Charm Mixing and Strong Phases Using Quantum Correlations at CLEO-c

Werner Sun, Cornell University

5-8 August 2007, Charm07 Workshop, Ithaca, NY

Motivation

Technique

Results

Charm Mixing So Far

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

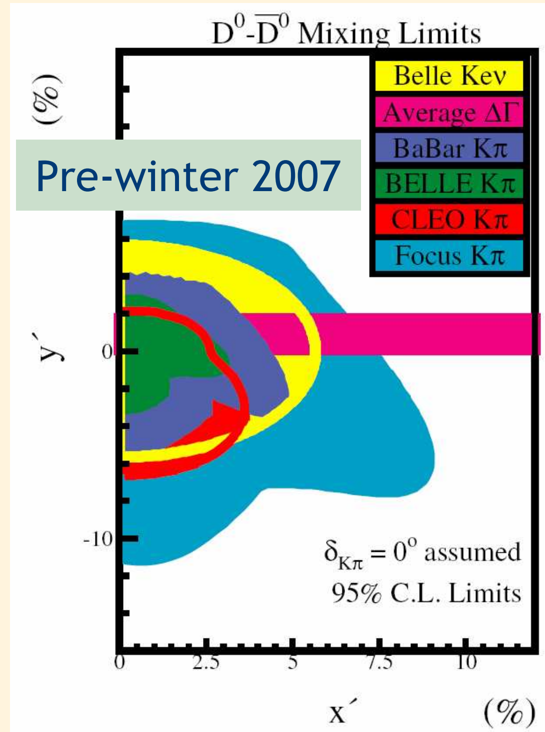
$$x = \frac{\Delta M}{\Gamma} \text{ and } y = \frac{\Delta\Gamma}{2\Gamma}$$

$$D_{1,2} = \frac{D^0 \pm \overline{D^0}}{\sqrt{2}}$$

- $H_{12}, H_{21} \neq 0 \Rightarrow$ flavor eigenstates $\neq$ mass eigenstates.
- Previous studies:
  - Direct lifetime measurements: $y = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1$
    - Compare K^+K^- and $\pi^+\pi^-$ with $K^-\pi^+$.
  - Time-dependent Dalitz analysis of $K^0_S\,\pi^+\pi^-$:
    - Intermediate *CP*-eigenstates give *y*.
    - Interference between *CP*+ and *CP*– gives *x*.
  - Time-dependent wrong-sign rate $D^0 \to K^-\pi^+$:
    - Interfering DCS and mixing amplitudes modulate exponential decay time.
    - Ambiguity from strong phase: $y' = y\cos\delta - x\sin\delta$

$$\langle K^-\pi^+|\overline{D^0}\rangle \,/\, \langle K^-\pi^+|D^0\rangle = -re^{-i\delta}$$

- Time-dependence gives 1st-order *x*/*y* sensitivity:
  - Need boosted *D* mesons to resolve decay time.



Quantum Correlations at CLEO-c

- At CLEO-c, interference comes for free.
  - Appears in *time-integrated* yields.

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

$C = -1$

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

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	$K^-\pi^+$	$CP\pm$
	$CP\pm$	$K^-\pi^+$
Unaffected	X	$K^+l^-\nu$

- 1st-order sensitivity to y:
  - Reconstruct K^+K^- ($CP+$) decay $\Rightarrow$ other side must be D_1 ($CP-$)
  - Inclusive K^+K^- rate probes y.

$$n_{KK} = 2B_{KK}\Gamma_1 = 2B_{KK}(1-y)\Gamma$$

$$1-y = \boxed{\frac{n_{KK}}{2N_{DD}}}\frac{1}{B_{KK}}$$

Effective $\mathcal{B}$ at $\psi(3770)$

- First measurement of $\cos\delta$:
  - Reconstruct K^+K^- with $K^-\pi^+ \Rightarrow$ $K^-\pi^+$ must come from D_1 ($CP-$).

$$\text{rate} \propto \left| \langle K^-\pi^+ | D^0 \rangle + \langle K^-\pi^+ | \overline{D^0} \rangle \right|^2$$

$$\propto B_{K\pi} \left| 1 + re^{-i\delta} \right|^2$$

$$= \boxed{B_{K\pi}(1 + 2r\cos\delta + r^2)}$$

Coherent vs. Incoherent Decay

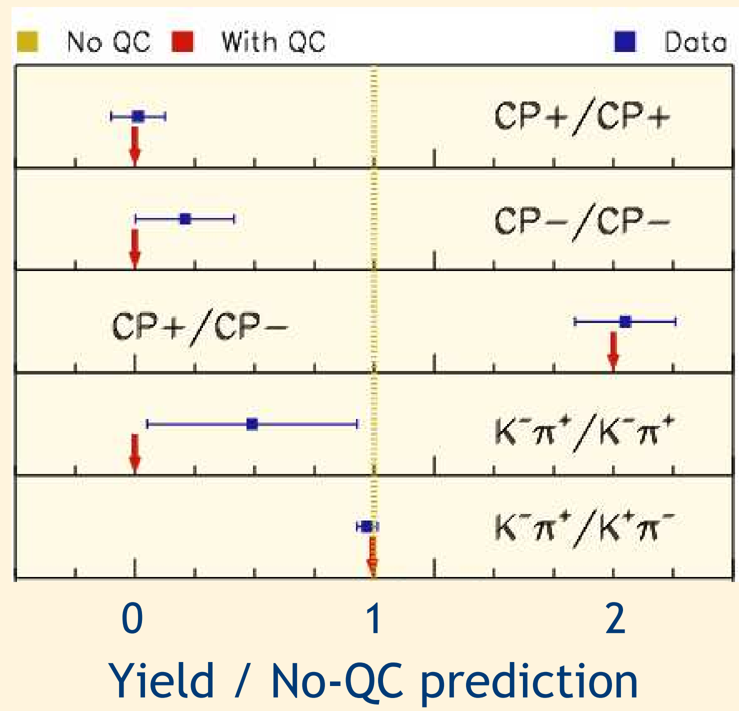
- We use yields for
  - single tags (one D reconstructed)
  - double tags (D and $\overline{D}$ reconstructed)

ST $X \leftarrow \overline{D}\ D \rightarrow i$

DT $j \leftarrow \overline{D}\ D \rightarrow i$

$\dfrac{\text{quantum-correlated rate}}{\text{incoherent rate}}$

DT	$K^-\pi^+$	e^+	$CP+$	$CP-$
$K^-\pi^+$	R_M/r^2			
$K^+\pi^-$	$1+2r^2(1-2\cos^2\delta)$			
e^-	1	1		
$CP+$	$1 + 2r\cos\delta + r^2$	1	0	
$CP-$	$1 - 2r\cos\delta + r^2$	1	2	0
ST	$1 + 2yr\cos\delta + r^2$	1	$1 - y$	$1 + y$



Quantum correlations are seen in data!

- Compare QC effective $\mathcal{B}$ with incoherent $\mathcal{B}$ to give y and $\cos\delta$.
- Sources of incoherent $\mathcal{B}$:
  - Externally measured $\mathcal{B}$s.
  - Semileptonic tags at $\psi(3770)$ (immune to QC).
- *CP* violation neglected.

Analysis Overview

- Dataset: 281 pb^{-1} = 10^6 C-odd $D^0\overline{D}^0$.
- Combine inputs + error matrix in a χ^2 fit.
  - ST and DT yields
  - Efficiencies (signal and background)
  - Crossfeed/background estimates
  - Systematic errors (small compared to stat.)
  - External $\mathcal{B}$ and y$^{(\prime)}$ measurements

- Single tag yields (8):

$K^-\pi^+$		$1 + 2yr\cos\delta + r^2$
$K^+\pi^-$		$1 + 2yr\cos\delta + r^2$
K^-K^+		$1 - y$
$\pi^-\pi^+$	$CP+$	$1 - y$
$K^0_S\pi^0\pi^0$		$1 - y$
$K^0_S\pi^0$		$1 + y$
$K^0_S\eta$	$CP-$	$1 + y$
$K^0_S\omega$		$1 + y$

- Fully-reconstructed DT yields (24):

$K^-\pi^+$	$K^+\pi^-$	(1)	$1+2r^2(1-2\cos^2\delta)+r^4$
$K^+\pi^-$	$K^+\pi^-$	(1)	$(x^2 + y^2)/2$
$K^-\pi^+$	$K^-\pi^+$	(1)	$(x^2 + y^2)/2$
$K\pi$	$CP+$	(3)	$1 + 2r\cos\delta + r^2$
$K\pi$	$CP-$	(3)	$1 - 2r\cos\delta + r^2$
$CP+$	$CP-$	(9)	2

- Inclusive e^+ or e^- vs. hadronic (14):

e^-	$K^-\pi^+$	(1)	1
e^+	$K^+\pi^-$	(1)	1
e^-/e^+	$CP+$	(6)	1
e^-/e^+	$CP-$	(6)	1

- $K^0_L\pi^0$ (=$CP+$) vs. hadronic (5):

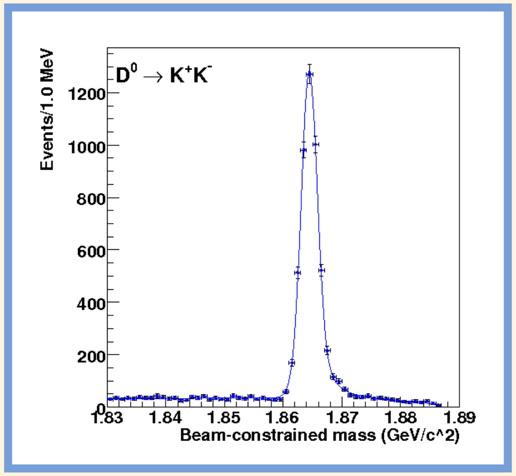
$K^0_L\pi^0$	$K\pi$	(2)	$1 + 2r\cos\delta + r^2$
$K^0_L\pi^0$	$CP-$	(3)	2

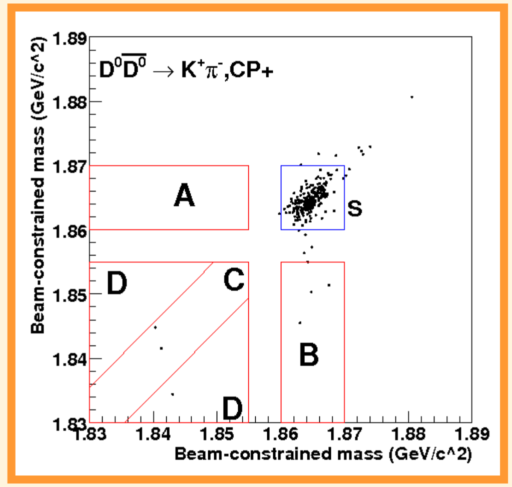
Yield Measurements

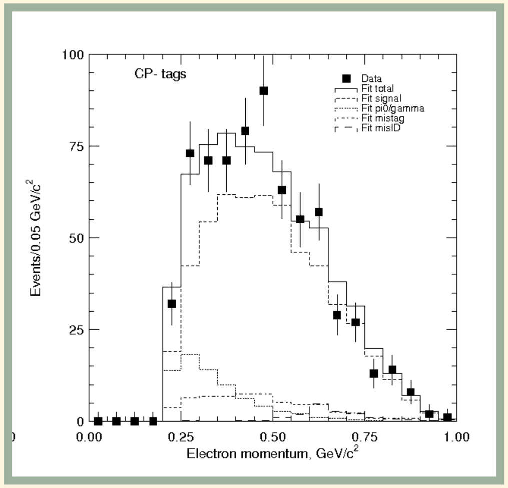
- Fully-reconstructed single tags:
  - Fit beam-constrained mass distribution.

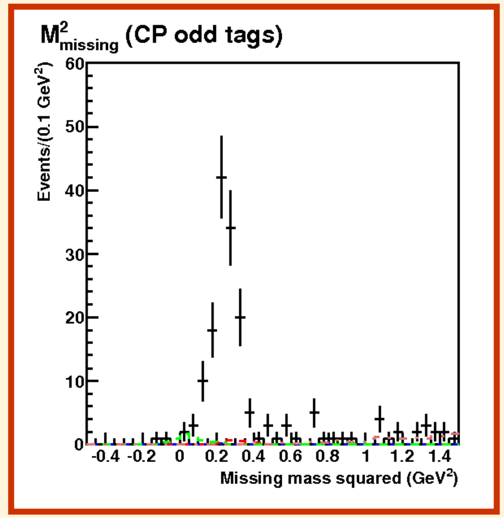
$$M_{BC} = \sqrt{E_{beam}^2 - |\, p_D \,|^2}$$

- Fully-reconstructed double tags:
  - Two fully-reconstructed STs
  - Count events in 2D M_{BC} plane.
- Inclusive semileptonic DTs:
  - One fully-reconstructed ST
  - Plus one electron candidate
  - Fit $e^{\pm}$ momentum spectrum
- $K^0_L\pi^0$ double tags:
  - One fully-reconstructed ST
  - Plus one π^0 candidate
  - Compute missing mass-squared
    - Signal peaks at $M^2(K^0)$.









External Measurements

- External inputs dramatically improve y and $\cos\delta$ precision.
- All correlations among measurements included in fit.
- Standard fit includes:
  - Info on r needed to obtain $\cos\delta$:
    - $R_{WS} = r^2 + ry' + R_M$
    - $R_M = (x^2 + y^2)/2$
    - Assume $x\sin\delta = 0 \Rightarrow y' \sim= y\cos\delta$
  - CP-eigenstate $\mathcal{B}$s:
    - Also $K\pi$ because correlated in PDG

Parameter	Average
R_{WS}	0.00409 ± 0.00022
R_M	0.00017 ± 0.00039
$K^-\pi^+$	0.0381 ± 0.0009
$K^-K^+/K^-\pi^+$	0.1010 ± 0.0016
$\pi^-\pi^+/K^-\pi^+$	0.0359 ± 0.0005
$K^0_L\pi^0$	0.0097 ± 0.0003
$K^0_S\pi^0$	0.0115 ± 0.0012
$K^0_S\eta$	0.00380 ± 0.00060
$K^0_S\omega$	0.0130 ± 0.0030

- Extended fit averages y and y':
  - CP+ lifetimes (y)
  - $K^0{}_S\,\pi^+\pi^-$ Dalitz analysis (x, y)
  - $K\pi$ CP-conserving fits (y', r^2, R_M)
    - Includes covariance matrices from Belle, BABAR, CLEO (thanks!)

Parameter	Average
y	0.00662 ± 0.00211
x	0.00811 ± 0.00334
r^2	0.00339 ± 0.00012
y'	0.0034 ± 0.0030
x'^2	0.00006 ± 0.00018

Fit Results

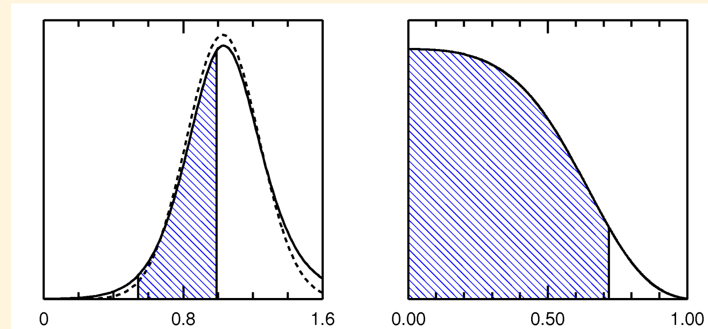
CLEO PRELIMINARY

[ ] = with external input

Parameter	Standard Fit	Extended Fit
$N_{D^0\bar{D}^0}$ (10^6)	1.046±0.019±0.013	1.044±0.019±0.012
y (10^{-3})	−33 ± 16 ± 10	[4.3 ± 1.3 ± 0.7]
r^2 (10^{-3})	[6.6 ± 1.9 ± 0.8]	[3.39 ± 0.08 ± 0.00]
$\cos\delta$	1.03 ± 0.19 ± 0.08	0.93 ± 0.32 ± 0.04
x^2 (10^{-3})	[−0.6 ± 1.3 ± 0.7]	[0.05 ± 0.05 ± 0.00]
$\mathcal{B}(K^-\pi^+)$ (%)	[3.77 ± 0.07 ± 0.03]	[3.77 ± 0.07 ± 0.03]
$\mathcal{B}(K^-K^+)$ (10^{-3})	[3.81 ± 0.09 ± 0.03]	[3.88 ± 0.08 ± 0.03]
$\mathcal{B}(\pi^-\pi^+)$ (10^{-3})	[1.35 ± 0.03 ± 0.01]	[1.36 ± 0.03 ± 0.01]
$\mathcal{B}(K^0_S\pi^0\pi^0)$($10^{-3}$)	8.08 ± 0.34 ± 0.51	8.35 ± 0.32 ± 0.52
$\mathcal{B}(K^0_S\pi^0)$ (%)	[1.18 ± 0.03 ± 0.03]	[1.14 ± 0.03 ± 0.03]
$\mathcal{B}(K^0_S\eta)$ (10^{-3})	[4.56 ± 0.21 ± 0.25]	[4.41 ± 0.19 ± 0.25]
$\mathcal{B}(K^0_S\omega)$ (%)	[1.16 ± 0.04 ± 0.06]	[1.11 ± 0.03 ± 0.05]
$\mathcal{B}(X^-e^+\nu)$ (%)	6.55 ± 0.16 ± 0.17	6.59 ± 0.16 ± 0.17
$\mathcal{B}(K^0_L\pi^0)$ (%)	[0.98 ± 0.03 ± 0.02]	[1.02 ± 0.03 ± 0.02]
χ^2/ndof	27.8/46	58.1/58

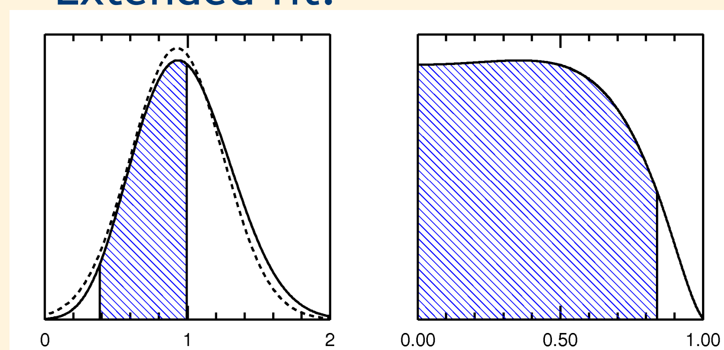
$\mathcal{B}$ measurements do not supersede other CLEO-c results!

- Likelihood curves +95% CL ULs
- Standard fit:



$\cos\delta > 0.54$ $|\sin\delta| < 0.72$

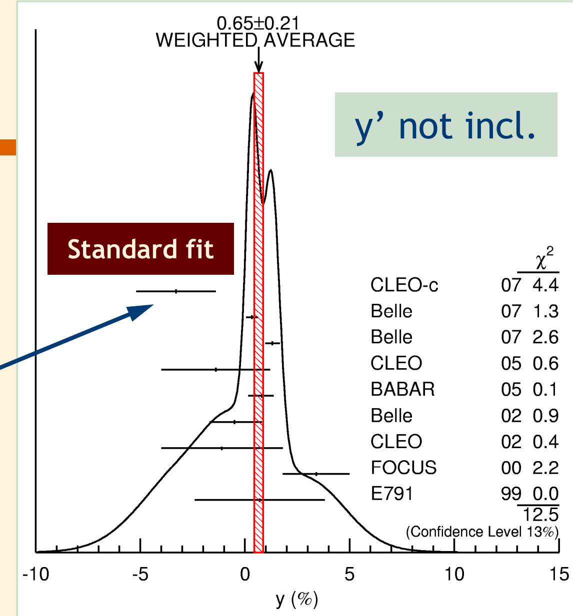
- Extended fit:

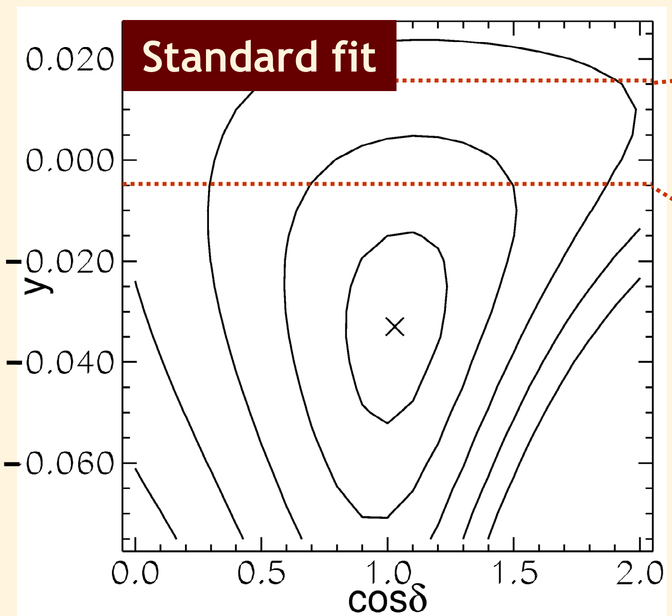


$\cos\delta > 0.38$ $|\sin\delta| < 0.84$

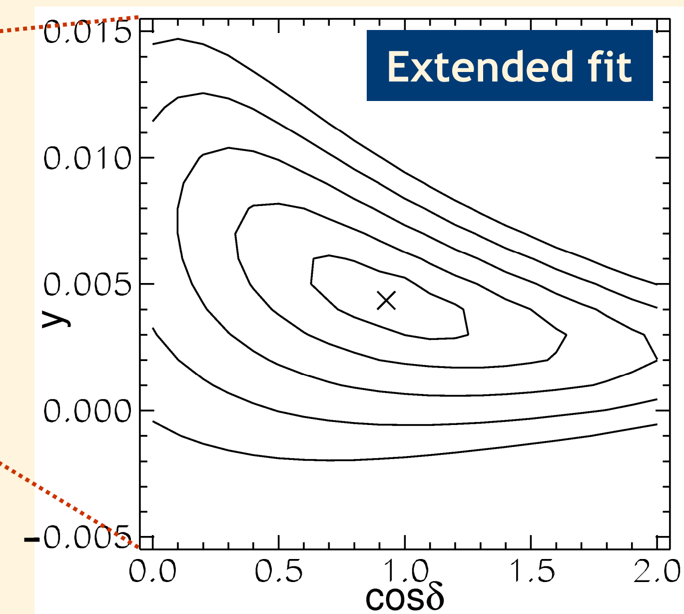
Comments on Results

- Information in inputs: observe change in parameter errors when removed from fit.
- y: [Info: 50% KK ST+$\mathcal{B}_{ext}$, 20% $\pi\pi$ ST+$\mathcal{B}_{ext}$, 15% $e^{\pm}/CP$ DTs]
  - 2.1σ discrepancy between CLEO-c and world average.
  - Checked extensively for bias; none found $\Rightarrow$ statistical fluctuation.
- cosδ: [Info: 45% $K\pi/CP+$ DTs, 45% $K\pi/CP-$ DTs]
  - Strong nonlinearity introduced by $R_{WS} \sim= r^2 + 2yr\cos\delta$:





1-σ likelihood contours in y vs. cosδ (excludes xsinδ error)



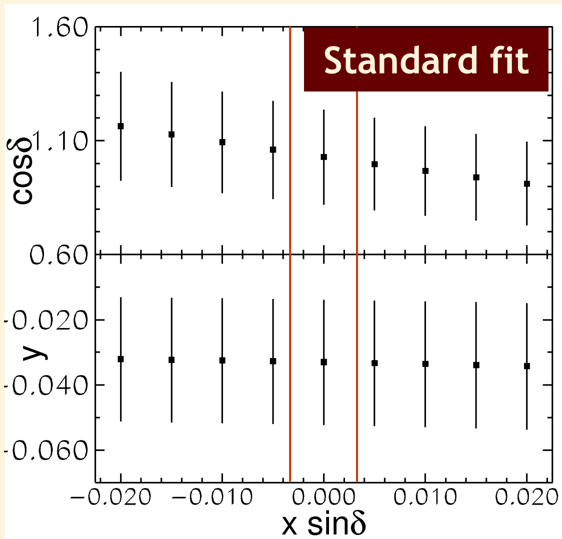
Error on cosδ depends on *value of y*

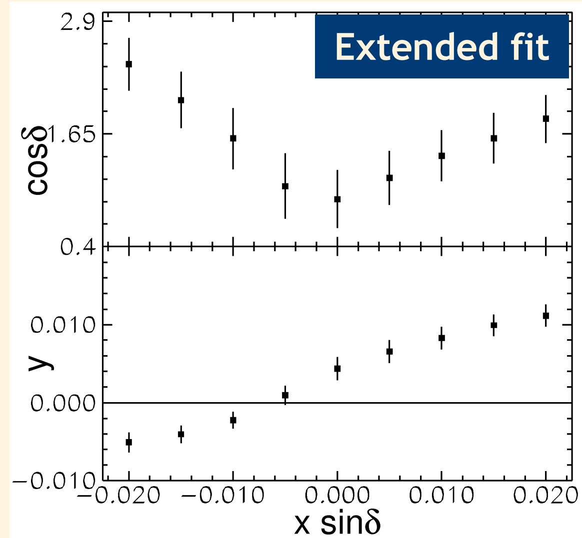
Other Systematic Effects (I)

- C+ contamination of initial 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 $\overline{D}^0$, or from $\psi(3770)$ itself.
  - 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: $C+/C- = -0.003 \pm 0.023$.
    - No evidence for C+.
    - Other results unchanged.

Other Systematic Effects (II)

- Variation of cosδ and *y* with *x*sinδ—include additional systematic error:





- Standard fit, for Δ(*x*sinδ) = ±0.0034:
  - cosδ = 1.03 ± 0.19 (stat) ± 0.08 (syst) ± 0.02 (*x*sinδ)
  - *y* = –0.033 ± 0.016 (stat) ± 0.10 (syst) ± 0.00 (*x*sinδ)

CLEO PRELIMINARY

- Extended fit, Δ(*x*sinδ) still under investigation:
  - cosδ = 0.93 ± 0.32 (stat) ± 0.04 (syst) ± 0.?? (*x*sinδ)
  - *y* = +0.0043 ± 0.0013 (stat) ± 0.0007 (syst) ± 0.00?? (*x*sinδ)
  - Alternative: fit for *x*sinδ by sacrificing improvement in *y* precision.

Summary

- First measurement of $\cos\delta$ (needed to interpret other D mixing results).
  - Allows y' to be added to world-average y, but with the assumption $x\sin\delta = 0$.
- Standard fit:
  - $\cos\delta = 1.03 \pm 0.19$ (stat) ± 0.08 (syst) ± 0.02 ($x\sin\delta$)
  - $y = -0.033 \pm 0.016$ (stat) ± 0.10 (syst) ± 0.00 ($x\sin\delta$)

CLEO PRELIMINARY

- Extended fit:
  - $\cos\delta = 0.93 \pm 0.32$ (stat) ± 0.04 (syst) $\pm 0.??$ ($x\sin\delta$)
  - $y = +0.0043 \pm 0.0013$ (stat) ± 0.0007 (syst) $\pm 0.00??$ ($x\sin\delta$)
  - Can measure $x\sin\delta$ using $C+$ $D^0\overline{D}^0$ pairs from $e^+e^- \to \gamma D^0\overline{D}^0$ at $E_{cm} = 4170$ MeV.
- Demonstrated new technique for charm mixing studies.
  - Time-independent 1st-order sensitivity to mixing parameters and phases.
  - Different systematics from other experiments.
  - With full CLEO-c dataset (E_{cm} = 3770 & 4170 MeV) expect:

$\sigma(\cos\delta)\sim\pm0.1$–$0.2$ $\sigma(y)\sim\pm0.01$ $\sigma(x\sin\delta)\sim\pm0.03$

BACKUP SLIDES

Previous Results (Oct 2005)

- PANIC'05 prelim. results:
  - 281 pb^{-1}.
  - No systematics.
  - Only one *CP*– mode.
  - With r^2 constrained to world average, $\cos\delta = 1.08 \pm 0.66$.
  - No other external measurements.
- Now:
  - Added 70% more *CP*–
    - $K^0_S\eta$, $K^0_S\omega$
  - Added $K^0_L\pi^0$.

Param.	Value	PDG04 or CLEO-c
$N_{D^0\bar{D}^0}$	$(1.09 \pm 0.04)\times10^6$	$(1.01 \pm 0.02)\times10^6$
y	-0.057 ± 0.066	0.008 ± 0.005
r^2	-0.028 ± 0.069	$(3.74 \pm 0.18)\times10^{-3}$ PDG + Belle + FOCUS
rz	0.130 ± 0.082	
R_M	$(1.74 \pm 1.47)\times10^{-3}$	$< \sim1\times10^{-3}$
$\mathcal{B}(K^-\pi^+)$	$(3.80 \pm 0.29)\%$	$(3.91 \pm 0.12)\%$
$\mathcal{B}(K^-K^+)$	$(0.357 \pm 0.029)\%$	$(0.389 \pm 0.012)\%$
$\mathcal{B}(\pi^-\pi^+)$	$(0.125 \pm 0.011)\%$	$(0.138 \pm 0.005)\%$
$\mathcal{B}(K^0_S\pi^0\pi^0)$	$(0.932 \pm 0.087)\%$	$(0.89 \pm 0.41)\%$
$\mathcal{B}(K^0_S\pi^0)$	$(1.27 \pm 0.09)\%$	$(1.55 \pm 0.12)\%$
$\mathcal{B}(X^-e^+\nu)$	$(6.21 \pm 0.42)\%$	$(6.87 \pm 0.28)\%$

Systematic Uncertainties

- Mode-dependent correlated uncertainties cancel in *y* and cosδ, but only if external measurements are not included.
  - Tracking, π^0, η, K^0_S, PID, EID efficiency, FSR systematics: use DHad.
  - ΔE cut, ω mass cut, K^0_S mass cut, K^0_S flight significance cut, K^0_S PID.
  - Peaking background BFs: values and errors from PDG.
  - Multiple candidates, SL form factor.
  - Event selection variations:
    - dominates y and cosd syst error.
- Uncorrelated uncertainties:
  - Fit function variations.

Source	Uncertainty (%)	Scheme
Track finding	0.3	per track
$K^\pm$ hadronic interactions	0.6	per $K^\pm$
K^0_S finding	1.9	per K^0_S
π^0 finding	4.0	per π^0
η finding	4.0	per η
dE/dx and RICH	0.3	per $\pi^\pm$ PID cut
dE/dx and RICH	0.3	per $K^\pm$ PID cut
EID	1.0	per $e^\pm$

	ΔE	ISR*	FSR*	Lepton Veto*	Other	
$K^\mp\pi^\pm$	0.5	0.5	1.2	0.5		
K^+K^-	0.9	0.5	0.8	0.4	0.5	$K^\pm$ $\cos\theta$ cut
$\pi^+\pi^-$	1.9	0.5	1.7	3.2		
$K^0_S\pi^0\pi^0$	2.6	0.5			1.5	K^0_S daughter PID
					0.7	resonant substructure
$K^0_S\pi^0$	0.9	0.5				
$K^0_S\eta$	5.5	0.5			0.3	η mass cut
					0.7	$\mathcal{B}(\eta \to \gamma\gamma)$ [22]
$K^0_S\omega$	1.2	0.5	0.8		1.4	ω mass cut
					0.8	$\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$ [22]
$Xe\nu$		0.5	0.3		2.0	spectrum extrapolation
					0.7	multiple $e^\pm$ candidates
$K^0_L\pi^0$		0.5			0.7	background subtraction
					0.3	extra track veto
					1.4	signal shape
					1.6	extra π^0 veto
					0.5	η veto
Scheme	per D	per yield	per D	per ST	per D	
$\lambda_{\rm DT}$	$\sqrt{\alpha^2+\beta^2}$	$(\alpha+\beta)/2$	$\alpha+\beta$	0	$\sqrt{\alpha^2+\beta^2}$	