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

relative strong phases

Model Independence

→ **Access to relative D^0, D^{0bar} *strong phase differences***

→ **Directly measure what B analyses need with *no models***

→ Useful inputs to *CKM γ extractions w/ $B \to D^{(*)}K^{(*)}$, $D^{(*)}\pi$*

→ 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

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

$$= -[\ D_{CP+}\ D_{CP-} - D_{CP-}\ D_{CP+}\ ] / \sqrt{2} \qquad \text{(Eq 2)}$$

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

Measure various combination of rates for:

one decay mode only → "single tags"
two decay modes → "double tags"

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

Truth Yes, but we get interference even ***without*** CP tags:
Terms in Eq 1 already interfere …
(1^{st} vs. 2^{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	$K_Sh^+h^-$, $K_Lh^+h^-$	CF + DCSD
Multi body	$K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0$	SCS
Neither	$K_SK^-\pi^+$	SCS
Both	* not possible *	

Blue modes: already used for γ green : future? [black: tag only]

"h" = K, π

CF : Cabibbo-Favored
SCS : Singly-Cabibbo-Suppressed
DCSD : Double-Cabibbo-Supressed (Decay)

Multi-Body "Coherence Factors"

Simplified Two body:

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

Generalization → Atwood-Soni :

Integrate over Dalitz plot; define real average amplitudes

[$\mathcal{A}$ → A below]

BUT this requires a "fudge factor" of $Re^{-i\delta}$ for interference term

Simplified Multi body:

$\int d\, Dalitz\ |\mathcal{A}_1 + \mathcal{A}_2|^2 = | A_1{}^2 + A_2{}^2 + 2\, R\, e^{-i\delta} A_1 A_2 |$

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

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

$$A^2_{K^\pm\pi^\mp\pi^0} = \int |\mathcal{A}_{K^\pm\pi^\mp\pi^0}(\mathbf{x})|^2 d\mathbf{x}$$

$$R_{K\pi\pi^0} e^{-i\delta_D^{K\pi\pi^0}} = \frac{\int \mathcal{A}_{K^-\pi^+\pi^0}(\mathbf{x}) \mathcal{A}_{K^+\pi^-\pi^0}(\mathbf{x}) d\mathbf{x}}{A_{K^-\pi^+\pi^0} A_{K^+\pi^-\pi^0}}$$

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 $1 + r_F^2 r_G^2 + \ldots$: factor out A_i such that $r < 1$

→ $r_{F,G}$ (averaged) amplitude ratios : ~ $\mathbf{A}(\bar{D}^0 \rightarrow F,G) \,/\, \mathbf{A}(D^0 \rightarrow F,G)$

1	for CP eigenstates
$\sim\tan^2(\theta_C)$	for hadronic K^- modes [DCSD / CF]
0	for semileptonic → no interference

→ R, δ: Atwood-Soni coherence factors

R=1; $\boldsymbol{\delta = 0}$, π for CP eigenstates;

R=1; $\boldsymbol{\delta = ?}$ 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 $\mathrm{Re}[R\, e^{-i\delta}] = R \cos\delta$, not separate (R, δ)

[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 γ, but trivial: no need to study w/ charm [GLW]

Semileptonic flavor tags:

No interference; clean normalization [but pesky ν…]

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

K^-K^+, $\pi^+\pi^-$	GLW	$\delta = 0, \pi$	
$K^-\pi^+$	ADS	δ (R=1)	get from threshold charm…
$K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_SK^-\pi^+$	ADS+	R, δ	
$K_S\pi^+\pi^-$, $K_SK^+K^-$	GGSZ	c_i, s_i	

R, δ are Atwood-Soni coherence factors for ADS modes

→ *No relative D^0-D^{0bar} phase* in separate D^0, D^{0bar} Dalitz fits

e.g., if one fits N amplitudes to D^0, D^{0bar} separately: [D*-tagged @ B factory]

only gets 2(N-1) = 2N-2 out of 2N-1 relative phases

→ Also ***avoid Dalitz models***

c_i, s_i are "Cartesian R, δ in Dalitz bins" for GGSZ modes

→ Here, relative D^0-D^{0bar} phase is trivial

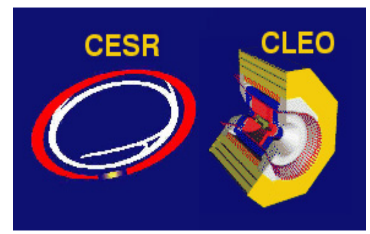
(distinction due to self-conjugate modes, not changing basis to c_i, s_i !)

→ 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}** (updated below)	**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^{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 ⅔ years) → 3.5x CLEO-c
Future ability : ~ 4 fb^{-1} / 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**

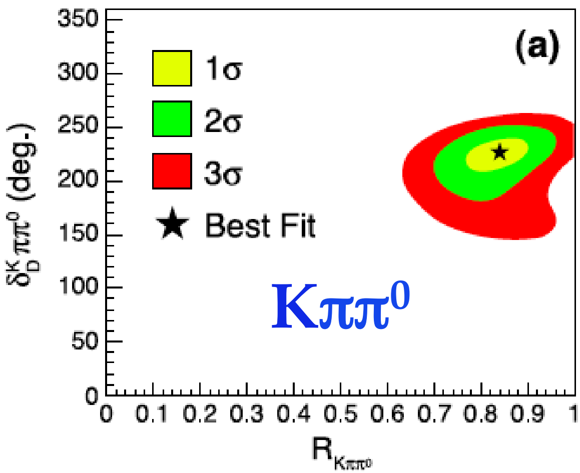
[y_{CP} : see slides by X.R. Lyu; talk running in parallel now !]

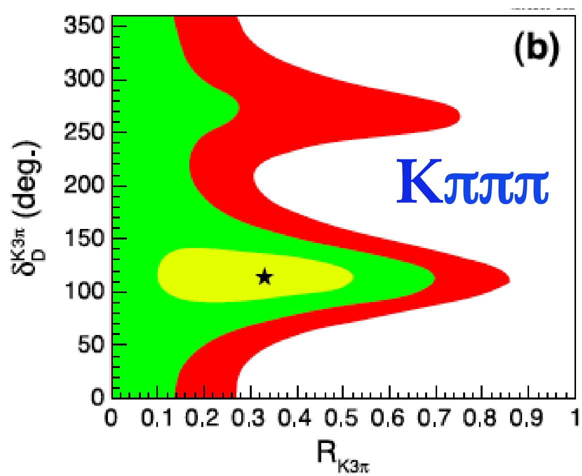
CLEO-c "Legacy" Result

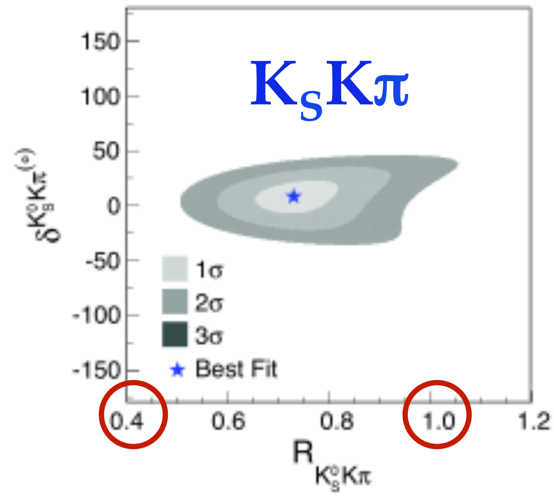
$K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$	**818 pb^{-1}**	**PLB 731, 197 (2014)**

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

CLEO-c Coherence Factors



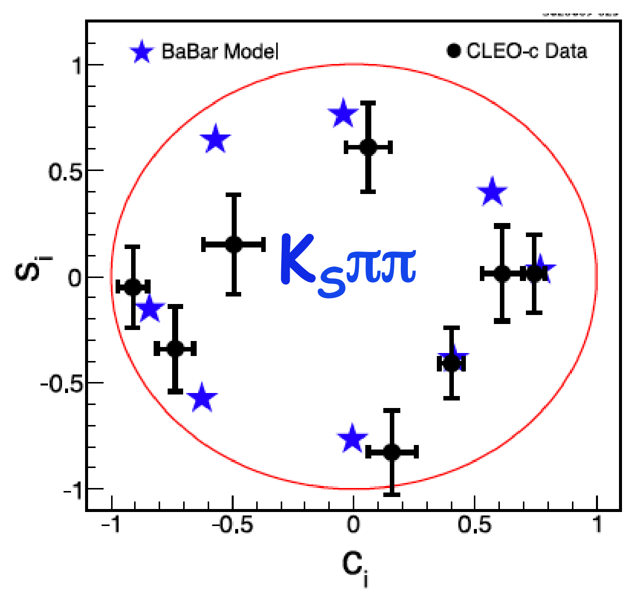




Small R for $K\pi\pi\pi$: still useful for r_B !

Or, we could bin across Dalitz plot

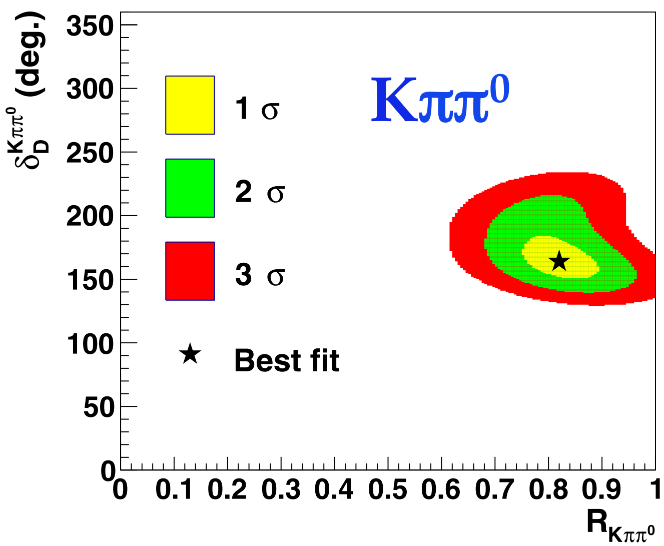
c_i and s_i: bin-averaged
<R cos δ> and <R sin δ>

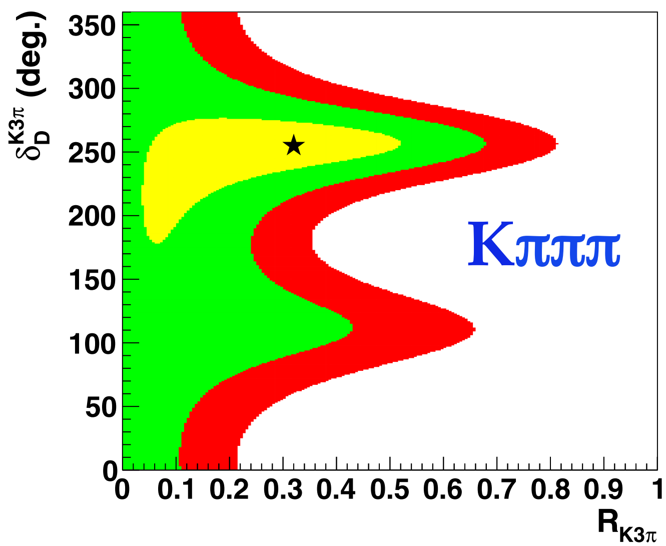


$K^- (n\pi)^+$ Update

PLB 731, 197 (2014) 818 pb^{-1}

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





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

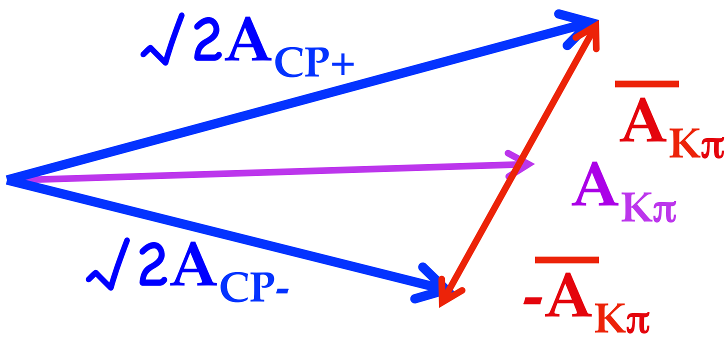
→ Now includes $K_S\pi^+\pi^-$ tags
→ Updated external inputs (BF, mixing, $K\pi$)

BESIII

Strong Phase $\delta_{K\pi}$

BESIII 2.9 fb^{-1}
PLB 734, 227 (2014)

Simplified Picture: (simple = no mixing)



Amplitude triangle:

$CP_{\pm}$ = CF ± DCSD

[DCSD enhanced for visibility !]

Complex ratio
DCSD/CF amplitude

$$\boxed{\frac{\langle K^-\pi^+|\overline{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle} = -re^{-i\delta_{K\pi}}}$$

Flip CP of tag: reverses interference term

CP-tagged rate asymmetry (essentially) measures r cos δ

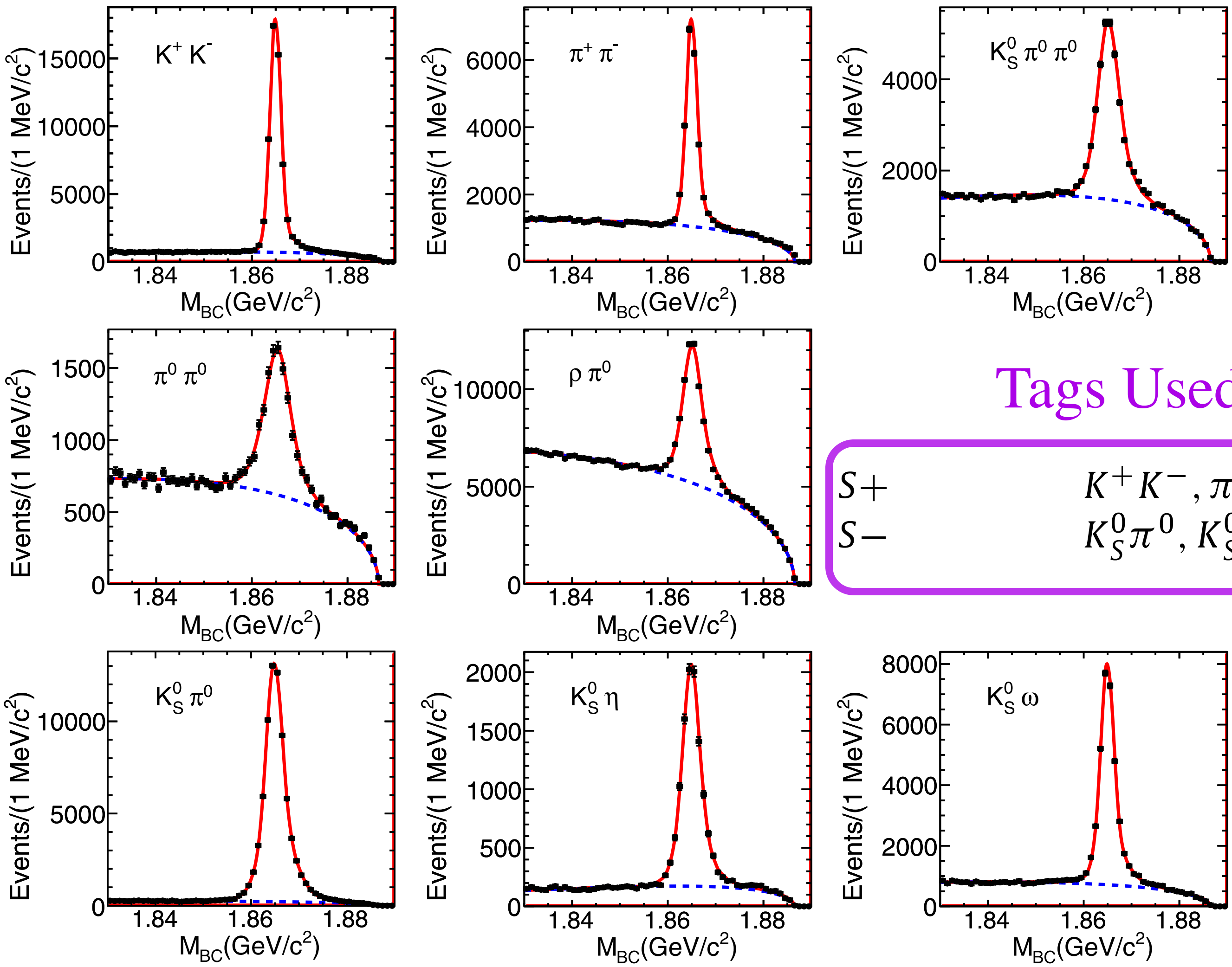
$$\mathcal{A}_{CP} = [\,|A_{CP-}|^2 - |A_{CP+}|^2\,] \,/\, [\,|A_{CP-}|^2 + |A_{CP+}|^2\,] \quad \longleftarrow \textbf{measure}$$

$$= r\cos\delta \quad (\text{+ D mixing corrections: } y,\ R_{WS}) \quad \longleftarrow \textbf{extract}$$

Strong Phase $\delta_{K\pi}$

BESIII 2.9 fb^{-1}
PLB 734, 227 (2014)

First BESIII Quantum Coherence result : *straightforward analysis*



Tags Used: 5 CP+, 3 CP-

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

Strong Phase $\delta_{K\pi}$

BESIII 2.9 fb^{-1}
PLB 734, 227 (2014)

$$\mathcal{A}^{CP}_{K\pi} \equiv \frac{\mathcal{B}_{D^{S-}\to K^-\pi^+} - \mathcal{B}_{D^{S+}\to K^-\pi^+}}{\mathcal{B}_{D^{S-}\to K^-\pi^+} + \mathcal{B}_{D^{S+}\to K^-\pi^+}}$$

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

Direct result : *

$\mathcal{A}_{CP} = (\,12.7 \pm 1.3 \pm 0.7\,)\%$

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

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:

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

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

* HFAG can use this, I believe: they now omit final $\delta_{K\pi}$ due to external inputs …

BESIII 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.

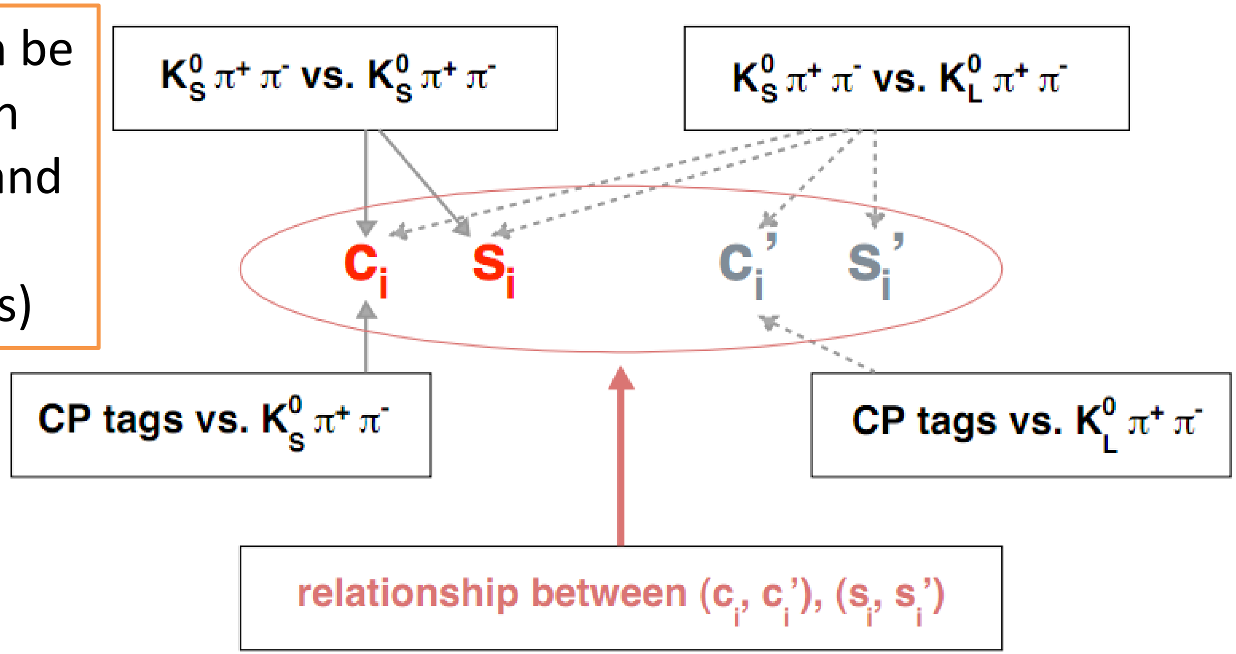
Aggressive use of tags, including partial reconstruction

All results preliminary; as presented at April 2014 AP meeting

New $K_S\pi^+\pi^-$ Results

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)

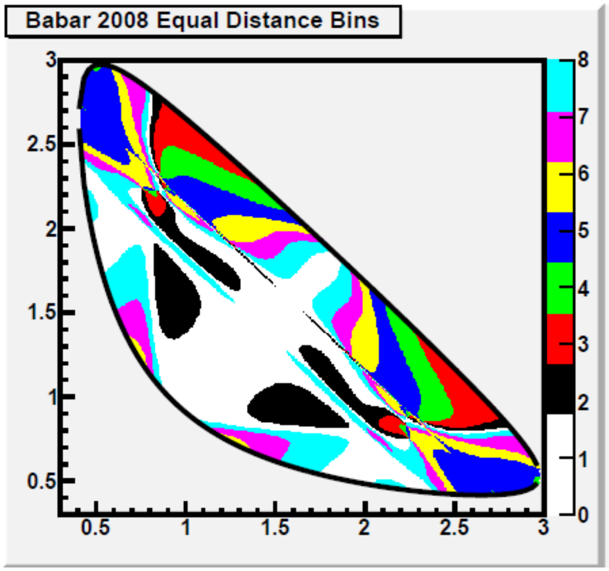
A relationship can be shown between Dalitz bin yields and c_i and s_i (in backup slides)

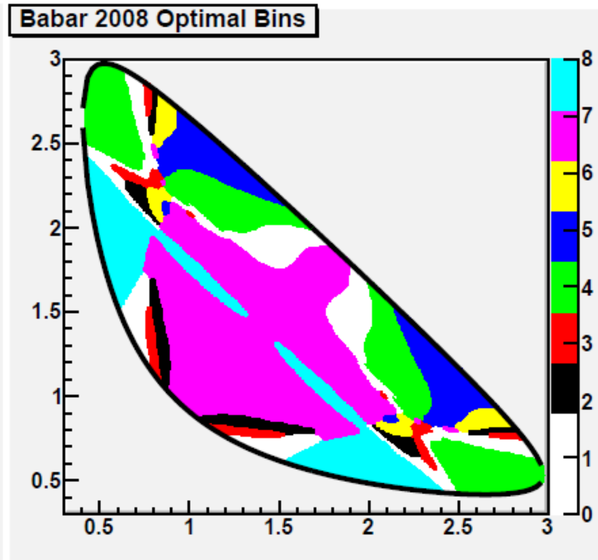


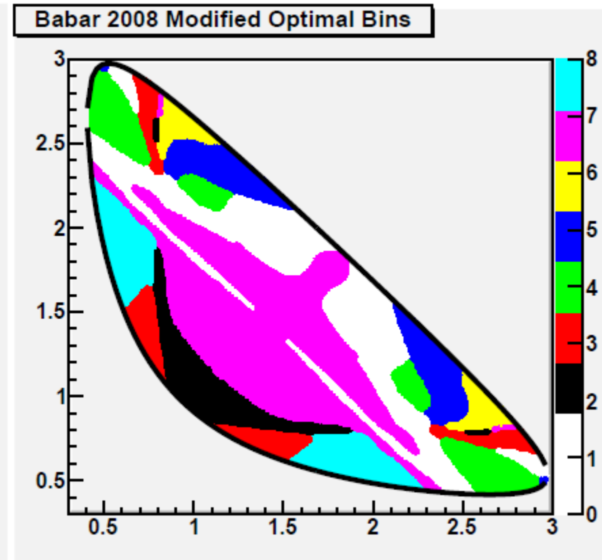
Only c_i, s_i from $K_s\pi^+\pi^-$ is used to calculate γ.
However adding in $D^0 \rightarrow K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

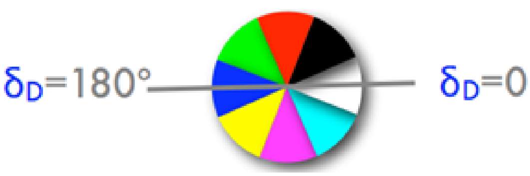
Slide from Dan Ambrose, APS 2014

New $K_S\pi^+\pi^-$ Results









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 γ. A secondary adjustment smooths binned areas smaller than detector resolution.

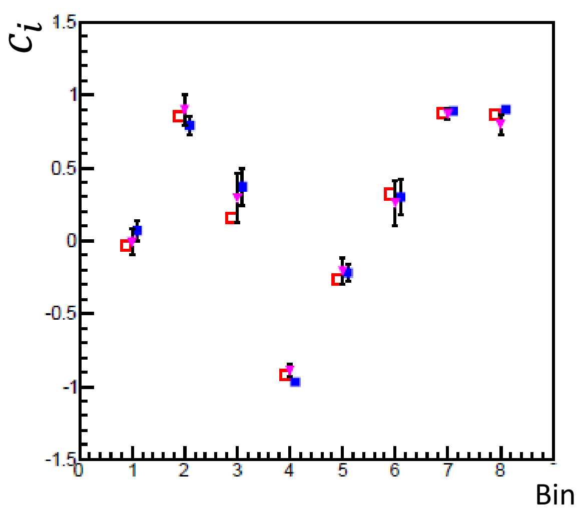
Similar to the "optimal binning" except the expected background is taken into account before optimizing for γ sensitivity.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

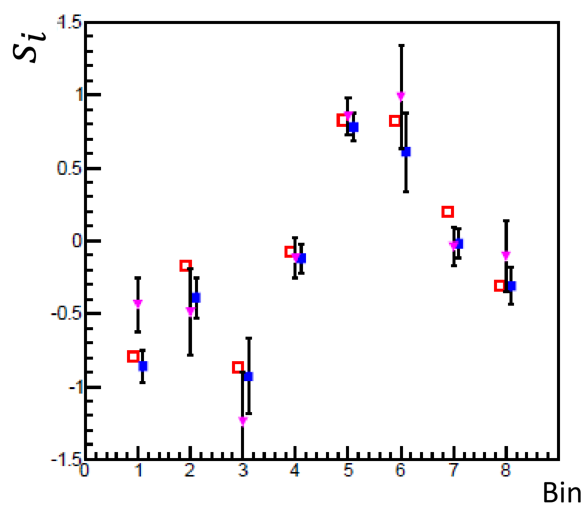
Slide from Dan Ambrose, APS 2014

New $K_S\pi^+\pi^-$ Results

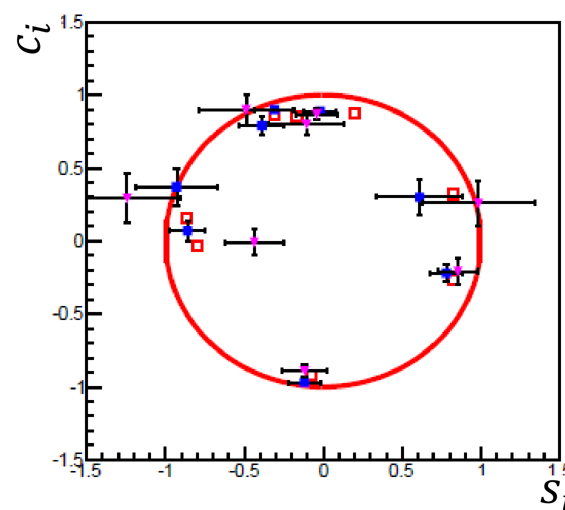
c_i



s_i



c_i s_i



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

***Only statistical uncertainty is listed

Model prediction
BESIII
CLEO-c

BESIII Preliminary

Consistent agreement with CLEO-c measurements.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Improved errors w.r.t. CLEO-c

Slide from Dan Ambrose, APS 2014

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 ←→ B interchange & forge ahead !

Everything is a Special Case !
(almost)

so if you were confused, you're probably not alone…

$K^-\pi^+$ **$K^-\pi^+\pi^0$** **$K^-\pi^+\pi^+\pi^-$** **$K_SK^+\pi$**

K^+K^- **$\pi^+\pi^-$** **$K^+K^-\pi^+\pi^-$** **$K_S\pi^+\pi^-$** **$\pi^+\pi^-\pi^0$**

$K^-\pi^+$ only δ ; $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ have both R & δ

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^{0bar} phase

4-body: more complicated angular momenta than 3-body

K_S modes: CF and DCSD give K^0, K^{0bar}, not K_S directly

Extracting CKM γ

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

Goldhaber & Rosner, Phys. Rev. D15, 1254 (1977)
Xing, Phys. Rev. D55, 196 (1997)
Gronau, Grossman & Rosner, Phys.Lett. B508, 37 (2001)
Atwood & Petrov, Phys. Rev. D71, 054032 (2005) [2002 eprint: hep-ph/0207165]
Asner & Sun, Phys. Rev. D73, 034024 (2006); E: ibid, D77, 019901 (2008)

DCSD mixing background cancels for correlated D pairs

Bigi & Sanda, Phys. Lett. B171, 320 (1986) [see Ref. 5 for other contributors…]

B physics: CKM Υ with "DK" modes

Gronau & London, Phys. Lett. B253, 483 (1991) — **"GLW"**: SCS CP-eigenstates
Gronau & Wyler, Phys. Lett. B265, 172 (1991)
Atwood, Dunetz & Soni, Phys. Rev. Lett. 78, 3257 (1997) — **"ADS"**: CF + DCSD
Atwood, Dunetz & Soni, Phys. Rev. D63, 036005 (2001) — (incl. D mixing)
Atwood & Soni, Phys. Rev. D68, 033003 (2003) — Coherence factors
Giri, Grossman, Soffer & Zupan, Phys. Rev. D68, 054018 (2003) — **"GGSZ"**: $K_S\pi\pi$
Bondar & Poluektov, Eur. Phys. J. C 47, 347 (2006) — CF multi-body: larger strong phases?
Bondar & Poluektov, Eur. Phys. J. C 55, 51 (2008) — optimizing GGSZ

D^0 Mixing with $K_SK\pi$

Malde & Wilkinson, Phys. Lett. B701, 353 (2011)

Selected Theory References

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

Bigi & Yamamoto, Phys. Lett. B349, 363 (1995)

D mixing and CKM ϒ from $K_S\pi\pi$

Bondar, Poluektov, & Vorobiev, Phys. Rev. D82, 034033 (2010)

D Direct CPV and CKM ϒ from B -> DK

Martone & Zupan, Phys. Rev. D 87, 034005 (2013)
Wang, Phys. Rev. Lett. 110, 061802 (2013)

CPV in K_S & CKM ϒ

Grossman & Savastio, JHEP 03, 008 (2014)

K_S decay time acceptance and CPV in tau, D

Bigi & Sanda, Phys. Lett. B 625, 47 (2005)
Grossman & Nir, JHEP 04, 002 (2012)

K_S detector interactions & B, D CPV

Ko, Won, Golob, Pakhlov, Phys. Rev. D 84, 111501(R) (2011)