Review of Charm Sector Mixing & CP Violation

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Brief History (I)

- Discovery of Charm at SPEAR in 1976
- Immediately several theoretical papers on mixing & CP violation in Charm sector
  - K^0 sector: Observed mixing ('56) & CPV ('64)
  - B^0 sector: Observed mixing ('87) & CPV ('99)
- Experimental searches for mixing & CPV in charm sector began immediately
  - 2 pubs in '77 from SPEAR
- Searches on going at BABAR, Belle, CLEO-c

Brief History (II)

- Many techniques used - not a complete of results
  - "Indirect": search for like sign muons
    - 1981 (CERN) $\mu^+ N \rightarrow \mu^+(\mu^+\mu^+)$ <20% @ 90% C.L.
    - 1982 (FNAL-E595) $\pi^- Fe \rightarrow X(\mu^+\mu^+)$ <4.4% @ 90% C.L.
    - 1985 (CERN -NA-004) $\mu^+ N \rightarrow \mu^+(\mu^-\mu^-)$ <1.2% @ 90% C.L.
    - 1985 (CERN-WA-001-2) $\nu N \rightarrow \mu^\pm\mu^\pm$ (5.1±2.3)%;(3.2±1.2)%
  - "Direct": reconstruct D^0. Tag production & decay flavor
    - Early measurements used $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$
      - 1977 (SPEAR) e+e- (6.8 GeV), $D^0 \rightarrow K^+\pi^-$ < 16% @ 90% C.L.
      - 1980 (E87) $\langle E_\gamma \rangle$ = 50 GeV < 11% @ 90% C.L.
      - 1983 (ACCMOR) $\langle E_\gamma \rangle$ ~ 120-200 GeV < 7% @ 90% C.L
      - 1987 (ARGUS) e+e- ~ 10.6 GeV < 1.4%@90% C.L.
      - 1991 (CLEO I.5) e+e- ~ 10.6 GeV < 1.1% @90% C.L.
      - 1997 (E791) π^- beam ~ 500 GeV (0.21±0.09)%

Brief History - III

- "Modern Era" - Constraints on charm mixing approach Standard Model expectation for doubly-Cabibbo suppressed (DCS) decay
  - CLEO II.V (2000) Observed $D^0 \rightarrow K^+\pi^-$ $R_D = \left(3.32^{+0.63}_{-0.65} \pm 0.40\right)‰$
  - DCS is distinguished from mixing using decay time
  - Need to resolve charm decay times
  - Combined B-factory precision now about 10x better
  - Search for mixing intimating tied to DCS processes
- PDG06 averages charm mixing results from
  - E791, FOCUS, CLEO, BABAR, Belle
    - More recent updates from BABAR, Belle, CLEO-c
  - CPV averages also include some old E687 & new CDF results
- Mixing & CPV not yet observed in Charm Sector
  - Still window to search for New Physics!

Charm Mixing Primer

- Flavor eigenstate $\neq$ mass eigenstate
- Expected to be small in Standard Model
  - GIM suppression
  - CKM suppression
- Sensitive to new physics
- Mixing amplitudes ~ 0 in the SU(3) limit
- "Interesting" experimental sensitivity to charm mixing amplitudes starts at ~ 10^{-3}
  - Experiments will achieve this soon (Belle, BESIII)

CPV in Brief

Baryon # of the universe ⇒ new physics in CPV dynamics

Three types of CP violation

1) CPV in mixing
2) CPV in direct decay
3) CPV in interference between 1) and 2)

Standard Model

- Highly diluted weak phase in 1xCabibbo suppressed decay
  - $V_{cs} = 1 + \ldots + i\lambda^4$
- No weak phases in Cabibbo favored or 2xCabibbo suppressed decay - except $D^{\pm} \to K_{S,L}\pi^{\pm}$
- CP asymmetry is linear in new physics amplitude
- Final state interactions are large
- CP eigenstate BR are large
- D mixing is slow

Require two coherent weak amplitudes to observe CPV

Direct CPV

- CF & DCS decay: Direct CPV requires New Physics
  - Exception: interference between CF & DCS amplitudes to $D^{\pm} \rightarrow K_{S,L}\pi^{\pm}$
  - SM contribution due to K^0 mixing is $A_S=[+]_S-[-]_S \sim -3.3\times10^{-3}; A_S = -A_L$
  - New Physics could be ~%
- SCS decay
  - expect $O(\lambda^4) \sim 10^{-3}$ from CKM matrix
  - New Physics could be ~%
- Only type of CPV possible for charge mesons
- Requires two amplitudes with different strong & weak phases
  - In SM different weak phases often from tree & penguin processes

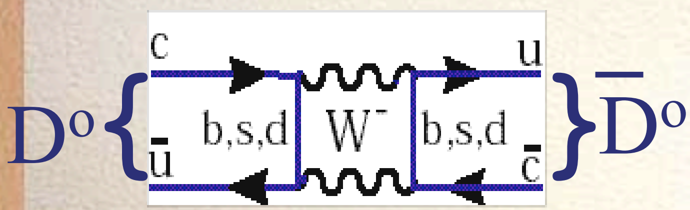
Experimentally:

- Measure asymmetry in time integrated partial widths
- Measure final state distributions on Dalitz plots, T-odd correlation

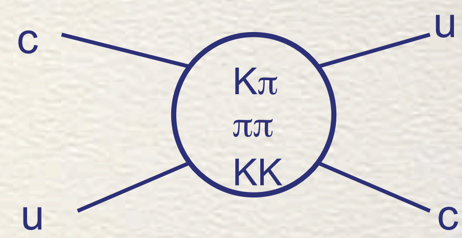
Direct CPV Results

	E791(%)	FOCUS(%)	CLEO(%)	BABAR(%)	Belle(%)	CDF(%)
A_{CP} mode						
$D^0 \to K^+\pi^-$		$18 \pm 14 \pm 4$	2^{+19}_{-20}	9.5 ± 10.3	2.3 ± 4.7	
$D^0 \to K^+\pi^-\pi^0$			9^{+25}_{-22}		-0.6 ± 5.3	
$D^0 \to K^-K^+$	$-1.0 \pm 4.9 \pm 1.2$	$-0.1 \pm 2.2 \pm 1.5$	$0.0 \pm 2.2 \pm 0.8$		0.2 ± 0.7	$1.0 \pm 1.3 \pm 0.6$
$D^0 \to \pi^-\pi^+$	$-4.9 \pm 7.8 \pm 3.0$	$4.8 \pm 3.9 \pm 2.5$	$1.9 \pm 3.2 \pm 0.8$			$2.0 \pm 1.2 \pm 0.6$
$D^0 \to \pi^0\pi^0$			0.1 ± 4.8			
$D^0 \to K^0_S K^0_S$			-23 ± 19			
$D^0 \to K^0_S \pi^0$			0.1 ± 1.3			
$D^0 \to K^0_S \pi^+\pi^-$			$-0.9 \pm 2.1^{+1.6}_{-5.7}$			
$D^0 \to K^0_S \phi$			2.8 ± 9.4			
$D^+ \to K^0_S \pi^+$		$-1.6 \pm 1.5 \pm 0.9$				
$D^+ \to K^0_S K^+$		$6.9 \pm 6.0 \pm 1.8$				
$D^0 \to K^-\pi^+\pi^0$			-3.1 ± 8.6			
$D^+ \to K^-K^+\pi^+$	-1.4 ± 2.9	$0.6 \pm 1.1 \pm 0.5$		$1.4 \pm 1.0 \pm 0.8$		
$D^+ \to \phi\pi^+$	-2.8 ± 3.6					
$D^+ \to K^* K^+$	-1.0 ± 5.0			$0.9 \pm 1.7 \pm 0.7$		
$D^+ \to \pi^-\pi^+\pi^+$	-1.7 ± 4.2					
$D^0 \to \pi^+\pi^-\pi^0$			$-1^{+9}_{-7} \pm 5$			
$D^0 \to K^+\pi^-\pi^+\pi^-$					-1.8 ± 4.4	
$D^0 \to K^+K^-\pi^+\pi^-$		$-8.2 \pm 5.6 \pm 4.7$				
$D^+ \to K^0_S K^+\pi^+\pi^-$		$-4.2 \pm 6.4 \pm 2.2$				
A_T mode						
$D^0 \to K^+K^-\pi^+\pi^-$		$1.0 \pm 5.7 \pm 3.7$				
$D^+ \to K^0_S K^+\pi^+\pi^-$		$2.3 \pm 6.2 \pm 2.2$				

D^0-$\bar{D}^0$ Mixing Formalism



- Double Cabibbo suppressed
- GIM mechanism cancellation
- Long Distance Contributions



Flavor eigenstates are not mass eigenstates

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M - i\Gamma/2\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \qquad |D_1(t)\rangle = |D_1\rangle \exp\left[-\left(\Gamma_1/2 + im_1\right)t\right]$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \qquad |D_2(t)\rangle = |D_2\rangle \exp\left[-\left(\Gamma_2/2 + im_2\right)t\right]$$

$$\bar{m} \equiv \frac{1}{2}(m_1 + m_2) \qquad \Gamma \equiv \frac{1}{2}(\Gamma_1 + \Gamma_2)$$

$$\Delta m \equiv m_2 - m_1 \qquad \Delta\gamma \equiv \Gamma_2 - \Gamma_1$$

$$|D^0\rangle = \frac{1}{2p}\left(|D_1\rangle + |D_2\rangle\right) \qquad |D^0(t)\rangle = \exp\left[-\left(\Gamma/2 + i\bar{m}\right)t\right]\left(\cosh\left(\Delta\gamma/4 + i\Delta m/2\right)|D^0\rangle + \frac{q}{p}\sinh\left(\Delta\gamma/4 + i\Delta m/2\right)|\bar{D}^0\rangle\right)$$

$$|\bar{D}^0\rangle = \frac{1}{2q}\left(|D_1\rangle - |D_2\rangle\right) \qquad |\bar{D}^0(t)\rangle = \exp\left[-\left(\Gamma/2 + i\bar{m}\right)t\right]\left(\frac{p}{q}\sinh\left(\Delta\gamma/4 + i\Delta m/2\right)|D^0\rangle + \cosh\left(\Delta\gamma/4 + i\Delta m/2\right)|\bar{D}^0\rangle\right)$$

Formalism Finale

$$\langle f|H|D^0(t)\rangle = \exp\left[-\left(\Gamma/2 + i\overline{m}\right)t\right]\left(\cosh\left(\Delta\gamma/4 + i\Delta m/2\right)A_f + \frac{q}{p}\sinh\left(\Delta\gamma/4 + i\Delta m/2\right)\overline{A}_f\right)$$

$$\langle \overline{f}|H|\overline{D}^0(t)\rangle = \exp\left[-\left(\Gamma/2 + i\overline{m}\right)t\right]\left(\frac{p}{q}\sinh\left(\Delta\gamma/4 + i\Delta m/2\right)A_{\overline{f}} + \cosh\left(\Delta\gamma/4 + i\Delta m/2\right)\overline{A}_{\overline{f}}\right)$$

$$A_f \equiv \langle f|H|D^0\rangle \quad \overline{A}_f \equiv \langle f|H|\overline{D}^0\rangle$$

$$A_{\overline{f}} \equiv \langle \overline{f}|H|D^0\rangle \quad \overline{A}_{\overline{f}} \equiv \langle \overline{f}|H|\overline{D}^0\rangle$$

Since $\Delta mt << 1$ & $\Delta\gamma t << 1$, expand sin, cos, sinh & cosh

$$R\left(D^0(t) \to f\right) = |A_f|^2 e^{-\Gamma t}\left[1 + \left[y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\right](\Gamma t) + |\lambda|^2 \frac{x^2+y^2}{4}(\Gamma t)^2\right]$$

Direct Decay | Interference | Mixing

$$R\left(\overline{D}^0(t) \to \overline{f}\right) = |\overline{A}_{\overline{f}}|^2 e^{-\Gamma t}\left[1 + \left[y\,\mathrm{Re}(\overline{\lambda}) - x\,\mathrm{Im}(\overline{\lambda})\right](\Gamma t) + |\overline{\lambda}|^2 \frac{x^2+y^2}{4}(\Gamma t)^2\right]$$

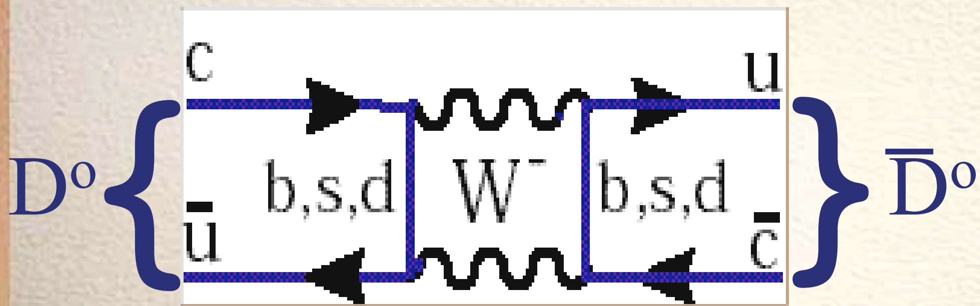
Mixing Parameters

$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma} \qquad R_M = \frac{\left(x^2+y^2\right)}{2}$$

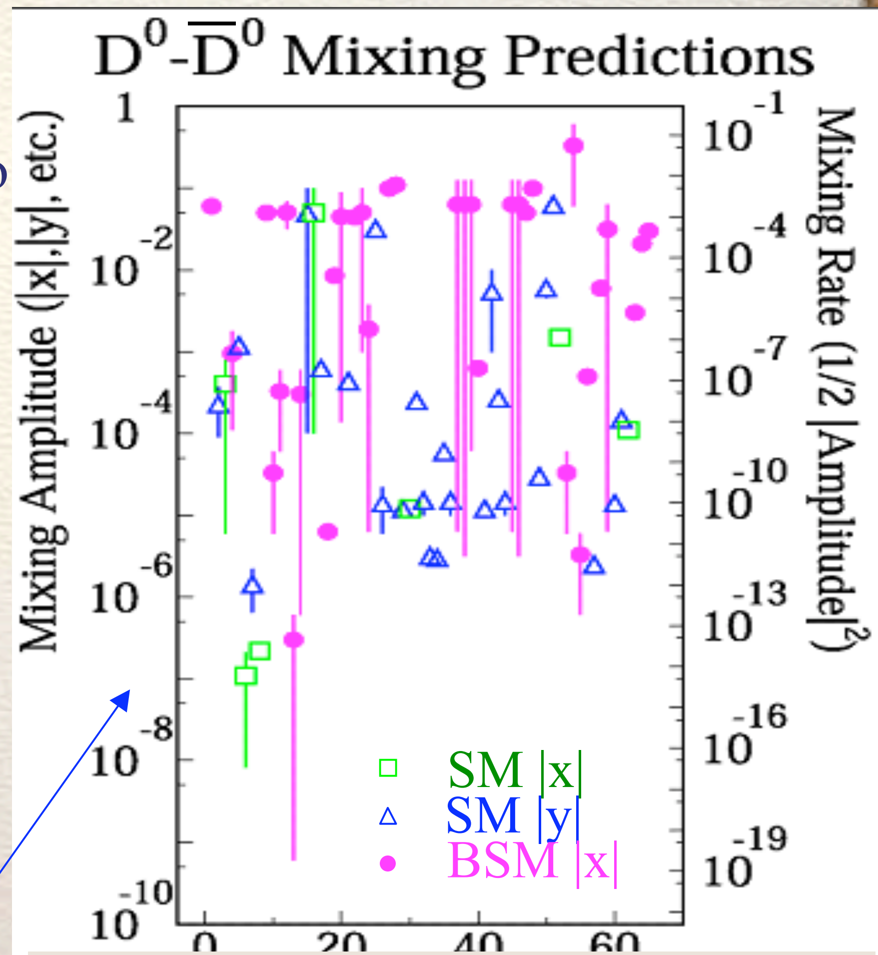
CPV Parameters

$$\lambda \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad \overline{\lambda} \equiv \frac{p}{q}\frac{A_{\overline{f}}}{\overline{A}_{\overline{f}}}$$

Expectations for D^0-$\bar{D}^0$ Mixing



- **presence of d-type quarks in the loop makes the SM expectations for D^0- $\bar{D}^0$ mixing small** compared with systems involving u-type quarks in the box diagram because these loops include 1 dominant super-heavy quark (t): K^0 (50%), B^0 (20%) & B_s (50%)
- In SM x≤y Short distance 10^{-6} - 10^{-3}
  Long distance 10^{-3} - 10^{-2}
- New physics (NP) in loops implies $x \equiv \Delta m/\Gamma >> y \equiv \Delta\Gamma/2\Gamma$; but long range effects complicate predictions.
- Large CPV in mixing indicates NP



From H. Nelson, hep-ex/9908021
updated by A.A. Petrov hep-ph/0311371

See also Golowich,Petrov PLB 625 (2005) 53
Bianco,Bigi et al., Riv.Nuov.Cim.26N7-8 (2003)

D Mixing @ B-factory, Fixed Target, Charm Threshold

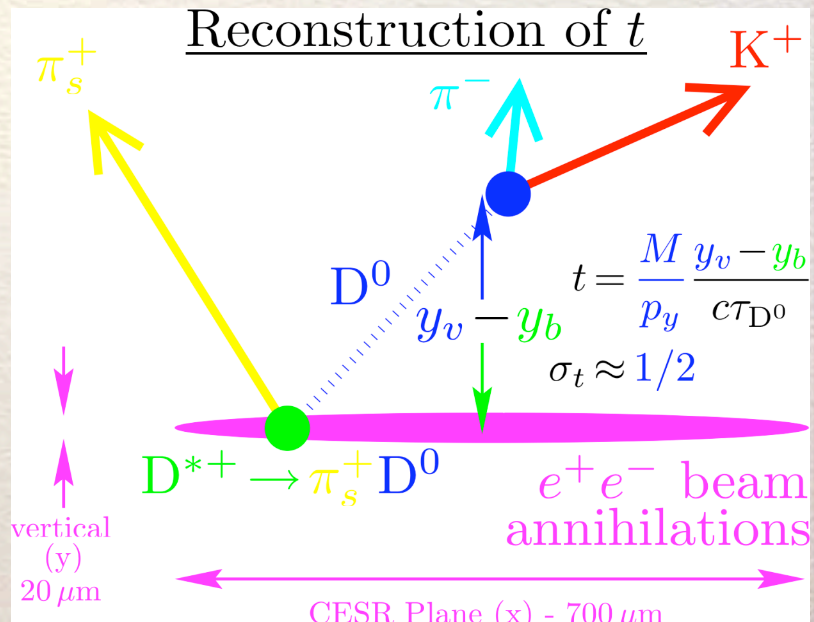
Recall parameter definitions

- Mixing parameters: $x=\Delta M/\Gamma$, $y=\Delta\Gamma/2\Gamma$
- Mixing Rate: $R_M = (x^2+y^2)/2$
- $D^0/\overline{D}^0$ relative strong phase δ
- Effective parameters $y' = y\cos\delta - x\sin\delta$; $x' = y\sin\delta + x\cos\delta$

• Several Experimental probes
  - Semileptonic Decay: Sensitive to R_M, No DCS process
    - Search for $\Gamma(D^0 \to K^{(*)+} l^- \nu)$ (E791, CLEO, BABAR, Belle)
  - $D^0(t) \to$ CP Eigenstate: Sensitive to y (E791,CLEO,FOCUS,BABAR,Belle)
  - Wrong-sign $D^0(t) \to K^+\pi^-$: Sensitive to x'^2, y' (CLEO,FOCUS,BABAR,Belle)
  - Wrong-sign multibody $D^0(t) \to K^+\pi^-\pi^0$, $K^+3\pi$ (CLEO, BABAR, Belle)
  - Dalitz plot $D^0(t) \to K_s\pi^+\pi^-$: Sensitive to x, y (CLEO, Belle*)
  - Quantum Correlations: e+e- $\to D^0\overline{D}^0(n)\gamma(m)\pi^0$: (CLEO-c)
    - Primarily sensitive to y, cos δ

Some Analysis Details

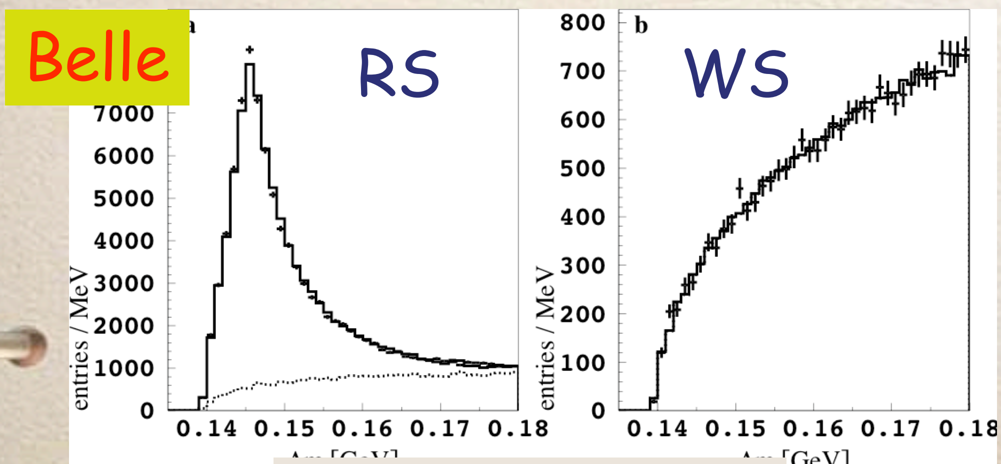
- All analyses (except CLEO-c) share many common features
- Initial flavor of $D^0(t)$ determined by $D^{*\pm} \to D^0 \pi^\pm$
  - $Q = m_{K\pi\pi} - m_{K\pi} - m_\pi \sim 6$ MeV (near threshold)
  - $\sigma_Q < 200$ keV @ CLEO II.V (suppresses background)
- Common backgrounds
  - Random π combining with Cabibbo favored (CF) $D^0 \to K^+\pi^-$
  - Multibody D^0 decay with $D^{*\pm} \to D^0 \pi^\pm$
  - Random $K\pi\pi$ combinatoral background
- Signal & bkgd yield taken from $m_{K\pi}$ vs Q
- Signal shape/resolution functions taken from CF modes
- x & y obtained from (unbinned) ML fit to $\Delta t = (l/p)(m/c)$
  - (l/p) at e+e- calculated in y projection due to beam profile
- p(D*) cut to suppress D's from B decay
- Mixing constraints obtained with & without CPV



Wrong-sign $D^0(t) \rightarrow K^{(*)+} l^- \nu$ Decays

- E.M. Aitala et al. (E791), PRL 77, 2384 (1996): 2504 RS events
- C. Cawlfield et al. (CLEO II), PRD 71, 077101 (2005): (9 1/fb) 638 RS events
- B. Aubert et al. (BABAR), PRD 70, 091102 (2004): (87 1/fb) 49620 RS events
- U. Bitenc et al. (Belle), PRD 72, 071101 (2005): (253 1/fb) 229452 RS events

- Tag production flavor with $D^{*+} \rightarrow D^0 \pi^+$ (pion charge)
- Tag decay flavor with $K^{(*)+} l^- \nu$ (kaon charge)
- Mixing signal is π+l- or π-l+ (wrong-sign)
- Normalize to $\pi \pm l \pm$ (right-sign)



$\Delta M = m_{K\pi\nu} - m_{Ke\nu}$

Belle measures
$R_M = (x^2+y^2)/2 = \#WS/\#RS$
in six bins of decay time

$R_M = (0.20 \pm 0.47 \pm 0.14) \times 10^{-3}$
$< 0.10\%$ @ 90% C.L.

$x,y < 4.5\%$ @ 90% C.L.

Wrong-sign $D^0(t)\to K^+\pi^-$ Decays - I

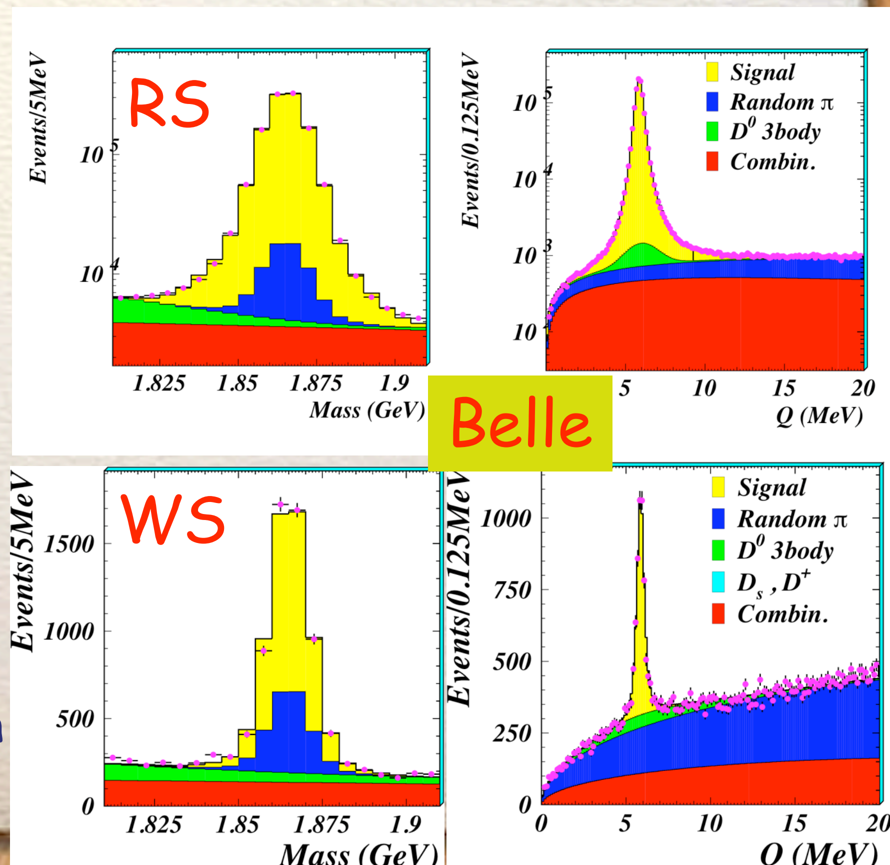
- R. Godang et al. (CLEO), PRL 84, 5038 (2000): (9 1/fb) 45 WS events
- J.M. Link et al. (FOCUS), PRL 86, 2955 (2001): 234 WS events
- PLB 618, 23 (2005)
- B. Aubert et al. (BABAR), PRL 91, 171801 (2003) (57.1 1/fb) 430 WS events
- J. Li et al. (Belle), PRL 94, 071801 (2005) (90 1/fb) 845 WS events
- L.M. Zhang et al. (Belle), PRL 96, 151801 (2006) (400 1/fb) 4024 WS events

Analysis Detail:

- P(D*) > 2.7 GeV/c to reject D's from B
- $m_{K\pi}$-Q fit to determine WS yield N_{WS}
- Δt fit to determine R_D, x'^2, y':
- Recall 'strong phase ambiguity'

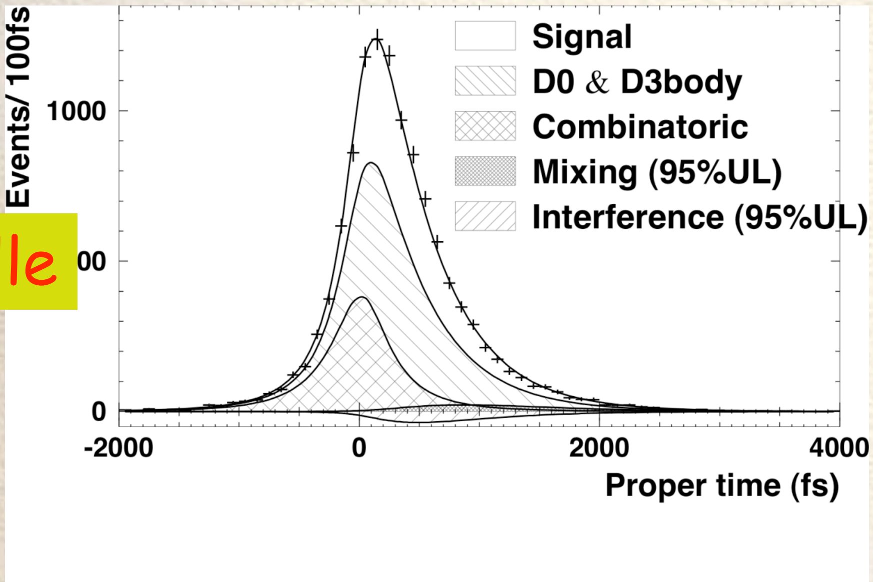
$$\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right|\sqrt{R_D}\,e^{i(\phi+\delta)} \quad \bar{\lambda} \equiv \frac{p}{q}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} = \left|\frac{p}{q}\right|\sqrt{R_D}\,e^{i(-\phi+\delta)}$$

- And mixing equations become
  - $R_{WS} = R_D + y'\sqrt{R_D} + R_M$
  - $y' = y\cos\delta - x\sin\delta$, $x' = y\sin\delta + x\cos\delta$
  - $R_M = (x^2+y^2)/2 = (x'^2+y'^2)/2$
- WS resolution fn fixed to RS resolution
- Δt bkgd shapes from m-Q sideband



Wrong-sign $D^0(t)\to K^+\pi^-$ Decays - II

Belle



Determine R_D,x,y Separately for D^{*+} & D^{*-} tags

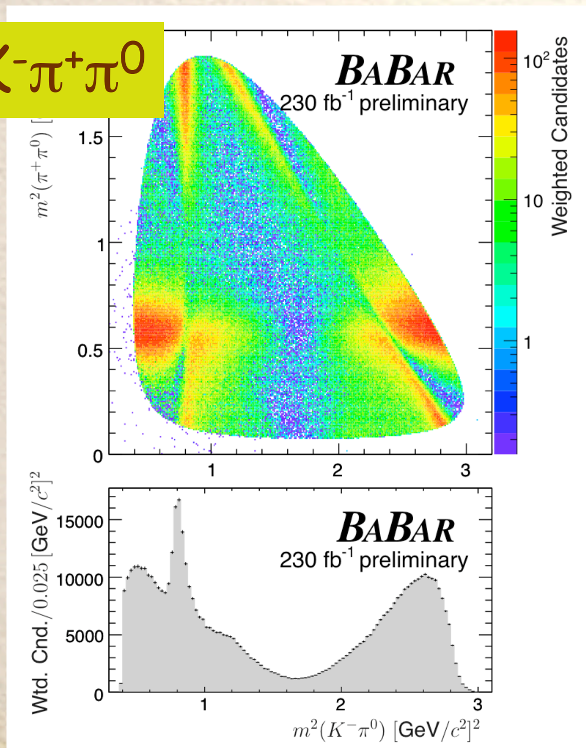
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} \qquad A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-}$$

Fit Case	Parameter	Fit Result ($\times 10^{-3}$)
No CPV	x'^2	$0.18^{+0.21}_{-0.23}$ < 0.72 @95% C.L.
No CPV	y'	$0.6^{+4.0}_{-3.9}$ $-9.9 < y' < 6.8$ @95% C.L.
No CPV	R_D	3.65±0.17
CPV	A_D	23 ±47 $-76 < A_D < 107$
CPV	A_M	670 ±1200 $-995 < A_M < 1000$
No mixing/No CPV	R_D	3.77 ± 0.08 ± 0.05

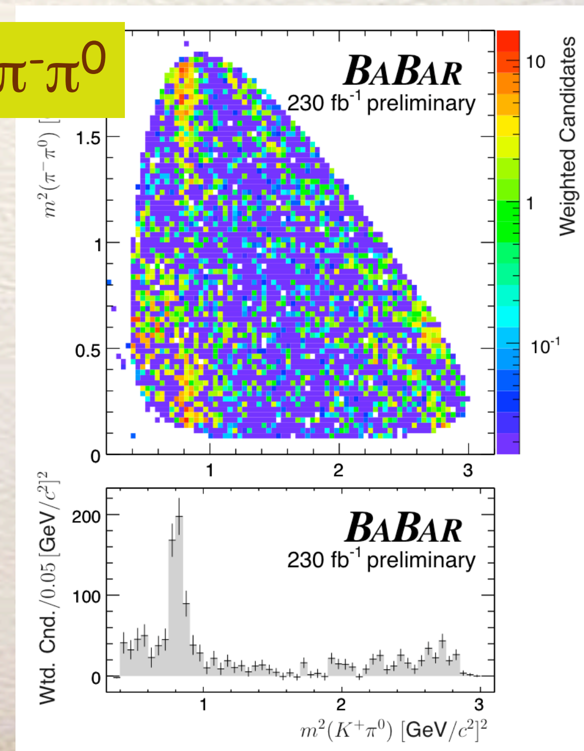
Wrong Sign Multibody Decay - I

- E.M. Aitala et al. (E791), PRD 57, 13 (1998) — 7 WS K+3π
- G. Brandenburg et al. (CLEO), PRL 87, 071802 (2001) (9 1/fb) — 38 WS $K+\pi-\pi^0$
- S. Dytman et al. (CLEO), PRD 64, 111101 (2001) (9 1/fb) — 54 WS K+3π
- X.C. Tian et al. (Belle), PRL 95, 231801 (2005): (281 1/fb) — 1978 WS $K+\pi-\pi^0$, 1721 WS K+3π
- B. Aubert et al. (BABAR), to PRL, hep-ex/0608006:(230 1/fb) — 1560 WS $K+\pi-\pi^0$
- B. Aubert et al. (BABAR), hep-ex/0607090: (230 1/fb) — 2002 WS K+3π

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



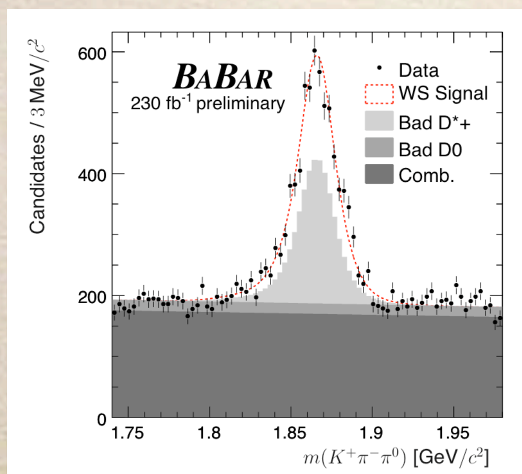
$D^0 \rightarrow K^+\pi^-\pi^0$

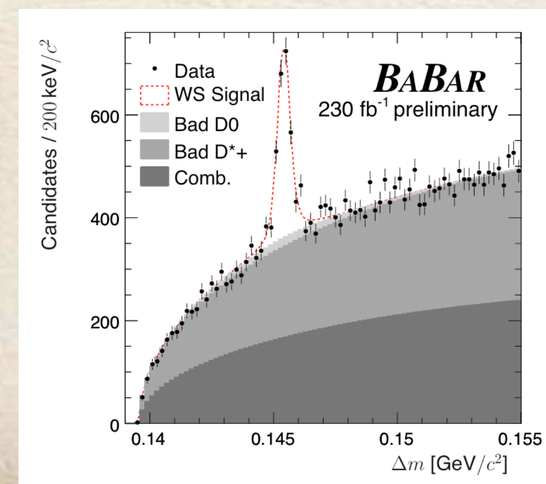


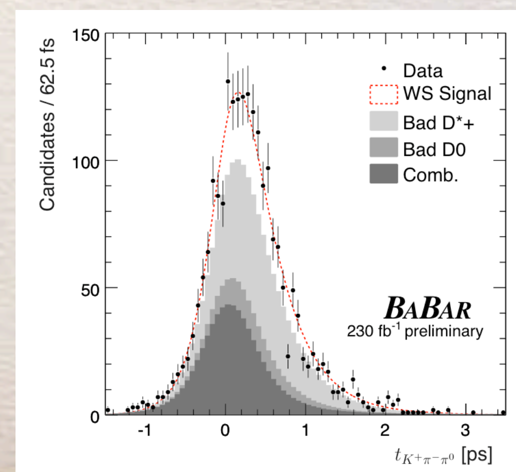
background subtracted & efficiency corrected

Wrong Sign Multibody Decay - II

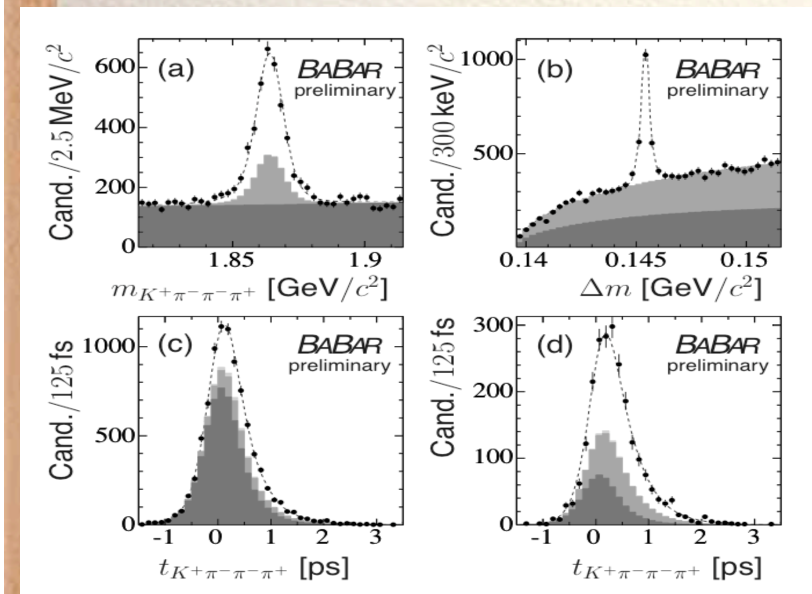
- Cut on Dalitz plot to remove DCS K*'s
- Reduces sensitivity to mixing but avoids complication of a time-dependent fit of the Dalitz plot
- Now similar to semileptonic mixing search but no ν
  - better mass & decay resolution (no ν)
  - Lower backgrounds (no ν)
  - R_M < 0.054% @ 95% C.L. (230 1/fb) compare with best (Belle) semileptonic results < 0.10% @90% C.L. (281 1/fb)



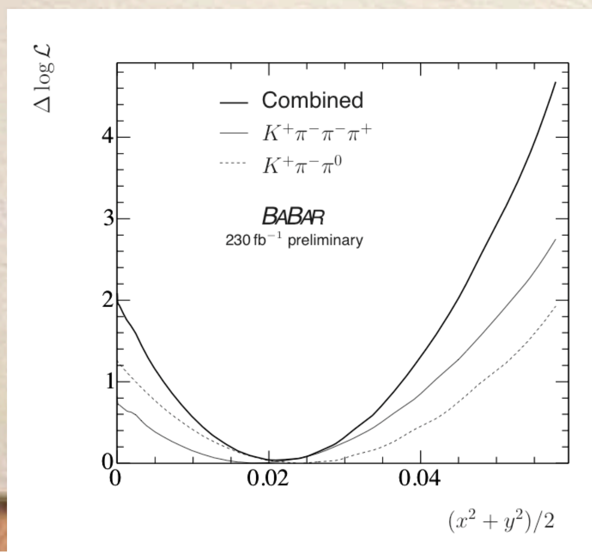




$D^0(t) \to K^+ 3\pi$



- Decay time resolution better than $K\pi\pi^0$
- Background is lower
- No cut on phase space
  - R_M < 0.048% @95% C.L.
- Combine with $K\pi\pi^0$
  - R_M < 0.042 @95% C.L.
- Note no mixing NOT inside 95% C.L.
  - $K\pi\pi^0$ consistent with no mixing @ 4.5%
  - $K3\pi$ consistent with no mixing @ 4.3%
  - $K\pi\pi^0$+$K3\pi$ consistent with no mixing@ 2.1%
- CPV results
  - $K\pi\pi^0$: $\left|\frac{p}{q}\right| = 2.2^{+1.9}_{-1.0} \pm 0.1$
  -
  - $K3\pi$: $\left|\frac{p}{q}\right| = 1.1^{+4.0}_{-0.6} \pm 0.1$



Dalitz plot analysis of $D^0(t) \rightarrow K_S \pi^+ \pi^-$

- D. M. Asner et al. (CLEO), PRD 72, 012001 (2005): (9 1/fb) 5299 events
- H. Muramatsu et al. (CLEO), PRL 89, 251802 (2002)

- Full time-dependent fit to Dalitz plot

$$\left\langle K_S^0 \pi^+ \pi^- \middle| H \middle| D^0(t) \right\rangle = \frac{1}{2p}\left(\left\langle K_S^0 \pi^+ \pi^- \middle| H \middle| D_1(t) \right\rangle + \left\langle K_S^0 \pi^+ \pi^- \middle| H \middle| D_2(t) \right\rangle \right)$$

$$\equiv A_1 e^{-(\Gamma_1/2 + i m_1)t} + A_2 e^{-(\Gamma_2/2 + i m_2)t}$$

$$R\left(D^0(t) \to K_S^0 \pi^+ \pi^-\right) = |A_1|^2 e^{-\Gamma(1+y)t} + |A_2|^2 e^{-\Gamma(1-y)t} + 2\left[\mathrm{Re}\left(A_1 A_2^*\right)\cos(xt) - \mathrm{Im}\left(A_1 A_2^*\right)\sin(xt)\right]$$

$$A_n \propto \sum_j a_j e^{i\delta_j} A^j$$

Note: Depends linearly on y and x
⇒ First sensitivity to the sign of x

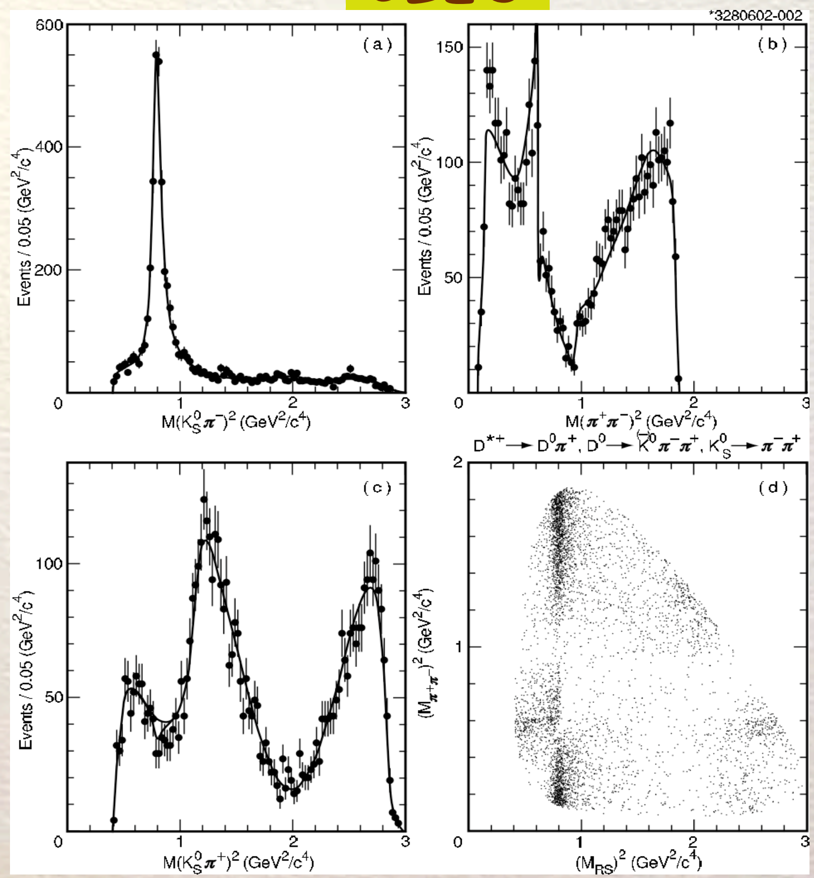
Dalitz plot analysis of $D^0(t) \to K_S \pi^+ \pi^-$

- Full time-dependent fit to Dalitz plot

Analysis Technique

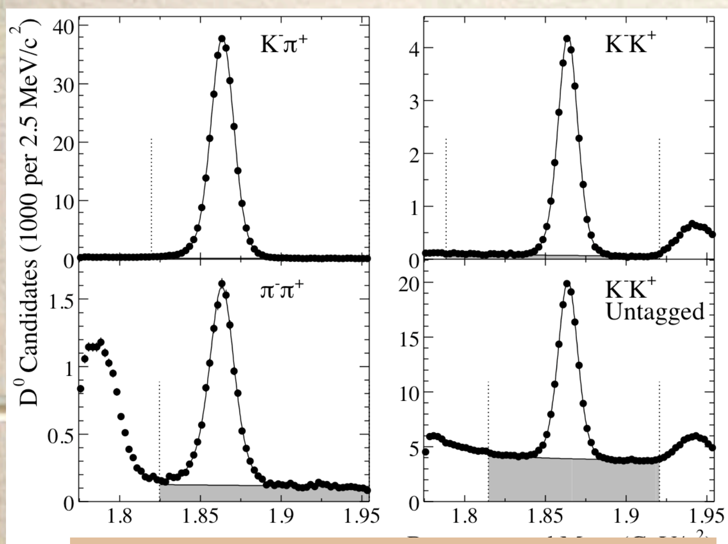
- Select $K_S\pi+\pi-$ final state consistent with $M(D^0)$Require $D^{*+} \to D^0\pi+$ to determine production flavor
- Do unbinned ML fit to Dt and Dalitz plot variable $m^2(K_S\pi+)$,$m^2(K_S\pi-)$
- 11 intermediate states:
  - $K^*(892)^-\pi^+$, $K_0(1430)^-\pi^+$,$K_2(1430)\pi^+$,$K^*(1680)^-\pi^+$
  - $K_S\rho$, $K_S\omega$
  - $K_Sf_0(980)$, $K_Sf_0(1370)$, $K_Sf_2(1270)$
  - $K^*(892)^+\pi^-$
  - Non-resonant
- Also CPV search at amplitude level
  - D. Asner et al. (CLEO) PRD 70, 091101 (2004)
  - CPV limits (95% C.L.) range from 3.5×10^{-4} to 28.4×10^{-4}

CLEO



CP eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$

Experiment	untagged events	tagged events	$\langle\sigma_\tau\rangle$
E791, PRL 83, 32 (1999)	3200		
FOCUS, PLB 485, 62 (2000)	*	16532	<40 fs
CLEO, PRD 65, 092001 (2002)		4159	170 fs
Belle, PRL 88, 162001 (2002)	18306		215 fs
BABAR, PRL 91, 121801 (2003)	145826	38933	160 fs
Belle, Lepton Photon 2004		36480	180 fs



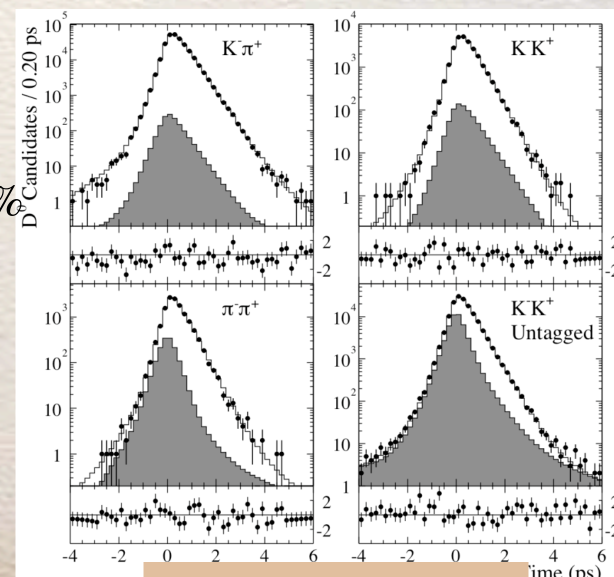
Reconstructed Mass

BABAR

$$y = \left(0.8 \pm 0.4^{+0.5}_{-0.4}\right)\%$$
$$\Delta Y = (-0.8 \pm 0.6 \pm 0.2)\%$$

PDG06

$$y = (0.7 \pm 0.5)\%$$
$$\Delta Y = (-0.5 \pm 0.5)\%$$

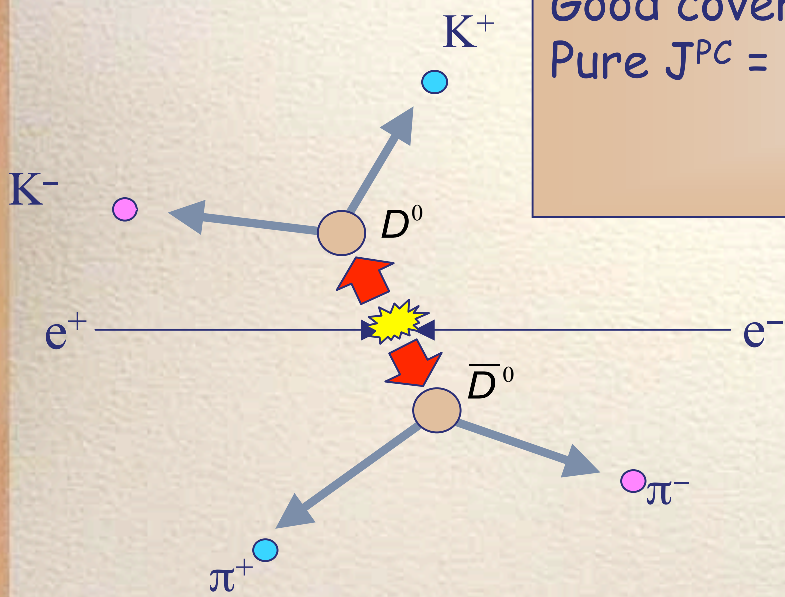


Decay Time

CLEO-c & D Tagging

$e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$

Pure DD final state, no additional particles ($E_D = E_{beam}$).
Low particle multiplicity ~ 5-6 charged particles/event
Good coverage to reconstruct ν in semileptonic decays
Pure $J^{PC} = 1^{--}$ initial state - flavor tags ($K^-\pi^+$),
CP tags (K^-K^+, $K_S\pi^0$)
Semileptonic ($Xe\nu$)



Reconstruct one D meson *single tag (ST)*
Reconstruct both D mesons *double tag (DT)*

Mixing Analyses

Targeted Analyses - Double Tags

- Mixing (x^2+y^2): $D\overline{D} \rightarrow (K^-l^+\nu)^2, (K^-\pi^+)^2$
- cosδ: Double Tag Events: $K^-\pi^+$ vs CP±
- Charm Mixing (y): FlavorTag vs CP±
- DCS: Wrong sign decay $K^-\pi^+$ vs $K^-l^+\nu$

Comprehensive Analysis - ST & DT

Combined analysis to extract mixing parameters, DCS, strong phase & charm hadronic branching fractions

Charm Mixing, DCS, & cosδ impact naïve interpretation of branching fractions

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

Introduction: Quantum Correlations

$e^+e^- \to \gamma^* \to D^0\overline{D}^0$ C = –1

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

- The Quantum Correlation Analysis (TQCA)
- Due to quantum correlation between D^0 and 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 $\cos\delta_{D\to K\pi}$ and mixing parameter $y = \Delta\Gamma/2\Gamma$
- $K^-\pi^+$ vs $K^-\pi^+$ forbidden without D mixing

Introduction: Quantum Correlations

$e^+e^- \rightarrow \gamma^* \rightarrow D^0\overline{D}^0$ C = –1

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

- $K^-\pi^+$ vs semileptonic measures isolated decay rate and tags flavor of decaying D
- Different sensitivity to mixing vs DCSD
- D decays to CP eigenstates also interfere and opposite semileptonics to get isolated rate, flavor tags for yet another dependence on y and strong phase
- CP eigenstate vs CP eigenstate shows maximal correlation

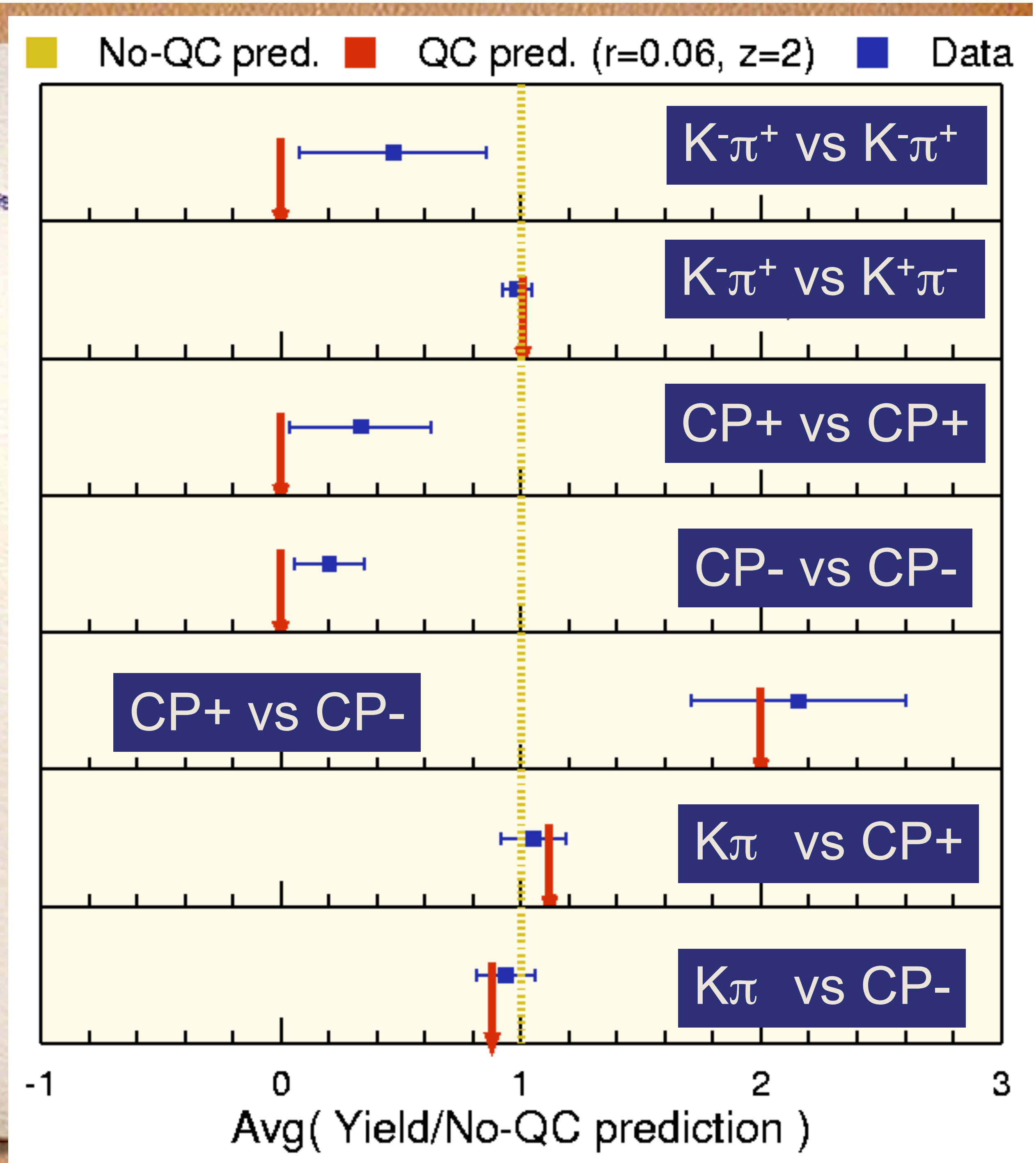
Single Tag & Double Tag Rates

	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	$1-y$	$1+y$

And measure branching fractions simultaneously

TQCA

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



PANIC'05 Prelim Results - update soon

Parameter	CLEO-c TQCA	PDG or CLEO-c
y	-0.057±0.066±?	0.008±0.005
r^2	-0.028±0.069±?	(3.74±0.18)X10^{-3}
$r\ (2\cos\delta_{D\to K\pi})$	0.130±0.082±?	
R_M	(1.74±1.47±?)x10^{-3}	< ~1x10^{-3}
$B(D\to K\pi)$	(3.80±0.029±?)%	(3.91±0.12)%
$B(D\to KK)$	(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)%

Fitted r^2 unphysical. If constrained to WA, $\cos\delta = 1.08 \pm 0.66 \pm ?$.

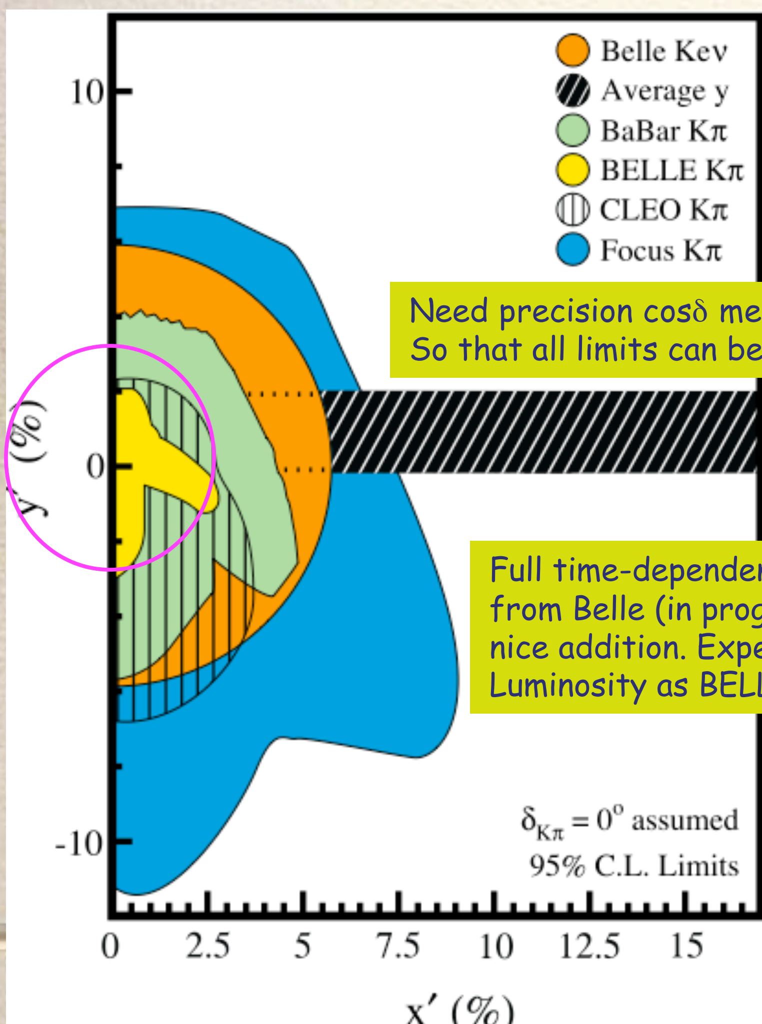
TQCA @ CLEO-c Summary

- With correlated D^0D^0 system, probe mixing & DCSD in time-integrated yields with double tag technique similar to hadronic BF analysis.
- Simultaneously fit for:
  - Hadronic/semileptonic/*CP* eigenstate branching fractions
  - Mixing parameters (x & y) and DCSD parameters (r & δ).
- Ultimate sensitivity with projected CLEO-c data set
  - y ±0.012, x^2 ±0.0006, $\cos\delta_{D\to K\pi}$ ±0.13, R_M< few 10^{-4}
  - $x(\sin\delta_{D\to K\pi})$ ±0.024 - Needs C=+1 initial state from $DD\gamma$ & $DD\gamma\pi^0$ from 4170 MeV
- TQCA currently limited by # of CP tags - working to add more
  - Add $D^0 \to K^0{}_S\omega$, $K^0{}_S\eta$, $K^0{}_S\eta'$, $K^0{}_S\phi$
  - Add $D^0 \to K^0{}_S\pi^+\pi^-$ with Dalitz plot fits
  - Add $D^0 \to K^0{}_L\pi^0$, etc..
- Other potential additions include
  - WS e- vs K-π+
  - Add 4170 data (320 1/pb in hand)

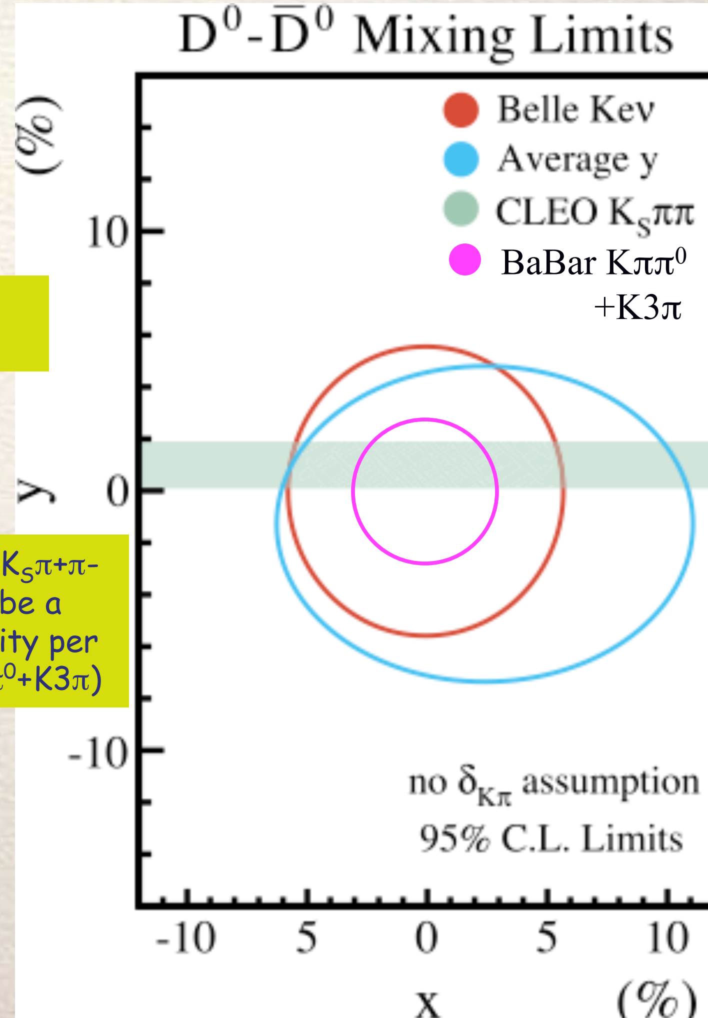
For winter conferences will update 281 1/pb to include $D^0 \to K^0{}_S\omega$, $K^0{}_S\eta$ (70% more CP- tags) and $D^0 \to K^0{}_L\pi^0$ vs. $\{K\pi, K^0{}_S\pi^0, K^0{}_S\eta, K^0{}_S\omega\}$.
Expect $\sigma(y)$~0.02 and $\sigma(\cos\delta)$~0.3

- *Preliminary* determination of *y* and first measurement of $\delta(K\pi)$.
  - C=+1 fraction < 0.06±0.05±? on $\psi(3770)$
- Systematic uncertainties being studied (<statistical error)

Summary of Mixing Results



Need precision cosδ measurement (CLEO-c)
So that all limits can be expressed in x vs y



Full time-dependent Dalitz plot of $D^0 \rightarrow K_S\pi^+\pi^-$ from Belle (in progress) & BaBar would be a nice addition. Expect twice the sensitivity per Luminosity as BELLE ($K\pi$) or BaBar ($K\pi\pi^0$+$K3\pi$)

Conclusions

- No mixing or CPV in observed charm sector
- Experiments approaching interesting sensitivity, 10^{-3} for both mixing & CPV searches
- 20 1/fb at 3770 MeV at BESIII will have sensitivity to SM SCS CPV
- CPV in CF, DCS is zero in SM - window for NP
- CPV in mixing is small in SM - window for NP
- 20 1/fb at BES III & 2 1/ab at B-factories will attain 10^{-3} sensitivity to x,y
- Reach of LHC-b is understudy - see talk by Raluca Muresan
- Best bet to observe D mixing is at a Super B factory

Final Comment

- Several times I have been asked what I make of the mixing "signals" at Belle & Babar
- My answer is "there has been a 2σ mixing signal for a decade!"
  - E791 (1997) R_M = (0.21±0.09±0.02)% $D^0 \rightarrow K\pi, K3\pi$
  - CLEO (2000) y' = (-2.5±1.5±0.3)% $D^0 \rightarrow K\pi$
  - FOCUS (2002) y=(3.4±1.4±0.7)% $D^0 \rightarrow KK$
  - BELLE (2006) x'^2=y'=0 @3.1% C.L. $D^0 \rightarrow K\pi$
  - BABAR(2006) R_M = 0 @4.5%, 4.3% C.L. $D^0 \rightarrow K\pi\pi^0, K3\pi$