CP/CPT Violation in Charm

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Talk Outline

I. Quick CP violation recap
II. Blurb about E791, FOCUS, & CLEO experiments
III. Recent direct CP violation search results
IV. A search for CPT violation
V. Summary & Future

CP violation generalities

Three types of CP violation

1 CP violation in mixing (indirect)

2 CP violation in decay (direct)

3 CP violation in decay/mixing interference (indirect or direct)

Current Status

- Experimentally, charm mixing is small $\Rightarrow$ CP violation in mixing or interference is small
- Standard Model predictions for all types of charm CP violation are well below current sensitivities
- Some Standard Model extensions predict direct CP violation up to 1% (almost within reach)
- $\Rightarrow$ Large window for new physics

CP violation generalities

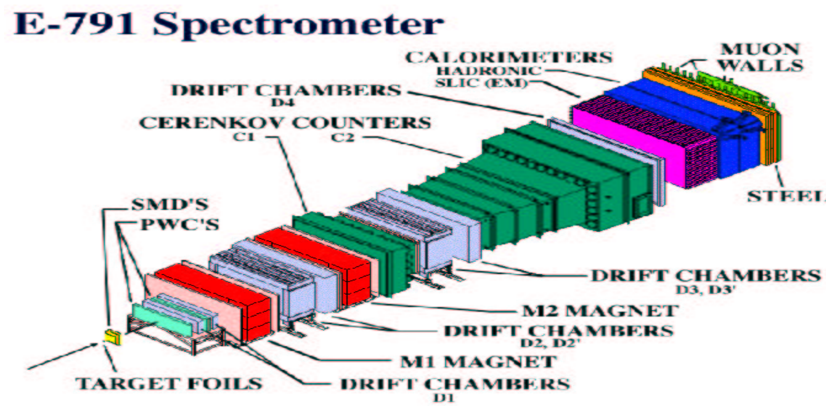
Direct CP violation

- Only type of CP violation possible for charged mesons
- Requires two decay terms with different CP violating (weak) and different CP conserving (strong) phases
- Differing strong phases comes from final state interactions
- In Standard Model differing weak phases often come from tree level and penguin diagrams
- Measure: $A_{CP} \equiv \dfrac{\Gamma(D\rightarrow f) - \Gamma(\overline{D}\rightarrow \overline{f})}{\Gamma(D\rightarrow f) + \Gamma(\overline{D}\rightarrow \overline{f})}$
- In fixed-target experiments (E791 & FOCUS), production asymmetries require normalizing by another (copious) mode, assumed to have no CP violation. Procedure also reduces systematic errors.

The usual suspects

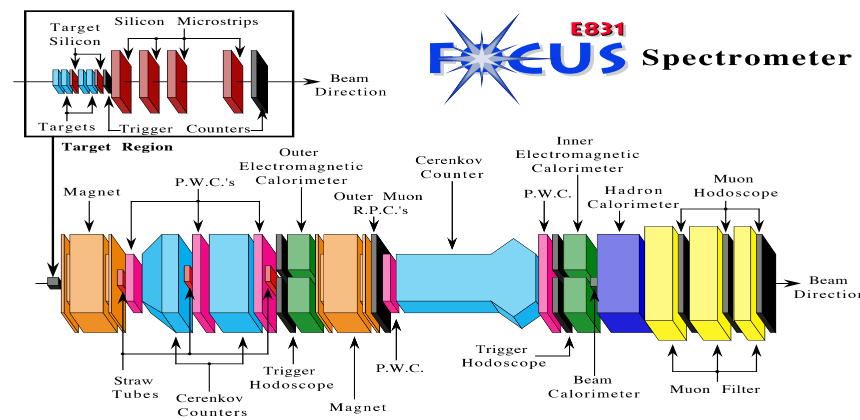
E791:

- 500 GeV π^- beam on nucleon target
- Took data at Fermilab 1991–2



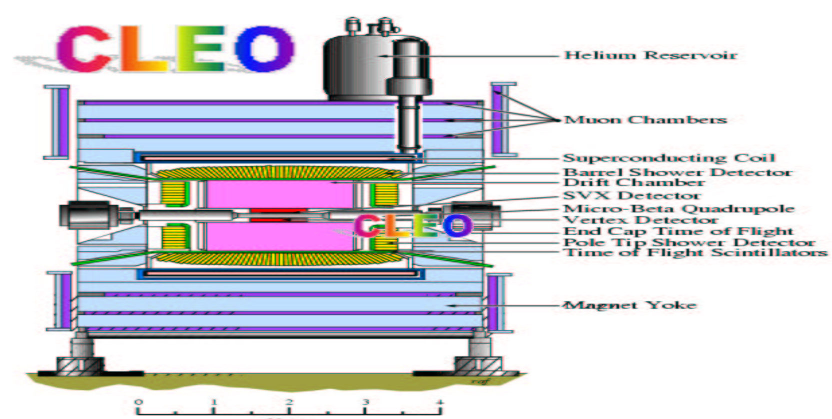
FOCUS:

- $\sim$ 180 GeV γ beam on nucleon target
- Took data at Fermilab 1996–7



CLEO:

- Symmetric e^+e^- at $\Upsilon(4S)$
- Most data from CLEO II.V (1996–9)



$D^+ \to K_S^0 h^+$ – FOCUS

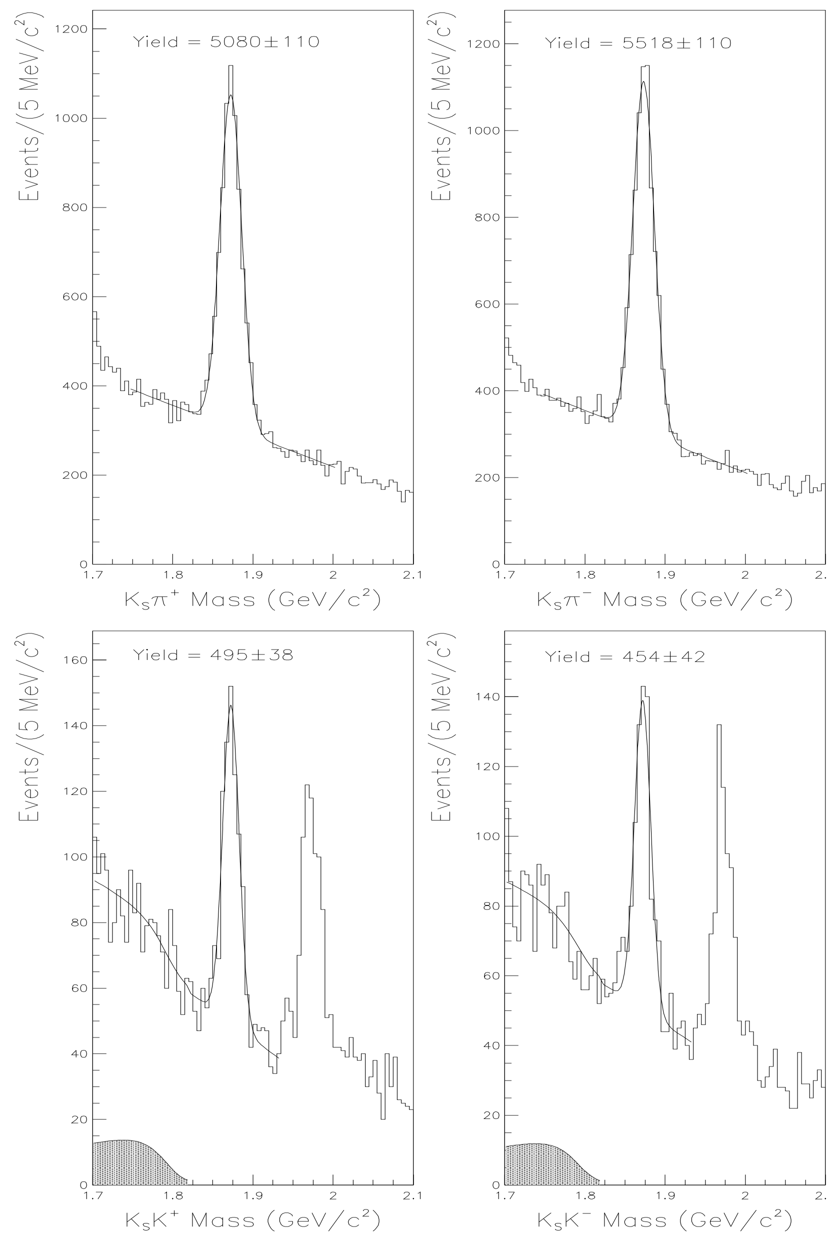
Branching Ratio Measurements:

D^+ BR	FOCUS	PDG Average
$\frac{\Gamma(\overline{K^0}\pi^+)}{\Gamma(K^-\pi^+\pi^+)}$	$(30.60\pm0.46\pm0.58)\%$	$(32.0\pm4.0)\%$
$\frac{\Gamma(\overline{K^0}K^+)}{\Gamma(K^-\pi^+\pi^+)}$	$(6.04\pm0.35\pm0.35)\%$	$(7.7\pm2.2)\%$
$\frac{\Gamma(\overline{K^0}K^+)}{\Gamma(\overline{K^0}\pi^+)}$	$(19.96\pm1.20\pm1.06)\%$	$(26.3\pm3.5)\%$

Direct CP Violation search:

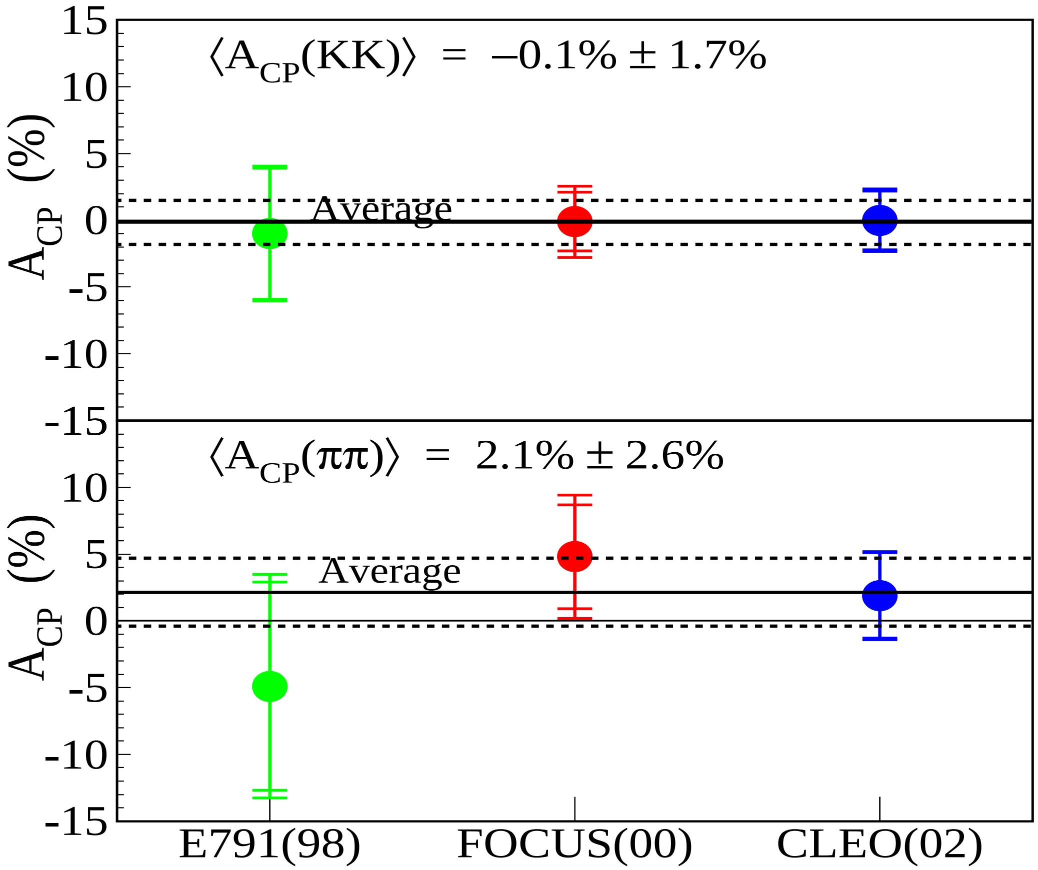
- Measure $A_{CP} = \frac{\eta(D^+\to K_s h^+) - \eta(D^-\to K_s h^-)}{\eta(D^+\to K_s h^+) + \eta(D^-\to K_s h^-)}$
- Normalize to another mode to account for production asymmetries

CP Asymmetry	FOCUS
$A_{CP}(K_S^0\pi^+)$ w.r.t. $K^-\pi^+\pi^+$	$(-1.6\pm1.5\pm0.9)\%$
$A_{CP}(K_S^0 K^+)$ w.r.t. $K^-\pi^+\pi^+$	$(6.9\pm6.0\pm1.8)\%$
$A_{CP}(K_S^0 K^+)$ w.r.t. $K_S^0\pi^+$	$(7.1\pm6.1\pm1.4)\%$

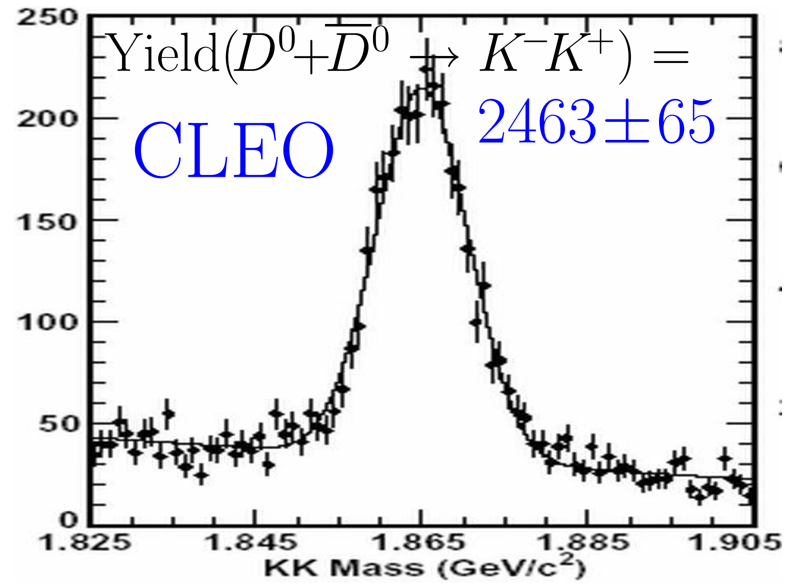


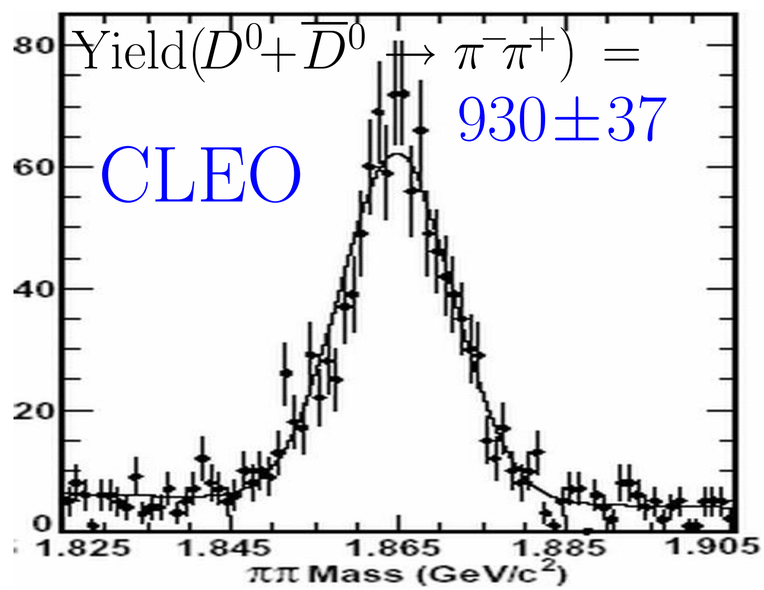
CP violation search in $D^0 \to \pi^+\pi^-, K^+K^-$ decays

- Use $D^{*+} \to D^0\pi^+$ decays to distinguish D^0 from $\overline{D}^0$



Expt	$A_{CP}(KK)$ (%)	$A_{CP}(\pi\pi)$ (%)
E791(98)	$-1.0 \pm 4.9 \pm 1.2$	$-4.9 \pm 7.8 \pm 3.0$
FOCUS(00)	$-0.1 \pm 2.2 \pm 1.5$	$4.8 \pm 3.9 \pm 2.5$
CLEO(02)	$0.0 \pm 2.2 \pm 0.8$	$1.9 \pm 3.2 \pm 0.8$





CP violation in three-body decays

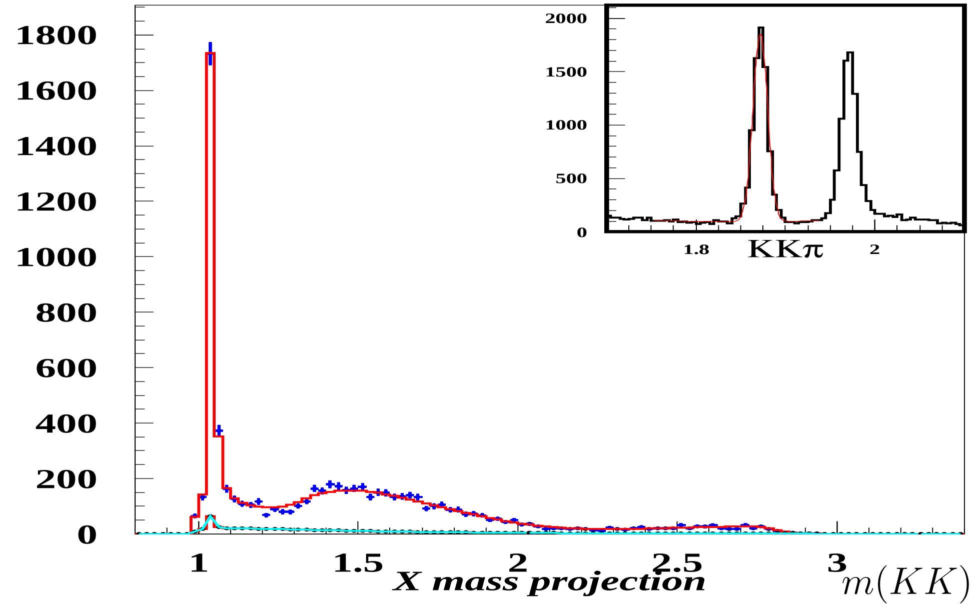
- Can look for CP violation integrated over phase space
- Can look for CP violation via effective two-body decays by cutting on resonances
- Can fit D and $\overline{D}$ Dalitz plots separately and compare magnitudes and phases (most sensitive)

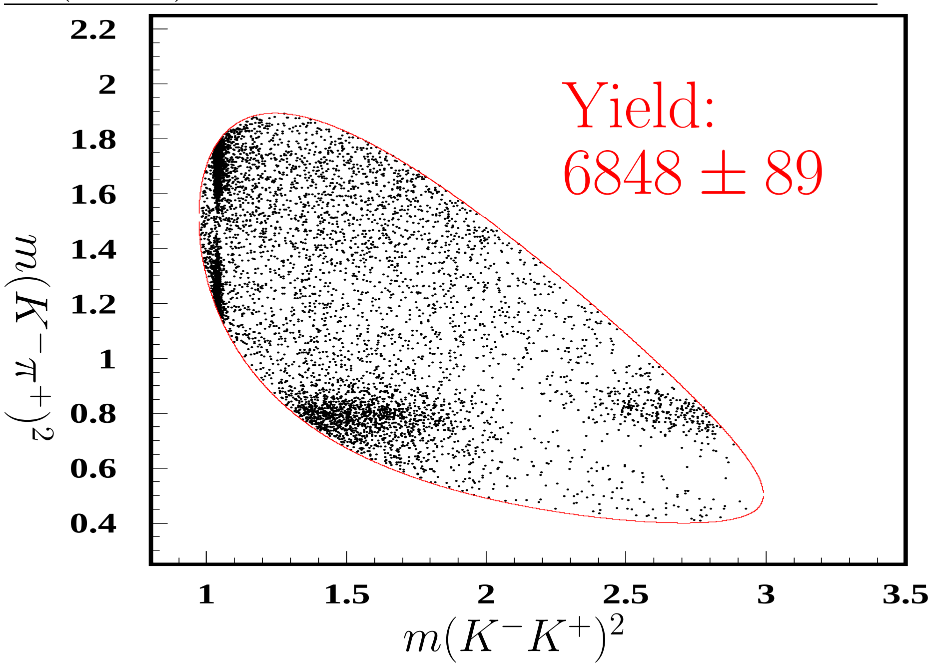
A_{CP} for $D^+ \to K^-K^+\pi^+, \pi^-\pi^+\pi^+$

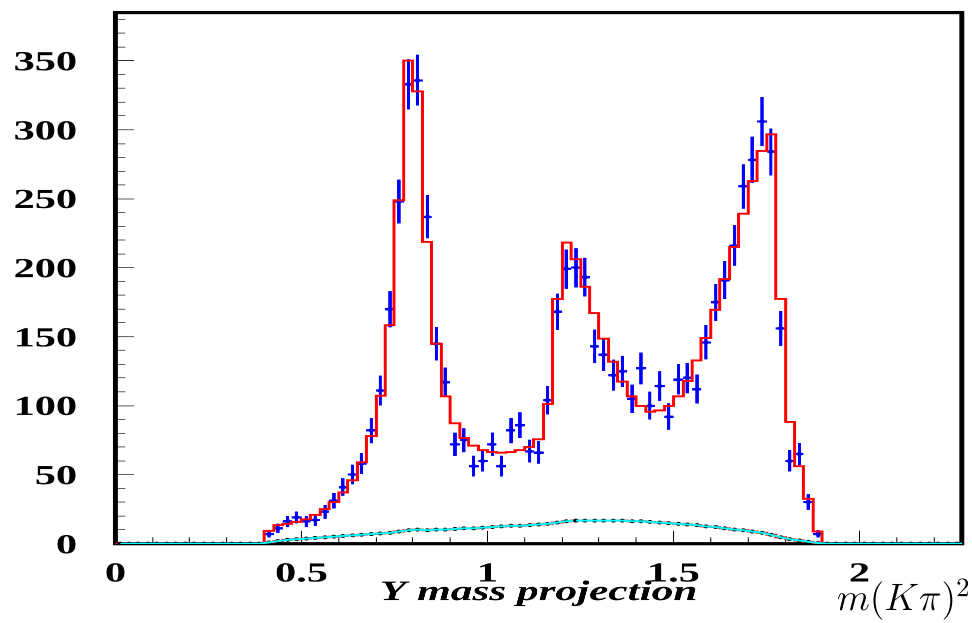
	E791	FOCUS
$A_{CP}(K^-K^+\pi^+)$	$(-1.4 \pm 2.9)\%$	$(0.6 \pm 1.1 \pm 0.5)\%$
$A_{CP}(\phi\pi^+)$	$(-2.8 \pm 3.6)\%$	Dalitz analyses
$A_{CP}(K^*K^+)$	$(-1.0 \pm 5.0)\%$	in
$A_{CP}(\pi^+\pi^-\pi^+)$	$(-1.7 \pm 4.2)\%$	progress

FOCUS $D^+ \to K^- K^+ \pi^+$ preliminary analysis

Mode	Fraction (%)	Phase (°)
$K^*(892)K^+$	22.0 ± 1.1	0 (fixed)
$a_0(980)\pi^+$	27.8 ± 4.8	146 ± 5
$\phi(1020)\pi^+$	27.8 ± 0.9	244 ± 6
$f_2(1270)\pi^+$	0.7 ± 0.2	12 ± 7
$f_0(1370)\pi^+$	5.9 ± 1.2	60 ± 6
$K^*(1410)K^+$	8.8 ± 1.9	135 ± 6
$K_0^*(1430)K^+$	69.3 ± 6.3	63 ± 4
$\phi(1680)\pi^+$	1.5 ± 0.5	-70 ± 9







- Will look for direct CP violation by comparing D^+ & D^- Dalitz plots

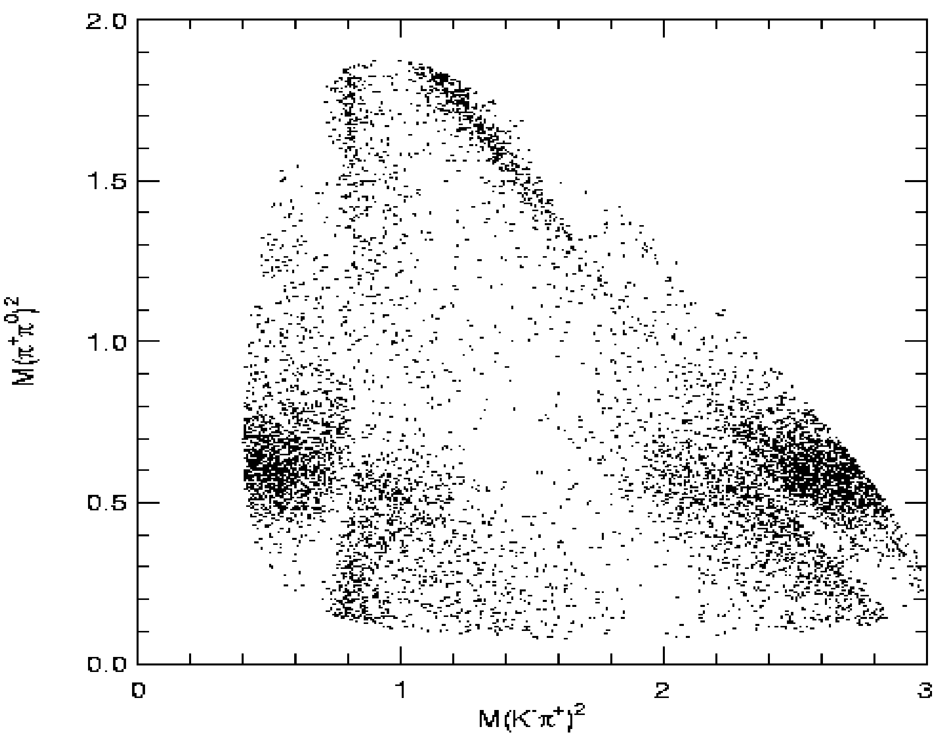
CLEO CP violation search in $D^0 \to K^-\pi^+\pi^0$

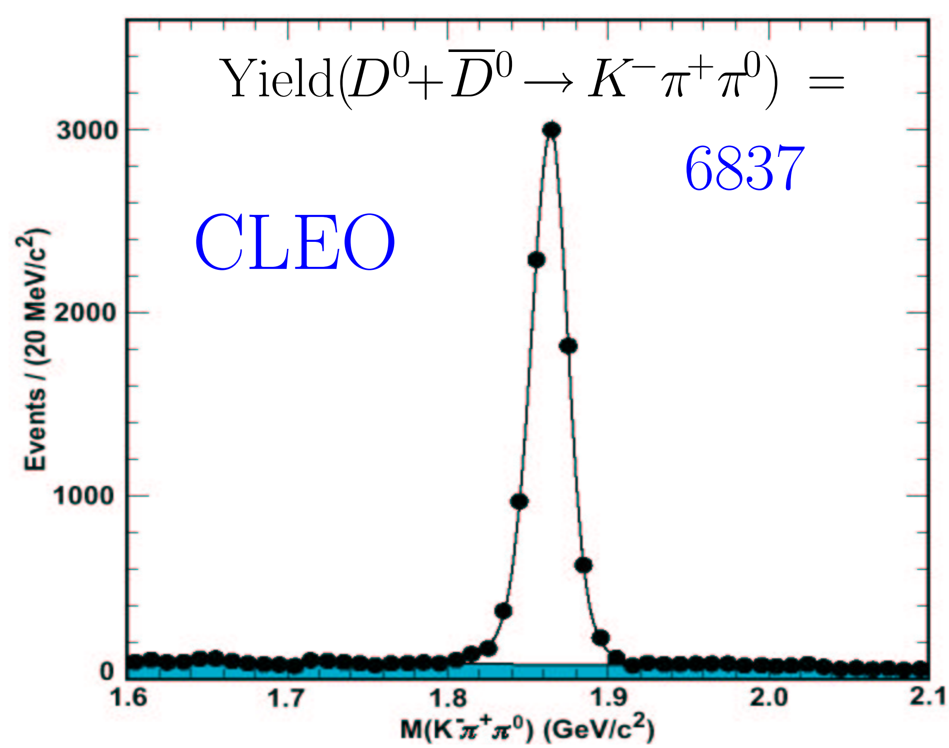
$$A_{CP} = \int \frac{|M_{D^0}|^2 - |M_{\overline{D}^0}|^2}{|M_{D^0}|^2 - |M_{\overline{D}^0}|^2} \, d\,DP$$

$$= (-3.1 \pm 8.6)\%$$

(not optimized to measure A_{CP})

Mode	Fraction (%)	Phase (°)
$\rho(770)K^-$	78.8 ± 2.3	0 (fixed)
$K^*(892)\pi^+$	16.1 ± 1.0	163 ± 4
$K^*(892)\pi^0$	12.7 ± 1.0	0 ± 4
$\rho(1700)K^-$	5.7 ± 1.1	171 ± 7
$K_0^*(1430)\pi^0$	4.1 ± 0.9	166 ± 7
$K_0^*(1430)\pi^+$	3.3 ± 0.9	56 ± 7
$K^*(1680)\pi^0$	1.3 ± 0.4	103 ± 11
NR	7.5 ± 1.1	31 ± 7





CPT Violation

- Point particle Lorentz invariant field theories $\Rightarrow$ CPT invariance
- Some Standard Model extensions need not be Lorentz-invariant
  - Example: strings are not point particles $\Rightarrow$ can elude requirement
  - Start with more fundamental theory operating at, *e.g.*, M_{Plank}
  - At current energies have spontanteous symmetry breaking in which vacuum acquires quantities oriented in 4-D $\Rightarrow$ violates particle Lorentz invariance (although not observer Lorentz invariance)
- One could find evidence for strings by precision tests of CPT and/or Lorentz invariance
- $\Rightarrow$ should search for CPT violation and Lorentz violation
- Limits have been set using neutral K and B mesons (mixing interferometry)
- No limits yet from charm system

Mostly follow formalism developed by Kostelecký (hep-ph/0104120)

- Standard effective Hamiltonian is rewritten:

$$\Lambda = M - \frac{1}{2}i\Gamma \qquad \Rightarrow \qquad \Lambda = \frac{1}{2}\Delta\lambda \begin{pmatrix} U+\xi & V\,W^{-1} \\ V\,W & U-\xi \end{pmatrix}$$

where U, V, W, ξ are complex and $\Delta\lambda = \Delta M - i\,\Delta\Gamma/2$

- The time-dependant right-sign $D^0 \to f$ decay probability, $P_f(t) =$ $\frac{1}{2}|F|^2 e^{-\Gamma t}\left[\left(1+|\xi|^2\right)\cosh\Delta\Gamma + \left(1-|\xi|^2\right)\cos\Delta M - 2\Re(\xi)\sinh\Delta\Gamma + 2\Im(\xi)\sin\Delta M\right]$

- The time-dependant $\overline{D}^0 \to \overline{f}$ decay probability $\overline{P}_{\overline{f}}(t)$ is $P_f(t)$ with $\xi \to -\xi$ and $F \to \overline{F}$

- Form the asymmetry for right-sign decays:

$$A_{CPT}(t) = \frac{\overline{P}_{\overline{f}}(t) - P_f(t)}{\overline{P}_{\overline{f}}(t) + P_f(t)} = \frac{2\Re(\xi)\sinh\Delta\Gamma t - 2\Im(\xi)\sin\Delta M t}{\left(1+|\xi|^2\right)\cosh\Delta\Gamma t + \left(1-|\xi|^2\right)\cos\Delta M t}$$

- Taylor expand sin, sinh, cos, cosh to 1st order and use standard mixing variables $x \equiv \Delta M/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$. Then:

$$A_{CPT}(t) \approx \left[\Re(\xi)\,y - \Im(\xi)\,x\right]\Gamma t$$

CPT formalism continued...

- From above, $A_{CPT}(t) \approx [\Re(\xi)\, y - \Im(\xi)\, x)]\, \Gamma t$
- Experimentally, $A_{CPT}(t') = \frac{N_{\overline{D}^0}(t') - N_{D^0}(t')}{N_{\overline{D}^0}(t') + N_{D^0}(t')}$
- Slope of distribution gives $[\Re(\xi)\, y - \Im(\xi)\, x]$

Lorentz invariance violating parameters

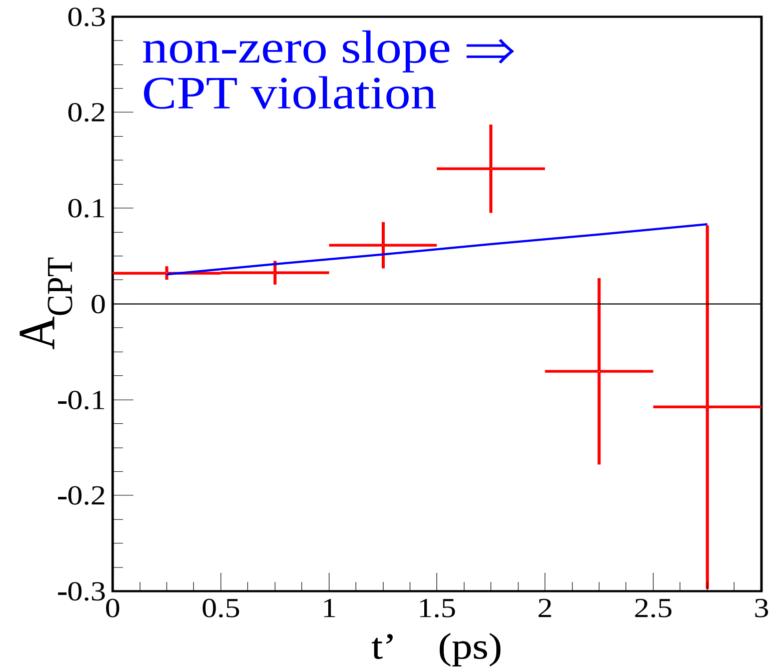
- In CPT and Lorentz violating extensions, CPT violating parameters (ξ) depend on lab momentum, orientation, and sidereal time
- Wind up with flavor dependant Lorentz violating coupling coefficients
- For FOCUS (a forward, fixed-target experiment):

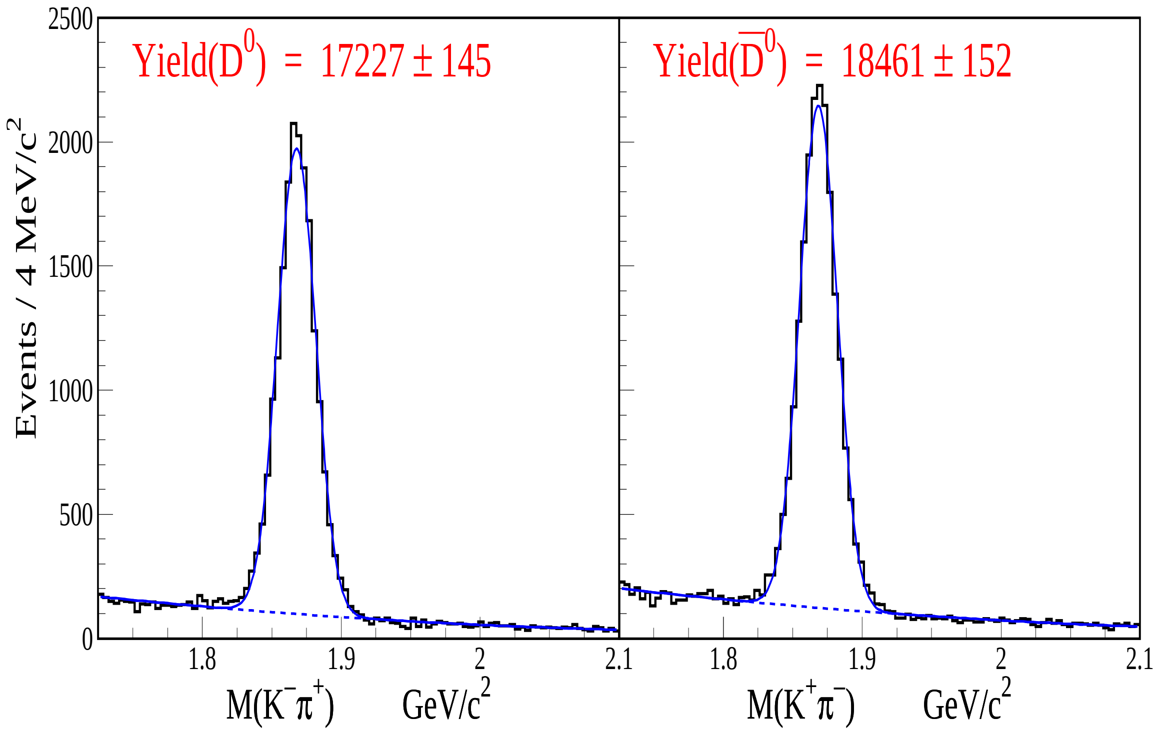
$$\xi(\hat{t},p) = \frac{\gamma(p)}{\Delta\lambda}\left[\Delta a_0 + \beta \Delta a_Z \cos\chi + \beta \sin\chi (\Delta a_Y \sin \Omega \hat{t} + \Delta a_X \cos \Omega \hat{t})\right]$$

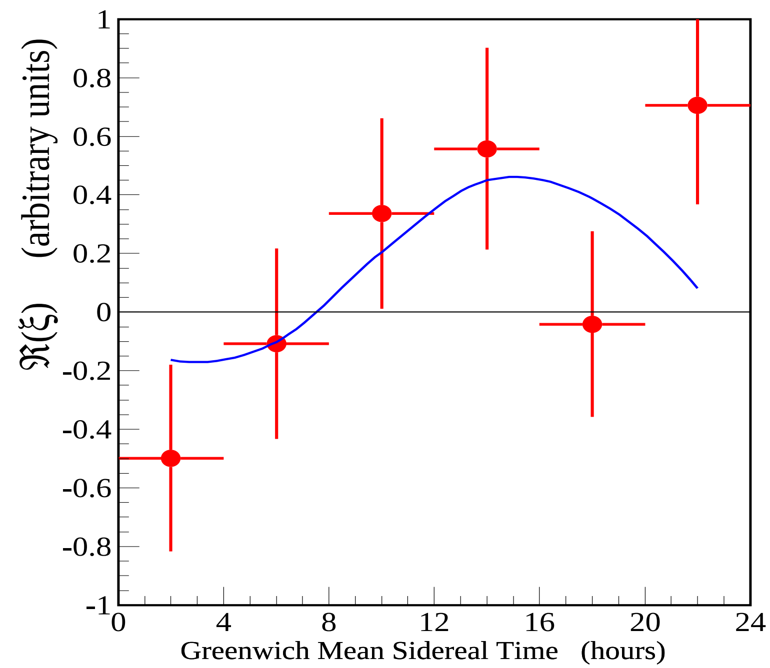
  - Ω ($\hat{t}$) $\equiv$ sidereal frequency (time)
  - $X, Y, Z \equiv$ non-rotating coordinates; Z along Earth's rotation axis
  - $\Delta\lambda = (x - iy)\Gamma$
  - $\gamma(p) = \sqrt{1 + p_D^2/M_D^2}$
  - $\beta = 1, \chi = 53^\circ$ for FOCUS

CPT Violation preliminary results – FOCUS

- $\Re(\xi)y - \Im(\xi)x = 0.0083 \pm 0.0065 \pm 0.0041$
  - Limits depend on mixing parameters
  - Example: $x = 0,\ y = 1\% \ \Rightarrow$ $\Re(\xi) = 0.83 \pm 0.65 \pm 0.41$
- Lorentz invariance violating parameters:
  - Still under study
  - Expect limits on $\Delta a_0 + .6\Delta a_Z, \Delta a_X, \& \Delta a_Y$ in range of $\sim 10^{-15}$ GeV







Summary of CP (& CPT) violation searches

A_{CP} mode	E791(98) (%)	FOCUS(00,02) (%)	CLEO(01,02) (%)
$D^0 \to K^- K^+$	$-1.0 \pm 4.9 \pm 1.2$	$-0.1 \pm 2.2 \pm 1.5$	$0.0 \pm 2.2 \pm 0.8$
$D^0 \to \pi^- \pi^+$	$-4.9 \pm 7.8 \pm 3.0$	$4.8 \pm 3.9 \pm 2.5$	$1.9 \pm 3.2 \pm 0.8$
$D^0 \to \pi^0 \pi^0$			0.1 ± 4.8
$D^0 \to K_S^0 K_S^0$			-23 ± 19
$D^0 \to K_S^0 \pi^0$			0.1 ± 1.3
$D^+ \to K_S^0 \pi^+$		$-1.6 \pm 1.5 \pm 0.9$	
$D^+ \to K_S^0 K^+$		$6.9 \pm 6.0 \pm 1.8$	
$D^0 \to K^- \pi^+ \pi^0$			-3.1 ± 8.6 (DP)
$D^+ \to K^- K^+ \pi^+$	-1.4 ± 2.9	$0.6 \pm 1.1 \pm 0.5$	
$D^+ \to \phi \pi^+$	-2.8 ± 3.6		
$D^+ \to K^* K^+$	-1.0 ± 5.0		
$D^+ \to \pi^- \pi^+ \pi^+$	-1.7 ± 4.2		

- First CPT violation search in charm from FOCUS (preliminary)

  $-\Re(\xi)\, y \;-\; \Im(\xi)\, x = 0.0083 \pm 0.0065 \pm 0.0041$

Future of CP violation searches in charm

- Short term: < 1 year
  - FOCUS is working on Dalitz analyses of 3-body D^+ decays such as $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$
  - CLEO is working on Dalitz analyses of 3-body D^0 decays such as $D^0 \rightarrow K_S^0 \pi^+ \pi^-$, $D^0 \rightarrow \pi^- \pi^+ \pi^0$, $D^0 \rightarrow K_S^0 \pi^0 \pi^0$ plus D^+ modes
  - Belle and BaBar will improve on current limits?
- Medium term: 1–5 years
  - CLEO-c will be collecting $\sim$30 million $D\overline{D}$ events at the $\psi(3770)$
  - Belle and BaBar will continue to provide excellent results
- Longer term: > 5 years
  - BTeV at the Fermilab Tevatron ($p\bar{p}$) will likely be the first experiment to reconstruct 1 billion charm decays