$D^0\bar{D}^0$ Quantum Correlations, Mixing, and Strong Phases

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Introduction and motivation
Experimental technique
Preliminary results and future plans

Effect of Quantum Correlations

$$C = -1$$

$$e^+e^- \to \boxed{\gamma^* \to D^0\bar{D}^0}$$

interference	$K^-\pi^+$	$K^+\pi^-$
	$K^+\pi^-$	$K^-\pi^+$
forbidden in absence of mixing	$K^-\pi^+$	$K^-\pi^+$
	$K^-\pi^+$	$K^+l^-\nu$
	$CP+$	$K^+l^-\nu$
	$CP-$	$K^+l^-\nu$
	$K^-l^+\nu$	$K^+l^-\nu$
maximal constructive interference	$CP+$	$CP-$
forbidden by *CP* conservation	$CP+$	$CP+$
	$CP-$	$CP-$

- $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- Because of quantum correlation between D^0 and $\bar{D}^0$, not all final states allowed. This affects:
  - total rate
  - apparent branching fractions
- Two entangled causes:
  - Interf. between CF and DCSD.
  - *D* mixing: single tag rates depend on $y = \mathcal{B}(CP+)-\mathcal{B}(CP-)$.
- Semileptonic decays tag flavor unambiguously (if no mixing) → If one *D* is SL, the other *D* decays as if isolated/incoherent.
- Exploit coherence to probe DCSD and mixing—shows up in *time-integrated* rates.

Introduction

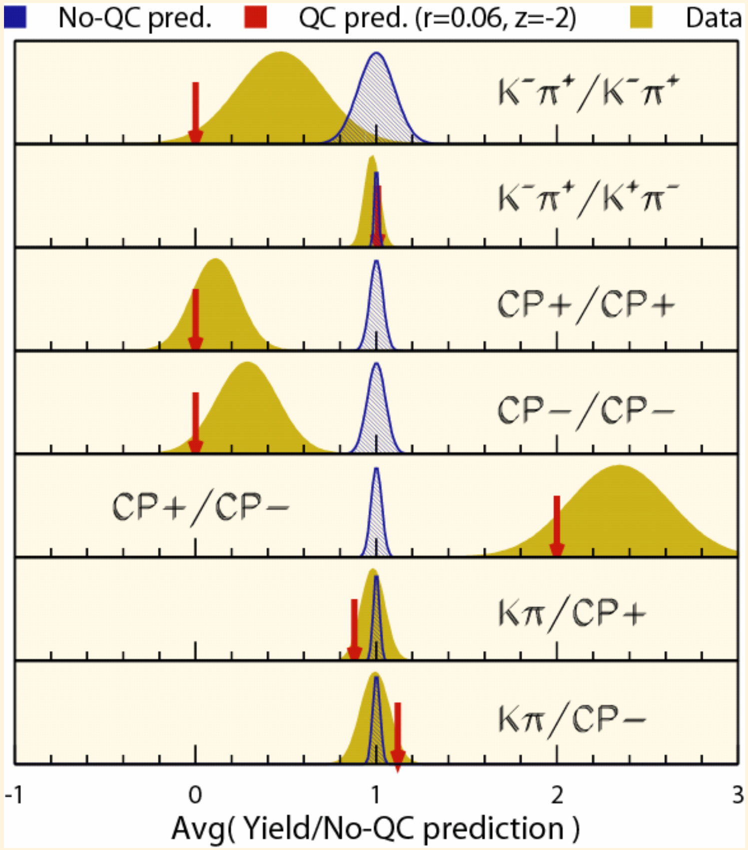
- In the Standard Model, *D* mixing strongly suppressed (CKM and GIM).
- Previous searches:
  - Double semileptonic rates give R_M.
  - Time-dependent $K\pi$: x and y rotated by δ.
- Current analysis:
  - Uses *time-independent* yields.
  - Sensitive to *y* at *first order*.
  - No sensitivity to $p/q \neq 1$; neglect *CPV* in decay.
- 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.**

	Definition	Current knowledge
y	$(\Gamma_2-\Gamma_1)/2\Gamma$ = $\mathcal{B}(CP+)-\mathcal{B}(CP-)$	0.008 ± 0.005
x	$(M_2-M_1)/\Gamma$ sensitive to NP	x' < 0.018
R_M	$(x^2+y^2)/2$	< ~1×10^{-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
$\mathcal{A}$	$\Sigma\, \mathcal{B}_f\, r_f\, z_f$	~-0.01 w/ SU(3)

Single and Double Tag Rates

Single tag: $X \leftarrow \bar{D}\ D \rightarrow i$

Double tag: $j \leftarrow \bar{D}\ D \rightarrow i$



- Hadronic rates (flavored and *CP* eigenstates) depend on mixing/DCSD.
- Semileptonic modes ($r = \delta = 0$) resolve mixing and DCSD.
- Rate enhancement factors, to leading order in x, y and r^2:

	f	$l+$	$CP+$	$CP-$
f	$\sim R_M$			
$\bar{f}$	$1+r^2(2-z^2)$			
$l-$	1	1		
$CP+$	$1+rz$	1	0	
$CP-$	$1-rz$	1	2	0
X	$1-rz(\mathcal{A}-y)$	1	$1+(\mathcal{A}-y)$	$1-(\mathcal{A}-y)$

With $C=-1$, cannot separate y and $\mathcal{A}$

- $\mathcal{A}$ comes from sum over recoil states.
- With C=+1 $D^0\bar{D}^0\gamma$ at higher energy,
  - Can separate $\mathcal{A}$ and y.
  - Sensitivity to wx at first order. Not much info if w is small.

Experimental Technique

- Use fitter from CLEO-c *D* absolute hadronic branching fraction analysis [**physics/0503050**].
- Based on MARK III double tag technique using:
  - single tags ($n_i \sim N_{DD}\mathcal{B}_i\varepsilon_i$) and double tags ($n_{ij} \sim N_{DD}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$)

$$A - y \approx \frac{\Gamma_{f,l}}{4\Gamma_{f,X}}\left(\frac{\Gamma_{CP+,X}}{\Gamma_{CP+,l}} - \frac{\Gamma_{CP-,X}}{\Gamma_{CP-,l}}\right) \qquad A - y - rz \approx \frac{\Gamma_{f,\bar{f}}}{4\Gamma_{\bar{f},X}}\left(\frac{\Gamma_{CP+,X}}{\Gamma_{CP+,f}} - \frac{\Gamma_{CP-,X}}{\Gamma_{CP-,f}}\right)$$

$\Gamma \sim n/\varepsilon$

$$B_i \approx \frac{n_{ij}}{n_j}\frac{\varepsilon_j}{\varepsilon_{ij}} \qquad N_{DD} \approx \frac{n_i n_j}{n_{ij}}\frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

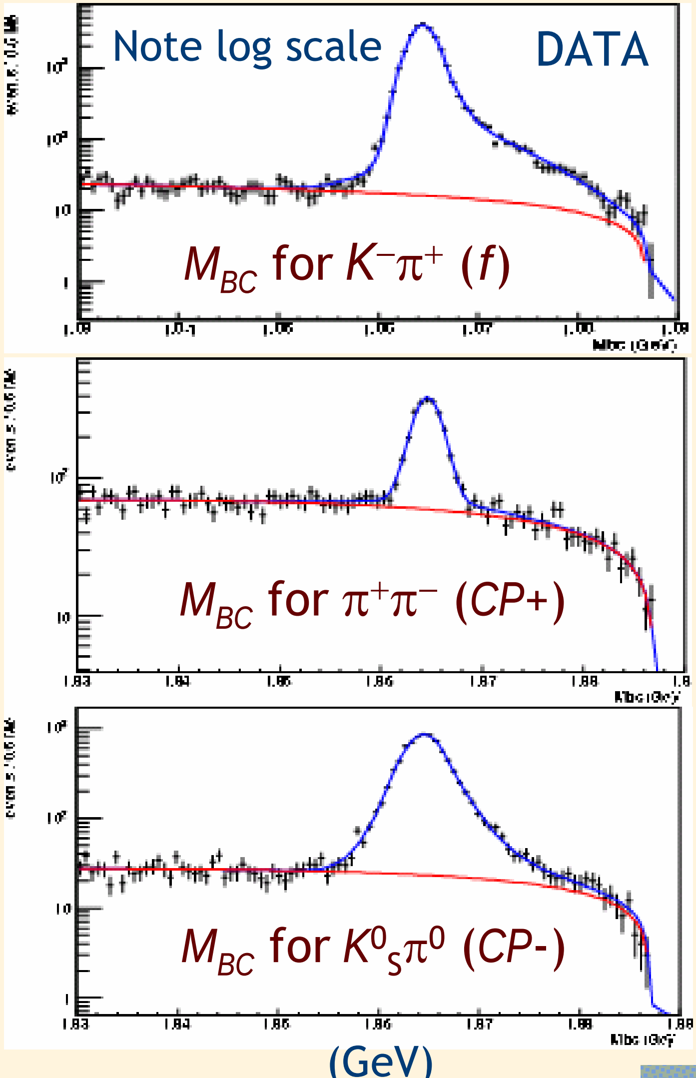
- 281 pb^{-1} = 1.0 x 10^6 C=-1 $D^0\bar{D}^0$ pairs.
- Limiting statistics: *CP* tags—our focus is not on $\mathcal{B}$s.
- Kinematics analogous to $\Upsilon(4S)\to B\bar{B}$: identify *D* with
  - $M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$ $\sigma(M_{BC})$ ~ 1.3 MeV, x2 with π^0
  - $\Delta E = E_{beam} - E_D$ $\sigma(\Delta E)$ ~ 7—10 MeV, x2 with π^0
- Procedure tested with *CP*-correlated MC.

Modes	
f	$K^-\pi^+$
	$K^+\pi^-$
CP+	K^-K^+
	$\pi^-\pi^+$
	$K^0_S\pi^0\pi^0$
CP-	$K^0_S\pi^0$
l	$X^-e^+\nu$
	$X^+e^-\bar{\nu}$

Hadronic Single Tags

- Standard *D* reconstruction.
- Cut on ΔE, fit M_{BC} distribution to signal and background shapes.
- 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)
f	$K^-\pi^+$	65.7 ± 0.1	0.13	26.0 ± 0.2
	$K^+\pi^-$	66.7 ± 0.1	0.14	26.3 ± 0.2
CP+	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
CP-	$K^0_S\pi^0$	31.4 ± 0.1	2.2	8.06 ± 0.11



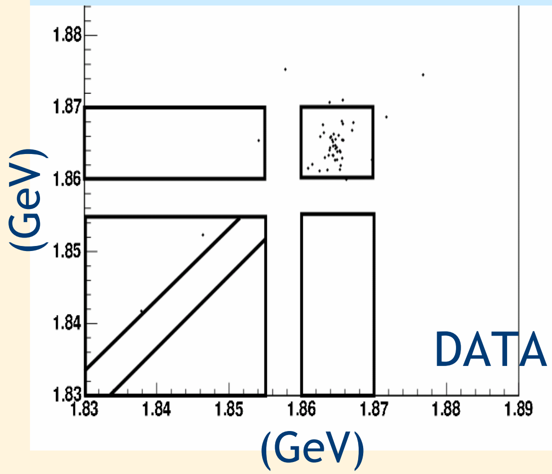
Hadronic Double Tags

- Cut and count in M_{BC1} vs. M_{BC2} plane, define four 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 $\overline{D}^0$.

Yields	$K^-\pi^+$	$K^+\pi^-$	K^-K^+	$\pi^-\pi^+$	$K^0_S\pi^0\pi^0$	$K^0_S\pi^0$
$K^-\pi^+$	2.5 ± 0.4 2.0 ± 0.4	622 ± 7 599 ± 25	62.3 ± 2.1 70.6 ± 8.4	25.3 ± 1.3 24.0 ± 4.9	31.2 ± 1.4 38.7 ± 6.2	78.3 ± 2.3 90.4 ± 9.5
$K^+\pi^-$		2.7 ± 0.4 2.0 ± 1.4	64.7 ± 2.1 53.0 ± 7.3	30.6 ± 1.4 24.3 ± 5.0	32.3 ± 1.5 37.6 ± 6.2	85.0 ± 2.4 77.0 ± 8.8
K^-K^+			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
$\pi^-\pi^+$				1.1 ± 0.2 0.2 ± 1.4	2.2 ± 0.2 1.6 ± 1.3	5.8 ± 0.4 14.0 ± 3.7
$K^0_S\pi^0\pi^0$					1.2 ± 0.2 1.0 ± 1.0	7.3 ± 0.4 19.0 ± 4.4
$K^0_S\pi^0$						9.7 ± 0.5 3.0 ± 1.7

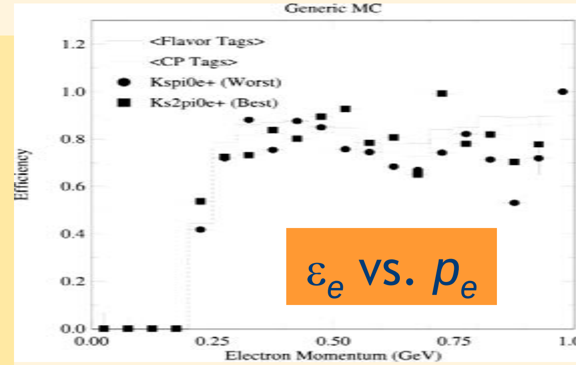
No-QC expectation
Observed in data

$M_{BC}(K^-K^+)$ vs. $M_{BC}(K^0_S\pi^0)$



Inclusive Semileptonic Double Tags

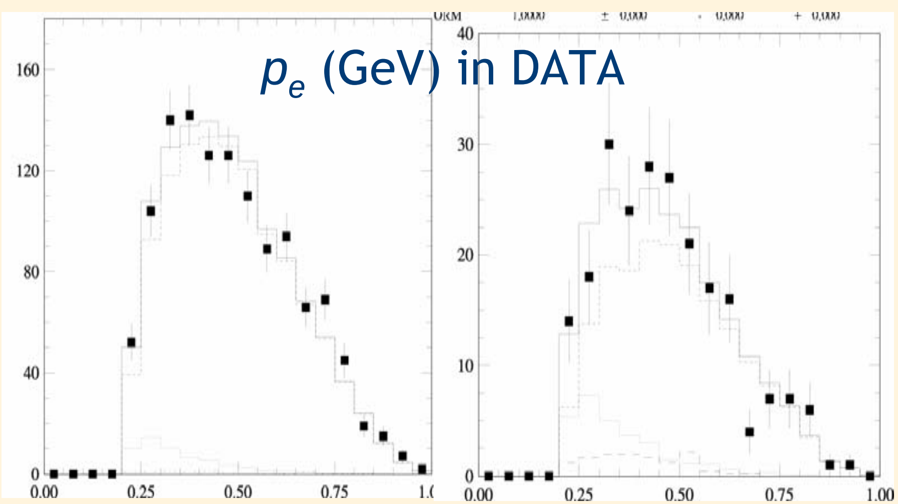
- Tag one side with $K\pi$ or CP eigenstate, search for electron in remainder of event:
- Fit electron spectrum for signal and background.
  - γ conversion, π^0 Dalitz decay: charge symmetric.
  - Mis-ID: hadrons faking electrons.
  - Mis-tag: estimate from tag-side M_{BC}-ΔE sideband.
- Require right-sign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



Tag	e	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

e^- vs. $K^-\pi^+$

e^+ vs. $K^0_S\pi^0$



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

Results

PRELIMINARY

- Fit inputs: 6 ST, 14 hadronic DT, 10 semileptonic DT, efficiencies, crossfeeds, background branching fractions and efficiencies.
- χ^2 = 17.0 for 19 d.o.f. (C.L. = 59%).
- Fitted r^2 unphysical. If constrain to WA, $\cos\delta$ = 1.08 ± 0.66 ± ?.
- Limit on C=+1 contamination:
  - Fit each yield to sum of C=-1 & C=+1 contribs.
  - Include CP+/CP+ and CP-/CP- DTs in fit.
  - No significant shifts in fit parameters.
  - C=+1 fraction = 0.06 ± 0.05 ± ?.
- Some branching fracs competitive with PDG.

Uncertainties are statistical *only*

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

Summary and Future Directions

- With correlated $D^0\overline{D}^0$ system, can probe mixing and DCSD in time-integrated yields with double tagging technique.
- Simultaneous fit for:
  - Hadronic/semileptonic/*CP* eigenstate branching fractions
  - Mixing and DCSD parameters.
- Different systematics from previous measurements.
- Method unique to threshold production—unavailable at Tevatron and *B* factories.

- Add $D^0 \to K^0{}_S\pi^+\pi^-$ with Dalitz fits to increase *CP* eigenstate statistics.
- Add wrong-sign e^+ vs. $K^-\pi^+$ double tags to separate r and z.
- Add C=+1 pairs from $D^0D^0\gamma$ in $\sqrt{s}$ ~4 GeV running to
  - separate $\mathcal{A}$ and y.
  - probe x.

- *Preliminary* first measurements of $\delta(K\pi)$ and $\mathcal{A}$-y.
- Systematic uncertainties being studied.
- Results affect other CLEO-c analyses.