Quantum Correlations in $D^0\overline{D}^0$ Decays at CLEO-c

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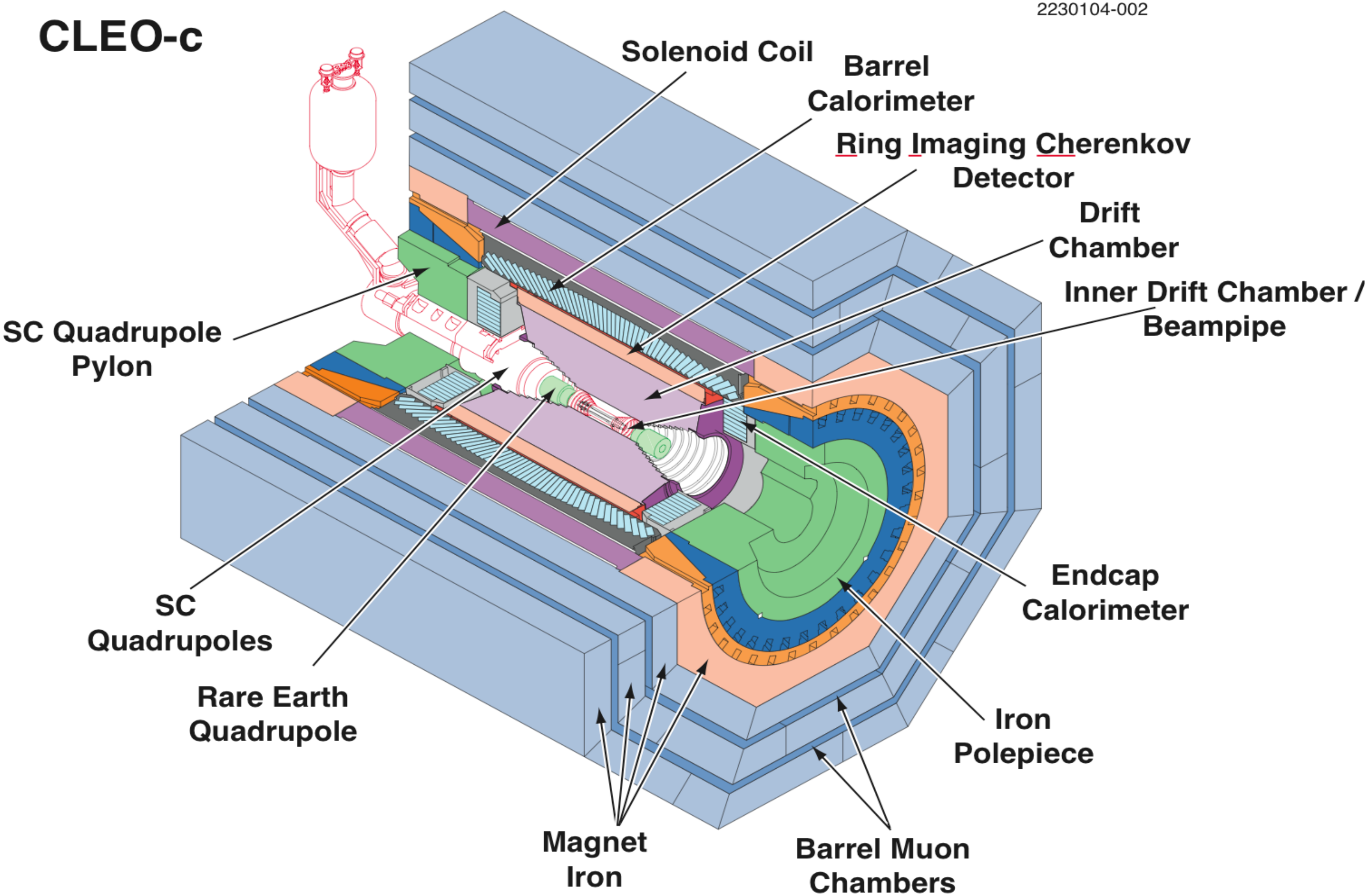
CLEO-c Detector



These results use CLEO-c data on the ψ'', 281 pb^{-1}, which corresponds to 1 million $D^0\bar{D}^0$ pairs.

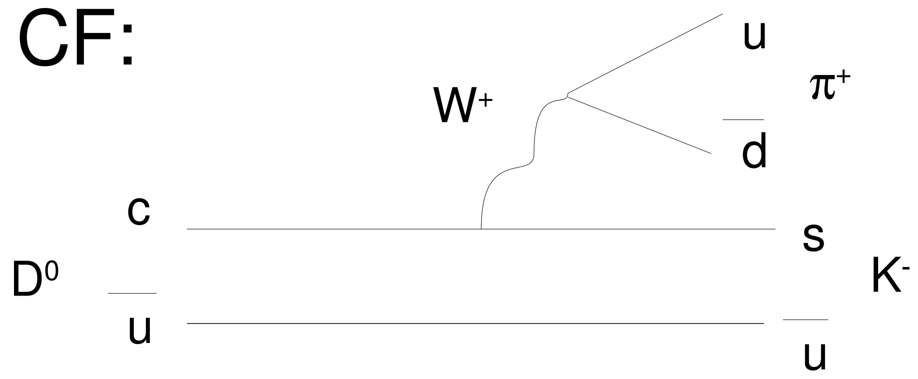
What are we measuring?

- x, y: D^0-$\overline{D}^0$ mixing amplitudes

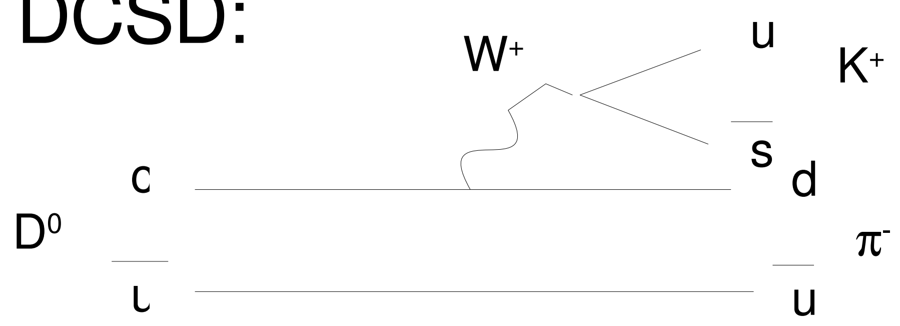
- r: $K\pi$ DCSD to CF amplitude

- $\delta_{K\pi}$: $K\pi$ DCSD to CF relative phase

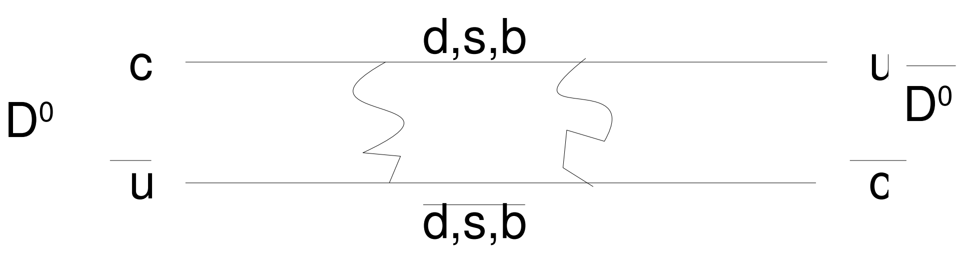
CF:



DCSD:



Mixing box diagram:



How can we measure them?

These quantities can be measured in various ways:

- in $D^{*+} \to D^0 \pi^+$ the charge of the slow pion determines D^0 or $\overline{D^0}$. Rates can be measured since we know the charm of the parent D.

- in $\psi(3770) \to D^0\overline{D^0}$, the pairs are C = -1, so indistinguishable final states interfere, and rates are more sensitive to mixing. These coherent pairs allow for a simultaneous fit to yields to determine x, y, $\cos\delta_{K\pi}$, and DCSD rate. This is our method.

CLEO-c: TQCA

$$ee \to \gamma^* \to D^0\overline{D}^0 \text{ is } C = -1$$

We use:

Flavor tags: hadronic decay to non-CP eigenstate. CF or DCSD are possible. We use $D^0 \to K^-\pi^+$ (f) and $\overline{D}^0 \to K^+\pi^-$ ($\overline{f}$).

CP tags: hadronic decay to state of definite CP. We use

$D^0/\overline{D}^0 \to K_s\ \pi^0$ (CP-)

$D^0/\overline{D}^0 \to K^+K^-$ (CP+)

$D^0/\overline{D}^0 \to \pi^+\ \pi^-$ (CP+)

$D^0/\overline{D}^0 \to K_s\ \pi^0\ \pi^0$ (CP+)

Semileptonics: inclusive, decay of form $D^0 \to X\ e^-\ \overline{\nu}$ (l-). Charge of lepton always tells us charm of parent D.

CLEO-c: TQCA

- We measure yields for:
  - f / $\bar{f}$ opposite anything, CP+/- opposite anything. These are single tags.
  - All combinations of f / $\bar{f}$ opposite CP+/-, f / $\bar{f}$ opposite f / $\bar{f}$, and CP+/- opposite CP+/-. These are hadronic double tags.
  - Semileptonic opposite f / $\bar{f}$ and semileptonic opposite CP+/-. These are semileptonic double tags.
- **Fit inputs**: 6 hadronic single tag yields, 14 hadronic double tag yields, 10 semileptonic double tag yields, efficiencies, crossfeeds, background branching fractions and efficiencies.
- Use fitter from CLEO-c *D* absolute hadronic branching fraction analysis [physics/0503050].
- **Fit outputs**: y, r^2, $r(2\cos\delta_{K\pi})$, R_M, and branching fractions for f, each CP mode, and $X e^- \bar{\nu}$
- Limiting statistics: *CP* tags
- Procedure tested with *CP*-correlated Monte Carlo, where existing non-QC MC was reweighted to mimic quantum correlation.

Rate enhancement factors

	f	$l+$	$CP+$	$CP-$
f	R_M/r^2			
$\bar{f}$	$1+r^2(2-(2\cos\delta)^2)$			
$l-$	1	1		
$CP+$	$1+r\,(2\cos\delta)$	1	0	
$CP-$	$1-r\,(2\cos\delta)$	1	2	0
X	$1+ry\,(2\cos\delta)$	1	$1-y$	$1+y$

$R_M = (x^2 + y^2)/2$

r = Ampl(DCS)/Ampl(CF)

Forbidden unless mixing

Forbidden by CP conservation

Maximal correlations

Interference, sensitive to both DCSD amplitude and strong phase

Isolated decay rates

Single tags

To 1st order. If no quantum correlation, all entries would be 1.

See PRD 73 034024 (2006) [hep-ph/0507238] by Asner and Sun

Hadronic Single Tags

- Standard *D* reconstruction.

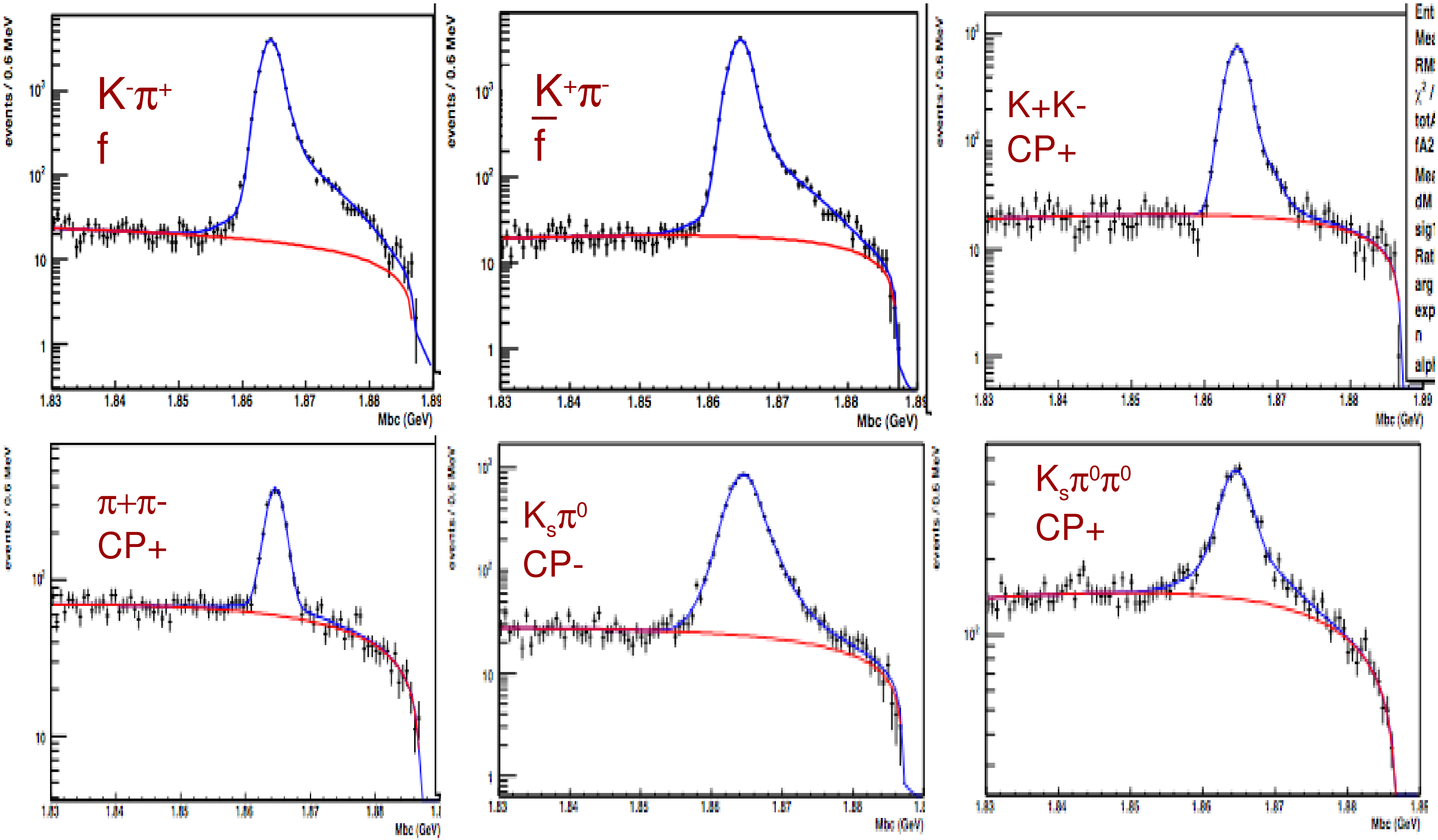
- Cut on ΔE, fit M_{BC} distribution to signal and background shapes. (M_{BC}: Beam Constrained Mass. $M_{BC} = \mathrm{sqrt}(E^2_{beam} - p^2_D)$)

- Efficiencies from (uncorrelated) $D\bar{D}$ Monte Carlo simulations.

- Peaking backgrounds for:
    - $K\pi$ from K/π particle ID swap.
    - Modes with K^0_S from non-resonant $\pi^+\pi^-$

Mode	ε (%)	% bkg	Signal Yield (10^3)
$K^-\pi^+$	65.7 ± 0.1	0.13	26.0 ± 0.2
$K^+\pi^-$	66.7 ± 0.1	0.14	26.3 ± 0.2
K^-K^+	58.9 ± 0.2	0.00	4.70 ± 0.08
$\pi^-\pi^+$	73.5 ± 0.3	0.00	2.13 ± 0.12
$K^0_S\pi^0\pi^0$	14.6 ± 0.1	13.8	3.58 ± 0.17
$K^0_S\pi^0$	31.4 ± 0.1	2.2	8.06 ± 0.11

Single Tags in Data



Vertical axes are log scale

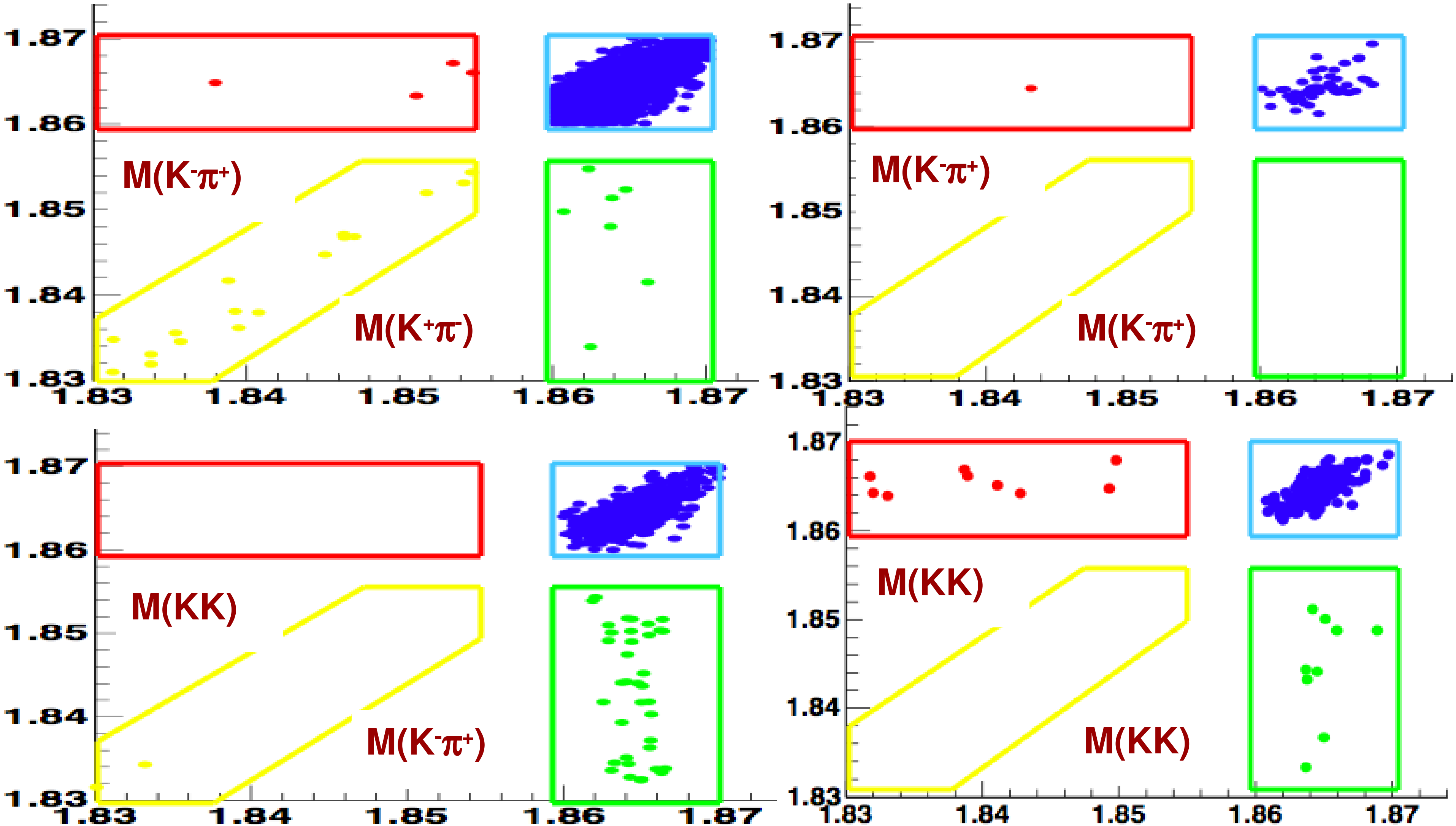
Hadronic Double Tags

- Cut and count in M_{BC1} vs. M_{BC2} plane, define three sidebands.

- Uncorrelated background: one D misreconstructed (sometimes both).
  - Signal/sideband scale factor: integrate background function from ST fits.

- Mispartition background: particles mis-assigned between D^0 and $\overline{D}^0$.

Double Tags in Simulation



Double Tags in Data

Enhancement

No QC Data	K-K+	π-π+	$K_s\pi^0\pi^0$	$K_s\pi^0$
	CP+			CP-
K-K+ (CP+)	5.2±0.4 / -2.2±1.9	4.5±0.3 / 0.1±0.9	5.7±0.4 / 1.6±1.3	16.0±0.6 / 39.6±6.3
π-π+ (CP+)		1.1±0.2 / 0.2±1.4	2.2±0.2 / 1.6±1.3	5.8±0.4 / 14.0±3.7
$K_s\pi^0\pi^0$ (CP+)			1.2±0.2 / 1.0±1.0	7.3±0.4 / 19.0±4.4
$K_s\pi^0$ (CP-)				9.7±0.5 / 3.0±1.7

Consistent with zero

CP tags vs CP tags clearly shows Quantum Correlation

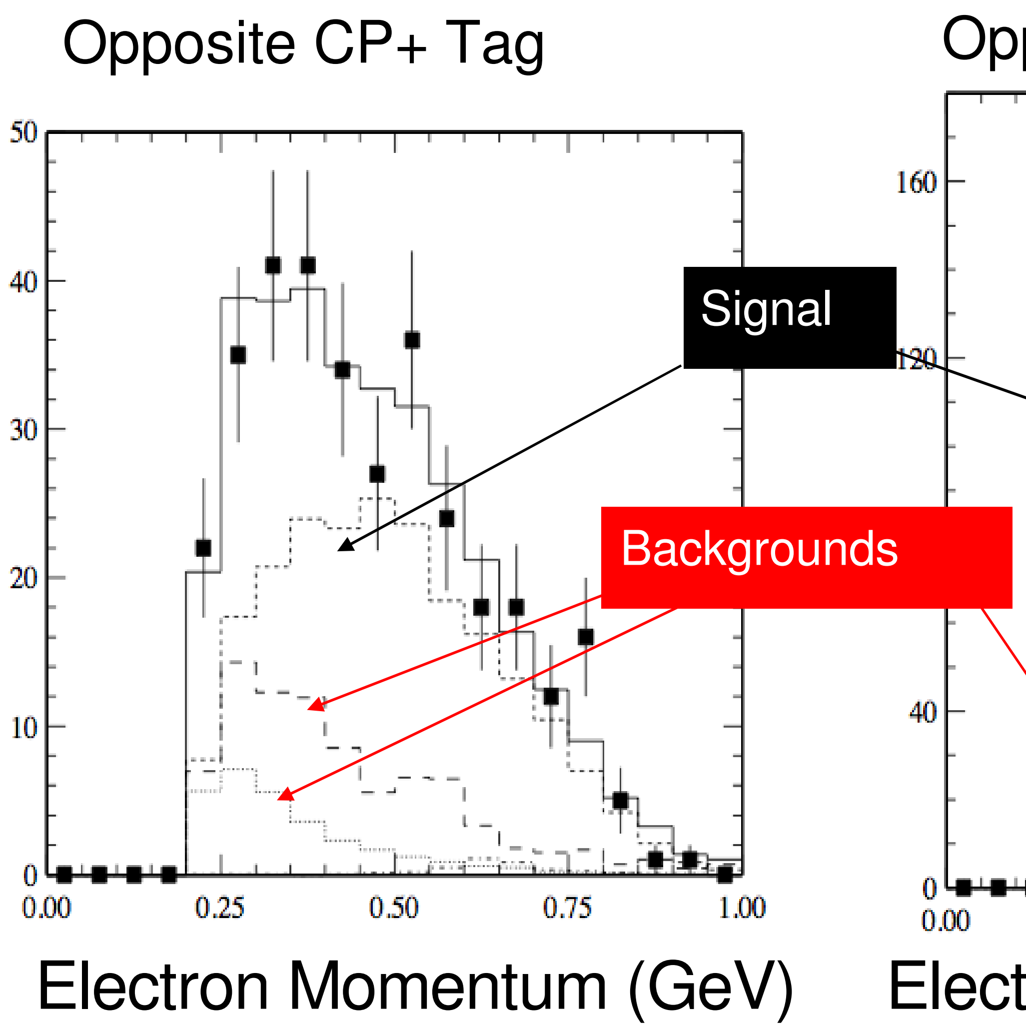
Inclusive Semileptonic Double Tags

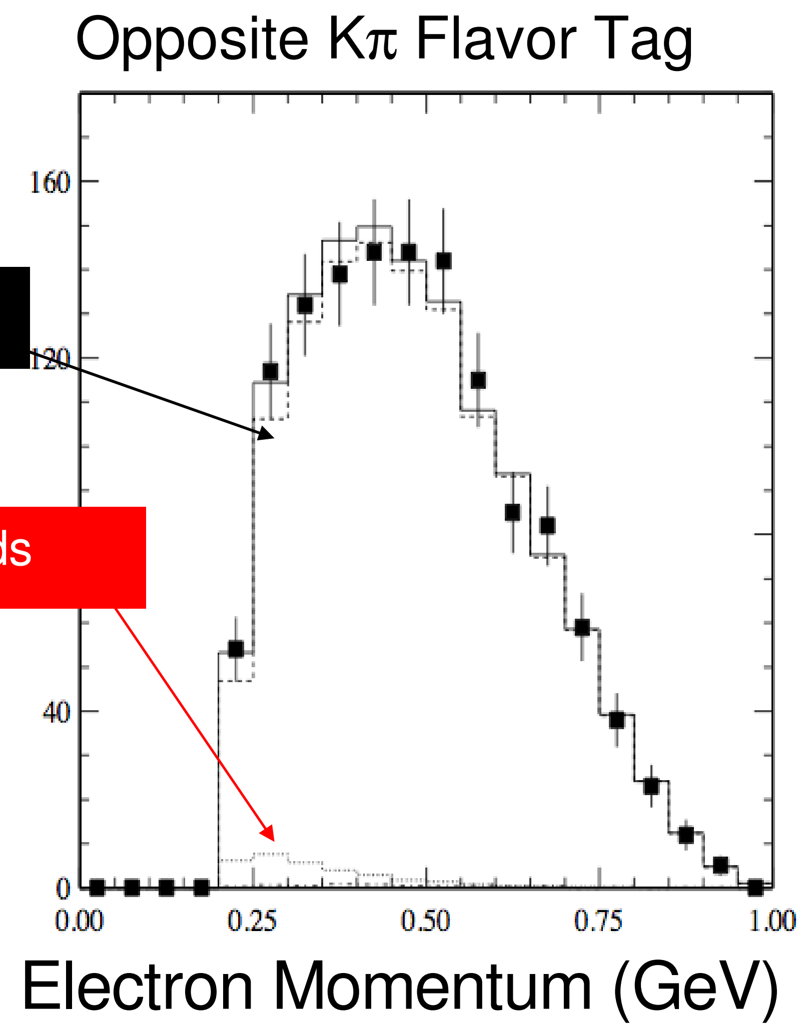
- Tag one side with $K\pi$ or CP+/-, search for electron in remainder of event.
- Fit electron spectrum for signal and background.
  - gamma conversion, π^0 Dalitz decay: charge symmetric.
  - Mis-ID: hadrons faking electrons.
  - Mis-tag: estimate from tag-side M_{BC}-ΔE sideband.
- Require right-sign electron charge for $K\pi$ tag.
- Efficiency correction in bins of p_e.

Tag	ϵ	ε_e (%)	% bkg	Signal Yield
$K^-\pi^+$	-	72.9	5.2	1206 ± 35
$K^+\pi^-$	+	71.9	2.8	1291 ± 36
K^-K^+	-	69.1	23.2	145 ± 12
K^-K^+	+	69.0	34.8	136 ± 12
$\pi^-\pi^+$	-	70.0	28.2	78 ± 9
$\pi^-\pi^+$	+	70.2	29.0	55 ± 7
$K^0_S\pi^0\pi^0$	-	69.2	43.8	146 ± 12
$K^0_S\pi^0\pi^0$	+	69.1	65.9	140 ± 12
$K^0_S\pi^0$	-	69.2	8.2	231 ± 15
$K^0_S\pi^0$	+	75.1	19.1	221 ± 15

Semileptonics

- Opposite flavor tags: very clean, low mis-tag background, almost no mis-ID as only right sign electrons are counted.
- Opposite CP tags: more mis-tags, and have mis-ID background.





Systematic Uncertainties

- Mixing/DCS parameters determined from ST/DT double ratios:
    - Correlated systematics cancel (tracking/π^0/K^0_S efficiencies).
    - Different systematics from branching fraction measurements.

- Uncorrelated systematic uncertainties included in the fit:
    - Yield fit variation.
    - Possible contribution from C=+1 initial state.

      Can limit with *CP*+/*CP*+, *CP*-/*CP*- double tags—forbidden for C=-1.

      Data provides self-calibration of initial state.
    - Signal yields have peaking backgrounds of opposite *CP* or flavor $\rightarrow$ bias in estimates from uncorrelated MC.
    - Possible bias from *CP*-correlated MC test.

Full systematic error analysis in progress.

Currently, $\sigma_{syst} \sim \sigma_{stat}$.

Fit Results

Preliminary

χ^2 = 17.0 for 19 d.o.f. (C.L. = 59%).

Fitted r^2 unphysical, and has large error. If we constrain to world average (PDG), $\cos\delta_{K\pi}$= 1.08 ± 0.66 ± ?.

Some branching fractions competitive with PDG

Parameter	CLEO TQCA	PDG or CLEOc
y	-0.057±0.066±?	0.008±0.005
r^2	$(-2.8\pm6.9\pm?)\times10^{-2}$	$(3.74\pm0.18)\times10^{-3}$
$r(2\cos\delta_{K\pi})$	0.130±0.082±?	
R_M	$(1.74\pm1.47\pm?)\times10^{-3}$	$< \sim1\times10^{-3}$
$B(D\to K\pi)$	(3.80±0.029±?)%	(3.91±0.12)%
$B(D\to K^+K^-)$	(0.357±0.029±?)%	(0.389±0.012)%
$B(D\to\pi^+\pi^-)$	(0.125±0.011±?)%	(0.138±0.005)%
$B(D\to K_s\pi^0\pi^0)$	(0.932±0.087±?)%	(0.89±0.41)%
$B(D\to K_s\pi^0)$	(1.27±0.09±?)%	(1.55±0.12)%
$B(D^0\to Xe\nu)$	(6.21±0.42±?)%	(6.46±0.21)%

First measurement of $\cos\delta_{K\pi}$

Errors are statistical only

Summary and Future Plans

- Obviously still preliminary, but very promising
- Systematics look tractable (< stats)
- Number of CP tags is limit so working on adding more
- Determination of x needs C = +1 initial state from running above the ψ''

- Add CP modes ($K_S\eta$, $K_s\omega$, $K_L\pi^0$)

- Ultimate sensitivity with projected CLEO-c data set y ±0.012, x^2 ±0.0006, $\cos\delta_{K\pi}$ ±0.13, $x(\sin\delta_{K\pi})$ ±0.024

	Definition	Current knowledge (PDG)
y	$(\Gamma_2-\Gamma_1)/2\Gamma$ = B(CP+)–B(CP-)	0.008 ± 0.005
x	$(M_2-M_1)/\Gamma$ sensitive to NP	x' < 0.018
R_M	$(x^2+y^2)/2$	< ~1 x 10^{-3}
r	$K\pi$ DCS-to-CF rel. amplitude	0.061 ± 0.001
δ	$K\pi$ DCS-to-CF relative phase	π(weak) + ? (strong)
z	$2\cos\delta$	None
w	$2\sin\delta$	None

References:

Goldhaber, Rosner:
PRD 15, 1254 (1977).

Xing: **PRD 55, 196 (1997).**

Gronau, Grossman, Rosner:
hep-ph/0103110.

Atwood, Petrov: **PRD 71, 054032 (2005)**.

Asner, Sun: **hep-ph/0507238.**