Understanding charm CP

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EPS 2019
Ghent, Belgium 07/11/19
Outline

• Recently, LHCb exciting obs of ΔACP
• Naturalness reasoning strongly suggests other BSM-CP phase(s) must exist. To discern computations essential
• CPV represents an imp. avenue for searching new pheno but precise calculations are highly desirable
• Crude estimate of ΔACP
• Propose a specific mechanism for understanding ΔACP
• Many testable implications
• This mechanism points to new difficulties for first principles (lattice) calculations addressing ΔACP
• Suggest mode(s) for precision testing the SM-CKM
• Lattice feasibility
• Summary + Outlook
\[ \Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \]

**Results**

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

- Compatible with previous LHCb results and the WA
- **Combination** with LHCb Run 1 gives:

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

**CP violation observed at 5.3\sigma!!**
**CP violation history**

- **1956**
  - Parity violation

- **1963**
  - Cabibbo Mixing
  - N. Cabibbo

- **1964**
  - Strange particles: CP violation in K meson decays
  - J. W. Cronin, V. L. Fitch *et al."

- **2001**
  - Beauty particle CP violation in meson decays
  - BaBar and Belle collaborations

- **2019**
  - Charm particle CP violation meson decays
  - LHCb collaboration

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**BNL-COLUMBIA**

**BNL**
Indirect CP
\( \approx 10^{-3} \)

**CERN/FNAL**

**E'**
Direct CP
\( \approx 10^{-6} \)

F. Betti - INFN Bologna, University of Bologna

EPS-2019; soni-BNL-HET

Moriond EW 2019 - 21/03/2019
Alas, we cannot compute!

• Sadly calculations of Direct CP remain a challenge for theory; we are not able to calculate with any precision \([\text{eps’ an exception as a result of over 3 decades of concerted lattice effort}]\). As a rule, we can just give crude (QCD) model-dependent estimates..

• Essential ingredient is CP-conserving scattering phases & usually complicated non-perturbative effect on weak decays....difficult for the lattice in general
BASICS OF DIRECT CP ASY

\[ \alpha_{PRA} = \frac{B[I \to F] - B[\bar{I} \to \bar{F}]}{B[I \to F] + B[\bar{I} \to \bar{F}]} \]

\[ A_{hh} = \lambda T_{hh} + \lambda^5 P_{hh} e^{i(\delta_{st} + \eta_{wk})} \]

\[ \alpha_{hh} = 2\lambda^4 P_{hh} \sin(\delta_{st}) \sin(\gamma)/T_{hh} \]

interferes with CBST

\[ V_{cb} V_{ub}^* \text{ CP-odd phase} \]
CRUDE ESTIMATE
SM expectation...DCP

- Dir CP..... See Bander, Silverman + AS, PRL 1979 for DCP when \(mq \gg \lambda_{\text{QCD}}\)…anticipate large corrections for charm from s-quark[K-decays]
- Key points: Penguin-Tree interference; SCS modes......Hall mark of BSS’79
- Need suitable simple changes
- SM-dominant CKM phase either in Vub or in Vtd
- For charm decays relevant is Vub

\[ 4 \text{CLA} \rightarrow DCP \sim g_{\text{SM}} [V_{cb} V_{ub}^*] \sim 4 \times 10^{-3} \]

\[ m_U > 4 [m_s^2, m_c^2] \]

\[ m_s > 10^{-3} \]

\[ \lambda \sim 10^{-3} \]

\[ L \leq 10^2 \]

\[ \text{Very difficult to reach in SM} \]
Lattice difficulties for ΔACP

- $m_D \sim 1.865$ GeV; $Br [D \rightarrow K^+ K^-] \sim 0.4$
  much larger $Br$ to multiparticle states...difficult on the lattice....see Hansen and Sharpe, PRD’12.
- However, strictly speaking $\Delta ACP$ requires only difference between $KK$ and $pipi$ states.
- Therefore, optimistically, one may hope for appreciable cancellation between multiparticle states; i.e $U$-spin or $SU(3)$ may provide a basis for such a cancellation.
- But unlikely to be viable as will be explained.
Interplay with resonances

- Charm region has many resonances
- Resonances that have appreciable Br to KK & pi pi are relevant
- In particular (ps) scalar resonances
- These can enter the weak decay dynamics via the penguin H_eff
b-penguin

• b-penguin fig
Penguin Hamiltonian

- Since \( mb >> \Lambda_{QCD} \), we can integrate it out along with \( W \) and get the familiar, \( H_{\text{eff}} \):
- \( H_{\text{eff}} = Ci \, Oi \)

\[
\begin{align*}
\Theta_3 &= (\bar{c}_\alpha u_\alpha)_V\!\!_A \left[ (\bar{u}_B u_\beta)_V\!\!_A + (\bar{d}_B d_\beta)_V\!\!_A + (\bar{s}_\beta s_\beta)_V\!\!_A + (\bar{c}_\beta c_\beta)_V\!\!_A \right], \\
\Theta_4 &= (\bar{c}_\alpha u_\beta)_V\!\!_A \left[ (\bar{u}_B u_\alpha)_V\!\!_A + (\bar{d}_B d_\alpha)_V\!\!_A + (\bar{s}_\beta s_\alpha)_V\!\!_A + (\bar{c}_\beta c_\alpha)_V\!\!_A \right], \\
\Theta_5 &= (\bar{c}_\alpha u_\alpha)_V\!\!_A \left[ (\bar{u}_B u_\beta)_V\!\!_A + (\bar{d}_B d_\beta)_V\!\!_A + (\bar{s}_\beta s_\beta)_V\!\!_A + (\bar{c}_\beta c_\beta)_V\!\!_A \right], \\
\Theta_6 &= (\bar{c}_\alpha u_\beta)_V\!\!_A \left[ (\bar{u}_B u_\alpha)_V\!\!_A + (\bar{d}_B d_\alpha)_V\!\!_A + (\bar{s}_\beta s_\alpha)_V\!\!_A + (\bar{c}_\beta c_\alpha)_V\!\!_A \right],
\end{align*}
\]

See Abbott, Sikivie, Wise '80; Goldman, Ginztein '89
Buchalla, Bunos, Lautenschlager '96
Penguin Ops + Resonance Coupling

\[ \mathcal{L} \mathcal{X} R \Rightarrow -2 [s + p] \times [s - p] \]

\[ \mathcal{O}_0 \Rightarrow \Phi \times S \rightarrow O^{+} \quad m_{f_0} = 1723 \text{ MeV} \]

\[ f_{(1710)}^0 \sim 150 \text{ MeV} \]

\[ \Rightarrow K \bar{K} \quad \tau \tau \]

See PRC Live

BR \( f_0 \rightarrow K \bar{K} \sim 40\% \)

\( \frac{BR (f_0 \rightarrow \pi \pi)}{BR (f_0 \rightarrow K K)} \sim 0.4 \)
FIG. 8. The mass spectrum of glueballs in the pure SU(3) gauge theory. The masses are given in terms of the hadronic scale $r_0$ along the left vertical axis and in terms of GeV along the right vertical axis (assuming $r_0^{-1} = 410$ MeV). The mass uncertainties indicated by the vertical extents of the boxes do not include the uncertainty in setting $r_0$. The locations of states whose interpretation requires further study are indicated by the dashed open boxes.
PDG gives Br’s of D0

\[ \begin{array}{l}
K^+ K^- \\
\pi^+ \pi^- \\
\end{array} \]
\[ \begin{array}{c}
(3.97 \pm 0.07) \times 10^{-3} \\
(1.407 \pm 0.025) \times 10^{-3} \\
\end{array} \]
New understanding of an old issue

Cornwall + AS, PRD '84, Cheng + Chiang 1001.0467

\[ \mathcal{L}_{\text{eff}} = - \bar{\psi} (G_S \sigma + i \gamma_5 G_P) \psi + \cdots, \quad (3.2) \]

\[ G_S = \frac{M_Q}{2 \langle S \rangle} \]

\[ \langle S \rangle \approx 130 \text{ MeV}. \quad (1.3) \]

Spontaneous flavor \textit{gauge} gluonia \( \sigma, \tau, \rho, \omega, \phi \)
f0 decay to KK & pi pi

• PDG live gives

• $\text{Br} \left[ f_0 \rightarrow \pi^+ + \pi^- \right] / \text{Br}[f_0 \rightarrow K^+ + K^-] \sim 0.4$

enhancing the SU3 breaking decays of the D0
WHEN DEALING WITH FINAL STATES THAT ARE DOMINATED BY RESONANCES, THEN THE WIDTH OF THE RESONANCE PROVIDES THE “STRONG”-CP-EVEN PHASE NEEDED FOR COMPUTING PRA...1ST ILLUSTRATED BY EILAM, HEWETT + AS, PRL’91
Resonance Idea

For basic idea see Eilam, Hewett + AS PRP 1991

See also ATLAS + AS EP 1994

For $D^0 \rightarrow K\bar{K}$

\[
t_{hh} = \left( \frac{G_F}{2\sqrt{2}} \right) (C_2 + C_1/3) f_K f(0) m_D^2
\]

$P_{hh} = \left( \frac{G_F}{2\sqrt{2}} \right) C_6 A^2 \sqrt{\rho^2 + \eta^2}
\]

\[
\left( f_D m_D/m_c \right) K f m_f^2
\]

(7)

$\alpha_{K^+ K^-} \approx 5.5 \times 10^{-4}$

$\Delta A \approx 12 \times 10^{-4}$

$k^+ \approx 3.7$

$N_{\text{ice paper}}$

$C\Delta H - N_{\text{LH}}$, C + D + + + Fm + SY + PRD 1986, 1988.
Interplay of CPT & resonant CP

Because of the CPT constraint that life-time of particle must equal to that of its antiparticle, we must have,

$$\sum_X \Delta \Gamma(X) = 0$$  \hspace{1cm} (9)

where \( X \) are the various final states that emerge from the decays of \( D^0 \) and

$$\Delta \Gamma(X) = \Gamma(D^0 \to X) - \Gamma(D^0 \to \bar{X})$$

Since at the quark level in charm decays there are only two channels, \( c \to u\bar{d}d \) and \( c \to u\bar{s}s \), this means because of CPT we must have [20, 21],

$$\Delta \Gamma(c \to u\bar{d}d) = -\Delta \Gamma(c \to u\bar{s}s)$$  \hspace{1cm} (10)

At the meson level, it is suggested [20] that this materializes into,

$$\Delta \Gamma(\pi^+\pi^-) = -\Delta \Gamma(K^+K^-)$$  \hspace{1cm} (11)

Using the tree dominance, as emphasized above, one then arrives at the relation,

$$\alpha_{K^+K^-} \propto -\alpha_{\pi^+\pi^-}/\sqrt{2.8}$$  \hspace{1cm} (12)

where, we have taken for simplicity that the two Brs differ by about \( \sqrt{2.8} \) [18].

However, f-dominance of the penguin amplitude, in the \( h h \) channel that is our central focus, appearing in the numerator of (4) modifies this expectation appreciably. This is because, it appears that [5],

$$Br(f_0 \to \pi\pi)/Br(f_0 \to KK) \approx 0.4$$  \hspace{1cm} (13)
On-shell rescattering phase

CP-even phase $\Rightarrow$ Total amplitude

$s$ $\rightarrow u d \bar{d}$ is complex
\[-\alpha_{\pi^+\pi^-}/\alpha_{K^+K^-} = \sqrt{(0.4 \times 2.8)} \approx 1.06\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR ((10^{-3}))</th>
<th>Current PRA bound ((10^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+K^-)</td>
<td>3.97 ± 0.07</td>
<td>−0.07 ± 0.11</td>
</tr>
<tr>
<td>(K_sK_s)</td>
<td>0.17 ± 0.012</td>
<td>−0.4 ± 1.5</td>
</tr>
<tr>
<td>(\pi^+\pi^-)</td>
<td>1.407 ± 0.025</td>
<td>0.13 ± 0.14</td>
</tr>
<tr>
<td>(\pi^0\pi^0)</td>
<td>0.822 ± 0.025</td>
<td>0.0 ± 0.6</td>
</tr>
</tbody>
</table>

\[\alpha_{K_sK_s}/\alpha_{K^+K^-} \approx \sqrt{(23/4)} \approx 2.4\]

\[\alpha_{\pi^0\pi^0} = 1.3 \alpha_{\pi^+\pi^-}\]
CANDIDATES FOR PRECISION TEST:
NEEDS TO BE EXPERIMENTALLY ACCESSIBLE AND BE ALSO AMENABLE TO PRECISE LATTICE CALCULATIONS
Candidate for precision test: CPV in D0 => gamma + [phi => K^+ K^-]

• Requires KK scattering phases for CM energy below around 1 GeV

• Differential photon energy spectrum can be used for precision test

• Integrated BR ~ 2.74 pm 0.19 X10^-5 well measured

• Belle-II expected ~10^10 D’s/yr ...precise measurement of differential spectrum is clearly feasible
Production mechanisms

• Dominant production: Tree $\sim$ Lambda

\[
\begin{array}{c}
\phi \\
\Phi \\
\end{array} \quad \Rightarrow \quad \begin{array}{c}
k^+ k^- \\
\end{array}
\]

• Interfering penguin $\sim$ Lamda$^5$
Feasibility of lattice extraction of KK phases in ~ 1 GeV energy region

- Good reason to expect that this is doable: see works of JLAB [Briceno et al PRL 2017], RBC-UKQCD [Tainle Wang, Chris Kelly, Aaron Meyer, Mattia Bruno, Dan Hoying, David Murphy et al, Lat2018 & 2019 presentations] paper(s) in preparation; see also G. Rendon et al Lat2018

- At ~ 1 GeV or below, relevant to radiative D0 decays, error due to KKpipi, 4 pi contamination likely small
BRIEF REMARKS ON RADIATIVE CHARM DECAYS

• New class of radiative decays...interesting nearby resonances relevant for radiative transitions: [see PDGLive]:would be useful to target these to confirm role of resonances

\[ \phi(1680), \Gamma \approx 50 \text{ MeV} \Rightarrow \pi \pi(1300) \]
\[ \phi(1700), \Gamma \approx 250 \text{ MeV} \Rightarrow \phi \pi, \rho \pi \ldots \]
\[ D^0 \rightarrow \pi \phi(1700), \quad \chi(1680) \leq 300 \text{ MeV} \]

• Best candidates for precision tests of the SM

\[ \pi \rightarrow \rho \omega(770), \quad \pi \phi(1020) \quad \text{BR} \approx 10^{-4} - 10^{-5} \]
Another important resonance nearby

$\eta(1760)$

$$\eta(1760) \quad I^G(J^{PC}) = 0^+ (0^{-+})$$

$\eta(1760)$ in the $pp$ system (BISELLO 1989B). Structure in this region has been reported before in the same system (BALTRUSAITIS 1986B) and in the $\omega\omega$ system (BALTRUSAITIS 1985C, BISELLO 1987).

<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>Fraction ($\Gamma_i / \Gamma$)</th>
<th>Scale Factor/Conf. Level</th>
<th>$P$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$4\pi$</td>
<td></td>
<td>823</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$2\pi^+ 2\pi^-$</td>
<td>seen</td>
<td>819</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>seen</td>
<td>822</td>
</tr>
<tr>
<td>$\Gamma_4$</td>
<td>$\rho^0 \rho$</td>
<td>seen</td>
<td>407</td>
</tr>
<tr>
<td>$\Gamma_5$</td>
<td>$\rho^+ \rho^-$</td>
<td></td>
<td>407</td>
</tr>
<tr>
<td>$\Gamma_6$</td>
<td>$2 (\pi^+ \pi^- \pi^0)$</td>
<td></td>
<td>733</td>
</tr>
<tr>
<td>$\Gamma_7$</td>
<td>$\omega \omega$</td>
<td>seen</td>
<td>393</td>
</tr>
<tr>
<td>$\Gamma_8$</td>
<td>$\eta \pi^+ \pi^-$</td>
<td>seen</td>
<td>572</td>
</tr>
<tr>
<td>$\Gamma_9$</td>
<td>$\gamma \gamma$</td>
<td>seen</td>
<td>876</td>
</tr>
</tbody>
</table>

$\rho \times \rho$
FIG. 2. b-penguin in charm decay; left $c$-$b$ (red) vertex may have a CP-odd phase endowed by new physics affecting $R_{D(*)}$ whereas the right $b$-$u$ (blue) vertex contains the SM-CKM phase.
Summary + outlook

- Charm region is rich with resonances
- Some of these are expected to play an important role in driving CP asymmetries, PRA, energy (3 or more particle FS), TCA (4 or more spin-less)
- New class of radiative decays with photon energy < ~300 MeV to resonances which cascade down to several diff FS, such as KK, pi pi, eta’(eta, pi0) pi pi....
- Resonant mechanism leads to predictions relating PRA’s in 2Ks, pi^+pi^-, and 2 pi0 to that in K^+ K^-
- Mixing of D0 weak decays with f0 accounts roughly for the observed size of ΔACP & large SU3 breaking seen for long. Resonances complicate addressing of ΔACP by lattice methods.
- Important target should be precise CP-tests for SM-CKM. For this purpose, it is suggested that the best candidate for precision test are CPV asymmetries (~O .1%), Br ~10^-5: D0=>γφ with φ => K+ K-
XTRAS
Repercussions of flavour symmetry breaking on CP violation in $D$-meson decays

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Abstract: We investigate to what extent the recently measured value for a non-vanishing direct CP asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays can be accommodated in the Standard Model (SM) or extensions with a constrained flavour sector, for instance from a sequential 4-th generation of quarks (4G). From the comparison with $D^0 \to K^-\pi^+$ branching ratios, we establish large U-spin symmetry $(d \leftrightarrow s)$ breaking effects with large strong phases between different interfering amplitudes. On the basis of conservative estimates on amplitude ratios — which are supported by an analysis of the breaking of a $c \leftrightarrow u$ symmetry in non-leptonic $B^0$ decays — we find that, in the SM, direct CP asymmetries in the $\pi^+\pi^-$ or $K^+K^-$ modes (or in their difference) of the order of several per mille are still plausible. Due to the constraints on the new CP phases in the 4G model, only moderate effects compared to the SM estimates are possible. We suggest CP studies at LHCb as well as at (Super)B-factories of several distinctive modes, such as $D^+ \to K^{(*)0}\pi^+, \phi\pi^+$ and $D_s \to K^{(*)0}\pi^+, \phi\pi^+(K^\pm)$ etc., which should shed more light on the short- and long-distance effects.

Reliable and accurate calculations remain a challenge to theorists!
\[ f_0(1710) \] \[ I^G(J^{PC}) = 0^+(0^{++}) \]

Mass \( m = 1723^{+6}_{-5} \text{MeV} \quad (S = 1.6) \)
Full width \( \Gamma = 139 \pm 8 \text{MeV} \quad (S = 1.1) \)

### \( f_0(1710) \) DECAY MODES

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ((\Gamma_i/\Gamma))</th>
<th>(\rho) (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K \bar{K} )</td>
<td>seen</td>
<td>706</td>
</tr>
<tr>
<td>( \eta \eta )</td>
<td>seen</td>
<td>665</td>
</tr>
<tr>
<td>( \pi \pi )</td>
<td>seen</td>
<td>851</td>
</tr>
<tr>
<td>( \omega \omega )</td>
<td>seen</td>
<td>360</td>
</tr>
</tbody>
</table>

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2018 Review of Particle Physics.

**LIGHT UNFLAVORED MESONS**

\((S = C = B = 0)\)
For \( I = 1 \) (\( \pi, \rho, a_1 \)); \( w \bar{q} \), \(( w \bar{u} - d \bar{d})/\sqrt{2}, d \bar{u} \);
for \( I = 0 \) (\( \eta, \eta' \), \( h, h', \omega, \phi, f, f' \)); \( c_0 ( w \bar{u} + d \bar{d}) + c_1 ( w \bar{d} + d \bar{u}) \)

\( \eta(1760) \) \[ I^G(J^{PC}) = 0^+(0^{++}) \]

Seen by DM2 in the \( \rho \rho \) system (BISELLO 1989B). Structure in this region has been reported before in the same system (BALTRUSAITIS 1988B) and in the \( \omega \omega \) system (BALTRUSAITIS 1985C, BISELLO 1987 ).

| \( \eta(1760) \) MASS | 1751 ± 15 MeV |
| \( \eta(1760) \) WIDTH | 240 ± 30 MeV |