Searches for hybrid mesons

- **Expectations for hybrid mesons**
- **Exotic quantum numbers ($J^{PC} = 1^{-+}$)**

Diffraction: $\pi^- N \rightarrow \eta\ \pi^- N$

$\pi^- N \rightarrow \eta`\ \pi^- N$

$\pi^- N \rightarrow b_1\ \pi\ N$

$\pi^- N \rightarrow \rho^0\ \pi^- N$

$\pi^- N \rightarrow \eta\ \pi^- \pi^- \pi^+ N$

Charge exchange: $\pi^- p \rightarrow \eta\ \pi^0 n$

$\pi^- p \rightarrow \eta`\ \pi^0 n$

- **Features of π (1800)**

Expectations for hybrid mesons

$q\bar{q}$ normal mesons

$q\bar{q}$ + $SU(3)_f$ **singlet** hybrids

$q\bar{q}$ mesons:

$P=(-1)^{L+1}$ $C=(-1)^{L+S}$ $J^{PC} = 0^{-+}, 1^{--}, 0^{++}, 1^{++}, 2^{++}, 1^{+-}$ ………

Hybrid mesons can have exotic quantum numbers (Okun',Vainshtein 76)

$J^{PC}_{exotics} = 1^{-+} \quad 0^{+-} \quad 2^{+-} \quad 0^{--}$ ……

Smoking gun:

$J^{PC} = 1^{-+}$: π_1

$J^{PC} = 0^{-+}$: $\pi(1800)$

Model predictions for hybrid mesons

Hybrids were studied in:

Potential models, Bag models, Flux tube model, QCD sum rules, Lattice QCD.

As a rule models predict that exotic hybrid resonance π_1 does exist.

Prediction for mass: $M(\pi_1) = 1.6 \div 2.1$ GeV

Specific prediction of QCD sum rules: $M(\pi_1') - M(\pi_1) \approx 0.2$ GeV

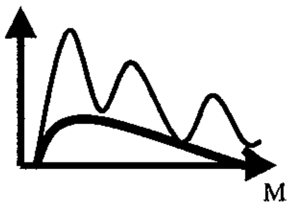
Predictions for decay widths are very model dependent:

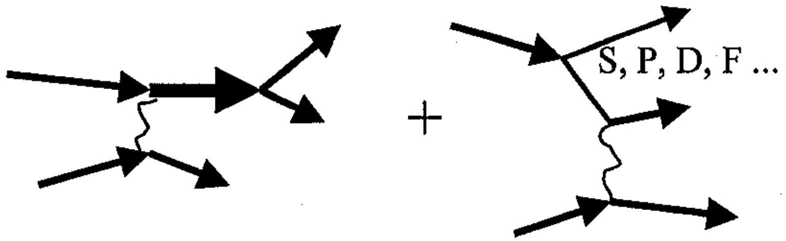
- **$\eta'\pi$, $\eta\pi$** — $A^2(\pi_1 \to \eta'\pi) / A^2(\pi_1 \to \eta\pi) = 1/tg^2\theta_{PS}$ {Close&Lipkin}
  - $\Gamma(\pi_1(1600) \to \eta'\pi) \approx 3$ MeV {Narison,99}
  - $\Gamma(\pi_1(1600) \to \eta'\pi) \approx 1$ GeV {Frere}
- **$\rho\pi$** — $\Gamma(\pi_1(1600) \to \rho\pi) = 2 \div 8$ MeV {Kokoski,Page}
  - $\Gamma(\pi_1(1600) \to \rho\pi) = 10 \div 100$ MeV {Viron}
  - $\Gamma(\pi_1(1600) \to \rho\pi) = 0.6$ GeV {Narison}
- **$b_1\pi$** — $\Gamma(\pi_1(1600) \to b_1\pi) = 50 \div 200$MeV {Iddir,Page}
- **$f_1\pi$** — $\Gamma(\pi_1(1600) \to f_1\pi) = 10 \div 50$MeV

Methods of hunting, problems

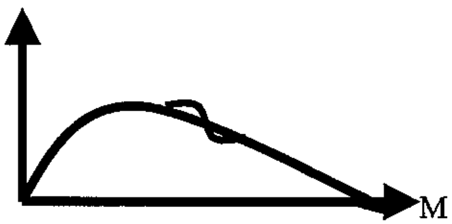
- search for “additional” states with normal quantum numbers
- search for “unusual” decays(suppression of decays to states with identical space wave functions, decays to {8}+{1})
- search for mesons with exotic quantum numbers

- **Main problem – large nonresonance background.**
  - normal mesons:





- hybrids

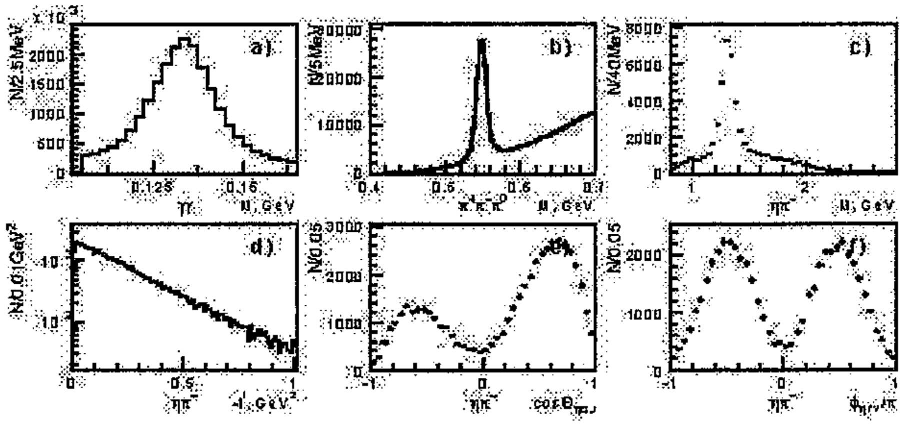


The wave $J^{PC}=1^{-+}$ in diffractive reactions

$\pi^- A \rightarrow \eta\ \pi^- A$

VES, 1993 , $P_\pi = 37$ GeV (confirmed by BNL)
2000 , $P_\pi = 28$ GeV

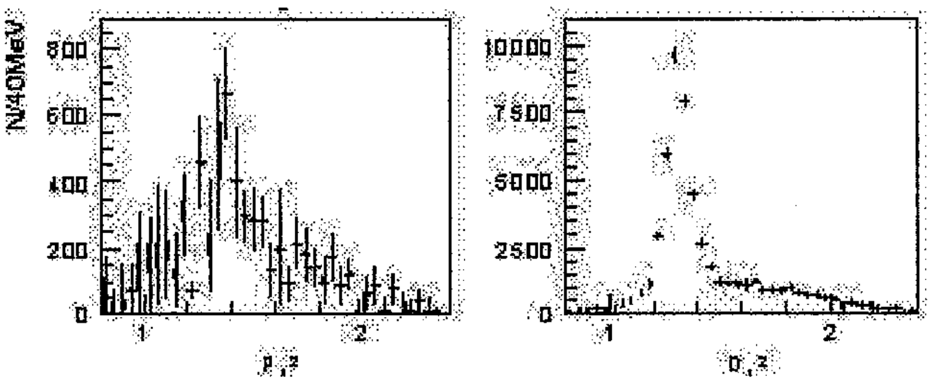
The amplitude depends on 5 variables:
s, t, $M_{\eta\pi}$, θ , φ
Assuming full coherency at fixed **s, t, $M_{\eta\pi}$** the intensity could be written as:
$I(\Omega) = |\Sigma_{J,M}\ a^J_{M-} F^J_{M-}|^2 + |\Sigma_{J,M}\ a^J_{M+} F^J_{M+}|^2$
$F^J_{M\eta}(\Omega) = Y^J_M(\Omega) - \eta\ (-1)^M\ Y^J_{-M}(\Omega)$
(η – "naturality")



Seven waves:
S0, P0, P-, D0, D- ; P+, D+

The wave **D+** dominates: a2(1320) and broad signal at m>1.4GeV

The wave **P+** is clearly seen. This wave does not demonstrate narrow structures.



$\pi^- A \to \eta\, \pi^- A$
Mass-dependent fit of D+ and P+ waves in $\eta\ \pi$

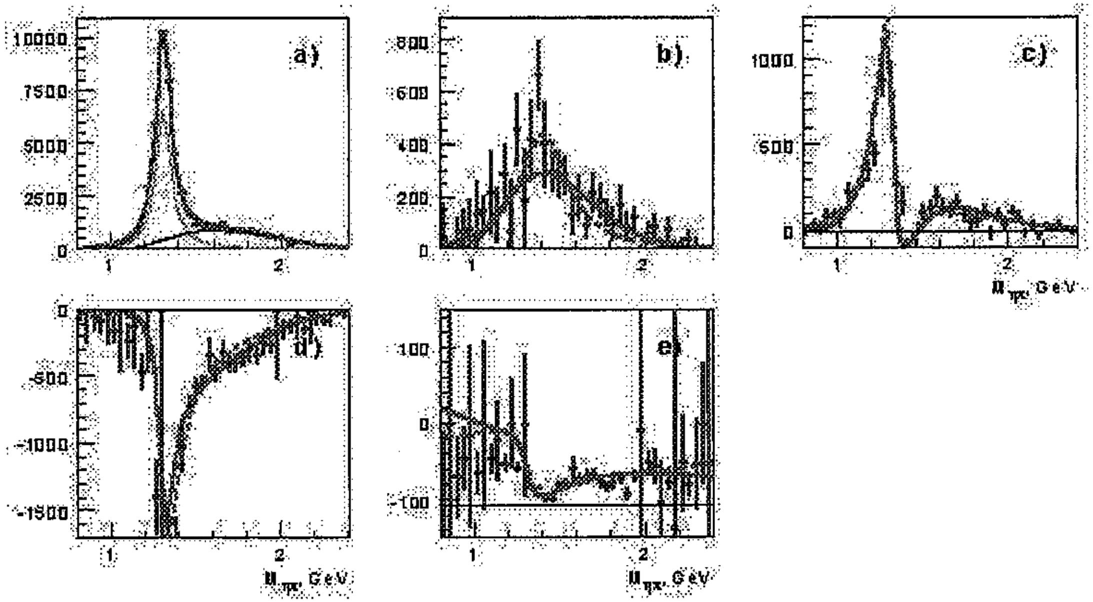
a) Intensity D+

b) Intensity P+

c) Real part of interference term

d) Imaginary part of interference term

e) Relative phase D+/P+



The results are fitted **equally well** by **broad resonance in P+,** as well as by **background** with constant phase.

Summary on exotic wave $I^G J^{PC} = 1^- 1^{-+}$ at M=1.4 GeV

1. GAMS	1988	$\pi^- p \to \eta \pi^0 n$	~~M=1406+-20 MeV~~	~~Γ=180+-20 MeV~~
2. KEK	1993	$\pi^- p \to \eta \pi^- p$	M=1323+-5 MeV	Γ=143+-12 MeV
3. VES	1993	$\pi^- N \to \eta \pi^- N$	Broad signal at M=1.4 GeV	
4. E-852	1997	$\pi^- p \to \eta \pi^- p$	M=1370+-60 MeV	Γ=380+-90 MeV
5. CB	1998	$n \bar{p} \to \eta \pi^- \pi^0$	M=1400+-30 MeV	Γ=310+-90 MeV
6. GAMS	1998	$\pi^- p \to \eta \pi^0 n$	Broad signal without BW phase	
7. GAMS	1999	$\pi^- p \to \eta \pi^0 n$	Mass dependent fit without resonance	
8. E-852	2003	$\pi^- p \to \eta \pi^0 n$		

- **Main problems**: relative phase of 1-+ and 2++ waves is unmeasurable

  the phase of 2++ wave is not known at M>1.45GeV

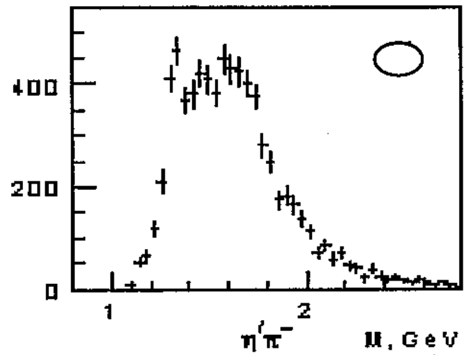
  different experiments give very different results

  the signal looks like ordinary nonresonant background

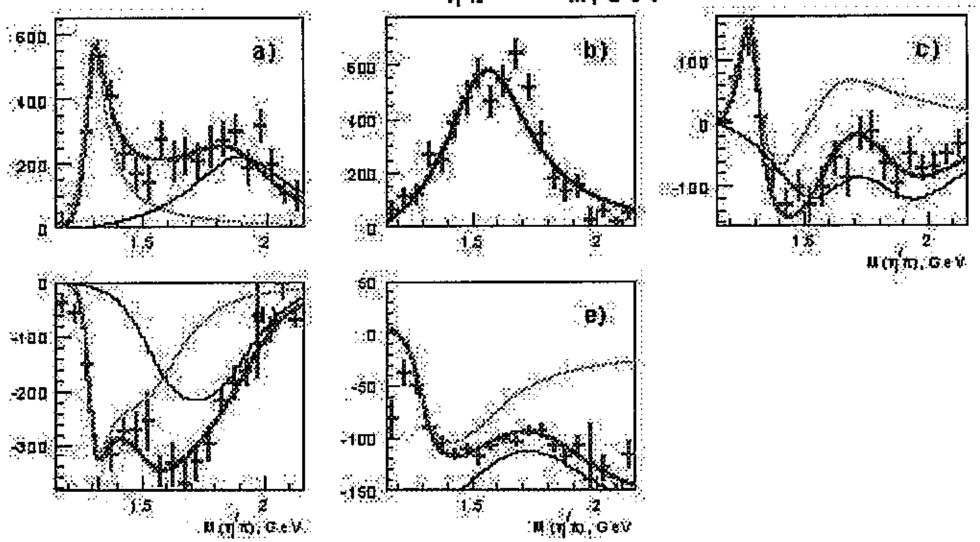
- **Conclusion: experimental results do not lead to unambiguous conclusion on the existence of exotic resonance at M ≈ 1.4GeV**

$\pi^- A \rightarrow \eta' \pi^- A$
PWA and mass-dependent fit of D+ and P+ waves in $\eta' \pi$

Two signals are clearly seen:
- the decay $a_2 \rightarrow \eta` \pi^-$
(VES, 1992)
- large signal in exotic wave
P+ at $M(\eta` \pi^-) \approx 1.6$ GeV.
This result was confirmed by E852 recently.



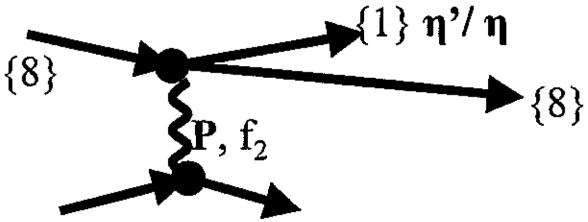
The results are fitted equally well/bad by broad resonance in **P+,** as well as by background with constant phase.



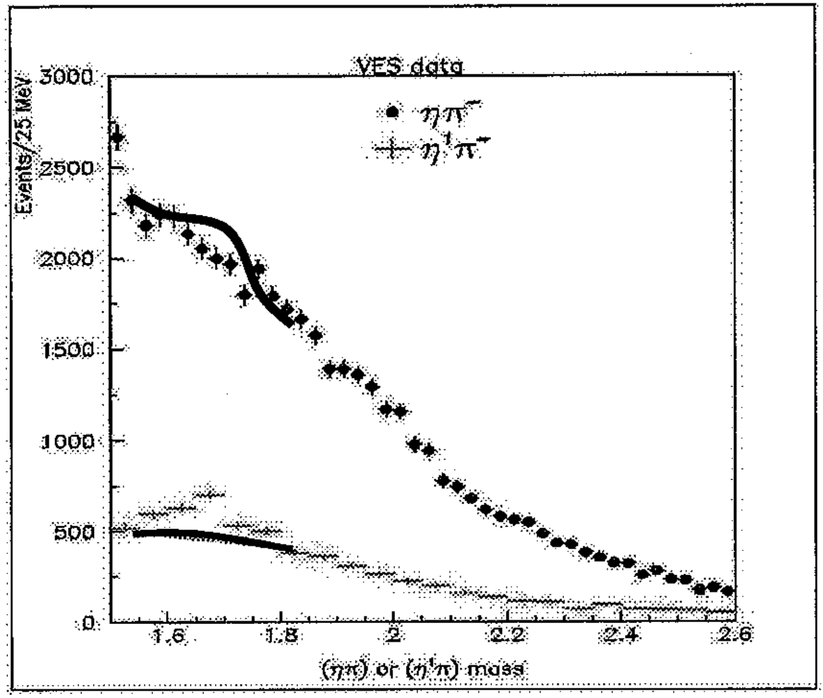
More complicated model is needed to describe possible fine structure at $M \approx 1.6$-1.8 GeV

Comparison of $\eta\ \pi^-$ and $\eta'\ \pi^-$

The diffractive-like production of $\eta\ \pi^-$ and $\eta'\ \pi^-$ in P-wave is described by one amplitude:



Therefore one and the same P-wave resonance has to be seen in $\eta\ \pi^-$ and $\eta'\ \pi^-$.



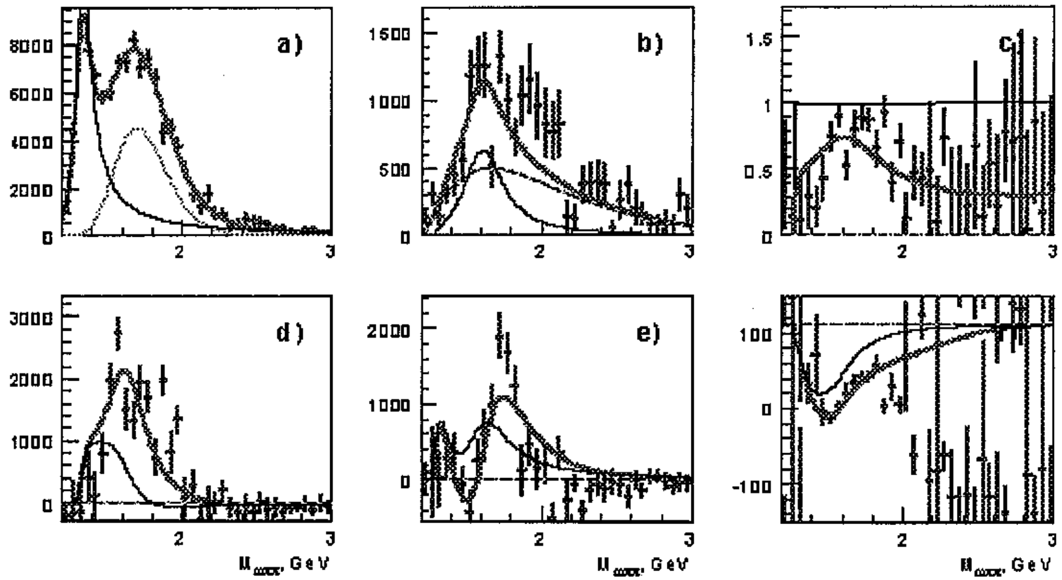
We do not see statistically significant structures in $\eta\ \pi^-$ P-wave around M≈1.6 GeV. To make analysis less model-dependent we can look at mass-spectra without PWA and sum-up all VES runs to increase statistics. The signal expected in $\eta\ \pi^-$ is shown by **red** curve. This signal is not seen in the $\eta\ \pi^-$ mass-spectrum. Possible irregularities at 1.75 GeV and 1.85 GeV have pure statistical significance.

The reaction $\pi^- A \rightarrow b_1 \pi A$

VES, 1997 , $P_\pi = 37$ GeV
2000 г, $P_\pi = 28$ GeV

The reaction under study is $\pi^- A \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 A$
The resonance $b_1(1235)$ was selected in the chanel $\omega(\pi^+ \pi^- \pi^0)\ \pi$

a) Intensity D+
b) Intensity P+
c) Coherency D+ P+
d) Real part of interferece term D+ P+
e) Imaginary part of interferece term D+ P+
f) Relative phase D+ / P+



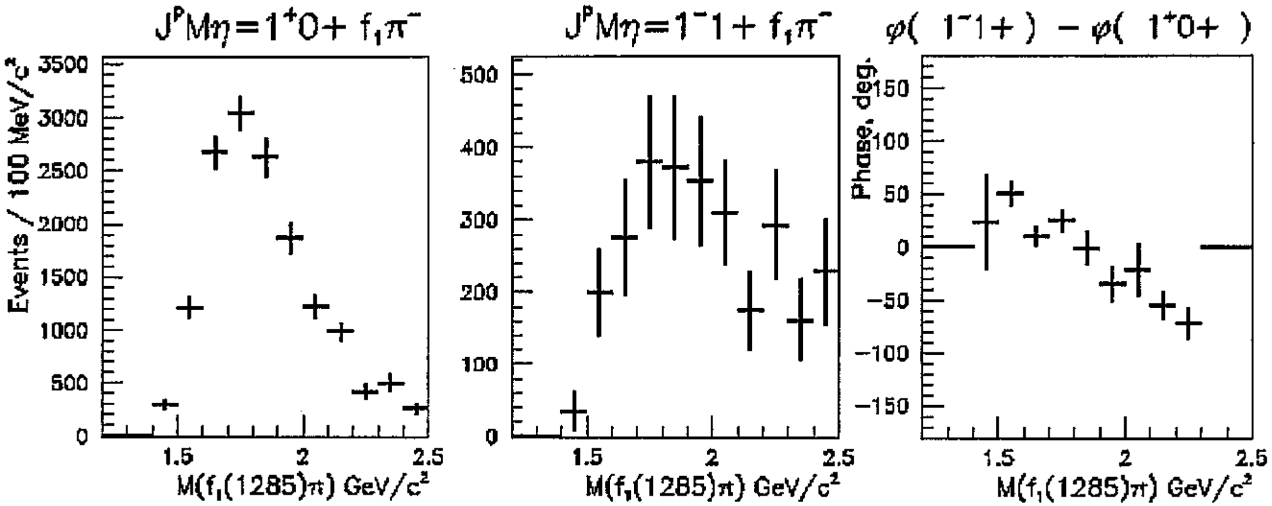
D+ wave: $a_2(1320)$ and broad bump at M=1.7 GeV
P+ wave: broad irregular structure. Rapid variation of **Im(D+/P+)** points to possible resonance at M=1.6÷1.8 ГэВ

The reaction $\pi^- A \rightarrow f_1 \pi^- A$

VES, 1995, $P_\pi = 37$ GeV
2002, $P_\pi = 28$ GeV

The reaction under study is: $\pi^- A \rightarrow \pi^+ \pi^- \pi^- \eta A$
The resonance $f_1(1285)$ was selected in the channel $\eta \pi^+ \pi^-$

a) Intensity of D+
b) Intensity of P+
c) Relative phase P+/D+

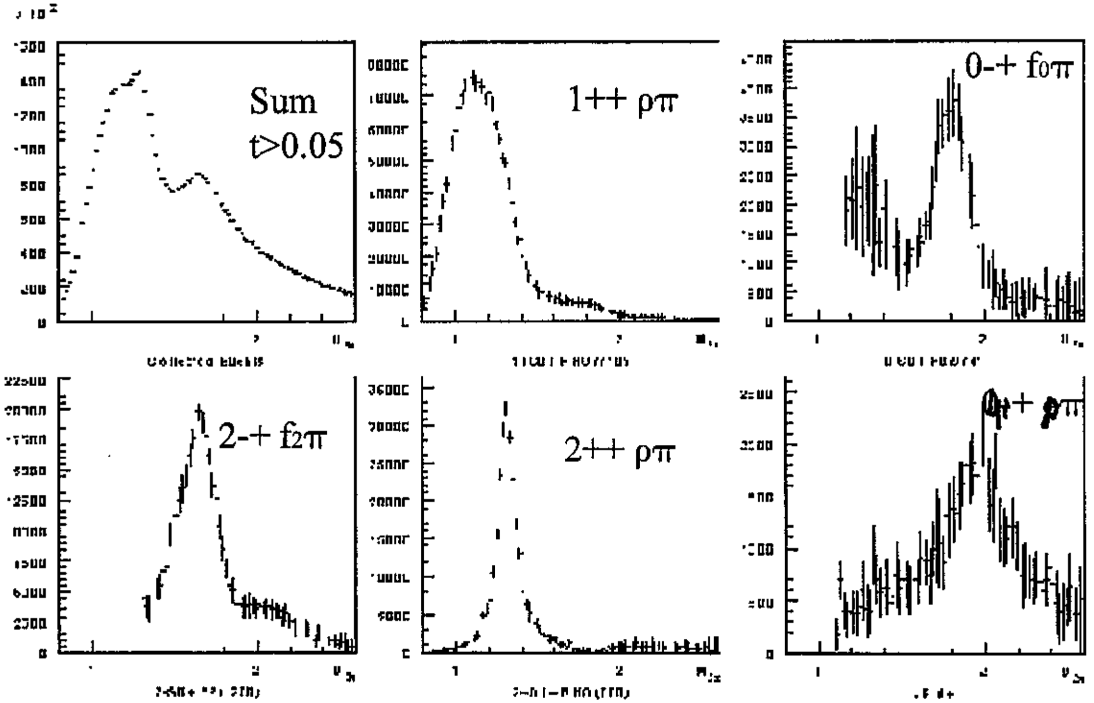


Most intensive wave $J^P M\eta=1^+0+$ has maximum at M=1.7 GeV

No indication to resonances in exotic wave $J^{PC} M\eta=1^{-+}1+$.

The reaction $\pi^- A \rightarrow \pi^+ \pi^- \pi^- A$

VES, 1995, $P_\pi = 37$ GeV
2000, $P_\pi = 28$ GeV



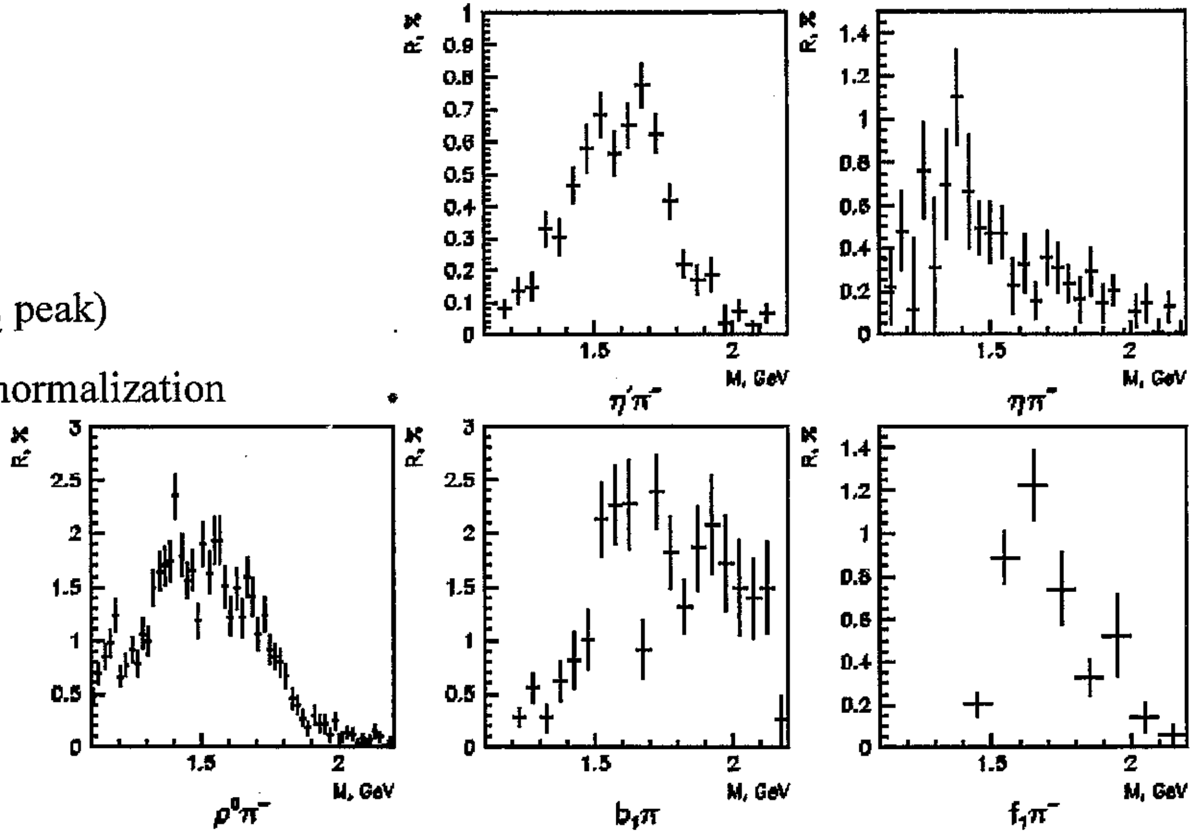
Clear resonances are seen in waves: $J^{PC} = 1^{++}, 2^{++}, 2^{-+}, 0^{-+}, 4^{++}$
Broad exotic wave $\mathbf{I^G(J^{PC})=1^-(1^{-+})}$ is clearly seen in the channel $\boldsymbol{\rho\pi}$ with very low intensity ~2% of the a_2 signal (next slide).
No evidence of narrow resonance at $M \approx 1.6$ GeV(difference with E852).

Conclusion on $J^{PC}=1^{-+}$ in diffractive reactions

Normalization:

dN(X) /dM / dN/dM(a_2 peak)

30% systematic error in normalization

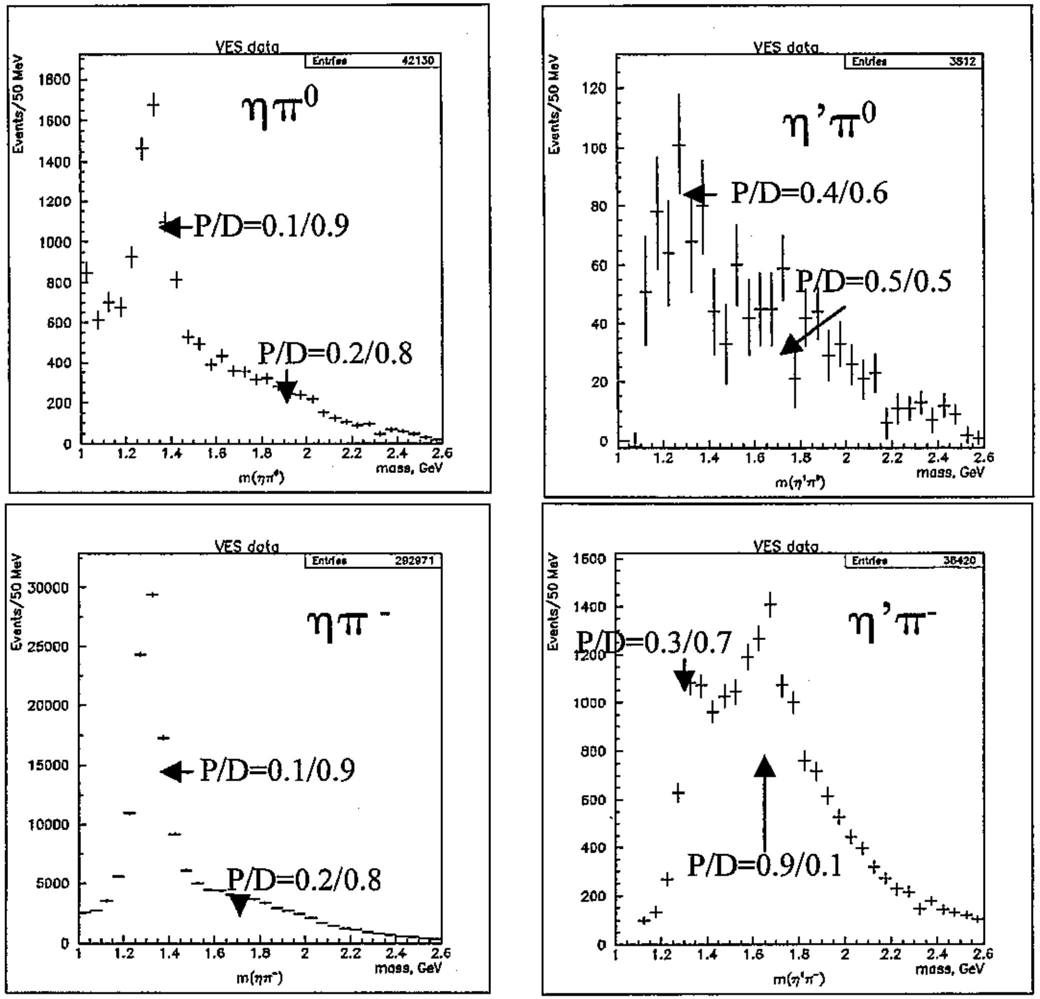


Exotic wave $I^G(J^{PC})=1^-(1^{-+})$ is clearly seen in a number of reactions. There are indications on the existence of exotic resonance in the channel $b_1\ \pi$ (and probably in $\eta`\ \pi^-$) at M=1.6÷1.8 GeV

Charge exchange reactions

VES, 2003, preliminary

Comparison of charge exchange and diffractive reactions shows that mass-spectra of all four reactions are very different. The most spectacular difference is between $\eta'\pi^0$ and $\eta'\pi^-$.

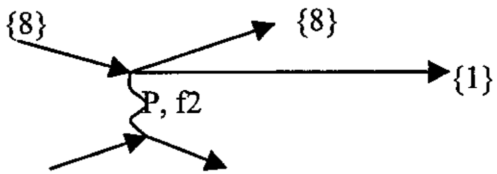


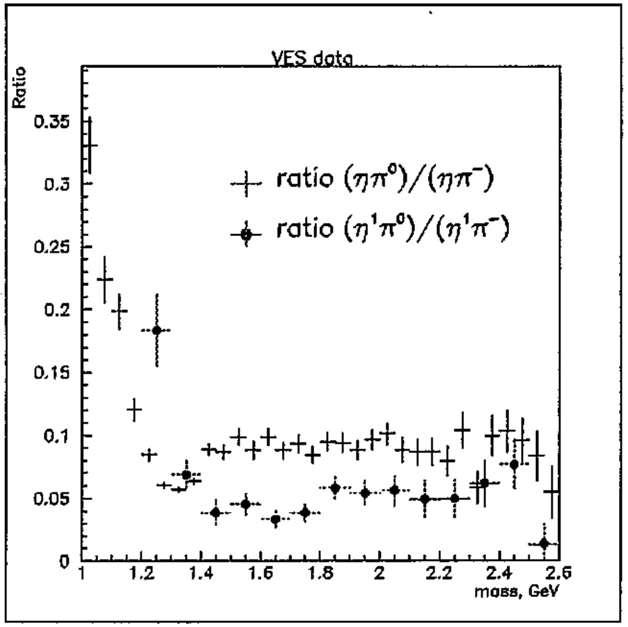
Question:
why bump at 1.65 GeV is not seen in $\eta'\pi^0$?

Answer:
P-wave in $\eta'\pi^0$ is not $SU(3)_f$-singlet, it is four-quark state (next slide).

$SU(3)_f$ structure of $J^{PC}=1^{-+}$ waves in $\eta'\pi$ and $\eta\pi$ channels

It follows from $SU(3)_f$-symmetry that in diffractive-like reactions only one P-wave amplitude is allowed: $\{8\}+\{1\} \rightarrow \{8\}+\{1\}$





Therefore in these reactions the ratio of P-wave amplitudes is expected as : $R=A(\eta'\pi)/A(\eta\pi) = 1/tg(\theta)_{PS}$. Experiments confirm this prediction. It does not depend whether P-wave is resonant or not.

In case of charge exchange reactions the $SU(3)_f$-symmetry allows P-wave amplitudes with two octets in final state ({8}+{8}). Hybrid ($SU(3)_f$-octet) can not decay to two octets in P-wave contrary to four-quark states, which can do it ({10}, {27}). Experimental data show that for charge exchange reactions the P-wave in $\eta'\pi^0$ -channel is suppressed, therefore **multiquark states ({10},{27}) are dominating in $\eta'\pi^0$ P-wave.**

Features of π (1800)
Is it nonexotic hybrid?

The resonance π (1800) is seen in following channels:

$f_0(980)\,\pi$, $\varepsilon\,\pi$, $a_0\,\eta$, $f_0\,(1500)\,\pi$.

Probably the same signal is seen in ωρ.

It is suppressed in ρ π и K*K .

(VES, 1993-1999)

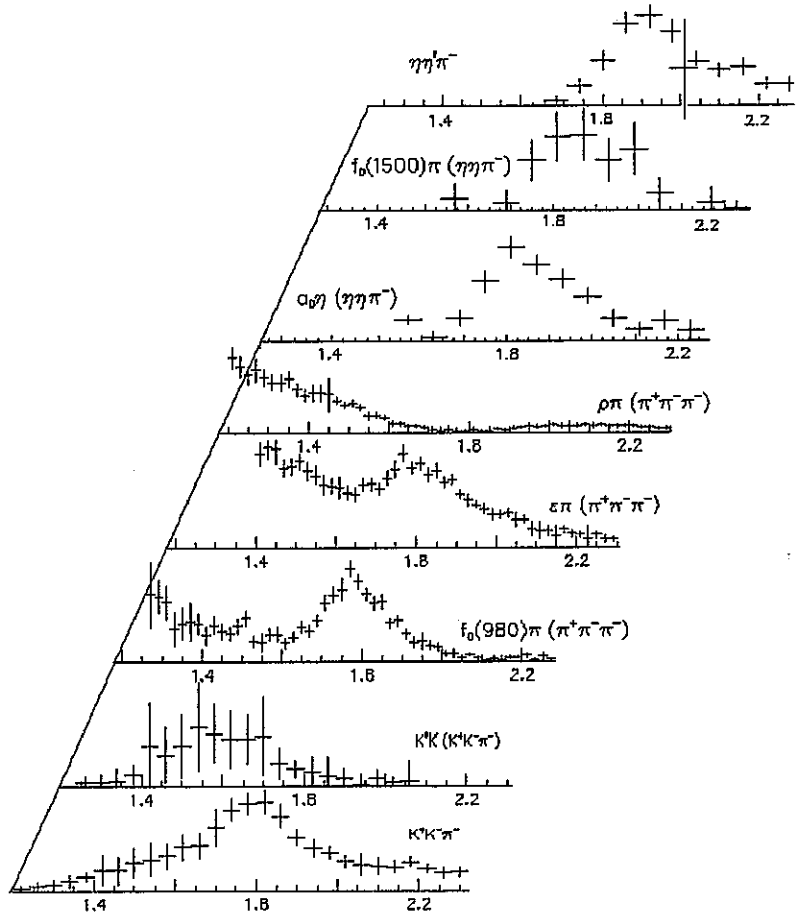
π (1800):   hybrid?

3^1S_0 ?

$K^*\,\bar{K}^*$ molecule ?

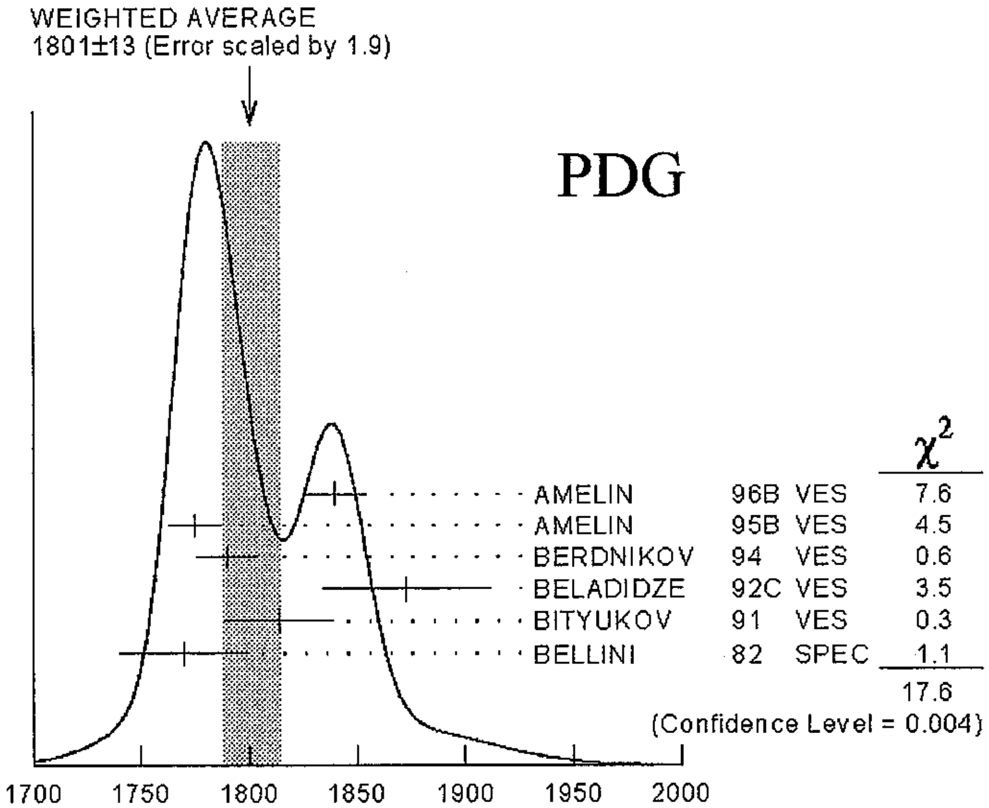
Main features:

- suppression of decays to V P
  (hybrids in FT model, 3^1S_0)
- decay to $f_0(1500)\,\pi$
  (hybrids)
- abnormally high branching to $f_0(980)\,\pi$
  (???)



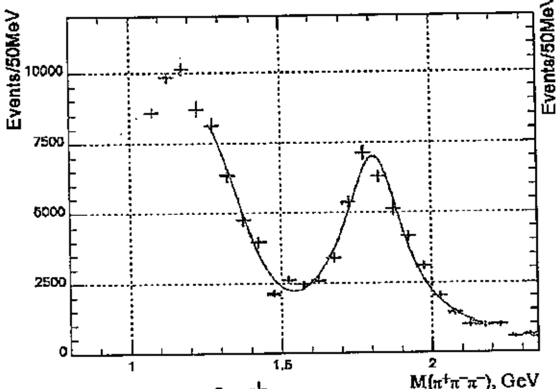
One resonance or more?

Spread of M(π(1800)) from one decay channels to another one points to possible existence of two different 0^{-+} states.

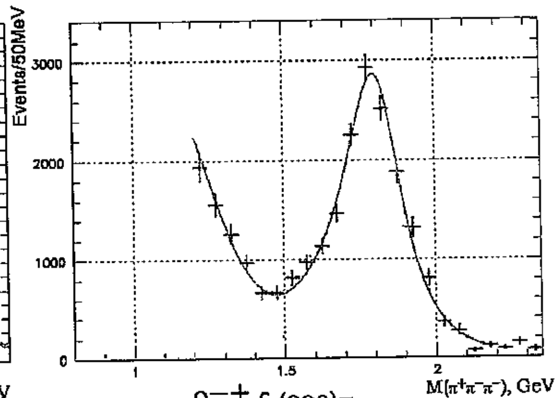


The reaction $\pi^- A \to \pi^+ \pi^- \pi^- A$

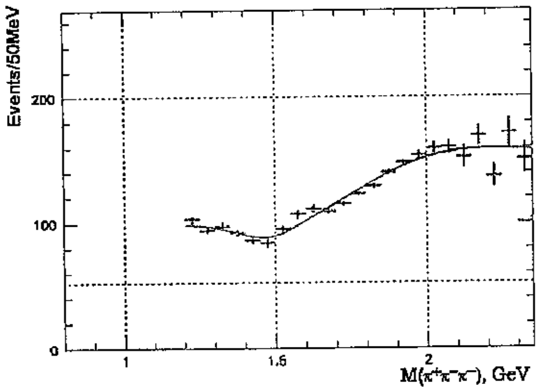
VES, 1997, $P_\pi = 37$ GeV



0^{-+} $\varepsilon\pi$



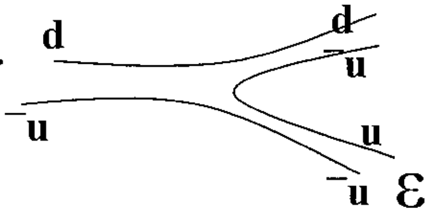
0^{-+} $f_0(980)\pi$



$\varphi(f_0(980)\pi) - \varphi(\varepsilon\pi)$

The f_0 /ε puzzle

It is expected that for conventional hybrids ($I^G J^{PC}=1^- 0^{-+}$)
as well as for second radial excitations of pion (**3^1S_0**)
the decay π(1800) → f_0(980) π is suppressed in comparison to π(1800) → ε π
(here ε is broad π π S-wave object describing f_0(600)+f_0(1370)).
The reason is that f_0(980) is coupled to srange quarks, it's narrow,
the ε is coupled to u,d quarks , it's broad.



VES: BR(π(1800) →f_0(980) π) ≈
BR(π(1800) → ε π)

This puzzle could be resolved assuming that these decays proceed via **emission of $SU(3)_f$ singlet** instead of tube/string breaking. The state

$f_0\{1\} \approx 1/\sqrt{2}$ (ε + f_0(980)) looks like $SU(3)_f$ singlet.

Decay π**(1800)** → {1}+{8} is natural one if π**(1800)** "consists of"
$\bar{q}$ q (in $^1S_0$ state?) **and** (scalar?) **$SU(3)_f$ singlet excitation**
(" glue ", "bag ", longitunal excitation of flux tube etc)

Conclusions

- Exotic wave $J^{PC} = 1^{-+}$ is seen in a number of reactions
- Broad bump at M=1.4 GeV in $\eta\pi$ could be described equally well with or without resonance
- There are some indications on exotic resonance $J^{PC} = 1^{-+}$ in $\eta'\pi$ and $b_1\pi$ at M= 1.7 ÷ 1.8 GeV
- Charge exchange reactions with $J^{PC} = 1^{-+}$ in $\eta\pi$ and $\eta'\pi$ channels proceed via multiquark intermediate states
- Features of the $\pi(1800)$ decays point to possible existence of new excitations in hadrons (scalar, $SU(3)_f$-singlet)