Dalitz Plot Analysis of 3-body charm decays.

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□ Summary.

- Introduction;
- The BaBar Experiment;
- Dalitz plot Analysis of $D^0 \to \bar{K}^0 K^+ K^-$;
  - Data selection;
  - Branching Fraction.
  - Partial Wave Analysis.
  - Dalitz Plot Analysis.
  - CP Asymmetries.
- Conclusions.

Introduction.

□ In the last few years Dalitz plot analysis of charm decays has received new interest mostly because:

- a) Study of the properties of the scalar mesons;
- b) Mesurement of γ in $B \to D^0 K$ through Dalitz plot analysis;
- c) Search for CP violation in interferences and phases in charm decays.

□ Understanding the properties of the scalar mesons is an essential item for the study CP violation in penguin decays such as $B \to 3h$.

□ In BaBar some B and charm physics are moving in parallel. High statistics samples from charm decays are used to fix the model to be used in B decays.

The structure of the scalar mesons.

☐ Too many scalar mesons below 2. GeV.

I = 1/2	I = 1	I = 0
$k(800)$		σ
	$a_0(980)$	$f_0(980)$
		$f_0(1370)$
$K_0^*(1430)$	$a_0(1490)$	$f_0(1500)$
		$f_0(1700)$
$K_0^*(1950)$		

☐ Two nonets? 4-quark states? Gluonium?

☐ Where is the scalar glueball?

☐ Many proposals.

Narrow: $f_0(1500)$, $f_0(1700)$.

Wide: σ.

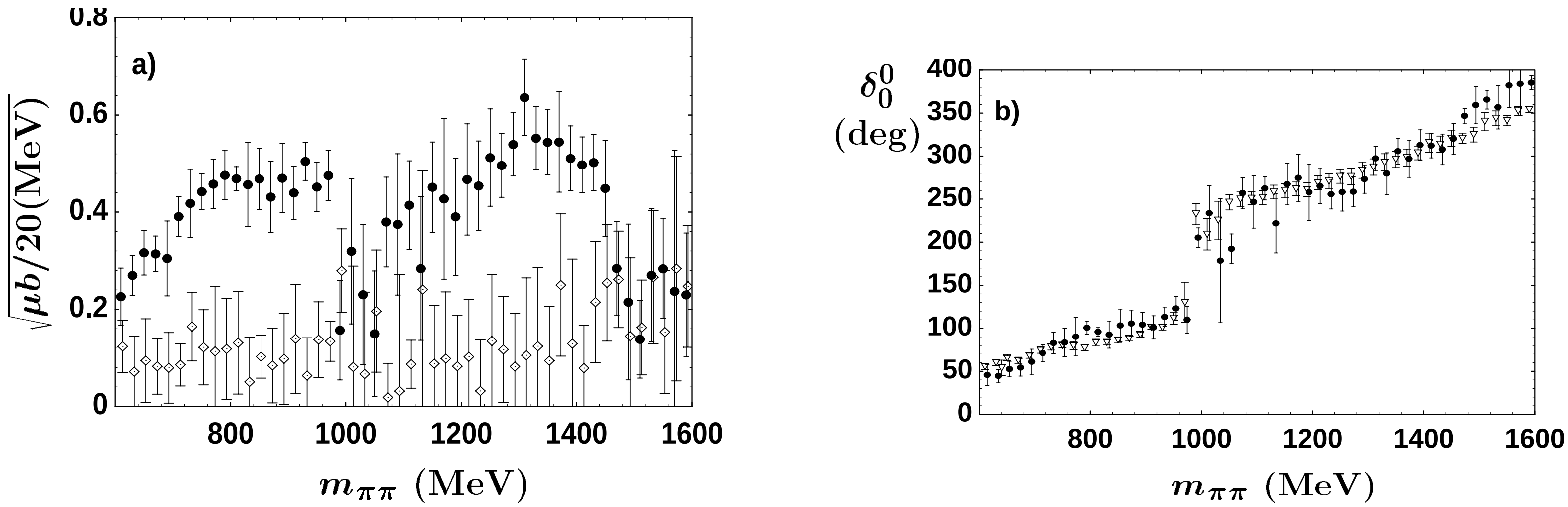
☐ Information on some of these states, such as the existence of $k(800)$ and σ can be extracted from existing data from charm decays.

☐ Unlikely to produce gluonium in charm decays.

$\pi\pi$ amplitude and phase.

□ The $\pi\pi$ amplitude and phase has been measured in:

$$\pi^- p \to \pi^+ \pi^- n$$



□ Watson theorem: phase shift is independent from the production mechanism up to the first inelastic threshold.

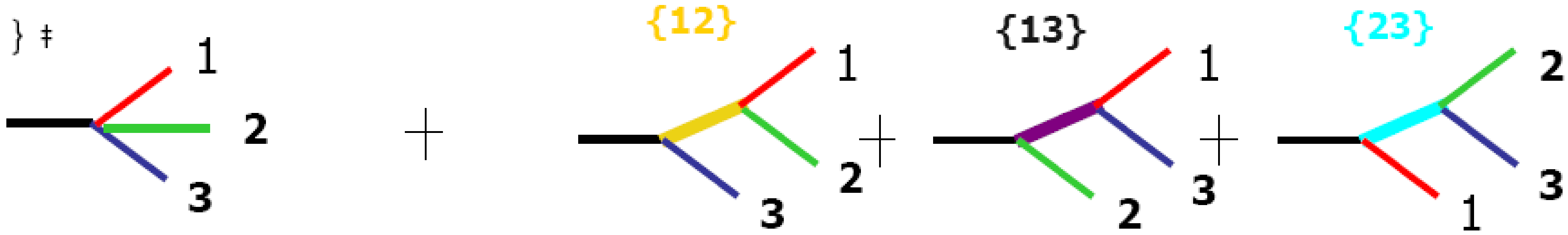
□ Phase motions in B and charm decays should be the same as in hadronic interactions.

□ No reason for the amplitude to be the same.

Dalitz plot analysis.

□ Charmed mesons decay to light hadrons, therefore a fundamental laboratory for studying light meson spectroscopy, especially for spin 0 and spin 1 mesons.

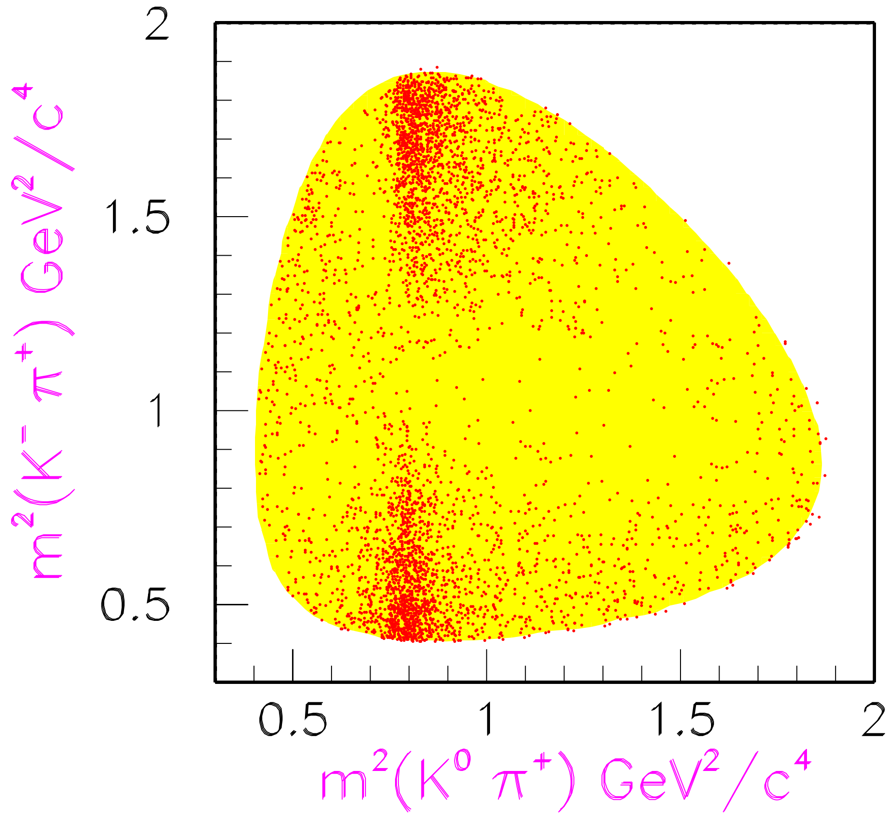
□ The method assumes an isobar model: the dacay proceedes through a flat Non Resonant contribution + intermediate resonance production:



□ In some cases some of the decay channels can be switched off by physics.

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

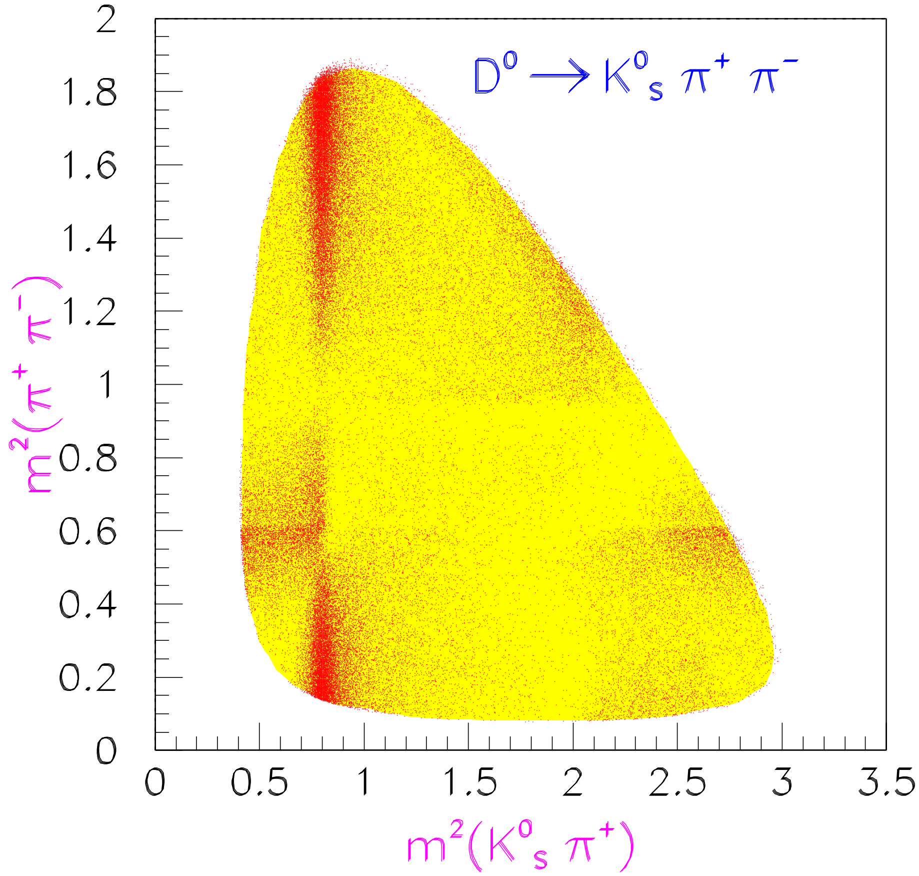
□ In some cases a rather simple structure. $D^0 \to K^0 K^- \pi^+$ (Cabibbo Suppressed) (BaBar):



□ Resonances only along the $K^0\pi^+$ axis.

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

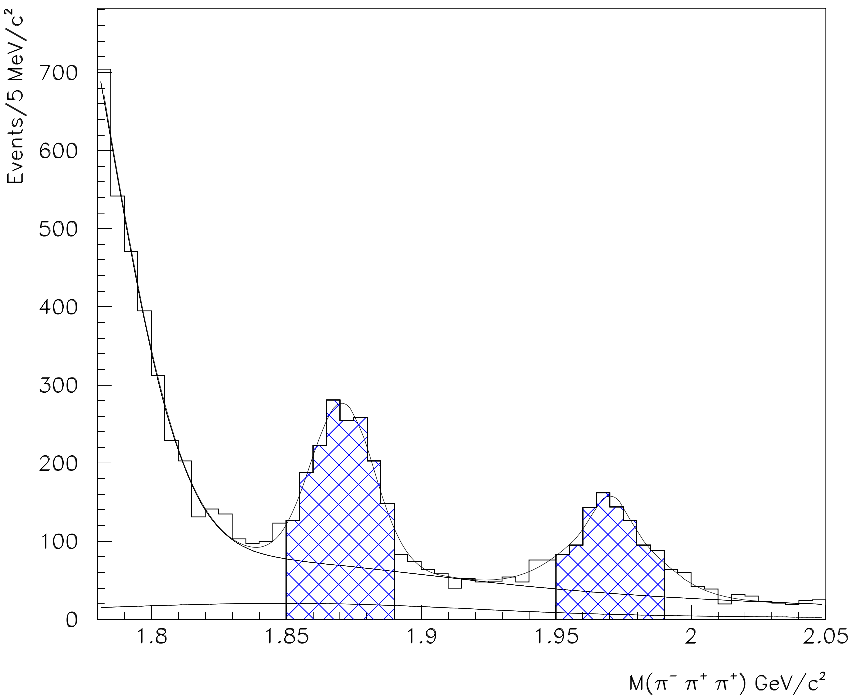
□ Very complex structure in $D^0 \to \bar{K}^0\pi^+\pi^-$: up to 13 resonances.(BaBar)



The evidence for $\sigma(500)$.

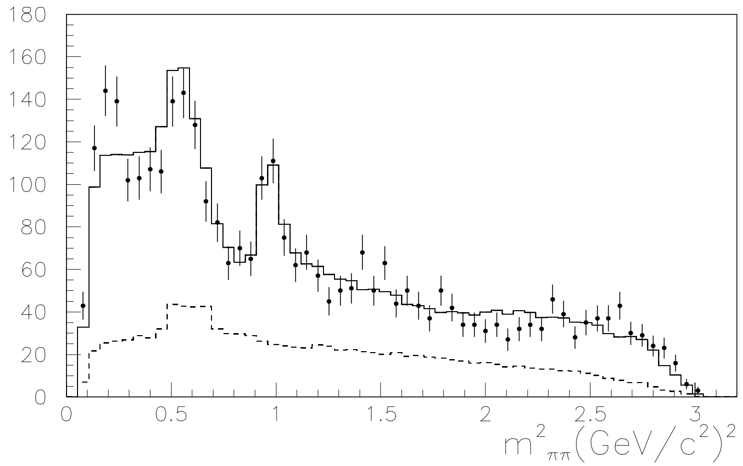
□ Experiment E791 at Fermilab has studied ≈ 1200 events from:

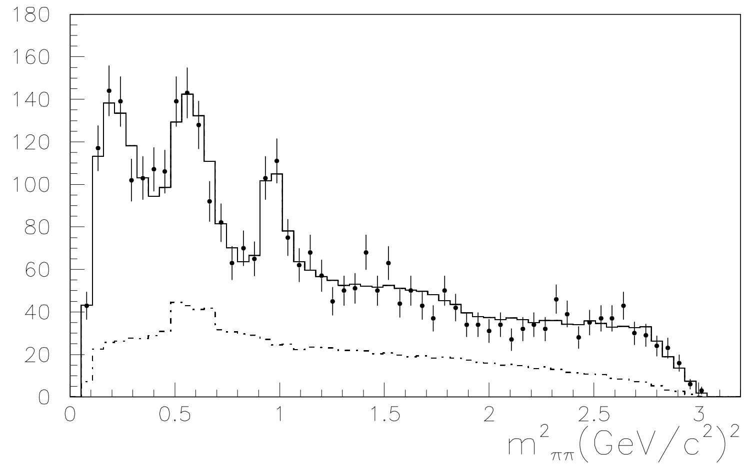
$$D^+ \to \pi^-\pi^+\pi^+$$



The evidence for $\sigma(500)$.

□ In order to obtain a good fit of the Dalitz plot they need to introduce a new wide scalar resonance:





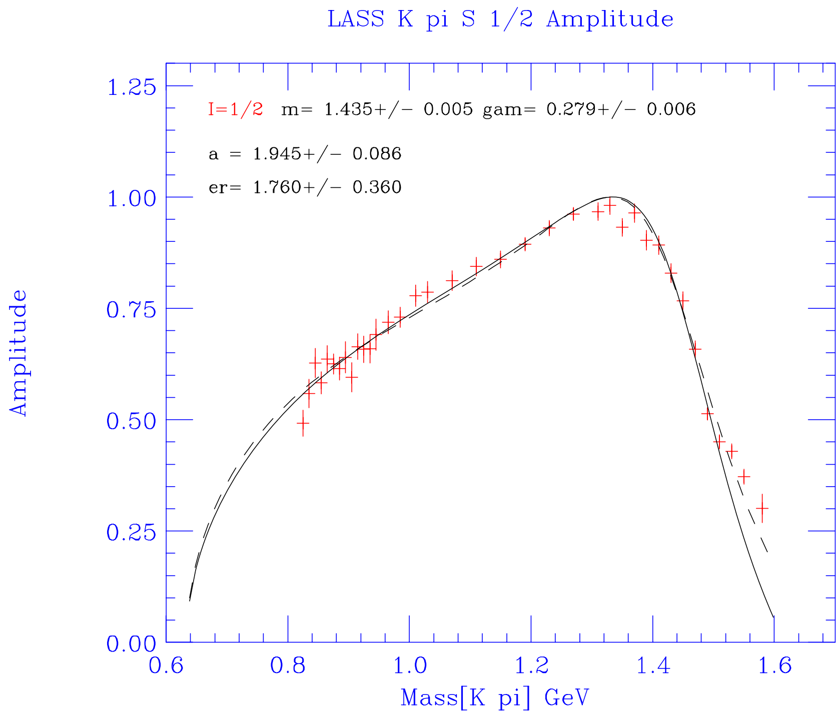
$$m = 478 \pm 24 \pm 17 \quad MeV$$

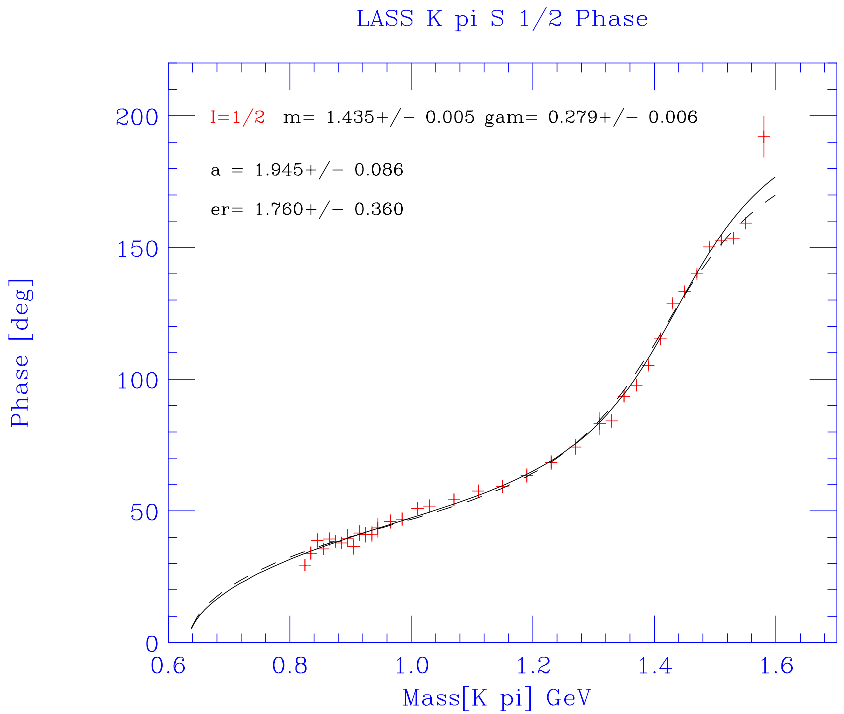
$$\Gamma = 324 \pm 41 \pm 21 \quad MeV$$

The evidence for $\kappa(800)$.

☐ The $K\pi$ S-wave amplitude and phase has been studied by LASS experiment in the reaction:

$$K^- p \to K^- \pi^+ n$$





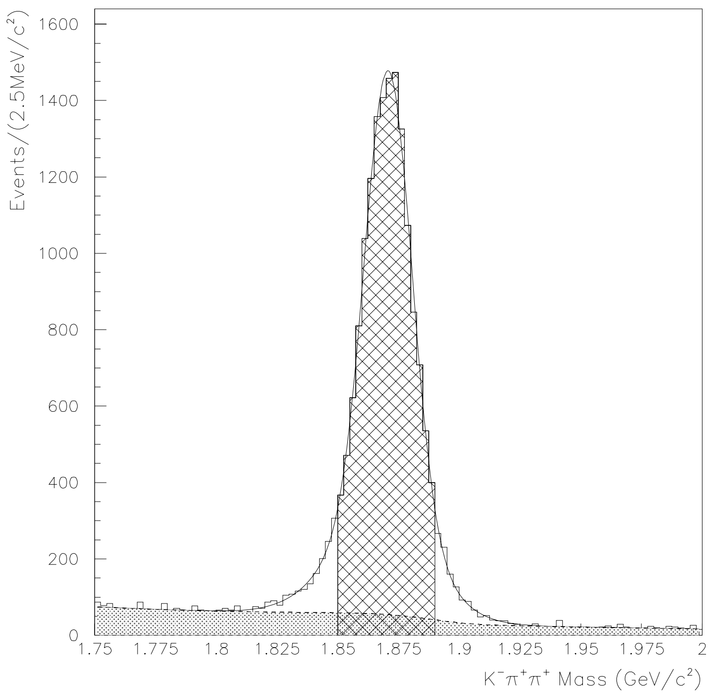
☐ No need to introduce $k(800)$.

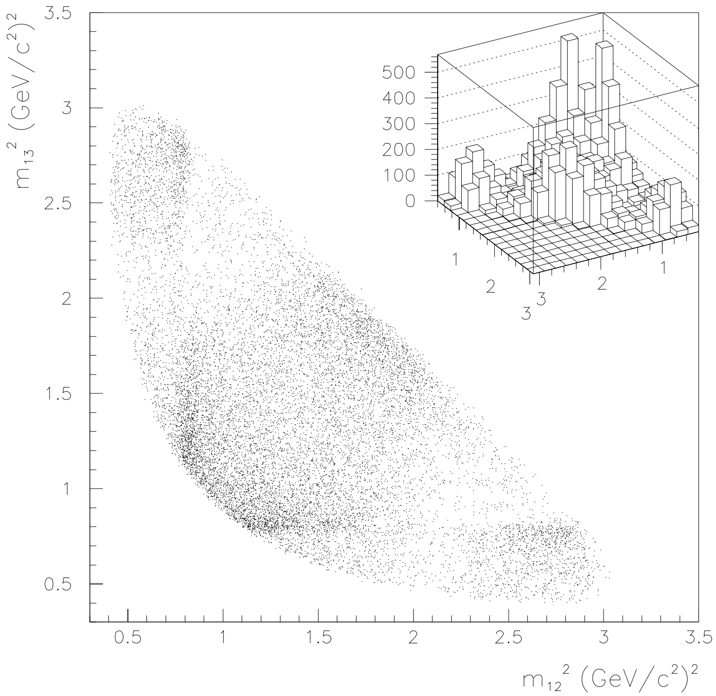
The evidence for $\kappa(800)$ from E791.

□ Experiment E791 at Fermilab has studied $\approx$ 15000 events from:

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

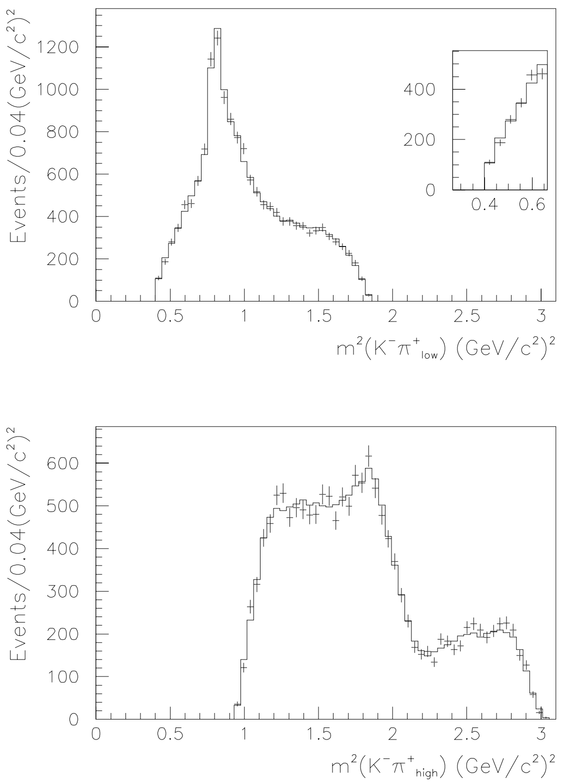
□ Mass spectrum and Dalitz plot.





The evidence for $\kappa(800)$ from E791.

- □ In order to fit the Dalitz plot a large Non Resonant contribution is needed.
- □ Or, better, a new low mass scalar resonance.



$$m = 797 \pm 19 \pm 42 \quad MeV, \qquad \Gamma = 410 \pm 43 \pm 85 \quad MeV$$

A new approach: Amplitude analysis.

□ A new method has been developed by E791 in the study of:

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

□ In this case only one channel is open $(K^- \pi^+)$ but combinatorial problem.

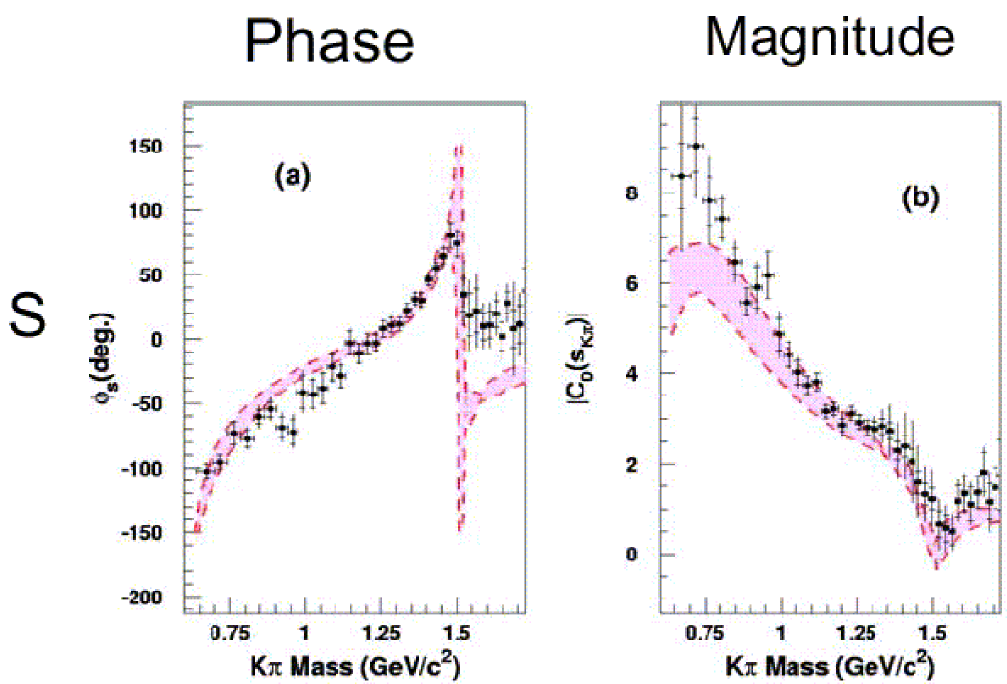
□ The scalar contribution is left free in the Dalitz plot analysis in terms of a complex number:

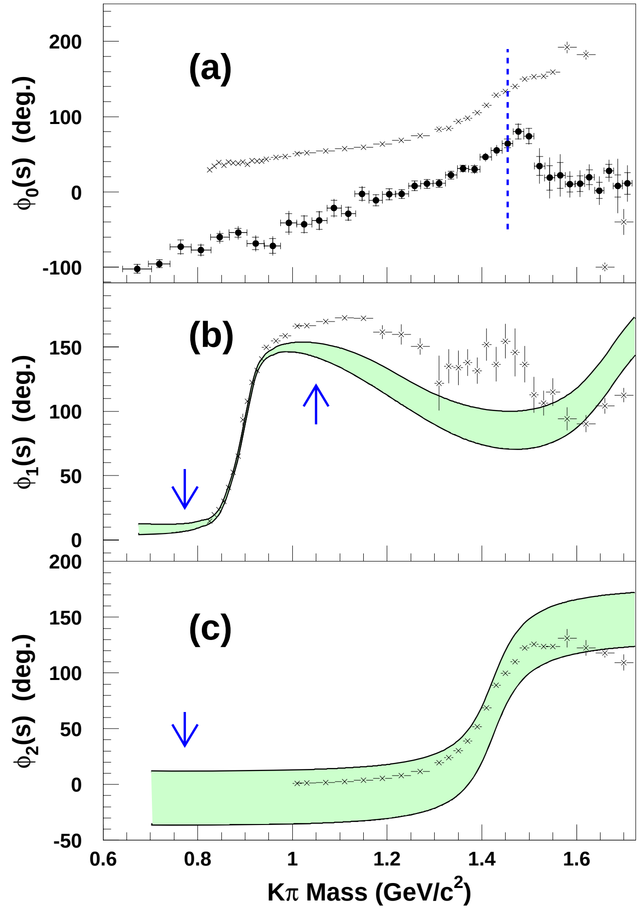
$$c_{m(K\pi)} e^{i\phi_{m(K\pi)}}$$

□ The fit measures amplitude and phase as a function of the $K\pi$ mass.

Results.

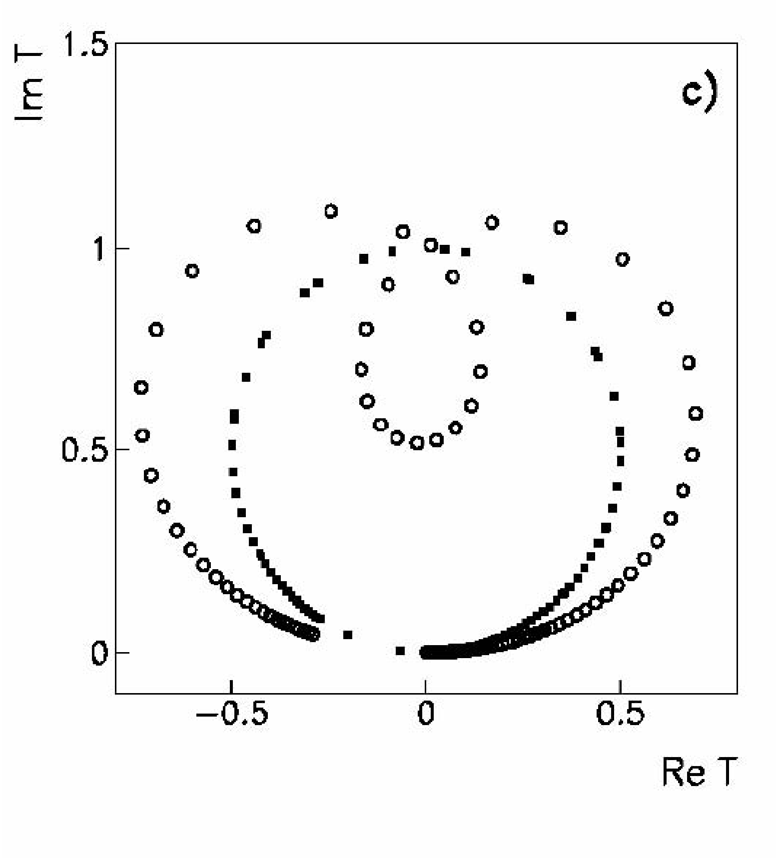
□ Comparison with LASS experiment: direct proof of the Watson theorem.

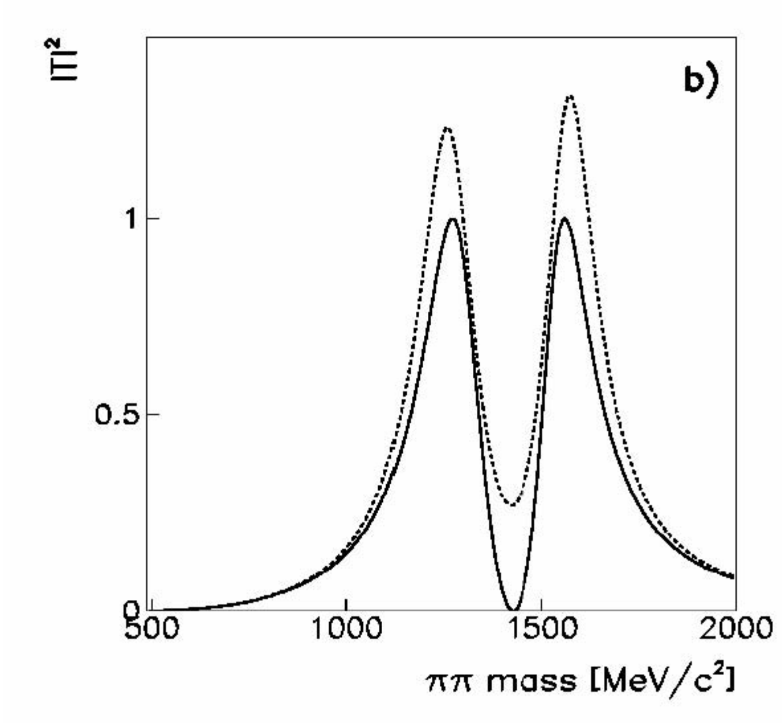




Resonances parametrization.

□ Key point: two relatively broad overlapping resonances:





□ The simple addition of two Breit Wigners violates unitarity.

The K-matrix formalism.

□ Transition Matrix written as:

$$T = (I - iK\rho)^{-1}K$$

$$K_{ij} = \sum_{\alpha} \frac{\gamma_{i\alpha}\gamma j\alpha m_\alpha \Gamma_\alpha}{m_\alpha^2 - m^2} + c_{ij}m^2$$

where the index ij extends to the different decay channels and the sum is over all the K matrix poles.

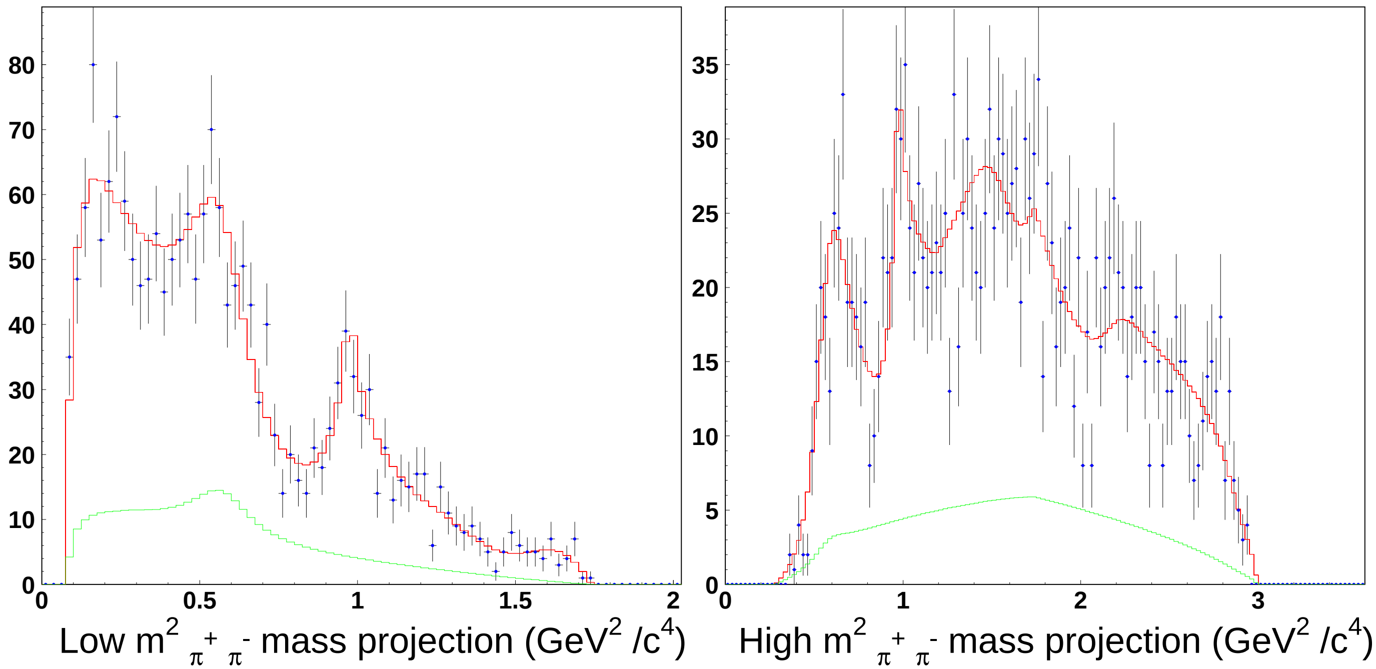
□ Problem: not possible to separate the different resonant contributions.

□ Poles and couplings taken from past experiments in a global fit.

□ Some of the measurements (such as for $f_0(980)$) not very accurate.

K-matrix fits to charm decays.

□ FOCUS: Analysis of $D^+ \to \pi^+\pi^+\pi^-$.

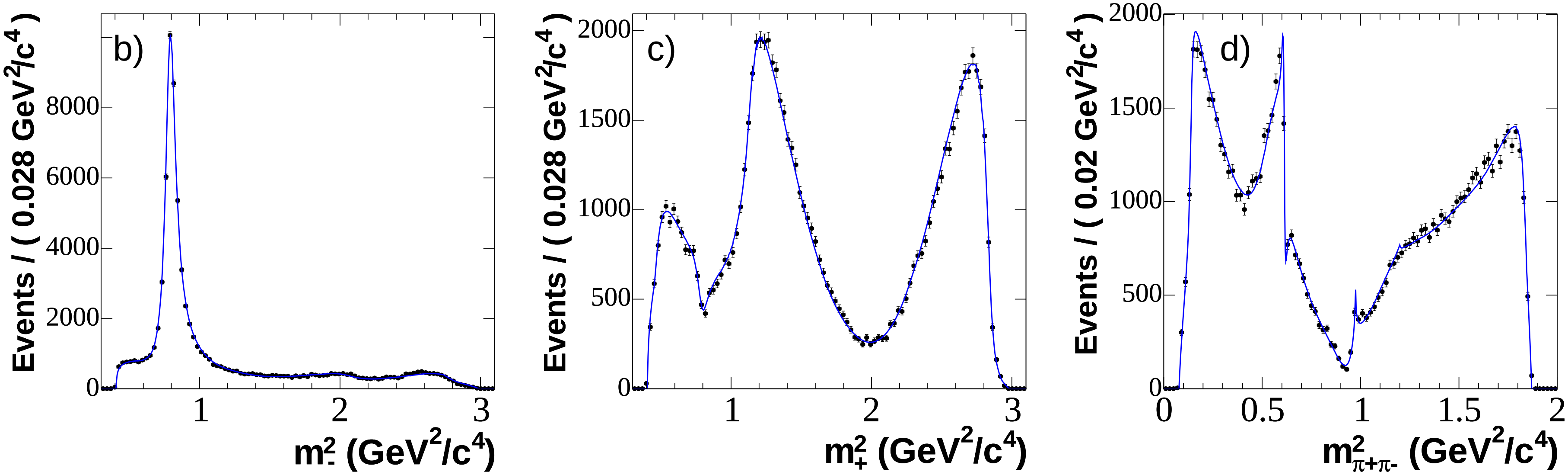


□ No need for a σ.

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

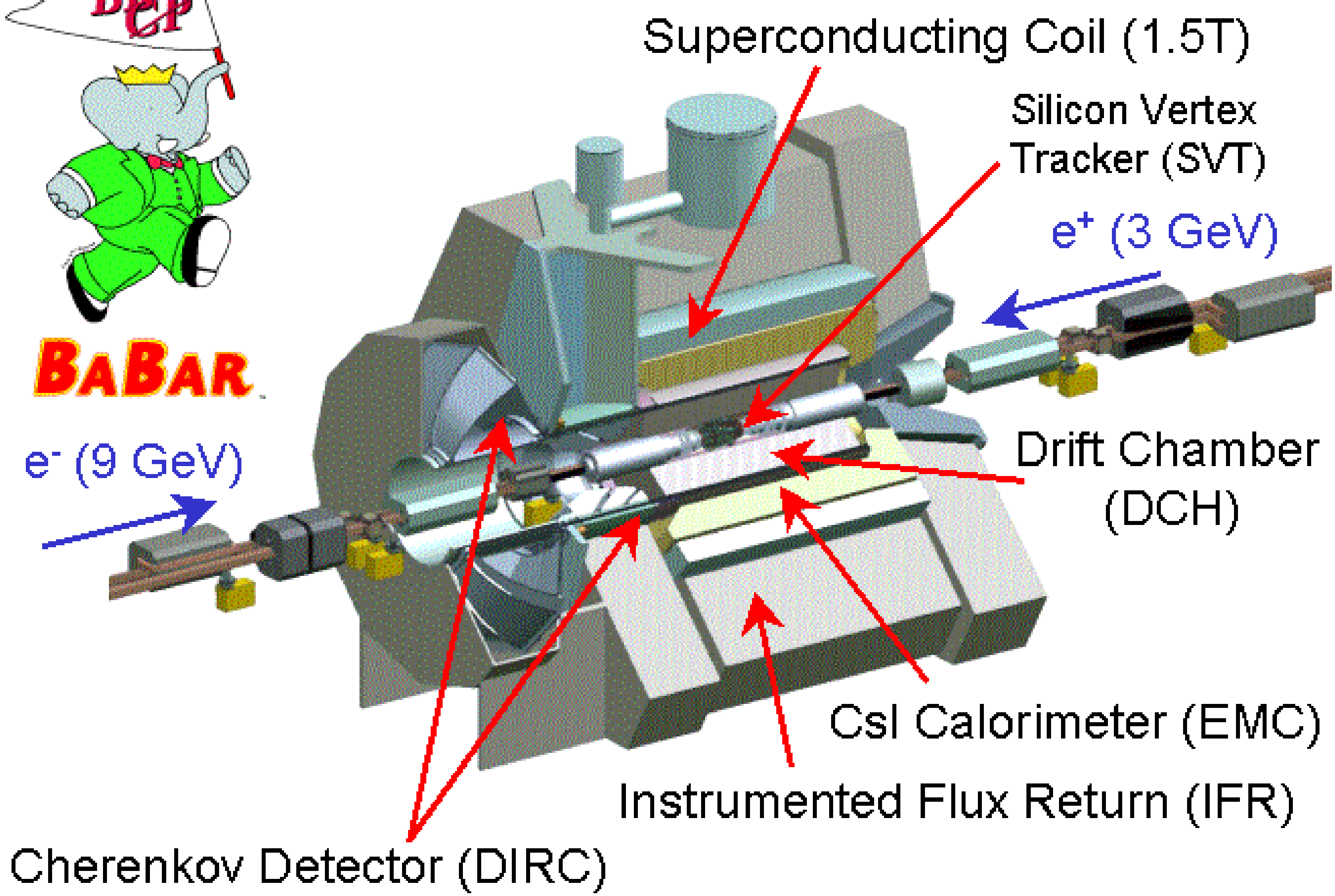
□ With standard Breit-Wigners: need to include new scalar mesons (including σ) and large Double Cabibbo Suppressed contributions.

□ Dalitz analysis using a K-matrix description of the S-wave: (BaBar, 82 K events)



□ Good fit.

BABAR Detector @ PEP-II



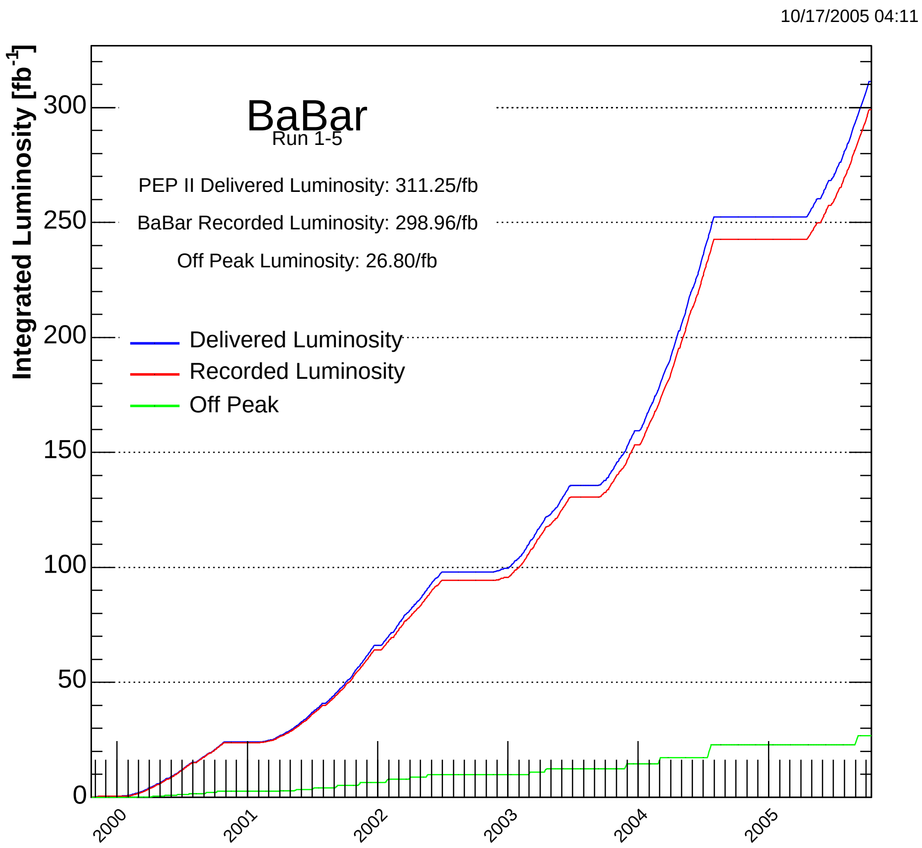
Charm physics at B-factories.

□ The power of B-factories in charm physics is based on:

- Relatively small combinatorial in e^+e^- interactions.
- Good tracking and vertexing.
- Good Particle Identification.
- Detection of all possible final states, with charged tracks and γ's.
- Very high statistics.

The BaBar Experiment.

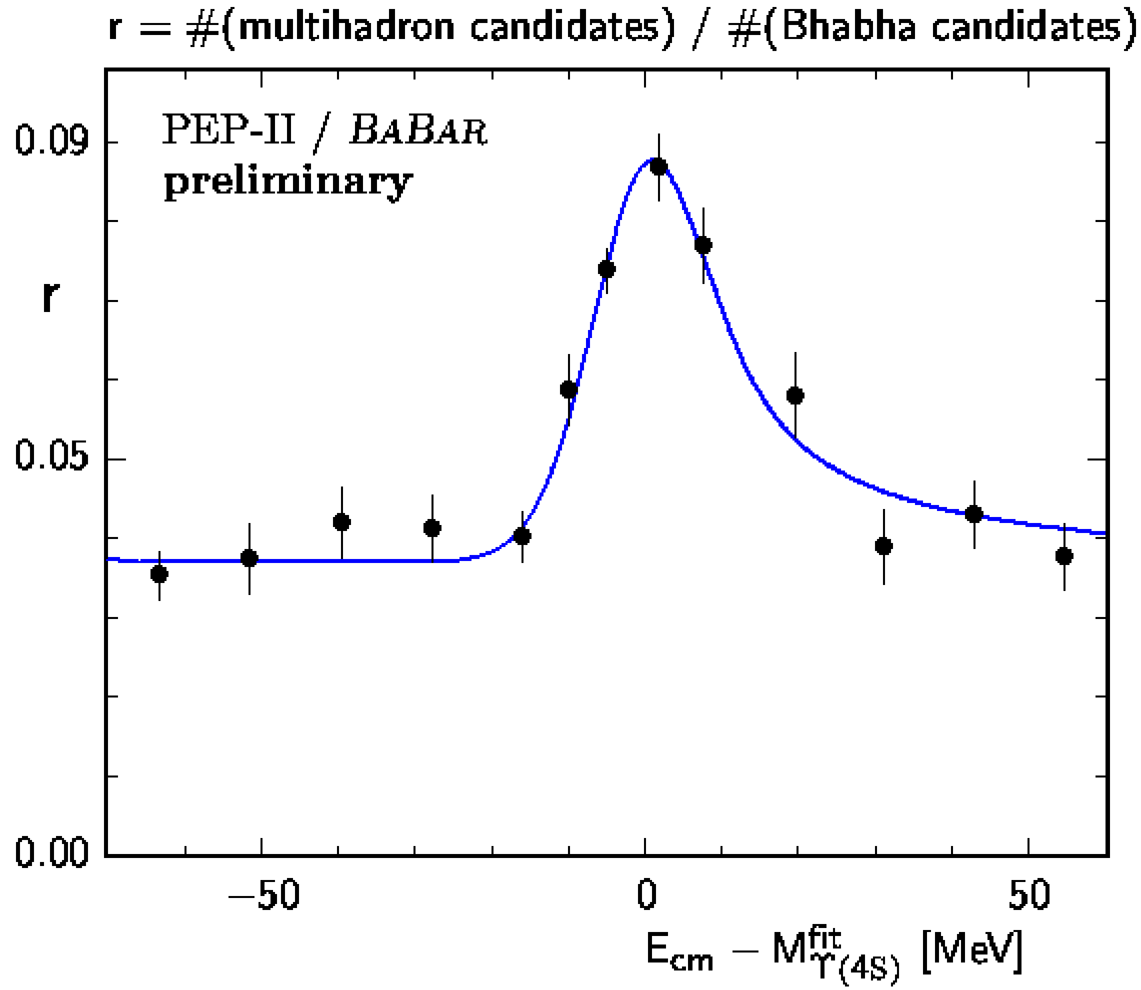
- ☐ Start data taking: end 1999.
- ☐ Present luminosity: 300 fb^{-1}



- ☐ The experiment will continue taking data up to the end of 2008 collecting 1000 fb^{-1}.

Separation from continuum.

□ At B-factories, the $\Upsilon(4S)$ resonance sits on a consistent continuum background.



Charm decays.

□ Cross sections for different processes, at the $\Upsilon(4S)$:

$e^+e^- \to$	σ (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

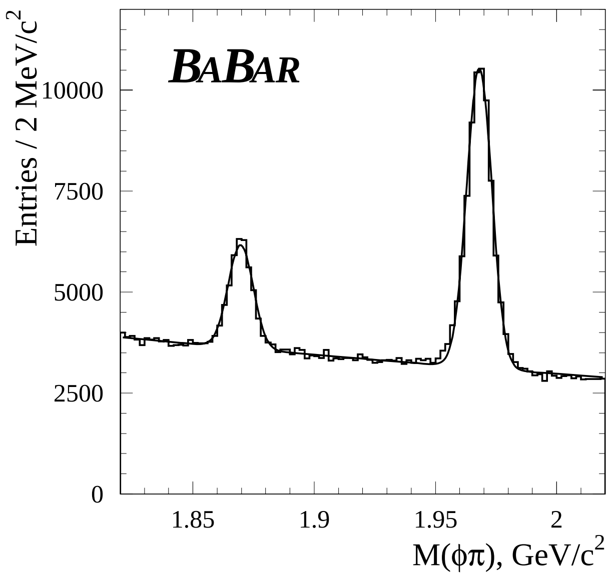
□ Inclusive Charm Physics is performed on events selected from continuum $e^+e^- \to \bar{c}c$

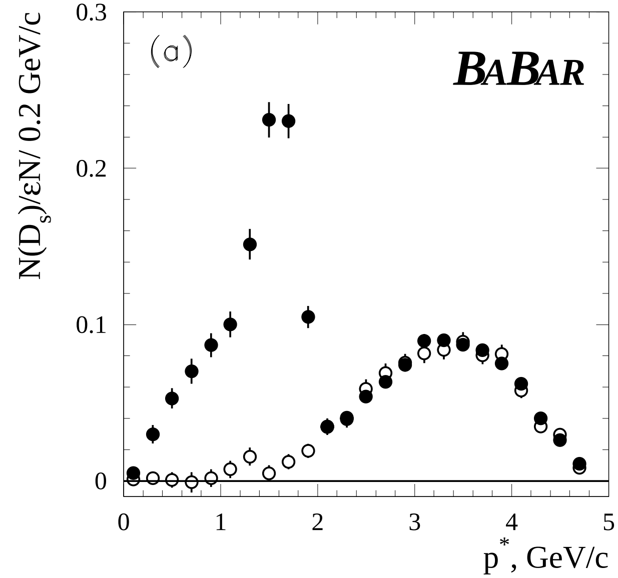
□ Very high statistics samples of charmed mesons actually available.

Study of D_s^+ in BaBar.

□ Example from BaBar: mass distribution and p^* momentum spectrum for $D_s^+ \to \phi\pi^+$.

Filled/open points: normalized on/off peak data.





□ By using inclusive continuum events combinatorial background is strongly reduced.

□ Kinematical selection: the center of mass momentum $(p^*) > 2.5$ GeV/c.

Comparison with other experiments.

□ Huge amount of charm produced.

□ Much more that any other dedicated (and expensive) charm experiments.

□ Example of tagged $D^0 \to K^-\pi^+$ decays:

$$E791 : 35K, \qquad FOCUS : 120K, \qquad BaBar : 500K$$

□ Information on scalar mesons can be extracted from selected D or D_s decay

channels where physics can be particularly simple.

□ D mesons are coupled to $u\bar{u} + d\bar{d}$, D_s mesons are coupled to $\bar{s}s$.

Dalitz plot Analysis of $D^0 \to \bar{K}^0 K^+ K^-$.

Antimo Palano

Summary:

- ☐ Physics Motivations.
- ☐ Data sample.
- ☐ $D^0 \to \bar{K}^0 \pi^+ \pi^-$ and $D^0 \to \bar{K}^0 K^+ K^-$ selection.
- ☐ Branching Fraction.
- ☐ Partial Wave Analysis.
- ☐ Dalitz Plot Analysis.
- ☐ CP Asymmetries.
- ☐ Conclusions.

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Physics Motivations.

□ The Dalitz Plot analysis is the most powerful method for understanding three body decays of resonances.

□ Previuos branching fractions of charmed mesons have been evaluated with poor statistics.

□ In this work we measure the ratio of branching fractions:

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

□ New information can be extracted on the properties of light mesons.

Charge conjugation is implied through all this work.

The Data sample.

- We are studying the following final state:

$$D^0 \to K_s^0 h^+ h^- \qquad + c.c.$$

- Tagged with D^*. For example:

$$\begin{aligned} D^{*+} \to\ & D^0 \pi^+ \\ & \to \bar{K}^0 \pi^+ \pi^- \end{aligned}$$

$$\begin{aligned} D^{*-} \to\ & \bar{D}^0 \pi^- \\ & \to K^0 \pi^+ \pi^- \end{aligned}$$

- The charge of the slow pion gives the flavor of the K^0.
- Events having more than one D^* candidate are removed.
- Data: $(92.5\ fb^{-1})$.

Data Selection.

- Fit all pairs of neutral charged tracks combinations to a K_s^0 with mass constraint;
- Combine the fitted K_s^0 with all pairs of neutral pairs of charged tracks combinations requiring a common vertex.
- The fitted D^0 candidate is refitted to a common vertex with all charged tracks with momentum < 600 MeV/c with beam spot contraint.
- The center of mass momentum p^* of the $K_s^0 h^+ h^-$ system is required to be:

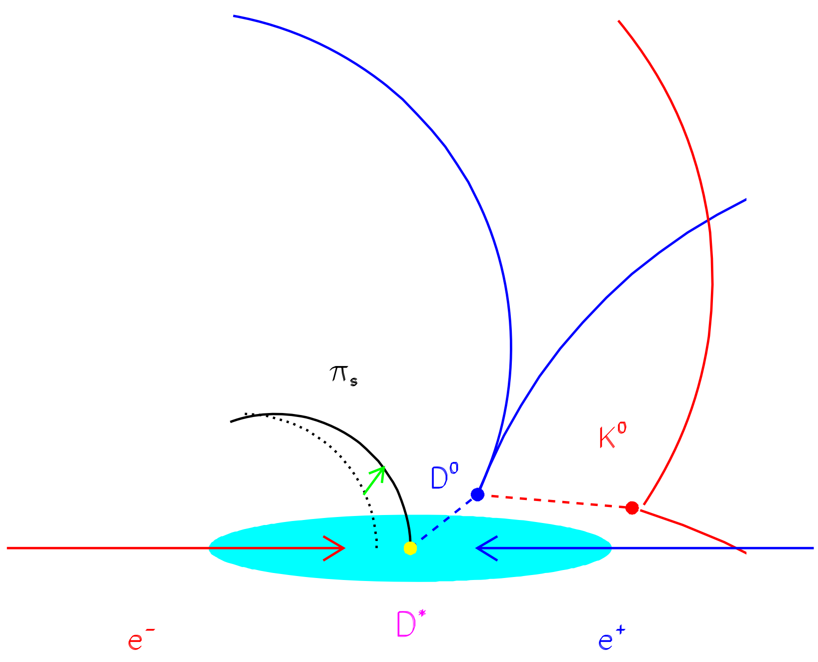
$$p^* > 2.2 \quad GeV/c$$

- No Particle Identification for $\bar{K}^0 \pi^+ \pi^-$.
- One of the two kaon candidates loosely identified for $\bar{K}^0 K^+ K^-$;

Slow pion refit.

□ Refitting of the slow pion.The momentum of the slow pion is usually below 500 MeV/c: badly measured.

□ Cartoon of one event:



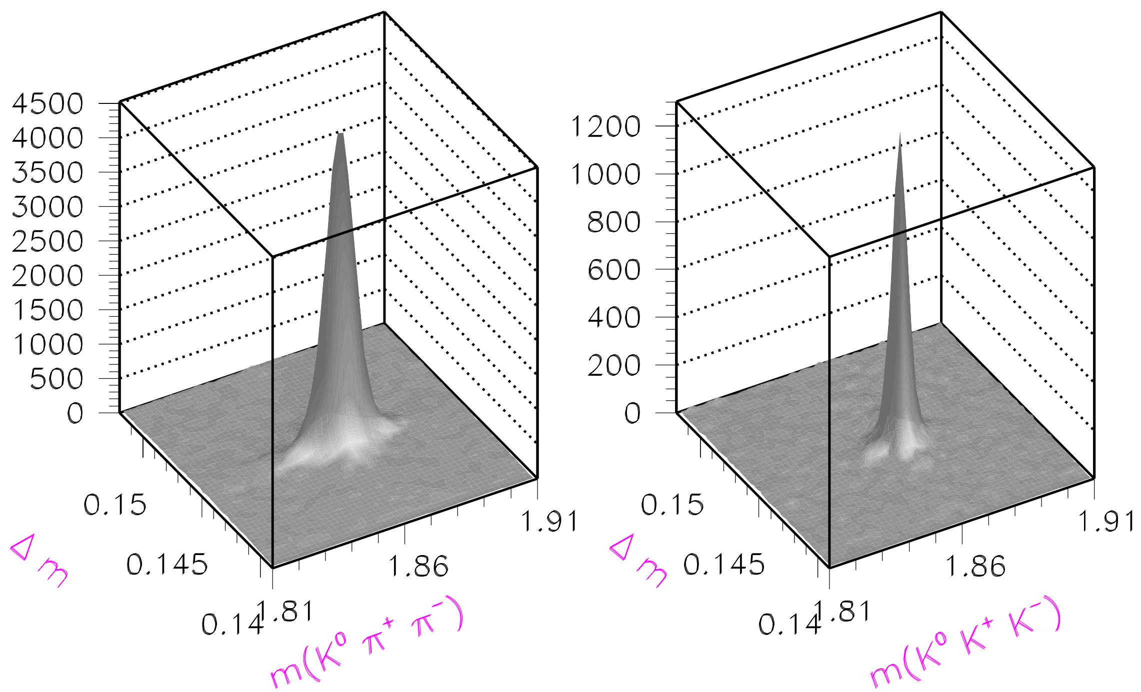
□ Using the event vertex in the fit of the slow pion momentum improves the resolution.

Δm selection:

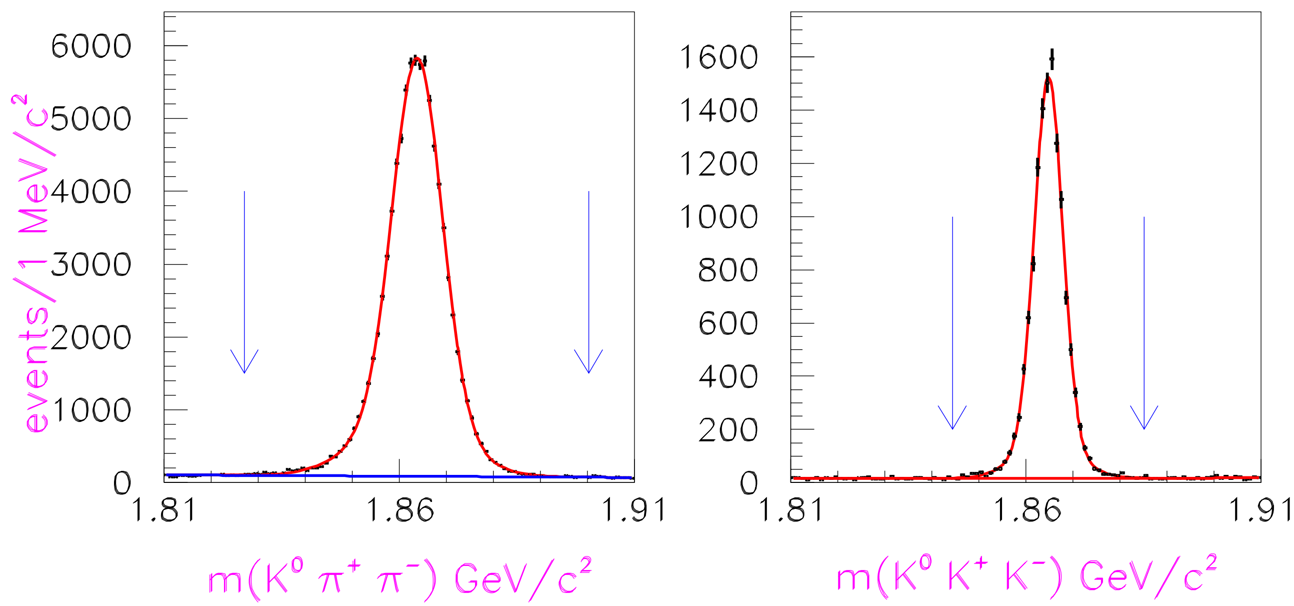
□ Plot of Δm:

$$\Delta m = m(K_s^0 h^+ h^- \pi^+) - m(K_s^0 h^+ h^-)$$

for: $\bar{K}^0 \pi^+ \pi^-$ and $\bar{K}^0 K^+ K^-$



☐ Selecting events within 2σ in Δm ($\sigma = 300$ KeV/c^2) we obtain the following $K^0_s h^+ h^-$ mass spectra:



☐ Results. Integrating within 6σ:

D^0 decay mode	mass (MeV/c^2)	σ (MeV/c^2)	events
$\bar{K}^0\pi^+\pi^-$	1863.7 ± 0.06	6.10 ± 0.02	92935 ± 305
$\bar{K}^0K^+K^-$	1864.7 ± 0.4	3.37 ± 0.09	13536 ± 116

Efficiency.

□ The branching fraction has been evaluated as:

$$BR = \frac{\sum_{x,y} \frac{N_1(x,y)}{\epsilon_1(x,y)}}{\sum_{x,y} \frac{N_0(x,y)}{\epsilon_0(x,y)}},$$

where $N_i(x, y)$ represents the number of events measured for channel i, and $\epsilon_i(x, y)$ is the corresponding efficiency in a given Dalitz plot cell (x, y).

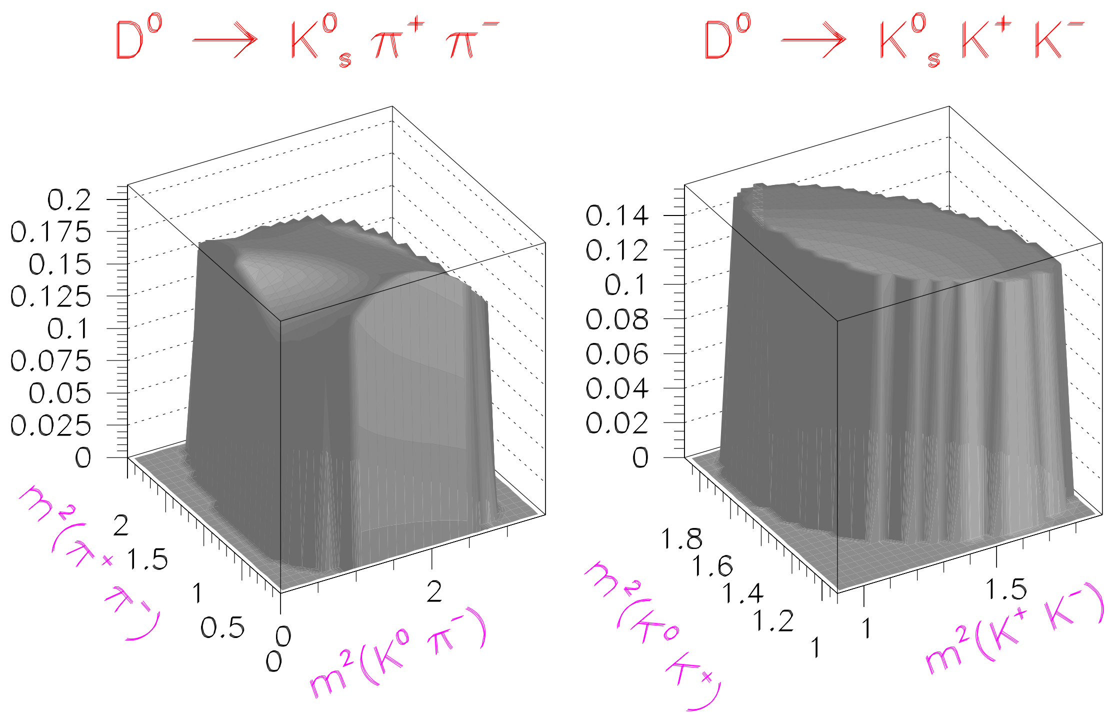
□ The efficiency has been evaluated on the Dalitz plot of the $K^0 h^+ h^-$ system.

□ $\approx 125 \times 10^3$ Phase Space Signal Monte Carlo events for each channel have been generated and reconstructed.

□ The Dalitz plot efficiency has been smoothed fitting a 3^{rd} order polynomial.

$$\eta(x, y) = a_0(1 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 xy + a_6 x^3 + a_7 y^3 + a_8 xy^2 + a_9 x^2 y)$$

Fitted polynomials.



- Efficiency:

D^0 decay mode	Weighted Efficiency %
$\bar{K}^0\pi^+\pi^-$	17.94 ± 0.25
$\bar{K}^0K^+K^-$	16.56 ± 0.38

Systematic errors.

□ Summary of systematic errors:

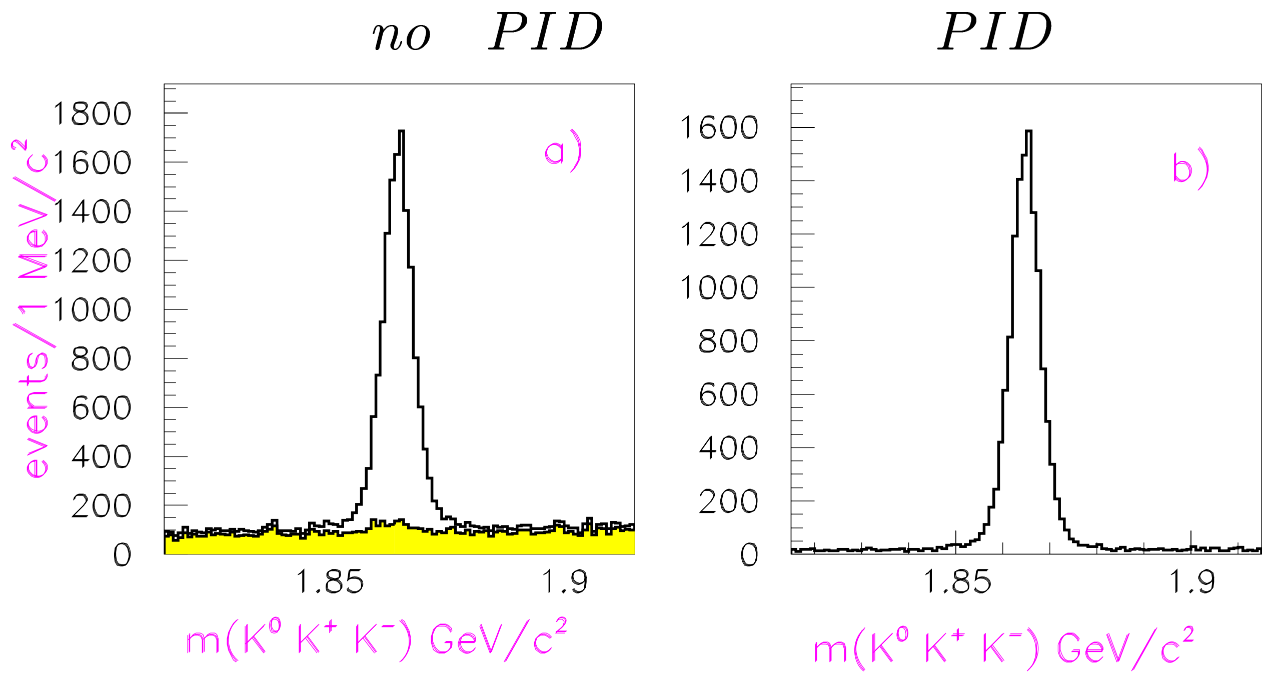
Effect	Systematic error ($\times 10^{-2}$)
Yields	0.13
Δm cut	0.12
Efficiency correction	0.42
PID	0.13
K_s^0 momentum	0.09
Total	0.48

□ Branching fractions have also been computed in different p^* regions and separately for D^0 and $\bar{D}^0$.

Example. Systematic error due to PID

□ Evaluation of the Branching fraction without and with the use of PID.

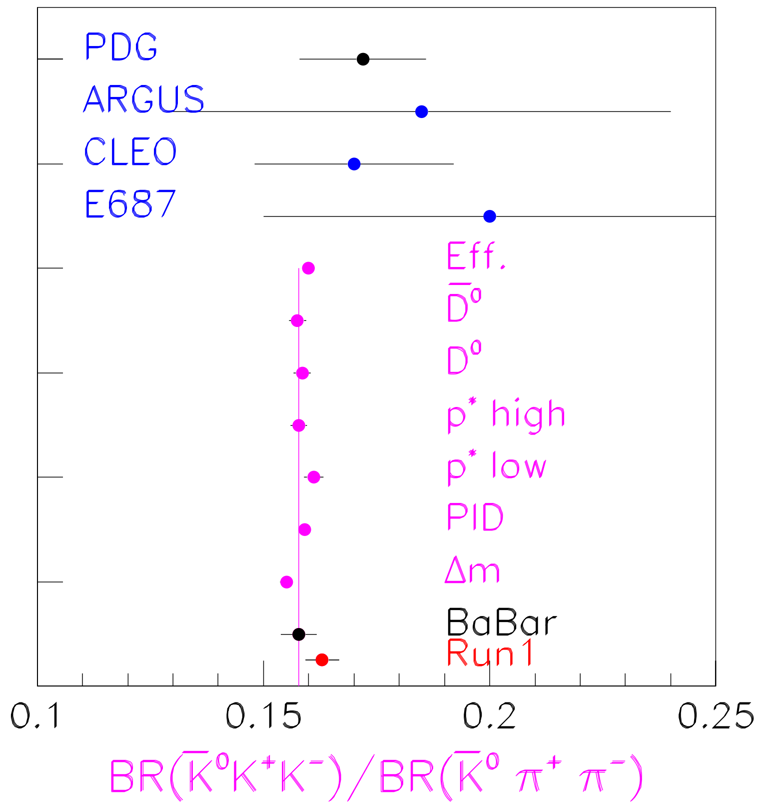
□ Shaded: $D^0 \rightarrow \bar{K}^0 K^+ K^-$ events removed by the PID request (one of the two charged tracks loosely identified as a kaon).



Branching Fraction.

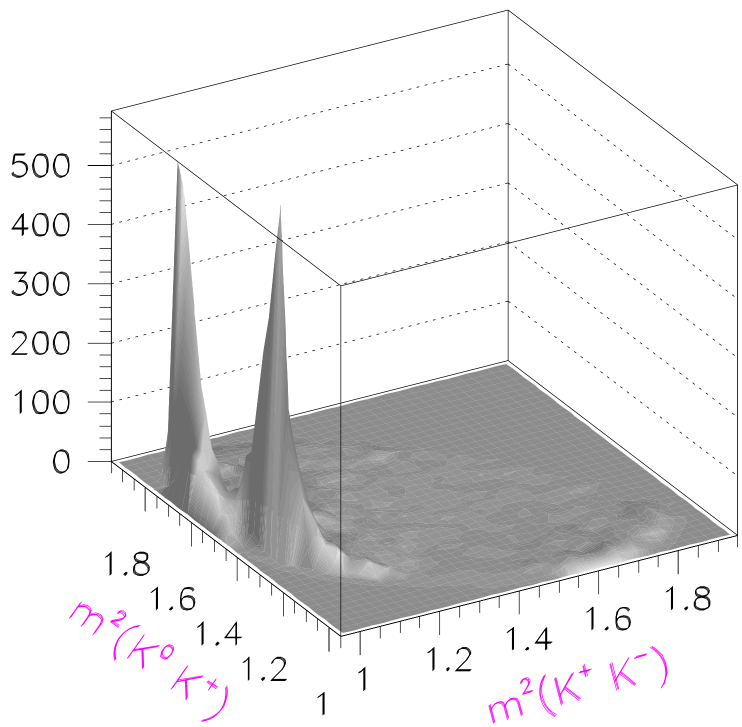
□ Resulting Branching Fraction compared with results from other experiments.

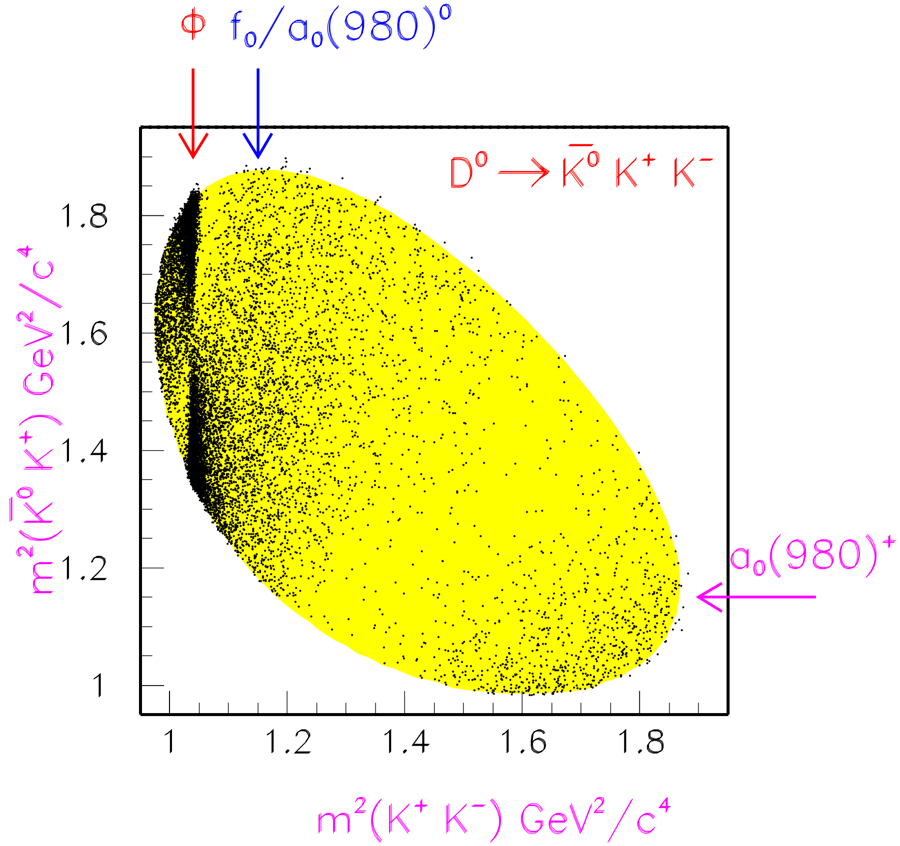
$$BR = \frac{\Gamma(D^0 \to \overline{K}^0 K^+ K^-)}{\Gamma(D^0 \to \overline{K}^0 \pi^+ \pi^-)} = (15.8 \pm 0.1\ (stat.) \pm 0.5\ (syst.)) \times 10^{-2}$$



Dalitz plot of $D^0 \to \bar{K}^0 K^+ K^-$.

□ Cutting at 2σ in the $\bar{K}^0 K^+ K^-$ mass we obtain 12541 events with a purity P=97.3 %





□ Presence of $\phi(1020)$ interfering with a threshold scalar $f_0/a_0(980)^0$.

□ Presence of $a_0(980)^+$.

Dalitz plot analysis of $D^0 \to \bar{K}^0 K^+ K^-$.

- Likelihood function:

$$L = P \cdot G(m)\eta(m_1^2, m_2^2)\frac{\sum c_i c_j^* A_i A_j^*}{\sum c_i c_j^* \int A_i A_j^* \eta(m_1^2, m_2^2) dDP} + (1 - P)$$

- $\eta(m_1^2, m_2^2)$ is the polynomial efficiency.
- P: Purity.
- G(m) is a Gaussian describing the D^0 lineshape.
- A complex amplitudes, expressed as:

$$A = BW(m) \times W(\Omega)$$

where BW(m) are relativistic Breit-Wigner and $W(\Omega)$ describe the angular distributions. The helicity formalism has been adopted.

- The amplitude $\bar{K}^0 a_0(980)^0$ has been taken as the reference wave so that $c_{a_0} = 1$ and $\phi_{a_0} = 0$.

$f_0(980)$ and $a_0(980)$ lineshapes.

□ The $f_0(980)$ resonance has been described by a coupled channel Breit-Wigner to $\pi^+\pi^-$ and $K\bar{K}$.

$$BW_{f_0}(m) = \frac{F_r}{m_0^2 - m^2 - im_0(\Gamma_\pi + \Gamma_K)}$$

where:

$$\Gamma_\pi = g_\pi(m^2/4 - m_\pi^2)^{1/2}$$

$$\Gamma_K = g_K/2[(m^2/4 - m_{K^+}^2)^{1/2} + (m^2/4 - m_{K^0}^2)^{1/2}]$$

□ Parameters varied within results from WA76, E791 and BES experiments.

□ The $a_0(980)$ has been parametrized as a coupled channel Breit Wigner with coupling to the $\eta\pi$ and $\bar{K}K$ systems.

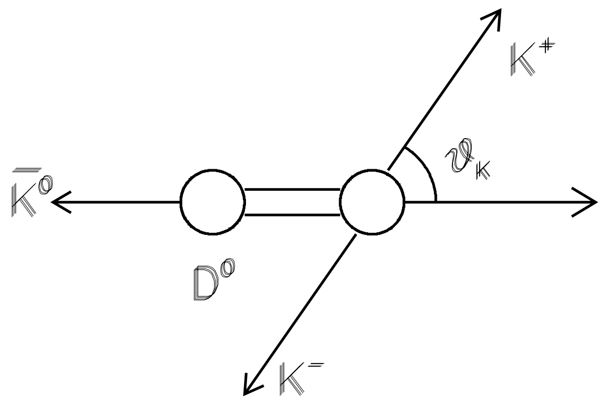
$$BW_{a_0}(m) = \frac{g_{K\bar{K}}}{m_0^2 - m^2 - i(\rho_{\eta\pi} g_{\eta\pi}^2 + \rho_{K\bar{K}} g_{K\bar{K}}^2)}$$

□ where $\rho(m) = 2q/m$.

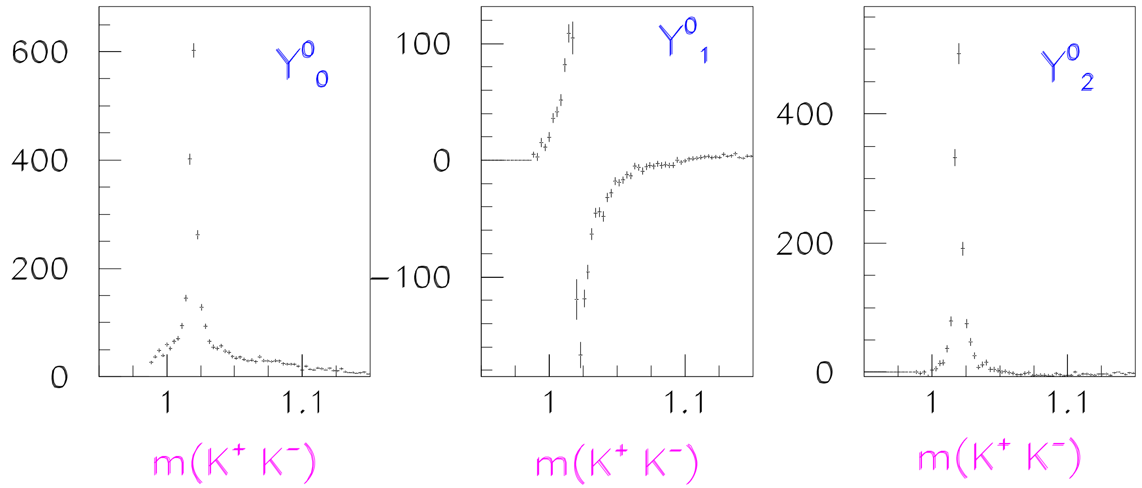
□ The $a_0(980)$ parameters are somewhat uncertain due to complexity of a state close to the $K\bar{K}$ threshold.

Partial Wave Analysis of the K^+K^- system.

- Assume, in the K^+K^- threshold region, a diagram:

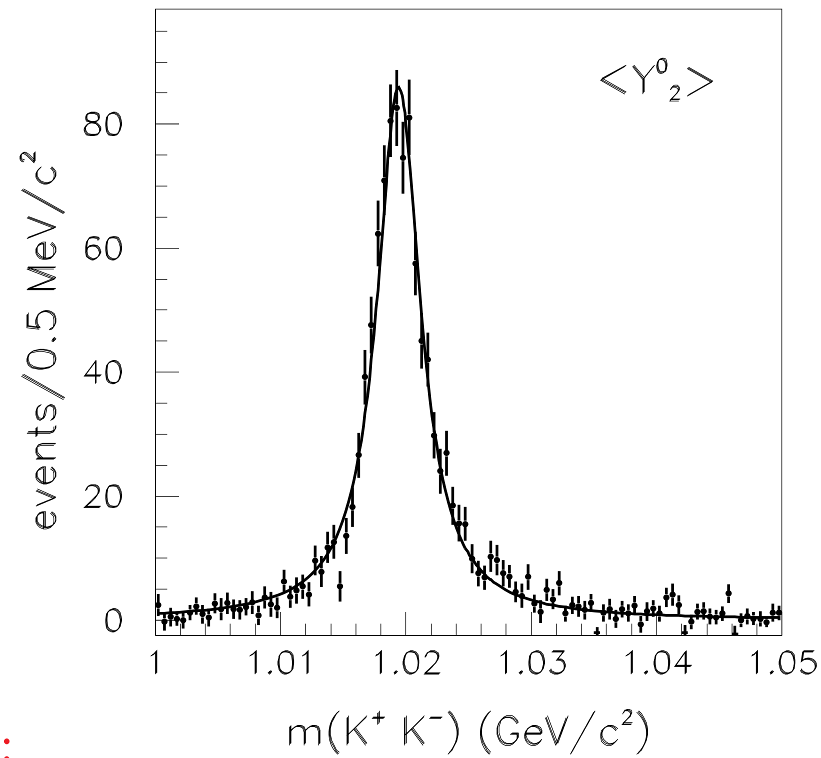


- Efficiency corrected unnormalized Y_l^m moments:



$\phi(1020)$ **lineshape.**

□ $\phi(1020)$ parameters fitted to the Y_2^0 moment using a relativisic P-wave Breit Wigner.



□ Fitted parameters:

$$m = 1019.63 \pm 0.07 \qquad \Gamma = 4.28 \pm 0.13 \quad MeV/c^2$$

Partial Wave Analysis of the K^+K^- system.

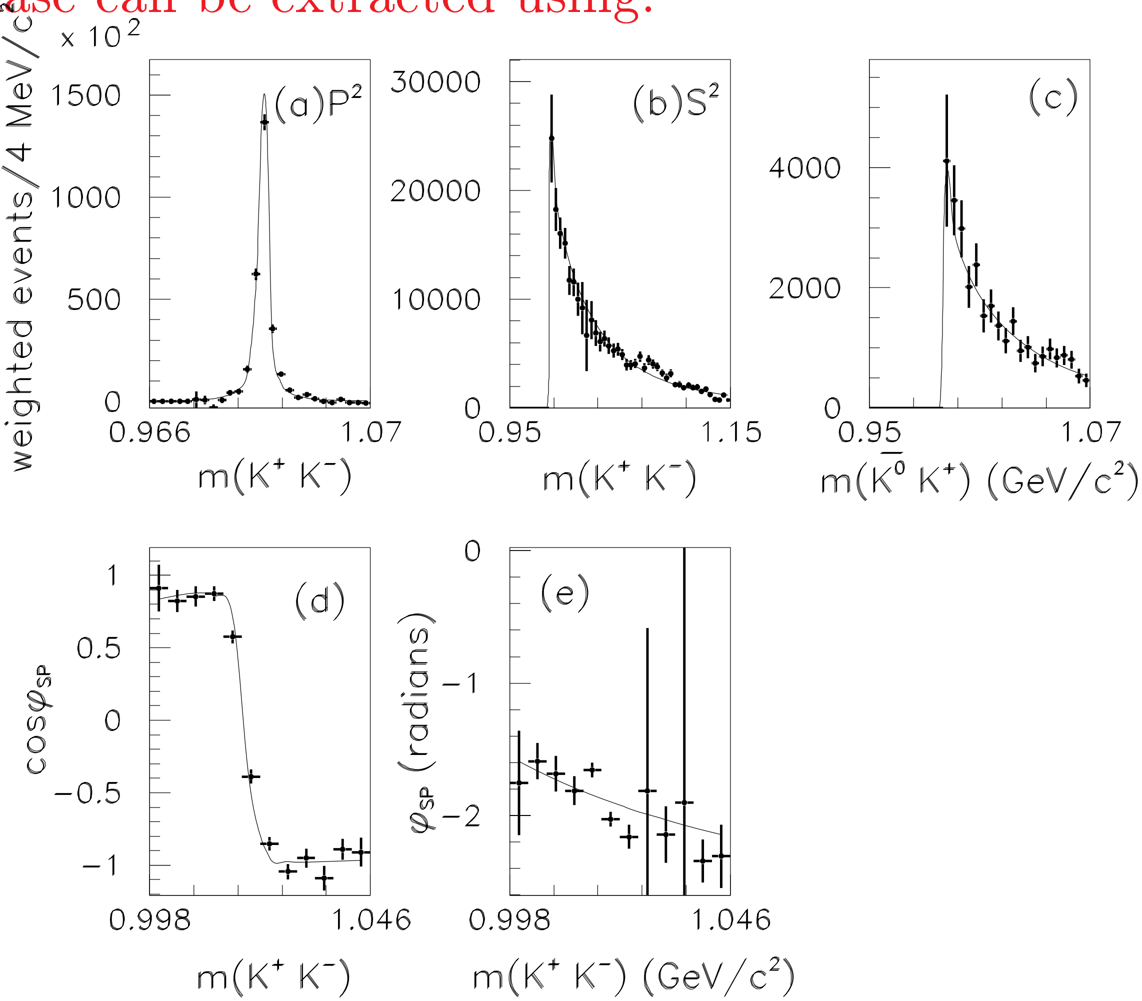
□ S, P waves and relative phase can be extracted using:

$$\sqrt{4\pi}Y_0^0 = S^2 + P^2$$

$$\sqrt{4\pi}Y_1^0 = 2SPcos\phi$$

$$\sqrt{4\pi}Y_2^0 = 0.894P^2$$

□ Correcting for phase space a symultaneous fit has been performed using also the $\bar{K}^0K^+$ projection:



Partial Wave Analysis of the K^+K^- system.

□ The distributions have been fitted using the following model:

- The P-wave is entirely due to the $\phi(1020)$ meson.
- The scalar contribution in the K^+K^- mass projection is entirely due to the $a_0(980)^0$.
- The $\overline{K}^0K^+$ mass distribution is entirely due to $a_0(980)^+$.
- The angle ϕ_{SP} is obtained fitting the S, P waves and $\cos\phi_{SP}$ with:

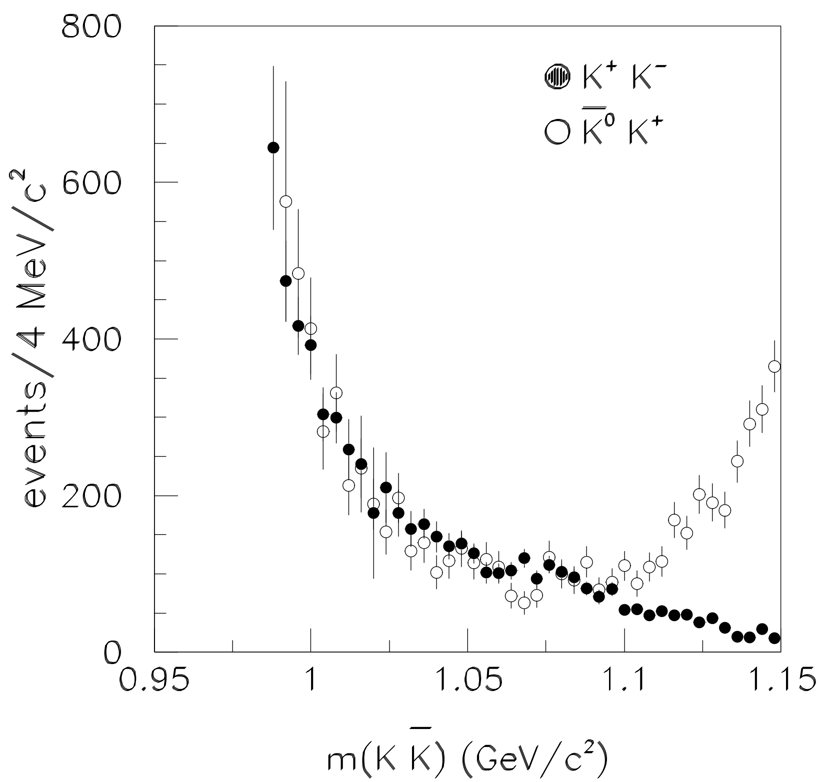
$$c_{a_0}BW_{a_0} + c_\phi BW_\phi e^{i\alpha}$$

  Here BW_{a_0} and BW_ϕ are the Breit-Wigner describing the $a_0(980)$ and $\phi(1020)$ resonances.

□ The $a_0(980)$ parameters have been fitted to Crystal Barrel results (from $\bar{p}p$), except $g_{\bar{K}K}$ which is a free parameter: $g_{\bar{K}K} = 464 \pm 29 \quad MeV$

Little $f_0(980)$ contribution.

- □ Since $f_0(980)$ has I=0, it cannot decay to $\bar{K}^0 K^+$.
- □ Therefore the $\bar{K}^0 K^+$ projection contains only $a_0(980)^+$.
- □ Superposition of the two normalized projections, phase space corrected:



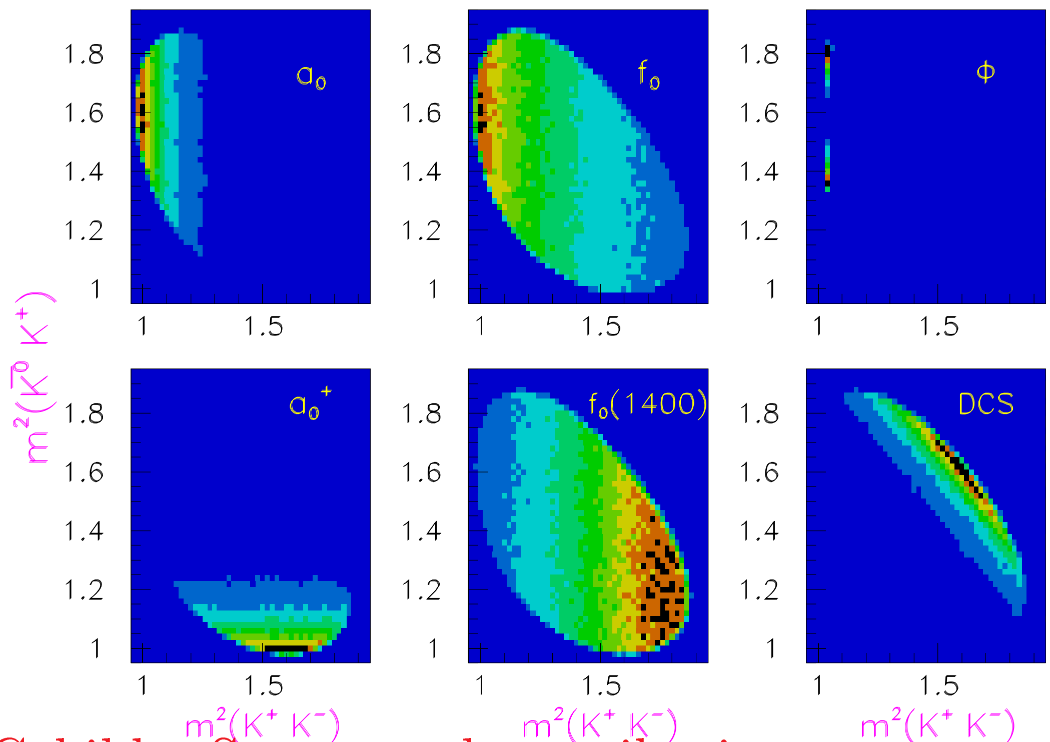
- □ Cosistent with little $f_0(980)$ contribution.

Amplitudes normalization.

□ The Amplitudes have been normalized using a phase space Monte Carlo weighted by the polynomial efficiency and generated according to the experimental D^0 lineshape.

□ Fractions:

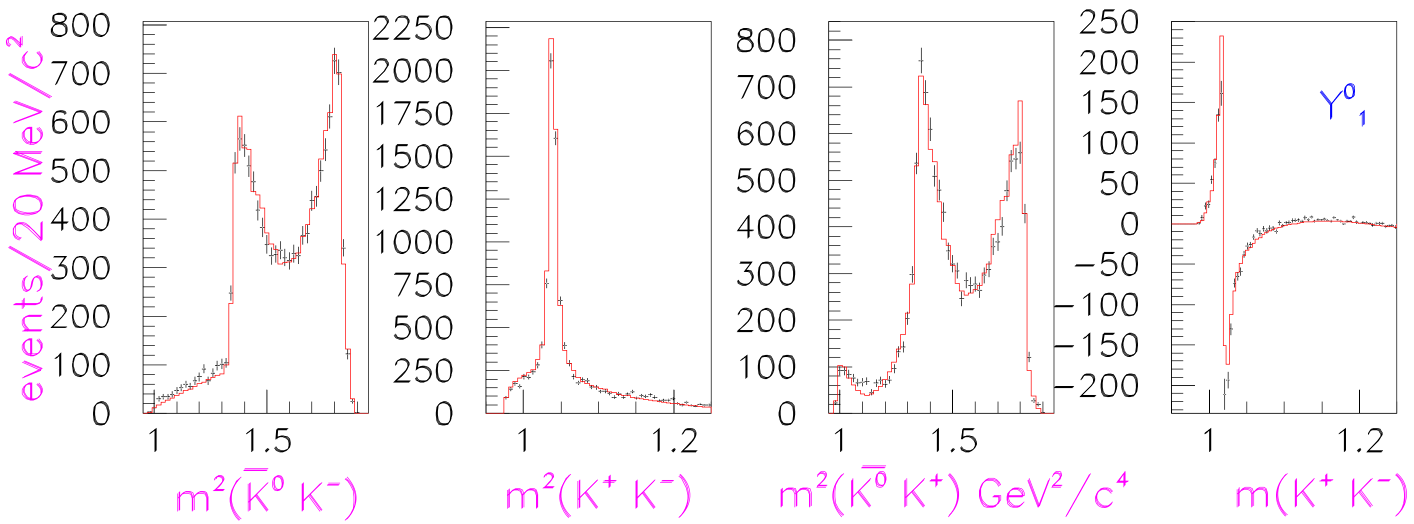
$$f_i = \frac{|c_i|^2 \int |A_i|^2 dm_x^2 dm_y^2}{\sum_{j,k} c_j c_k^* \int A_j A_k^* dm_x^2 dm_y^2}$$



□ Considered also the Double Cabibbo Suppressed contribution $D^0 \to K^+ a_0(980)^-$.

Dalitz plot fit.

- Need to include a small contribution from $f_0(1400)$.
- Superposition of the fit on the data:



- χ^2 computed on the Dalitz plot: $\chi^2/N_{cells} = 983/774$

Results from the fit.

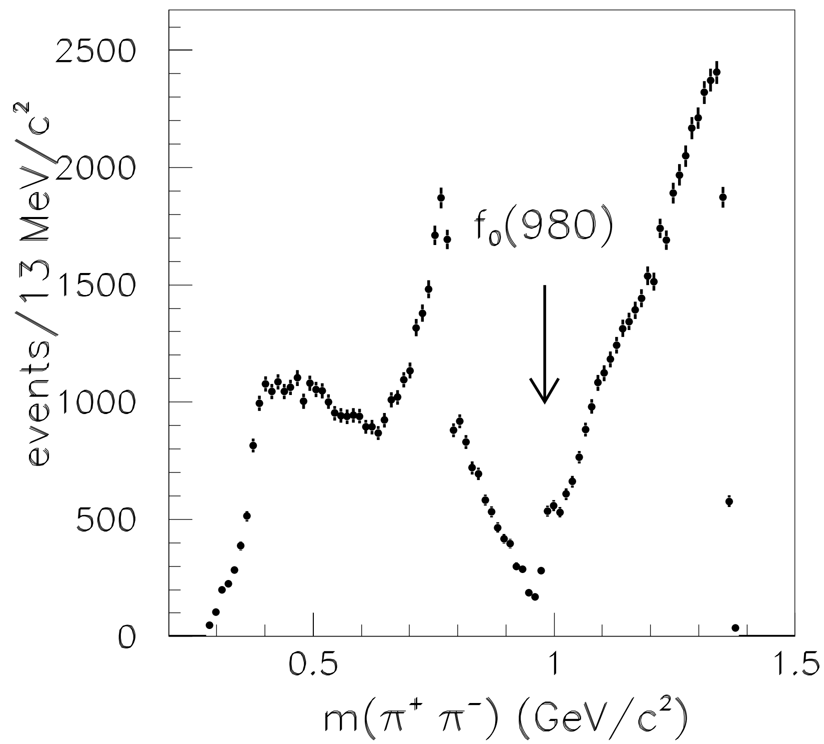
Final state	Phase (radians)	Fraction (%)
$\overline{K}^0 a_0(980)^0$	0.	$66.4 \pm 1.6 \pm 7.0$
$\overline{K}^0 \phi(1020)$	$1.91 \pm 0.02 \pm 0.10$	$45.9 \pm 0.7 \pm 0.7$
$K^- a_0(980)^+$	$3.59 \pm 0.05 \pm 0.20$	$13.4 \pm 1.1 \pm 3.7$
$\overline{K}^0 f_0(1400)$	$-2.63 \pm 0.10 \pm 0\ .71$	$3.8 \pm 0.7 \pm 2.3$
$\overline{K}^0 f_0(980)$		$0.4 \pm 0.2 \pm 0.8$
$K^+ a_0(980)^-$		$0.8 \pm 0.3 \pm 0.8$
Sum		$130.7 \pm 2.2 \pm 8.4$

□ Systematic errors come from maximum spread of fitted results.

□ Errors on the fractions obtained by Monte Carlo propagation of errors using the full fit covariance matrix.

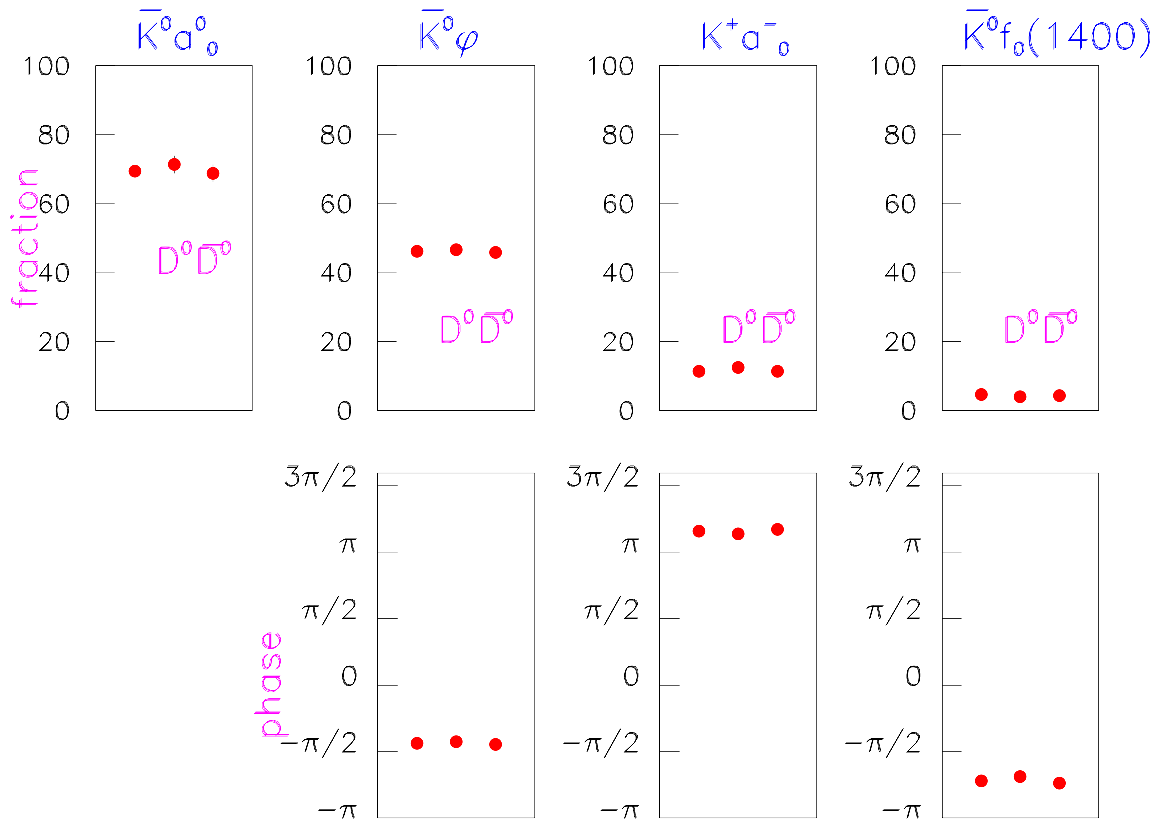
The $f_0(980)$ from $\pi^+\pi^-$.

□ The small $f_0(980)$ ($\approx 5.5\%$) signal observed in $D^0 \to \bar{K}^0\pi^+\pi^-$ is consistent with the absence of $f_0(980) \to K^+K^-$ in the $D^0 \to \bar{K}^0K^+K^-$ final state.



Fractions and phases for D^0 and $\bar{D}^0$.

□ D^0: $\chi^2/N = 671/649$, $\bar{D}^0$: $\chi^2/N = 643/646$.



□ No evidence for CP violation.

Conclusions

□ We have measured with high precision the Branching Fraction:

$$BR = \frac{\Gamma(D^0 \to \overline{K}^0 K^+ K^-)}{\Gamma(D^0 \to \overline{K}^0 \pi^+ \pi^-)} =$$

$$(15.8 \pm 0.1\ (stat.) \pm 0.5\ (syst)) \times 10^{-2}$$

□ We have performed the first Dalitz plot analysis of $D^0 \to \bar{K}^0 K^+ K^-$ measuring amplitudes and phases.

□ We have performed a Partial Wave Analysis of the K^+K^- system isolating, for the first time, a pure S-wave contribution close to threshold.

□ The Dalitz plot analysis, separated for D^0 and $\bar{D}^0$, does not show any CP violation effect in the amplitudes and phases.

In progress (Bari).

- ☐ Amplitude analysis of $D^+ \to K^-\pi^+\pi^+$, 430 000 events.
- ☐ Dalitz plot and amplitude analysis of $D_s^+ \to K^+K^-\pi^+$, 80 000 events.
- ☐ Dalitz plot and amplitude analysis of $D_s^+ \to \pi^+\pi^-\pi^+$, 10 000 events.
- ☐ Dalitz plot and amplitude analysis of $D^+ \to \pi^+\pi^-\pi^+$, 10 000 events.
- ☐ Dalitz plot analysis of $D^0 \to K^0K^-\pi^+$ and $D^0 \to \bar{K}^0K^+\pi^-$.