm}} + \mathcal{A}_{CP}^{D^{\pm}_s\to K^0_S \pi^{\pm}} = (+0.41 \pm 0.49 \pm 0.26)\%$$

The ΔA_{CP} saga

$$A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$



neglecting indirect CPV

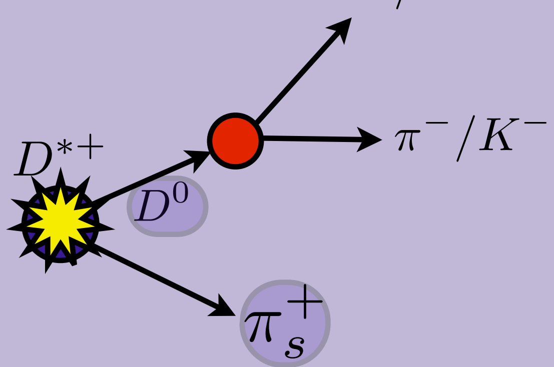
- Under SU(3) flavor symmetry, the direct CP asymmetries in these decays are expected to have equal magnitudes and opposite sign.
- ΔA_{CP} pre-Moriond 2013, measured by
  - BaBar (Phys. Rev. Lett. 100 (2008))
  - Belle (arXiv:1212.5320)
  - LHCb (Phys. Rev. Lett. 108 (2012))
  - CDF (Phys. Rev. Lett. 109 (2012))
- World average 4.6σ deviation from zero
- Level of CP violation potentially accommodated within SM (arXiv:1202.3795, many more)
- Can also be explained by NP (arXiv:1202.2866, many more)
- Lively debate amongst theorists.

ΔA_{CP} Tagging

LHCb uses two methods to tag the D^0 flavor

Recap

D* decays (Prompt)
Use slow pion from D* decays to tag D flavor $D^{*+} \to D^0\pi_s^+$ or
$D^{*-} \to \bar{D}^0\pi_s^-$



Semileptonic B decay (Secondary)
Use muon charge to tag D flavor
$B \to \bar{D}^0\mu^+\nu_\mu X$ or
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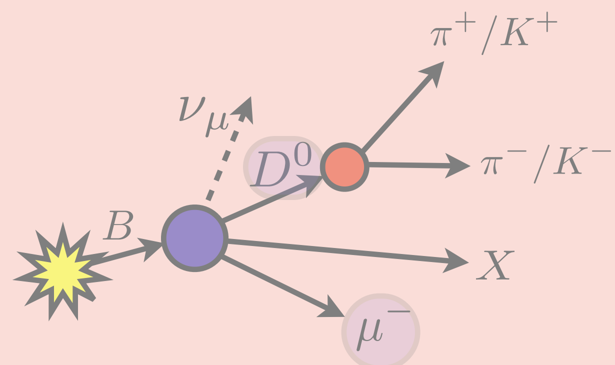


A_{CP} from D* decays

$$A_{RAW}(f) \simeq A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_p(D^{*+})$$

measure

want

f's detection asymmetry

π_s detection asymmetry

Production asymmetry

A_{CP} from D* decays

$$A_{RAW}(f) \simeq A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s^+) + A_p(D^{*+})$$

measure

want

~~f's detection asymmetry~~

π_s detection asymmetry

Production asymmetry

Zero for self-conjugate final states ($K^+K^-/\pi^+\pi^-$)

ΔA_{CP} from D* decays

$$A_{RAW}(f) \simeq A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s^+) + A_p(D^{*+})$$

measure | **want** | ~~f's detection asymmetry~~ | π_s detection asymmetry | Production asymmetry

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and slow pion detection asymmetries will cancel.

$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

Phys.Rev. D80 (2009) 076008

ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- LHCb Preliminary result

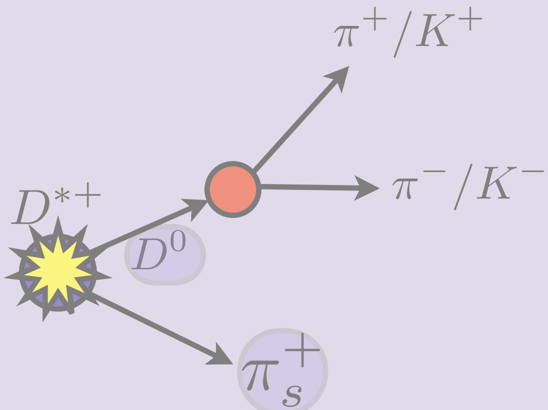
$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.}))\%$$

- Considerably closer to zero than previous (0.6 fb^{-1}) result [PRL 108 (2012) 111602]
- **Larger data set**
- **Improved detector alignment and calibration**
- **Improvement in analysis technique**
- **Detailed systematic studies**
- **Many cross checks confirm our result**

ΔA_{CP} Tagging

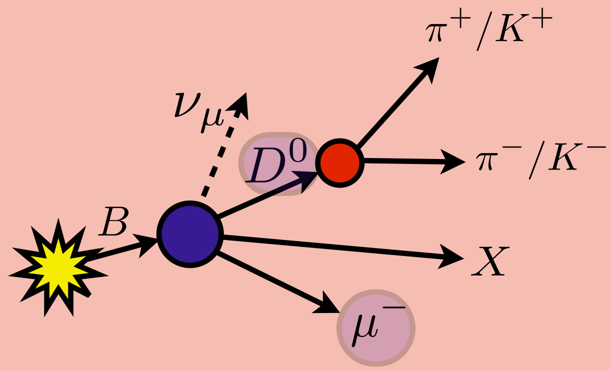
LHCb uses two methods to tag the D^0 flavor

D* decays (Prompt)
Use slow pion from D* decays to tag D flavor $D^{*+} \to D^0 \pi_s^+$ or
$D^{*-} \to \bar{D}^0 \pi_s^-$



Update

Semileptonic B decay (Secondary)
Use muon charge to tag D flavor
$B \to \bar{D}^0 \mu^+ \nu_\mu X$ or
$B \to D^0 \mu^- \nu_\mu X$



ΔA_{CP} from semileptonic B decays

$$A_{RAW}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\mu^+) + A_p(B)$$

μ detection asymmetry

b-hadron production asymmetry

Detection and production asymmetries **independent** from D* analysis

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and muon detection asymmetries will cancel.

$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

Comparison of D* and semileptonic (-tagged) ΔA_{CP}

see Marco's talk

Prompt tag LHCb Preliminary 1 fb^{-1}

LHCB-CONF-2013-003

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

Semileptonic (SL) decays 3 fb^{-1}

JHEP 07 (2014) 014

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

- **Statistical correlation** between the two data samples is **negligible**
- **Systematic uncertainties** essentially **uncorrelated**
- **Using $D^0 \to K\pi$ decays and D^+ decays, and similar cancellation techniques, with the SL data we obtain the world's most precise individual asymmetries:**

$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$
$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

Time-integrated CPV in $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays

- First LHCb CPV measurement using π^0 decays
- Search for direct CPV in the SCS $D^0 \rightarrow \pi^+\pi^-\pi^0$
- Resonances in the decay interfere and can carry different strong phases
  - Potential to have larger local CPV than phase-space integrated CPV

$$a_{CP} \propto \sin\Delta\delta \sin\Delta\phi$$

- Standard search techniques:
  - Fit contributing amplitudes, look for differences in fit parameters
  - Look for asymmetries in regions of phase space by “counting”
    - binned (chi-squared difference method) PLB 728 (2014) 585–595, PLB 726 (2013) 623–633

- Energy test: unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

Stat. Comp. Simul. 75, Issue 2 109-119 (2004),
NIM A537, 626-636 (2005),
PRD 84 (2011) 054015.

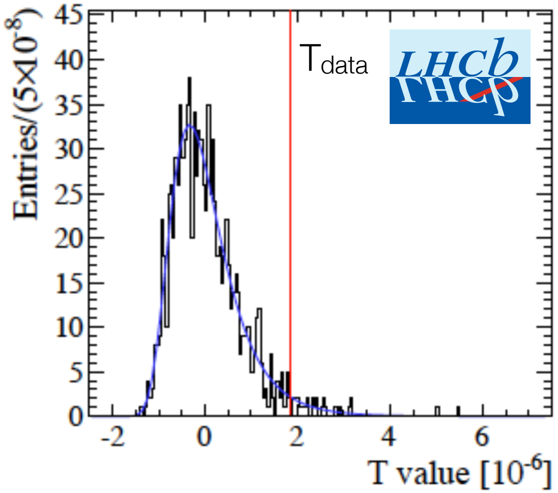
Time-integrated CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays

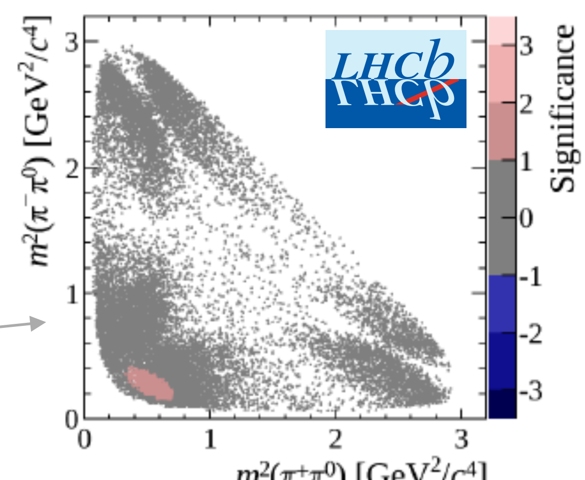
PLB 740 (2015) 158
2 fb^{-1} [2012 data]

- First use of the Energy test method to search for CPV

see Marco's talk

- Compare average-pairwise distance on Dalitz plot among all D^0 events, all anti-D^0 events, and all D^0 events to all anti-D^0 events.
- Test statistic T:
  - $T \to 0$ if all average distances are equal
  - $T > 0$ if average distances between D^0 events and anti-D^0 events is larger
- Compare nominal T-value to expected T-values for no-CPV hypothesis; a p-value of (2.6 +/- 0.5)% is calculated, consistent with no CPV.
- World's best sensitivity for CPV in $D^0 \to \pi^+\pi^-\pi^0$
- Method allows visualization of local CP asymmetries





CPV via T-odd moments in the SCS $D^0 \rightarrow KK\pi\pi$

- Search for CPV in the **SCS** decay $D \rightarrow KK\pi\pi$ using triple products

$$\overbrace{C_T = \mathbf{p}_{\mathbf{K}^+} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})}^{D^0 \rightarrow K^- K^+ \pi^- \pi^+} \qquad \overbrace{\overline{C}_T = \mathbf{p}_{\mathbf{K}^-} \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^+})}^{\overline{D}^0 \rightarrow K^+ K^- \pi^+ \pi^-}$$

- These are non-vanishing since there are four distinct final state particles
- These triple products are odd under T (hence the name "T-odd")
  - We cannot reverse the decay, their P-odd nature is more important

- In the absence of final state interactions (FSI) due to long-distance strong interaction effects, if the number of decays with $C_T < 0$ is different from the number of decays with $C_T > 0$ this implies parity violation.
- We form triple-product asymmetries for both D flavors:

$$A_{C_T} = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \overline{A}_{\overline{C}_T} = \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}$$

CPV via T-odd moments in $D^0 \to KK\pi\pi$

JHEP 10 (2014) 005
3.0fb^{-1}

see Maurizio's talk

- To eliminate the effects of FSI, which conserve P, we form an asymmetry of asymmetries which cancels out the FSI; any remaining asymmetry implies that either C or P is violated, i.e. we have CPV

$$a_{CP}^{T-\text{odd}}(D^0) \;=\; \frac{1}{2}\left(A_{C_T} - \overline{A}_{\overline{C}_T}\right)$$

- LHCb measured these asymmetries using SL flavor-tagged D decays.

$$A_{C_T} = (-71.8 \pm 4.1(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-3}$$
$$\overline{A}_{\overline{C}_T} = (-75.5 \pm 4.1(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-3}$$

$$\boxed{a_{CP}^{T-\text{odd}}(D^0) = (1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3}}$$

- We also searched for local CPV in bins of phase space, and evidence of CPV in bins of proper time. No CPV was found.

Search for indirect CPV in charm

- A_Γ in $D^0 \to h^+h^-$ decays
- CPV via mixing in "wrong-sign" $D^0 \to K\pi$ decays

A_Γ in $D^0 \rightarrow hh$ decays

JHEP 04 (2015) 043
3 fb^{-1}

see Stefanie's talk

$$A_\Gamma = \frac{\tau^- - \tau^+}{\tau^- + \tau^+}$$

$\tau^{\pm}$: lifetime of D^0 ($\bar{D}^0$) $\rightarrow$ CP+ eigenstates

- This gives a combined measure of CPV via mixing and decay

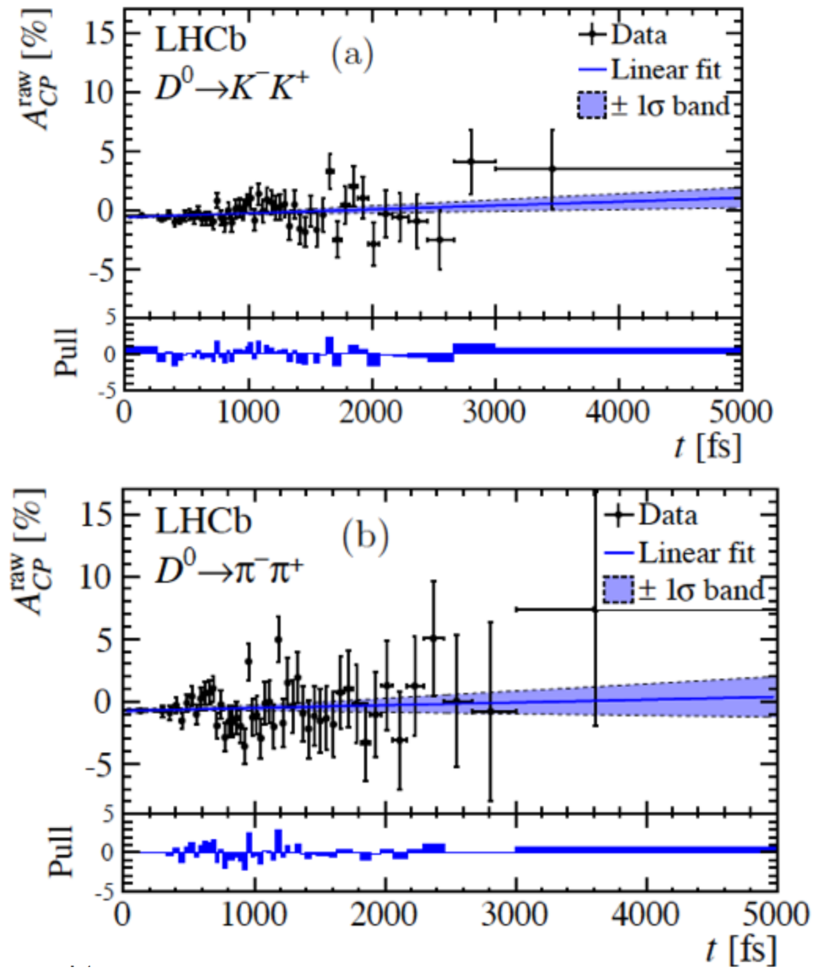
$$A_\Gamma \approx \left(A_{CP}^{\rm mix}/2 - A_{CP}^{\rm dir}\right)\, y\cos\phi - x\sin\phi$$

- Can obtain A_Γ via time-dependent fits to the measured A_{CP} distribution

$$A_{CP}(t) \approx A_{CP}^{\rm dir} - A_\Gamma \frac{t}{\tau}$$

- Using SL-tagged D decays, we find:

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\ \%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\ \%$$



A_Γ in $D^0 \to hh$ decays

JHEP 04 (2015) 043
3 fb^{-1}

see Stefanie's talk

- SL-tagged result can be compared to Prompt D*-tagged result:

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\ \%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\ \%$$

SL 3 fb^{-1}

$$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

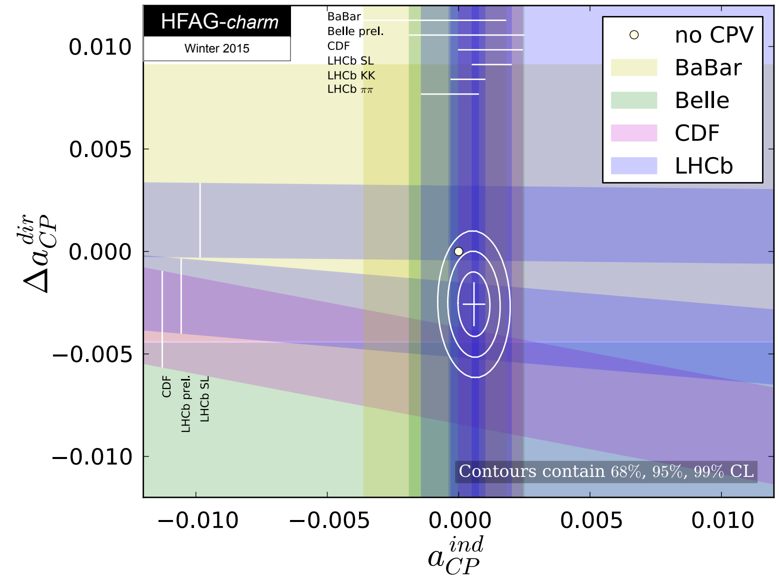
both prompt measurements are the world's most precise

Prompt 1 fb^{-1}
PRL 112 (2014) 041801

- HFAG combination including A_Γ and A_{CP} results:

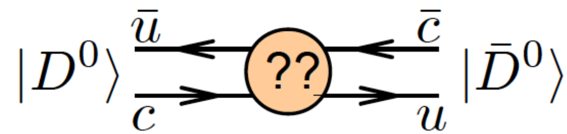
$a_{CP}^{ind} = 0.00058 \pm 0.00040$
$\Delta a_{CP}^{dir} = -0.00257 \pm 0.00104$

- Consistent with no CPV at 1.8% CL



CPV via mixing in WS $D^0 \to K\pi$

- $D^0 \to K^+\pi^-$ (WS) decays are affected by the interference between mixing and decay



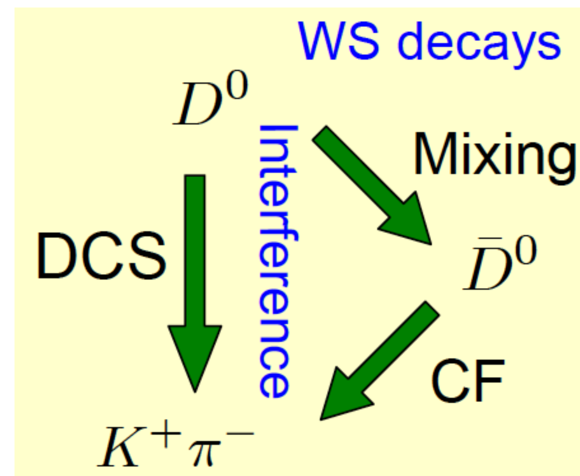
- The time-evolution of the WS decay rate can be compared for D^0 and anti-D^0 decays to test for CPV

$$T_{WS}(t) \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y'\,\Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

$\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \to K\pi$)

$$x' = \quad x \cos\delta_{K\pi} + y \sin\delta_{K\pi}$$
$$y' = -x \sin\delta_{K\pi} + y \cos\delta_{K\pi}$$

$$y'^2 + x'^2 = x^2 + y^2$$



CPV via mixing in WS $D^0 \to K\pi$

PRL 111 (2013) 251801
$3.0 fb^{-1}$, prompt-tagged D decays

see Stefanie's talk

- D^0 parameters

$$\begin{array}{lll} R_D^+ & [10^{-3}] & 3.545 \pm 0.082 \pm 0.048 \\ y'^+ & [10^{-3}] & 5.1 \pm 1.2 \pm 0.7 \\ x'^{2+} & [10^{-5}] & 4.9 \pm 6.0 \pm 3.6 \end{array}$$

- anti-D^0 parameters

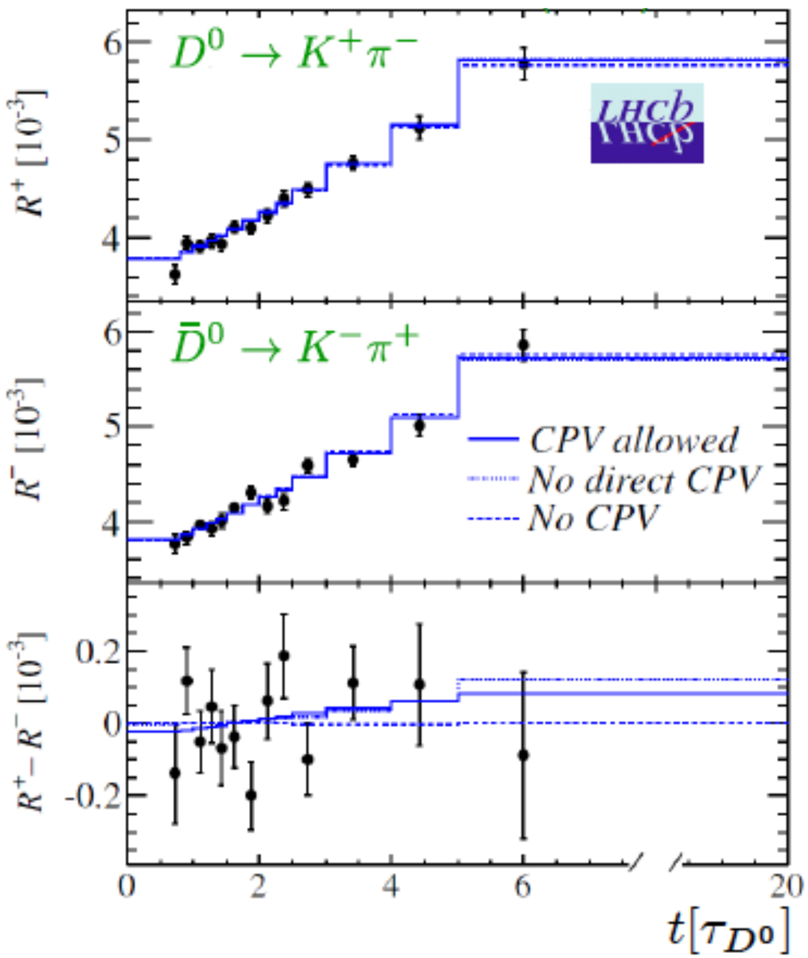
$$\begin{array}{lll} R_D^- & [10^{-3}] & 3.591 \pm 0.081 \pm 0.048 \\ y'^- & [10^{-3}] & 4.5 \pm 1.2 \pm 0.7 \\ x'^{2-} & [10^{-5}] & 6.0 \pm 5.8 \pm 3.6 \end{array}$$

- CPV in mixing

$$0.75 < |q/p| < 1.24 \quad @\ 68.3\,\%\ CL$$

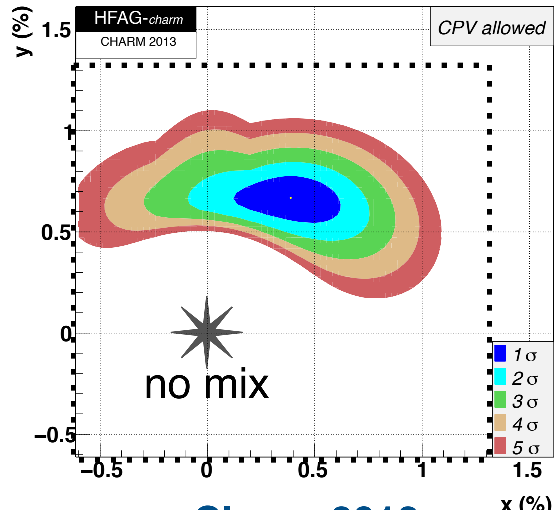
- Direct CPV of DCS component

$$A_D = \frac{R^+ - R^-}{R^+ + R^-} = (-0.7 \pm 1.9)\%$$

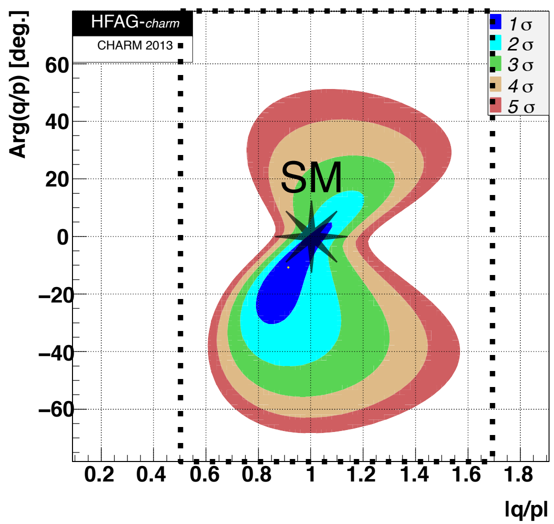


- Fit results show no evidence for CPV in mixing or decay

Knowledge of the Neutral Charm System in 2015



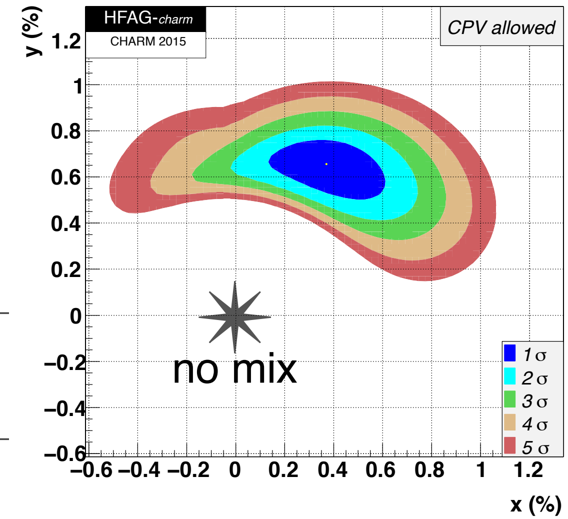
Charm 2013

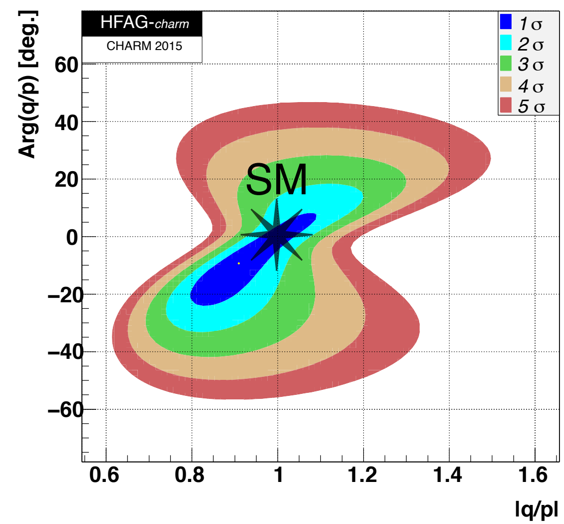


Charm 2015

Parameter	CPV-allowed
x (%)	0.37 ± 0.16
y (%)	$0.66\ ^{+0.07}_{-0.10}$
$\lvert q/p \rvert$	$0.91\ ^{+0.12}_{-0.08}$
ϕ (°)	$-9.4\ ^{+11.9}_{-9.8}$

Averages by HFAG





Conclusion

- LHCb in its first run has made many contributions to the search for CP violation in charm including, but not limited to:
  - World's most precise KK and ππ direct CP asymmetries.
  - World's most precise measurements of A_Γ in these modes as well.
  - World's best sensitivity for CPV in $D^0 \to \pi^+\pi^-\pi^0$

- No observation of CPV in the charm system, yet!

- Several Run 1 analyses are still ongoing
  - There is much more to look forward to in the coming year.

- The LHCb detector has worked "like a charm."
  - Expect even more charming LHCb results from Run 2!
  - (and beyond… see Chris's talk tomorrow!)

Additional Slides

ΔA_{CP} from D* decays

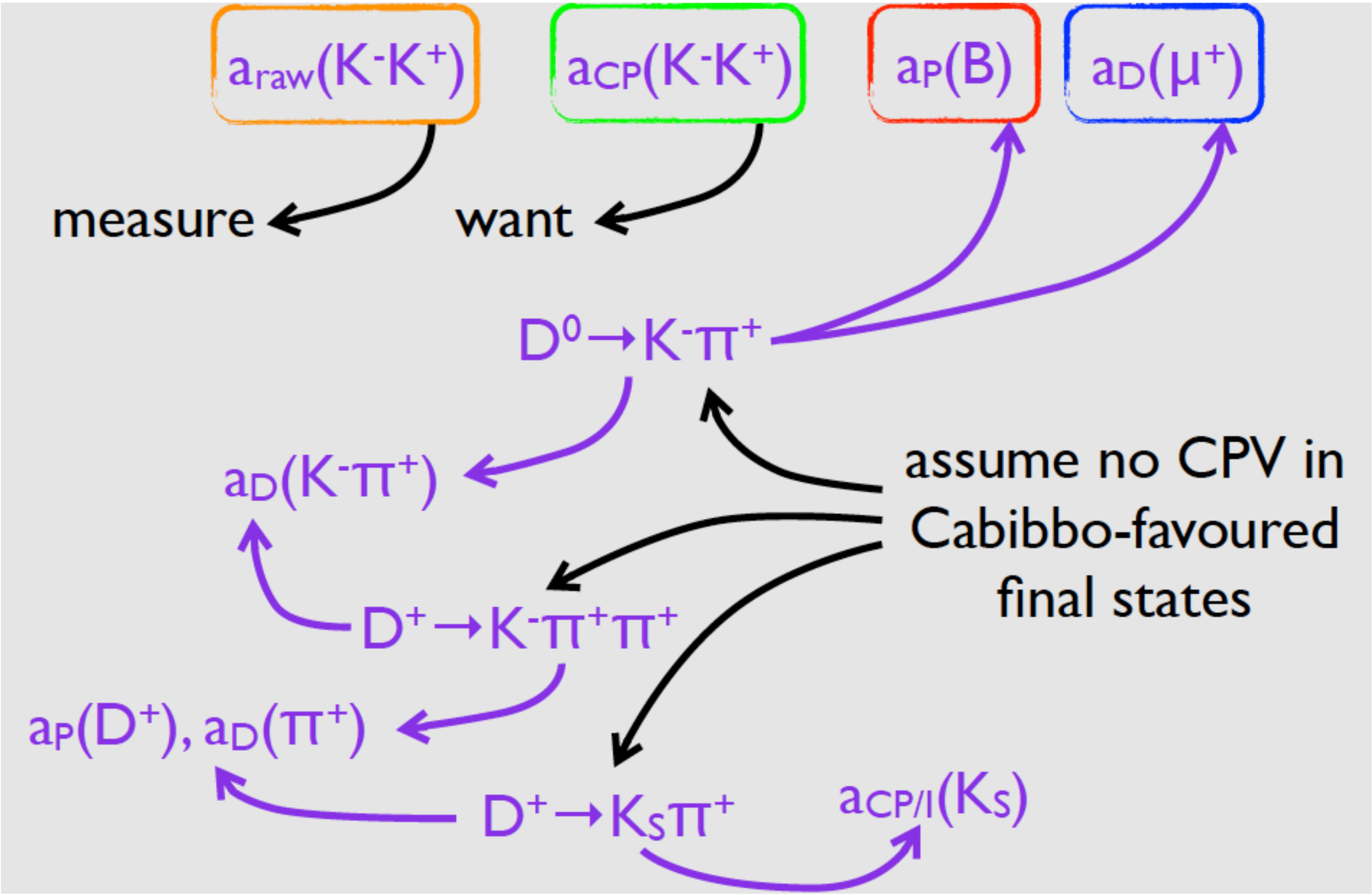
LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

- Indirect and direct CPV can contribute
- Indirect CPV is ~universal
  - Indirect CPV cancels in $A(K^+K^-)-A(\pi^+\pi^-)$ if lifetime acceptance same for KK and ππ
  - If not contribution $A^{ind}[\langle t_{KK}\rangle_{acc}-\langle t_{\pi\pi}\rangle_{acc}]/\tau_0$

Cancellation sequence for $A_{CP}(KK)$

from Marco's
parallel talk



Prompt A

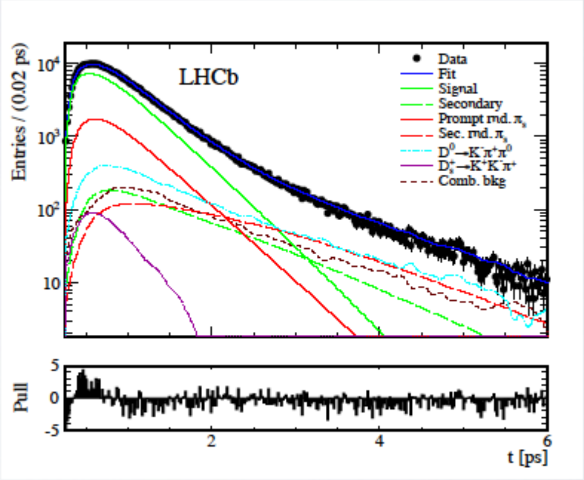
from Stefanie's parallel talk

PROMPT A$_\Gamma$

PRL 112 (2014) 041801

$$A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\overline{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\overline{D}^0}}$$

- Fit to decay time and $\ln(\chi^2_{\mathrm{IP}})$ to extract effective lifetimes
- Dominant systematic uncertainty from per-candidate acceptance functions (data-driven)



Fit of decay time to $\bar{D}^0 \to K^- K^+$

- Results
  - $A_\Gamma(K^+K^-) = (-0.035 \pm 0.062 \pm 0.012)\%$
  - $A_\Gamma(\pi^+\pi^-) = (0.033 \pm 0.16 \pm 0.014)\%$

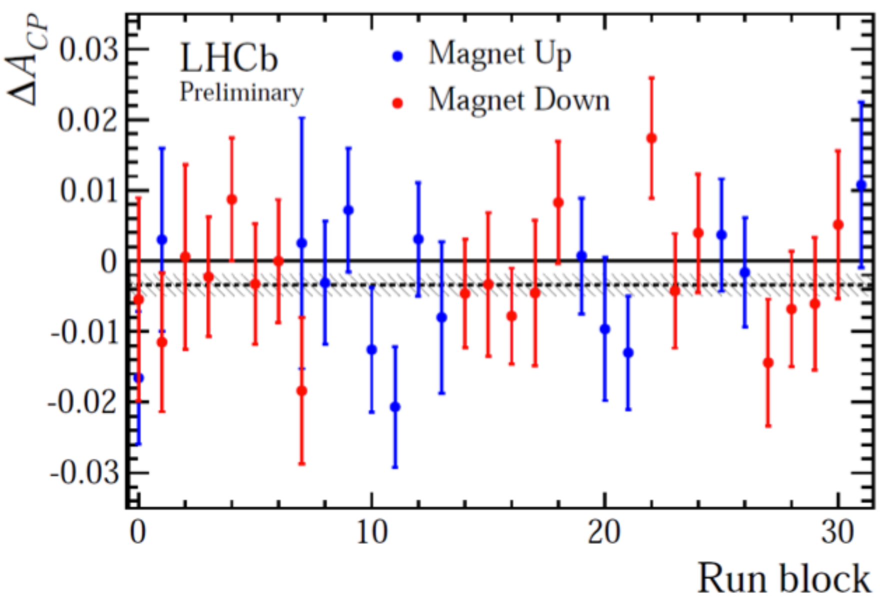
ΔA_{CP} from D* decays

- Update of analysis from 2011 **0.6 fb^{-1} → 1.0 fb^{-1}** (full 2011 dataset)
- Update includes new reconstruction
- **Improved tracking alignment**
- **Improved particle identification** from RICH calibration.
- **Constrain the D* vertex to the primary vertex**
- $\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$
- Improves δm resolution by factor ~2.5.
- **Kinematic re-weighting of D* (ensures $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ have the same kinematics)**

ΔA_{CP} from D* decays : Cross checks

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- ΔA_{CP} stability checked
- Against time at which data was taken
- Various reconstructed quantities:
  - D^0 p_T
  - D^0 η
  - D^0 p
  - D^0 decay time
- Analysis performed on large Monte Carlo samples to check for bias
- Many more



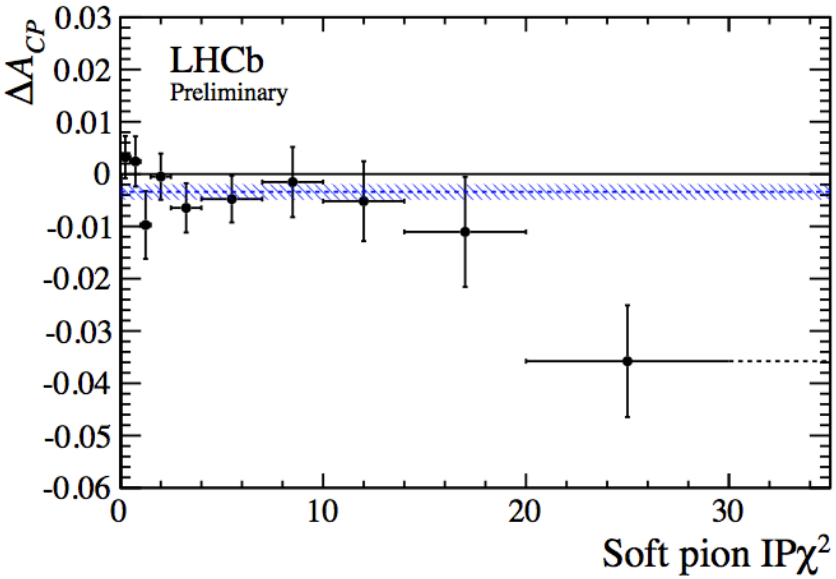
ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- Preliminary result

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

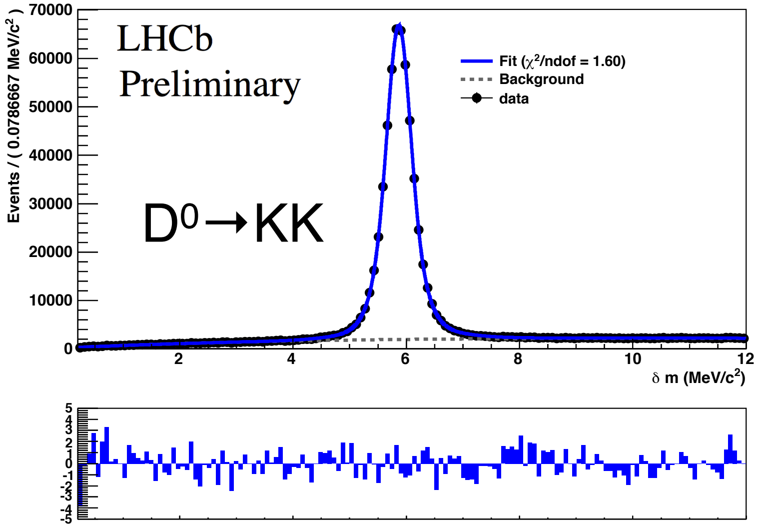
- Source of systematic uncertainties
- Soft pions with large IPχ^2 for pointing to PV
- Effect due to multiple scattering
  - Results in poor mass distribution
  - Should not depend on D^0 decay mode
    - Raw asymmetry observed in these candidates
- Analysis repeated with these candidates removed
- **Dominant systematic 0.08%**

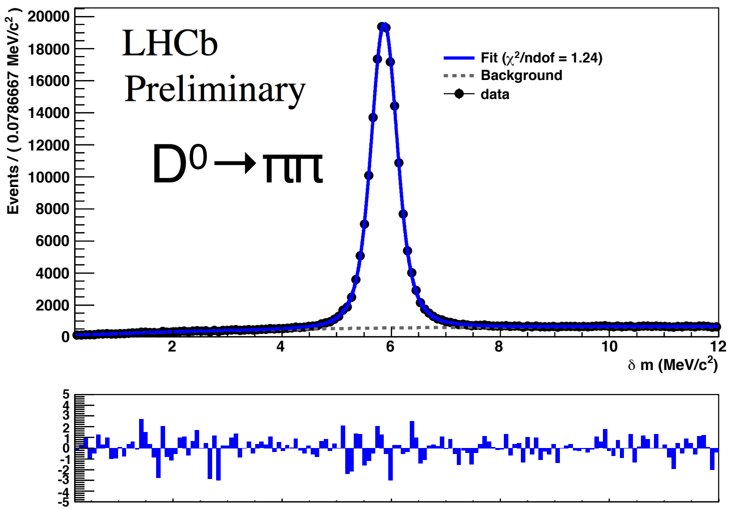


ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- Fit in δm
- $\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$

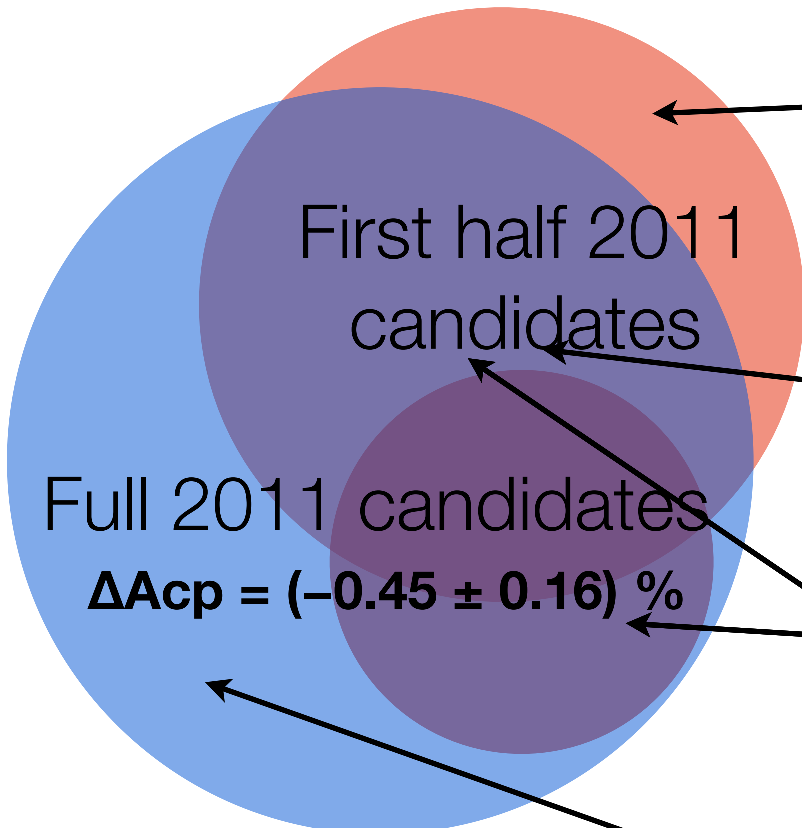




- **Extremely clean signal**
- 2.2 million $D^0 \rightarrow K^+K^-$ candidates
- 0.7 million $D^0 \rightarrow \pi^+\pi^-$ candidates

ΔA_{CP} from D* decays comparison to 2011 result

Analysis using method from 2011



15% not selected with new reconstruction

$\Delta A_{CP} = (-0.80 \pm 0.23)\%$

New Reconstruction

$\Delta A_{CP} = (-0.78 \pm 0.23)\%$

first 600 pb^{-1} including additional **17% KK** and **34% ππ** (improved RICH calibration)

last 400pb^{-1} recorded by LHCb 2011

$\Delta A_{CP} = (-0.28 \pm 0.26)\%$

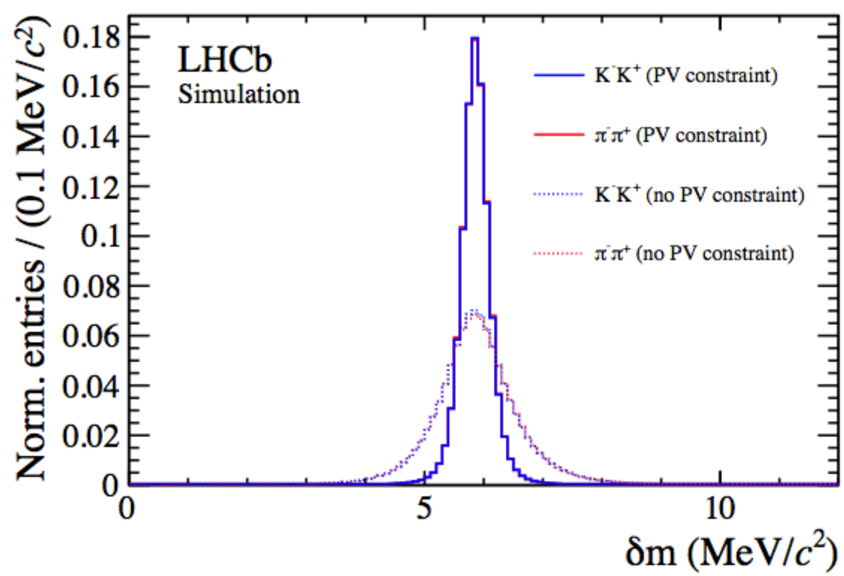
ΔA_{CP} from D* decays

kinematic re-weighting

$\Delta Acp = (-0.45 \pm 0.16)$ % → $\Delta Acp = (-0.45 \pm 0.17)$ %

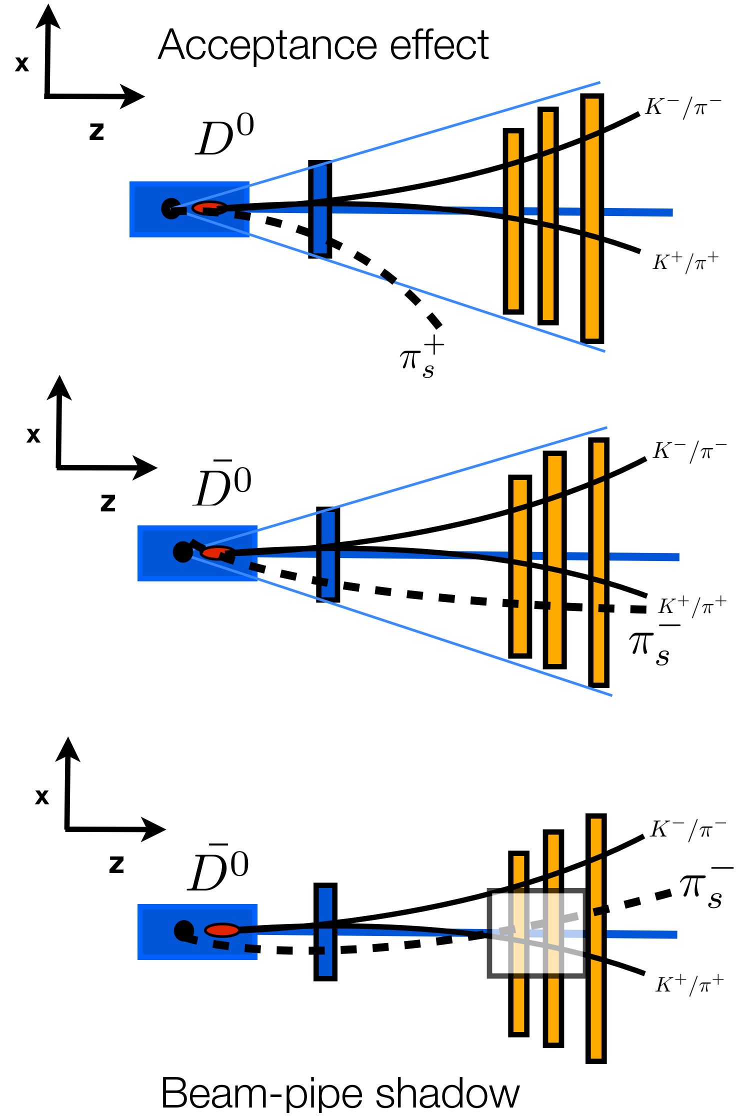
force D* vertex to the Primary Vertex

$\Delta Acp = (-0.45 \pm 0.17)$ % → **$\Delta Acp = (-0.34 \pm 0.15)$ %**



ΔA$_{CP}$

- Magnetic field induces left/right differences between the D^{*+} and D^{*-} due to the slow pion
- Acceptance effect at edges of detector
- Beam-pipe shadow
- We remove this asymmetry
- We remove areas of large asymmetry to avoid secondary effects
- Frequently flip the magnetic field
- Detector asymmetries removed in difference between RAW asymmetries



ΔA_{CP}

- Magnetic field induces left/right differences between the D^{*+} and D^{*-} due to the slow pion
    - Acceptance effect at edges of detector
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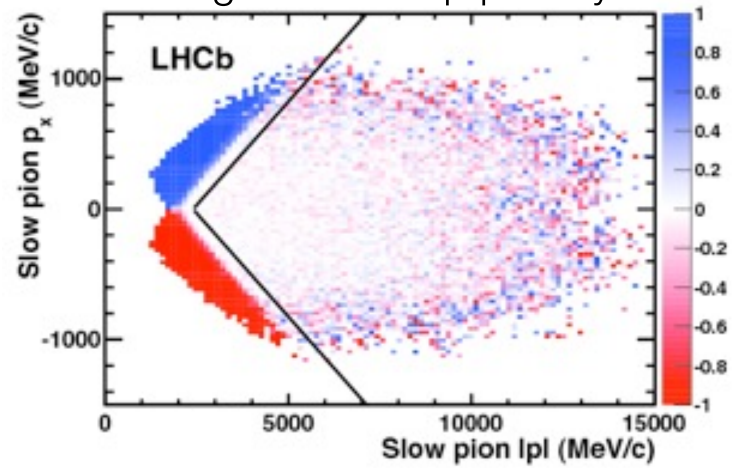
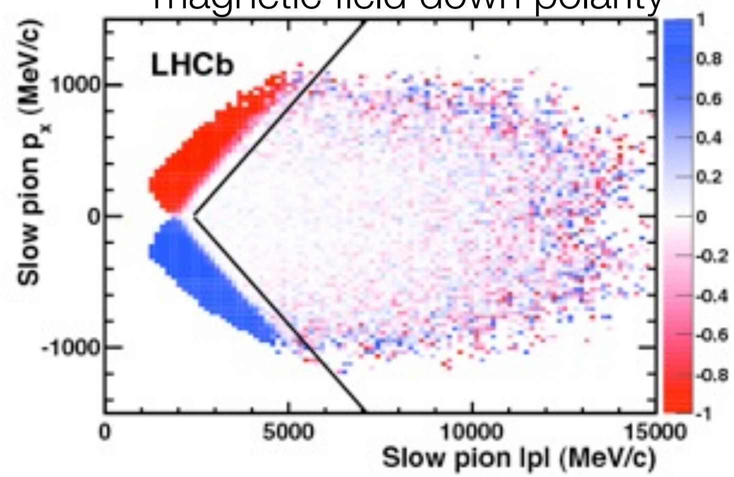
    - Frequently flip the magnetic field
    - Detector asymmetries removed in difference between RAW asymmetries

magnetic field up polarity



magnetic field down polarity



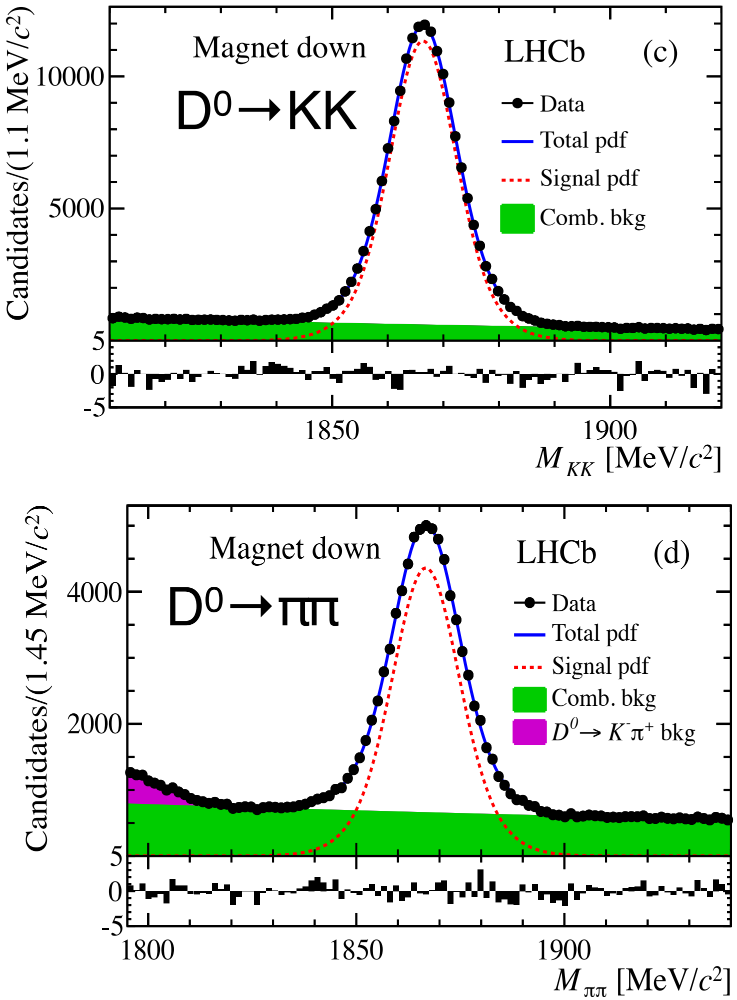
Phys. Rev. Lett. 108 (2012) 111602

Ancient History

ΔA_{CP} from semileptonic B decays

1.0 fb-1

- Clean signal
- 0.6M $D \to K^+K^-$ candidates
- 0.2M $D \to \pi^+\pi^-$ candidates



ΔA_{CP} via Semileptonic: Cross checks

arXiv:1303.2614
1.0fb^{-1} collected during 2011

- Many cross checks carried out
- **ΔA_{CP} stable with**
- reconstructed quantities:
    - **D^0 decay time**
    - **B flight distance**
    - **reconstructed D^0-μ mass**
    - **angle between μ and D^0 daughters**
    - **p_T of D^0 and μ**
    - **η of D^0 and μ**
- **data taking period**
- many more

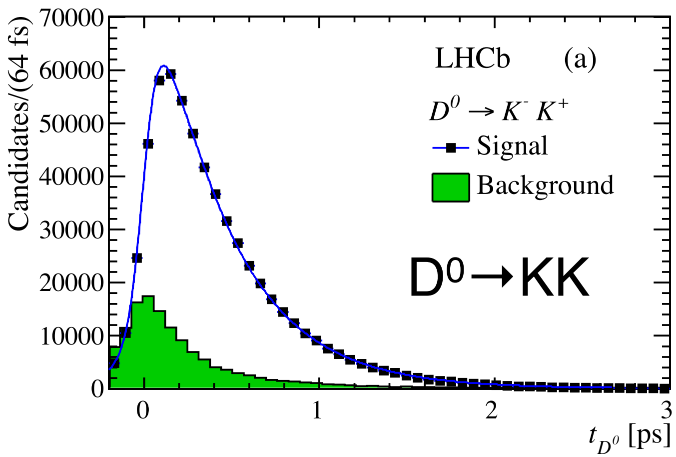
ΔA_{CP} from semileptonic B decays

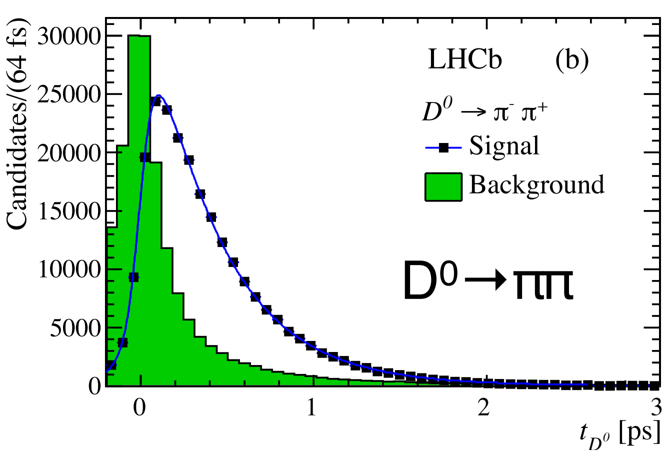
arXiv:1303.2614
$1.0 fb^{-1}$ collected during 2011

- Result

$$\Delta A_{CP} = (0.49 \pm 0.30\,(\text{stat}) \pm 0.14\,(\text{syst}))\%$$

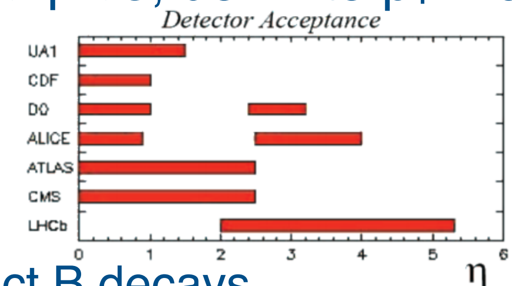
- Main source of systematic from low lifetime background in $D^0 \rightarrow \pi^+\pi^-$ decays
- More low lifetime background in $D^0 \rightarrow \pi^+\pi^-$ than $D^0 \rightarrow K^+K^-$
- We required positive decay times in our analysis
- Analysis repeated including negative decay times
- Systematic uncertainty of 0.11%

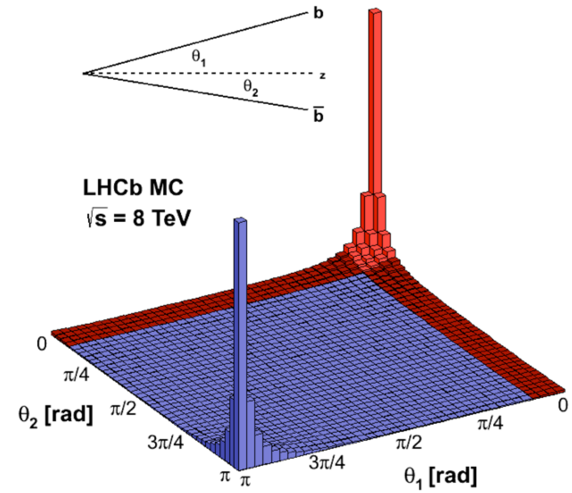




Experiment Overview

- The LHCb detector is a single arm forward spectrometer with a polar angular coverage from 10 to 300 mrad in the horizontal plane and 250 mrad in the vertical plane.
- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$



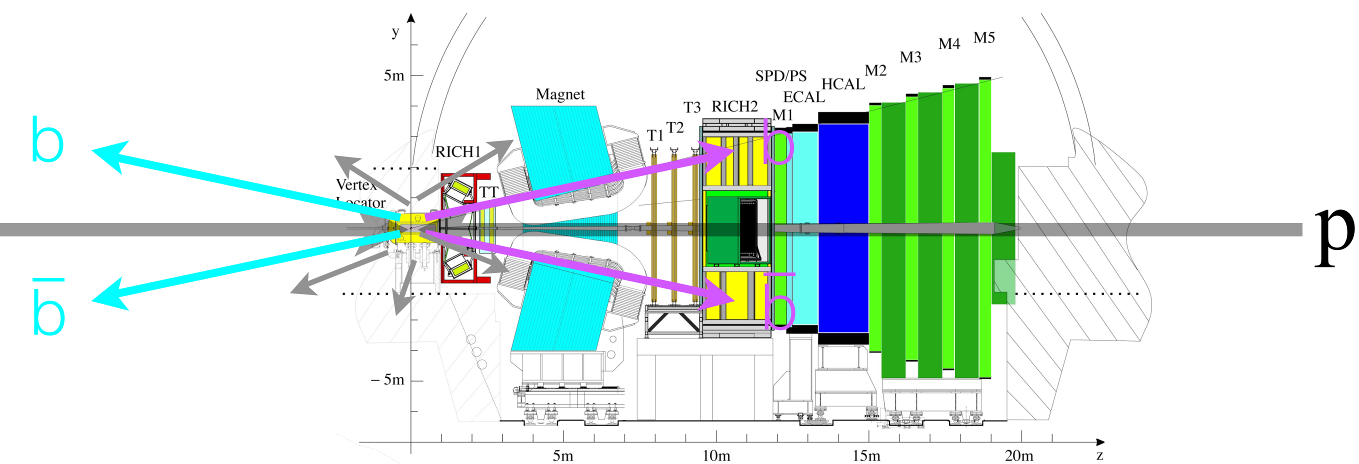


- Trigger
  - Designed to select B decays.
  - Also favors higher p_T secondary charm.

Designed for b!

(Also good for c!)

p



Common Strategies for D Mixing & CP Violation

- Use control modes / normalization channels for initial studies with data

- Perform systematic studies on data
  - Prompt-secondary distinction
  - Lifetime acceptance correction

- Using prompt charm
  - More events
  - Need to measure contribution from secondary

- Using charm from B decays
  - Lower cross-section, but higher p_T = higher trigger efficiency
  - Need to precisely measure D production vertex

Luminosity

- Nominal instantaneous luminosity: $\mathscr{L} = 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$
- LHCb instantaneous luminosity kept constant (luminosity leveling).