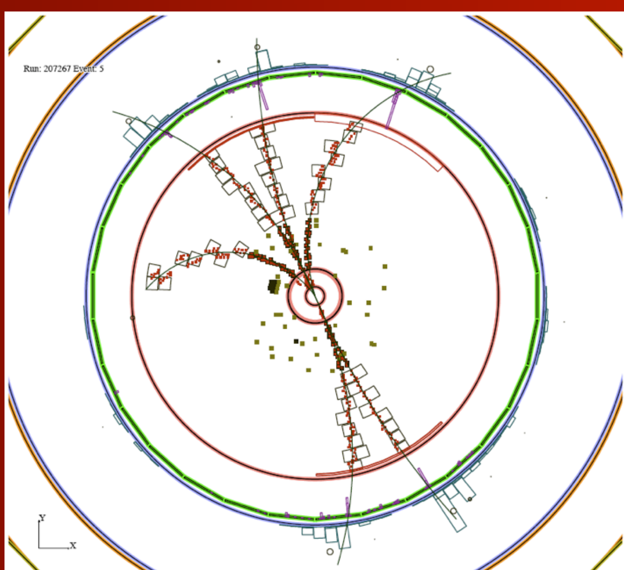
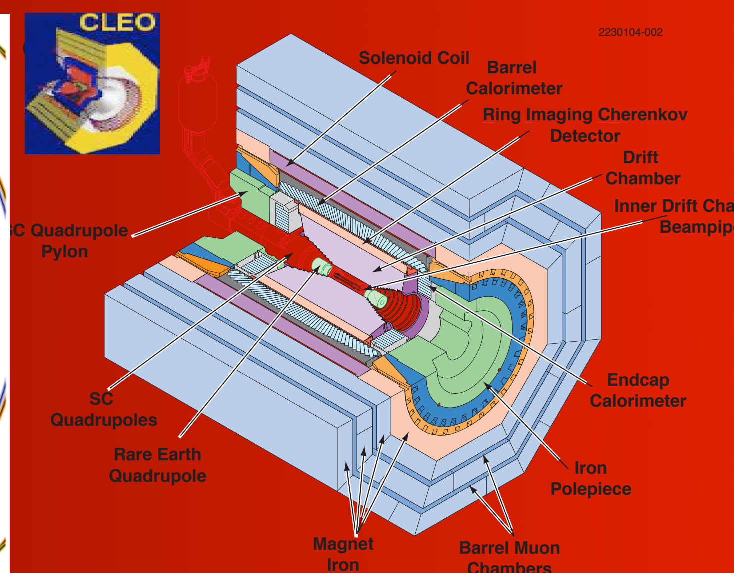
Measuring D-Mixing Parameters at CLEO-c

Paras Naik

University of BRISTOL

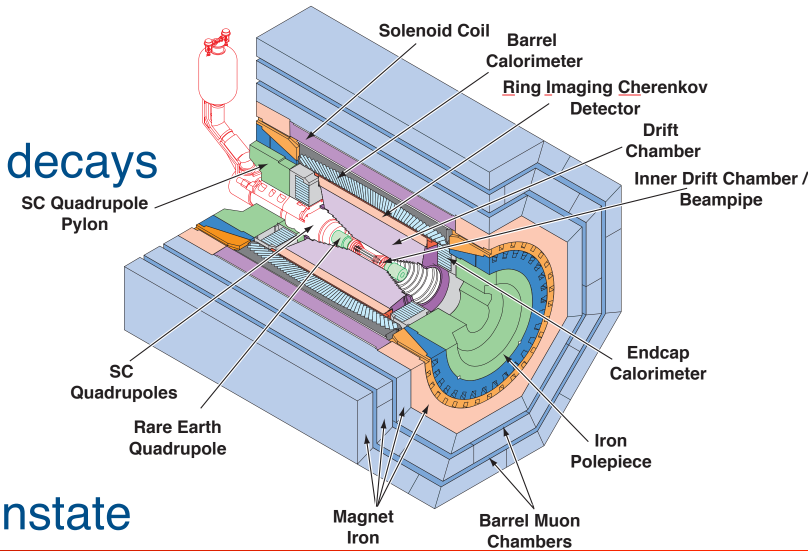




21 May 2009, Charm09 Workshop

CLEO-c

- Hermetic detector based at CESR (the Cornell Electron Storage Ring)
- Operated at energies around $c\bar{c}$ threshold
- We study $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D^0}$ decays
  - C = –1 for these decays at ψ(3770) threshold
  - Total integrated luminosity of this sample is 818 pb^{-1}
- Quantum correlated (QC) states
  - Example: Properly reconstructing one neutral D decay to a CP eigenstate uniquely identifies the other D decay to be of opposite CP
- Single Tag
  - We fully reconstruct one of the neutral D decays
- Double Tag
  - We fully reconstruct the event (both neutral D decays)
- CP-Tagged
  - Reconstruct other neutral D to a CP eigenstate



D-Mixing (in the no CPV limit)

$$i\frac{\partial}{\partial t}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} \text{ where } H_{11} = M_{11} - i\,\Gamma_{11}/2 \text{ etc...} \qquad x := \frac{\Delta M}{\Gamma} \text{ and } y := \frac{\Delta\Gamma}{2\Gamma} \qquad D_{1,2} = \frac{D^0 \pm \overline{D^0}}{\sqrt{2}}$$

- $H_{12}, H_{21} \neq 0$ implies that flavor and mass eigenstates are not equivalent.
- Just some of the methods to study D-Mixing:
  - Direct lifetime measurements: $y = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$
    - 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: $y' = y \cos\delta - x \sin\delta$
    - $\langle K^-\pi^+ | \overline{D^0} \rangle / \langle K^-\pi^+ | D^0 \rangle = -r\, e^{-i\delta}$
- In these studies, time-dependence gives 1st-order x/y sensitivity:
  - These studies need boosted D mesons to resolve decay time.

E791 Phys. Rev. Lett. 83, 32 (1999).
FOCUS Phys. Lett. B 485, 62 (2000).
CLEO Phys. Rev. D 65, 092001 (2002).
Belle Phys. Rev. Lett. 88, 162001 (2002).
Belle Phys. Rev. Lett. 98, 211803 (2007).
BaBar Phys. Rev. D 78, 011105 (2008).

CLEO Phys. Rev. D 72, 012001 (2005).
Belle Phys. Rev. Lett. 99, 131803 (2007).

E791 Phys. Rev. D 57, 13 (1998).
CLEO Phys. Rev. Lett. 84, 5038 (2000).
FOCUS Phys. Lett. B 618, 23 (2005).
Belle Phys. Rev. Lett. 96, 151801 (2006).
BaBar Phys. Rev. Lett. 98, 211802 (2007).
CDF Phys. Rev. Lett. 100, 121802 (2008).

Quantum Correlations at CLEO-c

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

- At CLEO-c, interference between D^0 and $\overline{D^0}$, gives us mixing parameters
  - Appears in time-integrated yields: $M_{ij}^2 = \left| \langle i | D^0 \rangle \langle j | \overline{D^0} \rangle - \langle j | D^0 \rangle \langle i | \overline{D^0} \rangle \right|^2$
- We measure the effect of quantum correlations (QC) on the normalized yields of single-tag (one D reconstructed) and double-tag (D and $\overline{D}$ reconstructed) modes
- We then input these yields into a global fit, where many decay modes are fit simultaneously: Compare effective BR (with QC) to incoherent BR to give y, cos δ.
  - Externally measured *BR*s.
  - Single tags at ψ(3770) (immune to QC).
- Using this method, we are capable of...
  - First measurement of cos δ
    - Example mode: Reconstruct K^+K^- with $K^-\pi^+$
      - ⇒ $K^-\pi^+$ must come from D_1 (*CP*–)
      - $\text{Rate}(K^-\pi^+, CP+)_{QC} = \text{BR}(K^-\pi^+)\,(1 + 2r\,\mathbf{\cos\delta} + r^2)$
  - First-order sensitivity to *y*
    - Example mode: Reconstruct K^+K^- (*CP*+) decay with semileptonic (SL)
      - ⇒ SL decay must come from a D_1 (*CP*–)
      - $\text{BR}(\text{Inclusive } e^-) = \text{Rate}(\text{Inclusive } e^-, CP+)_{QC}\,(1 - \mathbf{y})$
- *CP* violation is neglected in this analysis.

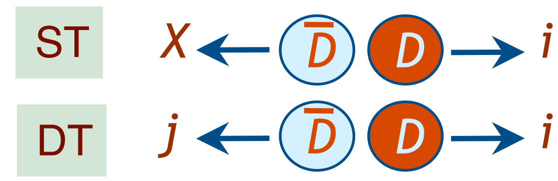
Coherent vs. Incoherent Decay

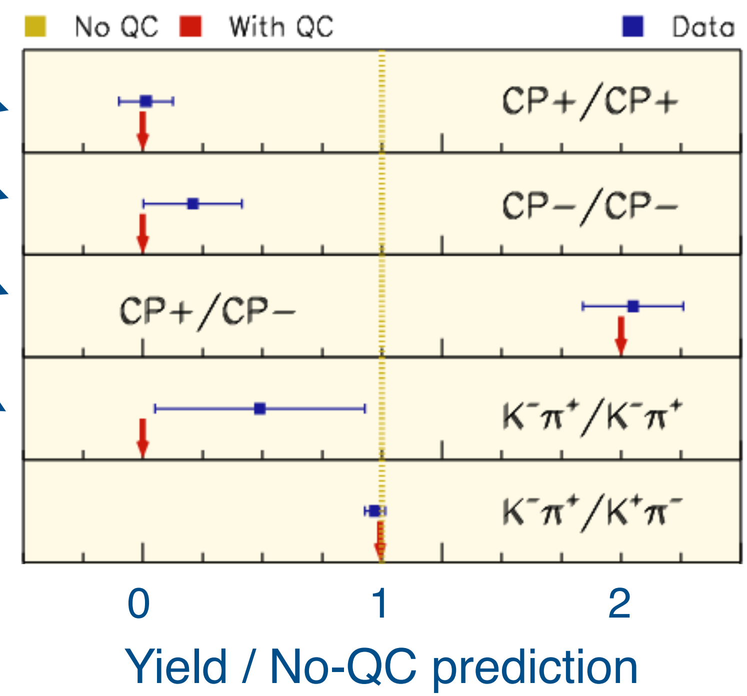
D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

$C = -1$

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

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	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP±*, $K^-\pi^+$, *SL*	X





Quantum correlations are seen in data!

Strategy

$$R_{WS} \equiv \frac{\Gamma(\overline{D^0} \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} = r^2 + ry' + R_M$$

$$R_M \equiv \frac{x^2 + y^2}{2}$$

- 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 *BR* and $y^{(\prime)}$ measurements

- Single tag yields (8):

ST		quantum-correlated rate / incoherent rate
$K^-\pi^+$		1
$K^+\pi^-$		1
K^-K^+	*CP*+	1
$\pi^-\pi^+$	*CP*+	1
$K^0_S\pi^0\pi^0$	*CP*+	1
$K^0_S\pi^0$	*CP*–	1
$K^0_S\eta$	*CP*–	1
$K^0_S\omega$	*CP*–	1

- Fully-reconstructed DT yields (24):

DT		(number of DT of this type)	quantum-correlated rate / incoherent rate
$K^-\pi^+$	$K^+\pi^-$	(1)	$1+2R_{WS}-4r\cos\delta(r\cos\delta+y)$
$K^\pm\pi^\mp$	$K^\pm\pi^\mp$	(2)	$(x^2+y^2)/2R_{WS}$
$K^\pm\pi^\mp$	*CP*+	(6)	$1 + (2r\cos\delta+y) / (1+R_{WS})$
$K^\pm\pi^\mp$	*CP*–	(6)	$1 - (2r\cos\delta+y) / (1+R_{WS})$
CP+	*CP*–	(9)	2

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

$e^\mp$	$K^\mp\pi^\pm$	(2)	$1 - r(y\cos\delta + x\sin\delta)$
e^-/e^+	*CP*+	(6)	$1 + y$
e^-/e^+	*CP*–	(6)	$1 - y$

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

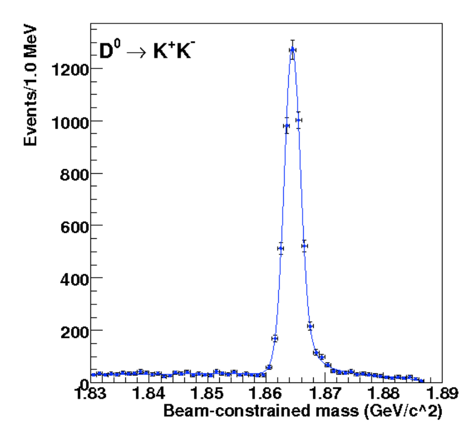
$K^0_L\pi^0$	$K^\pm\pi^\mp$	(2)	$1 + (2r\cos\delta+y) / (1+R_{WS})$
$K^0_L\pi^0$	*CP*–	(3)	2

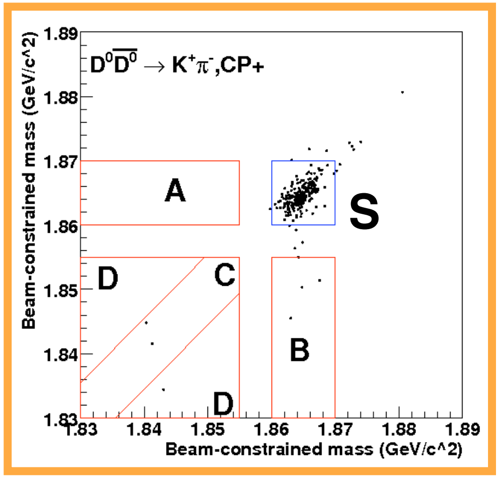
Yield Measurements

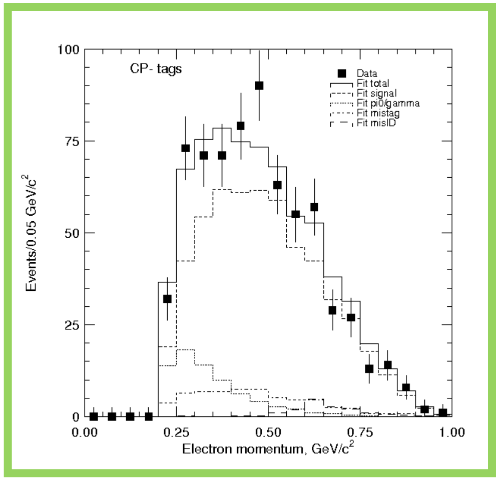
- Fully-reconstructed single tags:
  - Fit beam-constrained mass distribution.

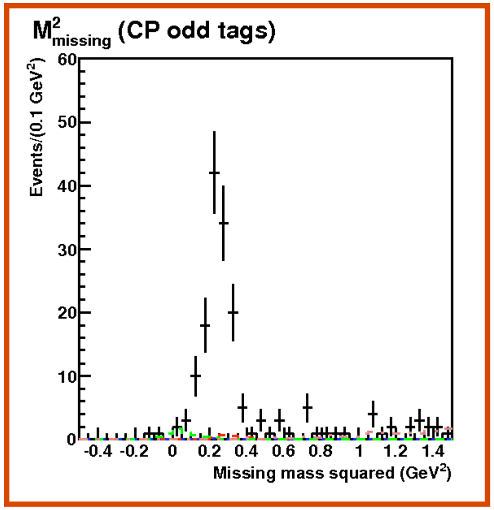
$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

- 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
- $K_L^0 \pi^0$ 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 improve *y* and cos δ precision.
- All correlations among measurements included in fit.
- Standard fit includes:
  - Info on *r* needed to obtain cosδ:
    - $R_{WS} = r^2 + ry' + R_M$
    - $R_M = (x^2 + y^2)/2$
    - Assume $x\sin\delta = 0 \Rightarrow y' \sim= y\cos\delta$
  - *Kπ and CP*-eigenstate BRs:

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
$K^0_L\pi^0$	$\mathbf{0.0100 \pm 0.0008}$
$K^0_S\pi^0$	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*)
  - *Kπ CP*-conserving fits (y', r^2, R_M)
    - Includes covariance matrices from Belle & BABAR (thanks!), CLEO

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

Results

PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

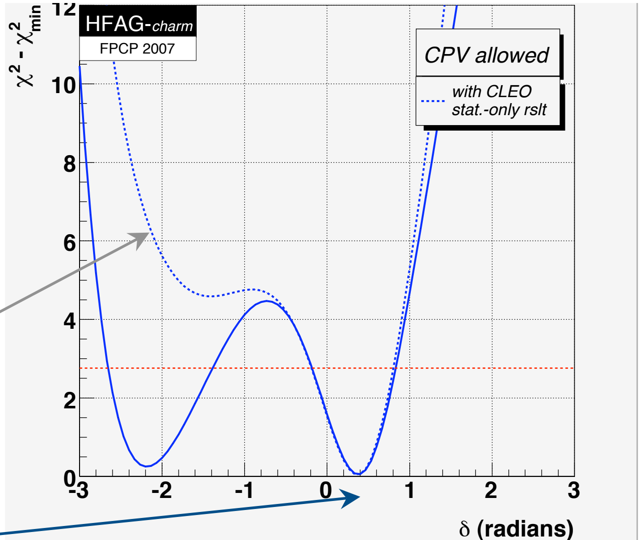
Parameter	Standard Fit	Extended Fit
y (10^{-3})	$-45 \pm 59 \pm 15$	$6.5 \pm 0.2 \pm 2.1$
r^2 (10^{-3})	$8.0 \pm 6.8 \pm 1.9$	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.03 \pm 0.19 \pm 0.06$	$1.10 \pm 0.35 \pm 0.07$
x^2 (10^{-3})	$-1.5 \pm 3.6 \pm 4.2$	$0.06 \pm 0.01 \pm 0.05$
$x\sin\delta$ (10^{-3})	0 (fixed)	$4.4 \pm 2.4 \pm 2.9$
$\chi^2_{\rm fit}/{\rm ndof}$	30.1/46	55.3/57

First determination ($281\ \mathrm{pb}^{-1}$)

- Extended fit with a likelihood scan of the physically allowed region leads to a measurement of:

$$\delta = \left(22^{+11+9}_{-12-11}\right)^\circ$$

- Fit result important component in average of charm mixing
  - Selects one of two possible solutions for δ



E. Barberio et al., "Averages of b-hadron and c-hadron Properties at the End of 2007," arXiv:0808.1297 and online update at http://www.slac.stanford.edu/xorg/hfag

Future Improvements

- We need better precision on y and r^2 to control non-linearities in the fit.
- Need more semileptonic vs. CP eigenstates for y.
  - Add **Keν vs. $K_L\pi^0$** (using two-missing-particle technique) ⇒ 70% more **Keν vs. CP-**
  - Add **Kμν** (new final state for CLEO-c) basically doubles **SL** statistics
- Add wrong-sign semileptonic vs. Kπ for r^2.
  - Add **wrong-sign Keν vs. Kπ**

Switching from inclusive to **exclusive** semileptonic modes

- Also
  - Add additional modes which contain a $\mathbf{K_L}$ ⇒ 30% more **CP+** and 60% more **CP-**
  - Add CP-tagged, flavor-tagged, and single-tagged $\mathbf{K_S\pi^+\pi^-}$ and $\mathbf{K_L\pi^+\pi^-}$ modes

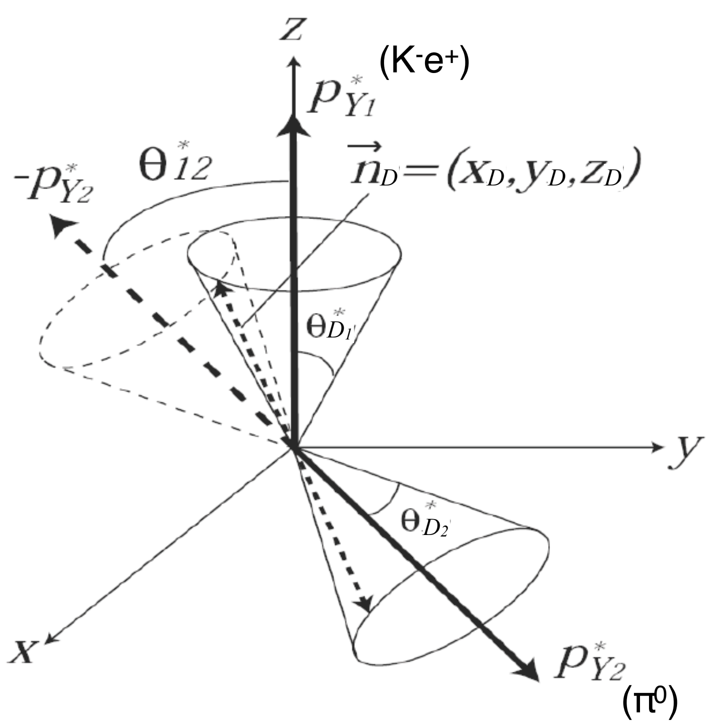
    roughly doubles the number of CP tags
- **Use our full 3.0 million $D^0\overline{D}^0$ pair sample (818 pb^{-1})**
- Expected sensitivities

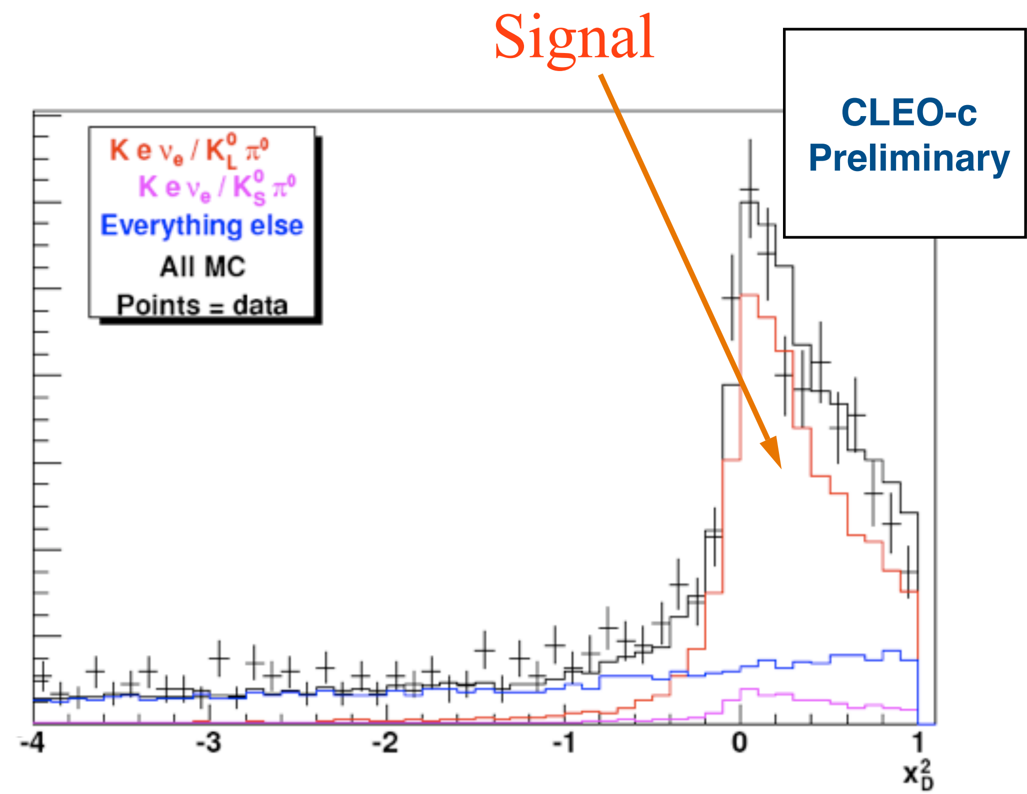
Parameter	± stat. ± syst. for N = 3 × 10^6 $D^0\overline{D}^0$
y	$\pm 0.012 \pm 0.005$
x^2 (10^{-3})	$\pm 0.6 \pm 0.6$
$\cos\delta_{K\pi}$	$\pm 0.20 \pm 0.04$
$x\sin\delta_{K\pi}$	$\pm 0.027 \pm 0.005$
r^2 (10^{-3})	$\pm 1.0 \pm 0.0$

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

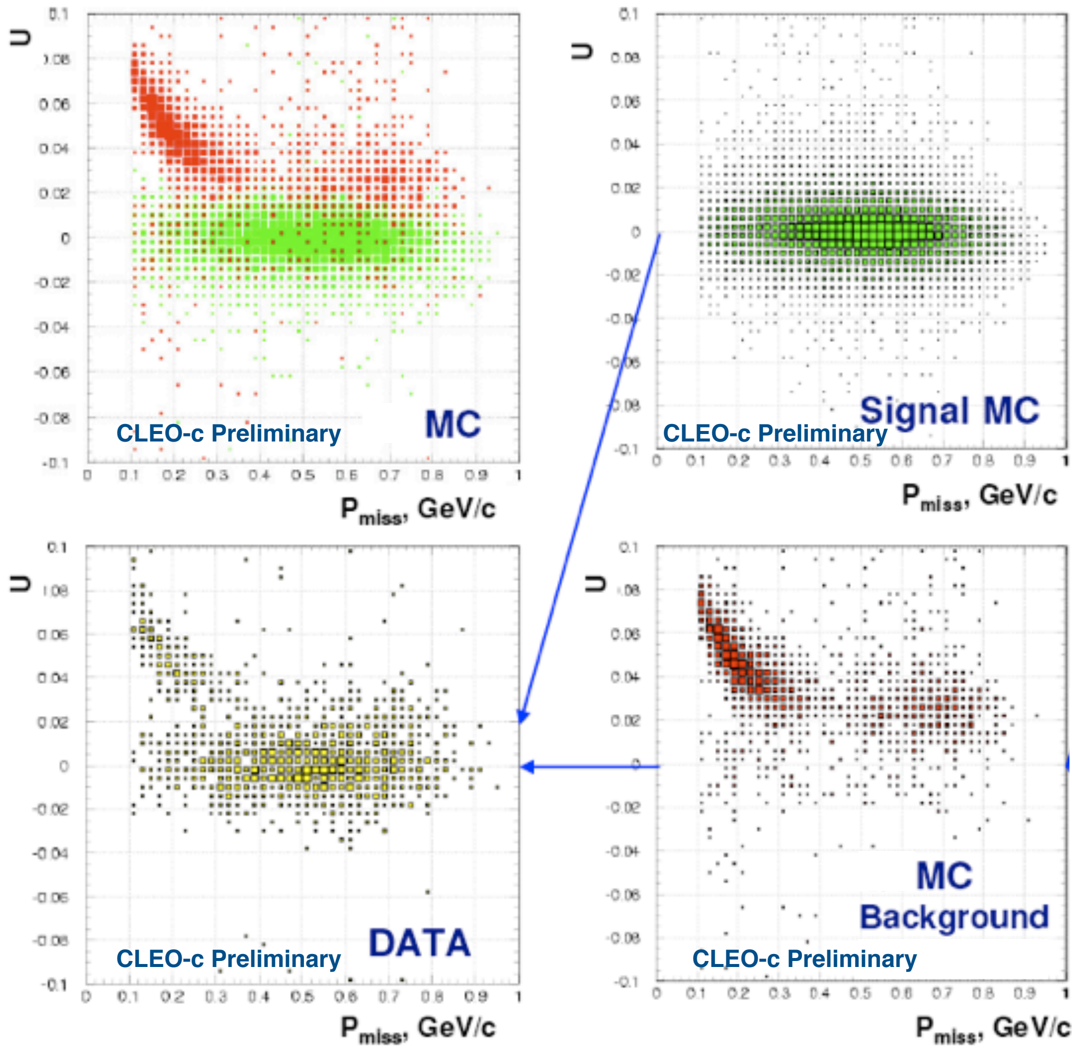
Example: Keν vs. $K_L\pi^0$

- We use the Paar-Brower technique (used by Belle and BaBar for B SL decays) to reconstruct a final state with two missing particles.
  - W.S. Brower and H.P. Paar, Nucl. Instrum. Meth. A 421, 411-416 (1999)
  - BaBar: Phys. Rev. Lett. 97, 211801 (2006)
  - Belle: Phys. Lett. B 648, 139 (2007)





Example: $K\mu\nu$



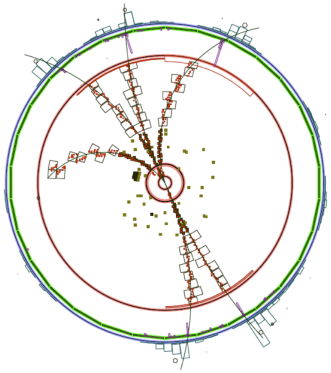
- CLEO-c was unable to use its muon chambers due low momenta of muons.
- However, we have learned to make selections to separate μ from π and e.
- We use P_{miss} and $U = E_{miss.} - |P_{miss.}|$ to isolate $K\mu\nu$
- $K\mu\nu$ signal is separable from main backgrounds
- May see more muon analyses at CLEO-c

Summary

- First measurement of cos δ (needed to interpret other *D*-mixing results).
  - Allows *y*' to be added to world-average *y*
- Demonstrated new technique for charm mixing studies.
  - Time-independent first-order sensitivity to mixing parameters and phases.
  - With full CLEO-c dataset (E_{cm} = 3770 MeV) expect:

$\sigma(\cos\delta) \sim \pm(0.1-0.2)$ $\sigma(y) \sim \pm0.01$ $\sigma(x\sin\delta) \sim \pm0.03$

- BES III expects ~25x more data
  - Factor of 5 improvement in sensitivity possible



A nice environment to study *D*-mixing parameters!

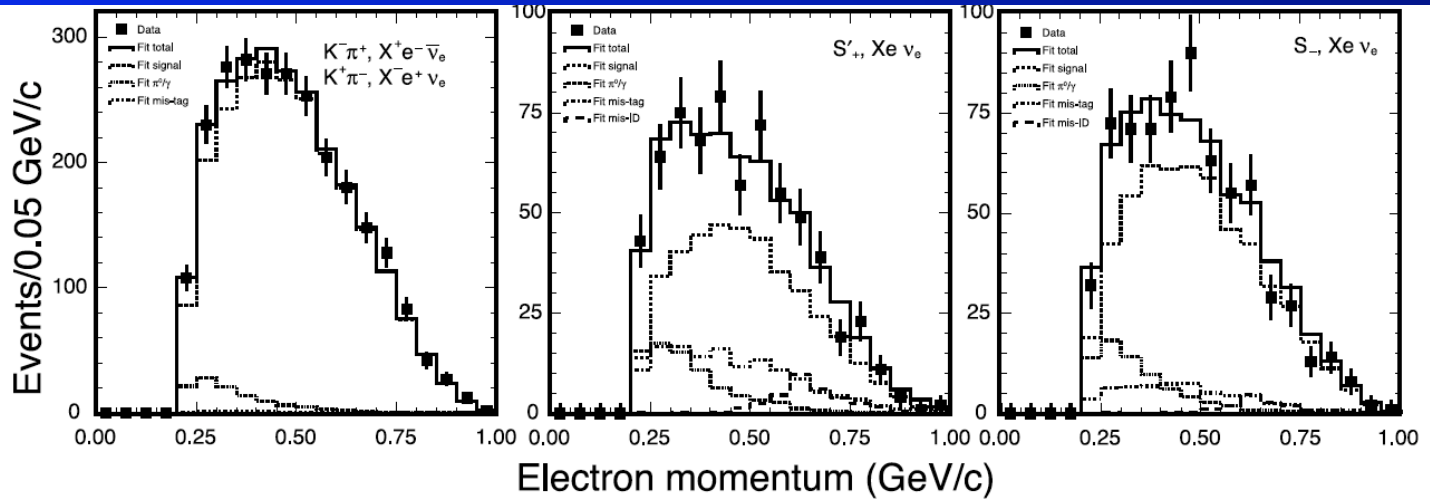
Backup slides

Switching from Inclusive e to Exclusive Keν

281pb^{-1}

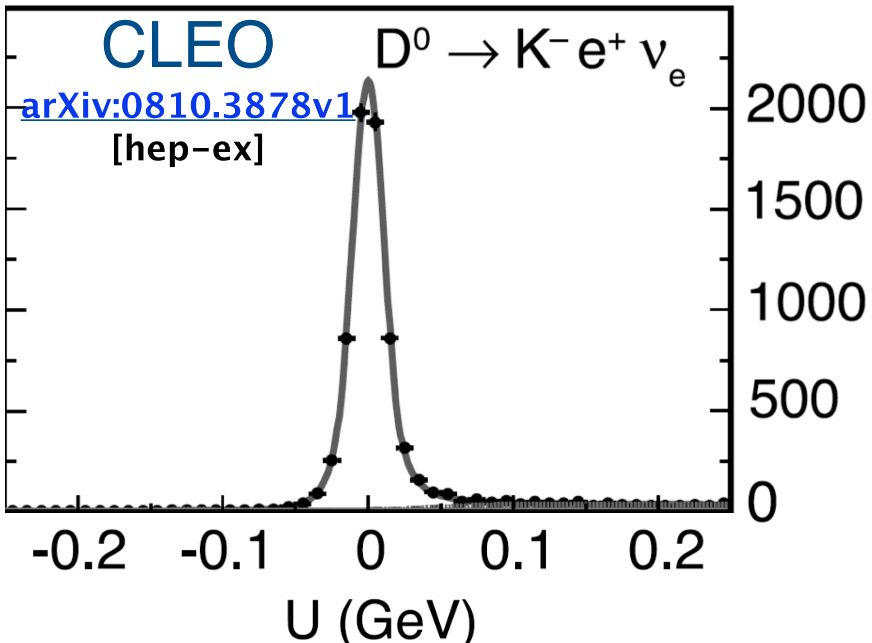
QC analysis with inclusive e

The difference between two highest histograms shown in each plot is the background for that mode



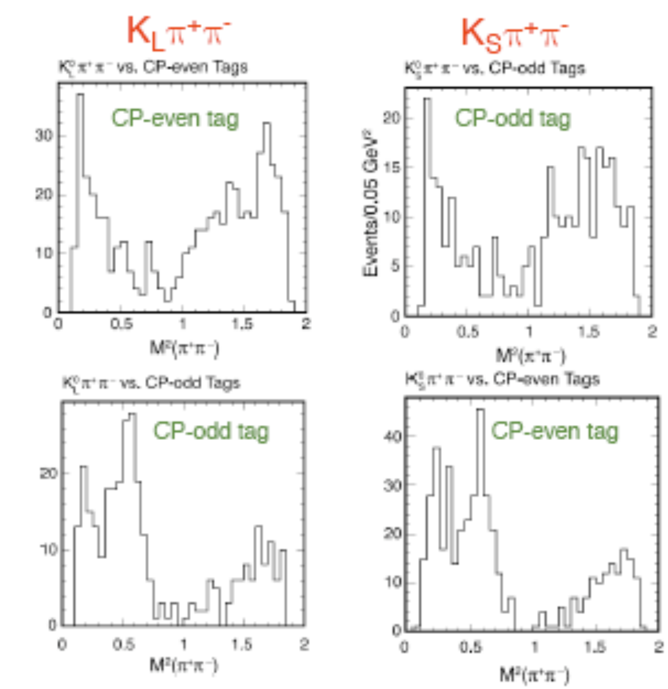
281pb^{-1}

SL analysis with exclusive Keν tagged with flavor and CP± modes



Inclusion of $K^0_S\pi^+\pi^-$ and $K^0_L\pi^+\pi^-$

- CLEO-c has **measured the average cosine and sine of $D \to K^0_S\pi\pi$ strong phase differences** (arXiv:0903.1681v1) to allow a model-independent determination of γ with $B^\pm \to D_{K_S\pi\pi} K^\pm$
- See Guy Wilkinson's talk yesterday
- In this analysis we already have the collected CP-tags and flavor-tags we need for our quantum-correlated analysis!



$$-A\left(D^0 \to K^0_L\pi^+\pi^-\right) =$$

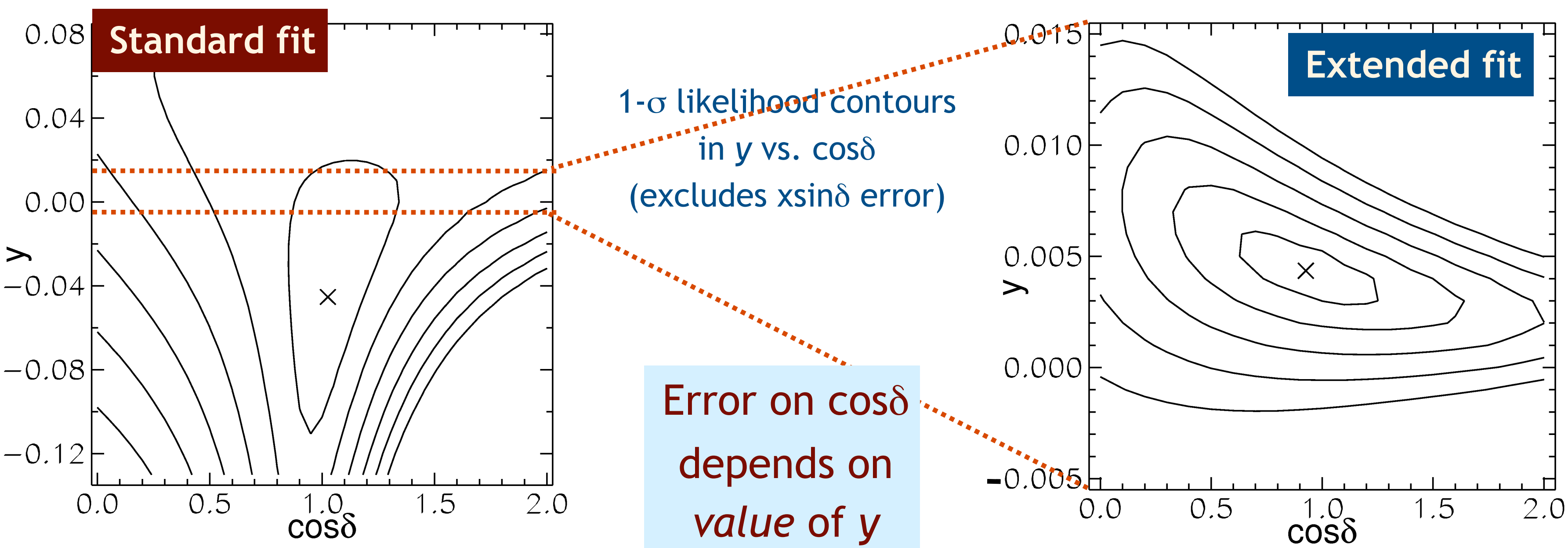
$$\underbrace{A\left(D^0 \to K^0_S\pi^+\pi^-\right)}_{\text{CF+DCS}} - \sqrt{2}\underbrace{A\left(D^0 \to K^0_{\text{flavour}}\pi^+\pi^-\right)}_{\text{DCS}}$$

Correction order $\tan^2\theta_c$ – accounting for this introduces small model dependence

- Adding $K^0_S\pi^+\pi^-$ single tags will be the next step.

Comment

- Information in inputs: observe change in parameter errors when removed from fit.
- *y*: [Info: 90% $e^{\pm}/CP$ DTs, 10% $e^{\pm}/K\pi$ DTs]
- $\cos\delta$: [Info: 50% $K\pi/CP+$ DTs, 50% $K\pi/CP-$ DTs]
  - Strong nonlinearity introduced by $R_{WS} \sim= r^2 + 2yr\cos\delta$:



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 cosδ 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	
λ_{DT}	$\sqrt{\alpha^2+\beta^2}$	$(\alpha+\beta)/2$	$\alpha+\beta$	0	$\sqrt{\alpha^2+\beta^2}$	

Other Systematic Effects

- C+ contamination of initial state (not expected, cf. A. Petrov):
  - e^+e^- --> $\gamma D^0\overline{D}^0$ 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.
- Variation of $\cos\delta$ and y with $x\sin\delta$—include additional systematic error: