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

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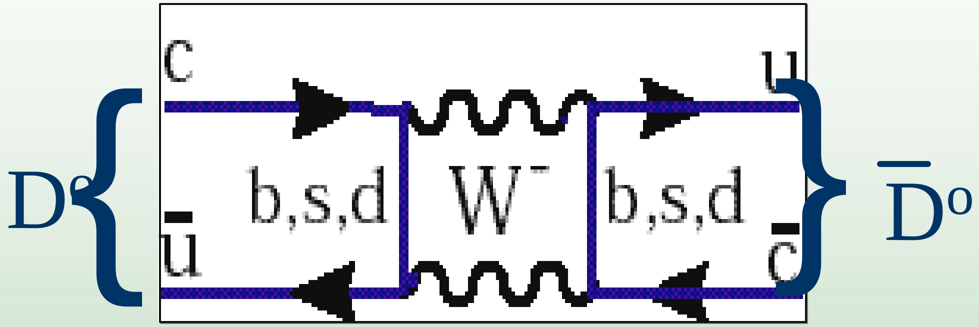
Charm as a probe of new physics

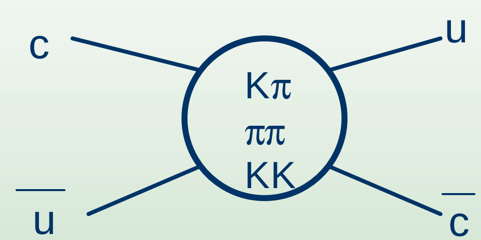
- Unique opportunities in three areas of investigation:
  - Mixing
  - CP violation
  - Rare decays
- Smoking gun or long distance effect?
  - Although all three phenomena suppressed in Standard Model, enhancement due to long distance effects may mimic new physics.

$D^0\bar{D}^0$mixing



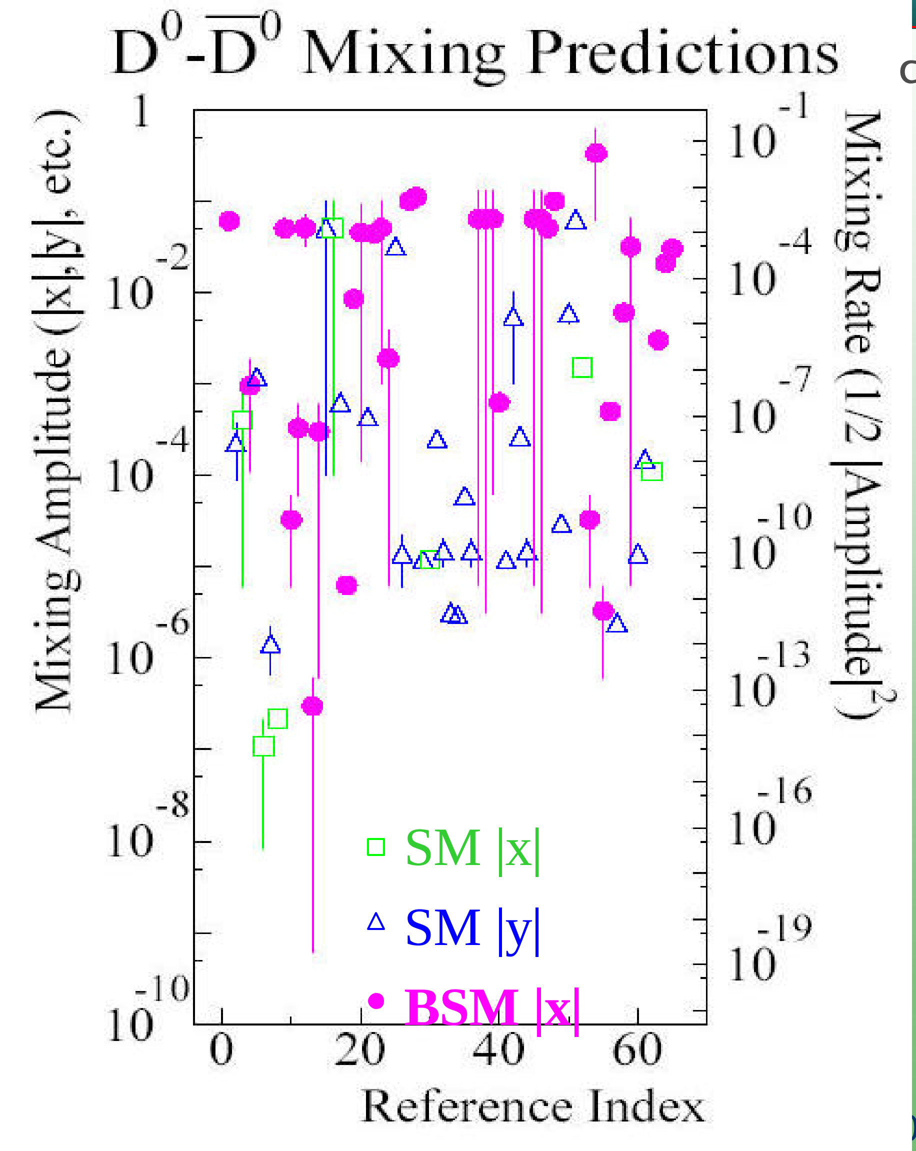
- **the presence of d-type quarks in the loop makes the SM expectations for $\bar{D}^o$-D^o mixing small** compared with systems involving u-type quarks in the box diagram (no super-heavy quark **(t)**:
  - K^o (50%), B^o (20%) & B_s (50%)
- New physics in loops implies $x \equiv \Delta M/\Gamma >> y \equiv \Delta\Gamma/2\Gamma$

$R_M \equiv (x^2+y^2)/2$



- long range effects complicate predictions

Predictions for D-Mixing



compiled by H. Nelson, Lepton-Photon 1999

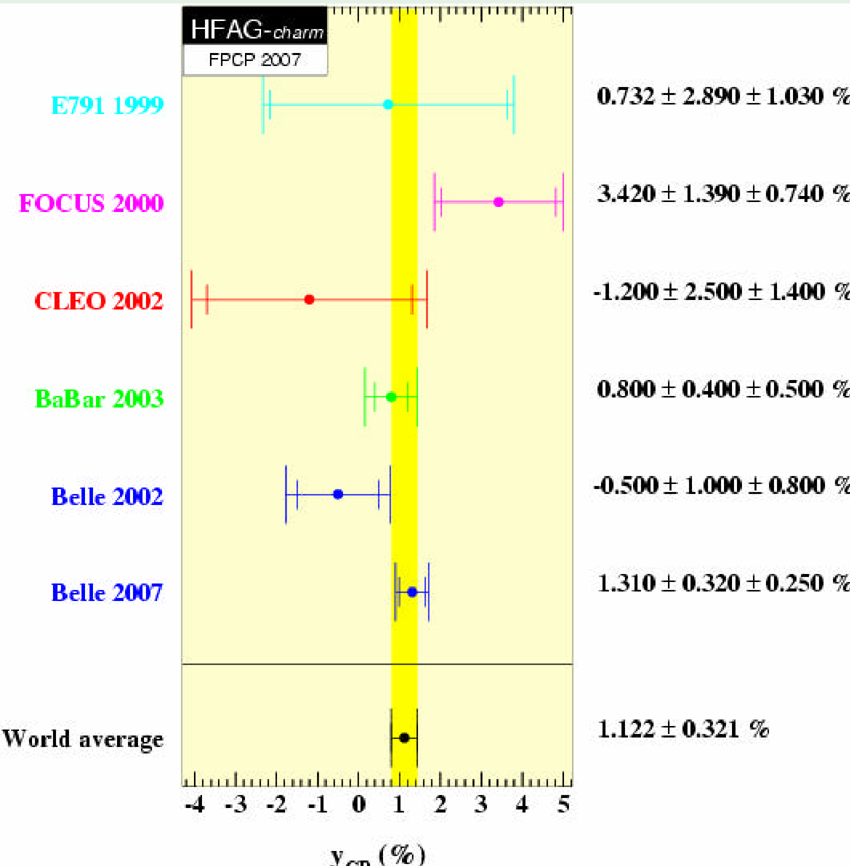
- **Although Standard Model contributions are difficult to pin down, D mixing can constrain several "Beyond the Standard Model" scenarios:**
  - **Many models poorly tested in +2/3 quark sector**
  - **Many models put the flavor violation into up-quark sector in order to satisfy K mixing Þ large effects in D mixing**

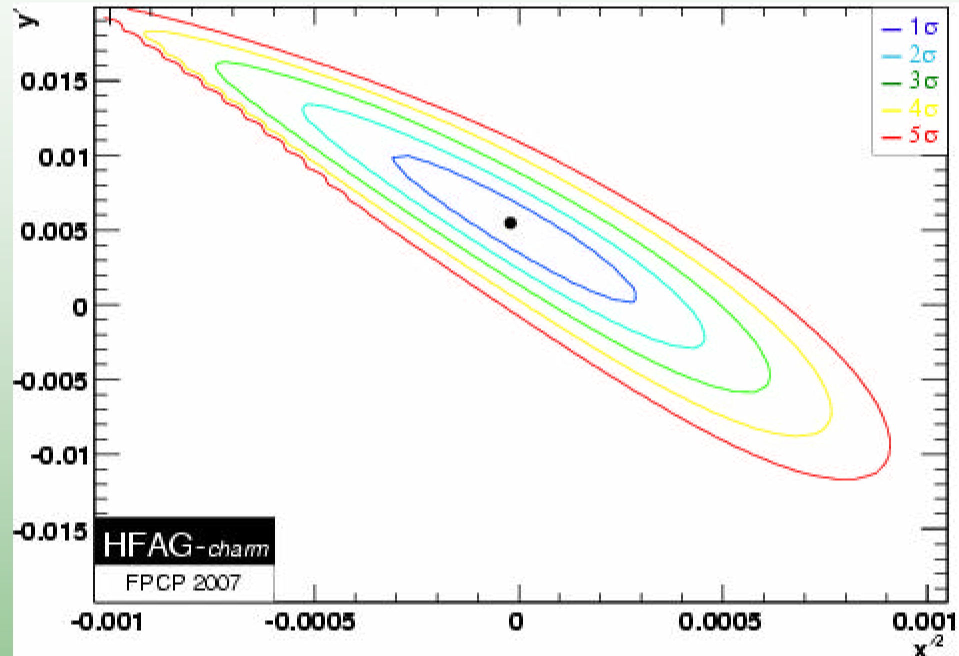
Catalogue of New Physics Contributions

- **Golowich, Hewett, Pakvasa, Petrov arXiv:0705.3650**

D mixing current status

HEAVY FLAVOR AVERAGING GROUP
May 2007





$$x'^2 = -0.00002 \pm 0.00020$$

$$y' \equiv y \cos\delta_{K\pi} - x \sin\delta_{K\pi} = 0.0055^{+0.0028}_{-0.0037}$$

Exploiting the quantum coherence of the initial state

- At a center-of-mass energy close to the $D\bar{D}$ threshold, the pair is produced in a C=-1 state (at the $\psi(3770)$) or in a C=1 state (at an energy above the $\gamma D\bar{D}$ threshold). The corresponding Quantum Correlation between the D and $\bar{D}$ final states affects:
  - Final states produced by mixing or Doubly Cabibbo Suppressed Decays (e.g. $K^+\pi^-K^+\pi^-$) [e.g. for C=-1 no interference between mixing and DCSD because of the $D\bar{D}$ wavefunction is antisymmetric]
  - Final states containing a lepton and a $K^+\pi^-$
  - Final states containing a lepton and a CP eigenstate

Exploiting the quantum coherence of the initial state

hep-ph/0103110
Gronau, Grossman & Rosner

Final state	$\Gamma(C=-1)$	$\Gamma(C=+1)$
$K^-\pi^+K^-\pi^+$	$A^4(x^2+y^2)/2$	$4A^4(r^2+ry'+3/8(x^2+y^2)$
$K^-\pi^+K^+\pi^-$	$A^4(1-2r^2\cos 2\delta-1/2(x^2-y^2))$	$A^4(1+2r^2\cos 2\delta-+4ry-3/2(x^2-y^2))$
$K^-\pi^+S_\zeta$	$A^2A_{S\zeta}{}^2(1+2\zeta\cos\delta)$	$A^2A_{S\zeta}{}^2(1-2\zeta y)$
$K^-p^+\ell^-$	$A^2A_{\ell^-}{}^2[1-1/2(x^2-y^2)]$	$A^2A_{\ell^-}^2[1+2r\tilde{y}-\frac{3}{2}(x^2-y^2)]$
$K^-p^+\ell^+$	$A^2A_{\ell^+}^2[r^2+\frac{1}{2}(x^2+y^2)]$	$A^2A_{\ell^+}^2[r^2+2ry'+\frac{3}{2}(x^2+y^2)]$
$K^-\pi^+S_\zeta$	$A_{S_z}{}^2A_{\ell^+}^2(1+y^2)$	$A_{S_z}{}^2A_{\ell^+}^2(1-2z\ y+3y^2)$

Linear in y

CP eigenstate, eigenvalue ζ

Quantum Correlations at the $\psi(3770)$

$e^+e^- \rightarrow \gamma^* \rightarrow D^0\overline{D}^0$

C = –1

interference

forbidden as C=-1

Wavefunction is

antisymmetric

	$K^-\pi^+$	$K^+\pi^-$
	$K^+\pi^-$	$K^-\pi^+$

[redacted]

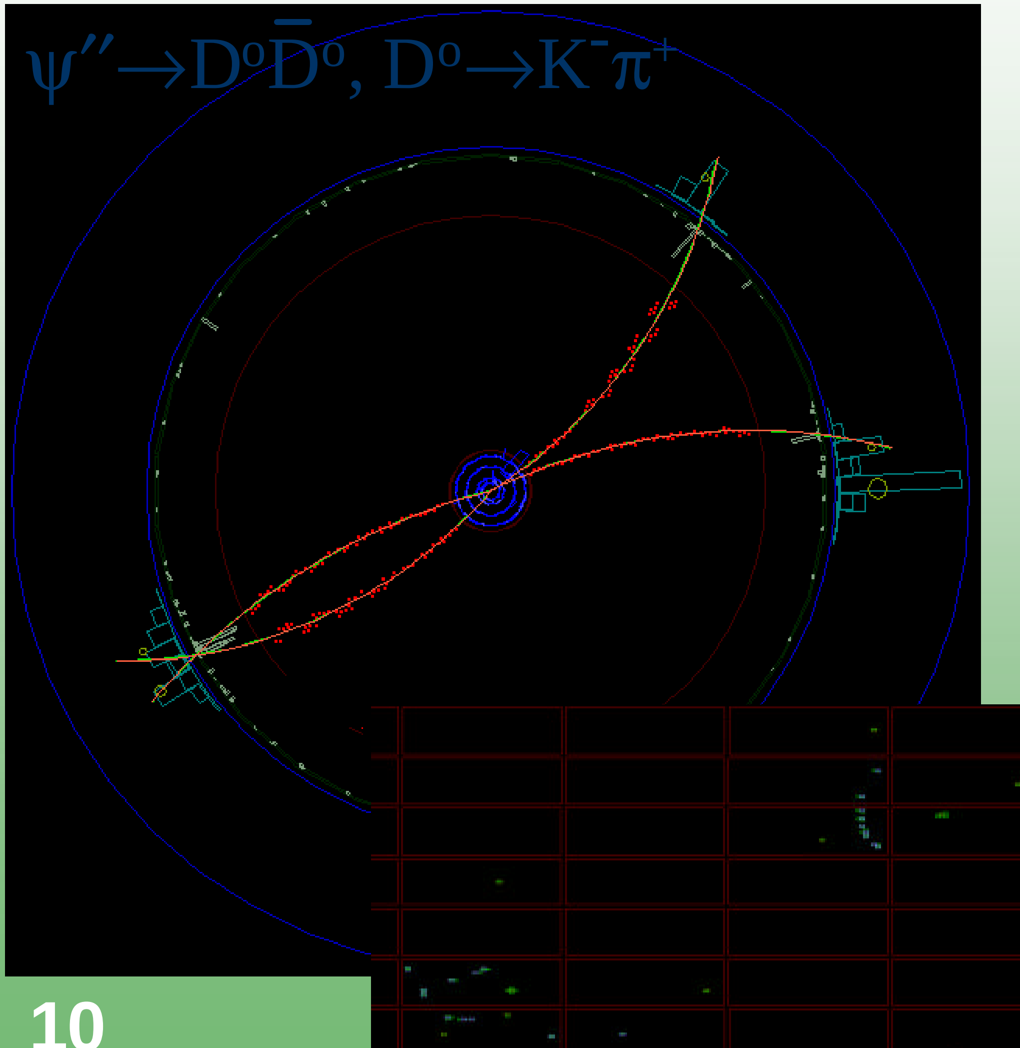
	$K^-\pi^+$	$K^+l^-\nu$
	CP+	$K^+l^-\nu$
	CP-	$K^+l^-\nu$
	$K^-l^+\nu$	$K^+l^-\nu$
maximal constructive interference	CP+	CP-
forbidden by CP conservation	CP+	CP+
	CP-	CP-

- The Quantum Correlation Analysis (TQCA)
- Due to quantum correlation between D^0 and $\overline{D}^0$, not all final states allowed.
- Two paths to $K^-\pi^+$ vs $K^+\pi^-$ interfere and thus the rate is sensitive to DCS & strong phase
- Time integrated rate depends on both $\cos\delta_{K\pi}$ and mixing parameter $y = \Delta\Gamma/2\Gamma$
- ($K^-\pi^+$ $K^-\pi^+$) forbidden without D mixing [interference with DCSD is forbidden because antisymmetry of the $\psi(3770)$ wave function]

Experimental Technique

- Use efficiency corrected yields for single tags (only one D^0 reconstructed) & double tags (both D^0 and D^0 decays reconstructed) in a least-squares fit developed to extract exclusive hadronic branching fractions to determine:
  - $\mathcal{N}$(number of $D^0\bar{D}^0$ pairs)
  - The mixing parameters y and R_M
  - The strong phase $\cos\delta_{k\pi}$
  - 6 exclusive branching fractions

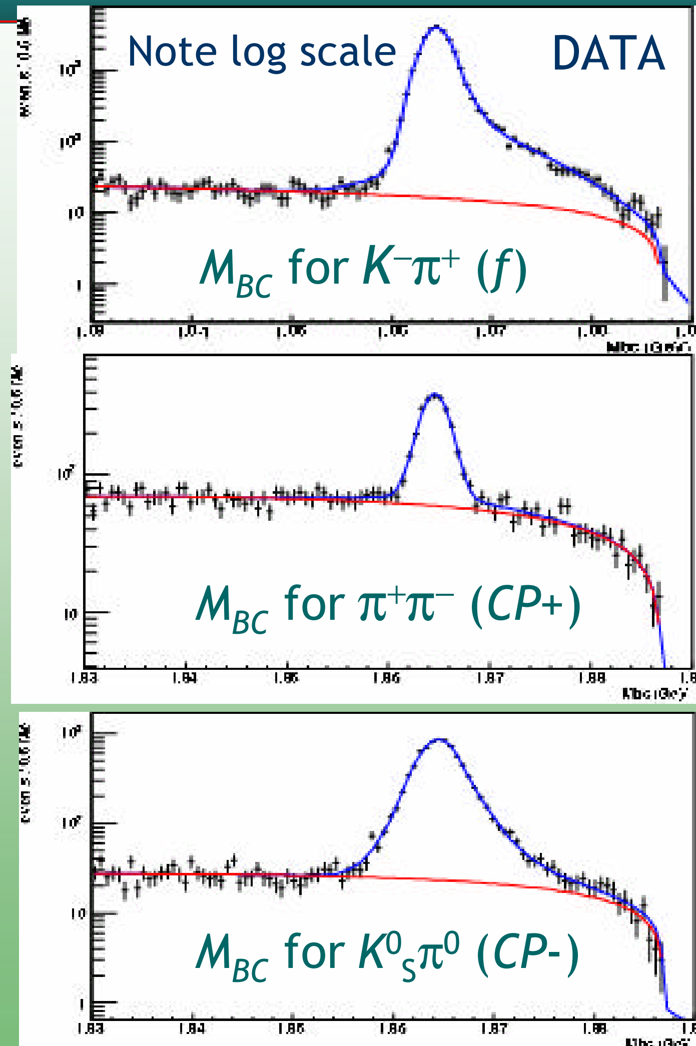
More details



- Data sample use in this analysis 281 pb^{-1} at $\psi(3770)$ center-of-mass energy
- Modes used:
  - Hadronic flavored states ($K^-\pi^+$, $K^+\pi^-$)
  - CP+ modes (K^-K^+, $\pi^-\pi^+$, $K_s\pi^0\pi^0$)
  - CP- modes ($K_S\pi^0$)
  - Inclusive semileptonic decays
- Procedure tested with CP correlated Monte Carlo

Hadronic Single Tags

- Identify the final state with $\Delta E \equiv E_{beam} - E_D$, $M_{BC} \equiv \sqrt{E_{beam}^2 - |p_D|^2}$
- 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 $\pi^+\pi^-$



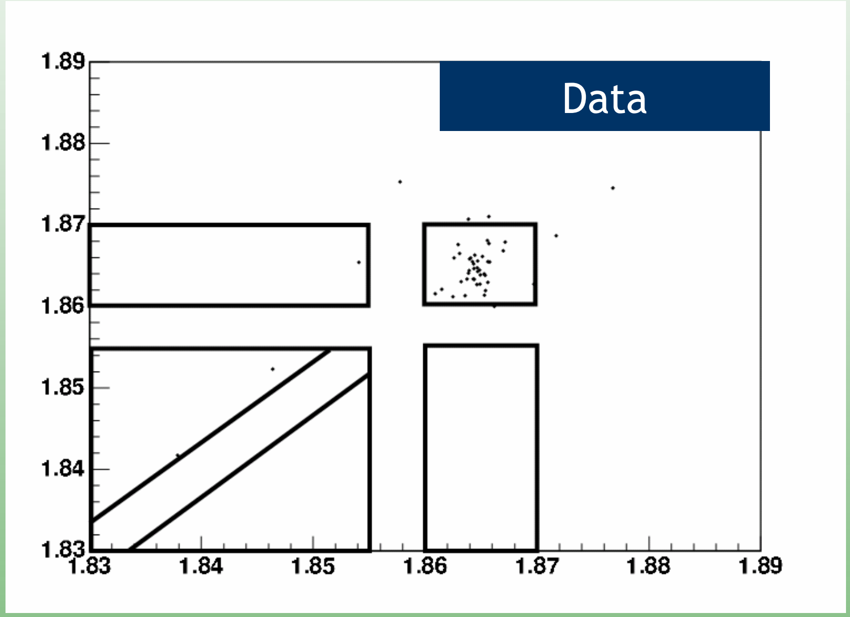
(GeV)

Hadronic Double Tags

- Cut and count in M_{BC1} vs. M_{BC2} plane, define four sidebands.
- Uncorrelated background: one (or, occasionally both) D incorrectly reconstructed.
  - Signal/sideband scale factor derived from ST fits.

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

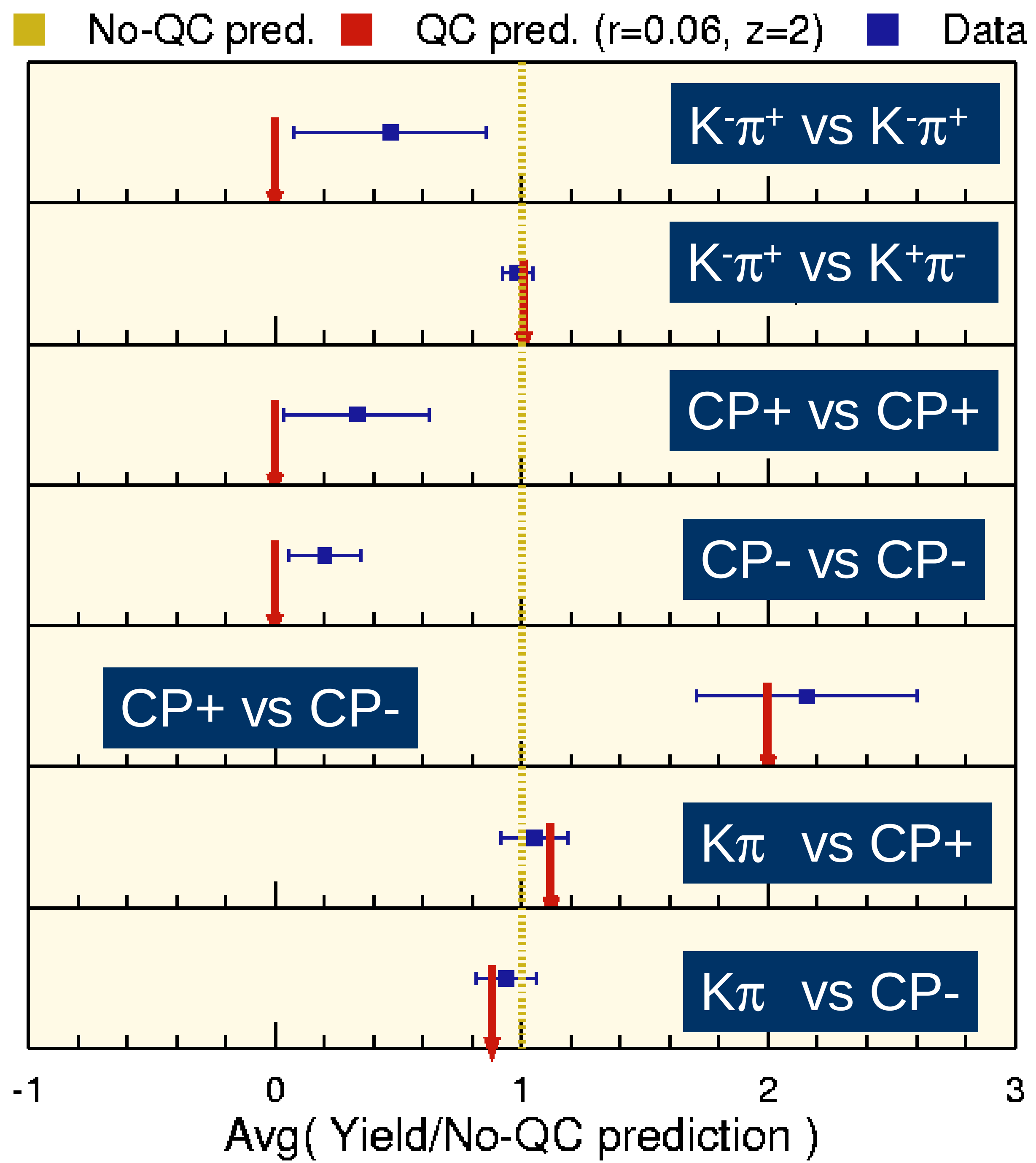
(GeV)



(GeV)

TQCA

Data clearly favors QC interpretation showing constructive and destructive interference and no effect as predicted



TQCA fit methodology

- Fit inputs: 6 single tag yields , 14 hadronic double tag yields, 10 semileptonic double tag yields, efficiencies, crossfeeds, background branching fractions and efficiencies.
- χ^2 = 17.0 for 19 d.o.f. (C.L. = 59%).
- 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 ± ?.

Prelim Results - update soon

Fit uncertainties statistical only

Parameter	CLEO-c TQCA	Other input	Ref.
y	-0.058±0.066	0.012±0.0032	HFAG y_{CP}
R_M	$(1.74\pm1.47)\times10^{-3}$	$(0.21\pm0.11)\times10^{-3}$	HFAG
$\cos\delta_{K\pi}$	1.09±0.66		
$B(D\to K\pi)$	(3.80±0.029)%	(3.80±0.07)%	PDG 06 fit
$B(D\to KK)$	(0.357±0.029)%	(0.389±0.012)%	PDG 06 fit
$B(D\to \pi\pi)$	(0.125±0.011)%	(0.136±0.003)%	PDG 06 fit
$B(D\to K_s\pi^0\pi^0)$	(0.932±0.087)%	(0.89±0.41)%	PDG 06
$B(D\to K_s\pi^0)$	(1.27±0.09)%	(1.14±0.12)%	PDG 06 fit
$B(D^0\to Xe\nu)$	(6.21±0.42)%	(6.46±0.21)%	CLEO-c

Systematic Uncertainties

- Mixing/DCS parameters determined from ST/DT double ratios:
  - Correlated systematic errors cancel (tracking/π^0/K^0_S efficiencies).
- 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.
- Currently, $\sigma_{syst} \sim \sigma_{stat}$.

Concluding remarks

- These measurements are affected by x, y, the strong phase $\delta_{k\pi}$, and the CPV phase ϕ.
- A detailed comparison between the Belle and BaBar evidence for $D^0\bar{D}^0$ mixing shows the importance of more information of the strong phase $\delta_{k\pi}$ [Nir-hep-ph/0703235v2…]
- More data will be added (~300 pb^{-1} available at 3.77 GeV CM energy) + ~ 300 pb^{-1} at 4.17 GeV CM energy may be used to investigate C=+1 $D^0\bar{D}^0$ pairs.

Backup slides

Hadronic Double tags Numbers

$K^-\pi^+$	$K^+\pi^-$	K^-K^+	$\pi^-\pi^+$	$K^0_S\pi^0\pi^0$	$K^0_S\pi^0$	Yields
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	$K^+\pi^-$
		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	K^-K^+
			1.1 ± 0.2 0.2 ± 1.4	2.2 ± 0.2 1.6 ± 1.3	5.8 ± 0.4 14.0 ± 3.7	$\pi^-\pi^+$
				1.2 ± 0.2 1.0 ± 1.0	7.3 ± 0.4 19.0 ± 4.4	$K^0_S\pi^0\pi^0$
					9.7 ± 0.5 3.0 ± 1.7	$K^0_S\pi^0$

No-QC expectation
Observed in data