Evidence for CP Violation in time integrated $D^0 \rightarrow hh$ Decays in LHCb

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Outline
- Introduction: CKM Picture & CP Violation
- LHCb experiment
- Recent CP Violation Measurements in Charm
- Summary
Introduction

• SM great success, but it “cannot” be the final word

• The case for New Physics is clear
  – Particle Physics
    • Hierarchy Problem and Unification with gravity
    • GR and Quantum theory
    • Origin of EWSB
    • Why 3 generations?
    • Masses & coupling constants
  – Cosmology
    • Dark Matter
    • Dark Energy
    • Cosmological constant problem
    • Baryon Asymmetry of the Universe
    • …

Decays involving quantum loops a great place to look for NP
CKM Formalism

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

\[
V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \delta V
\]

\[
\delta V = \begin{pmatrix}
0 & 0 & 0 \\
-iA^2 \lambda^5 \eta & 0 & 0 \\
A\lambda^5(\rho + i\eta)/2 & -A\lambda^4(1/2 - \rho - i\eta) & 0
\end{pmatrix}
\]

- All CPV phenomena attributable to a single complex phase in the CKM matrix with \(\eta \neq 0\).
- Another consequence: Neutral mesons (K^0, D^0, B^0, B_s) mix via 2\(^{nd}\) order weak interactions.

\[
H = \begin{pmatrix}
m & M_{12} \\
M_{12}^* & m
\end{pmatrix} - \frac{i}{2} \begin{pmatrix}
\Gamma & \Gamma_{12} \\
\Gamma_{12}^* & \Gamma
\end{pmatrix}
\]

- \(M_{12}\): off-shell (virtual) contributions
- \(\Gamma_{12}\): on-shell (real) contributions
- Diagonalize \(m_H, m_L, \Gamma_H, \Gamma_L\)

For example, in the \(B^0\) sector:

\[
|B_L\rangle = |B\rangle + \frac{q}{p} |\overline{B}\rangle \\
|B_H\rangle = |B\rangle - \frac{q}{p} |\overline{B}\rangle
\]

Mixing parameters:

\[
x = \frac{m_H - m_L}{\Gamma} \\
y = \frac{\Gamma_L - \Gamma_H}{2\Gamma}
\]

If CP conserved:

\[
\left|\frac{q}{p}\right| = 1 \\
\Delta m = 2 |M_{12}| \\
\Delta \Gamma = 2 |\Gamma_{12}|
\]
CP Violation

I: CPV in mixing (|q/p| ≠ 1): Mass eigenstates cannot be CP eigenstates

- \[|q/p| = \frac{(1-\varepsilon_K)}{(1+\varepsilon_K)}\]
  - Experimental result: \(\varepsilon_K = 2.228 \times 10^{-3}\).

Also:

\[
a_{s} = \frac{\Gamma(\bar{B} \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)}{\Gamma(\bar{B} \to X \ell^- \nu) - \Gamma(B \to X \ell^- \nu)} = \frac{1-|q/p|^4}{1+|q/p|^4}
\]
**CP Violation**

- **I: CPV in mixing** $|q/p| \neq 1$: Mass eigenstates cannot be CP eigenstates
  - $|q/p| = (1-\varepsilon_K)/(1+\varepsilon_K)$
  - Experimental result: $\varepsilon_K = 2.228 \times 10^{-3}$.

  Also:
  
  $$a_{sl} = \frac{\Gamma(B \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)}{\Gamma(B \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

- **II: CPV in decay** $|A/A| \neq 1$: $\geq 2$ amplitudes with different weak and strong phases.
  - $\text{Re}(\varepsilon'/\varepsilon) \sim 10^{-3}$, $B \to K\pi$ ..
  - $\gamma$ from $B^- \to D^0K^-$
  - $\Delta a_{CP}$ in $D^0 \to KK, \pi\pi$ from LHCb (coming up shortly!)
CP Violation

I: CPV in mixing ($|q/p| \neq 1$): Mass eigenstates cannot be CP eigenstates

- $|q/p| = (1-\varepsilon_K)/(1+\varepsilon_K)$
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Also:

$$a_{sl} = \frac{\Gamma(\bar{B} \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)}{\Gamma(\bar{B} \to X \ell^+ \nu) + \Gamma(B \to X \ell^- \nu)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

II: CPV in decay ($|A/A| \neq 1$): Two amplitudes with different weak and strong phases.

- $\text{Re}(\varepsilon'/\varepsilon) \sim 10^{-3}$, $B \to K\pi$ ..
- $\Delta a_{CP}$ in $D^0 \to KK, \pi\pi$ from LHCb (coming up shortly!)
- $\gamma$ from $B^- \to D^0K^-$

III: CPV in interference between decays with and without mixing,

- Much attention in last 10-15 years
- Clean extractions of weak phases when only 1 decay amplitude
  $[\sin(2\beta), \sin(2\beta_s), \ldots]$
Mixing and CPV: $B^0$

$$\Delta m_B \propto m_t^2 \lambda^6, \quad \Gamma_d \sim m_b^5 \lambda^4$$

$$\Rightarrow x = \Delta m_d / \Gamma_d \sim O(1)$$

(Large $\Delta m \Rightarrow$ large mixing rate)

$$\Delta \Gamma \propto m_B^2 \lambda^6$$

$$\Rightarrow \Delta \Gamma/\Delta m_d \sim O(m_B^2/m_t^2) \sim 10^{-3}$$

$$\Rightarrow \Delta \Gamma/\Gamma \text{ small}$$

Mass eigenstates labeled by masses ("heavy" and "light")

CP Violation:

- Large CPV in $B^0$ mixing: $\text{Arg}(V_{td}) \sim \eta/(1-\rho)$
- Large direct CPV in selected decays.
  - $B^0 \to \pi \pi, K \pi, \text{ etc}$
  - $B^- \to \bar{D} K^-, \bar{D} \to K K, \pi \pi, K \pi$
Mixing and CPV: $B_s$

$\Delta m_{B_s} \propto m_t^2 \lambda^4$, $\Gamma_s \sim m_b^5 \lambda^4$

$\rightarrow \Delta m_s \sim 20 \Gamma_s$

(Very large mixing rate)

$\Delta \Gamma_s \propto m_B^2 \lambda^4$

$\rightarrow \Delta \Gamma_s / \Delta m_s \sim O(m_B^2 / m_t^2) \sim 10^{-3}$

$\rightarrow \Delta \Gamma_s / \Gamma_s$ not small (~0.1)

**CP Violation:**

- Small $B_s$ mixing: $\text{Arg}(V_{ts}) \sim \eta \lambda^2$
- Large CPV in selected decays.
  - $B_s \rightarrow D_s K$

\[ V_{ts} V_{us}^* (\lambda^3) \]

\[ \lambda^3 \]

\[ V_{td} V_{ud}^* \]

\[ V_{tb} V_{ub}^* \]
Mixing and CPV: $D^0$  

$\Delta m_D \sim (m_s^2 - m_d^2)/m_W^2$. Large GIM suppression.

(Very slow mixing)

- Mixing parameters hard to compute (theoretically) due to long distance effects.
  - Theory: $x,y$ in range $10^{-2} - 10^{-3}$
  - CPV small, at the level $10^{-3}$

- Here, aim is to uncover CPV at a level “significantly larger” than $10^{-3}$.
Main aim of LHCb is to study a multitude of $b$- and $c$-hadron decays to search for inconsistencies in the CKM description of weak interactions.

- Loop diagrams, rare decays, sensitive to NP

Many other areas of exploration as well
- Hidden valley, precision mass & lifetimes, new $B$ decays, $\tau \rightarrow \mu \mu \mu$, $X, Y, Z$, Electroweak $W^\pm, Z^0$, etc
**LHCb Detector**

**Key strengths of LHCb**

- ~5x10^{11} \overline{b}b/year.
- ~5x10^{12} \overline{c}c/year
- Highly flexible/large BW trigger ( ~2 kHz bb, 1 kHz cc )
- Excellent momentum resolution
- Ability to swap dipole polarity
- Precision vertexing
- Excellent PID
In 2011, collected ~1 fb$^{-1}$, about a nominal LHC year for LHCb.

But, 50 ns bunch spacing → ~2X larger instantaneous lumi relative to design lumi.
Vertex and Tracking Performance

**Primary vertex resolution**

- Momentum resolution: 0.4\% - 0.6\%
- Mass resolution: \( J/\psi = 13 \text{ MeV} \)

**Vertex resolution**

- \( \sigma_x \approx 16 \mu m \)
- \( \sigma_y \approx 16 \mu m \)
- \( \sigma_z \approx 76 \mu m \)

Accurate field map and alignment
Primary vertex resolution $\approx 16 \mu m$

$\sim 2\times$ more precise $B_s$ mass than WA
Same for $\Lambda_b$
**RICH Performance - K/π Separation**

With RICH: $A_{CP}(B^0 \rightarrow K\pi) = -0.088 \pm 0.011 \pm 0.008$

similar: $A_{CP}(B_s \rightarrow K\pi) = (27 \pm 8 \pm 2)\%$, first evidence of *direct CPV* in this channel
Charm Physics

- Probing CPV in charm:
  - Time-dependent WS decays
  - Time-dependent $D^0 \rightarrow K_s \pi \pi$
  - Lifetimes in CP eigenstates
  - CP asymmetries (CS decays)
In $D^0$ decays: $x, y \sim 0.01 - 0.001$ (Let’s take $f_{CP} = K^+K^-$), then:

$$\Gamma_{D^0 \rightarrow KK}(t) = |A_{KK}|^2 e^{-\Gamma t} \left(1 - R_m (y \cos \phi - x \sin \phi) \Gamma t\right)$$

$$\Gamma_{D^0 \rightarrow KK}(t) = |A_{KK}|^2 e^{-\Gamma t} \left(1 - R_m^{-1} (y \cos \phi + x \sin \phi) \Gamma t\right)$$

Each can be re-expressed as an exponential with modified widths ($\tau$’s)

$$\bar{\Gamma}_{D^0 \rightarrow KK} = \Gamma \left(1 + R_m (y \cos \phi - x \sin \phi) \Gamma t\right)$$

$$\bar{\Gamma}_{D^0 \rightarrow KK} = \Gamma \left(1 + |q/p| (y \cos \phi + x \sin \phi) \Gamma t\right)$$

Lifetimes in CP Eigenstates

$$y_{CP} \equiv \frac{\bar{\Gamma}_{D^0 \rightarrow KK} + \bar{\Gamma}_{D^0 \rightarrow KK}}{2\Gamma} - 1 = \frac{\tau_{KK}}{\tau_{KK}} - 1 \approx \frac{y}{2} \left(R_m + \frac{1}{R_m}\right) \cos \phi - \frac{x}{2} \left(R_m - \frac{1}{R_m}\right) \sin \phi$$

$$A_{\Gamma} \equiv \frac{\bar{\Gamma}_{D^0 \rightarrow KK} - \bar{\Gamma}_{D^0 \rightarrow KK}}{2\Gamma_D} = \frac{\tau_{KK} - \tau_{D^0 \rightarrow KK}}{\tau_{D^0 \rightarrow KK} + \tau_{D^0 \rightarrow KK}} \approx \frac{y}{2} \left(R_m - R_m^{-1}\right) \cos \phi - \frac{x}{2} \left(R_m + R_m^{-1}\right) \sin \phi$$

If $R_m \rightarrow 1, \phi = 0 \Rightarrow y_{CP} = y$

$y_{CP} \neq y \Rightarrow$ indirect CPV

If $A_{\Gamma} \neq 0 \Rightarrow$ indirect CPV (ignores small direct CPV contribution)
\[ D^{*\pm} \rightarrow \pi^{\pm} \bar{D}^0, \quad \bar{D}^0 \rightarrow K^+K^-, K^-\pi^+ \]

- Charge of the \( \pi_s \) tags the \( D^0 \) flavor
- \( D^{*+} \) detection also helps the background suppression

\[
\begin{align*}
D^{*+} & \rightarrow d\bar{u}c & \pi_s^+ \\
D^0 & \rightarrow c\bar{d}u & \pi_s^- \\
D^{*+} \rightarrow \bar{d}d c & \rightarrow \bar{d}d c \\
D^0 \rightarrow uu c & \rightarrow uu c
\end{align*}
\]

\[ LHCb \]

\[ D^0 \rightarrow K^-\pi^+ \]

\[ N_{\text{sig}} = 286,000 \]

\[ 29 \text{ pb}^{-1} \]

\[ LHCb \]

\[ D^0 \rightarrow K^+K^- \]

\[ N_{\text{sig}} = 39,000 \]

\[ 29 \text{ pb}^{-1} \]

\[ \Delta m = M(D^0\pi^\pm) - m(D^0) \]
Charm mixing and CPV via effective lifetimes

- First measurements at a hadron collider.
- Not yet competitive with $e^+e^-$. With 2011 data $[1.1 \text{ fb}^{-1}] \sigma_{\text{stat}} (y_{CP}) \sim 1 \times 10^{-3}$. Will soon have most sensitive measurements.
- Expected statistical errors on $A_\Gamma$ with 5 fb$^{-1}$ (upgraded LHCb 50 fb$^{-1}$) $\sim 4 \times 10^{-4}$ (1 x 10$^{-4}$)

### Summary of Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$y_{CP} (10^{-3})$</th>
<th>$A_\Gamma (10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$5.6 \pm 6.3 \pm 4.1$</td>
<td>$-5.9 \pm 5.9 \pm 2.1$</td>
</tr>
<tr>
<td>BaBar$^{1,2}$</td>
<td>$11.2 \pm 2.2 \pm 1.8$</td>
<td>$2.6 \pm 3.6 \pm 0.8$</td>
</tr>
<tr>
<td>Belle$^3$</td>
<td>$13.1 \pm 3.2 \pm 2.5$</td>
<td>$0.1 \pm 3.0 \pm 1.5$</td>
</tr>
<tr>
<td>HFAG $y_{CP}$ Average</td>
<td>$11.07 \pm 2.17$</td>
<td>$1.23 \pm 2.48$</td>
</tr>
</tbody>
</table>

### HFAF fit for $y$: \((6.3 \pm 2.0) \times 10^{-3}\)

$y_{CP} \approx y \rightarrow$ No clear evidence for indirect CPV $A_\Gamma \approx 0$

- First measurements at a hadron collider.
- Not yet competitive with $e^+e^-$. With 2011 data $[1.1 \text{ fb}^{-1}] \sigma_{\text{stat}} (y_{CP}) \sim 1 \times 10^{-3}$. Will soon have most sensitive measurements.
- Expected statistical errors on $A_\Gamma$ with 5 fb$^{-1}$ (upgraded LHCb 50 fb$^{-1}$) $\sim 4 \times 10^{-4}$ (1 x 10$^{-4}$)
Evidence of Direct CPV in $D^0$ decays
Direct CPV in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$

Singly CS D decays receive extra penguin amplitudes that generally have a different weak phase.

To get direct CPV, need a different strong phase as well.

\[
A_f = A(1 + r_f e^{i(\delta + \phi_f)}) \\
\bar{A}_f = A(1 + r_f e^{i(\delta - \phi_f)})
\]

By CKM factors, $r_f \approx 6 \times 10^{-4}$

Since: $a_f^d = 2r_f \sin \phi \sin \delta_f$  expect direct CPV $\sim 10^{-3}$

( will depend on P/T, but "natural" level would be P/T $\sim 0.1$ )


The SM cannot account for asymmetries that are significantly larger than $\mathcal{O}(10^{-4})$.

Thus, CP violation from new physics must be playing a role if an asymmetry is observed with present experimental sensitivities [$\mathcal{O}(0.01)$].
CPV in time integrated $D^0 \rightarrow K^+K^-, \pi^+\pi^-$

Recall, time dependent decay rates

$$
\Gamma(t) = |A_f|^2 e^{-\Gamma} \left[ (1 + |\lambda_f|^2) \cosh(y\Gamma t) + (1 - |\lambda_f|^2) \cos(x\Gamma t) \right] + (2 \operatorname{Re} \lambda_f) \sinh(y\Gamma t) - (2 \operatorname{Im} \lambda_f) \sin(x\Gamma t)
$$

$$
\bar{\Gamma}(t) = |\bar{A}_f|^2 e^{-\Gamma} \left[ (1 + |\lambda_f^{-1}|^2) \cosh(y\Gamma t) + (1 - |\lambda_f^{-1}|^2) \cos(x\Gamma t) \right] + (2 \operatorname{Re} \lambda_f^{-1}) \sinh(y\Gamma t) - (2 \operatorname{Im} \lambda_f^{-1}) \sin(x\Gamma t)
$$

$$
A_f = A(1 + r_f e^{i(\delta + \phi_f)})
$$

$$
\bar{A}_f = A(1 + r_f e^{i(\delta - \phi_f)})
$$

In the limit $x, y, r_f << 1$

$$
\langle a_{CP} \rangle = \frac{\Gamma_{D^0 \rightarrow f}(t) - \Gamma_{\bar{D}^0 \rightarrow f}(t)}{\Gamma_{D^0 \rightarrow f}(t) + \Gamma_{\bar{D}^0 \rightarrow f}(t)} \approx a_f^d + \langle a_f^m(t) \rangle + \langle a_f^i(t) \rangle
$$

Indirect CPV

$$
\langle a_f^i(t) \rangle = \eta_{CP} \frac{x}{2} \left( \frac{\langle t \rangle}{\tau} \right) \left( R_m + R_m^{-1} \right) \sin \phi
$$

$$
\langle a_f^m(t) \rangle = -\eta_{CP} \frac{y}{2} \left( \frac{\langle t \rangle}{\tau} \right) \left( R_m - R_m^{-1} \right) \cos \phi
$$

Raw CP asymmetry is sensitive to both direct & indirect CPV

$$
A_{CP} \approx a_{CP}^{dir} - A_{\Gamma} \frac{\langle t \rangle}{\tau}
$$

In mixing + Interference between direct and mixed decay = $A_{\Gamma}$
What do we measure?

For any $D^*$-tagged decay $D^0 \to f$:

$$A_{RAW}(f)^* \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to D^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to D^0(f)\pi^-)}$$

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

- physics CP asymmetry
- Detection asymmetry of $D^0$
- Detection asymmetry of soft pion
- Production asymmetry

For a two-body decay of a spin-0 particle to a self-conjugate final state, no $D^0$ detector efficiency asymmetry, i.e.

$$A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$$

Then:

$$A_{RAW}(K^-K^+)^* = A_{CP}(K^-K^+) + A_D(\pi_s) + A_P(D^{*+})$$

$$A_{RAW}(\pi^-\pi^+)^* = A_{CP}(\pi^-\pi^+) + A_D(\pi_s) + A_P(D^{*+})$$

$$\Rightarrow A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

- Difference in asymmetry much more robust against systematic uncertainties
- Expect direct CP asymmetry to be opposite sign for KK and $\pi\pi$ ($V_{cd}$ and $V_{us}$ have phase diff of $\pi$)
\[ \Delta a_{CP} \text{ previous measurements} \]

- Different measurements are sensitive to different combinations of direct and indirect asymmetries

HFAG averages:
- \( \Delta a_{CP}^{\text{dir}} = (-0.42 \pm 0.27)\% \)
  - 1.6\( \sigma \) away from zero
- \( a_{CP}^{\text{ind}} = (-0.03 \pm 0.23)\% \)

Recent CDF measurement:
- \( \Delta A_{CP} = [-0.46 \pm 0.31 \pm 0.12]\% \)
  - arXiv:1111.5023
Data Sample

- Based on 60% of 2011 data
Fiducial Cuts

Certain regions of the detector are only accessible to D*+ or D*- depending on polarity of the field... Up to 100% asymmetry!

|p_y/p_z| > 0.02

We veto these Regions to avoid possible small second order effects.

75% of events retained after fiducial selection
**Additional fiducial subtleties**

- $\pi^+$ curves into the beampipe region in the downstream tracking chambers!
- Require $|p_y/p_z| > 0.02$

---

Soft pions go directly into the beam pipe (low $P_x$ and $P_y$). These events are lost. No charge dependents.
Determination of $\Delta A_{CP}$ in LHCb

Fit $\delta m = M(D^0\pi^\pm) - m(D^0) - M(\pi^\pm)$ to count number of candidates for each $D^0$ flavor.

- To suppress possible 2nd order detector asymmetries between KK and $\pi\pi$ divide the data into bins of:
  - $p_T(D^*)$, $\eta(D^*)$, $p$(slow $\pi$)
  - magnet polarity (up/down)
  - runs before/after technical stop

- fit $\delta m$ in each bin separately, then average.

- All together 432 fits to $\delta m$ distributions; 216 independent measurements of $\Delta A_{CP}$
  - good consistency among bins: $\chi^2/NDF=211/215$ (CL=56%)
  - average $\Delta A_{CP} = 0.82 \pm 0.21$(stat)%
Systematic Uncertainties

- Kinematic binning: 0.02%
  - Evaluated as change in $\Delta A_{CP}$ between full 216-bin kinematic binning and “global” analysis with just one giant bin.

- Fit procedure: 0.08%
  - Evaluated as change in $\Delta A_{CP}$ between baseline and not using any fitting at all (just sideband subtraction in $\delta m$ for KK and $\pi\pi$ modes).

- Peaking background: 0.04%
  - Evaluated with toy studies injecting peaking background with a level and asymmetry set according to $D^0$ mass sidebands (removing signal tails).

- Multiple candidates: 0.06%
  - Evaluated as mean change in $\Delta A_{CP}$ when removing multiple candidates, keeping only one per event chosen at random.

- Fiducial cuts: 0.01%
  - Evaluated as change in $\Delta A_{CP}$ when cuts are significantly loosened.

- Sum in quadrature: 0.11% small!
$\Delta A_{CP}$: additional cross checks

Final result (dashed line)

- many more not shown ... All OK!
\[ \Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.82 \pm 0.21 \pm 0.11)\% \]

\[ = a_{dir}^{CP}(K^+K^-) - a_{dir}^{CP}(\pi^+\pi^-) + (0.098 \pm 0.002 \pm 0.001)a_{ind}^{CP} \]

9.8% = difference in average decay time for KK and \( \pi\pi \) final states

Our result is consistent with the previous measurements (~1.1\( \sigma \)) but more precise

3.5\( \sigma \) away from no CPV

HFAG averages including LHCb:

\[ \Delta a_{CP}^{dir} = (-0.65 \pm 0.18)\% \]

3.6\( \sigma \) away from zero

\[ a_{CP}^{ind} = (-0.02 \pm 0.23)\% \]

Probability no CPV: 0.15%
\( A_{CP} \) in \( B \rightarrow D^0 X \mu \nu 

- Large inclusive \( \mu \) sample
- Charge of \( \mu \) tags the D flavor
- Orthogonal to prompt D* analysis

\[
A_{RAW}(f)^* = \frac{N(B \rightarrow D^0(f) \mu^+ \nu_\mu) - N(B \rightarrow D^0(\bar{f}) \mu^- \bar{\nu}_\mu)}{N(B \rightarrow D^0(f) \mu^+ \nu_\mu) + N(B \rightarrow D^0(\bar{f}) \mu^- \bar{\nu}_\mu)}
\]

\[
A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\mu) + A_P(B) + A_{CP}(B)
\]

Taking difference between \( D^0 \rightarrow KK \) and \( D^0 \rightarrow \pi \pi \), unwanted production and detection asymmetries cancel.

Expect stat. error \( \sim 0.3\% \) with 2011 data sample (1.1 fb\(^{-1}\)).
Searching for CPV in charged D decays ensures, if you see it, it’s direct CPV (no mixing).

Contributing amplitudes must have both a weak and strong phase difference.

CS $D^+ \rightarrow h^+h^-h^+$ good since:

- natural variation of strong phase across the Dalitz plot, all but guarantees a strong phase difference.
- Can look at asymmetry across the Dalitz plot
- Strength of LHCb for fully charged final states.
Search for CPV in $D^+ \rightarrow K^+K^-\pi^+$

2010 data: 38 pb$^{-1}$

No evidence for direct CPV with 2010 data

For each bin of Dalitz plot calculate standard deviation from no CP:

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

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

$$\chi^2 = \sum_i (S_{CP}^i)^2$$

Table:

<table>
<thead>
<tr>
<th>Binning</th>
<th>Fitted mean</th>
<th>Fitted width</th>
<th>$\chi^2$/ndf</th>
<th>p-value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive I</td>
<td>0.01 ± 0.23</td>
<td>1.13 ± 0.16</td>
<td>32.0/24</td>
<td>12.7</td>
</tr>
<tr>
<td>Adaptive II</td>
<td>-0.024 ± 0.010</td>
<td>1.078 ± 0.074</td>
<td>123.4/105</td>
<td>10.6</td>
</tr>
<tr>
<td>Uniform I</td>
<td>-0.043 ± 0.073</td>
<td>0.929 ± 0.051</td>
<td>191.3/198</td>
<td>82.1</td>
</tr>
<tr>
<td>Uniform II</td>
<td>-0.039 ± 0.045</td>
<td>1.011 ± 0.034</td>
<td>519.5/529</td>
<td>60.5</td>
</tr>
</tbody>
</table>
Looking ahead for CPV in $D^+ \rightarrow K^- K^+ \pi^+$

1/5 of 2011 data (0.22 fb$^{-1}$)

2010 data: 0.04 fb$^{-1}$
$D^+$ 370 000
Signal purity 91%

LHCb (0.22 fb$^{-1}$)
$D^+$ 2 042 620 events

CLEO-c (0.8 fb$^{-1}$)
$D^+$ 19 000 84%

BABAR (80 fb$^{-1}$)
$D^+$ 43 000 66%
Summary

Lots of excitement about charm physics lately, in great part due to a large measured CP asymmetry in $D^0 \rightarrow KK, \pi \pi$.

We eagerly anticipate analysis of the full 2011 data sample (~40% more data), and a doubling of Lint in 2012. Expect statistical error to shrink almost in half.

Many other charm measurements being pursued, but have not had time to discuss them.

- $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K_s \pi \pi$, $K_s KK$ (Linear sensitivity to $x$ and $y$)
- $D_{(s)} \rightarrow K_s h^+$
- Mixing with DCS $D^0 \rightarrow K \pi$
- …
Backup
CP Violation in Mixing & Decay

- Consider final states accessible to both $P^0$ and $\bar{P}^0$. Let’s assume it’s a CP eigenstate, for ease.

$$\Gamma(t) = \left| A_f \right|^2 e^{-\Gamma t} \left( (1 + |\lambda|^2) \cosh(y \Gamma t) + (1 - |\lambda|^2) \cos(x \Gamma t) \right) + (2 \text{Re} \lambda) \sinh(y \Gamma t) - (2 \text{Im} \lambda) \sin(x \Gamma t)$$

- Direct decay
- Mixing + decay (DCPV if $|\lambda| \neq 1$)
- Interference between mixing + decay

In $B^0$ decays: $\Delta \Gamma/\Gamma$ small $\Rightarrow$

$$\Gamma(t) \Rightarrow \left| A_f \right|^2 e^{-\Gamma t} \left( (1 + |\lambda|^2) \cos(\Delta mt) - (2 \text{Im} \lambda) \sin(\Delta mt) \right)$$

$$a_{CP} = \frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = \frac{(1 - |\lambda|^2) \cos(\Delta mt) - (2 \text{Im} \lambda) \sin(\Delta mt)}{(1 + |\lambda|^2)}$$

- $|\lambda| = 1 \Rightarrow \sin(2\phi) \sin(\Delta mt)$

In $B_s$ decays: $y = \Delta \Gamma_s / 2 \Gamma_s \sim 0.1$ not too small …. Keep all 4 terms

In $D^0$ decays: $x, y \sim 0.01 - 0.001$, can expand, e.g. $D^0 \to KK$

$$\Gamma_{D^0 \to KK}(t) = \left| A_{KK} \right|^2 e^{-\Gamma t} \left( 1 - \frac{q}{p} \right) (y \cos \phi - x \sin \phi) \Gamma t$$
Mixing and CPV: $K^0$

$\Delta m_K \propto m_t^2 \lambda^{10} \ll \Gamma_K \sim O(\lambda^4)$  
$\Rightarrow$ Slow mixing rate.

Mass eigenstates labeled by lifetimes ("short" and "long")

**CP Violation:** Kaon decays described almost by first two generations, which are $\sim$ real $\Rightarrow$ Small CPV

- (Indirect) CPV in mixing $\varepsilon_k \sim 10^{-3}$
- Direct CPV, $\varepsilon' \sim 10^{-3} \varepsilon$
- Long distance effects make lead to large uncertainties in CKM params