Some New Results for Exotic Mesons and Future Prospects

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http://www.phy.bnl.gov/~e852/reviews.html

Plan of Talk

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- Introduction:

  A brief overview of exotic mesons

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- Conclusions and Future Prospects

Allowed quantum numbers for Quarkonia

X

- Consider a $q\bar{q}$, where $q = \{u, d, s\}$, in a state of L and S
  $L =$ Orbital angular momentum $(= 0,\ 1,\ 2,\ 3, \cdots)^a$
  $S =$ Total intrinsic spin $(= 0,\ 1)^b$
- $P = (-)^{L+1}$ for any $q\bar{q}$ state^c
- $C = (-)^{L+S}$ for a neutral $q\bar{q}$ state^c
- $|L - S| \leq J \leq L + S$
- Forbidden J^{PC}'s: $(0^{--})^d$,
  0^{+-}, 1^{-+}, $(2^{+-})^e$, 3^{-+}, etc.

Allowed quantum numbers for Quarkonia

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- Consider a $q\bar{q}$, where $q = \{u, d, s\}$, in a state of L and S
  $L =$ Orbital angular momentum $(= 0,\ 1,\ 2,\ 3, \cdots)$[a]
  $S =$ Total intrinsic spin $(= 0,\ 1)$[b]
- $P = (-)^{L+1}$ for any $q\bar{q}$ state[c]
- $C = (-)^{L+S}$ for a neutral $q\bar{q}$ state[c]
- $|L - S| \le J \le L + S$
- Forbidden J^{PC}'s: (0^{--})[d], 0^{+-}, 1^{-+}, (2^{+-})[e], 3^{-+}, etc.

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[a] S. U. Chung, "Spin Formalisms," CERN Yellow Report 71-8 (Updated)

[b] S. U. Chung, "Quantum Lorentz Transformations"

[c] S. U. Chung, "C- and G-parity: a New Definition and Applications" (Version IV)

[d] S. U. Chung, "Quantum Numbers for Hybrid mesons in the Flux-tube Model" (Version III)

[e] S. U. Chung, "Meson Production in Photon-Pomeron Fusion Processes" (Version II)

Definition: Exotic Mesons

- Conventional $q\bar{q}$ mesons
  $\vec{J} = \vec{L} + \vec{S}$, $P = (-)^{L+1}$, $C = (-)^{L+S}$;
  Forbidden J^{PC}=0^{--}, 0^{+-},1^{-+}, 2^{+-}, 3^{-+}, etc.

- Exotic mesons:
  $n\bar{n} + g$, $n = \{u, d\}$, mass ~ 1.9 GeV with $J^{PC} = 1^{-+}$ at the lightest meson
  $n\bar{n} + n\bar{n}$; 4-quark exotics

- Notation for Exotic Mesons: The key determinant is $\{PC\}$, e.g.

$I^G(J^{PC})$	$1^-(0^{-+})$	$0^+(0^{-+})$	$1^-(1^{-+})$	$0^+(1^{-+})$
Name	π	η	$\pi_1(1600)$	$\eta_1(1600?)$

$I^G(J^{PC})$	$1^+(1^{+-})$	$0^-(1^{+-})$	$1^+(2^{+-})$	$0^-(2^{+-})$
Name	$b_1(1235)$	$h_1(1170)$	$b_2(1900?)$	$h_2(1900?)$

$I^G(J^{PC})$	$1^-(1^{--})$	$0^+(1^{--})$	$1^-(0^{--})$	$0^+(0^{--})$
Name	ρ	ω	$\rho_0(4000?)$	$\omega_0(4000?)$

Gluonic Excitations

Hybrid mesons $(q\bar{q}+g)$[a] with $J^{PC} = 0^{\pm\mp}, 1^{\pm\pm}, 1^{\pm\mp}, 2^{\pm\mp}$

$m(n\bar{n}+g) \sim$ 1.9 GeV where $n = \{u,d\}$

$m(s\bar{s}+g) \sim$ 2.1 GeV

$m(c\bar{c}+g) \sim$ 4.3 GeV

$m(b\bar{b}+g) \sim$ 10.8 GeV

Glueballs (gg and ggg)[b]

$m(J^{PC} = 0^{++}) \simeq 1710(50)(\ 80)$ MeV $(r_0 M_G)$ $(r_0^{-1} = 410(20)$ MeV$)$

$m(J^{PC} = 2^{++}) \simeq 2390(30)(120)$ MeV

$m(J^{PC} = 0^{-+}) \simeq 2560(35)(120)$ MeV

$m(J^{PC} = 1^{+-}) \simeq 2980(30)(140)$ MeV

$m(J^{PC} = 2^{-+}) \simeq 3040(40)(150)$ MeV

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[a] N. Isgur and J. Paton, Phys. Rev. D**31**, 2910 (1985)

[b] Y. Chen *et al.*, Phys. Rev. D**73**,014516 (2006);
C. Morningstar and M. Peardon, Phys. Rev. D**60**,034509 (1999)

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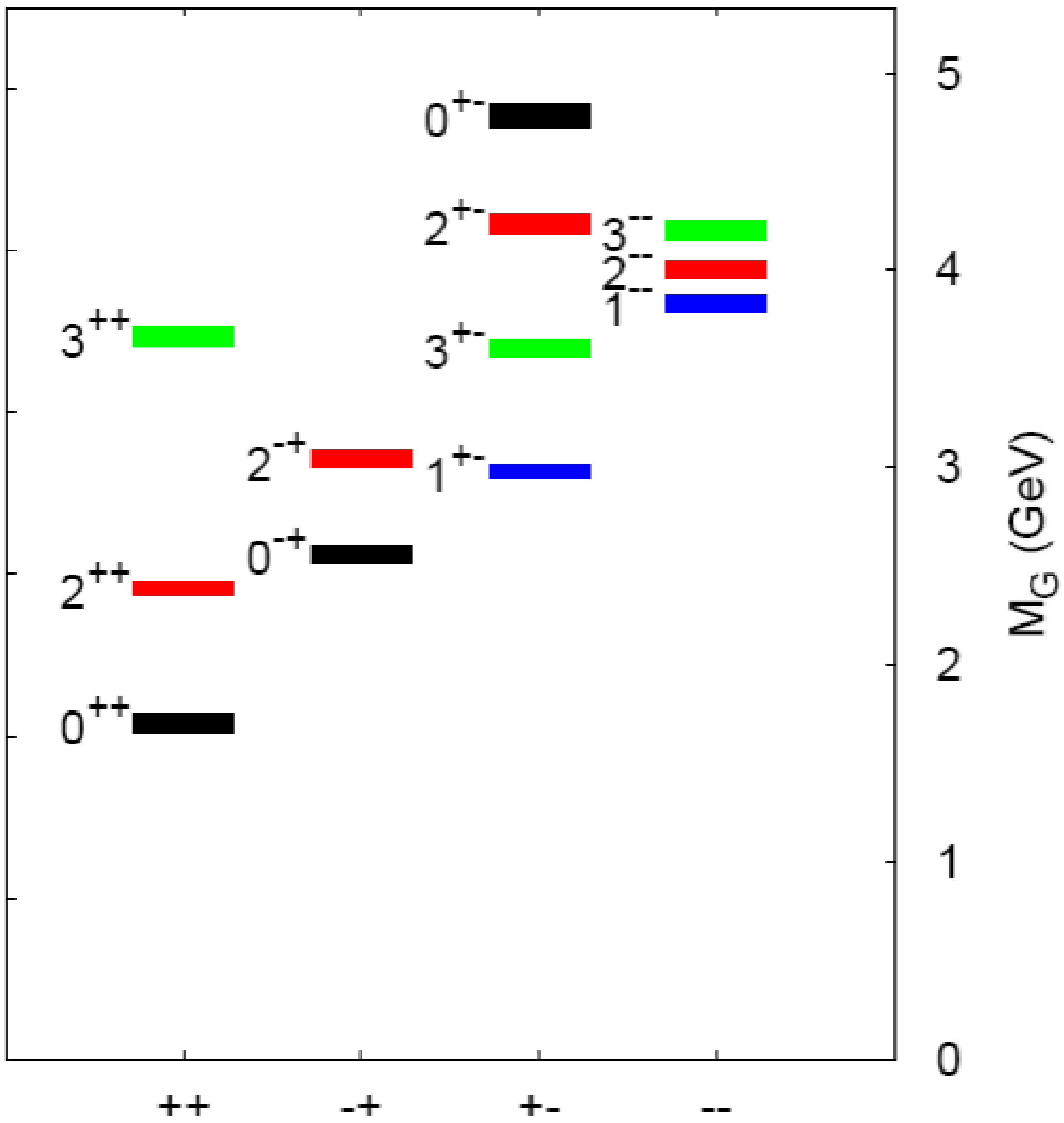
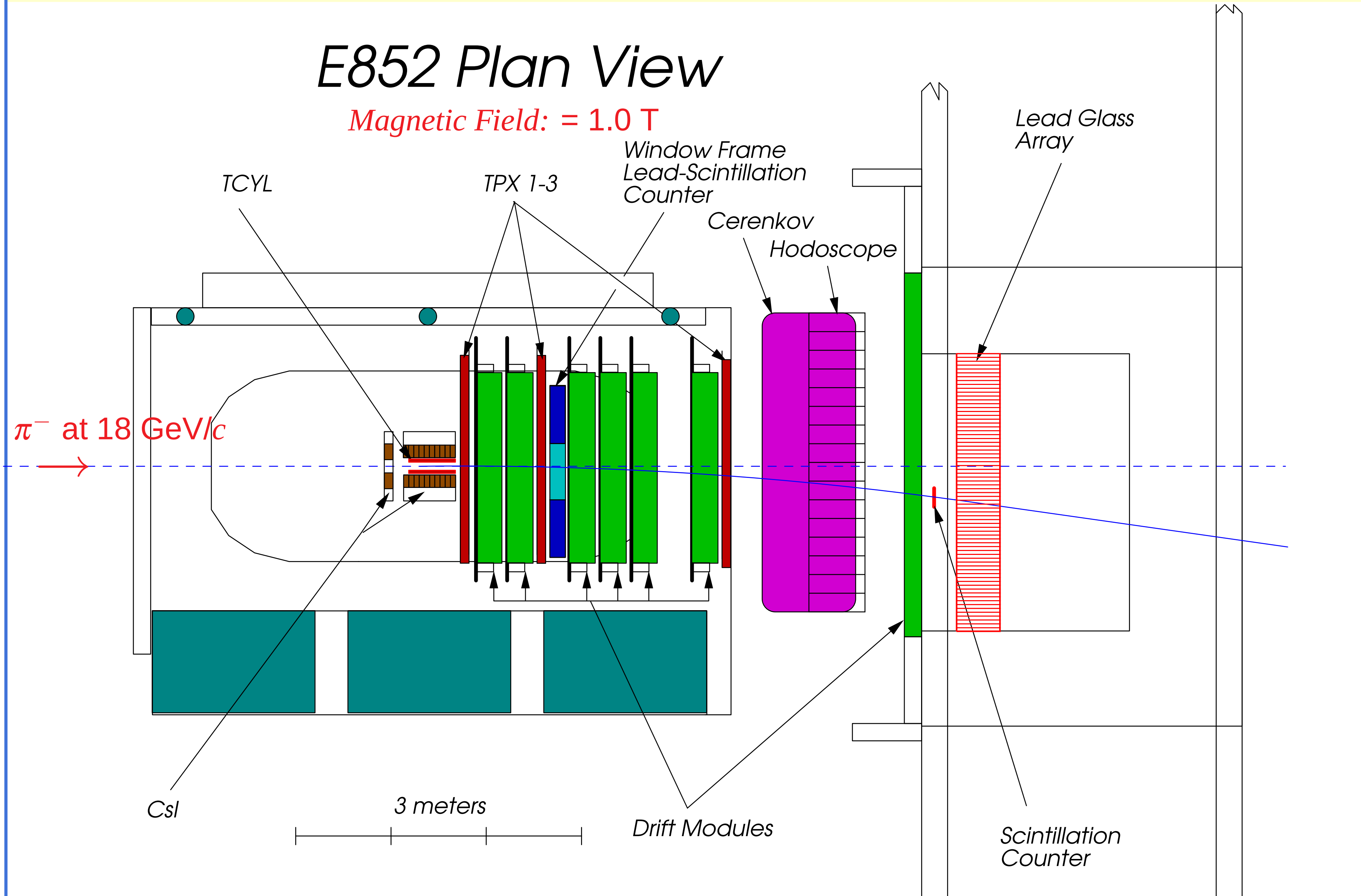


J^{PC}

BNL-E852 at the MultiParticle Spectrometer (MPS)

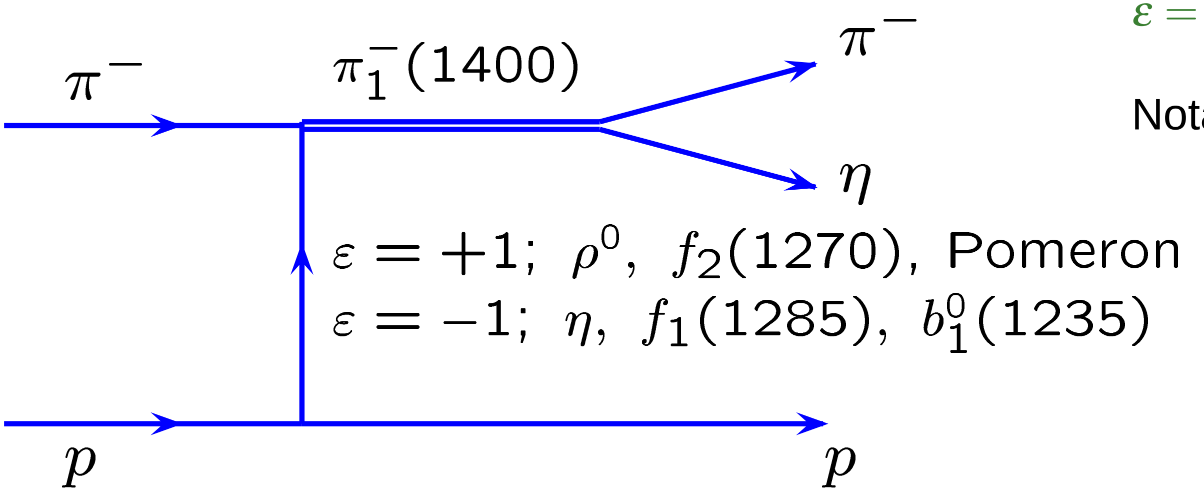


Reggeon exchange:

$\varepsilon = +1$ Natural-parity exchange

$\varepsilon = -1$ Unnatural-parity exchange

Notation: $J^{PC} M^{\varepsilon} R_1 \begin{bmatrix} L \\ S \end{bmatrix} R_2$



$1^{-+} 1^{+}\ \eta \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \longrightarrow P_+$

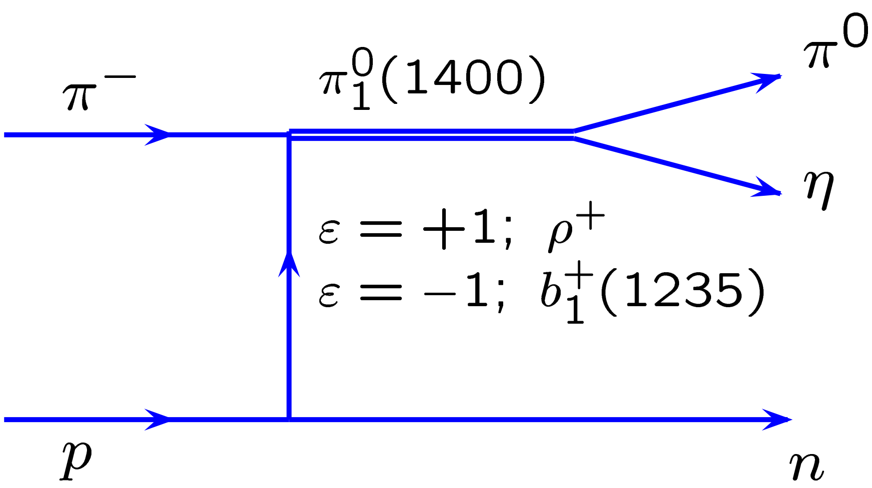
$2^{++} 1^{+}\ \eta \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \longrightarrow D_+$

$1^{-+} 0^{-}\ \eta \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \longrightarrow P_0$

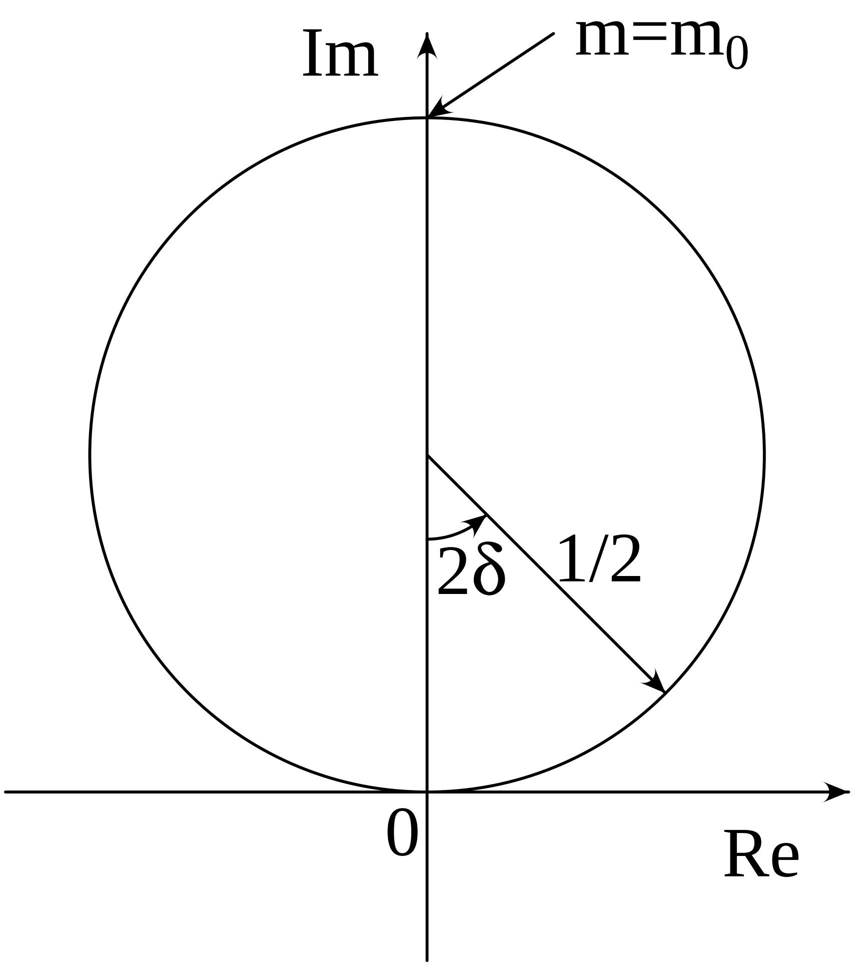
$1^{-+} 1^{-}\ \eta \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \longrightarrow P_-$

$2^{++} 0^{-}\ \eta \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \longrightarrow D_0$

$2^{++} 1^{-}\ \eta \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \longrightarrow D_-$



Phase motion of a Breit-Wigner form

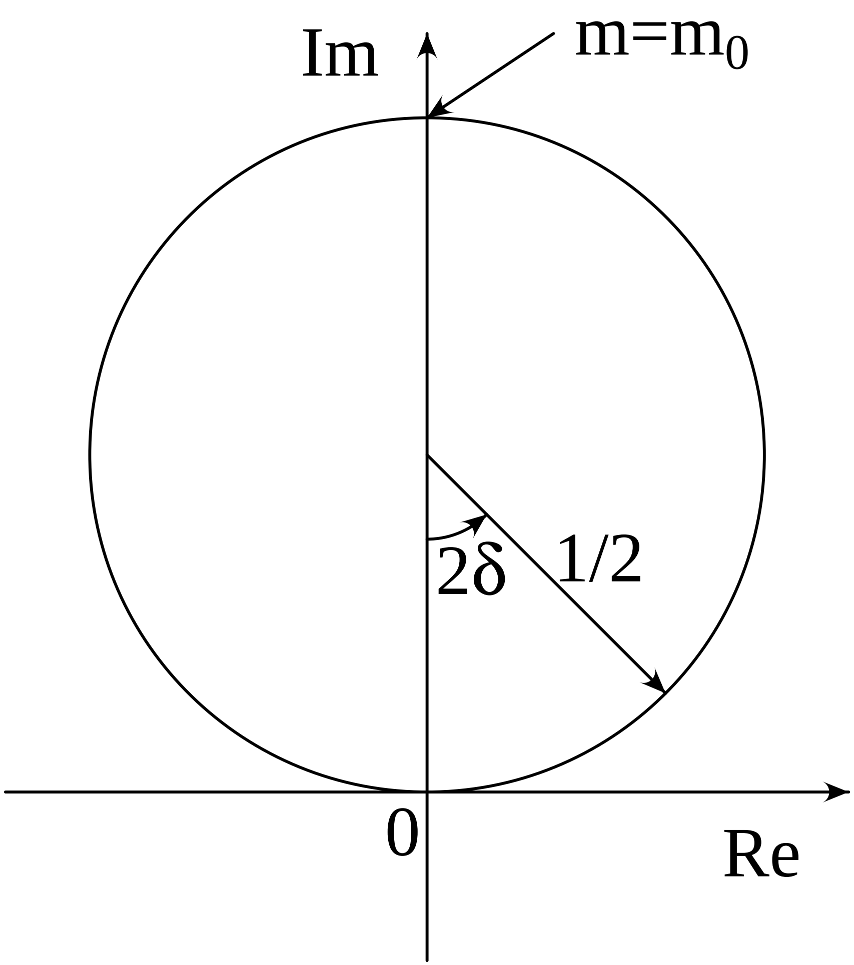


$$\Delta(m) = \frac{m_0\,\Gamma_0}{m_0^2 - m^2 - i\,m_0\,\Gamma_0}$$

$$= e^{i\,\delta(m)}\,\sin\delta(m)$$

$$\cot\delta(m) = \frac{m_0^2 - m^2}{m_0\,\Gamma_0}$$

Phase motion of a Breit-Wigner form



$$\Delta(m) = \frac{m_0\,\Gamma_0}{m_0^2 - m^2 - i\,m_0\,\Gamma_0}$$
$$= e^{i\,\delta(m)}\,\sin\delta(m)$$

$$\cot\delta(m) = \frac{m_0^2 - m^2}{m_0\,\Gamma_0}$$

Interference effect:

$A = 1 + \alpha, \quad \alpha \sim 0.1$

$|A|^2 = 1 + 2\alpha + \alpha^2$

$\alpha^2 = N/N_{\rm tot} = 0.01, \quad 2\alpha = 2\sqrt{N/N_{\rm tot}} = 0.2$

Reflectivity Basis for Density Matrix

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The distribution function in the reflectivity basis for $\pi^- + p \longrightarrow X^- + p$ can be written

$$I(\tau) = \sum_{\varepsilon}^{2} \sum_{ij} {}^{\varepsilon}\rho_{ij}\, {}^{\varepsilon}D_i(\tau)\, {}^{\varepsilon}D_j^*(\tau)$$

where i and j are any of the partial waves in a set and ${}^{\varepsilon}D^{\chi}(\tau)$ is the decay amplitude in the reflectivity basis. The density matrix, a square matrix, can be expressed as follows:

$${}^{\varepsilon}\rho_{ij} = \sum_{k=1}^{2} {}^{\varepsilon}V_{ik}\, {}^{\varepsilon}V_{jk}^* \quad \Longleftarrow \quad {}^{\varepsilon}\rho = {}^{\varepsilon}V\, {}^{\varepsilon}V^{\dagger}$$

where ${}^{\varepsilon}V$ is a rectangular matrix. Write

$${}^{\varepsilon}U_k(\tau) = \sum_{i} {}^{\varepsilon}V_{ik}\, {}^{\varepsilon}D_i(\tau)$$

and then

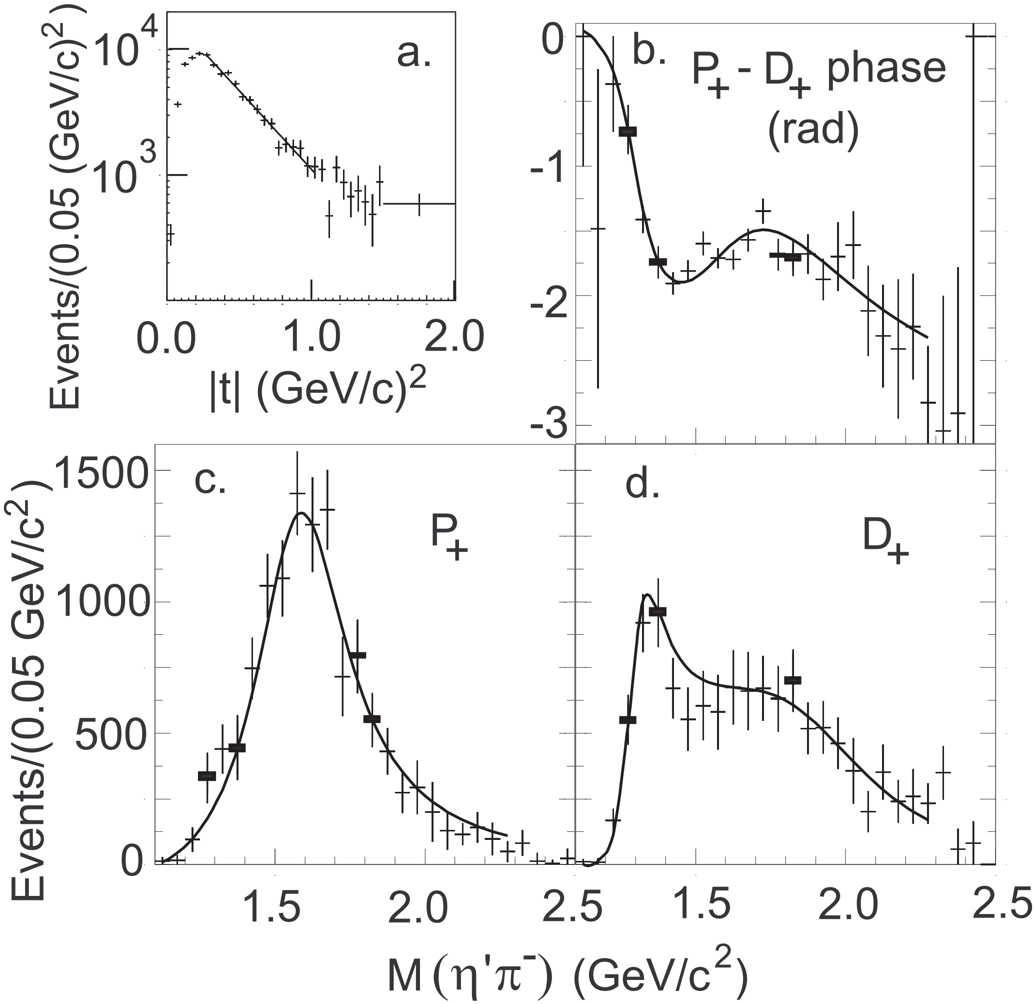
$$I(\tau) = \sum_{\varepsilon}^{2} \sum_{k=1}^{2} \left| {}^{\varepsilon}U_k(\tau) \right|^2$$

S. U. Chung and T. L. Trueman, Phys. Rev. D 11, 633 (1975)

Exotic Meson: $\pi_1^-(1600) \to \eta'\pi^-$ BNL-E852

Reaction: $\pi^- p \to \eta'\pi^- p$ at 18 GeV/c, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$

~ 6000 events



$1^{-+}1^+\ \eta' \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \to P_+$

$2^{++}1^+\ \eta' \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \to D_+$

$$\begin{cases} M(P_+) = 1597 \pm 10 \begin{array}{l} +\ 45 \\ -\ 10 \end{array} \\ \Gamma(P_+) = 340 \pm 40 \pm 50 \end{cases}$$

PRL 86, 3977 (2001)

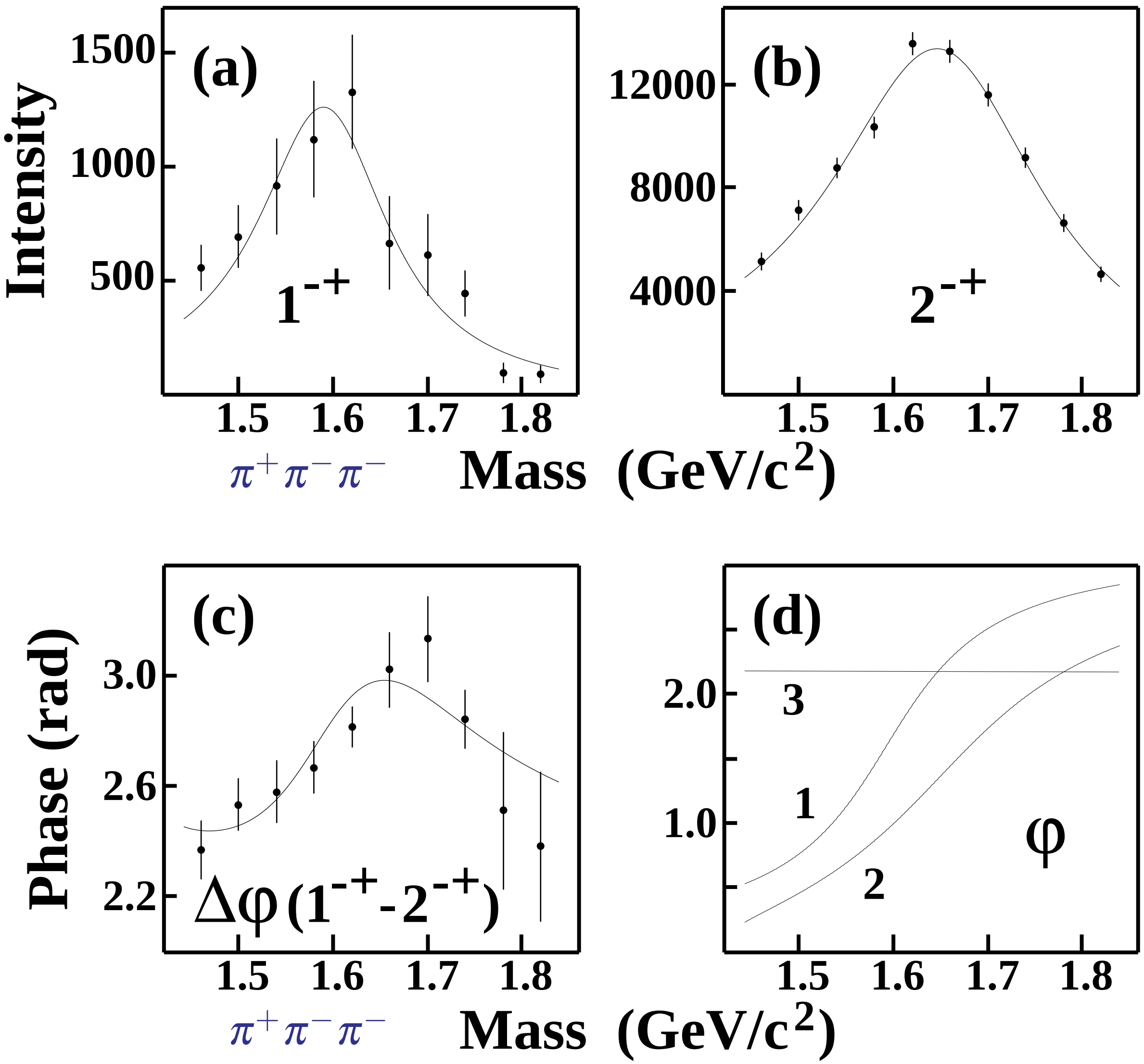
Exotic Meson (BNL E-852): $\pi_1^-(1600) \to \rho^0(770)\pi^-$, $\rho^0(770) \to \pi^+\pi^-$

Reaction: $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c
$\sim 250\,000$ events

Partial waves: $1^{-+}1^+\rho(770)[P]\pi$, $2^{-+}0^+ f_2(1270)[S]\pi$

$1^{-+}1^+\rho\begin{bmatrix}P\\1\end{bmatrix}\pi$

$2^{++}0^+ f_2\begin{bmatrix}S\\2\end{bmatrix}\pi$



Number of Waves = 21 and 27

$$\begin{cases} M = 1593 \pm 8 \begin{array}{c} +\ 29 \\ -\ 47 \end{array} \\ \Gamma = 168 \pm 20 \begin{array}{c} +\ 150 \\ -\ 12 \end{array} \end{cases}$$

PRL 81, 5760 (1998)
PRD 65, 072001 (2002)

A Comment on the Decay $\pi_1(1600) \rightarrow \rho\pi$

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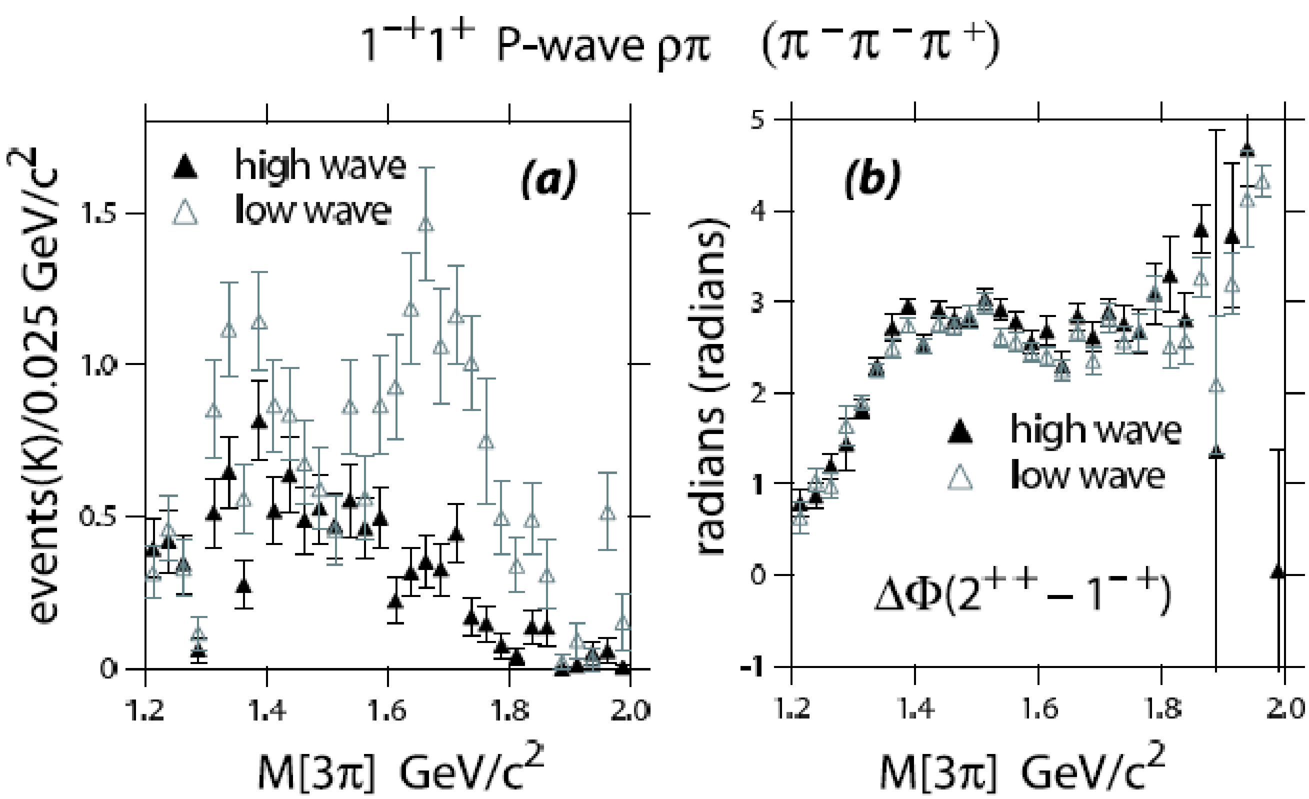
- Observe the quoted with by BNL-E852: $\Gamma[\pi_1(1600) \rightarrow \rho\pi] = 168 \pm 20 \begin{matrix} +150 \\ -12 \end{matrix}$ MeV

- Their reasoning is that the magnitude of the signal for $\pi_1(1600) \rightarrow \rho\pi$ varies enormously—the cross section difficult to quote—and the width varies along with the signal, when the number of partial waves in the fit is increased or when the rank of the density matrix is increased to two.

- But the phase motion between the partial waves 1^{-+} and 2^{-+} remains relatively stable and the two waves are always produced coherently.

- It is therefore not surprising to see that VES observe the same signal, although their official position is that they do not observe the $\rho\pi$ signal.

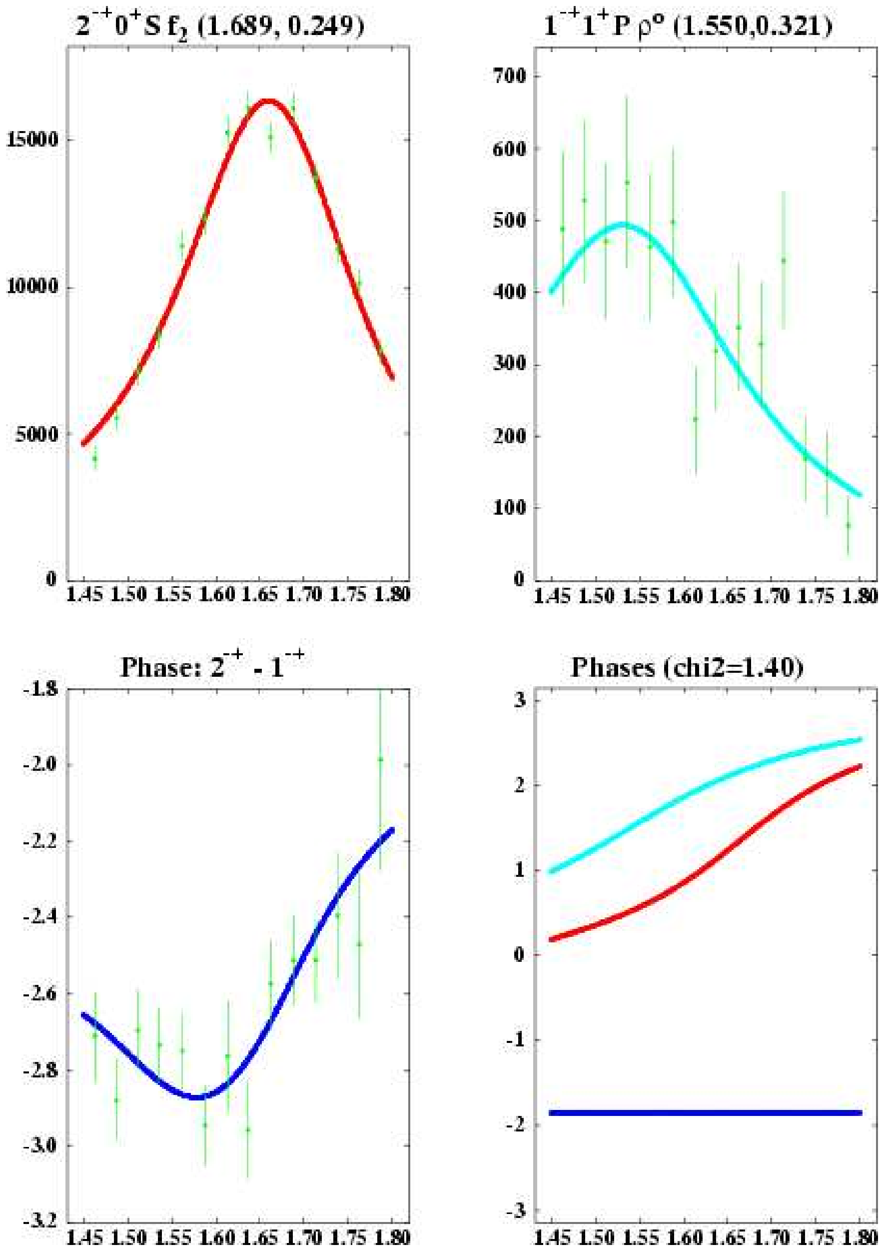
- The Indiana group, working on the BNL-E852 data, observe the same signal—giving the same mass and the width. Once again, they prefer to state that they do not observe the $\rho\pi$ signal.



High-wave set = 36; High-wave set = 20

The phase motion between 2^{++} and 1^{-+} is identical in the 1.6 GeV region

INDIANA Group X
PRD73, 072001(2006)



$$\begin{cases} M(1^{-+}) = 1550 \text{ MeV} \\ \Gamma(1^{-+}) = 321 \text{ MeV} \end{cases}$$

A. Ostrovidov
FSU

Exotic Meson: $\pi_1(1600)$

Experiments	M (MeV)	Γ (MeV)	Decay
BNL ($\pi^- p$ at 18 GeV/c)[a]	$1593 \pm 8 {}^{+20}_{-47}$	$168 \pm 20 {}^{+150}_{-12}$	$\rho\pi$
BNL ($\pi^- p$ at 18 GeV/c)[b]	$1596 \pm 10 {}^{+45}_{-10}$	$340 \pm 40 \pm 50$	$\eta'\pi$
BNL ($\pi^- p$ at 18 GeV/c)[c]	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	$f_1(1285)\pi$
BNL ($\pi^- p$ at 18 GeV/c)[d]	$1664 \pm 8 \pm 4$	$185 \pm 25 \pm 12$	$b_1(1235)\pi$
VES ($\pi^- N$ at 37 GeV/c)[e]	1560 ± 6	340 ± 5	$\rho\pi$
			$\eta'\pi$
			$b_1(1235)\pi$
CB ($\bar{p}p$ at rest)[f]	$1596 {}^{+25}_{-14} {}^{+50}_{-50}$	$312 {}^{+64}_{-24} {}^{+75}_{-75}$	$b_1(1235)\pi$

[a] PRD 65, 072001 (2002)

[b] PRL 86, 3977 (2001)

[c] PL B595, 109 (2004)

[d] PRL 94, 032002 (2005)

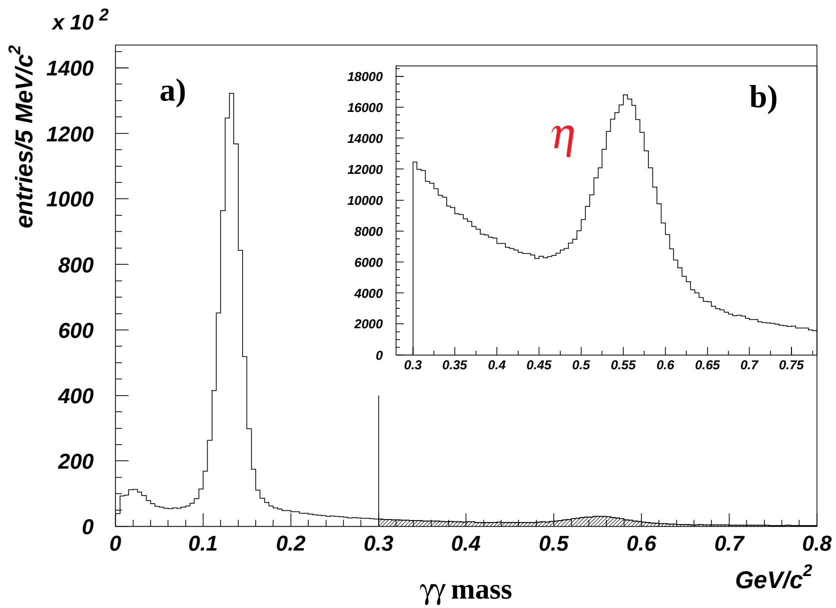
[e] V. Dorofeev, Proc. Workshop on Hadron Spectroscopy, Frascati, Italy (1999), p. 3.

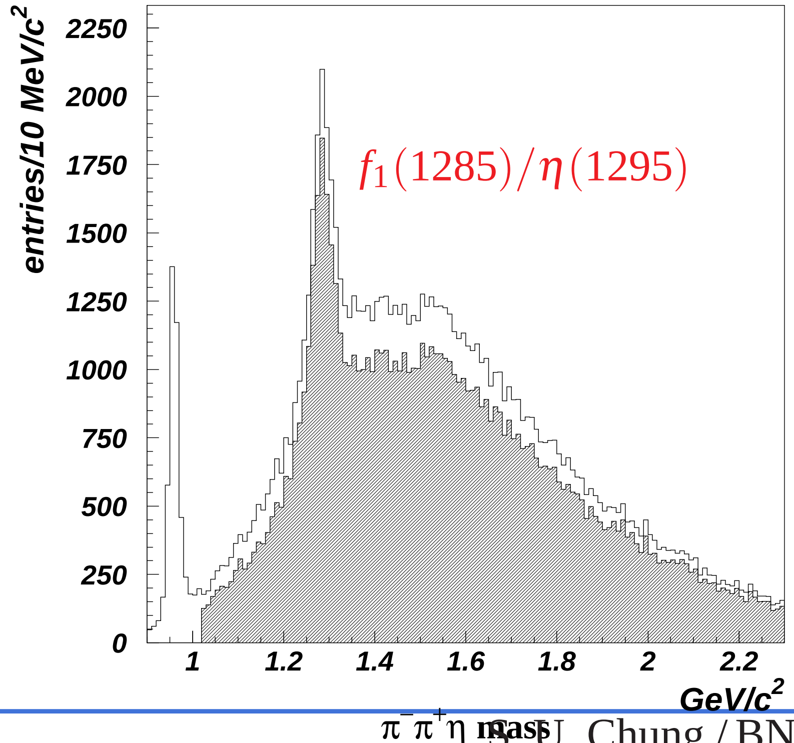
[f] PL B563, 140 (2003)—Mass and Width fixed to PDG values

Results on $f_1(1285)\pi$ BNL-E852

Reaction: $\pi^- p \to \eta\pi^+\pi^-\pi^- p$, $\sim 69\,000$ events

$$\pi^- p \to f_1(1285)\pi^- p,\; f_1(1285) \to \eta\pi^+\pi^-,\; \eta \to \gamma\gamma$$



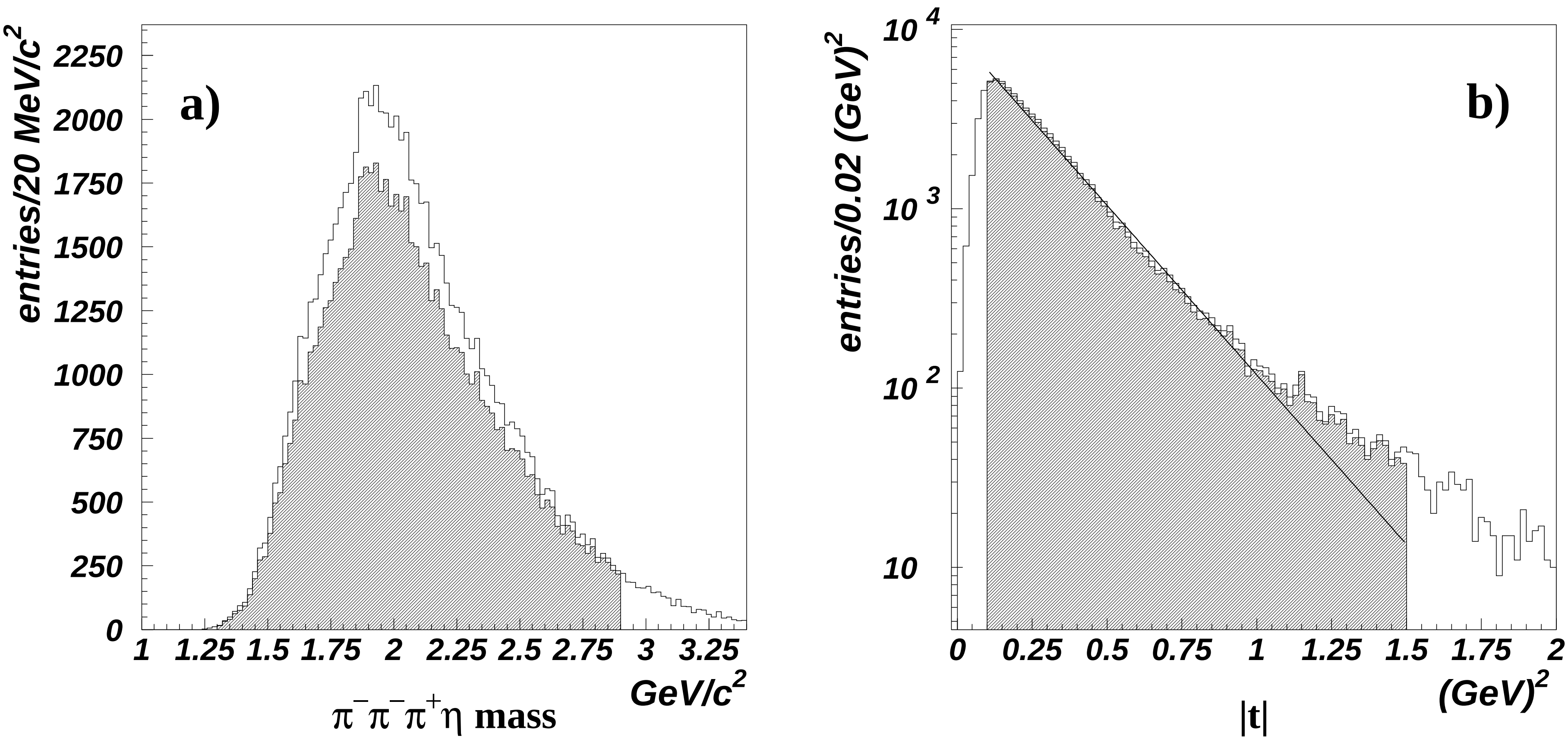


Results on $f_1(1285)\pi$ BNL-E852

X

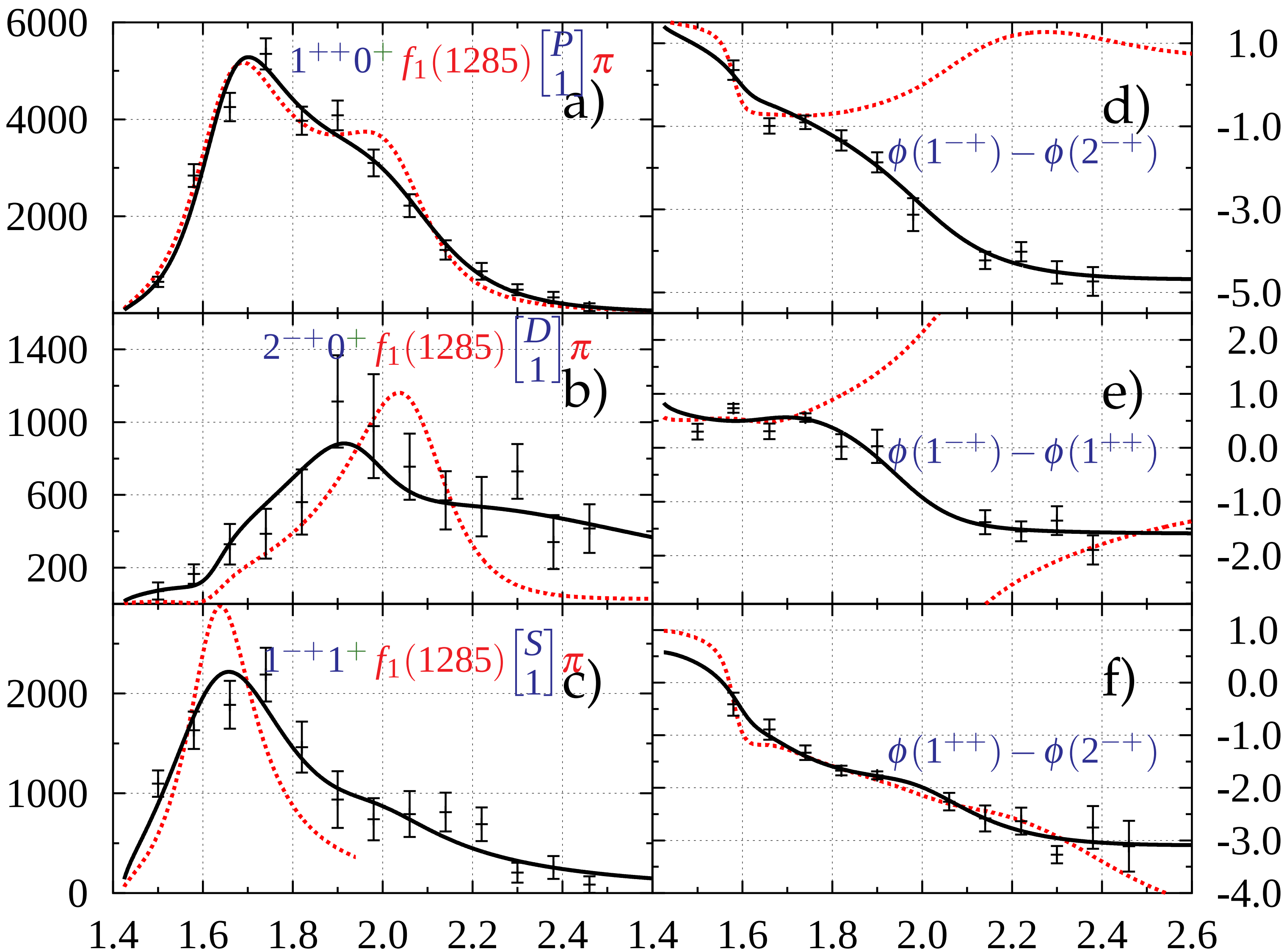
Reaction: $\pi^- p \to \eta\pi^+\pi^-\pi^- p$, $\sim 69\,000$ events

$\pi^- p \to f_1(1285)\pi^- p$, $f_1(1285) \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$



Results of Partial-wave Analysis BNL-E852

Intensity and phase difference for selected $f_1(1285)\pi^-$ waves: $J^{PC}M^{\varepsilon}\ f_1(1285)\begin{bmatrix}L\\1\end{bmatrix}\pi$



$\pi_1(1600)$ and $\pi_1(2000)$

Exotic Meson: $\pi_1(2000)$

Experiments	M (MeV)	Γ (MeV)	Decay
BNL ($\pi^- p$ at 18 GeV/c)[a]	$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$	$f_1(1285)\pi$
BNL ($\pi^- p$ at 18 GeV/c)[b]	$2014 \pm 20 \pm 10$	$230 \pm 32 \pm 15$	$b_1(1235)\pi$

[a] PL B595, 109 (2004)

[b] PRL 94, 032002 (2005)

Exotic Meson:

Reaction: $\pi^- p \to \eta \pi^- p$ at 18 GeV/c, $\eta \to \gamma\gamma$, $\sigma(\eta \to \gamma\gamma) \sim 30$ MeV

$\sim 47\,200$ events

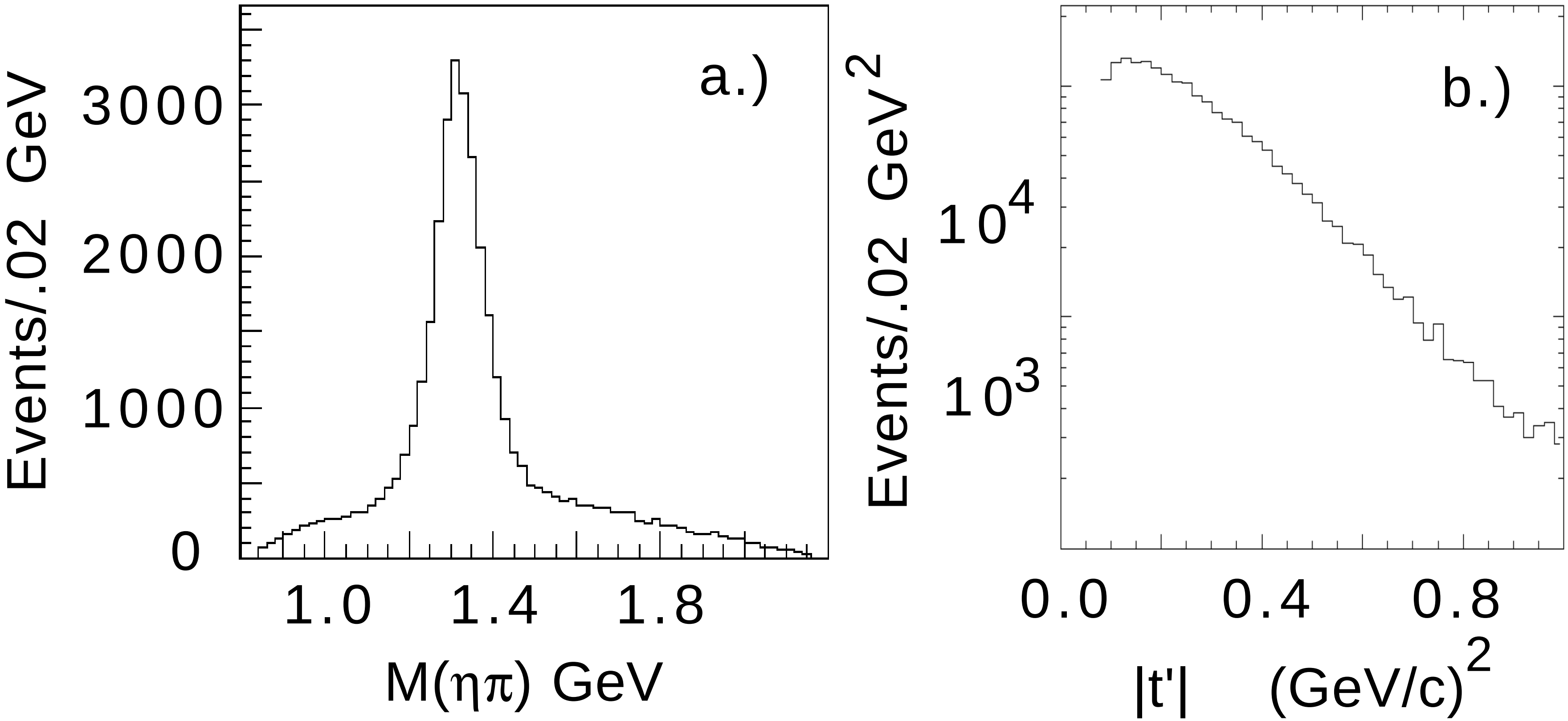


Figure 1

Exotic Meson: $\pi_1^-(1400) \to \eta\pi^-$

Reaction: $\pi^- p \to \eta\pi^- p$ at 18 GeV/c, $\eta \to \gamma\gamma$

$\sim$ 47 200 events

$1^{-+}1^+ \eta \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \to P_+$

$2^{++}1^+ \eta \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \to D_+$

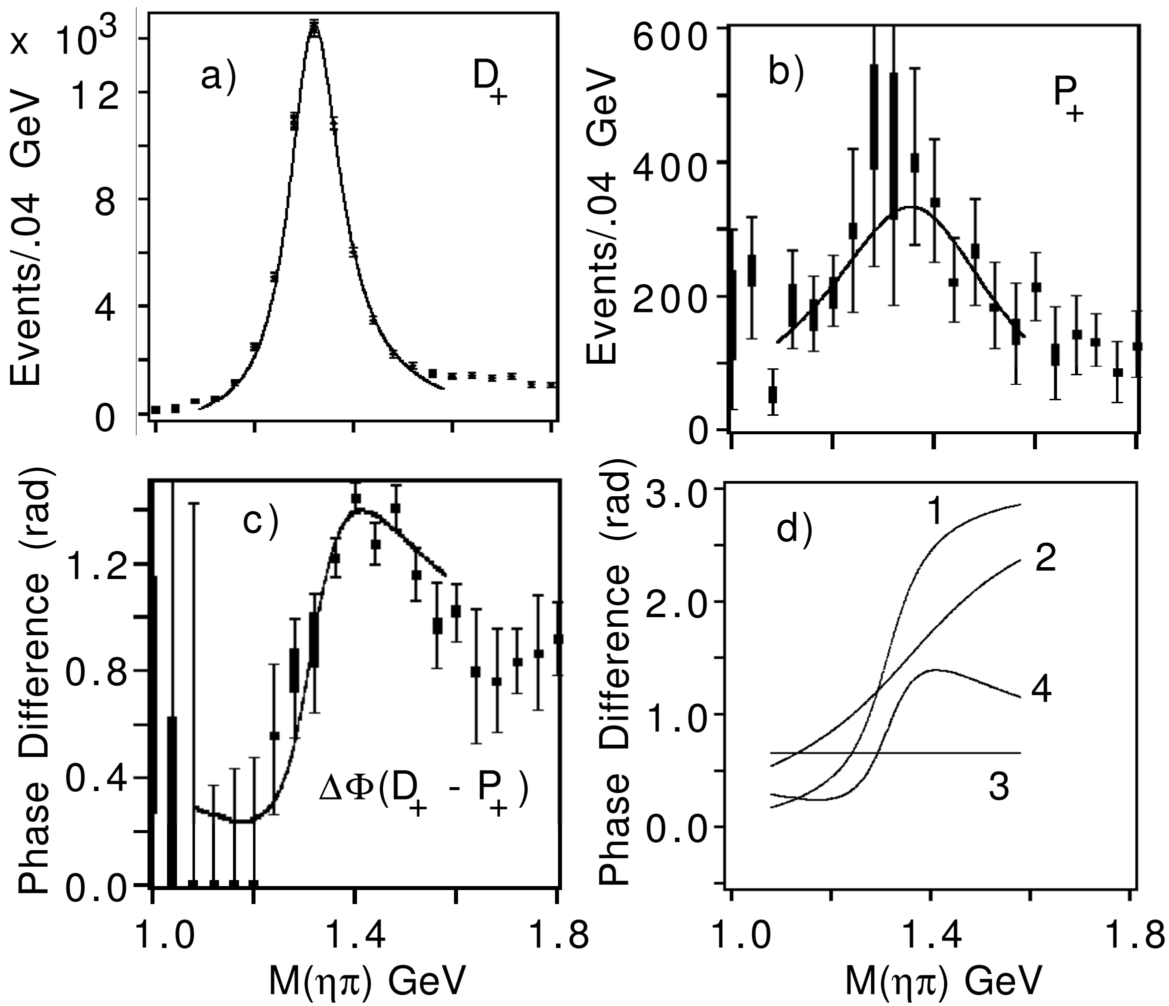


Figure 3

$$\begin{cases} M(P_+) = 1370 \pm 16 \begin{matrix} +\ 50 \\ -\ 30 \end{matrix} \\ \Gamma(P_+) = 385 \pm 40 \begin{matrix} +\ \ 65 \\ -\ 105 \end{matrix} \end{cases}$$

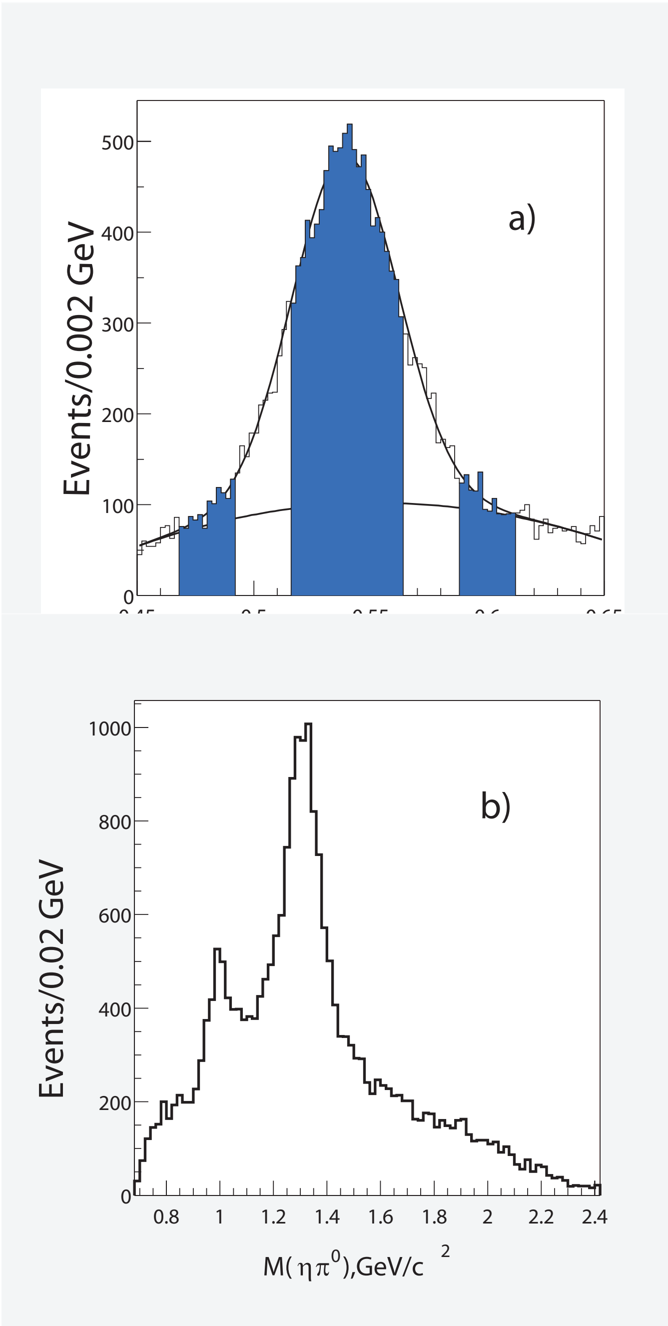
PRL 79, 1630 (1997)

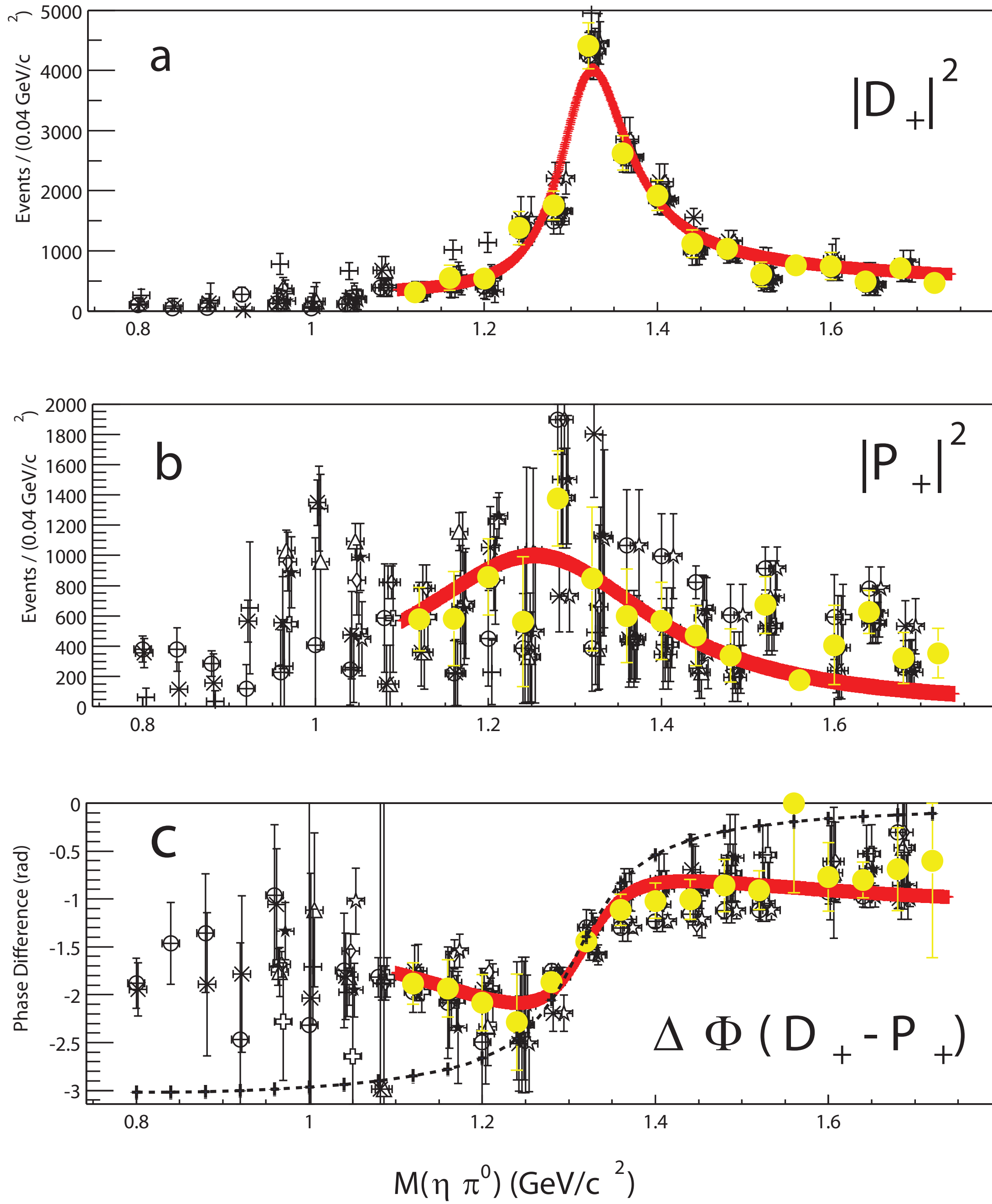
PRD 60, 092001 (1999)

$\pi^- p \to \eta\pi^0 n$ at 18 GeV/c with $\eta \to \pi^+\pi^0\pi^-$ and $\pi^0 \to \gamma\gamma$

$\sim 23\,500$ events

Moscow State University (BNL-E852)





Results of PWA on the $\eta\pi^0$ Decay Channel BNL-E852

- Three methods were used to study the D_+ and P_+ waves:

	Method	Mass (MeV)	Width (MeV)
1	Average Solutions	1265 ± 20	411 ± 64
2	Randomized Solutions	1257 ± 25	354 ± 58
3	Global Fit	1256 ± 10	319 ± 34

- Results quoted are:

  Mass = $1257 \pm 20 \pm 25$ and Width = $354 \pm 64 \pm 58$

Exotic Meson: $\pi_1(1400) \to \eta\pi$

x

Experiments	M (MeV)	Γ (MeV)
$\pi^- p \to \eta\pi^- p$ at 18 GeV/c, BNL-E852 '94 data[a]	$1370 \pm 16 {}^{+50}_{-30}$	$385 \pm 40 {}^{+65}_{-105}$
$\pi^- p \to \eta\pi^- p$ at 18 GeV/c, BNL-E852 '95 data	$1359 {}^{+16}_{-14} {}^{+50}_{-30}$	$385 {}^{+31}_{-29} {}^{+9}_{-66}$
$\pi^- p \to \eta\pi^0 n$, $\eta \to \gamma\gamma$ at 18 GeV/c, Indiana low-t' data[b]	1301 ± 14	190 ± 32
$\pi^- p \to \eta\pi^0 n$, $\eta \to \pi^+\pi^0\pi^-$ at 18 GeV/c, BNL-E852[c]	$1257 \pm 20 \pm 25$	$354 \pm 64 \pm 58$
$\bar{p}n\,({}^3S_1) \to \pi^-\pi^0\eta$ at rest, Crystal Barrel[d]	$1400 \pm 20 \pm 20$	$310 \pm 50 {}^{+50}_{-30}$
?? $\bar{p}p\,({}^1S_0) \to \pi^0\pi^0\eta$ at rest, Crystal Barrel[e]	1360 ± 25	220 ± 90
$\pi^- p \to \eta\pi^- p$ at 6.3 GeV/c, KEK[f]	1323.1 ± 4.6	143.2 ± 12.5
$\pi^-\mathrm{Be} \to \eta\pi^-\mathrm{Be}$ at 28 GeV/c, VES[g]	1316 ± 12	287 ± 25

[a] PRD 60, 092001 (1999).
[b] PRD 67, 094015 (2003).
[c] Paper submitted to the PRL
[d] PL B423, 175 (1998).
[e] PL B446, 349 (1999), A. Sarantsev, Proc. Hadron03, AIP Conf. Proc. **717** (2004) 65.
[f] PL B314, 246 (1993).
[g] V. Dorofeev (VES), Proc. Hadron01, AIP Conf. Proc. **619** (2002) 577.

Exotic Mesons: $\pi_1(1400) \to \eta\pi, \quad \pi_1'(1400) \to \rho\pi$

Experiments	M (MeV)	Γ (MeV)
$\pi^- p \to \eta\pi^- p$ at 18 GeV/c, BNL-E852 '94 data[a] $\text{Pomeron} + \pi \to \pi_1(1400) \to \pi\eta$	$1370 \pm 16 \begin{smallmatrix} +50 \\ -30 \end{smallmatrix}$	$385 \pm 40 \begin{smallmatrix} +65 \\ -105 \end{smallmatrix}$
$\pi^- p \to \eta\pi^0 n$, $\eta \to \pi^+\pi^0\pi^-$ at 18 GeV/c, BNL-E852[b] $\rho\pi \to \pi_1(1400) \to \pi\eta$	$1257 \pm 20 \pm 25$	$354 \pm 64 \pm 58$
$\bar{p}n\,(^3S_1) \to \pi^-\pi^0\eta$ at rest, Crystal Barrel[c] $p\bar{p}\,(^3S_1) + \pi \to \pi_1(1400) \to \pi\eta$	$1400 \pm 20 \pm 20$	$310 \pm 50 \begin{smallmatrix} +50 \\ -30 \end{smallmatrix}$
$\bar{p}n \to \pi^0\pi^0\rho^-$ at rest, Crystal Barrel[d] $p\bar{p}\,(^1P_1$ and $^1S_0) + \pi \to \pi_1(1400) \to \pi\rho$	$1400 \pm 20 \pm 20$	$310 \pm 50 \begin{smallmatrix} +50 \\ -30 \end{smallmatrix}$
$\bar{p}p \to \pi^+\pi^-\rho^0$ at rest, Obelix[e] $p\bar{p}\,(^1P_1$ and $^1S_0) + \pi \to \pi_1(1400) \to \pi\rho$	1360 ± 25	220 ± 90

[a] PRD 60, 092001 (1999).

[b] Paper submitted to the PRL

[c] PL B423, 175 (1998).

[d] W. Dünnweber and F. Meyer-Wildhagen, Hadron03, AIP Conf. Proc. **717** (2004) 388.

[e] P. Salvini *et al.*, Eur. Phys. J. C **35** (2004) 21.

Mesons in flavor 8×8

h

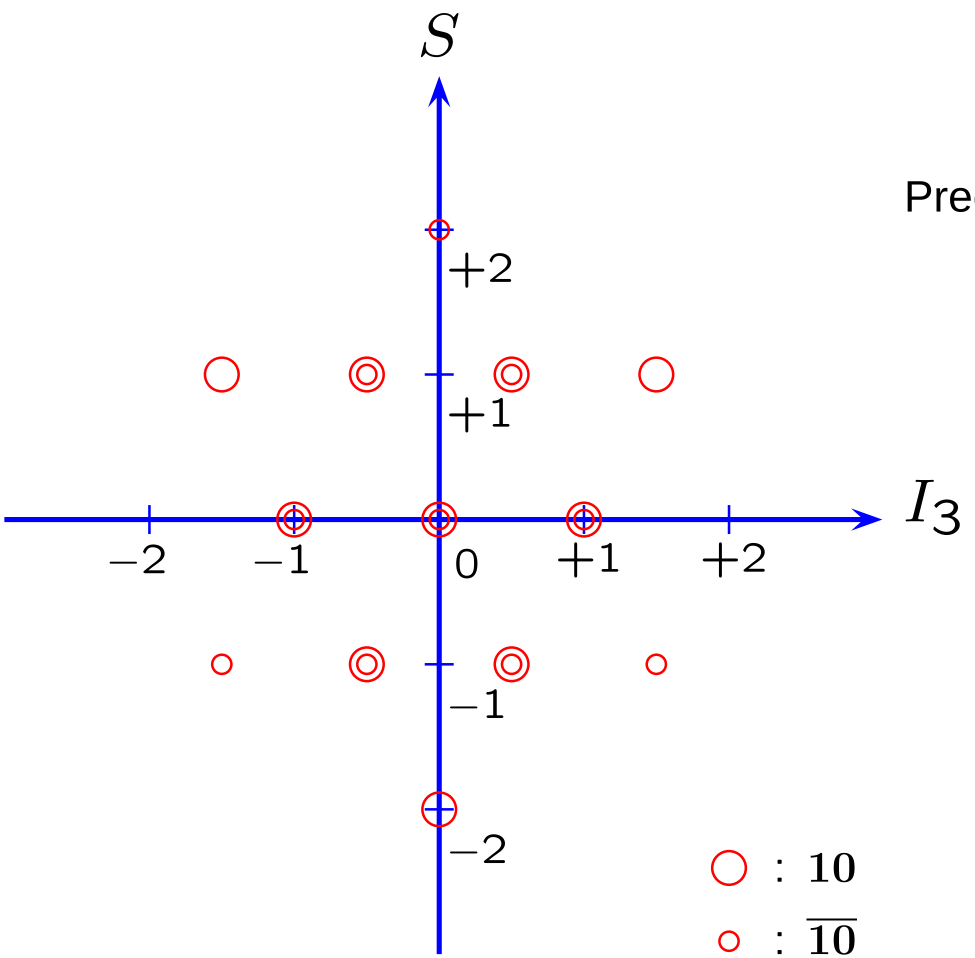
- $SU(3)$ Decomposition:
  $8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8_1 \oplus 8_2 \oplus 1$
- Decays into Two Ground-State Octets :
  ${}^1S_0 \otimes {}^1S_0$, e.g. $\pi\pi$, KK, $\pi\eta$, etc.
- Complete Normalized Wave Functions:
  $SU(3)$ Isoscalar Factors [J. J. de Swat, RMP 35, 916 (1963)]
  $\otimes$ Clebsch-Gordan Coefficients

$J^{PC} = 1^{-+}$ $(10 + \overline{10})$

Y	I	Q	wave functions
0	1	$+1$	$\frac{1}{\sqrt{2}}\,(\pi^+\eta - \eta\,\pi^+)$
		0	$\frac{1}{\sqrt{2}}\,(\pi^0\eta - \eta\,\pi^0)$
		-1	$\frac{1}{\sqrt{2}}\,(\pi^-\eta - \eta\,\pi^-)$

S. U. Chung, E. Klempt, and J. G. Körner
Eur. Phys. J. A15, 539 (2002)

A P-Wave $\pi\eta$ State: Mesons in flavor $10 \oplus \overline{10}$

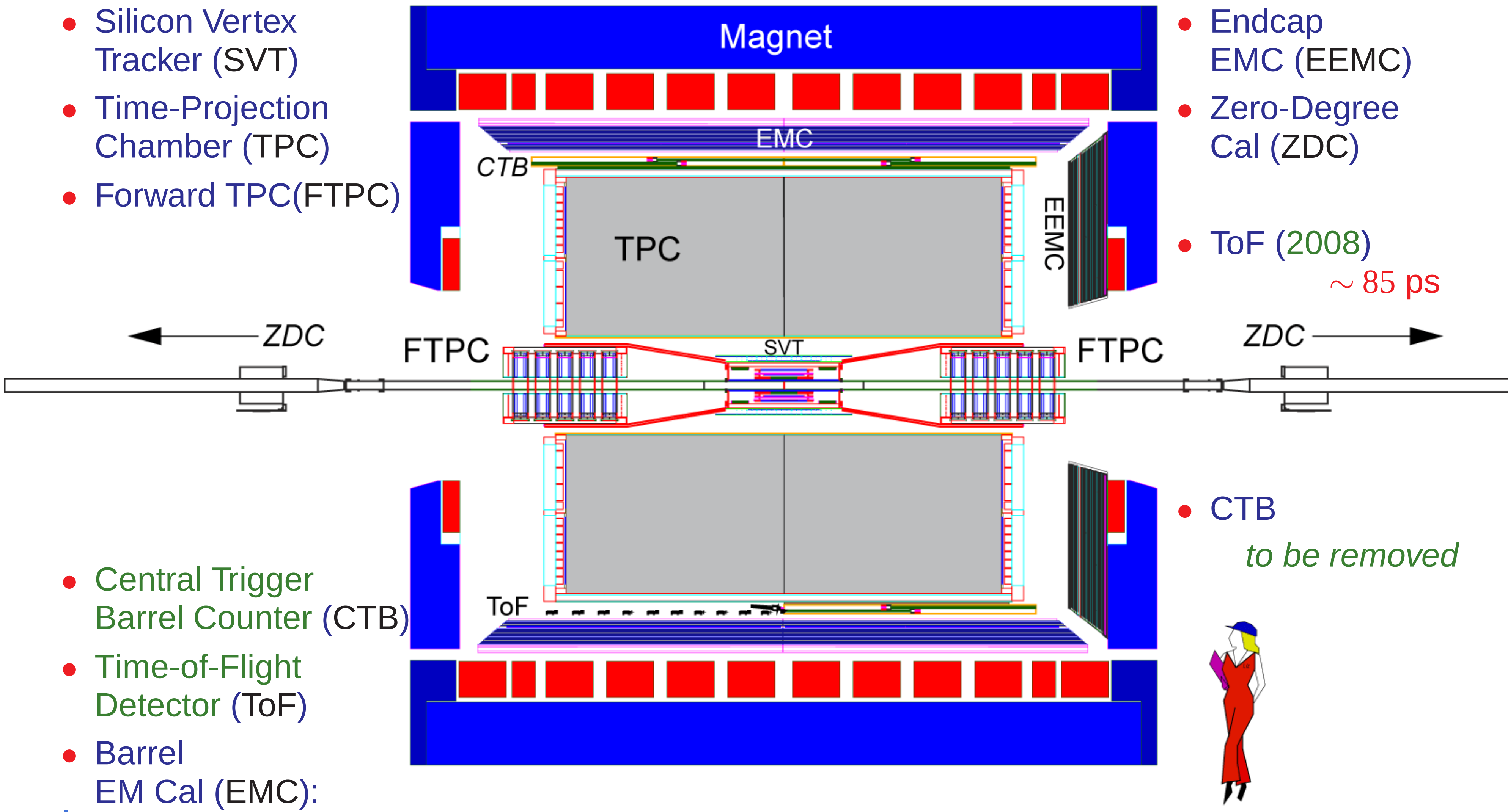


Predict: no $\eta_1(1400)$
one $\rho(1400)$

Single circles have just one member of the multiplet,
while the double circles indicate two occupancies by the members of the multiplet.

Magnetic Field : 0.5 T

- Silicon Vertex Tracker (SVT)
- Time-Projection Chamber (TPC)
- Forward TPC(FTPC)



- Endcap EMC (EEMC)
- Zero-Degree Cal (ZDC)
- ToF (2008)
  $\sim$ 85 ps
- CTB
  to be removed

- Central Trigger Barrel Counter (CTB)
- Time-of-Flight Detector (ToF)
- Barrel EM Cal (EMC):
  4,800 Towers

Hadron Spectroscopy Program of STAR within the Ultra-Peripheral Collisions (UPC) Group

- $\mathrm{Au} + \mathrm{Au} \to \mathrm{Au}^{(*)} + \mathrm{Au}^{(*)} + \rho$
  Photon+Pomeron$\to \rho \to \pi^+\pi^-$ $\qquad J^{PC} = 1^{--}$
  Trigger on events with two charged particles in CTB
  with or without ZDC

- $\mathrm{Au} + \mathrm{Au} \to \mathrm{Au}^{(*)} + \mathrm{Au}^{(*)} + \rho'$
  Photon+Pomeron$\to \rho' \to \pi^+\pi^-\pi^+\pi^-$ $\qquad J^{PC} = 1^{--}$
  Pilot run in 2004: search for exotic mesons with $J^{PC} = 0^{+-}$, $J^{PC} = 2^{+-}$

  Trigger on events with four or more charged particles in CTB and ZDC

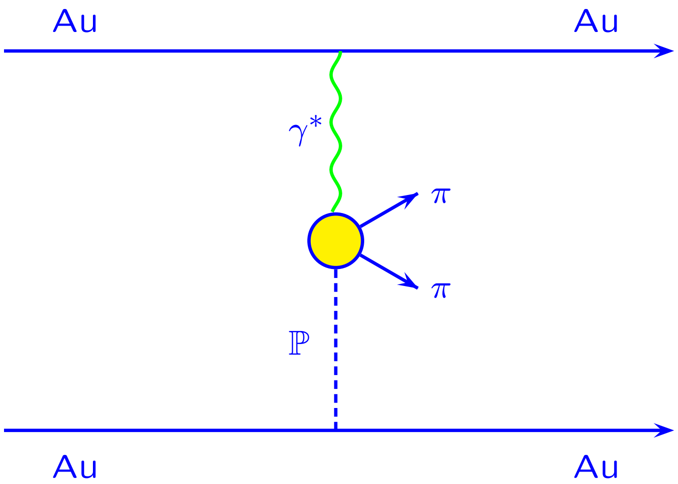
- Future Runs with a Ultra-Peripheral Detector (UPD) systems
  An example: $p + p \to p + (\pi^+\pi^+\pi^-\pi^-) + p$
  Pomeron+Pomeron$\to f_0(1500) \to \pi^+\pi^-\pi^+\pi^-$

  Central production of exotic mesons with $J^{PC} = 1^{-+}$

Photon+Pomeron→ ρ^0

Pioneering Work by S. Klein, *et al.* (UPC group):

RHIC run in 2000 at $\sqrt{s_{NN}} = 130$ GeV
Central Trigger Barrel (CTB) in quadrants
2-prong trigger⟹30 000 events

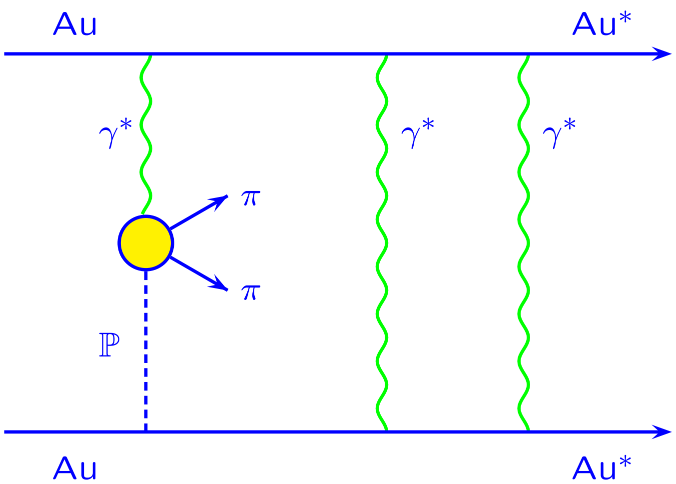


$$\mathrm{Au} + \mathrm{Au} \to \mathrm{Au} + \mathrm{Au} + \rho^0, \qquad \rho^0 \to \pi^+\pi^-$$

$\sigma = 370 \pm 170 \pm 80$ mb

S. Klein, *et al.* (UPC group):

Minimum-Bias Data at $\sqrt{s_{NN}} = 130$ GeV
Zero-degree Calorimeter (ZDC) in coincidence
800 000 events



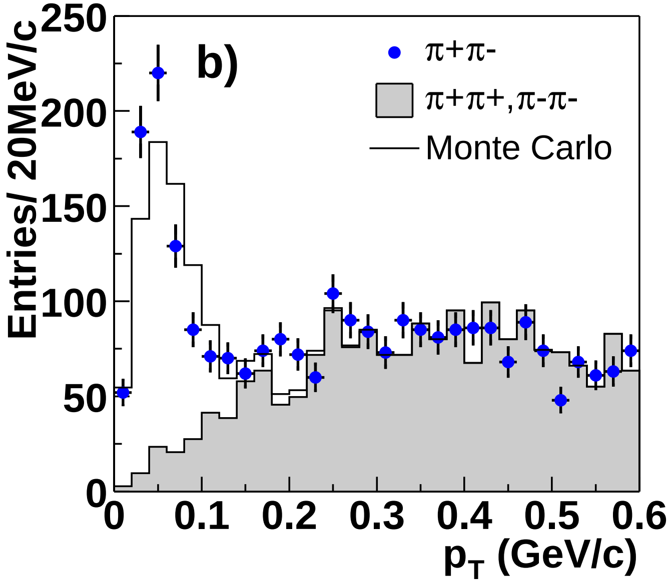
$$\mathrm{Au} + \mathrm{Au} \to \mathrm{Au}^* + \mathrm{Au}^* + \rho^0, \qquad \rho^0 \to \pi^+\pi^-$$

$\sigma = 39.7 \pm 2.8 \pm 9.7$ mb

PRL 89, 272302 (2002)

Photon+Pomeron→ ρ^0

S. Klein, *et al.* (UPC group):



ρ^0 candidates for $|y_\rho| < 1$

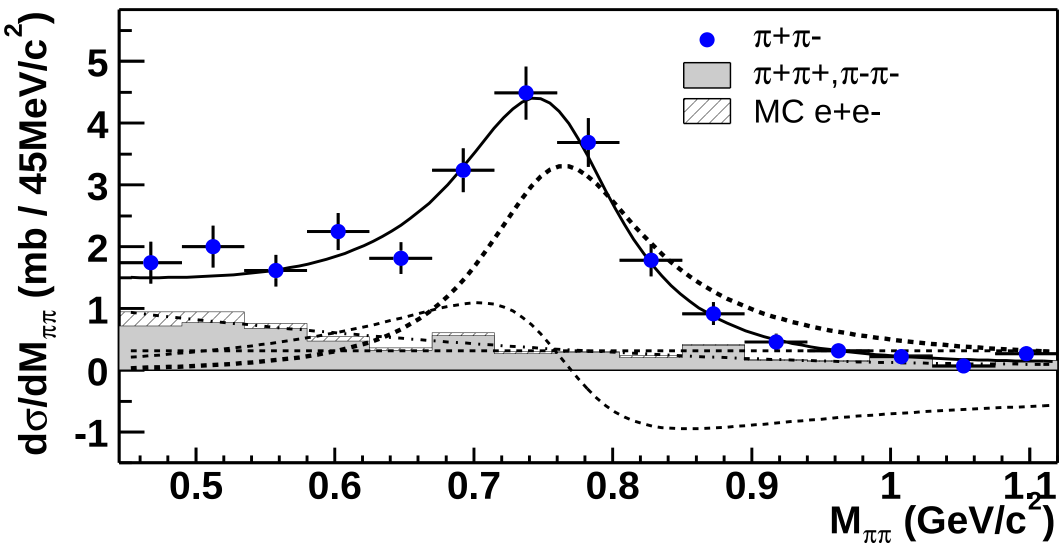
Minimum-Bias Data—(ZDC) Trigger

2-prong trigger similar—not shown

p_T peaked at 50 MeV/c

Like-sign background normalized for $p_T > 200$ MeV/c

MC p_T normalized to ρ^0 for $p_T < 150$ MeV/c



ρ^0 candidates for $|y_\rho| < 1$

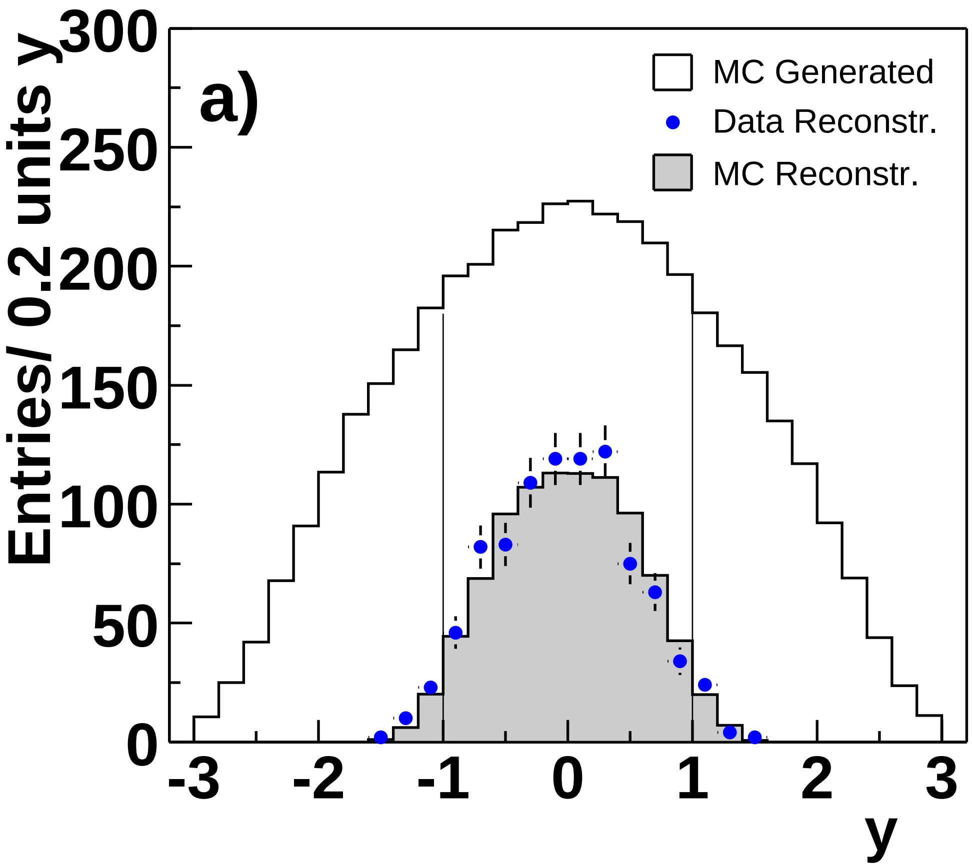
Minimum-Bias Data—(ZDC) Trigger

2-prong trigger similar—not shown

$p_T < 150$ MeV/c

M (MeV)	Γ (MeV)
778 ± 7	148 ± 14
777 ± 7	139 ± 13
773 ± 7	127 ± 13

ρ^0 Rapidity Distribution



Minimum-Bias Data—(ZDC) Trigger
2-prong trigger similar—not shown

Photon+Pomeron$\to X \to \pi^+\pi^-\pi^+\pi^-$

$\mathrm{Au} + \mathrm{Au} \to \mathrm{Au}^* + \mathrm{Au}^* + X, \qquad X \to \pi^+\pi^-\pi^+\pi^-$

Search for exotic mesons with $J^{PC} = 0^{+-}, 2^{+-}, \ldots$

Total number of triggers (2004) = 5×10^6 in 200 hours of run at RHIC

Total number of $\rho^0 \to \pi^+\pi^-$ = 12 000 events collected vs 50 000 events expected (1%)

Total number of $\pi^+\pi^-\pi^+\pi^-$ = 120 events collected vs 1 250 events (2.5×10^{-4})

Future: TOF Pads for more efficient trigger

DAQ upgrade for more efficient data-taking

$SU(3)$ Partners to the Exotic Mesons

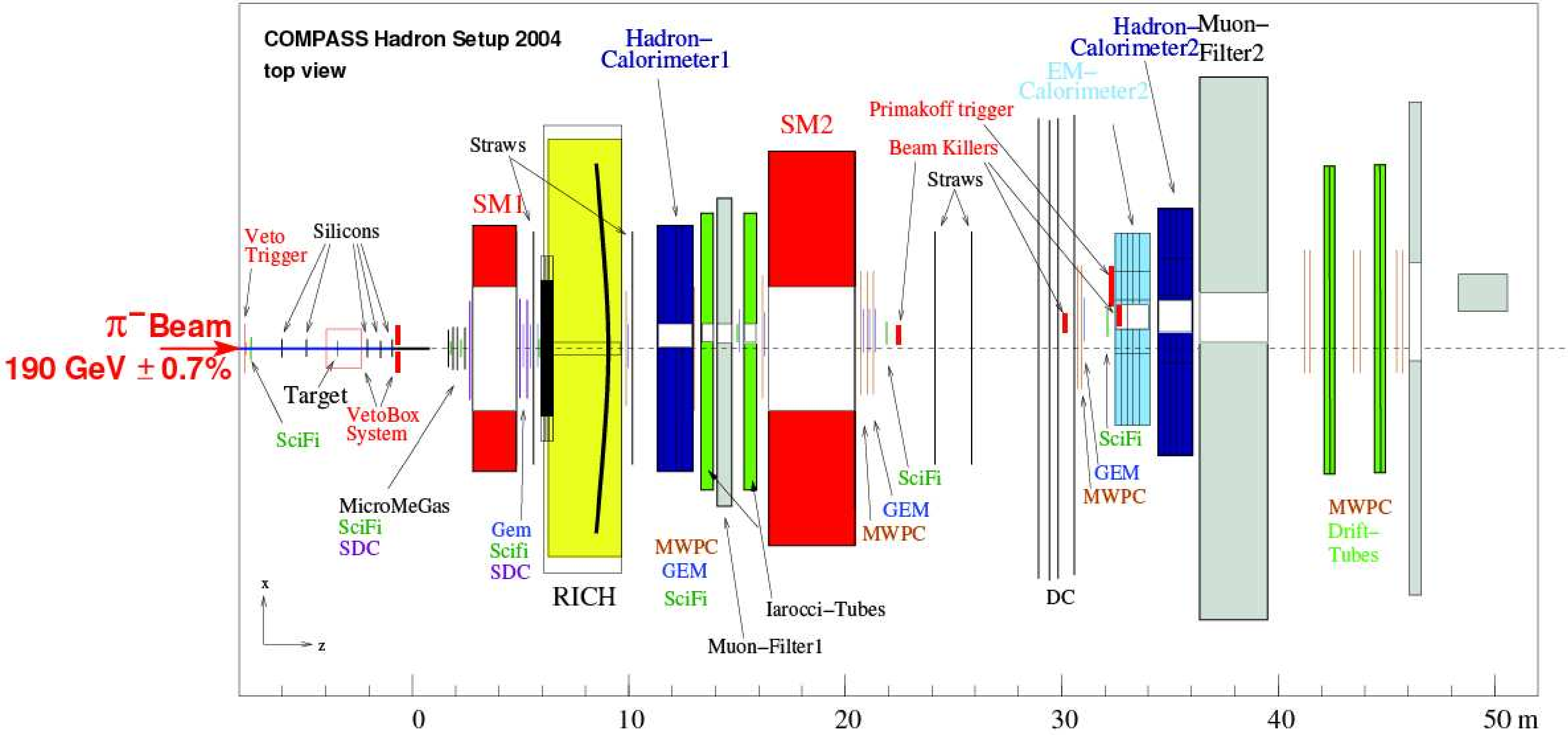
- Consider three species of quarks, i.e. $q = \{u,\ d,\ s\}$:

  Then there must exist
  $K(J^P = 0^-,\ 1^+,\ 2^-)$'s and $K^*(J^P = 0^+,\ 1^-,\ 2^+)$'s,

  $SU(3)$ Partners to
  $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2000)$ $(J^{PC} = 1^{-+})$

- Strangeonium $=$ Any hadrons containing an $s\bar{s}$ pair.
  Exotic Strangeonia: $s\bar{s} + g$, $s\bar{s} + n\bar{n}$, $n = \{u,\ d\}$
  $SU(3)$ Partners to the π_1's

Layout of COMPASS Experiment for Hadron Runs



K^- fraction in π^- beam $\simeq 3 - 5\%$

Conclusions and Future Prospects I

- Three Exotic Mesons from BNL-E852—A Review:

Conclusions and Future Prospects I

- Three Exotic Mesons from BNL-E852—A Review:

1. $\pi_1(1400)$: $M \sim 1370$ MeV, $\Gamma \sim 400$ MeV:

   $\rightarrow \eta\pi$

   $\not\rightarrow \eta'\pi,\ \rho\pi,\ f_1(1285)\pi,\ b_1(1235)\pi$

   $\Rightarrow$ If $10 \oplus \overline{10}$, then predict <u>no</u> $\eta_1(1400)$ partner but $\rho(1400)$

◇ Constituents: $(n\bar{n}) + (n\bar{n})$?

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   ◇ Constituents: $(n\bar{n}) + (n\bar{n})$? $\oplus$ $(n\bar{n}) + \text{gluon}$?

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3. $\pi_1(2000)$: $M \sim 2000$ MeV, $\Gamma \sim 300$ MeV

   $\rightarrow f_1(1285)\pi,\ b_1(1235)\pi$:

   ◇ Constituents: $(n\bar{n}) + \text{gluon}$?

Conclusions and Future Prospects II

- Future Prospects beyond

  BNL-E852, Crystal Barrel/CERN, FOCUS/Fermilab, BESII/China
  VES/Russia, CLEO-C (CESR/Cornell), BaBar/SLAC and Belle/KEK)

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   $\overline{p}$'s from 1.5–15 GeV/c ($\sqrt{s(\overline{p}p)} = 2.4$–5.7 GeV)

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   Photons with a maximum energy of 9 GeV

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4. GLUE-X (Hall D/JLAB) (2012+)
   Photons with a maximum energy of 9 GeV
5. GSI/Darmstadt/Germany, J-Parc/Japan and COMPASS/CERN (2007):
   ⋆ Use separated K^- beam to search for
   exotic strangeonia ($s\bar{s} + n\bar{n}$ and $s\bar{s} + g$), $n = \{u, d\}$
   ⋆ Search for exotic strange mesons,
   $SU(3)$ partners of the nonstrange exotic mesons

Background Material

Production of Vector and Exotic States

X

- Vector Mesons from the PDG Book:
  $\rho(770) \to \pi\pi$, $\rho(1450) \to \pi\pi$ or 4π, $\rho(7100) \to \rho\pi\pi$

- Vector Mesons in $q\bar{q}q\bar{q}$ Systems:

Supermultiplet	Count of the states
$\mathbb{V}_-(1^{--})$	$4\times\rho(\mathbf{8})$, $1\times\rho(\mathbf{27})$, $1\times{}^{(-)}\rho_x(\mathbf{10}\oplus\overline{\mathbf{10}})$, $1\times{}^{(-)}\pi_1(\mathbf{10}\oplus\overline{\mathbf{10}})$
$\mathbb{V}_+(1^{-+})$	$4\times\pi_1(\mathbf{8})$, $1\times\pi_1(\mathbf{27})$, $1\times{}^{(+)}\pi_1(\mathbf{10}\oplus\overline{\mathbf{10}})$, $1\times{}^{(+)}\rho_x(\mathbf{10}\oplus\overline{\mathbf{10}})$

- Allowed Systems for Gluonic Hybrids $q\bar{q}+g$:

L	S	${}^{2S+1}L_J(q\bar{q})$	$J^{PC}(q\bar{q})$	$J^{PC}(q\bar{q}+g)$
1	0	${}^1P_1$	1^{+-}	1^{++} $\boxed{\mathbf{1}^{--}}$
1	1	${}^3P_J$	0^{++}, 1^{++}, 2^{++}	0^{-+}, 1^{-+}, 2^{-+} 0^{+-}, 1^{+-}, 2^{+-}
2	0	${}^1D_2$	2^{-+}	2^{++} 2^{--}
2	1	${}^3D_J$	$\boxed{\mathbf{1}^{--}}$, 2^{--}, 3^{--}	1^{-+}, 2^{-+}, 3^{-+} 1^{+-}, 2^{+-}, 3^{+-}

Possible Decay Modes and Final States

X

★ Decays of $J^{PC}=1^{--}$ [$\rho(1600?)$] and $J^{PC}=0^{+-},\ 2^{+-}$ [$b_{0,2}(2000?),\ h_{0,2}(2000?)$]:

$I^G(J^{PC})$	Intermediate States	Final States
$1^+(1^{--})$	$[\rho^0(770)\,f_0(600)]_{S,D}$	$\pi^+\pi^-\pi^+\pi^-$
$1^+(0^{+-},\ 2^{+-})$	$[\rho^0(770)\,f_0(600)]_P$	$\pi^+\pi^-\pi^+\pi^-$
$1^+(0^{+-},\ 2^{+-})$	$f_0(980)\,\rho^0(770),\ f_2'(1525)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$
$0^-(0^{+-},\ 2^{+-})$	$a_0^0(980)\,\rho^0(770),\ a_2^0(1320)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$

★ Characteristics of a $J^{PC}=0^{--}$ State [$\rho_0(4000?),\ \omega_0(4000?)$]:

I^G	Intermediate States	Final States
1^+	$[a_2^\pm(1320)\,\pi^\mp]_D,\ [\rho^0(770)\,f_2(1270)]_D,$	$\pi^+\pi^-\pi^+\pi^-$
1^+	$f_2'(1525)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$
1^+	$K^*(890)\,\bar{K},\ K_2^*(1420)\,\bar{K},\ a_2^\pm(1320)\,\pi^\mp$	$K_sK^\pm\pi^\mp$
0^-	$K^*(890)\,\bar{K},\ K_2^*(1420)\,\bar{K}$	$K_sK^\pm\pi^\mp$
0^-	$a_2^0(1320)\,\rho^0(770)$	$K_sK^\pm\pi^\mp$

Exotic Meson:

Reaction: $\pi^- p \to \eta\pi^- p$ at 18 GeV/c, $\eta \to \gamma\gamma$, $\sigma(\eta \to \gamma\gamma) \sim 30$ MeV
$\sim 47\,200$ events

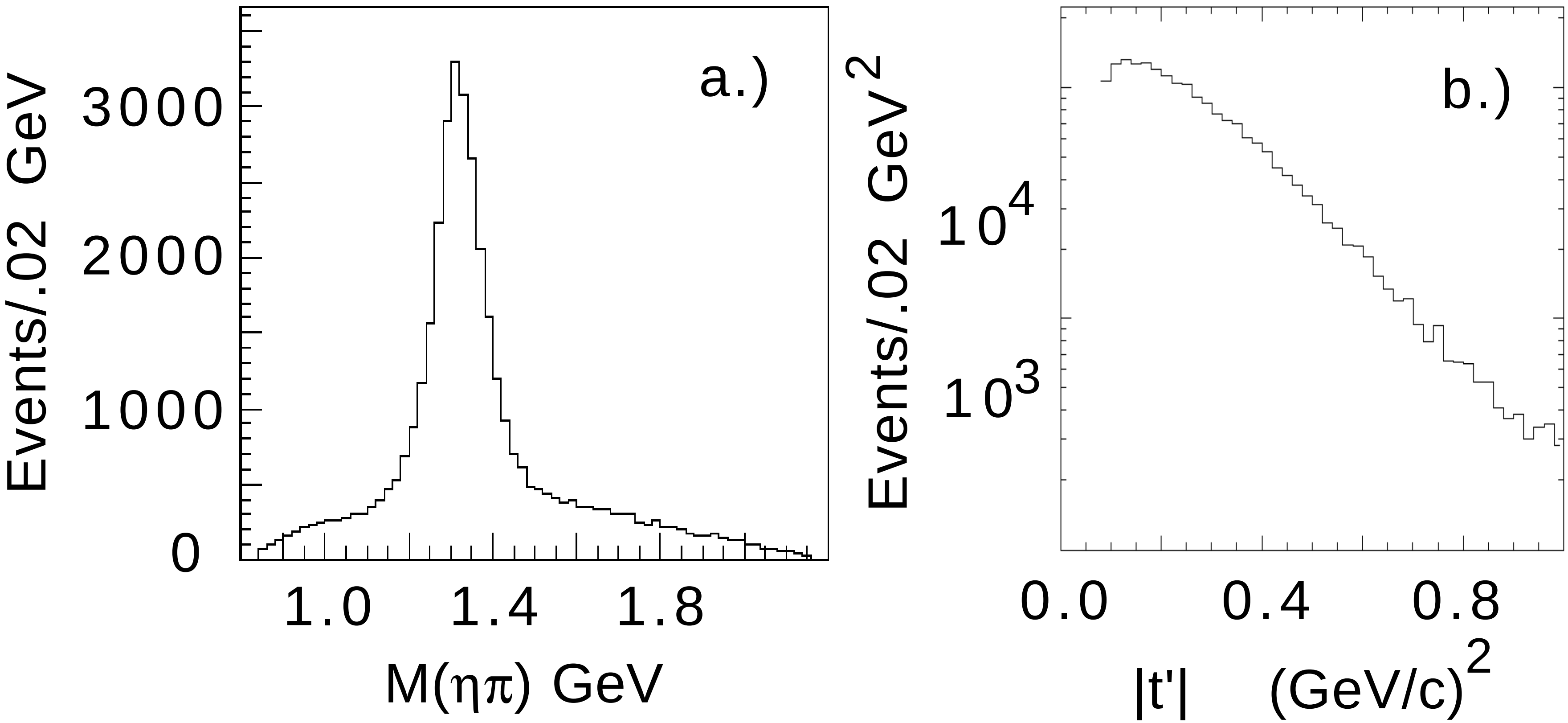


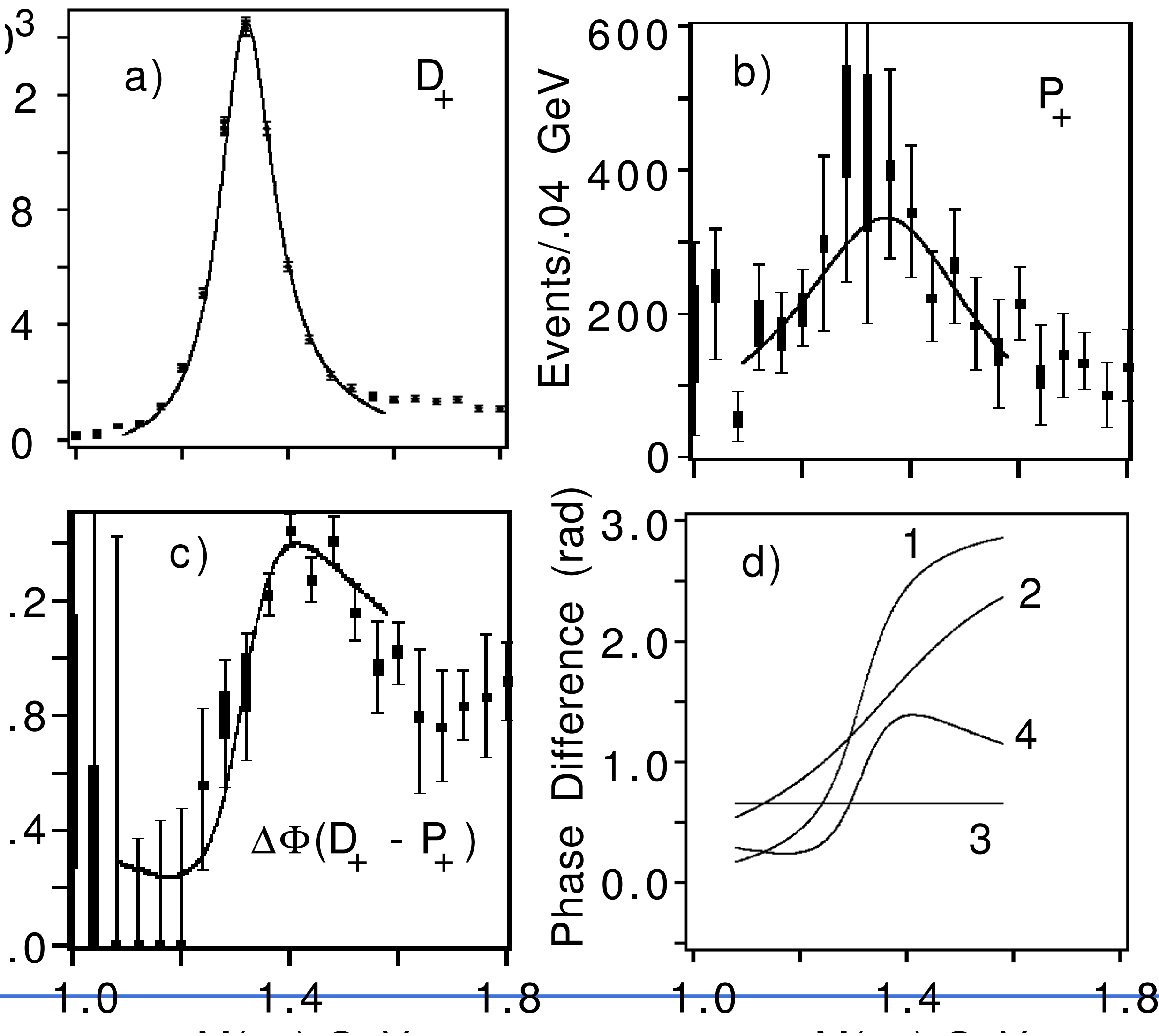
Figure 1

Reaction: $\pi^- p \to \eta\pi^- p$ at 18 GeV/c, $\eta \to \gamma\gamma$

$\sim 47\,200$ events

$1^{-+}1^+ \eta \begin{bmatrix} P \\ 0 \end{bmatrix} \pi \to P_+$

$2^{++}1^+ \eta \begin{bmatrix} D \\ 0 \end{bmatrix} \pi \to D_+$



$$\begin{cases} M(P_+) = 1370 \pm 16 \; {}^{+\,50}_{-\,30} \\ \Gamma(P_+) = 385 \pm 40 \; {}^{+\,65}_{-\,105} \end{cases}$$

PRL 79, 1630 (1997)

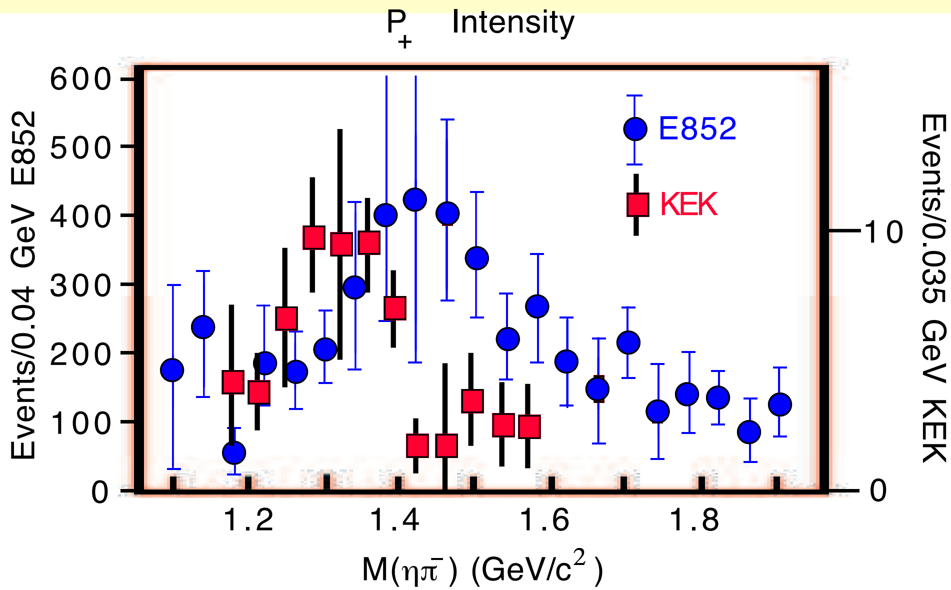
PRD 60, 092001 (1999)

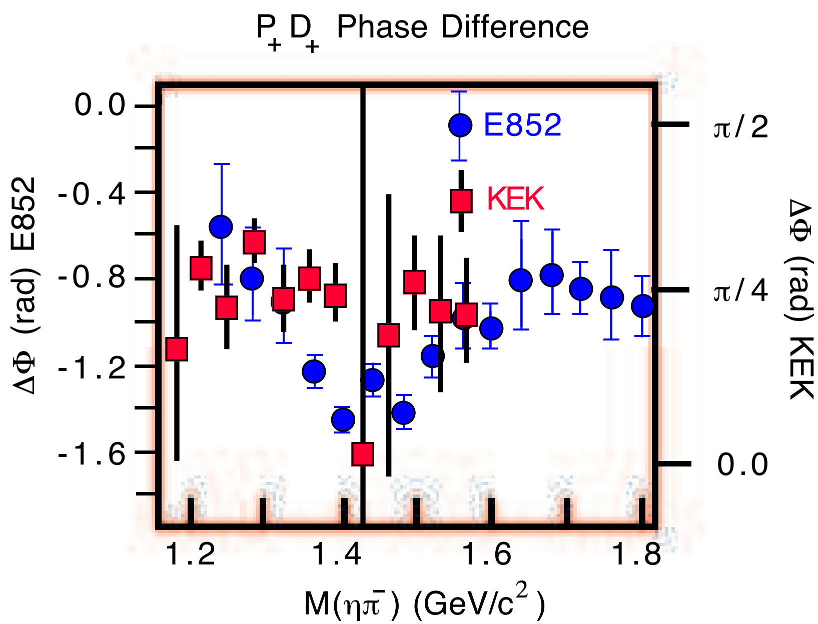
S. U. Chung,

PRD 56, 7299 (1997)

$\eta\pi^-$: E852 *vs.* KEK

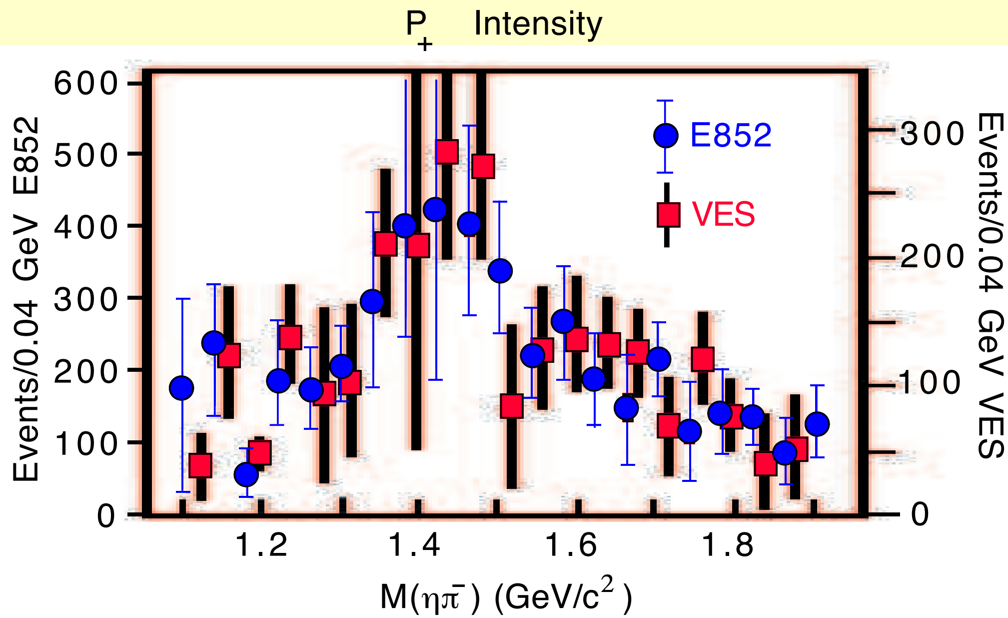
PL <u>B314</u>, 246 (1993)

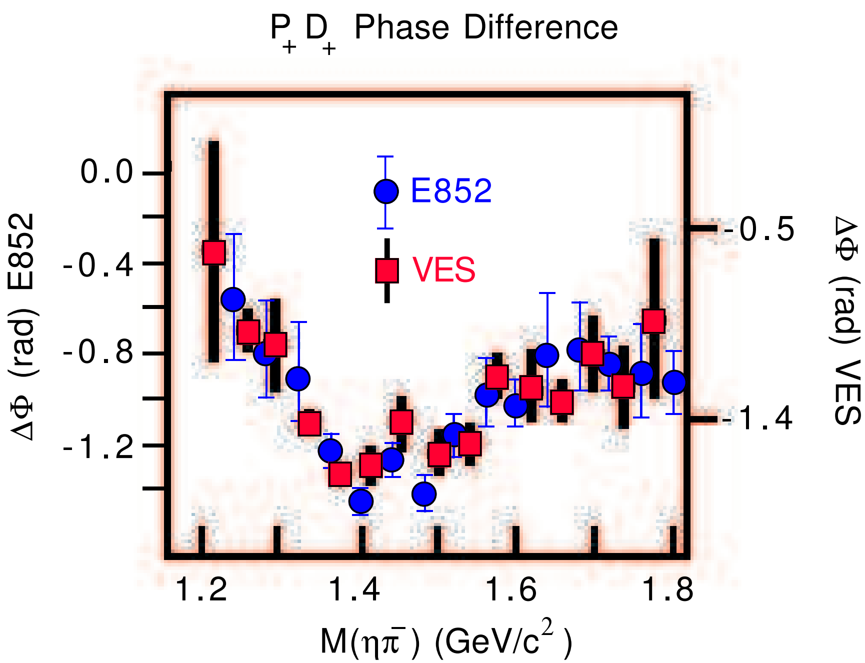




$\eta\pi^-$: E852 *vs.* VES

PL B313, 276 (1993)

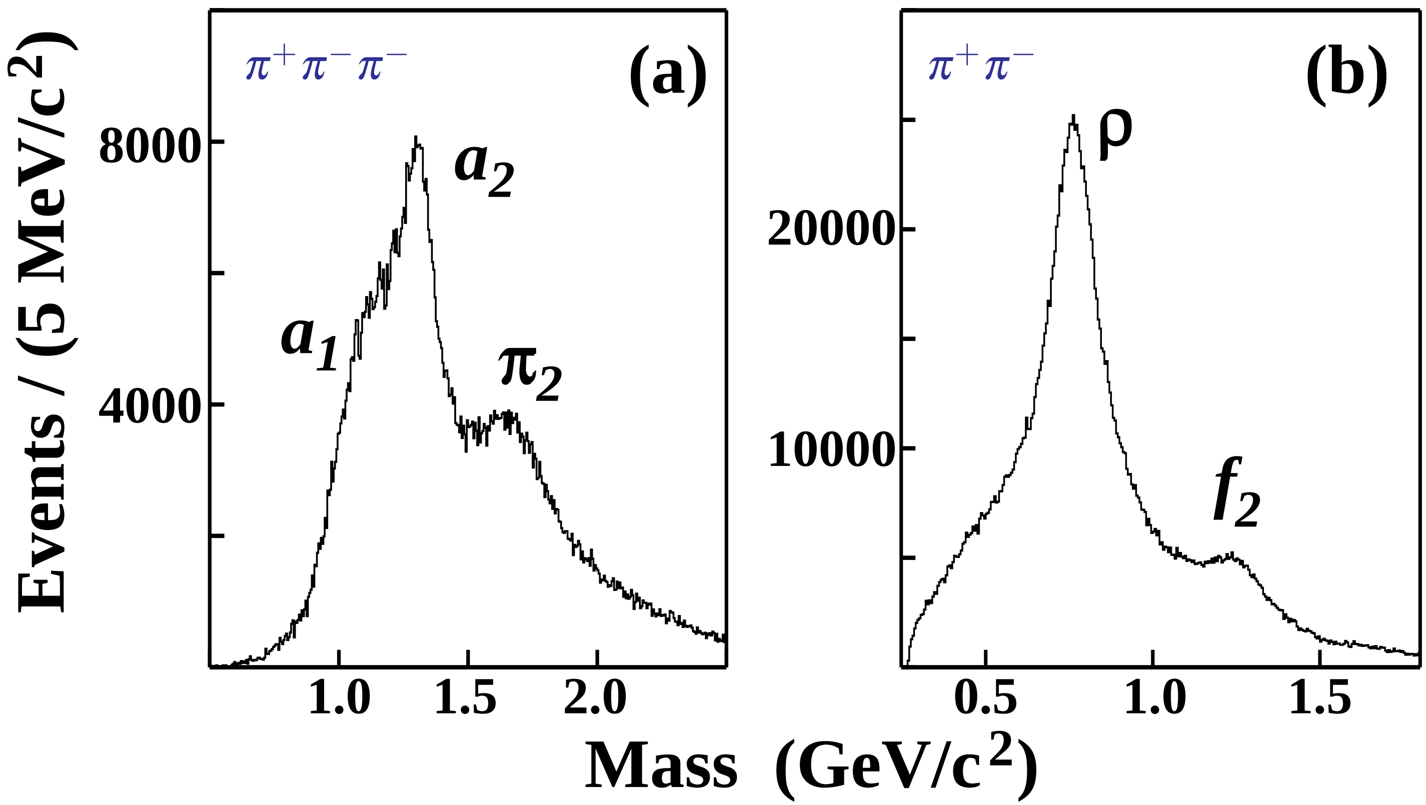




Exotic Meson: $\rho^0(770)\pi^-$

Reaction: $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c

$\sim 250\,000$ events



Exotic Meson: $\pi_1^-(1600) \to \rho^0(770)\pi^-,\ \rho^0(770) \to \pi^+\pi^-$

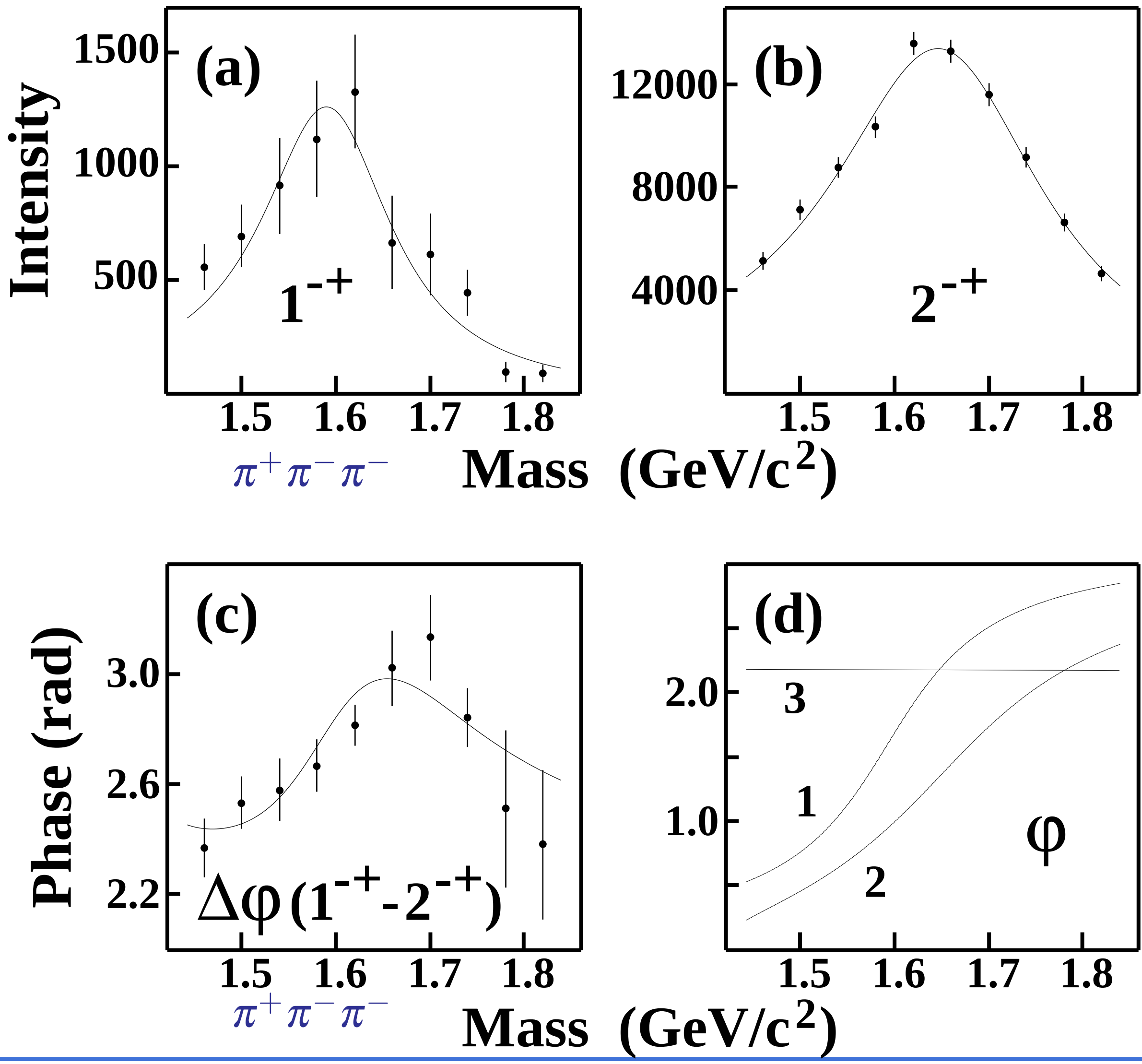
Reaction: $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c

$\sim 250\,000$ events

Partial waves: $1^{-+}1^+\rho(770)[P]\pi$, $2^{-+}0^+ f_2(1270)[S]\pi$

$1^{-+}1^+\rho\begin{bmatrix}P\\1\end{bmatrix}\pi$

$2^{++}0^+ f_2\begin{bmatrix}S\\2\end{bmatrix}\pi$



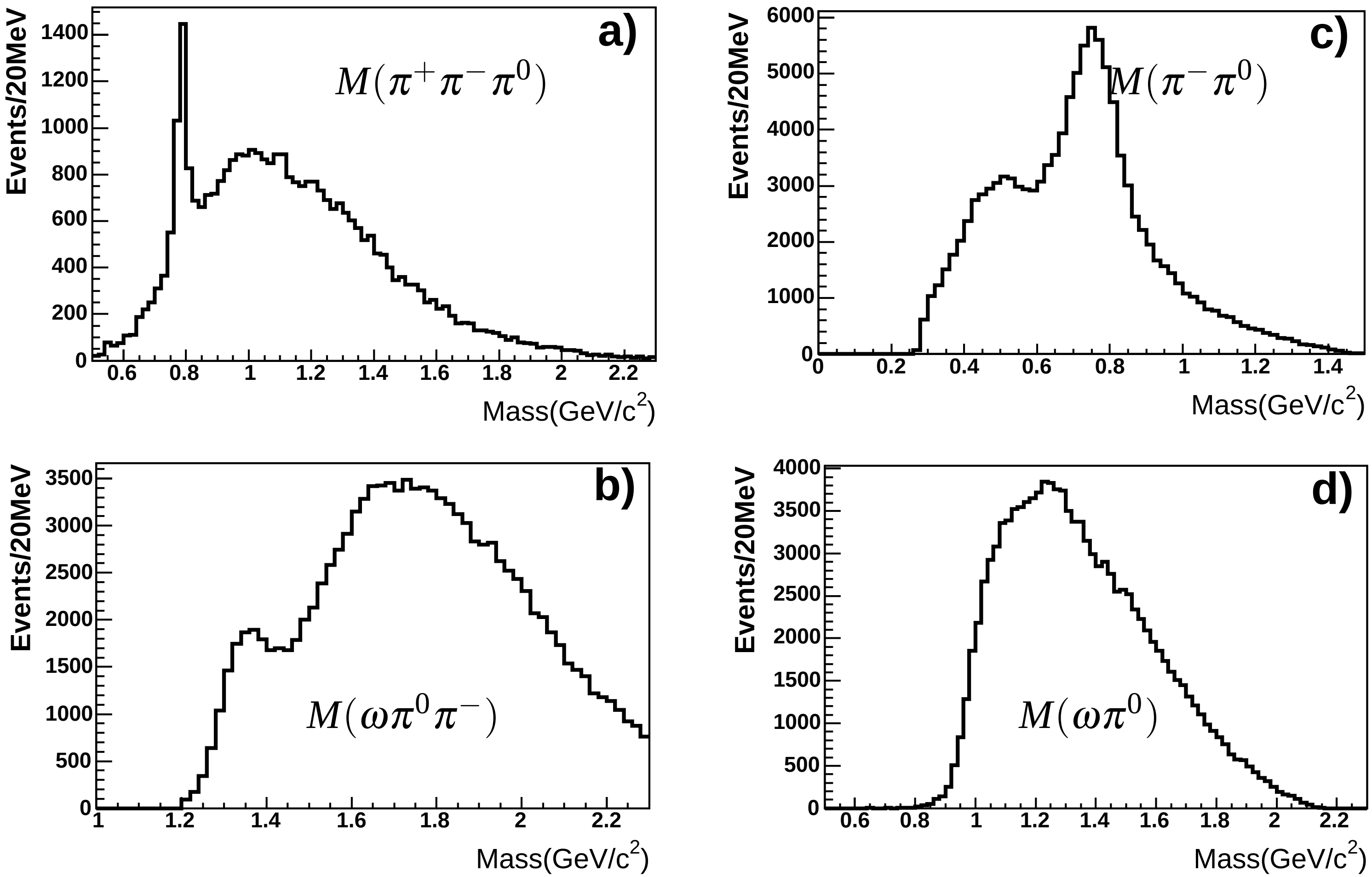
$$\begin{cases} M = 1593 \pm 8 \begin{matrix} + & 29 \\ - & 47 \end{matrix} \\ \Gamma = 168 \pm 20 \begin{matrix} + & 150 \\ - & 12 \end{matrix} \end{cases}$$

PRL 81, 5760 (1998)

PRD 65, 072001 (2002)

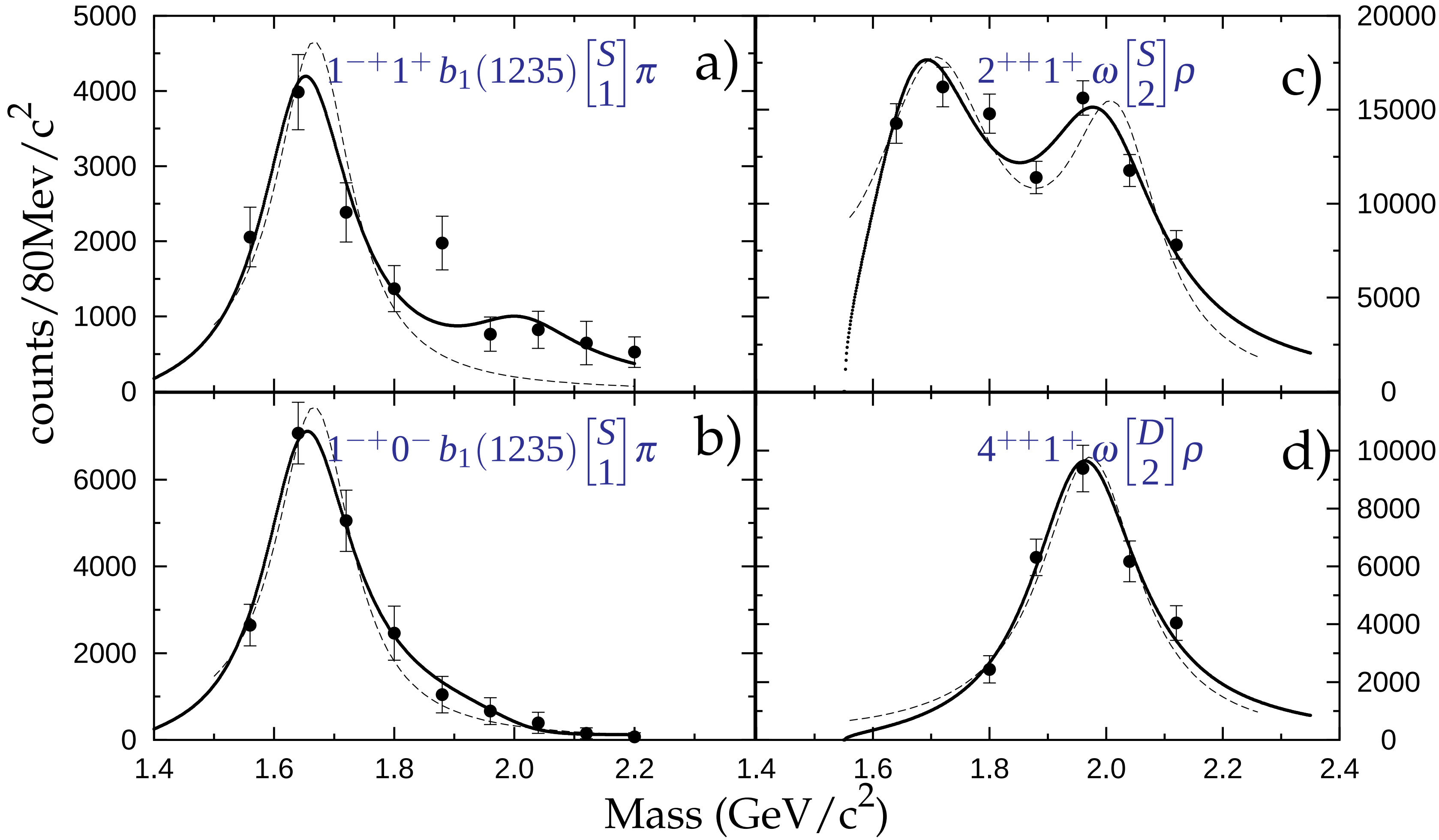
A Study of the $\omega\pi^-\pi^0$ System

Reaction: $\pi^- p \to \omega\pi^-\pi^0 p$, $\omega \to \pi^+\pi^-\pi^0$ $\sim 145\,000$ events $\sigma(\omega) \sim 22$ MeV



Parital-wave Analysis of the $\omega\pi^-\pi^0$ System

Reaction: $\pi^- p \to \omega\pi^-\pi^0 p$, $\omega \to \pi^+\pi^-\pi^0$ $\sim 145\,000$ events



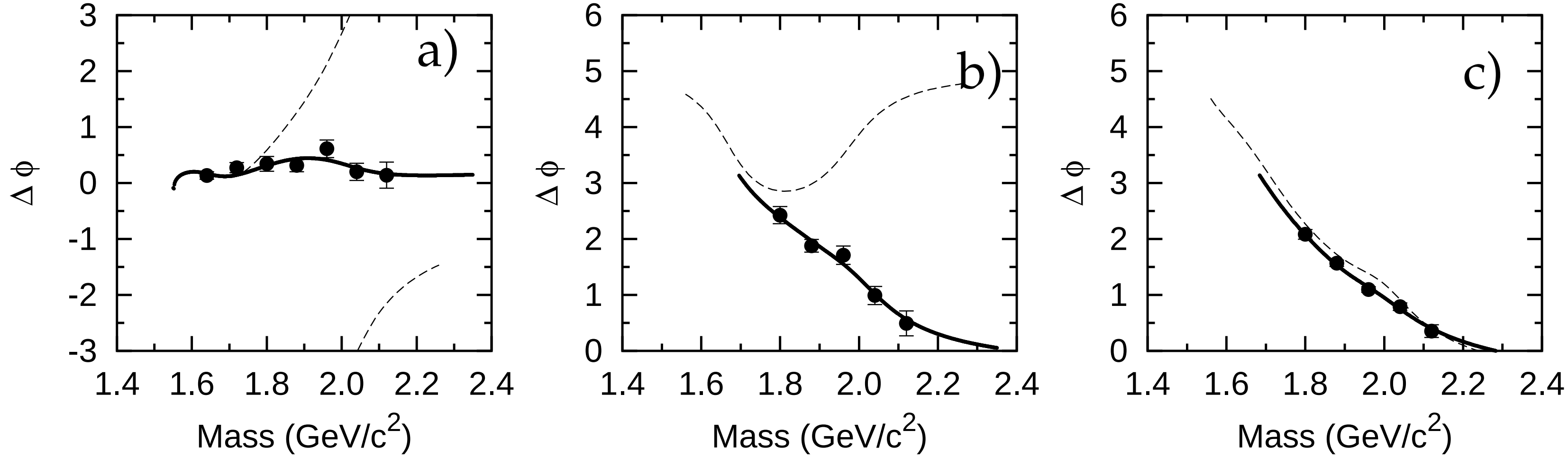
$\pi_1(1600)$ and $\pi_1(2000)$

Parital-wave Analysis of the $\omega\pi^-\pi^0$ System

a) $(1^{-+}1^+ b_1 \begin{bmatrix}S\\1\end{bmatrix}\pi) - (2^{++}1^+ \omega \begin{bmatrix}S\\2\end{bmatrix}\rho)$

b) $(1^{-+}1^+ b_1 \begin{bmatrix}S\\1\end{bmatrix}\pi) - (4^{++}1^+ \omega \begin{bmatrix}D\\2\end{bmatrix}\rho)$

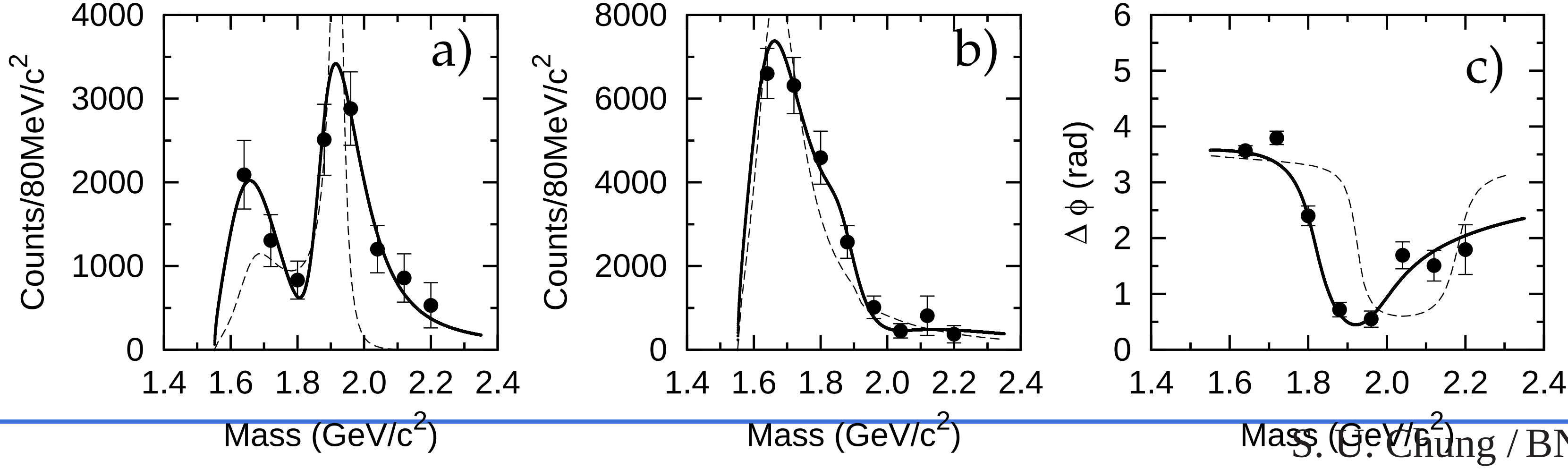
c) $(2^{++}1^+ \omega \begin{bmatrix}S\\2\end{bmatrix}\rho) - (4^{++}1^+ \omega \begin{bmatrix}D\\2\end{bmatrix}\rho)$



a) $2^{-+}0^+ \omega \begin{bmatrix}P\\1\end{bmatrix}\rho$

b) $2^{-+}0^+ \omega \begin{bmatrix}P\\2\end{bmatrix}\rho$

c) $(2^{-+}0^+ \omega \begin{bmatrix}P\\1\end{bmatrix}\rho) - (2^{-+}0^+ \omega \begin{bmatrix}P\\2\end{bmatrix}\rho)$



Background Material:

Consider

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

$$\pi^- p \to a_2^-(1320)\, p$$

$$\pi^- p \to \pi_1^-(1400)\, p$$

The cross section

$$\sigma\left[\pi^- p \to a_2(1320)^- p\right] = (5\,099 \pm 221)\ \mu\text{b} \times \left(\frac{p_L}{1\ \text{GeV}/c}\right)^{-(1.88\pm0.03)} + (39.2 \pm 2.0)\ \mu\text{b}$$

$$= (61.1 \pm 2.2)\ \mu\text{b} \quad \text{at} \quad 18.2\ \text{GeV}/c$$

For $M(\eta\pi^-)$=1.10—1.58 GeV,

$$N(D_+) = 60\,332 \pm 2\,060\ \text{events}, \quad N(P_+) = 3\,321 \pm 1\,245\ \text{events}\ (5.5 \pm 2.1)\%$$

So

$$\sigma\left[\pi^- p \to \pi_1^-(1400)\, p\right] \times \mathscr{B}\left[\pi_1^-(1400) \to \eta\pi^-\right] = (0.49 \pm 0.19)\ \mu\text{b}$$

Next

$$\frac{\mathscr{B}\left[\pi_1(1600) \to f_1(1285)\pi\right]}{\mathscr{B}\left[\pi_1(1600) \to \eta'\pi\right]} = 3.80 \pm 0.78$$

Background Material:

- **LGD:**

  Lead-Glass Detector (LGD)
  3053 elements, each 4 x 4 x 45 cm
  $L_r = 3.1$ **cm (**N_r**=14.5)**
  $L_c = 22.5$ **cm (**N_c**=2.0)**
  $\frac{\delta E}{E} = \left(2 + \frac{5}{\sqrt{E(\mathbf{GeV})}}\right)\%$
  Position resolution: 1 to 2 mm
  $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$
  $\omega \to \pi^0\gamma$
  $K_s \to \pi^0\pi^0$

- **TDX4:**

  Two-layer drift-chamber module
  Active area 2 $\times$ **3 m**
  drift space $=$ **8mm**
  resolution $=$ **150** μ**m**

- **DEA:**

  Downstream End-cap Array (DEA)
  A window-frame veto counter
  lead-scintillation sandwich
  18 layers; 8 radiation lengths

- **TCYL:**

  Cylindrical Drift-chamber module
  four layers, triggerable
  drift space $=$ **4mm**
  resolution $=$ **200** μ**m**
  charge division $=$ **8 mm**

- **CIV:**

  Barrel CsI veto Counter (CIV)
  198 crystals, each 7.5 cm high
  $\Delta\phi = 20^\circ$, $\Delta z = 5$**cm**
  L_r**=1.86 cm (**N_r**=4.0)**
  $L_c = 36.5$**cm (**$N_c = 0.21$**)**
  min energy $=$ **10 MeV**

Background Material:

- **HEUB:**

  π^- **beam at 18.3 GeV/**c
  flux = 2×10^6 **particles/sec**
  Momentum bite $\Delta p/p$ **= 3 %**
  Momentum resolution $\delta p/p < 1\%$
  Three Cerenkov Counter
  for e**,** π**,** K **separation**

- **Target:**

  Liquid Hydrogen 12-in long
  2.5-in diameter

- **MPS magnet:**

  A C-magnet, 450 cm long
  280 cm wide, 130 cm high
  Field Strength: 1 T

- **Cerenkov Hodocsope:**

  Threshold Counter, $\eta_{\text{threshold}} = 20$
  π/K **separation,** $3 \to 10$ **GeV/**c

- **Trigger:**

  Pretrigger: interacting beam
  Level 1: event topology
  (TCYL)-(TPX1)-(TPX2)
  Level 2: Mass(LGD) $>$ **Mass(**π**)**
  Fast processor $<$ **10** μ**sec**
  10^4 **triggers/sec with 10% dead time**

Background Material:

- **GlueX:**

  CEBAF Upgrade

  6$\to$12 GeV beam

  Tagged photon energy(max) at 9 GeV

  Solenoid magnet; D=185cm, L=465cm

  Axial Field Strength: 2.24 T

  TOF and LGD downstream

- **Panda:**

  $\bar{p}$ **from 1–15 GeV/*c***

  Solenoid magnet; D=190cm, L=250cm

  Axial Field Strength: 2.0 T

  Forward Spectrometer

  field integral of 2 Tm

  RICH and EMC downstream

  Hadron Calorimeter further downstream

Search for Strangeonium Hybrids

$s\bar{s} + n\bar{n}$ at masses from 1.6 to 1.8 GeV:

Decay modes include $K^*\bar{K}$, $K^*\bar{K}^*$, etc.

$s\bar{s} + g$ at masses from 2.1 to 2.3 GeV:

Decay modes are $K_1(1270)\bar{K}$, $K_1(1400)\bar{K}$, $K_2^*(1430)\bar{K}$

- **AGS**

  25% of 100×10^{12} protons incident on A target
  12 GeV/c RF-spearated K^- beam
  Flux at the MPS$\simeq 2.5 \times 10^5$ K^-'s/spill
  Total run time $= 5 \times 10^3$ hours at 10^3 spills/hour

- **MPS**

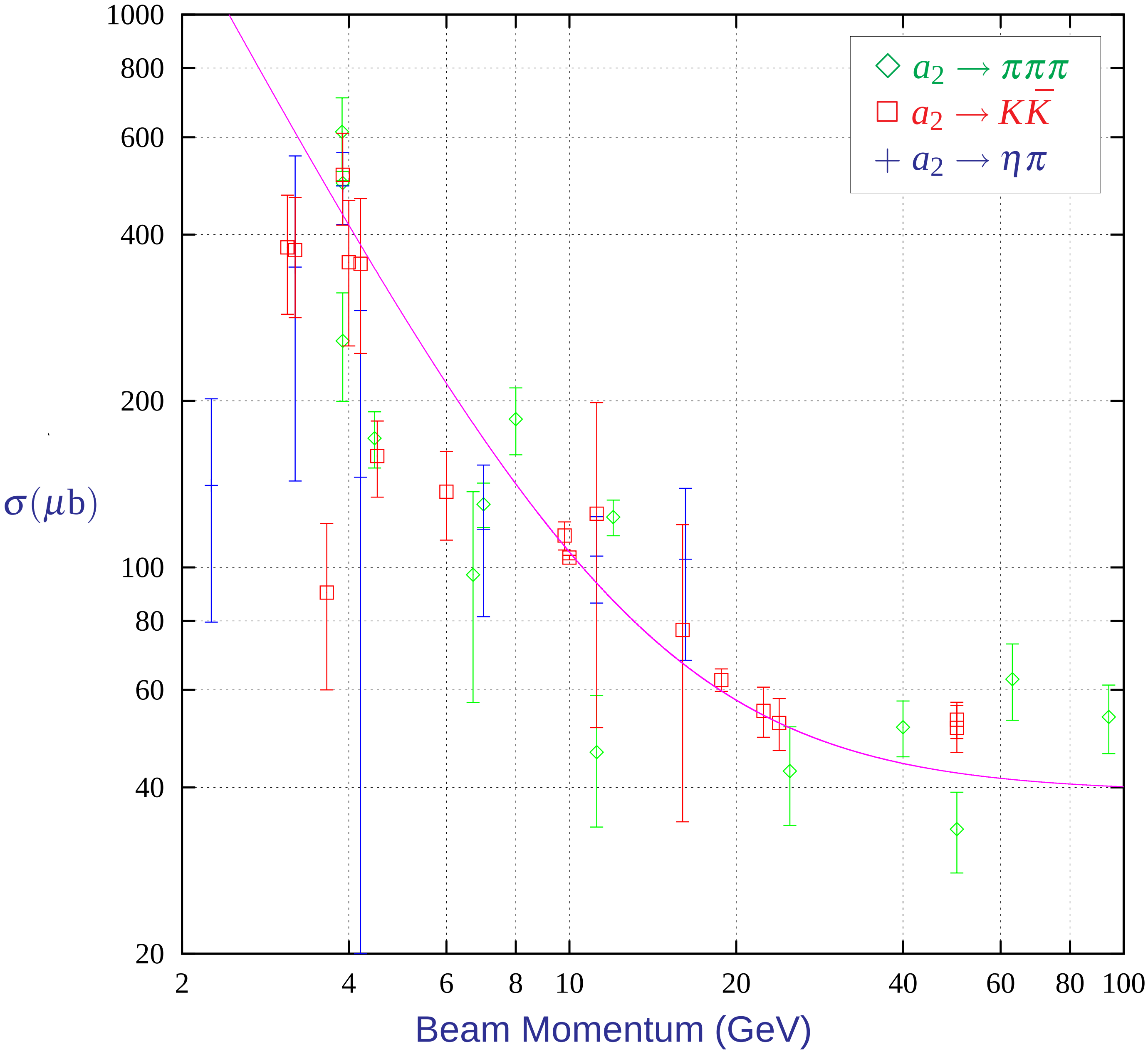
  2-foot LH_2 target
  Overall experimental acceptance $= 10\%$

Visible Sensitivity $= 330$ events/nb

4.1 events/nb for LASS at 11 GeV/c

$a_2(1320)$ **Cross Sections**

$\pi^- p \longrightarrow a_2^-(1320)\, p$

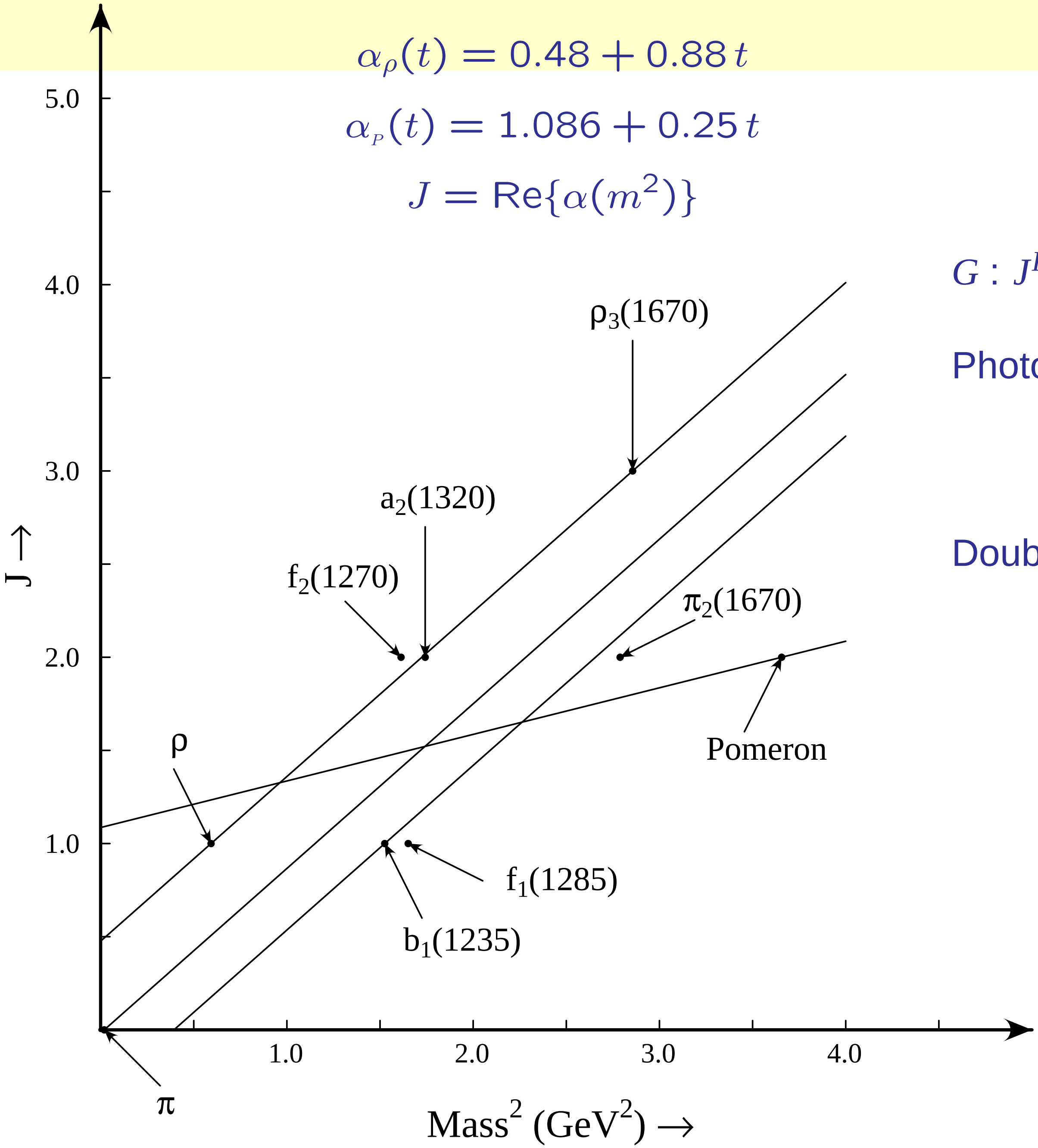


Regge Trajectories

$$\alpha_\rho(t) = 0.48 + 0.88\,t$$

$$\alpha_{_P}(t) = 1.086 + 0.25\,t$$

$$J = \text{Re}\{\alpha(m^2)\}$$



$G : J^{PC} = 2^{++}$ glueball

Photon-Pomeron Fusion Process:

$$\gamma + G \rightarrow X$$

Double-Pomeron Fusion Process:

$$G + G \rightarrow X$$

$J^{PC} = 1^{--}\ (10 - \overline{10})$

Y	I	Q	wave functions
0	1	$+1$	$\sqrt{\frac{1}{6}}\,(\pi^+\pi^0 - \pi^0\pi^+) + \sqrt{\frac{1}{3}}\,(\bar{K}^0 K^+ - K^+ \bar{K}^0)$
		0	$\sqrt{\frac{1}{6}}\,(\pi^+\pi^- - \pi^-\pi^+) + \sqrt{\frac{1}{6}}\,(\bar{K}^0 K^0 - K^0 \bar{K}^0) + \sqrt{\frac{1}{6}}\,(K^- K^+ - K^+ K^-)$
		-1	$\sqrt{\frac{1}{6}}\,(\pi^0\pi^- - \pi^-\pi^0) + \sqrt{\frac{1}{3}}\,(K^- K^0 - K^0 K^-)$

Predict: $\rho(1400)$

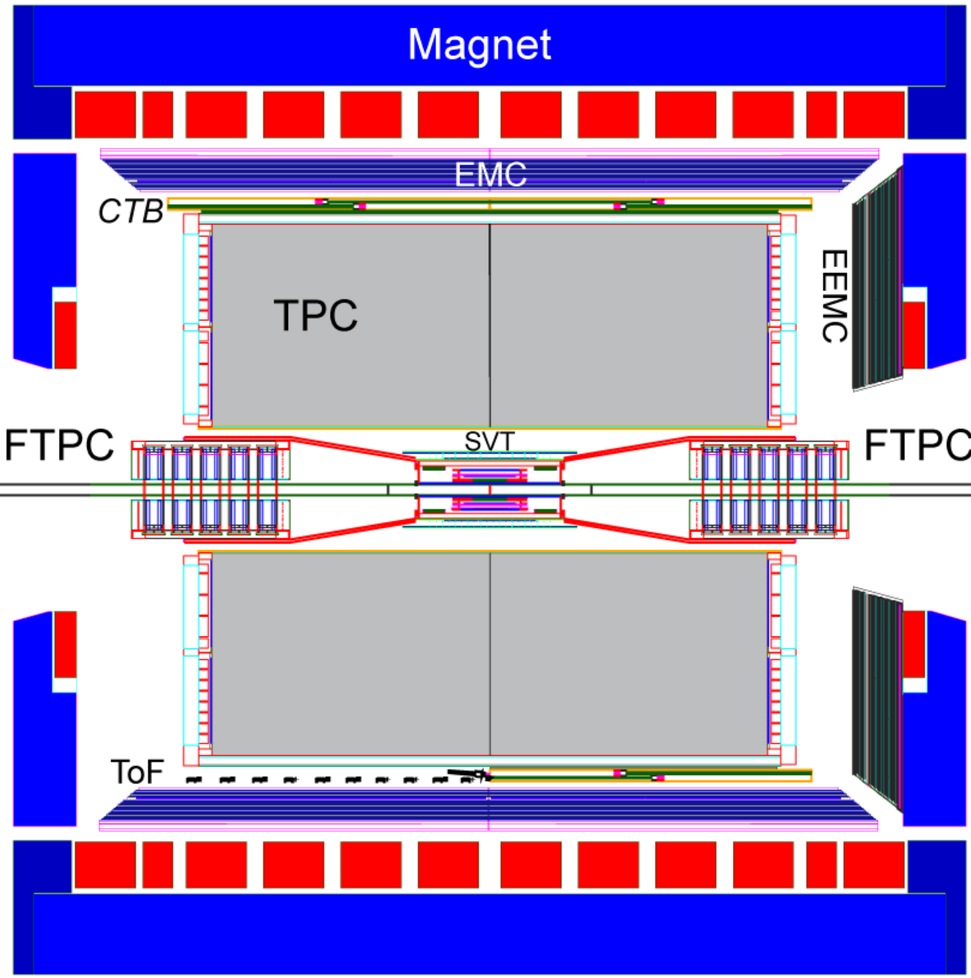
Internal Structure for Exotics $\pi_1(1400) \rightarrow \eta\pi$:

flavor $10 \oplus \overline{10}$	$(q\bar{q})_8 \otimes (q\bar{q})_8$	$(qq)_{\bar{3}} \otimes (\bar{q}\bar{q})_{\bar{6}}$ $(qq)_6 \otimes (\bar{q}\bar{q})_3$
color singlet	$(q\bar{q})_8 \otimes (q\bar{q})_8$ $(q\bar{q})_1 \otimes (q\bar{q})_1$	$(qq)_{\bar{3}} \otimes (\bar{q}\bar{q})_3$ $(qq)_6 \otimes (\bar{q}\bar{q})_{\bar{6}}$

$q = \{u, d, s\}$

Magnetic Field : 5 T

- Silicon Vertex Tracker (SVT)
- Time-Projection Chamber (TPC)
- Forward TPC(FTPC)



- Endcap EMC (EEMC)
- Zero-Degree Cal (ZDC)
- ToF (2008) $\sim$ 85 ps
- CTB *to be removed*

- Central Trigger Barrel Counter (CTB)
- Time-of-Flight Detector (ToF)
- Barrel EM Cal (EMC): 4,800 Towers