The $\pi\pi$ and $K\pi$ amplitudes from heavy flavor decays

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12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon – Williamsburg, June 2, 2010

Scalar mesons: a puzzle for over 40 years

- easily produced, but difficult to detected;
- Light scalars are broad, overlapping states, squeezed in a narrow ($\sim$1 GeV) mass window;
- other objects – glueballs, tetraquarks, etc. – may be around. What are the regular $q\bar{q}$ states forming the QM nonet(s)?
- a subject very interesting in its own. But lots of flavor physics depends on how well we understand the S-wave.

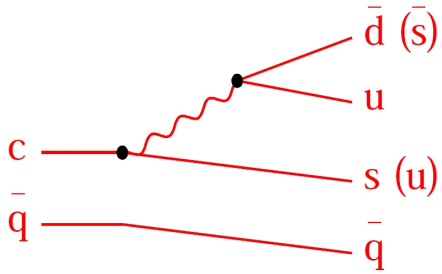
Fernando Botero – Los Musicos

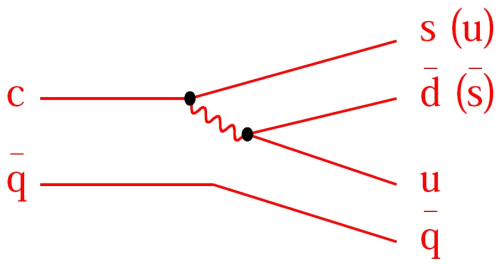
Decays of heavy flavor: a key to the physics of scalar mesons

- Heavy flavor decays are currently the unique processes allowing one to access, continuously and from threshold, the whole elastic $\pi\pi$ and $K\pi$ spectra.

- Statistics rapidly becoming "infinite", for essentially all channels: already limited by systematics in most cases;

- In the case of D and B mesons, the possible resonances are constrained by the 'final state' quarks from the c, b weak decay:





- The bulk of the hadronic decay width is well described in terms of valence quark diagrams connected to known $\boldsymbol{q\bar{q}}$.

- Hadronic decays are abundant, but complex (FSI). Semileptonic decays are easier to interpret, but harder to obtain, and with a small S-wave component.

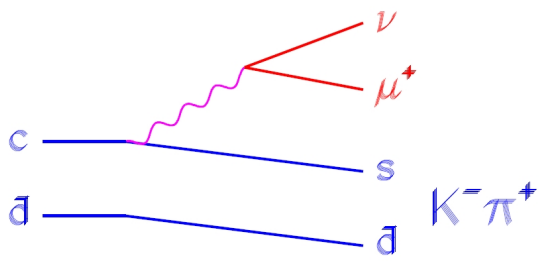
An example: the $K\pi$ S-wave and the κ (or $K_0^*(800)$) issue

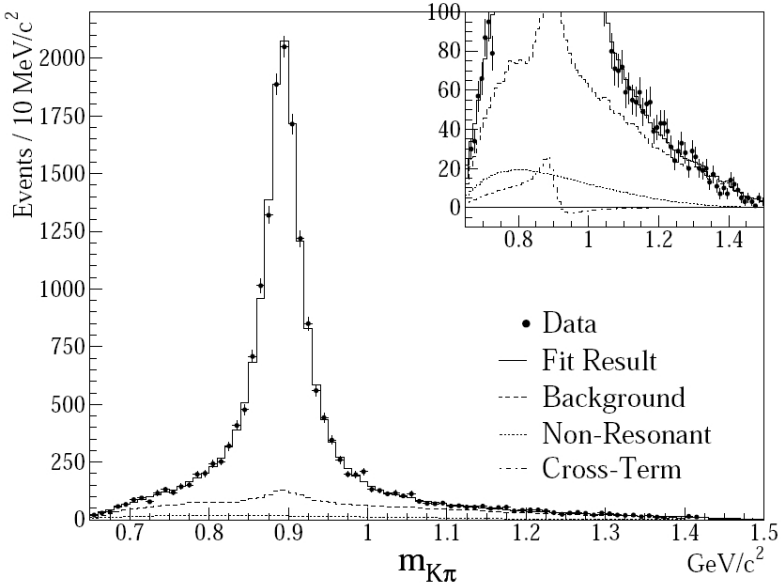
What is the content of the $K\pi$ S-wave near threshold?

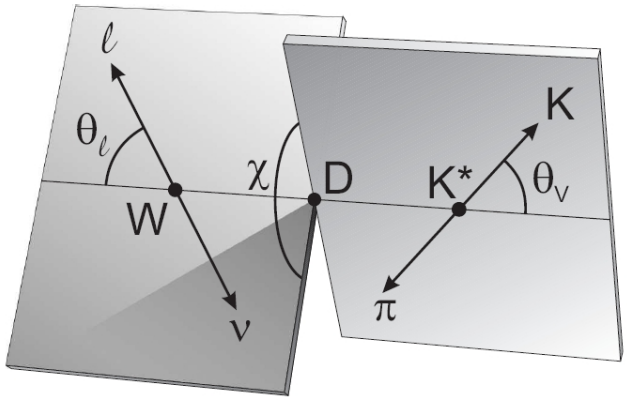
- The LASS experiment (1988) measured the $K^-\pi^+$ S-wave amplitude from 151 000 $K^-p \to K^-\pi^+n$ events with low momentum transfer.
- Unfortunately LASS data starts only at 200 MeV above threshold.
- In 2002, from a Dalitz plot analysis of the $D^+ \to K^-\pi^+\pi^+$ decay, Fermilab E791 reported on evidence for the neutral κ or $K_0^*(800)$ (PRL **89**, 121801), later confirmed by BES and FOCUS.
- The position of the κ was computed from LASS data through an extension of chiral perturbation theory to 3 flavors (EPJ **C48**, 553).
- If the κ is an I=1/2 $s\bar{d}$ state, a charged partner, $s\bar{u}$, should also exists.

The $K^-\pi^+$ S-wave from $D^+ \to K^-\pi^+\mu^+\nu$ – FOCUS

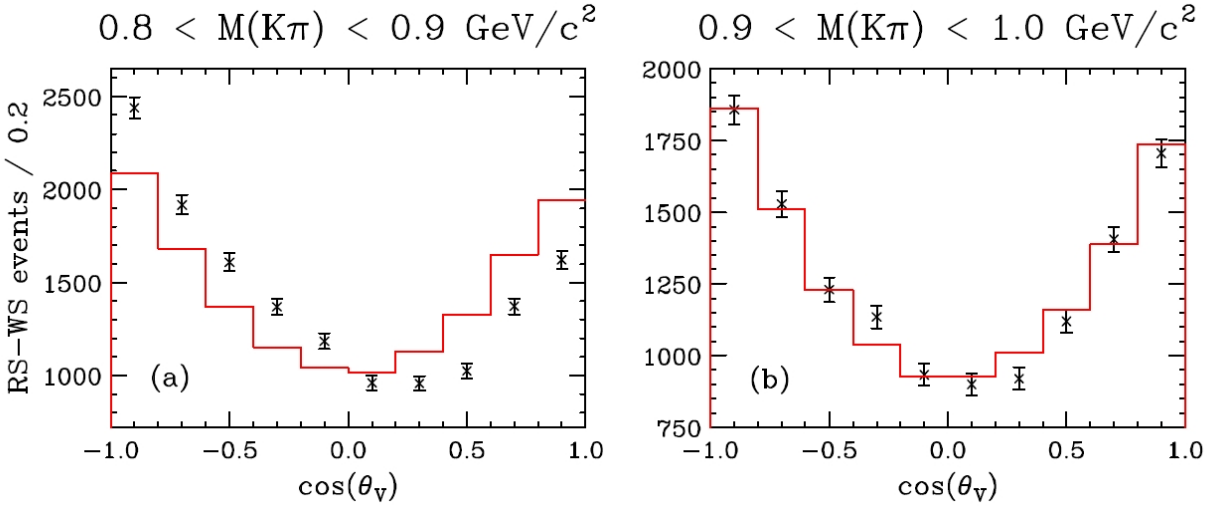
- Semileptonic decays: FSI is restricted to the $K\pi$ system.
- 7% contribution from S-wave, detectable through interference with the dominant P-wave.
- $K\pi$ mass spectrum is not sensitive to the S-wave model.





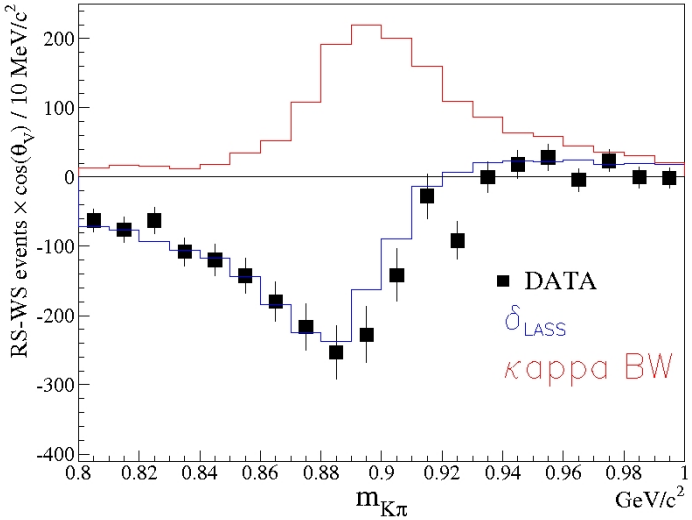


The $K^-\pi^+$ S-wave from $D^+ \to K^-\pi^+\mu^+\nu$ – FOCUS



The different S-wave models can be discriminated by an angular analysis.

The LASS $\delta_{1/2}$ $K\pi$ amplitude fits well the data. A simple Breit-Wigner for the κ cannot reproduce the observed asymmetry.

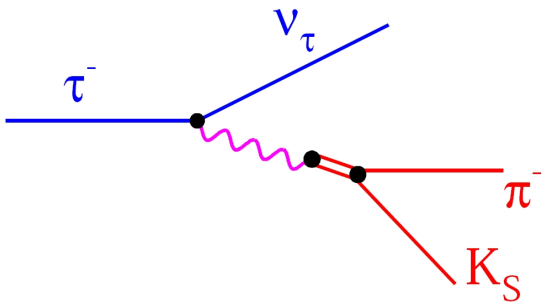


PL **621B**, 72 (2005)

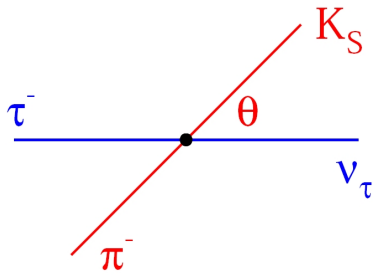
Is there a charged κ ? $\tau^- \to K_s\pi^-\nu$ from BaBar and Belle

- $e^+e^- \to \tau^+\tau^-, \qquad \tau^+ \to l^+\nu_\tau\nu_l, \qquad \tau^- \to K_S\pi^-\nu_\tau$

As in $D^+ \to K^-\pi^+\mu^+\nu$, tau decays are a very clear environment. The $K_s\pi^-$ system is free from FSI with the rest of the decay products.



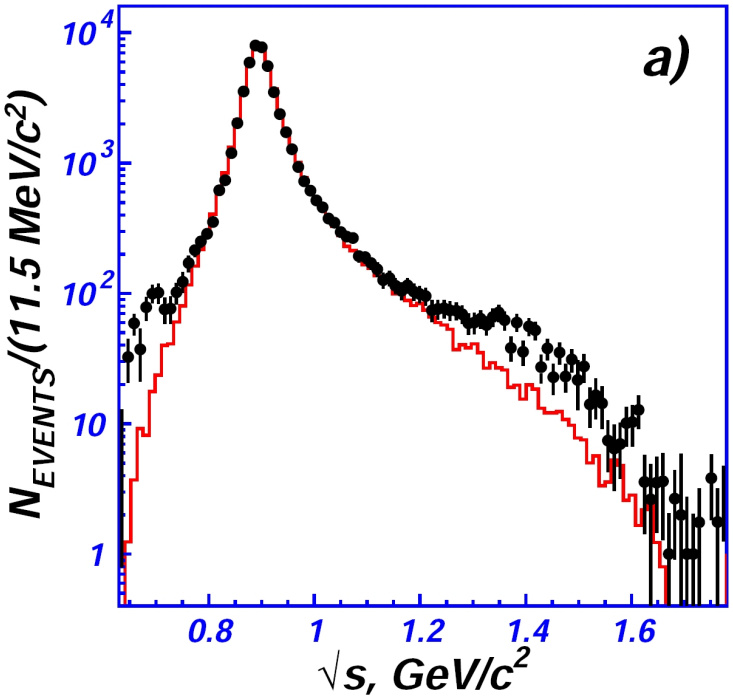
Unfortunately, with so many missing neutrinos, an angular analysis is very difficult.



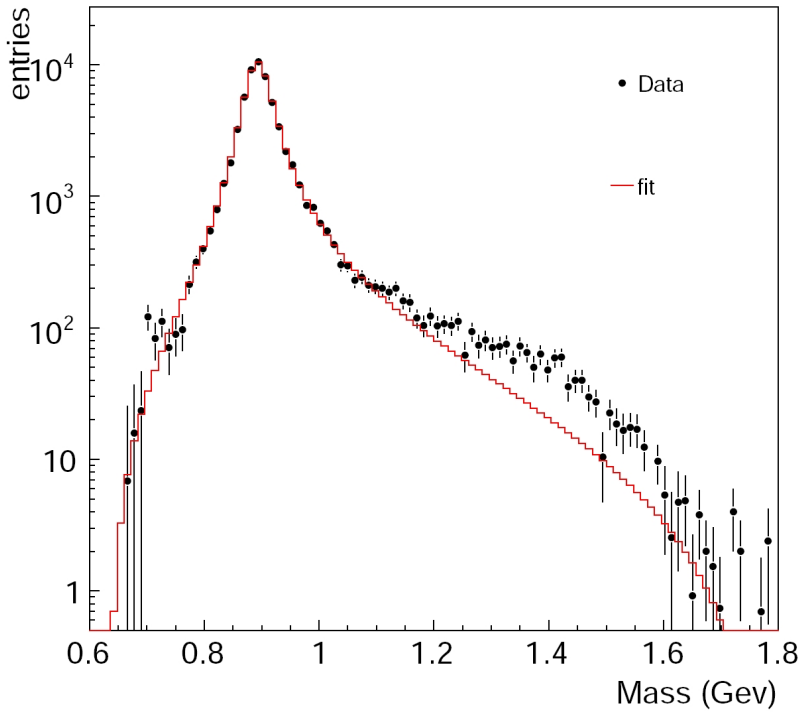
Is there a charged κ ? $\tau^- \to K_s \pi^- \nu$ from BaBar and Belle

In the $K_s\pi^-$ spectrum there is more than just the $\overline{K^*}(892)^-$:

Belle



BaBar



The $\overline{K^*}(1680)^-$ is highly suppressed by phase space. There should be an S-wave.

Surprisingly, a model with the LASS $\delta_{1/2}$ amplitude fails to fit the data!

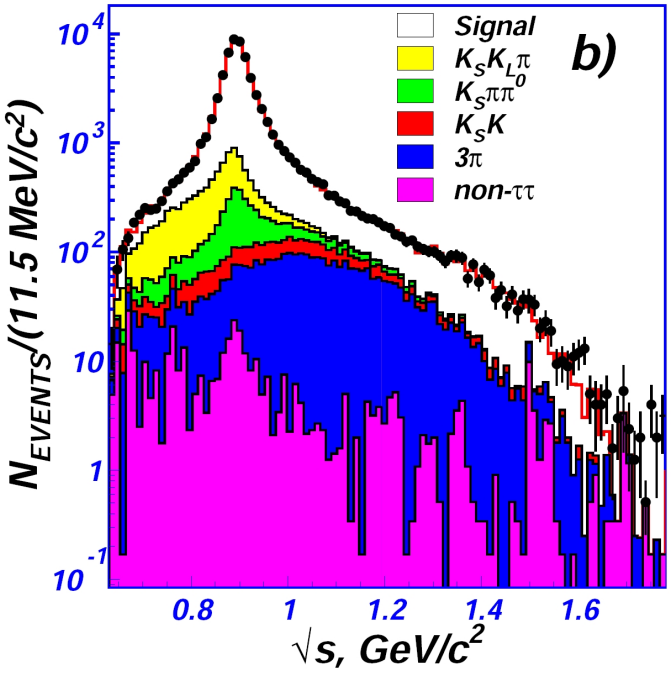
Is there a charged κ ? $\tau^- \to K_s \pi^- \nu$ from BaBar and Belle

A small S-wave component, including the κ, was required to describe the data:

$$S_{\rm pdf} \propto |F_V|^2 + |F_S|^2, \qquad F_S = \alpha \frac{s}{M^2_{\kappa^-}} BW_{\kappa^-}(s) + \beta \frac{s}{M^2_{K_0^*(1430)}} BW_{K_0^*(1430)}(s),$$

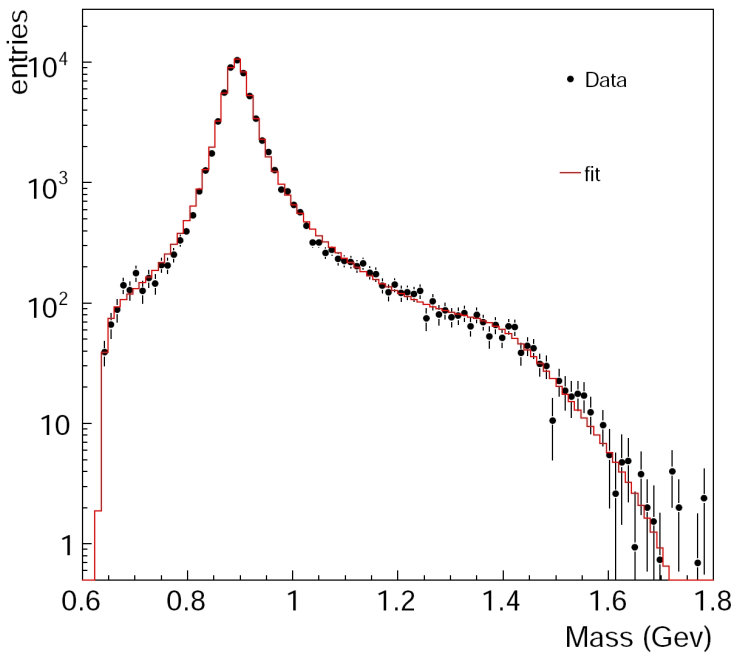
$$BW_{\kappa^-}(s) = \frac{m_\kappa \Gamma_\kappa}{m_\kappa^2 - m_{K\pi}^2 - i\, m_{K\pi}\Gamma(m_{K\pi})}, \qquad \Gamma(m_{K\pi}) = \frac{g^2 p^*}{8\pi m_{K\pi}^2}$$

Belle



PL **654B**, 65 (2007)

BaBar



arXiv:0910.2884

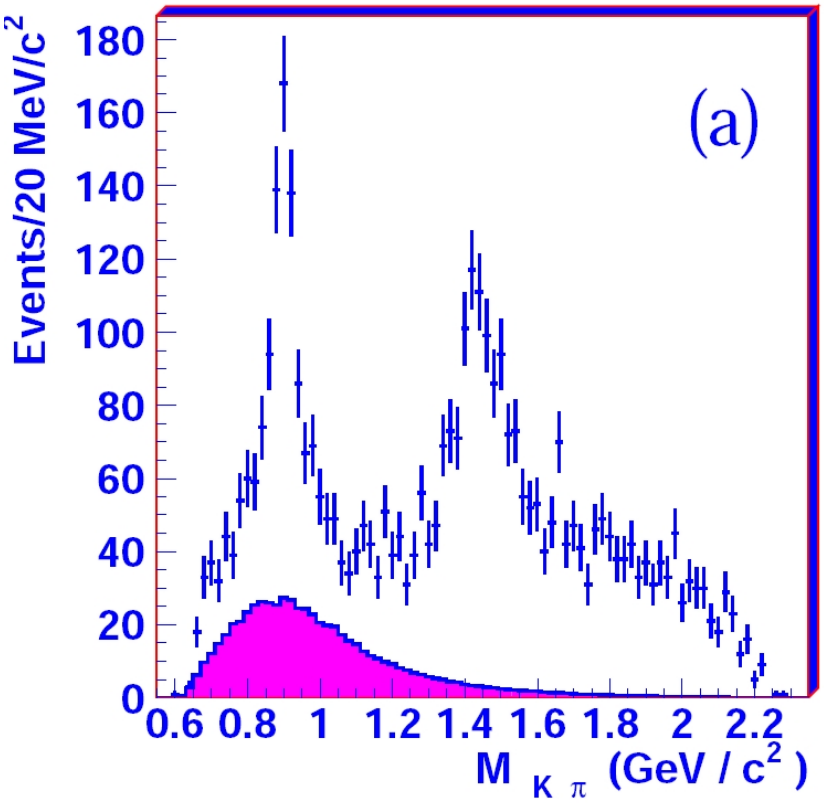
Is there a charged κ ? $J/\psi \to K^{\pm}\pi^{0}K_{s}\pi^{\mp}$ from BESII

- To study the charged κ, BES used the decay $J/\psi \to K^{\pm}\pi^{0}K_{s}\pi^{\pm}$;
- Events with a $(K\pi)^{\pm}$ system recoiling against a $K^{*}(892)^{\mp}$ were selected by a mass cut around the $K^{*}(892)$ mass:

$$J/\psi \to K^{*}(892)^{\pm}K_{s}\pi^{\mp}$$

$$J/\psi \to K^{*}(892)^{\pm}K^{\mp}\pi^{0}$$

- A sample with a total of 4000 decays was fitted with different models for the κ Breit-Wigner.



arXiv:1002.0893

An important contribution from the $\kappa^{\pm}$ was found in all models.

The position of the $\kappa^{\pm}$ and κ^{0} poles are consistent, but errors are still very large.

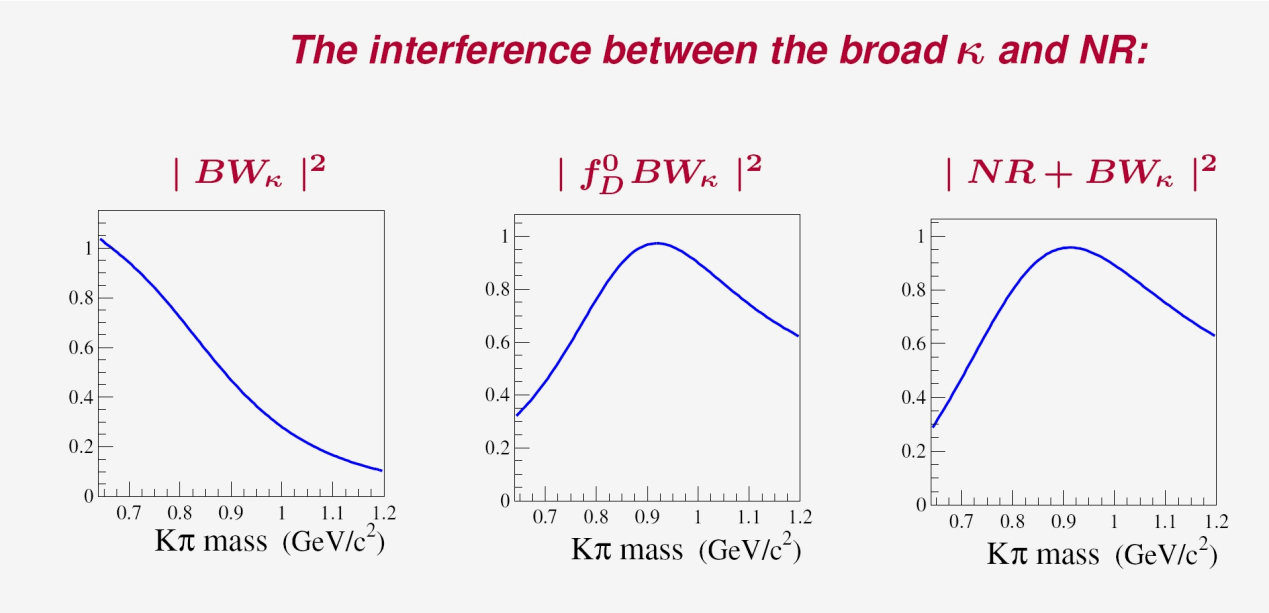
Hadronic decays of D mesons: limitations of the isobar model

The isobar model is simple, intuitive and widely used. The S-wave is represented as

$$\mathcal{A}^0 = \mathrm{NR} + \sum c_k e^{i\delta_k} A_k^0, \qquad A_k^0 = F_D^0 \times F_R^0 \times BW_k, \qquad \mathrm{NR} = c_0 e^{i\delta_0}$$

Good fits are obtained when the statistics is small and the S-wave is not significant.

Interpretation becomes a problem if one has to disentangle individual contributions of broad states, as in the case of the κ and NR in $D^+ \to K^-\pi^+\pi^+$ decay:



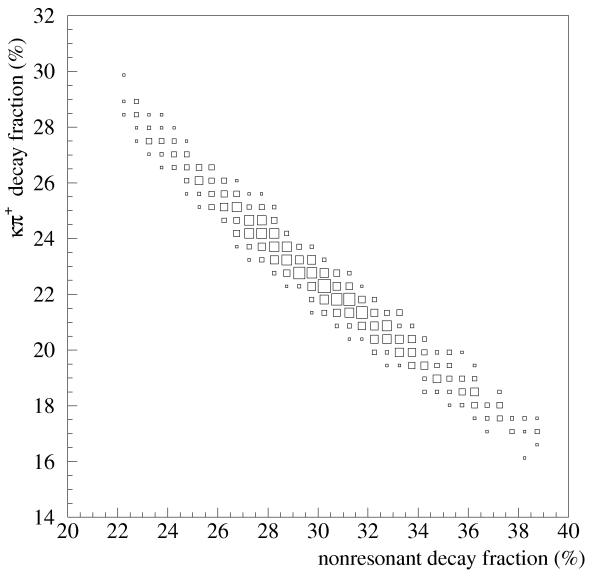
Limitations of the isobar model: $D^+ \to K^-\pi^+\pi^+$

mode	E791	CLEOc	FOCUS	FOCUS(b)
$\overline{K}^*(892)^0\pi^+$	12.3±1.4	11.2±1.4	13.7±0.3	11.2±0.3
$\overline{K}^*(1410)\pi^+$	-	-	1.2±0.3	1.3±0.3
$\overline{K}^*(1680)^0\pi^+$	2.5±0.8	1.4±0.2	3.3±0.3	3.8±0.3
$\overline{K}_2^*(1430)\pi^+$	0.5±0.2	0.4±0.4	0.20±0.05	0.20±0.05
$\overline{K}_0^*(1430)\pi^+$	12.5±1.4	10.5±1.3	17.5±0.8	18.7±1.2
$\kappa(800)\pi^+$	47.8±13.2	31.2±3.6	22.5±4.5	43.3±3.2
nonresonant	10.4±1.4	13.0±7.3	29.7±5.0	7.5±3.0

PL **653B**, 1 (2007)

2000 miniMC samples were generated with exactly the same input parameters, given by the result from an isobar fit of FOCUS data;

Each miniMC sample was fitted with the same model used to generate it;
The scatter plot of the κ and NR decay fractions show that they cannot be well distinguished.



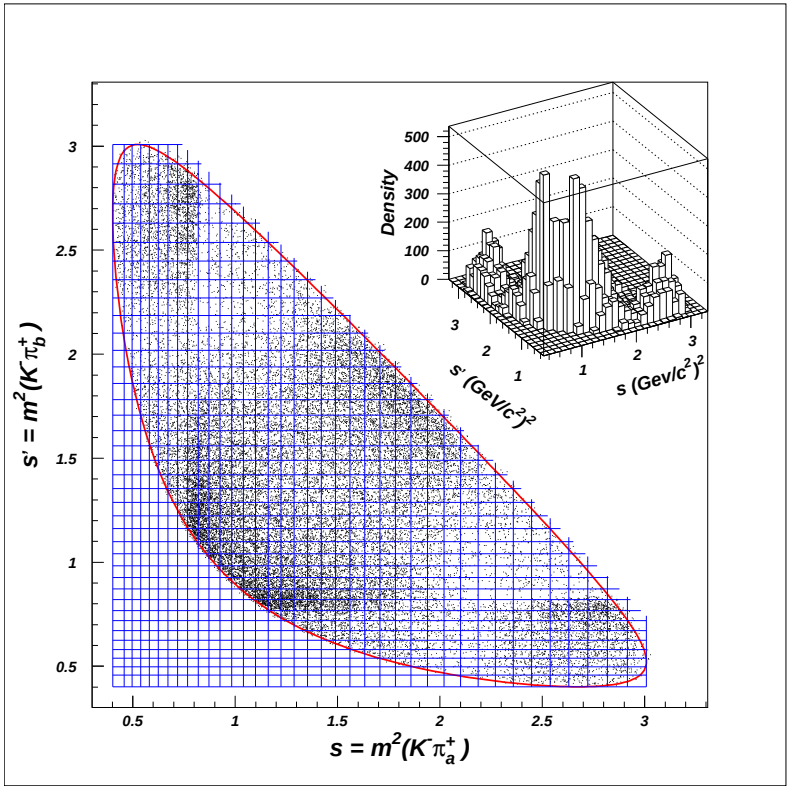
Model independent approach - MIPWA

The MIPWA technique, developed by E791: no assumption about the S-wave.

The S-wave is a generic complex funtcion, to be determined directly from data:

$$\mathcal{A}^0(s) = a(s)\, e^{i\,\phi(s)}, \qquad s \equiv m^2_{K\pi}$$

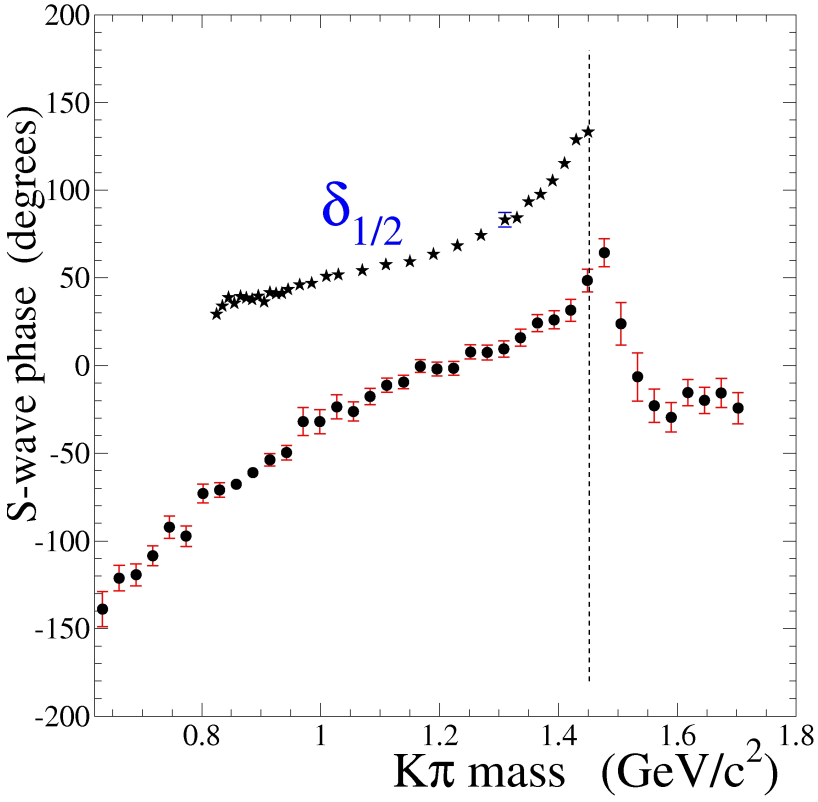
- The $K\pi$ mass spectrum is divided into n slices;
- at $s = s_k,\ \mathcal{A}_0 = a_k\, e^{i\,\phi_k}$
- at any s, $\mathcal{A}_0$ is given by an spline interpolation;
- there is no free lunch: $\{a_k, \phi_k\}$ are $2n$ free parameters. Very complex, slowly converging fit.

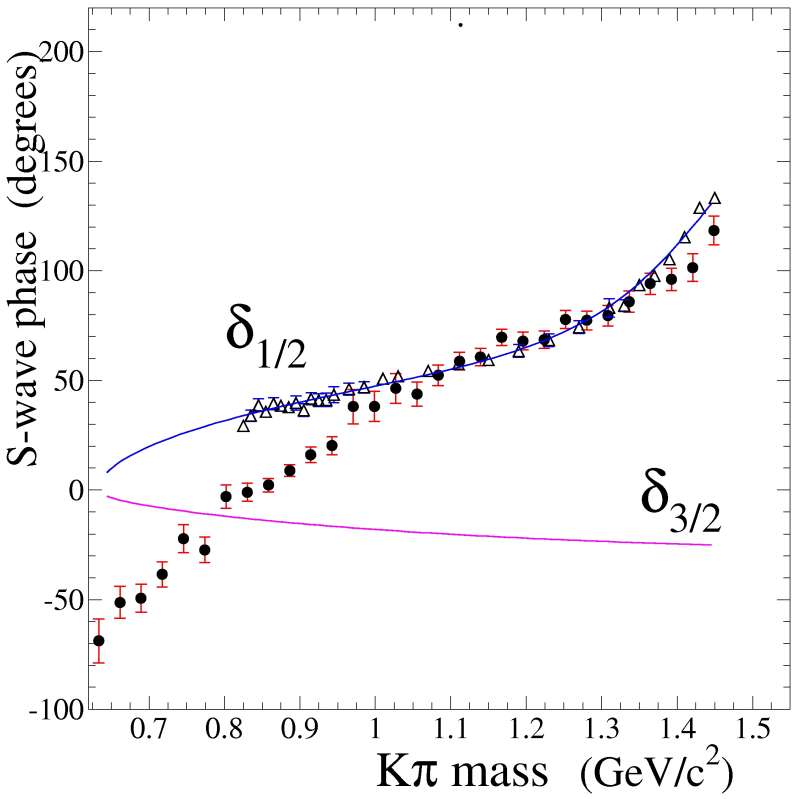


The $K^-\pi^+$ S-wave phase from FOCUS $D^+ \to K^-\pi^+\pi^+$

The MIPWA S-wave phase, $\phi(m_{K\pi})$, compared to the LASS I=1/2 phase. The $K\pi \to K\pi$ scattering is pure elastic up to the $K\eta'$ threshold (dashed vertical line).

The MIPWA S-wave phase shifted by 80° degrees. No combination of LASS $\delta_{1/2}$ and $\delta_{3/2}$ can match $\phi(m_{K\pi})$. This may be a clear indication of three-body FSI.





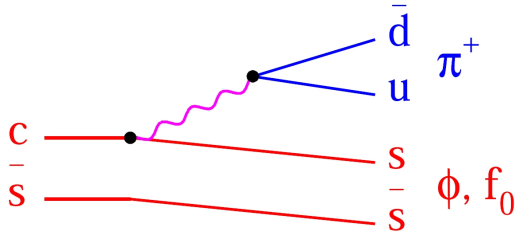
PLB 681, 14 (2009)

The $\pi\pi$ S-wave: MIPWA of the $D_s^+ \to \pi^-\pi^+\pi^+$ from BaBar

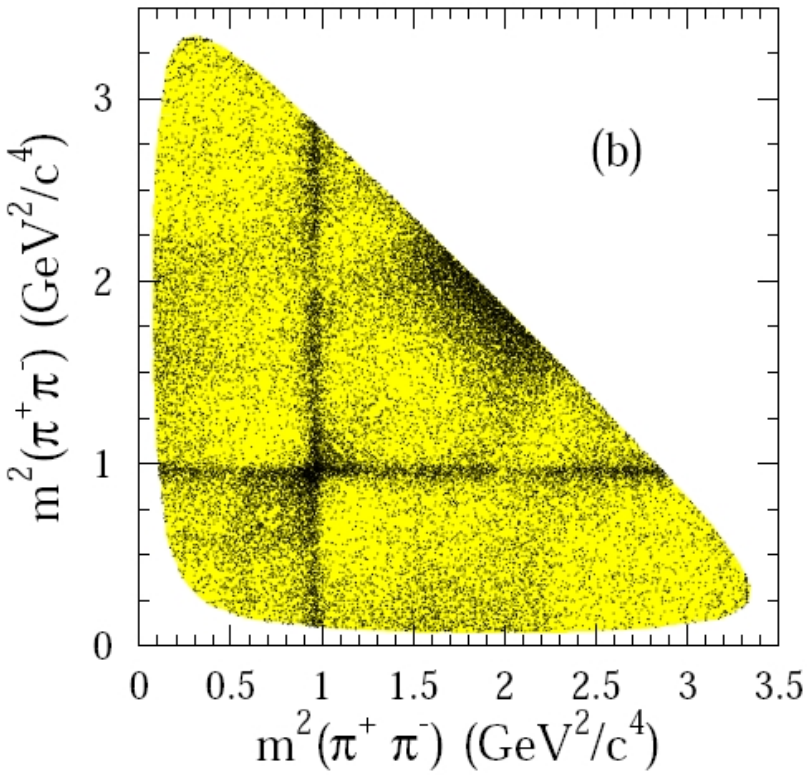
A very interesting decay: no strange quarks in the final state. Ideal to study states coupling both to $\pi\pi$ and KK.

Final states with two identical pions have a largely dominant S-wave component.

The dominant diagram:



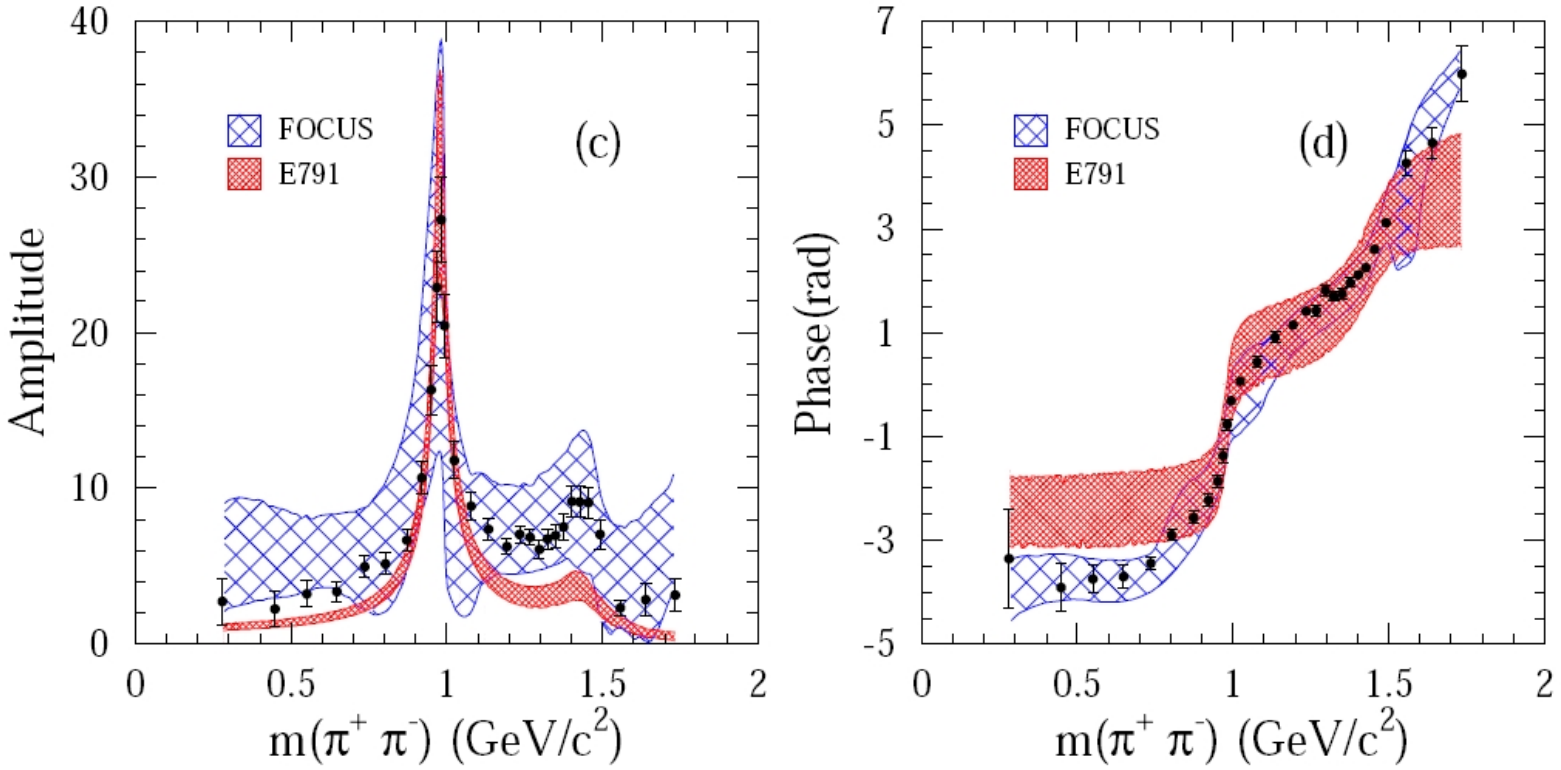
- No contribution from the σ is expected, since it is a $n\bar{n}$ state;
- S-wave should be dominated by the $f_0(980)$ and $f_0(1500)$;
- phase space allows a significant contribution of the $f_2(1270)$.



PRD **79**, 112004 (2009)

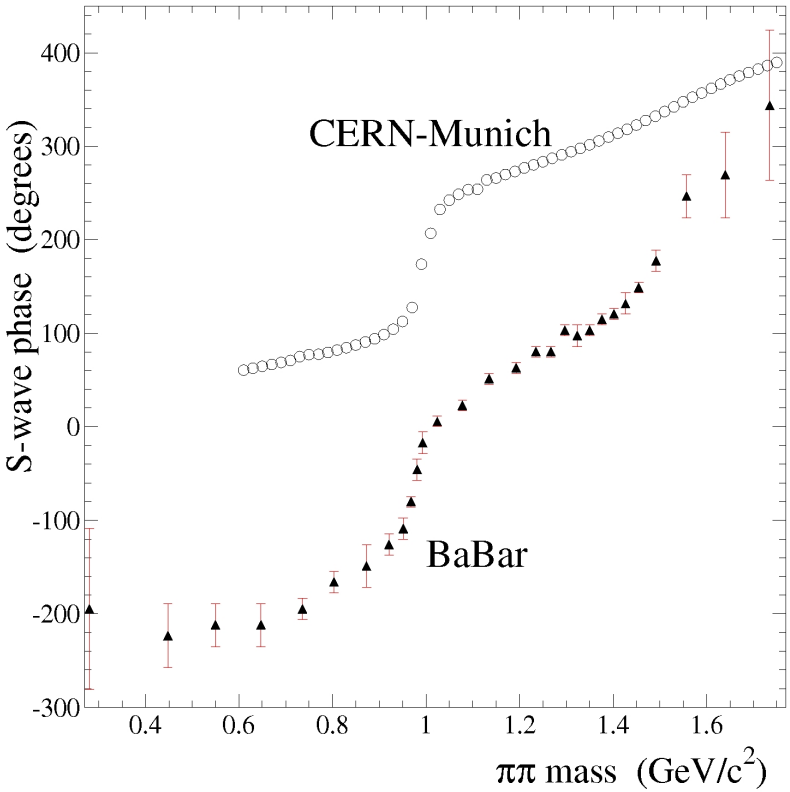
The $\pi\pi$ S-wave: MIPWA of the $D_s^+ \to \pi^-\pi^+\pi^+$ from BaBar

mode	decay fraction (%)
$f_2(1270)\pi^+$	10.1 ± 1.7
$\rho(770)\pi^+$	1.8 ± 1.1
$\rho(1450)\pi^+$	2.8 ± 1.8
S-wave	83.0 ± 2.0

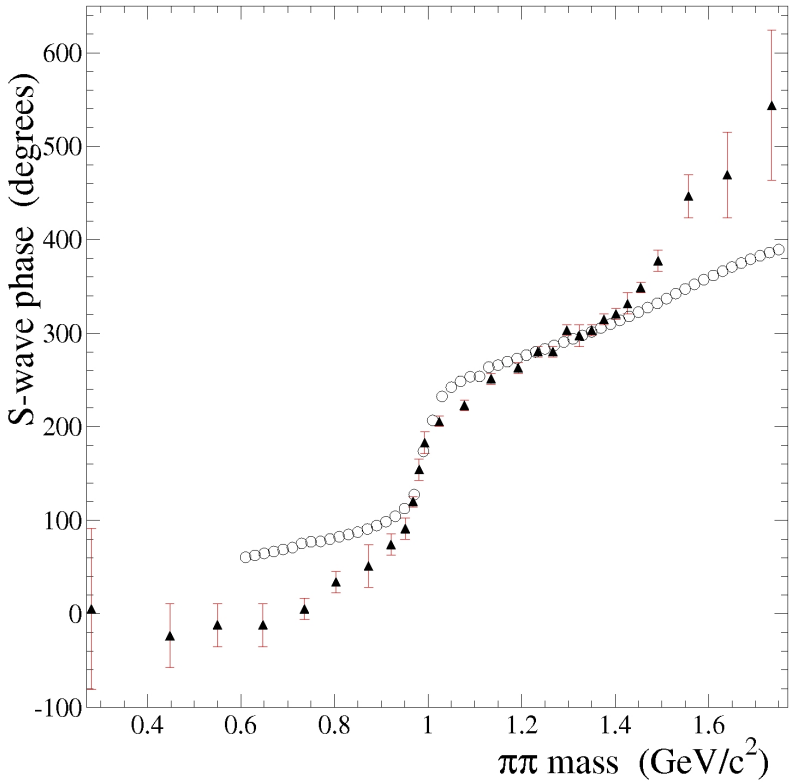


The $\pi\pi$ S-wave: MIPWA of the $D_s^+ \to \pi^-\pi^+\pi^+$ from BaBar

The MIPWA S-wave phase, compared to the $\pi\pi \to \pi\pi$ I=0 phase from the Cern-Münich Collaboration.



The MIPWA S-wave phase shifted by 200° degrees. The discrepancy between the two phases is even larger than that of the $K\pi$.



Final remarks

Decays of D (and B) mesons and τ leptons, have unique features that make them an excellent tool for studies of the $\pi\pi$ and $K\pi$ amplitudes in S-wave.

These decays have been, and they will be for a while, the only new data available. With them one can continuosly access the whole elastic region.

Semileptonic decays provide a cleaner environement, but the S-wave component is small. The undetected neutrinos pose additional difficulties.

Hadronic decays are abundant, but the S-wave comes entangled with other effects.

The $\pi\pi$ and $K\pi$ phases are universal. We need to learn how to extract the pure S-wave phases from D decays. What do we really measure with the MIPWA technique? In particular, what is the role of 3-body FSI?

The understanding of the S-wave is an important subject in its own. But since D and B decays are one of the main probes for new physics, the control of the S-wave becomes a crucial issue. Plenty of room for theoretical work.