Search for CP and T violation in charm decays

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Outline

- High impact physics
- CP violation in charm decays
- CP asymmetry: experimental status
- Dalitz plot analysis
- T-odd correlation
- Perspectives
- Conclusions

High impact Physics

Standard Model contains 2 key mysteries :

- the origin of the masses
- the existence of multiple fermion generations

The first mystery could be resolved by LHC

The second mystery appears to originate at higher mass scales → can only be studied indirectly

High impact Physics

CP violation, mixing and rare decays

↓

may investigate the physics at these new scales !!

Why charm ?

Because in the charm sector the SM contributions to these effects are small

↓

can provide unique information

High impact Physics

In addition charm is the unique probe of Up-type quark sector

but how small is small ?

- CP asymmetry ~ 10^{-3}
- D^0 - $\overline{D}^0$ mixing ~ 10^{-7} -- 10^{-10}
- Rare decays ~ 10^{-9} -- 10^{-19}

High statistics instead of High Energy

Large window to search for new physics

CP violation

- DIRECT CP VIOLATION: refers to CP violation in meson decays where some CP violating phases necessarily appear in $\Delta F = 1$ (decay) amplitudes

- INDIRECT CP VIOLATION: refers to CP violation in meson decays where the CP violating phases can all be chosen to appear in $\Delta F = 2$ (mixing) amplitudes

CP violation

Three types of CP violation in Meson Decays:

- CP violation in mixing:

$$A_{SL} = \frac{\Gamma(D^0_{phys}(t) \to l^+ \nu X) - \Gamma(\overline{D}^0_{phys}(t) \to l^- \overline{\nu} X)}{\Gamma(D^0_{phys}(t) \to l^+ \nu X) + \Gamma(\overline{D}^0_{phys}(t) \to l^- \overline{\nu} X)}$$

- CP violation in decay:

$$A_{f^\pm} = \frac{\Gamma(D^+ \to f^+) - \Gamma(D^- \to f^-)}{\Gamma(D^+ \to f^+) + \Gamma(D^- \to f^-)}$$

- CP violation in the interference between decays with and without mixing:

$$A_{f_{CP}} = \frac{\Gamma(D^0_{phys}(t) \to f_{CP}) - \Gamma(\overline{D}^0_{phys}(t) \to f_{CP})}{\Gamma(D^0_{phys}(t) \to f_{CP}) + \Gamma(\overline{D}^0_{phys}(t) \to f_{CP})}$$

[Yosef Nir, Lecture at SLAC Summer Inst.,hep-ph/9911321]

CP violation

- CP violating effects occur in a decay process only if the decay amplitude is the sum of 2 different parts, whose phases are made of a weak (CKM) and a strong (FSI) contribution:

$$\alpha = Ae^{i\delta_1} + Be^{i\delta_2}$$

The weak contributions to the phases change sign when going to the CP-conjugate process, while the strong ones do not.

The corresponding CP conjugate amplitude is:

$$\overline{\alpha} = A^* e^{i\delta_1} + B^* e^{i\delta_2}$$

CP violation

- Therefore the CP violating asymmetry in the decay rate will be :

$$A_{CP} = \frac{|\alpha|^2 - |\overline{\alpha}|^2}{|\alpha|^2 + |\overline{\alpha}|^2} = \frac{2\mathrm{Im}(\mathrm{AB}^*)\sin(\delta_2 - \delta_1)}{|A|^2 + |B|^2 + 2\,\mathrm{Re}(AB^*)\cos(\delta_2 - \delta_1)}$$

Both factors in the numerator should be nonvanishing to have a nonzero effect. Moreover to have a sizeable asymmetry the moduli of the 2 amplitudes, A and B, should not differ too much

- In singly Cabibbo suppressed decays (SCSD) the penguin diagram contributions may provide a different phase for the second weak amplitude

- FSI provide a strong phase shift [Buccella et al.,Phys.Lett.B302,319 (1993)]

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:

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

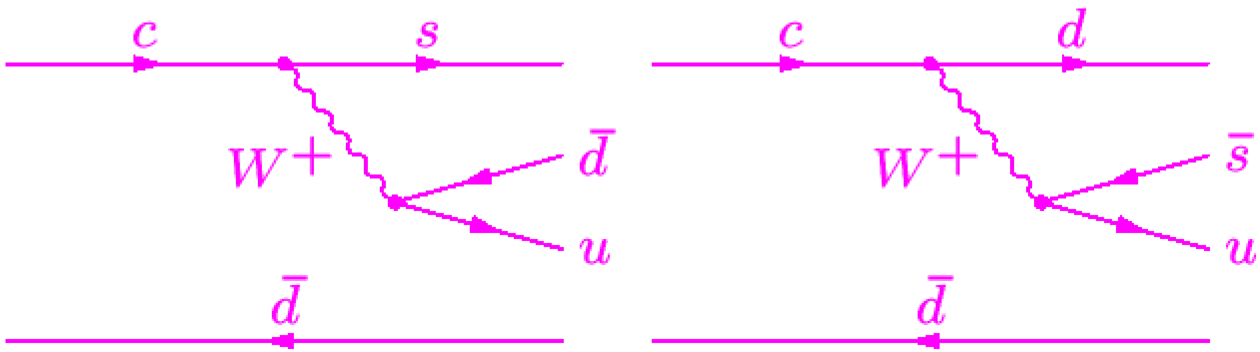
- In the Standard Model no direct CP asymmetry can arise in Cabibbo allowed or DCS modes since they are driven by a single weak amplitude

- However in $D \longrightarrow K_s$ π'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)

CP violation

"CP studies in charm transitions represent an almost zero background search for New Physics"

from "CP violation"(pag.252) by Bigi and Sanda

CP violation search in experiments with large statistics

- E791: fixed target experiment - hadroproduction of charm
  2.5×10^5 reconstructed charm

- CLEO: collider experiment - $e^+ e^-$ at Υ(4s)
  $9.0\ fb^{-1}$

- FOCUS: fixed target experiment - photoproduction of charm
  10^6 reconstructed charm

Experimental techniques

In hadroproduction and photoproduction one needs to ratio to a Cabibbo allowed reference states in order to correct for known production asymmetries.

$$A_{CP} = \frac{\eta(D) - \eta(\bar{D})}{\eta(D) + \eta(\bar{D})}$$

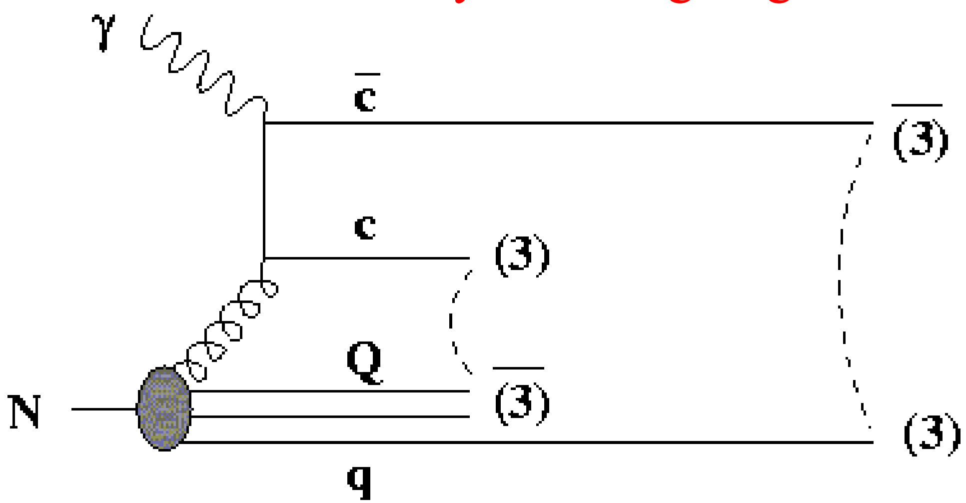
For example η for $D^+ \to K^- K^+ \pi^+$ would be: $\eta(D^+) = \frac{N(D^+ \to K^- K^+ \pi^+)}{N(D^+ \to K^- \pi^+ \pi^+)}$

For the D^0, the charm flavour is determined by tagging the charge of the bachelor pion from $D^{*+} \longrightarrow D^0 \pi^+$

Experimental techniques

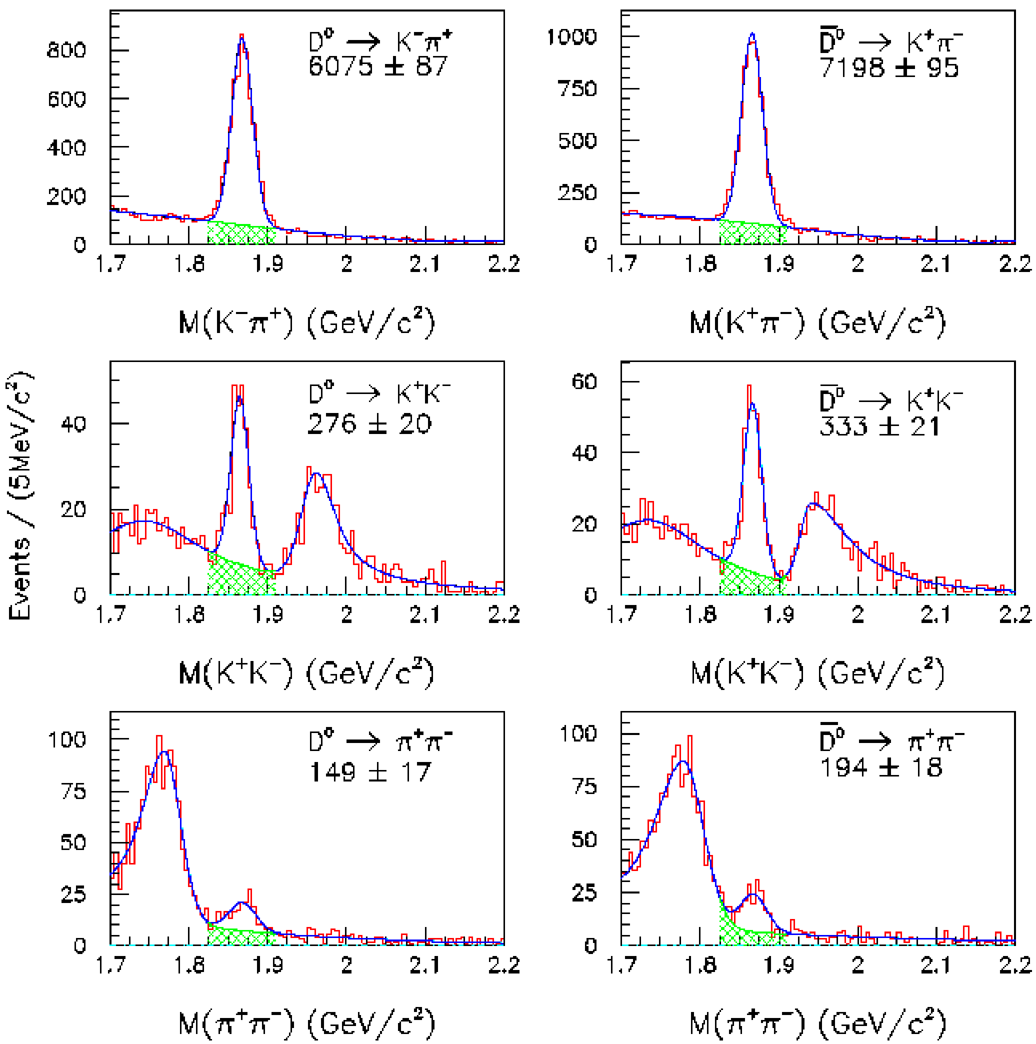
Why ratio the asymmetry at all?

Pythia string fragmentation model



Need to correct for known production asymmetries ~ -5% for photoproduced mesons. These likely arise from fragmentation dynamics. ***eg*** quark-diquark asymmetry

E791 results

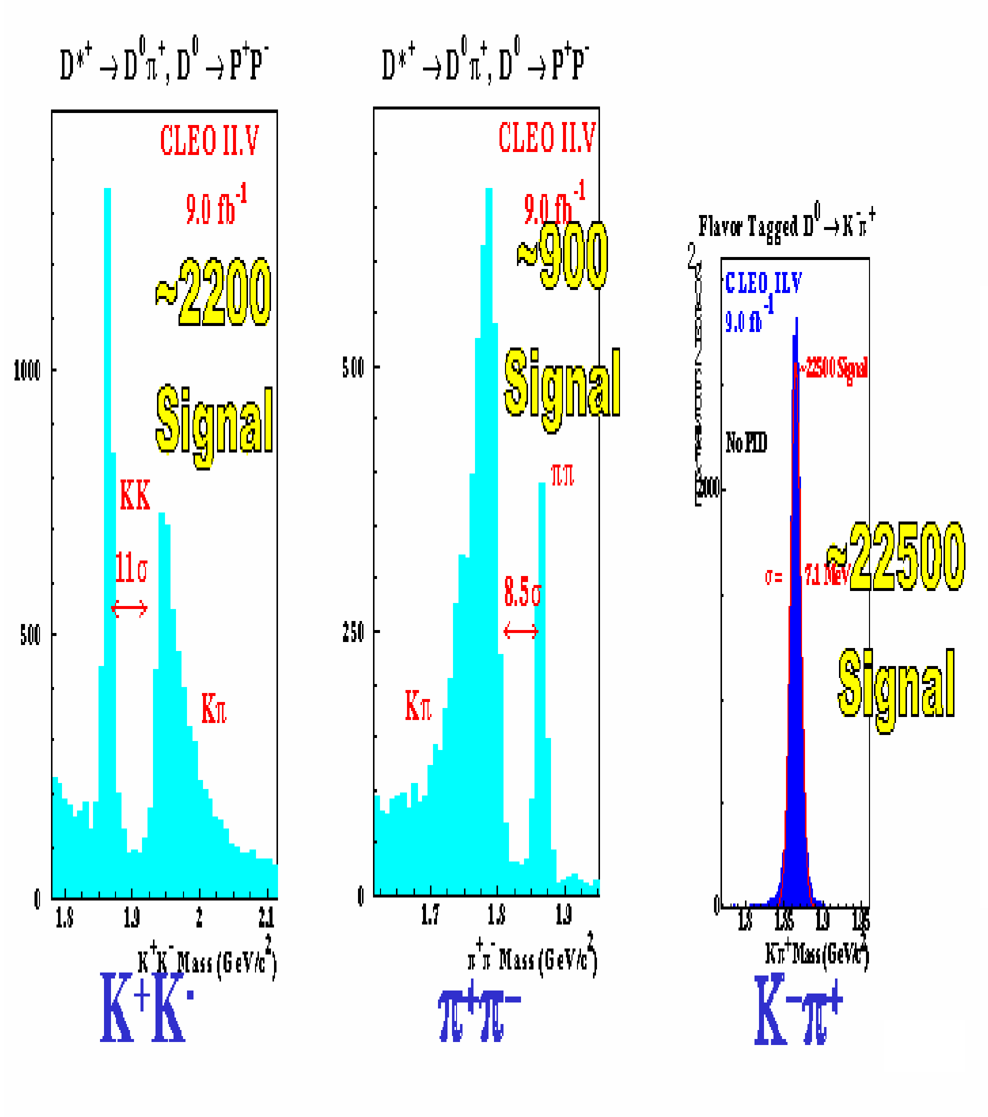


$$A_{CP} = \frac{\eta - \bar{\eta}}{\eta + \bar{\eta}}$$

Decay mode	CP asymmetry (E791)
$D^0 \to K^- K^+$	$-0.010 \pm 0.049 \pm 0.012$
$D^0 \to \pi^- \pi^+$	$-0.049 \pm 0.078 \pm 0.030$
$D^+ \to K^- K^+ \pi^+$	-0.014 ± 0.029
$D^+ \to \pi^- \pi^+ \pi^+$	-0.017 ± 0.042

(PDG 2000)

CLEO results

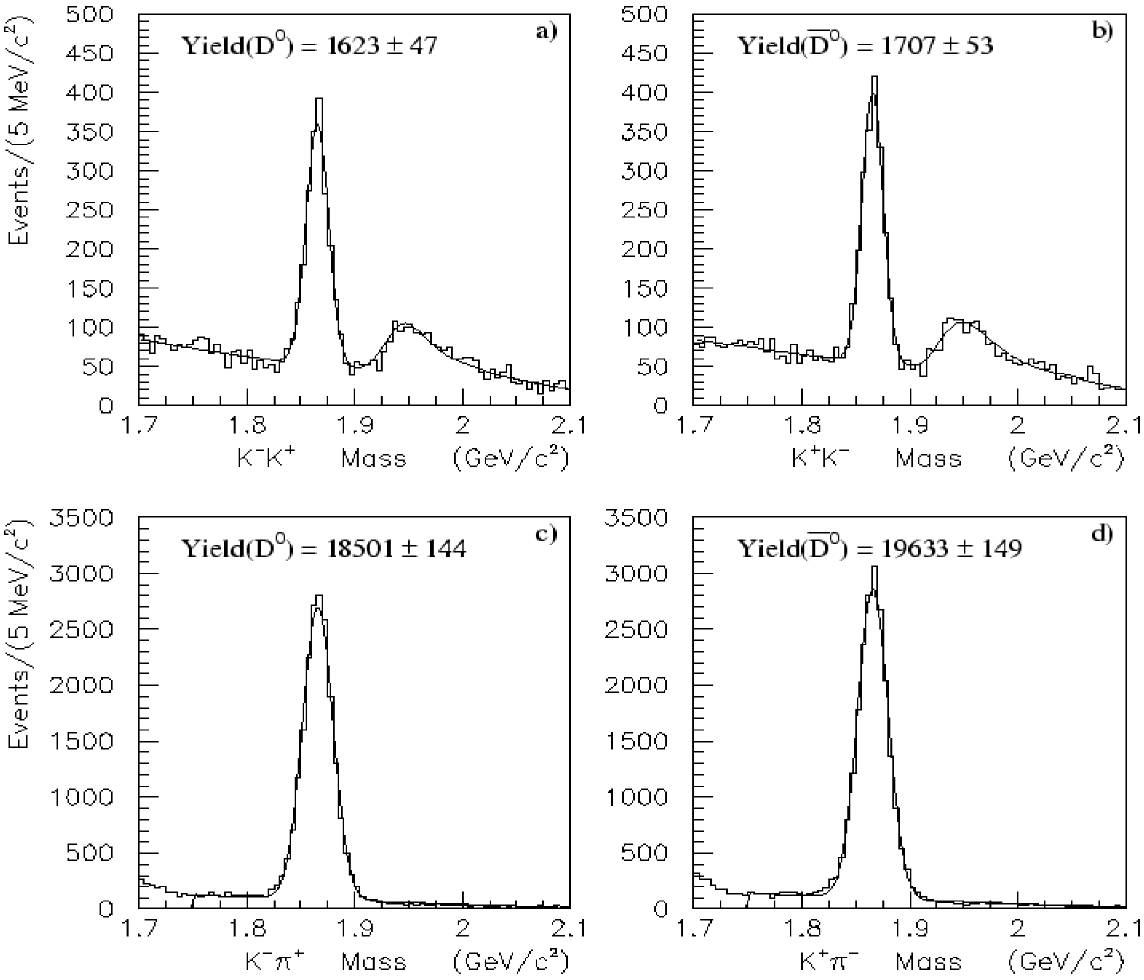


$$A_{CP} = \frac{N - \overline{N}}{N + \overline{N}}$$

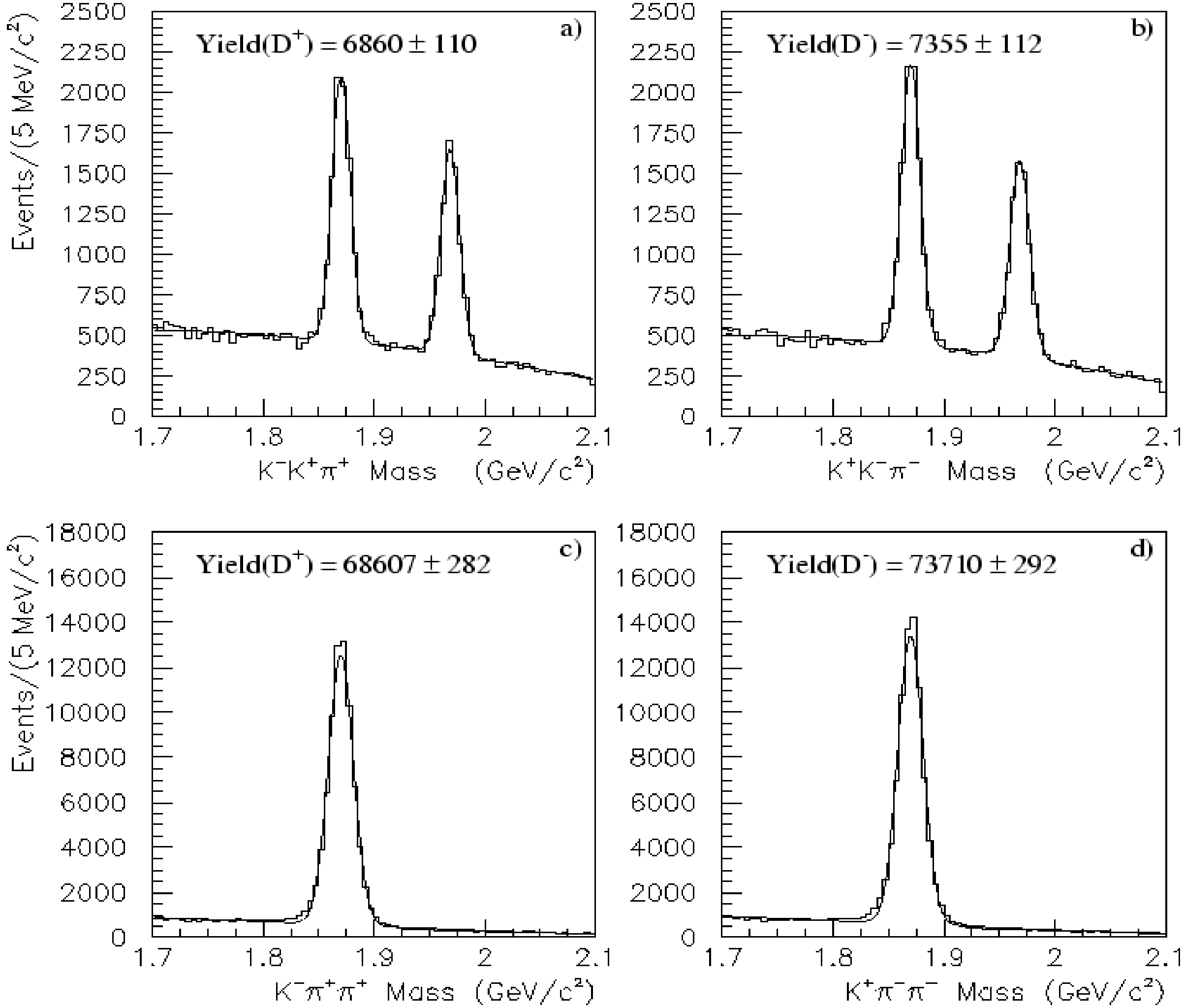
Decay mode	CP asymmetry (CLEO)
$D^0 \to K^- K^+$	$+0.0004 \pm 0.0218 \pm 0.0084$
$D^0 \to \pi^- \pi^+$	$+0.0194 \pm 0.0322 \pm 0.0084$
$D^0 \to K_S \pi^0$	-0.018 ± 0.030

(Talk by Alex Smith at CIPANP 2000)

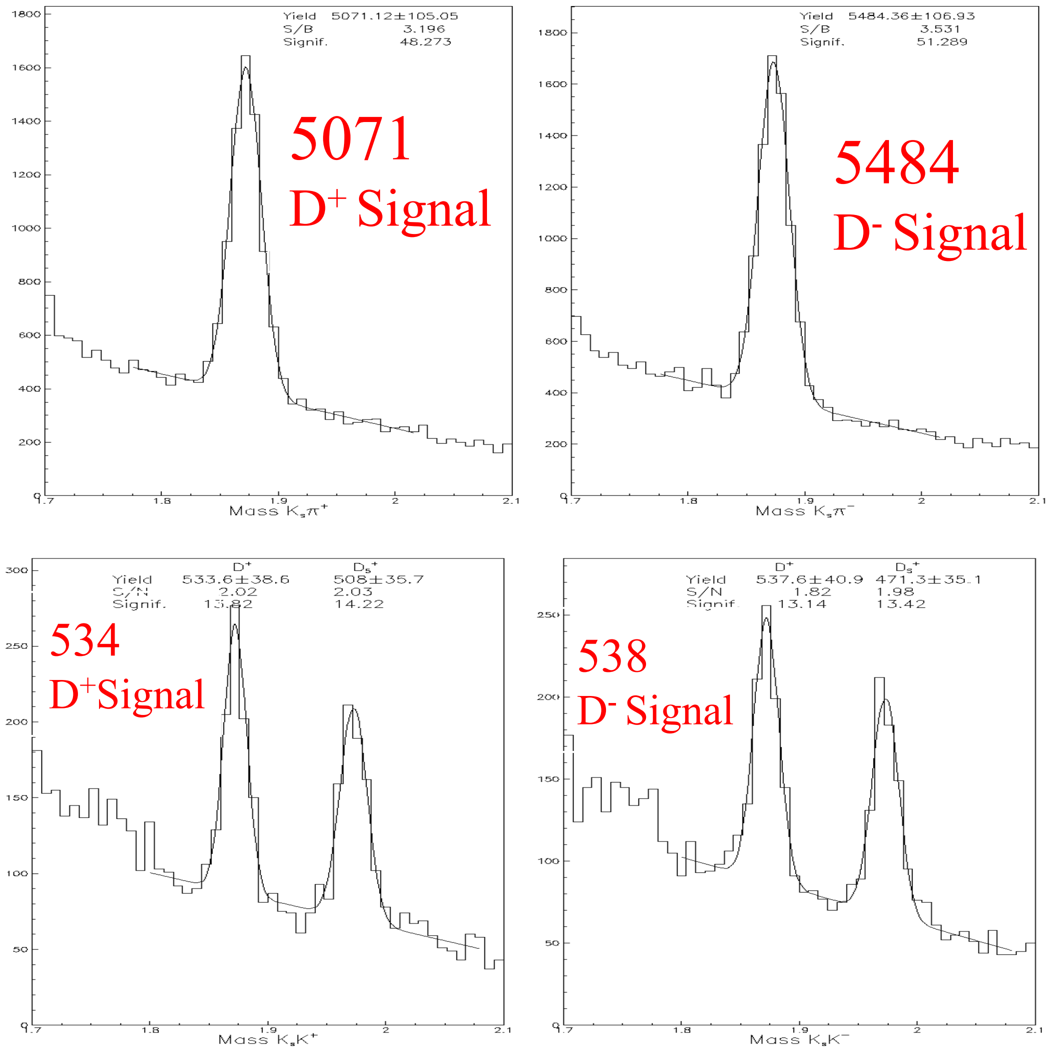
CP violation search $(D^0 \rightarrow K^-K^+)$



CP violation search $(D^+ \to K^- K^+ \pi^+)$



CP violation search $(D^+ \to K_s X^+)$



$D^+ \longrightarrow K_s\pi^+$

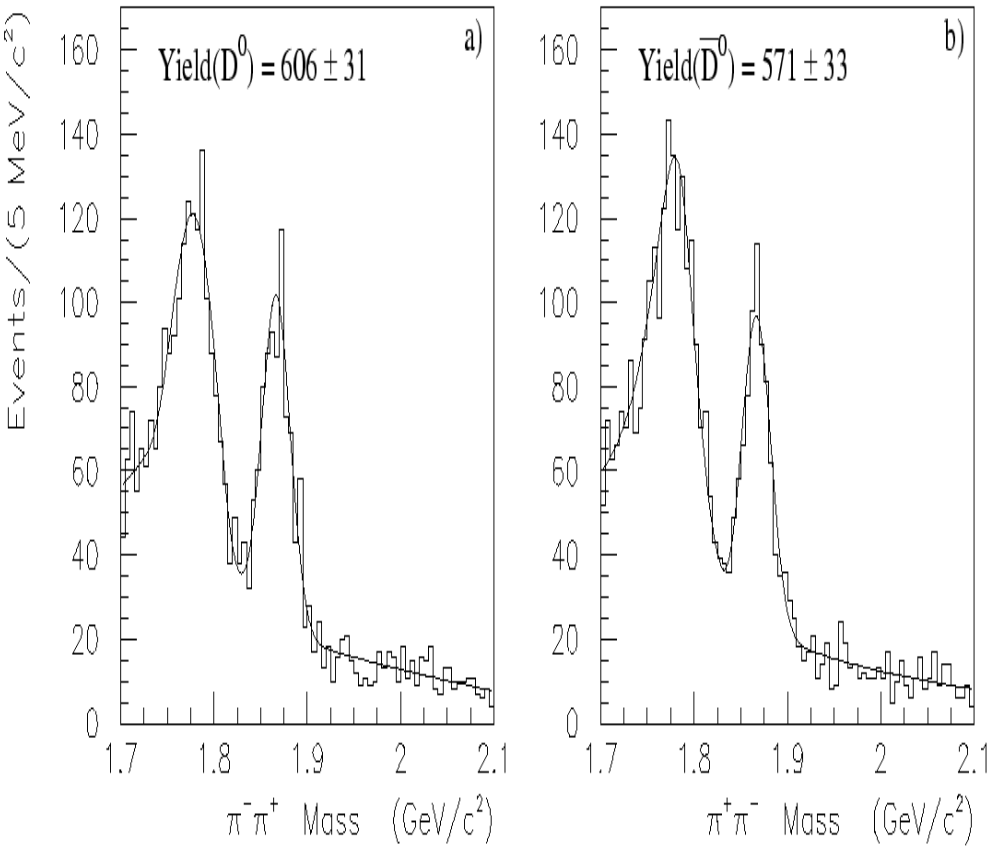
$D^+ \longrightarrow K_sK^+$

(Talk by Brian O'Reilly at DPF 2000)

FOCUS results

$D^0 \longrightarrow \pi^-\pi^+$

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



Decay mode	CP asymmetry (FOCUS)
$D^0 \to K^-K^+$	$-0.001 \pm 0.022 \pm 0.015$
$D^0 \to \pi^-\pi^+$	$+0.048 \pm 0.039 \pm 0.025$
$D^+ \to K^-K^+\pi^+$	$+0.006 \pm 0.011 \pm 0.005$
$D^+ \to K_S\pi^+$	$-0.016 \pm 0.015 \pm 0.009$
$D^+ \to K_S K^+$	$+0.069 \pm 0.060 \pm 0.015$

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

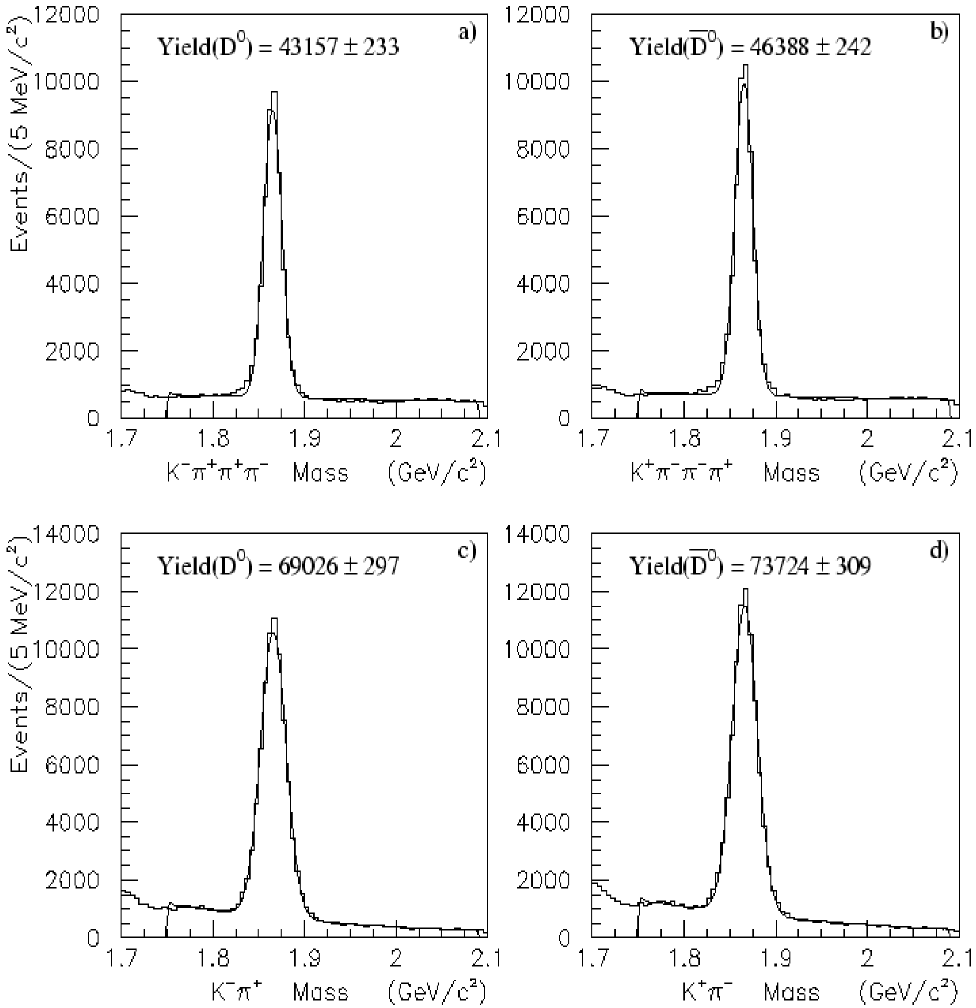
What's next…….

- 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

E831 FOCUS



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

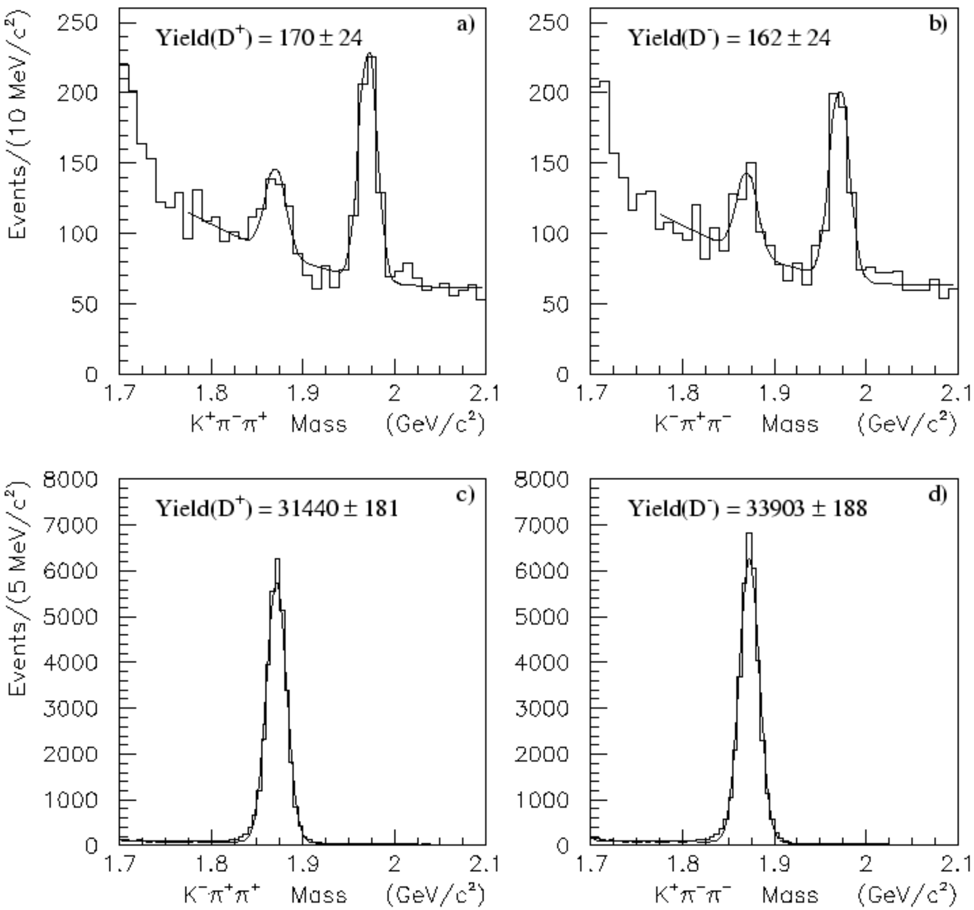
$$\eta = \frac{D^0 \to K^- \pi^+ \pi^- \pi^+}{D^0 \to K^- \pi^+}$$

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

Dalitz plot analysis

- Decay amplitude: fit parameters a_i and δ_I

(3-body decays)

$$A(D) = \sum_i a_i e^{i\delta_i} B(abc \mid r_i)$$

where a, b, c label the final state particles and r the resonance

$$B(abc \mid r) = BW(a,b \mid r) S(a,c)$$

BW is the relativistic Breit - Wigner function :

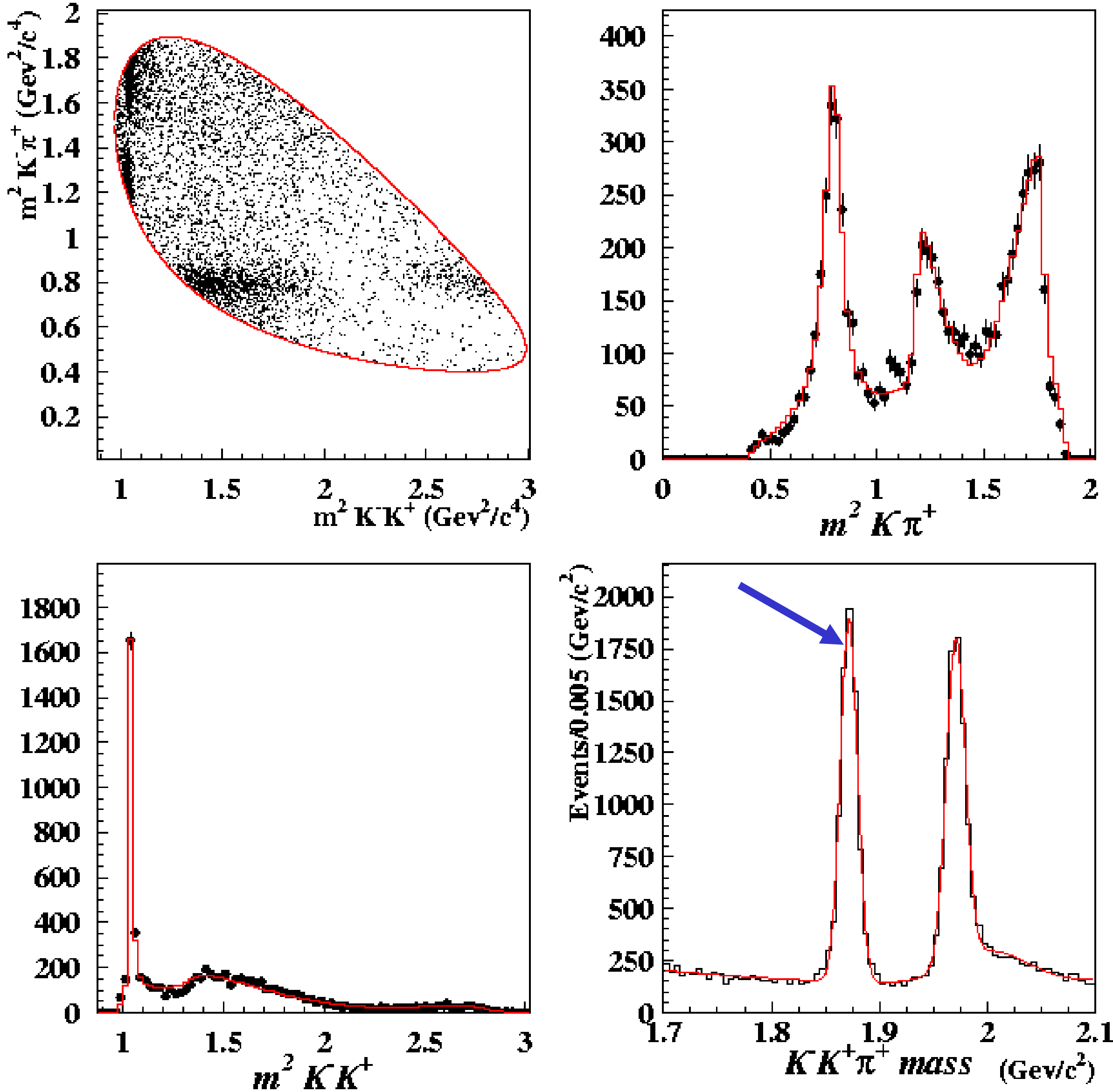
$$BW(a,b \mid r) = \frac{F_D F_r}{M_r^2 - M_{ab}^2 - i\Gamma M_r}$$

and S(a, c) is the spin term : 1 for spin 0 resonance

$-2\vec{c} \cdot \vec{a}$ for spin 1 resonance

....

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



Preliminary results

Fit results

	Fit frac.	Phase (Deg)
K^{*0} (892)	0.31 ± 0.01	0 (fixed)
K^*_0 (1430)	0.37 ± 0.01	69 ± 2
ϕ (1020)	0.29 ± 0.01	-171 ± 3

E687 published result

	Fit frac.	Phase (Deg)
K^{*0} (892)	0.30 ± 0.02	0 (fixed)
K^*_0 (1430)	0.37 ± 0.04	70 ±7
ϕ (1020)	0.29 ± 0.03	-159 ±8

(Talk by Sandra Malvezzi at CIPANP 2000)

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

Dalitz plot analysis

Any difference in the reconstructed pattern, by Dalitz plot analysis, between D^+ and D^- would be an evidence of CP violation

Discrete symmetry P and T

Quantity	P	T
r	$-r$	r
p	$-p$	$-p$
σ	σ	$-\sigma$
$\sigma \cdot p$	$-\sigma \cdot p$	$\sigma \cdot p$
$\sigma \cdot (p_1 \times p_2)$	$\sigma \cdot (p_1 \times p_2)$	$-\sigma \cdot (p_1 \times p_2)$

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

Assuming CPT invariance

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

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

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 $C_T \neq (C_T)_{CP} = -\overline{C}_T$ 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.)

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

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

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

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

- All the following results are VERY PRELIMINARY

- We are in touch with I.Bigi. He judged positevely our analysis, even if he considers this work as a pilot study due to the limited statistics

- I.Bigi gave us some interesting advices and suggestions on how to proceed on this topic, looking for example at other decay modes:

$D^0 \longrightarrow \overline{K}^0\pi^0\pi^+\pi^-$

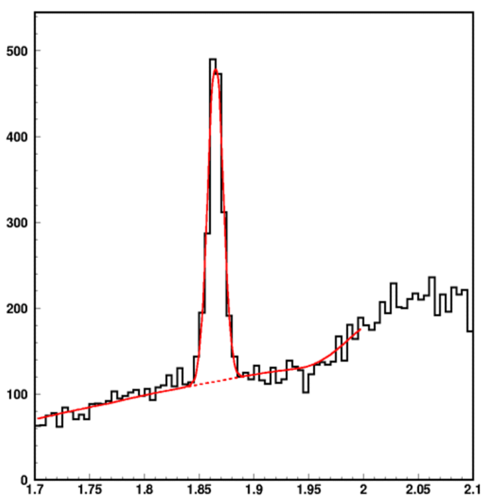
$D^+ \longrightarrow K^-K^+\pi^0\pi^+$

$D^0 \longrightarrow K^-\pi^+\pi^+\pi^-$ (using the $\pi^+\pi^-$ with largest invariant mass)

$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ selection cuts
(following Alberto Reis analysis)

Old cuts:

- L/S > 10
- Mulprim > 1
- Confidence Level > 0.10
- Iso2 < 0.005
- Pionicity > 0.5
- Kaonicity > 2



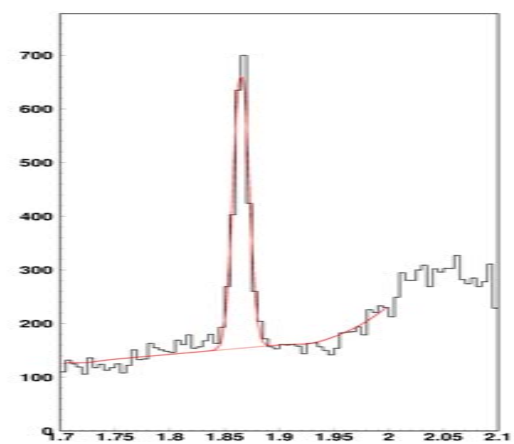
Y = 1304 ± 53

S/N = 3.2 ± 0.3

New cuts:

- L/S > 10
- Mulprim > 1
- Confidence Level > 0.01
- Iso2 < 0.10
- π- consistency < 5
- Kaonicity > 2
- Score > 0.15
- Zout > 0

$$score = \frac{1}{3}\left(\frac{L/\sigma}{(L/\sigma)\max} + \frac{C.L.}{(C.L.)\max} + \frac{Zout}{(Zout)\max}\right)$$



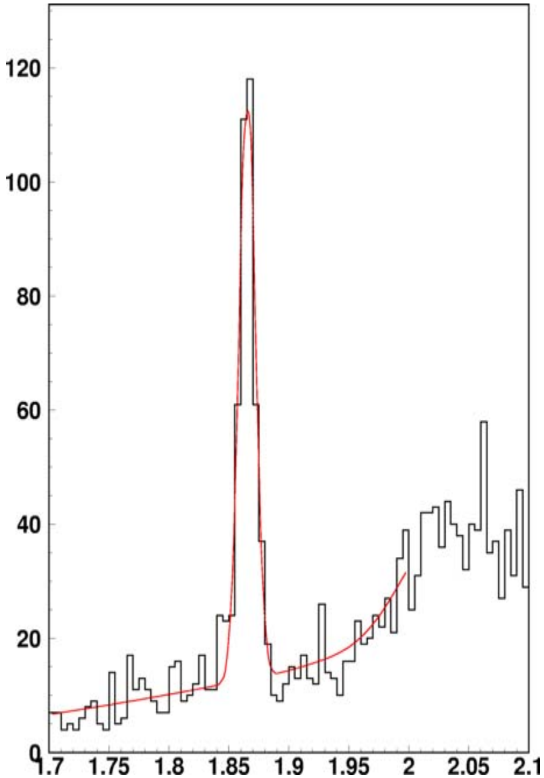
Y = 1831 ± 59

S/N = 2.9 ± 0.4

D^*-Tag

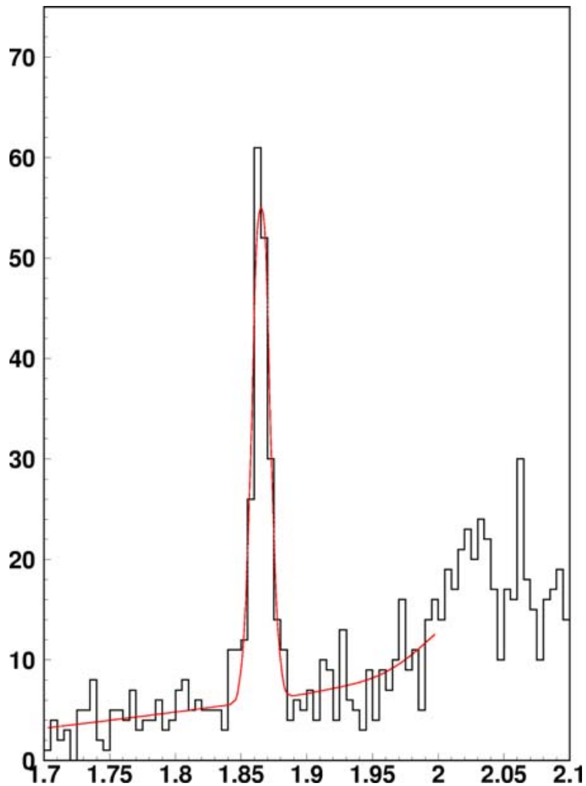
D^*-Tag sample

$D^{*\pm} \rightarrow D^0\ (\overline{D}^0\ )\pi^\pm$

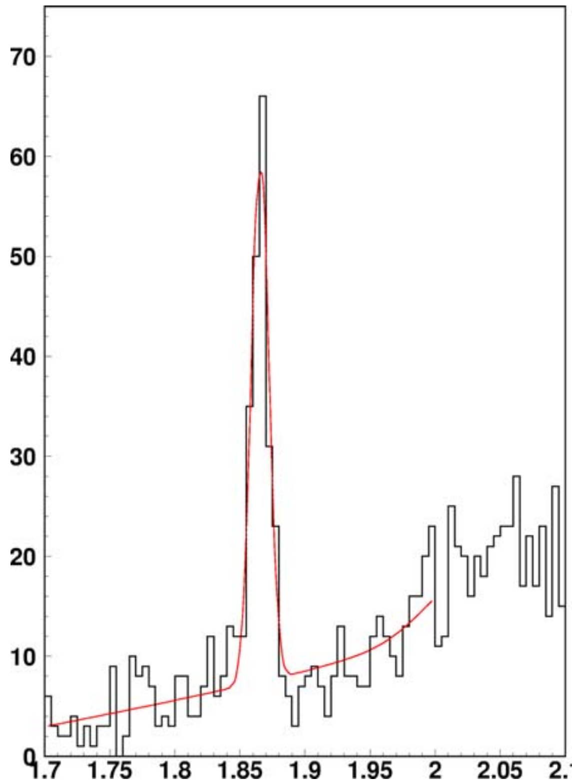


We can distinguish the particle from the antiparticle using the D^*-Tag:

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



$D^{*-} \rightarrow \overline{D}^0\ \pi^-$

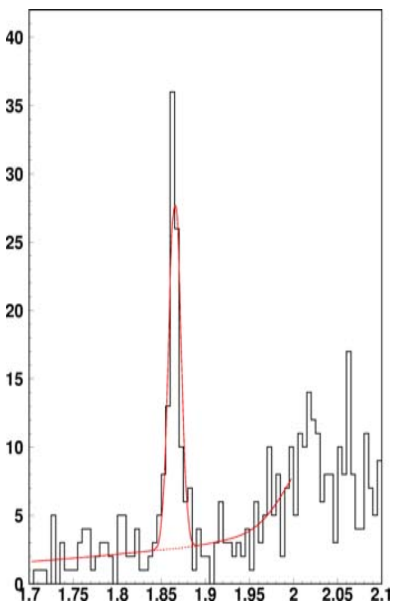


T-odd correlation in the decay mode $D^0 \to K^-K^+\pi^-\pi^+$

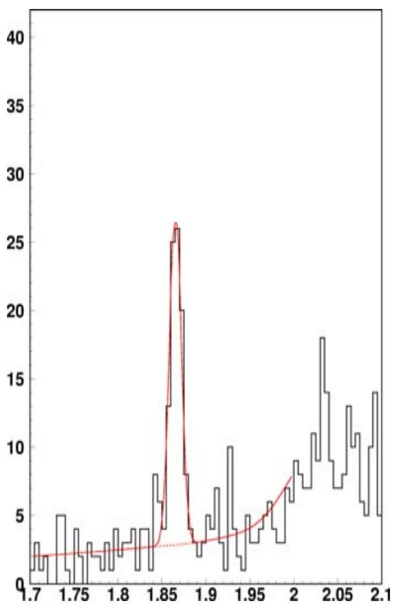
$D^0 \to K^-K^+\pi^-\pi^+$

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

T-odd correlation



$C_T > 0$

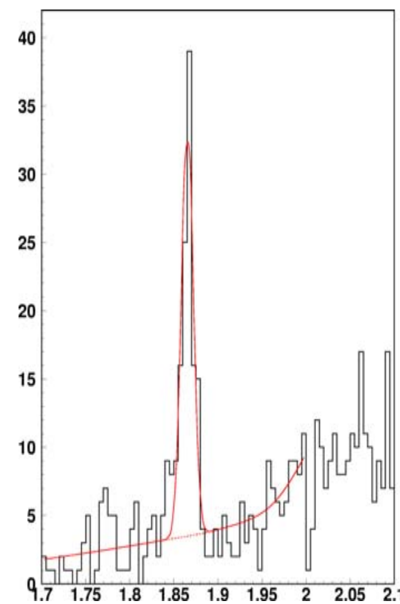


$C_T < 0$

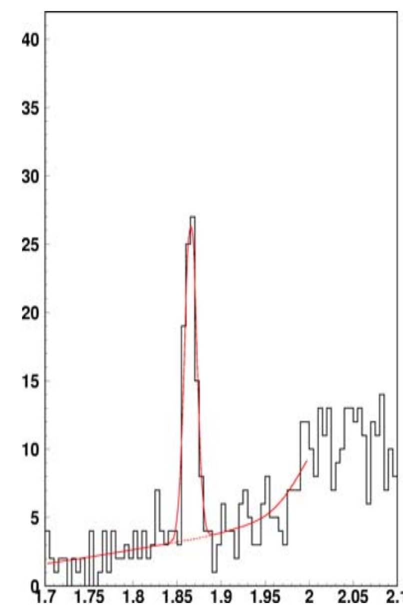
$\bar{D}^0 \to K^-K^+\pi^-\pi^+$

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

T-odd correlation



$\bar{C}_T > 0$



$\bar{C}_T < 0$

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

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

↓

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

↓

NO EVIDENCE of CP VIOLATION

Perspectives

In the end, a very promising future:

- new results are coming from FOCUS and CLEO
- and recently from BaBar, BELLE
- asymptotically from BTeV and LHC-B

Perspectives

Exp.	Beam	Lum.	Int. L (10**7 sec)	Cross Sec. cc	Cross Sec. bb	#evts cc prod.	#evts bb prod.	# evt cc ric. estim.	Physics start date
BABAR	e+e- Y(4s) asym.	3 x 10**33 cm-2s-1	30 fb-1		1.2 nb		3.6 x 10**7	3.6 x 10**6	1999
BELLE	e+e- Y(4s) asym.	3 x 10**33 cm-2 s-1	30 fb-1		1.2 nb		3.6 x 10**7	3.6 x 10**6	1999
COMPASS	FT π-Cu	~ 1 x 10**32 cm-2 s-1	1 fb-1	~ 10 μb		10**9		~ 5 x 10**6	2001
CESR/ CLEO-C (?)	e+e- 3-5 Gev	2 x 10**32 cm-2 s-1	2 fb-1	~ 10 nb		2 x 10**7		2 x 10**6	2003
BTeV	ppbar 2TeV	2 x 10**32 cm-2 s-1	2 fb-1	> 500 μb	100 μb	10**12	2 x 10*11	10**9	>2005
LHC-b	pp 14 TeV	2 x 10**32 cm-2 s-1	2 fb-1	> 500 μb	500 μb	> 10**12	10**12		>2005

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**

Two bodies Branching Ratio evaluation

This result:

$$\frac{\Gamma(D^0 \to K^+ K^-)}{\Gamma(D^0 \to K^- \pi^+)} = 0.1015 \pm 0.0013 \pm 0.0010$$

$$\frac{\Gamma(D^0 \to \pi^+ \pi^-)}{\Gamma(D^0 \to K^- \pi^+)} = 0.0374 \pm 0.0009 \pm 0.0004$$

$$\frac{\Gamma(D^0 \to K^+ K^-)}{\Gamma(D^0 \to \pi^- \pi^+)} = 2.71 \pm 0.09$$

Previous results:

0.1109±0.0033 (PDG)
0.109±0.003±0.003 (E791)
0.116±0.007±0.007 (CLEO)
0.109±0.007±0.009 (E687)

0.0397±0.0021 (PDG)
0.040±0.002±0.003 (E791)
0.043±0.007±0.003 (E687)
0.0348±0.0030±0.0023 (CLEO)

2.75 ± 0.15 ± 0.16 (E791)
2.53 ± 0.46 ± 0.19 (E687)

Four bodies Branching Ratio evaluation

This result:

$$\frac{\Gamma(D^0 \to K^+ K^- \pi^- \pi^+)}{\Gamma(D^0 \to K^- \pi^+ \pi^- \pi^+)} = 0.0297 \pm 0.0010 \pm 0.0008$$

$$\frac{\Gamma(D^0 \to \pi^+ \pi^- \pi^+ \pi^-)}{\Gamma(D^0 \to K^- \pi^+ \pi^+ \pi^-)} = 0.0866 \pm 0.0012 \pm 0.0005$$

$$\frac{\Gamma(D^0 \to K^+ K^- \pi^- \pi^+)}{\Gamma(D^0 \to \pi^- \pi^+ \pi^- \pi^+)} = 0.34 \pm 0.01$$

Previous results:

0.0334 ± 0.0028 (PDG)

0.0313 ± 0.0037 ± 0.0036 (E791)

0.035 ± 0.004 ± 0.002 (E687)

0.098 ± 0.006 (PDG)

0.095 ± 0.007 ± 0.002 (E687)

0.34 ± 0.04 (PDG)

Sum of the related 2 and 4 bodies final states

(Theoretical suggestion by I.Bigi)

$$\frac{\Gamma\left(D^0 \to K^- K^+ + D^0 \to K^- K^+ \pi^- \pi^+\right)}{\Gamma\left(D^0 \to \pi^- \pi^+ + D^0 \to \pi^- \pi^+ \pi^- \pi^+\right)} = 0.80 \pm 0.04$$

→ PDG result

0.8 ± 0.1

The ratio is close to 1

↓

Adding related decay modes in 2 and 4 bodies gives

REDUCTION OF THE $SU(3)_{fl}$ SIMMETRY BREAKING

Actually a complete analysis of the 4-body decay rates requires the study of the subresonant structure.

Isospin analysis of $D \to \pi\,\pi$ decay channel

Theoretical study

$D^0 \to \pi^- \pi^+$

$D^0 \to \pi^0 \pi^0$

$D^+ \to \pi^+ \pi^0$

Decay modes

Isospin space →

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle \to \sqrt{\frac{1}{3}}|2,0\rangle + \sqrt{\frac{2}{3}}|0,0\rangle$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle \to \sqrt{\frac{2}{3}}|2,0\rangle - \sqrt{\frac{1}{3}}|0,0\rangle$$

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle \to |2,+1\rangle$$

Decay modes in Isospin space

Hamiltonian

$$H = A_{3/2}\left|\frac{3}{2},+\frac{1}{2}\right\rangle + A_{1/2}\left|\frac{1}{2},+\frac{1}{2}\right\rangle$$

Lipkin,Nir,Quinn,Snyder
Phys.Rev.D 44:1454 (1991)

$A^{+-} = (\sqrt{2}\ A_0 + A_2)/\sqrt{3}$

$A^{00} = (A_0 + \sqrt{2}\ A_2)/\sqrt{3}$

$A^{+0} = A_2(\sqrt{3}/\sqrt{2})$

Decay amplitudes

Isospin space →

$$\left|\frac{A_2}{A_0}\right|^2 = \frac{\frac{2}{3}\left|A^{+0}\right|^2}{\left|A^{+-}\right|^2 - \frac{2}{3}\left|A^{+0}\right|^2}$$

$$\cos(\delta_2 - \delta_0) = \frac{3\left|A^{+-}\right|^2 - 6\left|A^{00}\right|^2 + 2\left|A^{+0}\right|^2}{4\sqrt{2\left|A^{+0}\right|^2}\sqrt{\frac{3}{2}\left(\left|A^{00}\right|^2 + \left|A^{+-}\right|^2\right) - \left|A^{+0}\right|^2}}$$

Isospin amplitudes and phases

Cleo collaboration
Phys.Rev. Lett. 71 (13)/1973 (1993)

where

$$A_2 := \frac{1}{\sqrt{2}} A_{3/2,2}$$

$$A_0 := \frac{1}{\sqrt{2}} A_{1/2,0}$$

A_{if} Isospin amplitudes

$A_{it,If}$ Transition amplitudes

Isospin analysis of $D \to \pi\pi$ decay channel

Experimental results

$\Gamma^{+-} = (0.227 \pm 0.009)\ 10^{-14}$ Gev

$\Gamma^{00} = (0.156 \pm 0.044)\ 10^{-14}$ Gev

$\Gamma^{+0} = (0.133 \pm 0.035)\ 10^{-14}$ Gev

Where

$$\Gamma^{+-} = \frac{\hbar}{\tau_{D^0}} \left(\frac{\Gamma(K^-\pi^+)}{\Gamma_{tot}} \right) \left(\frac{\Gamma(\pi^-\pi^+)}{\Gamma(K^-\pi^+)} \right)$$

$$\Gamma^{00} = \frac{\hbar}{\tau_{D^0}} \left(\frac{\Gamma(\pi^0\pi^0)}{\Gamma_{tot}} \right)$$

$$\Gamma^{+0} = \frac{\hbar}{\tau_{D^0}} \left(\frac{\Gamma(\pi^+\pi^0)}{\Gamma_{tot}} \right)$$

Our study

PDG

$|A_2/A_0| = 0.64 \pm 0.13$
$\cos(\Delta\delta) = 0.14 \pm 0.17$
$\Delta\delta = (81.9 \pm 9.8)^\circ$

This result

$|A_2/A_0| = 0.72 \pm 0.13 \pm 0.11$
$\cos(\Delta\delta) = 0.14 \pm 0.13 \pm 0.09$

Cleo result

Conclusions:

- Isospin amplitudes are of the same order
- Large phase difference between the two isospin amplitudes

→ Evidence of elastic F.S.I.

Isospin analysis of D → K K decay channel

Theoretical study

$D^0 \to K^- K^+$

$D^0 \to K^0 \bar{K}^0$

$D^+ \to K^+ K^0$

Decay modes

Isospin space →

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle \to \sqrt{\frac{1}{2}}\left(|1,0\rangle + |0,0\rangle\right)$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle \to \sqrt{\frac{1}{2}}\left(|1,0\rangle - |0,0\rangle\right)$$

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle \to |1,+1\rangle$$

Decay modes in Isospin space

$$H = A_{1/2}\left|\frac{1}{2},+\frac{1}{2}\right\rangle$$

Hamiltonian

$A^{+-} = (A_1 + A_0)/\sqrt{2}$

$A^{00} = (A_1 - A_0)/\sqrt{2}$

$A^{+0} = A_1\sqrt{2}$

Decay amplitudes

where

$$A_1 := \frac{1}{\sqrt{2}} A_{1/2,1}$$

$$A_0 := \frac{1}{\sqrt{2}} A_{1/2,0}$$

A_{If} Isospin amplitudes

$A_{it,If}$ Transition amplitudes

Isospin space →

$$\left|\frac{A_1}{A_0}\right|^2 = \frac{|A^{+0}|^2}{2|A^{+-}|^2 + 2|A^{00}|^2 - |A^{+0}|^2}$$

$$\cos(\delta_1 - \delta_0) = \frac{|A^{+-}|^2 - |A^{00}|^2}{\sqrt{|A^{+0}|^2}\sqrt{2|A^{+-}|^2 + 2|A^{00}|^2 - |A^{+0}|^2}}$$

Isospin amplitudes and phases

Cleo collaboration
Phys.Rev.Lett. 78 (1997) 3261

Isospin analysis of D → K K decay channel

Experimental results

Γ^{+-} = (0.616 ± 0.019) 10^{-14} Gev

Γ^{00} = (0.461 ± 0.063) 10^{-14} Gev

Γ^{+0} = (0.103 ± 0.029) 10^{-14} Gev

Where

$$\Gamma^{+-} = \frac{\hbar}{\tau_{D^0}}\left(\frac{\Gamma(K^-\pi^+)}{\Gamma_{tot}}\right)\left(\frac{\Gamma(K^-K^+)}{\Gamma(K^-\pi^+)}\right)$$

$$\Gamma^{00} = \frac{\hbar}{\tau_{D^0}}\left(\frac{\Gamma(K^0\overline{K}^0)}{\Gamma_{tot}}\right)$$

$$\Gamma^{+0} = \frac{\hbar}{\tau_{D^0}}\left(\frac{\Gamma(K^+K^0)}{\Gamma_{tot}}\right)$$

Our study

PDG

$|A_1/A_0| = 0.69 \pm 0.07$
$\cos(\Delta\delta) = 0.76 \pm 0.07$
$\Delta\delta = (40.3 \pm 6.3)^\circ$

This result

$|A_1/A_0| = 0.61^{+0.11}_{-0.10}$
$\cos(\Delta\delta) = 0.88^{+0.10}_{-0.08}$

Cleo result

Conclusions:

- Isospin amplitudes are of the same order
- Phase difference between the two isospin amplitudes (but smaller than the previous one)

→ Evidence of elastic F.S.I.

Effects of elastic F.S.I. on B.R. ($D^0 \to K^- K^+$) /($D^0 \to \pi^- \pi^+$)

Elastic F.S.I. - rotation in Isospin space

$\pi^- \pi^+ \xrightarrow[\text{F.S.I.}]{\text{Elastic}} \pi^0 \pi^0$ $\qquad$ $K^- K^+ \xrightarrow[\text{F.S.I.}]{\text{Elastic}} K^0 \bar{K}^0$

$$\frac{\Gamma(D^0 \to K^- K^+)}{\Gamma(D^0 \to \pi^- \pi^+)} = 2.71 \pm 0.09$$

→ Large SU(3) breaking

$$\frac{\Gamma(D^0 \to K^+ K^-) + \Gamma(D^0 \to K^0 \bar{K}^0)}{\Gamma(D^0 \to \pi^- \pi^+) + \Gamma(D^0 \to \pi^0 \pi^0)} = 1.97 \pm 0.20$$

Not affected by elastic F.S.I.

→ Large (but inferior) SU(3) breaking

Conclusions:

- Summing over Isospin rotated channels, SU(3) breaking is reduced.
- The effect of elastic F.S.I. on B.R. ($K^- K^+$) /($\pi^- \pi^+$) is significant, but is unable to explain the discrepancy between experimental results and theoretical predictions ($\Gamma(K^- K^+)/\Gamma(\pi^- \pi^+) < 1.4$)

→ **Possible solution : inelastic F.S.I.**

References for Isospin analysis

M.Gronau, D.London
Phys Rev. Lett. 65,, 27:3381 (1990)

H.J.Lipkin, Y.Nir, H.R.Quinn, A.E.Syder D.London
Phys. Rev. D 44,5:1454 (1991)

Cleo Collaboration
Phys. Rev. Lett. 71, 13:1973 (1993)

Cleo Collaboration
*hep-ex/*9701008 (1997)

References for T-odd correlation

I.Bigi *hep-ph*/0107102 (2001)

G.Valencia *Phys. Rev. D* 39,11:3339 (1989)

E.Golowich, G.Valencia *Phys. Rev. D* 40,112 (1989)

B.Kayser *Nucl. Phys B (Proc. Suppl.)* 13, 487:490 (1990)

W.Bensalem, D.London *hep-ph*/0005018 (2000)

J.G.Korner, K.Schilcher, Y.L.Wu *Phys. Lett. B* 242, 1:119 (1990)

B.Kayser *Nucl.Phys. B (Proc. Suppl.)* 13, 487 (1990)