Properties of the $\pi_1(1600)$ from BNL/E852 D. Weygang

The $J^{PC}=1^{-+}$ Exotic Spectrum from BNL/E852

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for the E852 Collaboration

E852: Multi-Particle Spectrometer 18 GeV/c π^- on LH_2 target

Data Runs: 1994, 1995, 1997, 1998 Cerenkov detector for π/K separation

$\pi_1(1400)$: $\eta\pi^-$

$\pi_1(1600)$: $\rho\,\pi$, $\eta'\,\pi$, $f_1(1285)\,\pi$, $b_1(1235)\,\pi$ Preliminary

$\pi_1(2000)$: $f_1(1285)\,\pi$, $b_1(1235)\,\pi$

Light Quark Hybrid Mass and Decays

Light Quark $J^{PC}=1^{-+}$ Lattice Mass

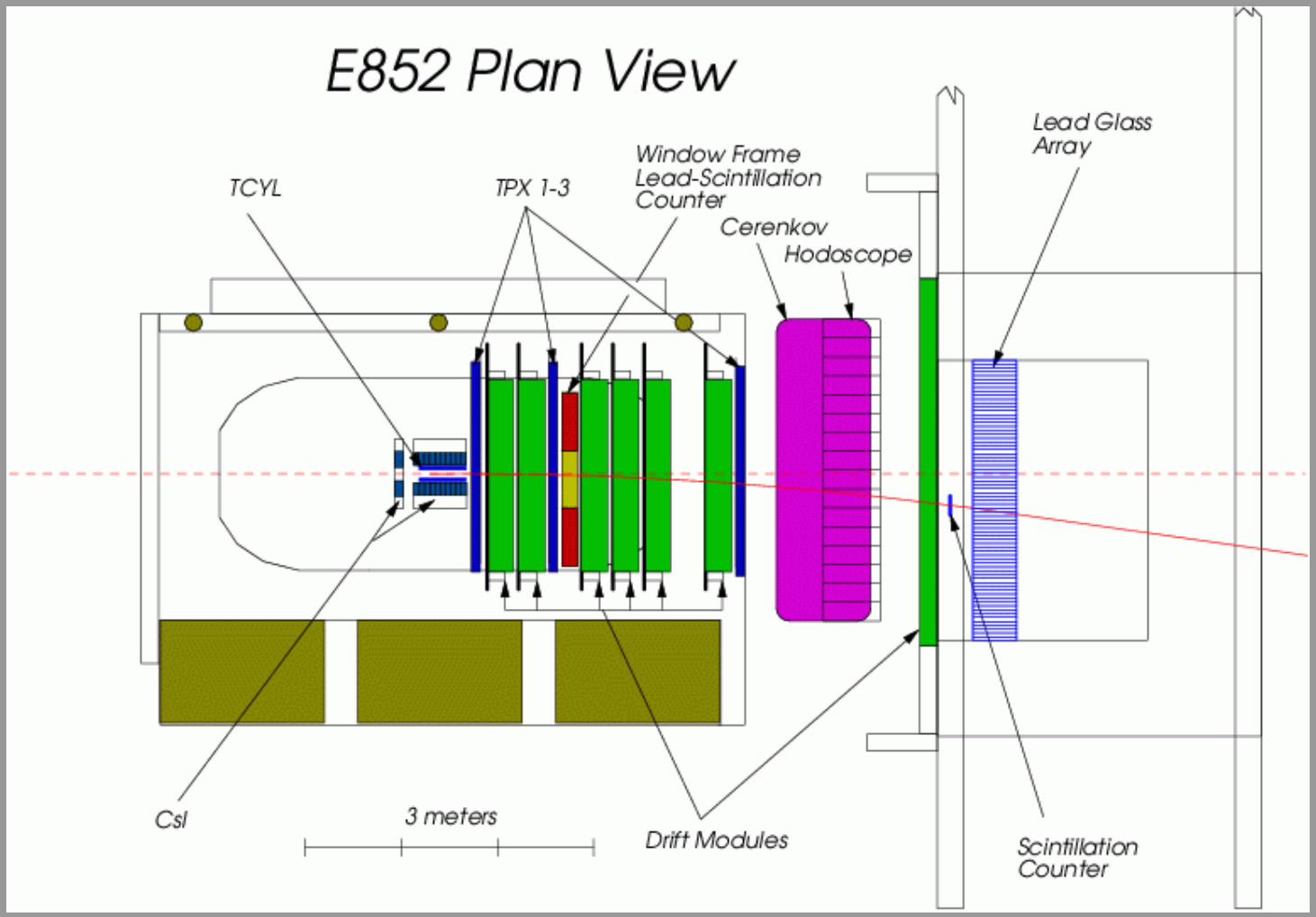
Collaboration	Mass (GeV/c^2)	
UKQCD '97	1.87	Lacock *et al.*, Phys. Lett. **B401**, 308.
MILC '97	1.97	Bernard *et al.*, Phys. Rev. **D56**, 7039.
MILC '99	2.11	Bernard *et al.*, Nucl. Phys. B **73**, 264.
Lacock&Schilling	1.9	Lacock & Schilling, Nucl. Phys. B **73**, 261.

Light Quark $J^{PC}=1^{-+}$ Flux-Tube $^3P_0$ Branching Ratio

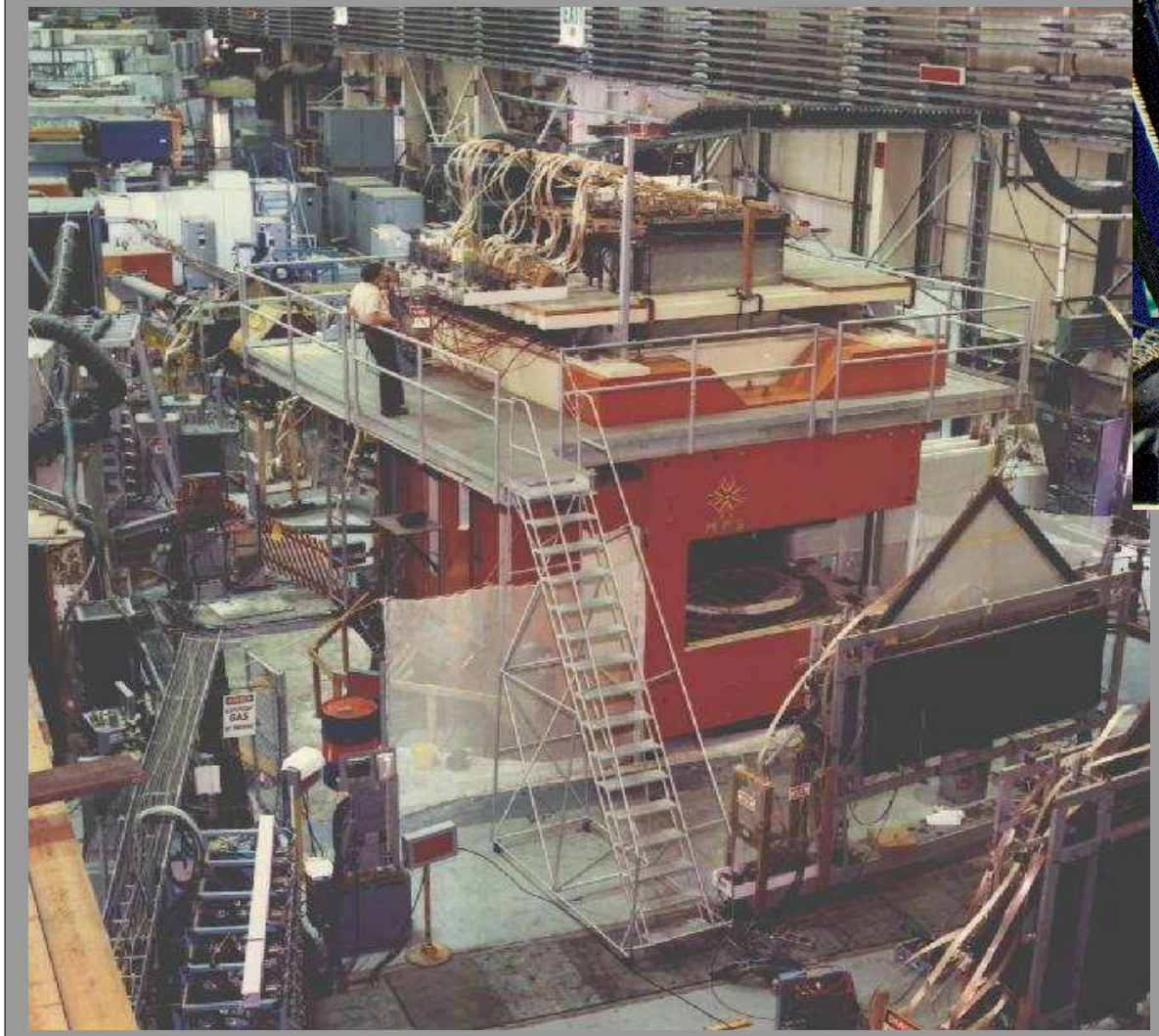
$f_1\pi$	$b_1\pi$	$\rho\pi$	$\eta\pi$	$\eta'\pi$
60	170	5-20	0-10	0-10

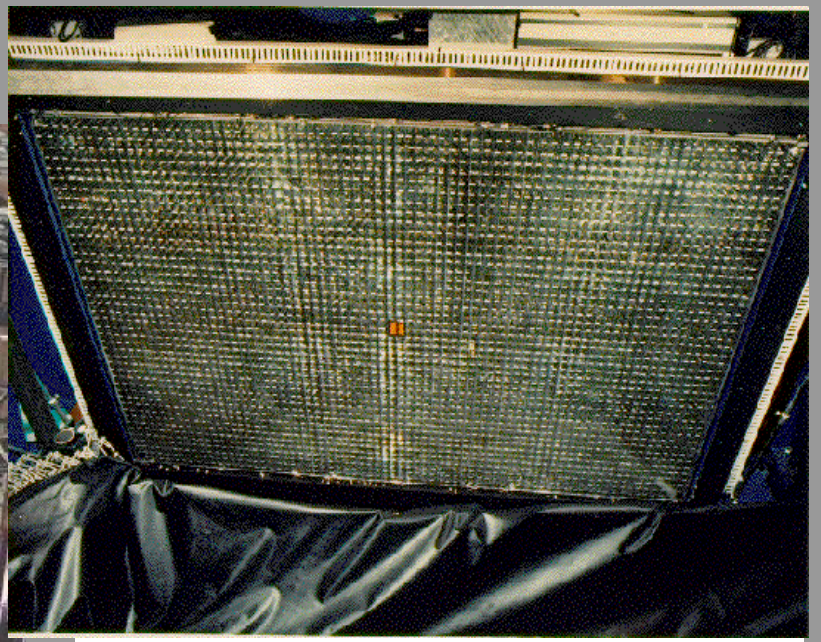
Close & Page, Nucl. Phys. B **443**, 233 (1995)

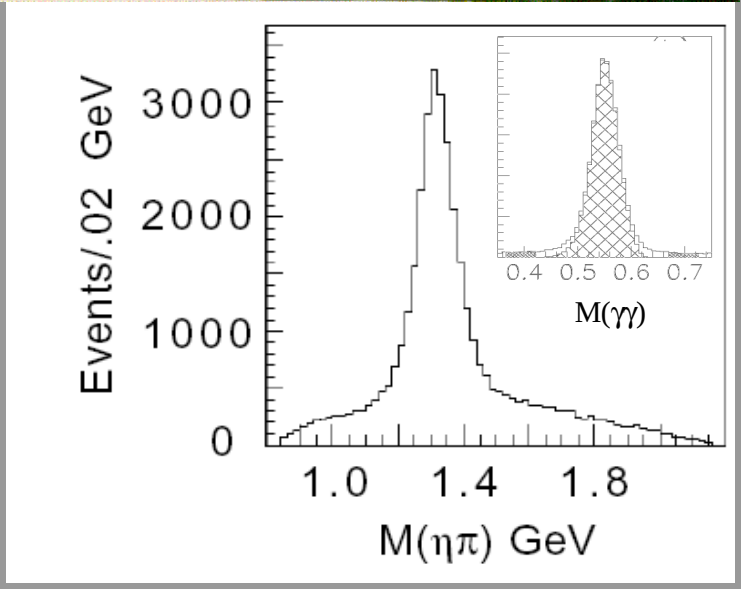
E852: MPS/Pb Glass/Cerenkov Counter



E852 (1994-1998) Brookhaven Multi-Particle Spectrometer



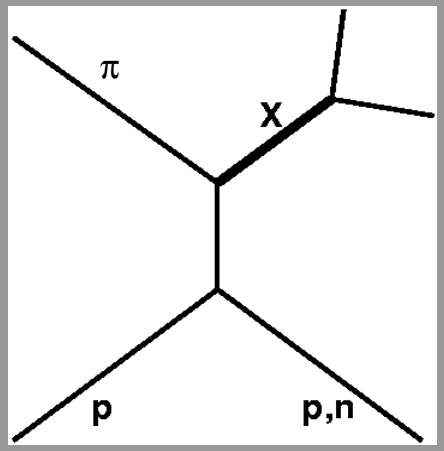


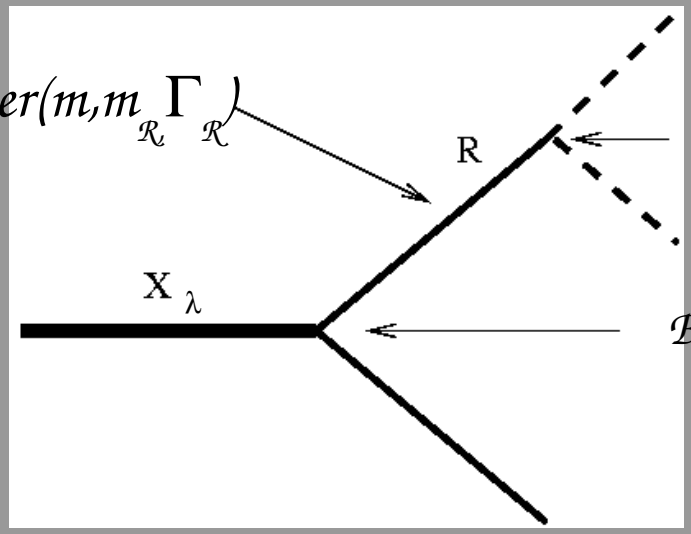


Partial Wave Analysis Formalism

Angular Distributions:

$$I(\tau) = \sum_{\epsilon k} \sum_{X} \left| \right|^2$$



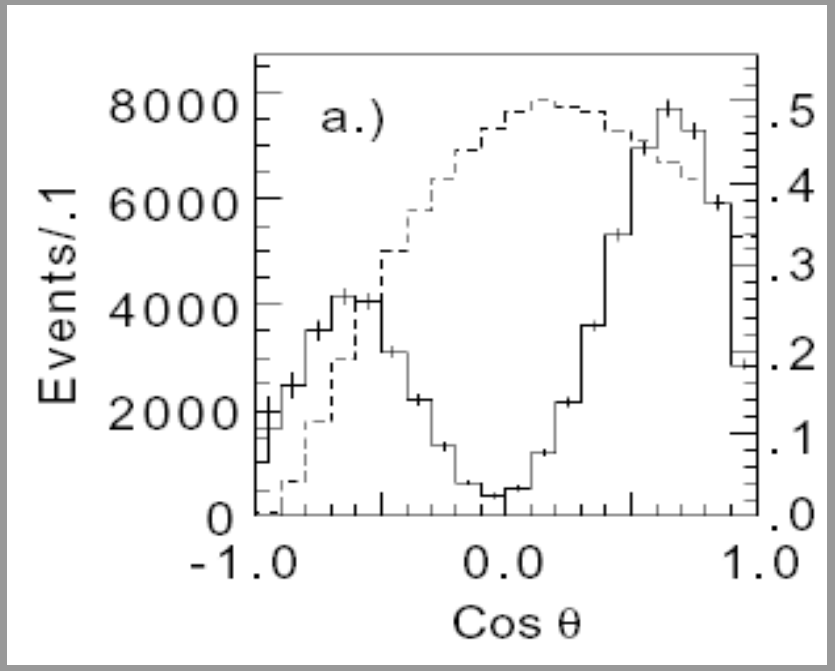


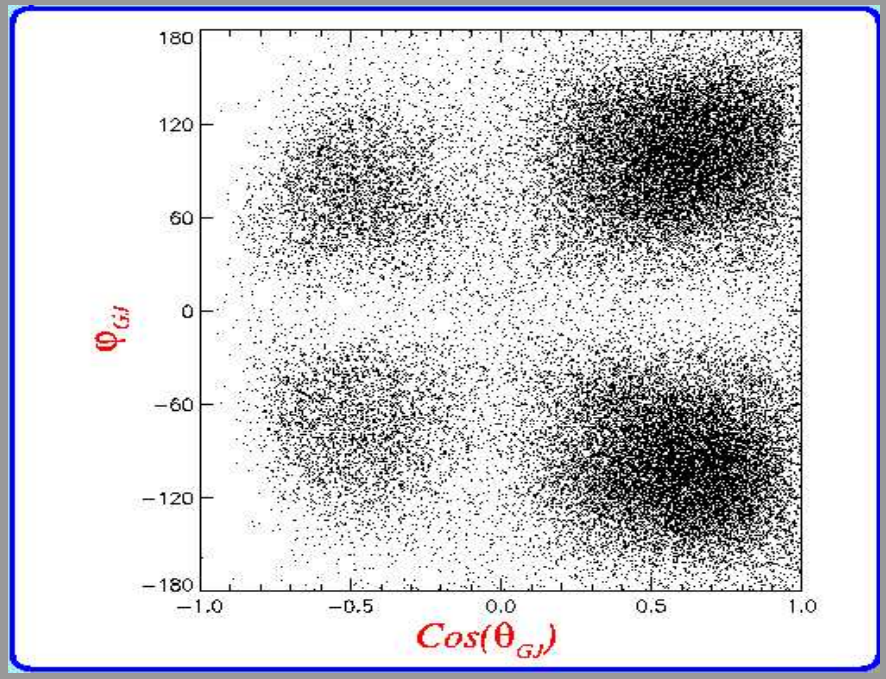
Breit-Wigner$(m, m_{\mathcal{R}}, \Gamma_{\mathcal{R}})$

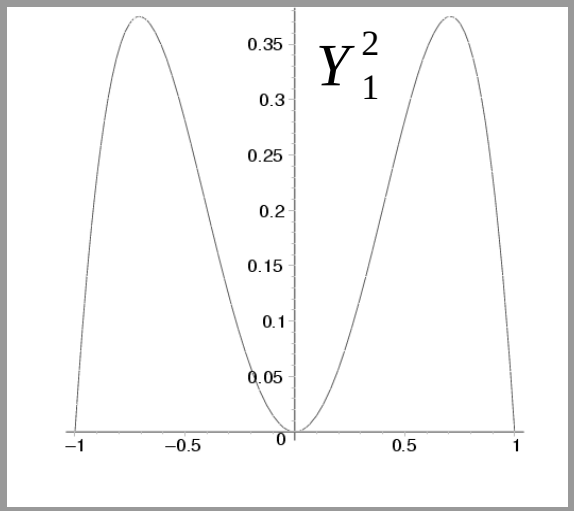
Blatt-Weisskopf Barrier$(p,\mathcal{L})$ $D^{J}_{M\lambda}(\phi\,\theta\,0)$

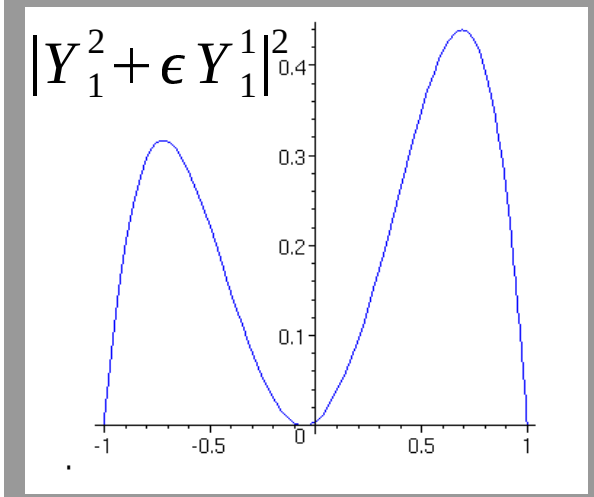
Blatt-Weisskopf Barrier$(p,\mathcal{L})$ $D^{J}_{M\lambda}(\phi\,\theta\,0)$

E852 (1994) $\pi^- p \to \eta \pi^- p$ P_1-D_1 Interference









$$\epsilon^+ : |+1\rangle - |-1\rangle \propto \sin^2(\phi)$$
$$\epsilon^- : |+1\rangle + |-1\rangle \propto \cos^2(\phi)$$

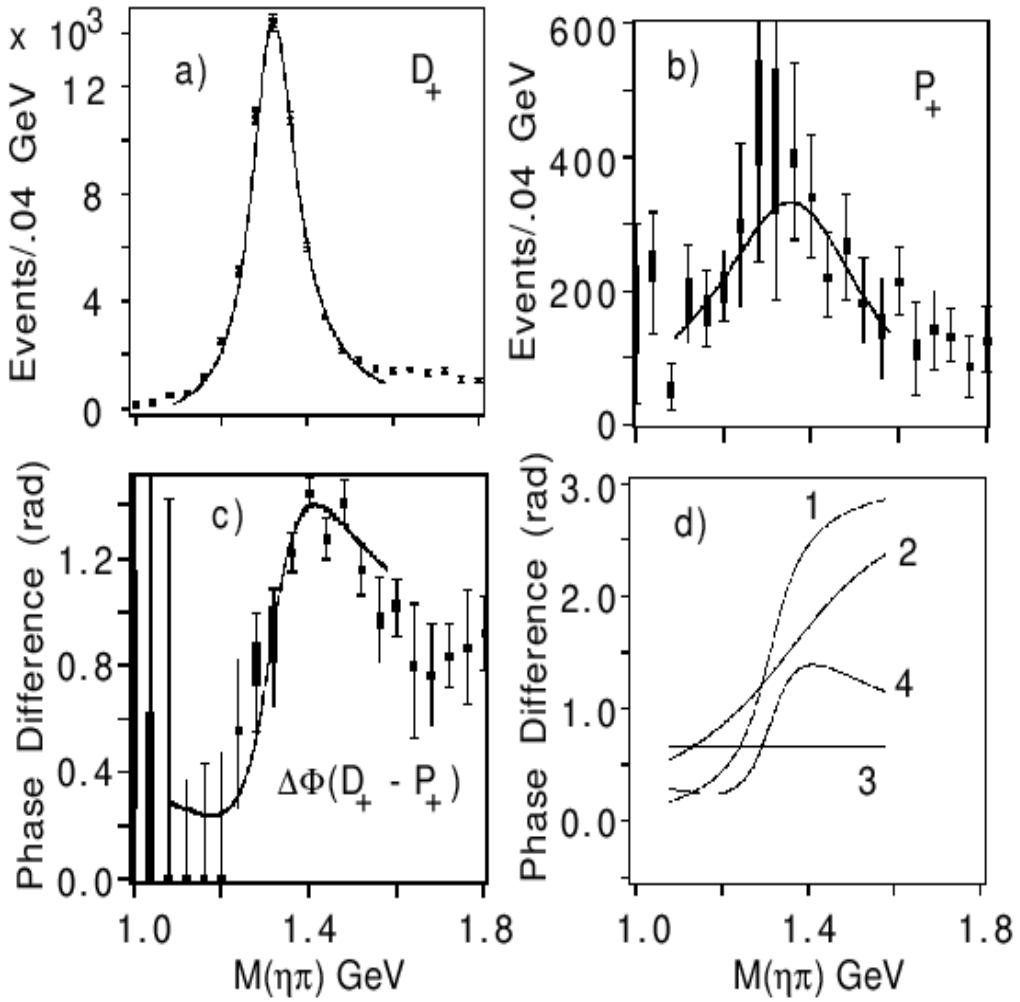
E852 (1994)

$\pi^- p \to \eta \pi^- p$

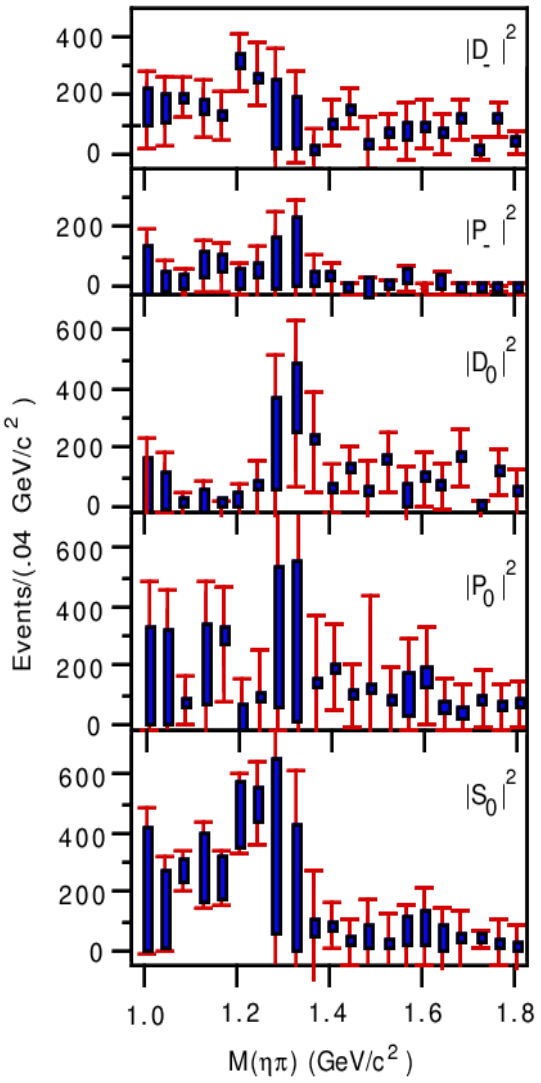
$M(\pi_1(1400)) = 1370 \pm 16^{+50}_{-30}\ MeV/c^2$

$\Gamma(\pi_1(1400)) = 385 \pm 40^{+29}_{-47}\ MeV/c^2$

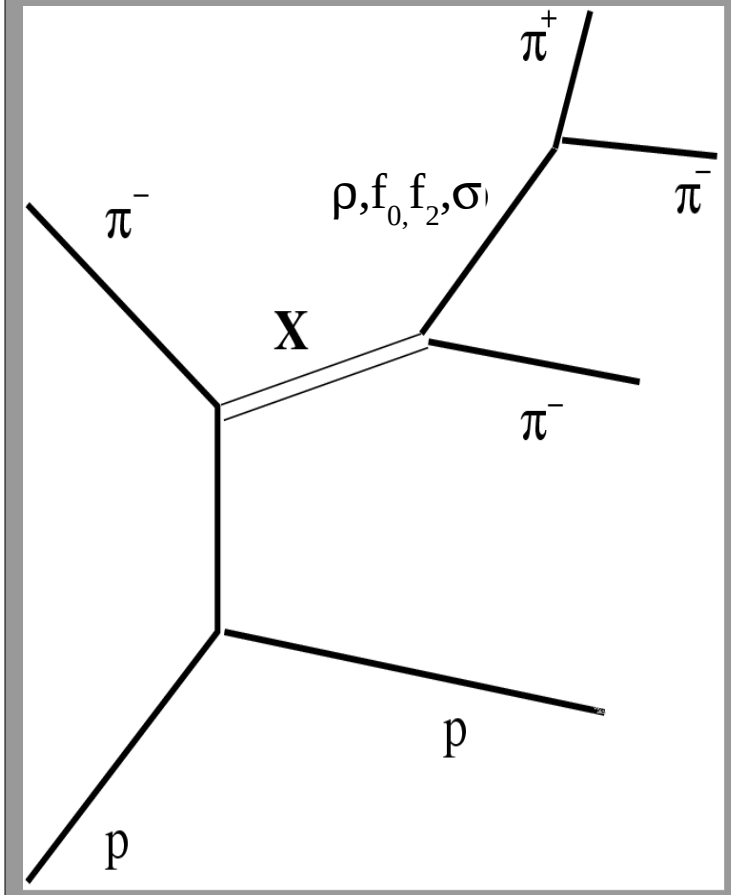
Natural Parity Exchange

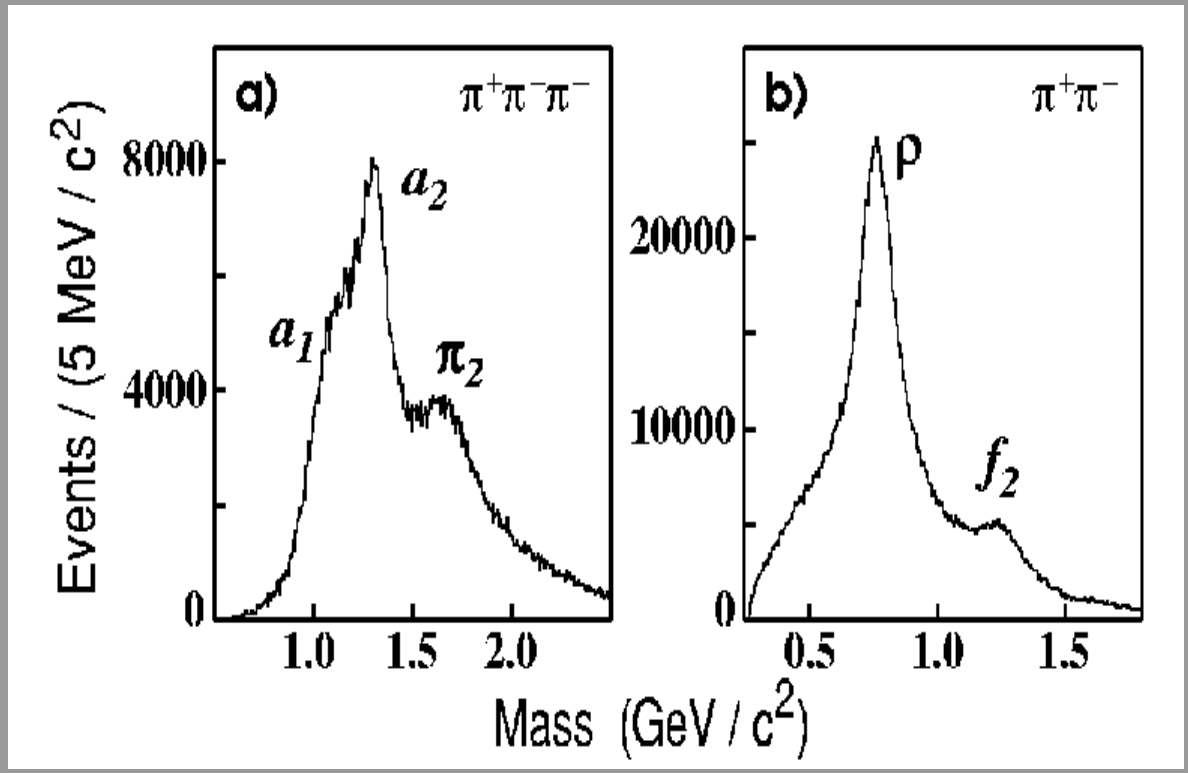


Unnatural Parity Exchange



E852 (1994) $\pi^- p \to \pi^+ \pi^- \pi^- p$ Phys. Rev. **D65**, 072001 (2002)



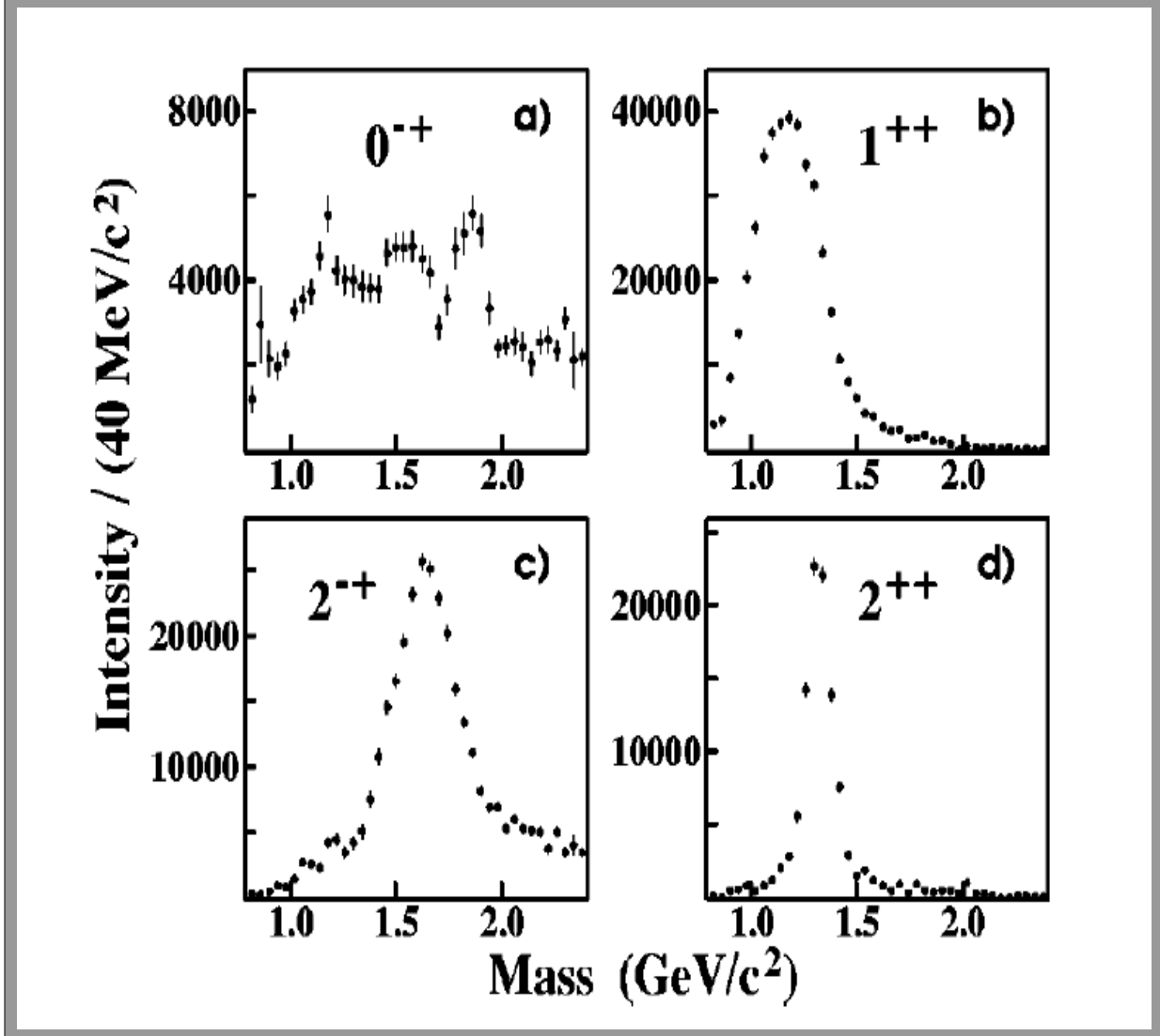


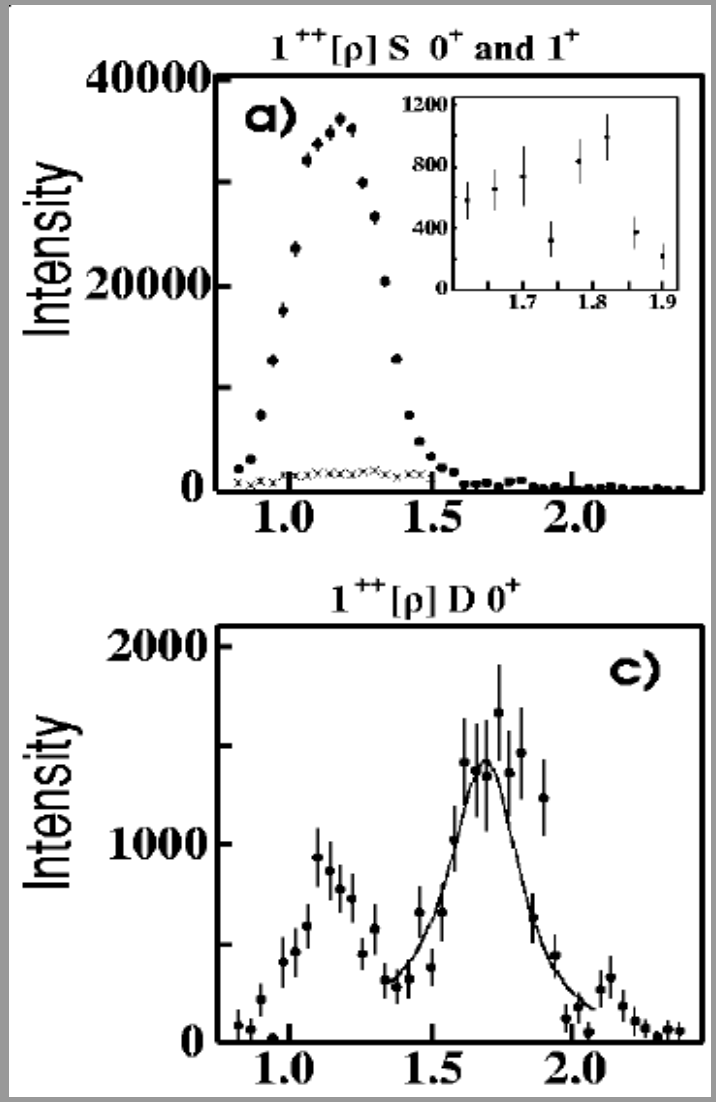
250,000 Events

E852 (1994) $\pi^- p \to \pi^+ \pi^- \pi^- p$

Principle Waves:

$J^{PC} = 1^{++}$ Wave





E852 (1994) $\pi^- p \to \pi^+ \pi^- \pi^- p$

$a_3(1874)$:

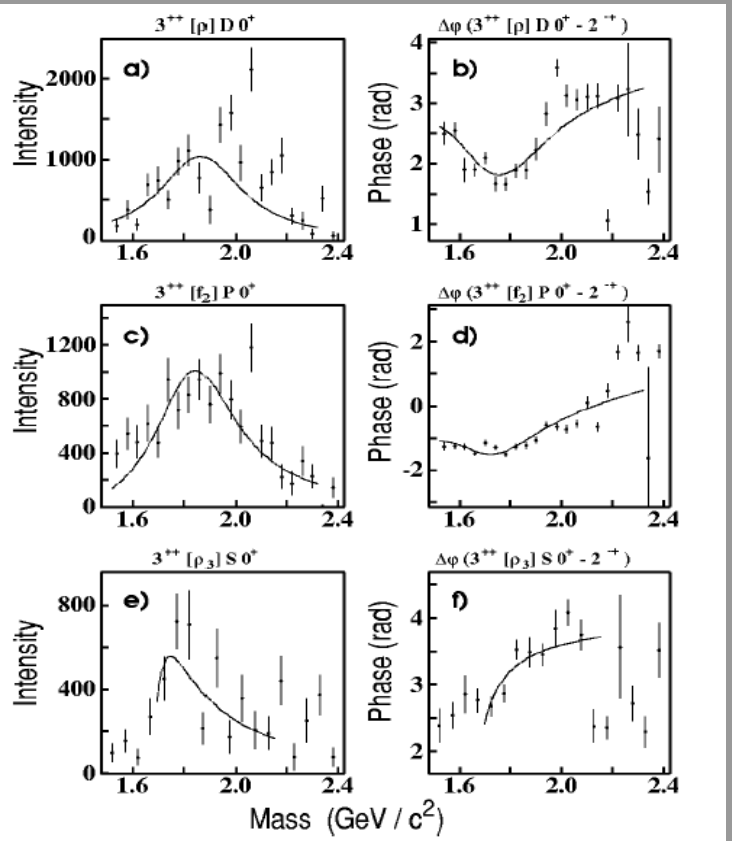


FIG. 16. Intensities of the (a) $3^{++}[\rho]D0^+$, (c) $3^{++}[f_2]P0^+$, (e) $3^{++}[\rho_3]S0^+$ waves and their corresponding phase differences (b,d,f) with respect to the $2^{-+}[f_2]S0^+$ wave. The 27-wave rank-1 fit is shown. Curves show the mass-dependent fits of the $a_3(1874)$ with parameters from Eq. (19). Note that the fitted $a_3(1874)$ mass and width vary considerably in the fits done separately for each decay mode leading to large parameter errors in Eq. (19).

$a_4(2040)$:

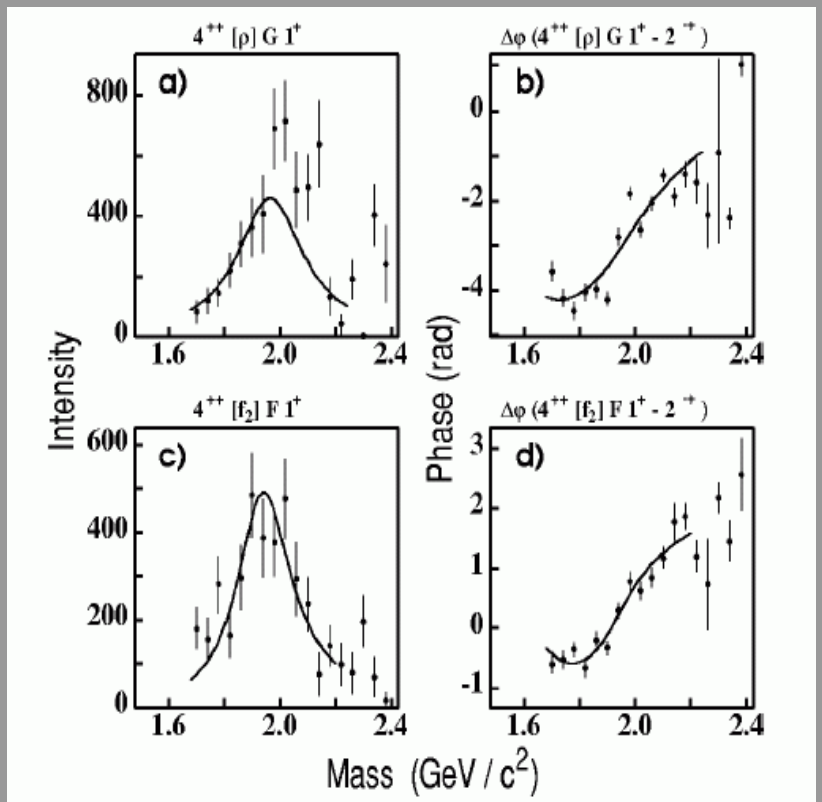


FIG. 17. Intensities of the (a) $4^{++}[\rho]G1^+$, (c) $4^{++}[f_2]F1^+$ waves and their corresponding phase differences (b,d) with respect to the $2^{-+}[f_2]S0^+$ wave. The 27-wave fit is shown. Curves show the mass-dependent fits of the $a_4(2040)$ with parameters from Eq. (21).

$\pi^-(18\,GeV/c)\,p \rightarrow \pi^+\pi^-\pi^-\,p$ $J^{PC} = 1^{-+}$ Exotic $\pi_1(1600)$

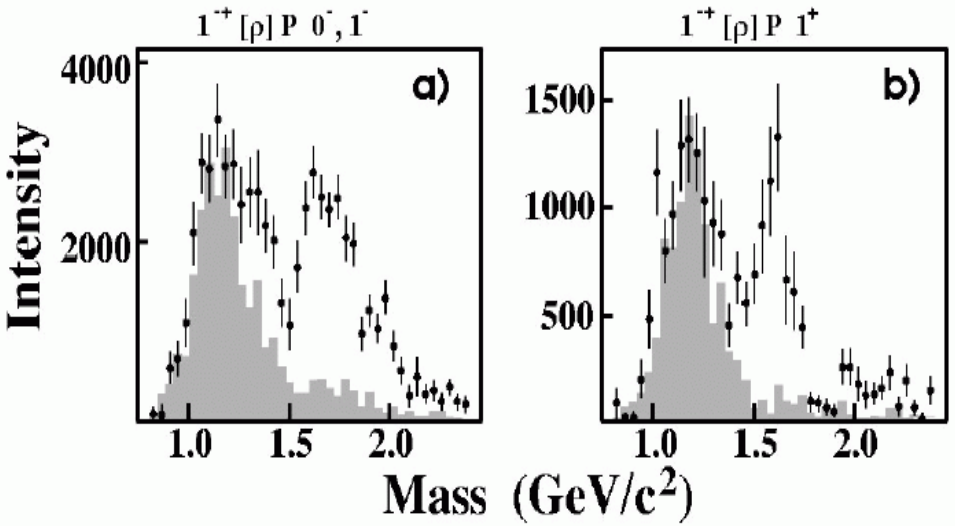
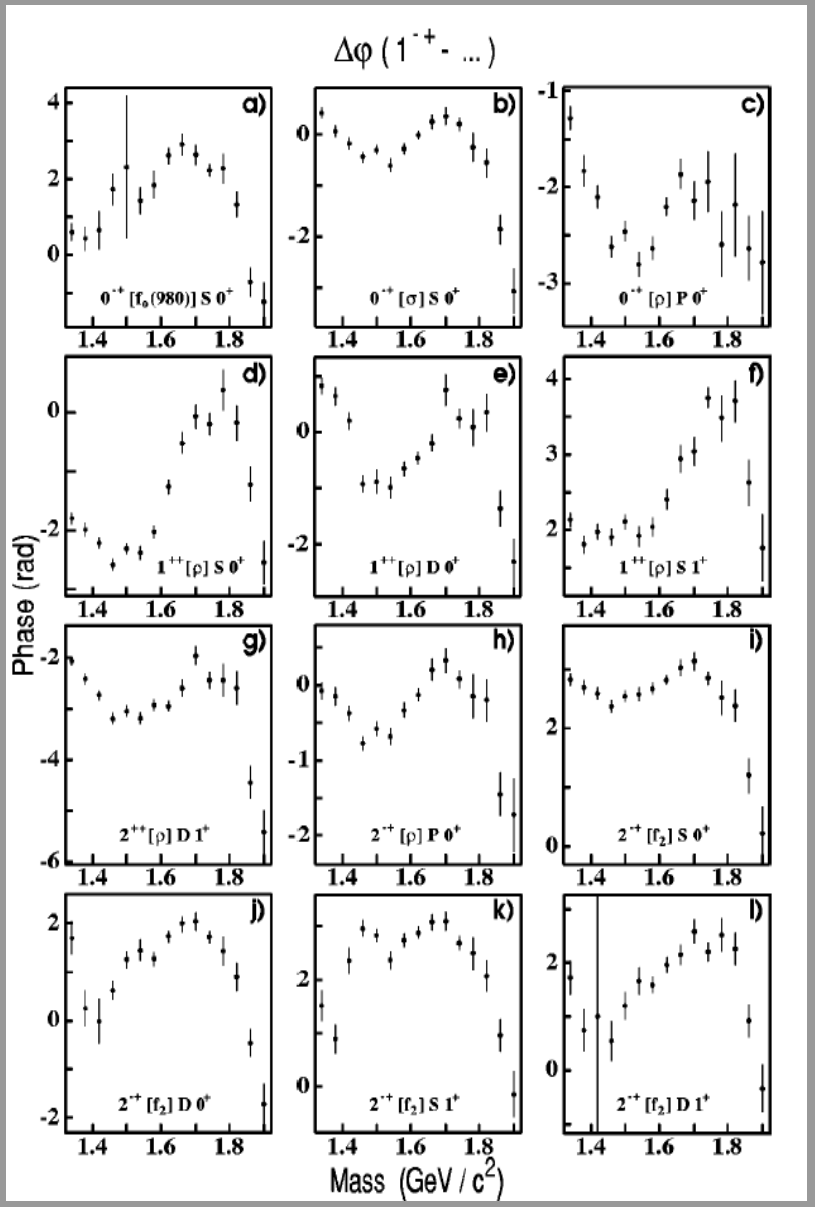


FIG. 18. Wave intensities of the $1^{-+}[\rho]P$ exotic waves: (a) the $M^{\epsilon}=0^-$ and 1^- waves combined; (b) the $M^{\epsilon}=1^+$ wave. The 21-wave rank-1 PWA fit to the data is shown as the points with error bars and the shaded histograms show estimated contributions from all non-exotic waves due to leakage.



E852 (1994) $\pi^- p \to \pi^+ \pi^- \pi^- p$ $J^{PC} = 1^{-+}$ Exotic $\pi_1(1600)/\pi_2(1670)$

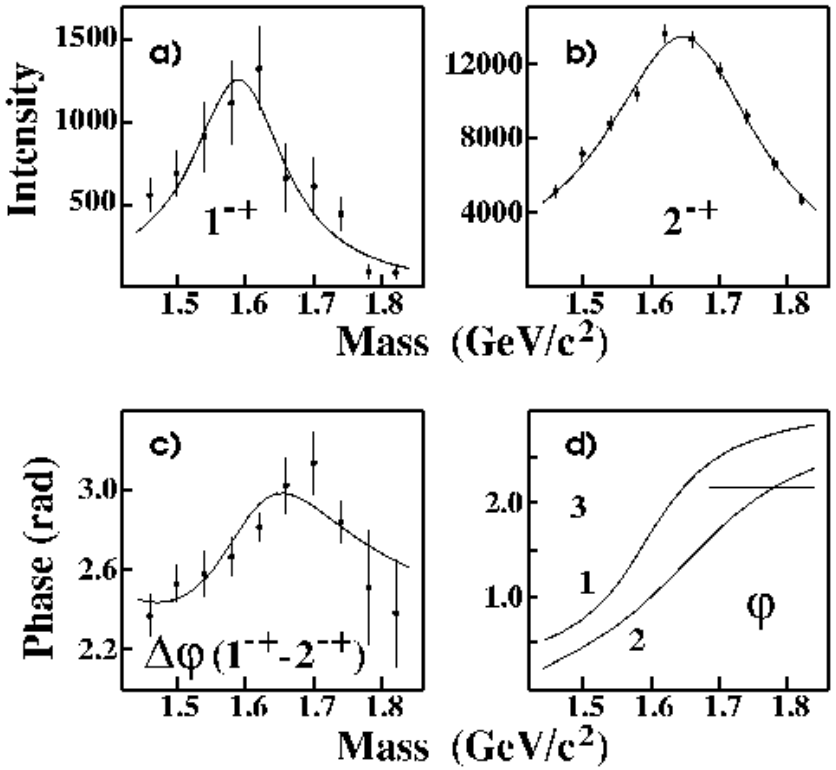


FIG. 24. A coupled mass-dependent Breit-Wigner fit of the $1^{-+}[\rho(770)]P1^+$ and $2^{-+}[f_2(1270)]S0^+$ waves. (a) $1^{-+}[\rho(770)]P1^+$ wave intensity. (b) $2^{-+}[f_2(1270)]S0^+$ wave intensity. (c) Phase difference between the $1^{-+}[\rho(770)]P1^+$ and $2^{-+}[f_2(1270)]S0^+$ waves. (d) Phase motion of the $1^{-+}[\rho(770)]P1^+$ wave (1), $2^{-+}[f_2(1270)]S0^+$ wave (2), and the production phase between them (3).

$$M(\pi_1(1600)) = 1598 \pm 8^{+29}_{-47}\ MeV/c^2$$

$$\Gamma(\pi_1(1600)) = 168 \pm 20^{+150}_{-12}\ MeV/c^2$$

E852 (1994) $\pi^- p \to \pi^+ \pi^- \pi^- p$ $J^{PC} = 1^{-+}$ Exotic $\pi_1(1600)/\pi_2(1670)$

$$M(\pi_1(1600)) = 1598 \pm 8^{+29}_{-47}\ MeV/c^2$$

$$\Gamma(\pi_1(1600)) = 168 \pm 20^{+150}_{-12}\ MeV/c^2$$

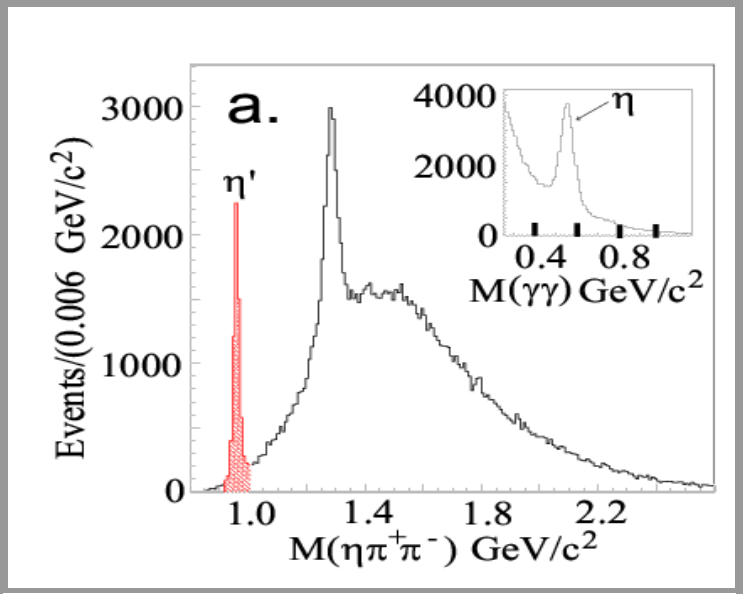
Resonance parameters

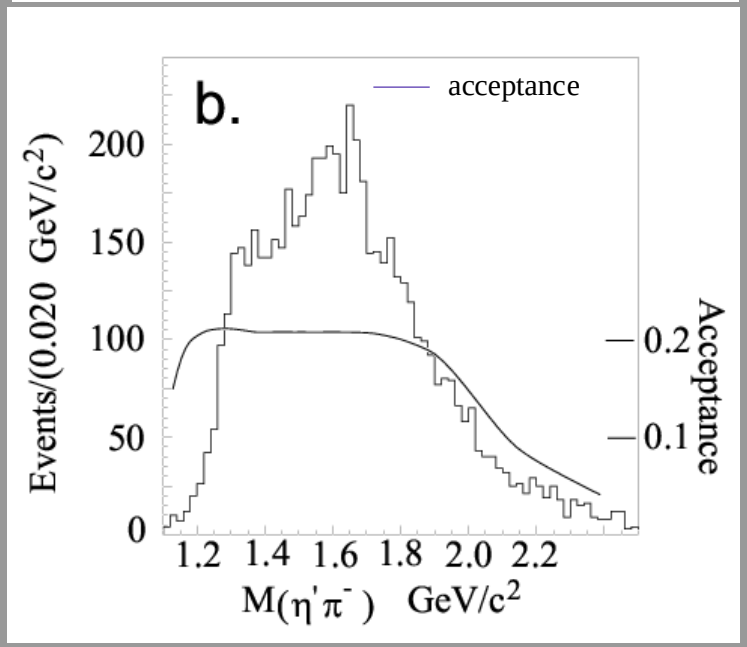
J^{PC} Resonance and decay mode(s) used	M, MeV/c^2	Γ, MeV/c^2
$0^{-+}\ \pi(1300) \to \rho(770)\pi$	$1343 \pm 15 \pm 24$	$449 \pm 39 \pm 47$
$0^{-+}\ \pi(1800) \to f_o(980)\pi$	$1774 \pm 18 \pm 20$	$223 \pm 48 \pm 50$
$0^{-+}\ \pi(1800) \to \sigma\pi$	$1863 \pm 9 \pm 10$	$191 \pm 21 \pm 20$
$1^{-+}\ \pi_1(1600) \to \rho(770)\pi$	$1593 \pm 8^{+29}_{-47}$	$168 \pm 20^{+150}_{-12}$
$1^{++}\ a_1(1700) \to \rho(770)\pi$	$1714 \pm 9 \pm 36$	$308 \pm 37 \pm 62$
$2^{-+}\ \pi_2(1670) \to f_2(1270)\pi$	$1676 \pm 3 \pm 8$	$254 \pm 3 \pm 31$
$2^{++}\ a_2(1320) \to \rho(770)\pi$	$1326 \pm 2 \pm 2$	$108 \pm 3 \pm 15$
$3^{++}\ a_3(1874) \to \rho(770)\pi, f_2(1270)\pi, \rho_3(1690)\pi$	$1874 \pm 43 \pm 96$	$385 \pm 121 \pm 114$
$4^{++}\ a_4(2040) \to \rho(770)\pi, f_2(1270)\pi$	$1996 \pm 25 \pm 43$	$298 \pm 81 \pm 85$

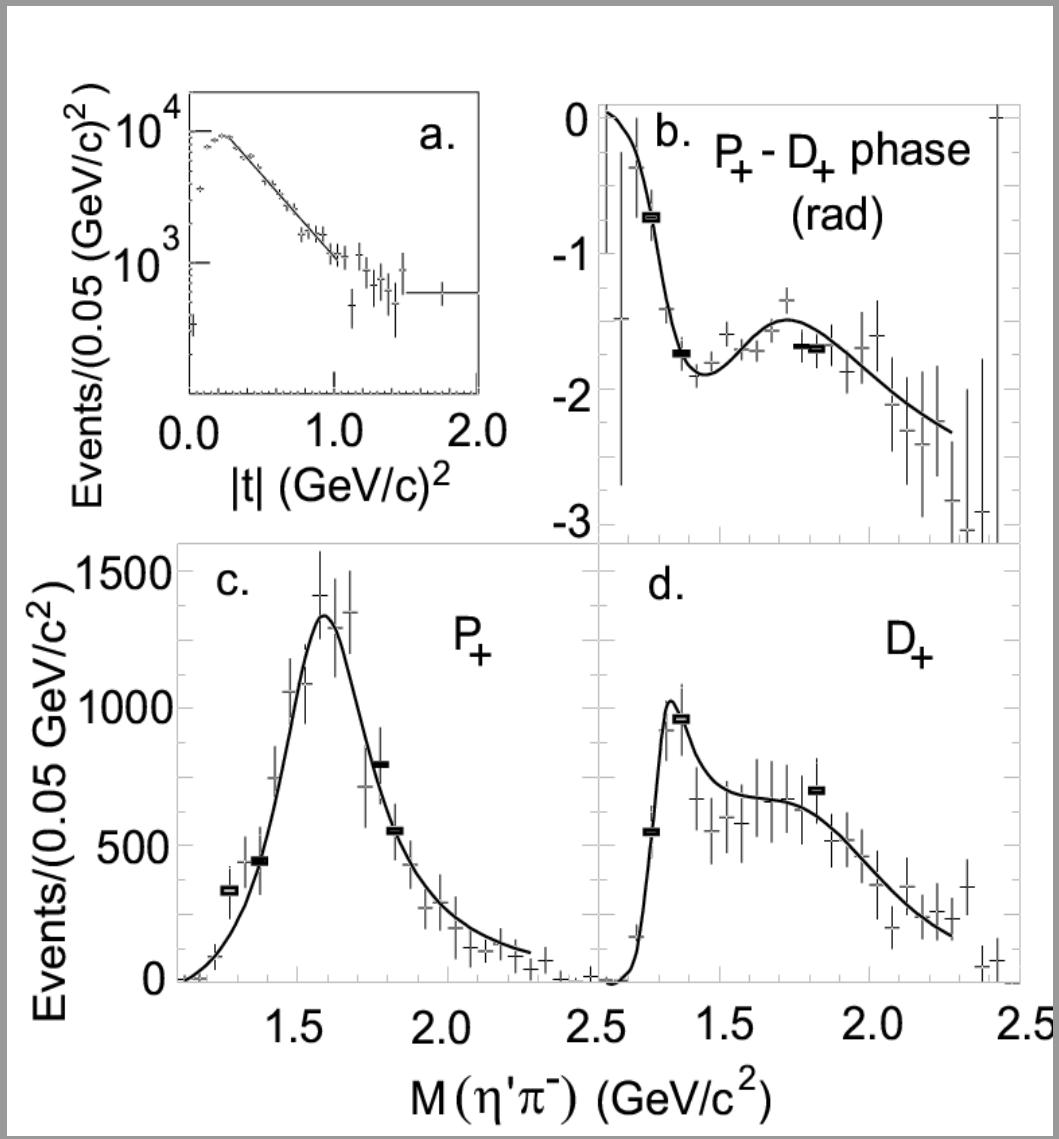
E852 (1995) $\pi^- p \to \eta' \pi^- p$, $\eta' \to \eta \pi^+ \pi^-$, $\eta \to \gamma\gamma$ 6048 Events

$M(\pi_1(1600)) = 1597 \pm 10^{+45}_{-10}\ MeV/c^2$

$\Gamma(\pi_1(1600)) = 340 \pm 40 \pm 50\ MeV/c^2$



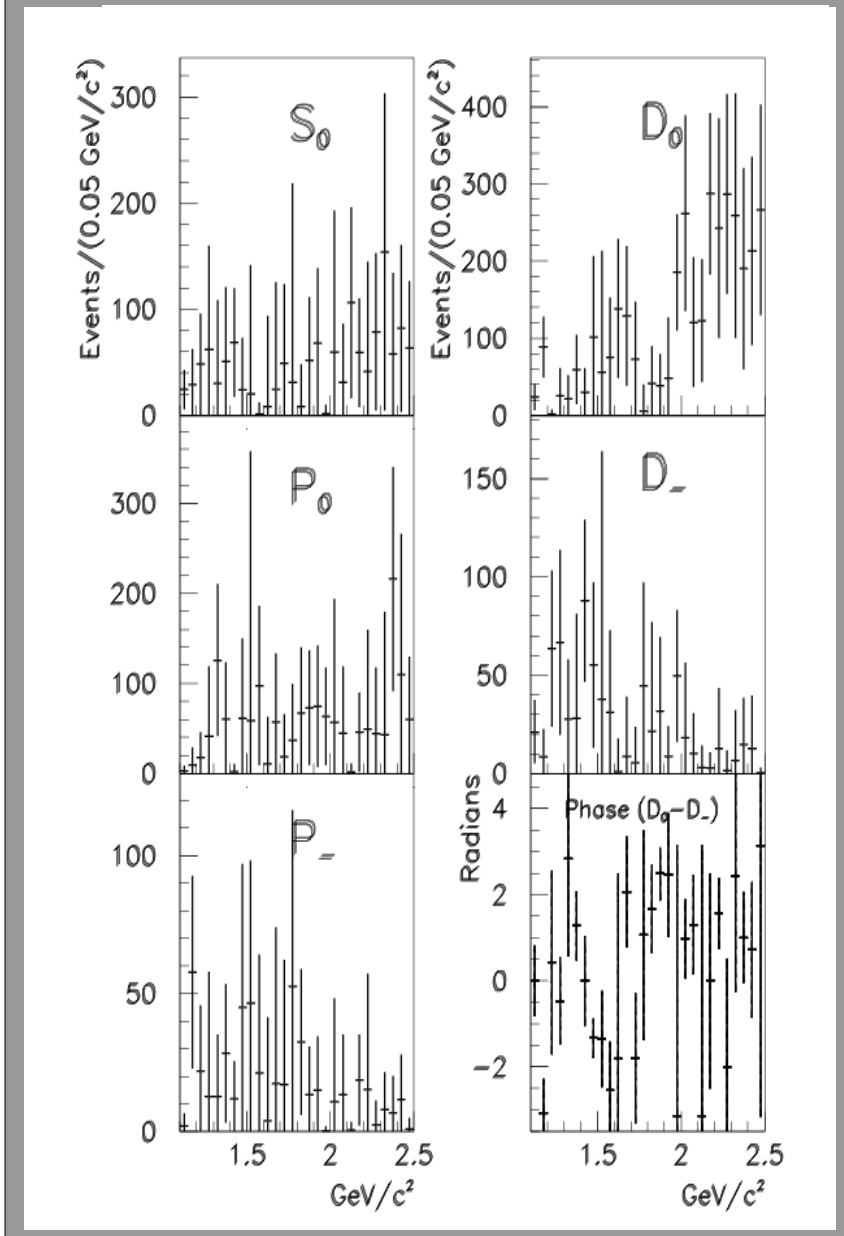


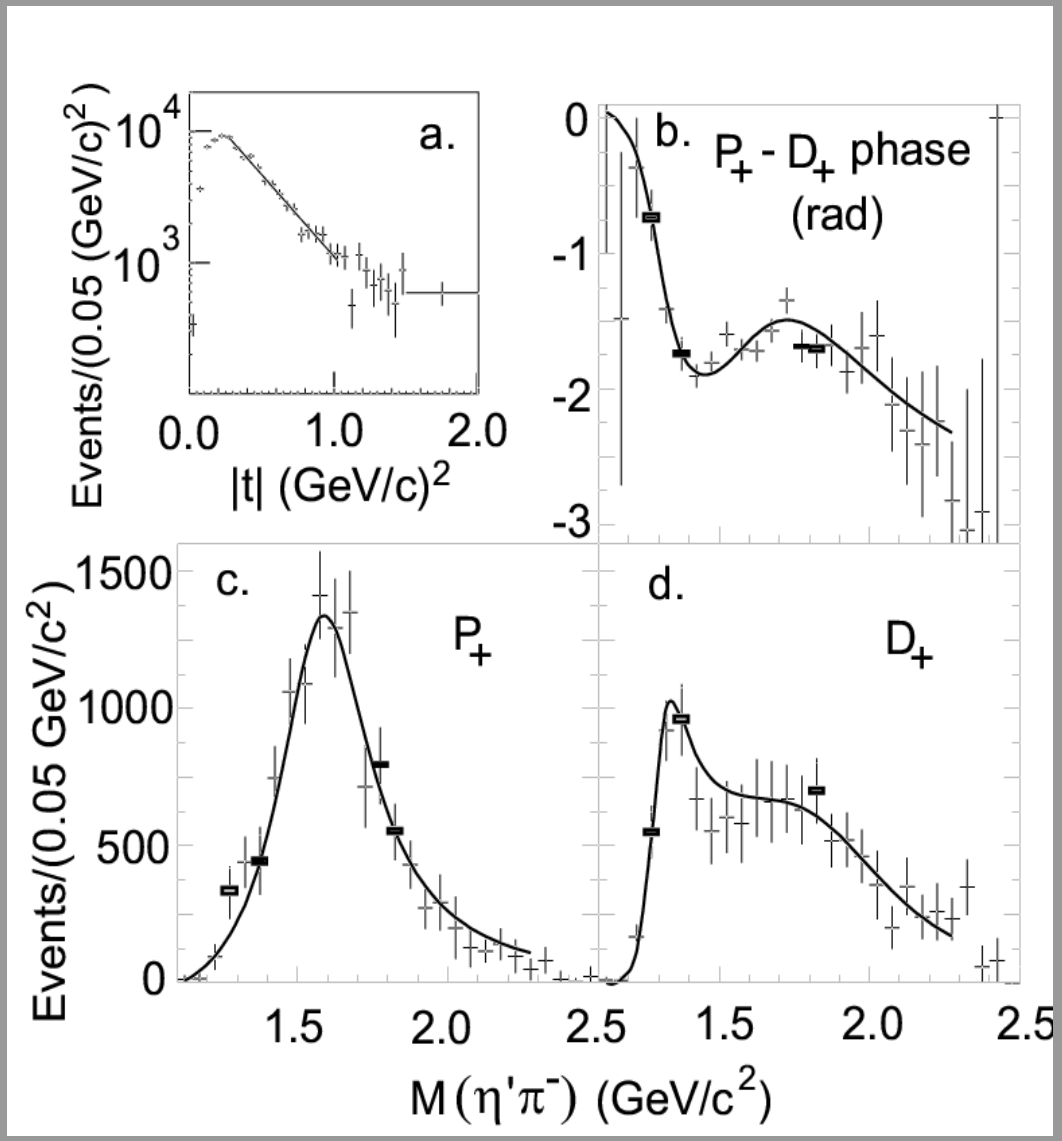


E852 (1995) $\pi^- p \to \eta' \pi^- p, \eta' \to \eta \pi^+ \pi^-, \eta \to \gamma\gamma$ 6048 Events

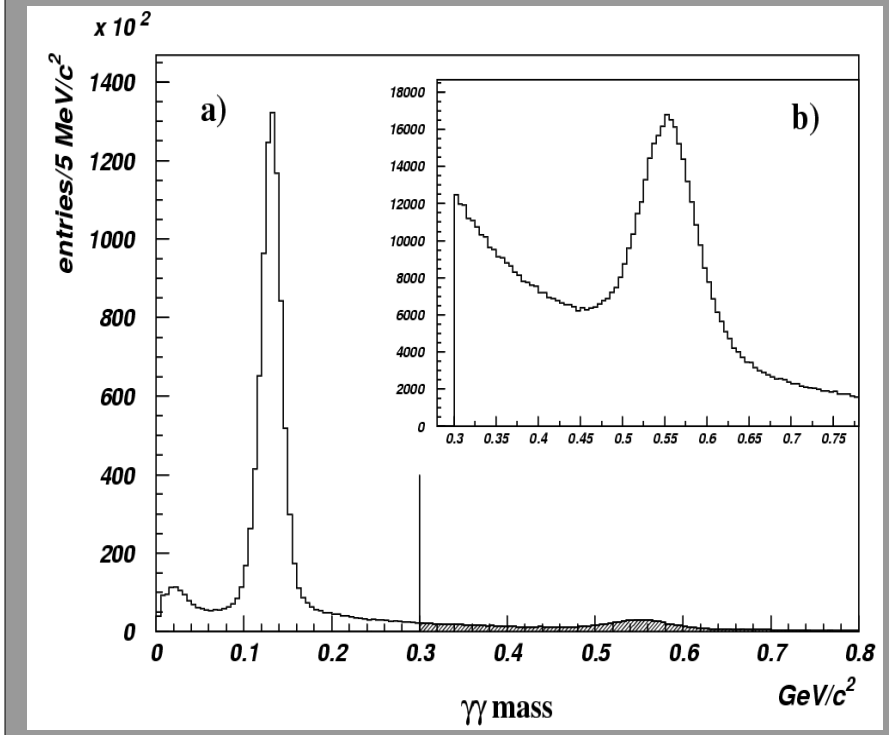
$M(\pi_1(1600)) = 1597 \pm 10^{+45}_{-10}\ MeV/c^2$

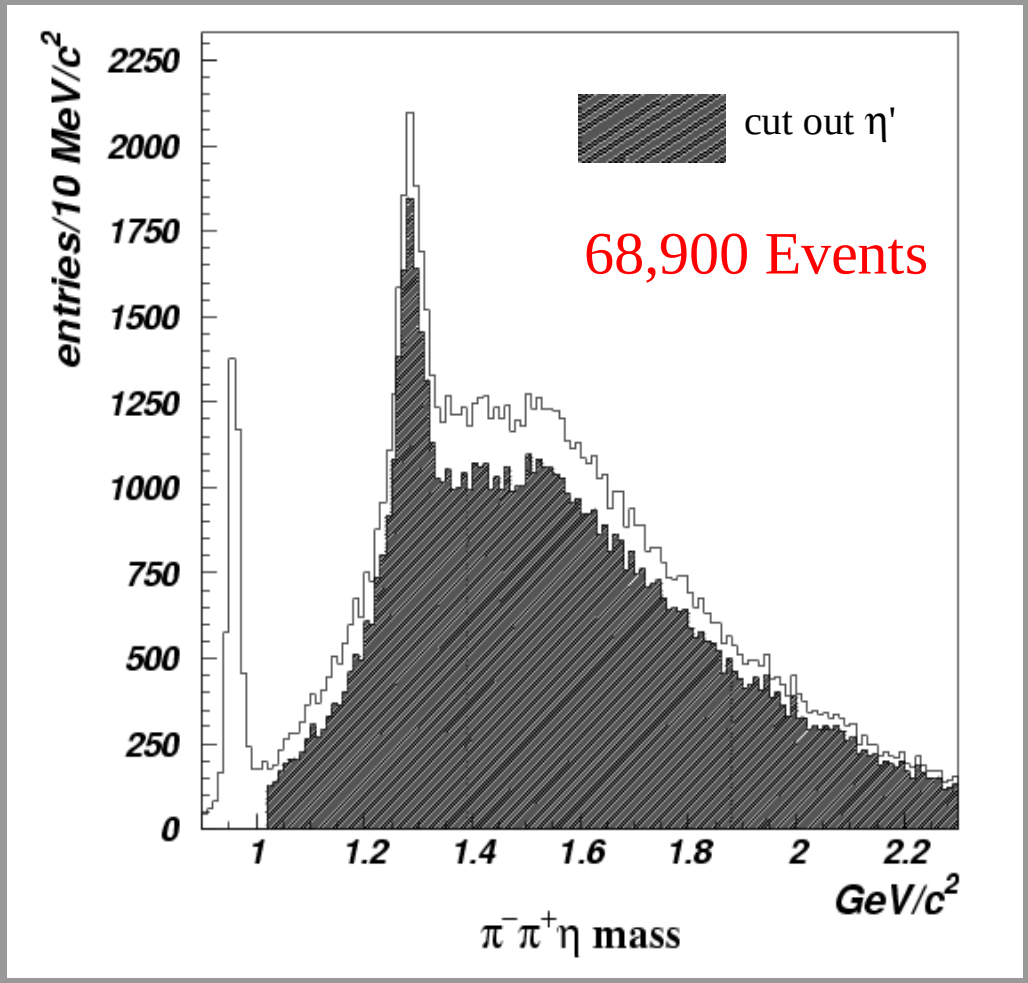
$\Gamma(\pi_1(1600)) = 340 \pm 40 \pm 50\ MeV/c^2$





E852 $\pi^- p \to \eta \pi^+ \pi^- \pi^- p$





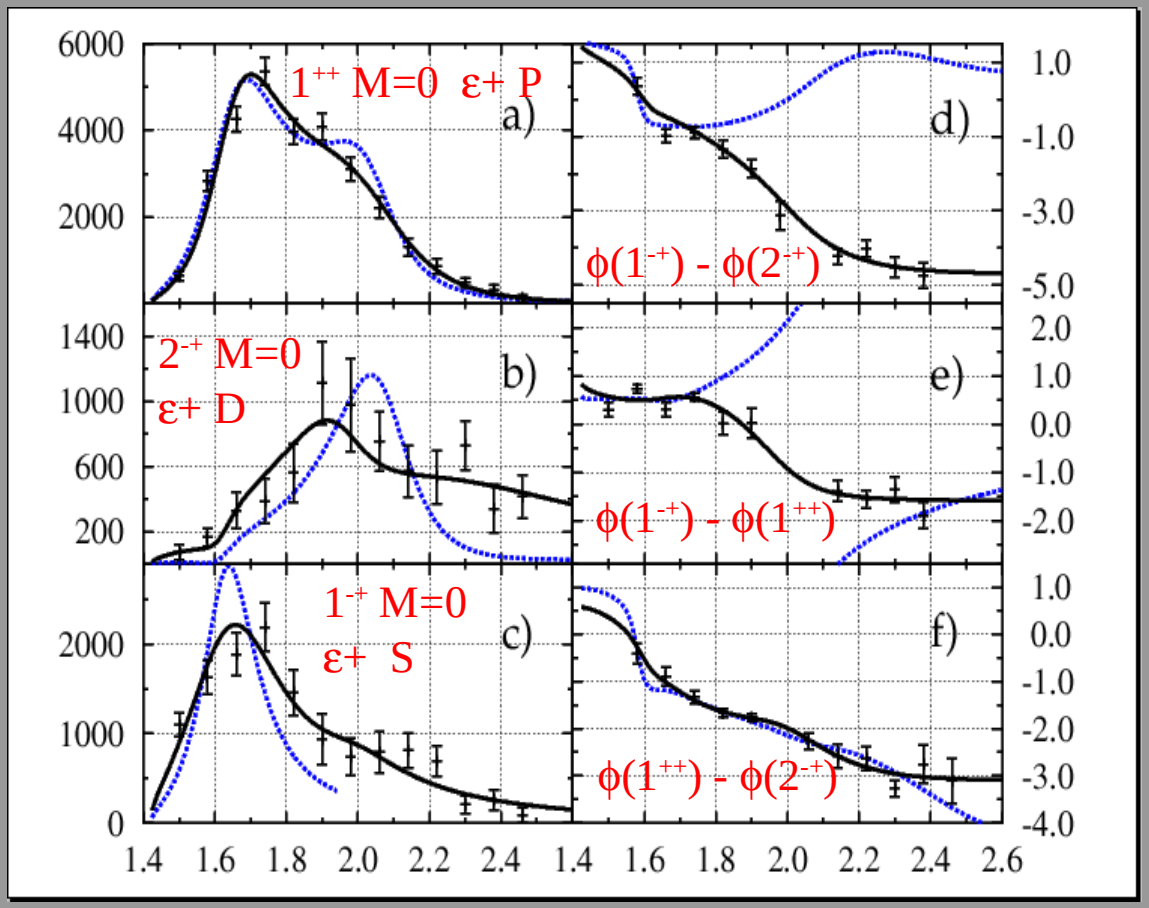
E852 $\pi^- p \to \eta \pi^+ \pi^- \pi^- p$ Partial Wave Analysis 53+1 waves

PWA Fit Waveset

$J^{PC} m^{\epsilon}$	primary decay	L	S	# of waves
$0^{-+}0^{-}$	$\eta(1295)\pi^-$	0	0	2
$0^{-+}0^{-}$	$a_0^-(980)\sigma$	1	0	1
$2^{++}0^{-}$	$a_2^-(1320)\sigma$	0	2	1
$2^{++}0^{-}$	$a_2^-(1320)\rho$	1,3	1,2,3	6
$1^{-+}1^{+}$	$a_0^-(980)\rho$	0	1	1
$1^{-+}1^{+}$	$a_1^-(1260)\eta$	0	1	2
$1^{-+}1^{+}$	$f_1(1285)\pi^-$	0	1	2
$1^{-+}1^{+}$	$\rho'(1460)\pi^-$	1	1	1
$1^{++}0^{+}$	$a_0^-(980)\rho$	1	1	1
$1^{++}0^{+}$	$a_1^-(1260)\eta$	1	1	2
$1^{++}0^{+}$	$f_1(1285)\pi^-$	1	1	2
$1^{++}0^{+}$	$a_2^-(1320)\eta$	1	2	1
$1^{++}0^{+}$	$\rho'(1460)\pi^-$	0,2	1	2
$1^{++}0^{+}$	$\rho_3(1690)\pi^-$	2	3	1
$2^{-+}0^{+}$	$a_2^-(1320)\eta$	0	2	1
$2^{-+}0^{+}$	$\rho'(1460)\pi^-$	1	1	1
$2^{-+}0^{+}$	$a_1^-(1260)\eta$	2	1	2
$2^{-+}0^{+}$	$f_1(1285)\pi^-$	2	1	2
$2^{++}1^{+}$	$\pi_2^-(1670)\eta$	0	2	2
$2^{++}1^{+}$	$a_2^-(1320)\rho$	1	1,2,3	3
$2^{++}1^{+}$	$a_2^-(1320)\eta$	1	2	1
$3^{++}0^{+}$	$a_2^-(1320)\eta$	1	2	1
$3^{++}0,1^{+}$	$a_2^-(1320)\rho$	1	2,3	4
$3^{++}0^{+}$	$a_1^-(1260)\eta$	3	1	2
$4^{++}1^{+}$	$a_2^-(1320)\rho$	1	3	1
$4^{++}1^{+}$	$a_2^-(1320)\rho$	3	1,2,3	3
$4^{++}1^{+}$	$a_1^-(1260)\eta$	3	1	2
$4^{++}1^{+}$	$a_2^-(1320)\eta$	1	2	1
$4^{++}1^{+}$	$\pi^-(1800)\eta$	4	0	2
	Background			1

$f_1(1285)\,\pi^-$ Partial Waves

2 $J^{PC}=1^{-+}$ poles
1 $J^{PC}=1^{-+}$ pole



$$\frac{\chi^2}{DOF} = \frac{70.6}{47} = 1.5 \qquad \frac{\chi^2}{DOF} = \frac{383.6}{46} = 8.4$$

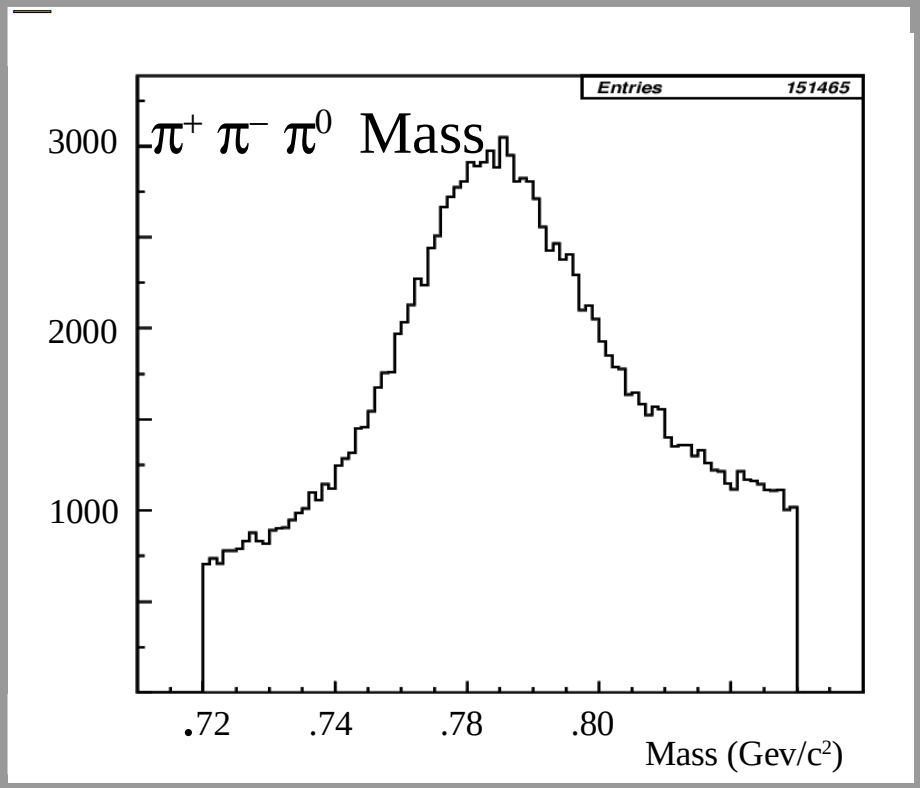
See P. Eugenio's talk, this conference

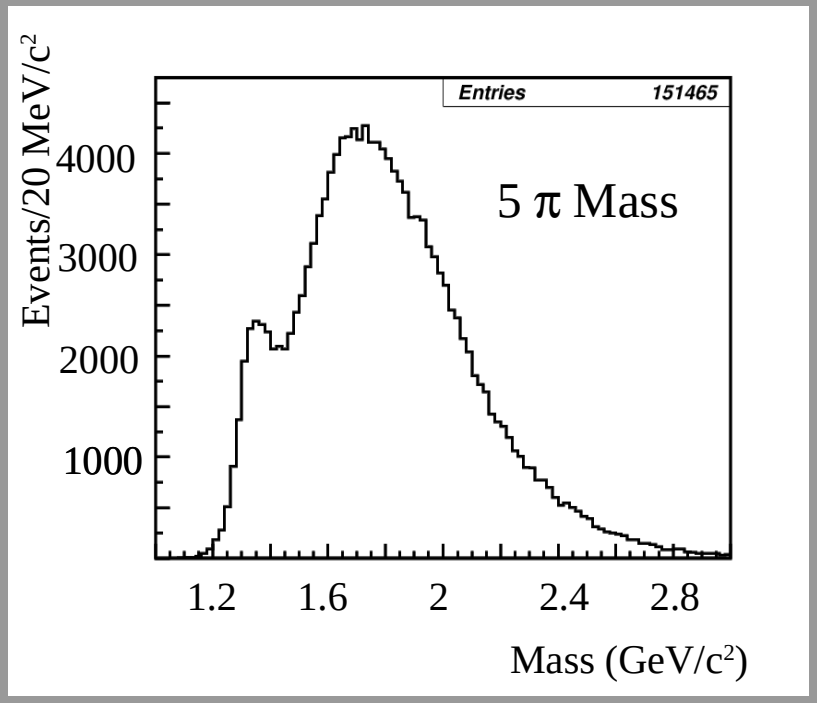
E852 (1995) $\pi^- p \to \eta \pi^+ \pi^- \pi^- p$

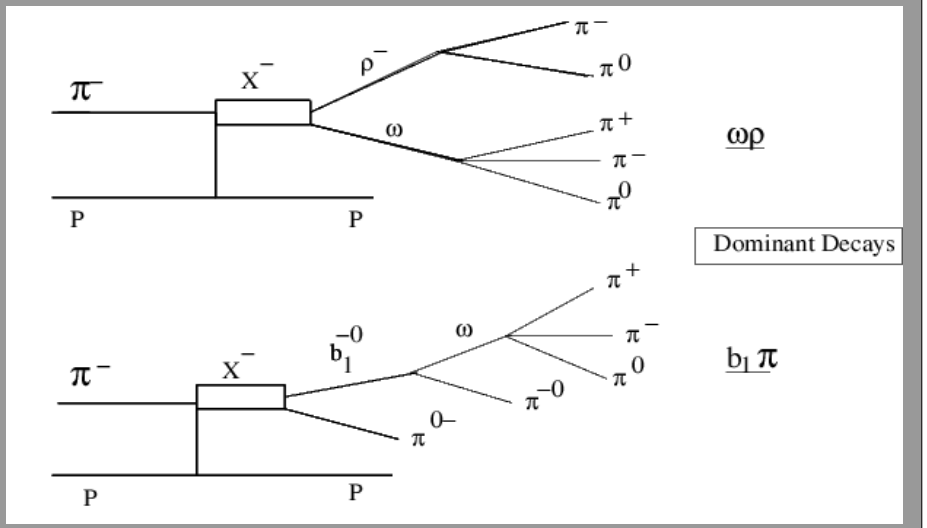
Partial Wave Analysis Results:

Wave	Mass $[\mathrm{MeV}/c^2]$	Γ $[\mathrm{MeV}/c^2]$
$1^{++}0^+ f_1\pi P$	1714 (fixed)	308 (fixed)
	2096 ± 17	451 ± 41
$2^{-+}0^+ f_1\pi D$	1676 (fixed)	254 (fixed)
	2003 ± 88	306 ± 132
	2460 ± 328	1540 ± 1214
$1^{-+}1^+ f_1\pi S$	1709 ± 24	403 ± 80
	2001 ± 30	333 ± 52

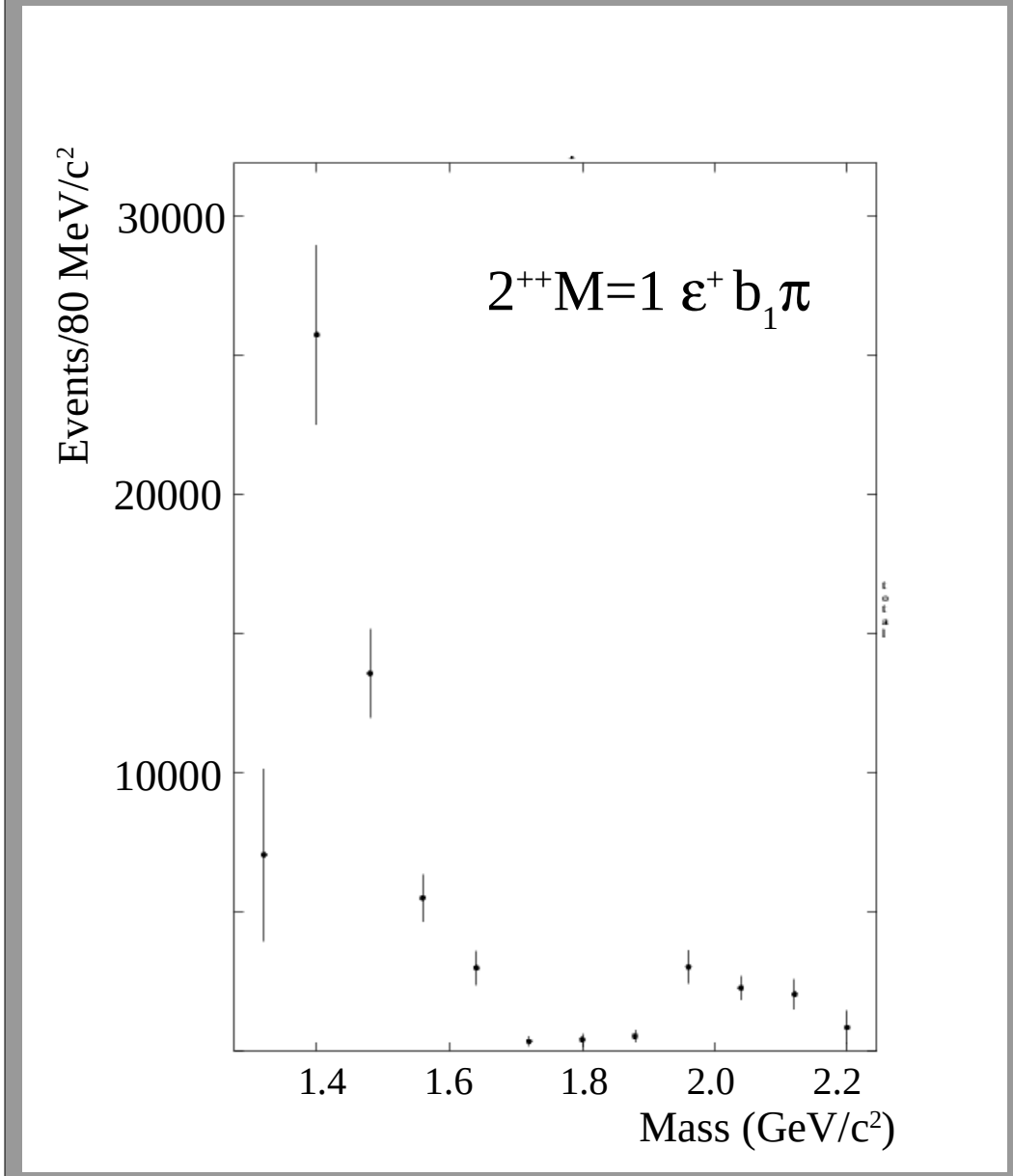
E852 (1995) $\pi^- p \to \omega \pi^0 \pi^- p$ 150,000 Events

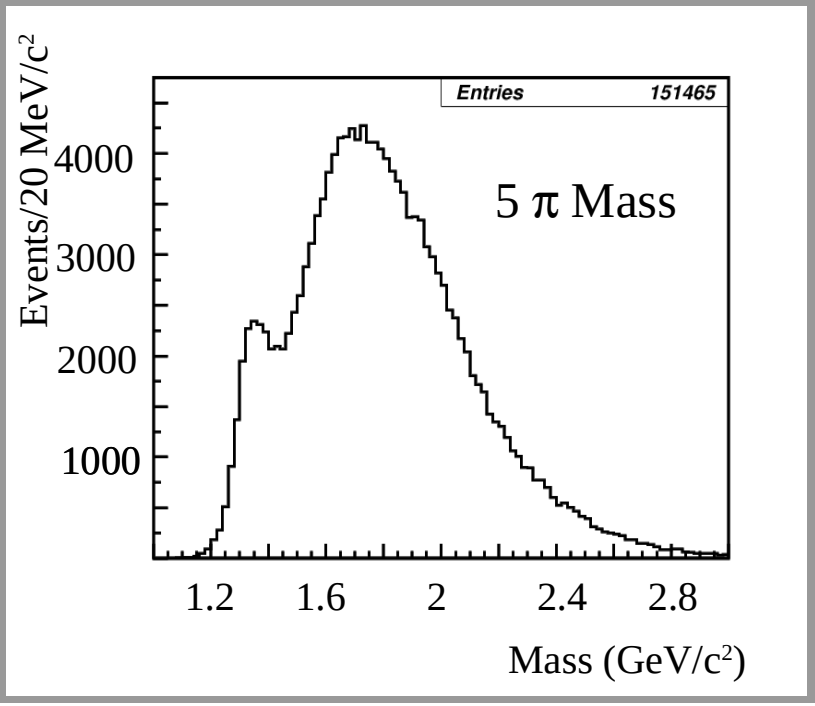


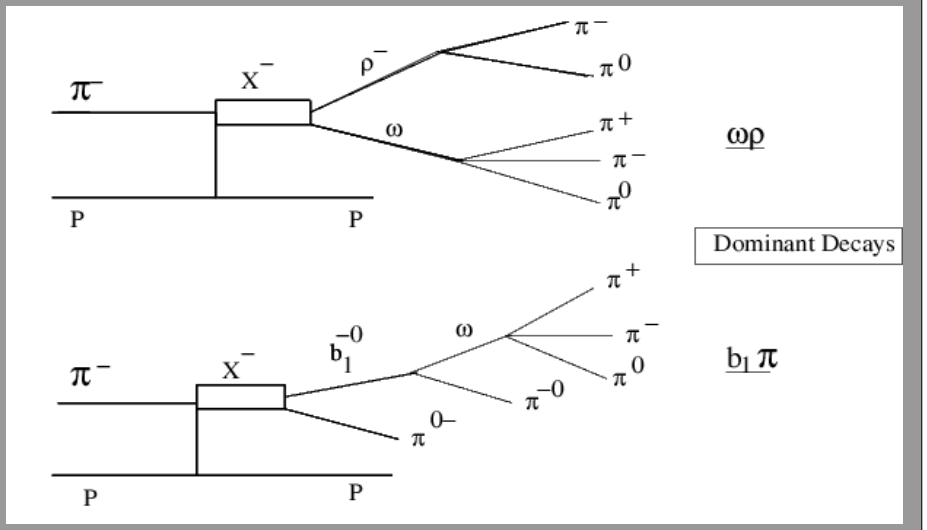




E852 (1995) $\pi^- p \to \omega \pi^0 \pi^- p$ 150,000 Events







E852 $\pi^- p \to \omega \pi^0 \pi^- p$ Partial Waves

$\mathbf{b_1}\pi(I^G = 1^-)$		
L	J^{PC}	M^ϵ
0	1^{-+}	1^+
	1^{-+}	1^-
	1^{-+}	0^-
1	1^{++}	0^+
	1^{++}	1^+
	2^{++}	1^+
	2^{++}	0^-
2	2^{-+}	0^+
	2^{-+}	1^-
	2^{-+}	1^+
3	2^{++}	1^+
	4^{++}	1^+

$\omega\rho(I^G = 1^-)$			
L	**S**	J^{PC}	M^ϵ
0	1	1^{++}	0^+
	2	2^{++}	0^-
	2	2^{++}	1^+
1	1	0^{-+}	0^+
	1	2^{-+}	0^+
	1	2^{-+}	1^-
	2	2^{-+}	0^+
	2	2^{-+}	1^+
2	2	1^{++}	0^+
	2	1^{++}	1^+
	2	3^{++}	0^+
	2	4^{++}	1^+
3	1	2^{-+}	0^+

Tested and rejected:

$\rho(1450)\,\pi$

$a_1(1260)\,\sigma$

$a_2(1320)\,\sigma$

Included:

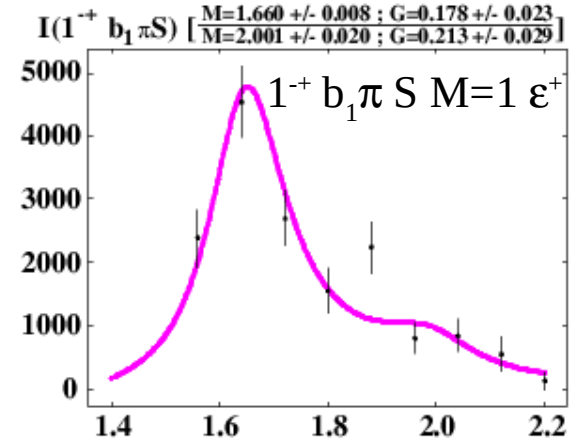
$\rho_3(1690)\pi$ $3^{++}0^+$

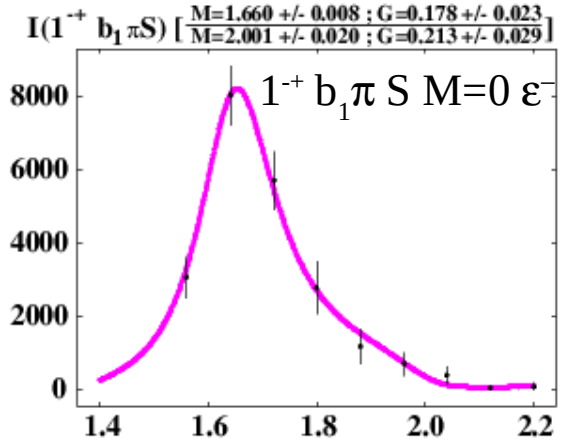
incoherent isotropic background

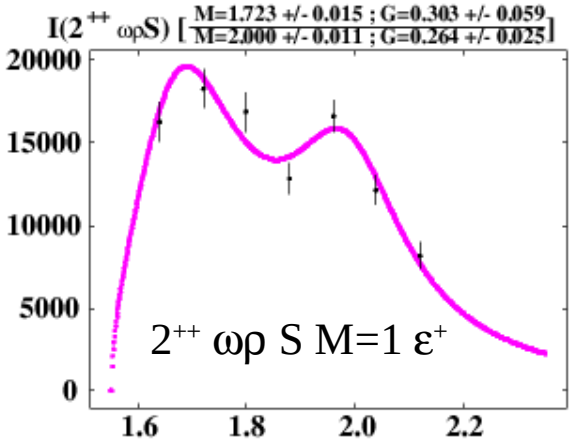
27 waves in fit

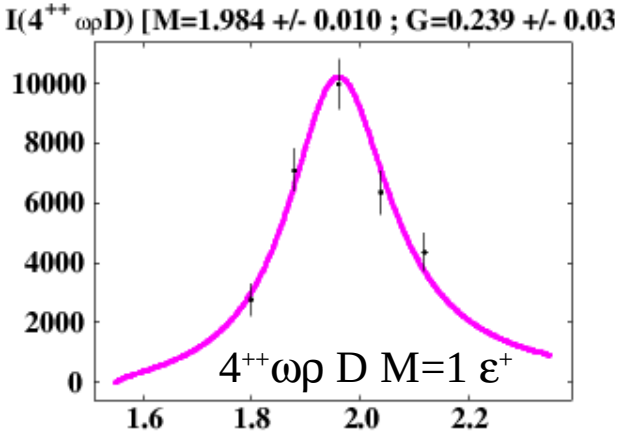
E852 1995 $\pi^- p \to \omega \pi^0 \pi^- p$

Intensity



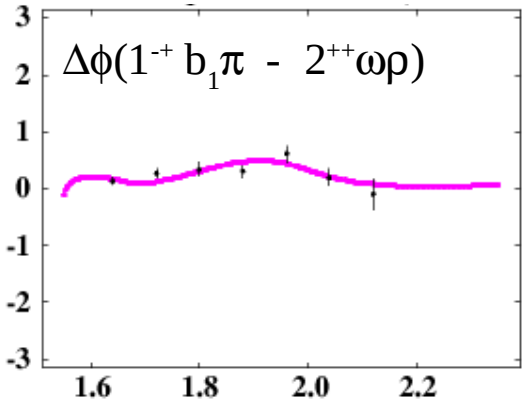


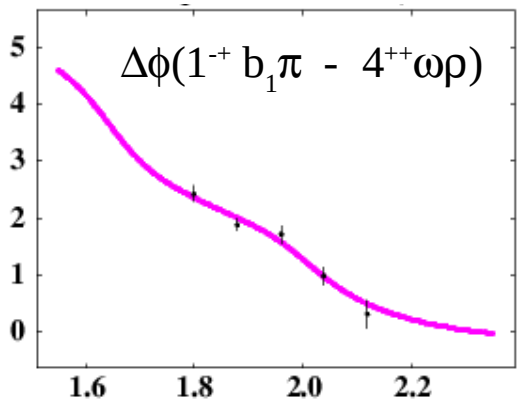


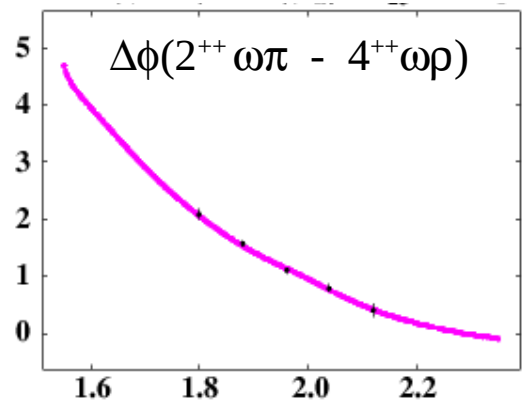


E852 1995 $\pi^- p \to \omega \pi^0 \pi^- p$

Phases Differences







$$\frac{\chi^2}{DOF} = \frac{32.97}{25} = 1.32$$

E852 (1995) $\pi^- p \to \omega \pi^0 \pi^- p$

Partial Wave Analysis Results:

Wave	Mass(MeV/c^2)	Width (MeV/c^2)
$1^{-+}1^+ b_1 \pi S$	1687 ± 11	206 ± 28
	2028 ± 19	214 ± 33
$2^{++}0^+ \omega \rho S$	1753 ± 16	279 ± 43
	2019 ± 9	232 ± 22
$4^{++}0^+ \omega \rho D$	1995 ± 10	208 ± 26

$SU(3)_{flavor}$ Symmetry

$$8 \otimes 8 = 27 \oplus 10 \oplus \bar{10} \oplus 8_1 \oplus 8_2 \oplus 1$$

Lipkin, PL**B196**, 245 (1989)

$$J^{PC} = 1^{-+} \quad \bar{q} G q \not\to \eta\pi$$

Chung & Klempt:

$$if \; X_{10 \oplus \bar{10}} \to \eta_8 \pi \;\Rightarrow\; X \not\to \rho\pi$$

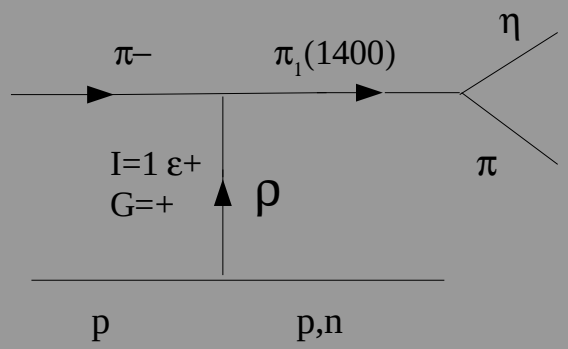


Table II: $SU(3)$ Multiplets and their Composition		
$SU(3)$ Multiplet	J^{PC} or J^P	Composition
Singlet (**1**)	even^{++}	$q\bar{q}$, $q\bar{q}+g$, $q\bar{q}+q\bar{q}$
Symmetric Octet ($\mathbf{8_1}$)	even^{++}	$q\bar{q}$, $q\bar{q}+g$, $q\bar{q}+q\bar{q}$
Antisymmetric Octet ($\mathbf{8_2}$)	odd^{--}	$q\bar{q}$, $q\bar{q}+g$, $q\bar{q}+q\bar{q}$
multiplet **20** ($\mathbf{10} \oplus \overline{\mathbf{10}}$)	odd^{-}	$q\bar{q}+q\bar{q}$ (14 strange states)
	odd^{-+}	$q\bar{q}+q\bar{q}$ (3 non-strange states)
	odd^{--}	$q\bar{q}+q\bar{q}$ (3 non-strange states)
Multiplet 27	even^{++}	$q\bar{q}+q\bar{q}$

Chung,Klempt, and Korner Eur.Phys.J.A15, 539 (2002)

Summary and Conclusions

$\pi_1(1400)$: 'First' $J^{PC}=1^{-+}$ Exotic Meson: $M \sim 1400$ MeV/c^2, $\Gamma \sim 340$ MeV

$q\bar{q}q\bar{q}$?

$\pi_1(1600)$: Seen now in $\rho\pi$, $\eta'\pi$, $f_1(1285)\pi$, $b_1(1235)\pi$

$M \sim 1600$ MeV/c2, $\Gamma \sim 340$ MeV gluonic hybrid?

$\varepsilon+$ $\varepsilon-$?

NEW: $\pi_1(2000)$: Seen in 'preferred' modes $f_1(1285)\pi$ and $b_1(1235)\pi$*

*Special thanks to Joaquim Kuhn and Minghui Lu