

The Physics of GlueX

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Outline

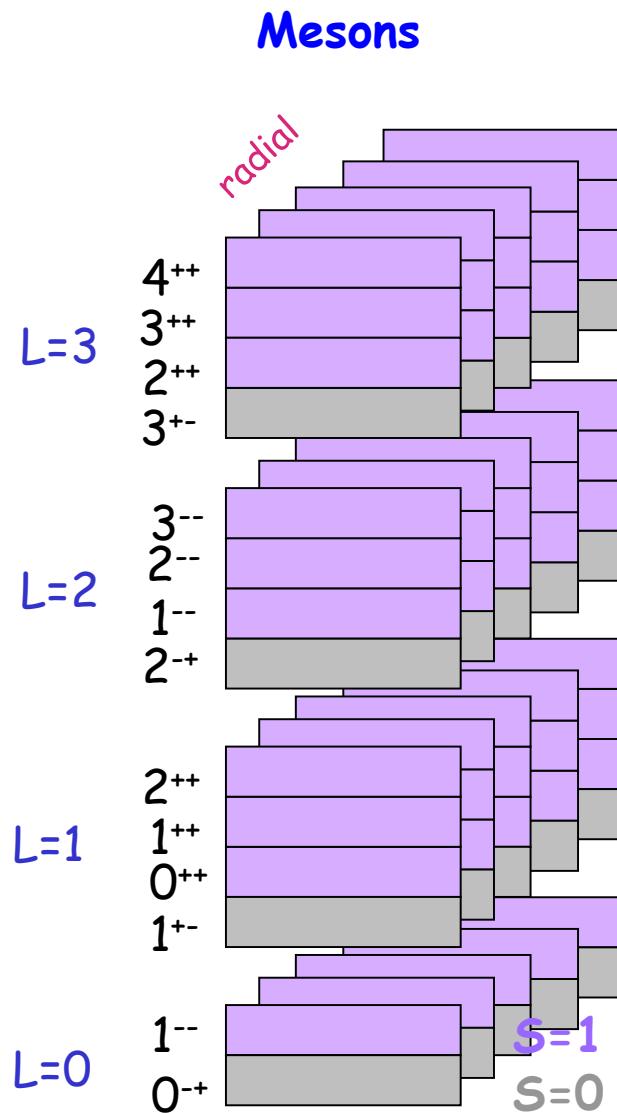
What are light-quark exotic mesons?

How should we look for these mesons?

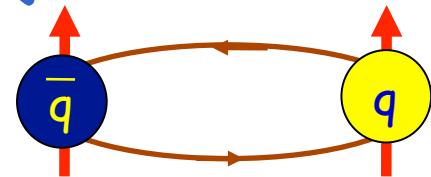
What is the Experimental Evidence?

The GlueX Detector.

Spectroscopy and QCD



Quarkonium



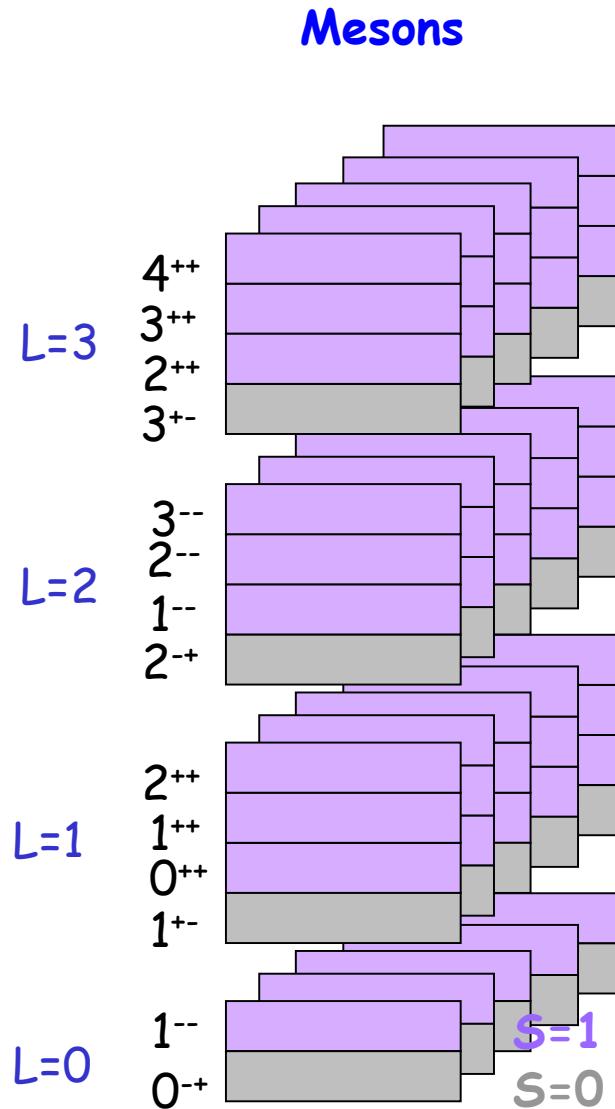
Consider the three lightest quarks

u, d, s

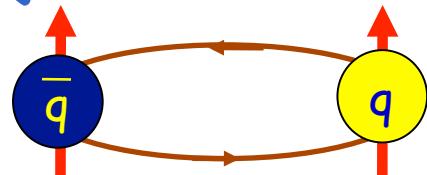
$\bar{u}, \bar{d}, \bar{s}$

9 Combinations

Spectroscopy an QCD



Quarkonium



ρ, K^*, ω, ϕ

π, K, η, η'

a, K, f, f'

b, K, h, h'

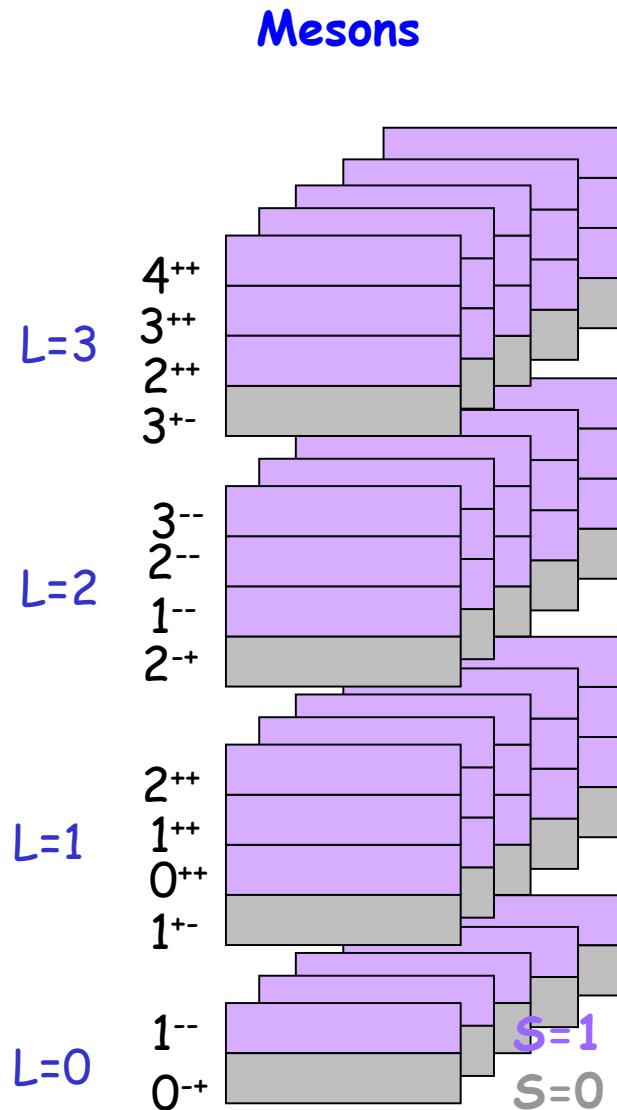
ρ, K^*, ω, ϕ

π, K, η, η'

Mesons come in
nonets of the same
 J^{PC} Quantum Numbers

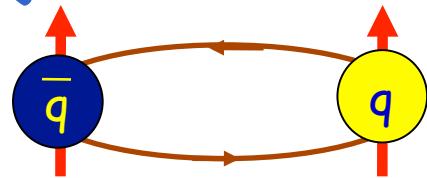
SU(3) is broken
last two members mix

Spectroscopy an QCD



Nothing to do
with Glue!

Quarkonium

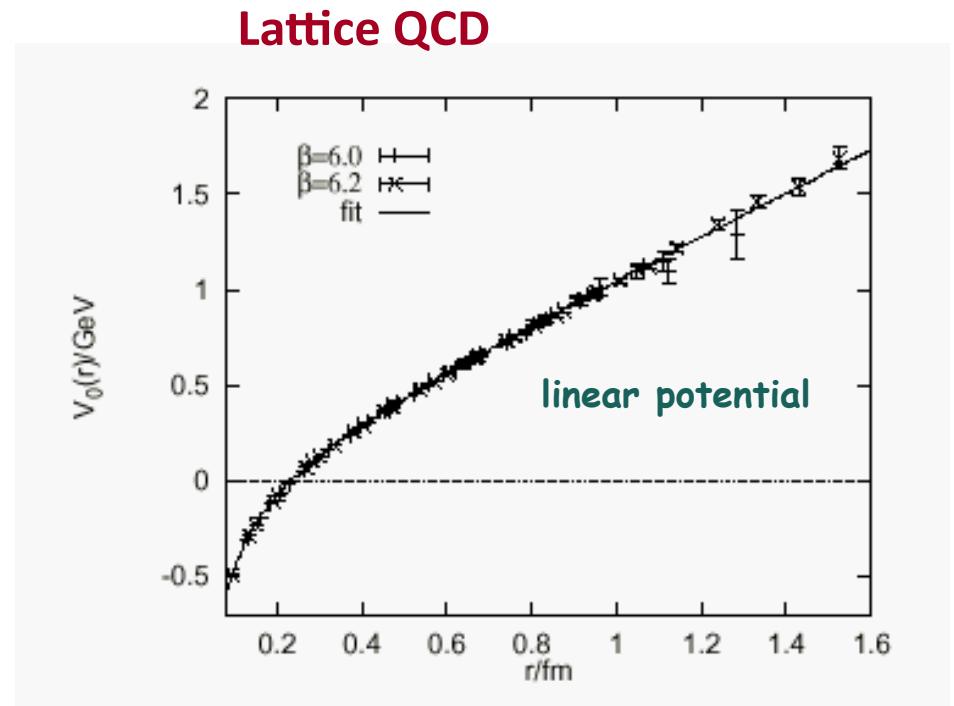
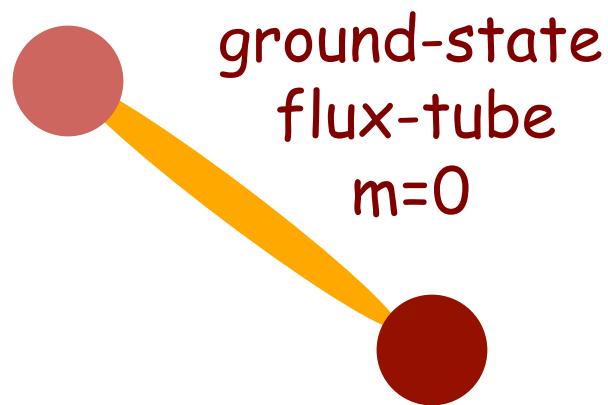


Allowed J^{PC} Quantum numbers:

0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

Exotic Quantum Numbers
non quark-antiquark description

QCD Potential



The normal mesons are built up from a “quark-antiquark pair” with and a “ground-state” flux tube.

(π, K, η, η')

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

$(\rho, K^*, \omega, \Phi)$

$J^{PC}=1^{--}$

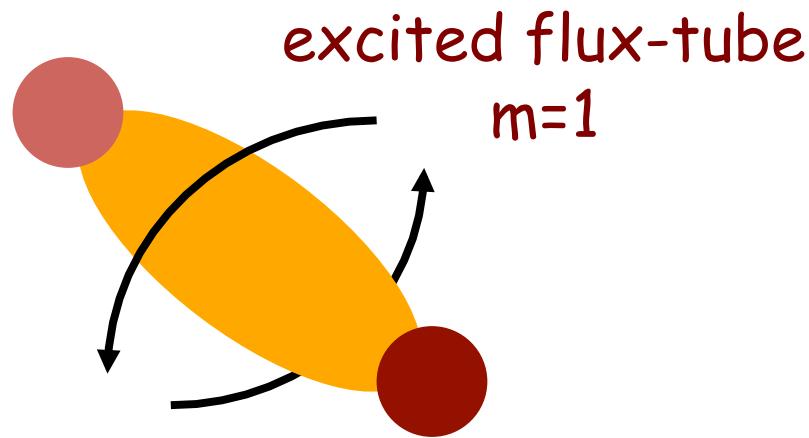
(b_1, K_1, h_1, h_1')

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

(\dots)

$0^{++}, 1^{++}, 2^{++}, 2^{--}, 2^{+-}, 3^{++}, 3^{--}, 3^{+-}$

QCD Potential



excited flux-tube

$m=1$

$S=0, L=0, m=1$

$J=1 \ CP=+$

$J^{PC}=1^{++}, 1^{--}$

(not exotic)

$S=1, L=0, m=1$

$J=1 \ CP=-$

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

$1^{-+}, 1^{+-}$

exotic $2^{-+}, 2^{+-}$

Gluonic Excitations provide an experimental measurement of the excited QCD potential.
Many of the hybrid nonets have *exotic* quantum numbers.

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$$\underbrace{1^{++}, 1^{--}}_{S=0} \underbrace{0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{++}, 2^{+-}}_{S=1} \sim 1.9 \text{ GeV}/c^2$$

Lattice calculations --- 1^{-+} nonet is the lightest

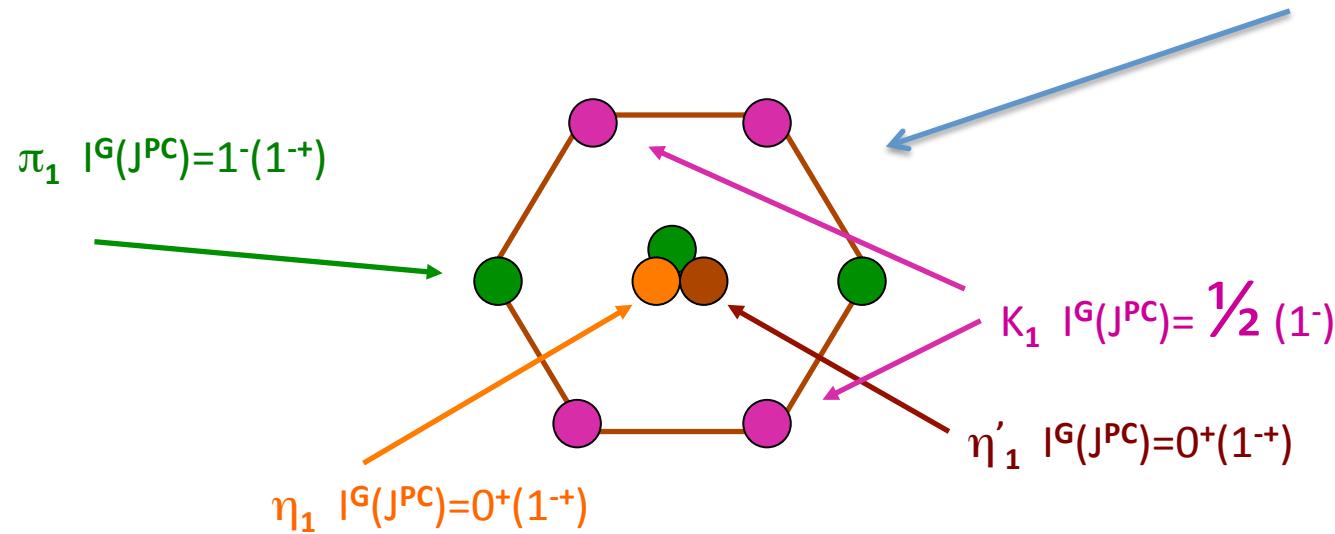
UKQCD (97)	1.87 ± 0.20	All masses in GeV/c^2
MILC (97)	1.97 ± 0.30	
MILC (99)	2.11 ± 0.10	
Lacock(99)	1.90 ± 0.20	
Mei(02)	2.01 ± 0.10	
Bernard(04)	1.792 ± 0.139	

In the charmonium sector:

1^{-+}	4.39 ± 0.08	Splitting = 0.20
0^{+-}	4.61 ± 0.11	

QCD Exotics

We expect 3 nonets of exotic-quantum-number mesons: 0^{+-} , 1^{-+} , 2^{+-}



$$\begin{array}{ll} \pi, \eta, \eta', K \rightarrow \pi_1, \eta_1, \eta'_1, K_1 & 1^{-+} \\ b_0, h_0, h'_0, K_0 & 0^{+-} \\ b_2, h_2, h'_2, K_2 & 2^{+-} \end{array}$$

Hybrid Decays

The angular momentum in the flux tube stays in one of the daughter mesons (an $(L=1)$ and $(L=0)$ meson).

Exotic Quantum Number Hybrids

$$\pi_1 \rightarrow \pi b_1, \pi f_1, \pi \rho, \eta a_1$$

$$\eta_1 \rightarrow \pi(1300)\pi, a_1\pi$$

$$b_2 \rightarrow a_1\pi, h_1\pi, \omega\pi, a_2\pi$$

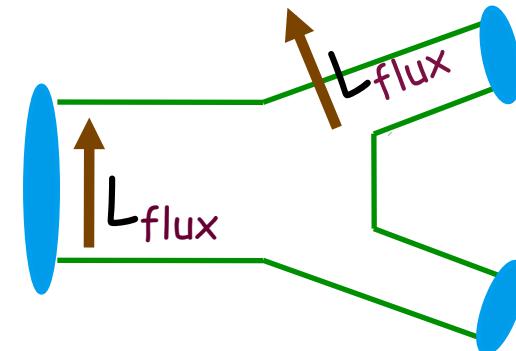
$$h_2 \rightarrow b_1\pi, \rho\pi, \omega\eta$$

$$b_0 \rightarrow \pi(1300)\pi, h_1\pi$$

$$h_0 \rightarrow b_1\pi, h_1\eta$$

Mass and model
dependent
predictions

Populate final states with
 $\pi^\pm, \pi^0, K^\pm, K^0, \eta, (\text{photons})$



Experimental Evidence for Hybrids

The most extensive data sets to date are from the **BNL E852 experiment**. There is also data from the **VES experiment** at Protvino and some results from the **Crystal Barrel experiment** at LEAR. Finally, there is a **CLAS (Jefferson Lab)** result. We have also just started to see results from the **COMPASS** experiment at CERN.

E852 Experiment

$\pi_1(1400)$ Mass = $1370 +16^{+50}_{-30}$ MeV/c²
 Width = $385 +40^{+65}_{-105}$ MeV/c²

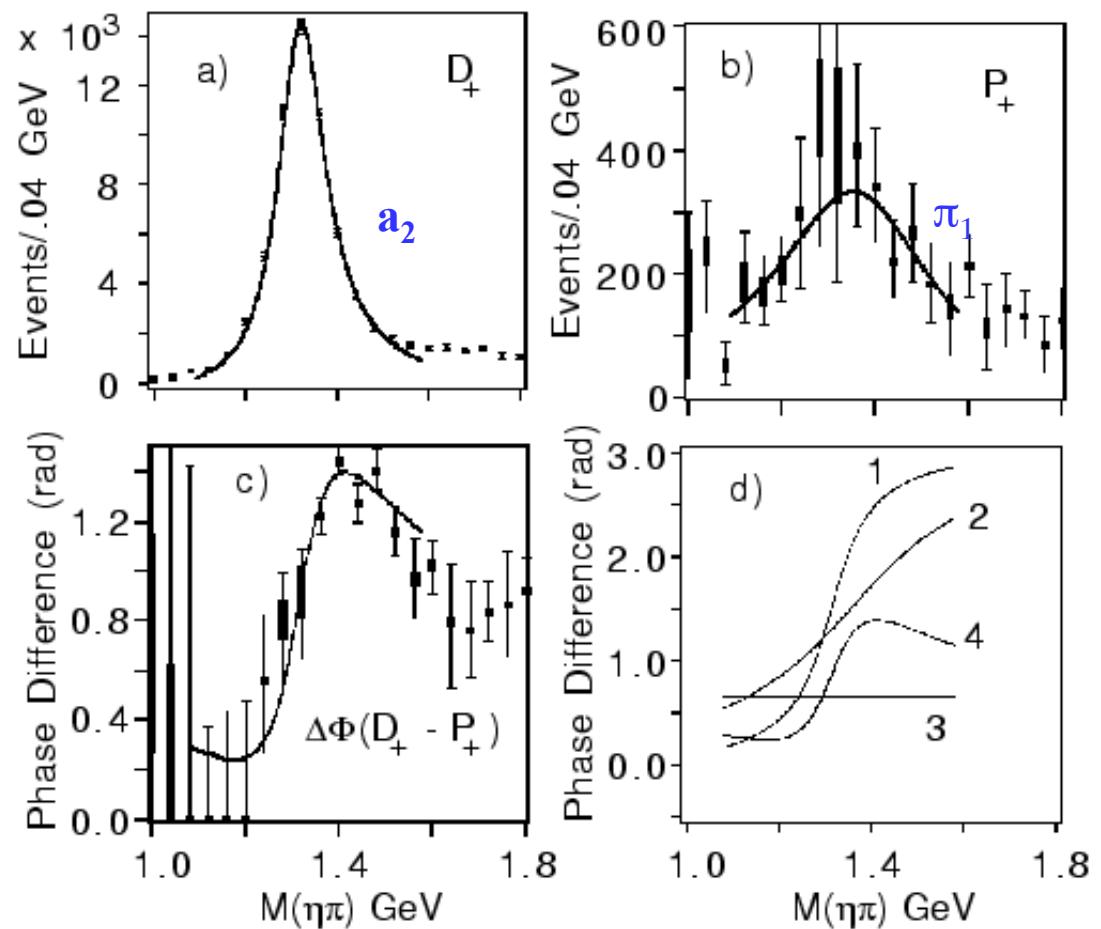
The $a_2(1320)$ is the dominant signal. There is a small (few %) exotic wave.

Interference effects show a resonant structure in 1^{-+} .
 (Assumption of flat background phase as shown as 3.)

Seen by Crystal Barrel in
 $\eta\pi^-$ and $\eta\pi^0$

$\pi^- p \rightarrow \eta\pi^- p$

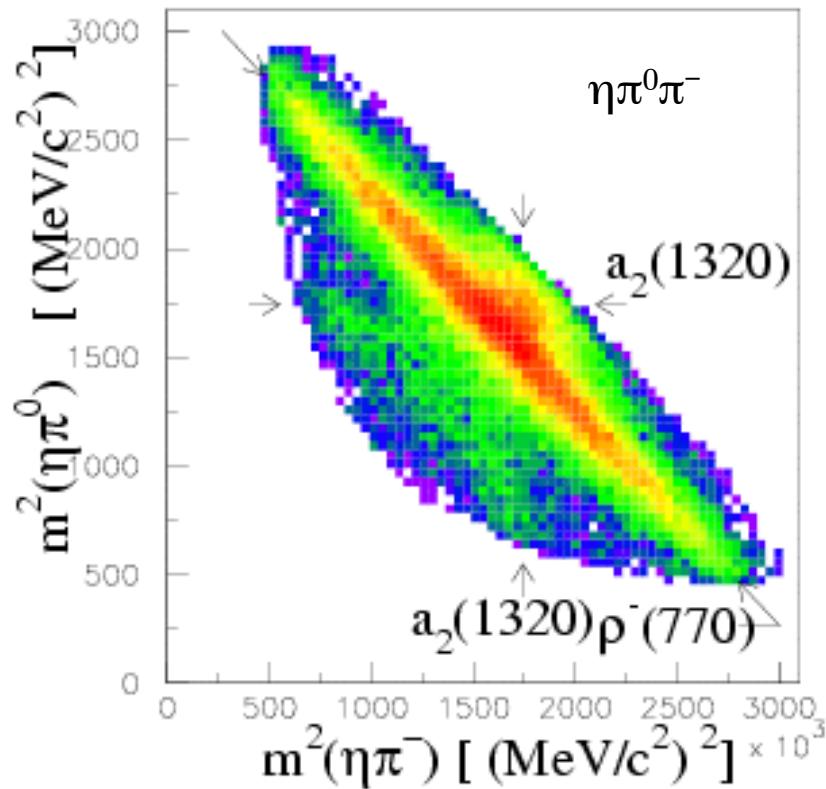
(1997)



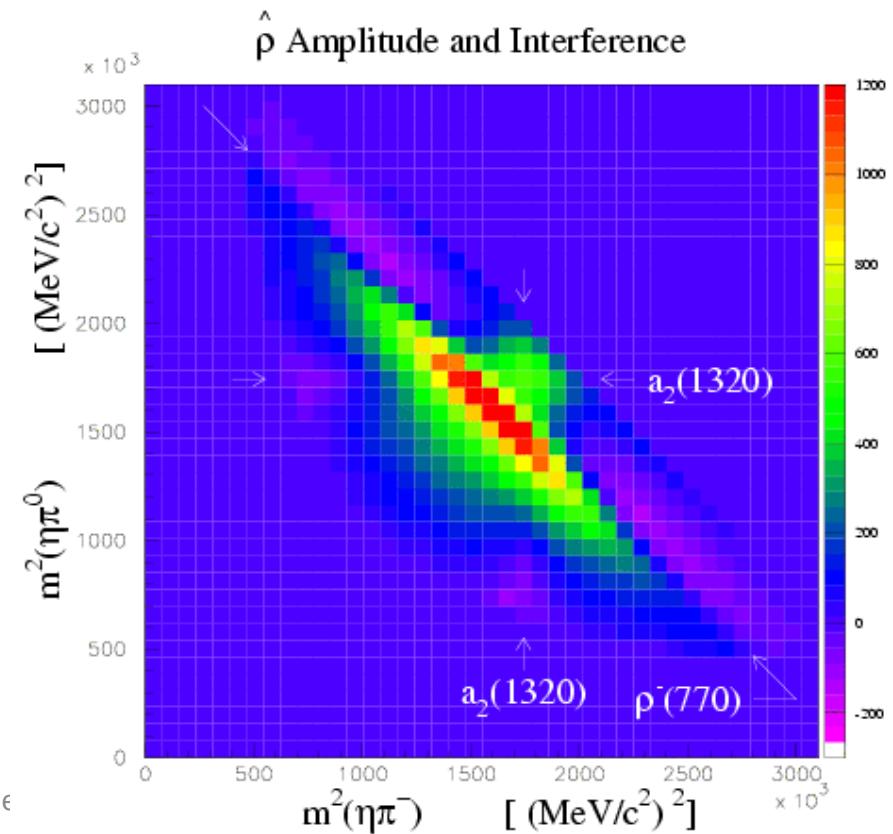
Crystal Barrel Experiment

$\pi_1(1400)$ Mass = $1400 + - 20 + - 20$ MeV/c²
Width = $310 + - 50^{+50}_{-30}$ MeV/c²

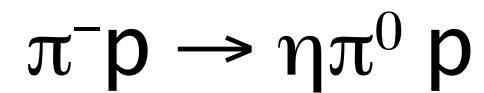
Without π_1 $\chi^2/\text{ndf} = 3$, with = 1.29



Same strength as the a_2 .
Produced from states with **one unit** of angular momentum.

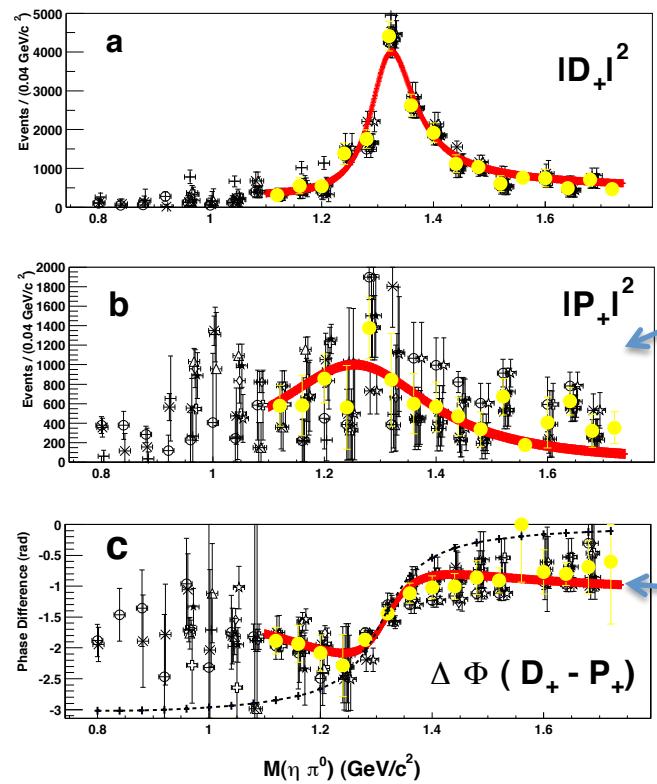


E852 Experiment

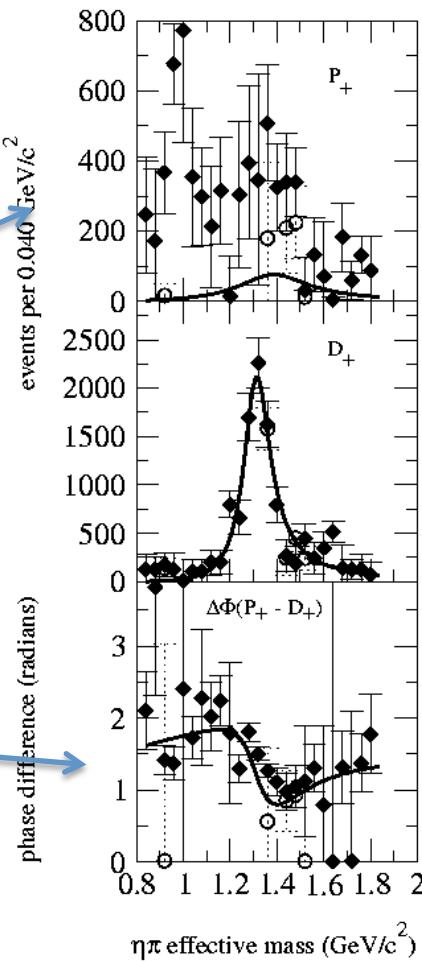


Dzierba (et. al) PRD67 (2003)

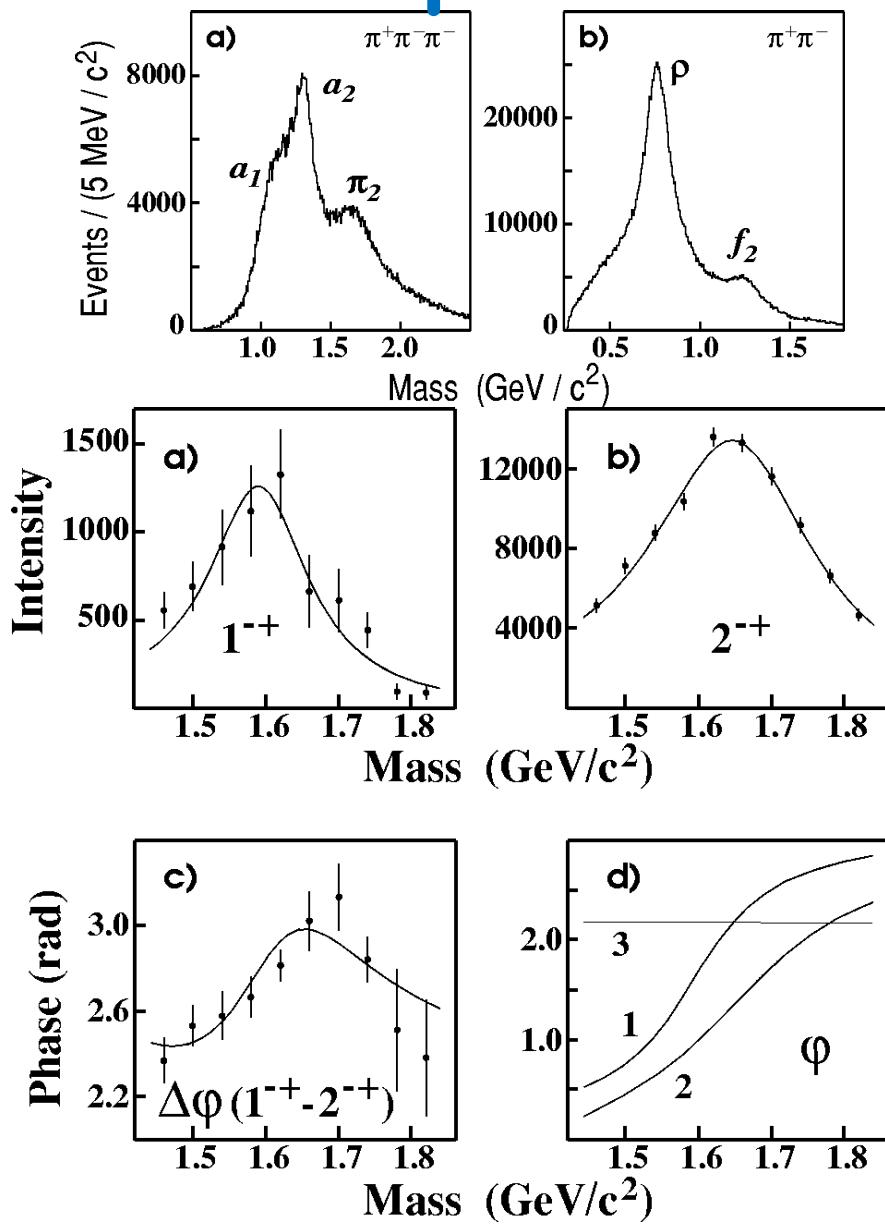
Adams (et. al) PLB657 (2007)
 (~23000 Events)
 Confirms the $\eta\pi^-$ results



(~45000 Events)
 Problematic Resonant Description



E852 Experiment



$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$$

(~250,000 Events)

Suggestive of $a_1, a_2, \pi_2 \rightarrow \rho\pi$
 $\pi_2 \rightarrow f_2\pi$

(1998)

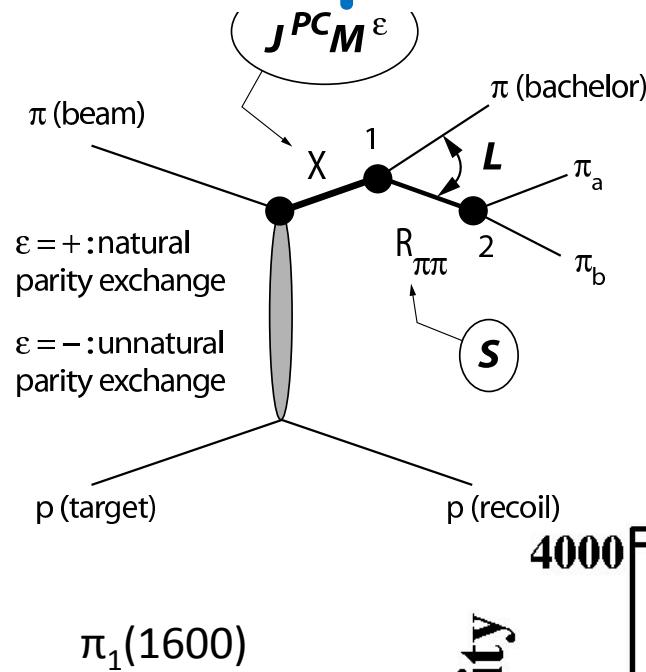
Partial Wave Analysis

$$\pi_1(1600) \rightarrow \rho\pi$$

$$M = 1598 \pm 8+29-47 \text{ MeV}/c^2$$

$$\Gamma = 168 \pm 20+150-12 \text{ MeV}/c^2$$

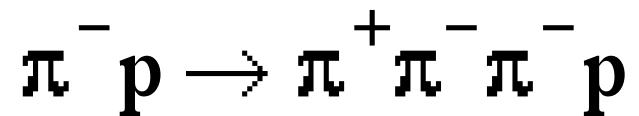
E852 Experiment



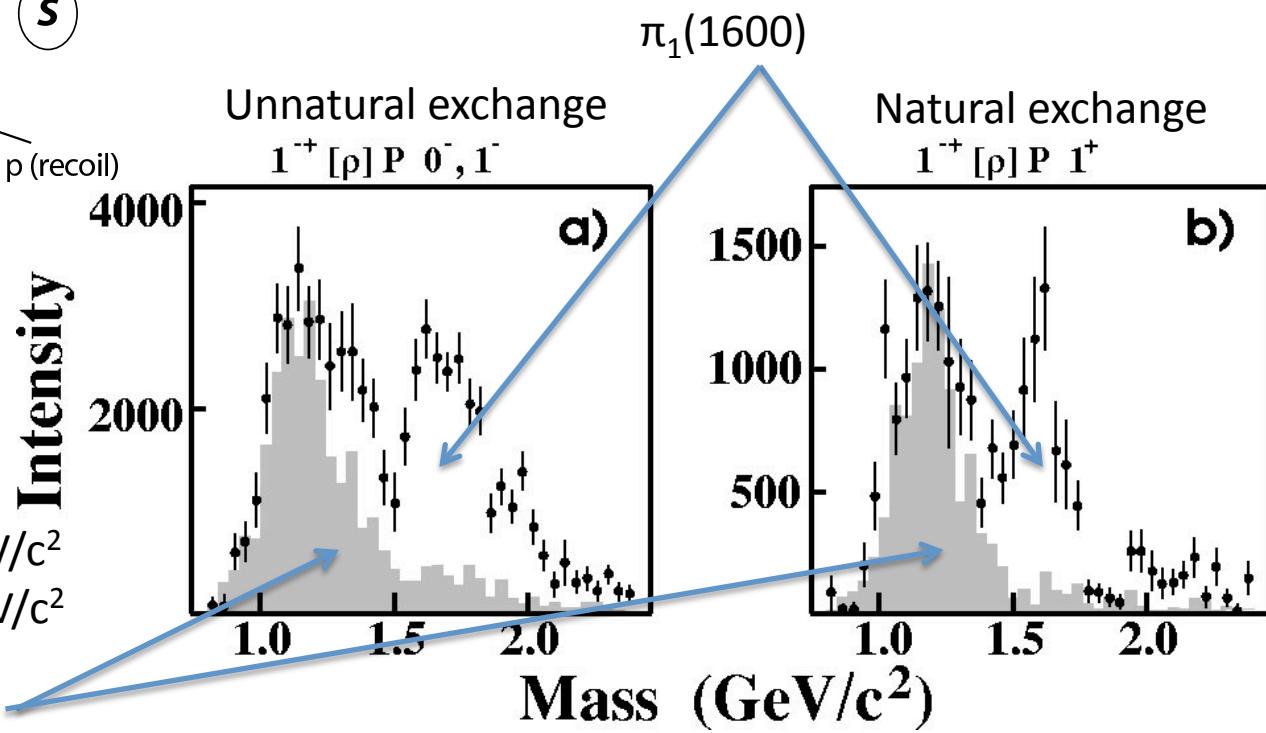
$$M = 1598 \pm 8+29-47 \text{ MeV}/c^2$$

$$\Gamma = 168 \pm 20+150-12 \text{ MeV}/c^2$$

Leakage from other partial waves.



Natural-parity exchange: $0^+, 1^-, 2^+, \dots$
 Unnatural-parity exchange: $0^-, 1^+, 2^-, \dots$



Only quote results from the 1^+ (natural parity) exchange.

E852 Experiment

$\pi^- p \rightarrow \eta' \pi^- p$

(~6000 Events)

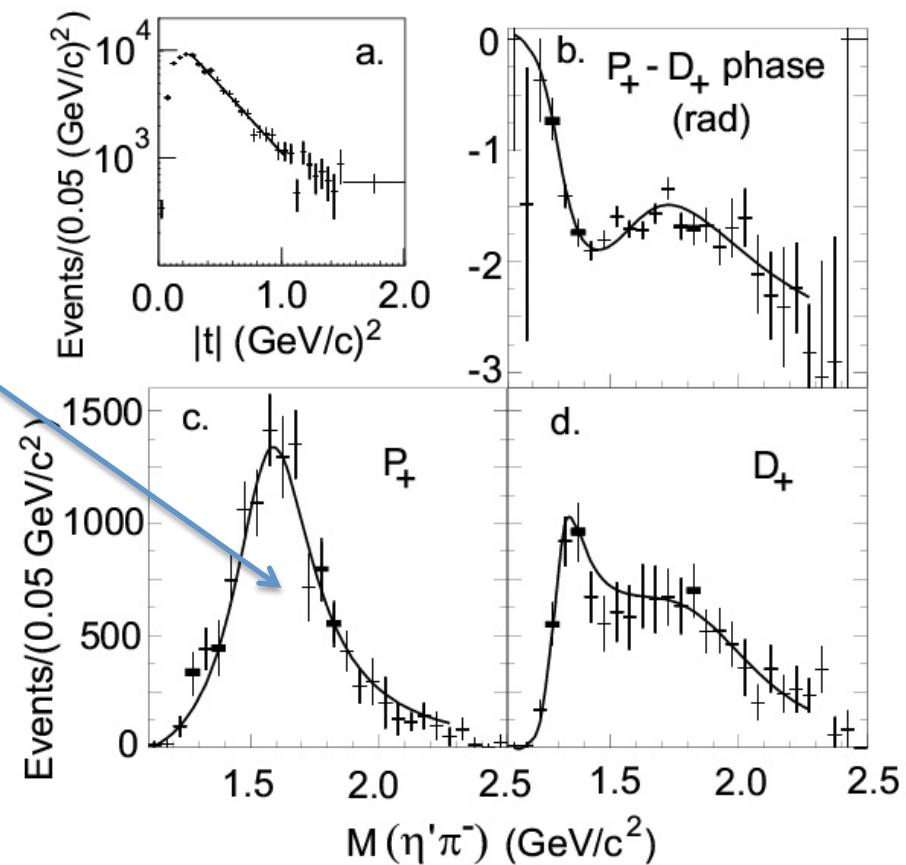
Data are dominated by 1^+ , 2^{++} and 4^{++} partial waves.

Data are dominated by natural parity exchange.

(2001)

$\pi_1(1600)$
 $M = 1597 \pm 10 \pm 45 \pm 10 \text{ MeV}/c^2$
 $\Gamma = 340 \pm 40 \pm 50 \text{ MeV}/c^2$

The exotic wave is the dominant wave in this channel.



E852 Experiment

(2004)

$$\pi_1(1600) \rightarrow b_1\pi$$

$$M = 1664 \pm 8 \pm 10 \text{ MeV}/c^2$$

$$\Gamma = 185 \pm 25 \pm 38 \text{ MeV}/c^2$$

Seen in both natural and unnatural parity exchange.
The unnatural dominates

$$\pi_1(2000) \rightarrow b_1\pi$$

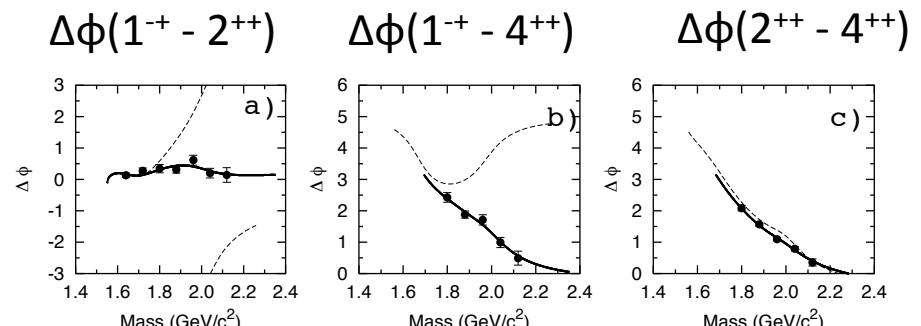
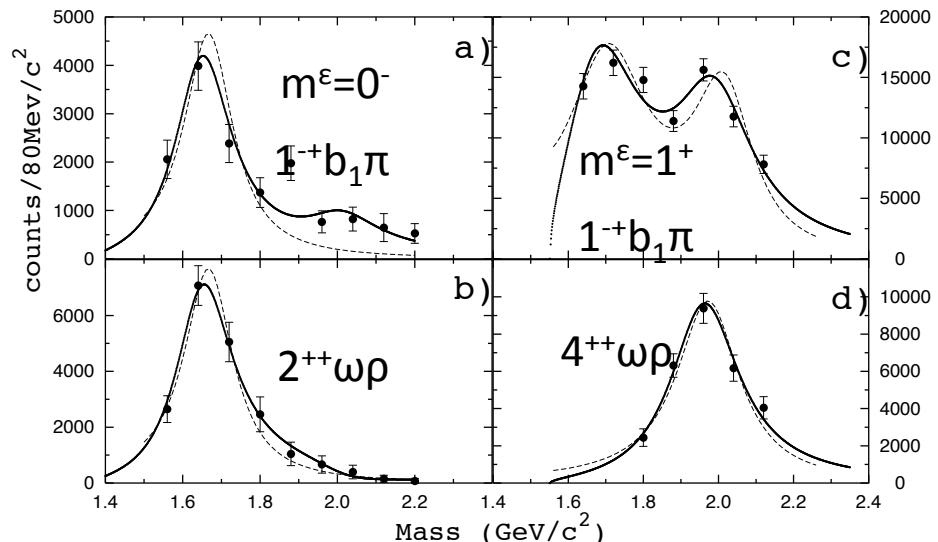
$$M = 2014 \pm 20 \pm 16 \text{ MeV}/c^2$$

$$\Gamma = 230 \pm 32 \pm 73 \text{ MeV}/c^2$$

Seen primarily in natural parity exchange.
The natural dominates

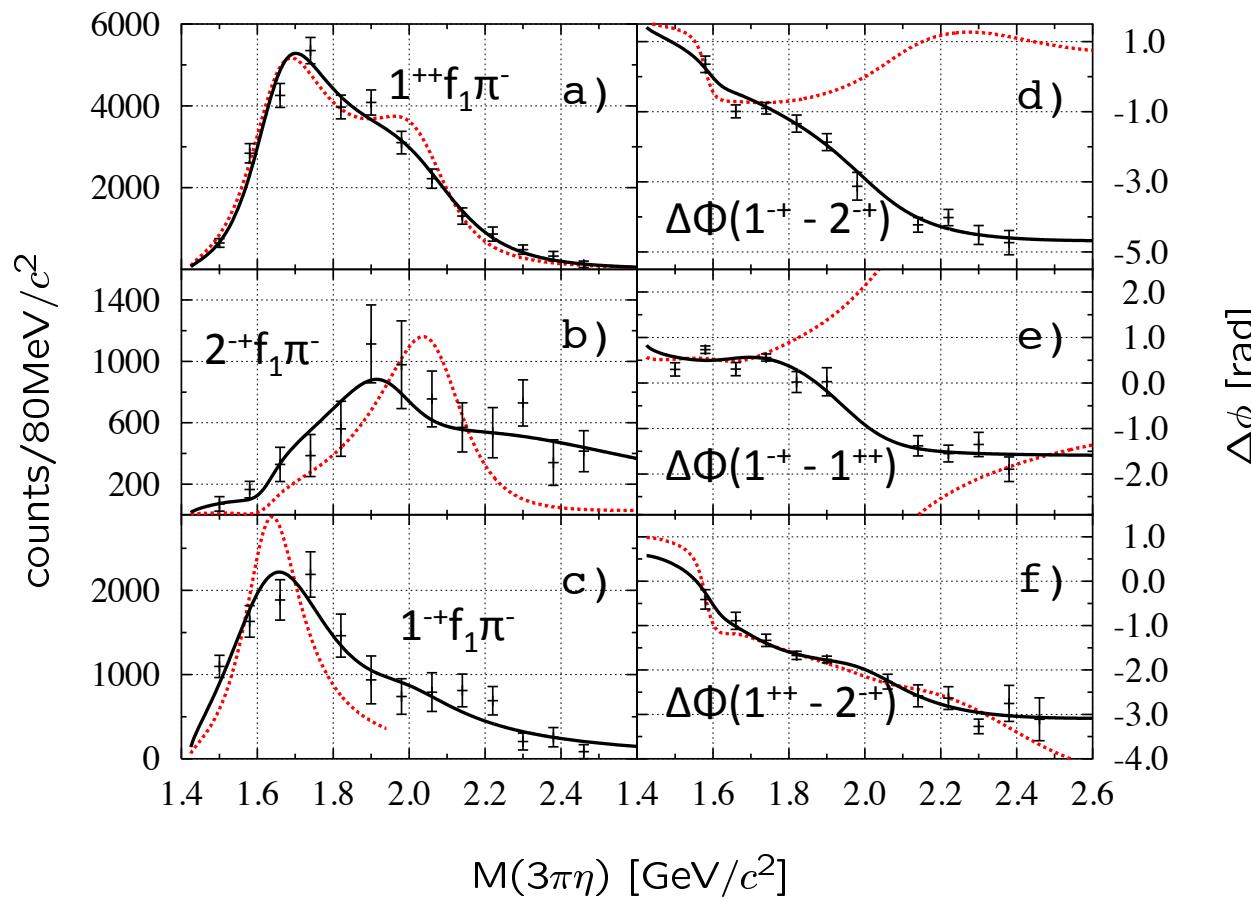
Solid curves are a two-pole 1^+ solution.
Dashed curves are a one-pole 1^+ solution.

$\pi^- p \rightarrow \omega \pi^0 \pi^- p$
(~145,000 Events)



E852 Experiment

(2004)



Black curves are a two-pole 1^+ solution.
Red curves are a one-pole 1^+ solution.

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

(~69000 Events)

$$\begin{aligned}\pi_1(1600) &\rightarrow f_1 \pi \\ M &= 1709 \pm 24 \pm 41 \text{ MeV}/c^2 \\ \Gamma &= 403 \pm 80 \pm 115 \text{ MeV}/c^2\end{aligned}$$

Natural parity exchange

$$\begin{aligned}\pi_1(2000) &\rightarrow f_1 \pi \\ M &= 2001 \pm 30 \pm 92 \text{ MeV}/c^2 \\ \Gamma &= 333 \pm 52 \pm 49 \text{ MeV}/c^2\end{aligned}$$

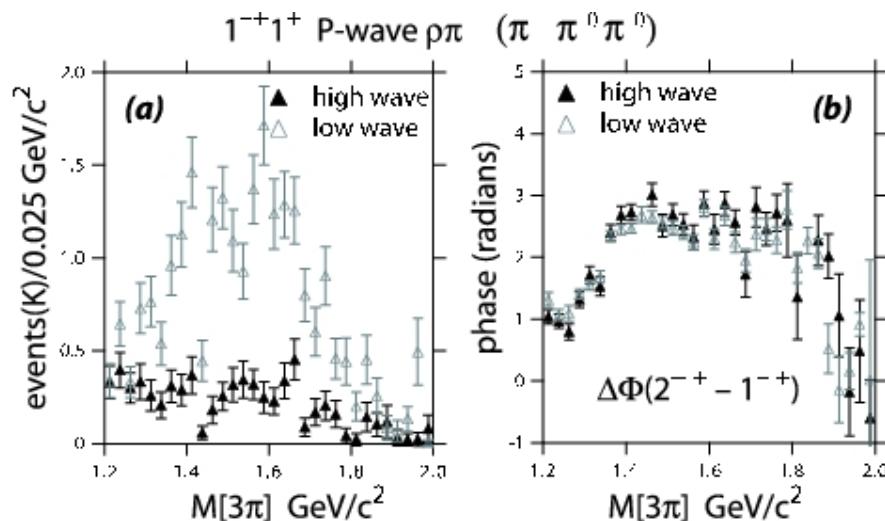
Natural parity exchange

New Analysis

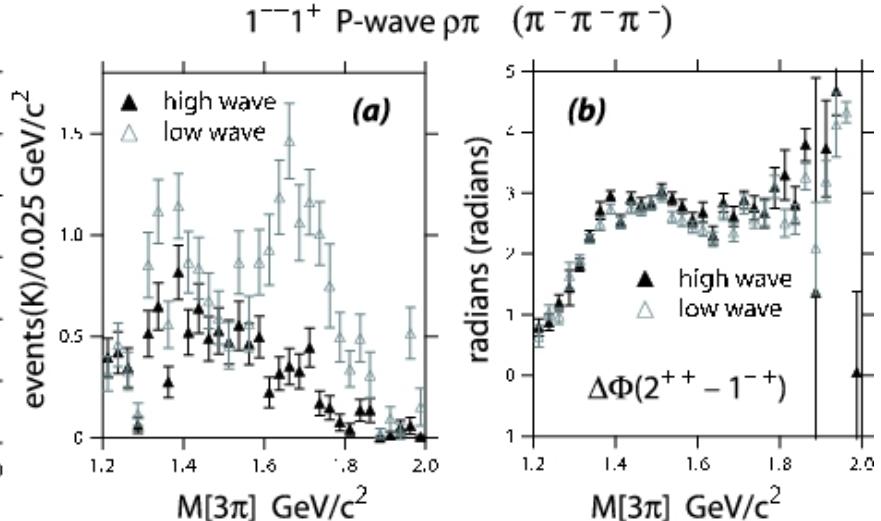
Dzierba et. al. PRD 73 (2006)

10 times statistics in each of two channels.

$\pi^- p \rightarrow p \pi^- \pi^0 \pi^0$ (3000000 Events)



$\pi^- p \rightarrow p \pi^- \pi^- \pi^+$ (2600000 Events)



Get a better description of the data via moments comparison.

Intensity for the exotic 1^+ wave goes away.

Phase motion between the 1^+ and the 2^{++} wave is not affected.

No Evidence for the $\pi_1(1600)$

New Analysis

Where does the intensity go?

PDG: $\pi_2(1670)$ Decays

3π 96%

$f_2\pi$ 56%

$\rho\pi$ 31%

Always Include:

$$(0^+)\pi_2(1670) \rightarrow f_2\pi(L=0)$$

$$(1^+)\pi_2(1670) \rightarrow f_2\pi(L=0)$$

$$(1^-)\pi_2(1670) \rightarrow f_2\pi(L=0)$$

$$(0^+)\pi_2(1670) \rightarrow f_2\pi(L=2)$$

$$(1^+)\pi_2(1670) \rightarrow f_2\pi(L=2)$$

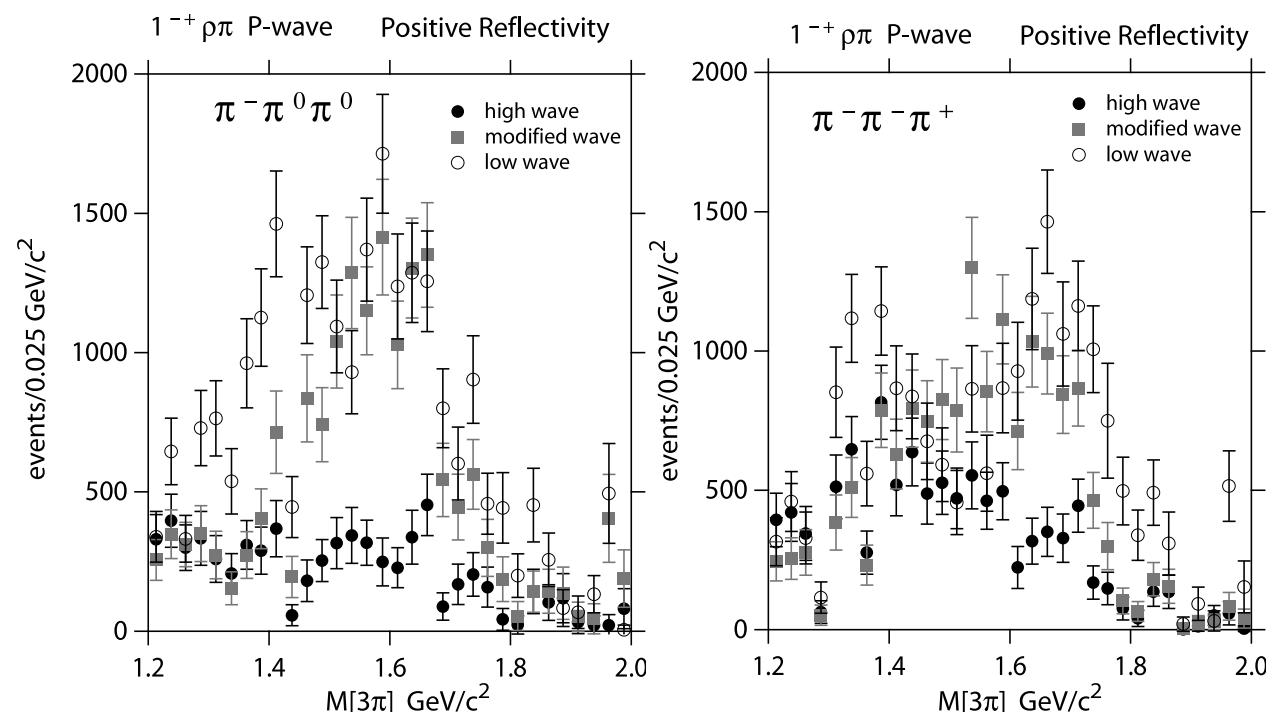
Modified wave set:

Leave out

$$(1^+)\pi_2(1670) \rightarrow \rho\pi(L=1)$$

$$(1^+)\pi_2(1670) \rightarrow \rho\pi(L=3)$$

$$(0^+)\pi_2(1670) \rightarrow \rho\pi(L=3)$$



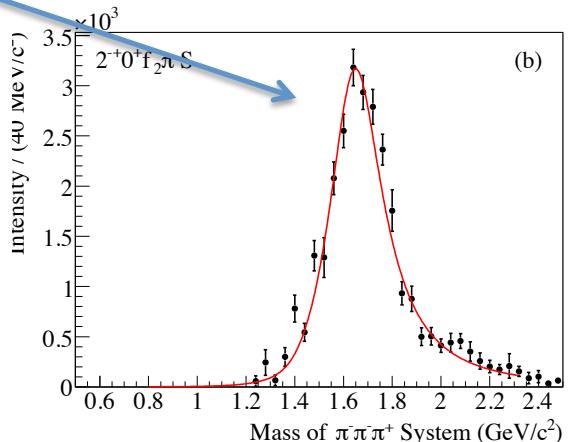
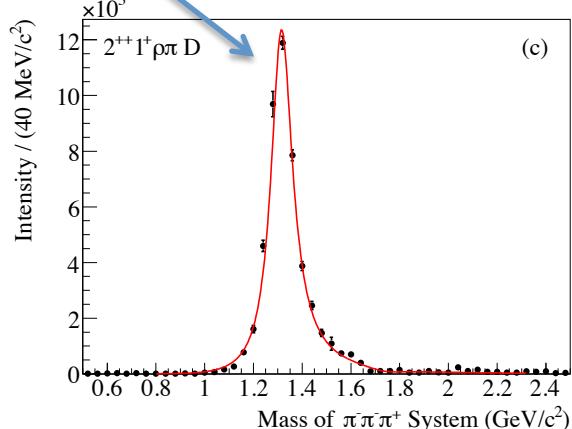
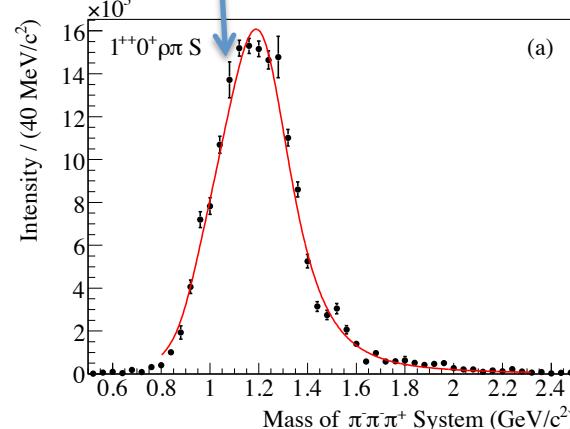
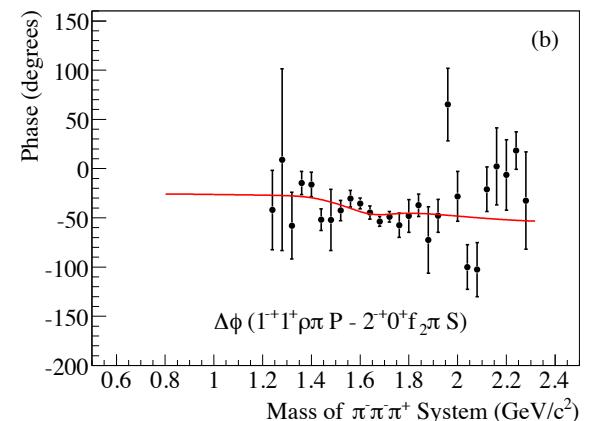
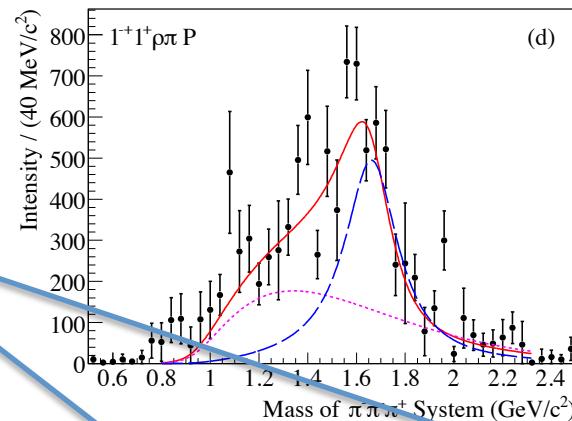
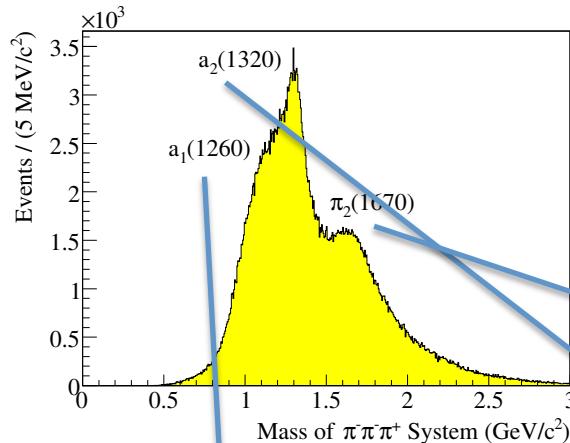
Most of the strength in the exotic $\pi_1(1600)$ is better described by known decays of the $\pi_2(1670)$.

COMPASS Experiment $\pi^- Pb \rightarrow \pi^+ \pi^- \pi^- (Pb)$

(420,000 Events)

1^- Exotic Wave

(180 GeV pions)



$$\pi_1(1600) \ m=1660 \ \Gamma=269 \quad \pi_2(1670) \ m=1658 \ \Gamma=271$$

arXiv:0910.5842

42 Partial waves included, exotic is dominantly 1^+ production.

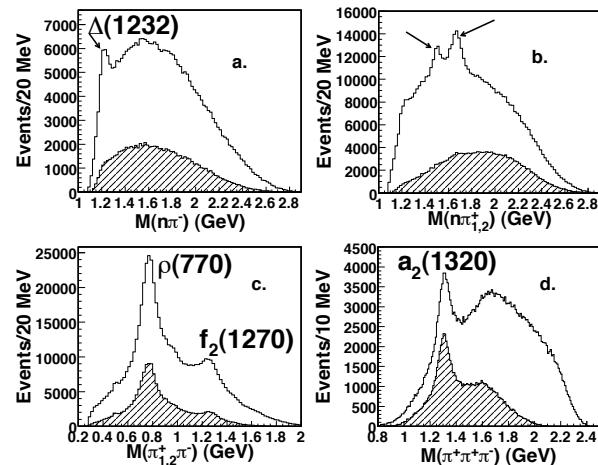
CLAS Experiment

$E_\gamma = 4.8 - 5.4 \text{ GeV}$

83000 Events after all cuts

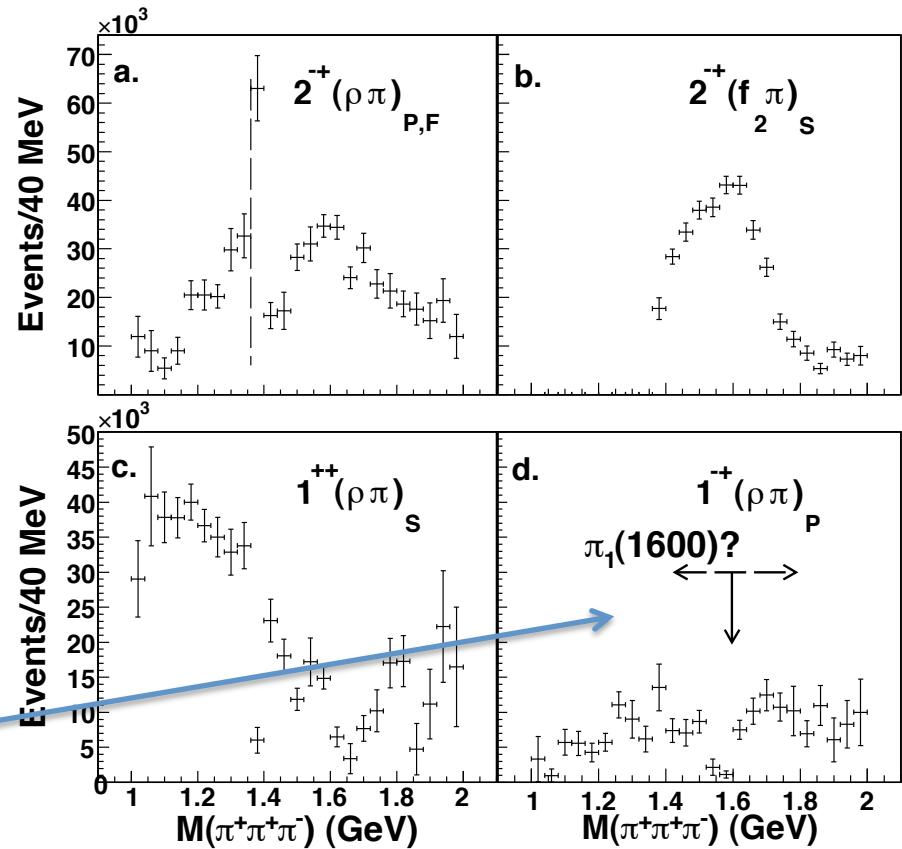
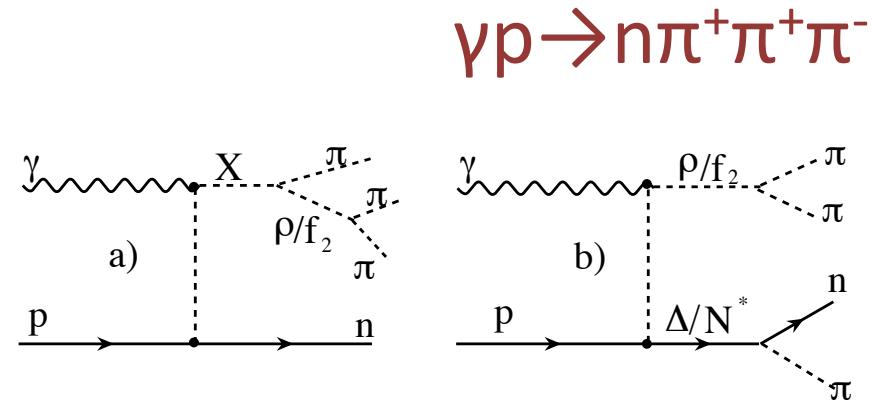
Overall Acceptance < 5%

Baryons “removed” by hard kinematic cuts.



PWA

No evidence of $\pi_1(1600) \rightarrow \rho\pi$,
(13.5 nb upper limit).



Summary of the $\pi_1(1400)$

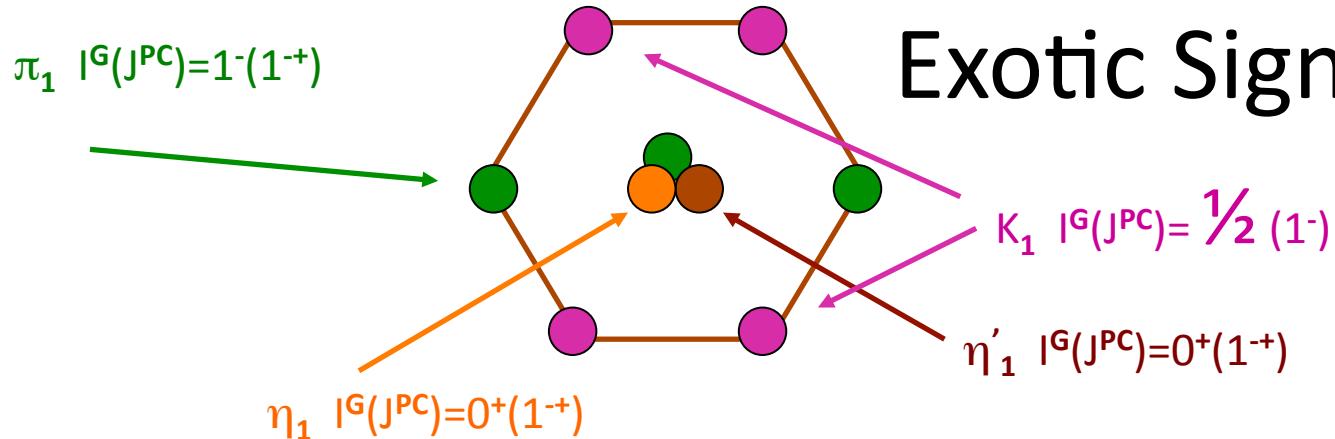
Mode	Mass	Width	Production
$\eta\pi^-$	$1370 \pm 15 \pm 50-30$	$385 \pm 40 \pm 65-105$	1^+
$\eta\pi^0$	$1257 \pm 20 \pm 25$	$354 \pm 64 \pm 60$	1^+ (controversial)
$\eta\pi$	1400	310	seen in proton-antiproton annihilation

Summary of the $\pi_1(1600)$

Mode	Mass	Width	Production	
3π	$1598 \pm 8 \pm 29-47$	$168 \pm 20 \pm 150-12$	$1^+, 0^-, 1^-$	(controversial)
$\eta'\pi$	$1597 \pm 10 \pm 45-10$	$340 \pm 40 \pm 50$	1^+	
$b_1\pi$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 38$	$0^-, 1^+$	3 π not seen in Photoproduction
$f_1\pi$	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	1^+	COMPASS
3π	$1660 \pm 10 \pm 64-0$	$269 \pm 21 \pm 42-64$	1^+	

Summary of the $\pi_1(2000)$

Mode	Mass	Width	Production
$b_1\pi$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$	1^+
$f_1\pi$	$2001 \pm 30 \pm 92$	$332 \pm 52 \pm 49$	1^+



Exotic Signals

$\pi_1(1400)$ Width ~ 0.3 GeV, Decays: only $\eta\pi$
 weak signal in πp production (scattering??)
 strong signal in antiproton-deuterium.

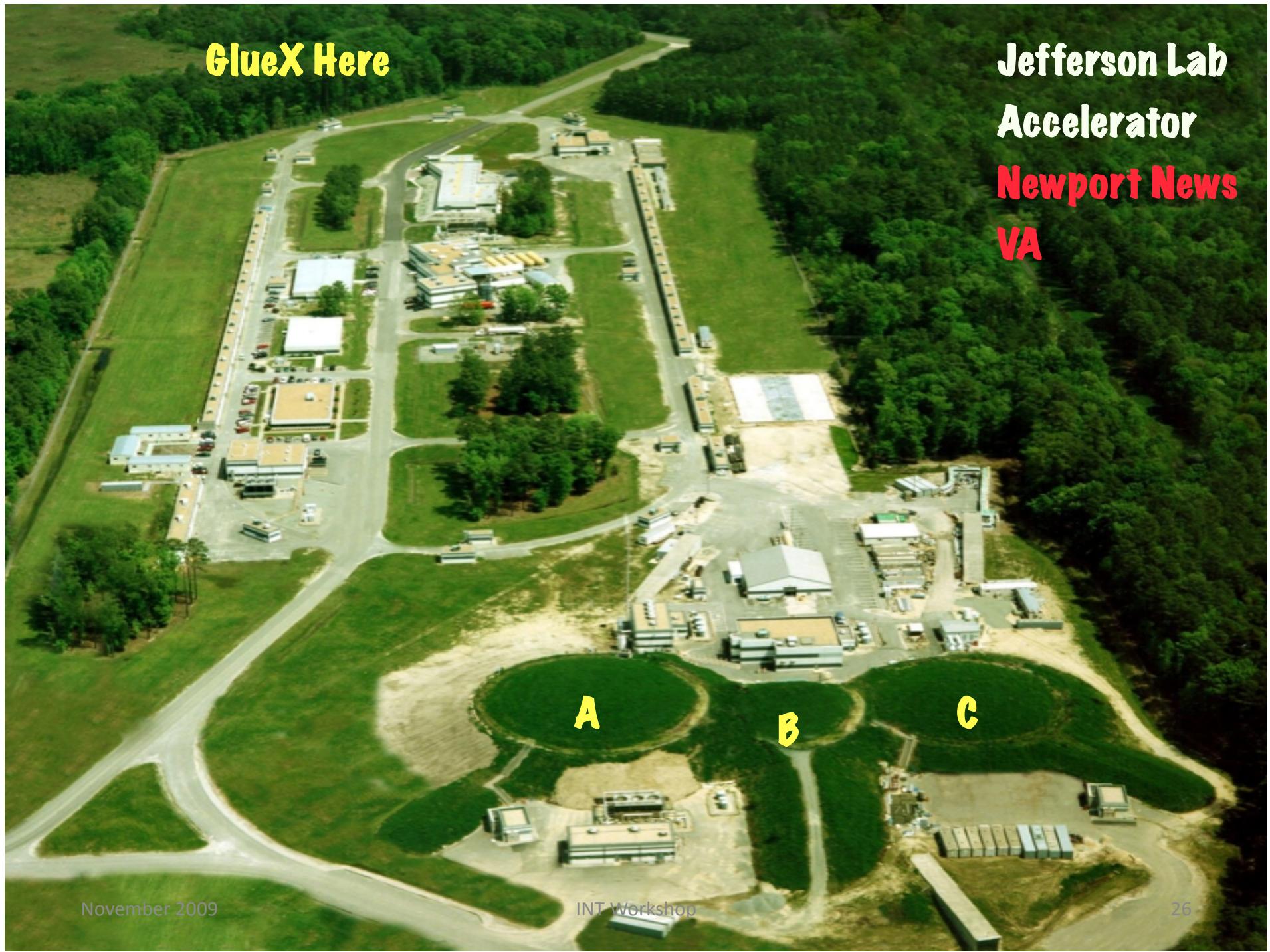
NOT A
HYBRID

$\pi_1(1600)$ Width ~ 0.30 GeV, Decays $\rho\pi, \eta'\pi, (b_1\pi)$
 Only seen in πp production, (E852 + VES)
 Production mechanisms not consistent.
 COMPASS sees a state with the same mass & width as the $\pi_2(1670)$.

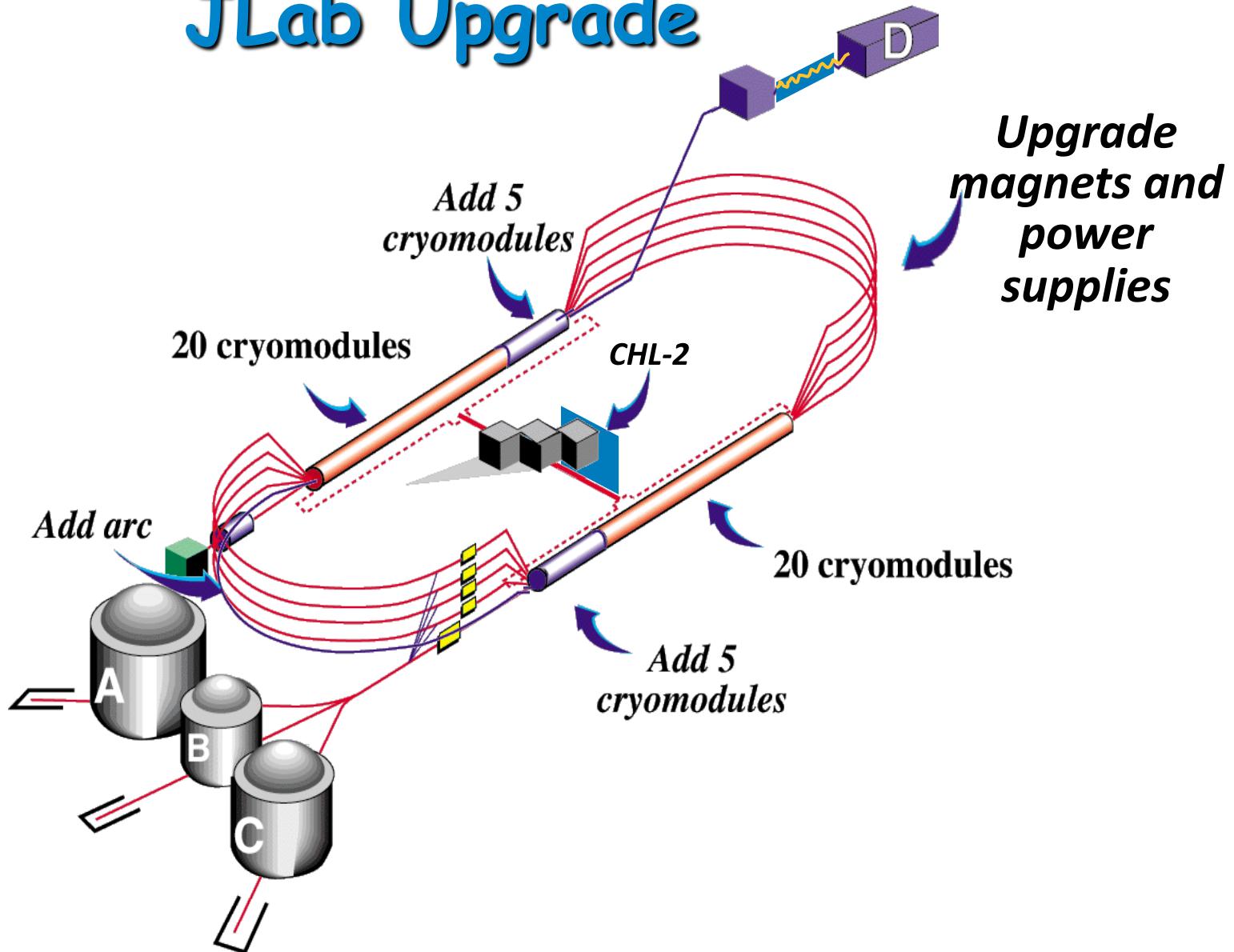
What is
going on?

$\pi_1(2000)$ Weak evidence in preferred hybrid modes $f_1\pi$ and $b_1\pi$
 natural parity exchange

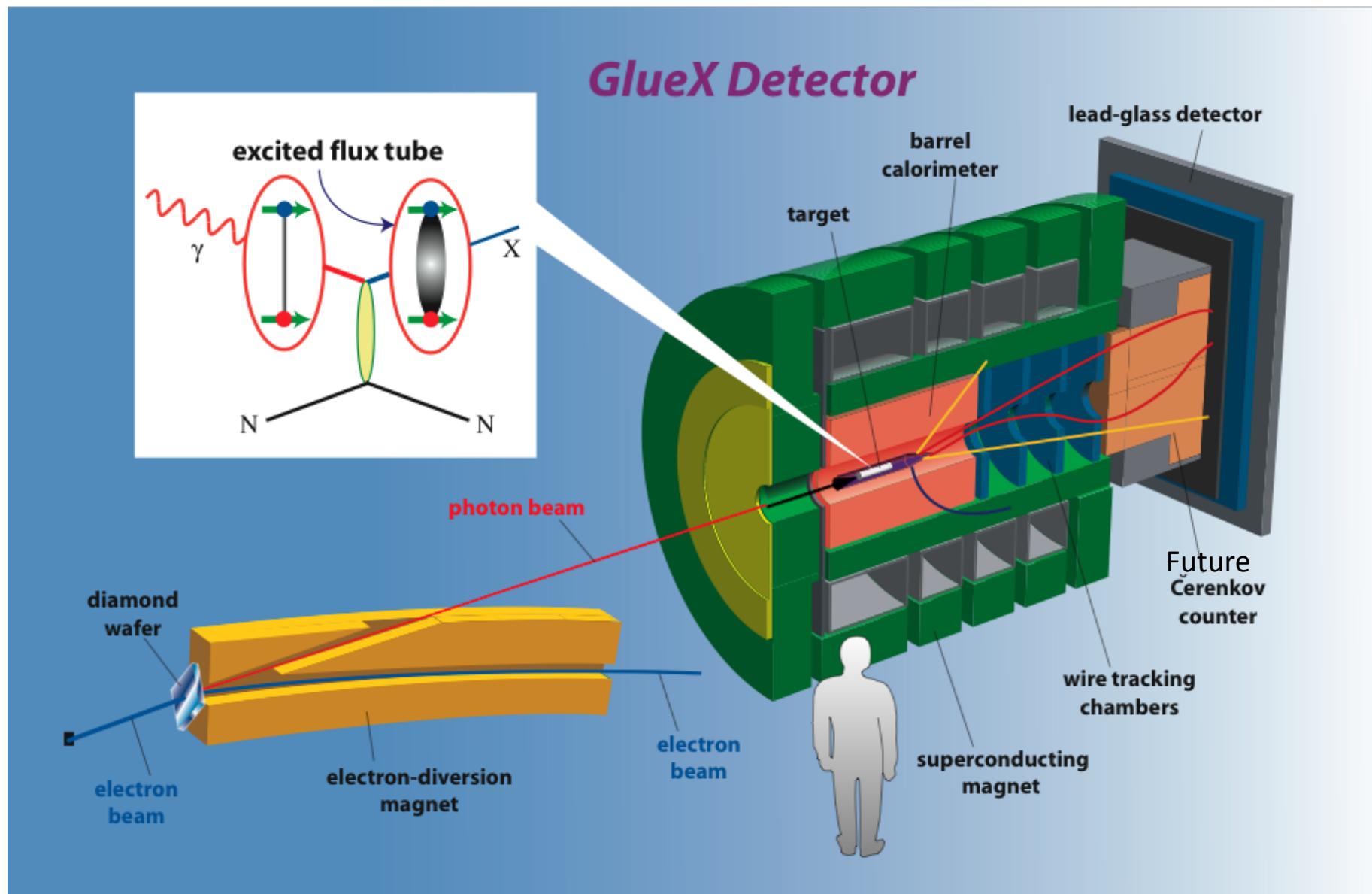
The right
place. Needs
confirmation.



JLab Upgrade

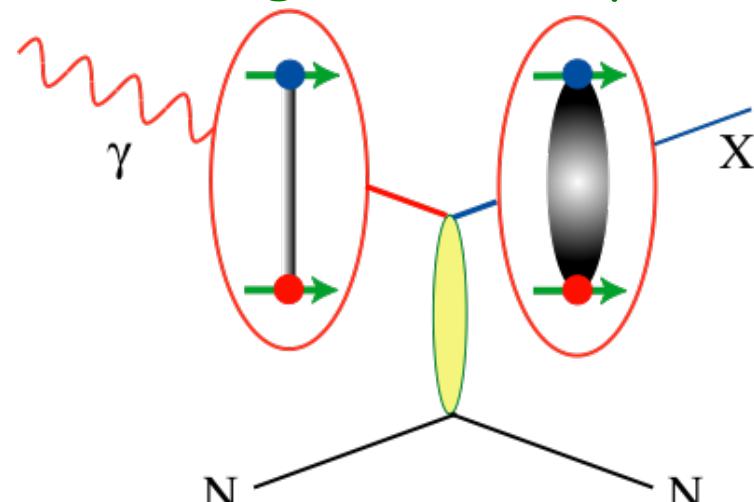
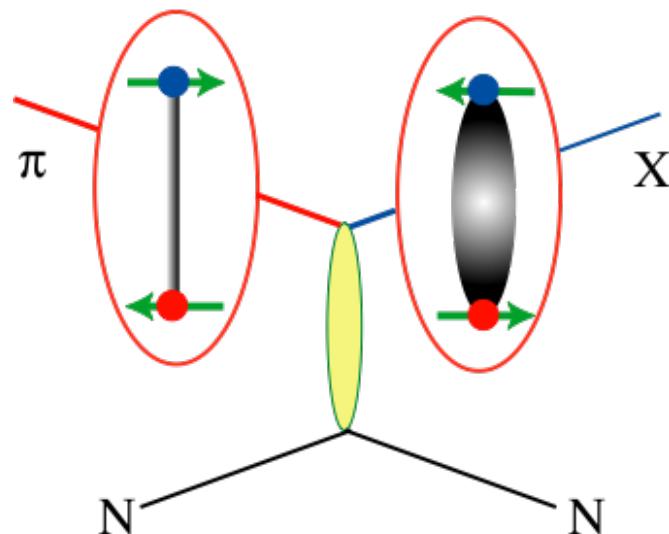


The GlueX Experiment



Photoproduction

More likely to find
exotic hybrid mesons
using beams of photons



Simple (0^{++}) natural parity exchange with $L=1$: $0^{+-}, 1^{+-}, 2^{+-}$

J. Dudek et. al, PRD 79 (2009) Compute radiative decays in charmonium to normal and hybrid mesons. Rates are comparable. Work currently underway to compute the same for light quarks.

8.4-9 GeV tagged, linearly polarized photon beam, up to $10^8/s$

Jlab 0^{+-} and 2^{+-}

In photoproduction, couple to ρ , ω or ϕ ?

$$b_0 \quad I^G(J^{PC})=1^+(0^{+-}) \quad \omega a_1, \rho f_0, \rho f_1$$

$$h_0 \quad I^G(J^{PC})=0^-(0^{+-}) \quad \omega f_0, \omega f_1, \rho a_1$$

$$h'_0 \quad I^G(J^{PC})=0^-(0^{+-}) \quad \phi f_0, \phi f_1, \rho a_1$$

$$K_0 \quad I(J^P)=\frac{1}{2}(0^+)$$

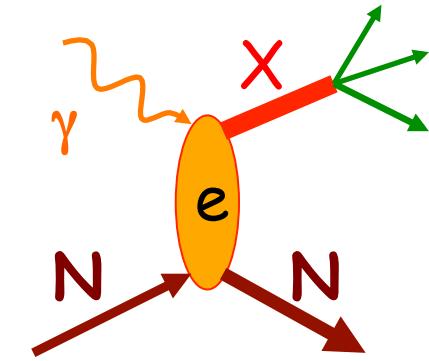
"Similar to π_1 "

$$\omega \pi \quad \omega a_1, \rho f_0, \rho f_1$$

$$\omega \eta, \rho \pi, \omega f_0, \omega f_1, \rho a_1$$

$$\phi \eta, \rho \pi, \phi f_0, \phi f_1, \rho a_1$$

Kaons do not have exotic QN's



$$b_2 \quad I^G(J^{PC})=1^+(2^{+-})$$

$$h_2 \quad I^G(J^{PC})=0^-(2^{+-})$$

$$h'_2 \quad I^G(J^{PC})=0^-(2^{+-})$$

$$K_2 \quad I(J^P)=\frac{1}{2}(2^+)$$

GlueX vs E852 Acceptance

GlueX

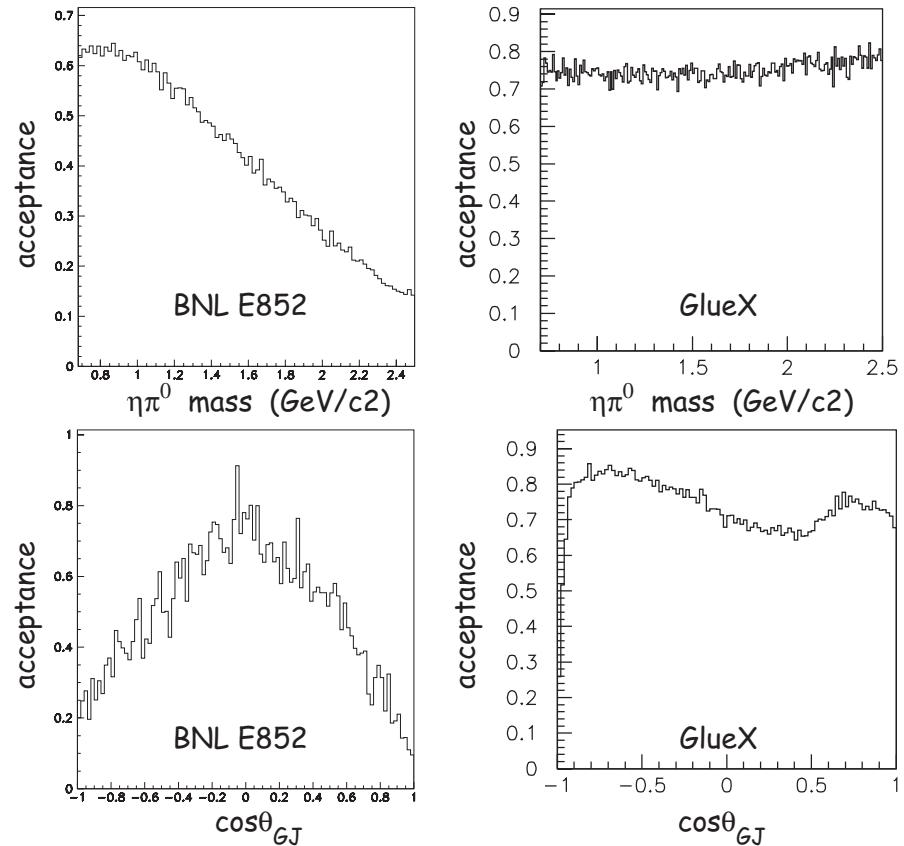
High, and reasonably uniform
Acceptance up to 2.5 GeV/c².

Sensitive to charged particles
And photons.

Some particle ID in the initial
phases, plans to upgrade this.

Able to fully reconstruct the 4-12
Particle final states.

$\pi^0\eta$ final state



The GlueX Experiment

The 12 GeV upgrade of Jefferson Lab is currently under construction.

Construction of Hall-D broke ground in April 2009.

Construction of the GlueX detector has started.



Current plans call for the first beam in HallD/GlueX in late 2014.

The GlueX Experiment



Exotics and QCD

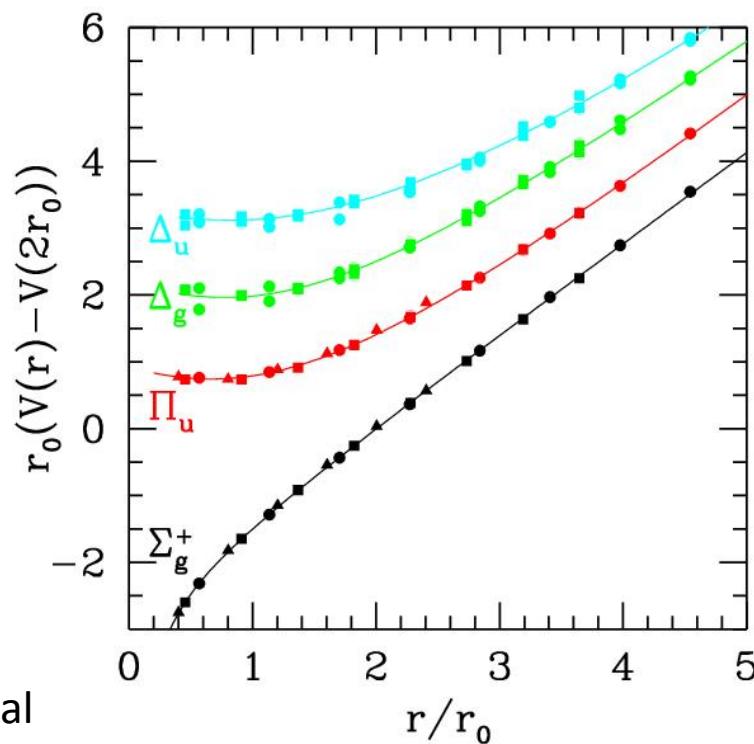
In order to establish the existence of gluonic excitations,
We need to establish the existence and nonet nature of the 1^{+-} state.
We need to establish at other exotic QN nonets – the 0^{+-} and 2^{+-} .

Decay Patterns are Crucial

Coupled Channel PWA Needed.

Very Large Data Sets Expected
From GlueX

The challenge is carrying out a PWA
with huge statistics and good theoretical
underpinnings to the method.



Summary

QCD predicts several nonets of exotic-quantum-number mesons.

Evidence hints at some exotic-quantum-number states, and two are consistent with a π_1 state. Where are the other states?

The first searches in photoproduction have come up negative, but the acceptance is poor, and the lower energy regime may not have been optimal.

Phenomenology was very poor for first photoproduction search.

The GlueX experiment at Jefferson Lab is now under construction with first beam in the hall expected in 2014.

The GlueX experiment has high acceptance for multi-particle final states, sensitivity to photons, and a linearly polarized photon beam.