Quantum Correlated Charm @ Threshold

and $\phi_3 = \gamma$

from B Decays

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*Full disclosure: member of CLEO-c / BESIII / BelleII
Outline

Introduction: Essentials
Overview of Results
Recent Published Results
Preliminary $K_S \pi^+ \pi^-$ Results
Conclusion

→ Access to relative $D^0, D^{0\text{bar}}$ strong phase differences
→ Directly measure what B analyses need with no models
→ Useful inputs to CKM $\gamma$ extractions w/ $B \rightarrow D^{(*)}K^{(*)}, D^{(*)}\pi$
→ Also relevant for $D$ mixing
( and just plain fun to see EPR-like correlations in HEP experiment! )
Introduction

Threshold production of charm with $e^+e^- \rightarrow \psi (3770)$

Decays to *coherent* pair of $D$ mesons

\[
\psi (3770) \rightarrow \left[ D^0 D^{0\bar{0}} - D^{0\bar{0}} D^0 \right] / \sqrt{2} \quad \text{(Eq 1)}
\]

\[
= - \left[ D_{CP+} D_{CP-} - D_{CP-} D_{CP+} \right] / \sqrt{2} \quad \text{(Eq 2)}
\]

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

Measure various combination of rates for:

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

**Naïve** Get interference with CP tags since they project 2\textsuperscript{nd} meson into a $D^0, D^{0\bar{0}}$ superposition (Eq 2)

**Truth** Yes, but we get interference even *without* CP tags:
Terms in Eq 1 already interfere …
( 1\textsuperscript{st} vs. 2\textsuperscript{nd} $D$ means $+z$ vs. $-z$ along decay axis)
## Decay Modes

### 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**: $K^-K^+$, $\pi^+\pi^-$, $K_S\pi^0$, …  
  - SCS
- **Multi body**: $K_S h^+h^-$, $K_L h^+h^-$  
  - CF + DCSD
- **Multi body**: $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0$  
  - SCS

### Neither
- $K_S K^-\pi^+$  
  - SCS

### Both
- "* not possible *"

**Blue modes: already used for $\gamma$**  
**green: future?**  
**[ black: tag only ]**

"h" = $K$, $\pi$

- **CF**: Cabibbo-Favored
- **SCS**: Singly-Cabibbo-Suppressed
- **DCSD**: Double-Cabibbo-Suppressed (Decay)
Multi-Body “Coherence Factors”

Simplified Two body:
\[ |A_1 + A_2|^2 = |A_1^2 + A_2^2 + 2A_1A_2e^{-i\delta}| \quad 1, 2 = CF, \text{DCSD} \]

Generalization \(\Rightarrow\) Atwood-Soni:
Integrate over Dalitz plot; define real average amplitudes
\[ [ \mathcal{A} \rightarrow A \text{ below}] \]

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

Simplified Multi body:
\[ \int d\text{ Dalitz } |\mathcal{A}_1 + \mathcal{A}_2|^2 = |A_1^2 + A_2^2 + 2R e^{-i\delta}A_1A_2| \]
Define: \(R e^{-i\delta} = (\text{true cross-term}) / (\text{naïve} = A_1A_2)\)

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

\[ A_{K^\pm}^{\pi^\mp\pi^0} = \int |\mathcal{A}_{K^\pm}^{\pi^\mp\pi^0}(x)|^2 dx \]

\[ R_{K^\mp}^{\pi^0} e^{-i\delta_D^{K^\mp\pi^0}} = \frac{\int \mathcal{A}_{K^-}^{\pi^+\pi^0}(x)\mathcal{A}_{K^+}^{\pi^-\pi^0}(x) dx}{A_{K^-}^{\pi^+\pi^0}A_{K^+}^{\pi^-\pi^0}} \]
**QC for Pedestrians I**

**Simplest effect:**
\[ \psi(3770) \rightarrow [ D_{CP+} D_{CP-} - D_{CP-} D_{CP+} ] / \sqrt{2} \]

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

**My favorite general form:**  
* Ignore mixing for now *

\[ \Gamma_{FG} / A_F^2 A_G^2 = [ r_F^2 + r_G^2 + 2 r_F r_G R_F R_G \cos(\delta_G - \delta_F) ] \]

or  
1 + r_F^2 r_G^2 + … :  
factor out A_i such that r < 1

\[ \rightarrow r_{FG} \text{ (averaged) amplitude ratios } : \sim A(D^{0\text{bar}} \rightarrow F,G) / A(D^0 \rightarrow F,G) \]

1 for CP eigenstates

~\(\tan^2(\theta_C)\) for hadronic K\(^-\) modes  
\[ \text{[ DCSD/CF ]} \]

0 for semileptonic  
\[ \rightarrow \text{ no interference} \]

\[ \rightarrow R, \delta: \text{ Atwood-Soni coherence factors} \]

R=1; \(\delta = 0, \pi\) for CP eigenstates;

R=1; \(\delta = ?\) for K\(^-\)\(\pi^+\)

Both non-trivial for multi-body hadronic
QC for Pedestrians II

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 this 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
From Tags to Physics

CP+ & CP- tags:
Switch of +- flips sign of interference term
Used for $\gamma$, but trivial: no need to study w/ charm  [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  [ADS]

Multi-body self-conjugate
Modes we want to under study  [GGSZ]

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

<table>
<thead>
<tr>
<th>Process</th>
<th>Framework</th>
<th>$\delta$ Notes</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>$K^-\pi^+\pi^0, K^-\pi^+\pi^\pm, K_SK^-\pi^+$</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
  - $\Rightarrow$ **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:  
      - [D*-tagged @ B factory] only gets $2(N-1) = 2N-2$ out of $2N-1$ relative phases
  - $\Rightarrow$ Also avoid Dalitz models

- $c_i, s_i$ are "Cartesian R, $\delta$ in Dalitz bins" for GGSZ modes
  - $\Rightarrow$ Here, relative $D^0$-$D^{0\text{bar}}$ phase is trivial
    - (distinction due to self-conjugate modes, not changing basis to $c_i, s_i$ !)
  - $\Rightarrow$ But we still avoid Dalitz models
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)

\[ K^-\pi^+ \rightarrow 818 \text{ pb}^{-1} \]  
(PRD 86, 112001 (2012)

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

also use high-E continuum  
\[ * + 15 \text{ fb}^{-1} \sim 10 \text{ GeV} \]  
\[ ** + 24 \text{ fb}^{-1} \sim 10 \text{ GeV} \ & 600 \text{ pb}^{-1} 4.17 \text{ GeV} \]
Today’s Main Topics

**BESIII Results**

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

Future ability: \(~ 4 \text{ fb}^{-1} / \text{running year}\)

[ note: \(\mathcal{L}_{2011} >> \mathcal{L}_{2010}\) ]

K\(^{-}\pi^{+}\) 2.92 fb\(^{-1}\) PLB 734, 227 (2014)

K\(_{S}\pi^{+}\pi^{-}\) 2.92 fb\(^{-1}\) Preliminary @ APS, Apr 2014

\(y_{CP}\) 2.92 fb\(^{-1}\) Preliminary; will submit soon

[ \(y_{CP}\): see slides by X.R. Lyu; talk running in parallel now! ]

**CLEO-c “Legacy” Result**

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

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

Small $R$ for $K\pi\pi\pi$: still useful for $r_B$!

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

**BaBar Model**
**CLEO-c 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 $K_S\pi^+\pi^-$ tags
→ Updated external inputs (BF, mixing, $K\pi$)

**Note:** $K\pi\pi\pi$ best fit now in other lobe...

**References**

2. Shi, et al., CLEO Collaboration, Updated measurements of absolute branching fractions and coherence factors.
3. Nayak, et al., Belle Collaboration, Evidence for the suppressed decay $D^0\rightarrow\pi^+\pi^-\gamma$.
Strong Phase $\delta_{K\pi}$

Simplified Picture: (simple = no mixing)

Amplitude triangle:

$\text{CP}_\pm = \text{CF} \pm \text{DCSD}$

[DCSD enhanced for visibility!]

Complex ratio

DCSD/CF amplitude

$\frac{\langle K^- \pi^+ | D^0 \rangle}{\langle K^- \pi^+ | D^0 \rangle} = -r e^{-i\delta_{K\pi}}$

Flip CP of tag: reverses interference term

$\text{CP-tagged rate asymmetry (essentially) measures } r \cos \delta$

$A_{CP} = \frac{[|A_{CP-}|^2 - |A_{CP+}|^2]}{[|A_{CP-}|^2 + |A_{CP+}|^2]}$

$= r \cos \delta$ ( + D mixing corrections: $y, R_{WS}$)
Strong Phase $\delta_{K\pi}$

First BESIII Quantum Coherence result: straightforward analysis

Tags Used: 5 CP+, 3 CP-

$S+$: $K^+K^-, \pi^+\pi^-, K^0\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$

$S-$: $K^0\pi^0, K^0\eta, K^0\omega$
Strong Phase $\delta_{K\pi}$

$$A_{CP}^{K\pi} \equiv \frac{B_{D^s \rightarrow K^{-}\pi^+} - B_{D^s \rightarrow K^{-}\pi^+}}{B_{D^s \rightarrow K^{-}\pi^+} + B_{D^s \rightarrow K^{-}\pi^+}}$$

$S+$ ($S-$) denotes the $CP$-even ($CP$-odd) eigenstate.

Direct result: *

$$A_{CP} = (12.7 \pm 1.3 \pm 0.7)\%$$

$$2r \cos \delta_{K\pi} + y = (1 + R_{WS}) \cdot A_{CP}^{K\pi}$$

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:

$$\cos \delta_{K\pi} = 0.81^{+0.22}_{-0.18}^{+0.07}_{-0.06} \quad (\text{no external inputs})$$

$$\cos \delta_{K\pi} = 1.15^{+0.19}_{-0.17}^{+0.00}_{-0.08} \quad (w/ \text{external inputs})$$

* HFAG can use this, I believe: they now omit final $\delta_{K\pi}$ due to external inputs ...
New $K_S \pi^+ \pi^-$ Results

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.

Slide from Dan Ambrose, APS 2014
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
New $K_S\pi^+\pi^-$ Results

<table>
<thead>
<tr>
<th>Bins</th>
<th>$c_i$ (BES-III)</th>
<th>$c_i$ (CLEO-c)</th>
<th>$s_i$ (BES-III)</th>
<th>$s_i$ (CLEO-c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.066 ± 0.066</td>
<td>-0.009 ± 0.088</td>
<td>-0.843 ± 0.119</td>
<td>-0.438 ± 0.184</td>
</tr>
<tr>
<td>2</td>
<td>0.796 ± 0.061</td>
<td>0.900 ± 0.106</td>
<td>-0.357 ± 0.148</td>
<td>-0.490 ± 0.295</td>
</tr>
<tr>
<td>3</td>
<td>0.361 ± 0.125</td>
<td>0.292 ± 0.168</td>
<td>-0.962 ± 0.258</td>
<td>-1.243 ± 0.341</td>
</tr>
<tr>
<td>4</td>
<td>-0.985 ± 0.017</td>
<td>-0.890 ± 0.041</td>
<td>-0.090 ± 0.093</td>
<td>-0.119 ± 0.141</td>
</tr>
<tr>
<td>5</td>
<td>-0.278 ± 0.056</td>
<td>-0.208 ± 0.085</td>
<td>0.778 ± 0.092</td>
<td>0.853 ± 0.123</td>
</tr>
<tr>
<td>6</td>
<td>0.267 ± 0.119</td>
<td>0.258 ± 0.155</td>
<td>0.635 ± 0.293</td>
<td>0.984 ± 0.357</td>
</tr>
<tr>
<td>7</td>
<td>0.902 ± 0.017</td>
<td>0.869 ± 0.034</td>
<td>-0.018 ± 0.103</td>
<td>-0.041 ± 0.132</td>
</tr>
<tr>
<td>8</td>
<td>0.888 ± 0.036</td>
<td>0.798 ± 0.070</td>
<td>-0.301 ± 0.140</td>
<td>-0.107 ± 0.240</td>
</tr>
</tbody>
</table>

Improved errors w.r.t. CLEO-c

Consistent agreement with CLEO-c measurements.

My Selected Issues

BaBar $K\pi\pi^0$ mixing result uses an isobar fit; gets rotated $x''$, $y''$
Can’t this be done in a model-independent way, using charm threshold data if needed ??? ( “Atwood-Soni for mixing” )

Efficiencies vary across D Dalitz plots
Charm and B factories differ; traffic in corrected variables
Current methods accurate? Need Dalitz models to do well?

Are studies of D mixing, D CPV, $K_S$ CPV effects complete?

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

Maintain a lively $D \leftrightarrow B$ interchange & forge ahead!
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
  - threshold data only to avoid model dependence;
  - no “essential” \(D^0-D^{0\bar{\text{bar}}}\) phase
- 4-body: more complicated angular momenta than 3-body
- \(K_S\) modes: CF and DCSD give \(K^0, K^{0\bar{\text{bar}}},\) not \(K_S\) directly
Extracting CKM $\gamma$

without charm

with charm
Conclusions

Unique access to strong phases & ability to extract model-independent results with charm at threshold

• Started with many CLEO-c Results
• Still some activity with CLEO-c “legacy data”  [ ≥1 more paper? ]
• Now, the 3.5x larger BESIII dataset is producing results

Interest of B physics users remains high

• LHCb is a huge addition to older B-factory data
• But $e^+e^-$ will return soon with BelleII
• 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

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…]

B physics: CKM $\Upsilon$ with “DK” modes
Atwood, Dunetz & Soni, Phys. Rev. D63, 036005 (2001)
“ADS”: CF + DCSD (incl. D mixing)
Coherence factors
“GGSZ”: $K_S\pi\pi$
CF multi-body: larger strong phases?
optimizing GGSZ

$D^0$ Mixing with $K_SK\pi$
Selected Theory References

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

D mixing and CKM $\Upsilon$ from $K_S\pi\pi$
Bondar, Poluektov, & Vorobiev, Phys. Rev. D82, 034033 (2010)

D Direct CPV and CKM $\Upsilon$ from $B \rightarrow DK$

CPV in $K_S$ & CKM $\Upsilon$
Grossman & Savastio, JHEP 03, 008 (2014)

$K_S$ decay time acceptance and CPV in tau, D

$K_S$ detector interactions & B, D CPV
Ko, Won, Golob, Pakhlov, Phys. Rev. D 84, 111501(R) (2011)