Search for CP and T violation in charm decays

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CP violation

- In addition to direct CP violation for D^0 decays there is the possibility of indirect CP violation due to mixing

- Buccella et al. predict CP violating decay asymmetries for charmed meson in the range:

$$0.002\ \% \longrightarrow 0.14\ \%$$

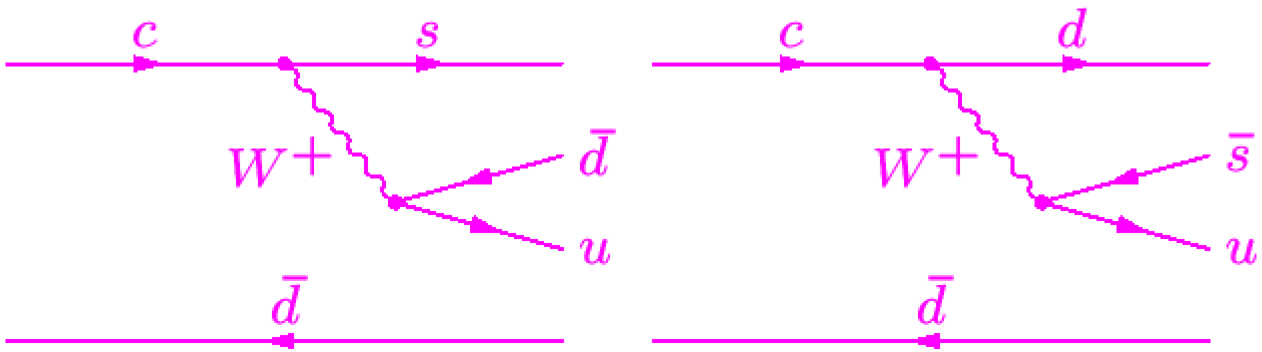
- In the Standard Model no direct CP asymmetry can arise in Cabibbo allowed or DCS modes since they are driven by a single weak amplitude

- However in $D \rightarrow K_s\ \pi$'s CP asymmetries can arise in two different ways:

  a) through the CP impurity in K_s

  b) through interference of two weak amplitudes

CP violation



because one cannot differentiate between a K^0 and a $\overline{K}^0$ in the final state

- if New Physics intervenes through DCSD, then it would have the cleanest impact on in $D^+ \longrightarrow K_{S,L}\ \pi^+$ (Bigi and Sanda)

Summary of CP asymmetry measurements

Decay mode	E791	CLEO	FOCUS
$D^0 \to K^- K^+$	$-0.010 \pm 0.049 \pm 0.012$	$+0.000 \pm 0.022 \pm 0.008$	$-0.001 \pm 0.022 \pm 0.015$
$D^0 \to \pi^- \pi^+$	$-0.049 \pm 0.078 \pm 0.030$	$+0.019 \pm 0.032 \pm 0.008$	$+0.048 \pm 0.039 \pm 0.025$
$D^0 \to K_S \pi^0$		-0.018 ± 0.030	
$D^+ \to K^- K^+ \pi^+$	-0.014 ± 0.029		$+0.006 \pm 0.011 \pm 0.005$
$D^+ \to \pi^- \pi^+ \pi^+$	$-0.017 \pm 0.042 \pm 0.005$		
$D^+ \to K_S \pi^+$			$-0.016 \pm 0.015 \pm 0.009$
$D^+ \to K_S K^+$			$+0.069 \pm 0.060 \pm 0.015$

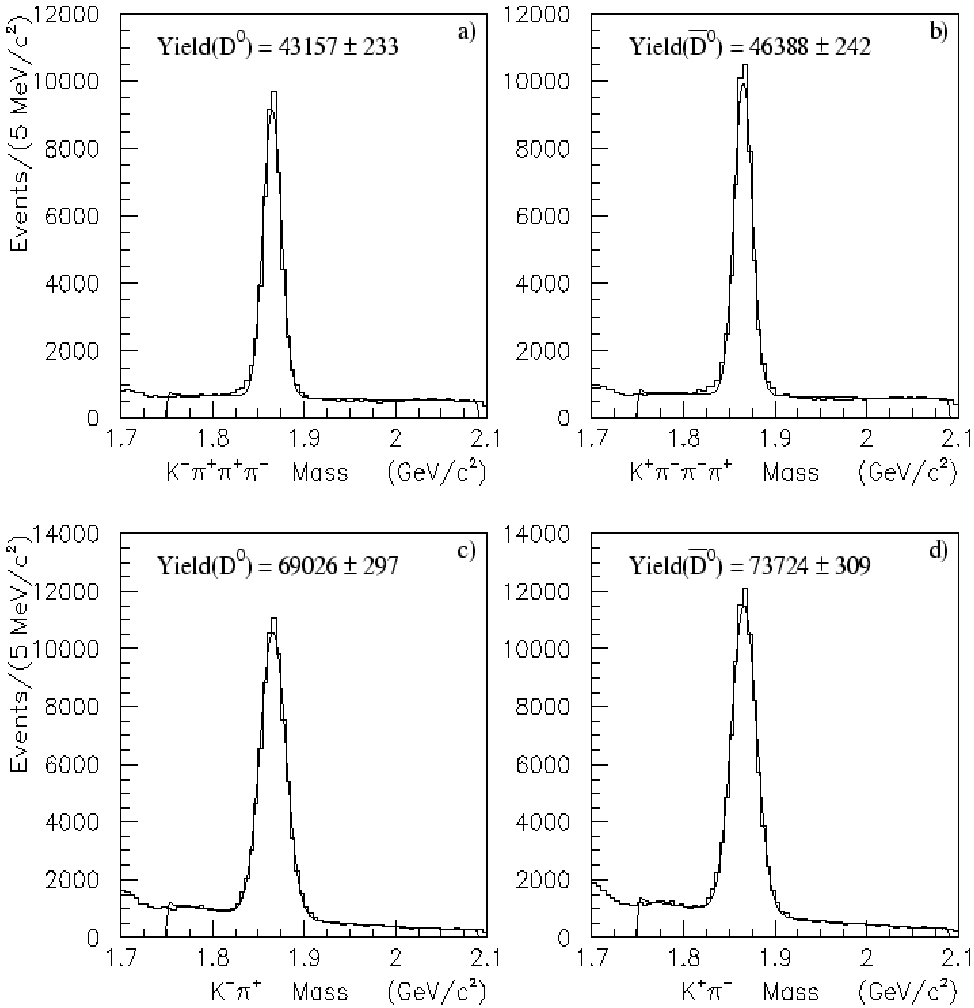
- 1% level reached for some decay modes
- measured CP asymmetries are consistent with zero within errors
- no evidence of CP violation

What's next…….

- To search for New Physics beyond the Standard Model, one should look at the Cabibbo favored decay modes since they are NOT expected to exhibit CP asymmetries

- or Doubly Cabibbo Suppressed Decays….

FOCUS data: An interesting exercise….CF



$$A_{CP} = \frac{\eta - \overline{\eta}}{\eta + \overline{\eta}}$$

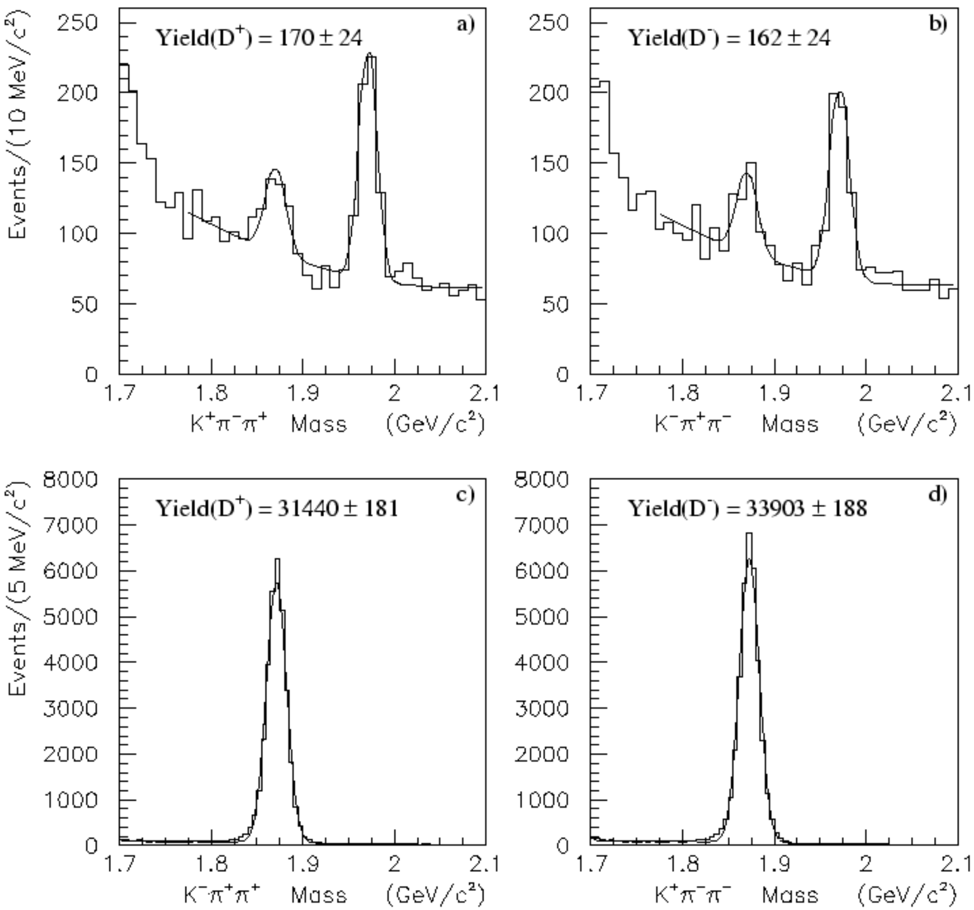
$$\eta = \frac{D^0 \to K^-\pi^+\pi^-\pi^+}{D^0 \to K^-\pi^+}$$

A_{CP} = 0.0018 +/- 0.0048(stat.)

A_{CP} = 0.0032+/- 0.0048(stat.)
(without MC efficiency correction)

not even preliminary !!

FOCUS data: CP violation search with DCSD



$$A_{CP} = \frac{\eta - \overline{\eta}}{\eta + \overline{\eta}}$$

$$\eta = \frac{D^+ \to K^+\pi^-\pi^+}{D^+ \to K^-\pi^+\pi^+}$$

A_{CP} = 0.063 +/- 0.074 (stat.)

not even preliminary !!

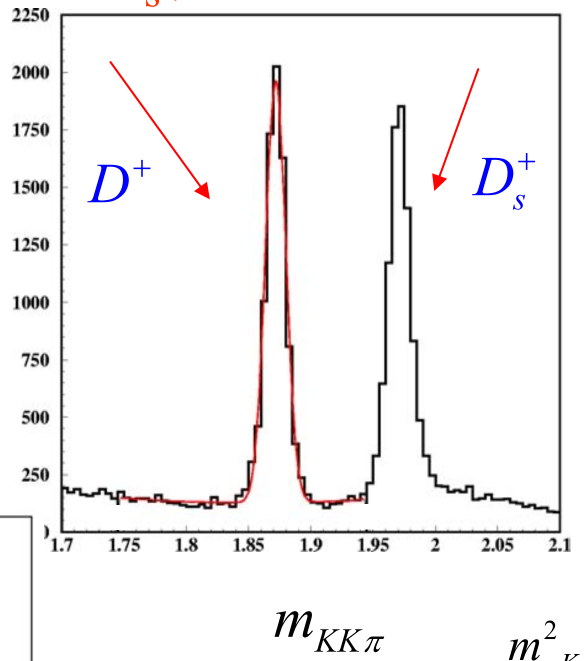
Dalitz plot analysis

- Main advantage:
  complete information not only the branching ratio

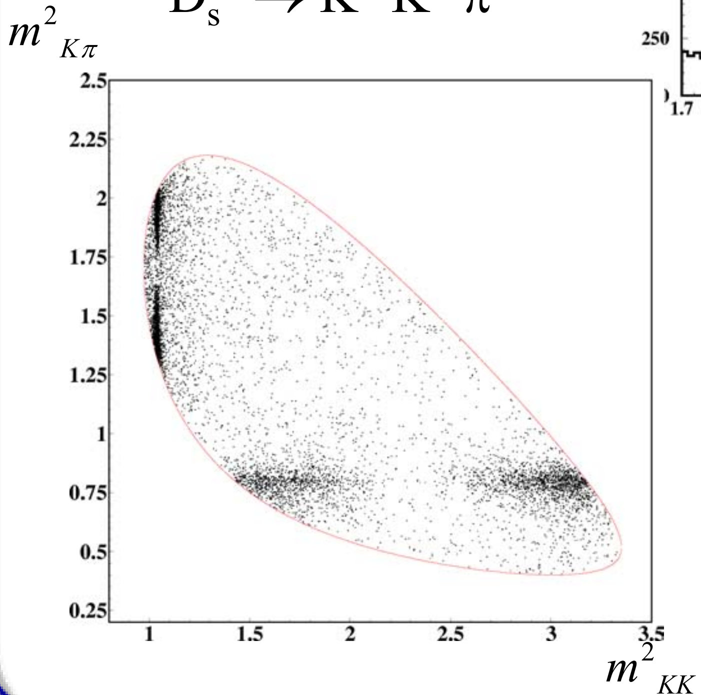
DETERMINATION OF AMPLITUDE COEFFICIENTS AND PHASES

- Final state is the result of the interference of all the intermediate states

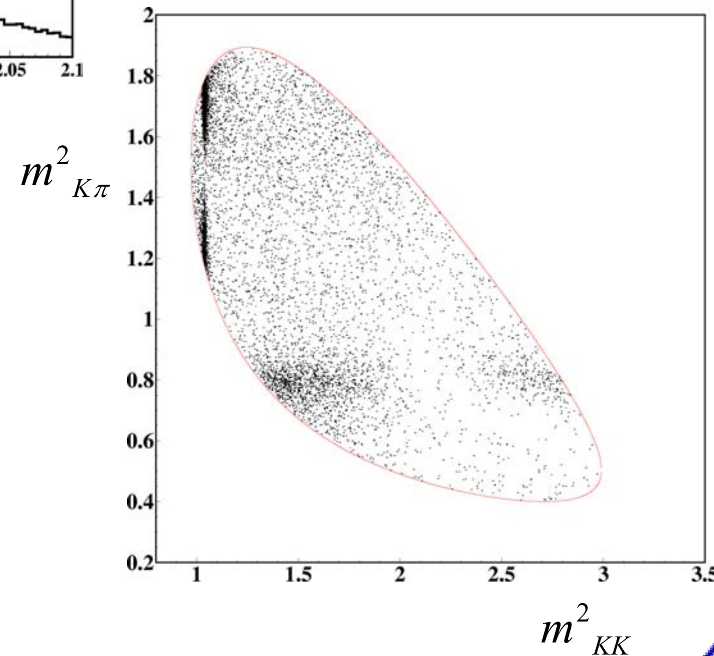
D_s , $D^+ \rightarrow KK\pi$

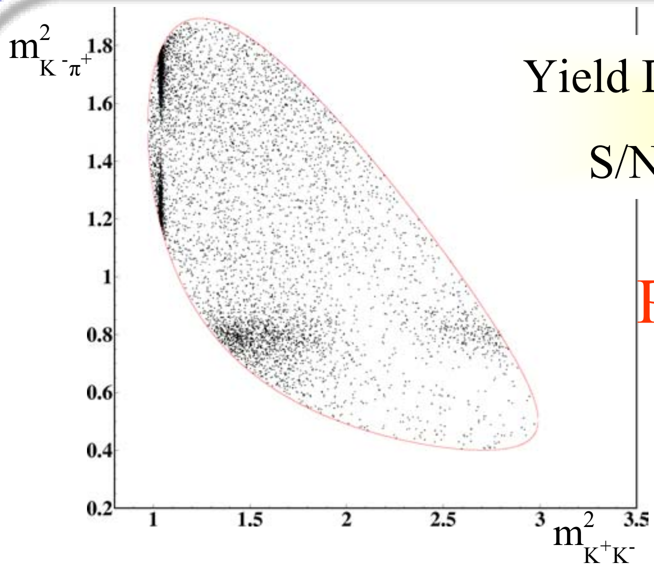


$D_s^+ \rightarrow K^+ K^- \pi^+$



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





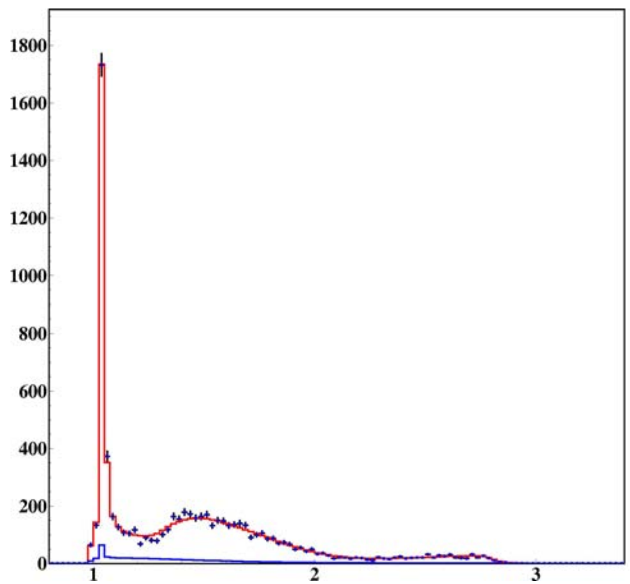
Yield D^+ = 7106 ±92

S/N D^+ = 8.62

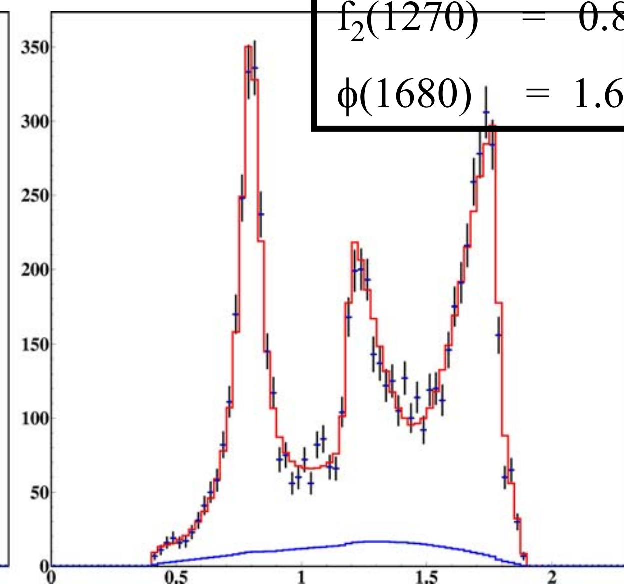
Preliminary

Decay Fraction and phases

K*(892)	= 20.7 ± 1.0	%	(0 fixed)
φ(1020)	= 27.8 ± 0.7	%	(243.1 ±5.2)°
K*(1410)	= 10.7 ± 1.9	%	(-47.4 ± 4.9) °
K^*(1430)	= 66.5 ± 6.0	%	(61.8 ± 3.8)°
f_0(1370)	= 7.0 ± 1.1	%	(60.0 ± 5.3) °
a_0(980)	= 27.0 ± 4.8	%	(145.6 ± 4.3)°
f_2(1270)	= 0.8 ± 0.2	%	(11.6 ± 7.0) °
φ(1680)	= 1.6 ± 0.4	%	(-74.3 ± 7.5) °



$K^+ K^-$ projection



$K^- \pi^+$ projection

Dalitz plot analysis

CP violating phase

- $\delta_i = \sigma_i + \omega_i$

CP conserving phase

under CP conjugation :

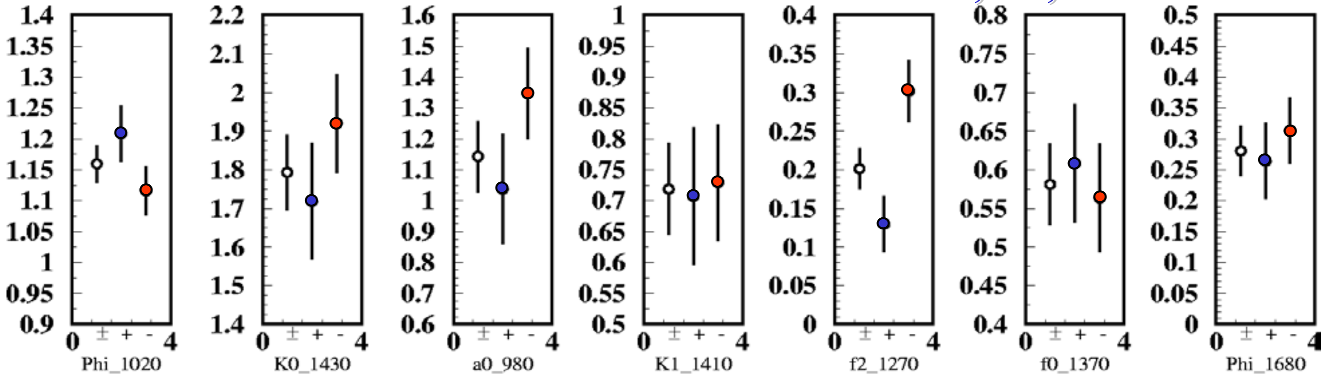
- $\bar{\delta}_i = \sigma_i - \omega_i$

- in general a difference between δ_i and $\bar{\delta}_i$ hints that CP is violated

D^+/D^- split sample analysis

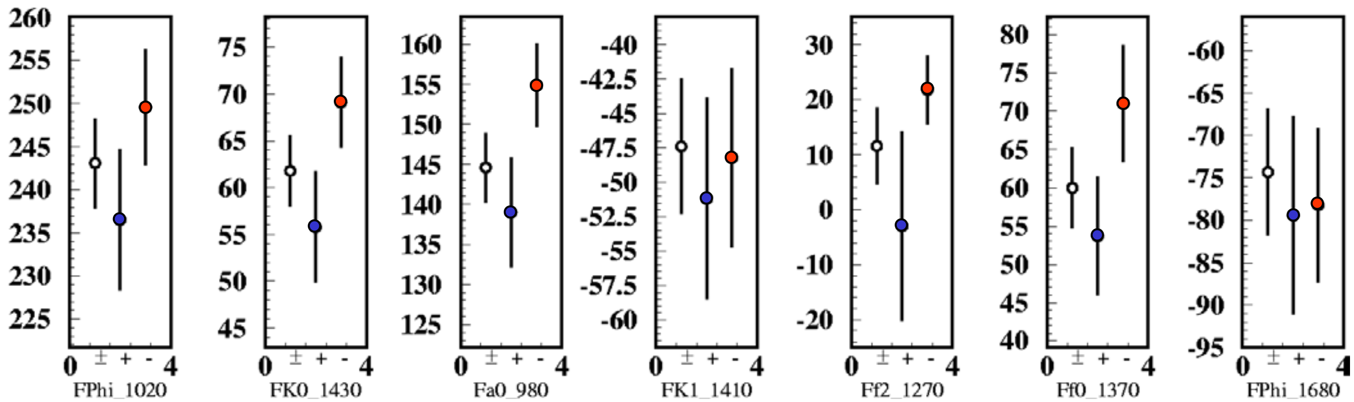
Coefficients: $D^\pm$, D^+, D^-

Preliminary!



Phases: $D^\pm$, D^+, D^-

No evidence of CPV



K-matrix approach to improve the quality of the analysis

Can we get a pure $K_s \phi$ CP odd from $D^0 \rightarrow K_s K^+K^-$?

$K_s \phi$ is a CP odd state: Ks and ϕ are CP even

$K_s \phi$ is in a relative p-wave with parity -1

$K_s f_0(980)$ is a CP even state: Ks and f_0 are CP even

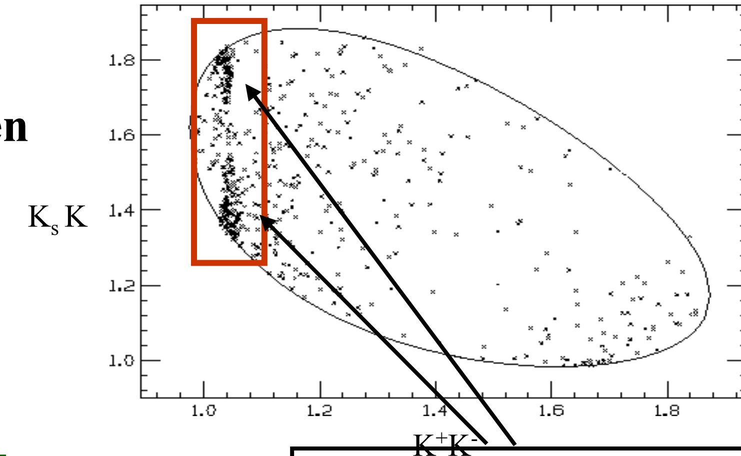
$K_s f_0(980)$ is relative s-wave with parity +1

Two states interfere in same region in Dalitz plot:

Is there a pure CP odd eigenstate near the ϕ ?

No. A CP even eigenstate will be present with a non-negligible fraction.

Tagged sample



asymmetry in ϕ lobes indicates interference

Fraction of events in the ϕ region due to ϕK_s is:

$$\frac{\int_{\phi\ region} A_\phi A_\phi}{\int_{\phi\ region} A^*_{total} A_{total}} = 62 \pm 3\%$$

Resonance	Fraction in the ϕ region ($M^2_{k^+K^-} < 1.1(MeV/c^2)^2$)
$f_0(980)$	$37.8 \pm 3.0\%$
$a_0^+(980)$	$0.5 \pm 0.1\%$
ϕ	$62.2 \pm 2.8\%$

Suggests $D^0 \rightarrow "\phi" K_s$ is 62% CP odd and 38% CP even

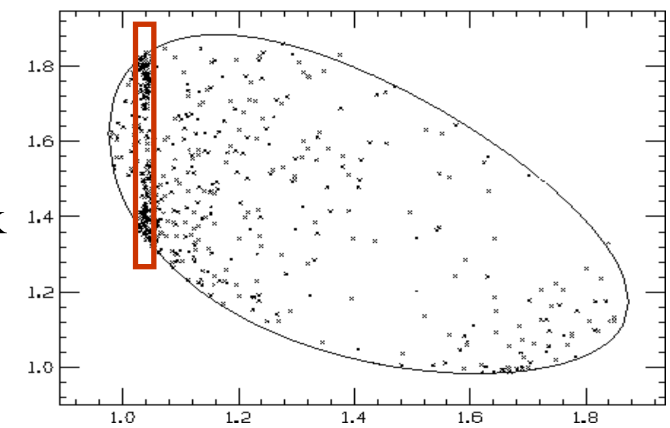
But $D^o \rightarrow K^-\pi^+$ is 50% CP odd + 50 CP even

E831 FOCUS

$K_s\ \phi$ CP odd purity can be improved with a tighter cut

The contaminating f_0 fraction rapidly reduces as we narrow the phi region from 50 MeV to 4 MeV

Tagged sample



Fraction of events in the ϕ region due to ϕK_s is:

$$\frac{\int_{\phi\ region} A^*_\phi A_\phi}{\int_{\phi\ region} A^*_{total} A_{total}} = 93 \pm 2 \pm 1\%$$

Resonance	Fraction in the ϕ region $((MeV/c^2)^2)$ $1.034 < M^2_{K^+K^-} < 1.042$
$f_0(980)$	$7.7 \pm 1.0 \pm 0.4\%$
$a_0^+(980)$	$0.05 \pm 0.01 \pm 0.1\%$
ϕ	$93.0 \pm 0.9 \pm 0.3\%$

Now $D^0 \to "\phi" K_s$ is 93% CP odd and 7% CP even

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Discrete symmetry P and T

Quantity	P	T
$\mathbf{r}$	$-\mathbf{r}$	$\mathbf{r}$
$\mathbf{p}$	$-\mathbf{p}$	$-\mathbf{p}$
σ	σ	$-\sigma$
$\sigma \cdot \mathbf{p}$	$-\sigma \cdot \mathbf{p}$	$\sigma \cdot \mathbf{p}$
$\sigma \cdot (\mathbf{p}_1 \times \mathbf{p}_2)$	$\sigma \cdot (\mathbf{p}_1 \times \mathbf{p}_2)$	$-\sigma \cdot (\mathbf{p}_1 \times \mathbf{p}_2)$

T-odd correlation

$$C_T = v_1 \bullet (v_2 \times v_3)$$

where v_i is can be spin or momentum of a final state particle

T-odd correlation

From I.I.Bigi 'Charm physics - Like Botticelli in the Sistine Chapel'
arXiv:hep-ph/0107102 v1 (2001)

" Consider,e.g., $D^0 \to K^- K^+ \pi^- \pi^+$,where one can form a T-odd correlation with the momenta:

$$C_T = \langle p_{K^+} \circ (p_{\pi^+} \times p_{\pi^-}) \rangle$$

Under time reversal T one has $C_T \to -C_T$ hence the name 'T-odd'.

Yet $C_T \neq 0$ does not necessarily establishes T violation.

Since time reversal is implemented by an antiunitary operator, $C_T \neq 0$ can be induced by FSI. While in contrast to the situation with partial width differences FSI are not required to produce an effect, they can act as an 'imposter' here, id est induce a T-odd correlation with T-invariant dynamics.

This ambiguity can unequivocally be resolved by measuring in $D^0 \to K^- K^+ \pi^- \pi^+$.

$$\overline{C}_T = \langle p_{K^-} \circ (p_{\pi^-} \times p_{\pi^+}) \rangle$$

Finding $C_T \neq -\overline{C}_T$ establishes CP violation without further ado."

T-odd correlation

Physical motivations

$$C_T = v_1 \bullet (v_2 \times v_3)$$

(where v_i is a spin or a moment of a final particle)

Assuming CPT invariance

T- odd correlation

($C_T \to - C_T$ under time inversion)

BUT

To find $C_T \neq 0$ doesn't imply CP violation

because

$C_T \neq 0$ can be produced through:

Weak phase
(which violates CP)

Strong phase from F.S.I.
(which doesn't violate CP)

SOLUTION

To study the CP conjugated process and to built C_T and $(C_T)_{CP}$

If $C_T \neq (C_T)_{CP} = -\bar{C}_T$ there is CP violation

T-odd correlation

Physical motivations

How to compute CP asymmetries?

1. We build T-odd asymmetries using decay rates for a certain process and its CP conjugated process, as following:

$$A_T := \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

where

$$A_T \div \sin(\delta_s + \phi_w)$$

$$(A_T)_{CP} := \frac{\Gamma((C_T)_{CP} > 0) - \Gamma((C_T)_{CP} < 0)}{\Gamma((C_T)_{CP} > 0) + \Gamma((C_T)_{CP} < 0)}$$

where

$$(A_T)_{CP} \div \sin(\delta_s - \phi_w)$$

→ NOT TRUE SIGNALS OF CP VIOLATION (because of F.S.I.)

2. We build a T-violation asymmetry, as following:

$$A_{Tviol} := \frac{1}{2}\left(A_T - (A_T)_{CP}\right)$$

where

$$A_{Tviol} \div \cos(\delta_s)\sin(\phi_w)$$

→ TRUE SIGNAL OF CP VIOLATION (even in presence of F.S.I.)

- W.Bensalem and D.London *ArXiv:hep-ph/*0005018 v1 (2000)
- G.Valencia *Phys.Rev.D* 39/11 (1989) 3339

To find $A_{Tviol} \neq 0$ implies CP VIOLATION !

T-odd correlation in the decay mode $D^0 \to K^- K^+ \pi^- \pi^+$

$D^0 \to K^- K^+ \pi^- \pi^+$ decay mode: final state with four different particles

We can build T-odd correlation:

$$C_T = \langle p_{K^+} \circ (p_{\pi^+} \times p_{\pi^-}) \rangle$$ for the $D^0 \to K^- K^+ \pi^- \pi^+$ decay mode

$$\overline{C}_T = \langle p_{K^-} \circ (p_{\pi^-} \times p_{\pi^+}) \rangle$$ for the $\overline{D}^0 \to K^- K^+ \pi^- \pi^+$ decay mode

$C_T \neq (C_T)_{CP} = -\overline{C}_T$ is an evidence of CP VIOLATION

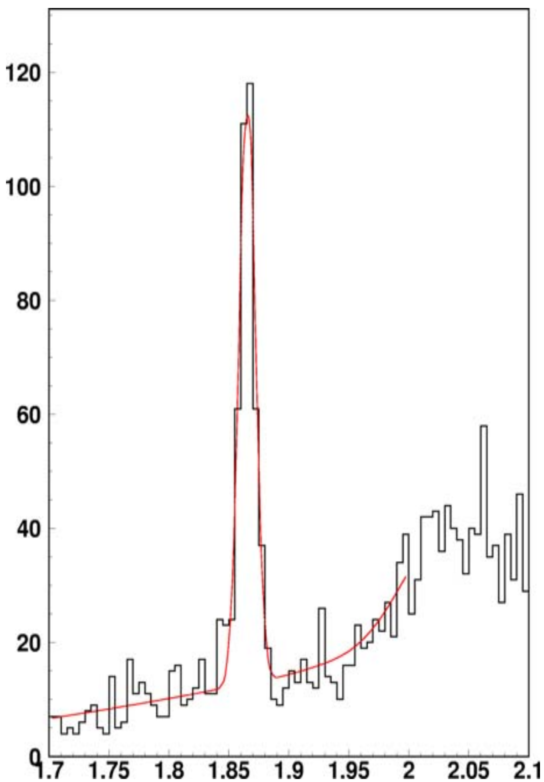
We can build the T-odd asymmetries A_T and $(A_T)_{CP}$ and the T-violation asymmetry A_{Tviol}

$A_{Tviol} \neq 0$ is an evidence of CP VIOLATION

D^*-Tag

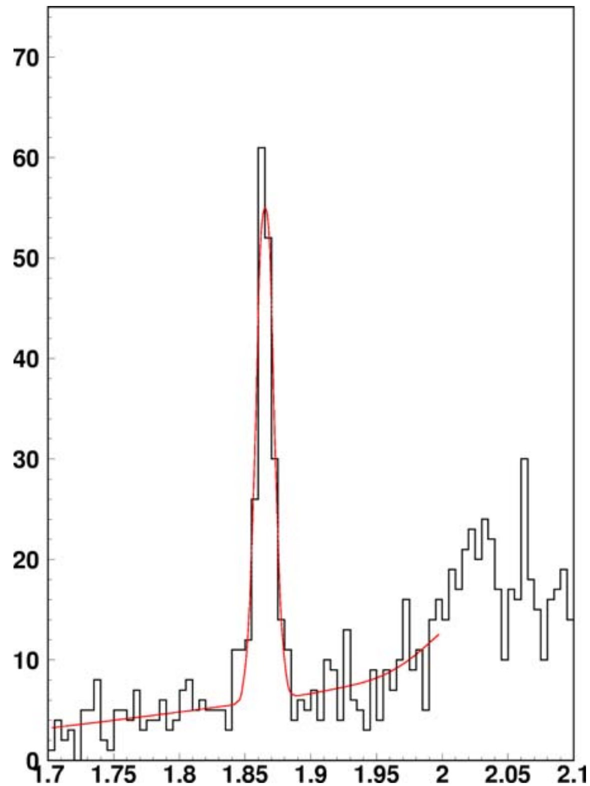
D^*-Tag sample

$D^{*\pm} \to D^0 (\bar{D}^0) \pi^\pm$

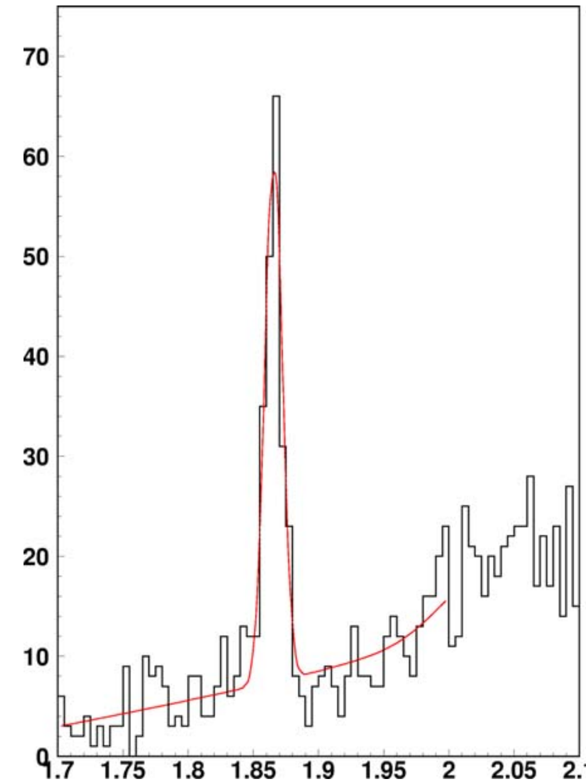


We can distinguish the particle from the antiparticle using the D^*-Tag:

$D^{*+} \to D^0 \pi^+$



$D^{*-} \to \bar{D}^0 \pi^-$

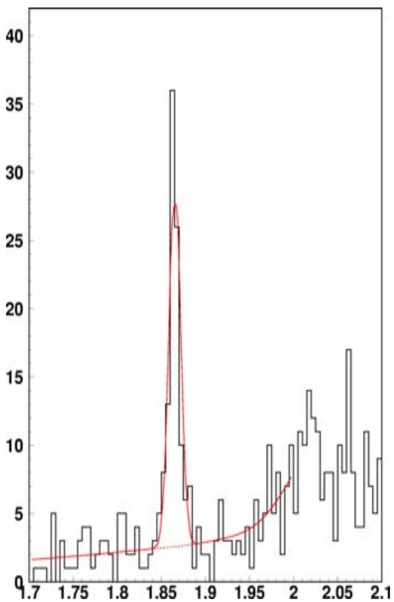


T-odd correlation in the decay mode $D^0 \rightarrow K^-K^+\pi^-\pi^+$

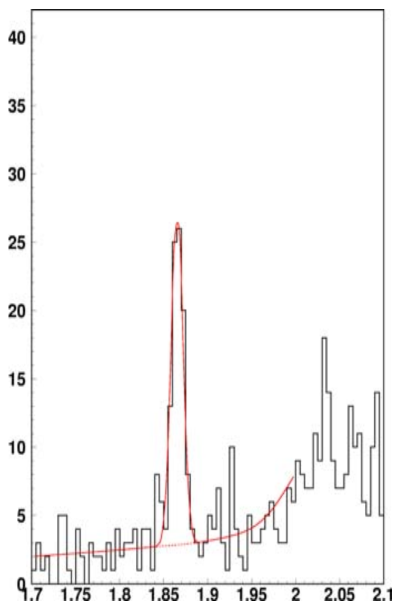
$D^0 \rightarrow K^-K^+\pi^-\pi^+$

$$C_T = \langle p_{K^+} \circ (p_{\pi^+} \times p_{\pi^-}) \rangle$$

T-odd correlation



$C_T > 0$

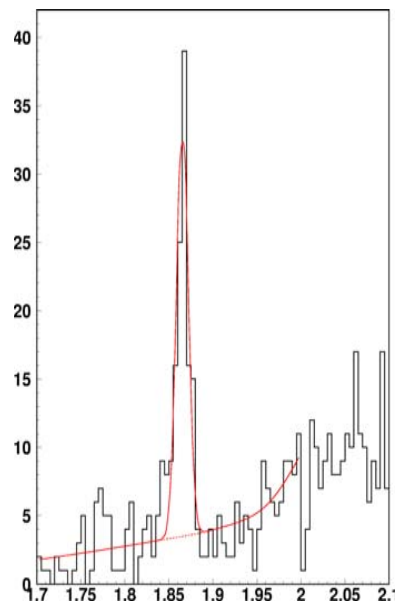


$C_T < 0$

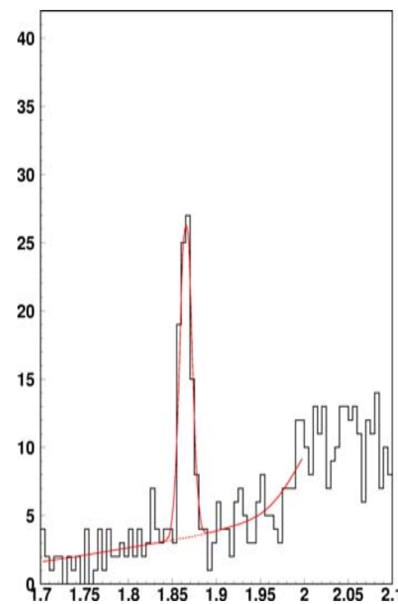
$\bar{D}^0 \rightarrow K^-K^+\pi^-\pi^+$

$$\overline{C}_T = \langle p_{K^-} \circ (p_{\pi^-} \times p_{\pi^+}) \rangle$$

T-odd correlation



$\overline{C}_T > 0$



$\overline{C}_T < 0$

T-odd correlation in the decay mode $D^0 \rightarrow K^- K^+ \pi^- \pi^+$

decay mode	request	yield
$D^0 \rightarrow K^- K^+ \pi^- \pi^+$	$C_T > 0$	88 ± 10
	$C_T < 0$	82 ± 10
$\overline{D}^0 \rightarrow K^- K^+ \pi^- \pi^+$	$\overline{C}_T > 0$	101 ± 11
	$\overline{C}_T < 0$	80 ± 10

$$A_{Tviol} = 0.075 \pm 0.064$$

NO EVIDENCE of CP VIOLATION

Conclusions

- No CP violation has been reported in the charm sector

- However the role of charm remains unique in probing SM and looking for New Physics

- the c quark is the only "u-type" quark for which the decay modes can be studied

- complementary to the "d-type" sector investigation

Conclusions

- Advantage of using Dalitz plot analysis

direct access to the phases

- **Possibility of studying T-odd correlation, in some particular decay modes, in order to determine T-violation**