QCD Exotics at BNL and JLab

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Outline

What are light-quark exotic mesons?

How should we look for these mesons?

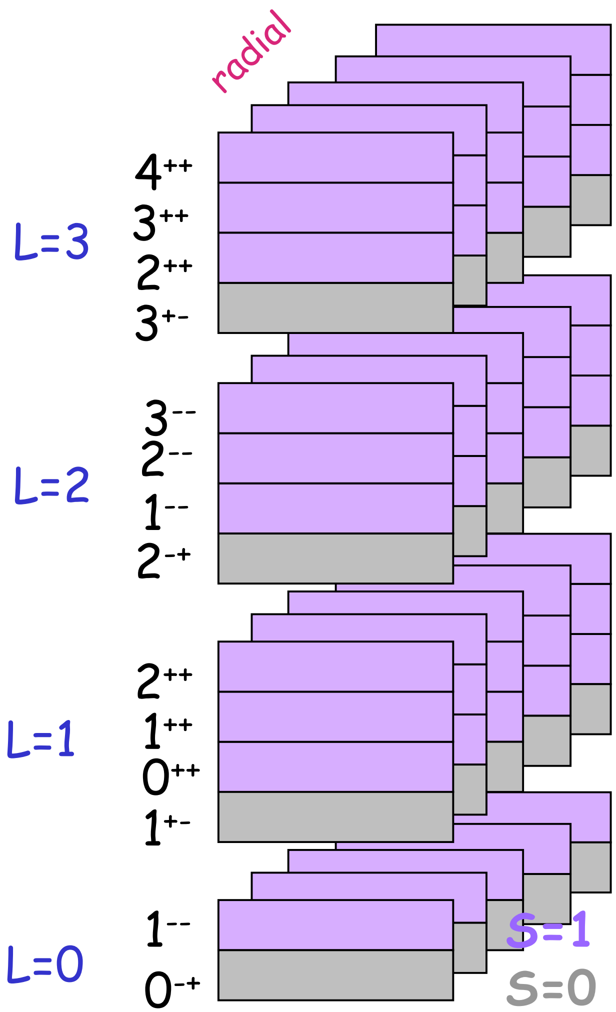
What is the Experimental Evidence?

BNL & JLab

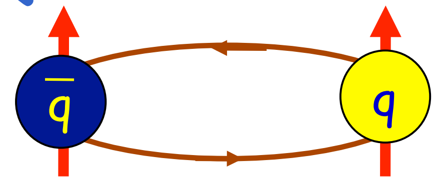
Where do we go from here?

Spectroscopy and QCD

Mesons



Quarkonium

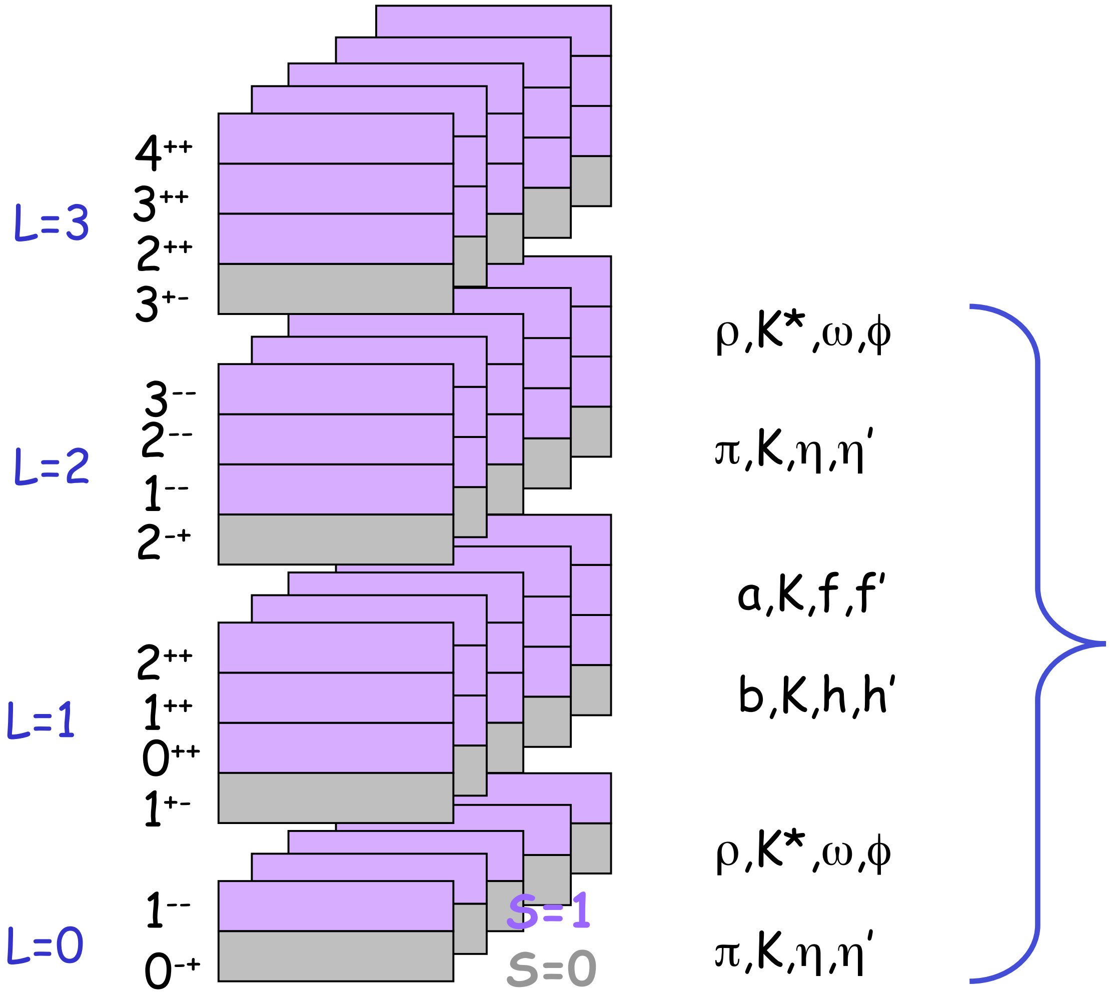


Consider the three lightest quarks

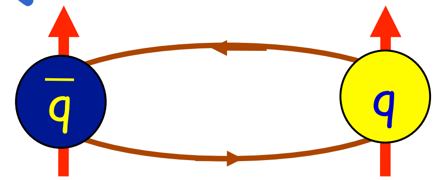
$$\left.\begin{array}{l} u, d, s \\ \bar{u}, \bar{d}, \bar{s} \end{array}\right\}$$ 9 Combinations

Spectroscopy an QCD

Mesons



Quarkonium

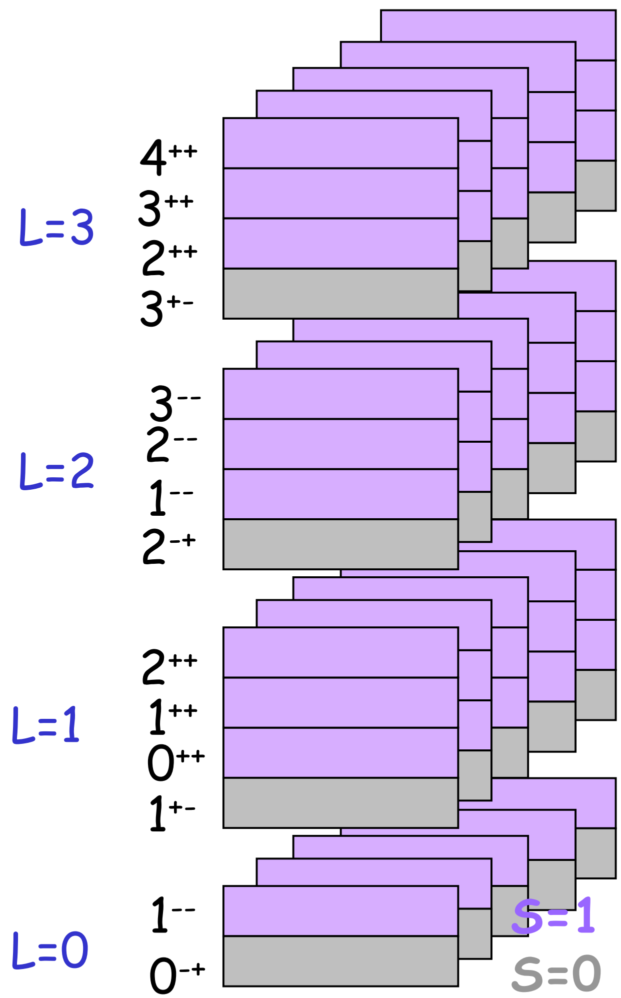


Mesons come in nonets of the same J^{PC} Quantum Numbers

SU(3) is broken
last two members mix

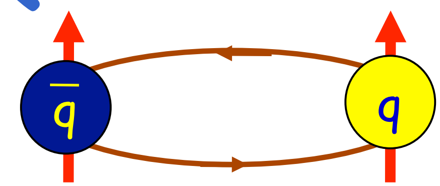
Spectroscopy an QCD

Mesons



Nothing to do with Glue!

Quarkonium

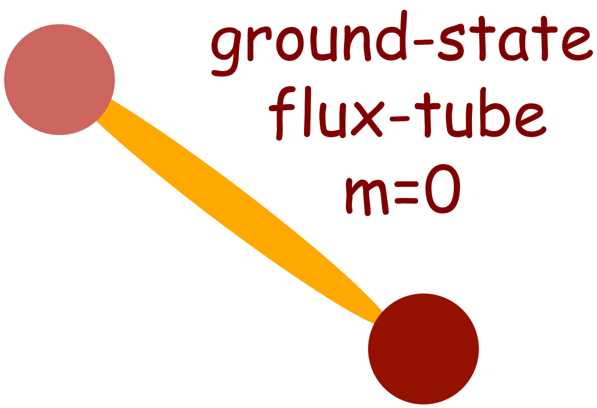


Allowed J^{PC} Quantum numbers:

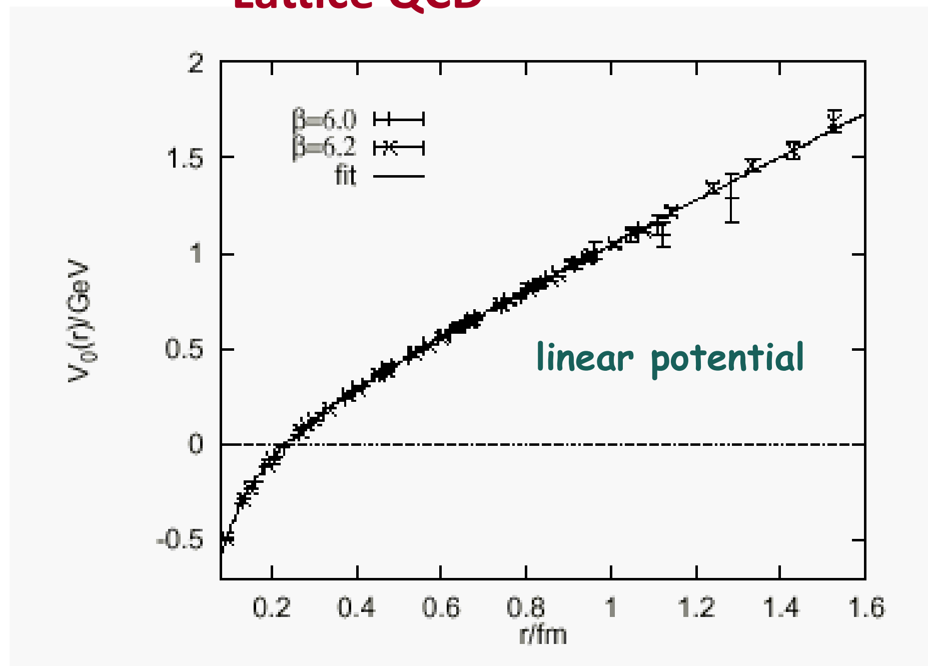
0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

Exotic Quantum Numbers
non quark-antiquark description

QCD Potential



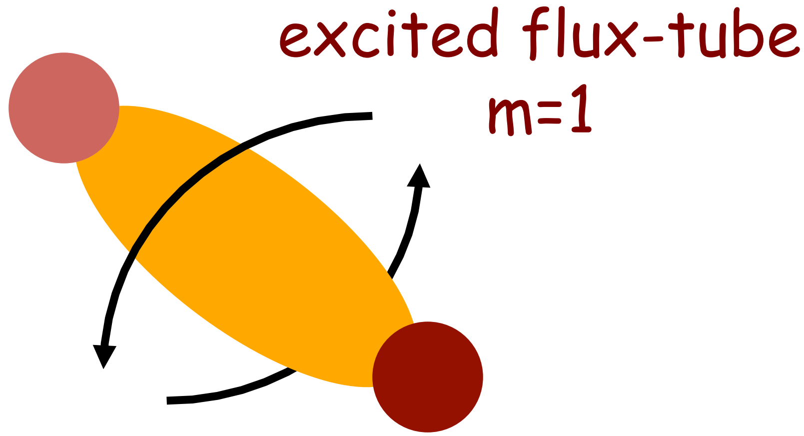
Lattice QCD



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

(π, K, η, η')	$(\rho, K^*, \omega, \Phi)$	(b_1, K_1, h_1, h_1')	$(\cdots)$
$J^{PC}=0^{-+}$	$J^{PC}=1^{--}$	$J^{PC}=1^{+-}$	$0^{++}, 1^{++}, 2^{++}, 2^{--}, 2^{-+}, 3^{++}, 3^{--}, 3^{+-}$

QCD Potential



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

$1^{++}, 1^{--}$ $0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$ **~1.9 GeV/c²**

S=0 ($1^{++}, 1^{--}$)   S=1 ($0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$)

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

UKQCD (97)	1.87 ±0.20
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

All masses in GeV/c²

1^{-+}	1.9± 0.2
2^{+-}	2.0± 0.11
0^{+-}	2.3± 0.6

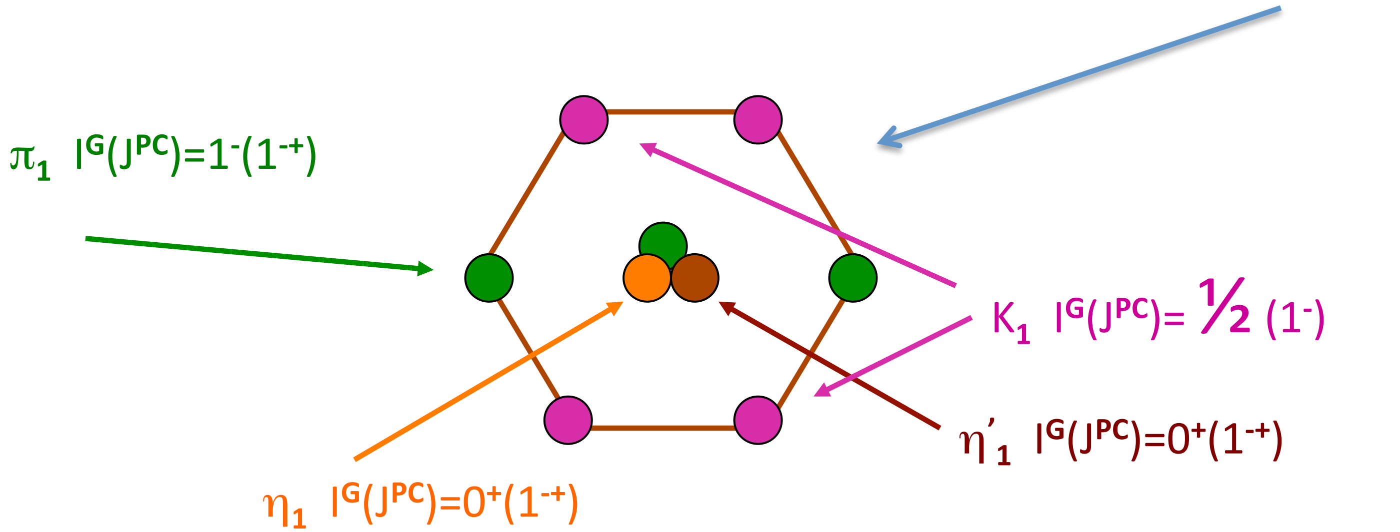
In the charmonium sector:

1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

Splitting = 0.20

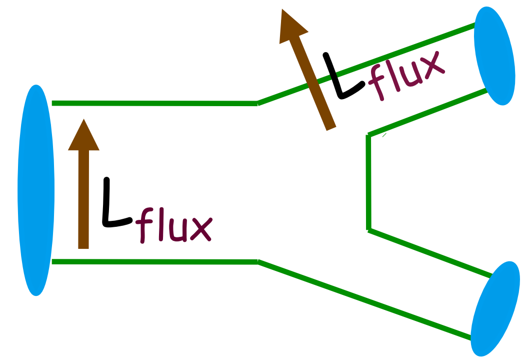
QCD Exotics

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



$\pi, \eta, \eta', K \rightarrow$	$\pi_1, \eta_1, \eta'_1, K_1$	1^{-+}
	b_0, h_0, h_0', K_0	0^{+-}
	b_2, h_2, h_2', K_2	2^{+-}

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

$\pi_1 \rightarrow \pi b_1$, πf_1 , $\pi\rho$, ηa_1
$\eta_1 \rightarrow \pi(1300)\pi$, $a_1\pi$

$b_2 \rightarrow a_1\pi$, $h_1\pi$, $\omega\pi$, $a_2\pi$
$h_2 \rightarrow b_1\pi$, $\rho\pi$, $\omega\eta$

$b_0 \rightarrow \pi(1300)\pi$, $h_1\pi$
$h_0 \rightarrow b_1\pi$, $h_1\eta$

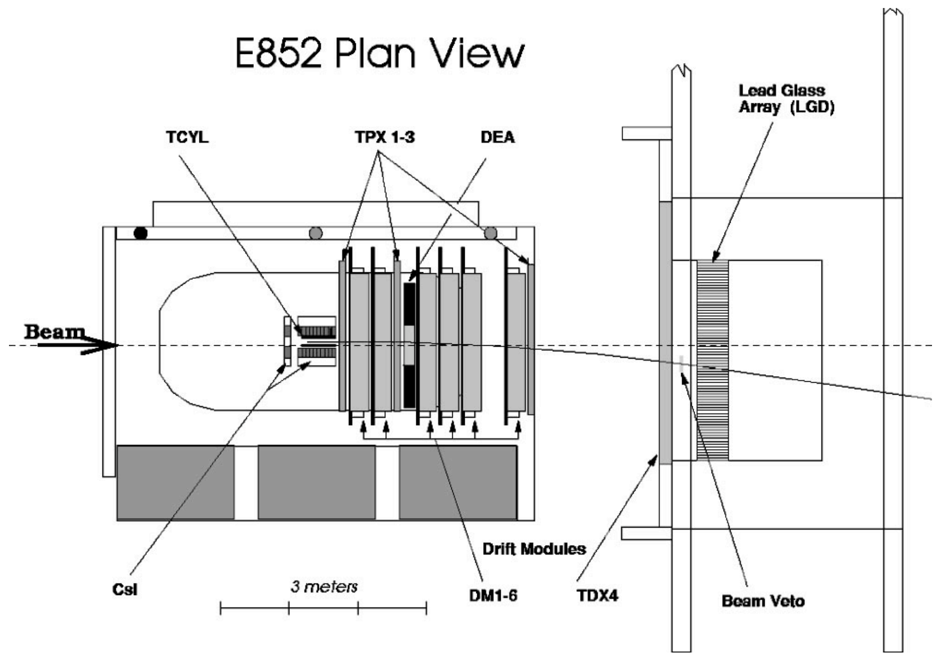
Mass and model dependent predictions

Populate final states with $\pi^{\pm}$,π^0,$K^{\pm}$,K^0,η, (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.

E852 used an 18 GeV/c beam of π^- on a hydrogen target. It detects photons and charged particles in the final state.



E852 Experiment

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

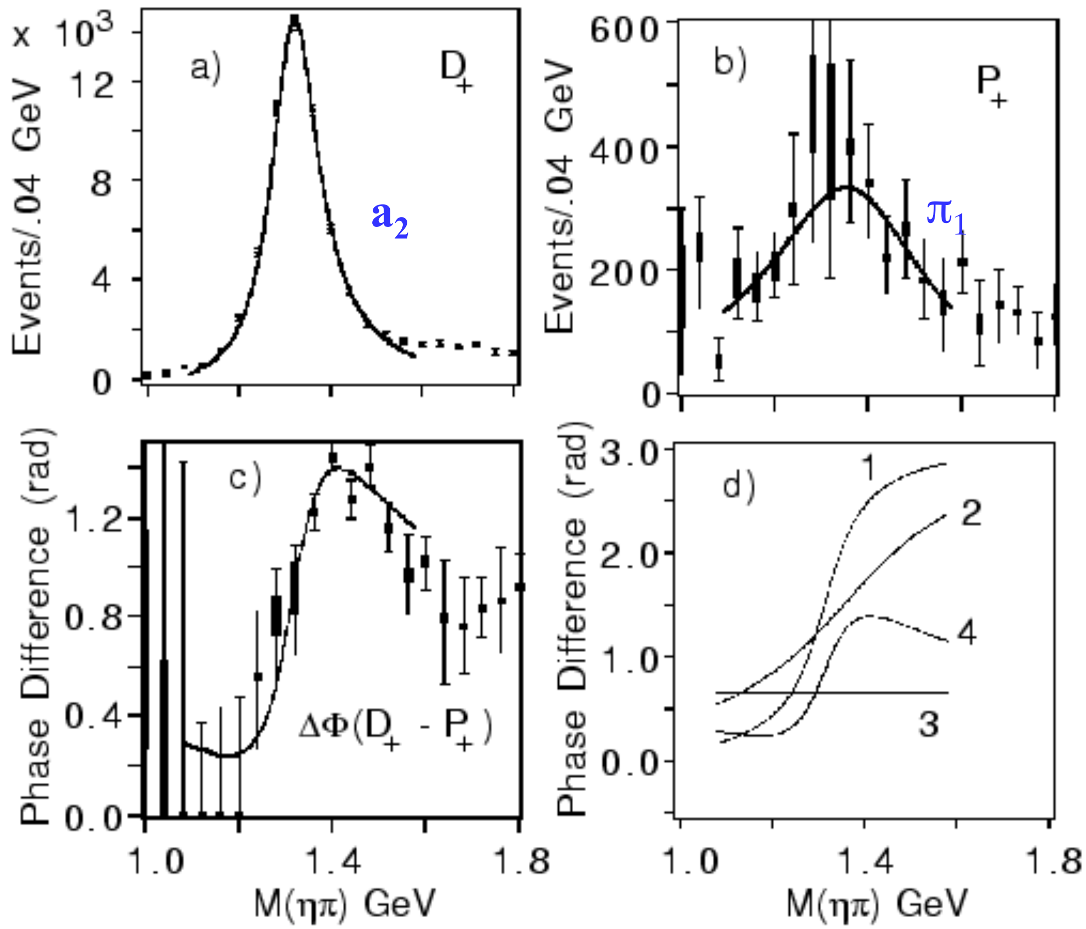
(1997)

$\pi_1(1400)$ Mass = $1370 \pm 16^{+50}_{-30}$ MeV/c^2
Width= $385 \pm 40^{+65}_{-105}$ MeV/c^2

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 $\eta\pi^0$



E852 Experiment

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

Dzierba (et. al) PRD67 (2003)

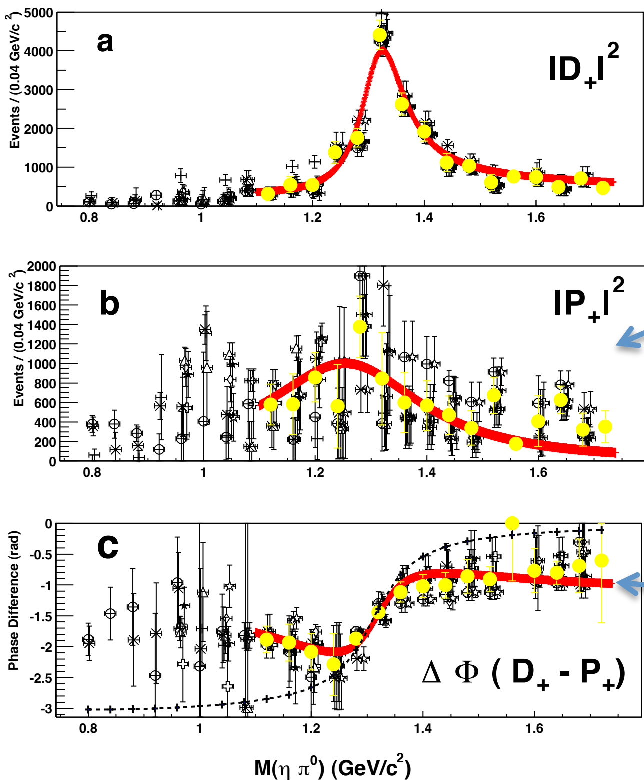
(~45000 Events)

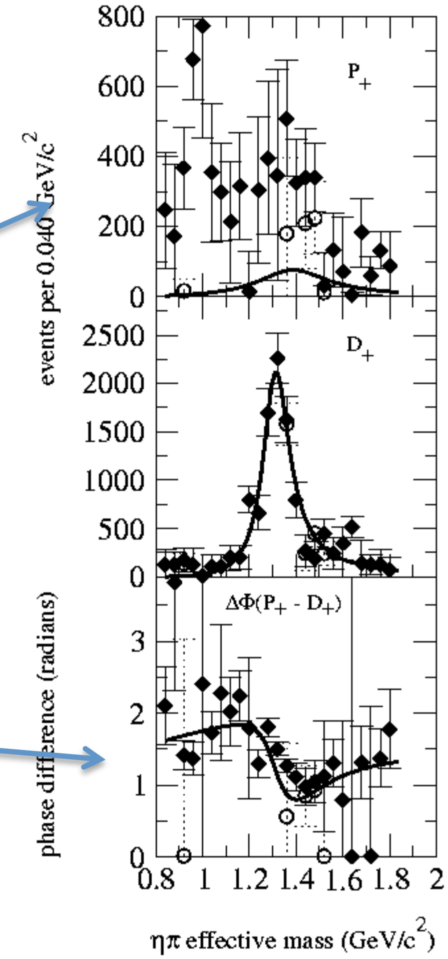
Problematic Resonant Description

Adams (et. al) PLB657 (2007)

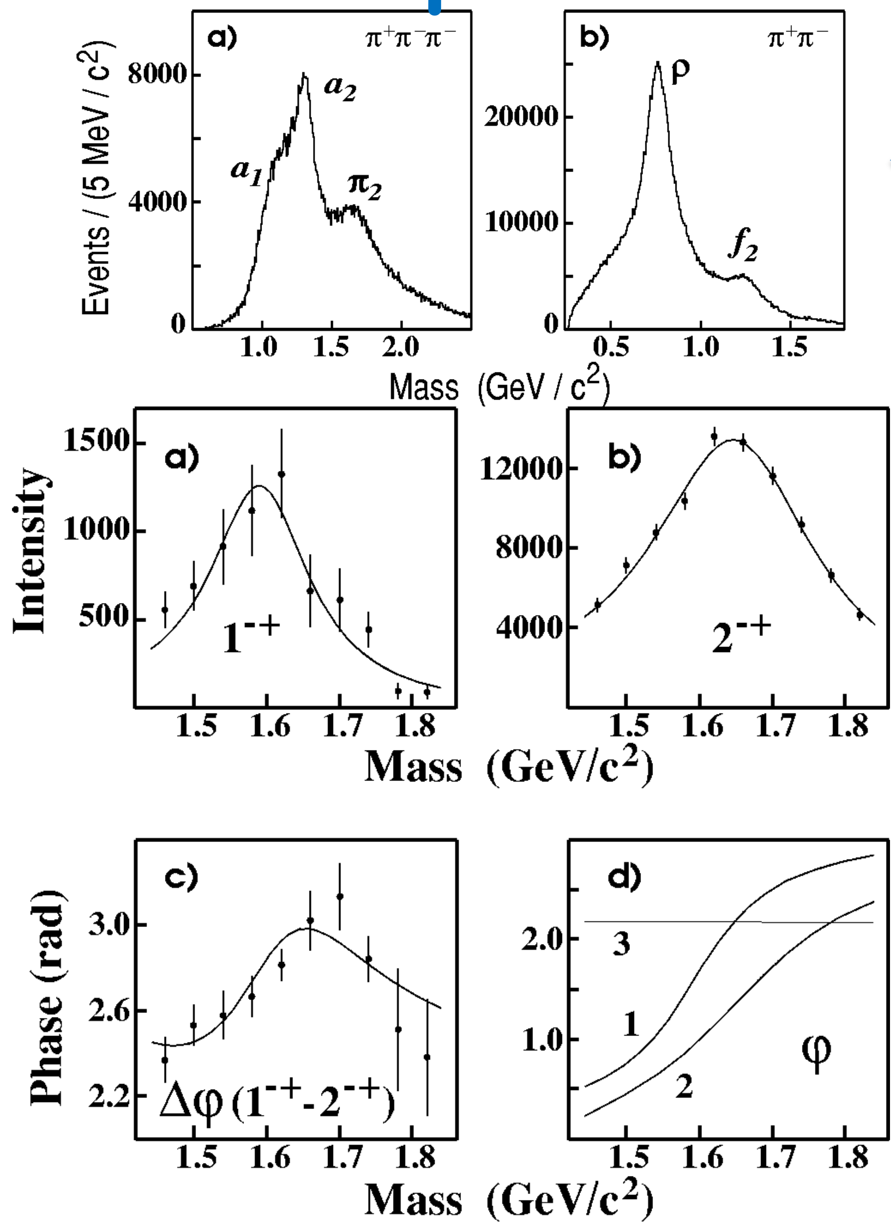
(~23000 Events)

Confirms the $\eta\pi^-$ results





E852 Experiment



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

(~250,000 Events)

Suggestive of a_1, a_2, $\pi_2 \to \rho\pi$

$\pi_2 \to f_2\pi$

(1998)

Partial Wave Analysis

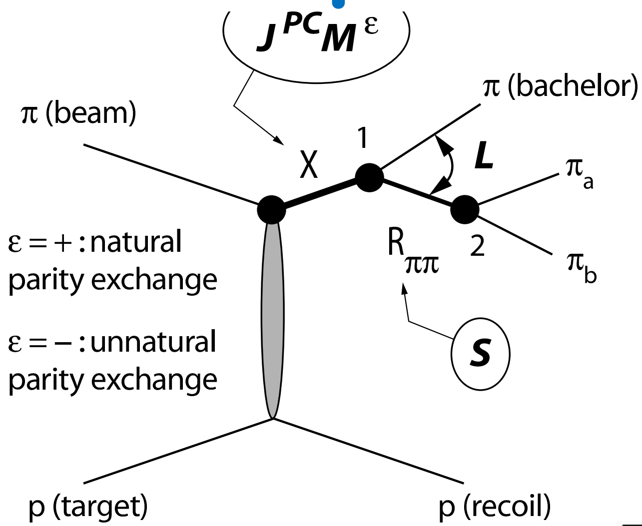
$\pi_1(1600) \to \rho\pi$

M = 1598 ±8+29-47 MeV/c^2

Γ = 168±20+150-12 MeV/c^2

E852 Experiment

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

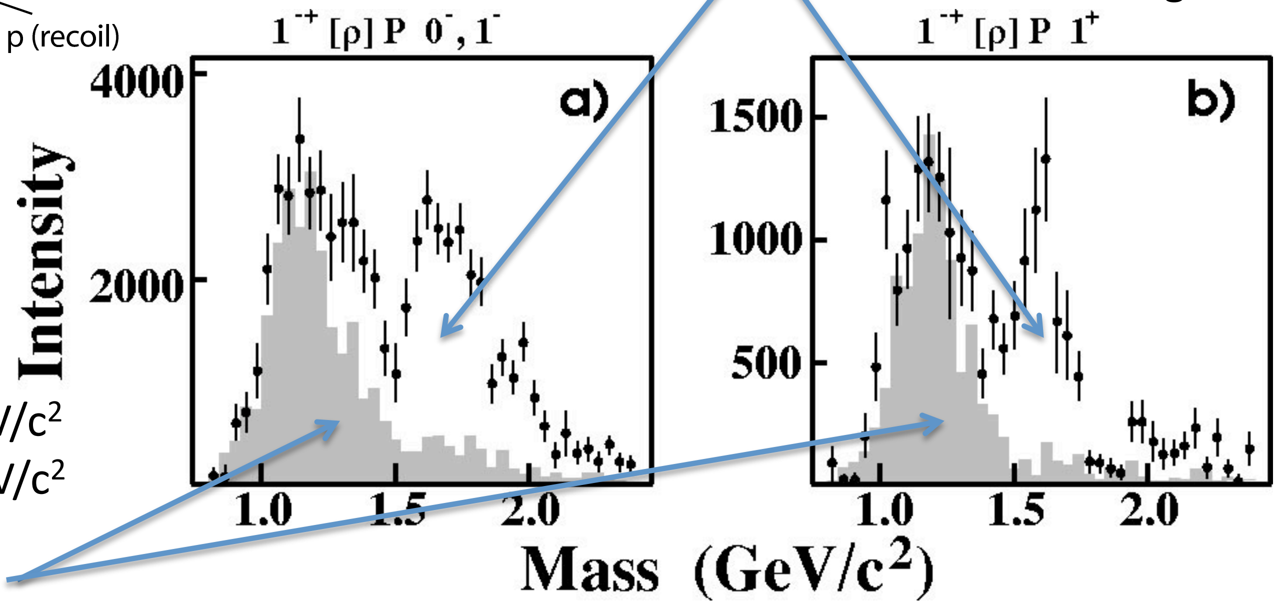


Natural-parity exchange: $0^+, 1^-, 2^+, \ldots$

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

$\pi_1(1600)$

$\pi_1(1600)$



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

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

Leakage from other partial waves.

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

E852 Experiment

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

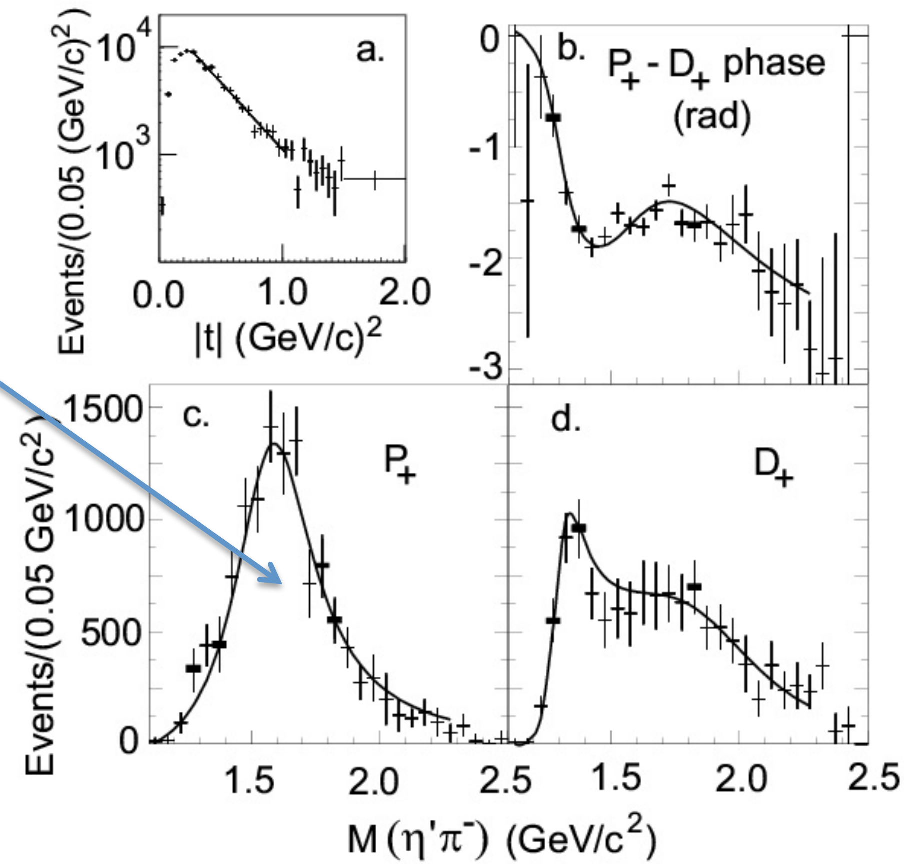
(~6000 Events)

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

(2001)

$\pi_1(1600)$
M = 1597±10+45-10 MeV/c^2
Γ = 340±40±50 MeV/c^2

The exotic wave is the dominant wave in this channel.



E852 Experiment

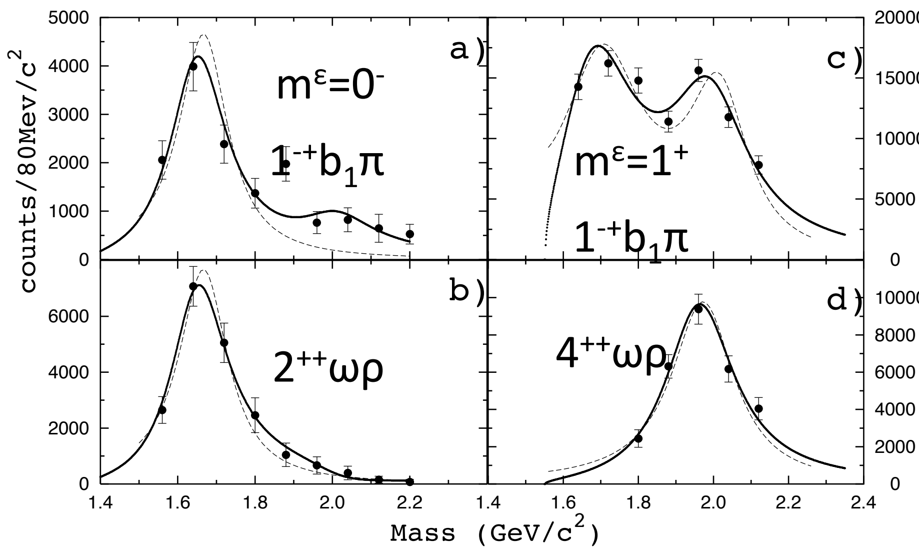
(2004)

$\pi^- p \rightarrow \omega\pi^0\pi^- p$

(~145,000 Events)

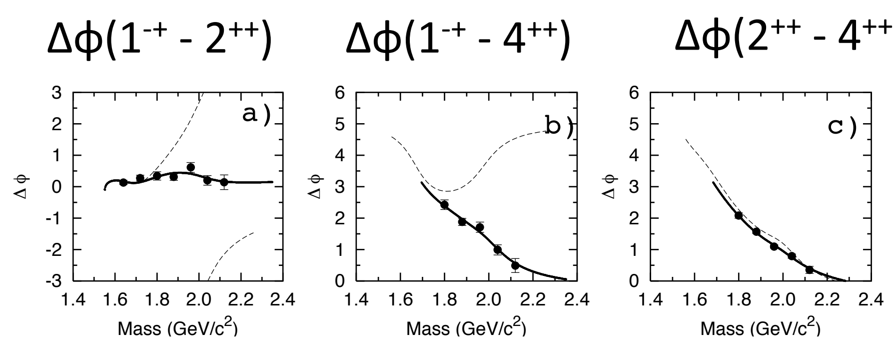
$\pi_1(1600) \rightarrow b_1\pi$
M = 1664±8±10 MeV/c²
Γ = 185±25±38 MeV/c²

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



$\pi_1(2000) \rightarrow b_1\pi$
M = 2014±20±16 MeV/c²
Γ = 230±32±73 MeV/c²

Seen primarily in natural parity exchange.
The natural dominates



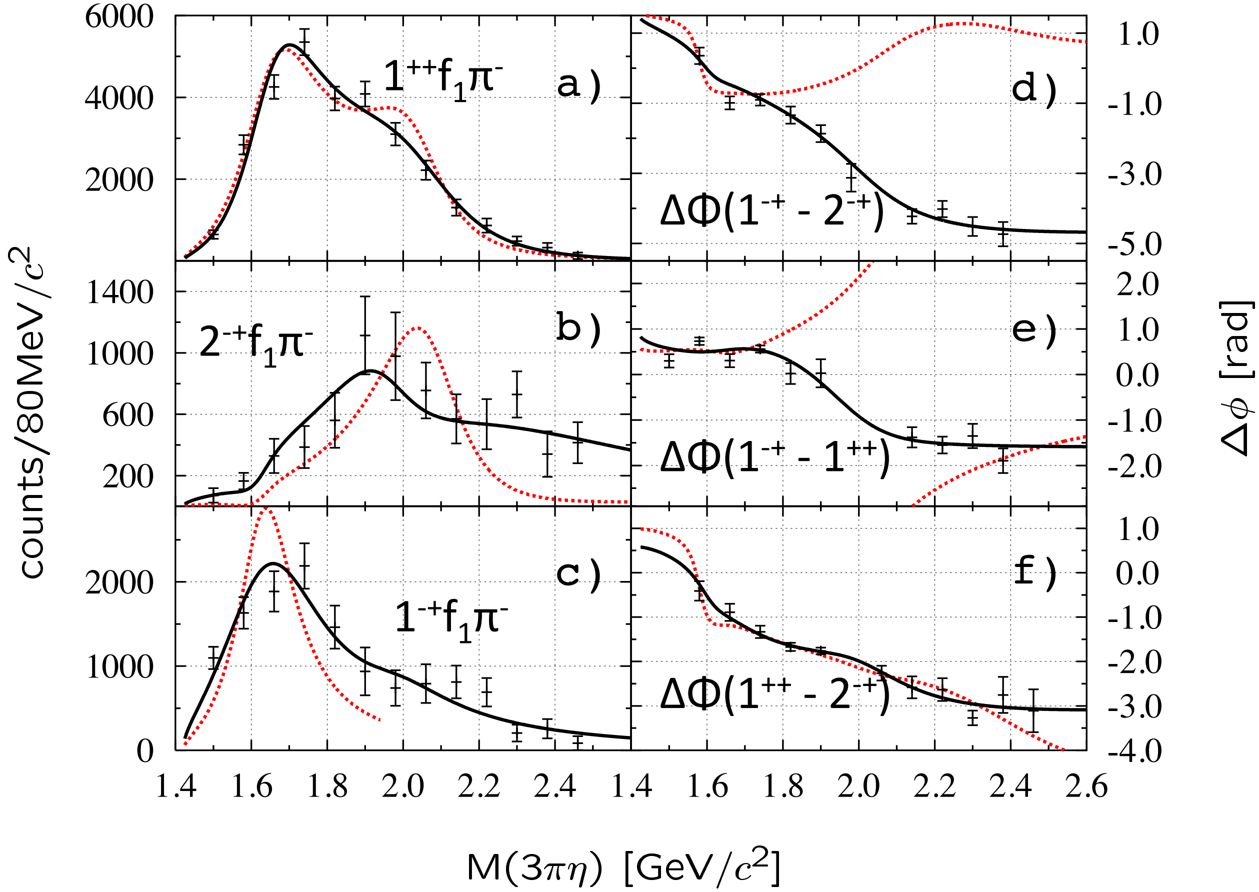
Solid curves are a two-pole 1^{-+} solution.
Dashed curves are a one-pole 1^{-+} solution.

E852 Experiment

(2004)

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

(~69000 Events)



$\pi_1(1600) \rightarrow f_1\pi$

M = 1709±24±41 MeV/c^2

Γ = 403±80±115 MeV/c^2

Natural parity exchange

$\pi_1(2000) \rightarrow f_1\pi$

M = 2001±30±92 MeV/c^2

Γ = 333±52±49 MeV/c^2

Natural parity exchange

Black curves are a two-pole 1^{-+} solution.

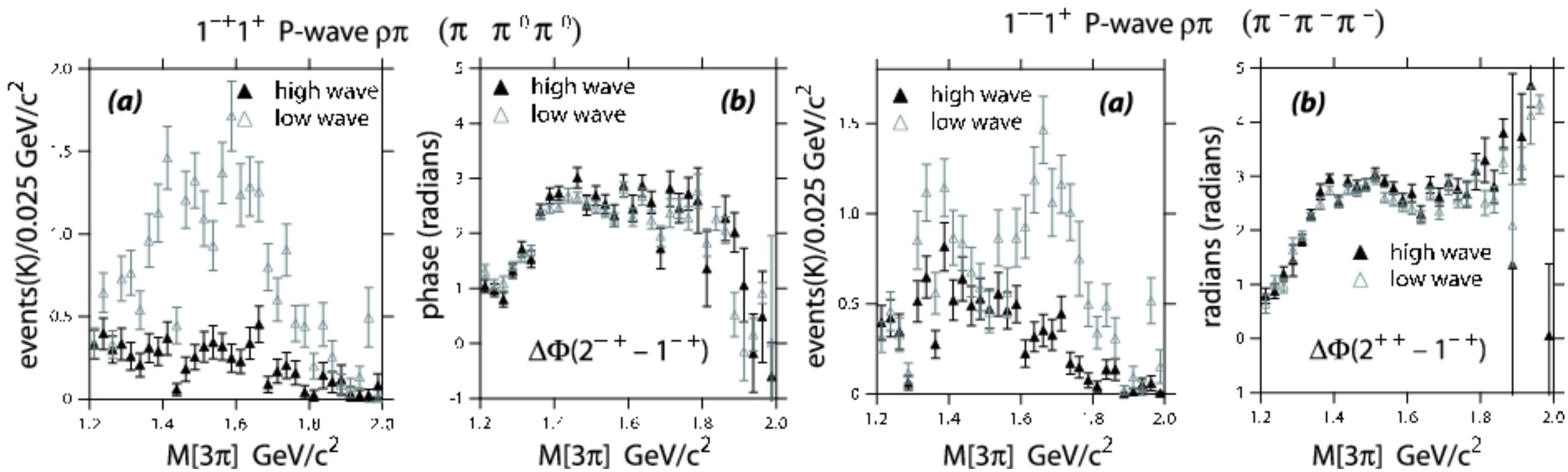
Red curves are a one-pole 1^{-+} solution.

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%

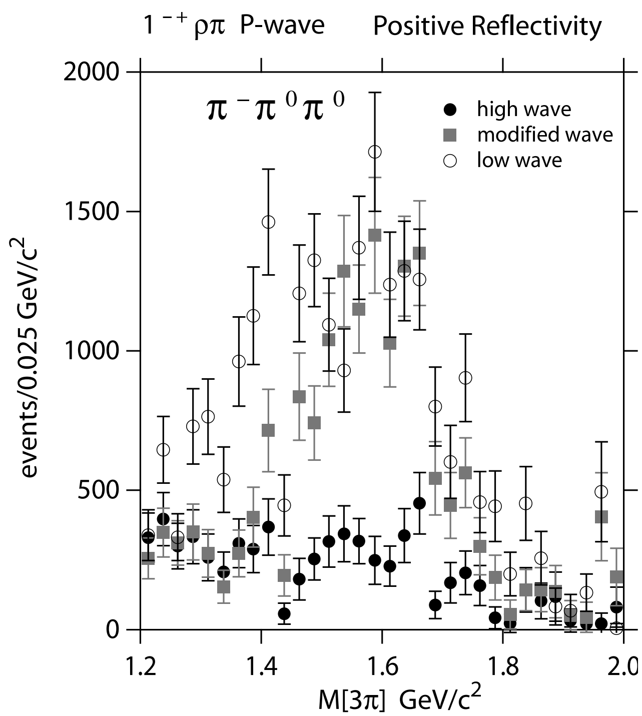
Always Include:

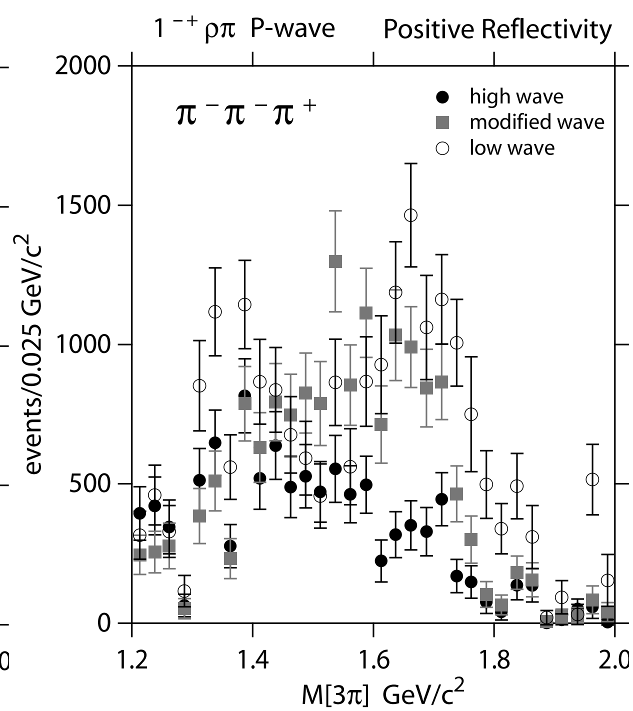
$(0^+)\pi_2(1670)\rightarrow f_2\pi(L=0)$
$(1^+)\pi_2(1670)\rightarrow f_2\pi(L=0)$
$(1-)\pi_2(1670)\rightarrow f_2\pi(L=0)$
$(0^+)\pi_2(1670)\rightarrow f_2\pi(L=2)$
$(1^+)\pi_2(1670)\rightarrow f_2\pi(L=2)$

Modified wave set:

Leave out

$(1^+)\pi_2(1670)\rightarrow \rho\pi(L=1)$
$(1^+)\pi_2(1670)\rightarrow \rho\pi(L=3)$
$(0^+)\pi_2(1670)\rightarrow \rho\pi(L=3)$





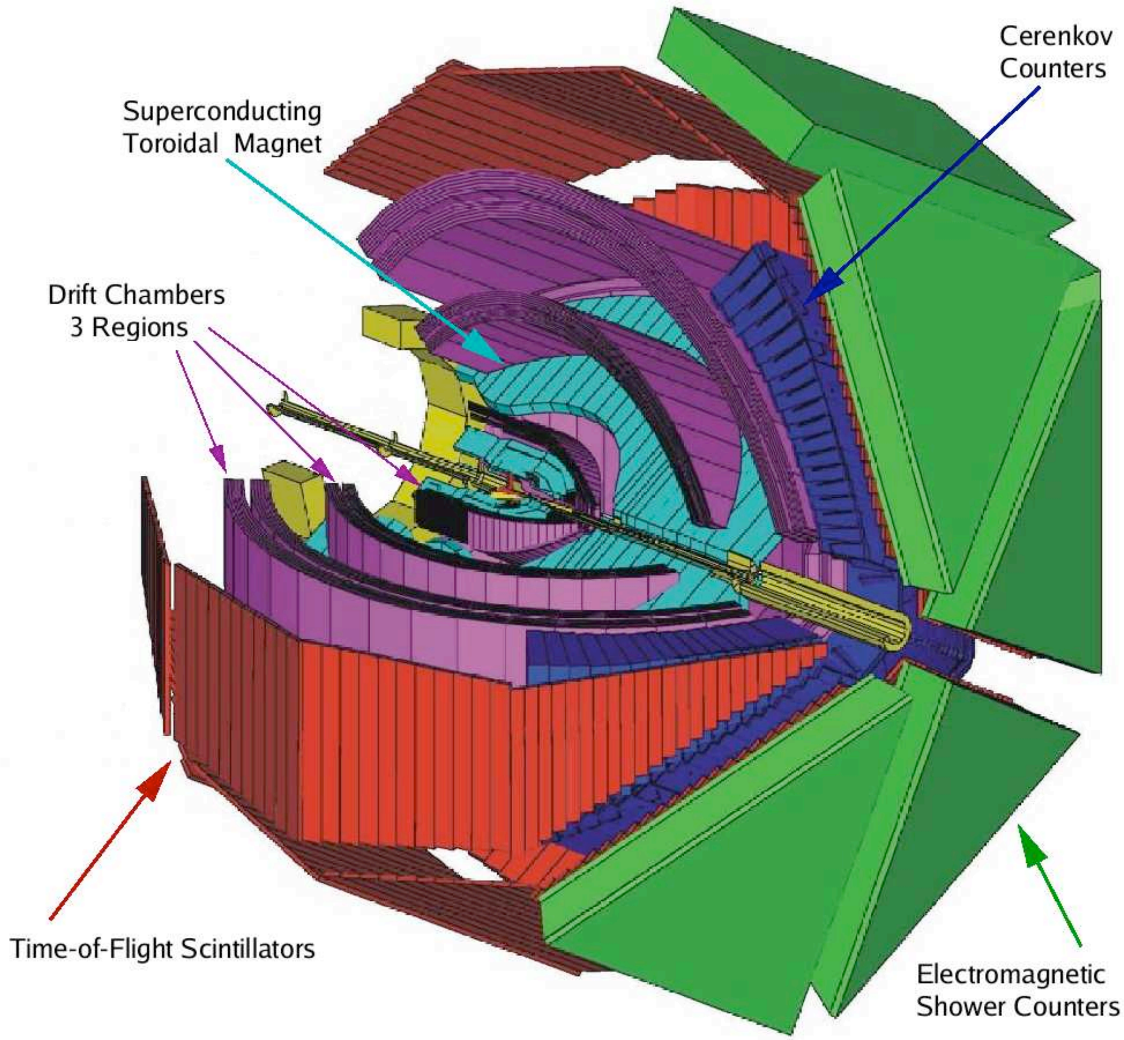
Most of the strength in the exotic $\pi_1(1600)$ is better described by known decays of the $\pi_2(1670)$.

CLAS Experiment

Tagged photon beam incident on a liquid hydrogen target.

Toroidal magnetic field with high acceptance and good resolution for charged particles.

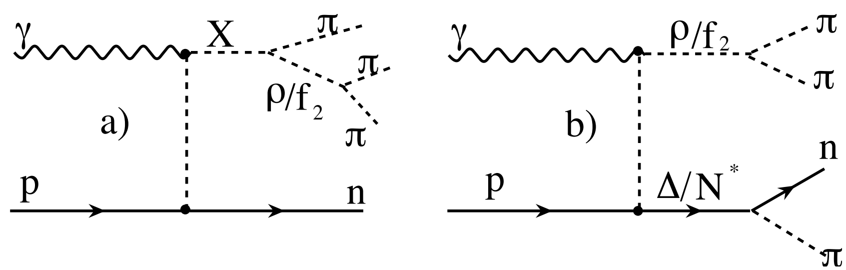
A number of acceptance holes make partial wave analysis difficult.



CLAS Experiment

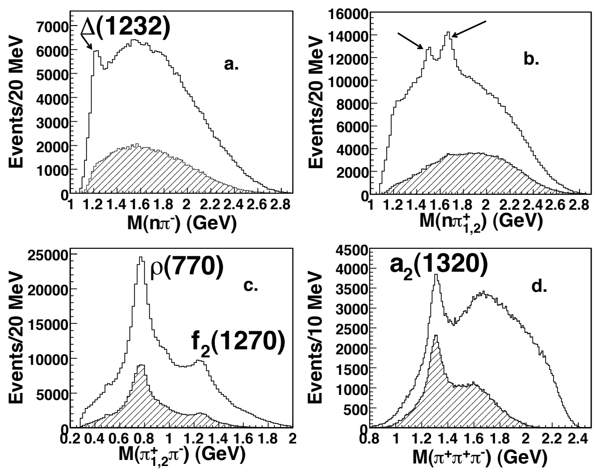
$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

E_γ = 4.8 – 5.4 GeV

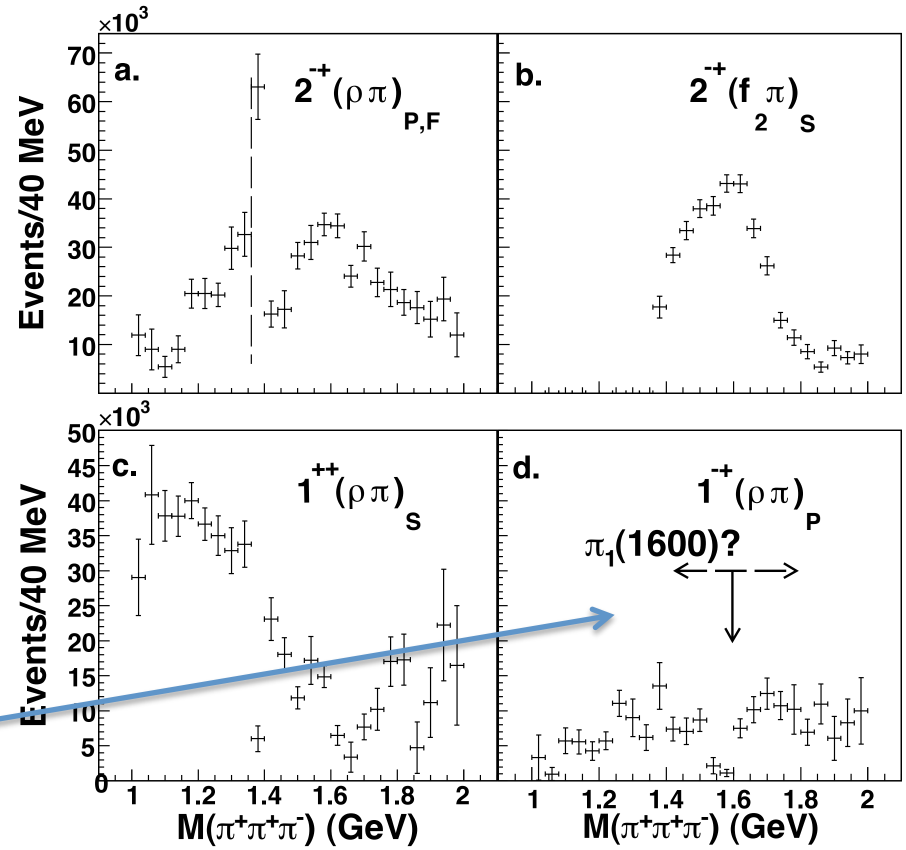


83000 Events after all cuts
Overall Acceptance < 5%

Baryons "removed" by hard kinematic cuts.



PWA



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

CLAS Experiment

New data collected in 2008 as part of the so-called "g12" run. Much higher statistics and E_e=5.715 GeV (up to ~5.4 GeV photons).

Polarized electron beam give circularly polarized photons.

Data are currently under analysis:

$\pi^+\pi^+\pi^-[n]$ $K^+K^-p[\eta]$ $\Delta^{++}\pi^-[\eta]$ & K+K-$[\Xi^{-*}]$

Summary of the $\pi_1(1400)$

Mode	Mass	Width	Production	
$\eta\pi^-$	1370±15+50-30	385±40+65-105	1^+	
$\eta\pi^0$	1257±20±25	354±64±60	1^+	(controversial)

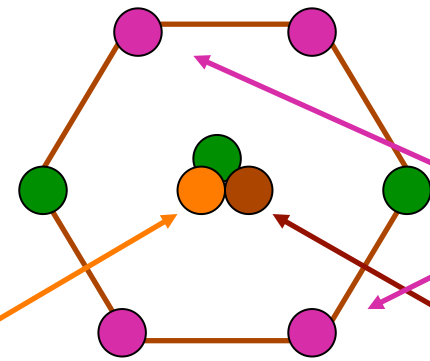
Summary of the $\pi_1(1600)$

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

Summary of the $\pi_1(2000)$

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

Exotic Signals



π_1(1400) Width ~ 0.3 GeV, Decays: only $\eta\pi$
weak signal in πp production (scattering??)
strong signal in antiproton-deuterium.

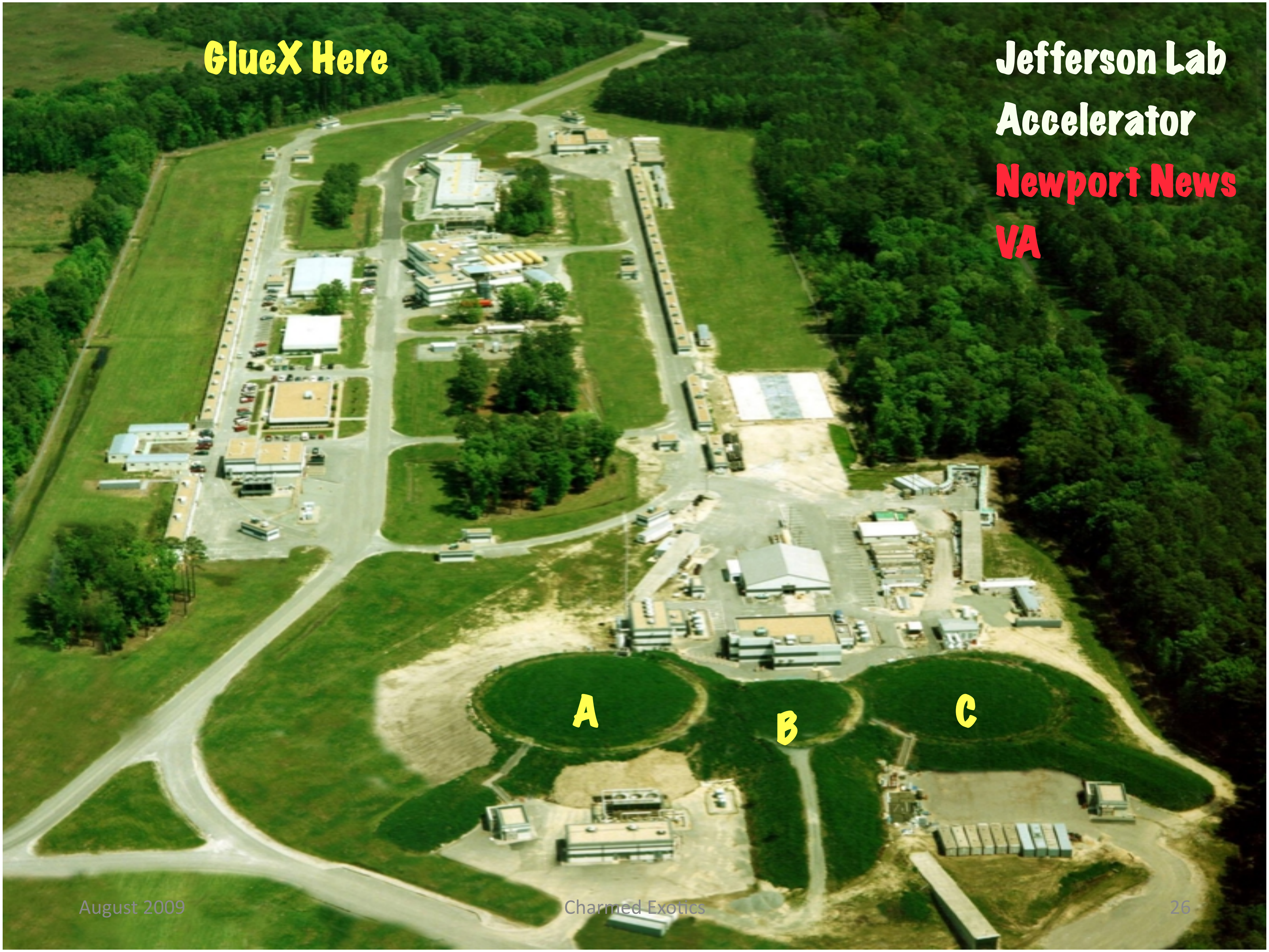
NOT A HYBRID

π_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.

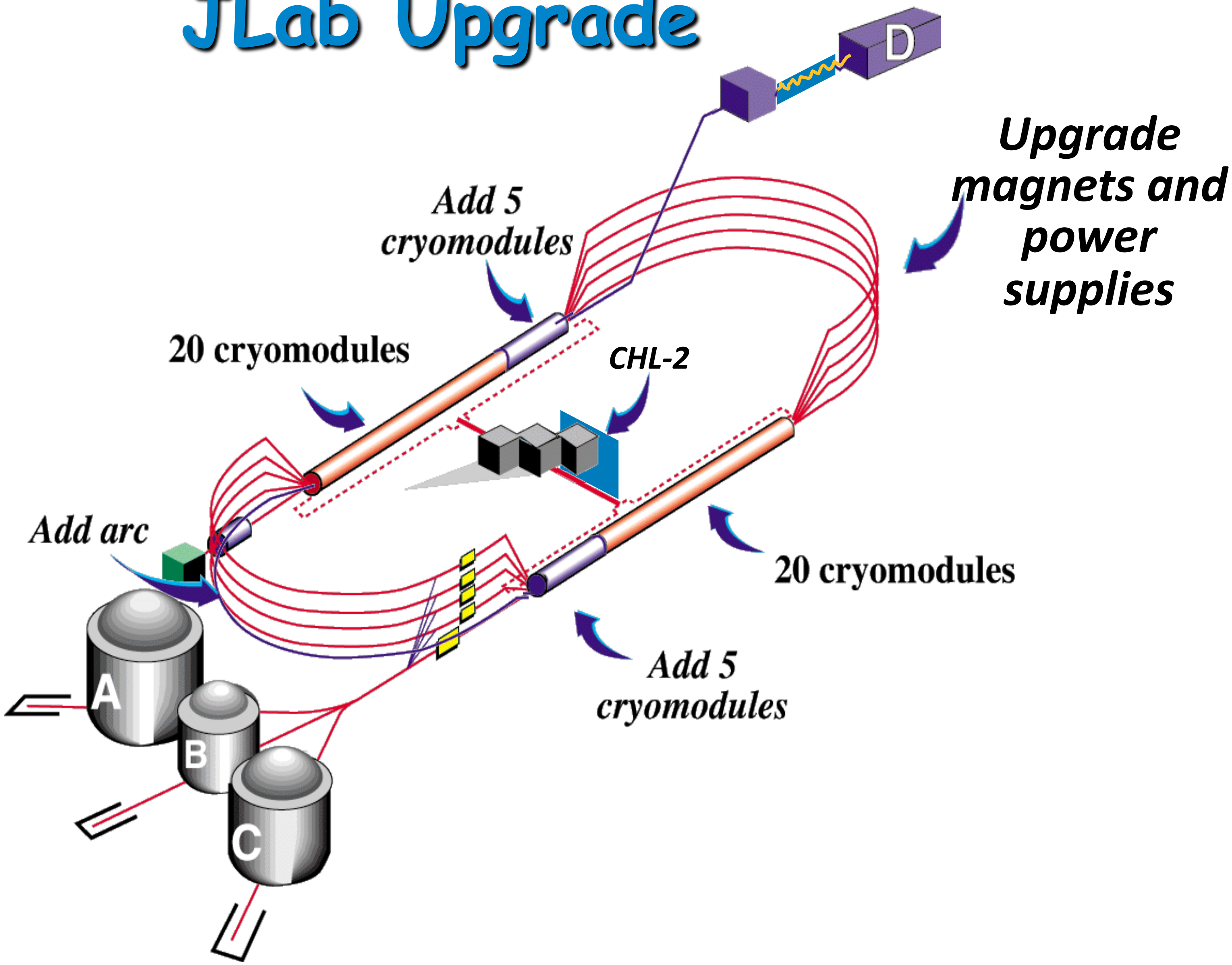
What is going on?

π_1(2000) Weak evidence in preferred hybrid modes $f_1\pi$ and $b_1\pi$
natural parity exchange

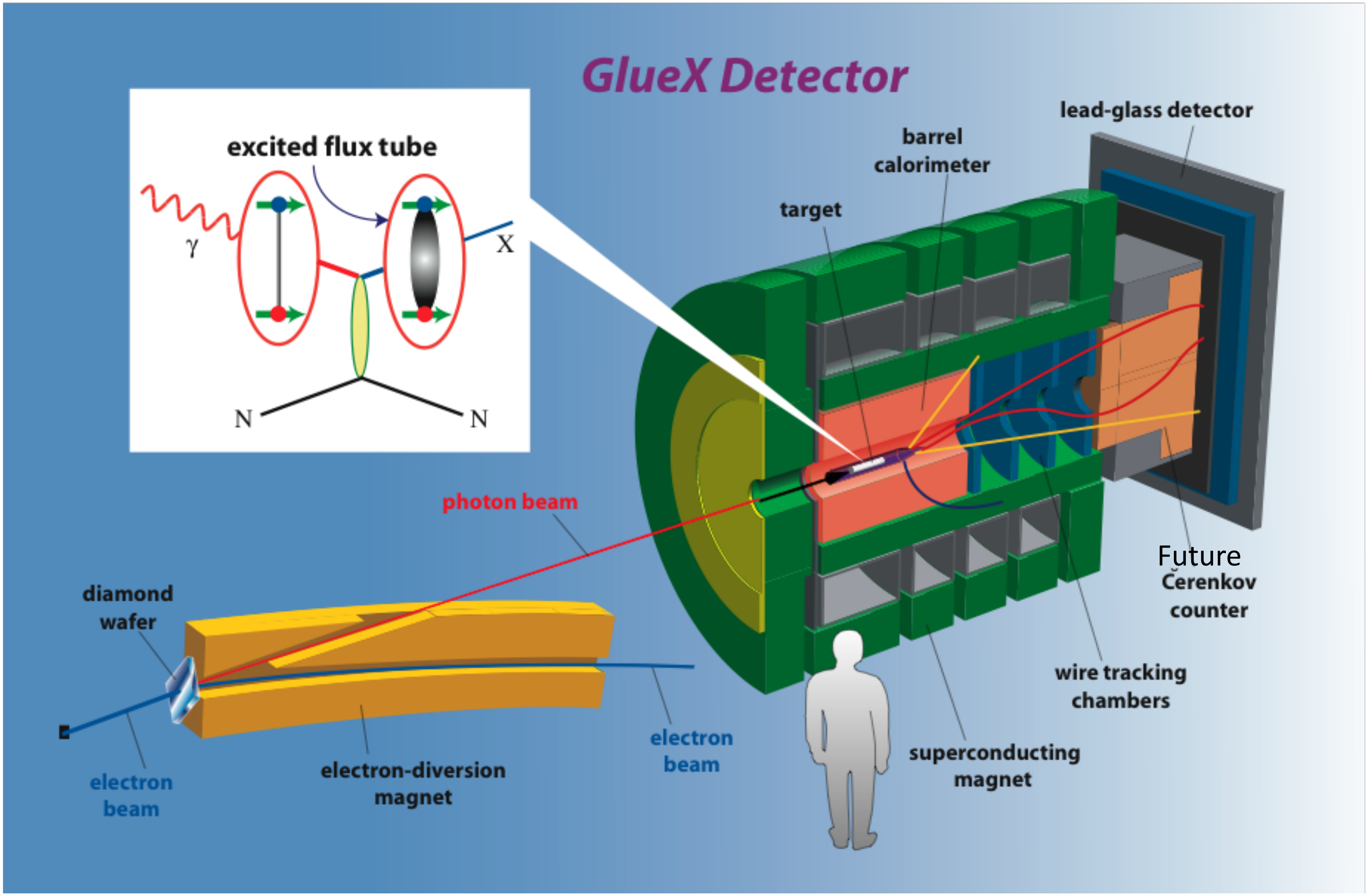
The right place. Needs confirmation.


GlueX Here
Jefferson Lab
Accelerator
Newport News
VA
A
B
C

JLab Upgrade

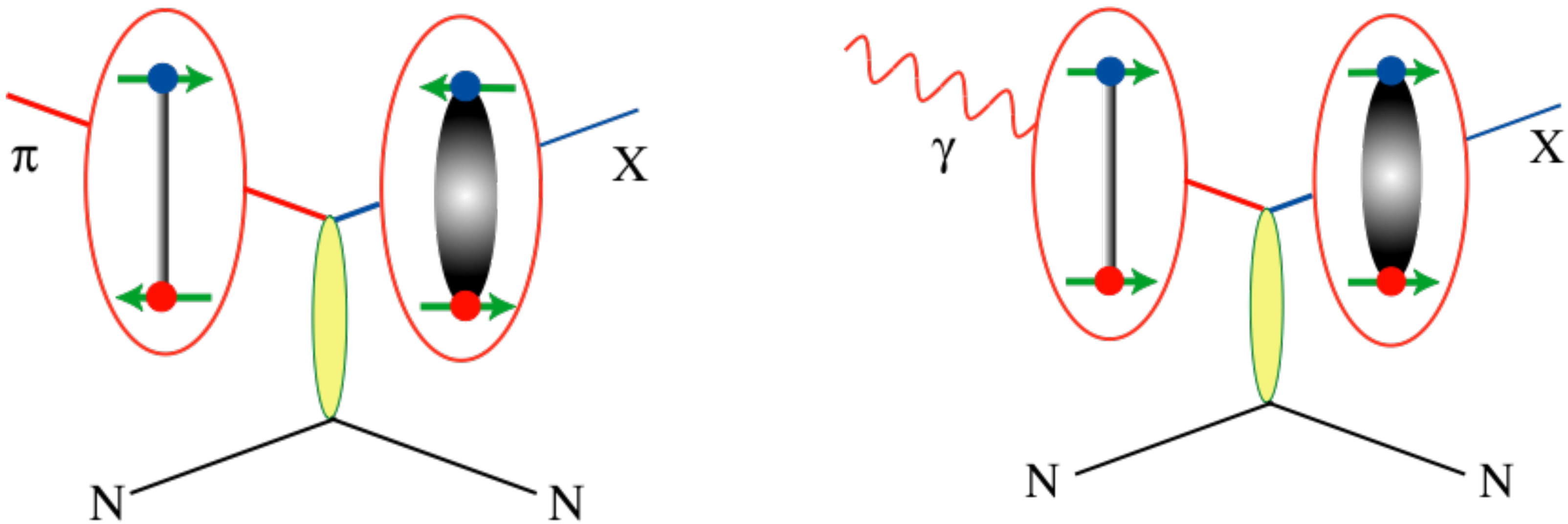


The GlueX Experiment



Photoproduction

More likely to find exotic hybrid mesons using beams of photons



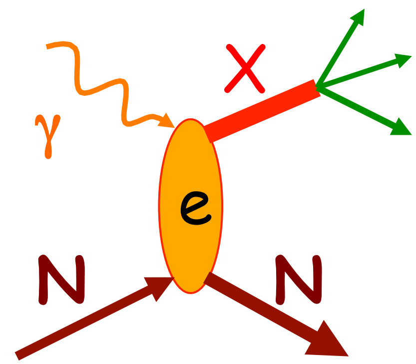
Simple (0^{++}) natural parity exchange with L=1: 0^{+-},1^{+-},2^{+-}

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

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

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

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

$\omega\pi$, $\omega a_1, \rho f_0, \rho f_1$ b_2 $I^G(J^{PC})=1^+(2^{+-})$

"Similar to π_1 " $\omega\eta, \rho\pi, \omega f_0, \omega f_1, \rho a_1$ h_2 $I^G(J^{PC})=0^-(2^{+-})$

$\phi\eta, \rho\pi, \phi f_0, \phi f_1, \rho a_1$ h'_2 $I^G(J^{PC})=0^-(2^{+-})$

Kaons do not have exotic QN's K_2 $I(J^P)= \frac{1}{2}(2^+)$

GlueX vs E852 Acceptance

GlueX

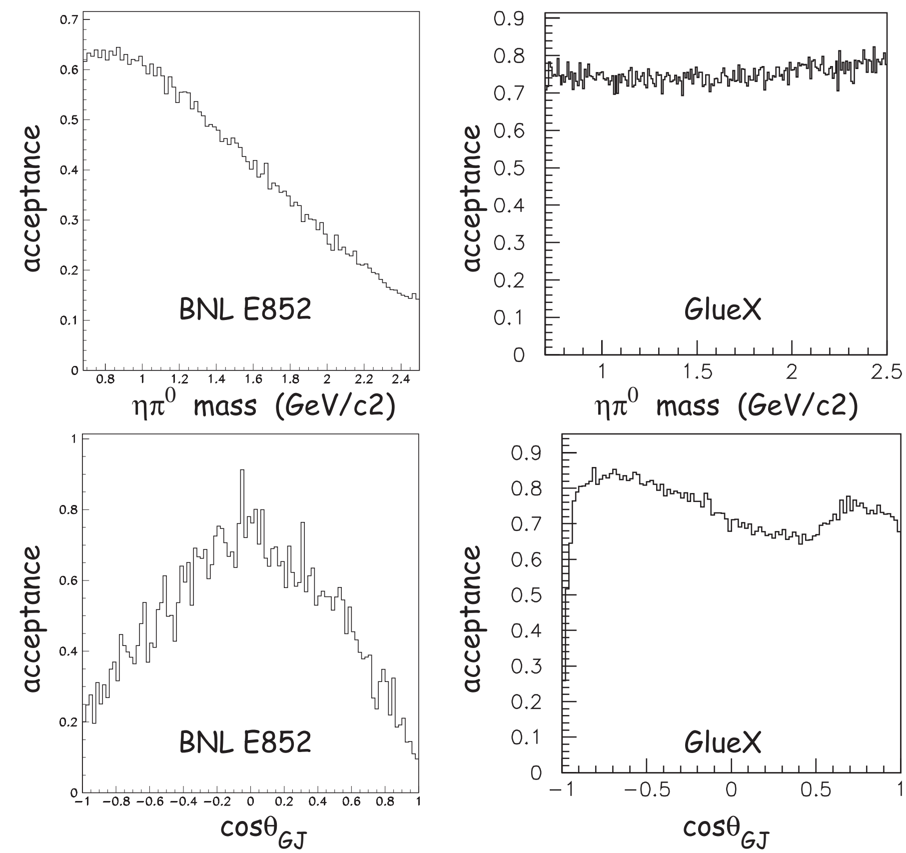
High, and reasonably uniform Acceptance up to 2.5 GeV/c^2.

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

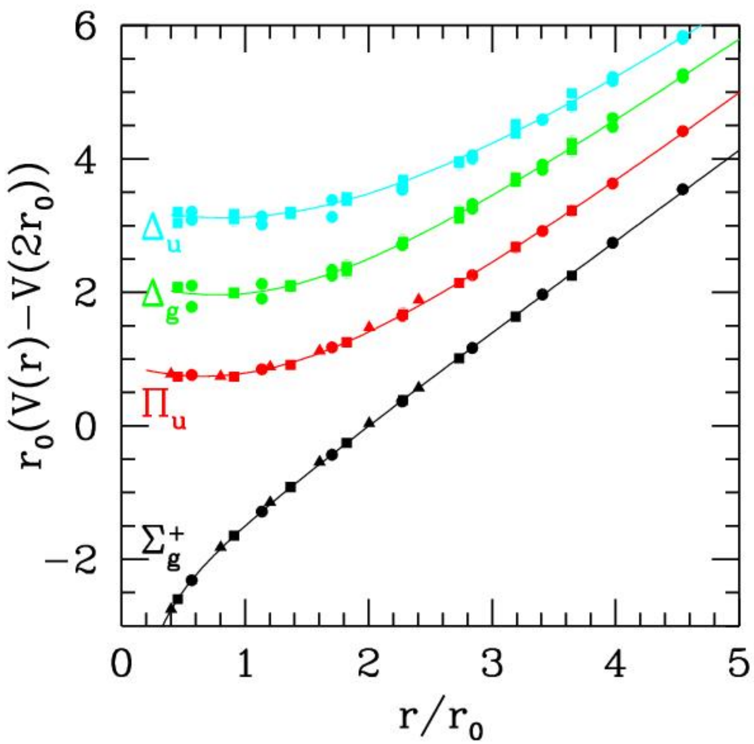
Exotics and QCD

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



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.

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 polarize photon beam.