A MAP TO HADRONIC PHYSICS FROM GlueX

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Outline

- What are gluonic excitations.
- How to search for gluonic excitations?
- The GlueX experiment.
- First physics from GlueX.
- GlueX moving forward.

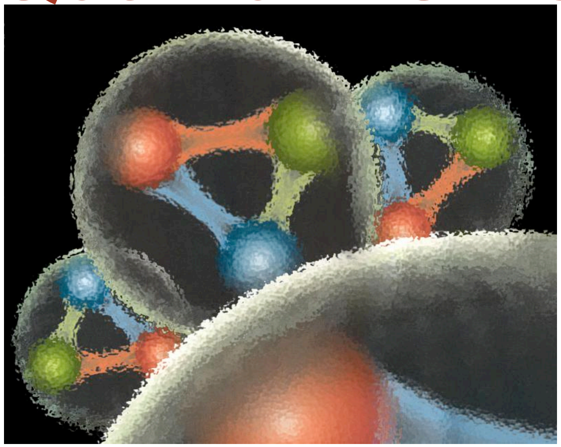
12-GeV beam, Dec. 2015

The GlueX Collaboration

Arizona State, Athens, Carnegie Mellon, Catholic University, Univ. of Connecticut, Florida International, Florida State, George Washington, Glasgow, GSI, Indiana University, ITEP, Jefferson Lab, U. Mass Amherst, MIT, MePhi, Norfolk State, North Carolina A&T, Univ. North Carolina Wilmington, Northwestern, Old Dominion, Santa Maria, University of Regina, Tomsk, Wuhan and Yerevan Physics Institute.

Over 125 collaborators from more than 25 institutions with others joining and more are welcome.

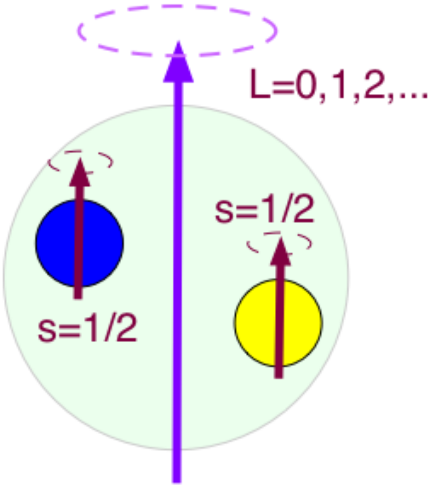
Quantum Chromo Dynamics



Focus on mesons built from the three lightest quarks, **u**, **d** and **s**, and their antiquarks.

Combine two spin **½** objects to S=**0** or S=**1**

Orbital angular momentum of two quarks: L=**0**,**1**,**2**,**3**,…

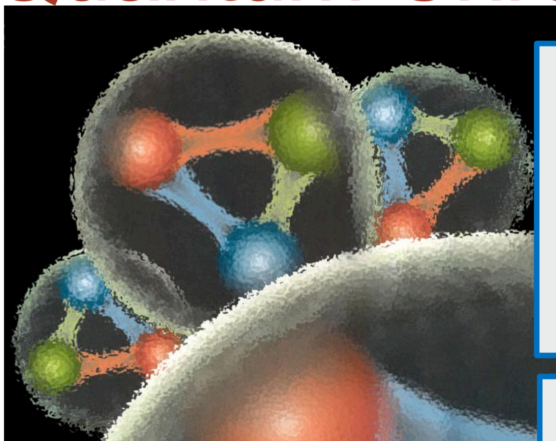


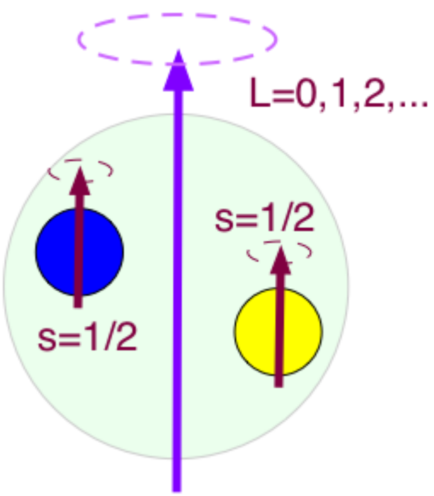
Total angular momentum, $J=L\oplus S$
J=**0**,**1**,**2**,**3**,…

Spatial Reflection Symmetry:
Parity **$P=-(-1)^L$**
Quark-antiquark Reflection:
C-parity **$C=(-1)^{L+S}$**

J^{PC}

Quantum Chromo Dynamics





L=3, S=1, $J^{PC}=4^{++}$
$J^{PC}=3^{++}$
$J^{PC}=2^{++}$
L=3, S=0, $J^{PC}=3^{+-}$

L=2, S=1, $J^{PC}=3^{--}$
$J^{PC}=2^{--}$
$J^{PC}=1^{--}$
L=2, S=0, $J^{PC}=2^{-+}$

L=1, S=1, $J^{PC}=2^{++}$
$J^{PC}=1^{++}$
$J^{PC}=0^{++}$
L=1, S=0, $J^{PC}=1^{+-}$

L=0, S=1, $J^{PC}=1^{--}$
L=0, S=0, $J^{PC}=0^{-+}$

Each J^{PC} corresponds to nine quark-antiquark states, *nonets* .

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

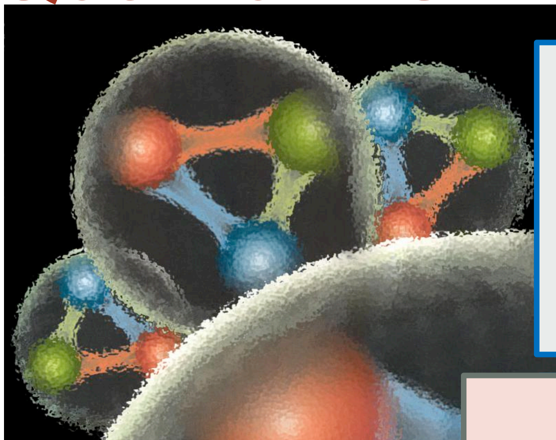
$$u\bar{d} \ , \ \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \ , \ d\bar{u}$$

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

$$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \ , \ s\bar{s}$$

Can mix

Quantum Chromo Dynamics



L=3, S=1, $J^{PC}=4^{++}$

$J^{PC}=3^{++}$

$J^{PC}=2^{++}$

L=3, S=0, $J^{PC}=3^{+-}$

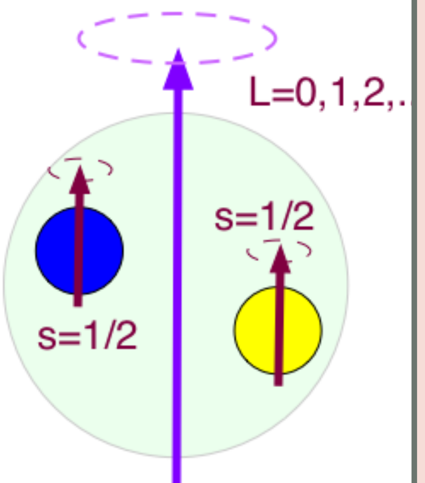
Each J^{PC} corresponds to nine quark-antiquark states.

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

$- d\bar{d})$, $d\bar{u}$

$s\bar{u}$

$- d\bar{d})$, $s\bar{s}$



0^{--} , 0^{-+} , 0^{+-} , 0^{++}

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

2^{--} , 2^{-+} , 2^{+-} , 2^{++}

3^{--} , 3^{-+} , 3^{+-} , 3^{++}

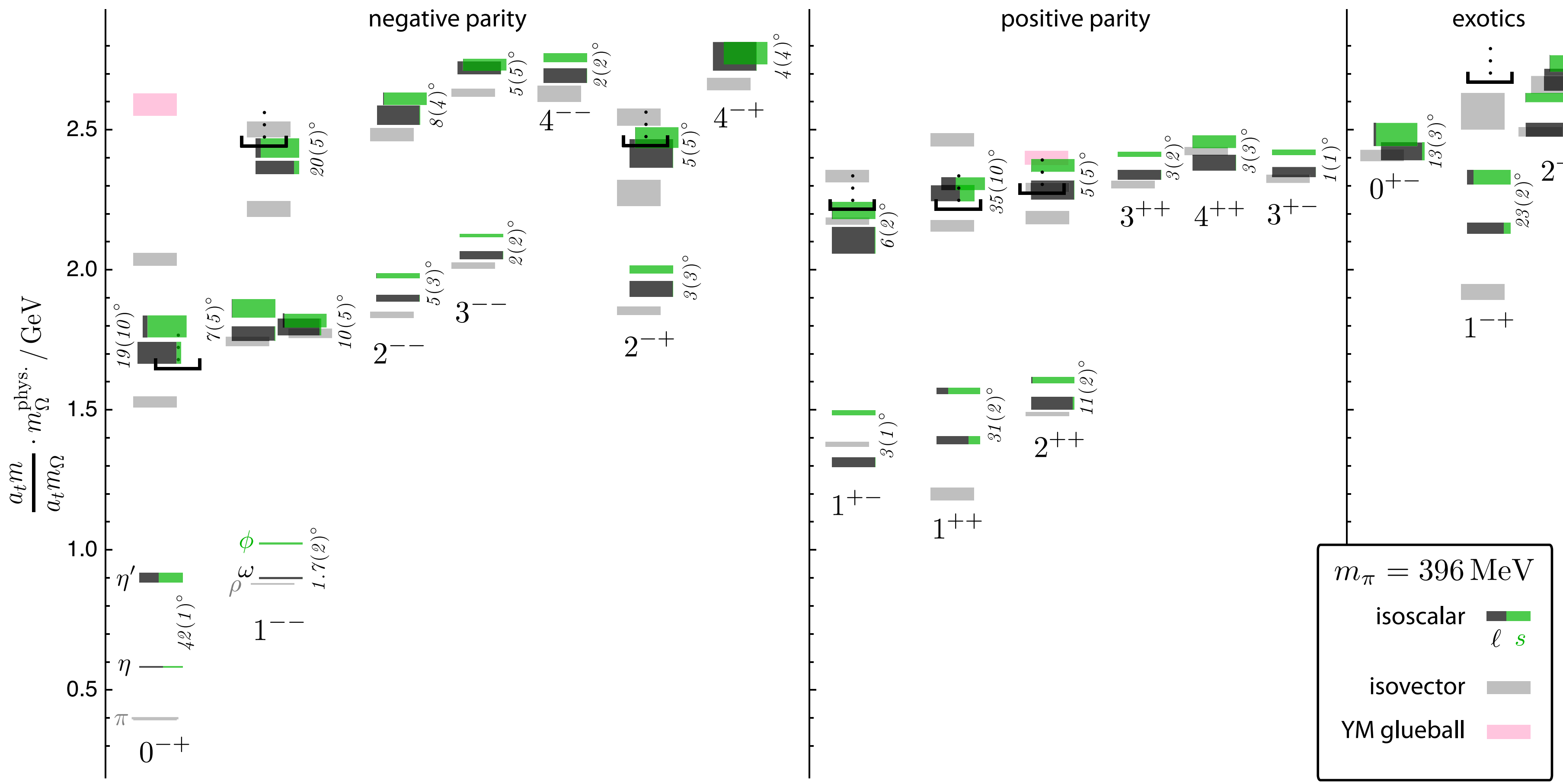
Exotic Quantum Numbers

mix

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

Lattice QCD

Light-quark Mesons (u,d,s)

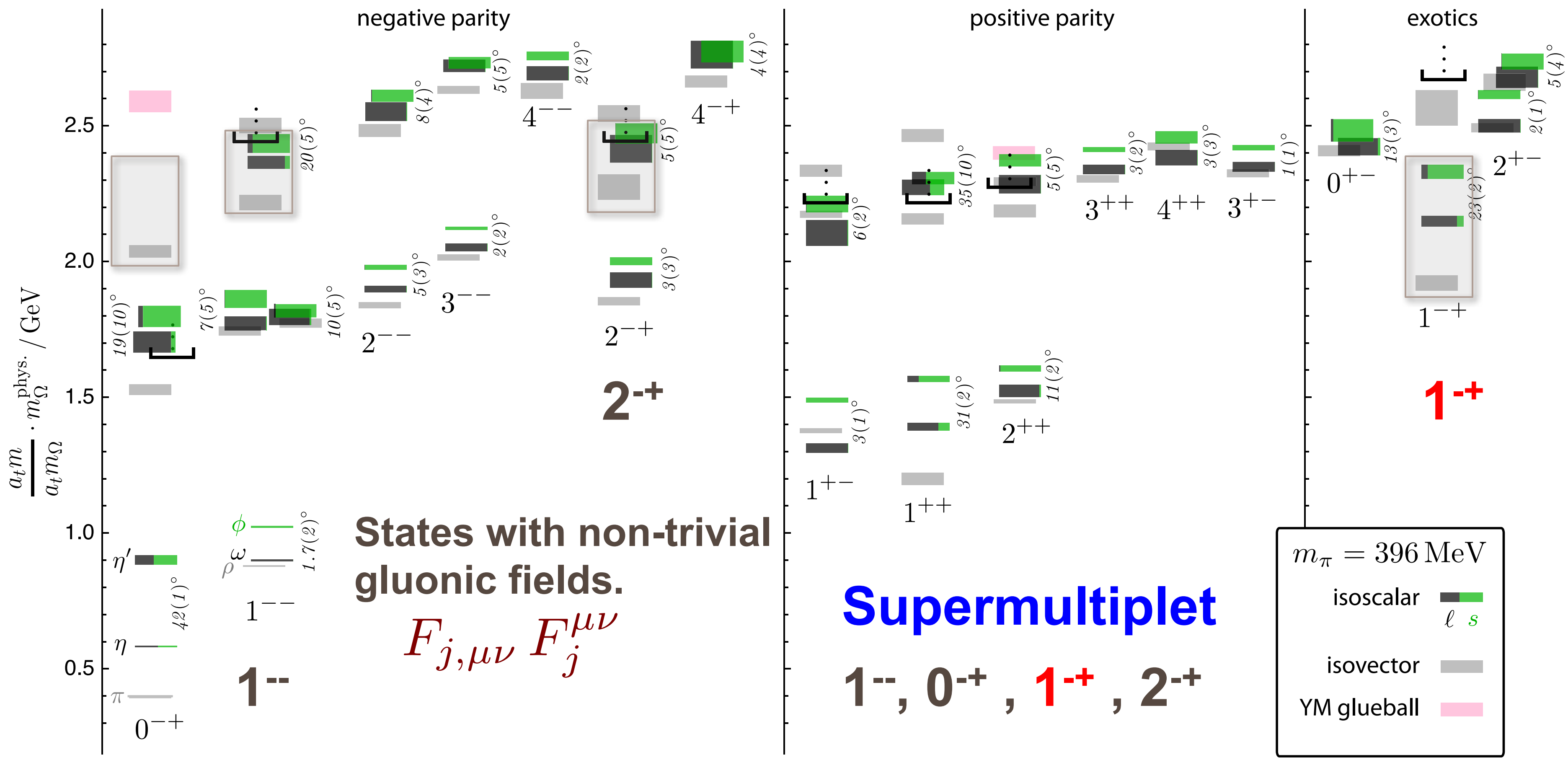


$$\frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \qquad \left(s\bar{s}\right)$$

PRD83, 111502 & PRD88, 094505

Lattice QCD

Light-quark Mesons (u,d,s)



1--

2-+

1-+

States with non-trivial gluonic fields.

$$F_{j,\mu\nu} F_j^{\mu\nu}$$

Supermultiplet

1--, 0-+ , 1-+ , 2-+

0-+

$$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \qquad \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \qquad (s\bar{s})$$

PRD83, 111502 & PRD88, 094505

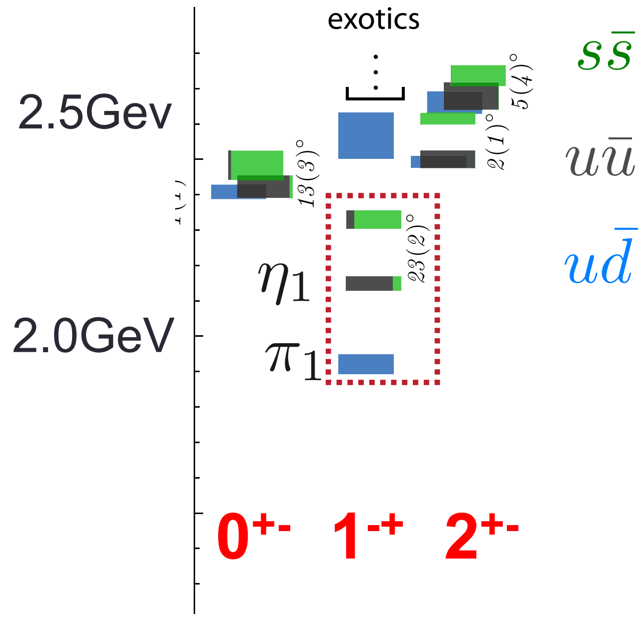
QCD Exotics

Lattice QCD suggests 5 nonets of mesons with exotic quantum number:

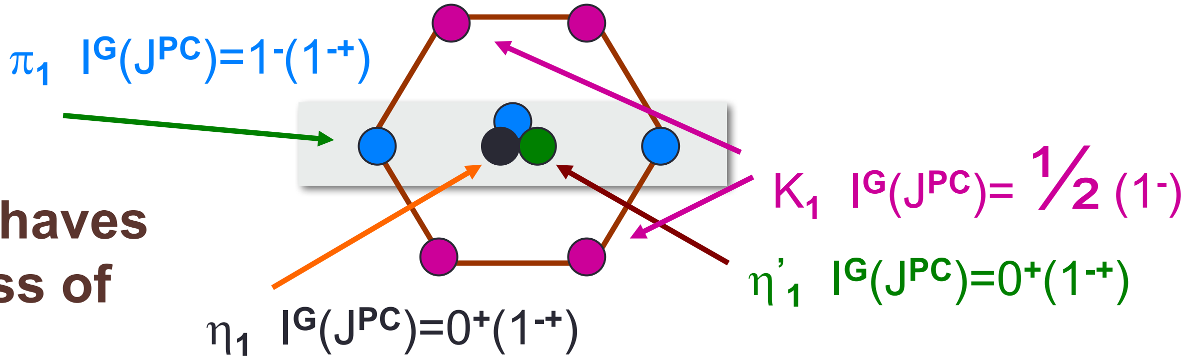
1 nonet of 0^{+-} exotic mesons

2 nonets of 1^{-+} exotic mesons

2 nonets of 2^{+-} exotic mesons



Experimental evidence exists for π_1 states.



``Constituent gluon" behaves like $J^{PC} = 1^{+-}$ with a mass of **1-1.5 GeV**

The lightest hybrid nonets:

1^{--}, (0^{-+}, 1^{-+}, 2^{-+})

Kaon states do not have exotic QNs

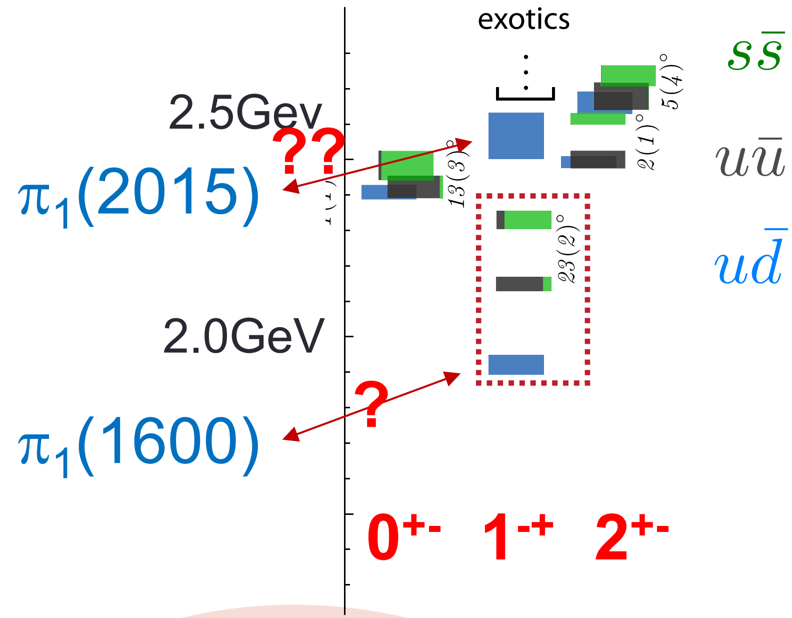
PRD84, 074023

QCD Exotics

Experimental Evidence for Exotics?

The $\pi_1(1600)$ has been observed by several experiments, mostly in pion-beam experiments. It has been seen in a number of decay modes, some of which are controversial.

The $\pi_1(2015)$ has been observed by a single low-statistics experiment. Confirmation is needed.



Not observed:

η_1 , η_1'
b_0 , h_0 , h_0'
b_2 , h_2 , h_2'

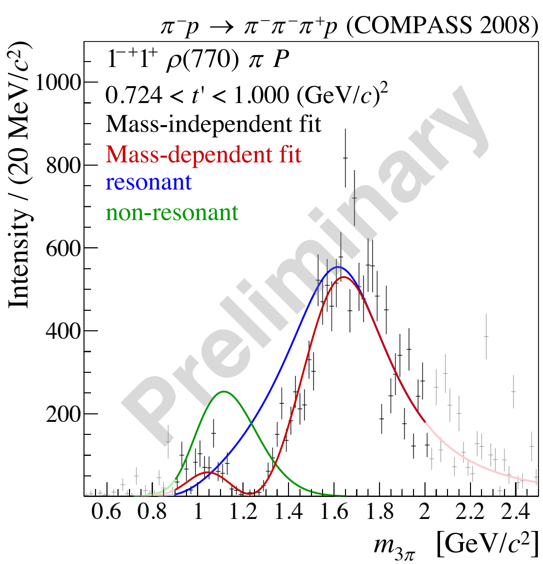
Prog. Part. and Nucl. Phys. B**82**, 21, (2015).

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

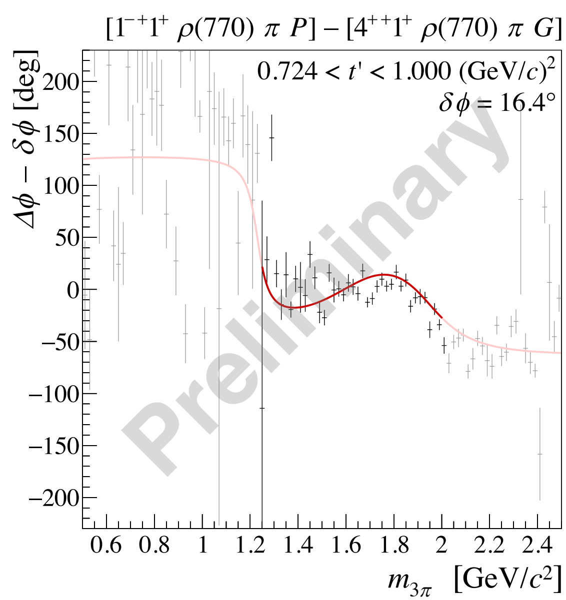
In the $\rho\pi$ system at larger momentum transfer, |t|, they observe a signal with phase motion in the 1^{-+} exotic wave, the $\pi_1(1600)$, They also see a signal in the $\eta'\pi$ channel.

Other reports in various decay modes from E852, VES and others.

Intensity of 1^{-+}



Phase Difference to 4^{++}



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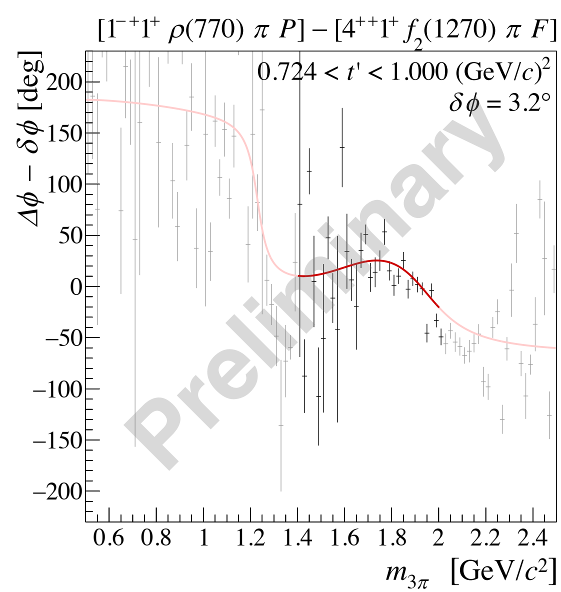
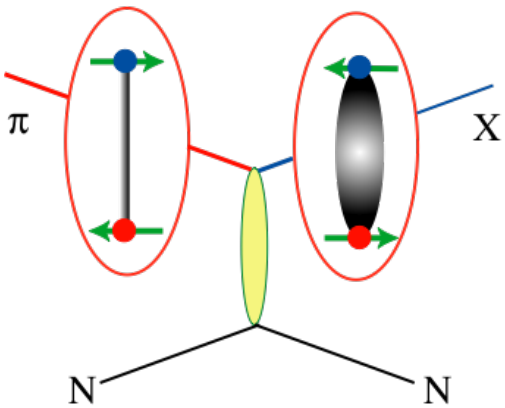


EPJ Web. Conf., 137 (2017) 05012.

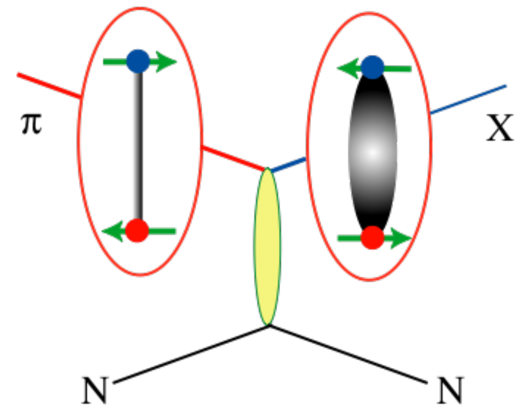
Producing QCD Exotics

High-statistics experiments have used pion beams to search for hybrids: **VES** at Protvino, **E852** at Brookhaven and **Compass** at CERN: $\pi^- p \rightarrow pX^-$ or nX^0



A pion undergoes t-channel exchange with a nucleon and creates an excited meson or hybrid. Involves charge exchange and/or isospin-1 particles. Easier to make pion-like states.

Producing QCD Exotics



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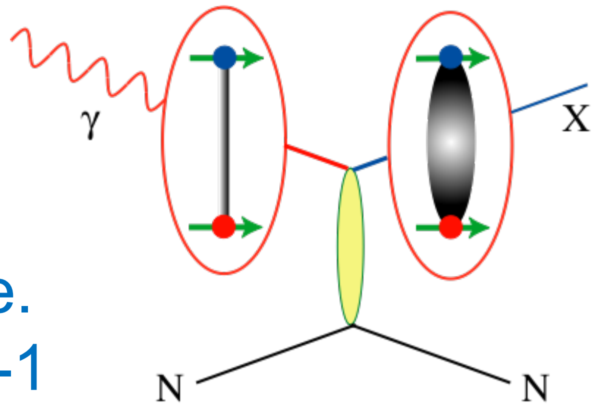
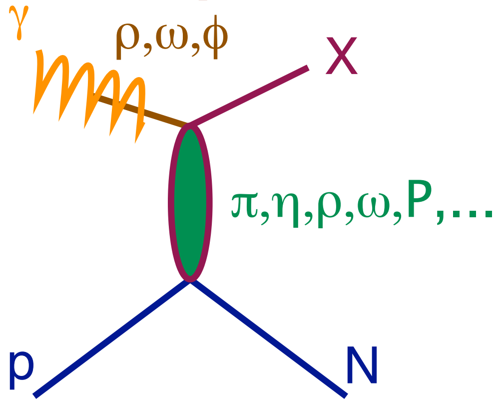
Photoproduction is a poorly-studied mechanism, ~1000s of events total.



Photon can fluctuate into a spin-1 particle. Do not need charge exchange or isospin-1 final states. Linear polarization filters exchange mechanisms.

Photoproduction Mechanisms



Simple quantum number counting for production: **$(I^G)J^{PC}$ up to L=2**

P = Pomeron exchange

$\rho\pi,\rho\omega \rightarrow \pi_1$

$\omega\omega,\rho\rho \rightarrow \eta_1$

$\omega\omega,\rho\rho,\phi\omega \rightarrow \eta'_1$

$\rho P \rightarrow b_0$

$\omega P \rightarrow h_0$

$\omega P, \phi P \rightarrow h'_0$

$\omega\pi,\rho\eta,\rho P \rightarrow b_2$

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

$\rho\pi,\omega\eta,\phi P \rightarrow h'_2$

ρπ is charge-exchange only

Can couple to all the lightest exotic hybrid nonets through photo-production and VMD.

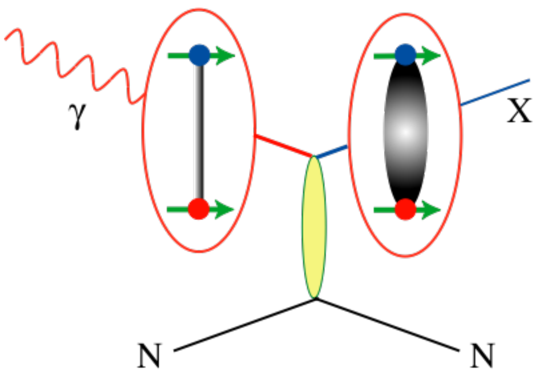
Linear polarization is a filter on the naturality of the exchanged particle.

Decay Modes of Exotic Hybrids

$\pi_1 \to \pi\rho$, πb_1, πf_1, $\pi\eta'$, ηa_1
$\eta_1 \to \eta f_2$, $a_2\pi$, ηf_1, $\eta\eta'$, $\pi(1300)\pi$, $a_1\pi$,
$\eta_1' \to K^*K$, $K_1(1270)K$, $K_1(1410)K$, $\eta\eta'$

$b_2 \to \omega\pi$, $a_2\pi$, $\rho\eta$, $f_1\rho$, $a_1\pi$, $h_1\pi$, $b_1\eta$
$h_2 \to \rho\pi$, $b_1\pi$, $\omega\eta$, $f_1\omega$
$h'_2 \to K_1(1270)K$, $K_1(1410)K$, K_2^*K, $\phi\eta$, $f_1\phi$

$b_0 \to \pi(1300)\pi$, $h_1\pi$, $f_1\rho$, $b_1\eta$
$h_0 \to b_1\pi$, $h_1\eta$
$h'_0 \to K_1(1270)K$, $K(1460)K$, $h_1\eta$



Early Reach **With Statistics** **Hard**

Hybrid kaons do not have exotic QN's

Models suggest narrower states are in the spin-1 and spin-2 nonets, while the spin-0 nonets are broad.

Decay Modes of Exotic Hybrids

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

$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1, \eta\eta', \pi(1300)\pi, a_1\pi,$

$\eta_1' \rightarrow K^*K, K_1(1270)K, K_1(1410)K, \eta\eta'$

$b_2 \rightarrow \omega\pi, a_2\pi, \rho\eta, f_1\rho, a_1\pi, h_1\pi, b_1\eta$

$h_2 \rightarrow \rho\pi, b_1\pi, \omega\eta, f_1\omega$

$h'_2 \rightarrow K_1(1270)K, K_1(1410)K, K_2^*K, \phi\eta, f_1\phi$

$b_0 \rightarrow \pi(1300)\pi, h_1\pi, f_1\rho, b_1\eta$

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

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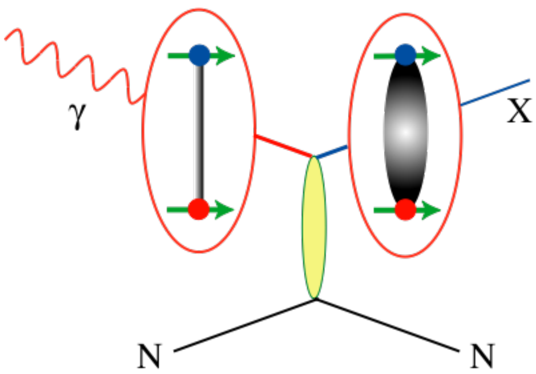

Early Reach **With Statistics** **Hard**

Hybrid kaons do not have exotic QN's

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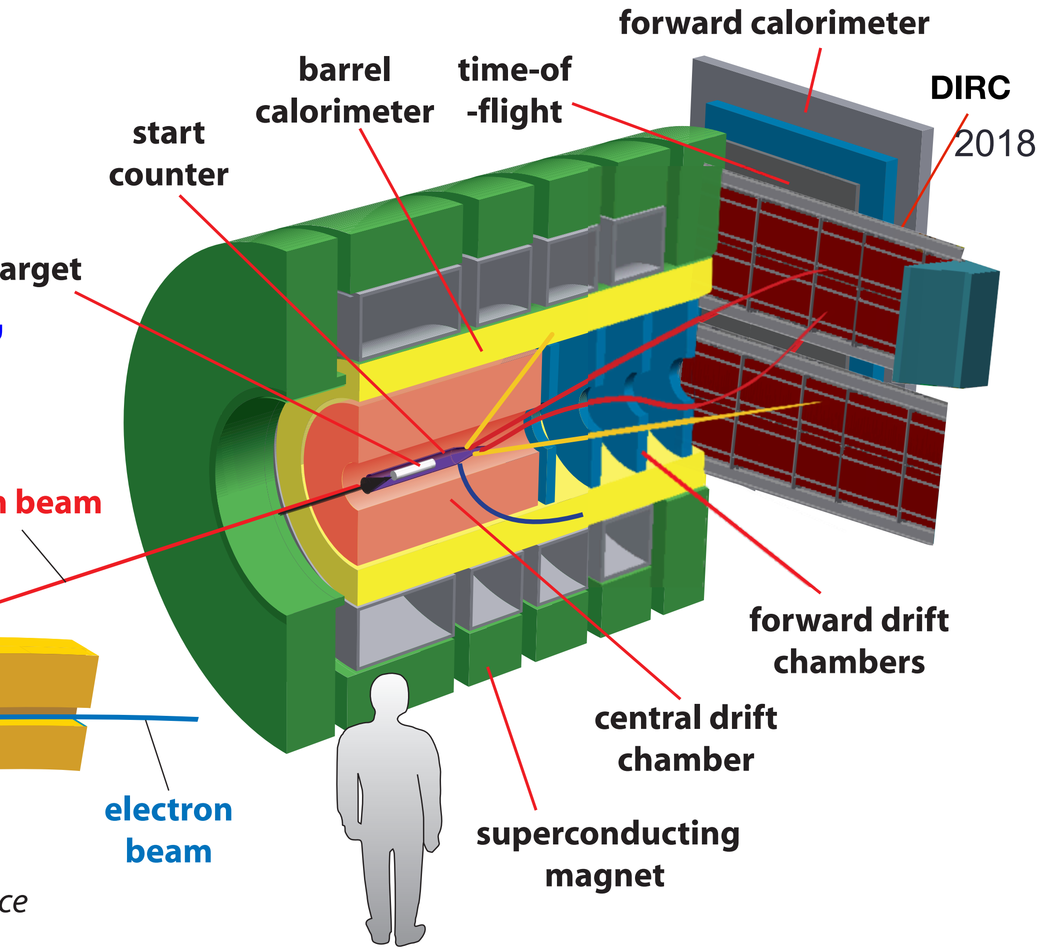
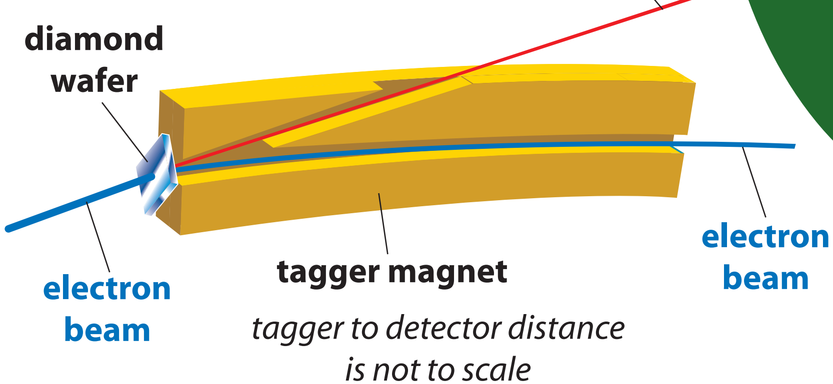
The GlueX Experiment

Photo Production of Hybrids,
Light-quark Mesons
and Strangeonium States

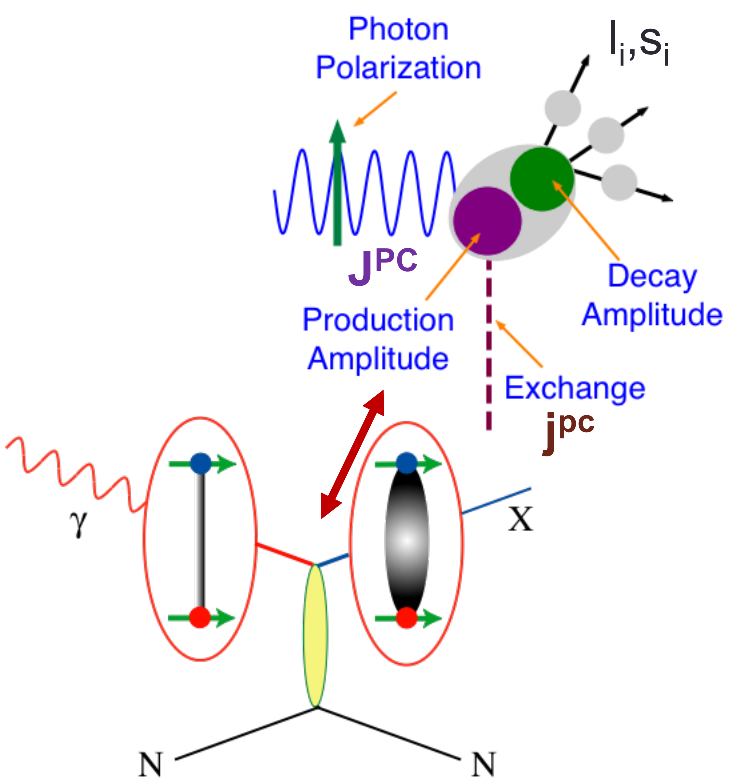




Physics Running started in 2017

(See Naomi Jarvis' talk on Friday for more details.)

Doing Physics with GlueX

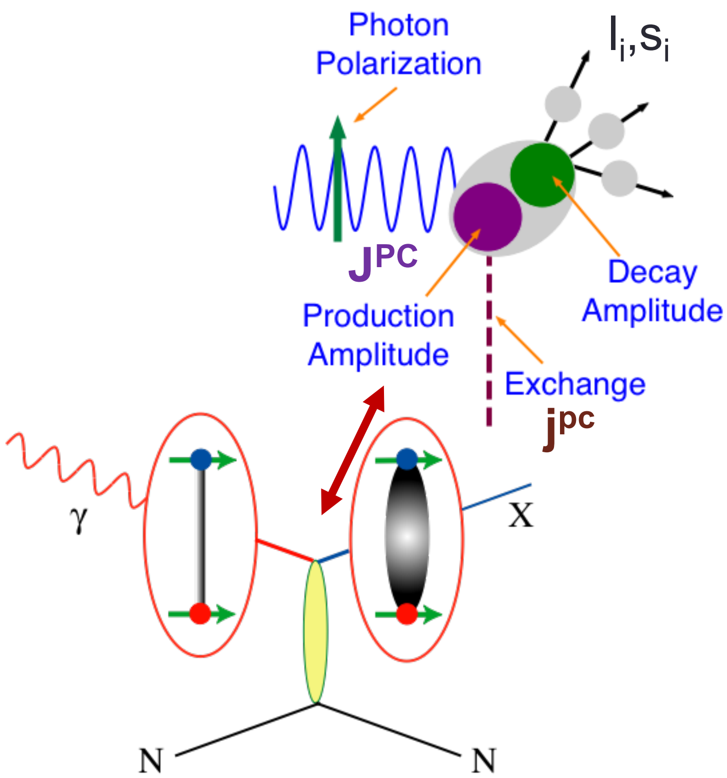


Production Amplitude produces a state **X** with **J^{PC}** quantum numbers and some polarization (density matrix, ρ).

Decay Amplitude describes the decay of **X** to final state particles. It is related to ρ and the spin and orbital angular momentum of the final-state particles.

Observables are the angular distributions of the final-state particles.

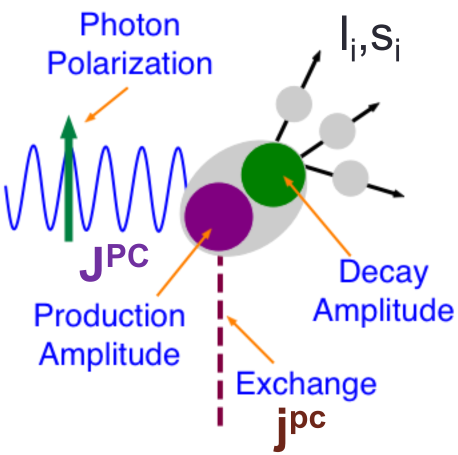
Doing Physics with GlueX



Theoretical work is necessary to extract the full physics potential from the GlueX program.

Of particular importance is Joint Physics Analysis Center (JPAC) with both their phenomenological work and the efforts to make this work available to experiment in analyzing data.

Doing Physics with GlueX



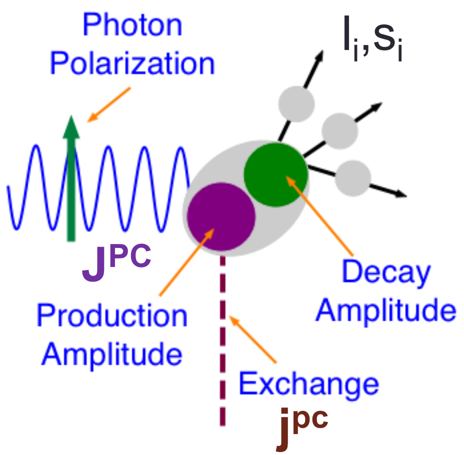
Several different states, all decaying to the same final particles are produced, and they interfere (complex amplitudes).

$$W(\theta, \phi, ...) = \sum |A|^2$$

$$A = \sum \alpha_j P_j D_j$$

Perform an un-binned log-likelihood fit to make our model for W agree with the experimental distribution for W by varying the α_j.

Doing Physics with GlueX



Several different states, all decaying to the same final particles are produced, and they interfere (complex amplitudes).

Understand the photon's polarization.

Understand the photon beam.

Know the efficiency and acceptance of the experimental apparatus.

Have a very accurate model of the detector (simulation).

Doing Physics with GlueX

Photon beam **asymmetry measurements**. Need to understand the photon polarization, but most other factors cancel out.

$$\gamma p \rightarrow (\pi^0, \eta, \eta')p$$

$$\gamma p \rightarrow (\rho^0, \omega, \phi)p$$

Understand the photon's polarization.

Understand the photon beam.

Know the efficiency and acceptance of the experimental apparatus.

Have a very accurate model of the detector (simulation).

(See talks on Friday by Tegan Beattie, William McGinley and Jonathan Zarling.)

Doing Physics with GlueX

Photon beam **asymmetry** Understand the photon's

Spin-density matrix elements of **vector mesons** are obtained by fitting complicated angular distributions.

$$W_h^1(\cos\theta,\phi,\rho^1) = \frac{3}{4\pi}\left[\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\,\mathrm{Re}\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi\right]$$

Requires understanding of detector acceptance.

on beam.

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perimental

model of the

Doing Physics with GlueX

Photon beam **asymmetry** Understand the photon's

Opportunistic Physics from data exploration!
Focus on results where small statistics and modest errors can have a big impact.

Charmonium
Double-strange Baryons
BSM Physics

n beam.

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Doing Physics with GlueX

Photon beam **asymmetry** Understand the photon's

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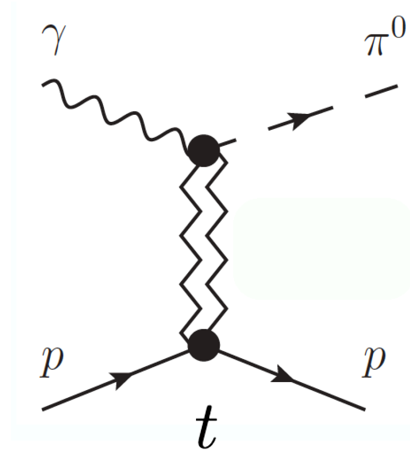
Amplitude analysis of known states. Full understanding of the detector where the answer is known.

This then leads to the search for new states, in particular the exotic hybrid mesons.

π^0 beam asymmetry

Beam asymmetry Σ provides insight into dominant production mechanism

$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$



Exchange J^{PC}

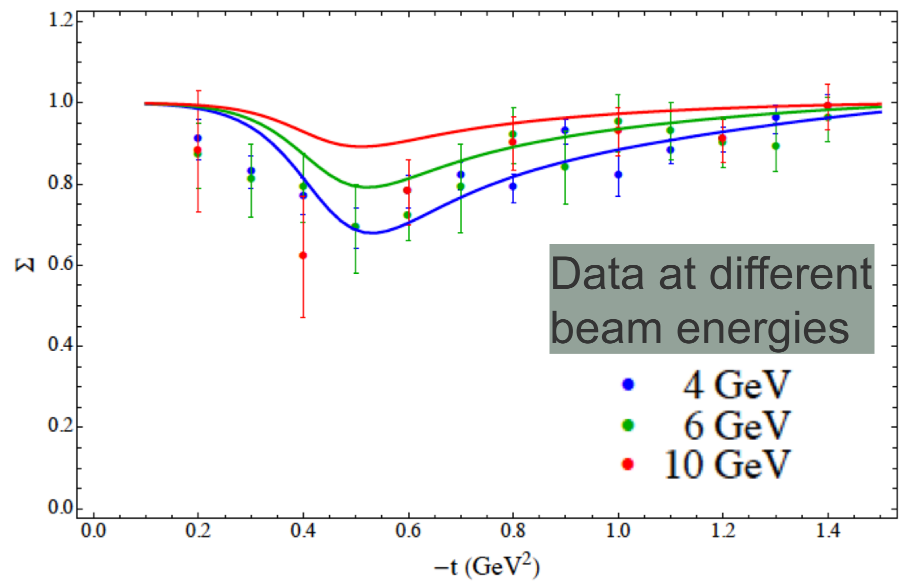
1^{--} : ω, ρ

1^{+-} : b, h

Understanding production mechanism critical to disentangling J^{PC} of observed states in exotic hybrid search.

From experimental standpoint easily extended to $\gamma p \rightarrow p\eta$ where there are no previous measurements!

Mathieu et al. PRD 92, 074013



Photon-beam Polarization

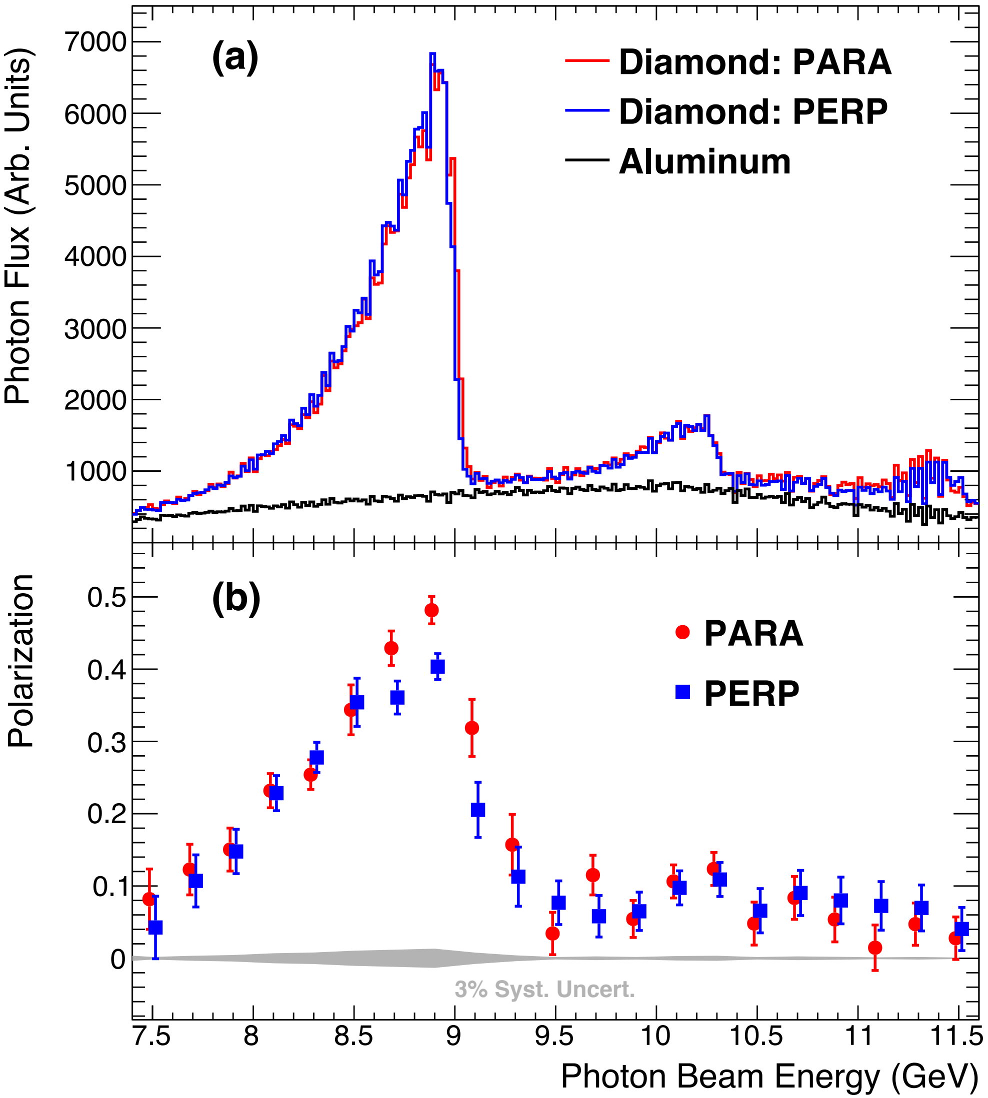
$$\vec{\gamma}p \to pX$$

$$\sigma \propto \left[1 - P_\gamma \Sigma_x \cos 2\left(\phi_x - \phi_\gamma\right)\right]$$

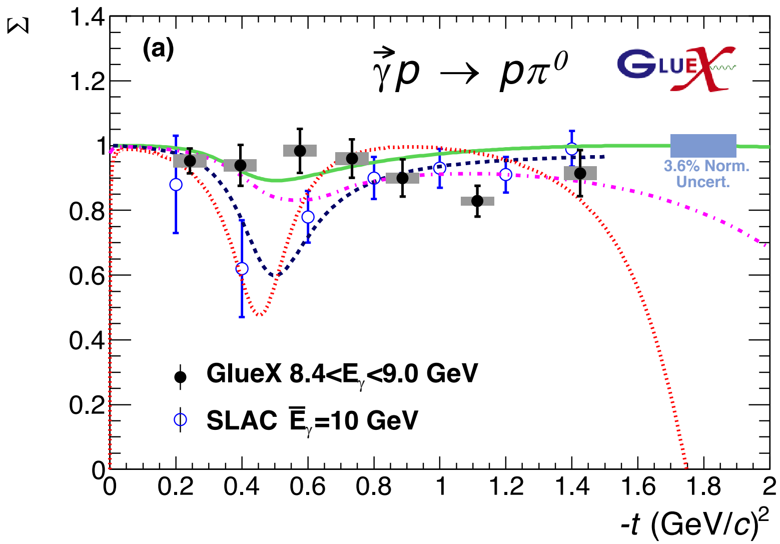
Coherent bremsstrahlung where we use the the 8.5 to 9.0 GeV photons.

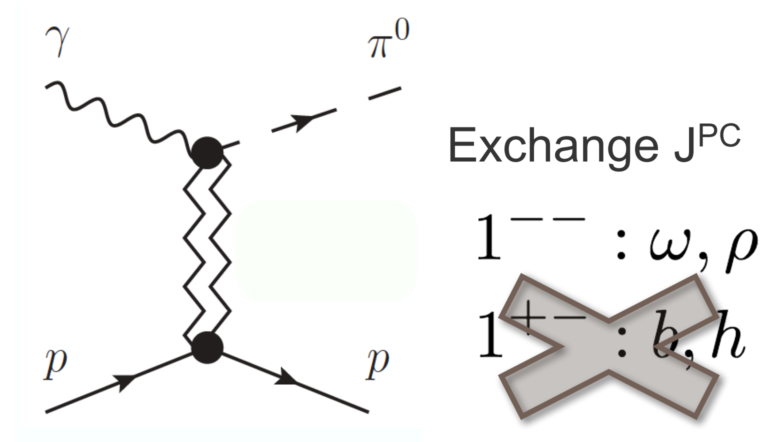
~40% Linear polarization which depends on the photon energy.

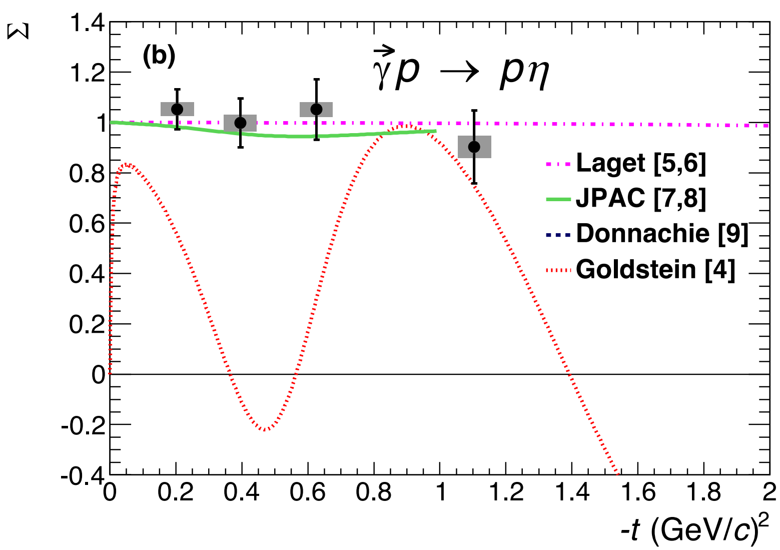
We measure the energy and then have the polarization of each incident photon.



Beam Asymmetry Measurement







Impacts extraction of baryon resonances from low-energy photoproduction experiments.

Understanding the meson production mechanisms at 9GeV is needed for our bigger program.

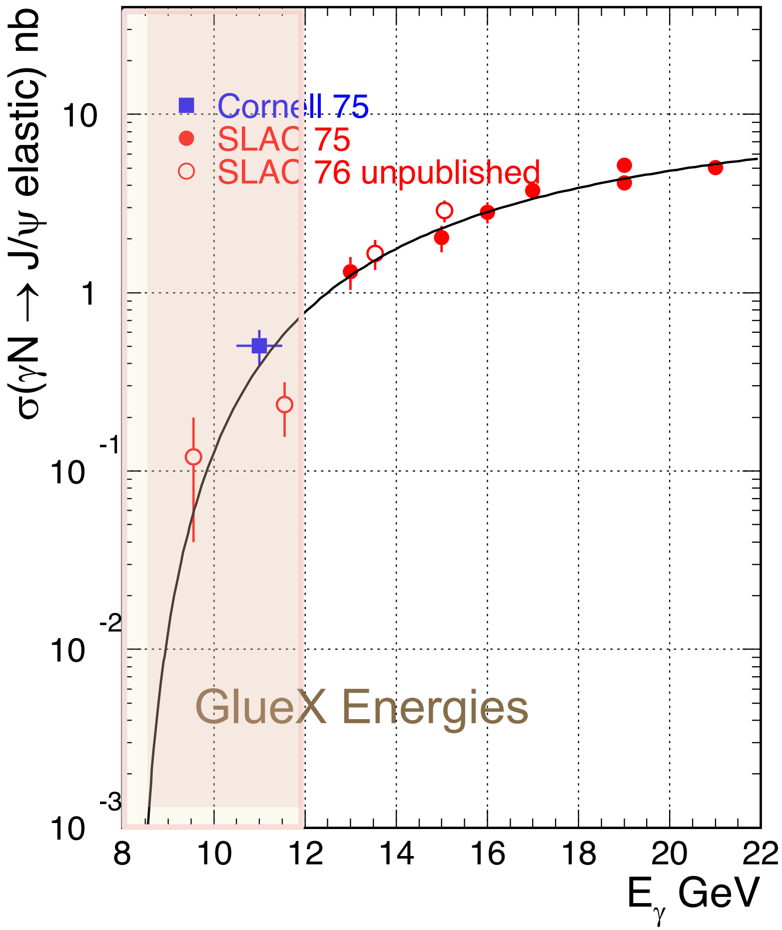
Phys. Rev. C**95**, 042201 (2017)

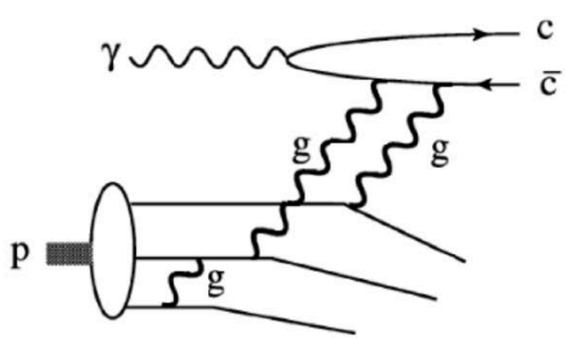
Opportunistic Physics

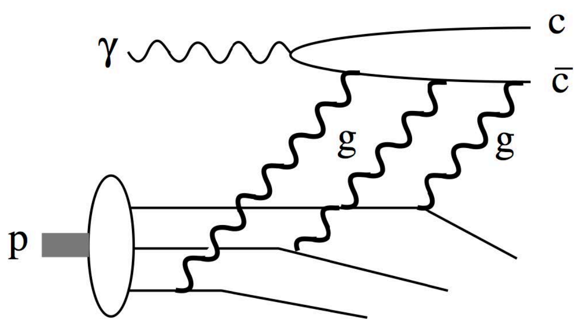
$\gamma p \rightarrow pJ/\psi$

Probes gluon distributions in proton
[Kharzeev et al., NPA 661, 568 (1999)]

Also multiquark correlations
[Brodsky et al., PLB 498, 23 (2001)]







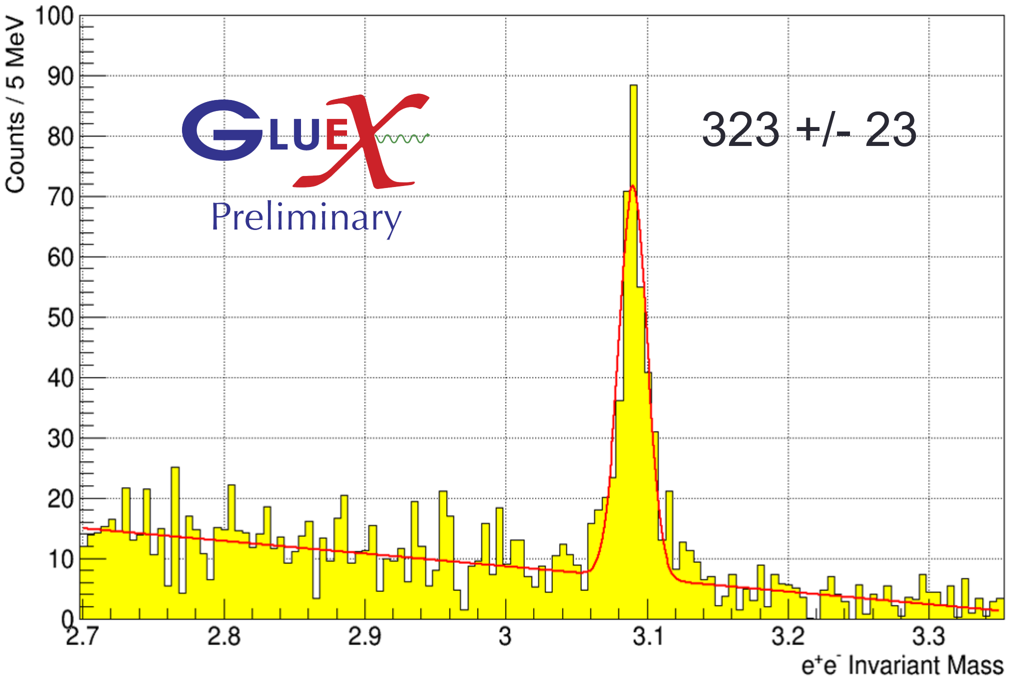
The two mechanisms have different energy dependences near threshold.

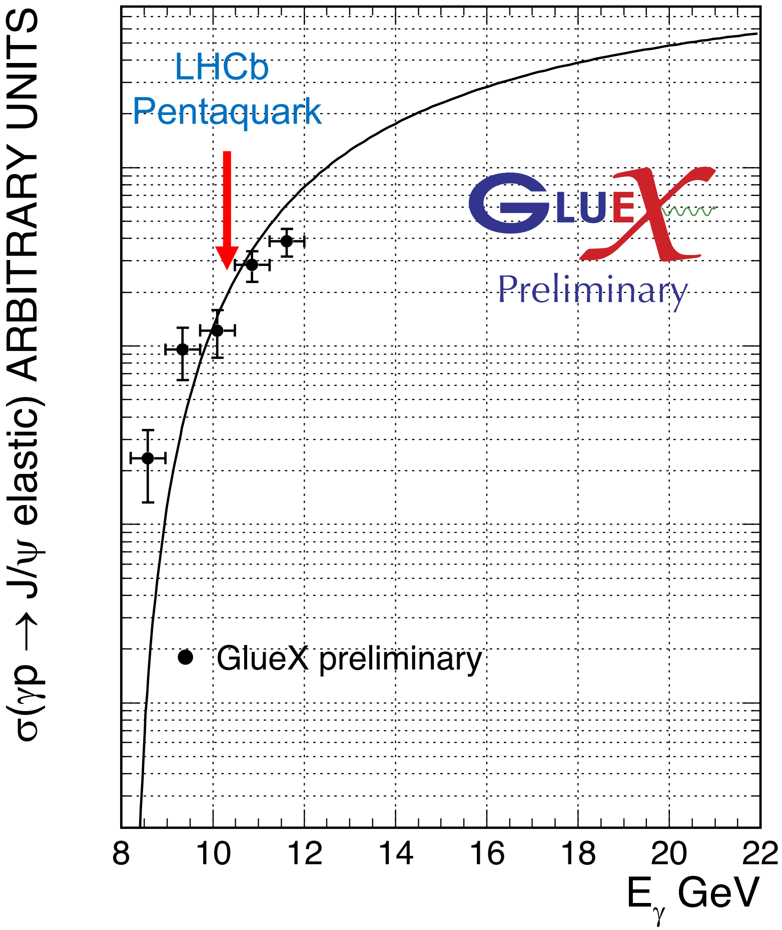
Opportunistic Physics

$\gamma p \rightarrow pJ/\psi$

Detect J/ψ through its e^+e^- decay
(2016 & 2017 Data)

(2016 Data)





(See talk on Friday by Luke Robison.)

Opportunistic Physics

Double-strange baryons: ssu (Ξ^0) & ssd (Ξ^-)

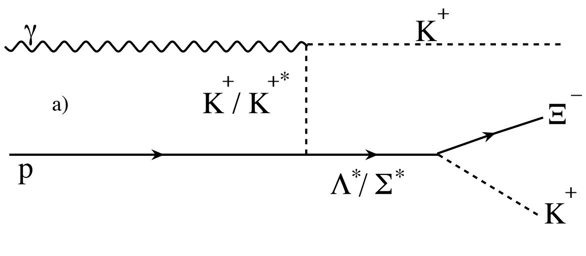
$\Xi(1320)$ $(1/2)^+$ ****
$\Xi(1530)$ $(3/2)^+$ ****
$\Xi(1690)$ ***
$\Xi(1820)$ $(3/2)^-$ ***
$\Xi(1950)$ ***
$\Xi(2030)$ ***

We expect many more of these states to exist, and many are expected to be relatively narrow.

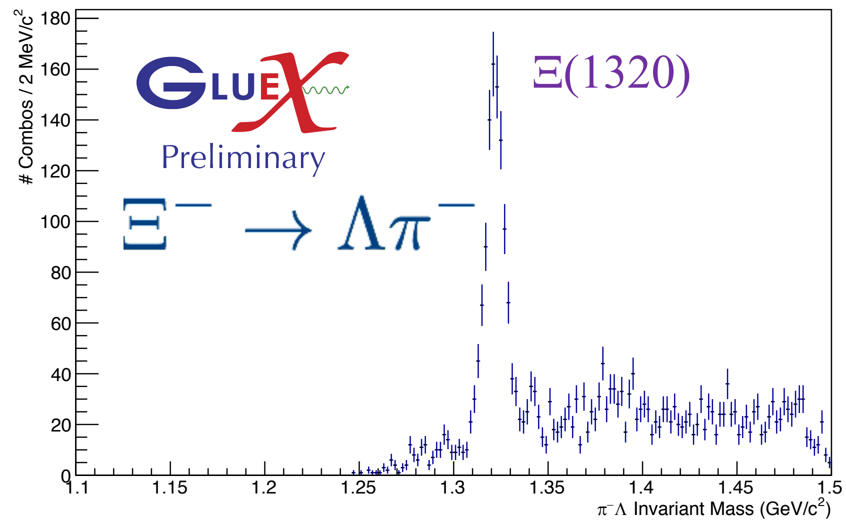
CLAS observed the lightest two in photoproduction at lower energies.

Any observation of a significant “bump” can add significantly to our knowledge of these states.

Opportunistic Physics $\gamma p \rightarrow \Xi^- K^+ K^+$

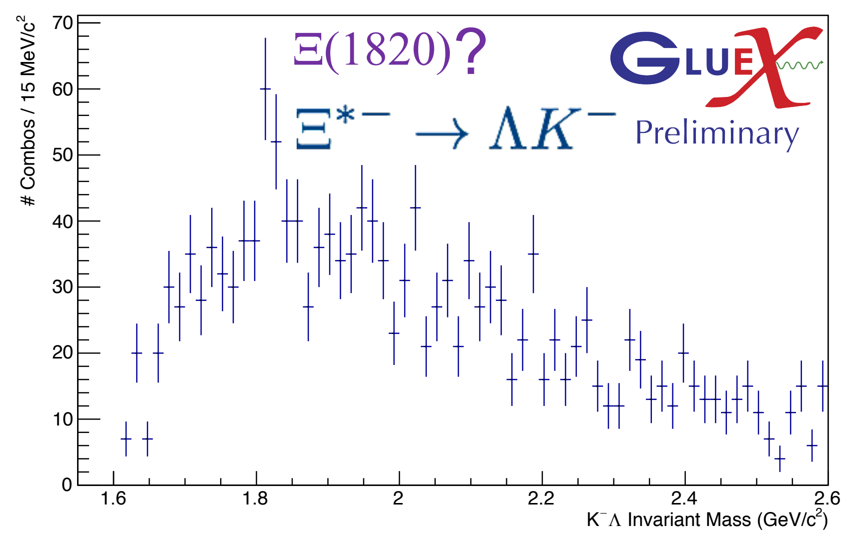


GlueX reconstructs exclusive final states, so decay distributions can be measured.



2017 Data: Expect more than an order of magnitude more data from initial GlueX running.

(See talk on Friday by Ashley Ernest.)



Spin-Density Matrix Elements

$$\gamma p \to p\rho$$

$$\gamma p \to p\omega$$

$$\gamma p \to p\phi$$

Measures the spin transfer from the polarized photon to the vector meson and is sensitive to the production mechanism.

These are important demonstrations of our understanding of the acceptance of the detector.

The can be used to monitor the linear polarization of the photon nearly online.

(See talk on Friday be Alex Barnes.)

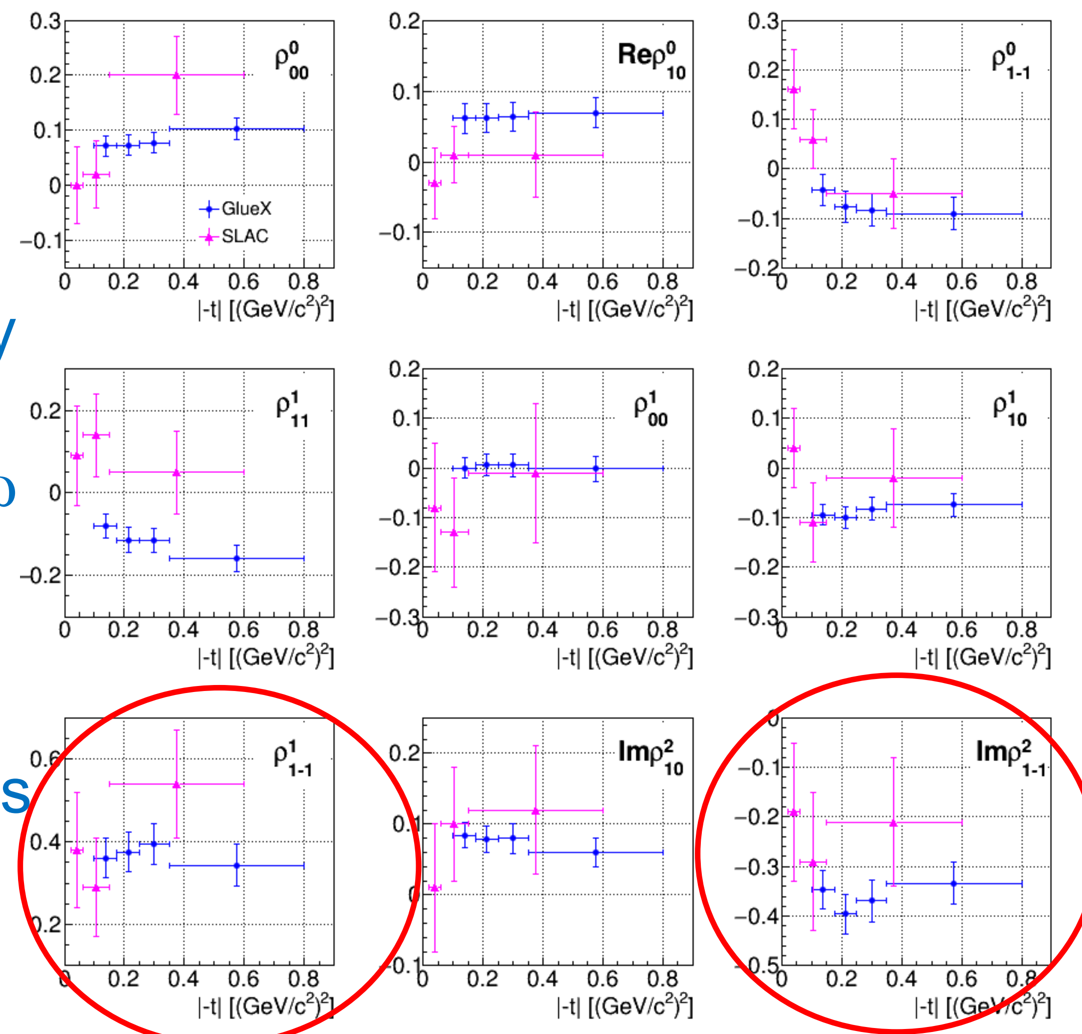
Spin-Density Matrix Elements

Preliminary

$$\gamma p \rightarrow p\omega$$

Two of the elements are very sensitive to the transfer of spin from the photon to the ω meson.

If the exchange is pure “pomeron”, +½ and –½. If it is pure pion exchange, -½ and +½. We see ~.35 and -.35.



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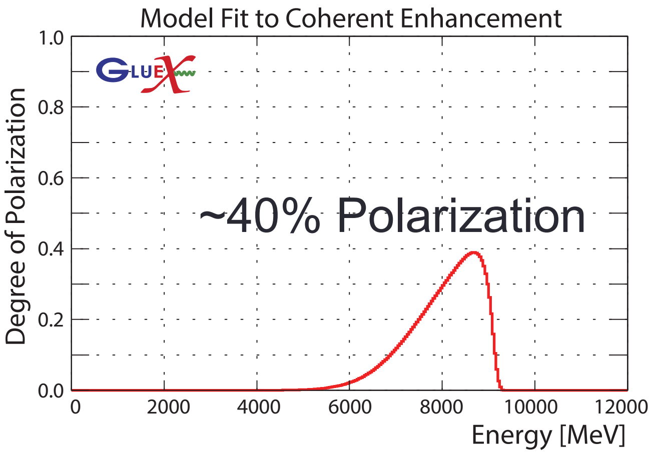
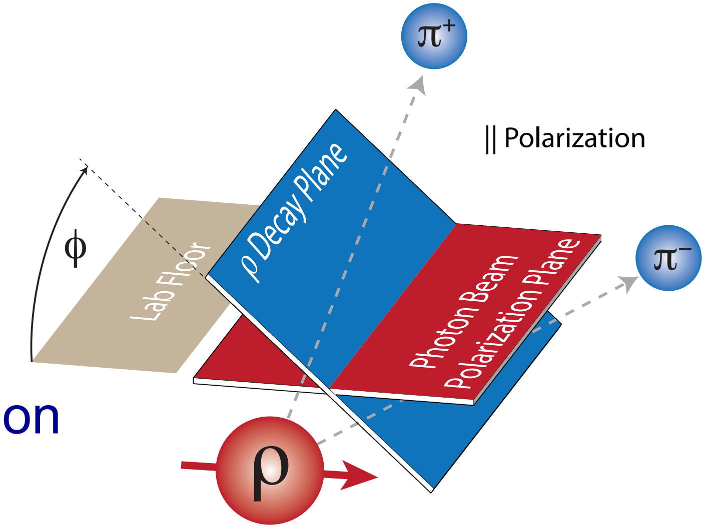
Beam Asymmetry in ρ Photoproduction



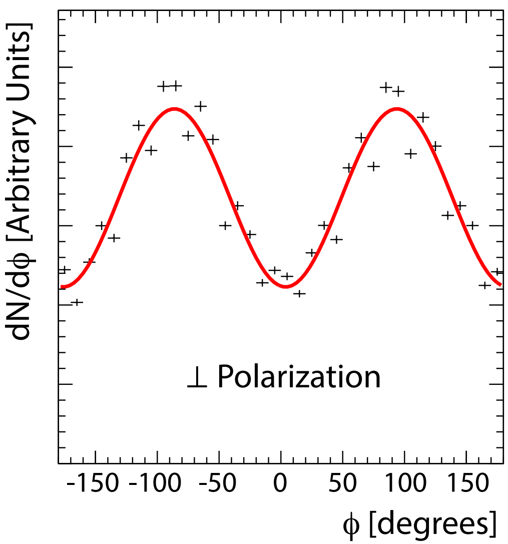
Huge increase in statistics over the existing data from SLAC.

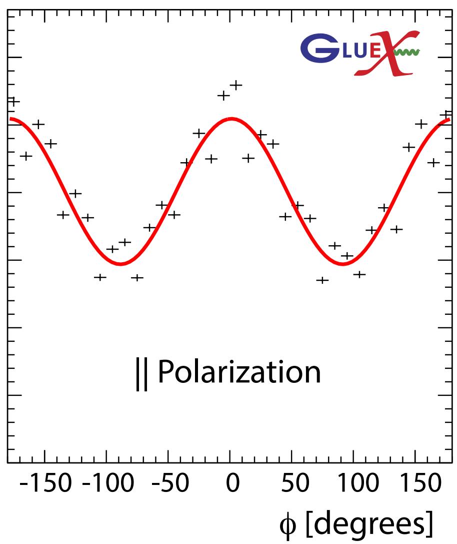
Working with JPAC on models for analysis

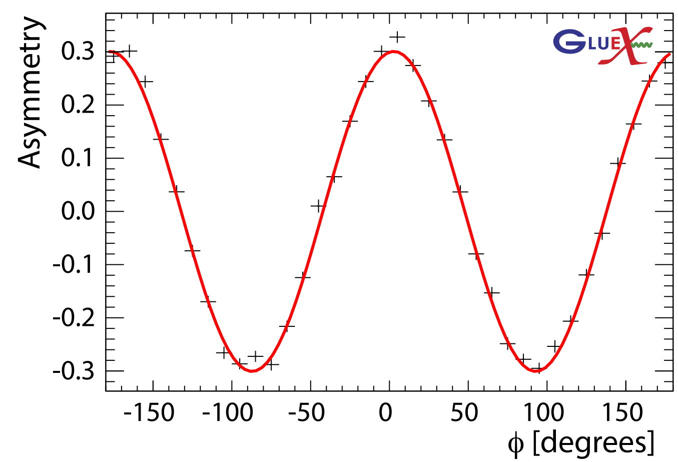


$$d\sigma_\perp \propto 1 - P_\perp \Sigma \cos 2\phi \qquad d\sigma_\parallel \propto 1 + P_\parallel \Sigma \cos 2\phi$$

$$P\Sigma \cos 2\phi = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}$$





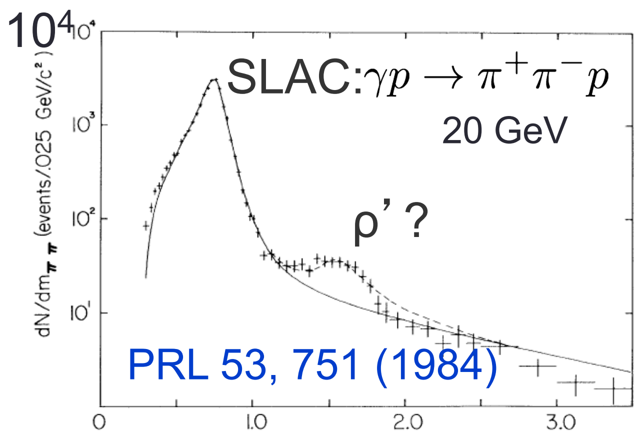


Acceptance errors not included

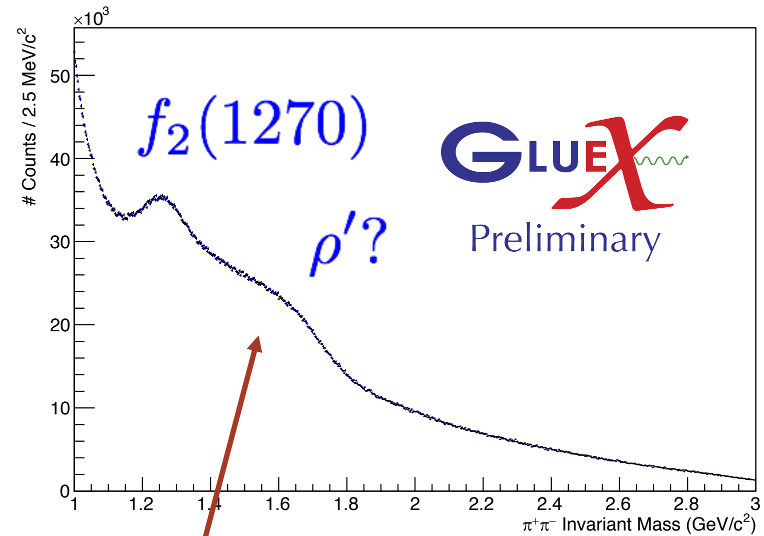
Large polarization transfer to the ρ

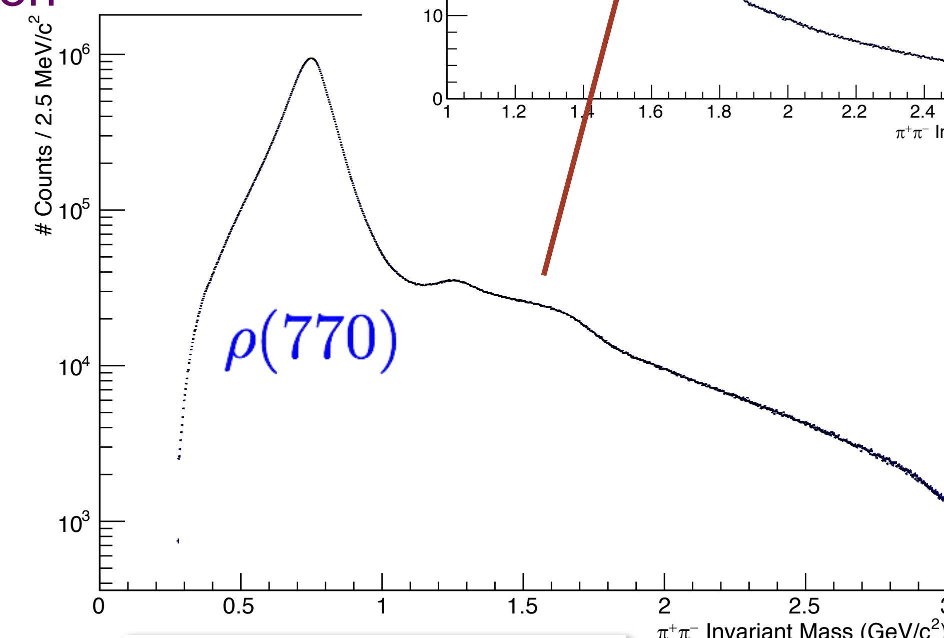
Observed Known States

In the ρ event sample, we can look for higher-mass vector mesons. We observe an enhancement around 1.6 GeV with significantly more statistics than existed; we should be able to measure polarization observables.



$$m_{\pi^+\pi^-}\,[GeV/c^2]$$





$$m_{\pi^+\pi^-}\,[GeV/c^2]$$

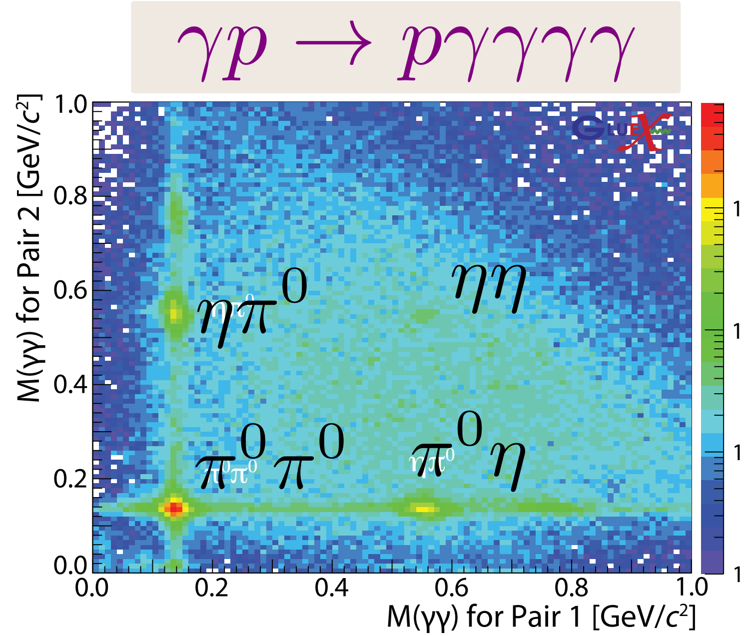
Observed Known States

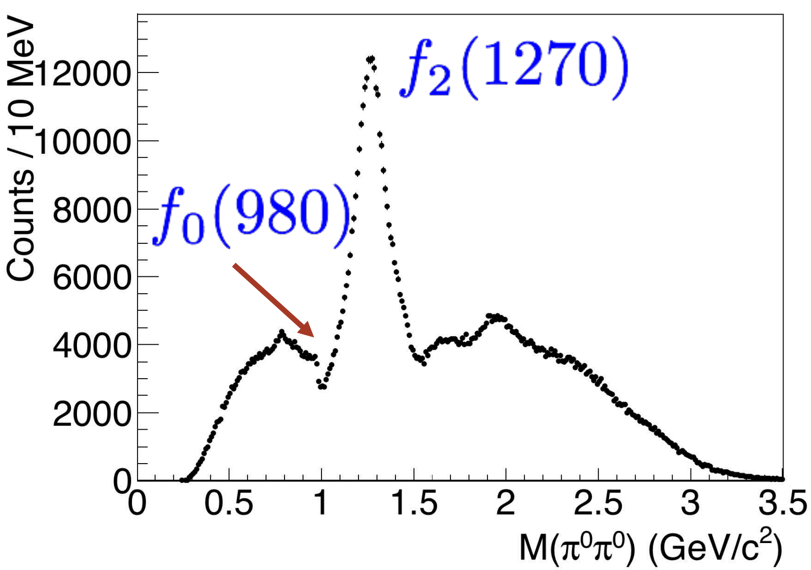
Preliminary

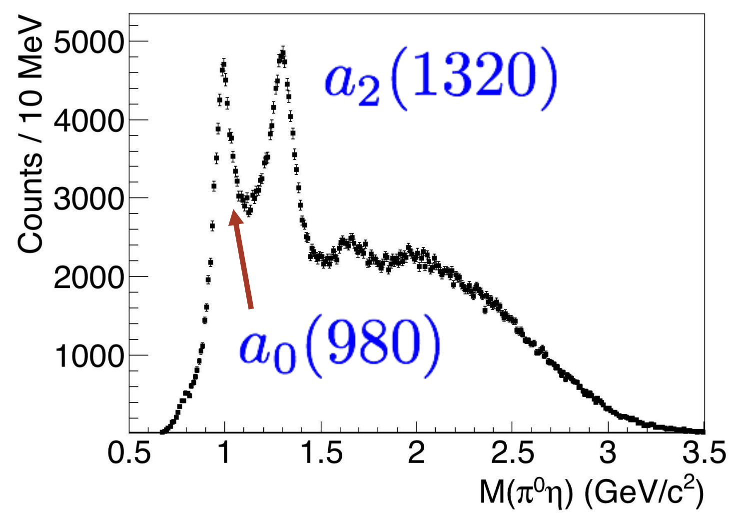
2016 and some 2017 statistics.

Clear signals for $f_0(980)$, $f_2(1270)$, $a_0(980)$ and $a_2(1320)$.

(See talk on Friday by Shuang Han.)







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

Interesting Hybrid Channels

$\gamma p \rightarrow p \eta_1$ $\gamma p \rightarrow p b_2$

$\eta_1 \rightarrow \eta f_2, a_2 \pi$ $b_2 \rightarrow a_2 \pi, \rho \eta$

$\rho \rightarrow \pi\pi$

$f_2 \rightarrow \pi\pi$

$a_2 \rightarrow \eta\pi$

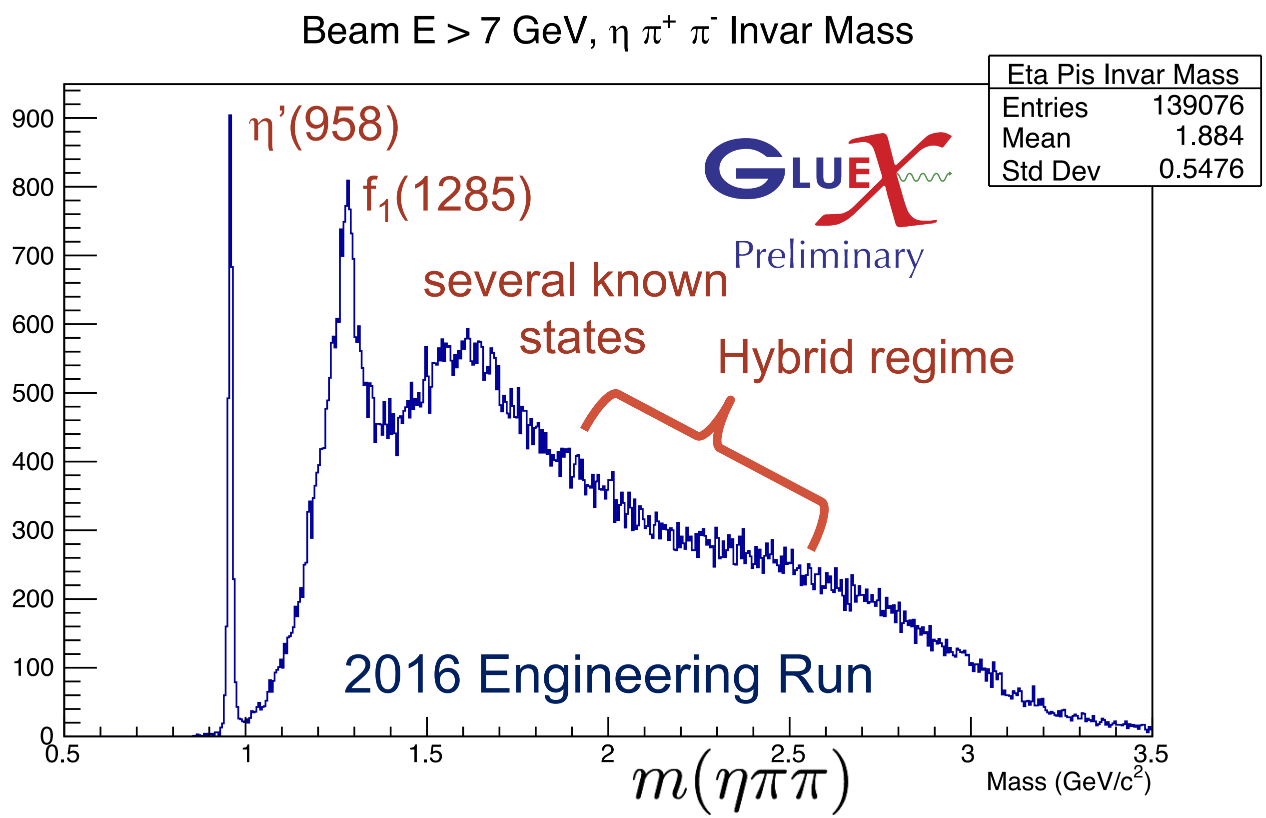
Look for these

$\gamma p \rightarrow p a_2^{\pm} \pi^{\mp}$

$\gamma p \rightarrow p f_2 \eta$

$\gamma p \rightarrow p \rho \eta$

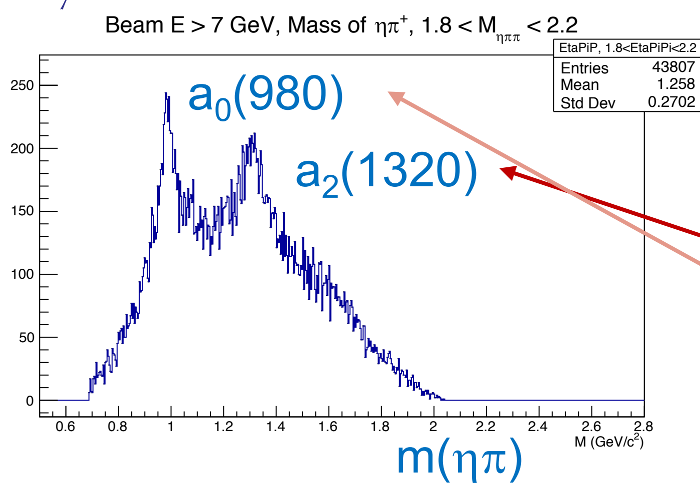
80 hours of beam

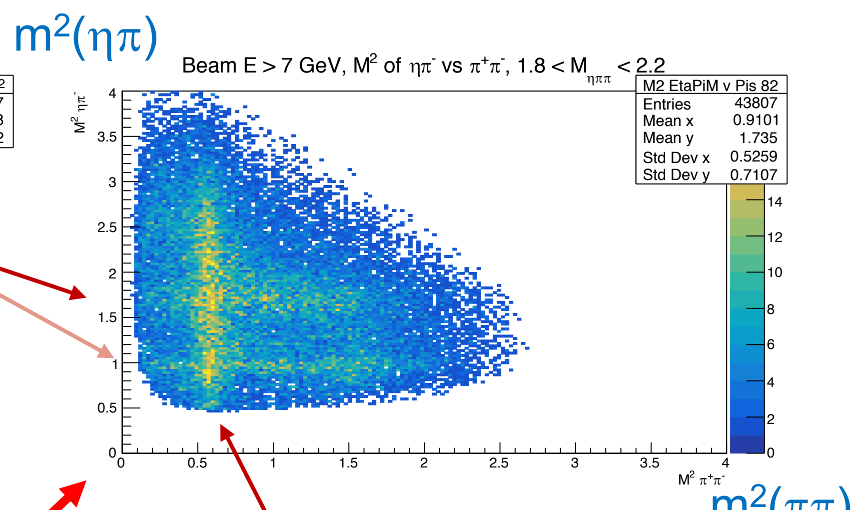


Interesting Hybrid Channels $\gamma p \to p \eta \pi^+ \pi^-$

2016 Engineering Run

GlueX Preliminary





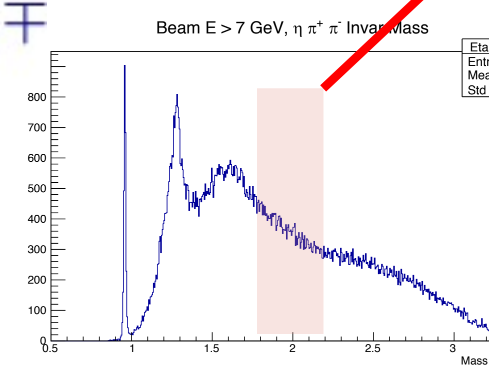
Clear signals for

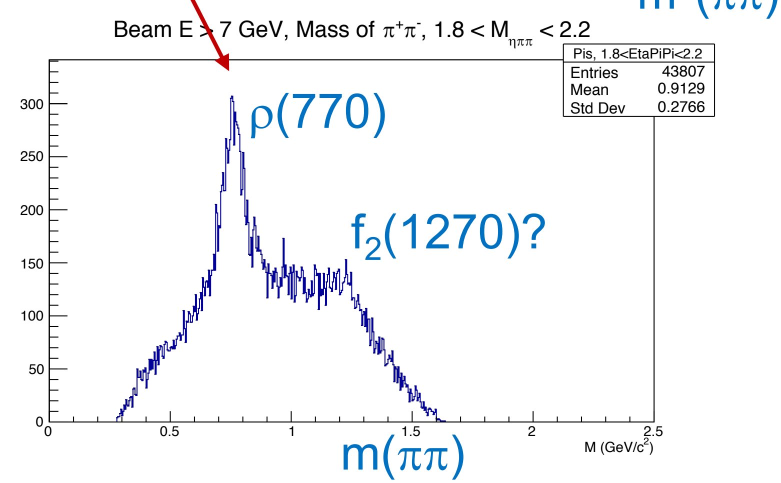
$$\gamma p \to p a_2^{\pm} \pi^{\mp}$$

$$\gamma p \to p \rho \eta$$

Weak signal for

$$\gamma p \to p f_2 \eta$$





Summary

- GlueX is installed, commissioned and started physics running in Spring 2017.
- All detector systems are near to or better than design specifications.
- We have published our first results, and are aggressively moving ahead on other physics measurements.
- The broader program of exotic mesons is in sight.
- A large number of GlueX results as well as related theoretical work will be presented in the GlueX Physics minisymposium on Friday.