Cornell University

BES

CLEO

Quantum Correlations in Charm Decays

Werner Sun, Cornell University (CLEO-c)

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Introduction
Formalism
Experimental results
Summary and outlook

Threshold Charm Production

- Running near $c\bar{c}$ threshold produces quantum correlated D^0 and $\bar{D}^0$:
  - $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ [$C = -1$] OR $e^+e^- \to \gamma^* \to D^0\bar{D}^0\gamma$ [$C = +1$]
  - At $\psi(3770)$, same-*CP* final states forbidden; opposite-*CP* states enhanced
    - Tagging the *CP* of one *D* identifies the *CP* of other *D*.
  - Unique access to amplitude ratios, phases, & charm mixing.
    - Exploit interference effects in time-integrated rates.

Correlated amplitudes

$$\Gamma_{ij}^2 = \left| \langle i \mid D^0 \rangle \langle j \mid \overline{D^0} \rangle \mp \langle j \mid D^0 \rangle \langle i \mid \overline{D^0} \rangle \right|^2$$

strong phase (weak phases are trivial in charm)

[Cabibbo-suppressed]

$$\frac{\langle i \mid \overline{D}^0 \rangle}{\langle i \mid D^0 \rangle} = -re^{-i\delta}$$

[Cabibbo-favored]

magnitude

- D^0 strong phases are necessary inputs for
  - Charm mixing studies at *B*-factories, CDF, FOCUS
  - CKM studies at *B*-factories and LHCb

- This talk: CLEO-c $\psi(3770)$ measurements of strong phases in

$D^0 \to$ $K^+\pi^-$ $K^+\pi^-\pi^0$ $K^+\pi^-\pi^+\pi^-$ $K_{S,L}^0h^+h^-$ ($h = K$ or π)

Charm Mixing (no CPV)

- Flavor eigenstates (D^0, $\overline{D}^0$) $\neq$ mass eigenstates (D_1, D_2).

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

- Mixing characterized by $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta \Gamma}{2\Gamma}$

- y = (0.73 ± 0.14)%:
  - Direct lifetime measurements:
    - Compare K^+K^- and $\pi^+\pi^-$ with $K^-\pi^+$.
  - Time-dependent Dalitz analysis of $K^0_S\pi^+\pi^-$ and $K^0_SK^+K^-$
    - Intermediate CP-eigenstates give y.
    - Interference between CP+ and CP– gives x.

$$\frac{\langle K^-\pi^+ | \overline{D}^0 \rangle}{\langle K^-\pi^+ | D^0 \rangle} = -r_{K\pi} e^{-i\delta_{K\pi}}$$

DCS

CF

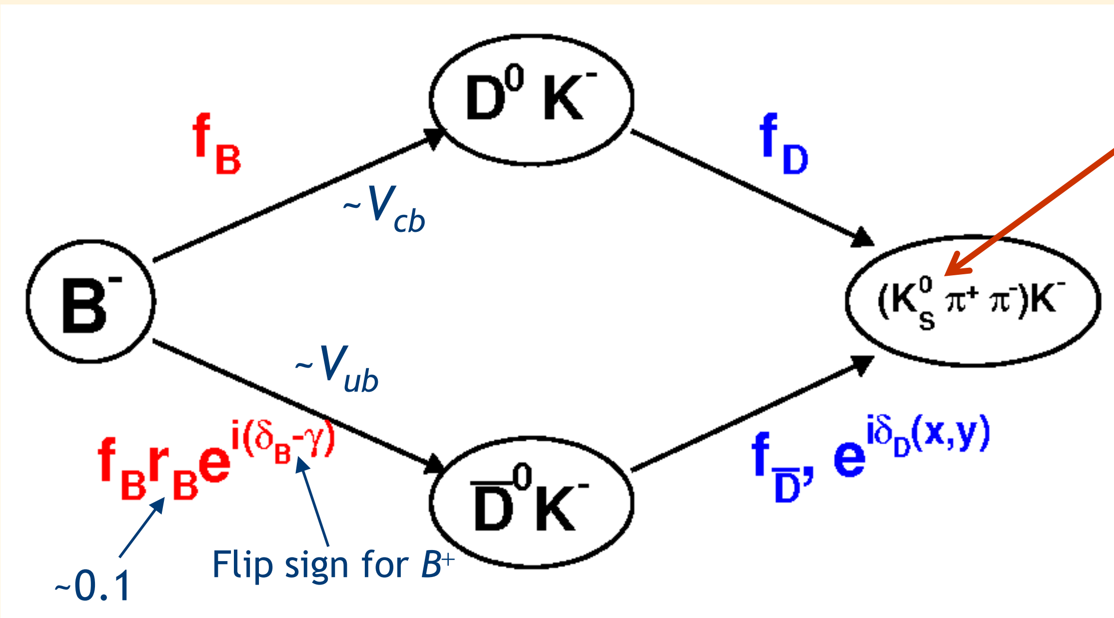
~0.06

- $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ = (0.48 ± 0.23)%
  - Time-dependent wrong-sign rate $D^0 \rightarrow K^+\pi^-$:
    - Interfering DCS and mixing amplitudes modulate exponential decay time.
    - Ambiguity from strong phase:

$\delta_{K\pi}$ connects measurements of y and y'

CKM Phenomenology for γ/ϕ_3

- Interference between $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$ is sensitive to γ/φ_3.
  - Need D final states that are common to D^0 and $\bar{D}^0$.



OR

$K^+\pi^-$

$K^+\pi^-\pi^0$

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

$K_{S,L}{}^0h^+h^-$

<u>For multibody decays:</u>

$$R_F e^{-i\delta_D^F} = \frac{\int |A(\mathbf{x})||\bar{A}(\mathbf{x})|e^{-i\zeta(\mathbf{x})}d\mathbf{x}}{A_F\bar{A}_F}$$

coherence factor $0 < R < 1$ (=1 for $K\pi$)

avg. strong phase

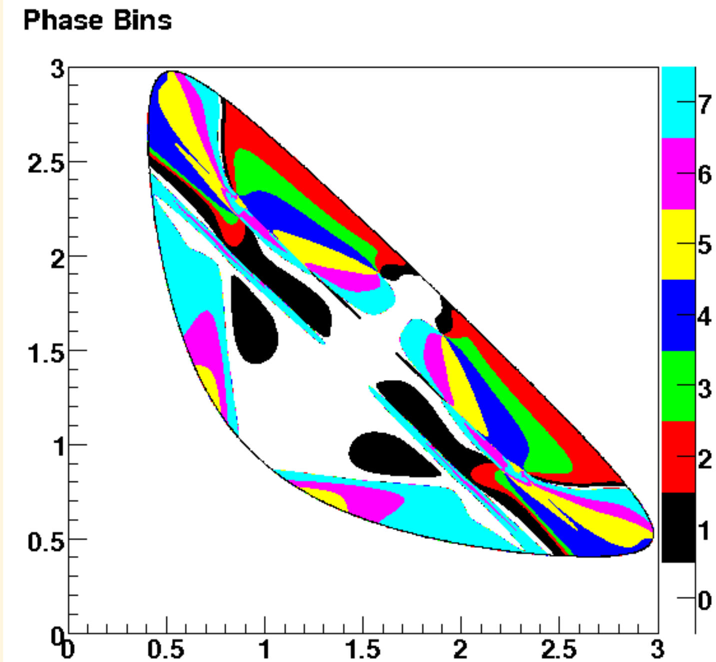
$\cos\delta \to R\cos\delta$

Need R & δ_D to extract γ	Accessible with $D^0\bar{D}^0$ quantum correlations

Removing Model Dependence in $K^0_{S,L} h^+h^-$

- Model-dependent $\delta_D(x,y)$ from amplitude analysis incurs model uncertainty of $\mathcal{O}(5^\circ)$ on γ/φ_3, independent of *B* decay statistics.

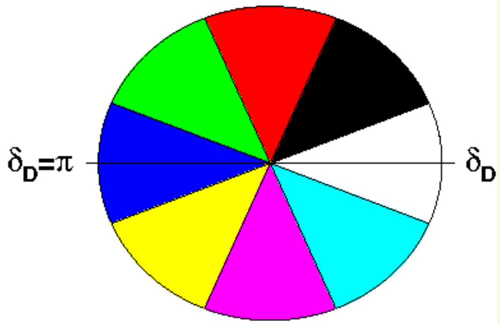
- Model independent analysis:
  - Divide Dalitz plot into bins.
  - 8 equal bins in predicted phase shown at right
  - Choice of bins coordinated with *B*-factories & LHCb.



Unknown strong phases:

16 symmetric bins

$\overline{c_i} = c_i \qquad \overline{s_i} = -s_i$



- Each bin is a separate decay mode with $c_i = R_i \cos\delta_i$ and $s_i = R_i \sin\delta_i$.
  - Bins with $\delta \sim 0$ or π act like *CP* eigenstates $\Rightarrow$ sensitive to cosines of phases.
  - Bins with $\delta \sim \pm\pi/2$ are sensitive to sines of phases.

Quantum-Correlated Decay Rates: ψ(3770)

Anti-symmetric wavefunction $\Gamma_{ij}^2 = \left| \langle i | D^0 \rangle \langle j | \overline{D^0} \rangle - \langle j | D^0 \rangle \langle i | \overline{D^0} \rangle \right|^2$

$$\frac{\langle i | \overline{D}^0 \rangle}{\langle i | D^0 \rangle} = -re^{-i\delta}$$

Final States			Time-Integrated Rate (x $A_i^2 A_j^2$)
Exclusive	i	$\bar{j}$	$1 + r_i^2 r_j^2 - 2 r_i\cos\delta_i r_j\cos\delta_j - 2 r_i\sin\delta_i r_j\sin\delta_j$
	i	j	$r_i^2 + r_j^2 - 2 r_i\cos\delta_i r_j\cos\delta_j + 2 r_i\sin\delta_i r_j\sin\delta_j$
Inclusive	i	X	$1 + r_i^2 + 2 \boxed{y} r_i\cos\delta_i$

No y dependence

Same as incoherent decay

$$y \propto 2\sum_i A_i^2 r_i \cos\delta_i$$

- For some final states, we know r and δ:
  - Semileptonic: r=0 *CP* eigenstates: r=1 and δ=0 or π
- Use *CP*-tagged exclusive rates to extract:
  - **$\cos\delta_{K\pi}$**: Reconstruct K^+K^- with $K^-\pi^+ \Rightarrow K^-\pi^+$ must come from D_1 (*CP*–).

$$\text{rate} \propto B_{KK}(1+y)B_{K\pi}\left|1+re^{-i\delta}\right|^2 \approx B_{KK}B_{K\pi}(1+2r\cos\delta + R_{WS} + y)$$

$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$
$= r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$

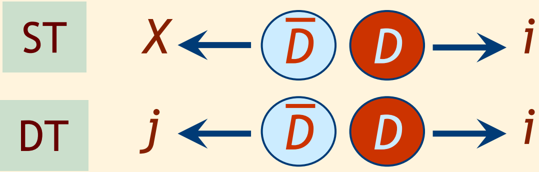
  - **y** at first order:
    - Reconstruct K^+K^- (*CP*+) with semileptonic $\Rightarrow$ SL must be D_1 (*CP*–).
    - Semileptonic width independent of *CP*, but total width depends on *CP*.

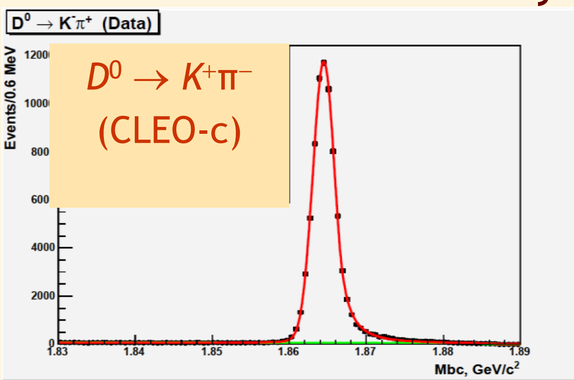
$$n_{e/KK} / n_{KK(ST)} = B_e\Gamma/\Gamma_1 = B_e/(1-y)$$

Experimental Technique

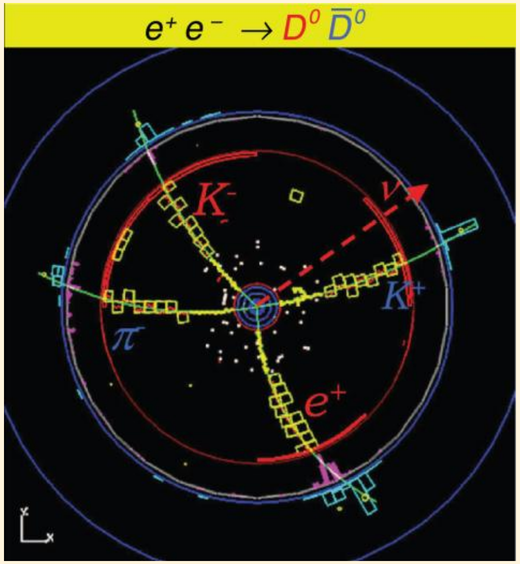
- Single tag: fully reconstruct one D
- Double tag: reconstruct both D^0 and $\bar{D}^0$
  - Both D^0 and $\bar{D}^0$ fully reconstructed.

Pair-produced D^0 and $\bar{D}^0$

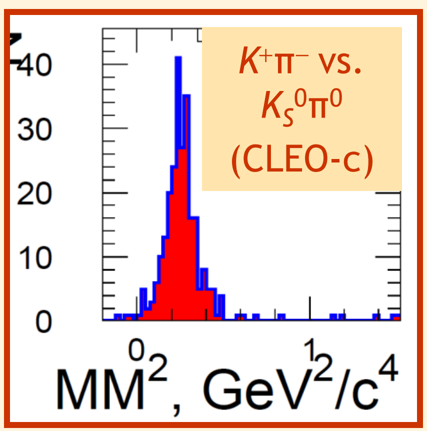




$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$



  - Or one missing particle (ν or K^0_L):



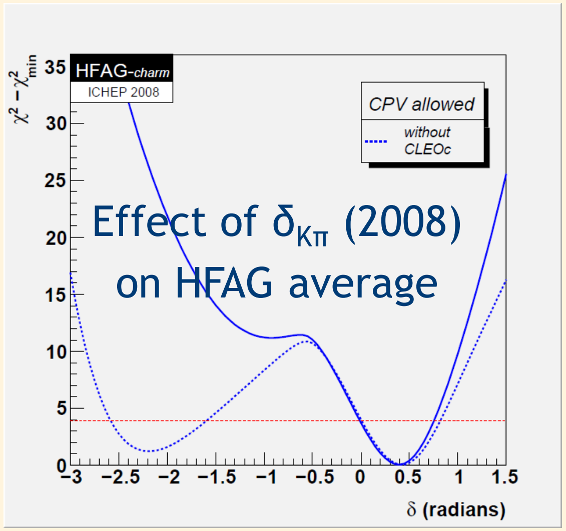
Use detector hermeticity and beam parameters to infer missing mass.

Clean event environment, very low backgrounds

Update: Strong Phase in $D^0 \to K\pi$ $[\delta_{K\pi}]$

- Previous publication: PRL 100, 221801 (2008) / PRD 78, 012001 (2008).
  - Dataset: 281 pb^{-1} at $\psi(3770)$ [*C*-odd initial state]
  - First meas. of strong phase between CF $A(D^0 \to K^-\pi^+)$ and DCS $A(D^0 \to K^+\pi^-)$.
  - Standard fit: $\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$
  - Extended fit: $\cos\delta = 1.10 \pm 0.35 \pm 0.07$
    $x \sin\delta = (4.4^{+2.7}_{-1.8} \pm 2.9) \times 10^{-3}$
    [Incl. external mixing meas.]

Type	Final States
Flavored	$K^-\pi^+$, $K^+\pi^-$
S_+	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$
S_-	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$
$e^\pm$	Inclusive $Xe^+\nu_e$, $Xe^-\bar{\nu}_e$



- **New today**: preliminary update with full CLEO-c dataset
  - 818 pb^{-1} at $\psi(3770)$.
  - Additional final states.
    - Includes direct measurements of $r_{K\pi}^2$ and $\sin\delta_{K\pi}$.

Not yet in HFAG average

Final States [$\delta_{K\pi}$]

- Single tags for all fully-reconstructed modes except $K^0_S\pi^+\pi^-$.
- Double tags for almost all combinations of modes.
  - Like-sign and opposite-sign.
  - At most one missing particle (K^0_L or ν).
    - Except for $Ke\nu$ vs. $K^0_L\pi^0$ (2 missing particles).
- 261 yield measurements
  - $K^0_S\pi^+\pi^-$ from PRD 80, 032002 (2009)

~1400 $K^0_S\pi^+\pi^-$ vs. $K\pi$ → $\sin\delta_{K\pi}$

~3000 CP-tagged $K\pi$ → $\cos\delta_{K\pi}$

Flavored hadronic	CP+	CP–	Semilep	Mixed
$K^-\pi^+$	K^-K^+	$K^0_S\pi^0$	$K^-e^+\nu$	$K^0_S\pi^+\pi^-$ (bin 0)
$K^+\pi^-$	$\pi^-\pi^+$	$K^0_S\eta$	$K^+e^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 1)
	$K^0_S\pi^0\pi^0$	$K^0_S\omega$	$K^-\mu^+\nu$	$K^0_S\pi^+\pi^-$ (bin 2)
	$K^0_L\pi^0$	$K^0_L\pi^0\pi^0$	$K^+\mu^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 3)
	$K^0_L\eta$			$K^0_S\pi^+\pi^-$ (bin 4)
	$K^0_L\omega$	New in update		$K^0_S\pi^+\pi^-$ (bin 5)
				$K^0_S\pi^+\pi^-$ (bin 6)
				$K^0_S\pi^+\pi^-$ (bin 7)

~3500 CP-tagged $Kl\nu$ → y

~30 WS $Kl\nu$ vs. $K\pi$ → $r_{K\pi}^2$

Semi-Muonic Decays $[\delta_{K\pi}]$

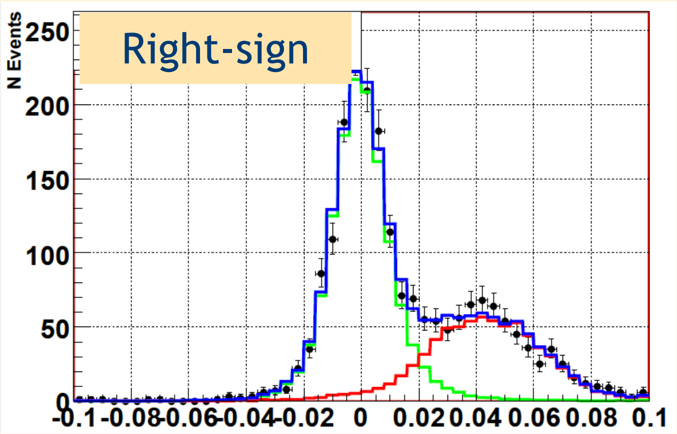
CLEO-c Preliminary

- CLEO muon chambers inefficient below 1 GeV.
- Identify right-sign $D^0 \to K^-\mu^+\nu$ using missing energy and momentum.
  - Main background: $D^0 \to K^-\pi^+\pi^0$ separated kinematically.
- Wrong-sign uses similar technique, but 300x lower yield.
  - Main background: mis-ID $K\pi$ flavor in RS decays.
  - Dramatically reduced by requiring kaon to be in Cherenkov counter acceptance.
    - S/(S+B) goes from 50% to 97%.
  - Combined $Ke\nu/K\mu\nu$ relative uncertainty ~25%.
- Unlike with incoherent D^0, wrong-sign gives r^2, not R_{WS}.

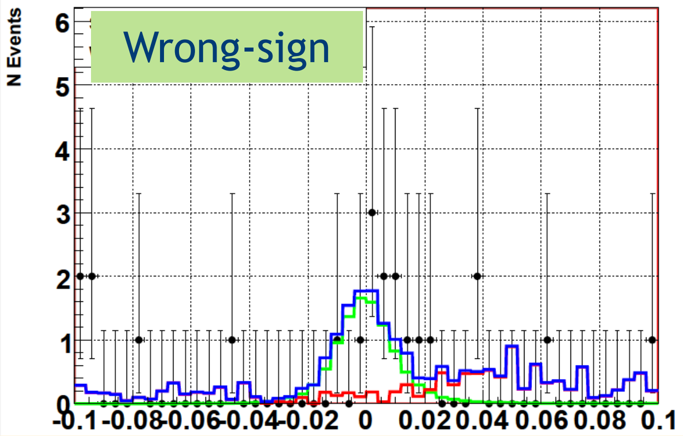
$$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+) = r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$$

  - Mixing effects cancel in the interference term

$K\mu\nu$ vs. $K\pi$



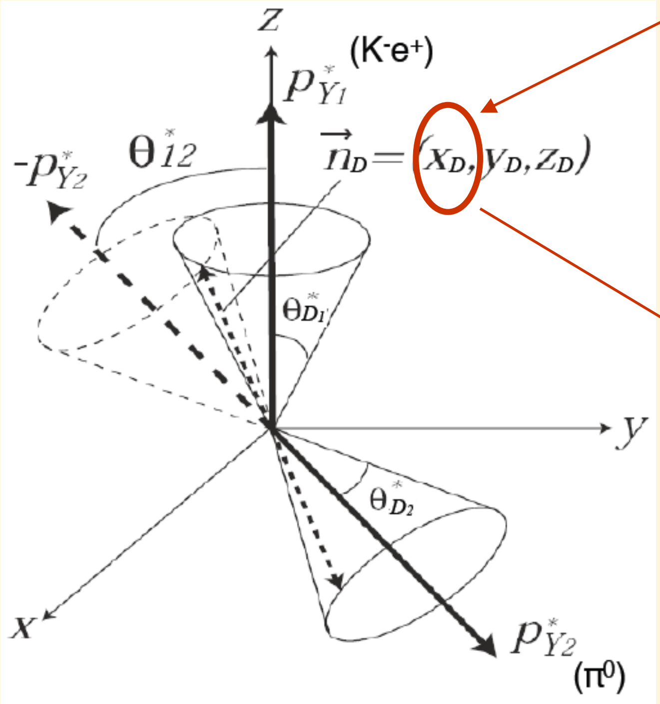
$U = E_{miss} - |P_{miss}|$

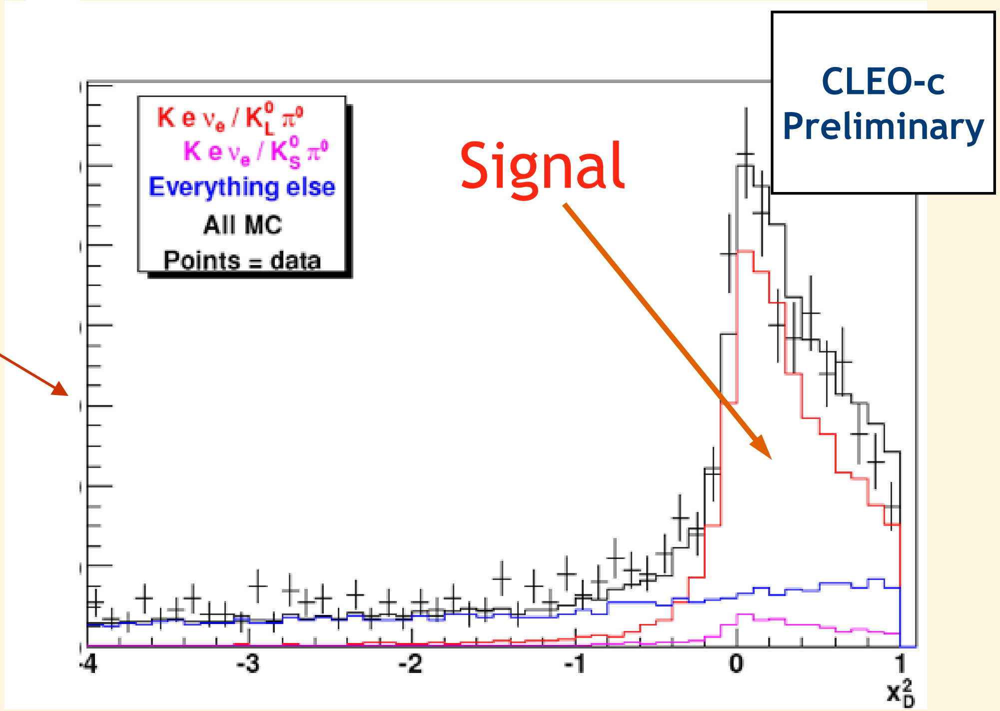


$K e \nu$ vs. $K_L \pi^0$ $[\delta_{K\pi}]$

Paar/Brower: NIM A 421, 411 (1999)
BaBar: PRL 97, 211801 (2006)
Belle: PLB 648, 139 (2007)

- Doubles the number of *Keν* vs. *CP*+
- Technique for two missing particles:
  - Used at B-factories for semileptonic decays
  - Kinematic constraints on ν and K^0_L define two cones for D^0 and $\overline{D^0}$.
  - If cones intersect, then $0 < x_D^2 < 1$.



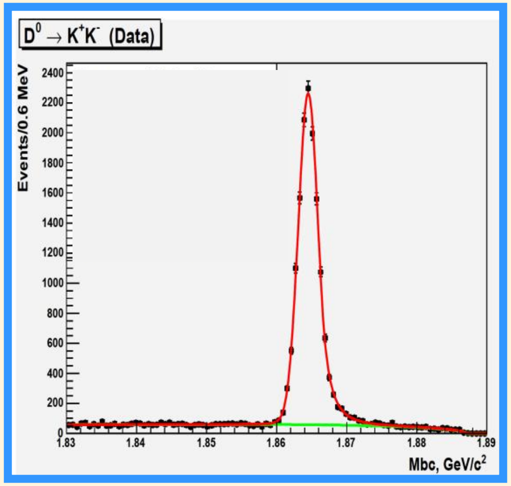


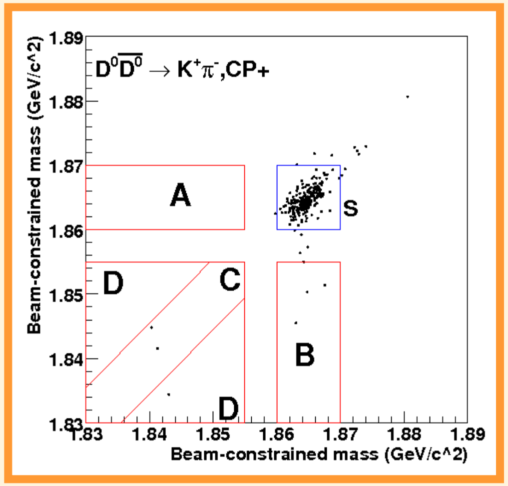
Other Yield Measurements $[\delta_{K\pi}]$

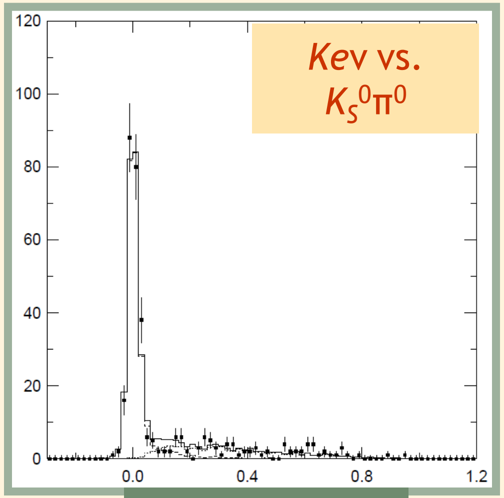
- Fully-reconstructed single tags:
  - Fit beam-constrained mass distribution.

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

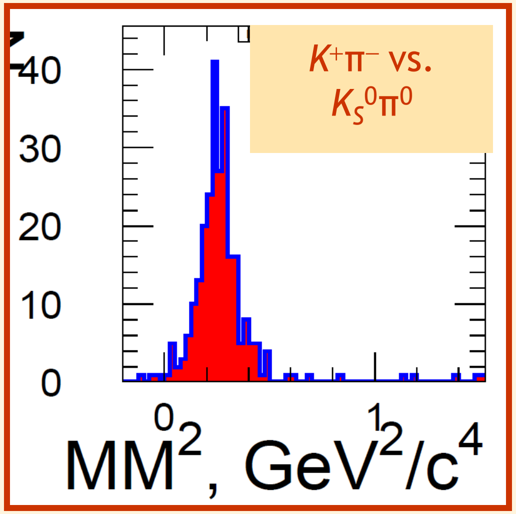
- Fully-reconstructed double tags:
  - Two fully-reconstructed STs
  - Count events in 2D M_{BC} plane.
- Exclusive *Kev* DTs:
  - One fully-reconstructed ST
  - Plus one *K* and one *e* candidate
  - Fit *U* distribution
- K^0_L $\{\pi^0, \eta, \omega, \pi^0\pi^0\}$ DTs:
  - One fully-reconstructed ST
  - Plus $\{\pi^0, \eta, \omega, \pi^0\pi^0\}$ candidate
  - Compute missing mass-squared
    - Signal peaks at $M^2(K^0)$.







$U = E_{miss} - |P_{miss}|$



Fit Results $[\delta_{K\pi}]$

CLEO-c Preliminary

- 51 free parameters
  - N_{DD}, 21 branching fractions
  - 24 amplitude/phase parameters for $K^0_S\pi^+\pi^-$
  - 5 $K\pi$ and mixing parameters
- Fit performed with and without external measurements of y, x, y' (same as in HFAG May 2010 avg.)
- Statistical uncertainties on $\boldsymbol{y}$ and $\boldsymbol{r_{K\pi}\cos\delta_{K\pi}}$ (w/o ext. meas.) 3x smaller than 2008 analysis.
  - Estimated impact on HFAG average: $\sigma(y)$ reduced by ~10%
  - First direct measurements of $r_{K\pi}^2$ and $\sin\delta_{K\pi}$
- Preliminary systematics.

Parameter	Previous: PDG, HFAG, or CLEO	Fit: no ext. meas.	Fit: with ext. y, x, y'
y (10^{-2})	0.79 ± 0.13	3.0 ± 2.0 ± 1.2	**0.635 ± 0.118**
x^2 (10^{-3})	0.037 ± 0.024	1.5 ± 2.0 ± 0.9	0.022 ± 0.017
$r_{K\pi}^2$ (10^{-3})	3.32 ± 0.08	4.12 ± 0.92 ± 0.23	3.32 ± 0.08
$\cos\delta_{K\pi}$	1.10 ± 0.36	**$0.98\ ^{+0.27}_{-0.20} \pm 0.08$**	**1.15 ± 0.16 ± 0.12**
$\sin\delta_{K\pi}$	---	**-0.04 ± 0.49 ± 0.08**	**$0.55\ ^{+0.36}_{-0.40} \pm 0.08$**
$\delta_{K\pi}$ (°) [derived]	$22\ ^{+11}_{-12}\ ^{+9}_{-11}$	0 ± 22 ± 6	$15\ ^{+11}_{-17} \pm 7$

Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ (now limited by $\sin\delta_{K\pi}$)

Likelihood Contours $[\delta_{K\pi}]$

CLEO-c Preliminary

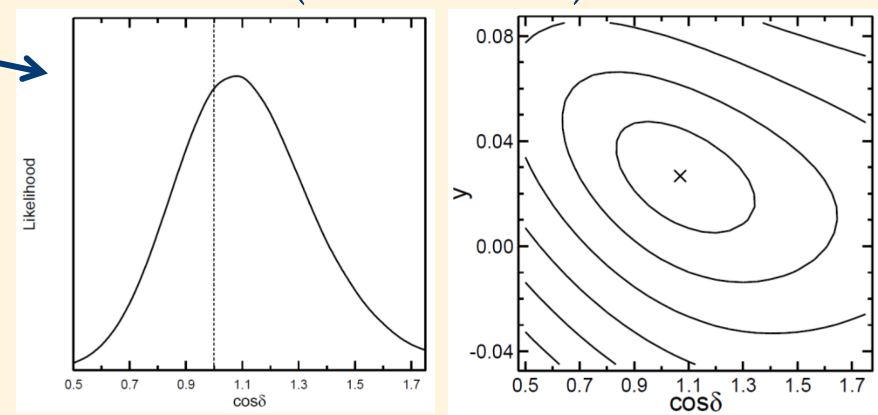
- Improved likelihood behavior over 2008 publication:
  - Previous nonlinearities from use of R_{WS} to derive $r_{K\pi}^2$

$$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$$
$$= r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$$

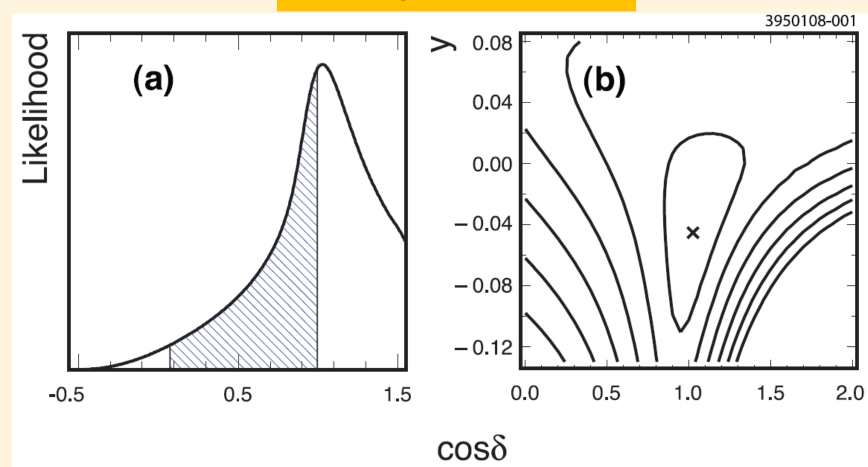
  - Solved by our new independent measurement of $r_{K\pi}^2$ (WS $Kl\nu$ vs. $K\pi$)
  - Will give more robust averages with other experiments (HFAG)

New prelim. results – statistics only

(no ext. meas.)



2008 publication



Strong Phase in $D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^-\pi^+$

- Published result using 818 pb^{-1} of $\psi(3770)$ data
  - [PRD 80, 031105(R) (2009)]
- Similar formalism for $K\pi$, except now include coherence factors (R) for multi-body decay as free parameters.

Type	Final states
Flavored	$K^\mp\pi^\pm$, $K^\mp\pi^\pm\pi^\pm\pi^\mp$, $K^\mp\pi^\pm\pi^0$
CP-even	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$
CP-odd	$K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\phi$, $K^0_S\eta$, $K^0_S\eta'$

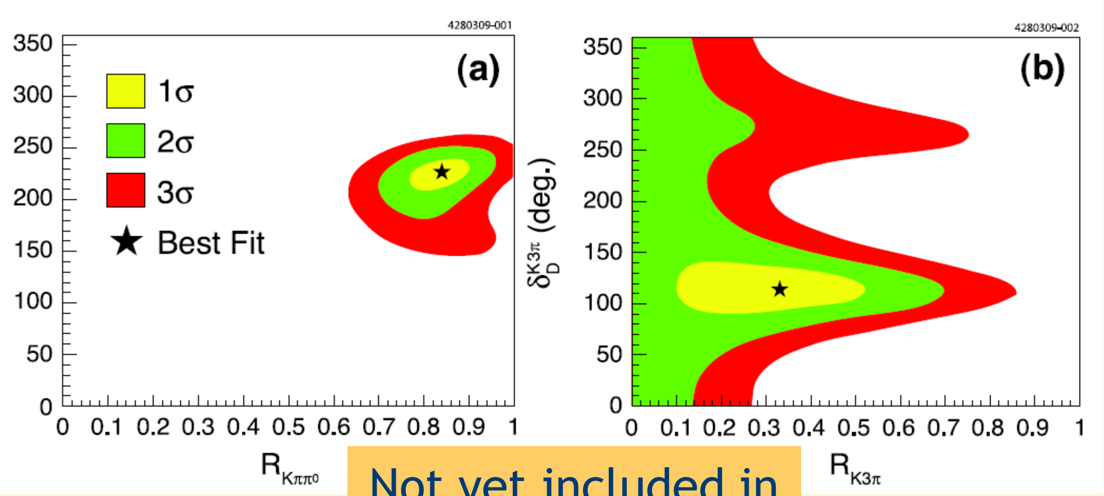
total CP-tagged events	~3200 vs. $K^+\pi^-\pi^+\pi^-$ ~4700 vs. $K^+\pi^-\pi^0$

- No single tags — estimate from external branching fractions

$D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^-\pi^+$ Results

- Low coherence in $K3\pi$ has advantages:
  - Gives sensitivity to y comparable to $K\pi$ analysis
  - Also increases sensitivity to r_B
- Expect ~40% reduction in error on γ/φ_3.
- Also useful for HFAG mixing average:
  - But first need to convert average $K^+\pi^-\pi^0$ phase to $K^*\pi$ phase

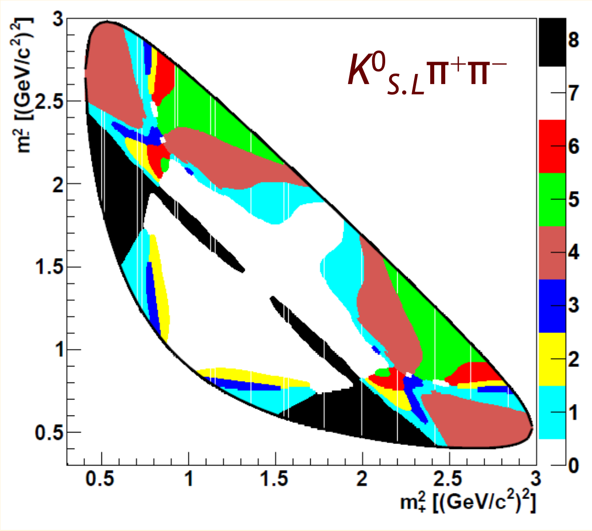
Parameter	Mixing constrained	Mixing unconstrained
$R_{K\pi\pi^0}$	0.84 ± 0.07	$0.78^{+0.11}_{-0.25}$
$\delta_D^{K\pi\pi^0}$ (°)	227^{+14}_{-17}	239^{+32}_{-28}
$R_{K3\pi}$	$0.33^{+0.26}_{-0.23}$	$0.36^{+0.24}_{-0.30}$
$\delta_D^{K3\pi}$ (°)	114^{+26}_{-23}	118^{+62}_{-53}
x (%)	0.96 ± 0.25	$-0.8^{+2.9}_{-2.5}$
y (%)	0.81 ± 0.16	$0.7^{+2.4}_{-2.7}$
$\delta_D^{K\pi}$	$-151.5^{+9.6}_{-9.5}$	-130^{+38}_{-28}

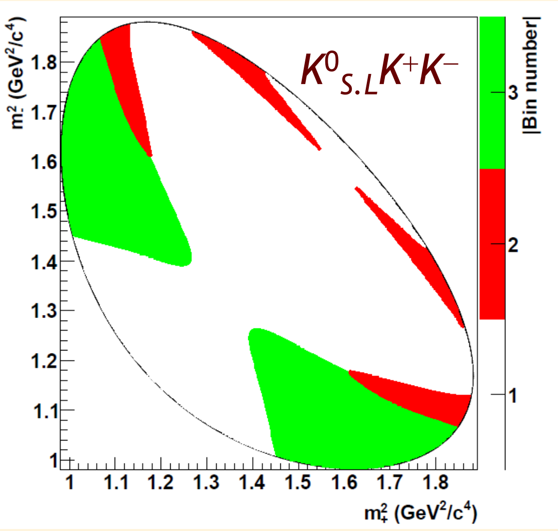


Not yet included in HFAG average

Update: Strong Phase in $D^0 \to K^0_{S,L} h^+h^-$

- Previous results on $K^0_{S.L}\pi^+\pi^-$ using 818 pb^{-1} of ψ(3770) data:
  - PRD 80, 032002 (2009), 8 equal phase bins [used in $\delta_{K\pi}$ analysis]
- <u>**New today**</u>: updated results with same dataset.
  - Phase binning optimized for precision on γ/φ_3.
    - Different schemes explored.
  - Add $K^0_{S.L}K^+K^-$:
    - Use {2, 3, 4} bins instead of 8 because of lower statistics.





total CP-tagged events for c_i
~800 vs. $K^0_{S.L}\pi^+\pi^-$
~4700 vs. $K^0_{S.L}K^+K^-$

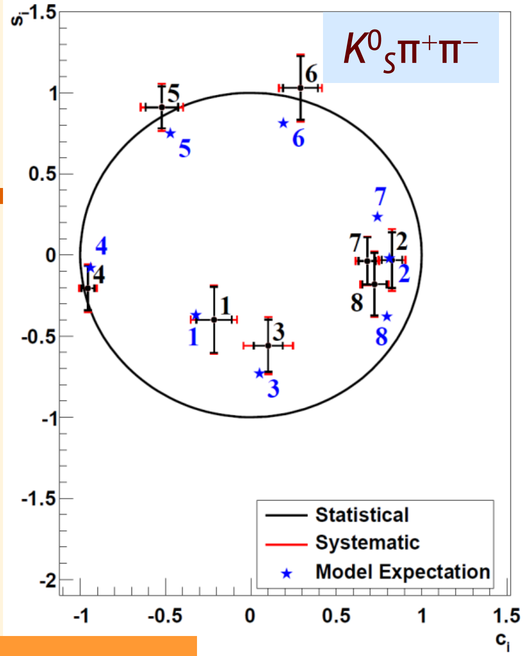
~2000 total $K^0_{S.L}h^+h^-$ vs. $K^0_{S.L}h^+h^-$ events for s_i

$D^0 \to K^0_{S,L}\, h^+h^-$ Results

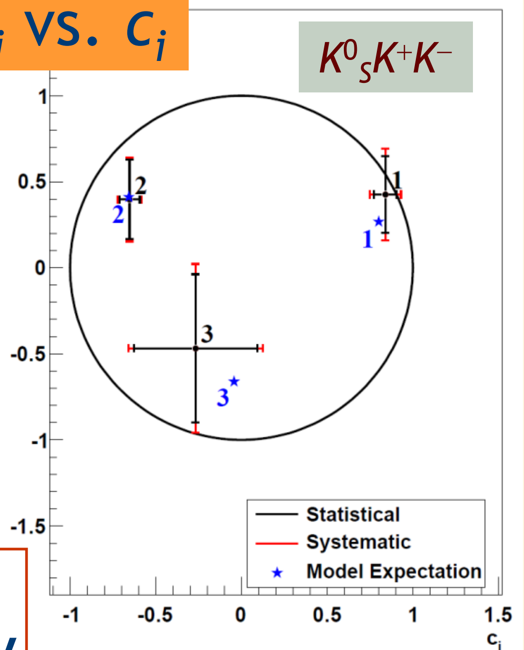
- One set of binning choices shown at right.

- For most binning schemes, induced uncertainty on γ/φ_3 is smaller than current model uncertainty of 3 to 9 degrees:
  - arXiv:1005.1096 [BaBar]
  - PRD 81, 112002 (2010) [Belle]

- Also useful for mixing studies at *B*-factories:
  - Time-dependent Dalitz plot fit of $K_S^0 h^+ h^-$ determines x and y simultaneously.
  - Depends on knowing strong phase across Dalitz plot.
  - Could be done w/o model dependence using CLEO-c measurements.



s_i vs. c_i



CLEO-c Preliminary

Summary and Outlook

- Quantum-correlated CLEO-c dataset has yielded direct determinations of amplitudes and strong phases in D^0 decays.

$$D^0 \rightarrow \quad K^+\pi^- \quad K^+\pi^-\pi^0 \quad K^+\pi^-\pi^+\pi^- \quad K_{S,L}^0 h^+h^-$$

  - All measurements are statistics-limited.
  - Already significant impact on charm mixing and CKM studies.

- BES-III has exceeded CLEO's ψ(3770) dataset.
  - Should be able to improve on CLEO-c results.
  - Eventually:
    - Competitive measurements of mixing parameters.
    - Use C=+1 $D^0D^0\gamma$ from higher-energy data.
      - Orthogonal sensitivity to mixing parameters and strong phases.
    - Access to CP violation.
- Many more possibilities to explore!

BACKUP

External Measurements $[\delta_{K\pi}]$

Table 5: External measurements of y and y' with associated measurements of r^2 and x'^2.

Parameter	Value (%)	Source	Average (%)		
y_{CP}		HFAG	1.107 ± 0.217		
x	$1.9^{+3.2}_{-3.3} \pm 0.4 \pm 0.4$	CLEO II.V [47]	0.419 ± 0.211 [41]		
	$0.80 \pm 0.29 \pm 0.17$	Belle [48]			
	$0.16 \pm 0.23 \pm 0.12 \pm 0.08$	BABAR			
y	$-1.4 \pm 2.4 \pm 0.8 \pm 0.4$	CLEO II.V [47]	0.456 ± 0.186 [41]		
	$0.33 \pm 0.24 \pm 0.15$	Belle [48]			
	$0.57 \pm 0.20 \pm 0.13 \pm 0.07$	BABAR			
			Correlation Coefficients		
r^2	0.364 ± 0.017	Belle [50]	1	-0.834	$+0.655$
y'	$0.06^{+0.40}_{-0.39}$			1	-0.909
x'^2	$0.018^{+0.021}_{-0.023}$				1
r^2	$0.303 \pm 0.016 \pm 0.010$	BABAR [51]	1	-0.87	$+0.77$
y'	$0.97 \pm 0.44 \pm 0.31$			1	-0.94
x'^2	$-0.022 \pm 0.030 \pm 0.021$				1
r^2	0.304 ± 0.055	CDF	1	-0.971	$+0.923$
y'	0.85 ± 0.76			1	-0.984
x'^2	-0.012 ± 0.035				1
r^2	0.333 ± 0.011	Average	1	-0.848	$+0.701$
y'	0.48 ± 0.23			1	-0.942
x'^2	0.002 ± 0.012				1

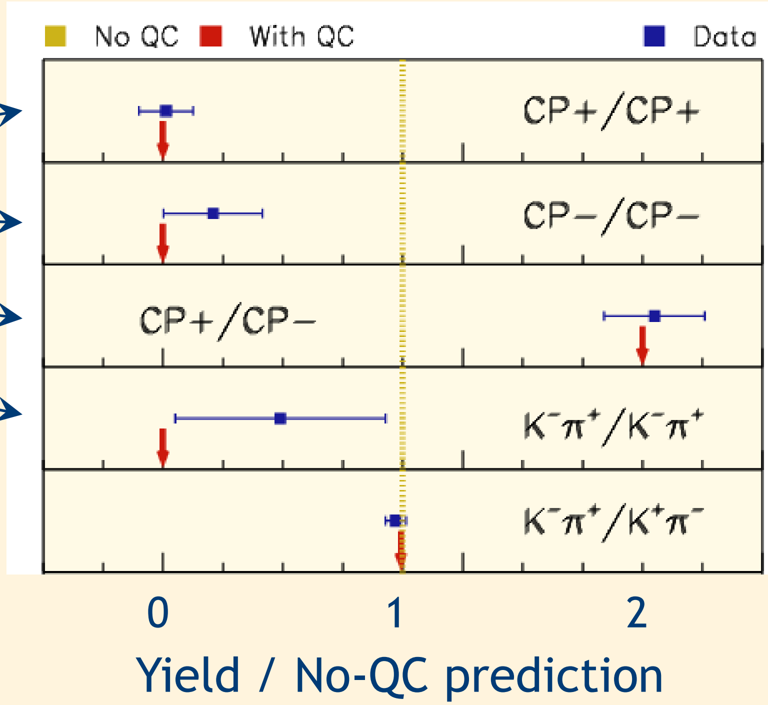
Coherent vs. Incoherent Decay

$C = -1$

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

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 (gives cosδ)	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP±* $K^-\pi^+$ *SL*	X

- Overview of quantum correlation effects:



Quantum correlations are seen in data!