Quantum Correlated Neutral D Meson Decays

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CLEO Collaboration

DPF
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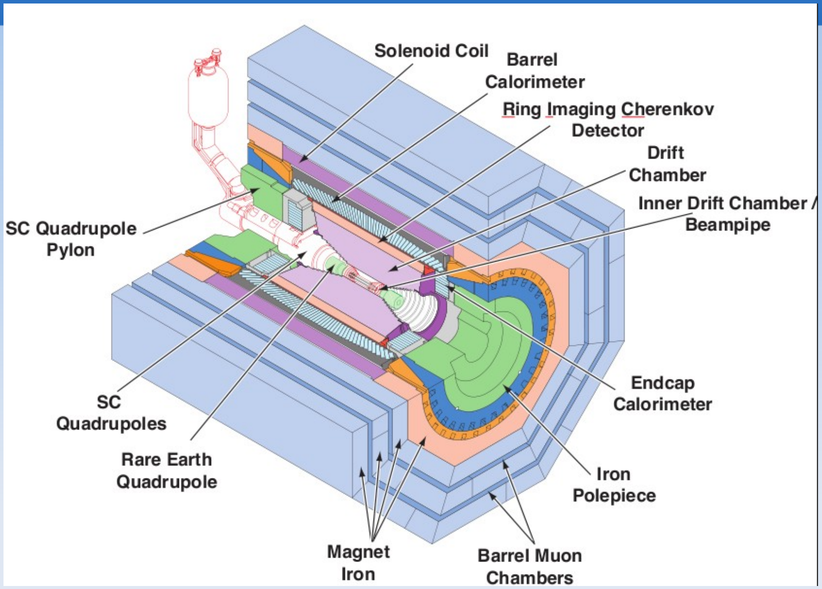
CLEO-c and $D^0\bar{D}^0$ pairs



- Detector for CESR, based at Cornell Univ.
- For these results, we use
  $$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$$
- Dataset used here: 281 pb^{-1}, one-third the total CLEO-c dataset for $e^+e^- \rightarrow \psi(3770)$
- These neutral D mesons do not decay in isolation. They are quantum correlated.
  - If we know the CP of one side, we know the CP of the other side.
- Single tag (ST): one of the pair is fully reconstructed
- Double tag (DT): both are reconstructed, not always fully

D Mixing (no CPV)

$$i\frac{\partial}{\partial t}\begin{pmatrix}D\\ \bar{D}\end{pmatrix}=\begin{pmatrix}M-\frac{i}{2}\Gamma & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{21}-\frac{i}{2}\Gamma_{21} & M-\frac{i}{2}\Gamma\end{pmatrix}\begin{pmatrix}D\\ \bar{D}\end{pmatrix}$$

with nonzero off-diagonal terms has eigenstates

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

Conventionally, two variables defined:

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

- So how to measure *x* and *y*? (1st order)
  - Compare lifetime measurements of decays to K^+K^- and $\pi^+\pi^-$ with $K^-\pi^+$: access to *y* (E791, FOCUS, CLEO, Belle, BaBar)
  - Time dependent Dalitz analysis of decays to $K_S\pi^+\pi^-$: access to *x* and *y* (CLEO, Belle)
  - Time dep. "wrong sign" $D^0 \rightarrow K^+\pi^-$: access to $y'=y\cos\delta-x\sin\delta$ (E791, CLEO, FOCUS, Belle, BaBar, CDF)

where $$\frac{\langle K^+\pi^-|D^0\rangle}{\langle K^-\pi^+|D^0\rangle}=-re^{-i\delta}$$

Quantum correlations (QC) at CLEO-c

- Instead of relying on time dependent measurements, at CLEO-c the $D^0 - \bar{D}^0$ pairs are correlated, so time integrated yields for DTs can be compared to yields for STs (not sensitive to QC).
- E.g.: a DT with $X^+e^-\nu$ and K^+K^-. ($X^+e^-\nu$ means inclusive semileptonics)
  - K^+K^- is CP+, so $X^+e^-\nu$ must come from the D_1 (CP-)
  - Effective DT BF: $B_{Xe^-\nu} B_{KK} (1+y)$
  - If no QC, it's: $B_{Xe^-\nu} B_{KK}$
  - So here is 1st order sensitivity to *y*.

D. Asner and W. Sun, PRD 73, 034024 (2006) PRD 77, 019901(E)(2008)

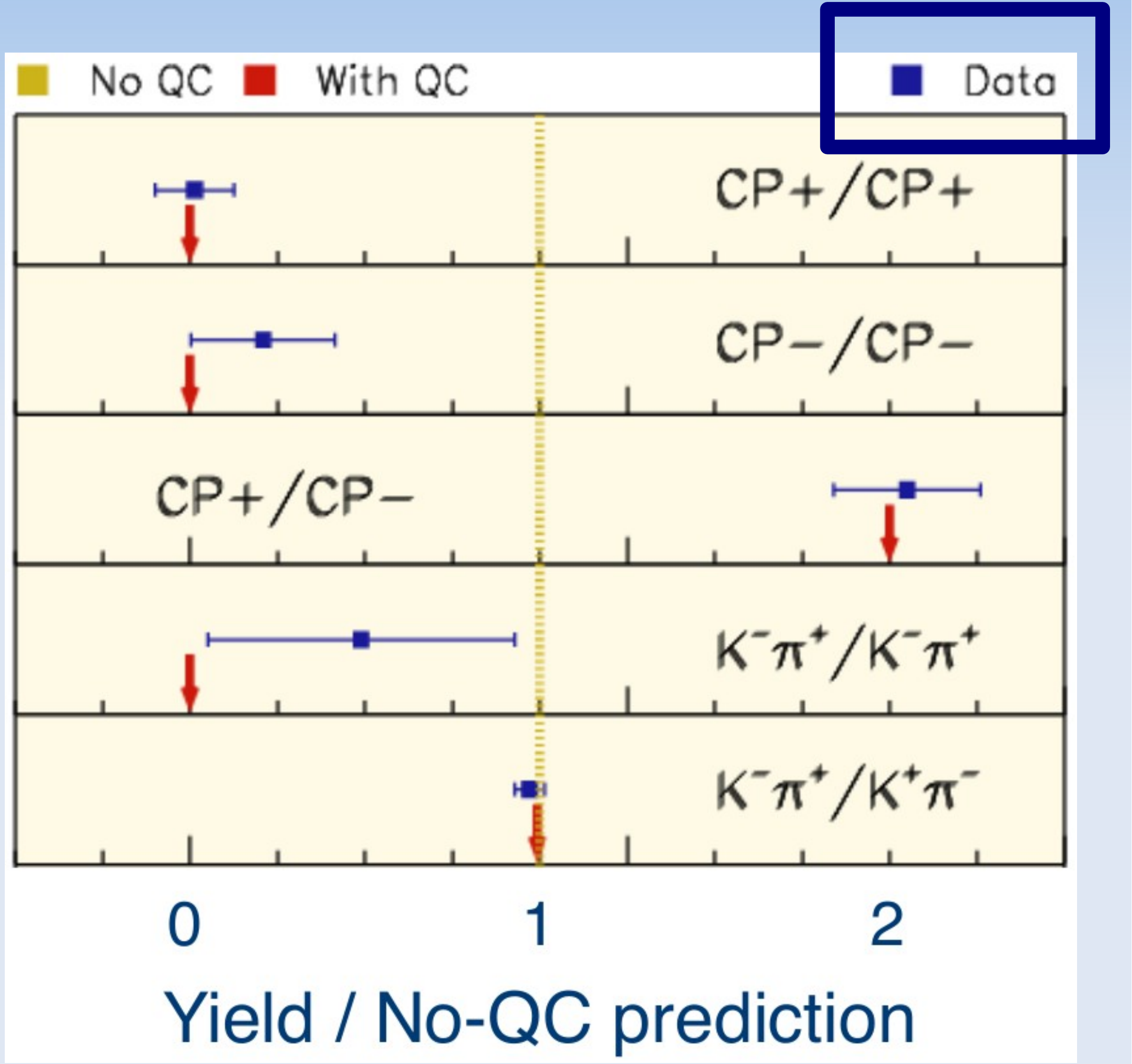
D. Atwood and A. A. Petrov, PRD 71, 054032 (2005)

M. Gronau, Y. Grossman, and J. L. Rosner, Phys. Lett. B 508, 37 (2001)

In CLEO-c hadronic DTs

- DTs where both sides go to CP eigenstates with same CP: forbidden
- DTs where each side is a CP eigenstate with opposite CP: maximally enhanced

Others can have more complicated effects, as shown on next slide.



Measure yields, $\longrightarrow \chi^2$ fit

- In 281 pb^{-1}, we have about 1 million $D^0\overline{D}^0$ pairs. We measure yields:

ST yields (8)

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

e⁻ and $K_L\pi^0$ not measured as STs – missing particle

DT yields (43) — QC rate/non-QC rate

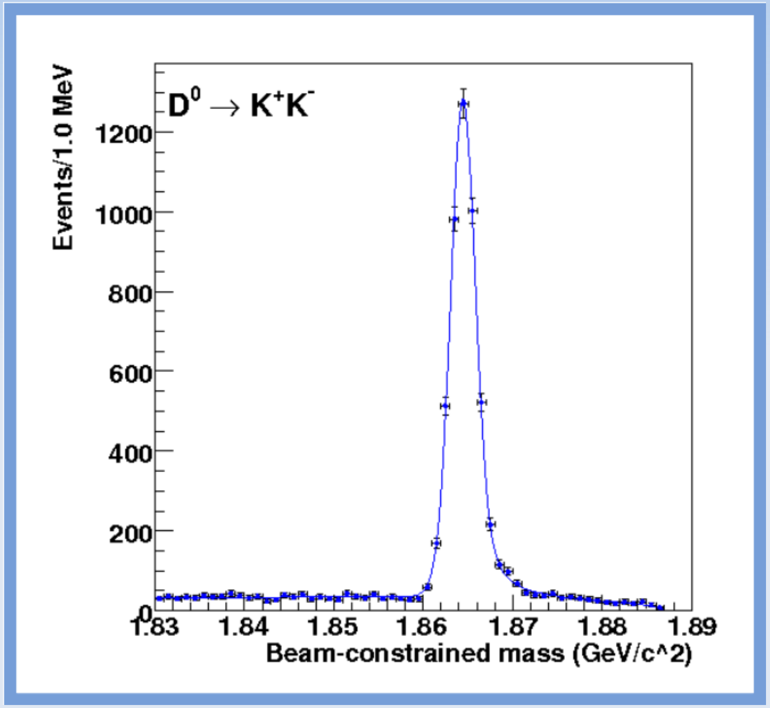
				QC rate/non-QC rate
1	$K^-\pi^+$	$K^+\pi^-$		$1+2R_{WS}-4r\cos\delta(r\cos\delta+y)$
2	$K^-\pi^+$	$K^-\pi^+$		$(x^2+y^2)/2R_{WS}$
6	$K^-\pi^+$	CP+		$1+(2r\cos\delta+y)/(1+R_{WS})$
6	$K^-\pi^+$	CP-		$1-(2r\cos\delta+y)/(1+R_{WS})$
9	CP+	CP-		2
2	e^-	$K^-\pi^+$		$1-r(y\cos\delta+x\sin\delta)$
6	e^-	CP+		$1-y$
6	e^-	CP-		$1+y$
2	$K_L\pi^0$	$K^-\pi^+$		$1+(2r\cos\delta+y)/(1+R_{WS})$
3	$K_L\pi^0$	CP-		2

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

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

Yields

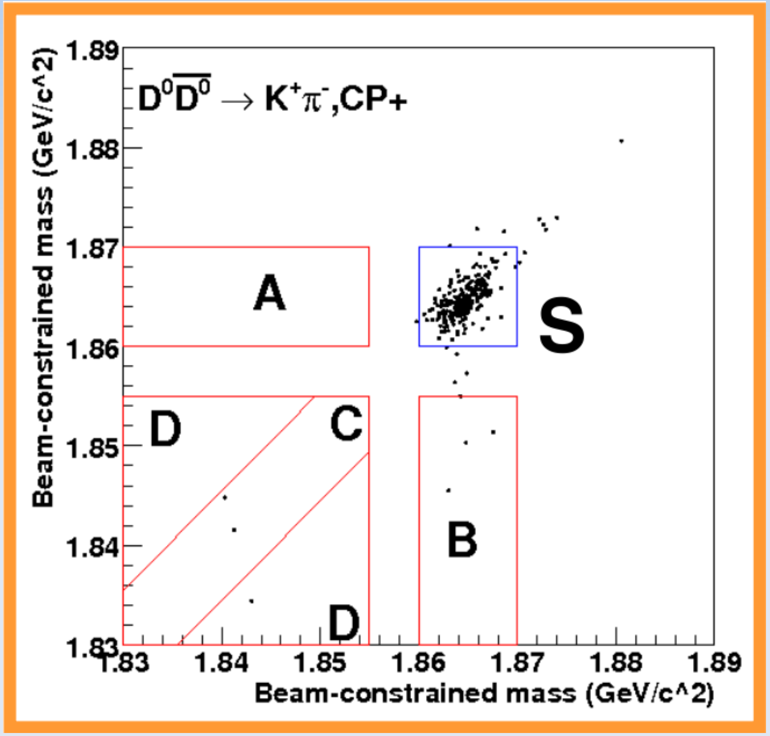
Single Tags



Find yield by fitting beam constrained mass:

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

Hadronic Double Tags

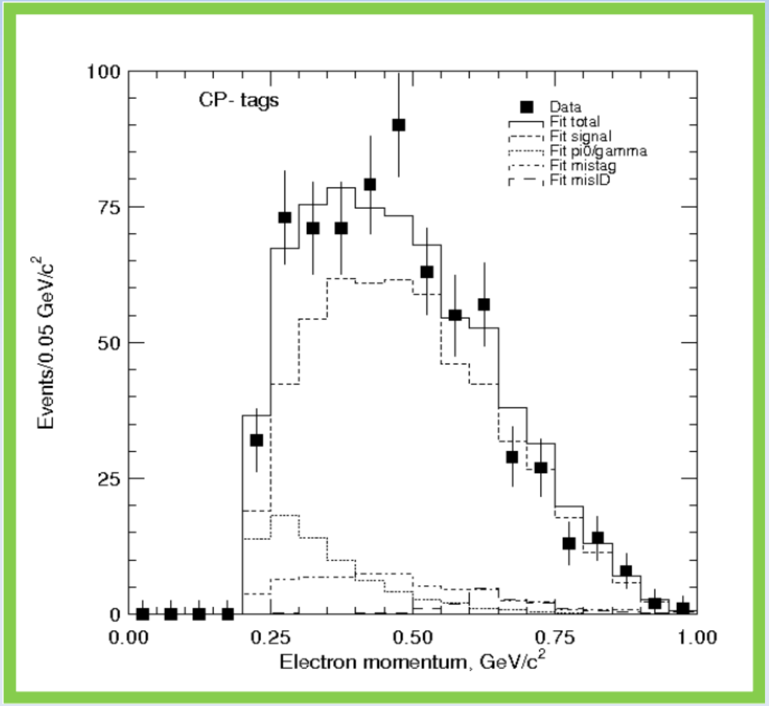


Both tags are fully reconstructed.

Plot in 2D M_{BC} plane and count.

Yields

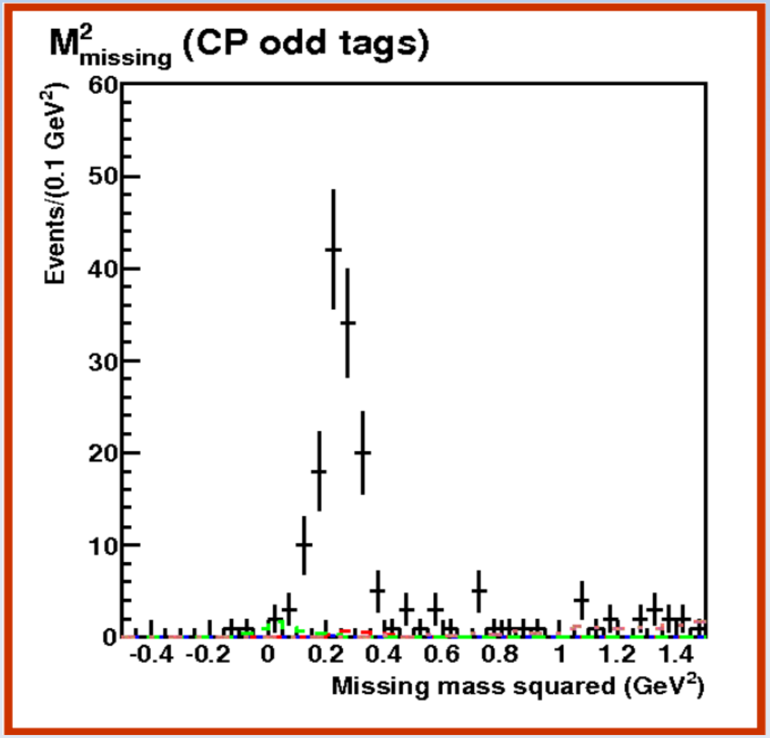
Inclusive semileptonic DTs



Find one fully reconstructed ST, look for one electron in same event.

Fit e^-/e^+ momentum spectrum.

Double Tags with $K_L^0\pi^0$



Find one fully reconstructed ST, look for one π^0 in same event.

Missing mass squared peaks at the K^0 mass.

External measurements

E791, FOCUS, CLEO, Belle, CDF, BaBar

- Including external measurements in the fit improve precision on y and $\cos\delta$. Where these are correlated, it's included in the fit.

"Standard" Fit

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

Information on r improves $\cos\delta$

ST branching ratios

Also, assumes $x \sin\delta = 0$

"Extended" Fit

All standard fit ext. meas., plus

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

Direct measurements of mixing parameters via CP+ lifetimes (y), $K_S^0\pi^+\pi^-$ Dalitz analysis (x, y), and $K\pi$ fits (y', r^2, R_M)

Includes covariance matrices from Belle, BaBar, CLEO

Thanks to Belle and BaBar

Results

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

- In addition to yields and external measurements, other fit inputs are
  - Signal and background efficiencies
  - Crossfeed estimates
  - Systematic errors (< stat.)

We obtain a first determination of cos δ:

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

Results

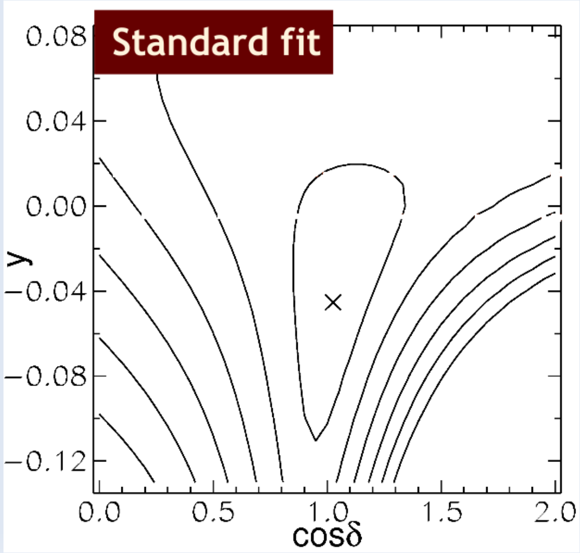
PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

- Using the extended fit, a likelihood scan of the physically allowed region gives:

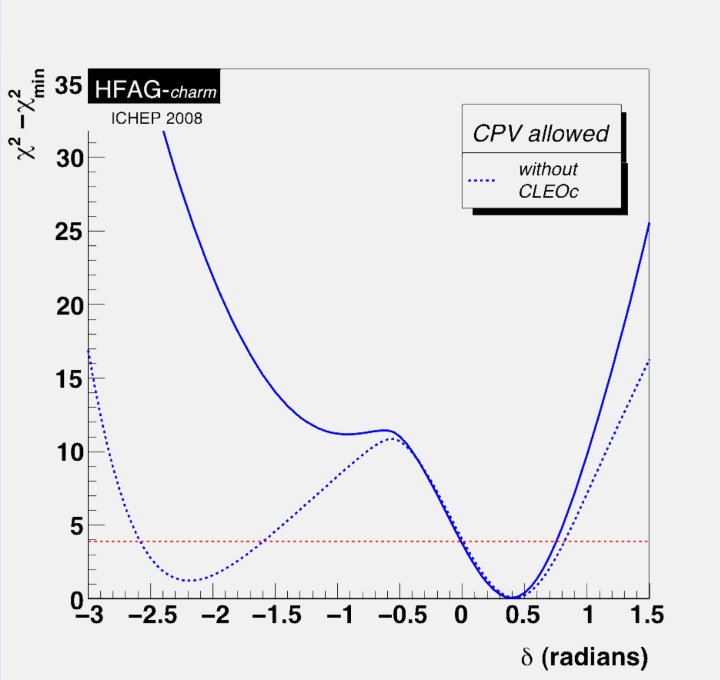
$$\delta = \left(22 \,{}^{+11+9}_{-12-11} \right)^{o}$$

1-σ likelihood contours for standard fit

Note that error on cos δ depends on value for y



HFAG
E. Barberio et al. (arXiv:0808.1297)
Update at http://www.slac.stanford.edu/xorg/hfag/



This CLEO-c result selects one of two solutions for δ

Planned improvements

- For better precision on *y*:
  - Switching from inclusive to exclusive semileptonic modes allows:
    - $Ke\nu$ vs. $K_L\pi^0$
    - $K\mu\nu$ in addition to $Ke\nu$
- For better precision on r^2:
  - Exclusive SL also allows wrong sign $Ke\nu/K\mu\nu$ vs. $K\pi$
- Increase CP statistics by:
  - Adding K_L modes
  - Adding CP, flavor, and single tagged $K_{S/L}\pi^+\pi^-$ modes
- Use entire 818 pb^{-1} $D^0\bar{D}^0$ sample (about 3 million pairs)

Expected sensitivities

Parameter	$\pm$ stat. $\pm$ syst. for $N = 3 \times 10^6$ $D^0\bar{D}^0$
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,
PRD 73, 034024 (2006)
PRD 77, 019901(E)(2008)

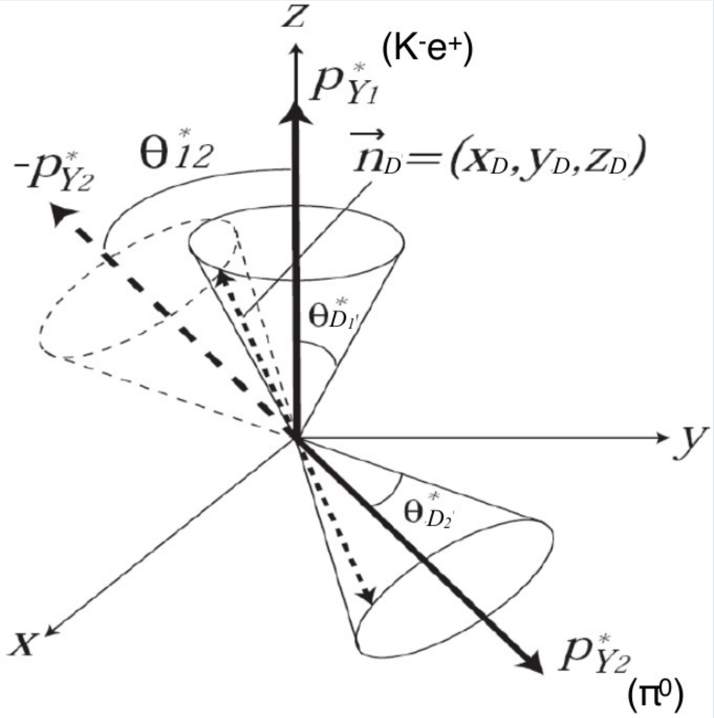
$K_L\pi^0$ vs $Ke\nu$

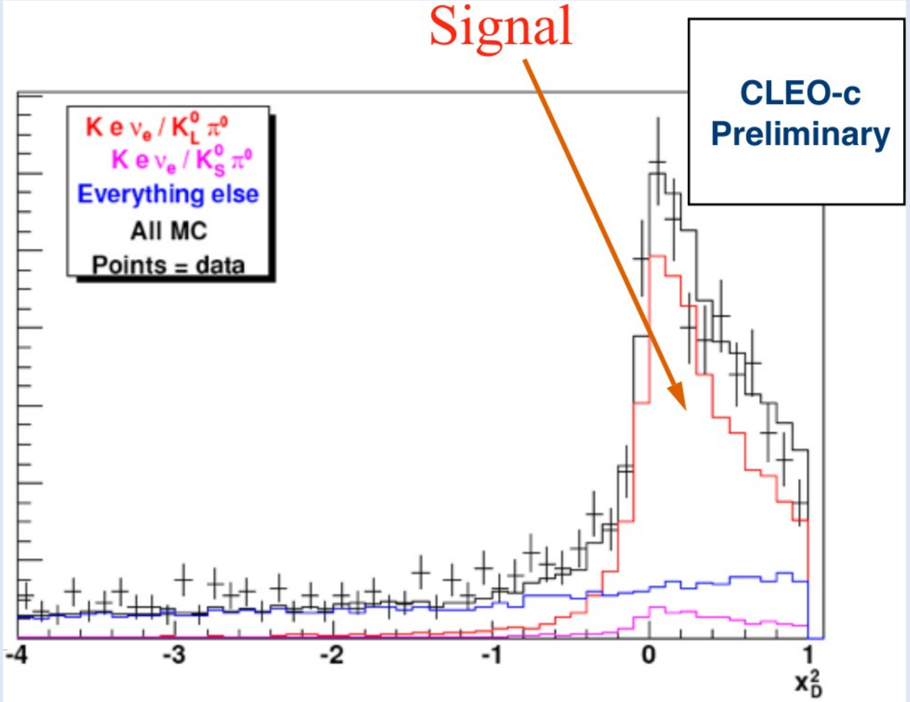
- We reconstruct using the Paar-Brower technique
  - Two missing particles
  - Used by BaBar and Belle in B semileptonic decays

W.S. Brower and H.P. Paar, Nucl. Instrum. Meth. A 421, 411-416 (1999)

BaBar: Phys. Rev. Lett. 97, 211801 (2006)

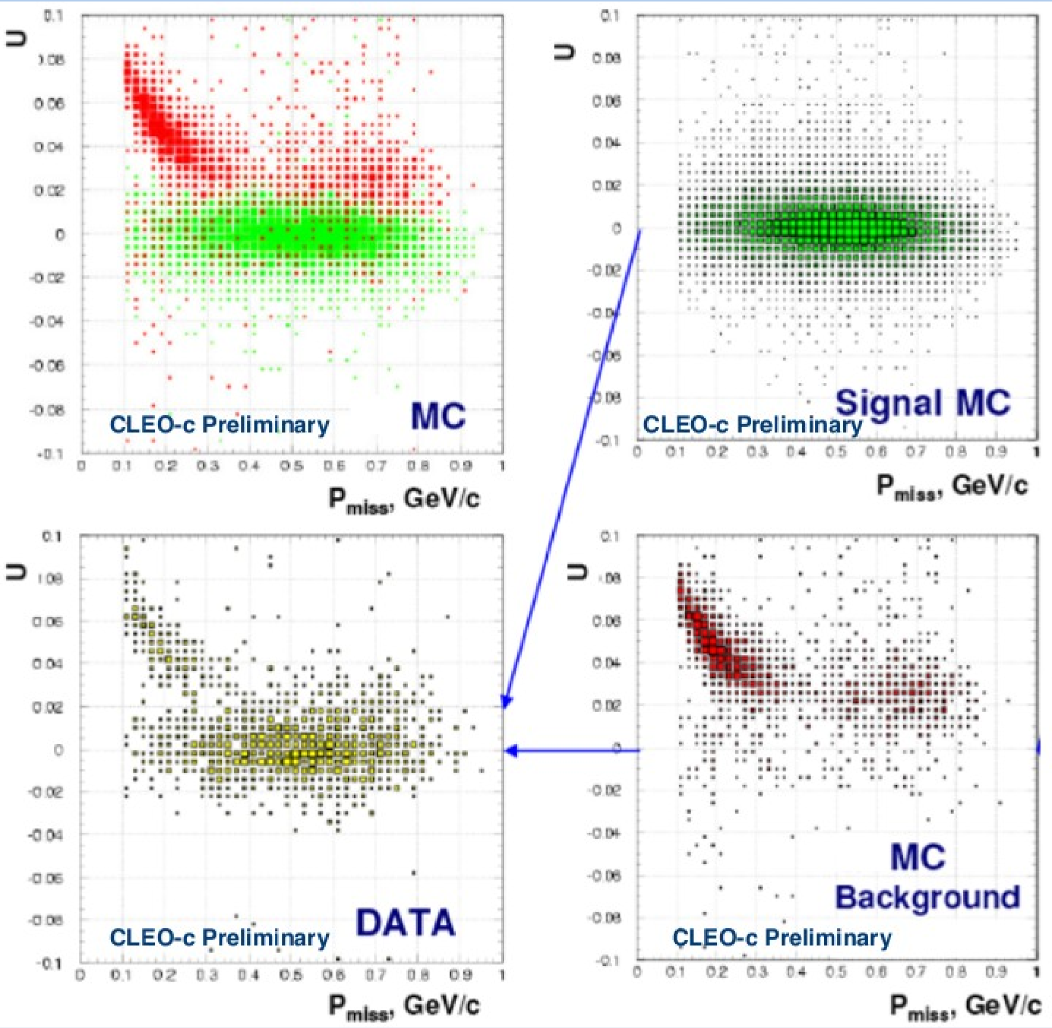
Belle: Phys. Lett. B 648, 139 (2007)





$K\mu\nu$

- The muon chambers on CLEO-c were not useful due to low muon momenta, but we can separate muons from e and π.
- P_{miss} and $U = E_{miss} - |P_{miss}|$ isolate $K\mu\nu$



Summary

- This first measurement of cos δ improves error when combining measurements on mixing parameters

- With the full CLEO-c $\psi(3770)$ dataset, we expect
  - σ(cos δ) ~ +/-(0.1 – 0.2)
  - $\sigma(y)$ ~ +/- 0.01
  - σ(x sin δ) ~ +/- 0.03