Charm Mixing and Strong Phases at Threshold

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4th International Workshop on Charm Physics, Beijing, China

Introduction

Formalism

Experimental results

Summary and outlook

Threshold Charm Production

Action at a distance!

- 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

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

[Cabibbo-suppressed]

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

[Cabibbo-favored]

magnitude

strong phase (weak phases are trivial in charm)

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

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

$D^0 \to K^+\pi^-$ $K^+\pi^-\pi^0$ $K^+\pi^-\pi^+\pi^-$ $K_{S,L}{}^0 h^+h^-$ ($h = K$ 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 $y = \frac{\Delta\Gamma}{2\Gamma}$
- $y = (0.73 \pm 0.14)\%$:
  - 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*.

$$\frac{\langle K^-\pi^+ | \overline{D^0}\rangle_{\text{DCS}}}{\langle K^-\pi^+ | D^0\rangle_{\text{CF}}} = -\underbrace{\boxed{r_{K\pi}}}_{\sim 0.06} e^{-i\delta_{K\pi}}$$

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

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

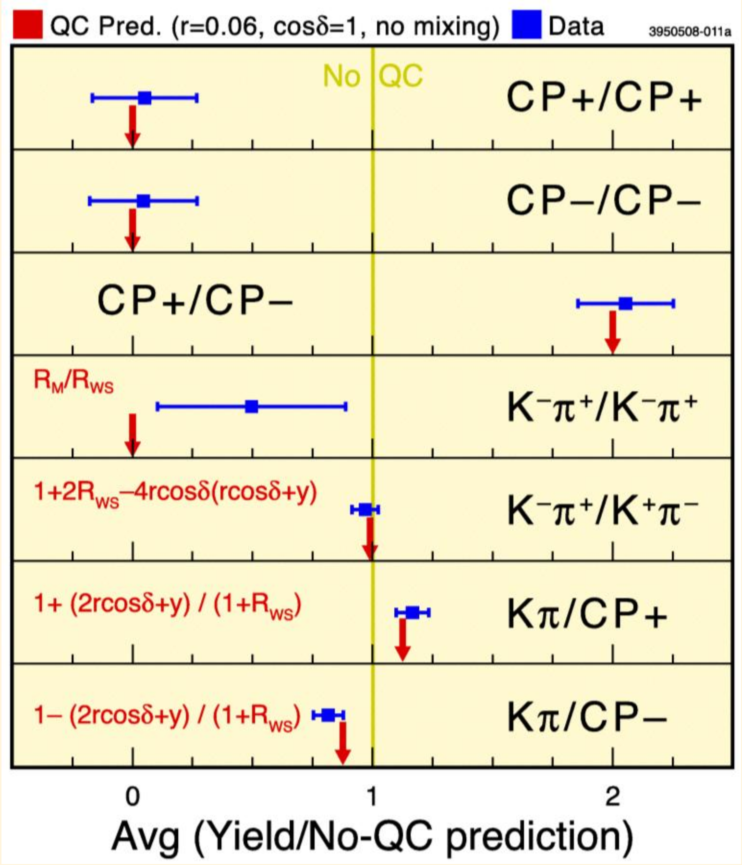
Quantum-Correlations Overview: $\psi(3770)$

$C = -1$

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

	D^0	$\bar{D}^0$
Forbidden by CP conservation	*CP+*	*CP+*
	CP–	*CP–*
<u>Maximal enhancement</u>	*CP+*	*CP–*
<u>Forbidden if no mixing</u>	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS (gives $\cos\delta_{K\pi}$)	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP±* $K^-\pi^+$ *SL*	X

Quantum correlations are seen in data!



Quantum-Correlated Decay Rates: ψ(3770)

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

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

  Anti-symmetric wavefunction

Selected references:
- Goldhaber & Rosner, PRD 15, 1254 (1977)
- Bigi & Sanda, PLB 171, 320 (1986)
- Xing, PRD 55, 196 (1997)
- Gronau, Grossman, Rosner, PLB 508, 37 (2001)
- Atwood & Petrov, PRD 71, 054032 (2005)
- Asner & Sun, PRD 73, 034024 (2006); PRD 77, 019901(E) (2008)

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

No y dependence

Same as incoherent decay

- Interference with mixed amplitudes vanishes for $C = -1$
  - Exclusive rates probe bare amplitudes and strong phases directly.
- Inclusive rates come from summing exclusive rates.
  - Dependence on y appears in the sum.
  - Interference between unmixed and mixed+DCS amplitudes.

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

Extracting Physical Parameters from Yields

DT rate ~ $A_i^2 A_j^2 [\, 1 + r_i^2 r_j^2 - 2\, r_i r_j \cos(\delta_i + \delta_j)\,]$

- For some final states, we know r and δ: reference points for interference
  - *CP* eigenstates: r=1 and δ=0 or π — sensitive to **cosδ** of the other side.
  - Semileptonic: r=0 — sensitive to $\boldsymbol{A^2}$ and $\boldsymbol{r^2}$ of the other side.
  - To probe **sinδ**, need to interfere with a final state with $\delta \neq 0$ or π.

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

- Use *CP*-tagged exclusive rates to extract:
  - **$\cos\delta_{K\pi}$**: reconstruct K^+K^- (*CP*+) with $K^-\pi^+ \Rightarrow K^-\pi^+$ must come from D_1 (*CP*–).

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

  - **y**: reconstruct K^+K^- (*CP*+) with semileptonic $\Rightarrow$ SL must come from D_1 (*CP*–).
    - Semileptonic width independent of *CP*, but total width depends on *CP*.

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

- Mixing/amplitude/phase parameters from double ratios of yields:

$$y + 2r\cos\delta \approx \frac{n(f,\bar{f})}{4n(f)}\left[\frac{n(CP-)}{n(CP-,f)} - \frac{n(CP+)}{n(CP+,f)}\right] \qquad y \approx \frac{n(f,l)}{4n(f)}\left[\frac{n(CP-)}{n(CP-,l)} - \frac{n(CP+)}{n(CP+,l)}\right]$$

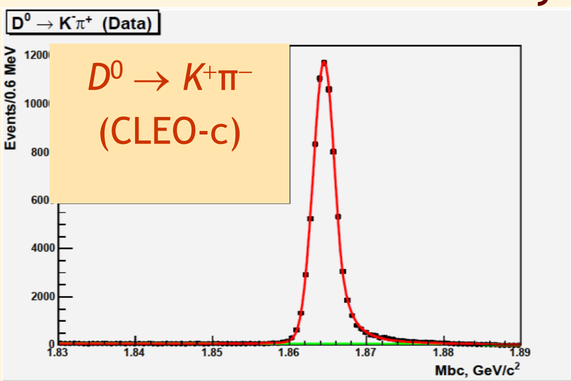
Experimental Technique

- 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 $\bar{D}^0$

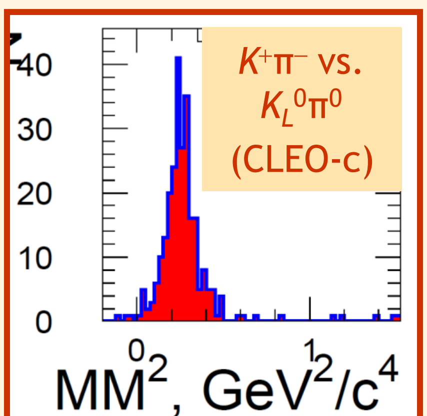
ST $X \leftarrow \bar{D}\ D \rightarrow i$

DT $j \leftarrow \bar{D}\ D \rightarrow i$

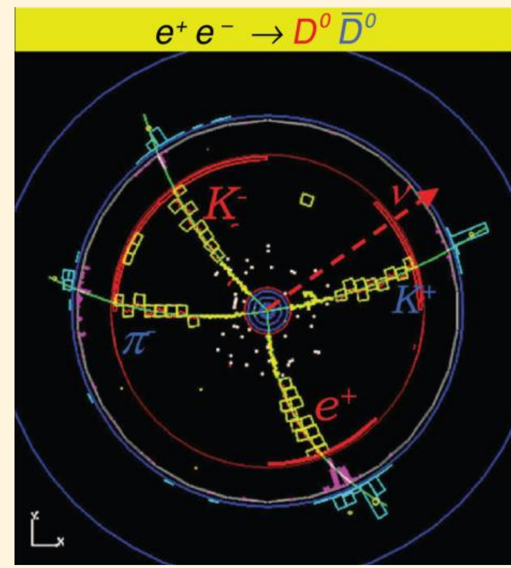


$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

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



Use detector hermeticity and beam parameters to infer missing mass.



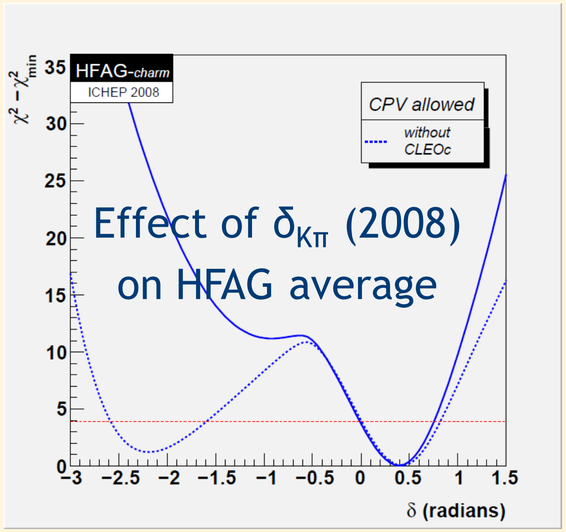
Clean event environment, very low backgrounds

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 $\psi(3770)$ = 1 million *C*-odd $D^0\bar{D}^0$
  - 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: $\cos\delta = 1.10 \pm 0.35 \pm 0.07$

    [Incl. external mixing meas.] $x\sin\delta = (4.4^{+2.7}_{-1.8} \pm 2.9) \times 10^{-3}$

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 $\psi(3770)$ = 3 million *C*-odd $D^0\bar{D}^0$.
  - 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. $K\pi$
→ $r_{K\pi}^2$

Fit Parameters

- 51 fit parameters (3.5x TQCA-I)
- Number of DD pair and 21 branching fractions (8 for $K^0{}_S\pi^+\pi^-$)
  - $\mathcal{B}(K^-\mu^+\nu)$, $\mathcal{B}(K^0{}_L\eta)$, $\mathcal{B}(K^0{}_L\pi^0\pi^0)$ will be new CLEO-c measurements.

- We fit for all non-trivial r and $\cos\delta$ and $\sin\delta$ (9 fit parameters each), plus mixing parameters y and x^2.
  - ST yield f ~ Br ~ $1 + r_f^2 + 2\,y\,r_f\cos\delta_f$
  - DT yield f/g ~ $1 + r_f^2\,r_g^2 - 2\,r_f\cos\delta_f\,r_g\cos\delta_g - 2\,r_f\sin\delta_f\,r_g\sin\delta_g$
  - DT yield f/gbar ~ $r_f^2 + r_g^2 - 2\,r_f\cos\delta_f\,r_g\cos\delta_g + 2\,r_f\sin\delta_f\,r_g\sin\delta_g$

  - Semileptonic: $r = 0$
  - CP+: $r = 1,\ \delta = \pi$
  - CP-: $r = 1,\ \delta = 0$

- Main focus is on $\delta_{K\pi}$, with secondary focus on y.

$K^0{}_S\pi^+\pi^-$ and $K^0{}_L\pi^+\pi^-$

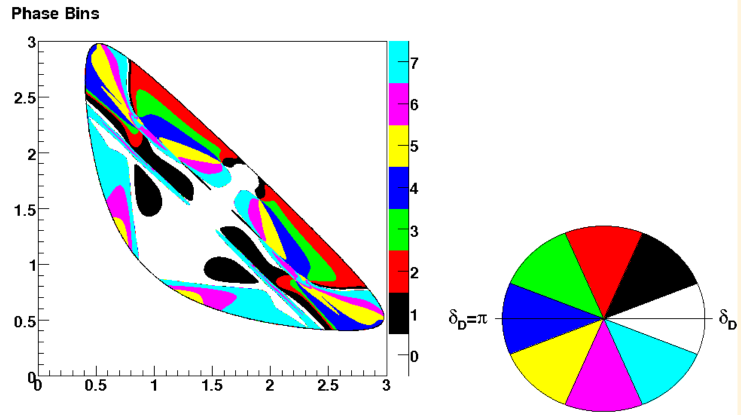
Phys.Rev.D80:032002,2009
arXiv:0903.1681

- CLEO-c has studied strong phases in $D \to K^0{}_S\pi^+\pi^-$
  - Main tool: CP tagging, analogous to $K\pi$.
  - For multibody modes, must also account for coherence:

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

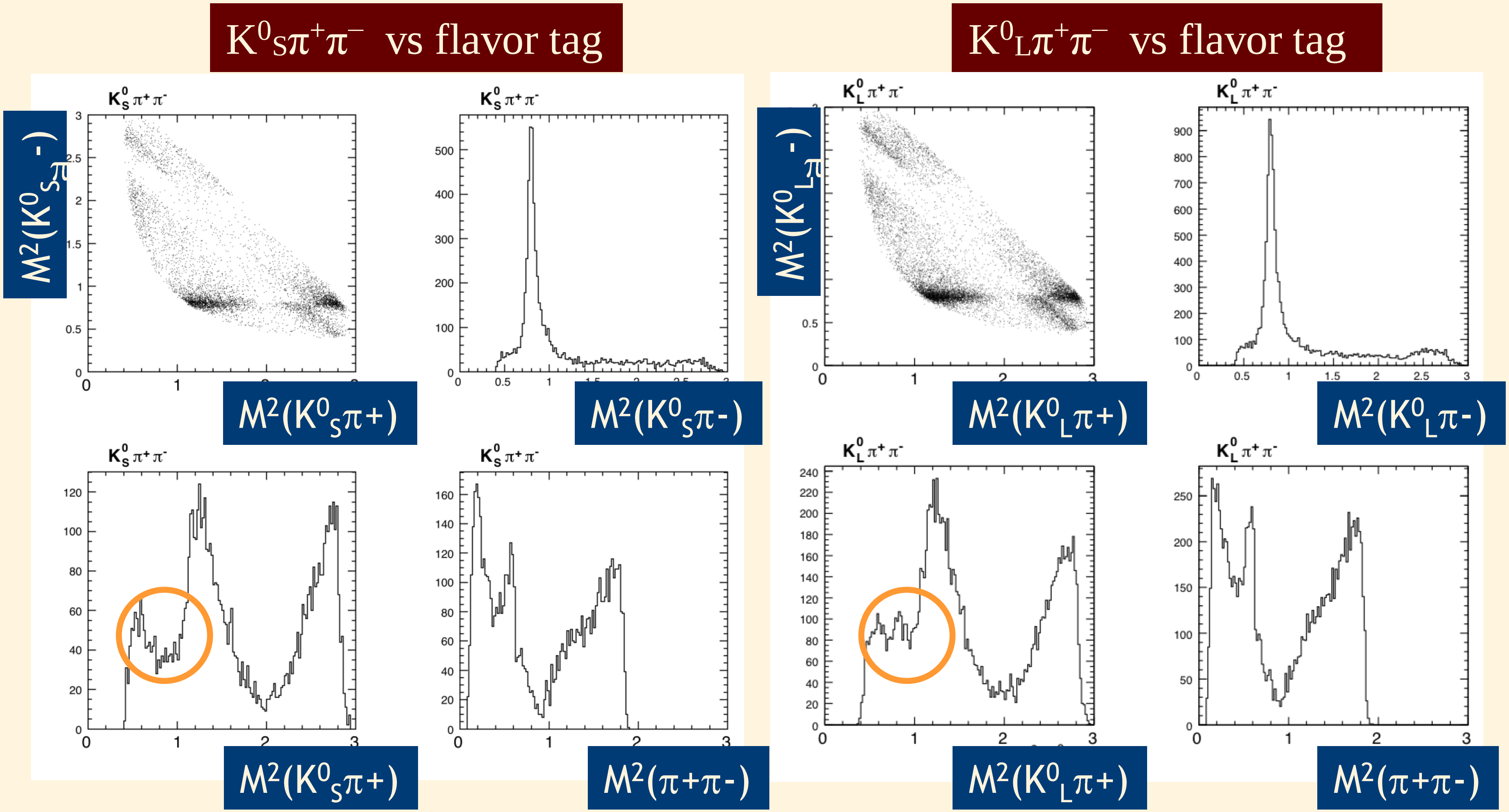
coherence factor

average strong phase



  - Measure yields in 8 Dalitz plot bins against CP/$K\pi$/SL/$K^0{}_S\pi^+\pi^-$ tags:
    - Use missing mass technique for $K^0{}_L\pi^+\pi^-$. Single tags for $K^0{}_S\pi^+\pi^-$ only, not $K^0{}_L\pi^+\pi^-$.
  - Each bin treated as separate decay mode with its own $R\cos\delta$ and $R\sin\delta$.
    - Bins with $\delta \sim 0$ or π act like *CP* eigenstates.
      - Statistics roughly equal to sum of all other (pure) *CP* eigenstates.
    - Bins with $\delta \sim \pm\pi/2$ allows measurement of $\sin\delta_{K\pi}$.
    - Include $R\cos\delta$ and $R\sin\delta$ as free parameters in fit.

$K^0_S\pi^+\pi^-$ & $K^0_L\pi^+\pi^-$

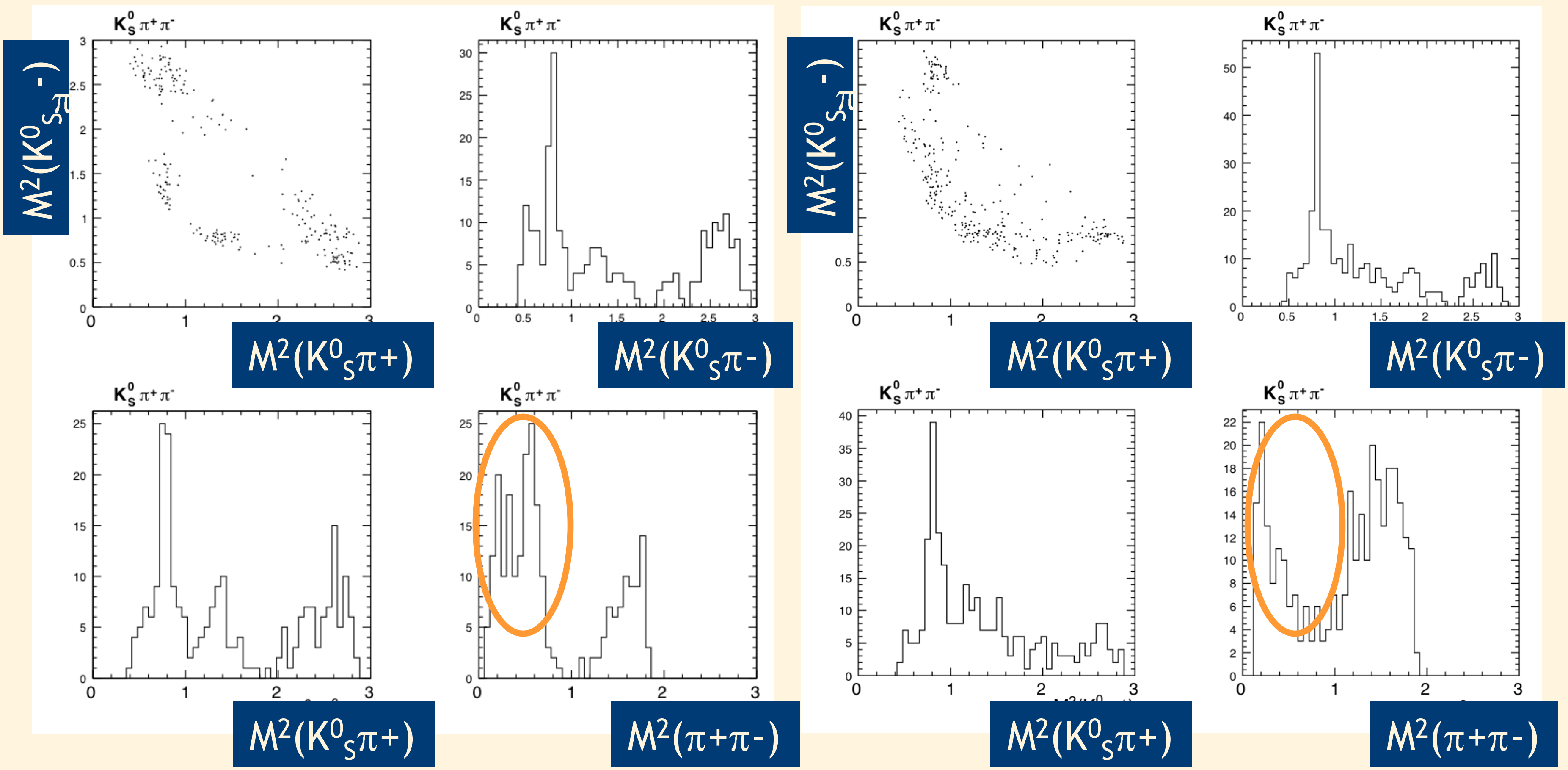


- Not identical – 180° phase difference for Doubly Cabibbo suppressed amplitudes

CP tagged $K^0{}_S\pi^+\pi^-$

$K^0{}_S\pi^+\pi^-$ vs CP-even tag

$K^0{}_S\pi^+\pi^-$ vs CP-odd tag



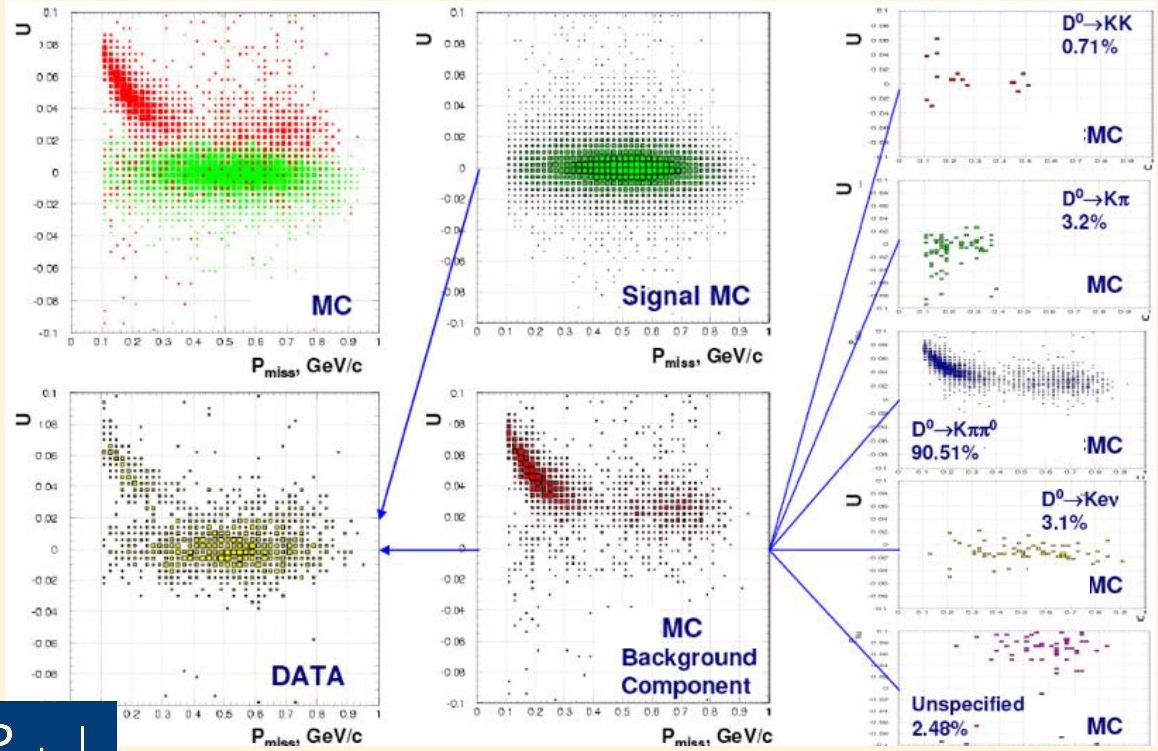
- Not identical – CP-odd $K^0{}_S\rho$ not in CP-odd tag, CP-even $\pi\pi$ S,D-wave not in CP-even tag

Semi-Muonic Decays

- CLEO muon chambers inefficient below 1 GeV.
- Instead, use kinematics to separate $D^0 \rightarrow K^-\mu^+\nu$ from backgrounds using missing energy and momentum.
  - Main background: $D^0 \rightarrow K^-\pi^+\pi^0$
  - Roughly doubles semileptonic statistics.

CLEO-c Preliminary

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



$|P_{miss}|$

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

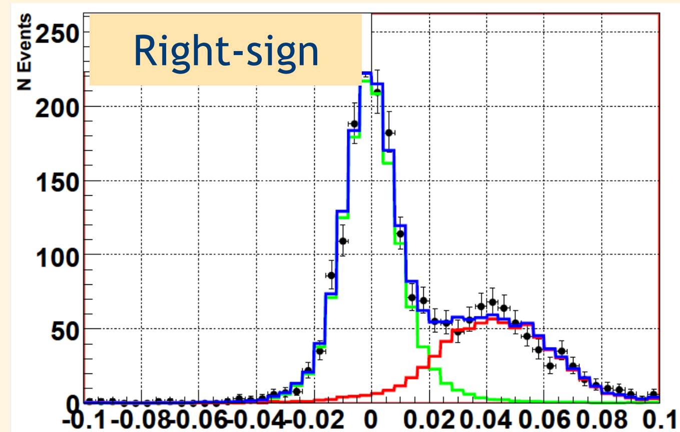
CLEO-c Preliminary

- Wrong-sign uses similar technique, but 300x lower yield.
  - Primary 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}.

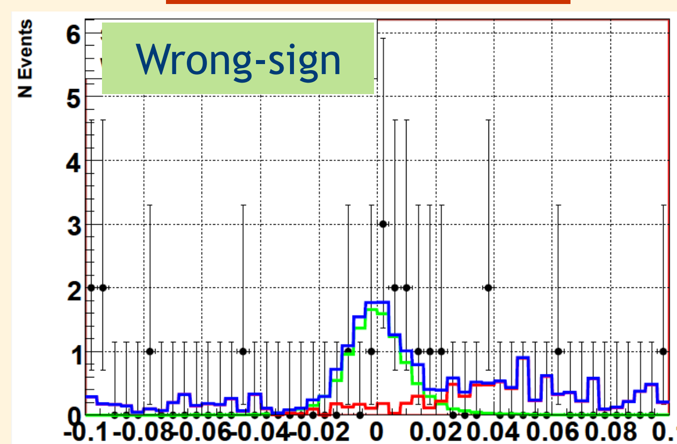
$$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$$
$$= r_{K\pi}^2 + r_{K\pi}y' + (x^2+y^2)/2$$

  - Mixing effects cancel in the interference term

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



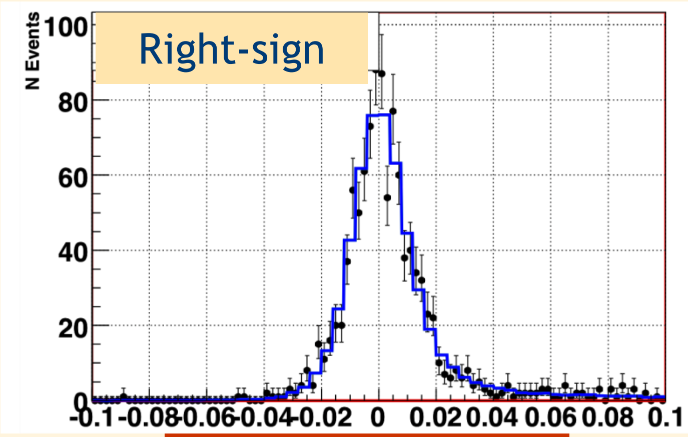
$U = E_{miss} - |P_{miss}|$



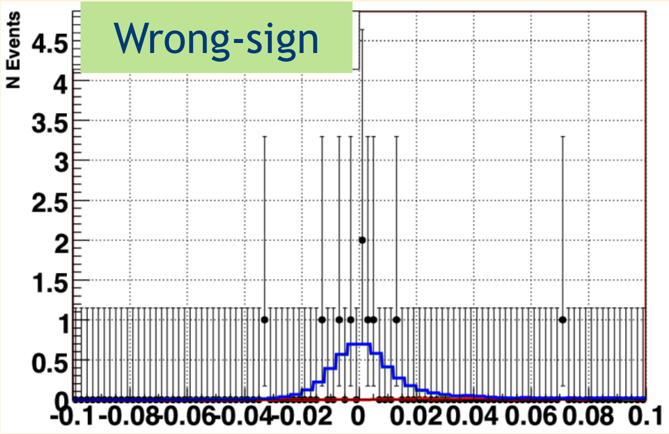
Semi-Electronic Decays $[\delta_{K\pi}]$

CLEO-c Preliminary

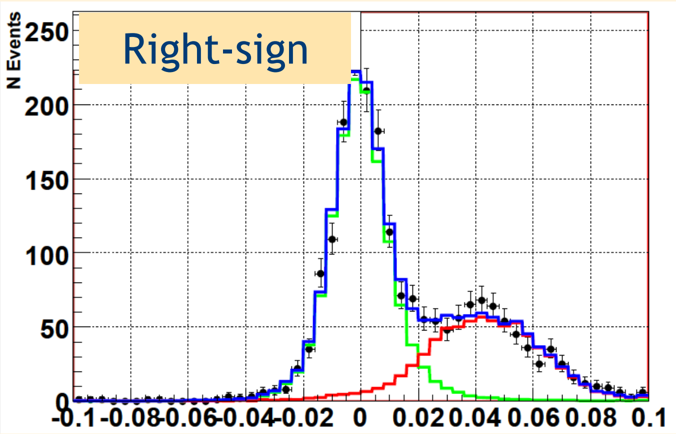
$Ke\nu$ vs. $K\pi$



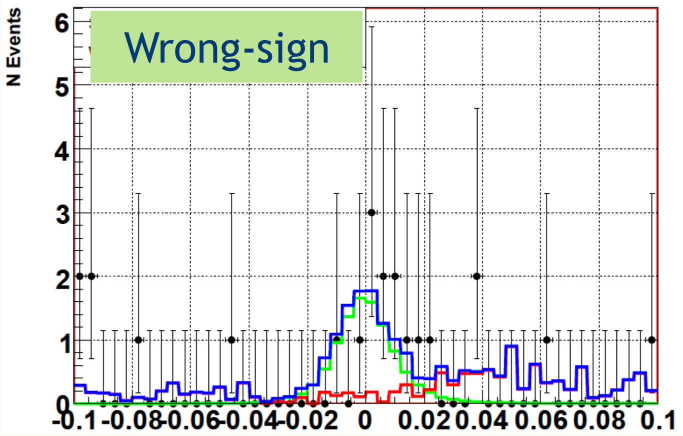
$U = E_{miss} - |P_{miss}|$



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



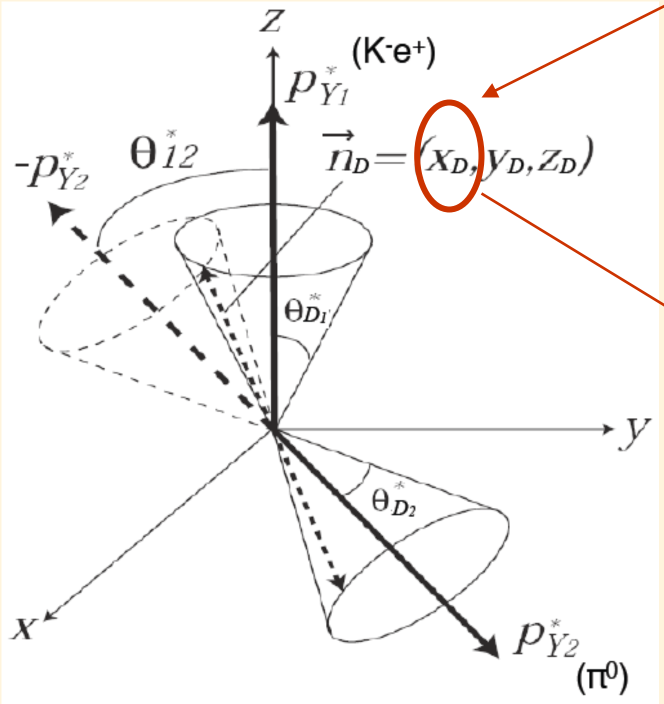
$U = E_{miss} - |P_{miss}|$

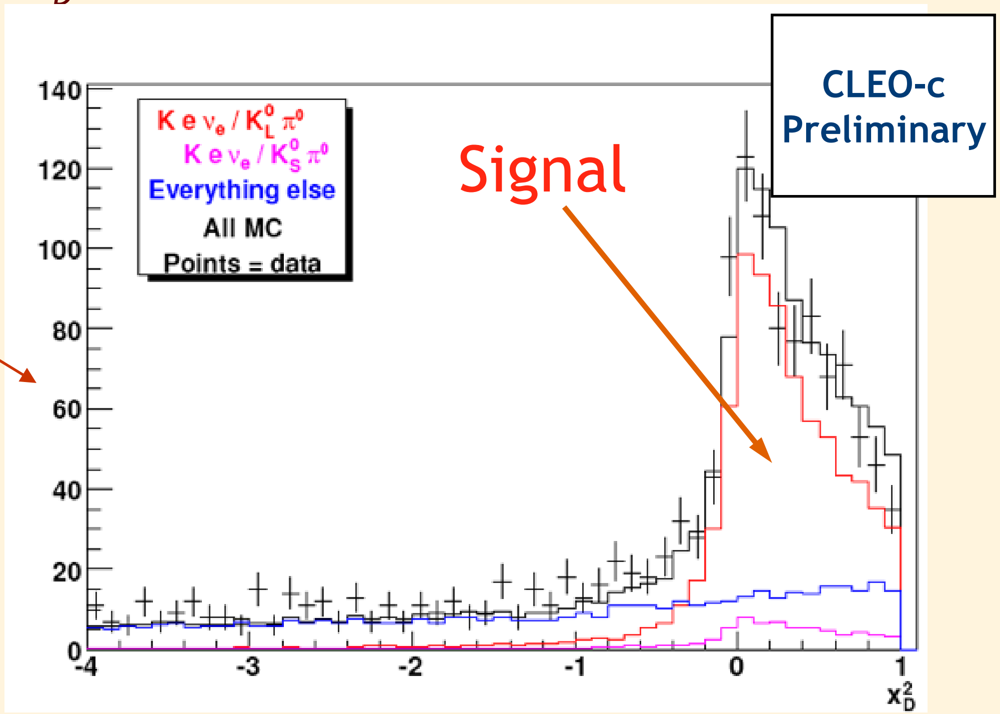


$K e \nu$ vs. $K_L \pi^0$ [$\delta_{K\pi}$]

- Doubles the number of *Ke*ν 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 $\bar{D}^0$ and D^0.
  - If cones intersect, then $0 < x_D^2 < 1$.

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



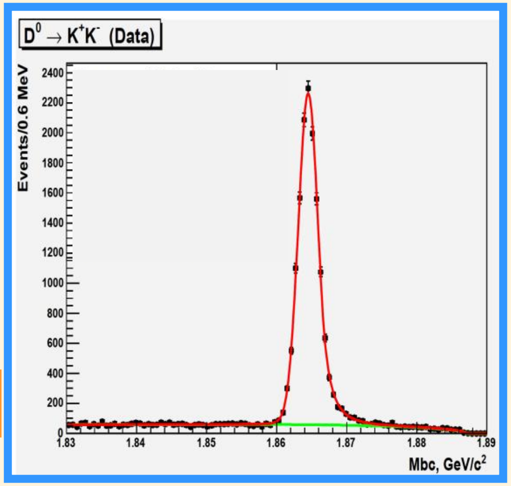


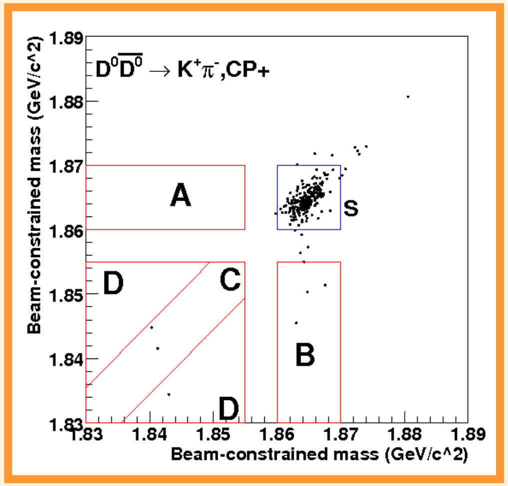
Other Yield Measurements $[\delta_{K\pi}]$

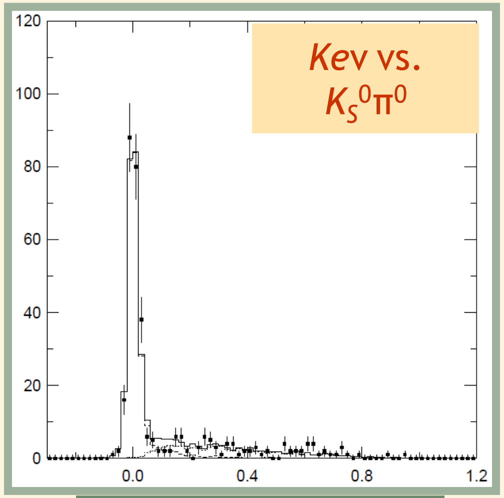
- Fully-reconstructed single tags:
  - Fit beam-constrained mass distribution.

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

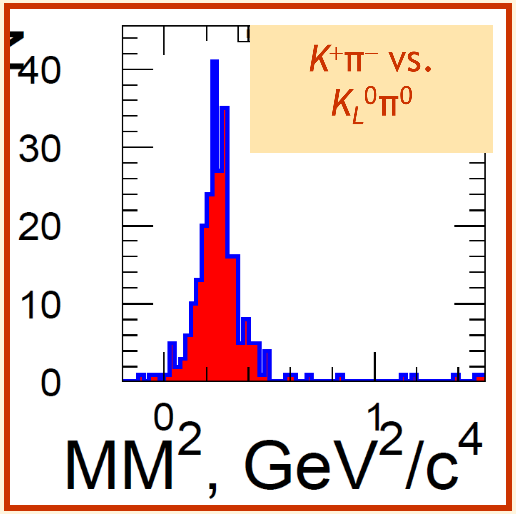
- Fully-reconstructed double tags:
  - Two fully-reconstructed STs
  - Count events in 2D M_{BC} plane.
- Exclusive *Kev* DTs:
  - One fully-reconstructed ST
  - Plus one *K* and one *e* candidate
  - Fit *U* distribution
- K^0_L $\{\pi^0, \eta, \omega, \pi^0\pi^0\}$ DTs:
  - One fully-reconstructed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







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



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

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

Systematic Uncertainties [$\delta_{K\pi}$]

- Mixing/amplitude/phase parameters determined from double ratios.
  - Reduces effect of correlated uncertainties.
- Efficiency systematic uncertainties (correlated) determined with missing mass technique.

Source	Uncertainty (%)	Scheme
Track finding	0.3	per track
$K^{\pm}$ hadronic interactions	0.5	per $K^{\pm}$
K^0_S finding, flight signif. & mass cuts	0.94	per K^0_S
π^0 finding	2.0	per π^0
η finding	4.0	per η
dE/dx and RICH	0.1	per $\pi^{\pm}$ PID cut
dE/dx and RICH	0.1	per $K^{\pm}$ PID cut
EID	0.4	per $e^{\pm}$

- Other correlated uncertainties: modeling of ISR and FSR, ΔE cut, mass cuts, vetoes on extra tracks/showers O(1%) each.

$$\boxed{\Delta E = E_{cand} - E_{beam}}$$

- Uncorrelated uncertainties: yield fit variations, sideband subtractions
- In the end, statistical uncertainties dominate.

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 y and $r_{K\pi}\cos\delta_{K\pi}$ (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 systematic uncertainties

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 $\sin\delta_{K\pi}$)

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

- Published result using 818 pb^{-1} of ψ(3770) data
  - [PRD 80, 031105(R) (2009)]

- Similar formalism for *K*π, 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. $K^+\pi^-\pi^0$

From like-sign DT rates of
$K^+\pi^-\pi^0$ vs. $K^+\pi^-\pi^0$
$K^+\pi^-\pi^+\pi^-$ vs. $K^+\pi^-\pi^+\pi^-$
~ (1 - R^2)

- 41 DT yield measurements.
- No single tags — estimate from external branching fractions.

Combining $K^-\pi^+$ and $K^-\pi^+\pi^0/K^-\pi^+\pi^-\pi^+$

- $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ analysis includes $\delta_{K\pi}$ as external input.
- But there is also independent sensitivity to $\delta_{K\pi}$.

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}

- In particular, $\delta(K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-) \neq 0$ or π
  $\Rightarrow$ $K^+\pi^-$ vs. $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ DTs have enhanced sensitivity to **$\sin\delta_{K\pi}$**.

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

$\cos(\delta_i + \delta_j) =$
$\cos\delta_i \cos\delta_j - \sin\delta_i \sin\delta_j$

No sensitivity to $\sin\delta_i$ *when* $\sin\delta_j \sim 0$

- Combined analysis of $K^+\pi^-$ and $K^+\pi^-\pi^0/K^+\pi^-\pi^+\pi^-$ in progress.

Summary and Outlook

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

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

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

See talk by Jim Libby

- BES-III has exceeded CLEO's ψ(3770) integrated luminosity.
  - 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.

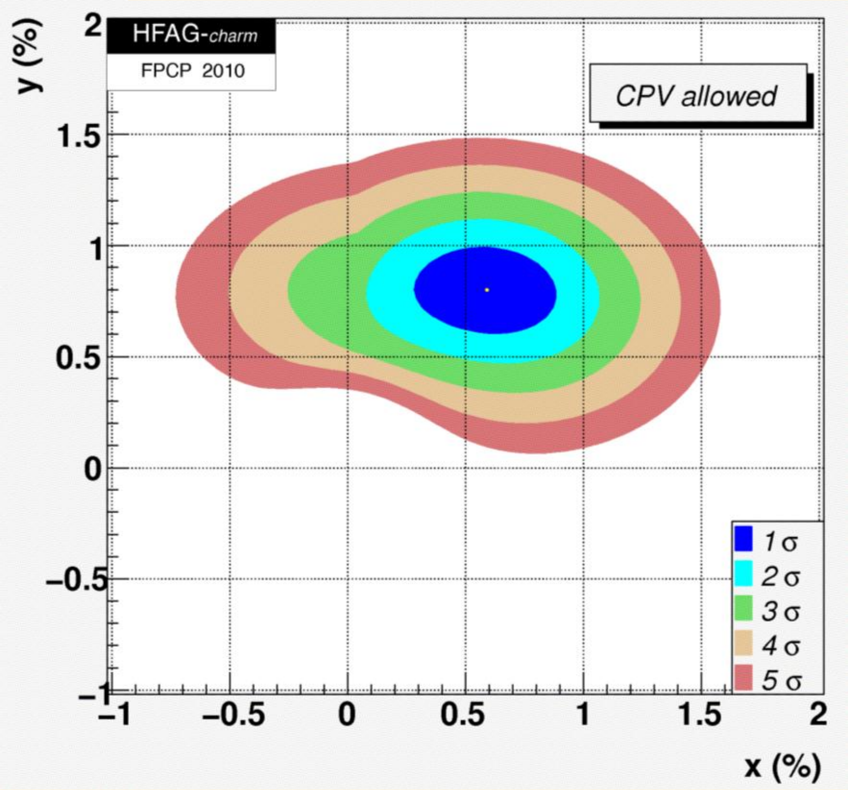
n.b. CLEO-c analysis relies on RICH detector

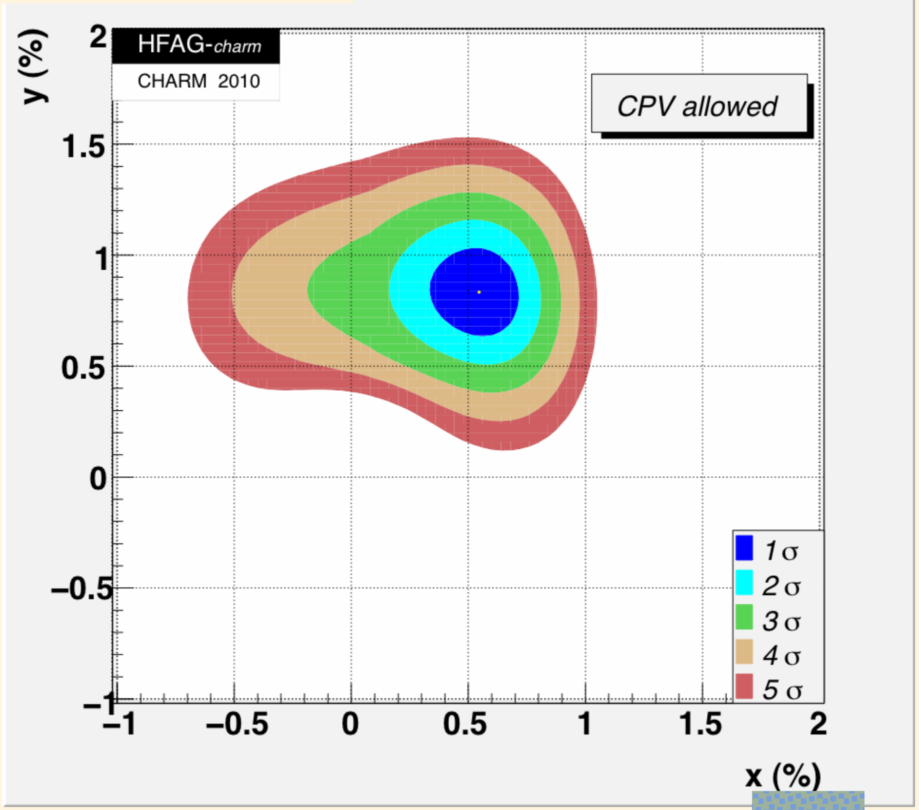
- Super B-factories: radiative return to ψ(3770)?
  - Also gives boosted D^0D^0 pairs—time dependent analysis is sensitive to x.
- Many more possibilities to explore!

HFAG: New Charm Mixing Average with CLEO-c

Parameter	HFAG:FPCP2010	HFAG:CHARM2010
y (10^{-2})	0.79 ± 0.13	0.83 ± 0.13
x (10^{-2})	0.59 ± 0.20	$0.55\ ^{+0.12}_{-0.13}$
$r_{K\pi}^2$ (10^{-3})	3.32 ± 0.08	3.32 ± 0.08
$\delta_{K\pi}$ ($^\circ$)	$27.6\ ^{+11.2}_{-12.2}$	$31.0\ ^{+10.7}_{-12.2}$

Surprising? Large impact on x uncertainty

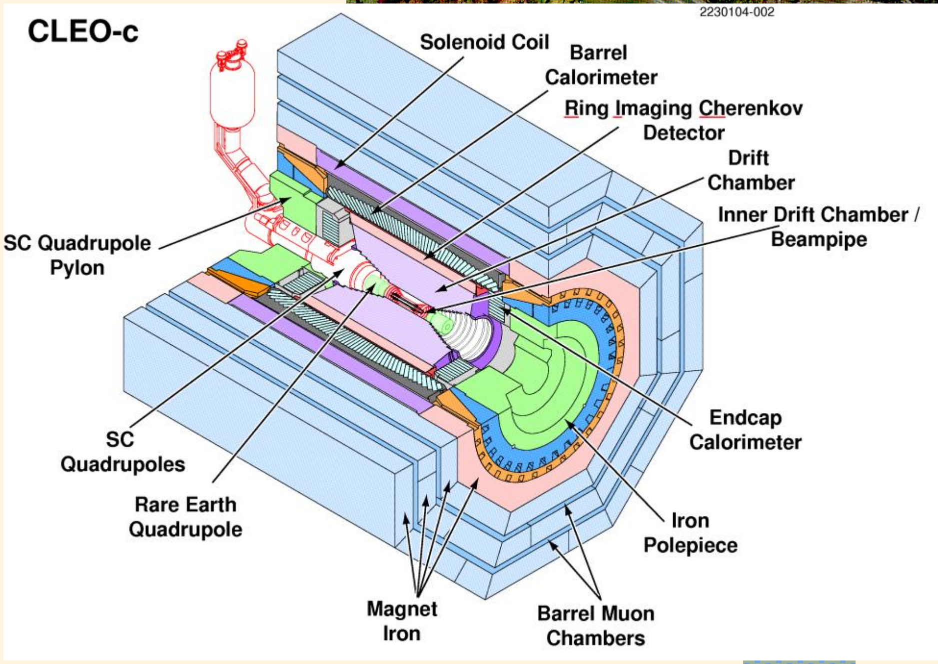




BACKUP

CESR & CLEO

- 1979—2008, symmetric e^+e^- collisions @ $\sqrt{s}$ = 2—12 GeV.
  - Last 5 years: CESR-c/CLEO-c, $\sqrt{s}$ ~ 4 GeV
- Good for flavor physics (weak interaction):
  - Threshold production: clean events
  - $e^+e^- \to \gamma^*$: initial state w/ known energy and quantum numbers.
  - Hermetic detector with excellent particle ID.
- Contributions to HEP for 30+ years
  - "Small" collaboration: ~20 institutions, < 250 authors.
  - Over 500 papers.
- Relevance of flavor to LHC era:
  - New Physics constraints from flavor are much higher than TeV scale.
  - NP that solves hierarchy problem must have non-trivial flavor structure.



Purity of Initial State

- $C+$ contamination of initial $C-$ state (not expected, cf. A. Petrov):
  - $e^+e^- \to \gamma D^0\overline{D}^0$ is $C+$, but photon must be radiated from
    - D^0 or $\overline{D}^0$
    - $\psi(3770)$
    - virtual D^* intermediate state.
  - ISR, FSR, bremsstrahlung photons do not flip C eigenvalue.

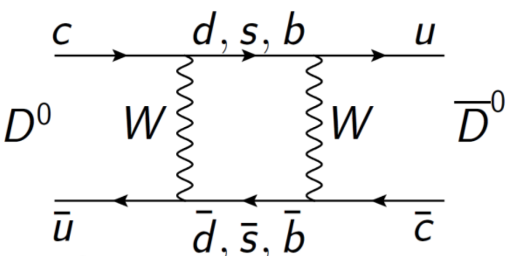
- Allow fit to determine $C+$ fraction.
  - Include same-CP double tags ($CP\pm/CP\pm$).
    - Allowed decay only for $C+$.
    - All yields consistent with zero.
  - Fit each yield to sum of $C-$ and $C+$ contributions.
  - Results (from 2008 publication): $C+/C- = -0.001 \pm 0.023$.
    - No evidence for $C+$.
    - Other results unchanged.

Charm Mixing (no CPV)

$$i\frac{\partial}{\partial t}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D \\ \bar{D} \end{pmatrix} \text{ where } H_{11} = M_{11} - i\,{}^{\Gamma_{11}}\!/_{2} \text{ etc...}$$

- $H_{12}, H_{21} \neq 0 \Rightarrow$ flavor eigenstates (D^0, $\bar{D}^0$) $\neq$ mass eigenstates (D_1, D_2).
- Mixing characterized by $\boxed{x = \frac{\Delta M}{\Gamma} \text{ and } y = \frac{\Delta\Gamma}{2\Gamma}}$ $\qquad D_{1,2} = \frac{D^0 \pm \overline{D^0}}{\sqrt{2}}$

Short distance

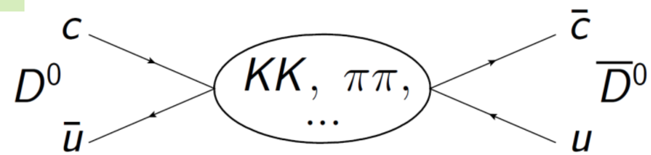


Effective CKM and GIM suppression

$|x|, \ |y| \leq 10^{-3}$

No mixing in SU(3) limit

Long distance [A. Zupanc]



Contribution from hadronic intermediate states

$x, \ y \sim$ up to 1%

- Standard Model predictions for *x* and *y* have large uncertainties.
- But measurements of *x* and *y* can constrain New Physics models.

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

CLEO-c Preliminary

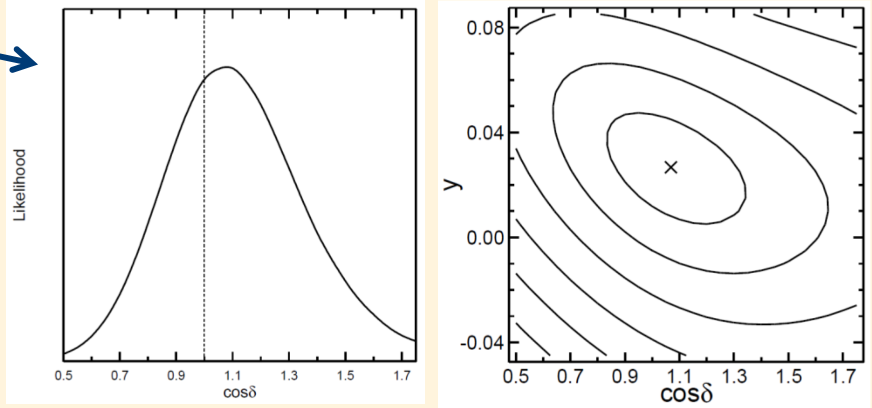
- Improved likelihood behavior over 2008 publication:
  - Previous nonlinearities from use of R_{WS} to derive $r_{K\pi}^2$

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

  - 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