

# *Observation of the $\pi(1800)$ and $\pi_2(1880)$ mesons in the $\eta\eta\pi$ decay*



Paul Eugenio



[Blake Sharin & Alexander Ostrovidov]

Florida State University

Tallahassee, FL USA

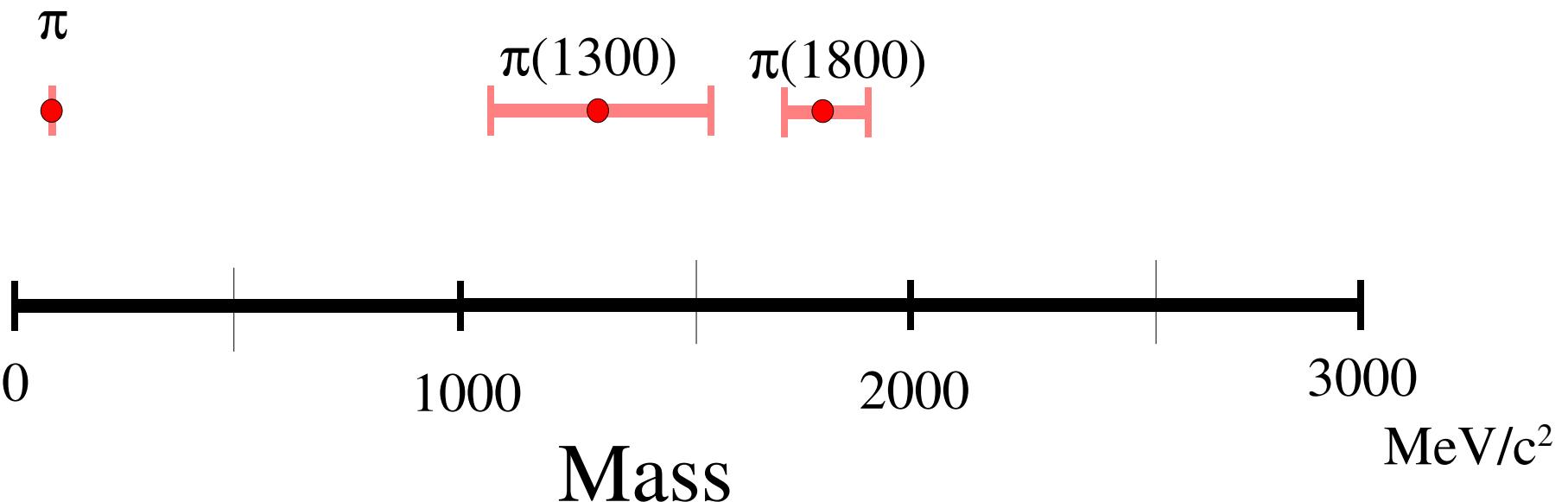
# *Overview*

- Motivation
- Experimental Setup
- Features of  $\pi^- p \rightarrow \pi^- \pi^- \pi^+ \pi^0 \eta^- p$
- Partial Wave Analysis of  $\eta \eta^- \pi^-$
- Observation of  $\pi(1800)$  &  $\pi_2(1880)$
- Conclusions & Summary

# Radial Excitations of the Pion

$J^{PC} = 0^{-+}$

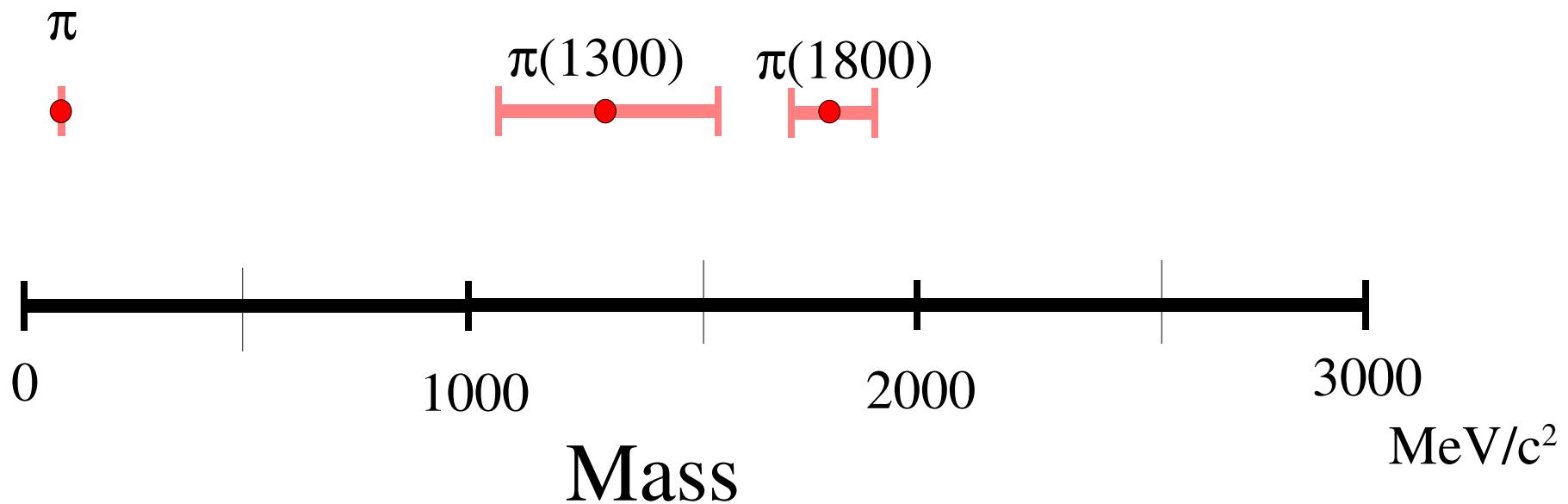
Width



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— Width



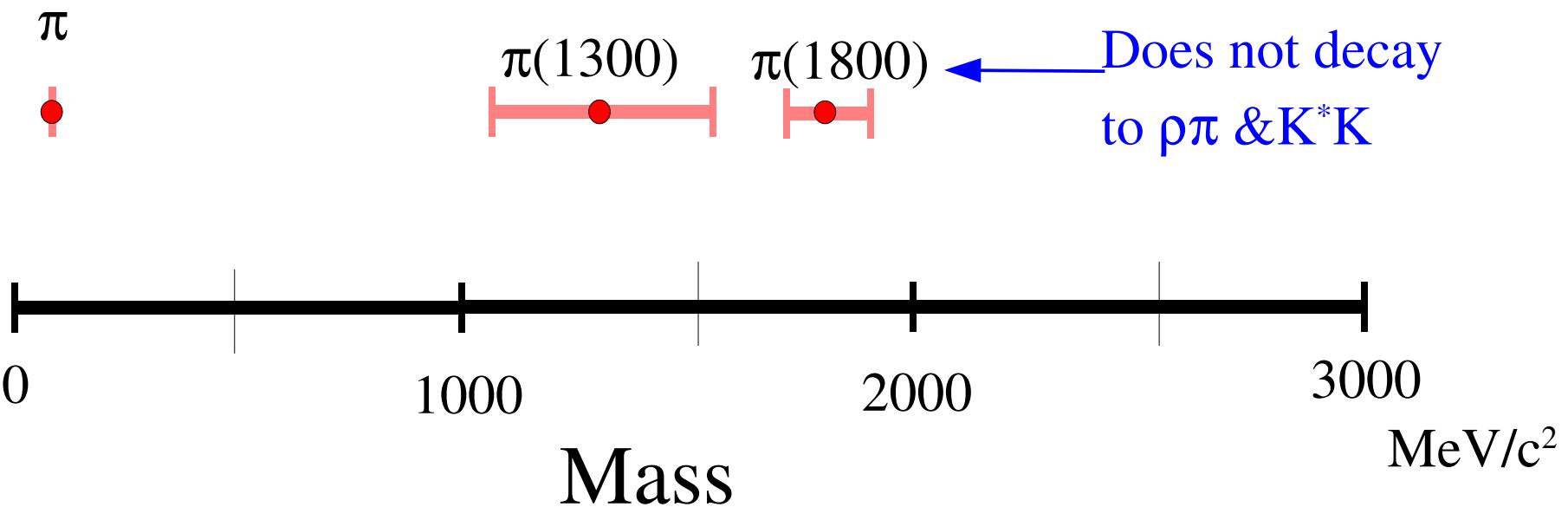
Many<sup>†</sup> have suggested that the  $\pi(1800)$  is a  $0^+$  hybrid meson

<sup>†</sup>See for example T. Barnes, F. E. Close, P. R. Page, & E. S. Swanson Phys. Rev. D55 4157 (1997)

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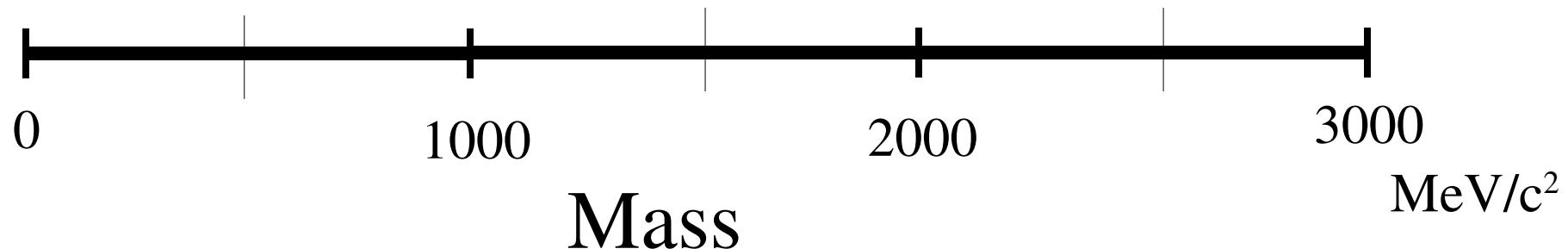
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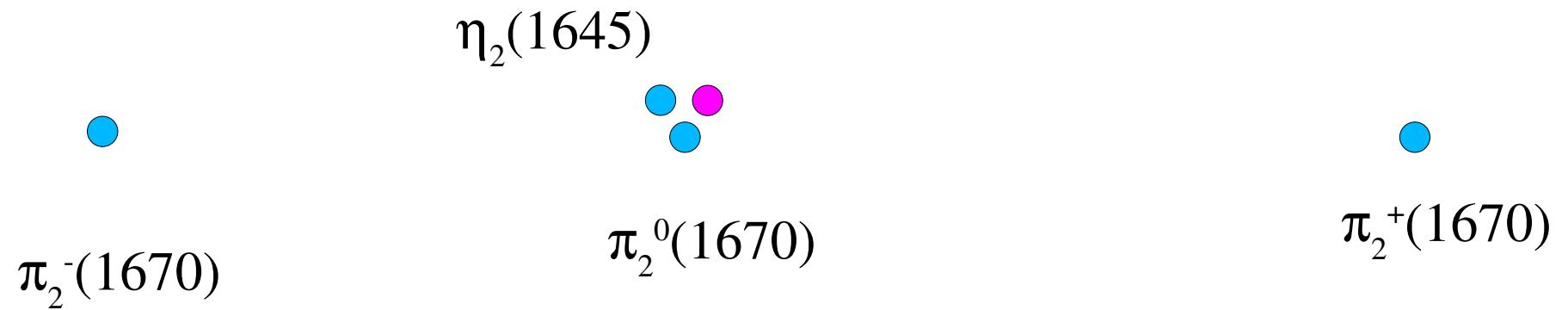
$\pi$



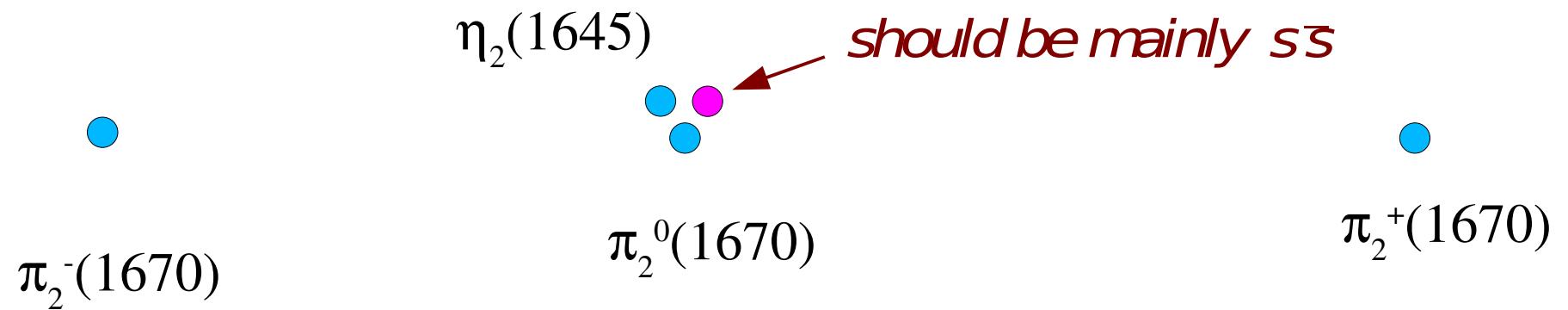
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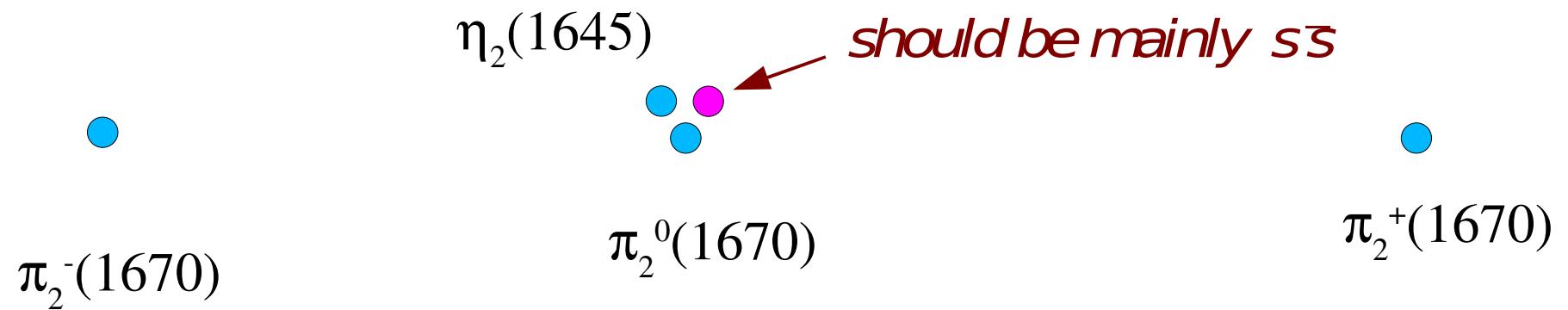
# The $\pi_2/\eta_2$ States [J<sup>PC</sup>=2<sup>-+</sup>]



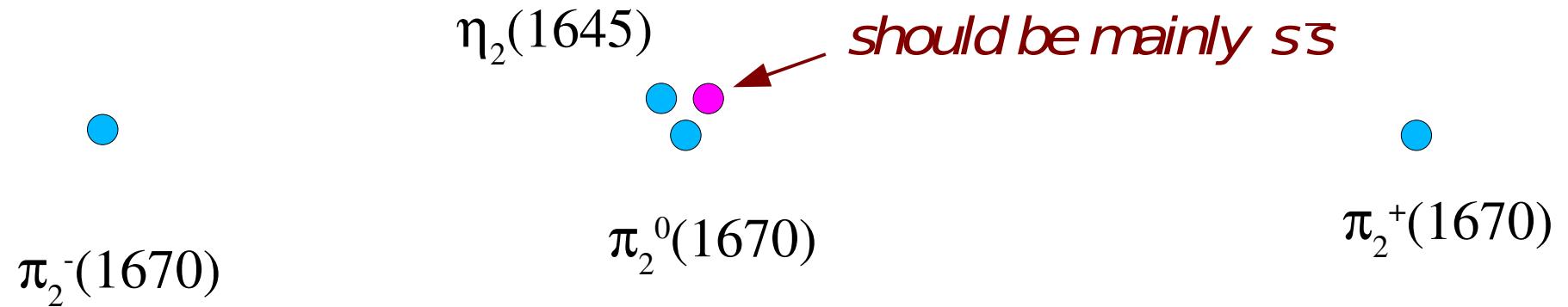
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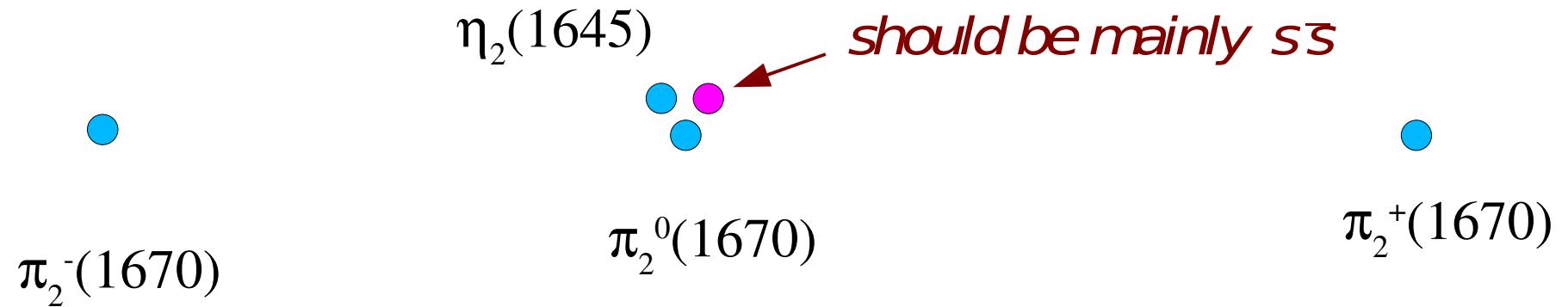


$\eta_2(1870)$  has been reported  
in  $\gamma\gamma$  interactions,  $p\bar{p}$  interactions,  
& central production

*should be mainly s $\bar{s}$*

However decays are mainly to,  
 $\eta_2(1870) \rightarrow a_2(1320)\pi$   
 $\rightarrow f_2(1270)\pi$

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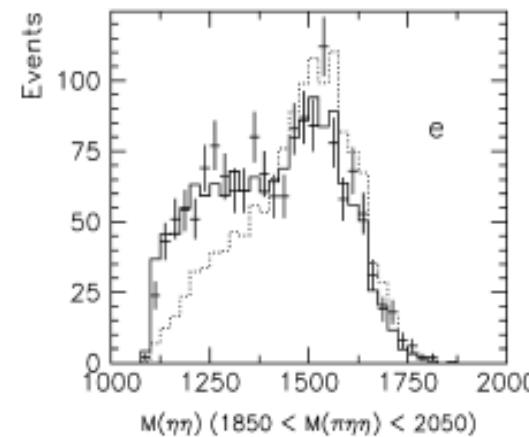
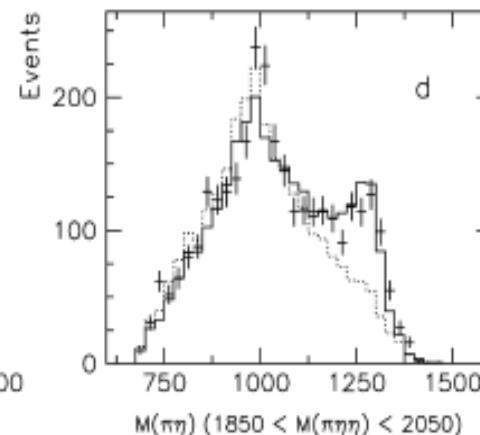
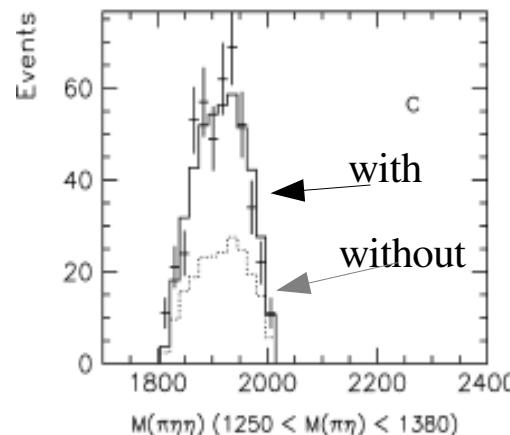
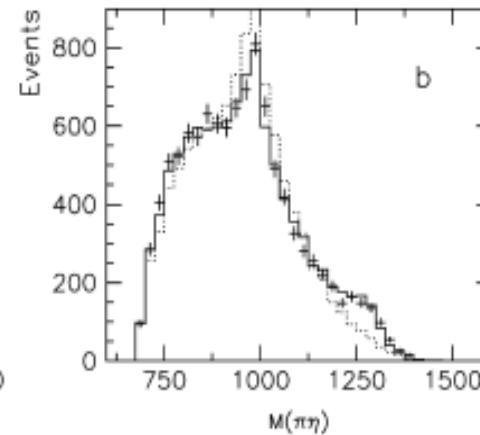
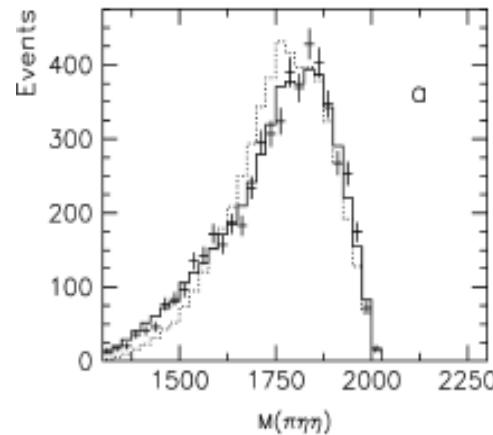
However decays are mainly to,  
 $\eta_2(1870) \rightarrow a_2(1320)\pi$   
 $\rightarrow f_2(1270)\pi$

Close and Page note that the relative decay rate is  
compatible with a hybrid interpretation

# A new $\pi_2(1880)$ state has been observed

- \* Hybrid partner to  $\eta_2(1870)$ ?

$$\bar{p} p \rightarrow \eta \eta \pi^0 \pi^0 \text{ (in flight)}$$



New  $\pi_2$  resonance not yet  
widely accepted.

$\pi_2(1880)$  parameters

$$M = 1880 \pm 20 \text{ MeV}/c^2$$

$$\Gamma = 255 \pm 45 \text{ MeV}/c^2$$

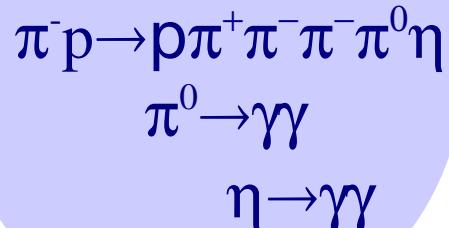
data strongly requires

$$\pi_2(1900) \rightarrow a_2(1320)\eta$$

projections of the data and pwa results

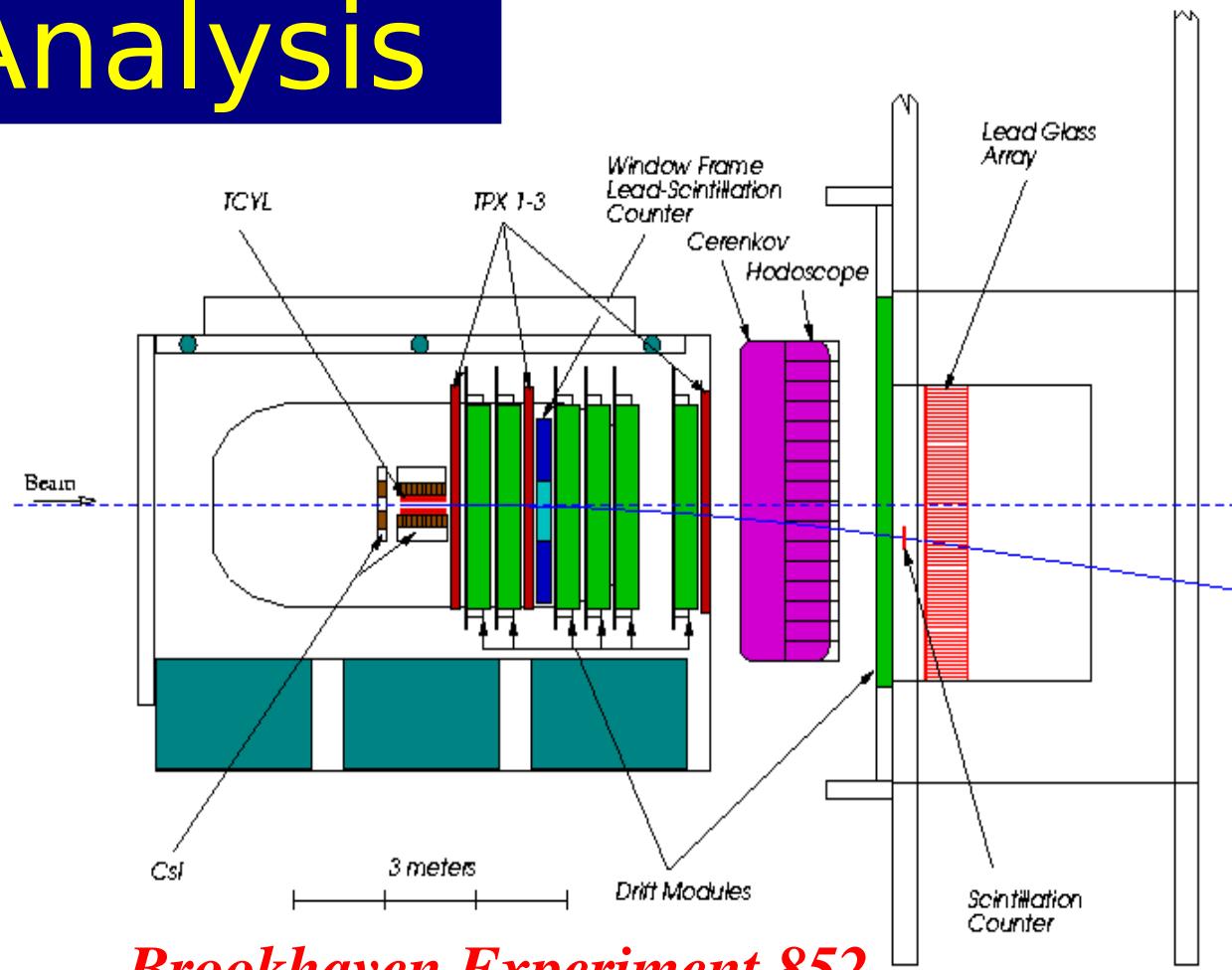
# BNL-E852 Analysis

## Reaction:



18 GeV/c pion beam

256 Million triggers of  
this type acquired

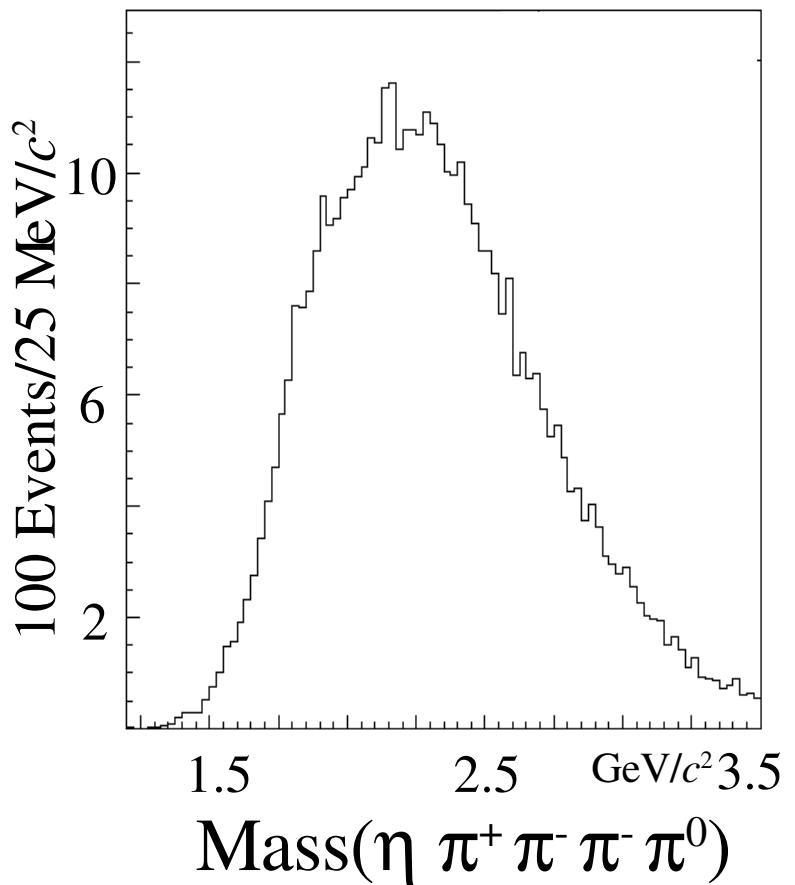
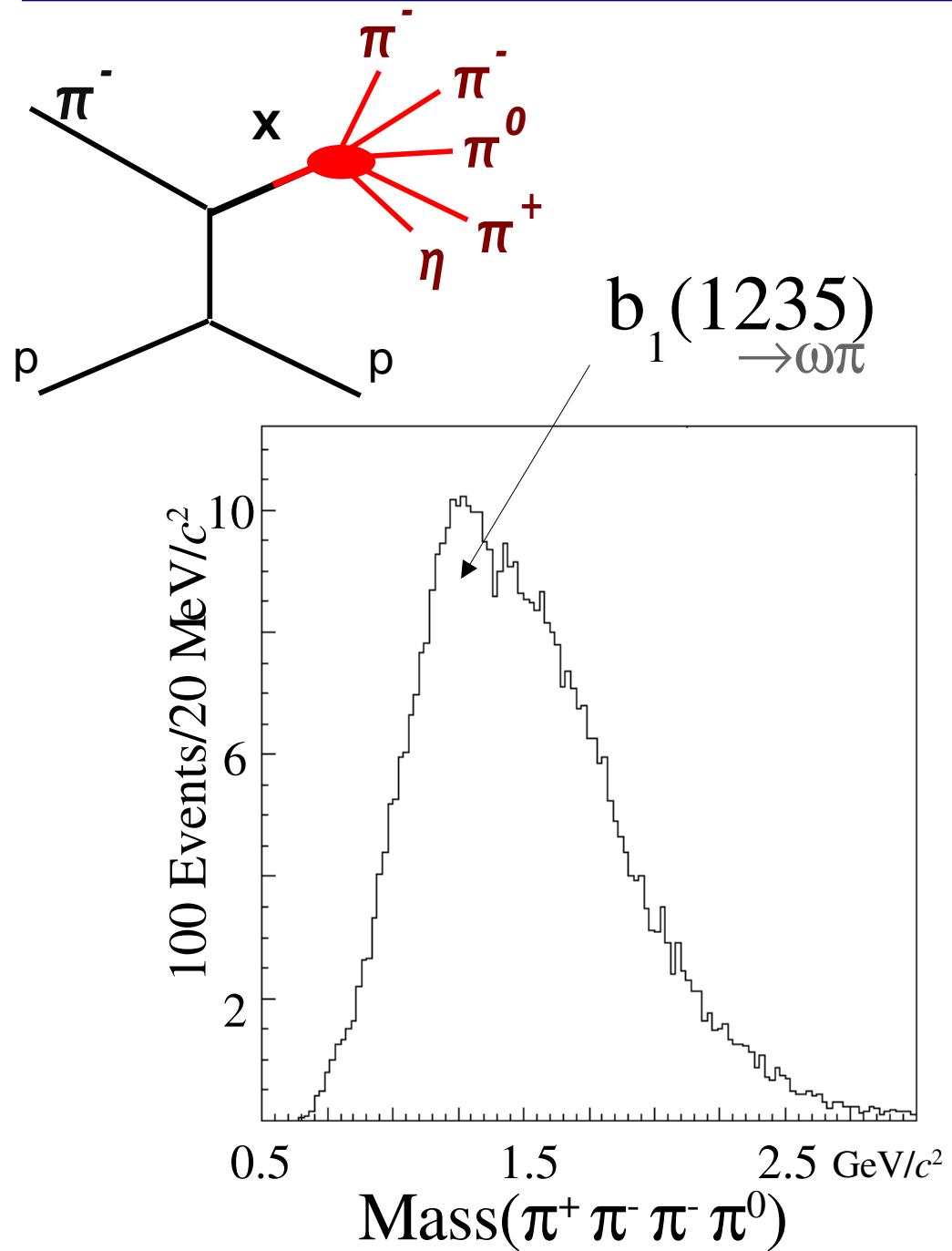


**Brookhaven Experiment 852**

Events reconstructed with:

- 4 photon clusters in LGD
- 3 forward charged particle tracks (total charge of -1) with vertex at the beam
- Consistent recoil track
- Fiducial volume (target & Lead Glass Detector) cuts
- Hadron tagging at the LDG
- CsI barrel rejection
- Kinematic fitting:  $p \pi^+ 2\pi^- \pi^0 \eta$

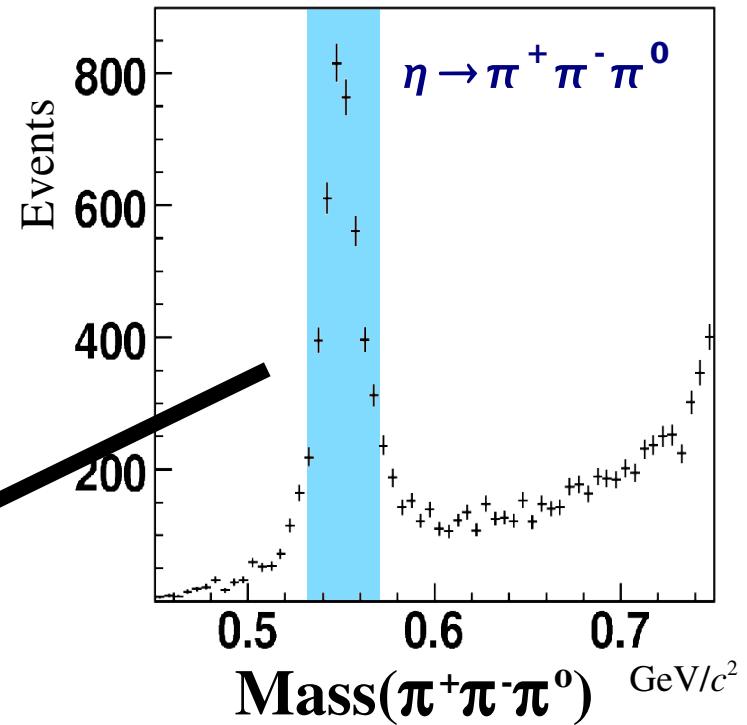
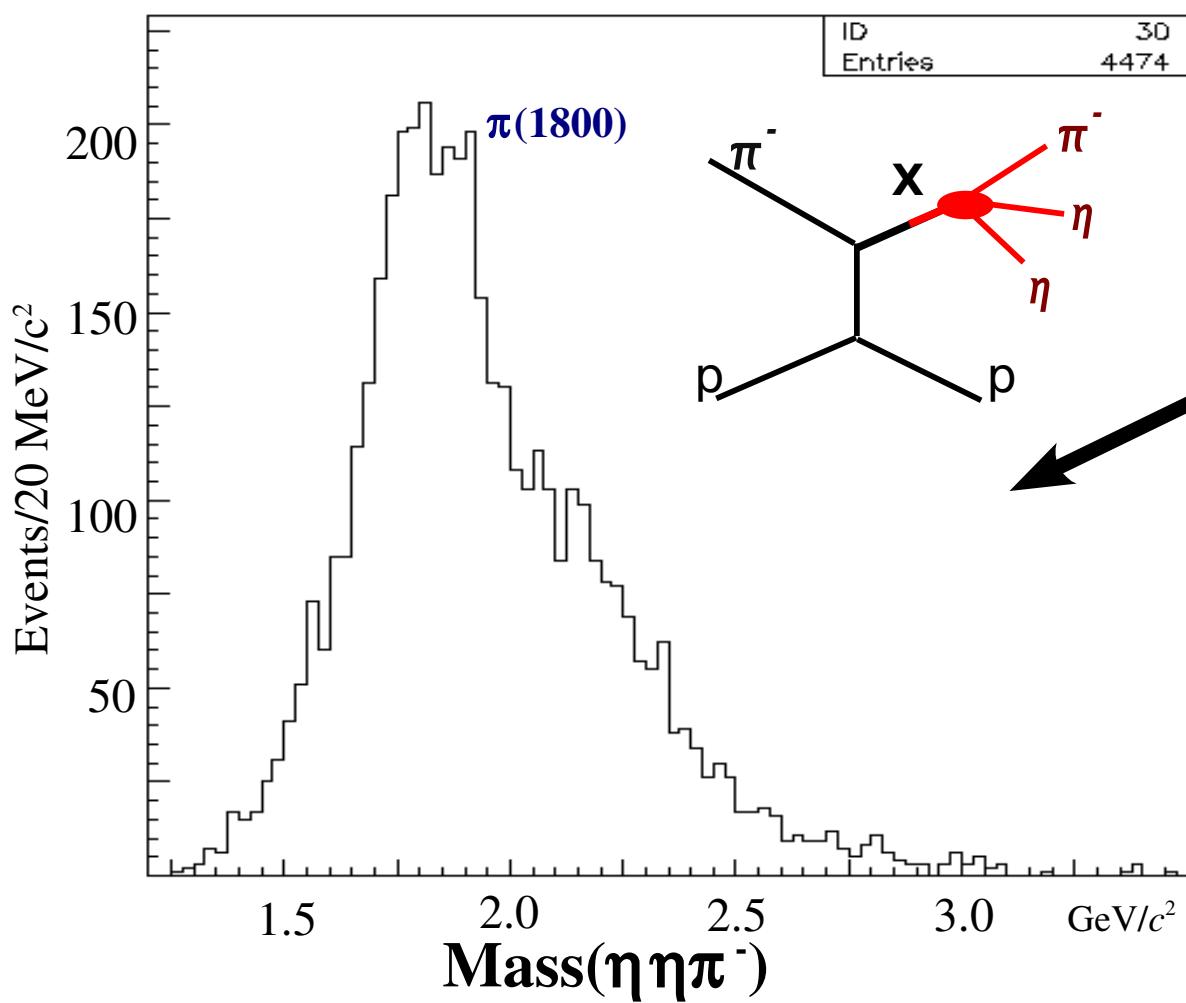
# Features of the $\pi^- p \rightarrow p \pi^+ \pi^- \pi^- \pi^0 \eta$ System



## Kinematic fitting

- ✗ 45600  $\pi^- p \rightarrow \pi^+ \pi^- \pi^- \pi^0 \eta p$  events
- ✗ Rejected  $\pi^- p \rightarrow p \pi^+ \pi^- \pi^- \pi^0 \pi^0$  ambiguous events

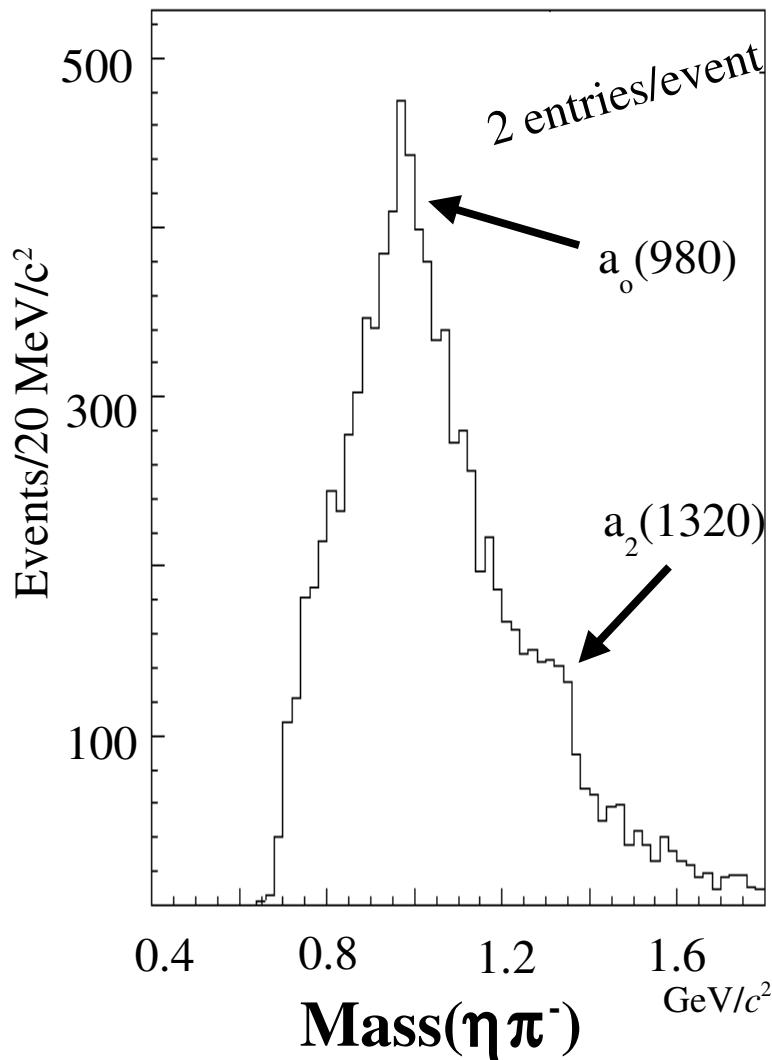
# Selecting $\eta\eta\pi^-$ from $\eta\pi^-\pi^+\pi^0\pi^-$



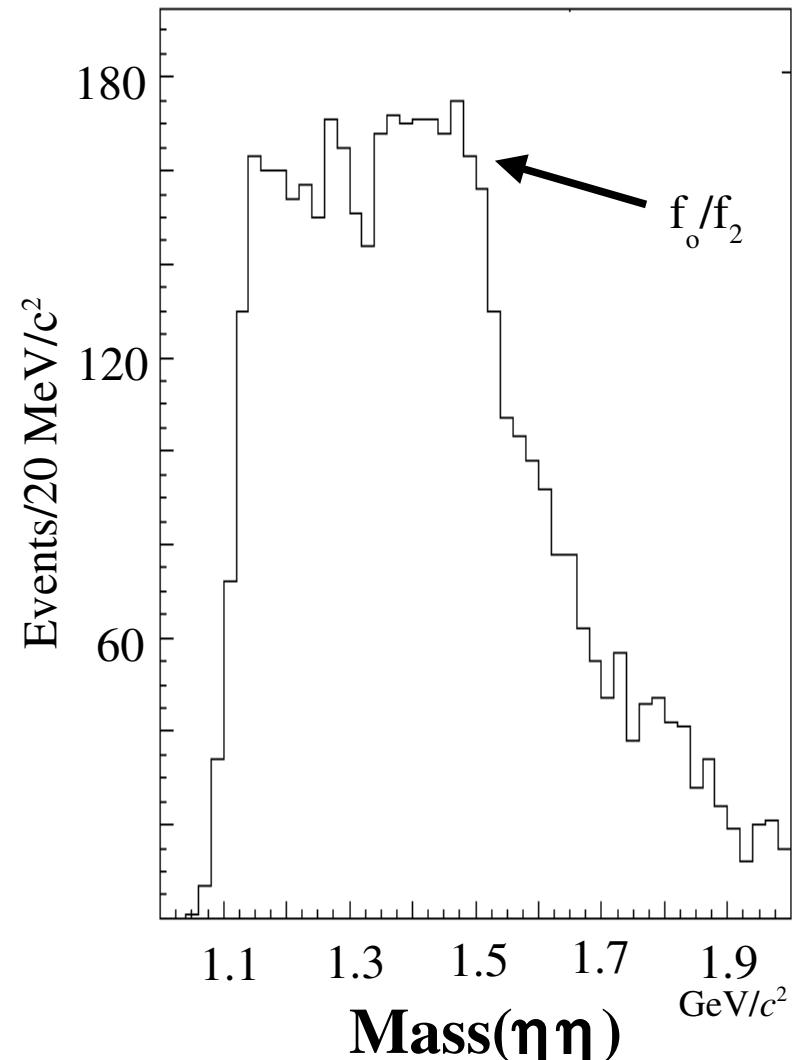
$\pi(1800)$   
First observed by VES  
Mass(1770 – 1875) MeV/ $c^2$   
Also observed by BNL-E852

# Intermediate Isobar Decays

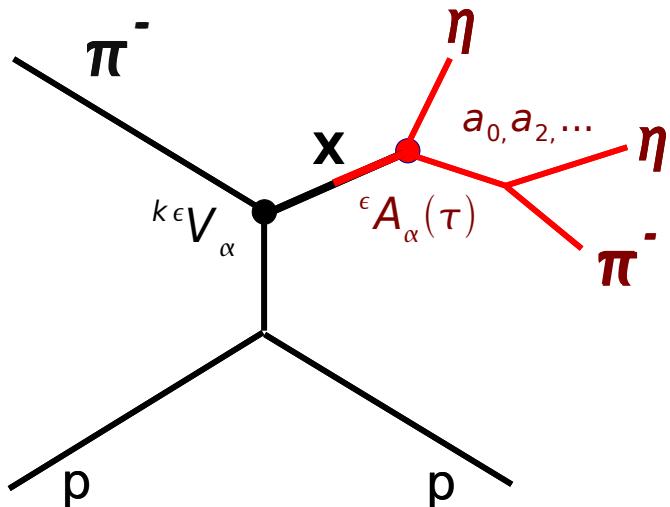
$X \rightarrow \eta [y] \rightarrow \eta [\eta \pi^-]$



$X \rightarrow [y]\pi^- \rightarrow [\eta\eta]\pi^-$



# Partial Wave Analysis



$$I(\tau) = \sum_{k\epsilon\epsilon'} \epsilon\epsilon' \rho_{\epsilon\epsilon'}(\tau) \sum_{\alpha\alpha'} {}^{k\epsilon}V_{\alpha'}^* {}^{\epsilon'}A_{\alpha'}^*(\tau) {}^{k\epsilon}V_{\alpha}^{} \epsilon A_{\alpha}(\tau)$$

For pion beam & unpolarized target:

$$I(\tau) = \frac{1}{2} \sum_{k\epsilon} \left| \sum_{\alpha} {}^{k\epsilon}V_{\alpha} \epsilon A_{\alpha}(\tau) \right|^2$$

**unknown**

Complex parameters varied in the PWA to fit the data

$$A_X^{\lambda_1\lambda_2;M} = D_{\lambda M}^J(\theta, \phi) \frac{\tilde{L}}{J}(L0; S\lambda | J\lambda)(S_1\lambda_1; S_2 - \lambda_2 | S\lambda) K$$

Wigner  
D-functions

Clebsch-Gordan  
Coefficients

Mass Dependent  
Factor

$${}^{\epsilon}A_{\alpha}(\tau) = a [A_{\alpha,M}(\tau) \pm b A_{\alpha,-M}(\tau)]$$

$$\tilde{J} = \sqrt{J(J+1)}$$

# Partial Wave Amplitudes

- Considered all Possible States with:
- ✓  $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}, 3^{++}$
- ✓  $L = S, P, D, \& F$
- ✓  $|M| \leq 1 \quad \epsilon = \pm 1$
- ✓ Isobars
  - ✓  $a_0(980)\eta, f_0(1500)^*\pi,$   
 $a_2(1320)\eta$
  - ✓  $f_0(1300)\pi, f_2(1270)\pi$

<sup>†</sup>Mass=1480 $\pm$ 25 MeV  $\Gamma=120\text{ }^{+50}_{-30}$  MeV

Maximum-Likelihood Fitting in  
50 MeV/c<sup>2</sup>  $\eta\eta\pi^-$  mass bins

Acceptance Correction via MC

- Minimal set of waves

$J^{PC}M^\epsilon L$  (isobar decay)

$0^{-+}0^+S \ a_0(980)\eta$

$0^{-+}0^+S \ f_0(1500)\pi$

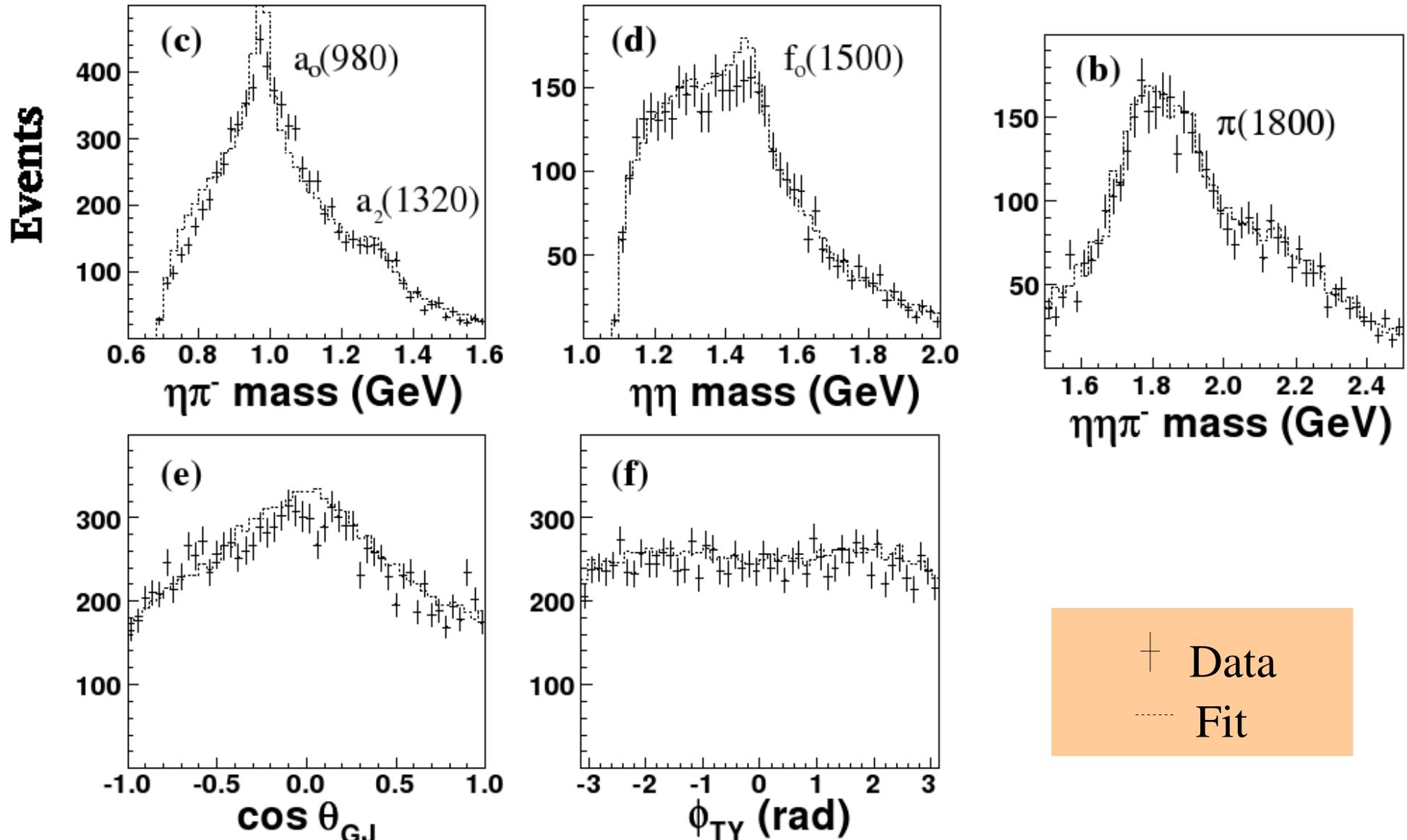
$2^{-+}0^+S \ a_2(1320)\eta$

$2^{-+}0^+D \ a_0(980)\eta$

background

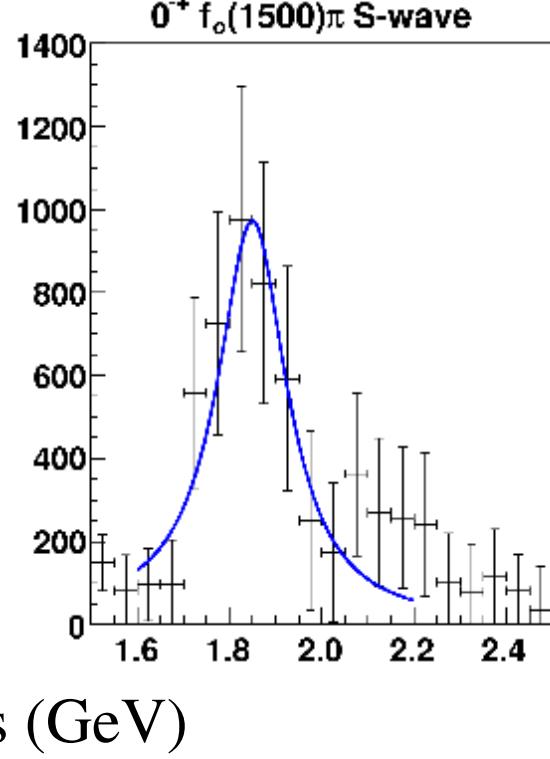
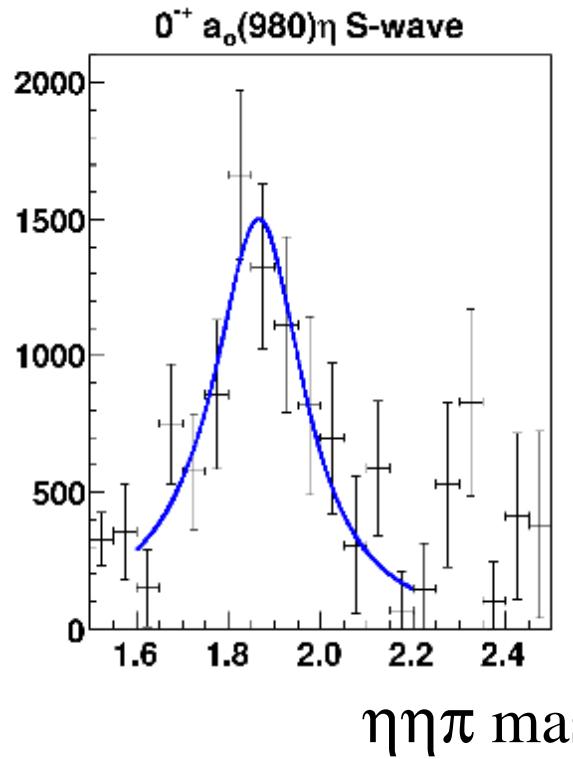
# Quality of the PWA Fit

*The quality of the fit was judged by comparing data distributions with PWA spin-density matrix weighted Monte Carlo events.*



# The $J^{PC} = 0^{++}$ $\pi(1800) \rightarrow \eta\eta\pi^-$

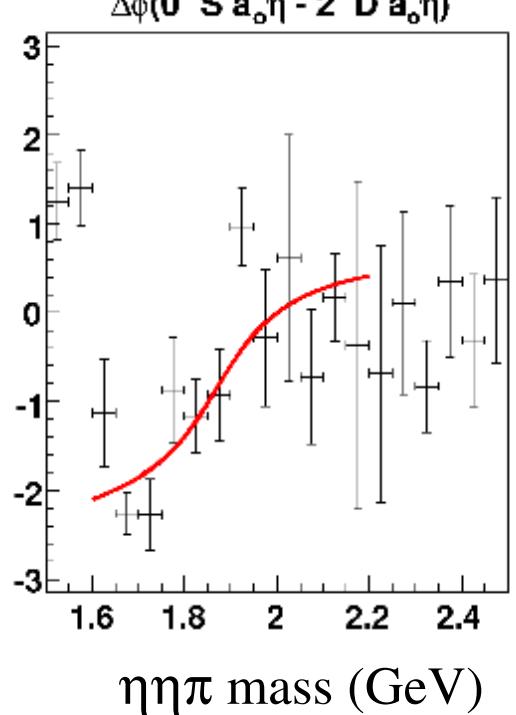
## Partial Wave Intensities



smooth lines show results of mass-dependent relativistic Breit-Wigner  $\chi^2$  fits

parameters of the  $\pi(1800)$   
 $M = 1876 \pm 18 \pm 16$  MeV/c<sup>2</sup>,  $\Gamma = 221 \pm 26 \pm 38$  MeV/c<sup>2</sup>  
 $\chi^2/\text{dof} = 23.9/20$

## Partial Wave Phase Difference



# Relative Branching Ratio for $\pi(1800)$

The fitted Breit-Wigner shapes were integrated to determine the predicted number of events for each state

The following branching ratio was obtained

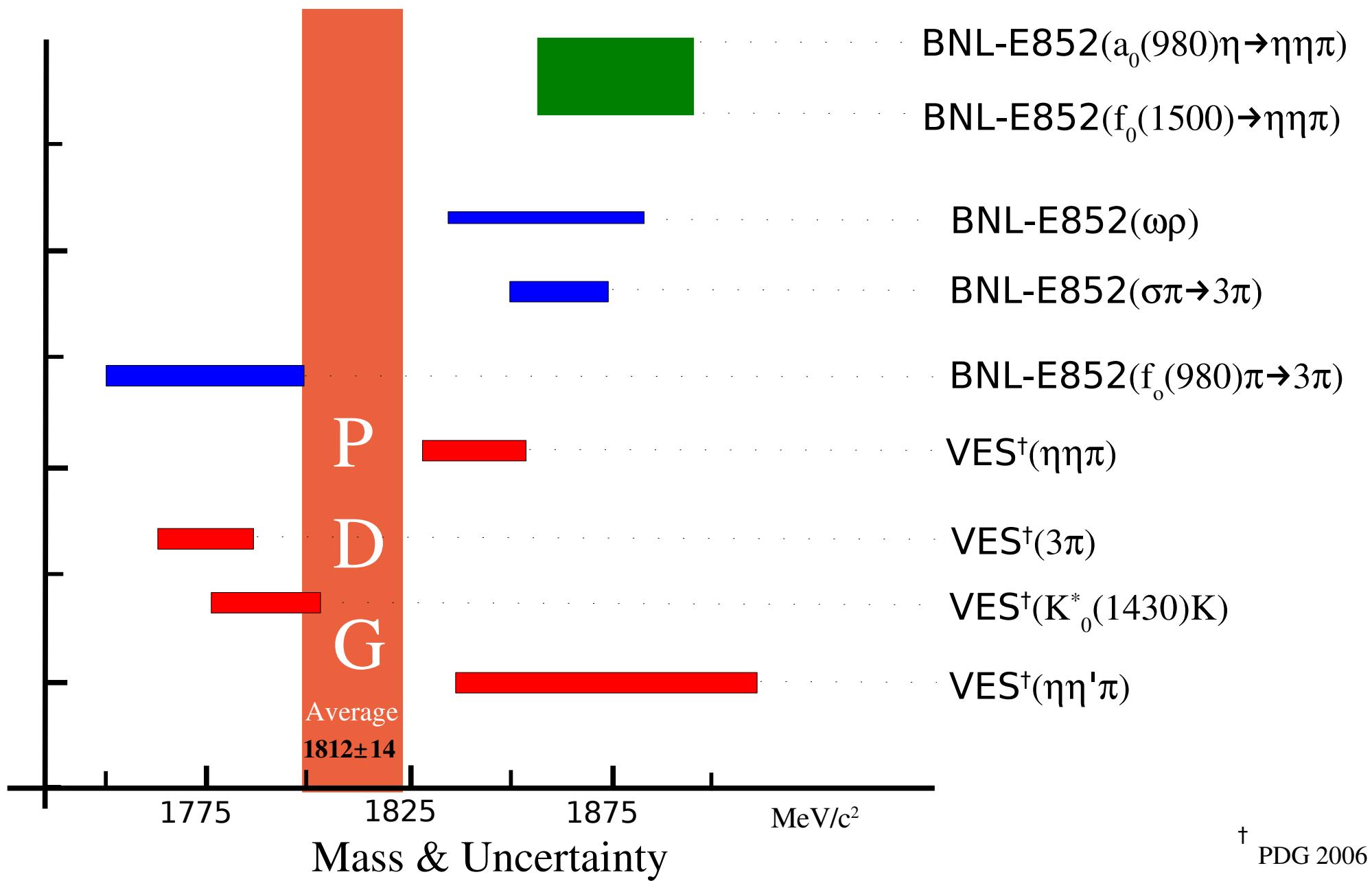
$$\frac{BR[\pi(1800) \rightarrow f_0(1500)\pi, f_0 \rightarrow \eta\eta]}{BR[\pi(1800) \rightarrow a_0(980)\eta, a_0 \rightarrow \eta\pi]} = 0.48 \pm 0.17$$

A similar value of  $0.40 \pm 0.15$  was obtained in a different maximum-likelihood PWA fit in which the branching ratio itself was one of the fitted parameters

In both cases our value is higher than the value determined by  
VES<sup>†</sup> [ Ratio =  $0.08 \pm 0.03$  ]

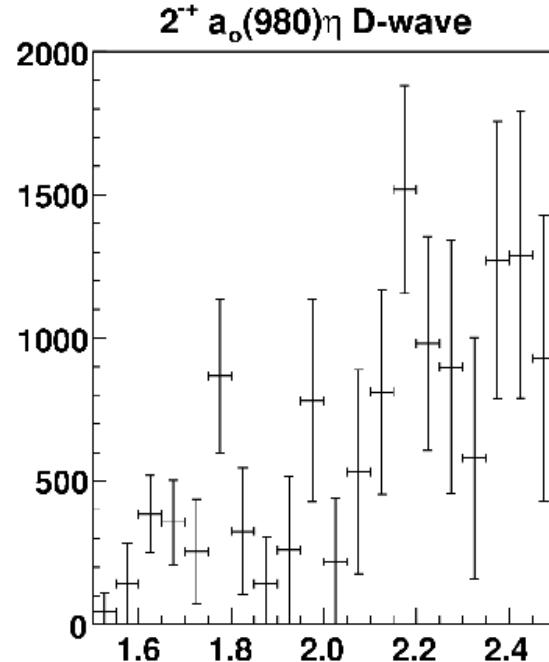
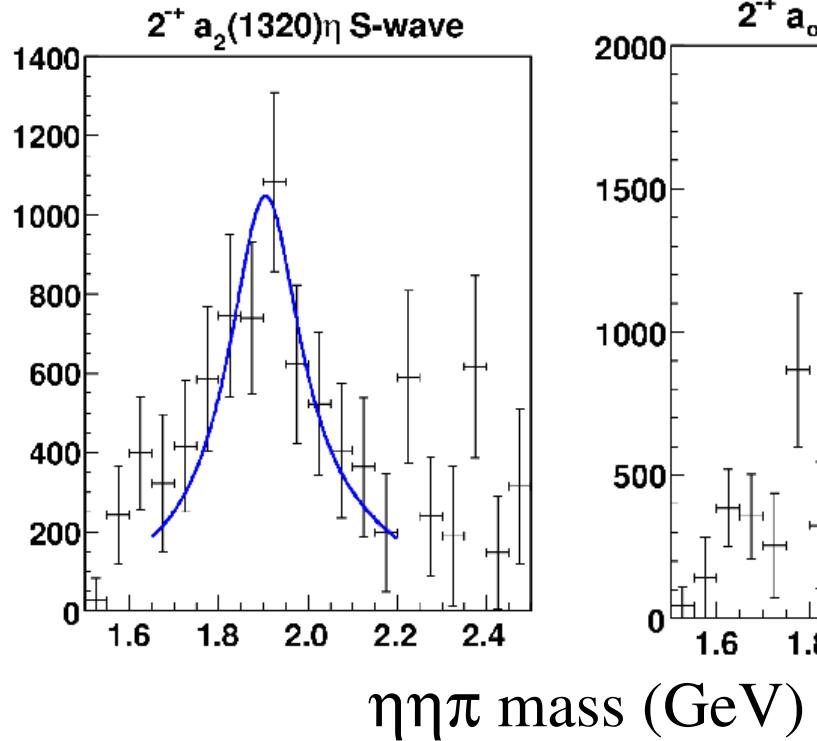
<sup>†</sup> Phys. At. Nucl. 59, 976 (1996)

# The Mass of the $\pi(1800)$



# The $J^{PC} = 2^{-+}$ $\pi_2$ Waves

## Partial Wave Intensities



with  $\pi(1800)$  parameters fixed, the intensity of the  $2^+ a_2 \eta$  wave and its phase relative to the  $0^+ a_0 \eta$  wave were fitted

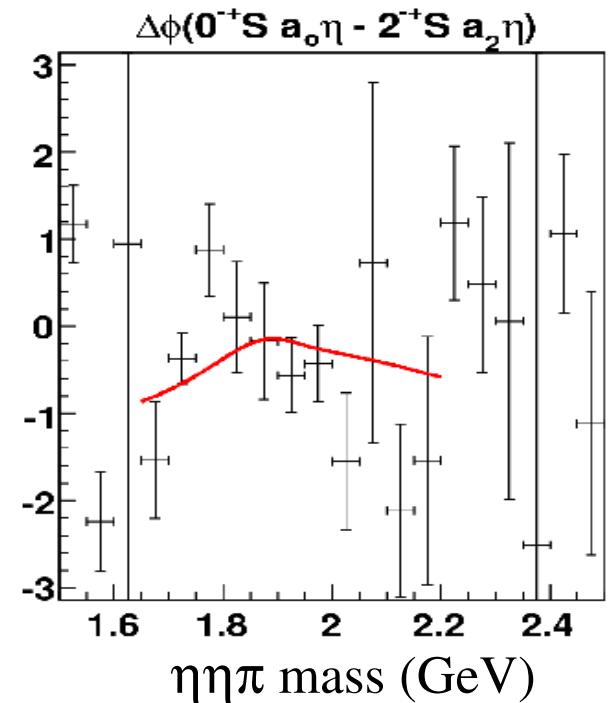
parameters of the  $\pi_2(1880)$

$$M = 1929 \pm 24 \pm 18 \text{ MeV}/c^2, \quad \Gamma = 323 \pm 87 \pm 43 \text{ MeV}/c^2$$

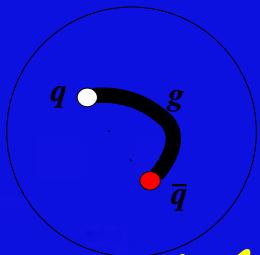
$$\chi^2/\text{dof} = 19.9/18$$

***Observation of***  
 ***$\pi_2(1880)$***

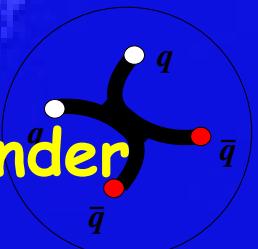
Partial Wave  
Phase Difference



# Summary



- A partial-wave analysis of the reaction  $\pi^- p \rightarrow \eta\eta\pi^- p$  at 18 GeV/c was performed on a data sample of ~4,000 events
- The  $J^{PC} = 0^{-+}$   $\pi(1800)$  state is observed in the  $a_0(980)\eta$  and  $f_0(1500)\pi$  decay modes
  - ◆ mass of  $1876 \pm 18 \pm 16$  MeV/c<sup>2</sup> and width of  $221 \pm 26 \pm 38$  MeV/c<sup>2</sup>
  - ◆ relative branching ratio of  $\frac{BR[\pi(1800) \rightarrow f_0(1500)\pi, f_0 \rightarrow \eta\eta]}{BR[\pi(1800) \rightarrow a_0(980)\eta, a_0 \rightarrow \eta\pi]} = 0.48 \pm 0.17$
- The  $J^{PC} = 2^{-+}$   $\pi_2(1880)$  meson is observed decaying through  $a_2(1320)\eta$ 
  - ◆ mass of  $1929 \pm 24 \pm 18$  MeV/c<sup>2</sup> and width of  $323 \pm 87 \pm 43$  MeV/c<sup>2</sup>
- Both states are potential candidates for non-exotic hybrid mesons
- These results have been submitted to PLB & are under review



# Is the $\pi(1800)$ a Gluonic Hybrid?

*Hybrid*  $\rightarrow q\bar{q}(L=1) + q\bar{q}(L=0)$

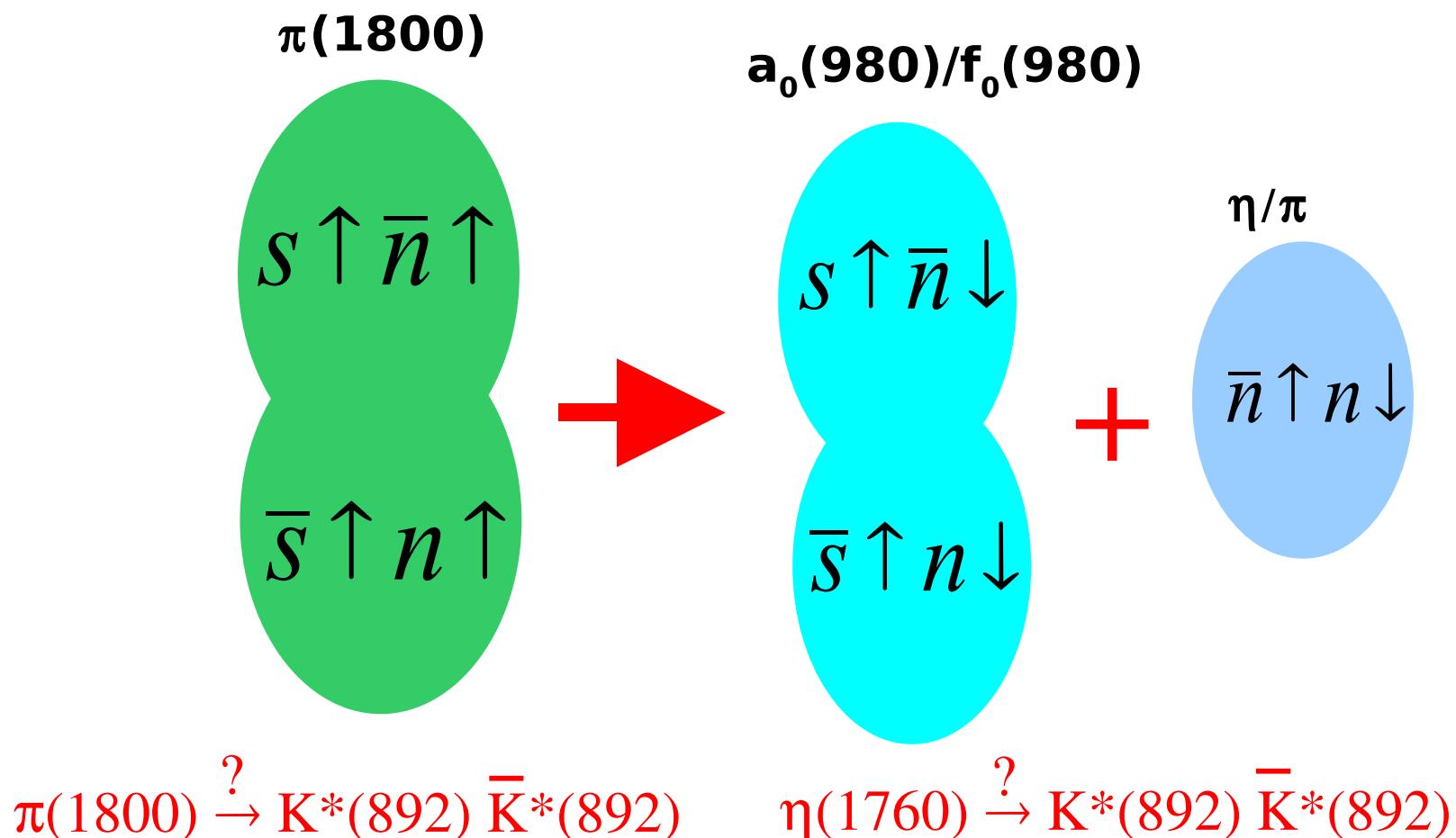
$\pi(1800) \rightarrow f_0(980)\pi$	✓ ?
$\rightarrow \sigma \pi [f_0(1370)\pi]$	✓ ?
$\rightarrow f_0(1500)\pi$	✓ ?
$\rightarrow a_0(980)\eta$	✓ ?
$\rightarrow \omega\rho$	✗
$\rightarrow \eta\eta'\pi$	
$\rightarrow K_0^*(1430)K$	✓

*Hybrid*  $\rightarrow q\bar{q}(L=0) + q\bar{q}(L=0)$

$\pi(1800) \rightarrow \rho\pi$	✓
$\rightarrow K^*K$	✓

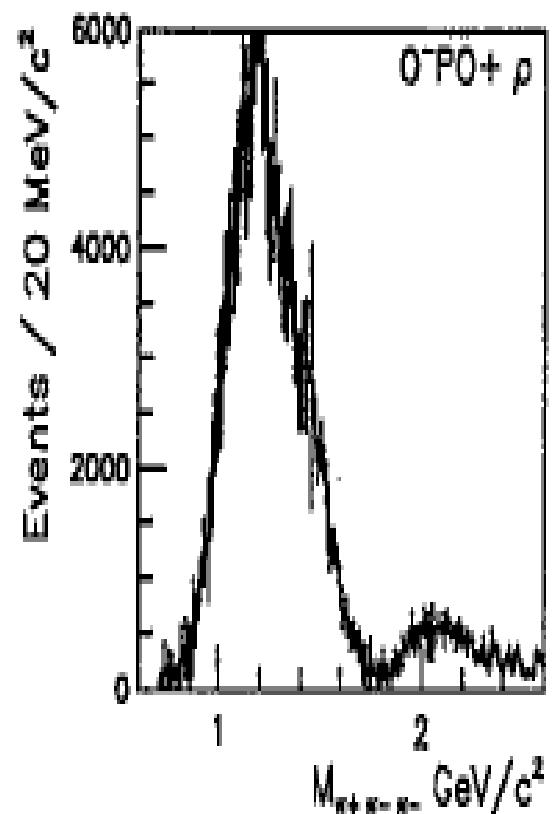
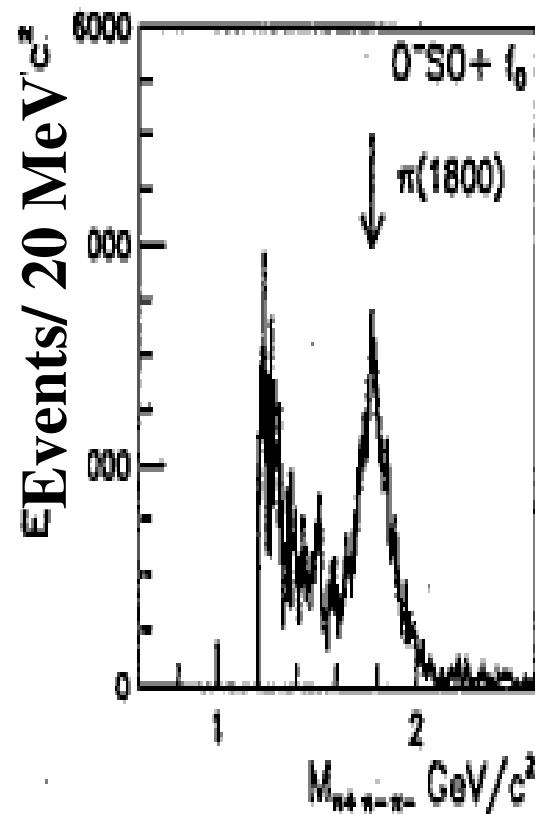
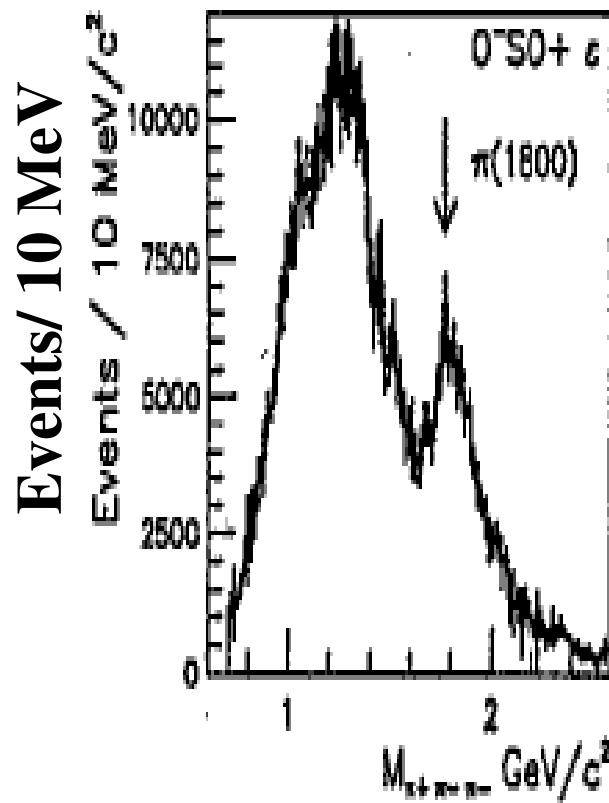
$\pi(1800)$  is not likely a  $qq$  meson, and probably not a hybrid meson either

The  $\pi(1800)$  could be a Multiquark or  
 $K^*(892)\bar{K}^*(892)$  Molecule similar to  
the  $a_0(980)/f_0(980)$



# $\pi(1800) \rightarrow \pi^+ \pi^- \pi^-$

$M = 1775 \pm 7 \pm 10 \text{ MeV}/c^2$   
 $\Gamma = 190 \pm 15 \pm 15 \text{ MeV}/c^2$



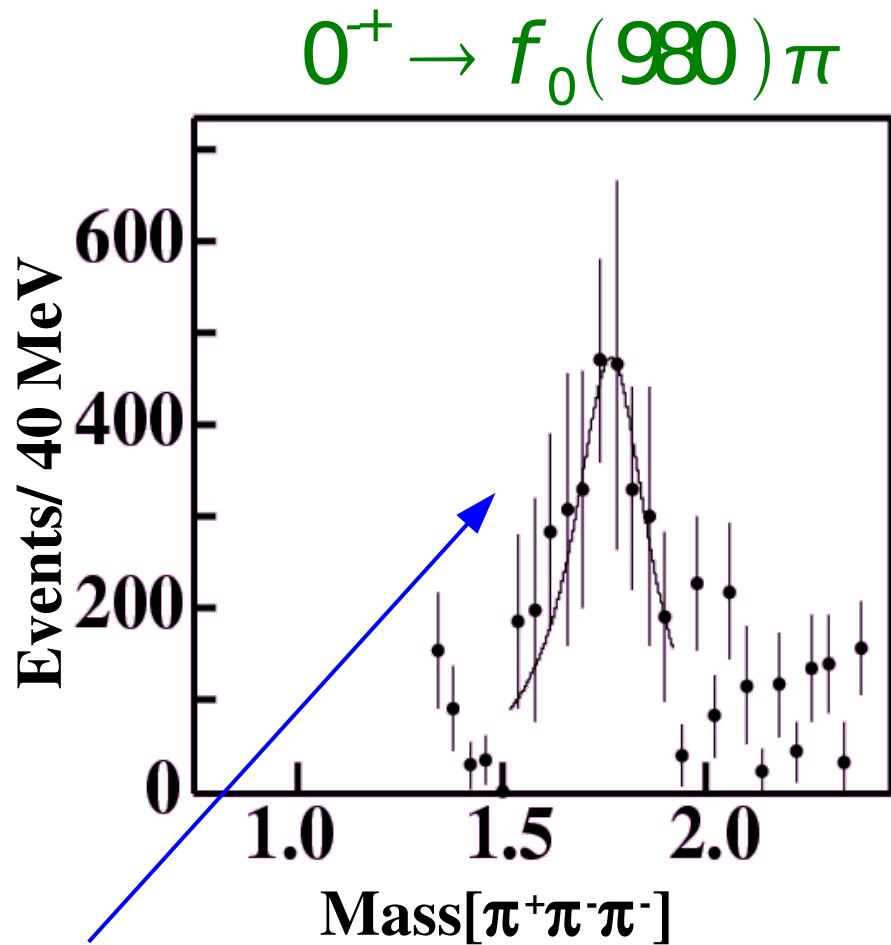
Study of resonance production in diffractive reaction  $\pi^- A \rightarrow \pi^+ \pi^- \pi^- A$ .

By VES Collaboration (D.V. Amelin et al.)

Phys.Lett.B356:595-600,1995.

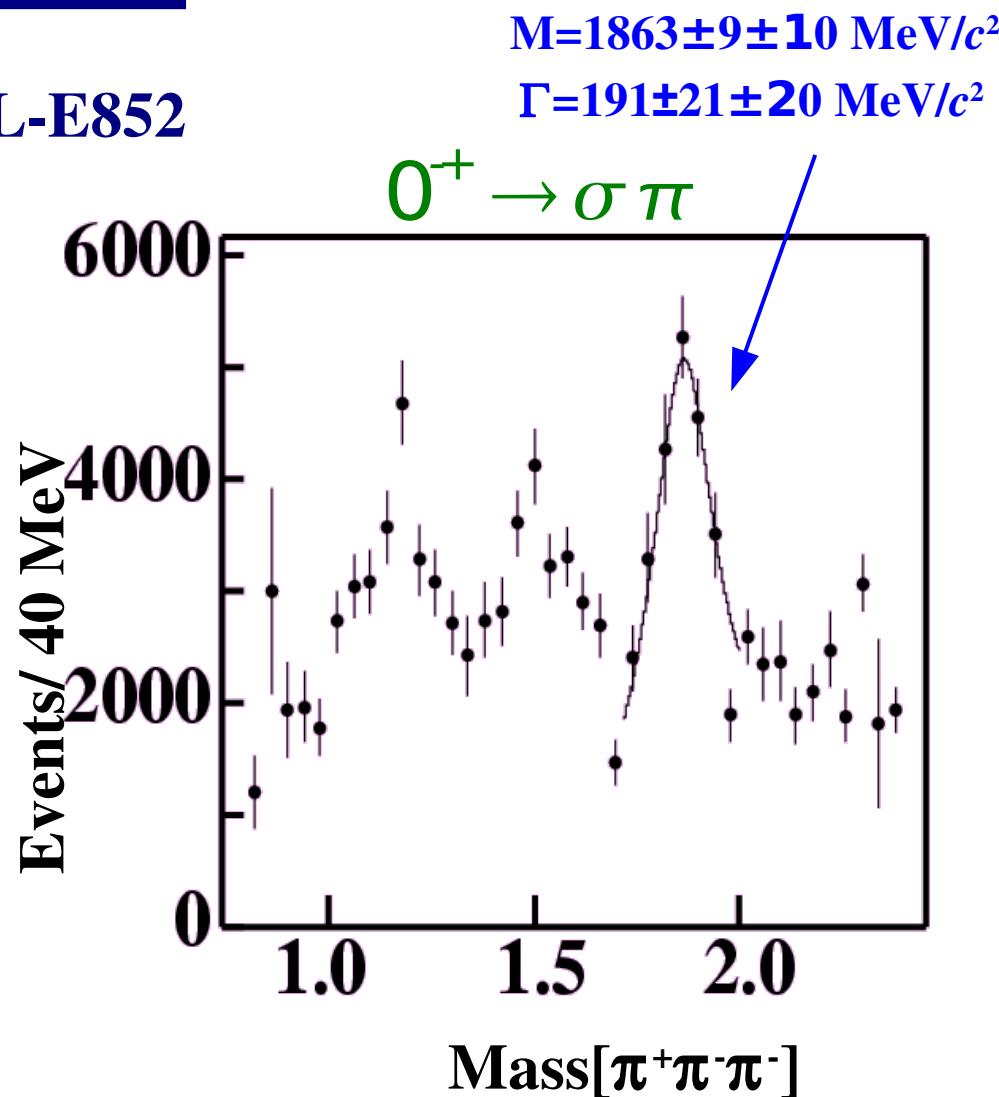
$\pi(1800) \rightarrow \pi^+ \pi^- \pi^-$

$\pi(1800) \not\rightarrow \rho \pi$



$M = 1774 \pm 18 \pm 20 \text{ MeV}/c^2$   
 $\Gamma = 223 \pm 48 \pm 50 \text{ MeV}/c^2$

BNL-E852



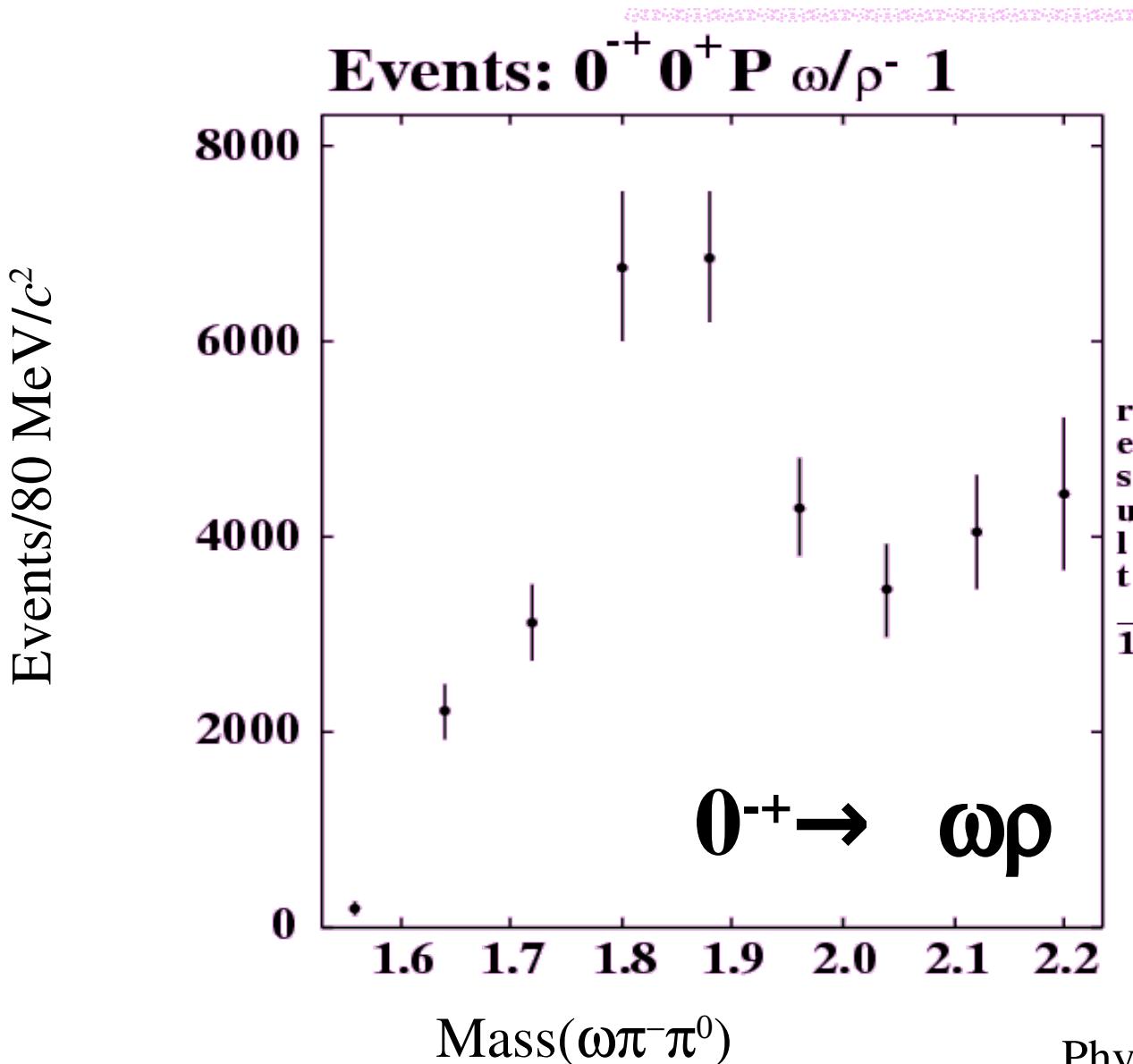
$M = 1863 \pm 9 \pm 10 \text{ MeV}/c^2$

$\Gamma = 191 \pm 21 \pm 20 \text{ MeV}/c^2$

$$\frac{\mathcal{BR} [\pi(1800) \rightarrow f_0(980)\pi, f_0 \rightarrow \pi\pi]}{\mathcal{BR} [\pi(1800) \rightarrow \sigma\pi, \sigma \rightarrow \pi\pi]} = 0.44 \pm 0.08 \pm 0.38$$

# $\pi(1800) \rightarrow \omega\rho$

BNL-E852



120k events; 27 waves

Same PWA as  $b_1\pi$

$J^{PC} = 0^{-+}$

$M = \sim 1850 \text{ MeV}/c^2$

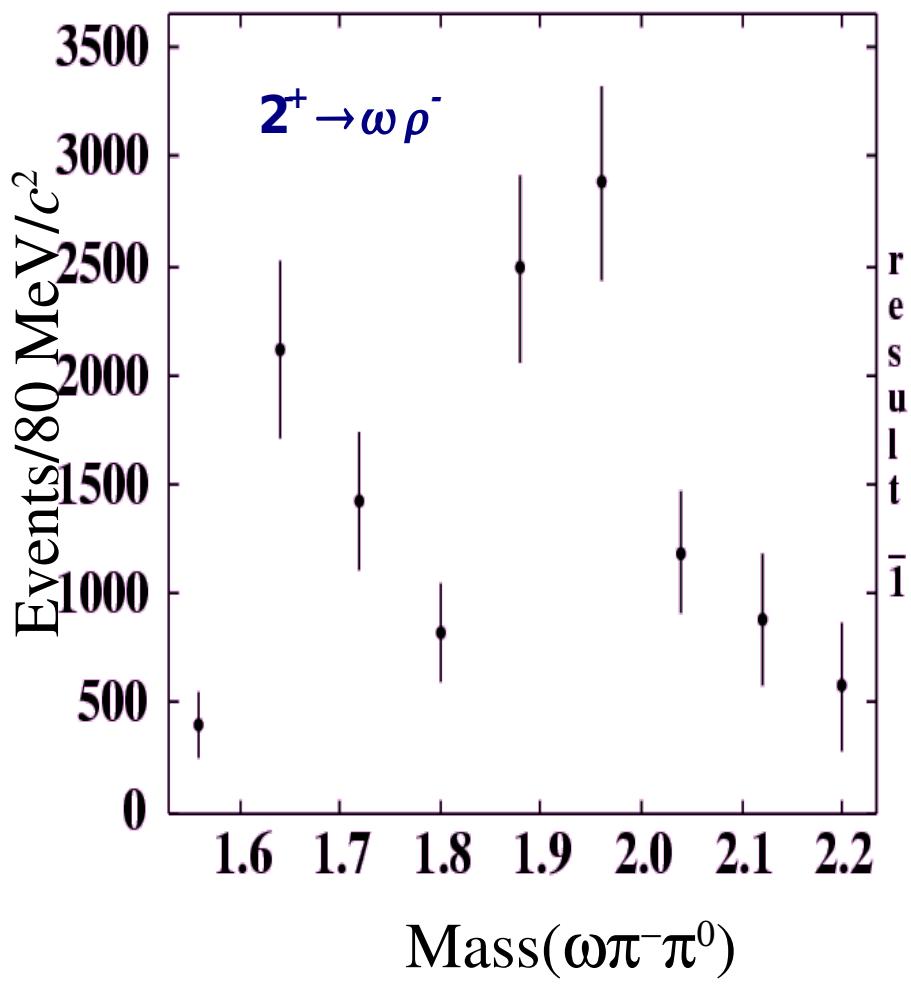
$\Gamma = \sim 250 \text{ MeV}/c^2$

# $\pi_2(1880)$ observed at BNL

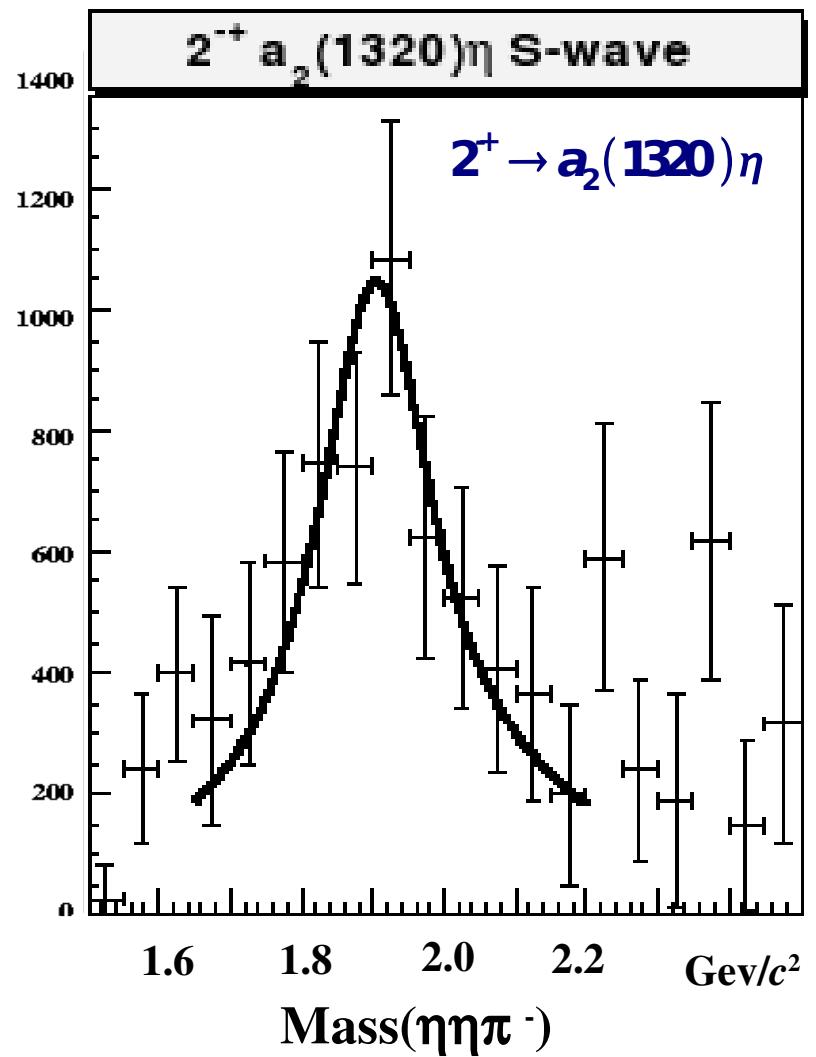
BNL-E852

$\pi^- p \rightarrow p\pi_2(1900) \rightarrow p\omega\pi\pi$

Events:  $2^+ 0^+ P$   $\omega/\rho^- 1$



$\pi^- p \rightarrow p\pi_2(1900) \rightarrow p\eta\eta\pi^-$



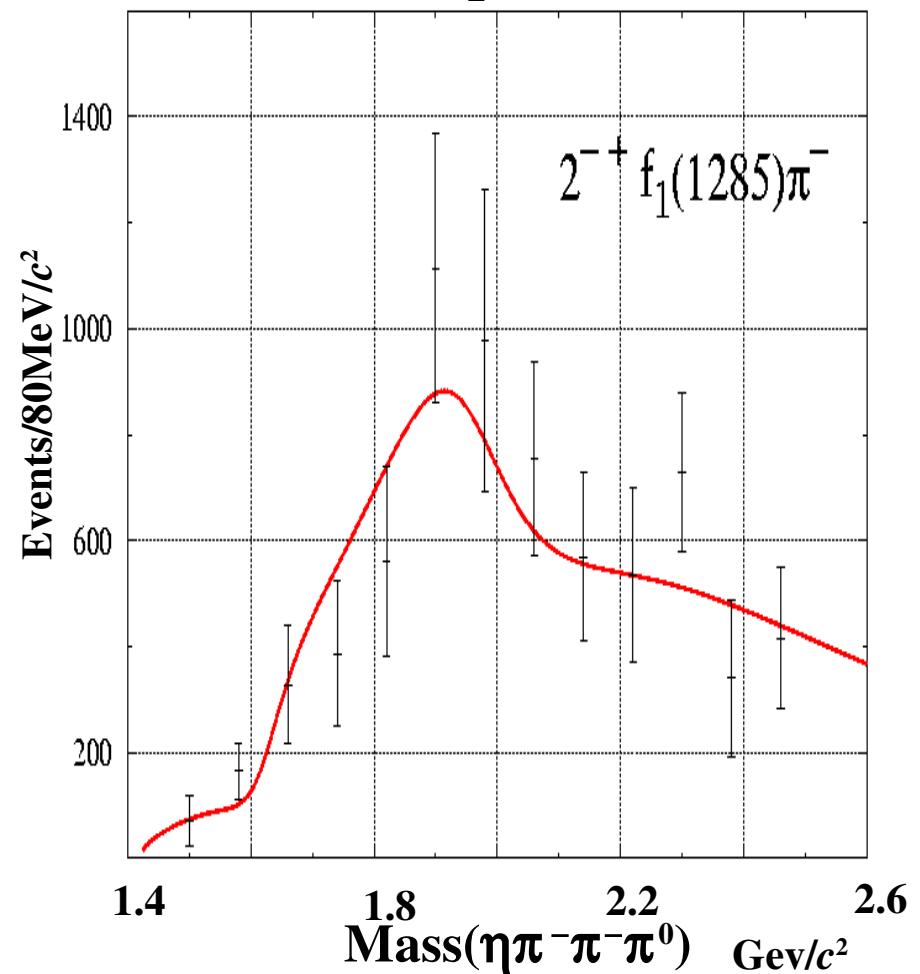
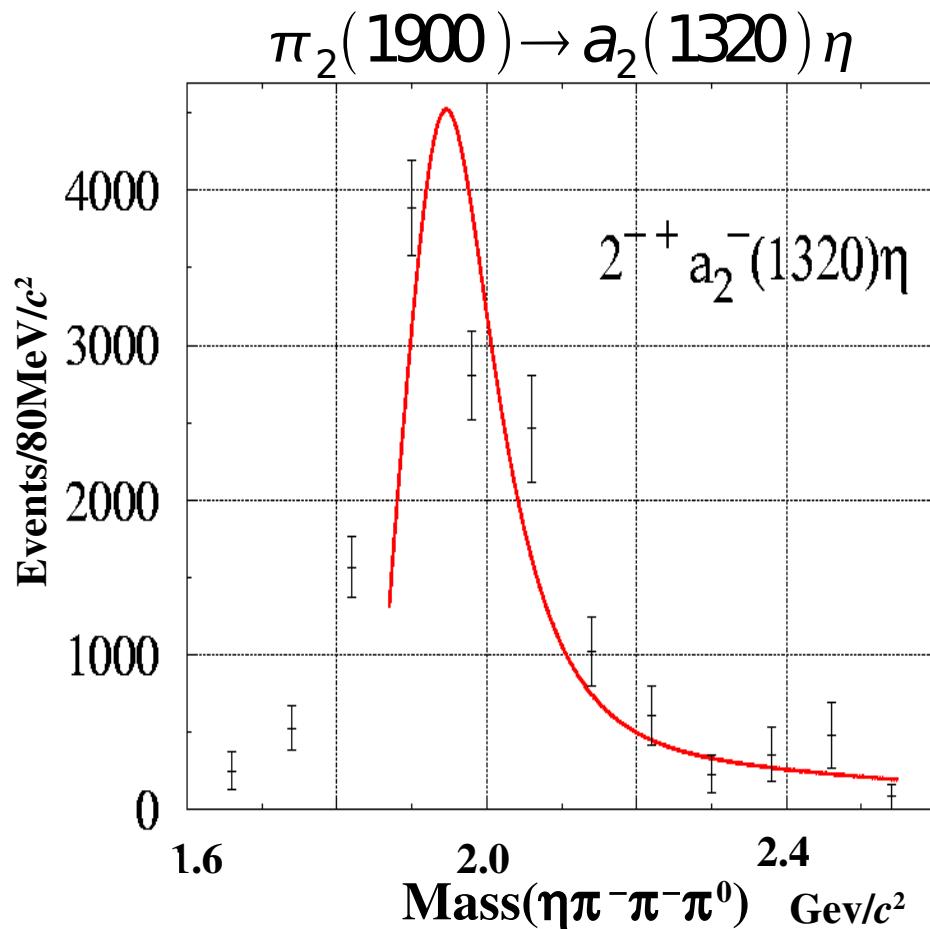
# $\pi_2(1900) \rightarrow \eta \pi^+ \pi^- \pi^0$

BNL  
E852

$M \sim 2000 \pm 100 \text{ MeV}/c^2$   
 $\Gamma \sim 300 \pm 150 \text{ MeV}/c^2$

$$2^+ \rightarrow f_1(1285)\pi$$

$$R = \frac{BR[\pi_2(1900) \rightarrow a_2(1320)\eta]}{BR[\pi_2(1900) \rightarrow f_1(1285)\pi]} \sim 38$$



Flux Tube Model Prediction  
 $R = 23$

P. Page *et al.*, Phys. Rev. D59, 34016 (1999)