Cornell University

A Flavor of Entangled Charm

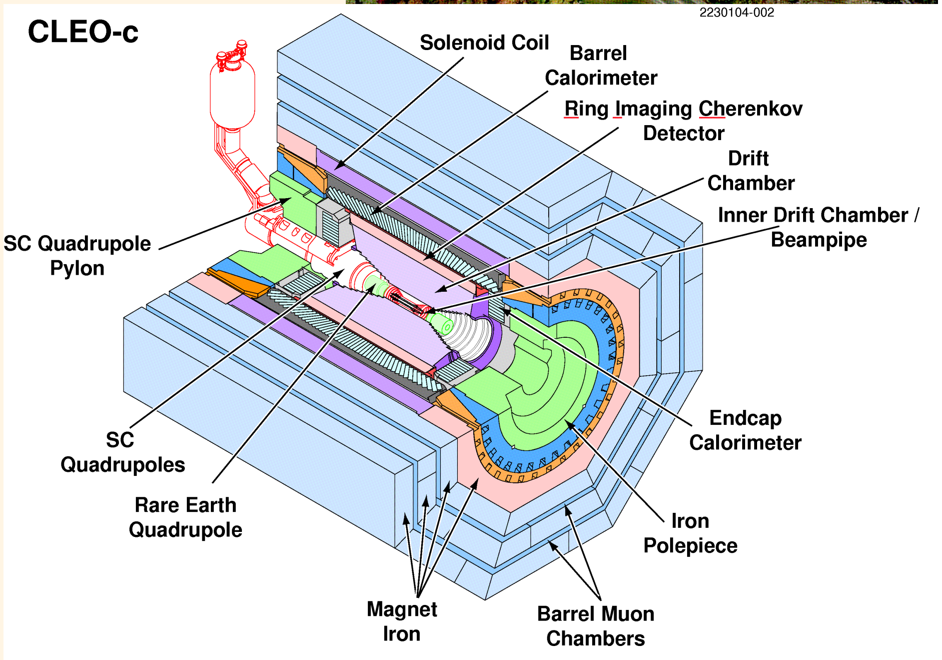
Werner Sun, Cornell University (CLEO-c)

1 October 2010, LEPP Journal Club, Cornell University

Introduction
Formalism
Experimental results
Summary and outlook

CESR & CLEO

- 1979—2008, symmetric e^+e^- collisions @ $\sqrt{s}$ = 2—12 GeV.
  - Last 5 years: CESR-c/CLEO-c, $\sqrt{s}$ ~ 4 GeV
- Good for flavor physics (weak interaction):
  - Threshold production: clean events
  - $e^+e^- \to \gamma^*$: initial state w/ known energy and quantum numbers.
  - Hermetic detector with excellent particle ID.
- Contributions to HEP for 30+ years
  - "Small" collaboration: ~20 institutions, < 250 authors.
  - Over 500 papers.
- Relevance of flavor to LHC era:
  - New Physics constraints from flavor are much higher than TeV scale.
  - NP that solves hierarchy problem must have non-trivial flavor structure.



Threshold Charm Production

Action at a distance!

- Running near $c\bar{c}$ threshold produces quantum correlated D^0 and $\bar{D}^0$:
  - $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ [$C = -1$] OR $e^+e^- \to \gamma^* \to D^0\bar{D}^0\gamma$ [$C = +1$]
  - At $\psi(3770)$, same-*CP* final states forbidden; opposite-*CP* states enhanced
    - Tagging the *CP* of one *D* identifies the *CP* of other *D*.
  - Unique access to amplitude ratios, phases, & charm mixing.
    - Exploit interference effects in time-integrated rates.

Correlated amplitudes

$$\Gamma_{ij}^2 = \left| \langle i | D^0 \rangle \langle j | \overline{D^0} \rangle \mp \langle j | D^0 \rangle \langle i | \overline{D^0} \rangle \right|^2$$

$$\frac{\langle i | \overline{D}^0 \rangle}{\langle i | D^0 \rangle} = -re^{-i\delta}$$

[Cabibbo-suppressed]

[Cabibbo-favored]

magnitude

strong phase
(weak phases are trivial in charm)

- D^0 strong phases are necessary inputs for
  - Charm mixing studies at *B*-factories, CDF, FOCUS
  - CKM studies at *B*-factories and LHCb

- This talk: CLEO-c $\psi(3770)$ measurements of strong phases in

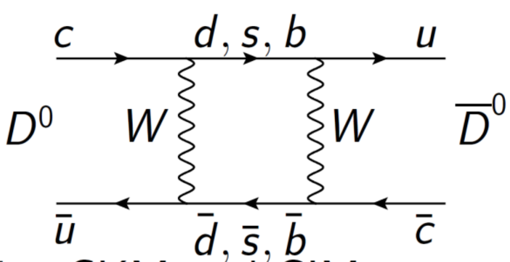
$D^0 \to K^+\pi^-$ $K^+\pi^-\pi^0$ $K^+\pi^-\pi^+\pi^-$ $K_{S,L}^0 h^+h^-$ ($h = K$ or π)

Charm Mixing (no CPV)

$$i\frac{\partial}{\partial t}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} \text{ where } H_{11} = M_{11} - i\,\Gamma_{11}/2 \text{ etc...}$$

- $H_{12}, H_{21} \neq 0 \Rightarrow$ flavor eigenstates (D^0, $\overline{D^0}$) $\neq$ mass eigenstates (D_1, D_2).
- Mixing characterized by $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$ $\qquad D_{1,2} = \frac{D^0 \pm \overline{D^0}}{\sqrt{2}}$

Short distance

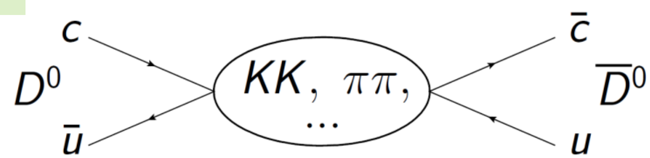


Effective CKM and GIM suppression

$|x|,\ |y| \leq 10^{-3}$

No mixing in SU(3) limit

Long distance [A. Zupanc]



Contribution from hadronic intermediate states

$x,\ y \sim$ up to 1%

- Standard Model predictions for *x* and *y* have large uncertainties.
- But measurements of *x* and *y* can constrain New Physics models.

Charm Mixing Measurements I

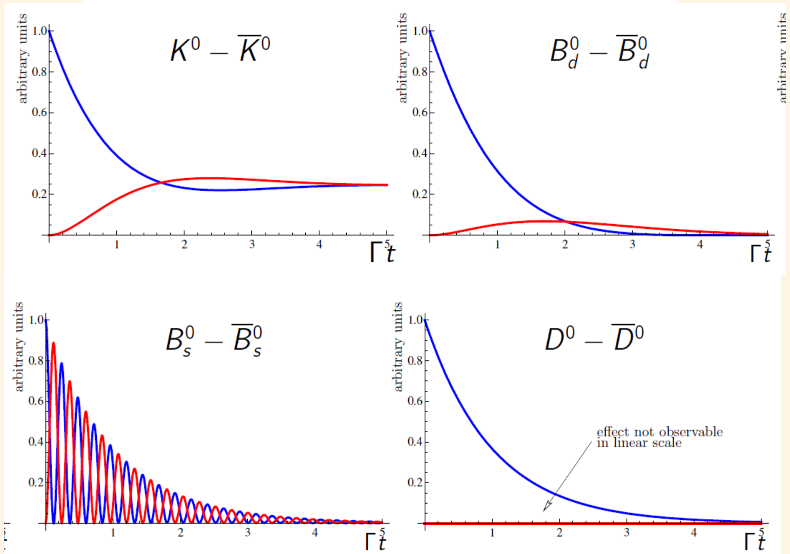
- time integrated mixing rate

$$R_M = \frac{\int_0^\infty \mathcal{P}_{\mathrm{mix}}(t)dt}{\int_0^\infty \mathcal{P}_{\mathrm{non-mix}}(t)dt} = \frac{x^2+y^2}{2+x^2-y^2}$$

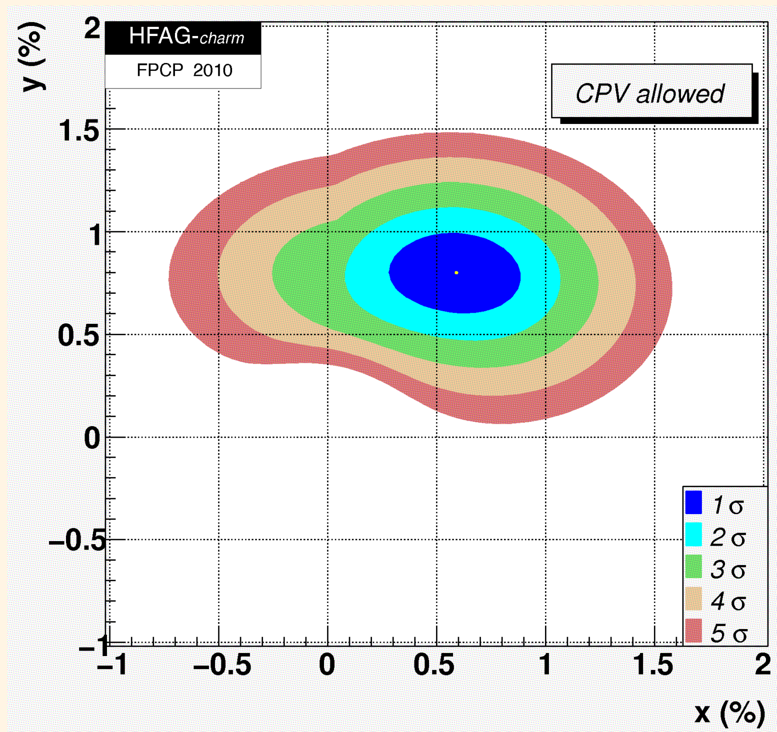
[A. Zupanc]

M^0	x	y	R_M	
K^0	0.946	0.997	0.994	[1956]
B_d^0	0.776	< 0.01	0.23	[1987]
B_s^0	26.1	0.15	0.997	[2006]
D^0	0.01	0.01	**10^{-4}**	[2007]

1 out of 10^4 D^0 mesons oscillates before it decays



- First evidence for mixing in 2007.
- Currently, no-mixing point excluded at 10.2 σ.
- But no evidence for CP violation

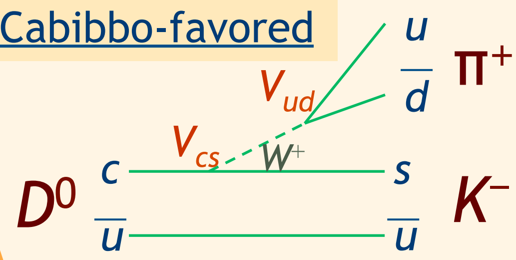


Charm Mixing Measurements II

CLEO II.V
BABAR
Belle
CDF
FOCUS

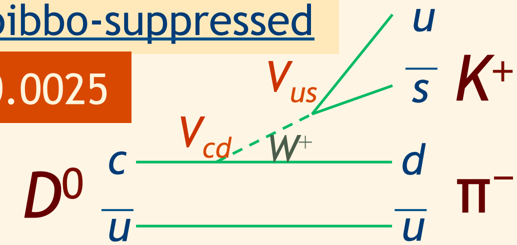
- $y = (0.73 \pm 0.14)\%$:
  - Direct lifetime measurements:
    - Compare K^+K^- and $\pi^+\pi^-$ with $K^-\pi^+$.
  - Time-dependent Dalitz analysis of $K^0{}_S\pi^+\pi^-$ and $K^0{}_SK^+K^-$
    - Intermediate *CP*-eigenstates give *y*.
    - Interference between *CP*+ and *CP*– gives *x*.
- $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} = (0.48 \pm 0.23)\%$
  - Time-dependent wrong-sign rate $D^0 \to K^+\pi^-$:
    - Interfering DCS and mixing amplitudes modulate exponential decay time.
    - Ambiguity from strong phase.

Cabibbo-favored



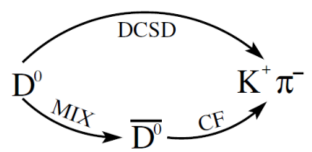
Doubly Cabibbo-suppressed

$\Gamma \sim \lambda^4 \sim 0.0025$



$\delta_{K\pi}$ connects measurements of *y* and *y'*

[A. Zupanc]



$$\Gamma_{WS} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2+y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

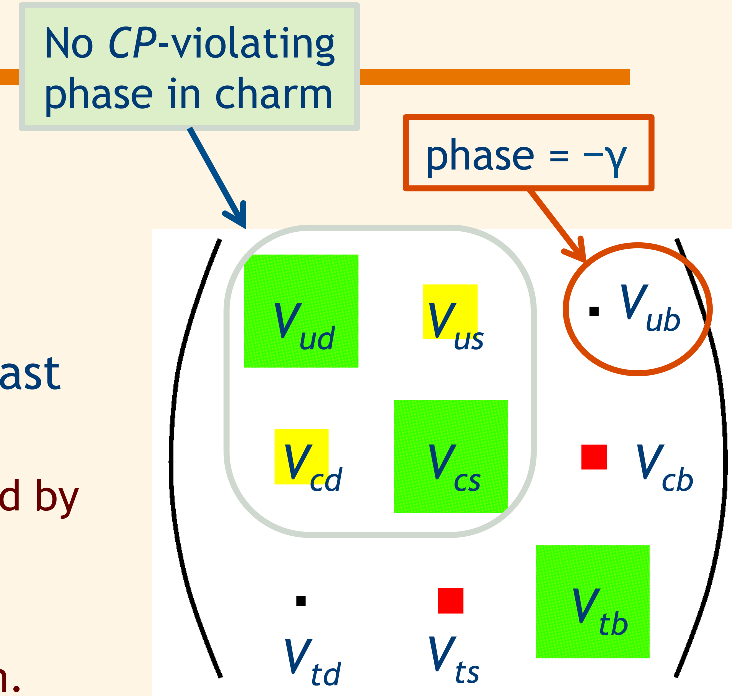
● DCS ● interference ● mixing

$$\frac{\langle K^-\pi^+ | \bar{D}^0 \rangle_{DCS}}{\langle K^-\pi^+ | D^0 \rangle_{CF}} = -r_{K\pi} e^{-i\delta_{K\pi}}$$

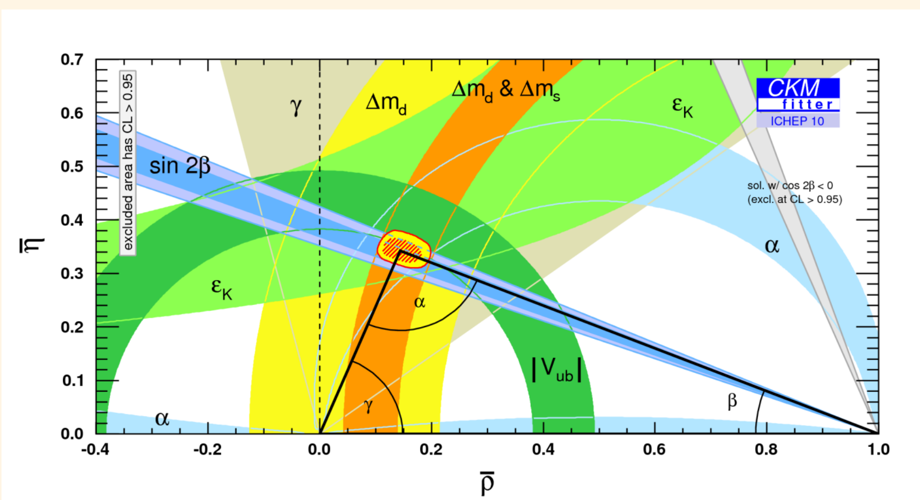
$r_{K\pi}$ ~0.06

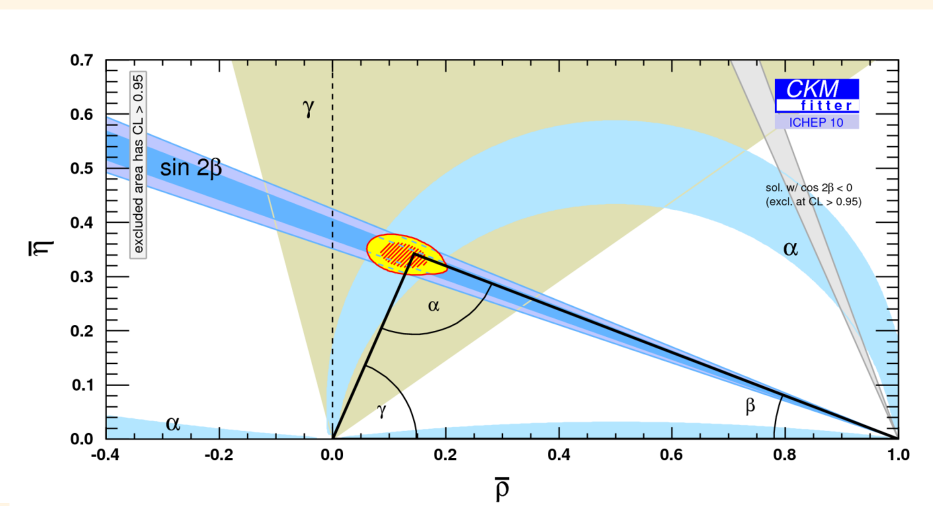
$\delta_{K\pi} = 0$ in SU(3) limit

The CKM Matrix



- Unitary matrix of complex quark couplings.
- Only source of *CP* violation in SM.
  - Non-zero area of unitary triangle.
- Coherent experimental picture has emerged in last decade.
  - CKM measurements (weak interaction) are plagued by hadronic uncertainties (strong interaction).
- The most poorly-measured angle is still γ.
  - CLEO-c sheds light on strong interactions in charm.



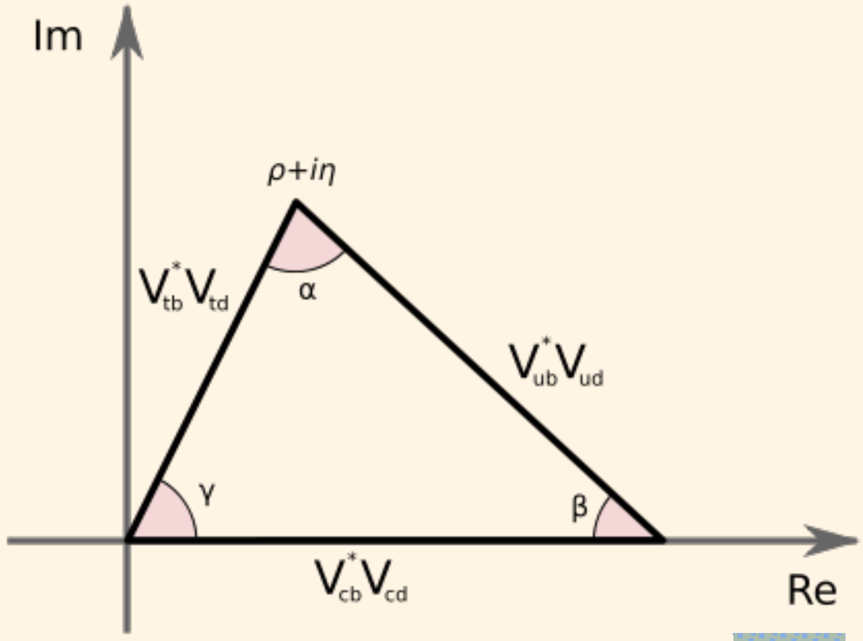


Wolfenstein Parametrization

- Expand CKM matrix in powers of λ = sine of Cabibbo angle ~ 0.22

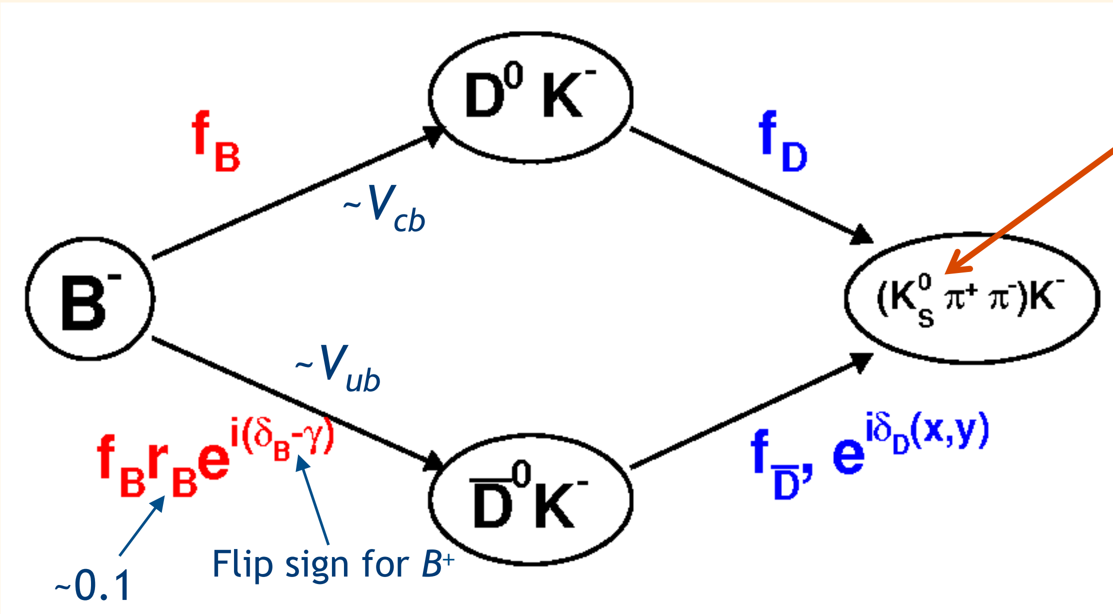
$$\mathbf{V}_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - \mathbf{i}\eta\mathbf{A}^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Unitarity condition using columns 1 and 3 leads to triangle relation:



CKM Phenomenology for γ/ϕ_3

- Interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$ is sensitive to γ/φ_3.
  - Need D final states that are common to D^0 and $\bar{D}^0$.



OR

$K^+\pi^-$

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

$K^+\pi^-\pi^+\pi^-$

$K_{S,L}{}^0 h^+ h^-$

For multibody decays:

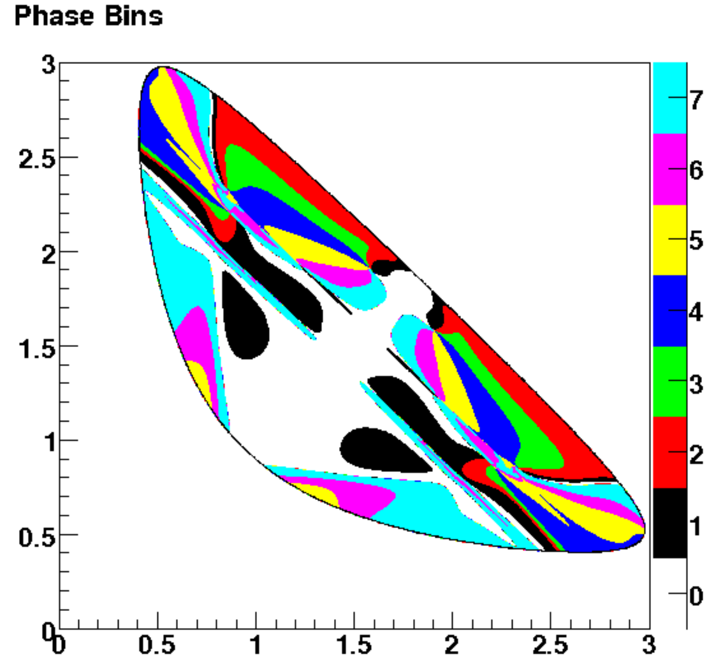
$$R_F e^{-i\delta_D^F} = \frac{\int |A(\mathbf{x})||\bar{A}(\mathbf{x})|e^{-i\zeta(\mathbf{x})}d\mathbf{x}}{A_F \bar{A}_F}$$

coherence factor $0 < R < 1$ (=1 for $K\pi$)	avg. strong phase	$\cos\delta \to R\cos\delta$

Need R & δ_D to extract γ	Accessible with $D^0\bar{D}^0$ quantum correlations

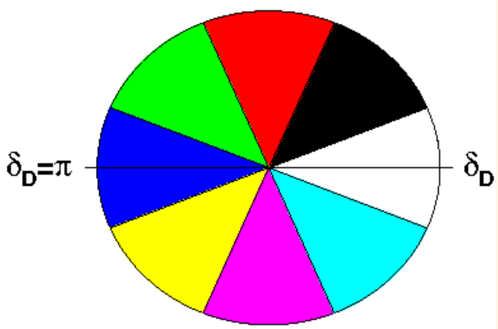
Removing Model Dependence in $K^0_{S,L} h^+h^-$

- Model-dependent $\delta_D(x,y)$ from amplitude analysis incurs model uncertainty of $\mathcal{O}(5^\circ)$ on γ/φ_3, independent of *B* decay statistics.
- Model independent analysis:
  - Divide Dalitz plot into bins.
  - 8 equal bins in predicted phase shown at right
  - Choice of bins coordinated with *B*-factories & LHCb.



Unknown strong phases:

16 symmetric bins
$\overline{c_i} = c_i \quad \overline{s_i} = -s_i$



- Each bin is a separate decay mode with $c_i = R_i \cos\delta_i$ and $s_i = R_i \sin\delta_i$.
  - Bins with $\delta \sim 0$ or π act like *CP* eigenstates ⇒ sensitive to cosines of phases.
  - Bins with $\delta \sim \pm\pi/2$ are sensitive to sines of phases.

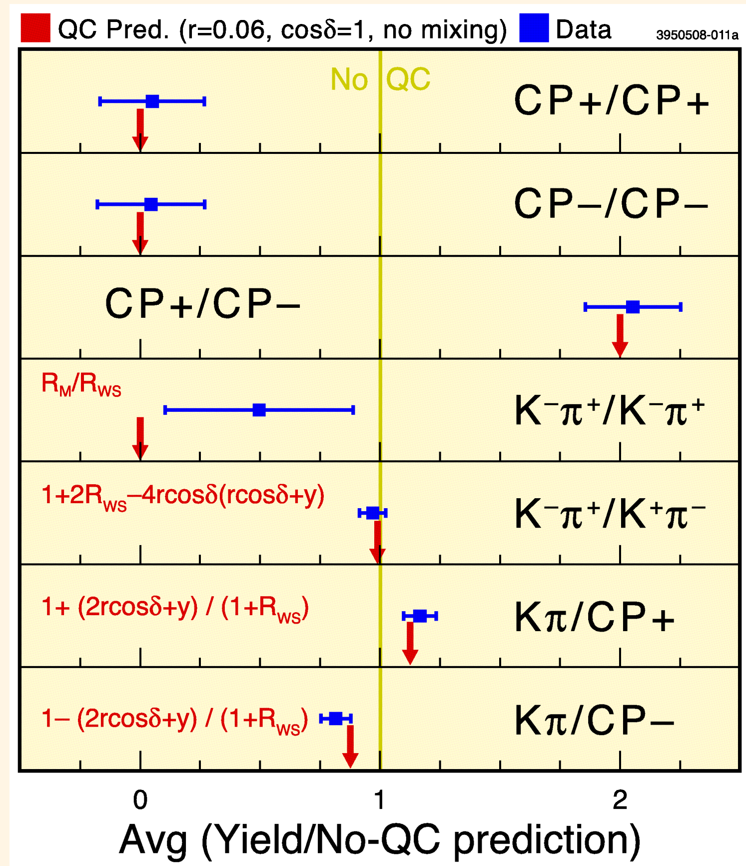
Quantum-Correlations Overview: ψ(3770)

$C = -1$

$e^+e^- \rightarrow \gamma^* \xrightarrow{\psi(3770)} D^0\bar{D}^0$

Forbidden by CP conservation	*CP+*	*CP+*
	CP−	*CP−*
Maximal enhancement	*CP+*	*CP−*
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS (gives $\cos\delta_{K\pi}$)	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP±* $K^-\pi^+$ *SL*	X

Quantum correlations are seen in data!



Quantum-Correlated Decay Rates: ψ(3770)

- Evaluating $\Gamma_{ij}^2 = \left| \langle i | D^0 \rangle \langle j | \overline{D^0} \rangle - \langle j | D^0 \rangle \langle i | \overline{D^0} \rangle \right|^2$

  with $\frac{\langle i | \overline{D}^0 \rangle}{\langle i | D^0 \rangle} = -re^{-i\delta}$ gives

  Anti-symmetric wavefunction

Selected references:

- Goldhaber and Rosner, PRD 15, 1254 (1977)
- Bigi and Sanda, PLB 171, 320 (1986)
- Xing, PRD 55, 196 (1997)
- Gronau, Grossman, Rosner, PLB 508, 37 (2001)
- Atwood and Petrov, PRD 71, 054032 (2005)
- Asner and Sun, PRD 73, 034024 (2006); PRD 77, 019901(E) (2008)

Final States			Time-Integrated Rate (x $A_i^2 A_j^2$)
Exclusive	i	$\bar{j}$	$1 + r_i^2 r_j^2 - 2 r_i r_j \cos(\delta_i + \delta_j)$
	i	j	$r_i^2 + r_j^2 - 2 r_i r_j \cos(\delta_i - \delta_j)$
Inclusive	i	X	$1 + r_i^2 + 2 y r_i \cos\delta_i$

No y dependence

Same as incoherent decay

- Interference with mixed amplitudes vanishes for $C = -1$
  - Exclusive rates probe bare amplitudes and strong phases directly.
- Inclusive rates come from summing exclusive rates.
  - Dependence on y appears in the sum.
  - Interference between unmixed and mixed+DCS amplitudes.

$$y \propto -2 \sum_i A_i^2 r_i \cos\delta_i$$

Extracting Physical Parameters from Yields

DT rate ~ $A_i^2 A_j^2 [\, 1 + r_i^2\, r_j^2 - 2\, r_i r_j \cos(\delta_i + \delta_j)\,]$

- For some final states, we know r and δ: reference points for interference
  - *CP* eigenstates: r=1 and δ=0 or π — sensitive to **cosδ** of the other side.
  - Semileptonic: r=0 — sensitive to A^2 and r^2 of the other side.
  - To probe **sinδ**, need to interfere with a final state with δ ≠ 0 or π.

$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$
$= r_{K\pi}^2 + r_{K\pi} y' + (x^2+y^2)/2$

- Use *CP*-tagged exclusive rates to extract:
  - **$\cos\delta_{K\pi}$**: reconstruct K^+K^- (*CP*+) with $K^-\pi^+ \Rightarrow K^-\pi^+$ must come from D_1 (*CP*−).
    - Signal is O(10%) deviation from uncorrelated expectation:

$$\text{rate} \propto B_{KK}(1+y)B_{K\pi}\left|1+re^{-i\delta}\right|^2 \approx B_{KK}B_{K\pi}(1+2r\cos\delta + R_{WS} + y)$$

  - **y**: reconstruct K^+K^- (*CP*+) with semileptonic ⇒ SL must come from D_1 (*CP*−).
    - Semileptonic width independent of *CP*, but total width depends on *CP*.

$$n_{e/KK} / n_{KK(ST)} = B_e \Gamma / \Gamma_1 \approx B_e (1+y)$$

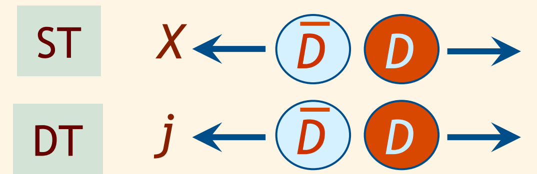
- Mixing/amplitude/phase parameters from double ratios of yields:

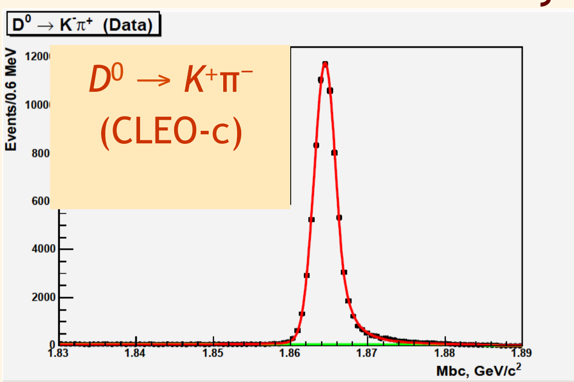
$$y + 2r\cos\delta \approx \frac{n(f,\bar{f})}{4n(f)}\left[\frac{n(CP-)}{n(CP-,f)} - \frac{n(CP+)}{n(CP+,f)}\right] \qquad y \approx \frac{n(f,l)}{4n(f)}\left[\frac{n(CP-)}{n(CP-,l)} - \frac{n(CP+)}{n(CP+,l)}\right]$$

Experimental Technique

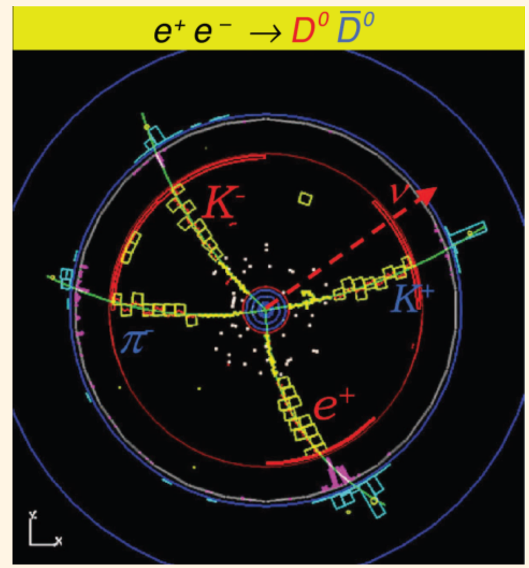
- Single tag: fully reconstruct one D
- Double tag: reconstruct both D^0 and $\bar{D}^0$
  - Both D^0 and $\bar{D}^0$ fully reconstructed.

Pair-produced D^0 and $\bar{D}^0$

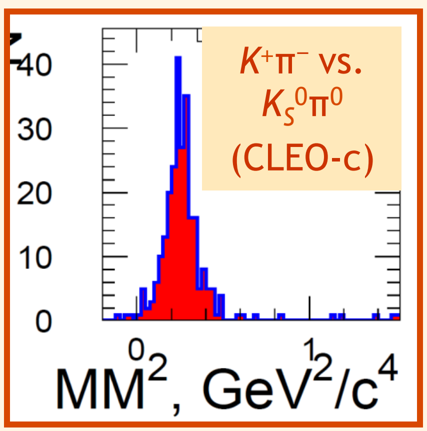




$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$



- Or one missing particle (ν or K^0_L):



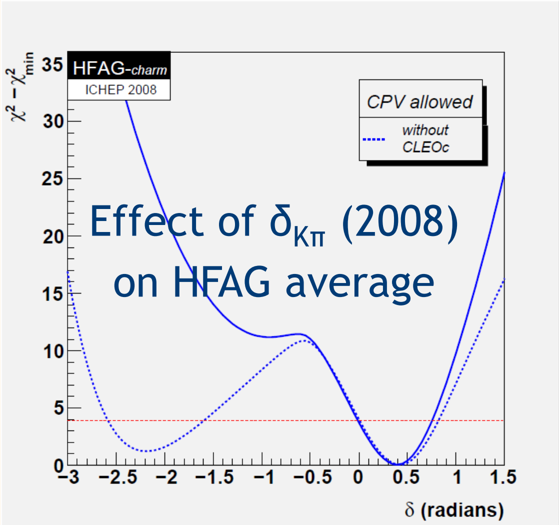
Use detector hermeticity and beam parameters to infer missing mass.

Clean event environment, very low backgrounds

Update: Strong Phase in $D^0 \to K\pi$ [$\delta_{K\pi}$]

- Previous publication: PRL 100, 221801 (2008) / PRD 78, 012001 (2008).
  - Dataset: 281 pb^{-1} at $\psi(3770)$ = 1 million *C*-odd $D^0\overline{D}^0$
  - First meas. of strong phase between CF $A(D^0 \to K^-\pi^+)$ and DCS $A(D^0 \to K^+\pi^-)$.
  - Standard fit: $\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$
  - Extended fit: $\cos\delta = 1.10 \pm 0.35 \pm 0.07$
    $x \sin\delta = (4.4^{+2.7}_{-1.8} \pm 2.9) \times 10^{-3}$
    [Incl. external mixing meas.]

Type	Final States
Flavored	$K^-\pi^+$, $K^+\pi^-$
S_+	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$
S_-	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$
$e^\pm$	Inclusive $Xe^+\nu_e$, $Xe^-\bar{\nu}_e$



- **New today**: preliminary update with full CLEO-c dataset
  - 818 pb^{-1} at $\psi(3770)$ = 3 million *C*-odd $D^0\overline{D}^0$.
  - Additional final states.
    - Includes direct measurements of $r_{K\pi}^2$ and $\sin\delta_{K\pi}$.

Not yet in HFAG average

Final States $[\delta_{K\pi}]$

- Single tags for all fully-reconstructed modes except $K^0_S\pi^+\pi^-$.
- Double tags for almost all combinations of modes.
  - Like-sign and opposite-sign.
  - At most one missing particle (K^0_L or ν).
    - Except for $Ke\nu$ vs. $K^0_L\pi^0$ (2 missing particles).
- 261 yield measurements
  - $K^0_S\pi^+\pi^-$ from PRD 80, 032002 (2009)

~1400 $K^0_S\pi^+\pi^-$ vs. $K\pi$ → $\sin\delta_{K\pi}$

~3000 *CP*-tagged $K\pi$ → $\cos\delta_{K\pi}$

Flavored hadronic	CP+	CP−	Semilep	Mixed
$K^-\pi^+$	K^-K^+	$K^0_S\pi^0$	$K^-e^+\nu$	$K^0_S\pi^+\pi^-$ (bin 0)
$K^+\pi^-$	$\pi^-\pi^+$	$K^0_S\eta$	$K^+e^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 1)
	$K^0_S\pi^0\pi^0$	$K^0_S\omega$	$K^-\mu^+\nu$	$K^0_S\pi^+\pi^-$ (bin 2)
	$K^0_L\pi^0$	$K^0_L\pi^0\pi^0$	$K^+\mu^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 3)
	$K^0_L\eta$			$K^0_S\pi^+\pi^-$ (bin 4)
	$K^0_L\omega$	New in update		$K^0_S\pi^+\pi^-$ (bin 5)
				$K^0_S\pi^+\pi^-$ (bin 6)
				$K^0_S\pi^+\pi^-$ (bin 7)

~3500 *CP*-tagged $Kl\nu$ → y

~30 WS $Kl\nu$ vs. $K\pi$ → $r_{K\pi}^2$

Semi-Muonic Decays [$\delta_{K\pi}$]

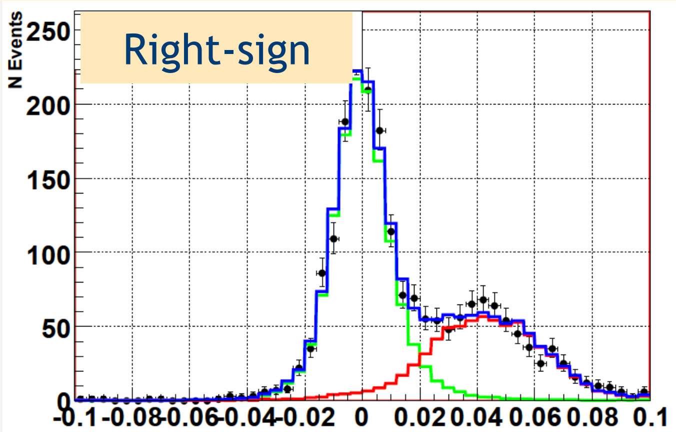
CLEO-c Preliminary

- CLEO muon chambers inefficient below 1 GeV.
- Identify right-sign $D^0 \to K^- \mu^+ \nu$ using missing energy and momentum.
  - Main background: $D^0 \to K^- \pi^+ \pi^0$ separated kinematically.
- Wrong-sign uses similar technique, but 300x lower yield.
  - Main background: mis-ID $K\pi$ flavor in RS decays.
  - Dramatically reduced by requiring kaon to be in Cherenkov counter acceptance.
    - S/(S+B) goes from 50% to 97%.
  - Combined $Ke\nu/K\mu\nu$ relative uncertainty ~25%.
- Unlike with incoherent D^0, wrong-sign gives r^2, not R_{WS}.

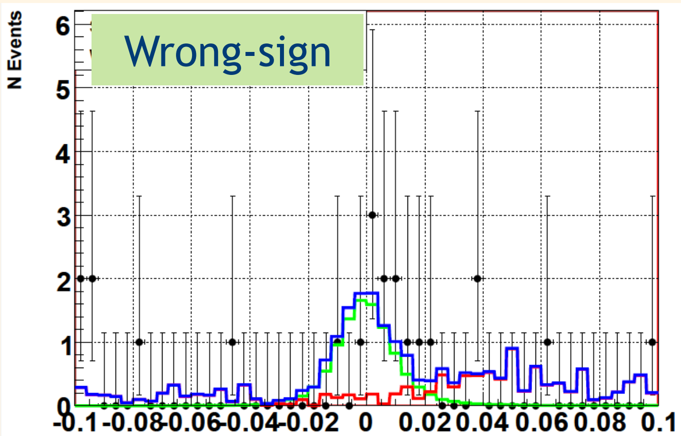
$$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+) = r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$$

  - Mixing effects cancel in the interference term

$K\mu\nu$ vs. $K\pi$



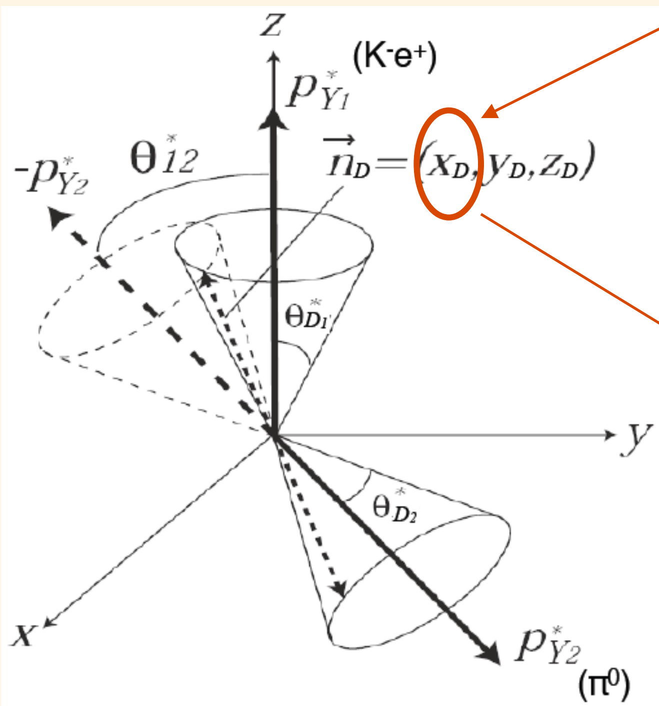
$U = E_{miss} - |P_{miss}|$

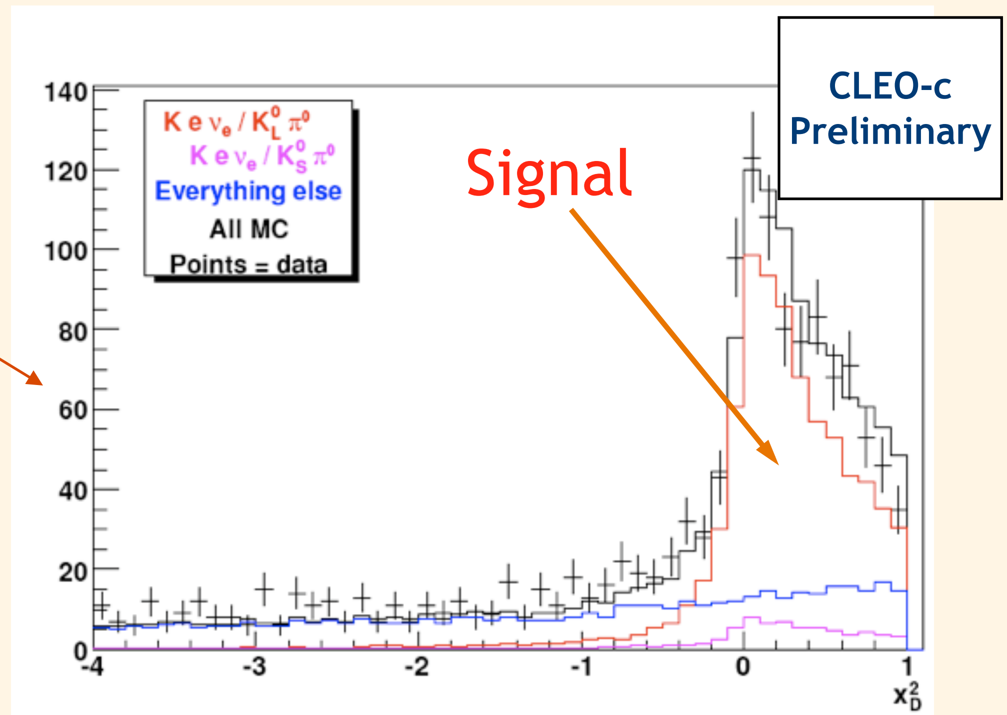


Keν vs. $K_L \pi^0$ [$\delta_{K\pi}$]

Paar/Brower: NIM A 421, 411 (1999)
BaBar: PRL 97, 211801 (2006)
Belle: PLB 648, 139 (2007)

- Doubles the number of *Ke*ν vs. *CP*+
- Technique for two missing particles:
  - Used at B-factories for semileptonic decays
  - Kinematic constraints on ν and K^0_L define two cones for D^0 and $\overline{D^0}$.
  - If cones intersect, then $0 < x_D^2 < 1$.



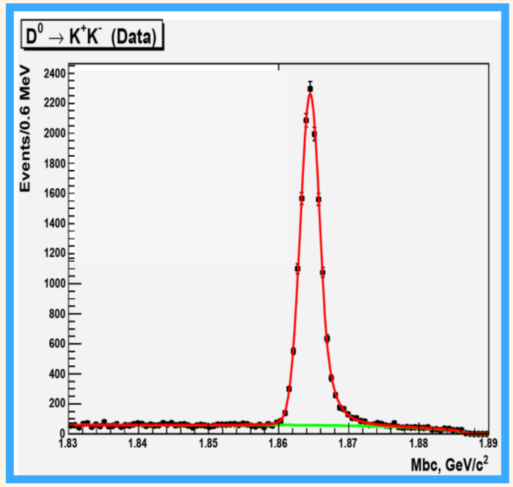


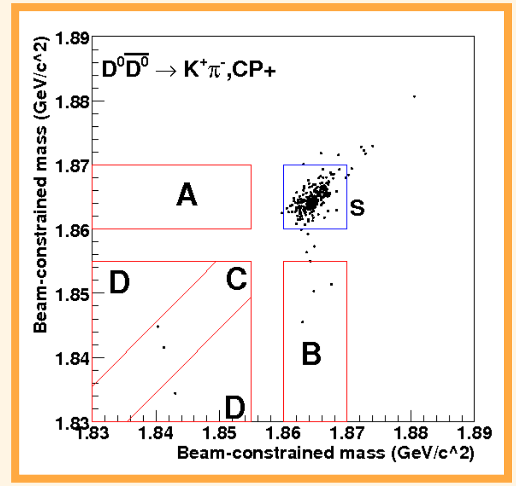
Other Yield Measurements [$\delta_{K\pi}$]

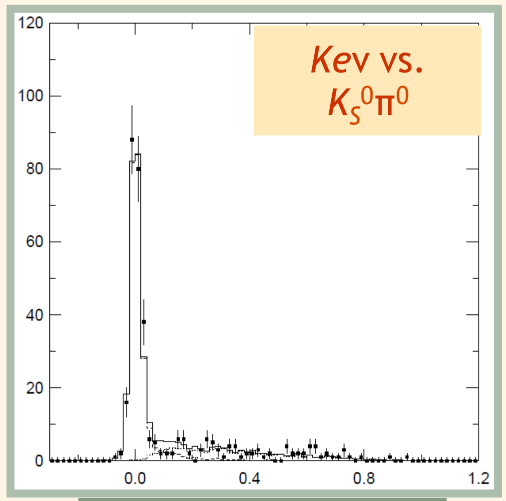
- Fully-reconstructed single tags:
  - Fit beam-constrained mass distribution.

$$M_{BC} = \sqrt{E_{beam}^2 - |\, p_D \,|^2}$$

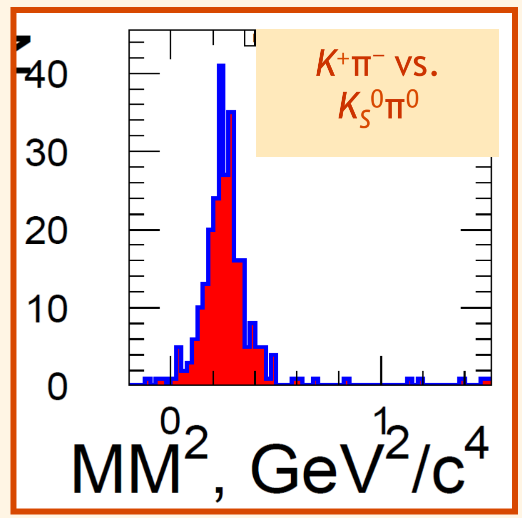
- Fully-reconstructed double tags:
  - Two fully-reconstructed STs
  - Count events in 2D M_{BC} plane.
- Exclusive Kev DTs:
  - One fully-reconstructed ST
  - Plus one K and one e candidate
  - Fit U distribution
- K^0_L $\{\pi^0, \eta, \omega, \pi^0\pi^0\}$ DTs:
  - One fully-reconstructed ST
  - Plus $\{\pi^0, \eta, \omega, \pi^0\pi^0\}$ candidate
  - Compute missing mass-squared
    - Signal peaks at $M^2(K^0)$.







$U = E_{miss} - |P_{miss}|$



External Measurements $[\delta_{K\pi}]$

Parameter	Value (%)	Source	Average (%)		
y_{CP}		HFAG	1.107 ± 0.217		
x	$1.9^{+3.2}_{-3.3} \pm 0.4 \pm 0.4$	CLEO II.V [47]	0.419 ± 0.211 [41]		
	$0.80 \pm 0.29 \pm 0.17$	Belle [48]			
	$0.16 \pm 0.23 \pm 0.12 \pm 0.08$	BABAR			
y	$-1.4 \pm 2.4 \pm 0.8 \pm 0.4$	CLEO II.V [47]	0.456 ± 0.186 [41]		
	$0.33 \pm 0.24 \pm 0.15$	Belle [48]			
	$0.57 \pm 0.20 \pm 0.13 \pm 0.07$	BABAR			
			Correlation Coefficients		
r^2	0.364 ± 0.017	Belle [50]	1	-0.834	$+0.655$
y'	$0.06^{+0.40}_{-0.39}$			1	-0.909
x'^2	$0.018^{+0.021}_{-0.023}$				1
r^2	$0.303 \pm 0.016 \pm 0.010$	BABAR [51]	1	-0.87	$+0.77$
y'	$0.97 \pm 0.44 \pm 0.31$			1	-0.94
x'^2	$-0.022 \pm 0.030 \pm 0.021$				1
r^2	0.304 ± 0.055	CDF	1	-0.971	$+0.923$
y'	0.85 ± 0.76			1	-0.984
x'^2	-0.012 ± 0.035				1
r^2	0.333 ± 0.011	Average	1	-0.848	$+0.701$
y'	0.48 ± 0.23			1	-0.942
x'^2	0.002 ± 0.012				1

Systematic Uncertainties $[\delta_{K\pi}]$

- Mixing/amplitude/phase parameters determined from double ratios.
  - Reduces effect of correlated uncertainties.
- Efficiency systematics (correlated) determined with missing mass technique.

Source	Uncertainty (%)	Scheme
Track finding	0.3	per track
$K^\pm$ hadronic interactions	0.5	per $K^\pm$
K_S^0 finding, flight signif. & mass cuts	0.94	per K_S^0
π^0 finding	2.0	per π^0
η finding	4.0	per η
dE/dx and RICH	0.1	per $\pi^\pm$ PID cut
dE/dx and RICH	0.1	per $K^\pm$ PID cut
EID	0.4	per $e^\pm$

- Other correlated uncertainties: modeling of ISR and FSR, ΔE cut, mass cuts, vetos on extra tracks/showers O(1%) each.

$$\Delta E = E_{cand} - E_{beam}$$

- Uncorrelated uncertainties: yield fit variations, sideband subtractions
- In the end, statistical uncertainties dominate.

Fit Results [$\delta_{K\pi}$]

CLEO-c Preliminary

- 51 free parameters
  - N_{DD}, 21 branching fractions
  - 24 amplitude/phase parameters for $K^0{}_S\pi^+\pi^-$
  - 5 $K\pi$ and mixing parameters
- Fit performed with and without external measurements of y, x, y' (same as in HFAG May 2010 avg.)
- Statistical uncertainties on ***y*** and $\boldsymbol{r_{K\pi}\cos\delta_{K\pi}}$ (w/o ext. meas.) 3x smaller than 2008 analysis.
  - Estimated impact on HFAG average: $\sigma(y)$ reduced by ~10%
  - First direct measurements of $r_{K\pi}{}^2$ and $\sin\delta_{K\pi}$
- Preliminary systematics.

Parameter	Previous: PDG, HFAG, or CLEO	Fit: no ext. meas.	Fit: with ext. y, x, y'
y (10^{-2})	0.79 ± 0.13	3.0 ± 2.0 ± 1.2	**0.635 ± 0.118**
x^2 (10^{-3})	0.037 ± 0.024	1.5 ± 2.0 ± 0.9	0.022 ± 0.017
$r_{K\pi}{}^2$ (10^{-3})	3.32 ± 0.08	4.12 ± 0.92 ± 0.23	3.32 ± 0.08
$\cos\delta_{K\pi}$	1.10 ± 0.36	**$0.98^{+0.27}_{-0.20} \pm 0.08$**	**1.15 ± 0.16 ± 0.12**
$\sin\delta_{K\pi}$	---	**-0.04 ± 0.49 ± 0.08**	**$0.55^{+0.36}_{-0.40} \pm 0.08$**
$\delta_{K\pi}$ (°) [derived]	$22^{+11}_{-12}{}^{+9}_{-11}$	0 ± 22 ± 6	$15^{+11}_{-17} \pm 7$

Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ (now limited by $\sin\delta_{K\pi}$)

Purity of Initial State [$\delta_{K\pi}$]

- C+ contamination of initial C− state (not expected, cf. A. Petrov):
  - $e^+e^- \to \gamma D^0\overline{D}^0$ is C+, but photon must be radiated from
    - D^0 or $\overline{D}^0$
    - ψ(3770)
    - virtual D^* intermediate state.
  - ISR, FSR, bremsstrahlung photons do not flip C eigenvalue.

- Allow fit to determine C+ fraction.
  - Include same-CP double tags ($CP\pm/CP\pm$).
    - Allowed decay only for C+.
    - All yields consistent with zero.
  - Fit each yield to sum of C− and C+ contributions.
  - Results (from 2008 publication): $C+/C- = -0.001 \pm 0.023$.
    - No evidence for C+.
    - Other results unchanged.

Likelihood Contours $[\delta_{K\pi}]$

CLEO-c Preliminary

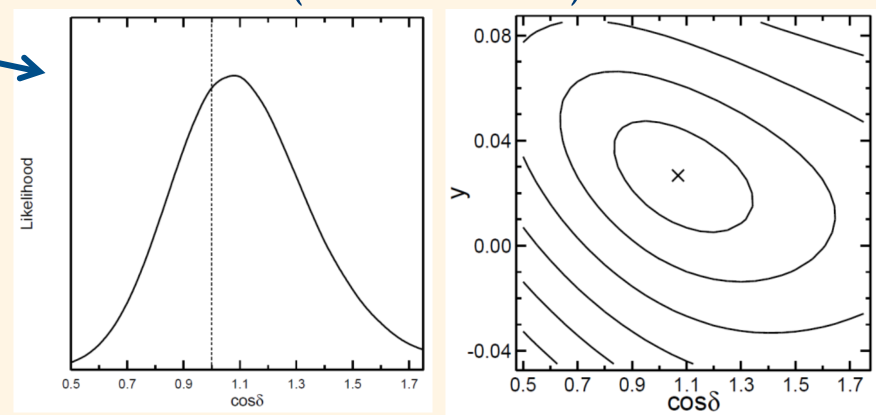
- Improved likelihood behavior over 2008 publication:
  - Previous nonlinearities from use of R_{WS} to derive $r_{K\pi}^2$

$$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$$
$$= r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$$

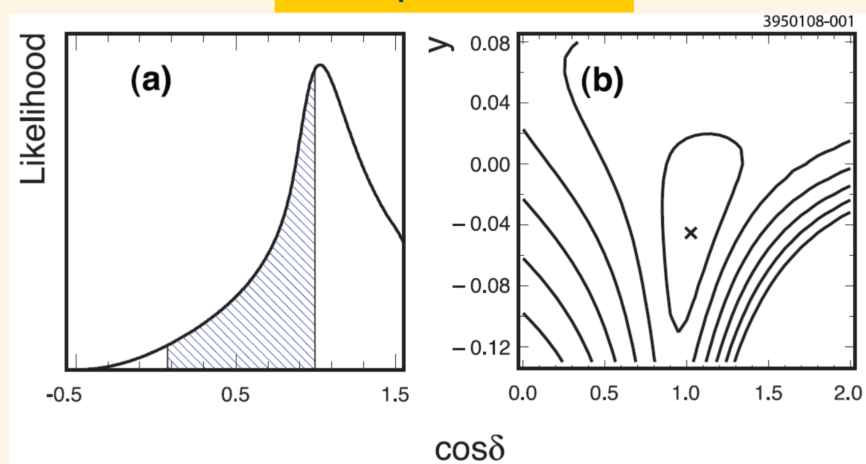
  - Solved by our new independent measurement of $r_{K\pi}^2$ (WS $Kl\nu$ vs. $K\pi$)
  - Will give more robust averages with other experiments (HFAG)

New prelim. results – statistics only

(no ext. meas.)



2008 publication



Strong Phase in $D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^-\pi^+$

- Published result using 818 pb^{-1} of ψ(3770) data
  - [PRD 80, 031105(R) (2009)]

- Similar formalism for *K*π, except now include coherence factors (*R*) for multi-body decay as free parameters.

Type	Final states
Flavored	$K^\mp\pi^\pm$, $K^\mp\pi^\pm\pi^\pm\pi^\mp$, $K^\mp\pi^\pm\pi^0$
CP-even	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$
CP-odd	$K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\phi$, $K^0_S\eta$, $K^0_S\eta'$

total CP-tagged events	~3200 vs. $K^+\pi^-\pi^+\pi^-$
	~4700 vs. $K^+\pi^-\pi^0$

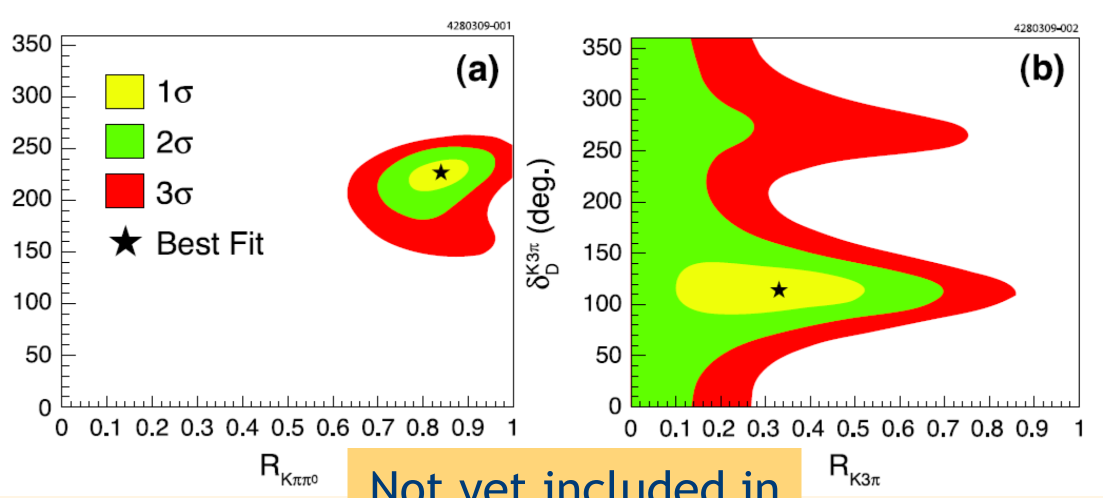
From like-sign DT rates of
$K^+\pi^-\pi^0$ vs. $K^+\pi^-\pi^0$
$K^+\pi^-\pi^+\pi^-$ vs. $K^+\pi^-\pi^+\pi^-$
~ ($1 - R^2$)

- 41 DT yield measurements.
- No single tags — estimate from external branching fractions.

$D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^-\pi^+$ Results

- Low coherence in $K3\pi$ has advantages:
  - Gives sensitivity to y comparable to $K\pi$ analysis
  - Also increases sensitivity to r_B
- Expect ~40% reduction in error on γ/φ_3.
- Also useful for HFAG mixing average:
  - But first need to convert average $K^+\pi^-\pi^0$ phase to $K^*\pi$ phase

Parameter	Mixing constrained	Mixing unconstrained
$R_{K\pi\pi^0}$	0.84 ± 0.07	$0.78^{+0.11}_{-0.25}$
$\delta_D^{K\pi\pi^0}$ (°)	227^{+14}_{-17}	239^{+32}_{-28}
$R_{K3\pi}$	$0.33^{+0.26}_{-0.23}$	$0.36^{+0.24}_{-0.30}$
$\delta_D^{K3\pi}$ (°)	114^{+26}_{-23}	118^{+62}_{-53}
x (%)	0.96 ± 0.25	$-0.8^{+2.9}_{-2.5}$
y (%)	0.81 ± 0.16	$0.7^{+2.4}_{-2.7}$
$\delta_D^{K\pi}$	$-151.5^{+9.6}_{-9.5}$	-130^{+38}_{-28}



Not yet included in HFAG average

Combining $K^-\pi^+$ and $K^-\pi^+\pi^0/K^-\pi^+\pi^-\pi^+$

- $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ analysis includes $\delta_{K\pi}$ as external input.
- But there is also independent sensitivity to $\delta_{K\pi}$.

Parameter	Mixing constrained	Mixing unconstrained
$R_{K\pi\pi^0}$	0.84 ± 0.07	$0.78^{+0.11}_{-0.25}$
$\delta_D^{K\pi\pi^0}$ (°)	227^{+14}_{-17}	239^{+32}_{-28}
$R_{K3\pi}$	$0.33^{+0.26}_{-0.23}$	$0.36^{+0.24}_{-0.30}$
$\delta_D^{K3\pi}$ (°)	114^{+26}_{-23}	118^{+62}_{-53}
x (%)	0.96 ± 0.25	$-0.8^{+2.9}_{-2.5}$
y (%)	0.81 ± 0.16	$0.7^{+2.4}_{-2.7}$
$\delta_D^{K\pi}$	$-151.5^{+9.6}_{-9.5}$	-130^{+38}_{-28}

- In particular, $\delta(K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-) \neq 0$ or π

  $\Rightarrow$ $K^+\pi^-$ vs. $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ DTs have enhanced sensitivity to $\sin\delta_{K\pi}$.

Final States			Time-Integrated Rate (x $A_i^2 A_j^2$)
Exclusive	i	$\bar{j}$	$1 + r_i^2 r_j^2 - 2 r_i r_j \cos(\delta_i + \delta_j)$
	i	j	$r_i^2 + r_j^2 - 2 r_i r_j \cos(\delta_i - \delta_j)$
Inclusive	i	X	$1 + r_i^2 + 2 y r_i \cos\delta_i$

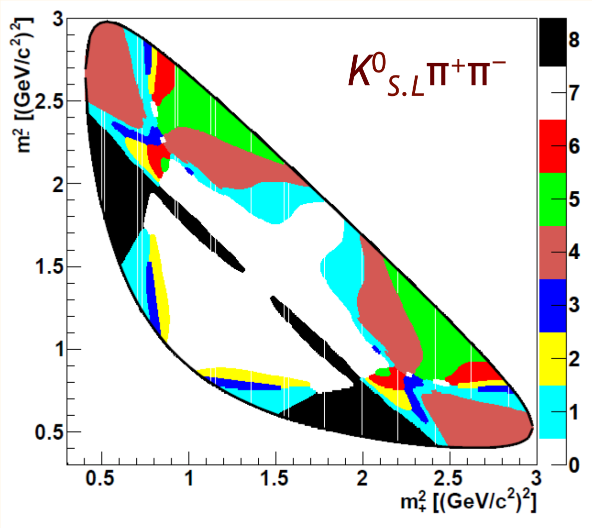
$\cos(\delta_i + \delta_j) =$
$\cos\delta_i \cos\delta_j - \sin\delta_i \sin\delta_j$

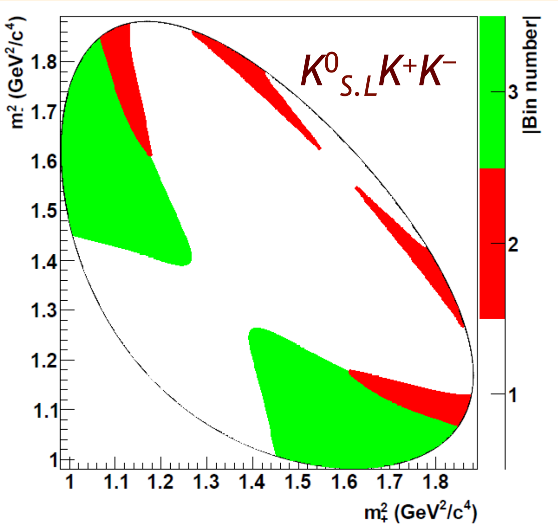
No sensitivity to $\sin\delta_i$ *when* $\sin\delta_j \sim 0$

- Combined analysis of $K^+\pi^-$ and $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ in progress.

Update: Strong Phase in $D^0 \rightarrow K^0_{S,L} h^+h^-$

- Previous results on $K^0_{S.L}\pi^+\pi^-$ using 818 pb^{-1} of ψ(3770) data:
  - PRD 80, 032002 (2009), 8 equal phase bins [used in $\delta_{K\pi}$ analysis]
- **New today**: updated results with same dataset.
  - Phase binning optimized for precision on γ/φ_3.
    - Different schemes explored.
  - Add $K^0_{S.L}K^+K^-$:
    - Use {2, 3, 4} bins instead of 8 because of lower statistics.





total CP-tagged events for c_i
~800 vs. $K^0_{S.L}\pi^+\pi^-$
~4700 vs. $K^0_{S.L}K^+K^-$

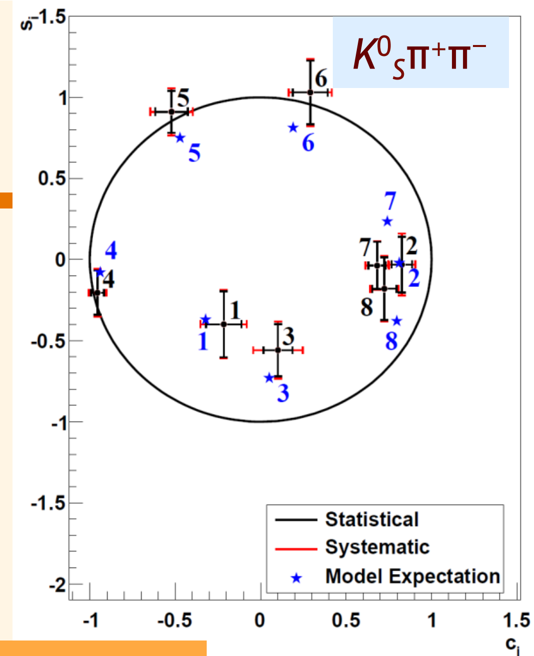
~2000 total $K^0_{S.L}h^+h^-$ vs. $K^0_{S.L}h^+h^-$ events for s_i

$D^0 \rightarrow K^0_{S,L}\, h^+h^-$ Results

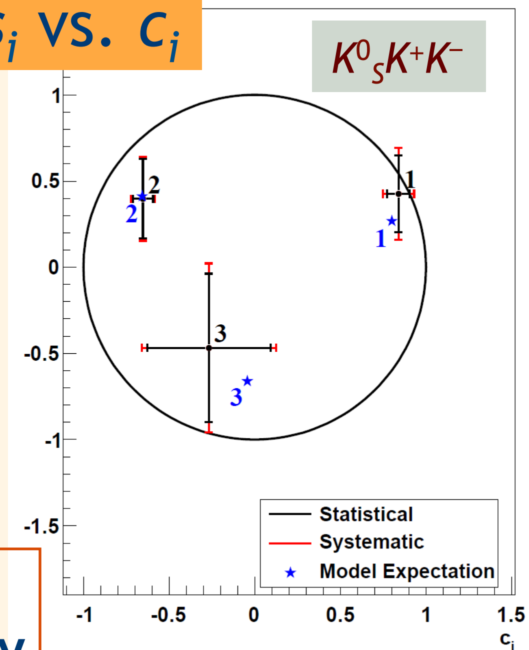
- One set of binning choices shown at right.

- For most binning schemes, induced uncertainty on γ/φ_3 is smaller than current model uncertainty of 3 to 9 degrees:
  - arXiv:1005.1096 [BaBar]
  - PRD 81, 112002 (2010) [Belle]

- Also useful for mixing studies at *B*-factories:
  - Time-dependent Dalitz plot fit of $K_S^0 h^+ h^-$ determines ***x*** and ***y*** simultaneously.
  - Depends on knowing strong phase across Dalitz plot.
  - Could be done w/o model dependence using CLEO-c measurements.



s_i vs. c_i



CLEO-c Preliminary

Summary and Outlook

- Quantum-correlated CLEO-c dataset has yielded direct determinations of amplitudes and strong phases in D^0 decays.

$$D^0 \rightarrow K^+\pi^- \quad K^+\pi^-\pi^0 \quad K^+\pi^-\pi^+\pi^- \quad K_{S,L}^0 h^+ h^-$$

  - All measurements are statistics-limited.
  - Already significant impact on charm mixing and CKM studies.
- BES-III has exceeded CLEO's $\psi(3770)$ dataset.
  - Should be able to improve on CLEO-c results.
  - Eventually:
    - Competitive measurements of mixing parameters.
    - Use C=+1 $D^0 D^0 \gamma$ from higher-energy data.
      - Orthogonal sensitivity to mixing parameters and strong phases.
    - Access to CP violation.
- *B*-factories: radiative return to $\psi(3770)$?
  - Also gives boosted $D^0 D^0$ pairs—time dependent analysis is sensitive to x.
- Many more possibilities to explore!