Selected topics from
FOCUS CHARM HADRONIC DECAYS RESULTS

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On behalf of the FOCUS Collaboration

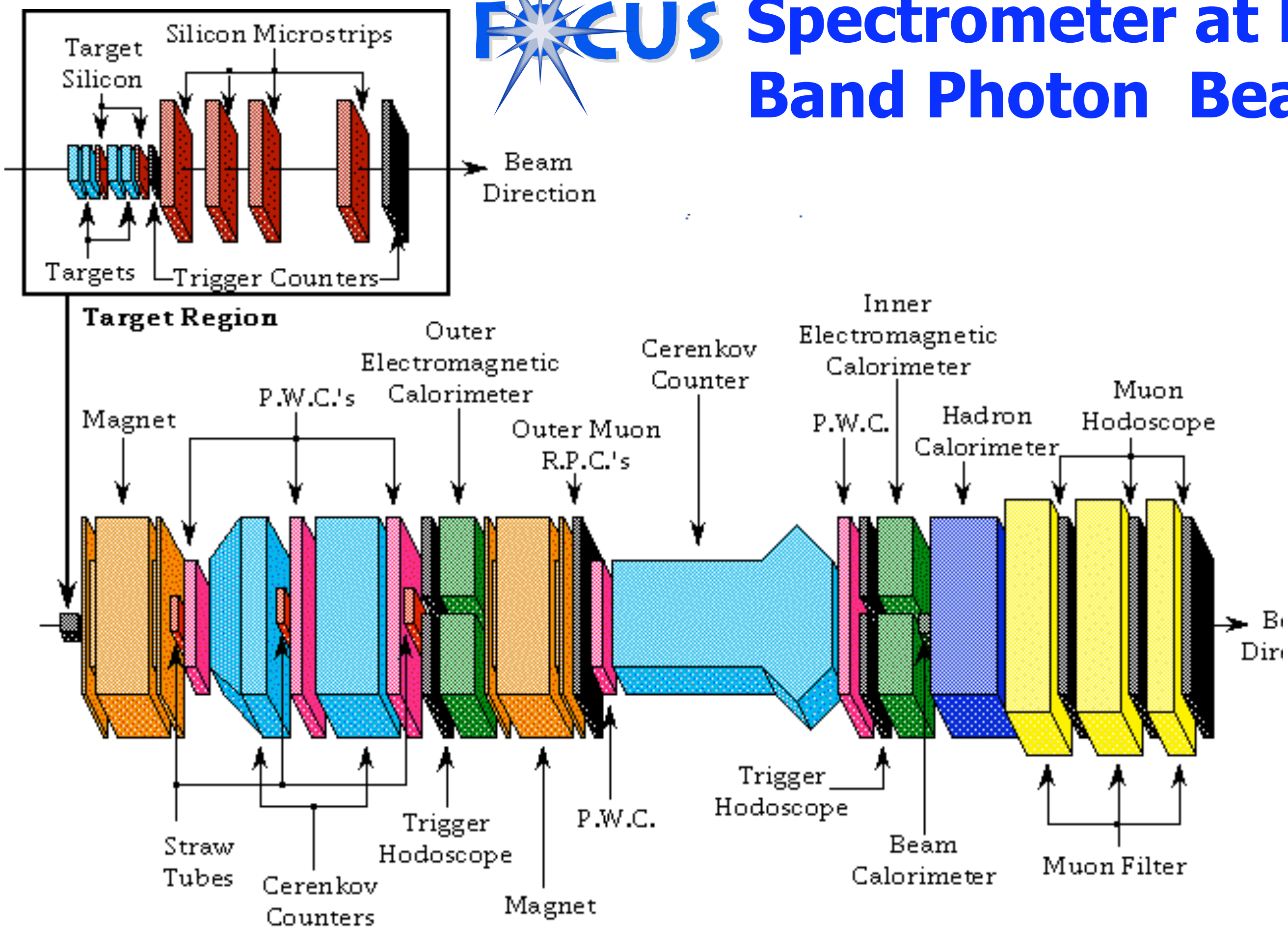
E831 FOCUS

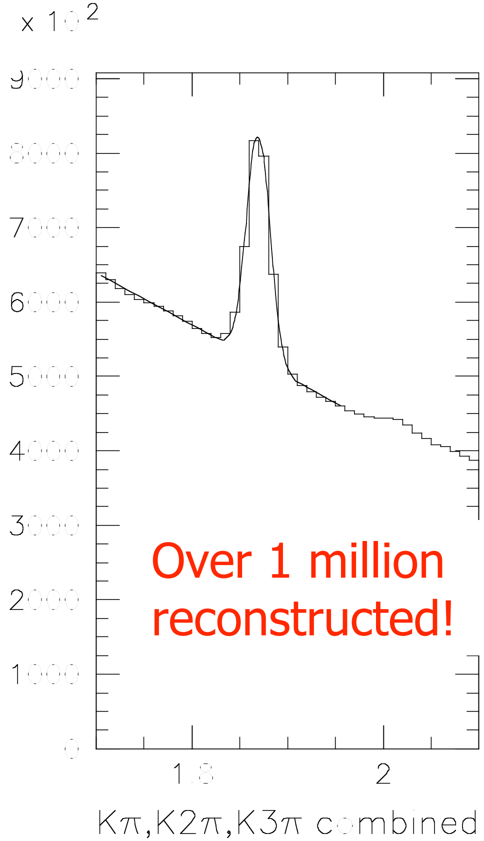
Presented at CHARM 2010 - IHEP Beijing

Motivations and Outline

- A retrospective discussion of selected FOCUS hadronic decays results which have interest and implications for ongoing and future studies in charm and beauty decays
  - y_{cp} parameter in D mixing J.M.Link et al. PL B485, 62-70 (2000) First evidence for nonzero mixing, followed by measurements from B-factories. Algorithm and selection used by FOCUS may be used by LHCb with much larger statistics very soon.
  - T-odd correlations J.M.Link et al. PL B622 (2005) 239–248. First limit on $KK\pi\pi$. New limit from BABAR in 2010 using same formalism.
  - 4 body amplitude analysis J.M.Link et al. PR D75 052003 (2007); PL B610 (2005) 225–234; PL B575 (2003) 190–197 . First study with a complete 4-body formalism of $KK\pi\pi$, $KKK\pi$, $\pi\pi\pi\pi$. Direct connection to decays used for extraction of CKM parameters in B decays.
- Conclusions and Outlook

E831 FOCUS Spectrometer at FERMILAB Wide Band Photon Beam





Successor to E687. Designed to study charm particles produced by ~200 GeV photons using a fixed target spectrometer with updated Vertexing, Cerenkov, EM Calorimeters, and Muon id capabilities. Member groups from USA, Italy, Brazil, Mexico, Korea. <u>DATA COLLECTED IN 1996-1997</u>

The FOCUS Collaboration

Univ. of California-Davis, CBPF-Rio de Janeiro, CINVESTAV-Mexico City,
Univ. Colorado-Boulder, FERMILAB, Laboratori Nazionali di Frascati,
Univ. of Illinois-Urbana-Champaign, Indiana Univ.-Bloomington,
Korea Univ.-Seoul, INFN and Univ.-Milano,
Univ. of North Carolina-Asheville, INFN and Univ.-Pavia, Univ. of Puerto Rico-Mayaguez,
Univ. of South Carolina-Columbia, Univ. of Tennessee-Knoxville,
Vanderbilt Univ.-Nashville, Univ. of Wisconsin-Madison, Yonsei Univ.-Seoul

1. y_{CP}: A RETROSPECTIVE

J.M.Link et al. PL B485, 62-70 (2000)

y_{cp} master formulas

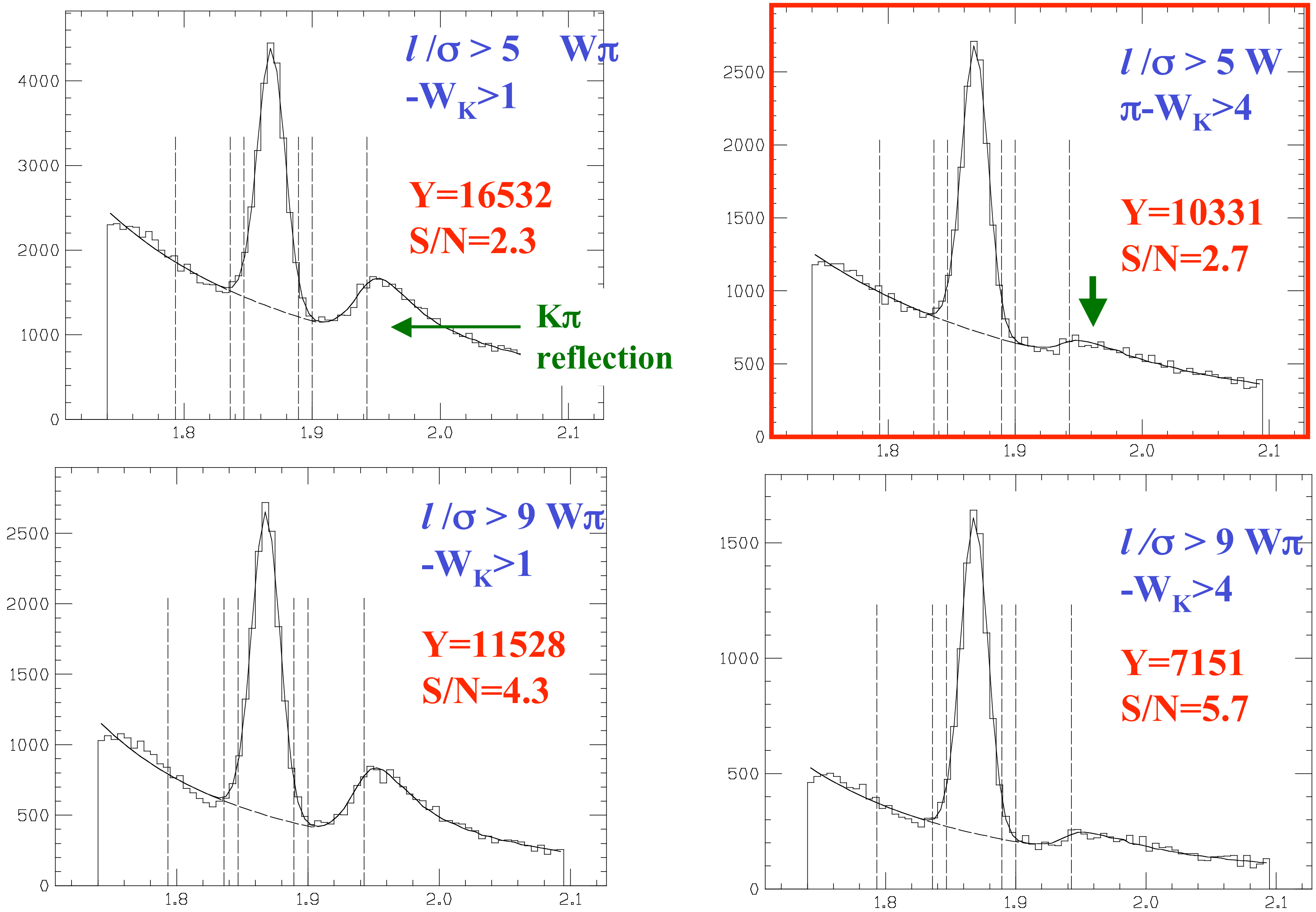
$$y \equiv \frac{\Delta\Gamma}{2\overline{\Gamma}}$$

$$CP\left|KK\right\rangle = +\left|KK\right\rangle \qquad CP\left|K\pi\right\rangle \neq \left|K\pi\right\rangle$$

$$y_{CP} = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1$$

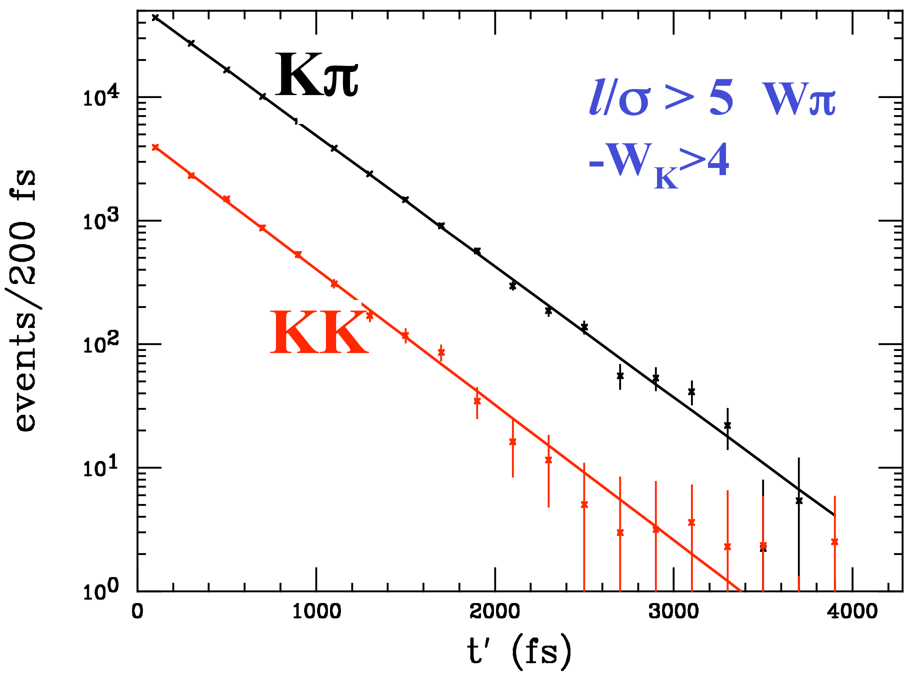
D→KK signal for several cleanups

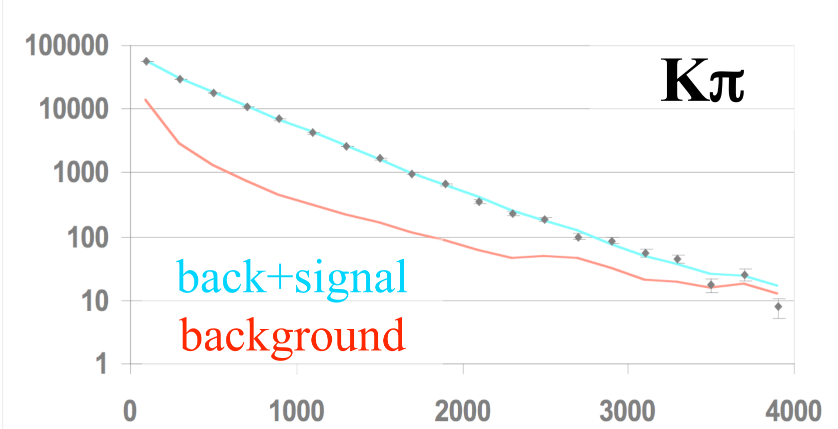
J.M.Link et al. PL B485, 62-70 (2000)

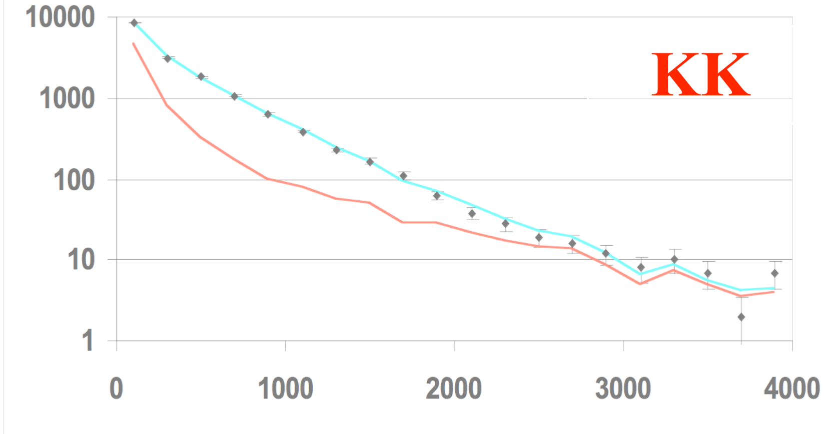


Fitted time evolutions

J.M.Link et al. PL B485, 62-70 (2000)



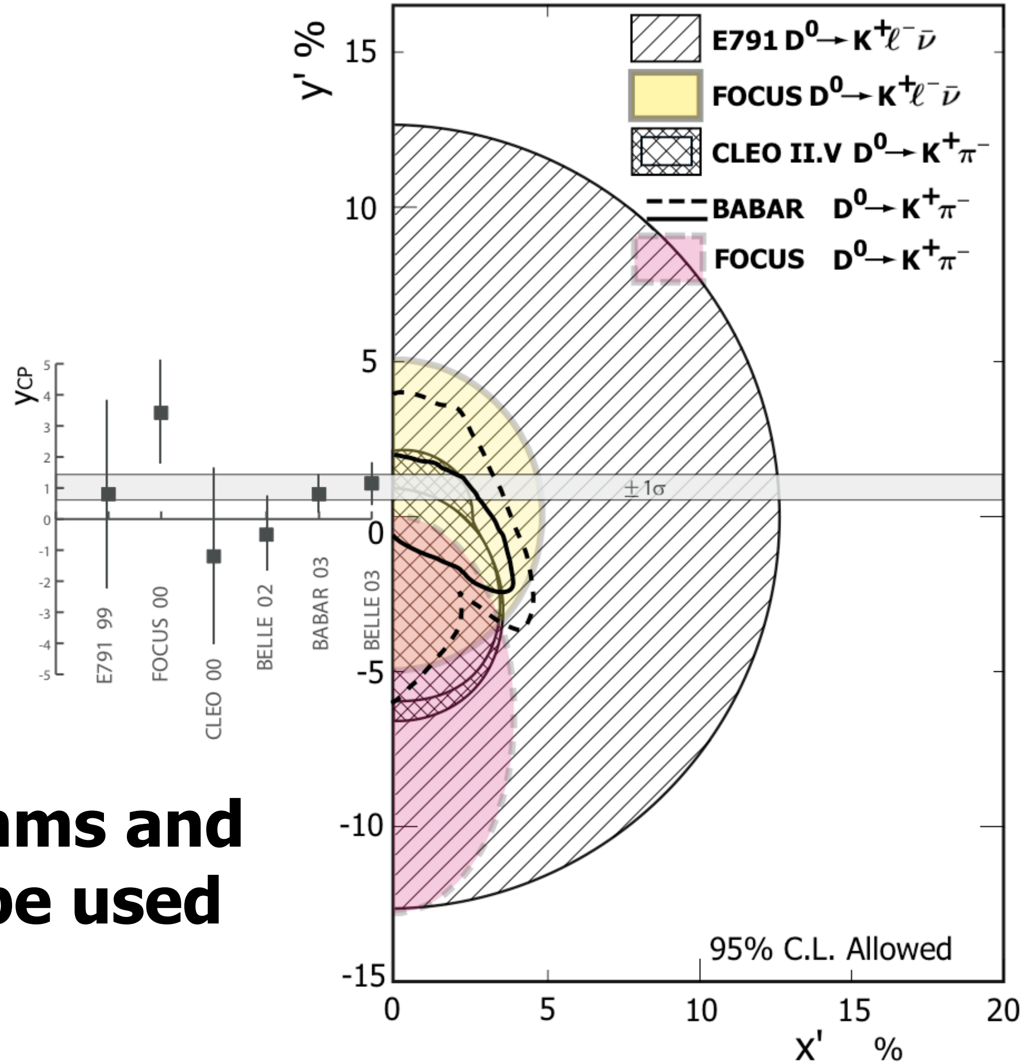




- Background subtracted and f(t') corrected time evolution of **Kπ** and **KK** events in the final fit.

Summary plot from 2003, many more measurements available now

S.Bianco, F.L.Fabbri, I.Bigi, D.Benson, *A Cicerone for the physics of charm*, Riv. Nuovo Cimento **26**, 1-200 (2003)



FOCUS

$y_{CP} = 3.42 \pm 1.39 \pm 0.74$ %

J.M.Link et al. PL B485, 62-70 (2000)

Similar analysis algorithms and selection cuts likely to be used by LHCb soon

2. T-odd CORRELATIONS

J.M.Link et al. PL B622 (2005) 239–248.

A search for T-violation in the D system which, assuming CPT holds, is equivalent to 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

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

($C_T \rightarrow - C_T$ 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 build C_T and $(C_T)_{CP}$

If $C_T \neq (C_T)_{CP} = -\overline{C}_T$ there is CP violation (if CPT holds)

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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:

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

where

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

$$\left(A_T\right)_{CP} \equiv \frac{\Gamma((C_T)_{CP} > 0) - \Gamma((C_T)_{CP} < 0)}{\Gamma((C_T)_{CP} > 0) + \Gamma((C_T)_{CP} < 0)}$$

where

$$\left(A_T\right)_{CP} \propto \sin(\delta_s - \phi_w)$$

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

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

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

where

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

→ 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 (1989) 3339**

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

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.

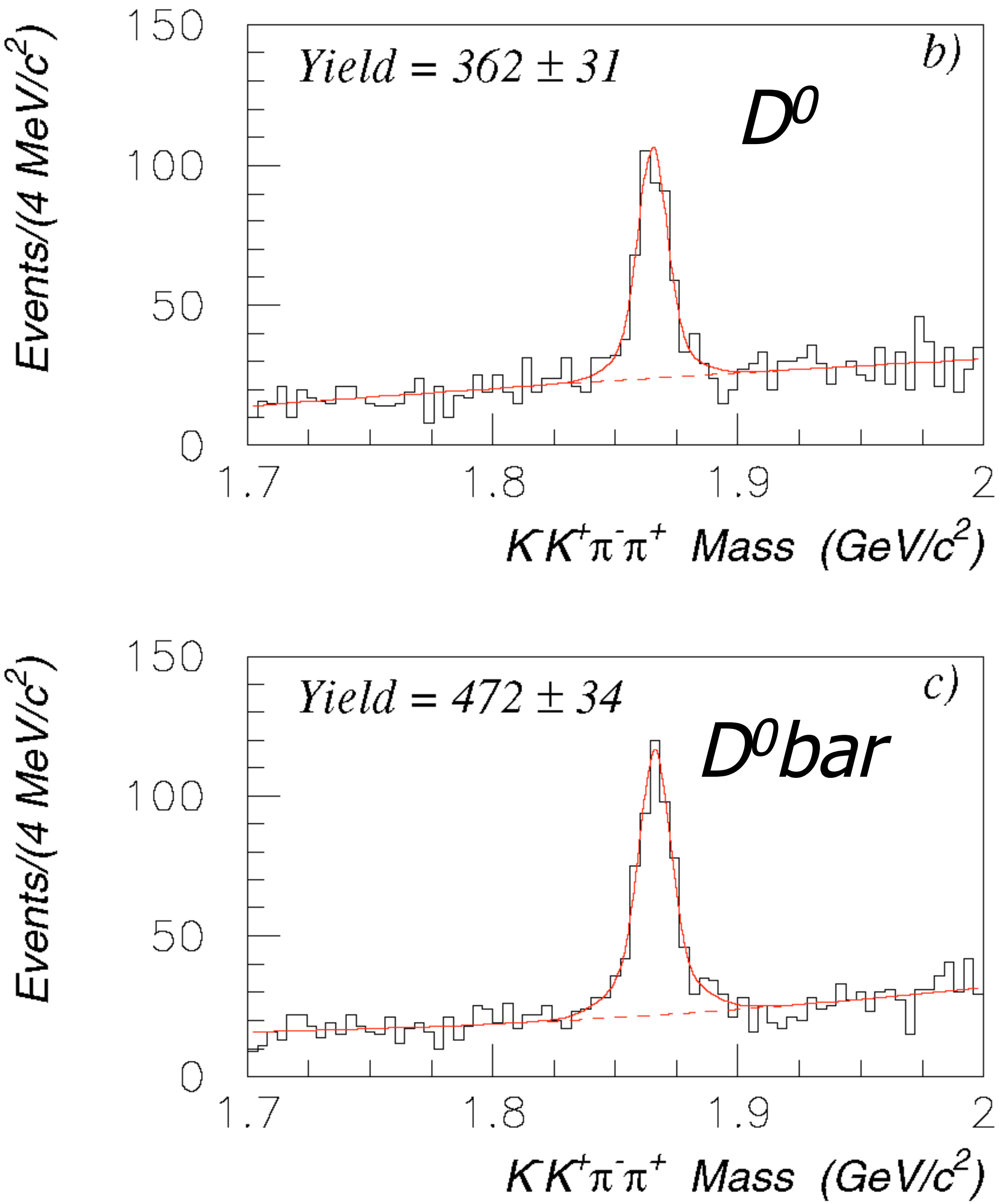
This ambiguity can unequivocally be resolved by measuring in $D^0 \to K^- K^+ \pi^- \pi^+$.

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

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

D^*-Tag

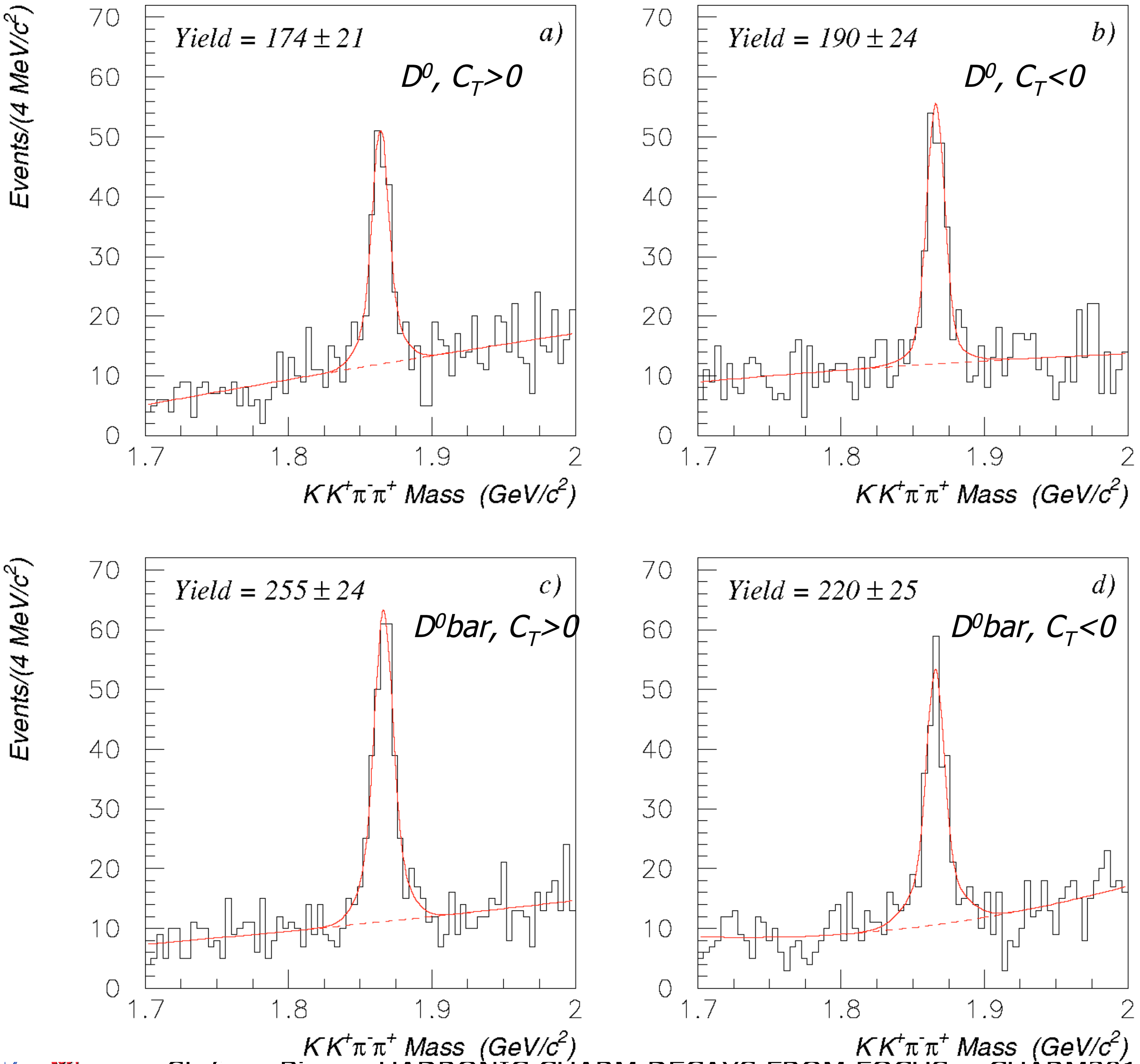
J.M.Link et al. PL B622 (2005) 239–248.



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

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

J.M.Link et al. PL B622 (2005) 239–248.



Systematic error

J.M.Link et al. PL B622 (2005) 239–248.

Table 3
Contribution to the systematic uncertainties of the T-violation parameters for D^0, D^+, and D_s^+

Source	D^0 uncertainty	D^+ uncertainty	D_s^+ uncertainty
Split sample	0.000	0.000	0.000
Fit variant	0.009	0.006	0.004
Set of cuts	0.035	0.021	0.022
D^*-tag dilution	0.002	–	–
MC statistics	0.009	0.004	0.006
Total systematic error	0.037	0.022	0.023

RESULTS

table and average from D.Pedrini, in arXiv:1010.1589v1 [hep-ex] 8 Oct 2010
www.slac.stanford.edu/xorg/hfag/charm/cp_asym/charm_todd_asym_29mar10.html

Table 159: T-violating asymmetries $A_{T\,\mathrm{viol}} = (A_T - \overline{A}_T)/2$.

Mode	Year	Collaboration	$A_{T\,\mathrm{viol}}$	
$D^0 \to K^+K^-\pi^+\pi^-$	2010	BABAR [537]	$+0.0010 \pm 0.0051 \pm 0.0044$	4.7×10^4 evts
	2005	FOCUS [516]	$+0.010 \pm 0.057 \pm 0.037$	800evts
		COMBOS average	$+0.0010 \pm 0.0067$	
$D^+ \to K_s^0 K^+\pi^+\pi^-$	2005	FOCUS [516]	$+0.023 \pm 0.062 \pm 0.022$	
$D_s^+ \to K_s^0 K^+\pi^+\pi^-$	2005	FOCUS [516]	$-0.036 \pm 0.067 \pm 0.023$	

FOCUS J.Link et al., Phys. Lett. B622, 239 (2005)

BABAR P.del Amo Sanchez et al., PHYSICAL REVIEW D 81, 111103(R) (2010)

Now at the 10^{-3} sensitivity with B-factories

•3. 4-BODY AMPLITUDE ANALYSIS

J.M.Link et al. PR D75 052003 (2007); PL B610 (2005) 225–234; PL B575 (2003) 190–197.

First study with a complete 4-body formalism of $KK\pi\pi$, $KKK\pi$, $\pi\pi\pi\pi$.

Discuss here $\pi\pi\pi\pi$ (6.3k events).
Direct connection to decays used for extraction of CKM parameters in B decays such as the angle α from B--> $\rho^0\rho^0$

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

J.M.Link et al. PR D75 052003 (2007)

1. D--> $R_1\ \pi$
   - R_1 --> $R_2\ \pi$
     - R_2--> $\pi\ \pi$
2. D--> R $\pi\ \pi$
   - R--> $\pi\ \pi$
3. D--> $R_1\ R_2$
   - R_1--> $\pi\ \pi$
   - R_2--> $\pi\ \pi$

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

J.M.Link et al. PR D75 052003 (2007)

- A simple model to describe the data, avoiding the inclusion of too many amplitudes that populate the whole phase space, giving rise to large interference terms:
  - $D \to \rho^0\rho^0$ (3 helicity states);
  - $D \to a_1\pi, \quad a_1 \to \rho^0\pi$ ($\rho^0\pi$ in relative S- and D-wave);
  - $D \to R\pi\pi, \quad R = \sigma, \ \rho^0, \ f_0(980)$ and $f_2(1270)$.
- A total of 9 amplitudes (16 free parameters);
- FSI not fully accounted by the usual isobar model.

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

J.M.Link et al. PR D75 052003 (2007)

- **Many possible intermediate states:** $a_1(1260)\pi,\ \rho^0\rho^0,\ \sigma\sigma,\ \rho\pi\pi,\ \sigma\pi\pi,\ f_0\pi\pi$, etc.

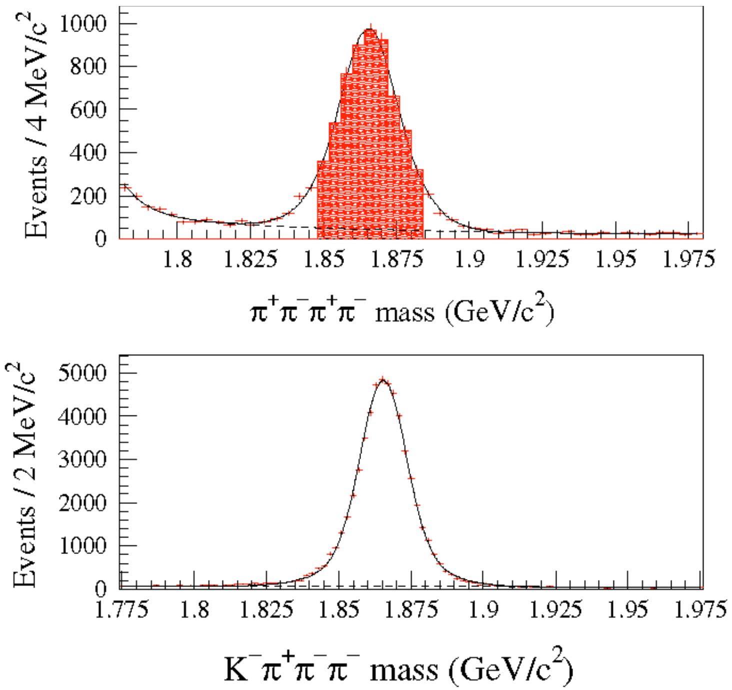


FIG. 1 (color online). Invariant mass distributions used to determine the ratio of branching fractions. The upper plot is the $\pi^-\pi^+\pi^-\pi^+$ signal; the lower plot is the normalizing channel $K^-\pi^+\pi^-\pi^+$. The fits (solid curves) are explained in the text; the dashed line shows the background. The hatched area on the $\pi^-\pi^+\pi^-\pi^+$ signal corresponds to the events used in the amplitude analysis.

As for 3-body decays, amplitude analysis uses the isobar model, but now the kinematics is determined by 5 invariants (2-body masses squared)

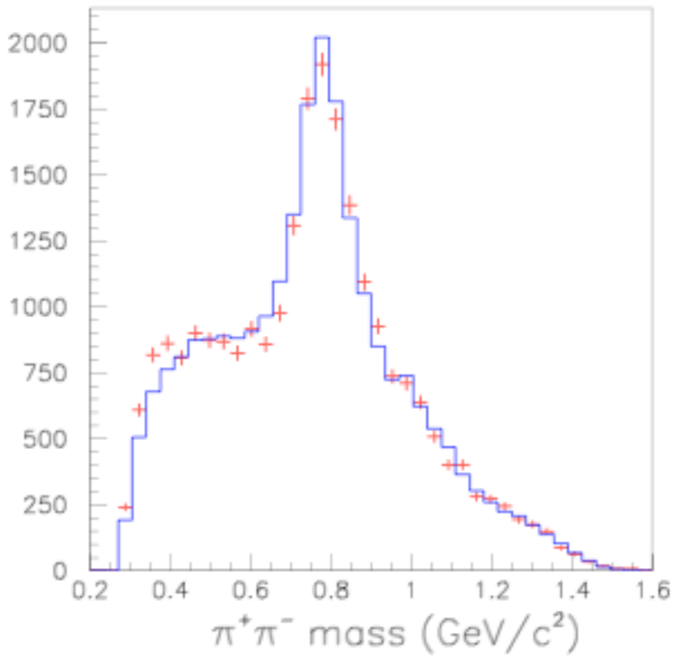
Re-scattering in ðnal state may play an important role!

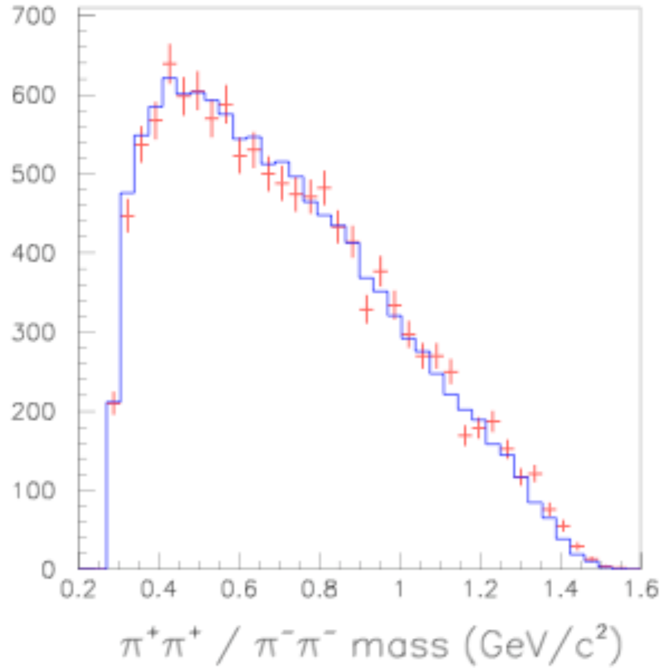
FB18, Santos ñ p.16/??

The $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decay

J.M.Link et al. PR D75 052003 (2007)

2-body mass projections: $\pi^+\pi^-$ and $\pi^\pm\pi^\pm$.

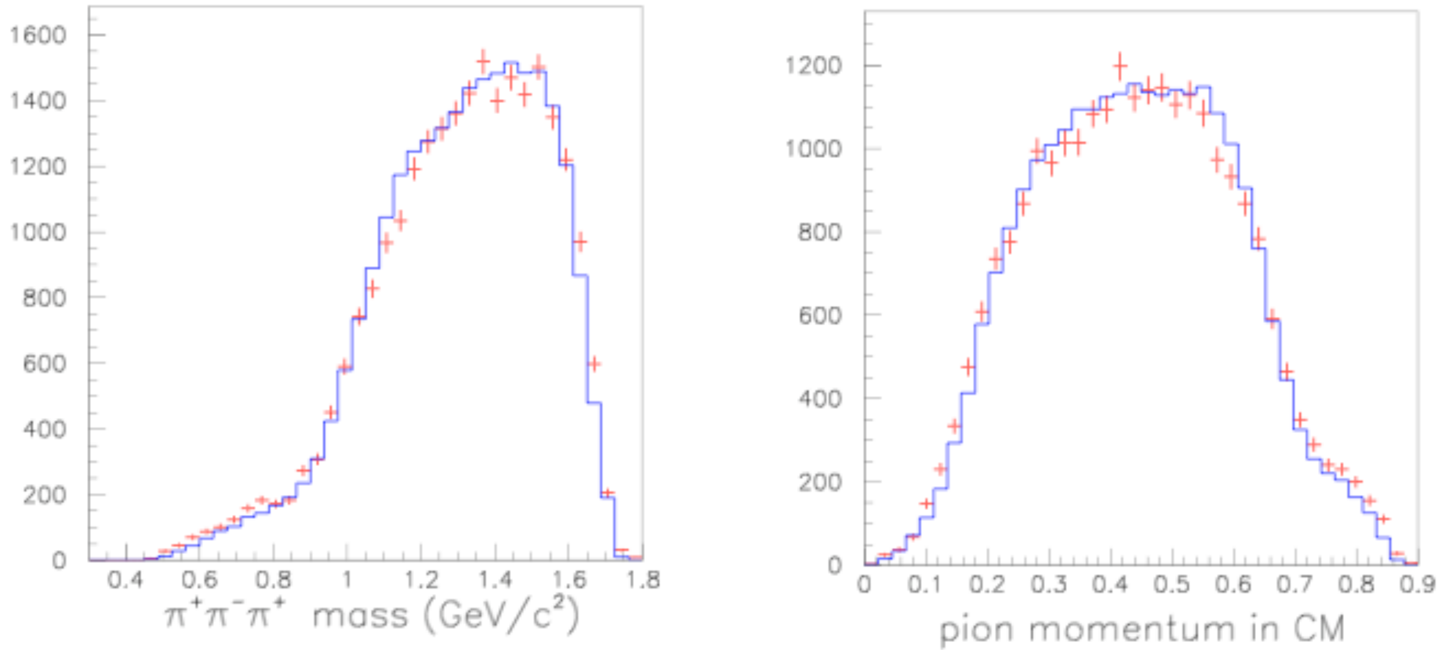




The $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decay

J.M.Link et al. PR D75 052003 (2007)

3-body mass projections and π momentum in CM.



Alberto Reis

FB18, Santos ñ p.20/??

J.M.Link et al. PR D75 052003 (2007)

J. M. LINK *et al.* PHYSICAL REVIEW D **75**, 052003 (2007)

TABLE III. Results from the best fit. The first error is statistical, and the second one is systematic.

Mode	Magnitude	Phase (degrees)	Fraction (%)
$a_1^+\pi^-$, $a_1 \to \rho^0\pi^+$ (S-wave)	1. (fixed)	0 (fixed)	$43.3 \pm 2.5 \pm 1.9$
$a_1^+\pi^-$, $a_1 \to \rho^0\pi^+$ (D-wave)	$0.241 \pm 0.033 \pm 0.024$	$82 \pm 5 \pm 4$	$2.5 \pm 0.5 \pm 0.4$
$a_1^+\pi^-$, $a_1 \to \sigma\pi^+$	$0.439 \pm 0.026 \pm 0.021$	$193 \pm 4 \pm 4$	$8.3 \pm 0.7 \pm 0.6$
$a_1^+\pi^-$ (all)	...	...	$60.0 \pm 3.0 \pm 2.4$
$\rho^0\rho^0$ (parallel)	$0.157 \pm 0.027 \pm 0.020$	$120 \pm 7 \pm 8$	$1.1 \pm 0.3 \pm 0.3$
$\rho^0\rho^0$ (perpendicular)	$0.384 \pm 0.020 \pm 0.015$	$163 \pm 3 \pm 3$	$6.4 \pm 0.6 \pm 0.5$
$\rho^0\rho^0$ (longitudinal)	$0.624 \pm 0.023 \pm 0.015$	$357 \pm 3 \pm 3$	$16.8 \pm 1.0 \pm 0.8$
$\rho^0\rho^0$ (all)	...	...	$24.5 \pm 1.3 \pm 1.0$
$f_0(980)\pi^+\pi^-$	$0.233 \pm 0.019 \pm 0.015$	$261 \pm 7 \pm 4$	$2.4 \pm 0.5 \pm 0.4$
$f_2(1270)\pi^+\pi^-$	$0.338 \pm 0.021 \pm 0.016$	$317 \pm 4 \pm 4$	$4.9 \pm 0.6 \pm 0.5$
$\sigma\pi^+\pi^-$	$0.432 \pm 0.027 \pm 0.022$	$254 \pm 4 \pm 5$	$8.2 \pm 0.9 \pm 0.7$
$R\pi^+\pi^-$ (all)	...	...	$20.0 \pm 1.2 \pm 1.0$

The D0 --> $\pi^+\pi^-\pi^+\pi^-$ decay - Conclusions

J.M.Link et al. PR D75 052003 (2007)

•The dominant contribution to the $\pi^+\pi^-\pi^+\pi^-$ state comes from the $a_1^+(1260)\pi^-$ mode, accounting for over 60% of the total decay rate.

•The remaining part of the decay rate is equally divided between the $\rho^0\rho^0$ and the nonresonant-like modes, D-->R$\pi\pi$

• Although fit on projections are good, the 5D fit confidence level is not good. FSI must play an important role.

•A better description of the data would require the inclusion of FSI terms, besides what is already built in the isobar model

•There is the need to find a model for these FSI terms, based on χ-PT.

EPILOGUE

ON THE IMPORTANCE OF DALITZ ANALYSIS IN THE EXTRACTION OF CKM PARAMETERS

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

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

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

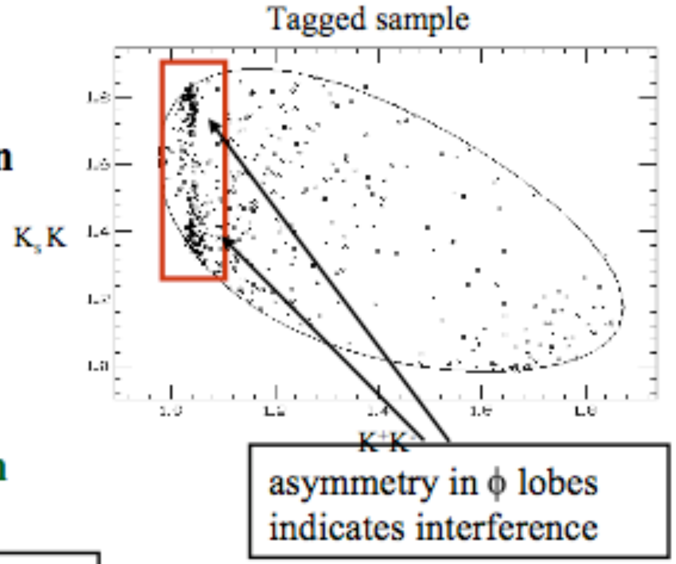
$K_s f_0(980)$ is a CP even state: **Ks and f_0 are CP even**

$K_s f_0(980)$ 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.



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

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

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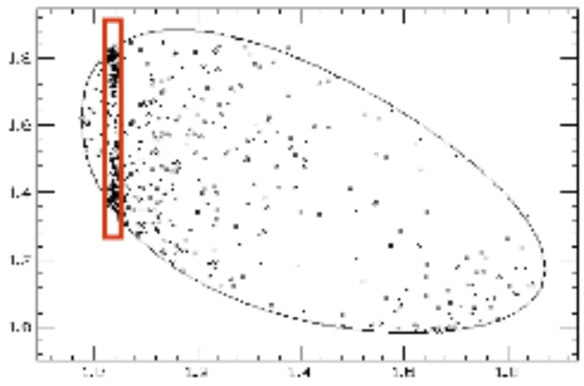
$K_s \phi$ CP odd purity can be improved with a tighter cut

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

Tagged sample



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	$93.0 \pm 0.9 \pm 0.3\%$

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

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

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

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CONCLUSIONS

- Discussed a few old FOCUS hadronic decays results which have implications on upcoming new results from the contemporary charm and beauty experiments
- Algorithm and selection used by FOCUS in the study of y_{cp} in D mixing may be used by LHCb with much larger statistics.
- T-odd correlations. First limit on $KK\pi\pi$. New limit from BABAR in 2010 using same formalism.
- 4 body amplitude analysis. First study with a complete 4-body formalism of $KK\pi\pi$, $KKK\pi$, $\pi\pi\pi\pi$. Direct connection to decays used for extraction of CKM angle α in B decays. Poor 5D fit quality emerges in high-statistics studies --> need better understanding of nonresonant component
- Importance of studying the resonant structure of hadronic decays. S-waves often cannot be taken out with a simple mass cut.

Question Slides