Meson Spectroscopy Overview: What is the role of GlueX in the global spectroscopy program?

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Outline

What are light-quark exotic mesons?

How should we look for these mesons?

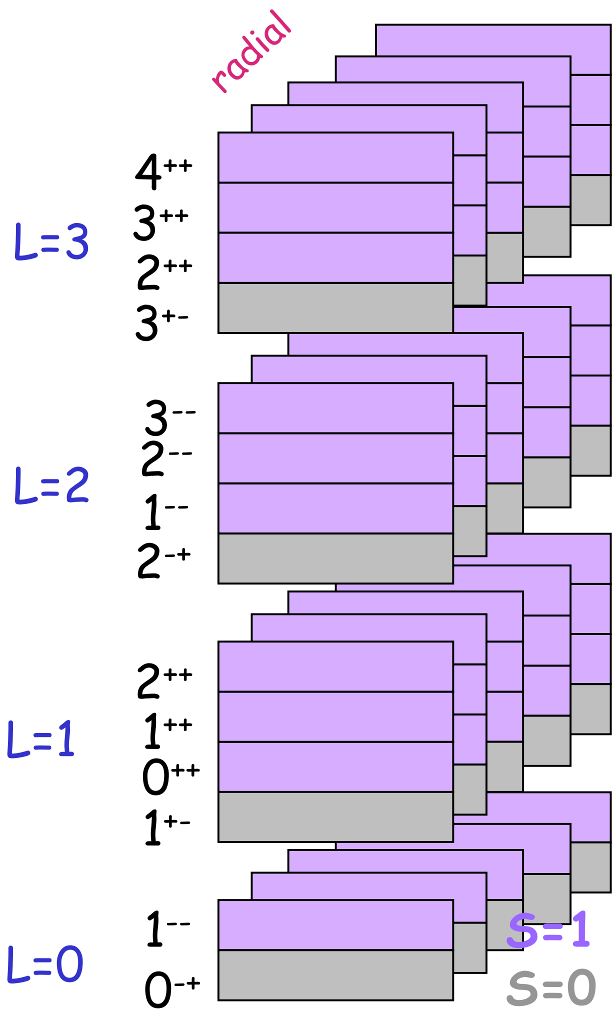
What is the experimental evidence?

What are the experimental programs?

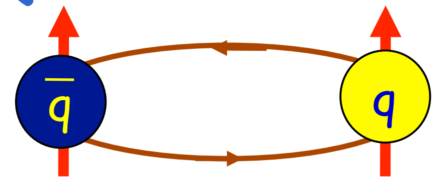
What is special about GlueX?

Spectroscopy and QCD

Mesons



Quarkonium

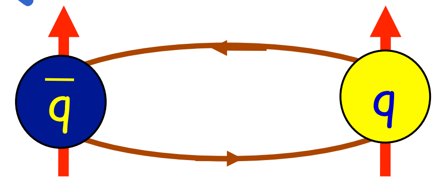


Consider the three lightest quarks

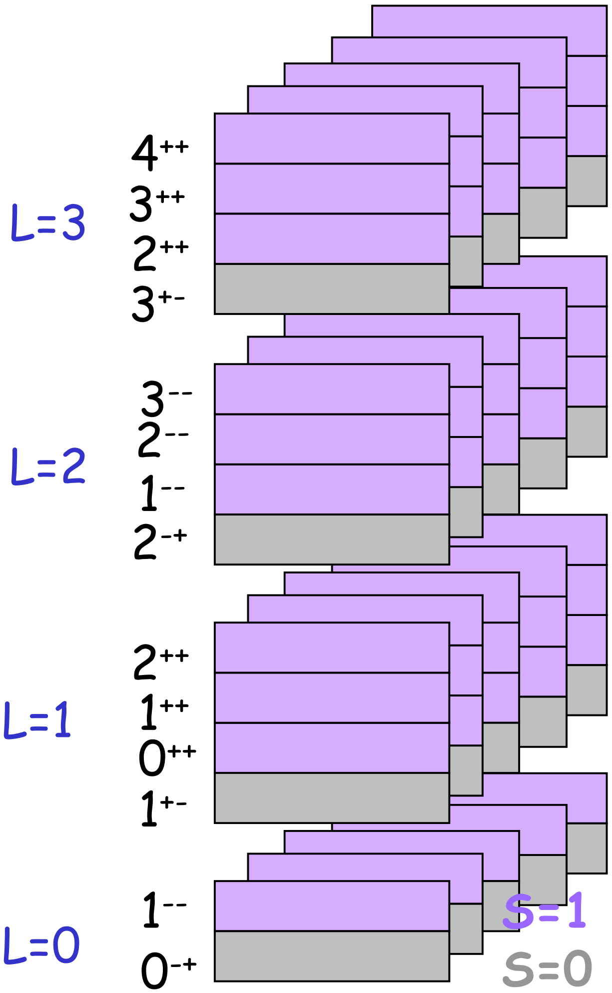
$$\left.\begin{matrix} u, d, s \\ \bar{u}, \bar{d}, \bar{s} \end{matrix}\right\} \text{ 9 Combinations}$$

Spectroscopy an QCD

Quarkonium



Mesons



ρ, K^*, ω, ϕ

π, K, η, η'

a, K, f, f'

b, K, h, h'

ρ, K^*, ω, ϕ

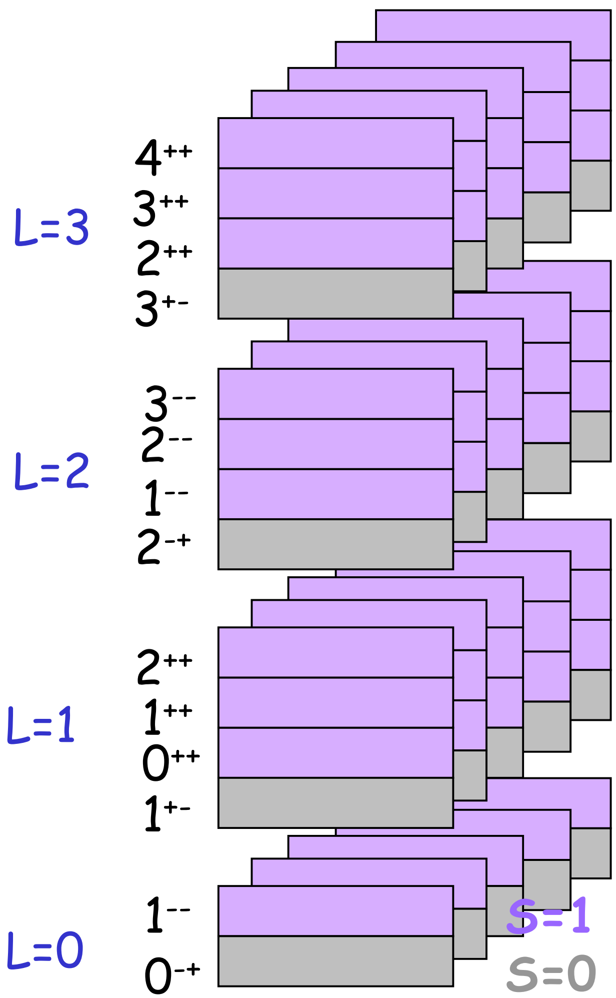
π, K, η, η'

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

SU(3) is broken
last two members mix

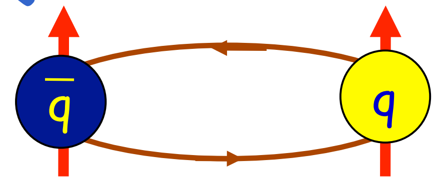
Spectroscopy an QCD

Mesons



Nothing to do with Glue!

Quarkonium



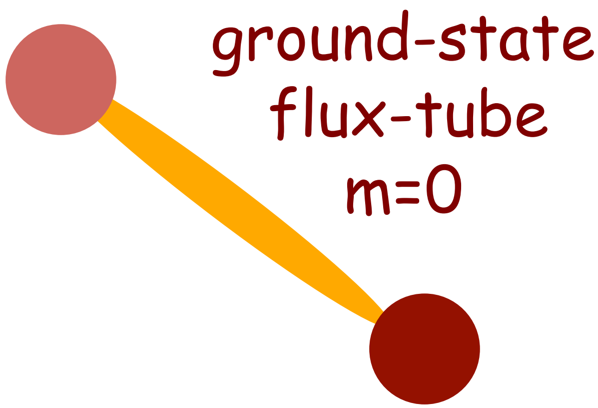
Allowed J^{PC} Quantum numbers:

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

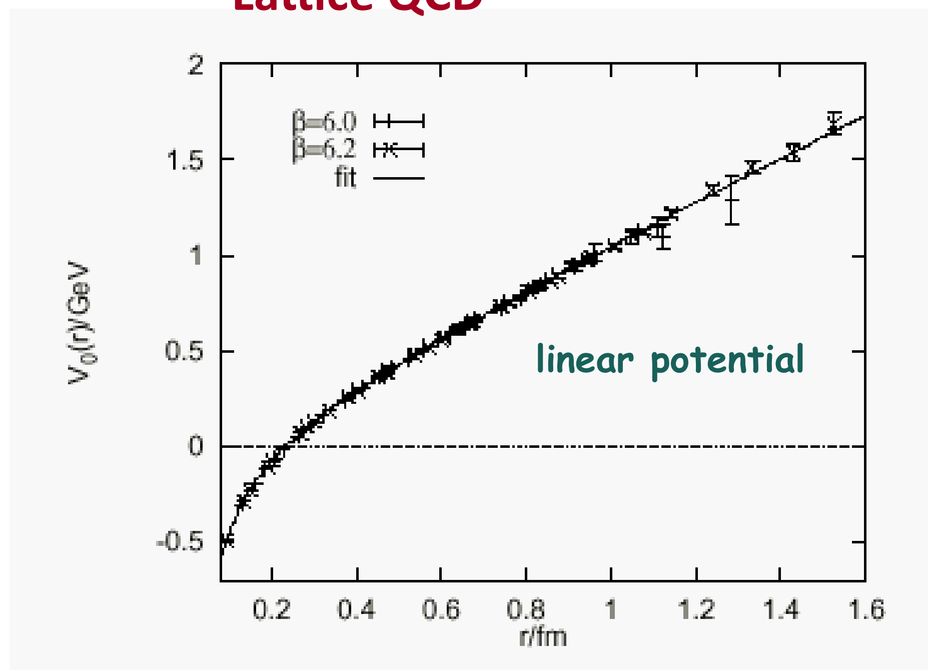
Exotic Quantum Numbers

non quark-antiquark description

QCD Potential



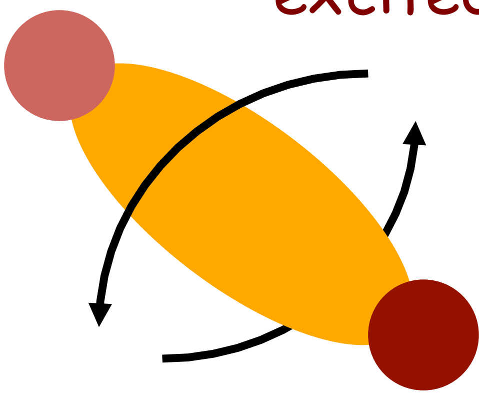
Lattice QCD



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

(π,K,η,η')	(ρ,K^*,ω,Φ)	(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



excited flux-tube
m=1

S=0,L=0,m=1	S=1,L=0,m=1
J=1 CP=+	J=1 CP=-
$J^{PC}=1^{++},1^{--}$	$J^{PC}=0^{-+},0^{+-}$
(not exotic)	$1^{-+},1^{+-}$
	exotic $2^{-+},2^{+-}$

Gluonic Excitations provide an experimental measurement of the excited QCD potential.

Many of the hybrid nonets have exotic quantum numbers.

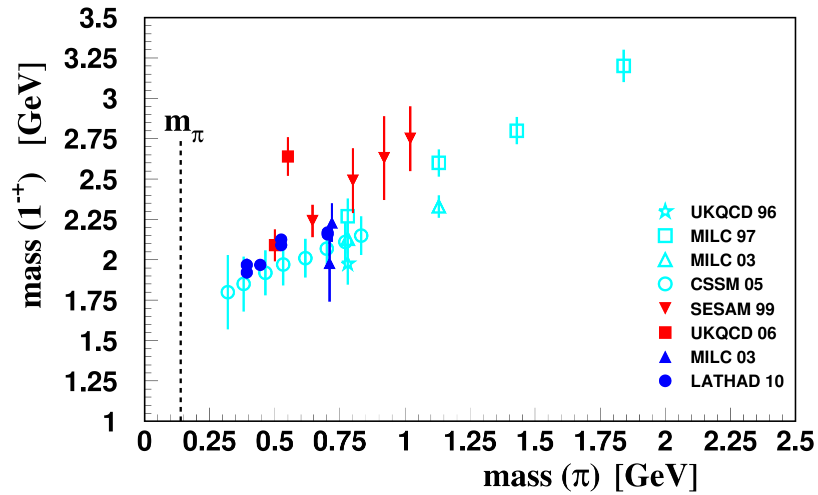
Hybrid Predictions

Flux-tube model: 8 degenerate nonets

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

S=0 S=1

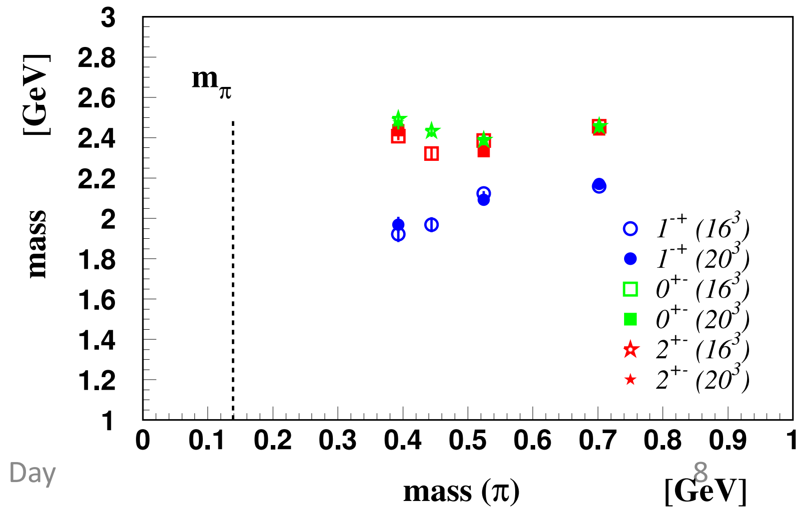
Lattice QCD Calculations



Lattice QCD Calculations

1^{-+}	~1.9
2^{+-}	~2.2
0^{+-}	~2.2

At the physical pion mass?

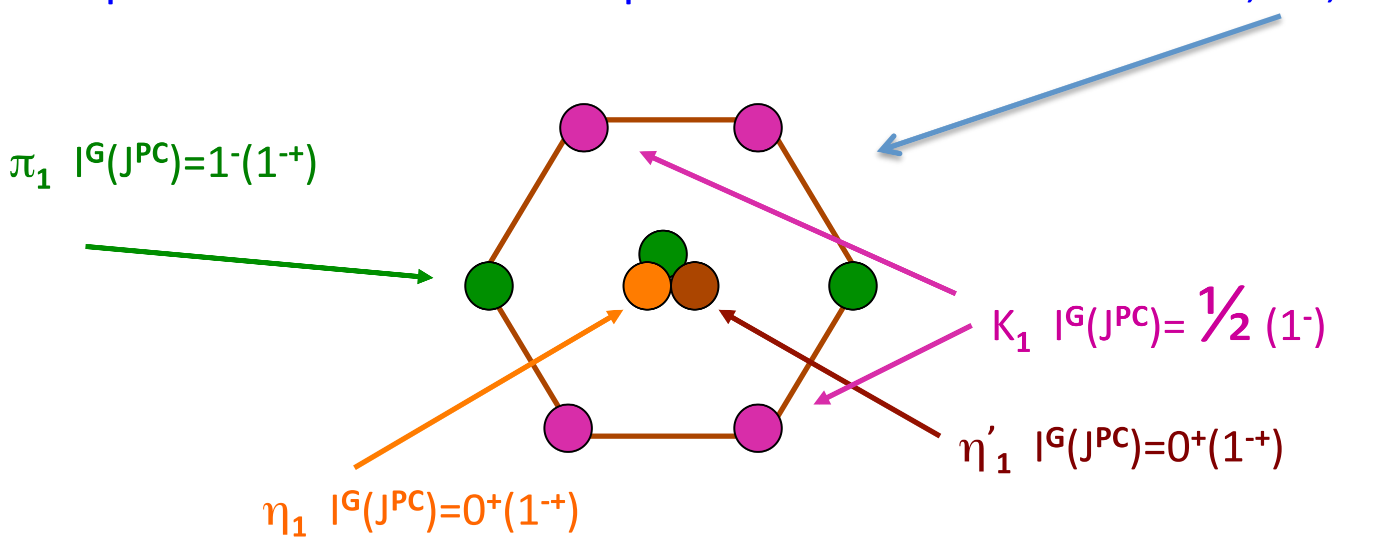


In the charmonium sector:

1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

QCD Exotics

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



π , η , η' , K $\rightarrow$ π_1 , η_1 , η'_1, K_1 1^{-+}

b_0, h_0, h_0', K_0 0^{+-}

b_2, h_2, h_2', K_2 2^{+-}

QCD Exotics

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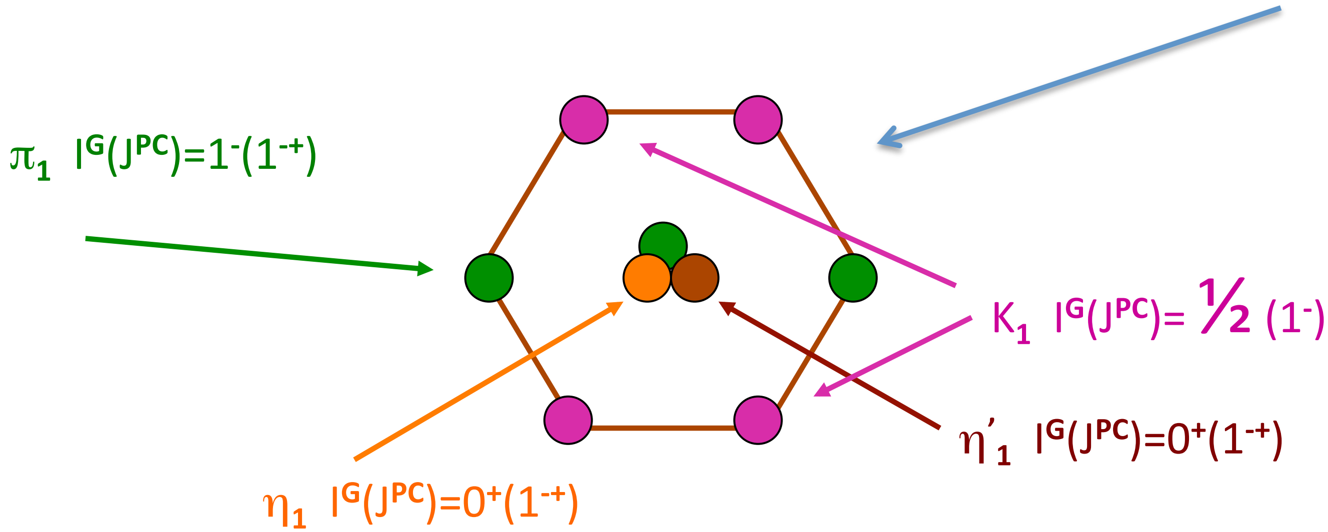


$\pi, \eta, \eta', K \rightarrow \pi_1, \eta_1, \eta'_1, K_1$ 1^{-+}

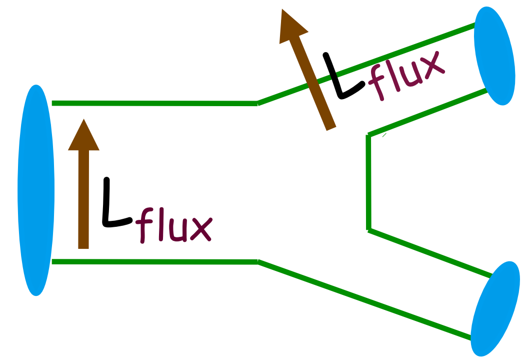
b_0, h_0, h_0', K_0 0^{+-}

b_2, h_2, h_2', K_2 2^{+-}

What are the mixing angles Between the isoscalar states?

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 $\pi^{\pm}, \pi^0, K^{\pm}, K^0, \eta$, (photons)

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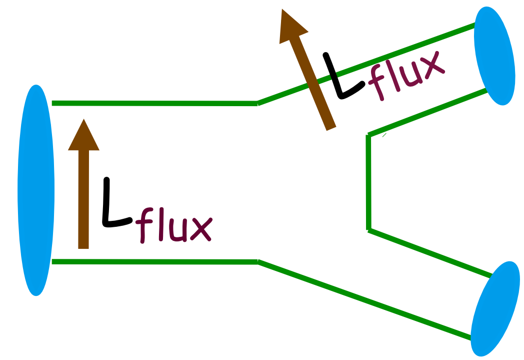

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$\eta_1 \rightarrow \pi(1300)\pi$, $a_1\pi$

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

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

Mass and model dependent predictions

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

The channels we are looking at for PWA.

Hybrid Decays

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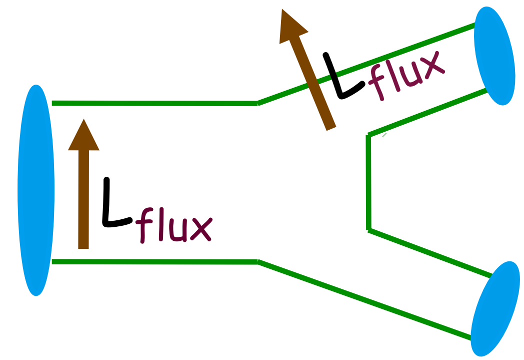


Exotic Quantum Number Hybrids

$\pi_1 \to \pi b_1 , \pi f_1 , \pi\rho , \eta a_1$
$\eta_1 \to \pi(1300)\pi , a_1\pi$

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

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

Mass and model dependent predictions

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

The channels we are looking at for PWA.

Other interesting channels for PWA.

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

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

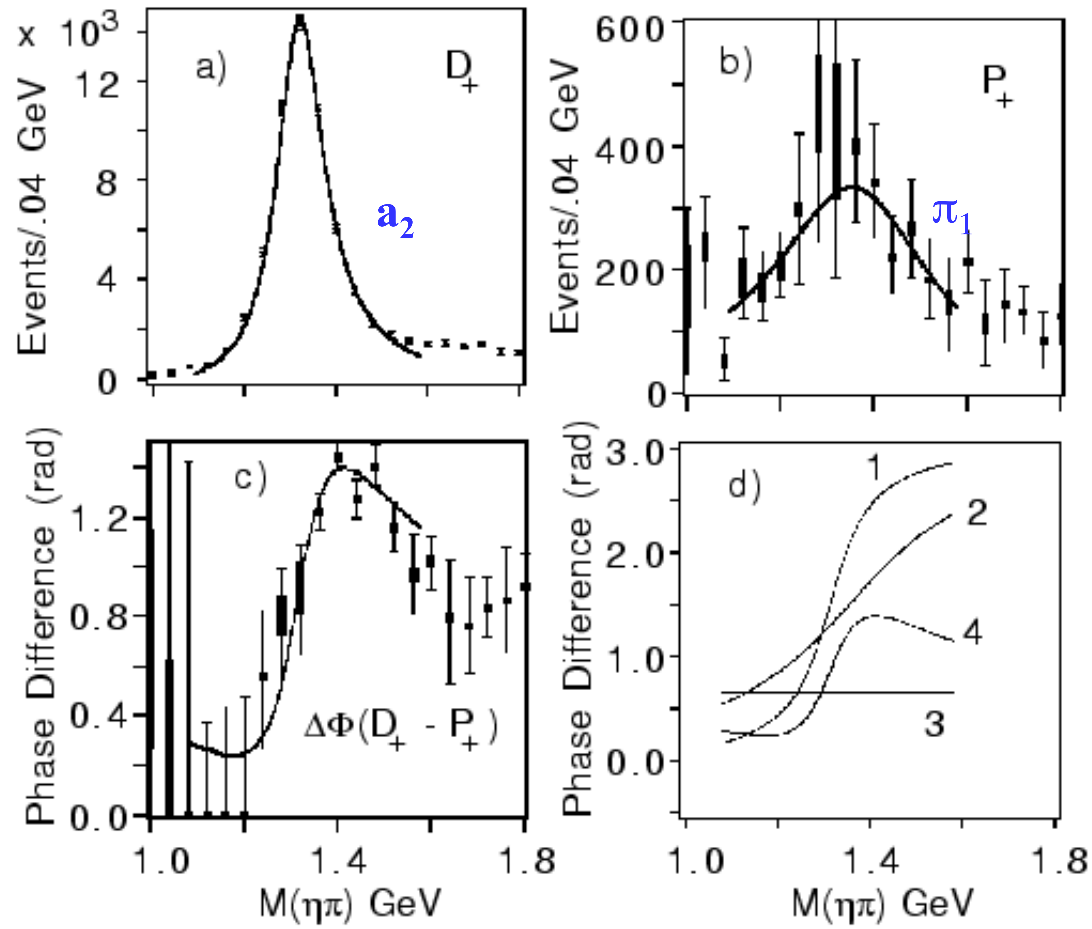
(1997)

$\pi_1(1400)$ Mass = 1370 +-16$^{+50}_{-30}$ MeV/c^2
Width= 385 +- 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 $\eta\pi^0$



Crystal Barrel Experiment

$\pi_1(1400)$

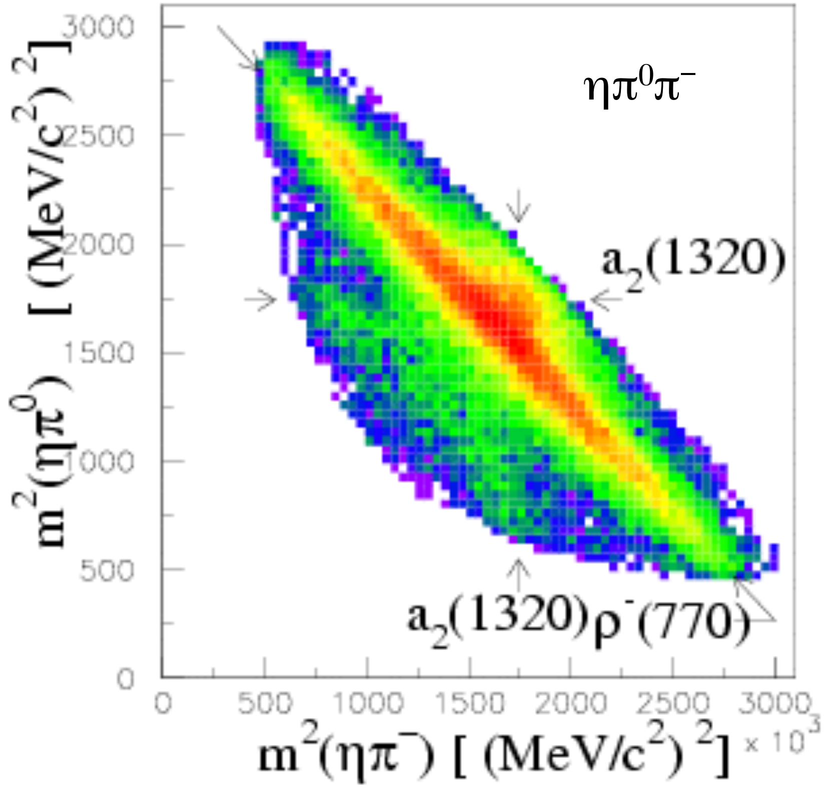
Mass = 1400 +- 20 +- 20 MeV/c^2

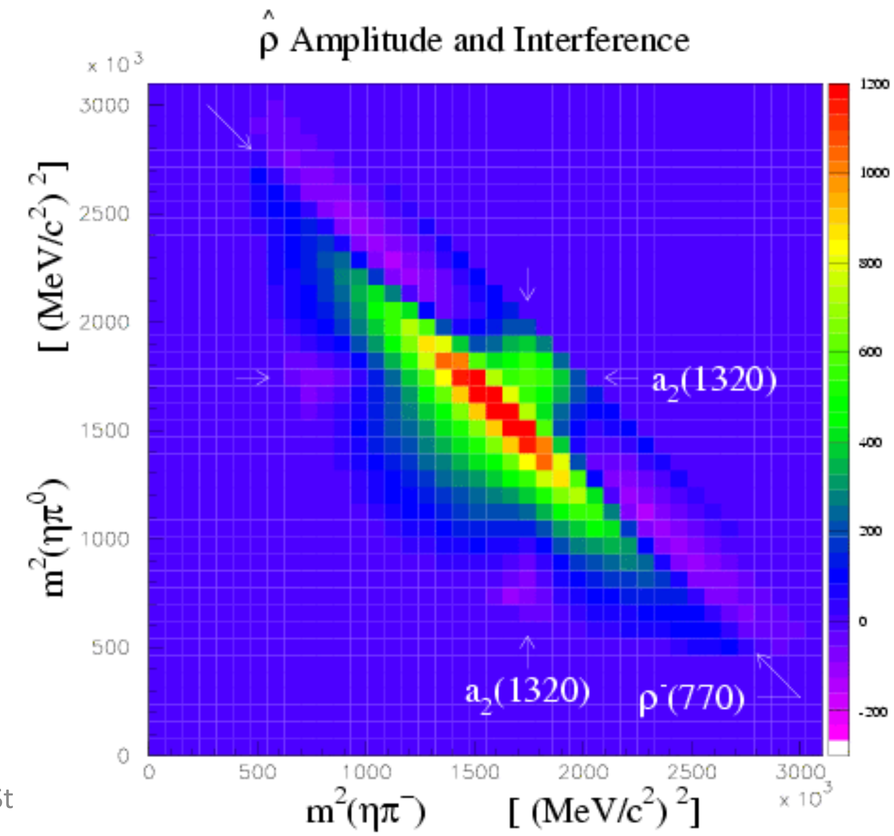
Width= 310+-50$^{+50}_{-30}$ MeV/c^2

Same strength as the a_2.

Produced from states with **one unit** of angular momentum.

Without π_1 χ^2/ndf = 3, with = 1.29





E852 Experiment

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

Dzierba (et. al) PRD67 (2003)

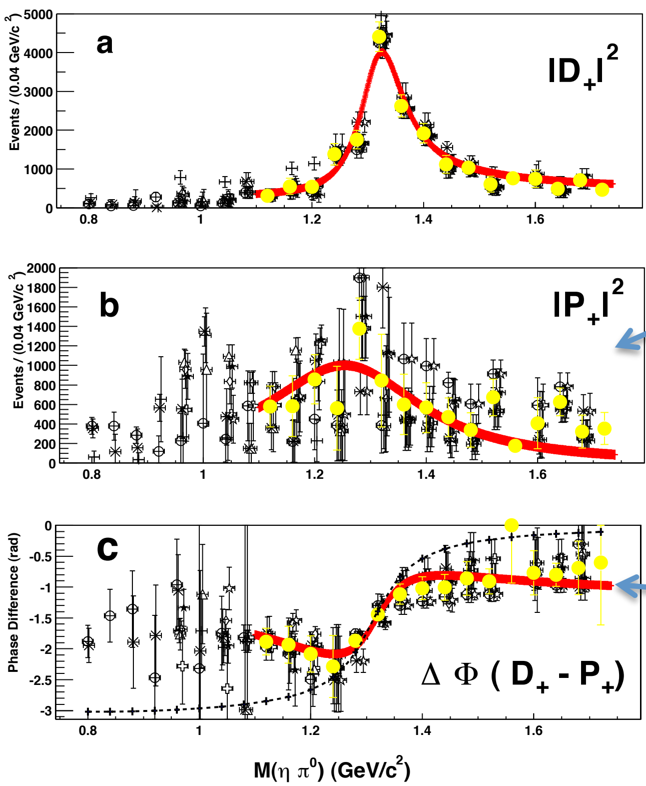
(~45000 Events)

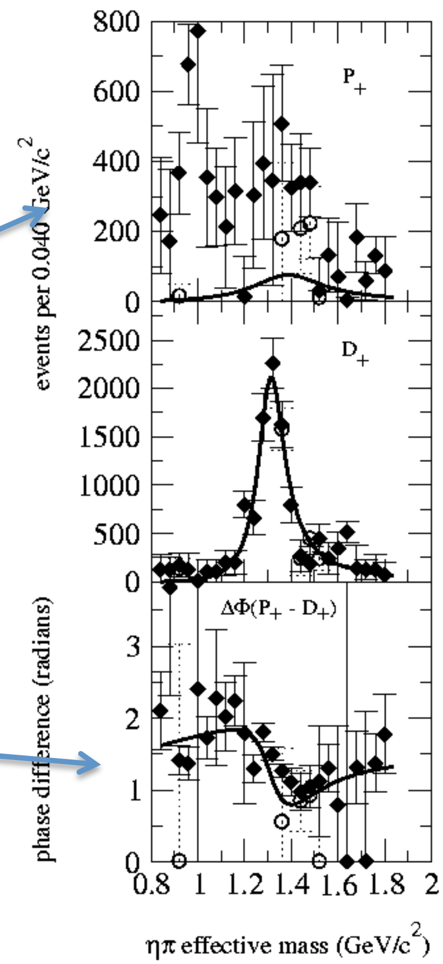
Problematic Resonant Description

Adams (et. al) PLB657 (2007)

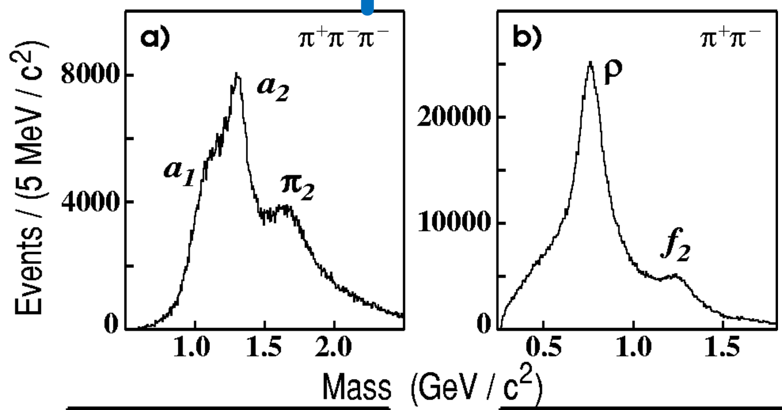
(~23000 Events)

Confirms the $\eta\pi^-$ results





E852 Experiment



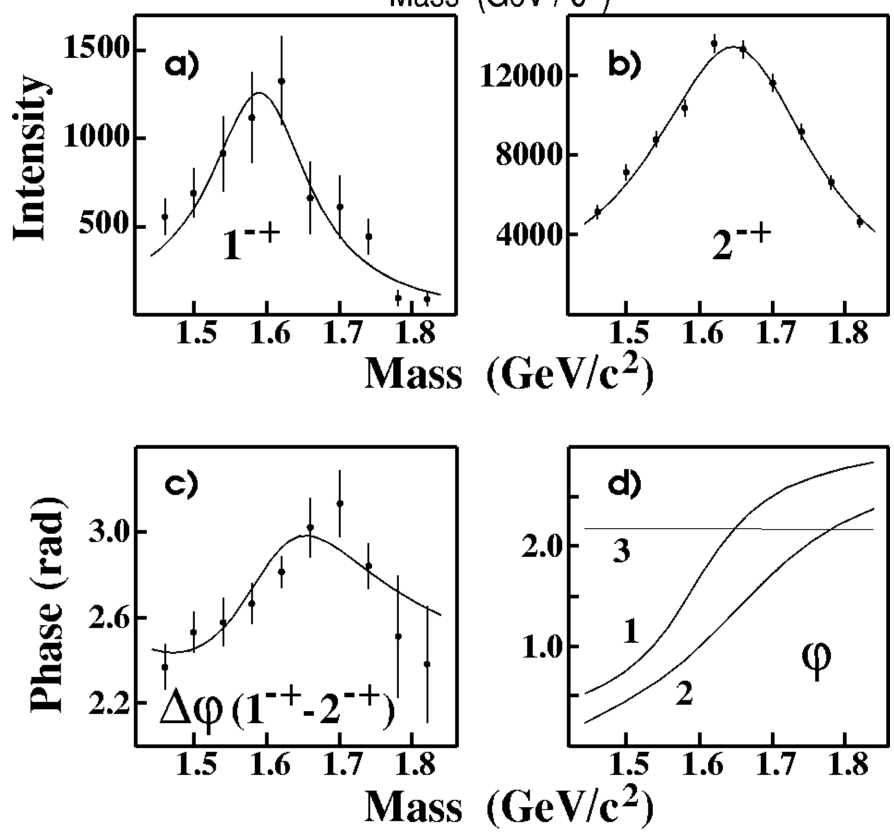
$\pi^- p \rightarrow \pi^+\pi^-\pi^- p$

(~250,000 Events)

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

$\pi_2 \rightarrow f_2\pi$

(1998)



Partial Wave Analysis

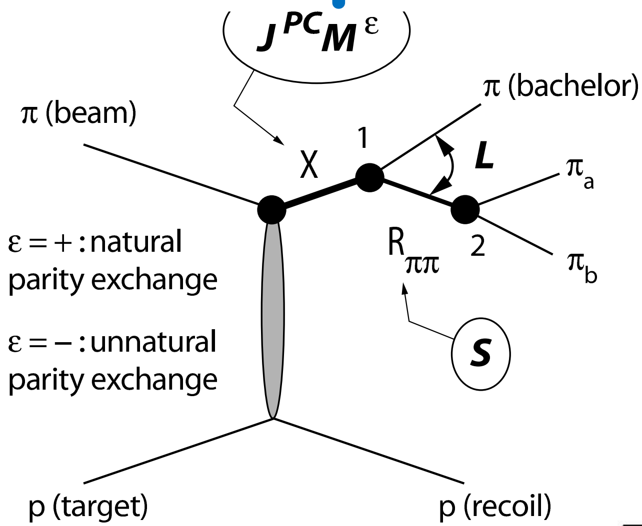
$\pi_1(1600) \rightarrow \rho\pi$

M = 1598 ±8+29-47 MeV/c²

Γ = 168±20+150-12 MeV/c²

E852 Experiment

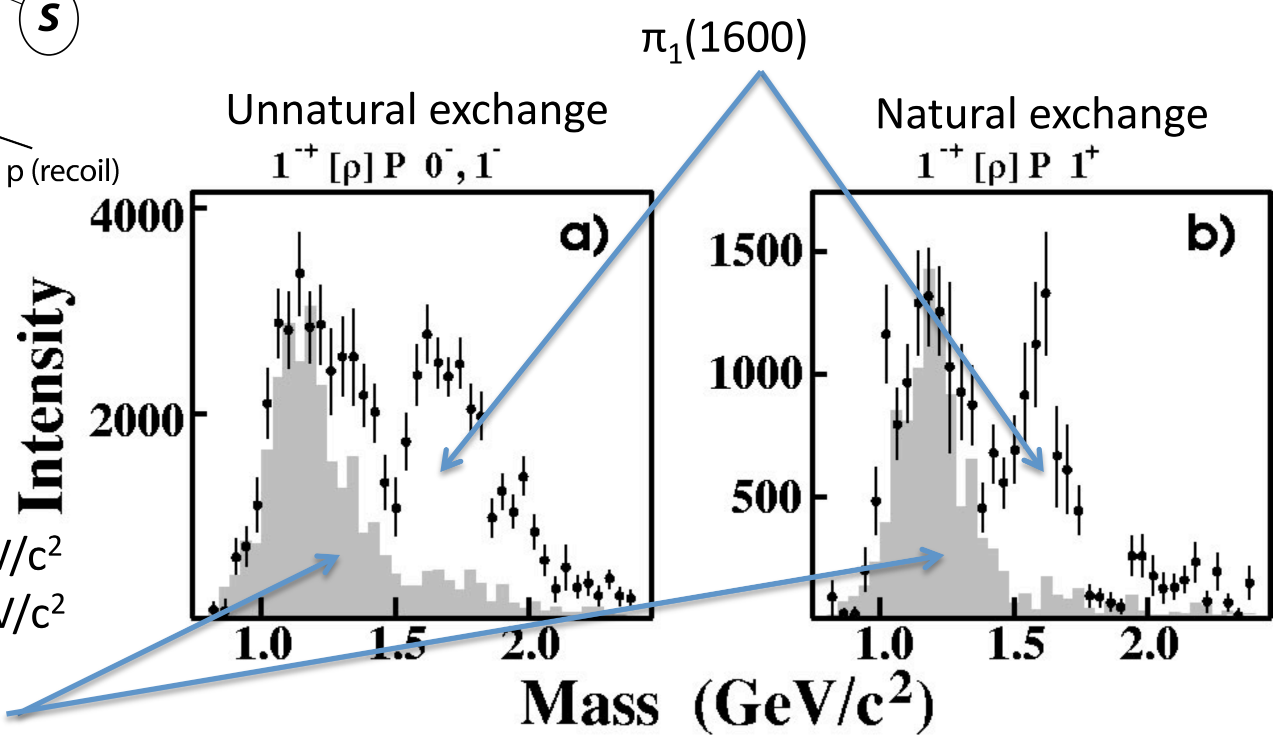
$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$



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

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

$\pi_1(1600)$



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

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

Leakage from other partial waves.

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

E852 Experiment

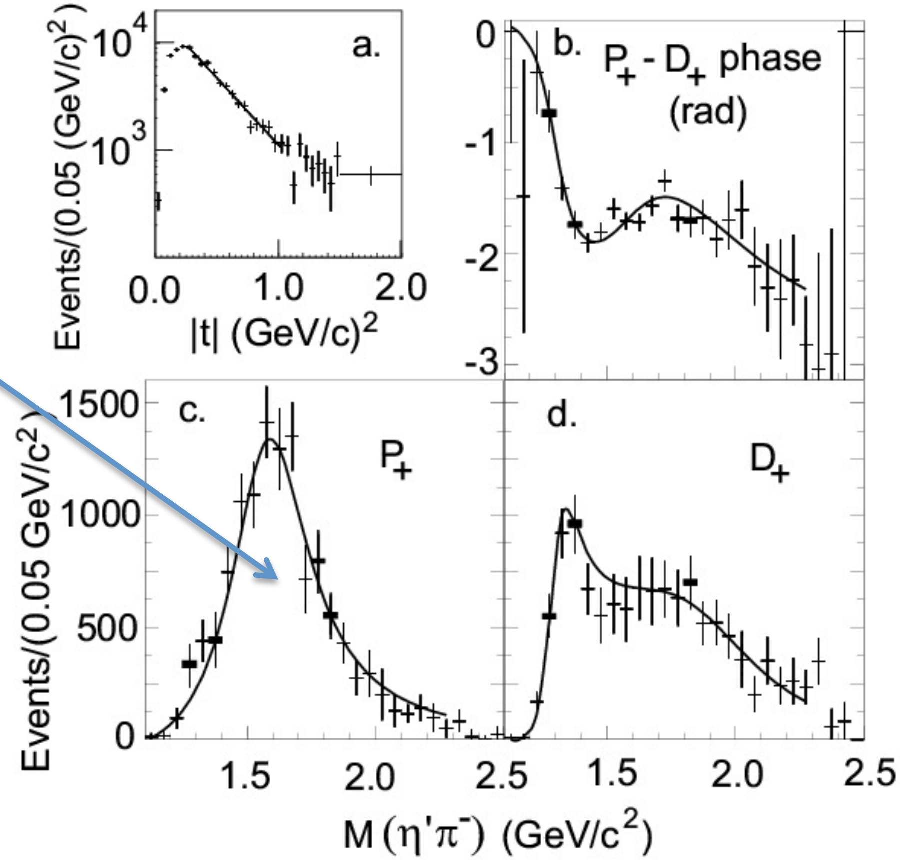
$\pi^- p \rightarrow \eta' \pi^- p$

(~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)

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

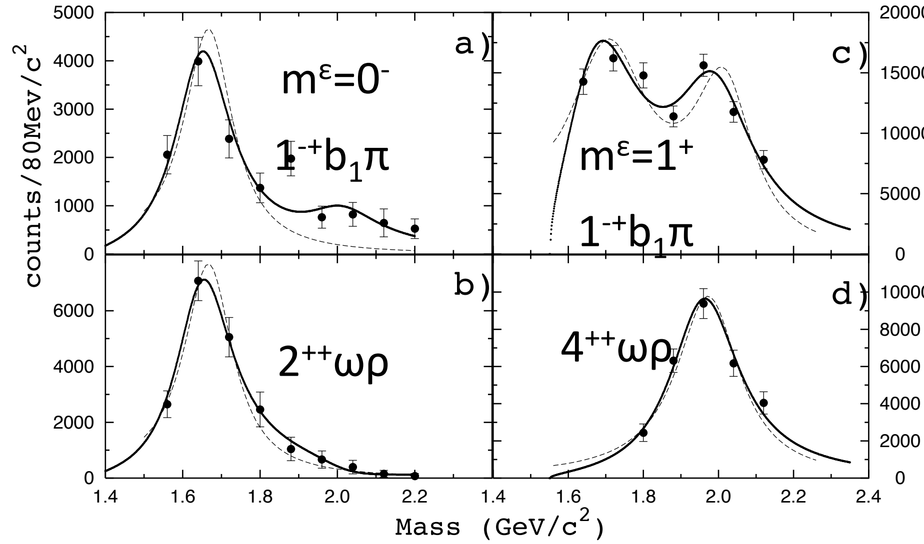
(~145,000 Events)

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

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

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

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

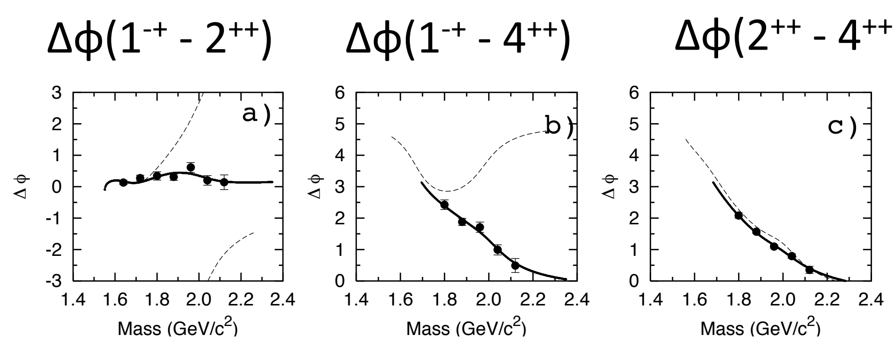


$\pi_1(2000) \rightarrow b_1\pi$

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

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

Seen primarily in natural parity exchange.
The natural dominates

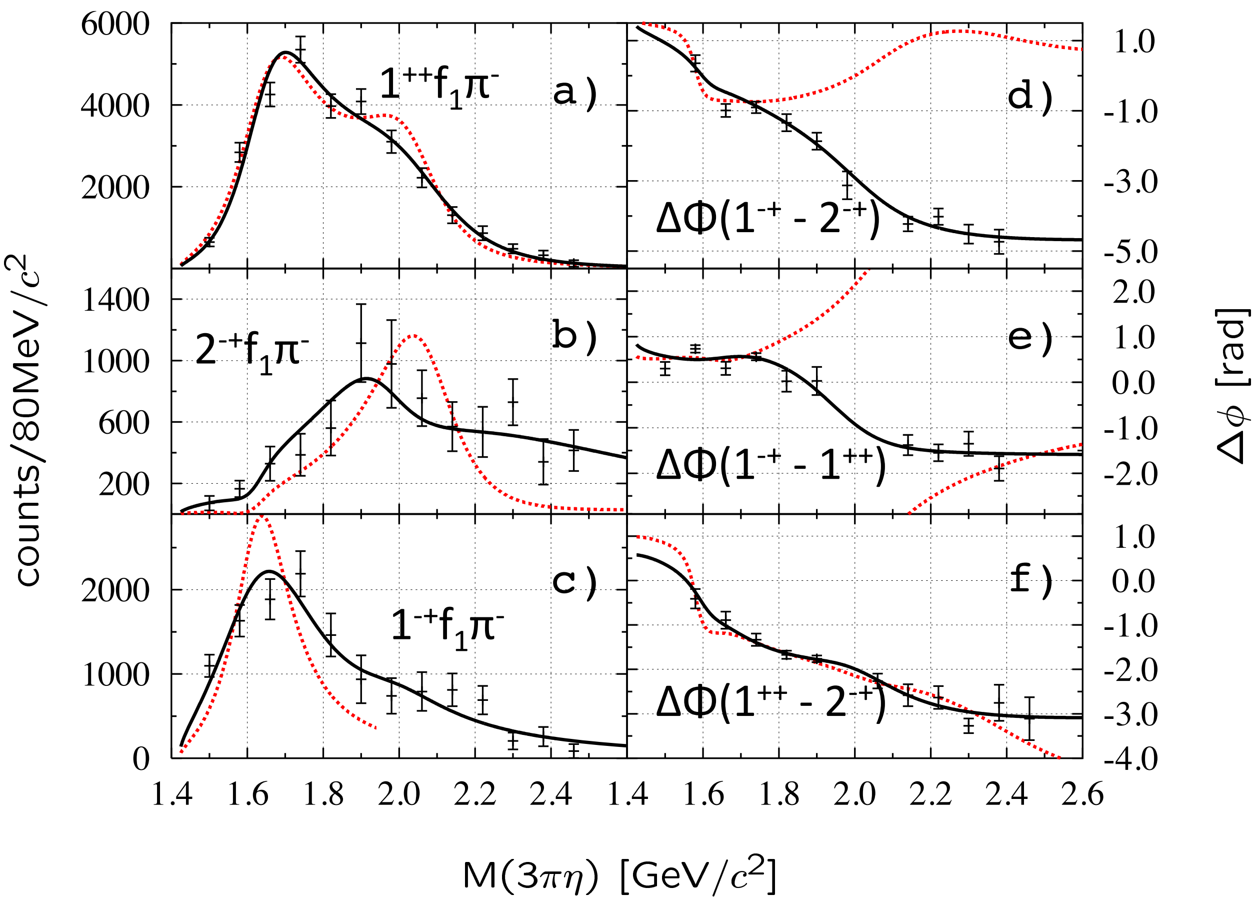


Solid curves are a two-pole 1^{-+} solution.
Dashed curves are a one-pole 1^{-+} solution.

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.

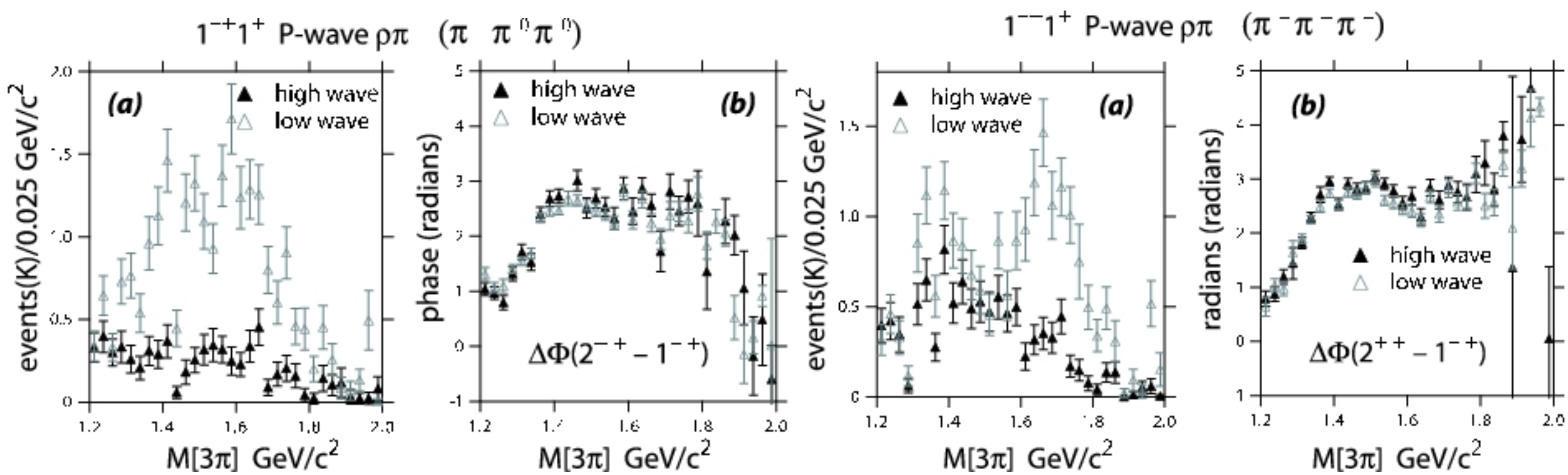
Red curves are a one-pole 1^{-+} solution.

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%

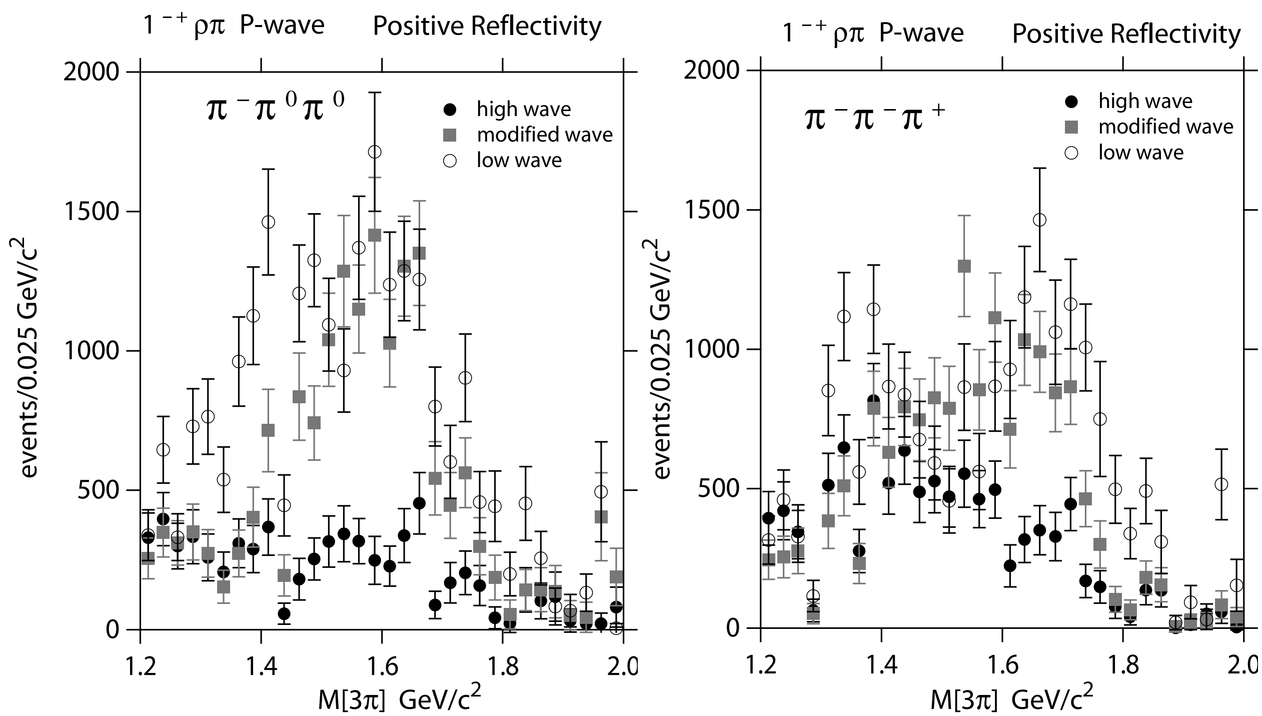
Always Include:

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

Modified wave set:

Leave out

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



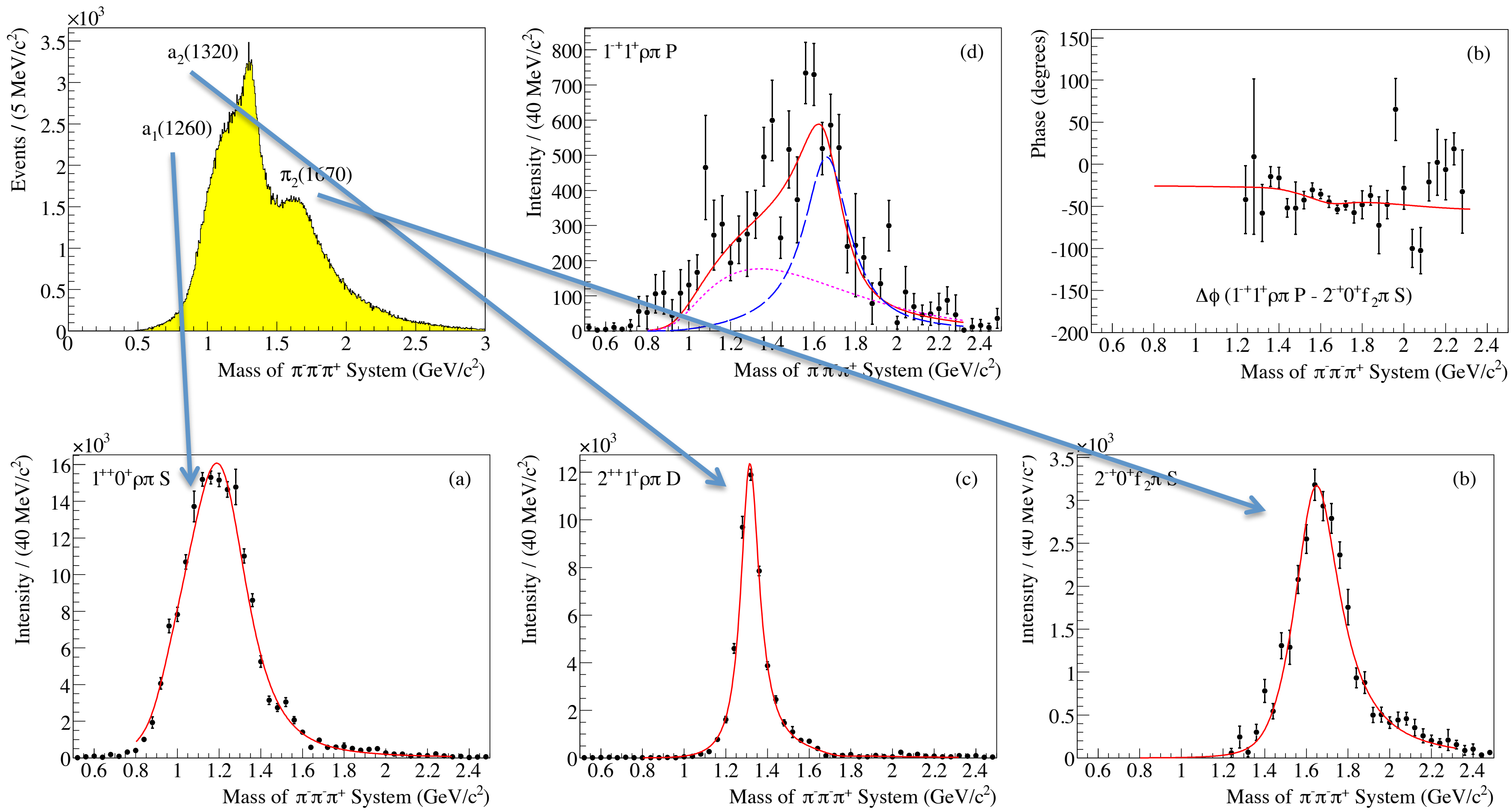
Most of the strength in the exotic $\pi_1(1600)$ is better described by known decays of the $\pi_2(1670)$.

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

(180 GeV pions)

(420,000 Events)

1 $^{-+}$ Exotic Wave

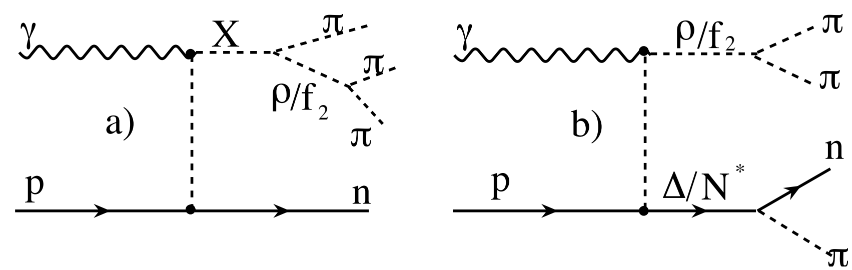


$\pi_1(1600)$ m=1660 Γ=269 $\pi_2(1670)$ m=1658 Γ=271

arXiv:0910.5842 42 Partial waves included, exotic is dominantly 1$^+$ production.

CLAS Experiment

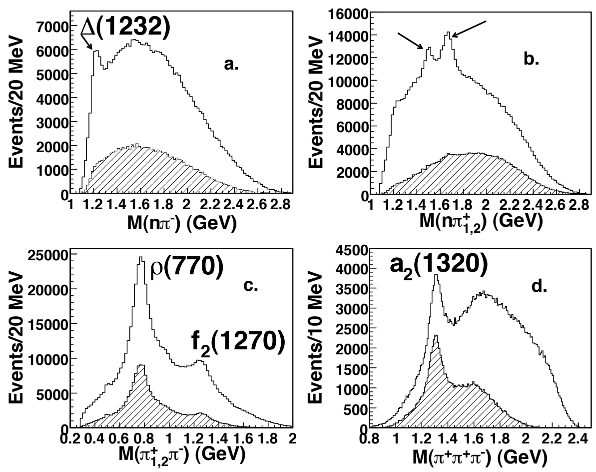
$\gamma p \rightarrow n\pi^+\pi^+\pi^-$



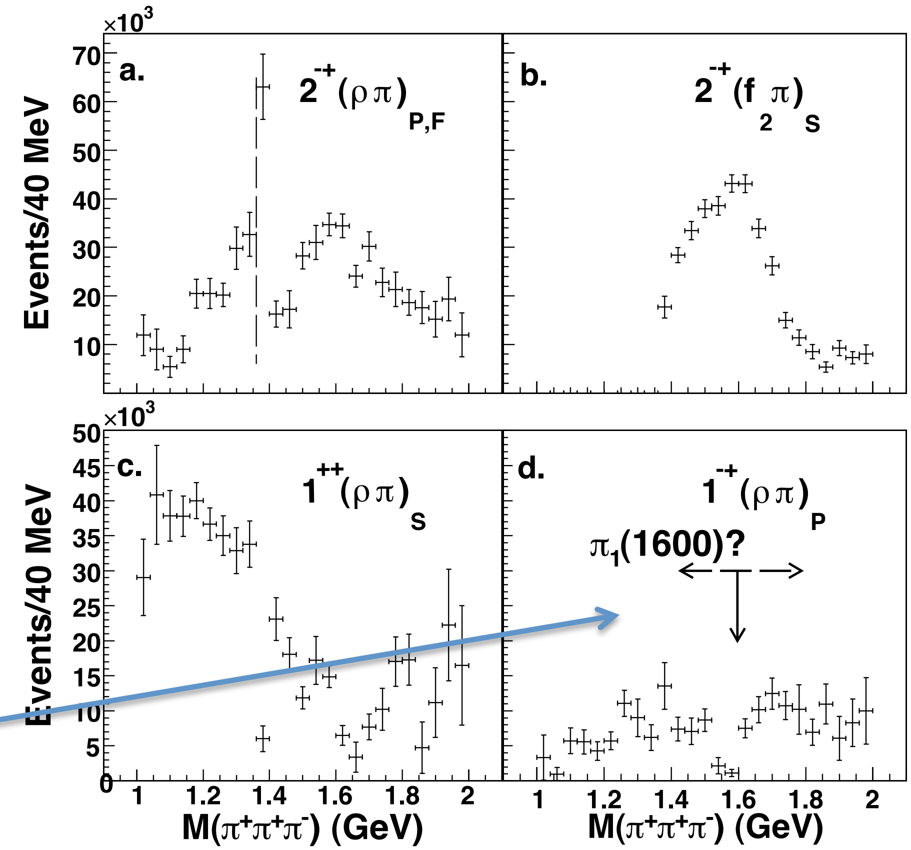
$E_\gamma = 4.8 - 5.4$ GeV

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).

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)
$\eta\pi$	1400	310	seen in proton-antiproton annihilation	

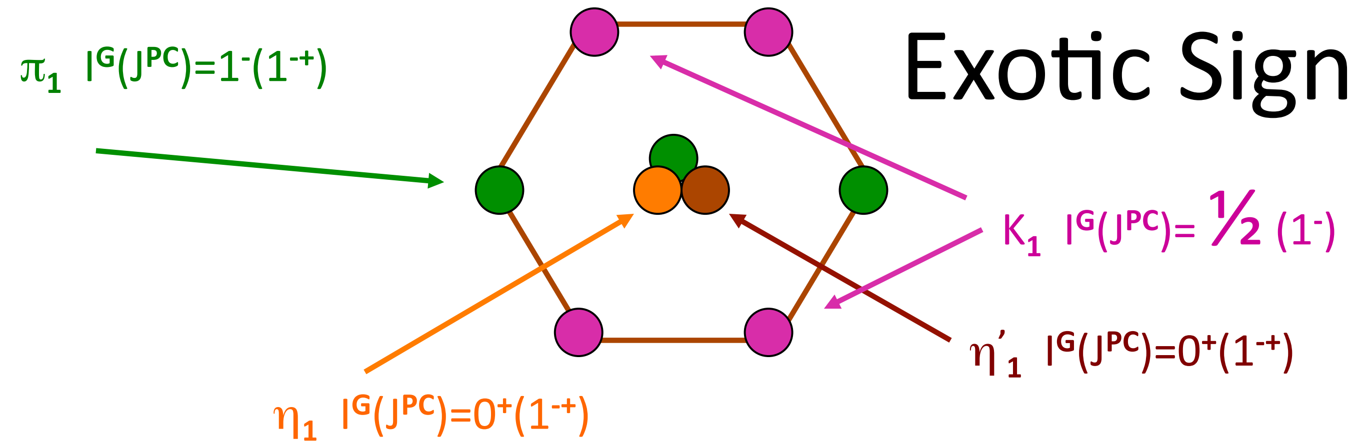
Summary of the $\pi_1(1600)$

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
$f_1\pi$	1709±24±41	403±80±115	1^+	Photoproduction
3π	1660 ±10+64-0	269±21+42-64	1^+	COMPASS

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

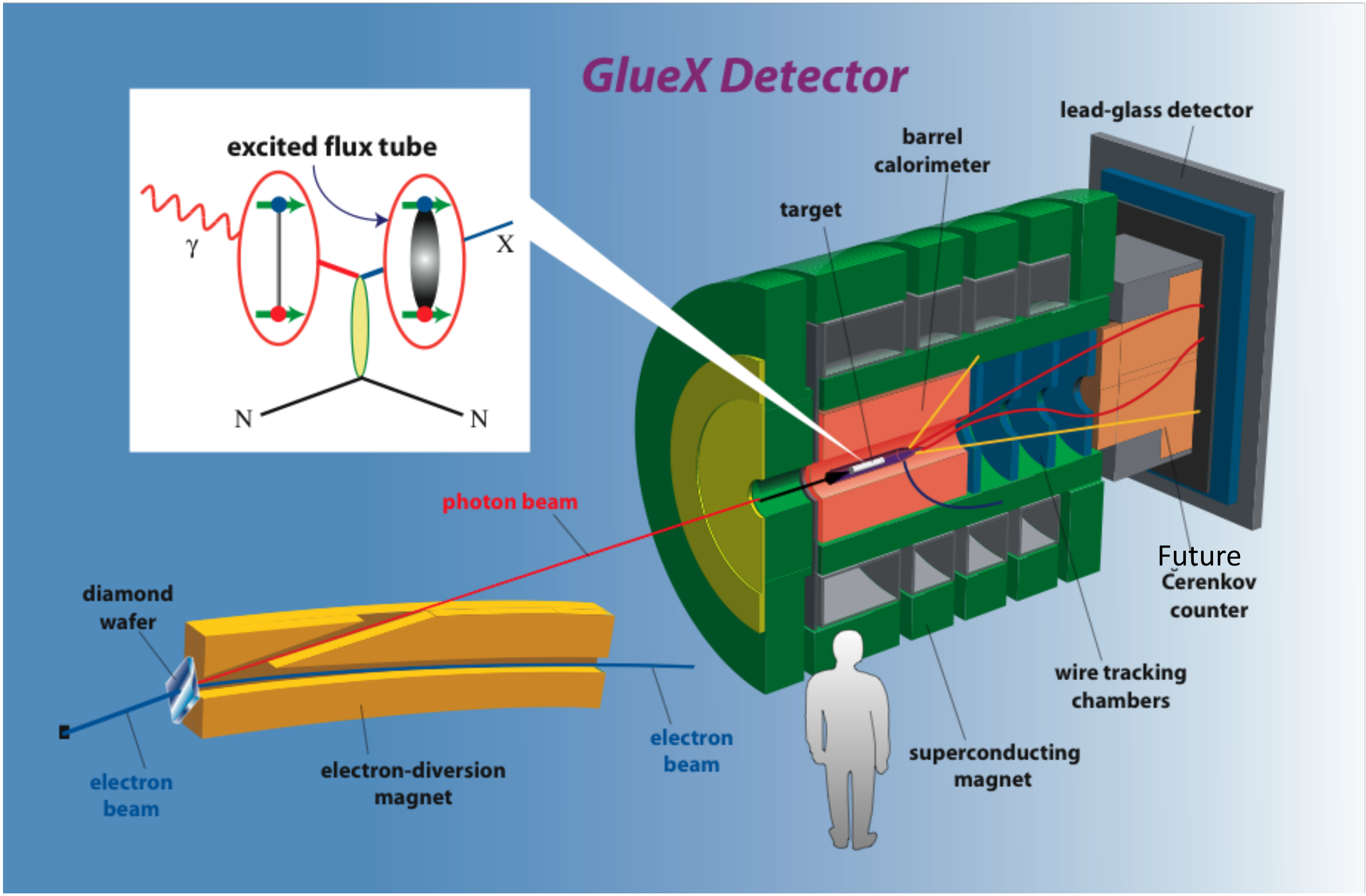
π_1(1600) Width ~ 0.30 GeV, Decays $\rho\pi$,$\eta'\pi$,($b_1\pi$)
Only seen in πp production, (E852 + VES)
Production mechanisms not consistent.
COMPASS sees a state with the same mass & width as the π_2(1670).

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.

The GlueX Experiment



COMPASS

Currently running at CERN
Detect charged particles and photons.
Good PID

190 GeV/c beam.
Diffractive production:

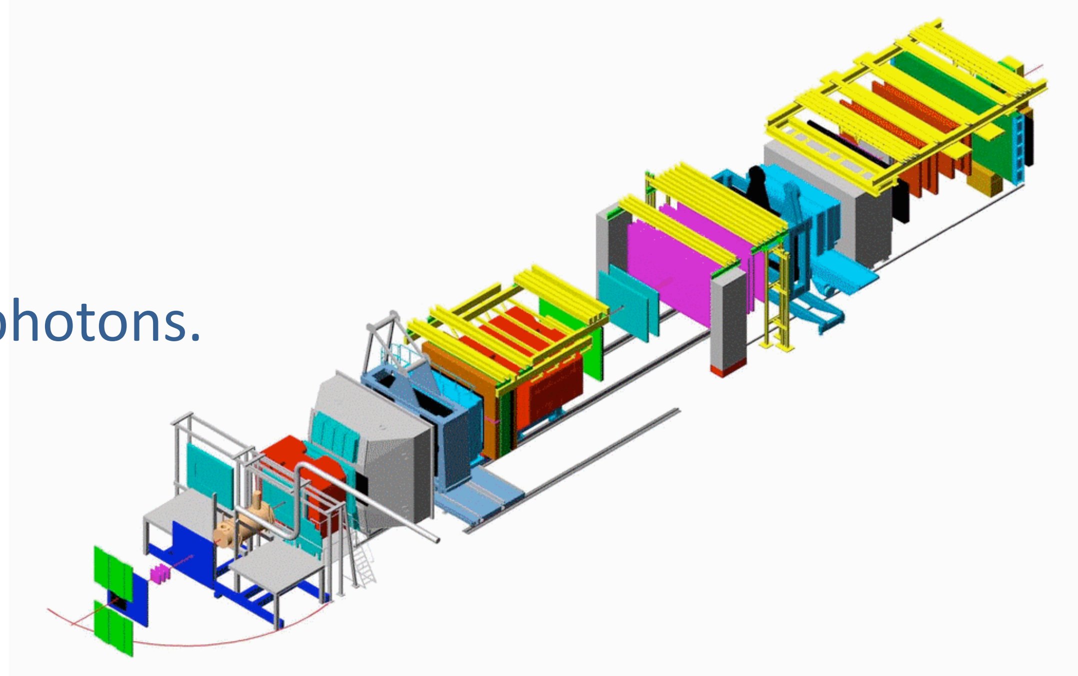
$$\pi^- p \to pX$$

repeat E852 studies, but at much higher energy.

Central production:

$$pp \to p_f p_s X$$

repeat studies done by WA102 at CERN (glueballs).



Partial wave analysis reported on three-pion final state.

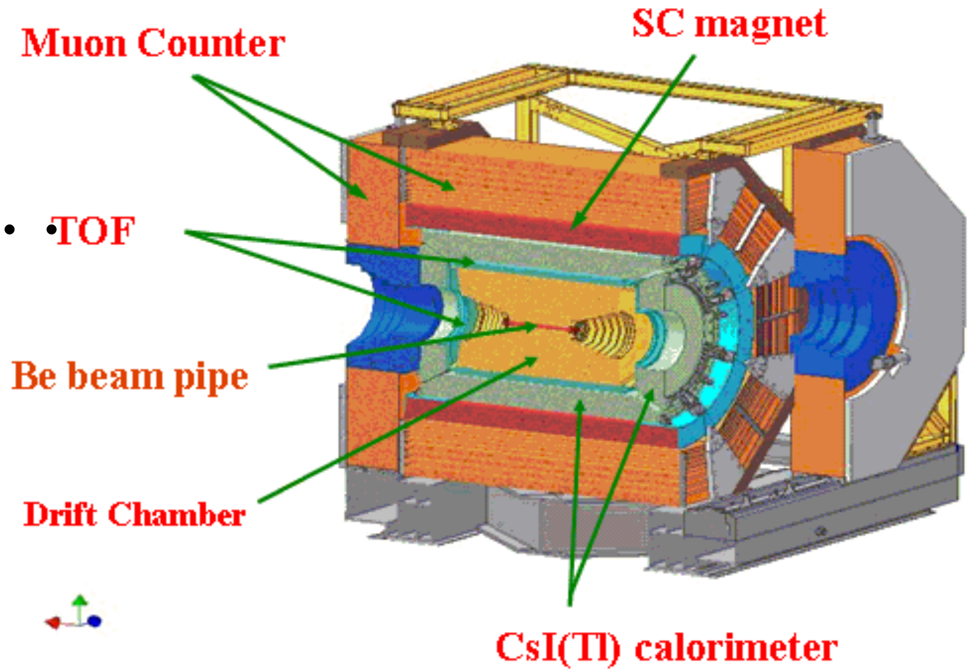
$$\pi_1(1600) \to \pi\pi\pi$$

Mass and width of the exotic exactly match the $\pi_2(1670)$

With large wave set, they see the $\pi_1(1600)$

BES III

$$e^+e^- \rightarrow J/\Psi\,,\ \Psi'\,,\ \cdots$$



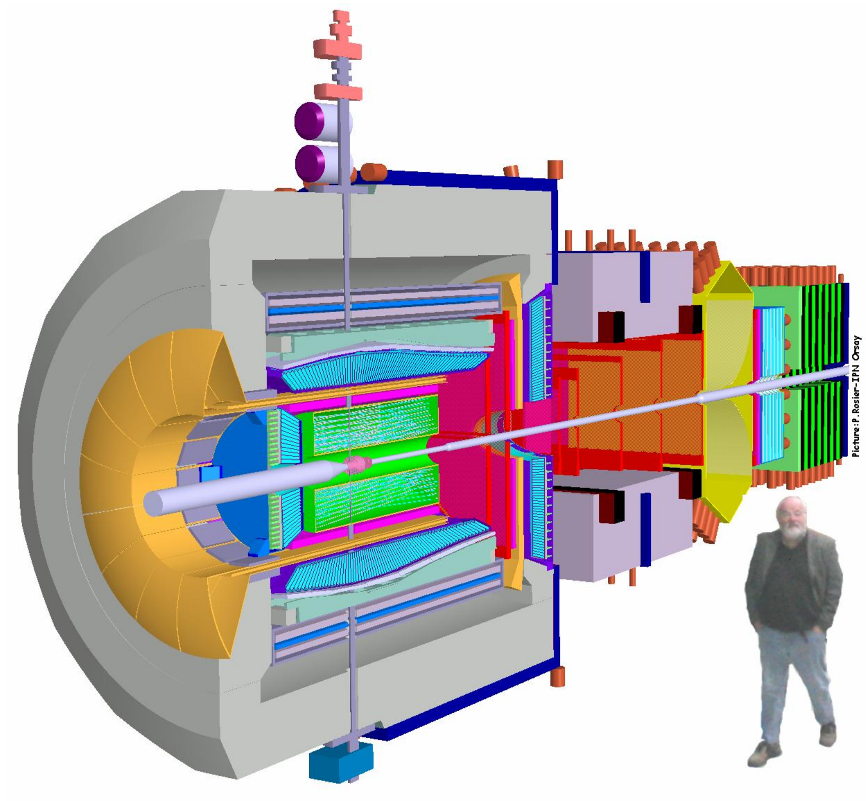
Currently running in Beijing

Tagged decays of Ψ-states to look for glueballs and hybrids. Possible to look for charmed hybrids, but rates may be a limiting factor.

Can also look for exotic hybrids in the decay of these states. I am not certain What the expected rates are.

Radiative J/Ψ decays are supposed to be glue-rich, oddly a prime candidate is not seen --- $f_0(1500)$.

PANDA



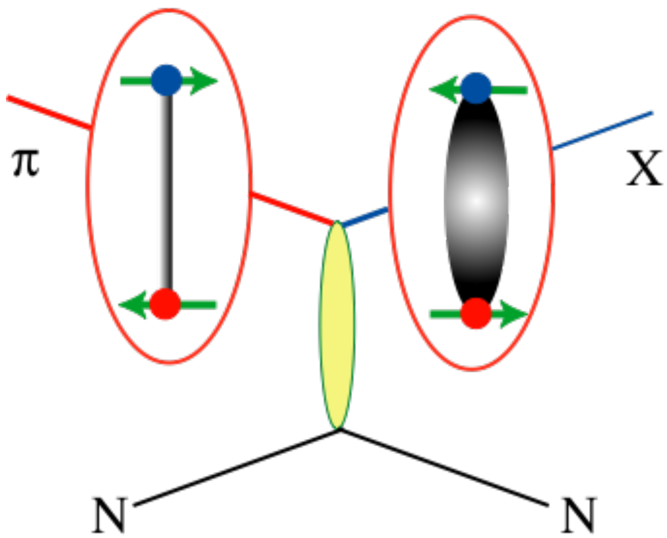
Proton-antiproton annihilation at new facility in Germany (GSI). Time scale is similar to GlueX (probably later).

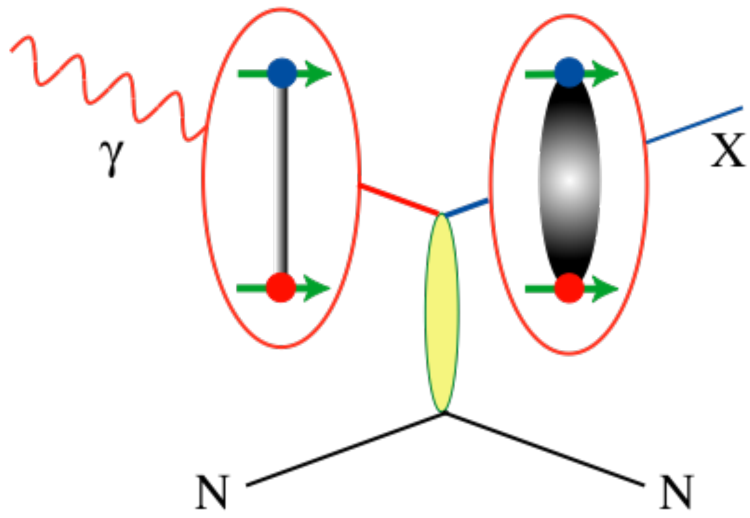
Main program is in the charm sector with emphasis on charmed hybrid mesons. Some hints that it is easier to produce exotic hybrids in these reactions.

Also search for glueballs. There should also be a light exotic meson program here.

Photoproduction

More likely to find exotic hybrid mesons using beams of photons





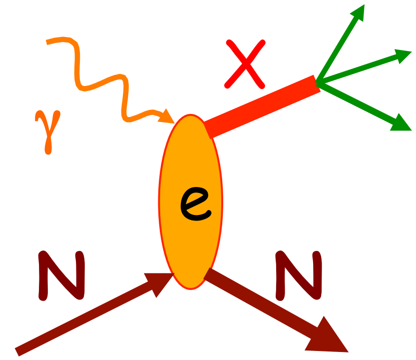
Simple (0^{++}) natural parity exchange with L=1: 0^{+-},1^{+-},2^{+-}

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

$\pi^0\eta$ final state

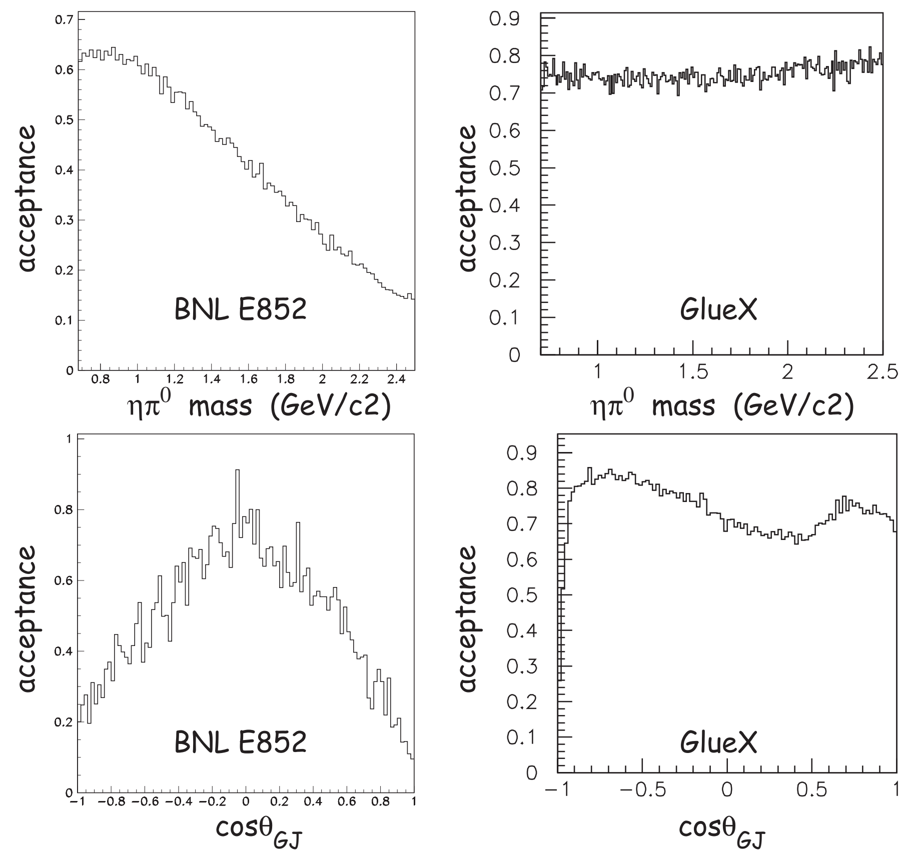
GlueX

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.



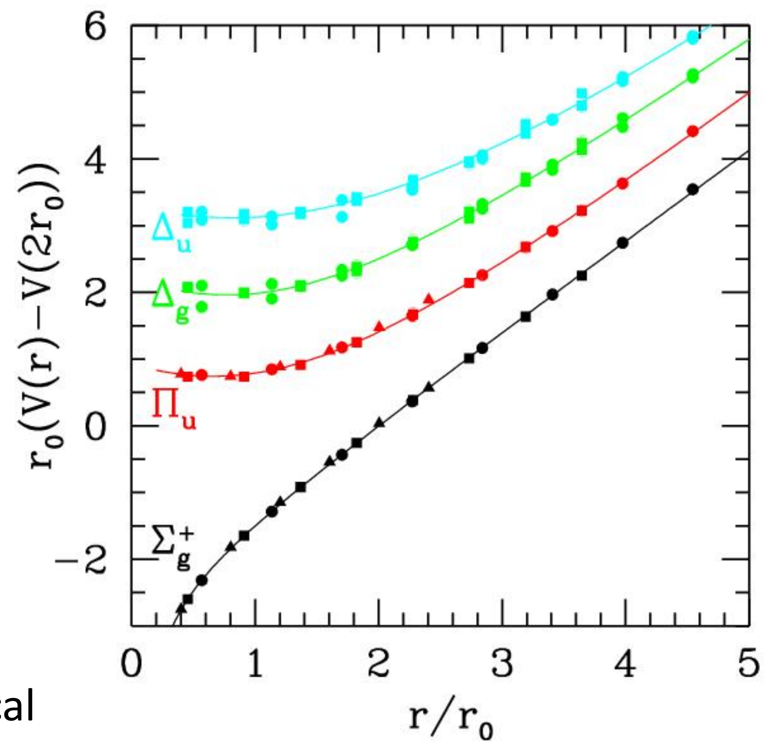
Exotics and QCD

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 polarize photon beam.