Quantum Coherence and Charm

Roy A. Briere *

Carnegie Mellon

CHARM 2016
Bologna
06 Sep 2016

*Full disclosure: member of CLEO-c / BESIII / Belle II
Quantum coherence analyses allow us to form a more solid foundation for our studies in flavor physics...

They gives us unique access to strong phases, and it’s fun to work with EPR-entangled states in an HEP context!

→ It takes TWO amplitudes to have a relative phase…
Of course, our goal is to find some flaw in the structure of the Standard Model…

We always seem to have a few hints of failure; the Standard Model bends yet does not break! (thus far…)

→ Phases are angles…
Outline

Introduction: Essentials
Overview of Older Results
Survey of Recent Results
Selected Issues Going Forward

Conclusion

For a written overview, see my CKM2014 proceedings:
arXiv:1411.7327
The Big Picture: Phase Inputs

Places where relative $D^0, D^{0\bar{b}ar}$ phases can show up:

1) Quantum-correlated (“EPR”) $D$ pairs @ threshold: $\psi(3770)$
2) $D^0 - D^{0\bar{b}ar}$ mixing
3) $B \rightarrow DX$, with common $D^0, D^{0\bar{b}ar}$ final states [ re: CKM $\gamma$ ]

Generally, 1) is viewed as a source of information to be input for use by 2) & 3) [ more on this later… ]

The relevant datasets are CLEO-c and BESIII:

$\rightarrow$ Access to relative $D^0, D^{0\bar{b}ar}$ strong phase differences
$\rightarrow$ Can obtain model-independent results

For 2) Rotate measured $K\pi$ mode $x', y'$ parameters to get $x, y$
For 3) Reduce model-dep. of CKM $\gamma$ from $B \rightarrow D^{(*)} K^{(*)}, D^{(*)}\pi$
Main Customer: CKM $\gamma$ Extraction

CKM Angle $\gamma$ Measurement

- Gronau, London, Wyler (GLW)
- Atwood, Dunietz, Soni (ADS)

Final states are CP eigenstates. Interference is $O(10\%)$.

Final states are flavor modes ($K\pi$, $K3\pi$). CF and DCSD decays. Interference is large.

Borrowed from C. Wallace (LHC-b), talk @ Pheno 2014
Using The $\psi (3770)$

Threshold production of charm with $e^+e^- \rightarrow \psi (3770)$
The $\psi (3770)$ decays to coherent pair of D mesons

$$\psi (3770) \rightarrow \frac{1}{\sqrt{2}} \left[ D^0(+)D^0(-) - \bar{D}^0(+)\bar{D}^0(-) \right]$$

$$\psi (3770) \rightarrow \frac{1}{\sqrt{2}} \left[ D_{CP-}(+)D_{CP+}(-) - D_{CP+}(+)D_{CP-}(-) \right]$$

**CP eigen-states:**

$$D_{CP\pm} = [D^0 \pm \bar{D}^0]/\sqrt{2}$$

Measure various combination of rates for:

- one decay mode only $\rightarrow$ “single tags”
- two decay modes $\rightarrow$ “double tags”

Easiest way to see access to relative phases:

$\rightarrow$ Reconstruct one meson in a CP eigenstate: a “CP tag”

$\rightarrow$ Projects 2\textsuperscript{nd} meson into a $D^0, D^0\bar{D}^0$ superposition (Eq 2)

$\rightarrow$ So, $D^0, D^0\bar{D}^0$ amplitudes to common final state interfere

Also can change the sign of interference! Use $CP+ \text{ or } CP-$ tag
**Decay Mode Jargon**

**Flavored**
- Flavored semileptonic: $K^-e^+\nu$, $K^-\mu^+\nu$  
  Pure CF
- Flavored hadronic: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$  
  CF + DCSD

**Self-Conjugate**
- 2-body CP eigenstate: $K^-K^+$, $\pi^+\pi^-$, ...
  SCS
- 2-body CP eigenstate: $K_S\pi^0$, ...
  CF + DCSD
- Multi body: $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0$  
  SCS
- Multi body: $K_Sh^+h^-, K_Lh^+h^-$
  CF + DCSD

**Neither**
- $K_SK^-\pi^+$  
  SCS

[Note: “Both” is not possible!]

**Blue modes: used for $\gamma$**

**Green : future?**

**Black: tag only**

( ? out-of-date now ?)

**Shorthand:** hadron “$h$” = $K$, $\pi$

- **CF**: Cabibbo-Favored  
  right-sign Kaon: $D \rightarrow K^{\text{bar}} X + \text{c.c.}$
- **SCS**: Singly-Cabibbo-Suppressed
- **DCSD**: Double-Cabibbo-Suppressed (Decay)  
  wrong-sign Kaon: $D \rightarrow K X + \text{c.c.}$
Multi-Body “Coherence Factors”

Simplified Two body:

\[ | A_1 + A_2 |^2 = | A_1^2 + A_2^2 + 2 A_1 A_2 e^{-i\delta} | \quad 1, 2 = CF, DCSD \]

Generalization \( \rightarrow \) Atwood-Soni:

Integrate over Dalitz plot; define real average amplitudes

\[ [A \rightarrow A \text{ below }] \]

BUT this requires a “fudge factor” of \( \text{Re}^{-i\delta} \) for interference term

Simplified Multi body:

\[ \int d \text{Dalitz} \quad | A_1 + A_2 |^2 = | A_1^2 + A_2^2 + 2 R e^{-i\delta} A_1 A_2 | \]

Define: \( R e^{-i\delta} = ( \text{true cross-term} ) / ( \text{naïve} = A_1 A_2 ) \)

Note: \( R < 1 \) due to two reasons: varying phase & “\( | r(x) | \neq 1 \)”

\[ r = A_2 / A_1 \]

\[ A_{K^\pm \pi^\mp \pi^0}^2 = \int | A_{K^\pm \pi^\mp \pi^0}(x) |^2 d\mathbf{x}. \]

\[ R_{K\pi\pi^0} e^{-i\delta_D^{K\pi\pi^0}} = \frac{\int A_{K^-\pi^+\pi^0}(x) A_{K^+\pi^-\pi^0}(x) d\mathbf{x}}{A_{K^-\pi^+\pi^0}A_{K^+\pi^-\pi^0}} \]
From Tags to Physics

CP+ & CP- tags:
Switch of +- flips sign of interference term
Also used directly for $\gamma$, but *phases are trivial* [GLW]

Semileptonic flavor tags:
No interference; clean normalization [ but pesky $\nu$… ]

Hadronic flavor tags:
Normalization, modulo DCSD [ easier than semilep for exp. ]
Also modes we want to study for $\gamma$ [ADS]

Multi-body self-conjugate
Modes we want to under study for $\gamma$ [GGSZ]

Different analyses use different numbers of tag modes
CLEO $K^-\pi^+$ & CLEO-c, BESIII $K_S\pi^+\pi^-$ use *many* tags
BESIII $K^-\pi^+$ analysis uses only signal and CP tags
### Experimental Output

<table>
<thead>
<tr>
<th>System</th>
<th>Model</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-K^+, \pi^+\pi^-$</td>
<td>GLW</td>
<td>$\delta = 0, \pi$</td>
</tr>
<tr>
<td>$K^-\pi^+$</td>
<td>ADS</td>
<td>$\delta (R=1)$</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K_SK^-\pi^+$</td>
<td>ADS+</td>
<td>$R, \delta$</td>
</tr>
<tr>
<td>$K_S\pi^+\pi^-, K_SK^+K^-$</td>
<td>GGSZ</td>
<td>$c_i, s_i$</td>
</tr>
</tbody>
</table>

$R, \delta$ are Atwood-Soni coherence factors for ADS modes

→ *No relative $D^0$-$D^{0\text{bar}}$ phase* in separate $D^0, D^{0\text{bar}}$ Dalitz fits
  e.g., if one fits $N$ amplitudes to $D^0, D^{0\text{bar}}$ separately:  
  only gets $2(N-1) = 2N-2$ out of $2N-1$ relative phases

→ Also *avoid Dalitz models*

$c_i, s_i$ are “Cartesian $R, \delta$ in Dalitz bins” for GGSZ modes

→ Here, relative $D^0$-$D^{0\text{bar}}$ phase is trivial
  ( distinction due to self-conjugate modes, not changing basis to $c_i, s_i$! )

→ But we still *avoid Dalitz models*
Simplest effect:
\[ \psi(3770) \to \left[ D_{\text{CP}+} D_{\text{CP}-} - D_{\text{CP}-} D_{\text{CP}+} \right] / \sqrt{2} \]

Like CP (++, --): cancels
Unlike CP (+-, -+): doubled

My favorite general form: * Ignore mixing for now *
\[ \frac{\Gamma_{FG}}{A_F^2 A_G^2} = \left[ r_F^2 + r_G^2 + 2 r_F r_G R_F R_G \cos(\delta_G - \delta_F) \right] \]

or \[ 1 + r_F^2 r_G^2 + \ldots : \text{ factor out } A_i \text{ such that } r < 1 \]

→ \( r_{FG} \) (averaged) amplitude ratios:
  ~ \( A(D^{0\text{bar}} \to F,G) / A(D^0 \to F,G) \)
  1 for CP eigenstates
  ~\( \tan^2(\theta_C) \) for hadronic \( K^- \) modes [ DCSD/CF ]
  0 for semileptonic → no interference

→ \( R, \delta \): Atwood-Soni coherence factors
  \( R=1; \delta = 0, \pi \) for CP eigenstates;
  \( R=1; \delta = ? \) for \( K^-\pi^+ \)
  Both non-trivial for multi-body hadronic
Need some double-tag rate with two “non-trivial” modes to fully separate parameters
→ If not, get only $\text{Re}[R e^{-i\delta}] = R \cos \delta$, not separate $(R, \delta)$
  [ Or, only $c_i$, not both $c_i, s_i$ ]

The reason that having two works is simple trigonometry:
$$\cos(\delta_2 - \delta_1) = \cos \delta_1 \cos \delta_2 - \sin \delta_1 \sin \delta_2$$
With this, one has enough observables to separate
( can still use modes where one $\delta_i = 0$ )

Two “non-trivial” modes?
→ Can be different values of $n$ in $K^-(n\pi)^+$ analyses
→ Can even be different bins $(i)$ in $K_S \pi^+ \pi^- c_i, s_i$ analyses
CLEO-c Results

CLEO-c Data: 0.8 fb\(^{-1}\) @ \(\Psi(3770)\) & 0.6 fb\(^{-1}\) @ 4170 MeV 2003 - 08

\(K^-\pi^+\) 281 pb\(^{-1}\) PRL 100, 221801 (2008); PRD, 78, 012001 (2008) [ = more details ]

\(K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-\) 818 pb\(^{-1}\) PRD 80, 031105(R) (2009)

\(K_S\pi^+\pi^-\) 818 pb\(^{-1}\) PRD 80, 032002 (2009)

\(K_{S,L}h^+h^-\) 818 pb\(^{-1}\) PRD 82, 112006 (2010)

\(K_SK^+\pi^-\) 818 pb\(^{-1}\)* PRD 85, 092016 (2012)

\(K^-\pi^+\) → 818 pb\(^{-1}\) PRD 86, 112001 (2012)

\(K^+K^-\pi^+\pi^-\) 818 pb\(^{-1}\)** PRD 85, 122002 (2012) \{ isobar analysis; but first \(D, D^{\text{bar}}\) \}

also use high-E continuum \{ * + 15 fb\(^{-1}\) ~10 GeV 
** + 24 fb\(^{-1}\) ~10 GeV & 600 pb\(^{-1}\) 4.17 GeV \}
Today’s Main Topics

**BESIII Results**

Dataset :  2.92 fb\(^{-1}\)  2010 - 11 (1 2/3 years)  →  3.5x CLEO-c

Future ability :  ~ 4 fb\(^{-1}\) / running year  [note: \(L_{2011} \gg L_{2010}\)]

---

**CLEO-c “Legacy” Results**

\[K^-\pi^+, K^-\pi^+\pi^0\pi^-, 818 \text{ pb}\(^{-1}\)  PLB 731, 197 (2014)\]

\[\pi^+\pi^-\pi^0, K^+K^-\pi^0, 818 \text{ pb}\(^{-1}\)  PLB 740, 1  (2015)\]

\[\pi^+\pi^+\pi^-\pi^-, \pi^+\pi^-\pi^0, K^+K^-\pi^0, 818 \text{ pb}\(^{-1}\)  PLB 747, 9 (2015)\]

[CLEO-c data analyzed by past members, after collaboration disbanded]

Also: 2016 joint analysis of CLEO-c Legacy = LHC-b for \(K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-\)
Simplified Picture: (simple = no mixing)

Amplitude triangle:
\[ \text{CP}_\pm = \text{CF} \pm \text{DCSD} \]
[DCSD enhanced for visibility!]

Complex ratio
DCSD/CF amplitude
\[ \frac{\langle K^- \pi^+ | \bar{D}^0 \rangle}{\langle K^- \pi^+ | D^0 \rangle} = -re^{-i\delta_{K\pi}} \]

Flip CP of tag: reverses interference term
CP-tagged rate asymmetry (essentially) measures \( r \cos \delta \)

\[ A_{\text{CP}} = \left[ |A_{\text{CP}^-}|^2 - |A_{\text{CP}^+}|^2 \right] / \left[ |A_{\text{CP}^-}|^2 + |A_{\text{CP}^+}|^2 \right] \]
\[ = r \cos \delta \quad (+\text{D mixing corrections: } y, R_{WS}) \]
First BESIII Quantum Coherence result: straightforward analysis

Tags Used: 5 CP+, 3 CP-

$S+\quad K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$

$S-\quad K_S^0\pi^0, K_S^0\eta, K_S^0\omega$
\[ \mathcal{A}_{K\pi}^{CP} = \frac{\mathcal{B}_{D^{s-}\rightarrow K^-\pi^+} - \mathcal{B}_{D^{s+}\rightarrow K^-\pi^+}}{\mathcal{B}_{D^{s-}\rightarrow K^-\pi^+} + \mathcal{B}_{D^{s+}\rightarrow K^-\pi^+}} \]

\( S^\pm (S^-) \) denotes the \( CP\)-even (\( CP\)-odd) eigenstate.

**Direct result:**
\[ \mathcal{A}_{CP} = (12.7 \pm 1.3 \pm 0.7)\% \]

\[ 2r \cos \delta_{K\pi} + y = (1 + R_{WS}) \cdot \mathcal{A}_{K\pi}^{CP} \]

Using external inputs for \( r_{K\pi}, R_{WS}, y \), we extract:
\[ \cos \delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01 \]

Compare to CLEO-c:
\[ \cos \delta_{K\pi} = 0.81^{+0.22}_{-0.18}^{+0.07}_{-0.06} \quad (\text{no external inputs}) \]
\[ \cos \delta_{K\pi} = 1.15^{+0.19}_{-0.17}^{+0.00}_{-0.08} \quad (\text{w/ external inputs}) \]

* HFAG can use this, I believe: they now omit final \( \delta_{K\pi} \) due to external inputs …
Original CLEO-c Coherence Factors

Or, we could bin across Dalitz plot
c_i and s_i: bin-averaged
<R cos δ> and <R sin δ>

Small R for Kπππ: still useful for r_B!

K_S Kπ

Kπππ

Kππ0

BaBar Model
CLEO Data
**K^− (nπ)^+ Update**

CLEO-c “Legacy data” publication → not a collaboration result (but I personally believe it to be of equal quality)

→ Now includes K_Sπ^+π^- tags
→ Updated external inputs (BF, mixing, Kπ)

**Kππ updated again in**
PLB 757, 520  
(2016) Now including LHCb data...
**K^- (nπ)^+ Update II**

Combined fit to:  
CLEO-c “Legacy data”  
+ LHC-b data for D mixing

Note: now Kππ “lobes” are almost gone…
π⁺π⁻π⁰ & K⁺K⁻π⁰ CP Fractions

More CLEO-c “Legacy data” results

CP fraction for a mixed-CP final state:

\[ F_+ = \frac{N(\text{CP}^+)}{N(\text{CP}^+) + N(\text{CP}^-)} \]

These states act similar to CP eigenstates, but suffer from a statistical “Dilution factor” of \( w = (2F_+ - 1) \)

If the CP-content is nearly pure (\( F_+ \) is near 1 or 0), then the loss is small

Results:

\( \pi^+ \pi^- \pi^0 \): \( F_+ = 0.968 \pm 0.017 \pm 0.006 \)
\( K^+ K^- \pi^0 \): \( F_+ = 0.731 \pm 0.058 \pm 0.021 \)

The three-pion mode is nearly pure: acts almost like a CP-eigenstate
\[ \pi^+ \pi^- \pi^+ \pi^- \text{ CP Fraction & More} \]

These CLEO-c “Legacy data” results also imake use of more complex non-CP-eigenstate \( K_S \pi^+ \pi^- \) & \( K_L \pi^+ \pi^- \) tags

Results:

\[ \pi^+ \pi^- \pi^+ \pi^- : \quad F_+ = 0.737 \pm 0.028 \]

The new tags can be used to update the previous modes

New \( \pi^+ \pi^- \pi^0 \):
\[ F_+ = 1.014 \pm 0.045 \pm 0.022 \]

Combined:
\[ F_+ = 0.973 \pm 0.017 \]

New \( K^+ K^- \pi^0 \):
\[ F_+ = 0.734 \pm 0.106 \pm 0.054 \]

Combined:
\[ F_+ = 0.732 \pm 0.055 \]
Another somewhat related topic, also involving phases

*Study rate asymmetries for specific mode pairs of the form:*  
\[ K_S n\pi \& K_L n\pi \]

The \( K_S \) & \( K_L \) wave-functions lead to net amplitudes that are sums and differences of the CF and DCSD amplitudes  ➔ up to 10% effects, depending on a relative phase

Some results from CLEO-c ; many more in progress @ BESIII
Selected Issues I

Places to make progress on existing ideas:

→ Use data to un-rotate mixing results for multi-body modes!
  e.g., $K\pi\pi^0$: “Atwood-Soni for mixing”  [ Bondar et al. 2010 ]

→ Explore suggestion to use Charm mixing as a *SOURCE* of
  strong phase information  [ Harnew & Rademacker 2014, 2015 ]

And, of course:
  Maintain a lively $D \leftrightarrow B$ interchange & forge ahead!
Selected Issues II

Places to Be Careful…

→ Efficiencies vary across D Dalitz plots
  Charm and B factories differ; we traffic in corrected variables
  Current methods accurate? Need Dalitz models to do well?
  So, *take care if using A-S coherence factors or CP fractions*

→ Are studies of D mixing, D CPV, K$_S$ CPV effects complete?
  [Probably; see excellent review by Matteo Rama, CKM14, Vienna]

→ Assumptions of SM re: CPV could be more explicit
  e.g., GGSZ assumes no *weak phase* between CF & DCSD (?)

→ Take care with Kaon regeneration and Kaon interactions!
Everything is a Special Case!
(almost)

So if you were confused, you’re probably not alone…

\[
\begin{align*}
K^-\pi^+ & \quad K^-\pi^+\pi^0 & \quad K^-\pi^+\pi^+\pi^- & \quad K_SK^+\pi \\
K^+K^- & \quad \pi^+\pi^- & \quad K^+K^-\pi^+\pi^- & \quad K_S\pi^+\pi^- & \quad \pi^+\pi^-\pi^0
\end{align*}
\]

\(K^-\pi^+\) only \(\delta\); \(K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-\) have both \(R\) & \(\delta\)

Multi-body Self-conjugate modes:
If no CPV, only \(2(n-1)\) isobar phases, not \(2n-1\)
Need threshold data only to avoid model dependence;
there is no “essential” \(D^0-D^{0\text{bar}}\) phase

4-body: more complicated angular momenta than 3-body
\(K_S\) modes: CF and DCSD give \(K^0, K^{0\text{bar}}\), not \(K_S\) directly
Conclusions

Unique access to strong phases & ability to extract model-independent results with charm at threshold
• Started with many CLEO-c Results, added “legacy” results
• Perhaps a tiny bit more activity with CLEO-c “legacy data”? 
• Now, the 3.5x larger BESIII dataset is producing results
  Many modes in progress…stay tuned!

Interest of B physics users remains high
• LHCb is a huge addition to older B-factory data
• But… $e^+e^-$ will return soon with Belle II [ beams stored ! ]
• Important to keep active interaction between B & D

Future prospects are bright
• More precision, new modes, new variables !
• Need to maintain threshold analysis manpower
Selected Theory References: Insights, Old & New

Quantum Correlations
Xing, Phys. Rev. D55, 196 (1997)

DCSD mixing background cancels for correlated D pairs
Bigi & Sanda, Phys. Lett. B171, 320 (1986) [see Ref. 5 for other contributors…]

“Attention PDG” : $K_S \neq 1/2$ of $K^0$ or $K^{0\bar{b}ar}$

$D^0$ Mixing with $K_S K\pi$

$D^0$ Mixing as the Source of Phase Info for CKM $\gamma$ with “DK” modes
Harnew & Rademacker, JHEP 03, 169 (2015)
Selected Theory References: Alphabet Methods

B physics: CKM $\Upsilon$ with “DK” modes


Atwood, Dunetz & Soni, Phys. Rev. D63, 036005 (2001)  

Bondar. Proc. of BINP Special Analysis Meeting on Dalitz Analysis (2002) [first “GGSZ”]


B to $D^*K$, with $D^* \to D^0\pi^0, D^0\gamma$
Selected Theory References: Corrections

Early Explorations of D Mixing

D mixing and CKM ϒ from K_{Sππ} ; Model-ind’t D mixing from multi-body modes

D mixing and CKM ϒ from B -> DK, Dπ

D Direct CPV and CKM ϒ from B -> DK

CPV in K_{S} & CKM ϒ
Grossman & Savastio JHEP 03, 008 (2014)

K_{S} decay time acceptance and CPV in tau, D

K_{S} detector interactions & B, D CPV
Classic “GGSZ mode”; better precision than CLEO-c

Preliminary results presented @ APS meeting, Apr 2014

$K_S \pi^+ \pi^-$ is the main topic: extract $c_i$, $s_i$

$K_L \pi^+ \pi^-$ is also used: extract $c'_i$, $s'_i$

relate to $c_i$, $s_i$ with model corrections.

Aggressive use of tags, including partial reconstruction

All results preliminary; as presented at April 2014 AP meeting
We can calculate $c_i$ and $s_i$ from double tags of $D^0 \rightarrow K_S \pi^+ \pi^-$ vs $D^0 \rightarrow (K_{S,L} \pi^+ \pi^-$ or CP eigenstates).

A relationship can be shown between Dalitz bin yields and $c_i$ and $s_i$ (in backup slides).

Only $c_i, s_i$ from $K_S \pi^+ \pi^-$ is used to calculate $\gamma$.

However adding in $D^0 \rightarrow K_L \pi^+ \pi^-$ we can calculate $c'_i, s'_i$ and use how they relate to $c_i, s_i$ to further constrain our results in a Global fit.
Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to $\gamma$. A secondary adjustment smooths binned areas smaller than detector resolution.

Similar to the “optimal binning” except the expected background is taken into account before optimizing for $\gamma$ sensitivity.


Slide from Dan Ambrose, APS 2014
Comparison to CLEO-
c's Previous Measurement

Consistent agreement with CLEO-
c measurements.

\[ s_i \]

Model prediction

BESIII Preliminary

Consistent agreement with CLEO-c measurements.


Improved errors w.r.t. CLEO-c

Slide from Dan Ambrose, APS 2014