# Analysis Plans for the GlueX Experiment

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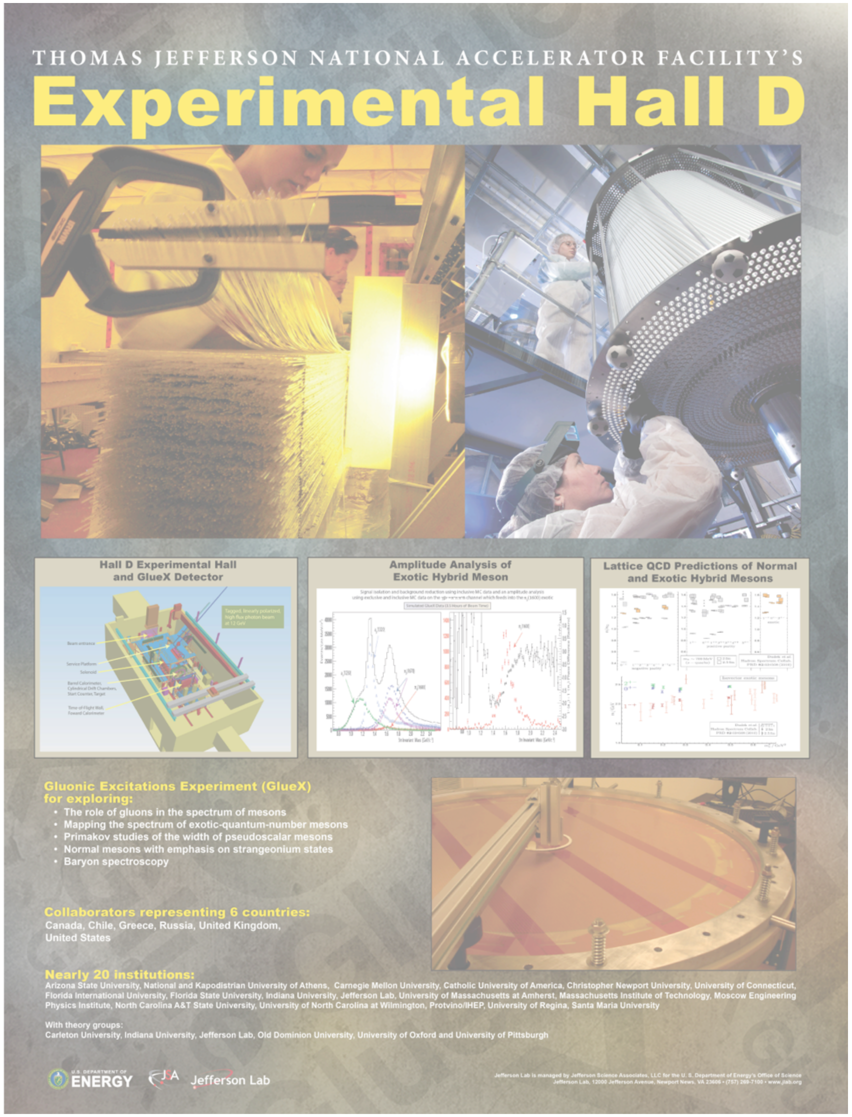
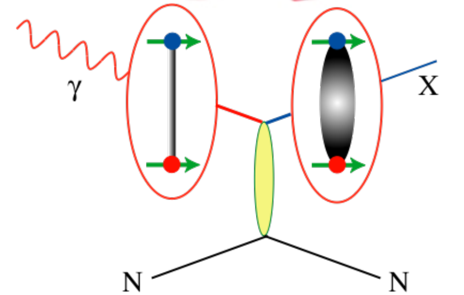
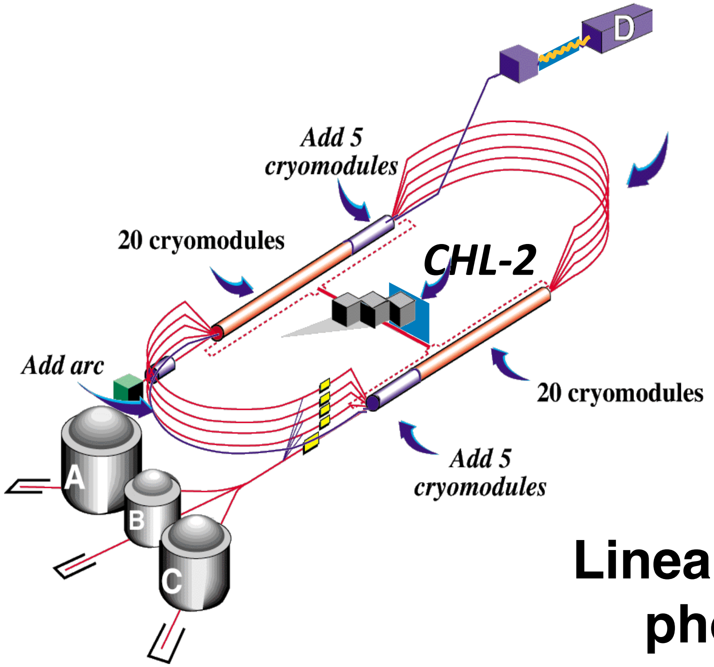
# Outline

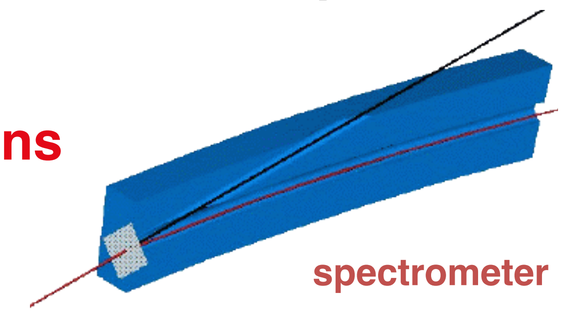



- The GlueX Experiment.
- Exotic Hybrid Mesons.
- Reactions of Interest.
- GlueX Timelines.
- Approaches to Analysis.

# 12-GeV CEBAF – Photoproduction

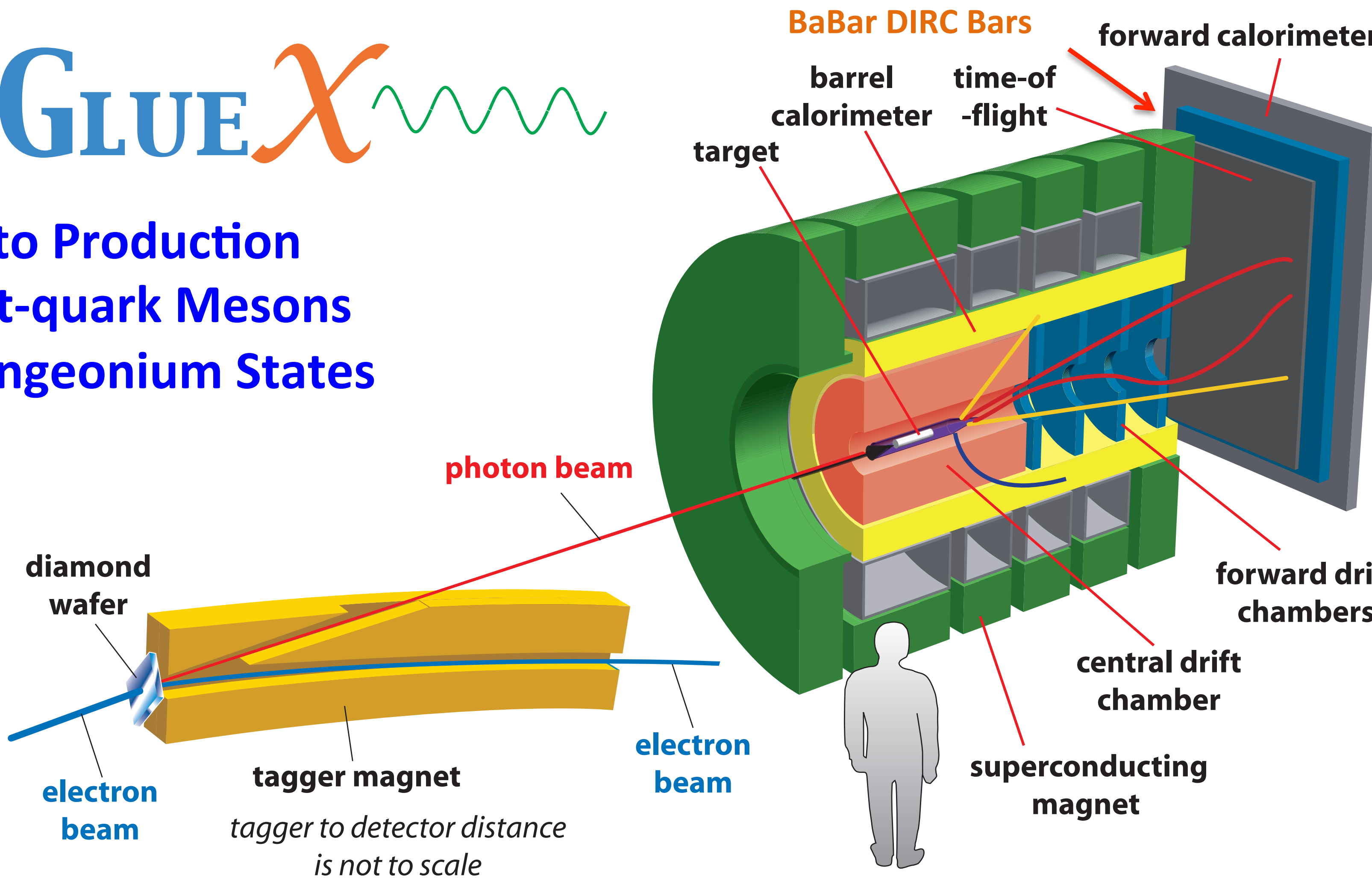



# The GlueX Experiment at Jefferson Lab

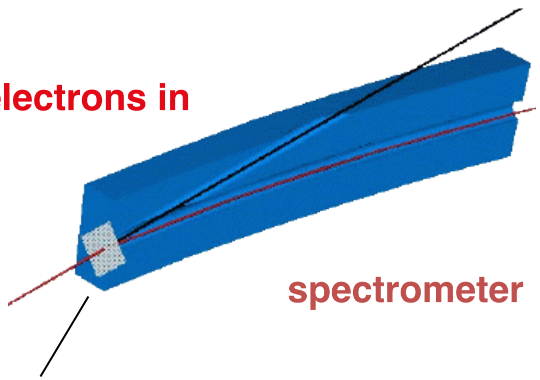
**Photo Production**
**Light-quark Mesons**
**Strangeonium States**

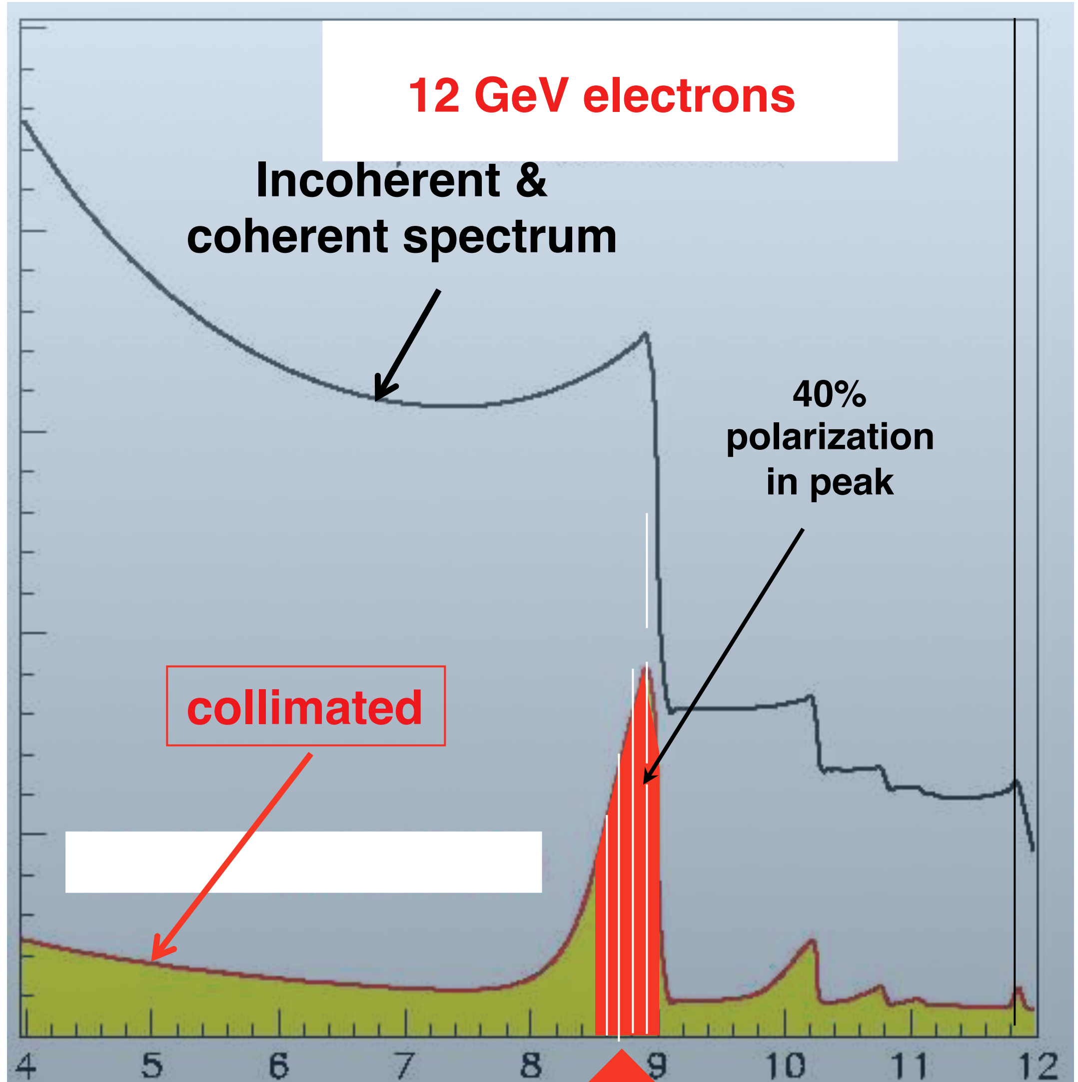



## Physics in 2015

# Coherent Bremsstrahlung

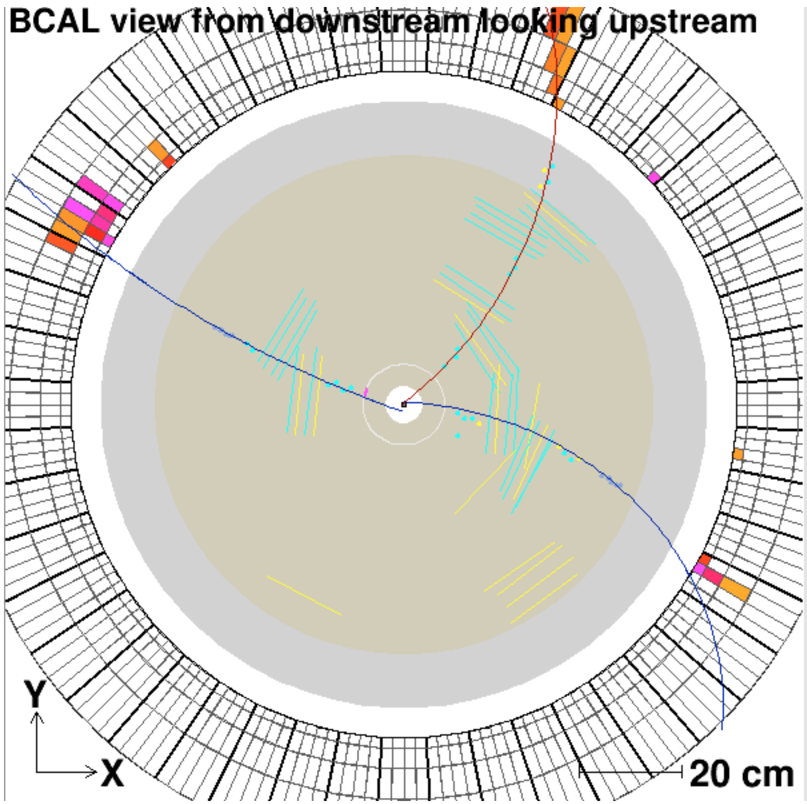
This technique provides requisite energy, flux and polarization

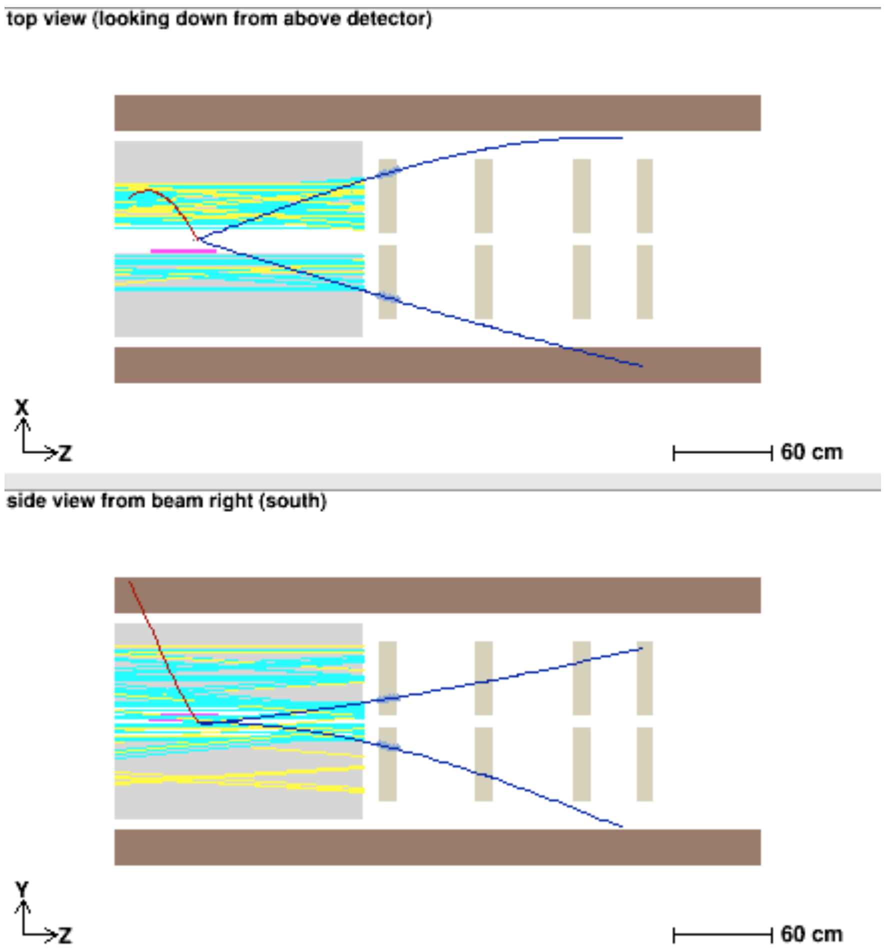


# The GlueX Experiment

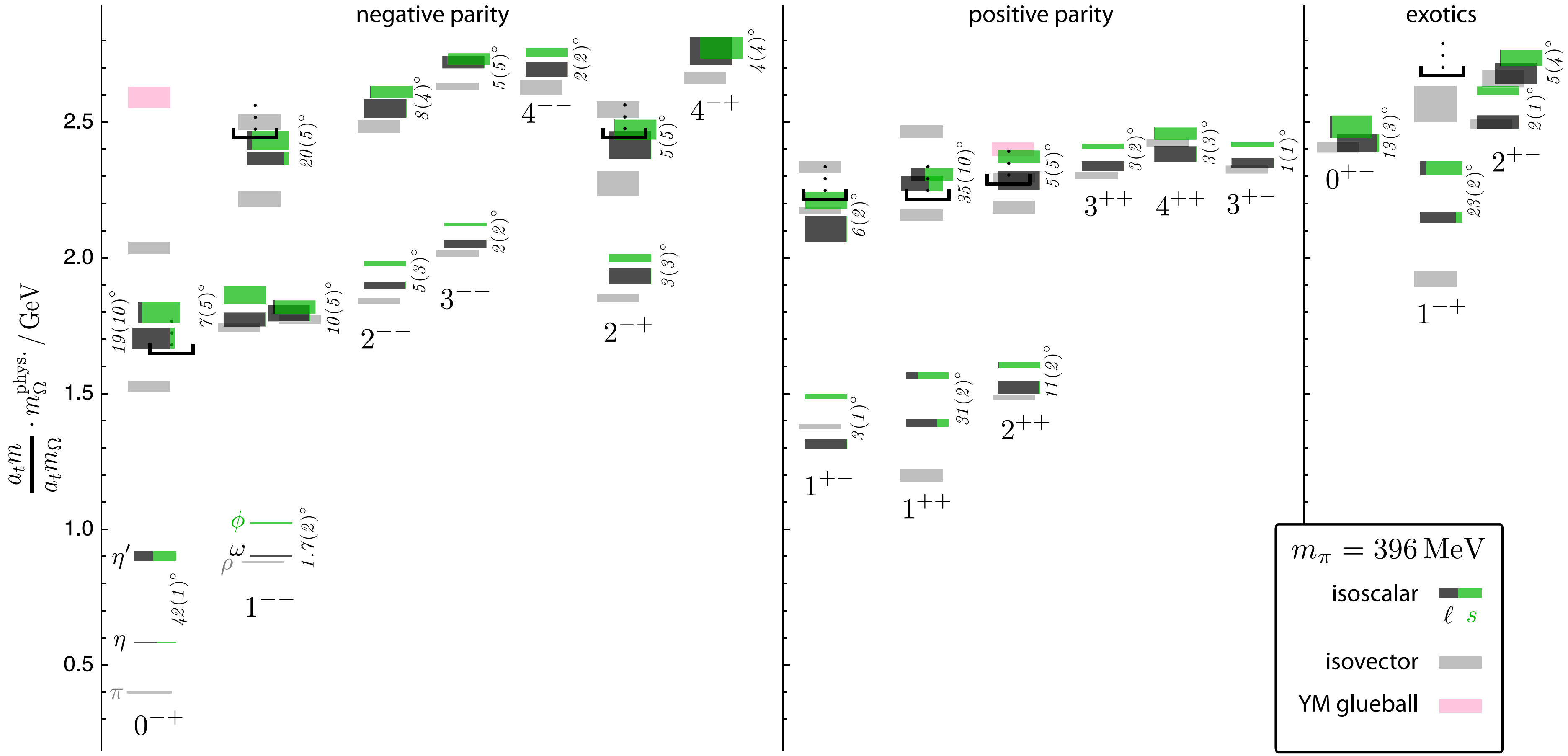
# Ongoing Commissioning Run



# Lattice QCD

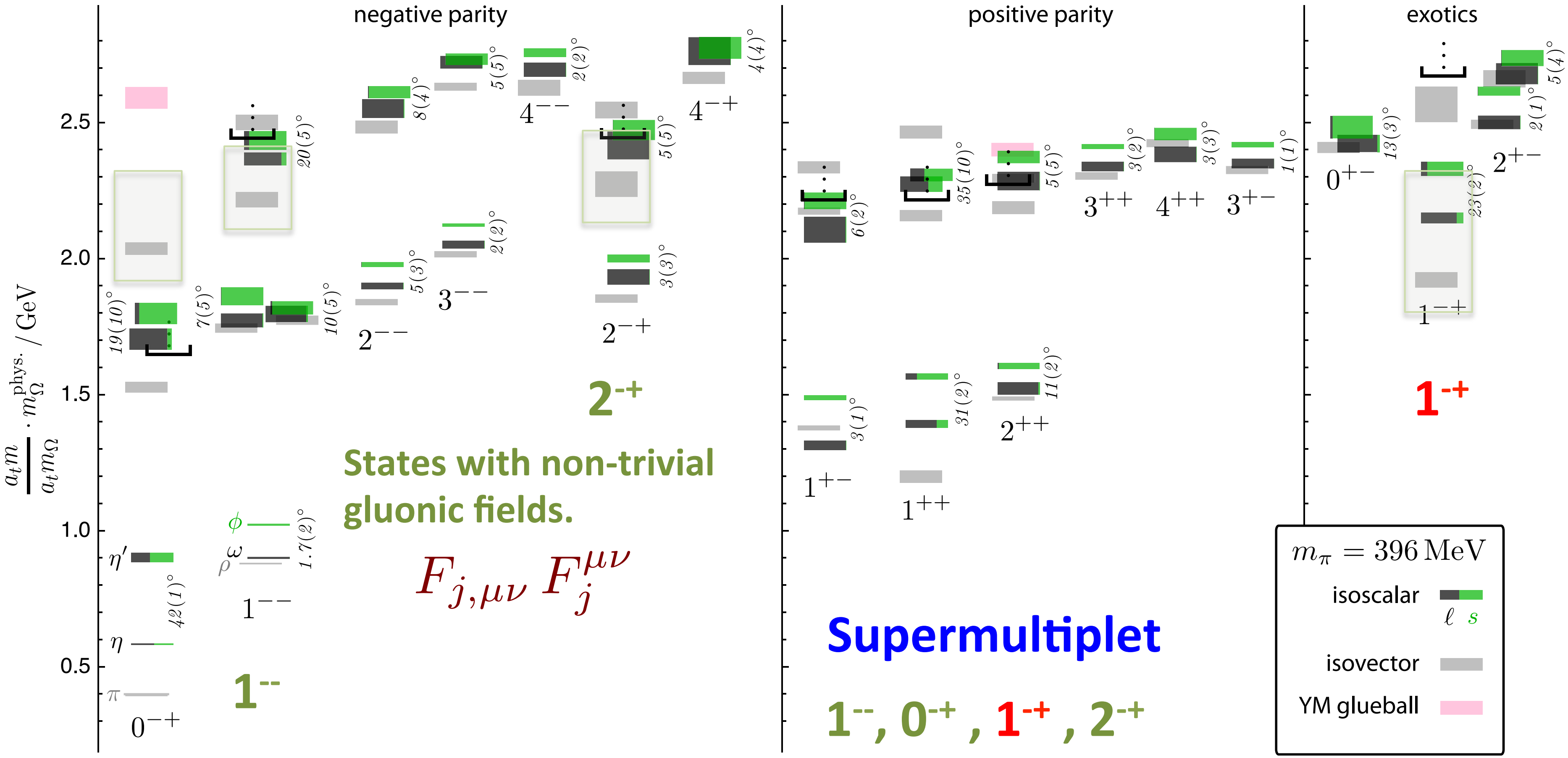
## Light-quark Mesons (u,d,s)




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

# 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**

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

**$0^{-+}$**

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

# Spectroscopy and QCD

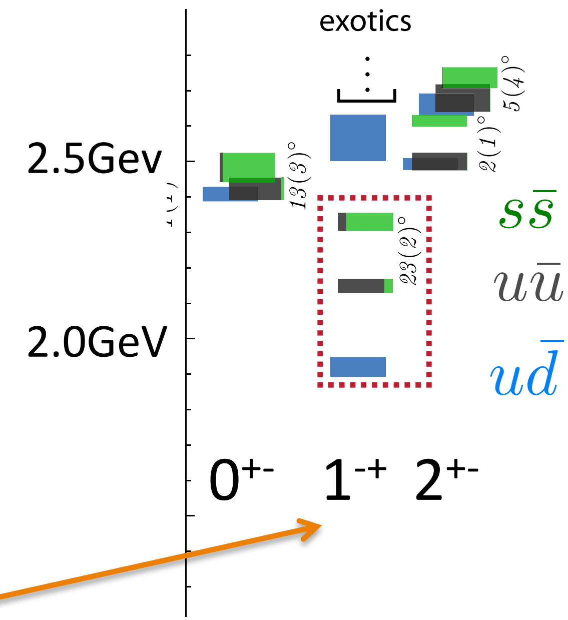
Phys. Rev. D84 (2011) 074023

``Constituent gluon'' behaves like it has $J^{PC} = 1^{+-}$

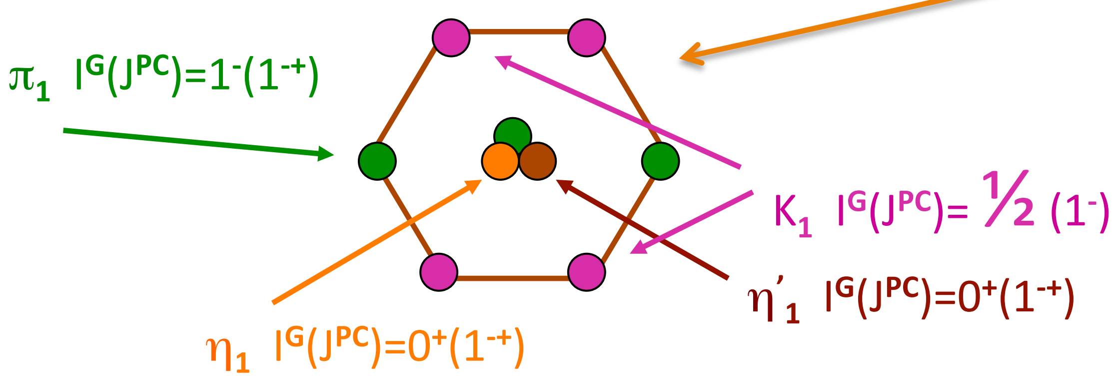
Mass ~ 1-1.5 GeV

Lightest hybrid nonets: $1^{--}$, ($0^{-+}$,$1^{-+}$, $2^{-+}$)

The 0+- and two 2+- exotic nonets and also a second $1^{-+}$ nonet p-wave meson plus a ``gluon''

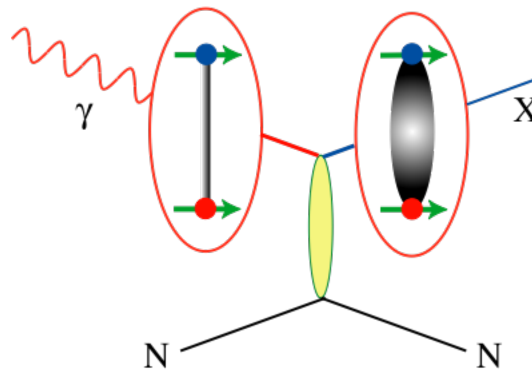



Several nonets predicted



# Expected Decay Modes

$\pi_1 \rightarrow \pi\rho, \pi b_1, \pi f_1, \pi\eta', \eta a_1$
$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1, \eta\eta', \pi(1300)\pi, a_1\pi,$
$\eta_1' \rightarrow K^*K, K_1(1270)K, K_1(1270)K, \eta\eta'$




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

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

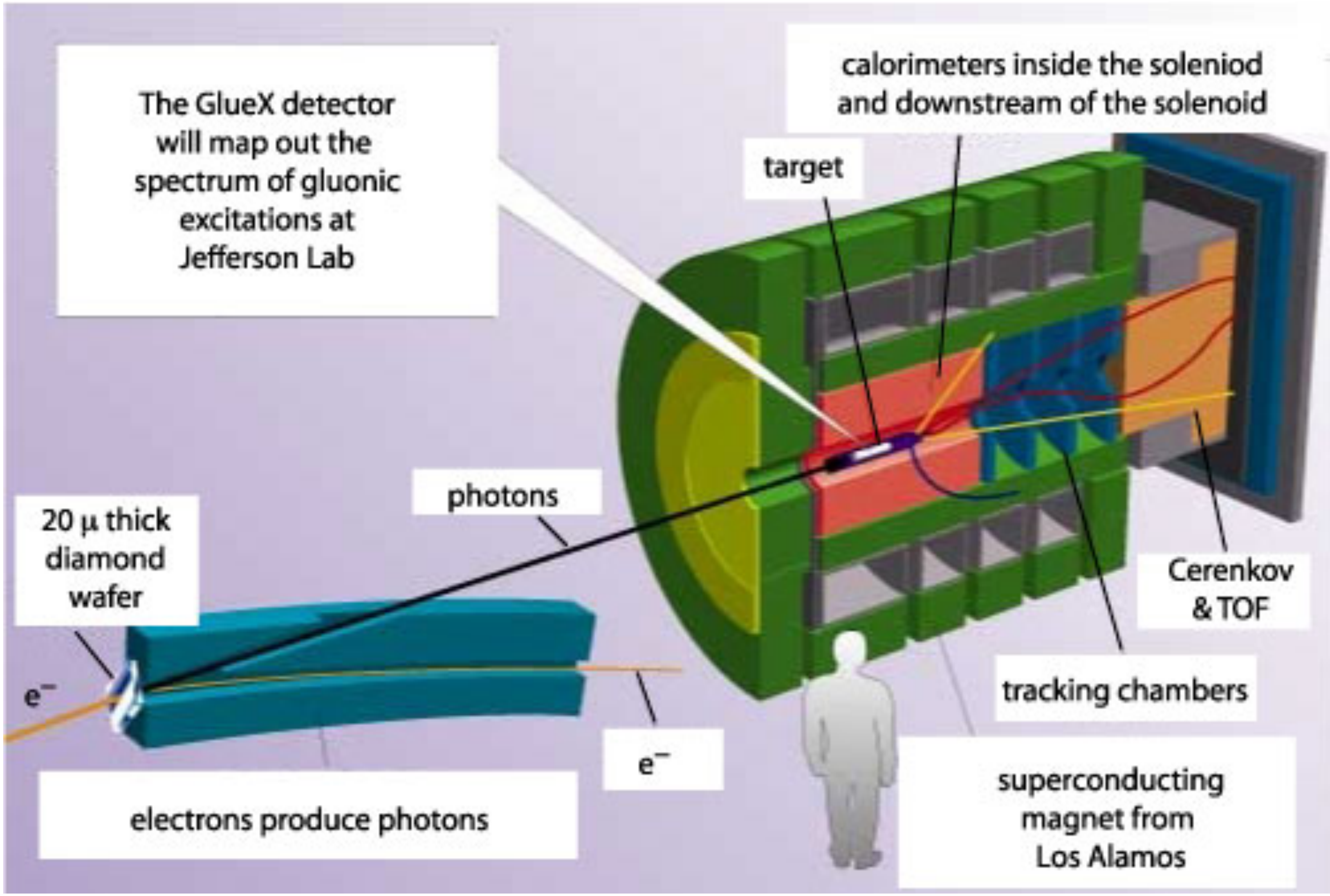
**Early Reach** **With Statistics** **Hard**

Kaons do not have exotic QN's

$n2\pi^+\pi^-$
$n\pi^+\eta$
$n2\pi^+\pi^-\pi^0$
$n2\pi^+\pi^-2\pi^0$
$n2\pi^+\pi^-\eta$
$pK^+K^-$
$pK^+K^-\pi^0$
$pK^+K^-\pi^+\pi^-$
$pK^+K^-\eta$
$pK_SK^\pm\pi^\mp$
$\Lambda K^+n\pi$

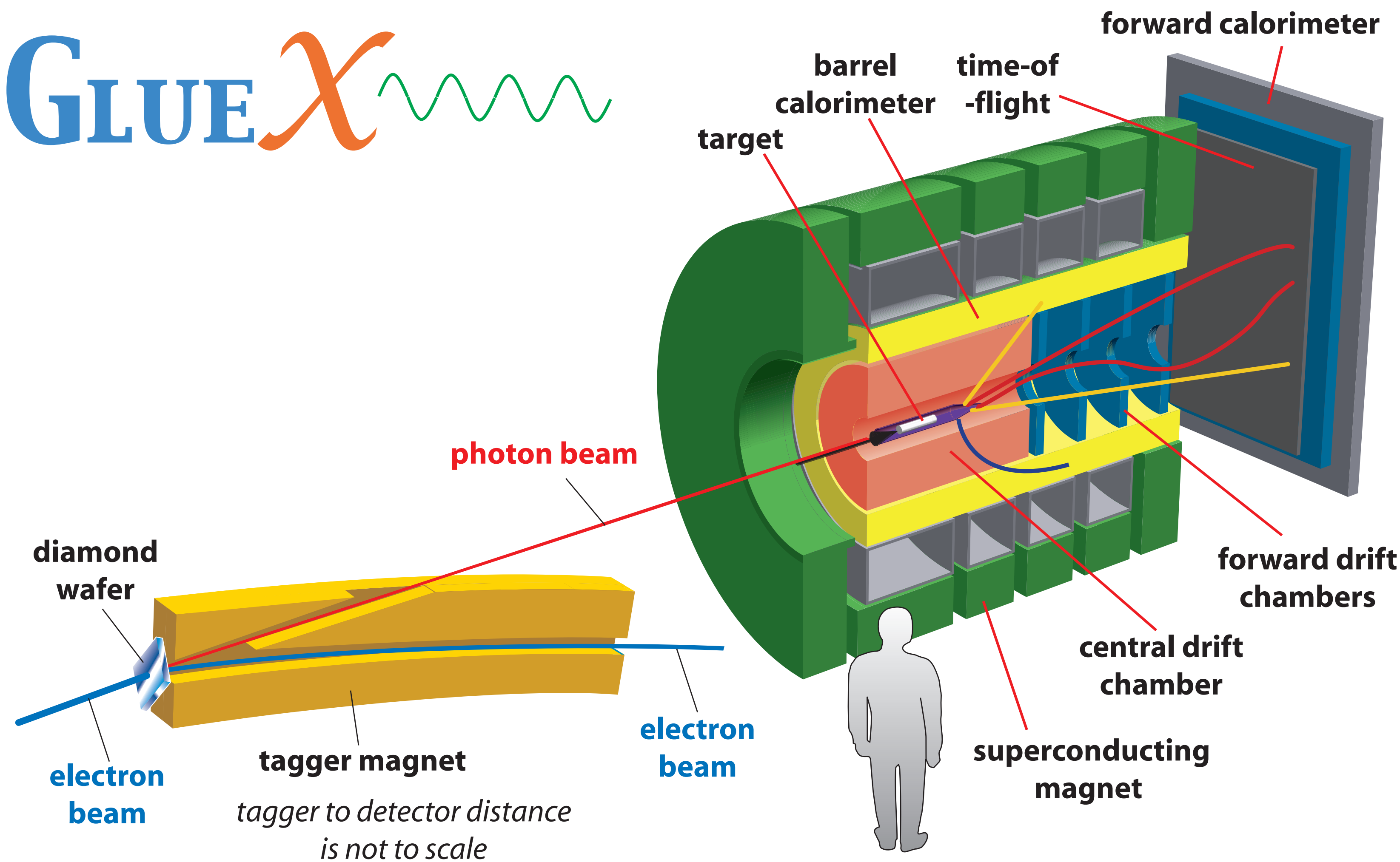
$p\pi^+\pi^-\pi^0$
$p\pi^+\pi^-\eta$
$p\pi^+\pi^-2\pi^0$
$p\pi^+\pi^-3\pi^0$
$p2\pi^+2\pi^-$
$p2\pi^+2\pi^-\pi^0$
$p2\pi^+2\pi^-\eta$

# Forward Kaon Identification



# Forward Kaon Identification

De-scoped in 2008



# Baseline Kaon Identification

Focus on reactions where the recoil **proton is detected.**
At least 4-constraint kinematic fitting possible.

**Train a BDT to isolate final states with kaons.**

$\gamma p \to pK^+K^-$

$\gamma p \to pK^+K^-\pi^+\pi^-$

$\gamma p \to pK^+K_S\pi^- \to pK^+\pi^+\pi^-\pi^-$

$\gamma p \to K^+Y^* \to K^+\Xi^*K$

$\Xi^* \to \Xi\pi\ ,\ K\Lambda$

**Focus on charged final states with kaons.**

$\gamma p \to ph'_2(2600) \to pK_1^+K^- \to pK^+K^-\pi^+\pi^-$

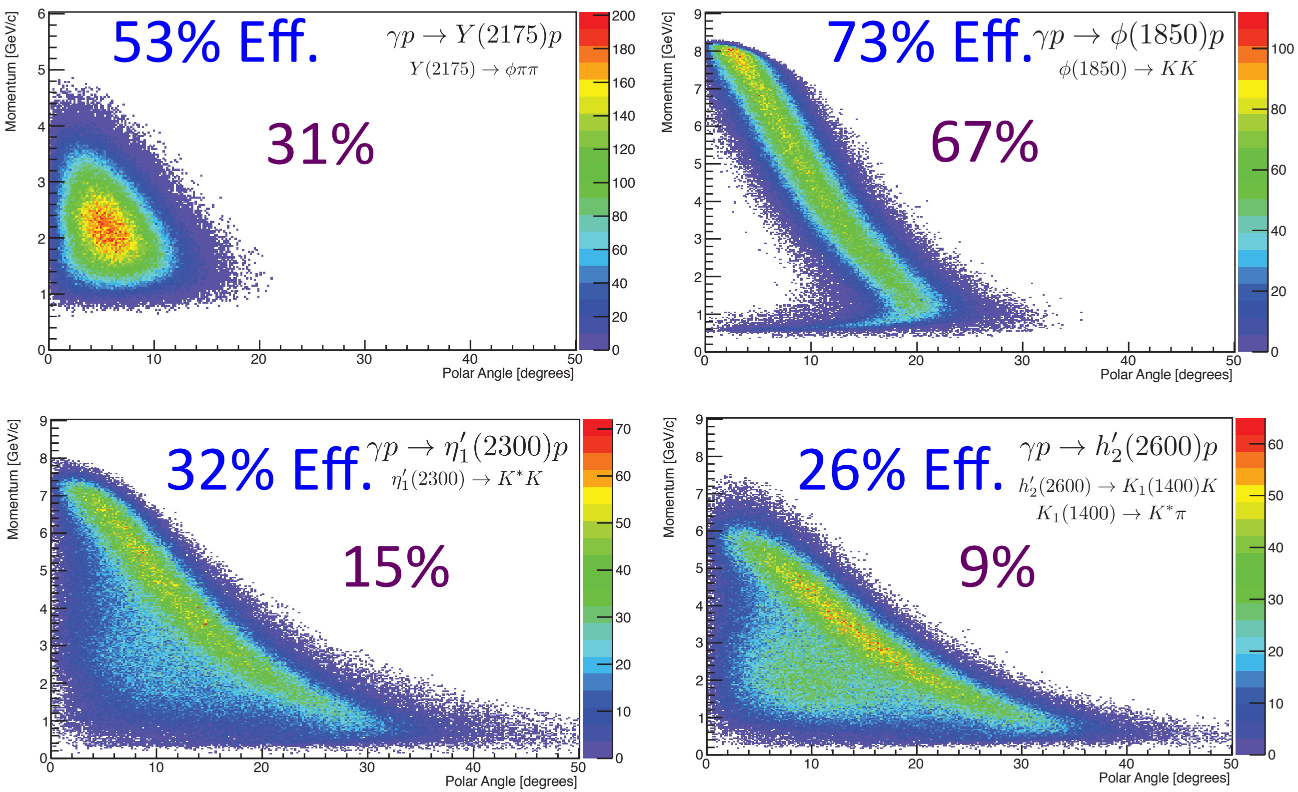
$\gamma p \to p\eta'_1(2300) \to pK^{*0}K_S \to pK^+\pi^+\pi^-\pi^-$

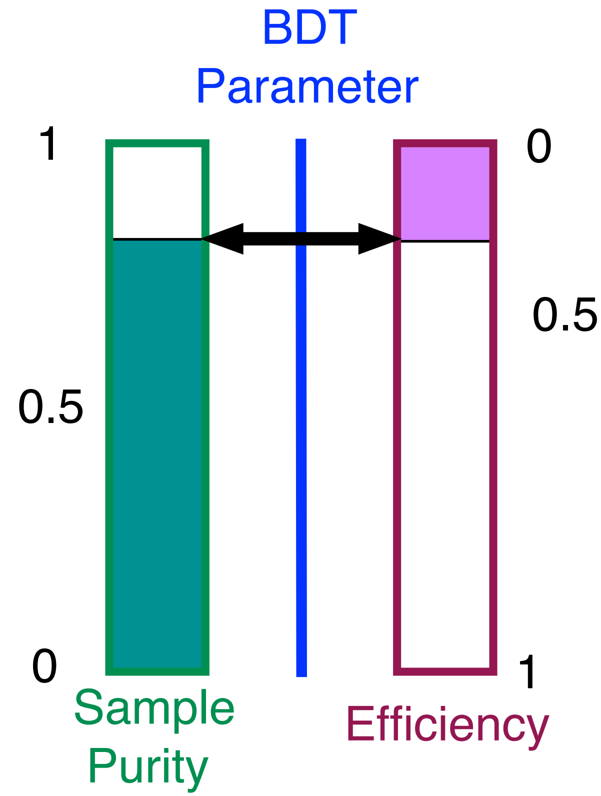
$\gamma p \to pY(2175) \to p\phi f_0 \to pK^+K^-\pi^+\pi^-$

$\gamma p \to p\phi_3(1850) \to pK^+K$

A sampling of related final states

# Global Particle Identification



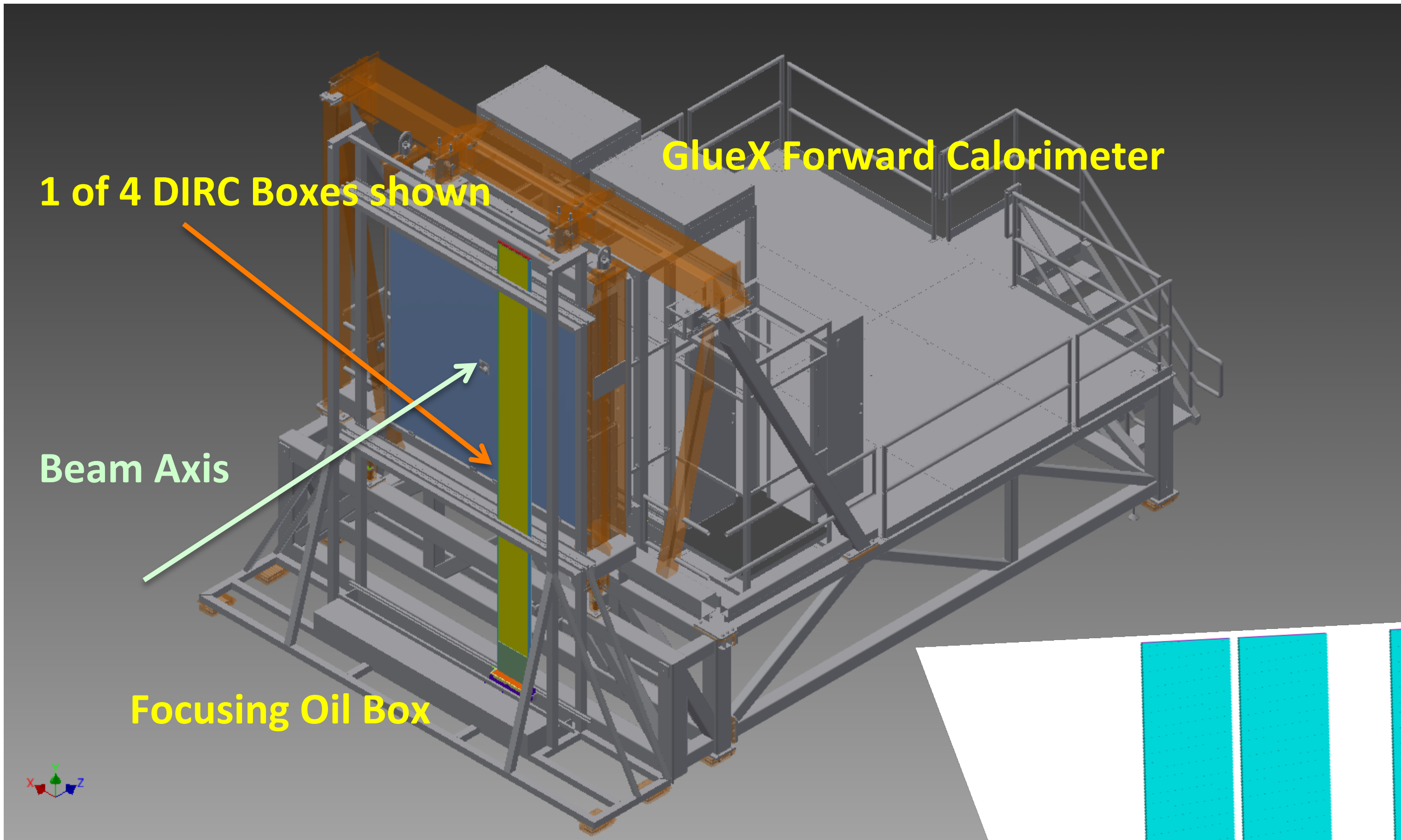

Request 90% purity in the event sample.

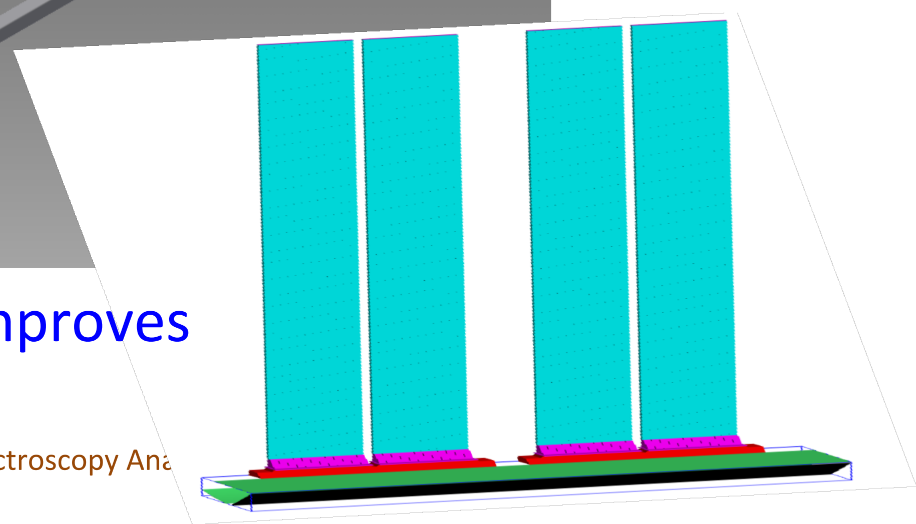
Request 95% purity in the event sample.

The baseline GlueX detector can provide pure kaonic event samples with good efficiency.

# Forward Kaon Identification

In June 2014, GlueX was given four of the twelve BaBar DIRC boxes.



Extends the range of reactions and improves the purity.

# GlueX Running

- GlueX is taking commissioning data now (Phase I).
- There is an engineering/physics run in Spring of 2015 (Phase II).
  - Beam energy is below 12-GeV.
  - Some linear polarization.
  - Hydrogen target.
- Low-intensity physics running in late 2015.
  - 12-GeV electron beam.
  - Linearly polarized photons.
  - Software trigger tests.
- High-intensity physics running starting in 2016.
- Forward kaon identification in 2017.

| Phased Running: | | | | Event Rates | | Data Volume | | Yearly Data Storage | |
|---|---|---|---|---|---|---|---|---|---|
| Phase | Rate $\gamma$/s | Year | $E_e$ GeV | Raw kHz | DST kHz | Raw MB/s | DST MB/s | Raw PB | DST PB |
| I | $10^6$ | 2014 | 10 | 2 | 0.1 | 30 | 1.5 | 0.1 | 0.1 |
| II | $10^7$ | 2015 | 11 | 20 | 1 | 300 | 15 | 0.8 | 0.2 |
| III | $10^7$ | 2015 | 12 | 20 | 2 | 300 | 30 | 1.6 | 0.2 |
| IV | $5\ 10^7$ | 2016 | 12 | 20 | 10 | 300 | 150 | 1.6 | 1.0 |

# GlueX Physics Analysis

GlueX is ready to do physics and several analyses are already being worked out using the full suite of GlueX/Hall-D software and data from large-scale data challenges.

Physics reactions of interest:

| Understand the detector | Initial exotic hybrid searches | Strange Baryons |
| --- | --- | --- |
| $\gamma p \to \pi^0 p$ | $\gamma p \to \eta\pi(n,p)$ | $\gamma p \to K^+\Lambda$ |
| $\gamma p \to \eta p$ | $\gamma p \to \eta'\pi(n,p)$ | $\gamma p \to K\Sigma$ |
| $\gamma p \to \rho p$ | $\gamma p \to \rho\pi(n,p)$ | $\gamma p \to KK\Xi$ |
| $\gamma p \to \omega p$ | $\gamma p \to \omega\pi(n,p)$ | |
| $\gamma p \to \eta' p$ | $\gamma p \to \omega\pi\pi(n,p)$ | |
| $\gamma p \to \phi p$ | $\gamma p \to \eta\pi\pi(n,p)$ | |

# Key First Measurements

Demonstrate that we understand the detector and the reconstruction software.

$$\gamma p \to (\eta, \omega, \eta')p$$

Measure cross sections and polarization observables.

$$\frac{d\sigma}{d\Omega} \quad \Sigma \quad \rho_{ij}^{0,1,2}$$

Meson ``two body” final states.

$$\gamma p \to (\pi, \eta, \omega, \eta')\pi p$$

The $\eta\pi$ and $\eta'\pi$ reactions are of high interest.

# Interesting for Exotic Searches

$\gamma p \to \pi\pi\pi p$ $\qquad$ $X \to \rho\pi, f_2\pi, \pi\pi\pi \ldots$

Lots of challenges in this reaction. No signal in CLAS at 5GeV.

$\gamma p \to \eta\pi\pi p$ $\qquad$ $X \to \rho\eta, f_2\eta, a_2\pi, \eta\pi\pi \ldots$

Couples to a number of exotic hybrids through several decay paths. In principle, these can couple to $\pi_1$, $\eta_1$, $b_2$, $h_2$

**These channels should provide a framework to test new amplitudes developed for these.**

# Amplitude Analysis

Describe the process of producing a particular final state as a set of possible amplitudes : $\mathcal{A}_j(\gamma p \rightarrow p\pi^+\pi^-\pi^0)$

E.g. $\mathcal{A}_1(\gamma p \rightarrow pX_i \rightarrow p\rho^+\pi^- \rightarrow p\pi^+\pi^-\pi^0)$

Build a total amplitude by coherently summing all the individual amplitudes. This total amplitude yields a probability that the given sum describes a particular event ``k''.

$\mathcal{N}$ is a normalization factor and
$a_j$ are complex coefficients.

$$P(e_k) = \frac{1}{\mathcal{N}} \left| \sum_j a_j \mathcal{A}_j(e_k) \right|^2$$

Form the likelihood $\ln \mathcal{L} = \sum_k \ln P(e_k)$ and then minimize the natural log of it with respect to the $a_j$. This is a CPU-intensive problem that appears to scale well on graphical processor units (**GPUs**). To do this requires the four-vectors of all events plus a comparable Monte Carlo data sample to do the normalization.

# Amplitude Analysis

- We generally try to find the smallest set of $a_j$ to describe the data.
- This is done summing over all of the experimental and simulated data.
- We look at the amplitudes described by each of the partial waves and look for intensity and phase motion between them.

# Observables

- What if we take a very large number of ,
  but do not attribute meaning to the individual ones. Instead, we try to extract the complex amplitude.

$$A_{tot} = \sum_j a_j A_j$$

- It is easier to compare a model to an observable than to the original data.
- With a good model, one can then fit the data directly.

# Amplitudes Lead to Observables

- What are the observables that can be measured in a reaction?
- $A_{tot}$ has indices associated with initial and final spin states.
  - Cross sections. $$\frac{d\sigma}{d\Omega} \propto A_{tot} A^*_{tot}$$
  - Spin Observables. Sum over A's with flipped spin indices.
  - Moments ….

# Example of ω Photo Production

We use a ``complete set'' of s-channel amplitudes: $\mathcal{A}^{J^P}_{m_i,m_\gamma,m_f,m_\omega}$

Build a total amplitude as:

$$\mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha}) \approx \sum_{j=\frac{1}{2}}^{\frac{21}{2}} \sum_{P=\pm} \mathcal{A}^{J^P}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha})$$

Essentially fit the intensity of each event, x, with complex coefficients α

$$I_i = \sum_{m_i,m_\gamma,m_f} \left| \sum_{m_\omega} \mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha}) \right|^2$$

$$N = \sum_{m_i,m_\gamma,m_f} \left| \sum_{M} \mathcal{A}_{m_i,m_\gamma,m_f,M} \right|^2$$

Proportional to cross section

$$\rho^0_{MM'} = \frac{1}{N} \sum_{m_i,m_\gamma,m_f} \mathcal{A}_{m_i,m_\gamma,m_f,M} \mathcal{A}^*_{m_i,m_\gamma,m_f,M'}$$

SDMEs

# Example of ω Photo Production

Total amplitude is an excellent description of all the data in all of its dimensions:

$$\mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha}) \approx \sum_{j=\frac{1}{2}}^{\frac{21}{2}} \sum_{P=\pm} \mathcal{A}^{J^P}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha})$$

However, the fit coefficients $\alpha_i$ may have no physics meaning, they are just fitting parameters.

Because the amplitude does describe the data, it can be used to project observables.

The method handles both circularly and linearly polarized photons on an event-by-event basis.

# Example of ω Photo Production

- The method also does detector acceptance automatically. Use the fit parameters to determine the intensity of a given event.

$$I_i = \sum_{m_i,m_\gamma,m_f} \left| \sum_{m_\omega} \mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\vec{x},\vec{\alpha}) \right|^2$$

- The acceptance for a set of events near some event, $\vec{x}$ is

$$Acc(\vec{x}) = \frac{\sum_{i=1}^{N_{acc}} I_i}{\sum_{j=1}^{N_{th}} I_j}$$

Sum over accepted MC events

Sum over generated MC events

# Extensive Program in CLAS

PHYSICAL REVIEW C **80**, 045213 (2009)
**Differential cross sections for the reactions $\gamma$ *p* → *p*$\eta$ and $\gamma$ *p* → *p*$\eta'$**

PHYSICAL REVIEW C **80**, 065208 (2009)
**Differential cross sections and spin density matrix elements for the reaction $\gamma$ *p* → *p*$\omega$**

PHYSICAL REVIEW C **81**, 025201 (2010)
**Differential cross section and recoil polarization measurements for the $\gamma$ *p* → *K*+$\Lambda$ reaction using CLAS at Jefferson Lab**

PHYSICAL REVIEW C **82**, 025202 (2010)
**Differential cross sections and recoil polarizations for the reaction $\gamma$ *p* → *K*+$\Sigma$0**

PHYSICAL REVIEW C **89**, 055208 (2014)

**Data analysis techniques, differential cross sections, and spin density matrix elements for the reaction $\gamma$ *p* → $\phi$*p***

PHYSICAL REVIEW C **83**, 055208 (2011)
**Polarization observables in the longitudinal basis for pseudo-scalar meson photoproduction using a density matrix approach**

**Measurement of SDMEs for $\gamma$ *p* → *p*$\omega$ using linearly polrized photons**

**Differential cross section and SDME measurements for the $\gamma$ *p* → *K*+$\Lambda(1520)$**

# What are the Observables?

- Can we define observables that can be extracted independent of a partial-wave interpretation of a particular reaction?

- With such observables, many (complicated) models of the data can be tested.

- A smaller subsets of vetted models can then be used to directly confront the data.

# Summary

- GlueX is very close to having its first physics data.
- Amplitude analysis issues will quickly move into the forefront of our experimental efforts.
- The work being done now will be crucial to our ultimate success.
- Can we define observables that make sense?