Mapping the Spectrum of Gluonic Excitations & Confinement in QCD

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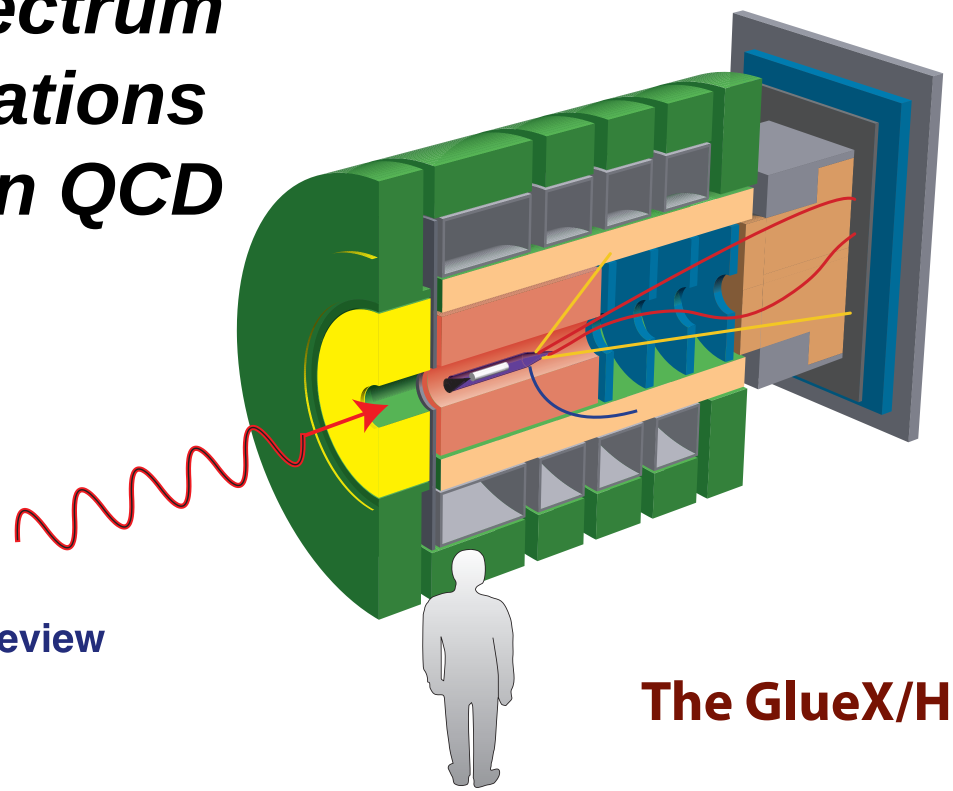
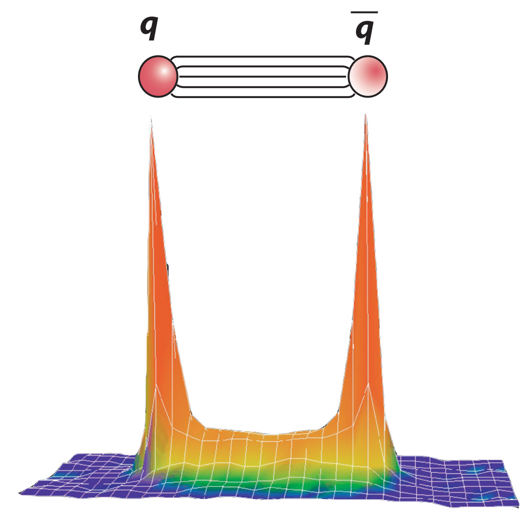
DOE NP Division Science Review
of the JLab Upgrade
April 6-8, 2005





The GlueX/Hall D Project

QCD predicts a rich spectrum of - as yet to be discovered - gluonic excitations - whose experimental verification is crucial for an understanding of QCD in the confinement regime.

With the (a) upgraded CEBAF, (b) linearly polarized photon beam and (c) the GlueX detector, Jefferson Lab will be <u>uniquely poised</u> to: (1) discover these states, (2) map out their spectrum and (3) measure their properties.

The Fundamental Science Issue

- The failure to observe isolated quarks or gluons provides overwhelming experimental evidence that they are confined in nature.

- A quantitative understanding of the confinement of quarks and gluons in quantum chromodynamics (QCD) is one of the outstanding fundamental questions in physics.

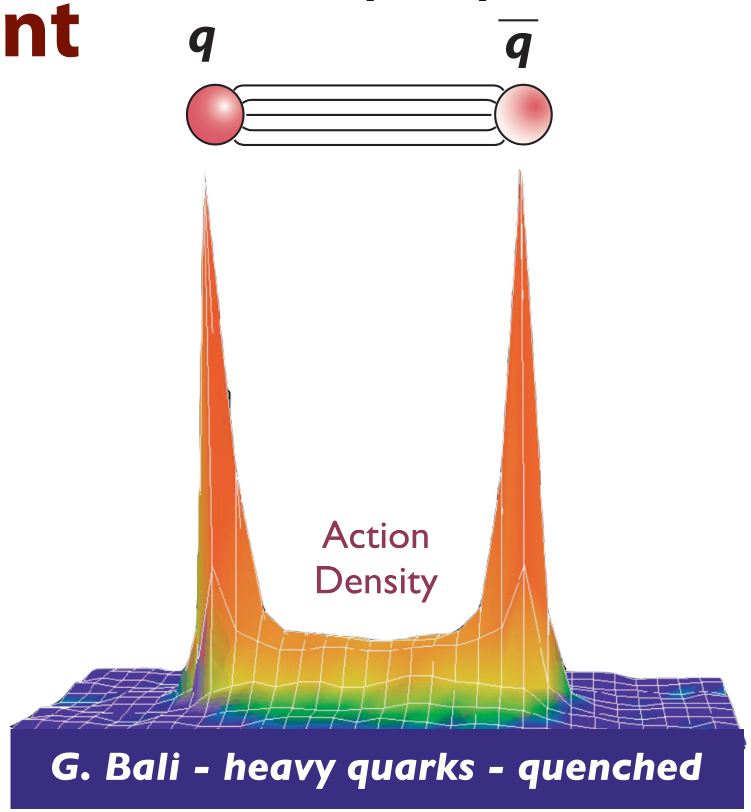
- QCD is our preeminent example of a strongly-coupled field theory.

- Understanding QCD in this long-distance regime - as a strongly-coupled field theory - is an outstanding challenge, not only for hadronic physics, but also for all theoretical physics.

- For example, it is likely that physics at the LHC and beyond has strongly-coupled sectors and QCD provides an analogy for constructing new theories such as technicolor.

Gluonic Excitations and Confinement

from first-principles LQCD:



The quarks in a meson are sources of color electric flux and that flux is trapped in a flux tube connecting the quarks. The formation of the flux tube is related to the self-interaction of gluons via their color charge.

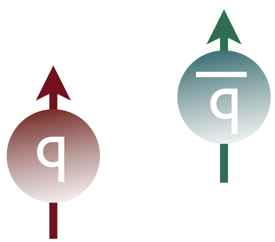
Flux tubes lead to a linear confining potential.

- **Do flux tubes apply in detail to light-quark systems?**
  - still an open question

- **In LQCD the excited gluonic field has J^{PC} quantum numbers that couple with those of the quarks to produce mesons with exotic quantum numbers. This spectrum is the window to QCD in the non-perturbative regime.**

Conventional and Hybrid Mesons

With the flux tube in its ground state the conventional mesons result - their quantum numbers are determined solely from the quark degrees of freedom:



$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

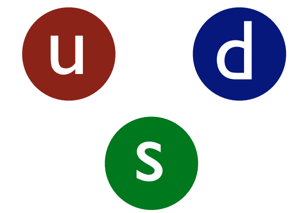
$$C = (-1)^{L+S}$$

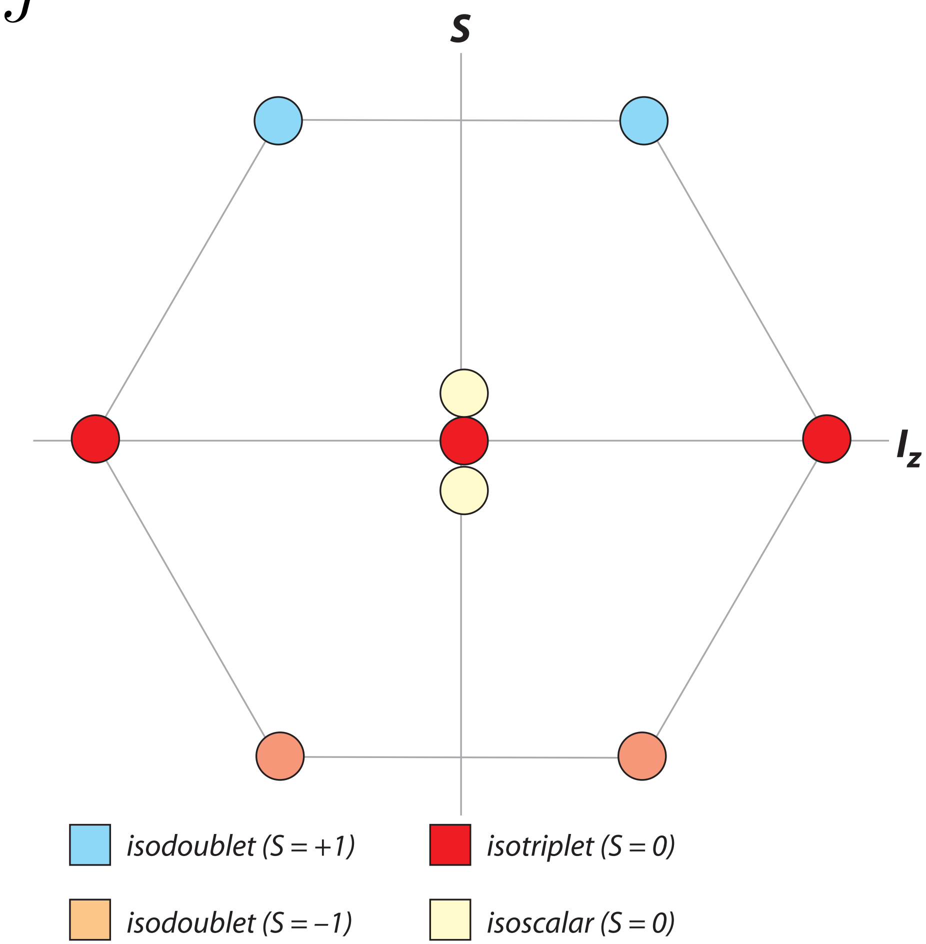
these exotic combinations not allowed:

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

With the flux tube in its excited state the hybrid mesons arise and the QN of the excited flux tube combine with those of quarks giving rise to hybrid mesons with conventional and exotic J^{PC}

With three light quarks the conventional and hybrid mesons form flavor nonets - for each J^{PC}





Masses and Widths of Hybrid Mesons

Masses and Widths

widths are expected to similar to those of conventional strongly-decaying mesons

LQCD Mass Predictions for: $J^{PC} = 1^{-+}$

Author		1^{-+} Mass (GeV/c^2)	
Collab.	Year	$u\bar{u}/d\bar{d}$	$s\bar{s}$
UKQCD	(1997)	1.87 ± 0.20	2.0 ± 0.2
MILC	(1997)	$1.97 \pm 0.09 \pm 0.30$	$2.170 \pm 0.080 \pm 0.30$
MILC	(1999)	$2.11 \pm 0.10 \pm (sys)$	
SESAM	(1998)	1.9 ± 0.20	
Mei& Luo	(2003)	$2.013 \pm 0.026 \pm 0.071$	
Bernard *et al.*	(2004)	1.792 ± 0.139	2.100 ± 0.120

LQCD Mass Predictions for other exotic J^{PC}

Multiplet	J^{PC}	Mass (GeV/c^2)
π_1	1^{-+}	1.9 ± 0.2
b_2	2^{+-}	2.0 ± 0.11
b_0	0^{+-}	2.3 ± 0.6

above for $u\bar{u}/d\bar{d}$ for $s\bar{s}$ add ≈ 0.3 GeV

Decay Modes of Hybrid Mesons

Decay Modes

Selection rule (though not absolute): ***the hybrid meson cannot transfer its angular momentum to the final state meson pairs as relative angular momentum, but instead to the internal angular momentum.***

favored modes: $b_1\pi,\ f_1\pi,\ a_2\pi,\ldots$ *suppressed modes:* $\rho\pi,\ \eta\pi,\ldots$

The more complicated nature of the favored modes may explain why they might not have been detected.

Examples:

$$(b_1\pi)^+ \longrightarrow \omega\pi^0\pi^+ \longrightarrow \pi^+\pi^-\pi^0\pi^0\pi^+$$

$$(b_1\pi)^+ \longrightarrow \omega\pi^0\pi^+ \longrightarrow \pi^0\gamma\pi^0\pi^+$$

$$(a_2\pi)^+ \longrightarrow (\pi^+\pi^+\pi^-)\pi^0 \text{ or } (\pi^+\pi^-\pi^0)\pi^+$$

$$(a_2\pi)^+ \longrightarrow (\eta\pi^+)\pi^0 \text{ or } (\eta\pi^0)\pi^+$$

$$\eta \longrightarrow 2\gamma \text{ or } \longrightarrow 3\pi^0 \text{ or } \pi^+\pi^-\pi^0$$

check various modes to certify PWA results

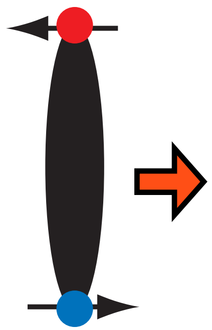
Have Exotic Hybrids Been Observed?

All of the following are reports of $J^{PC} = 1^{-+}$ exotics

$\pi_1(1400) \rightarrow \eta\pi$	Observed in the charged mode by E852 and confirmed by Crystal Barrel in charged/neutral modes. P-wave observed in neutral mode but not resonant. This state is controversial.
$\pi_1(1600) \rightarrow \rho\pi$	Hint of an exotic signal in the $\rho\pi$ mode based on an analysis of 250K $\pi^+\pi^-\pi^-$ events. A recent analysis of 3M $\pi^+\pi^-\pi^-$ and $\pi^0\pi^0\pi^-$ events (each) shows no exotic. More on this...
$\pi_1(1600) \rightarrow \eta'\pi^-$	Large P-wave present but not clear if it is resonant. Reported by E852.
$\pi_1(2000) \rightarrow b_1\pi$	Reported by E852. Statistics are relatively low and confirmation is needed.
$\pi_1(2000) \rightarrow f_1\pi$	Reported by E852. Statistics are relatively low and confirmation is needed.

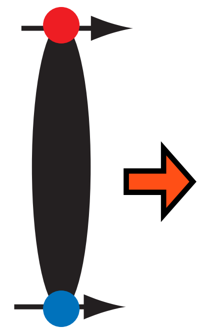
Production of Hybrid Mesons

Combine excited glue QN $J^{PC} = 1^{+-}$ *or* 1^{-+} with those of the quarks:



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

$\vec{L} = 0,\ \vec{S} = 0$

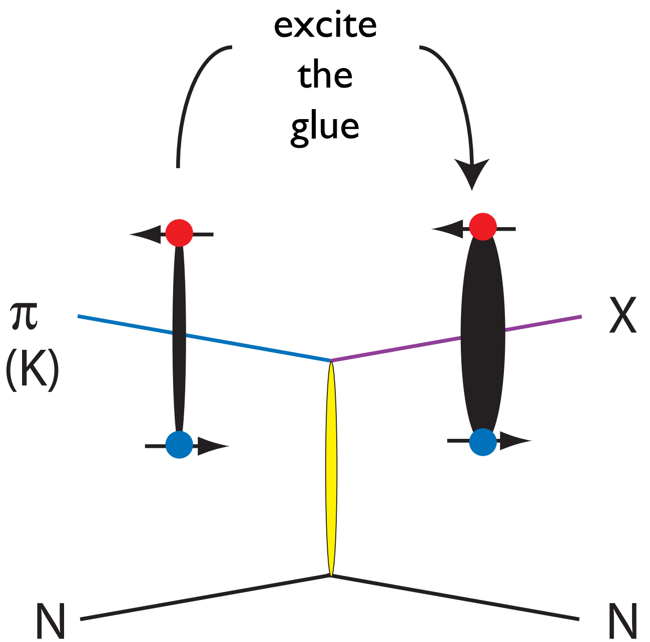


$J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}$

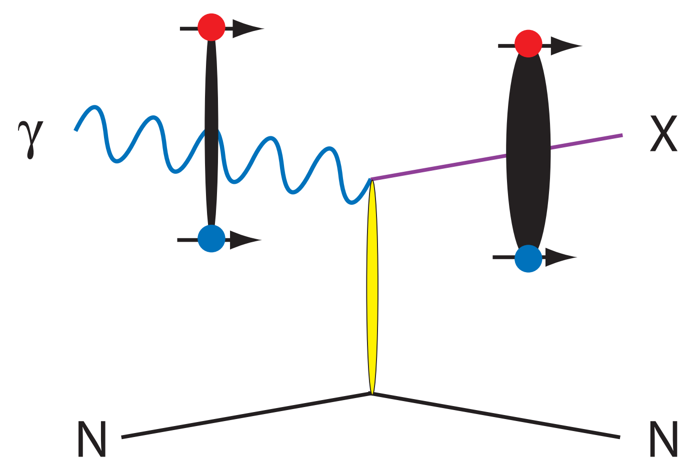
$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$

exotic

$\vec{L} = 0,\ \vec{S} = 1$



produced hybrids
are not expected to be exotic



produced hybrids
can be exotic

Strategy for Hybrid Meson Discovery

- **Initially focus on hybrids with exotic J, P and C quantum numbers thus avoiding ambiguities from mixing with conventional mesons.**

- **Identify several members of a given exotic nonet and establish more than one exotic nonet.**

- **Have a meson mass reach up to 2.5 GeV.**

- **Use a photon probe as suggested by previous arguments.**

- **Data from photoproduction of light-quark mesons are sparse highlighting the importance of this venue for searches.**

- **Optimize the detector, the probe and the analysis tools (software and phenomenology) to carry out a partial wave analysis (PWA) needed to unambiguously identify the meson quantum numbers.**

- **Be sensitive to a wide variety of decay modes needed to certify the PWA results and to compare with LQCD predictions.**

Requirements for Hybrid Meson Discovery Will Be Met by the Upgrade

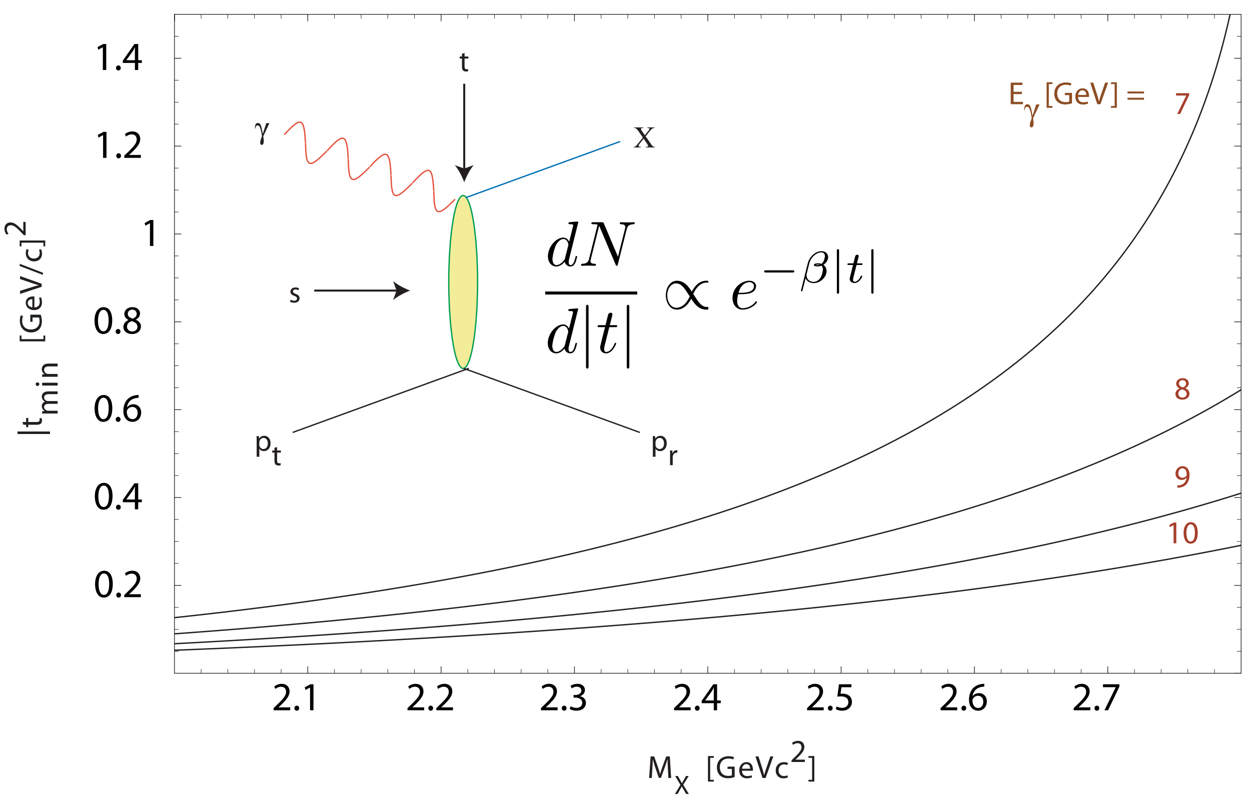
- **Photon beam with sufficient energy for the mass reach.**
  - *9 GeV photons ideal.*

- **Linearly polarized photons of a degree and flux needed for the PWA.**
  - *Using coherent bremsstrahlung this implies 12 GeV electrons with the appropriate emittance, spot size and duty-factor.*

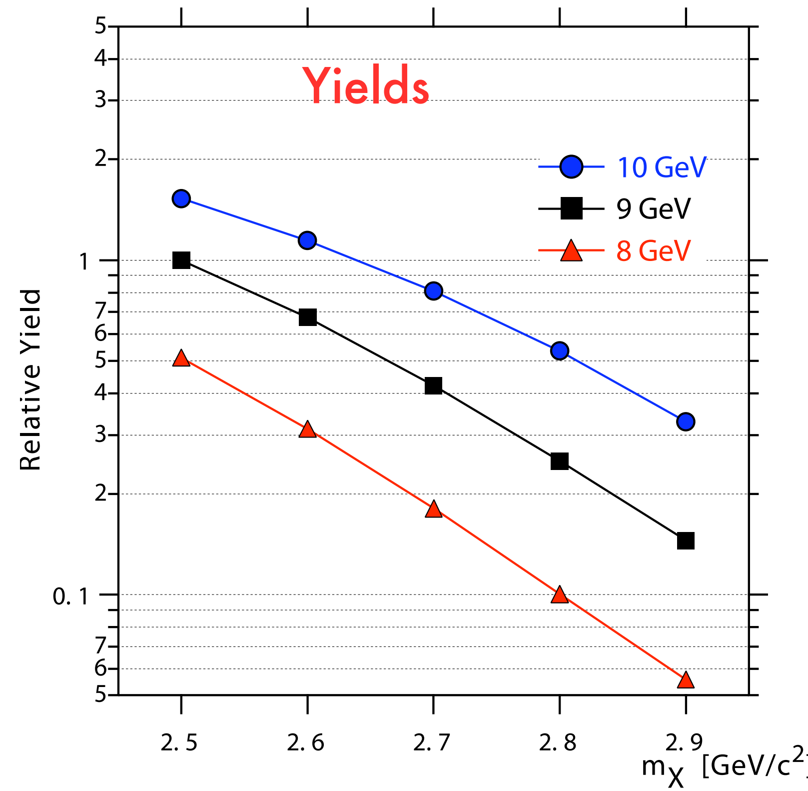
- **Detector optimized for PWA and detecting a variety of decay modes.**
  - *The GlueX detector design optimizes:*
    - *(1) hermeticity*
    - *(2) energy and momentum resolution*
    - *(3) particle identification*
    - *(4) data rate*

Meson Production Kinematics

$$\gamma p \rightarrow X p$$



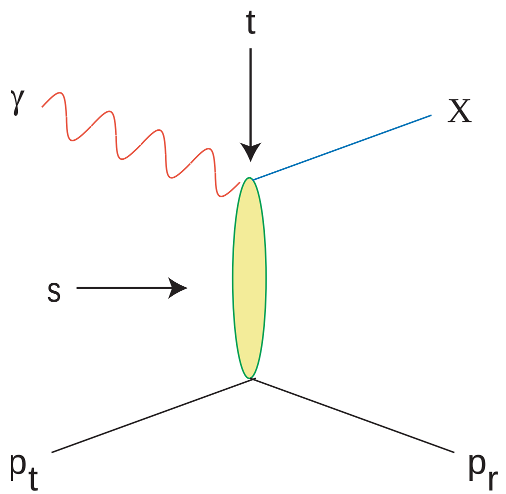
$$N(m_X) = A \cdot BW(m_X) \cdot e^{-8|t|}$$

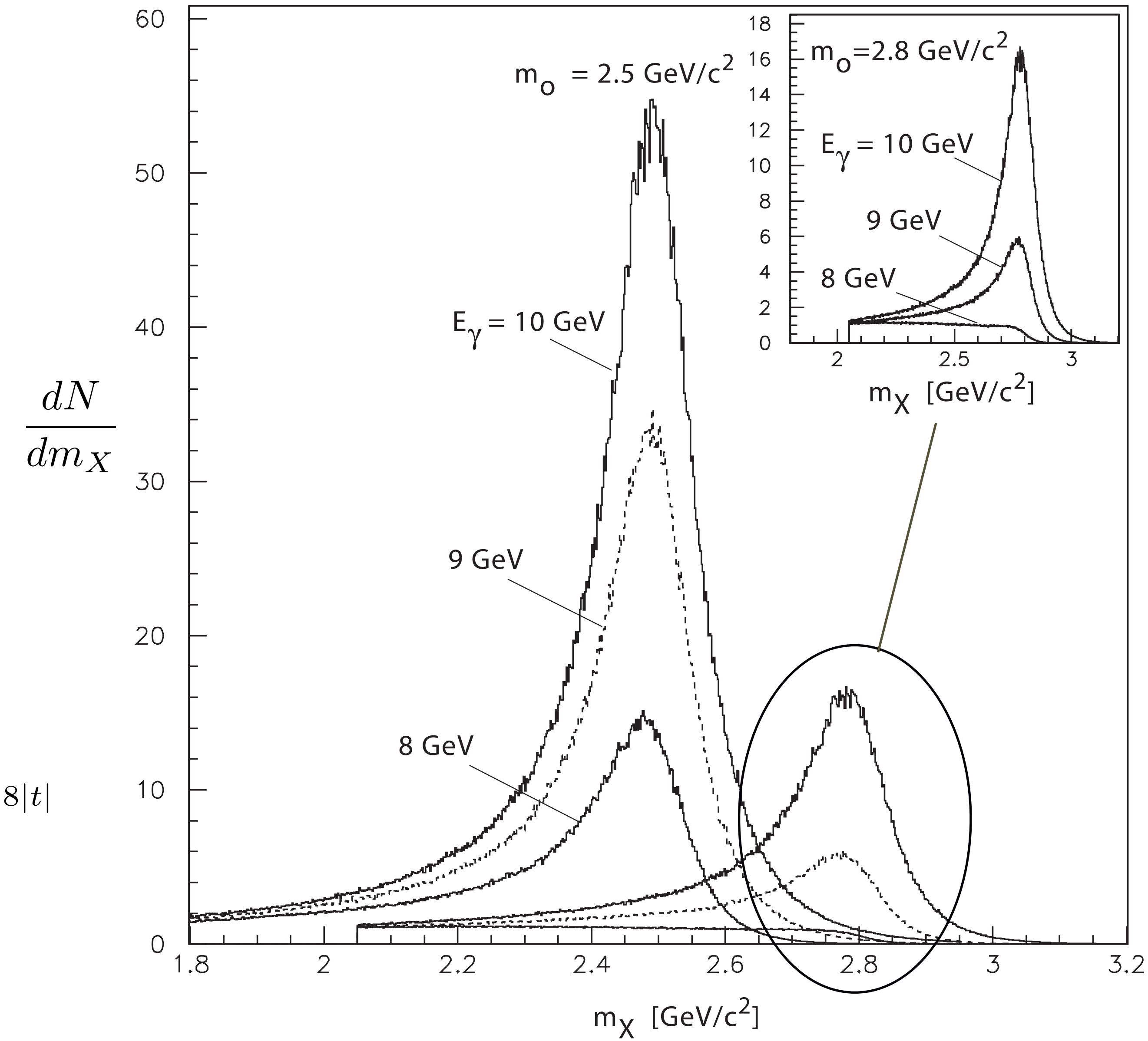


Variation of t_{min} as a function of meson mass and photon energy:

- ***affects production rate and***
- ***line shape (if t_{min} varies rapidly across width of resonance)***

Line Shapes and Photon Energy

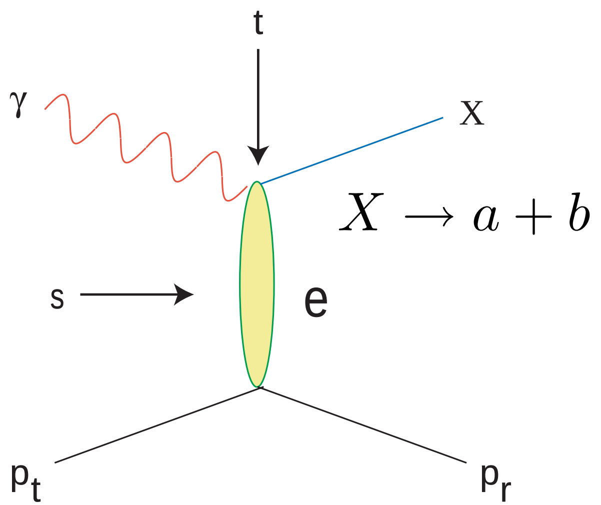




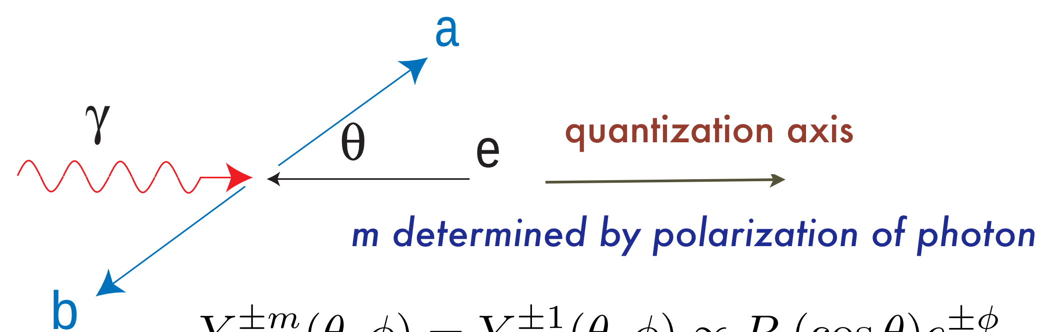
$$N(m_X) = A \cdot BW(m_X) \cdot e^{-8|t|}$$

Start with resonances of same width and production cross-sections. The final yield and line shape determined by peripheral production and kinematics.

Linear Polarization



assume that X decays into two spin-less mesons: a and b
and that e is also spin-less



$$Y_\ell^{\pm m}(\theta,\phi) = Y_\ell^{\pm 1}(\theta,\phi) \propto P_\ell(\cos\theta)e^{\pm\phi}$$

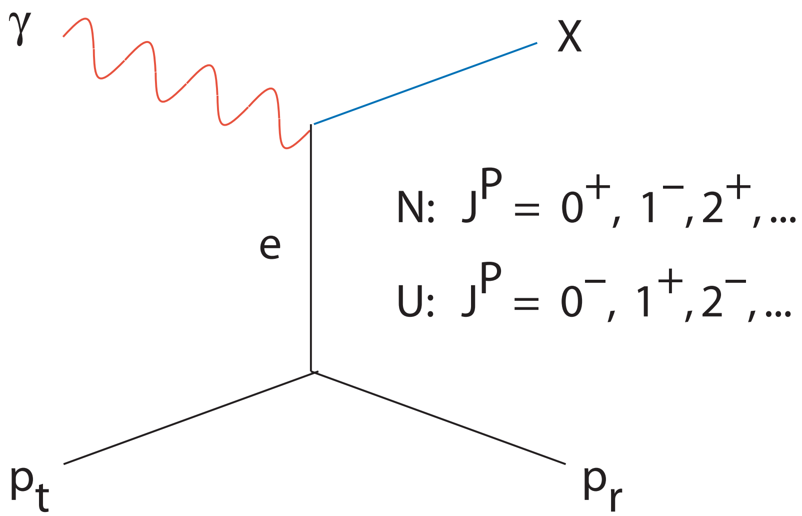
For circularly polarized photons: m = +1 or m = −1 ➡ $W(\theta,\phi) \propto |P_\ell(\cos\theta)|^2$

For unpolarized photons:
equal mixture of m = +1 and m = −1 ➡ $W(\theta,\phi) \propto |P_\ell(\cos\theta)|^2$

For x - linear polarization: ➡ $W(\theta,\phi) = |Y_\ell^{+1} - Y_\ell^{-1}|^2 \propto |P_\ell(\cos\theta)|^2 \sin^2\phi$

For y - linear polarization: ➡ $W(\theta,\phi) = |Y_\ell^{+1} + Y_\ell^{-1}|^2 \propto |P_\ell(\cos\theta)|^2 \cos^2\phi$

Linear Polarization



Exotic Production:
Takes place via unnatural (U) parity exchange
Diffractive Production:
Through natural parity (N) exchange

Unpolarized or circular polarized photons cannot distinguish between U and N.

With longitudinal polarization one can distinguish by selection based on the angle the polarization vector makes with the production plane.

PHYSICAL REVIEW D, VOLUME 61, 114008

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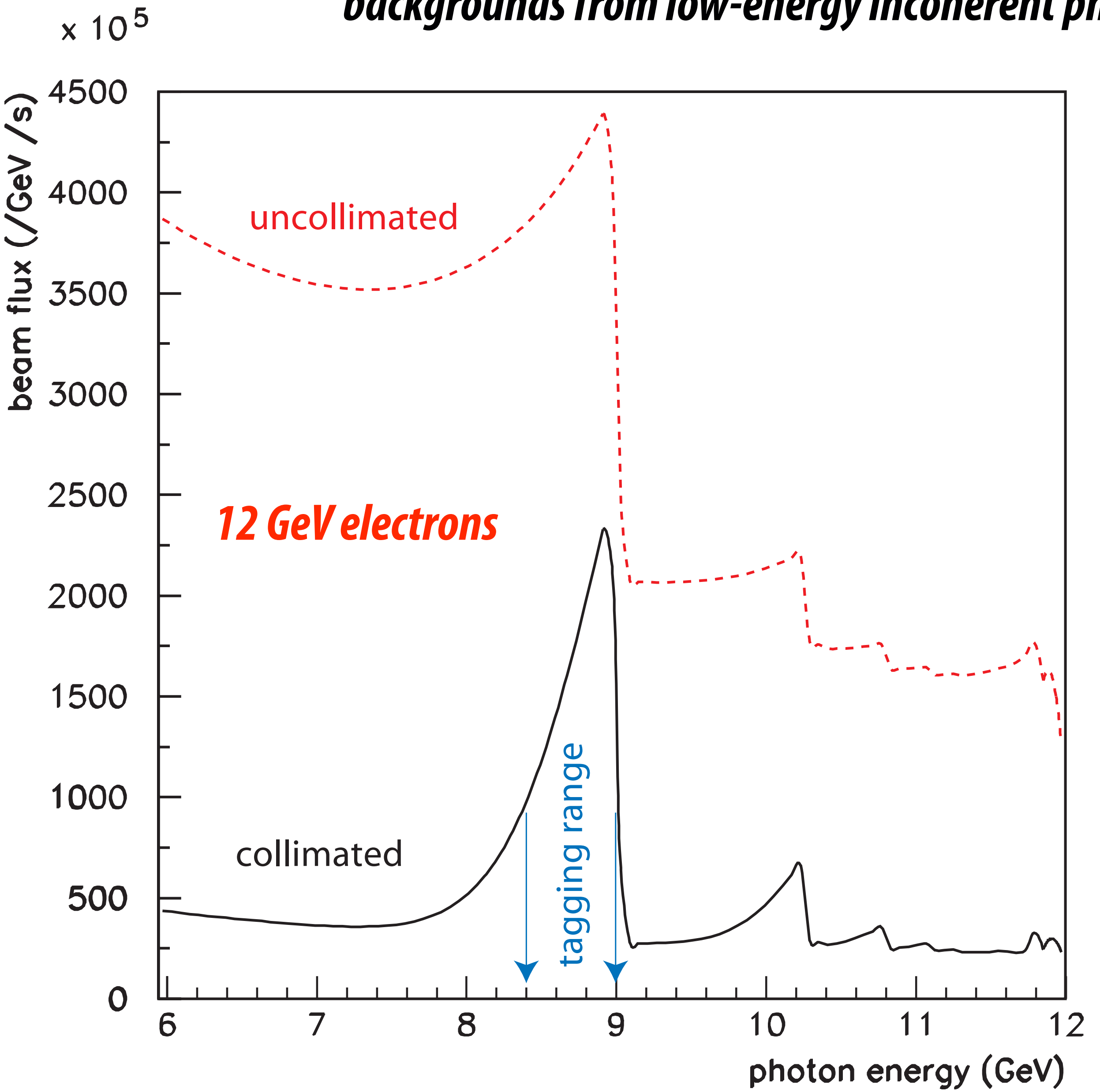
Charge exchange $\rho^0\pi^+$ photoproduction and implications for searches for exotic mesons

We analyze the processes $\vec{\gamma}+p\rightarrow\rho^0\pi^+n$ at low momentum transfer focusing on the possibility of the production of an exotic $J^{PC}=1^{-+}$ meson state. In particular we discuss polarization observables and conclude that linear photon polarization is instrumental for separating the exotic wave.

Coherent Bremsstrahlung

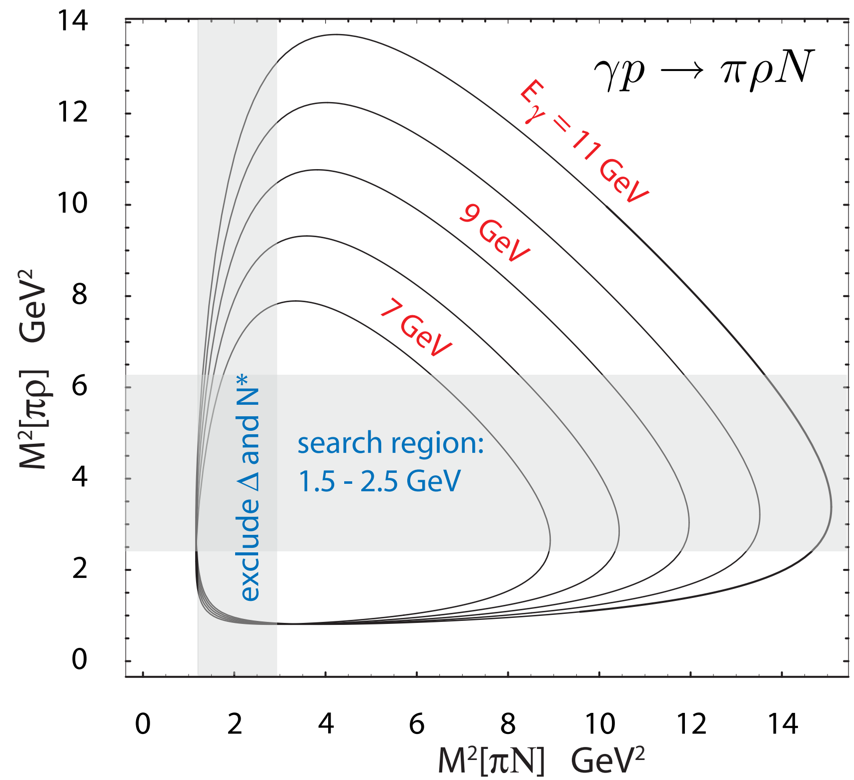
provides linear polarization and with collimation reduces backgrounds from low-energy incoherent photons

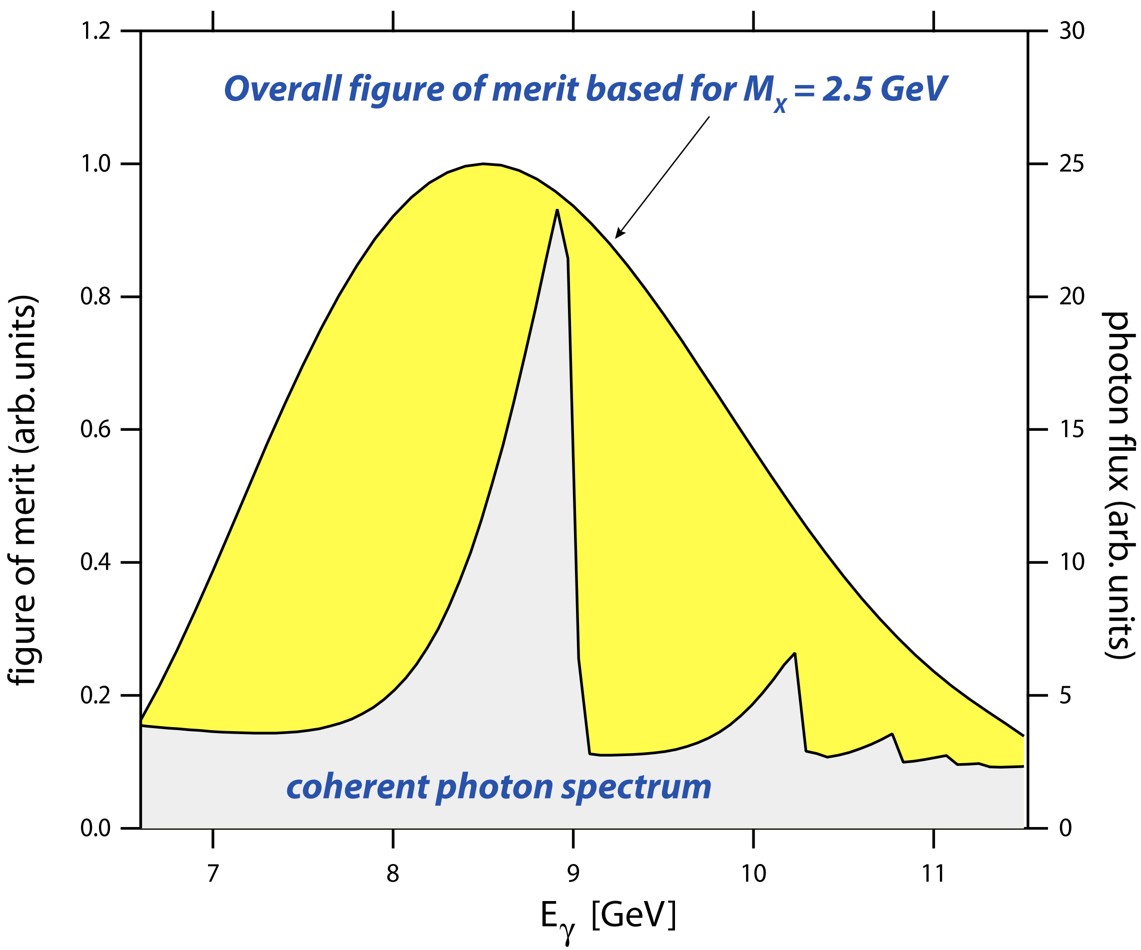


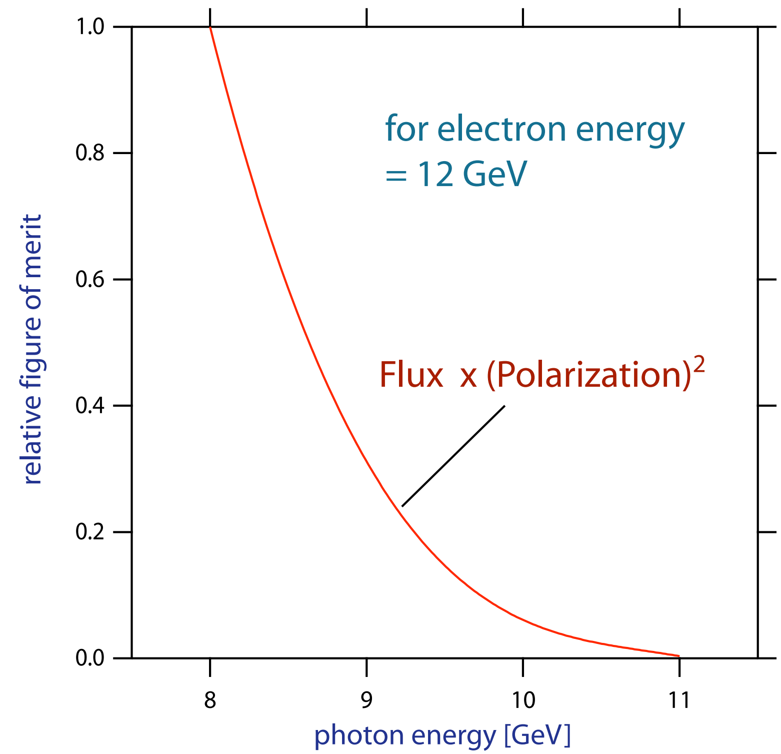
Ideal Photon Beam Energy

Based on:

- meson yield for high mass region
- maintain sufficient beam flux/polarization
- separate baryon from meson resonances
- assume 12 GeV electrons







Need for 12 GeV electrons

9 GeV photons ideal for the meson mass reach and is well-matched to solenoidal detector.

Keep the photon energy fixed at 9 GeV and vary the energy of the electron beam to understand the figure of merit.

Conclusion:

12 GeV electrons essential

electron energy:	10 GeV	11 GeV	12 GeV
Photon flux in peak (million per sec)	32	67	100
Average degree of polarization	0.08	0.24	0.37
Figure of merit relative to 12 GeV	0.015	0.263	1.0

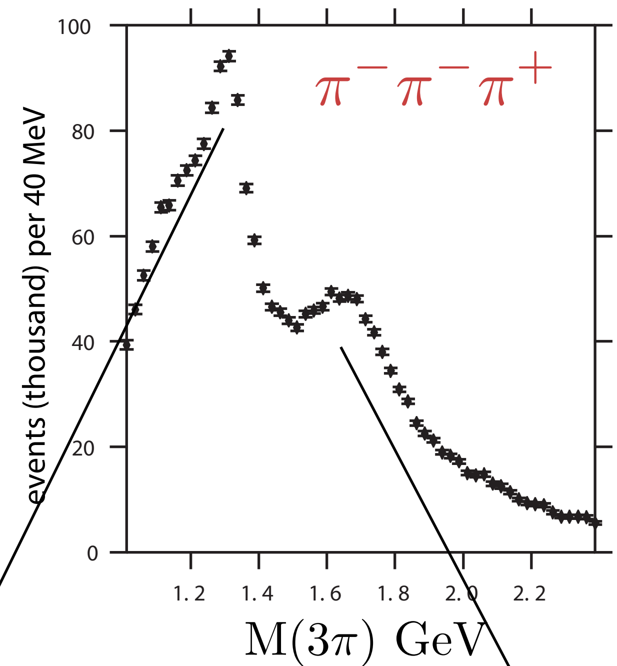
total hadronic rate fixed at 370 kHz

Exotic Hybrid in the 3π System? - E852

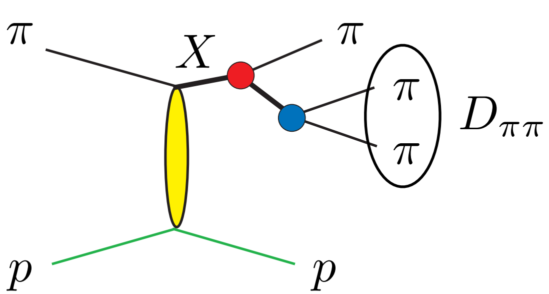
In 1998 - E852 published evidence for an exotic meson:

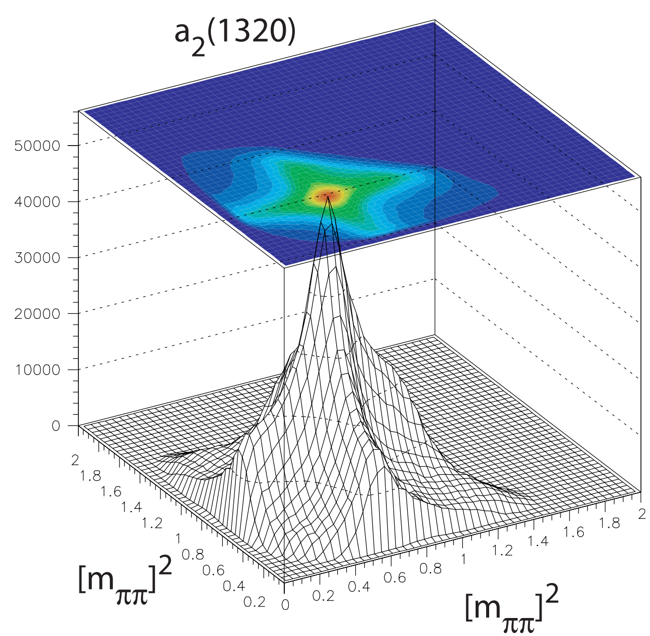
$$J^{PC} = 1^{-+} \quad \pi_1(1600) \rightarrow \rho\pi$$

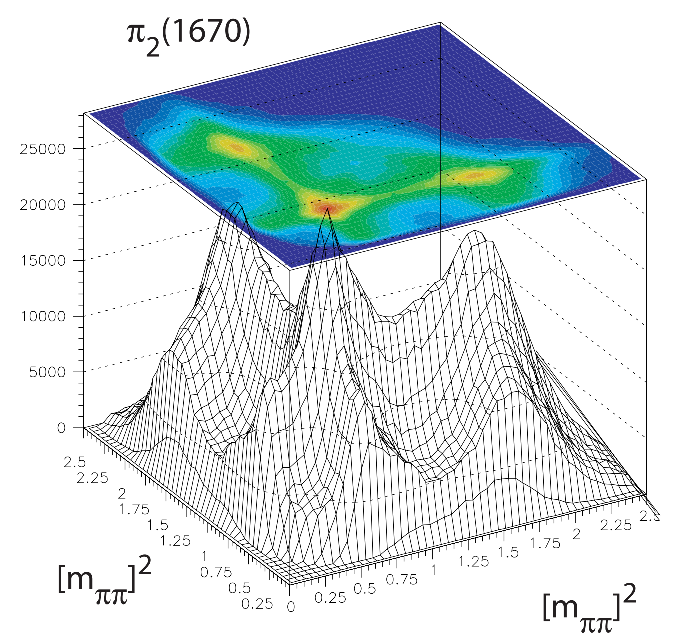
$$\frac{\sigma(\pi_1)}{\sigma(a_2)} \approx 5\%$$



PWA based on the isobar model:

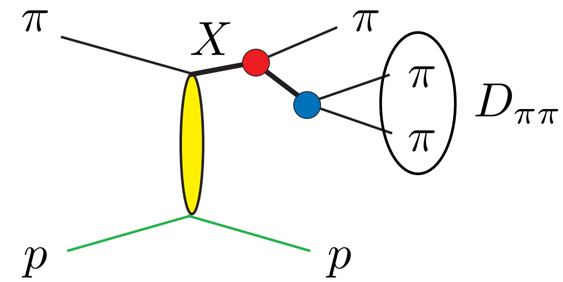






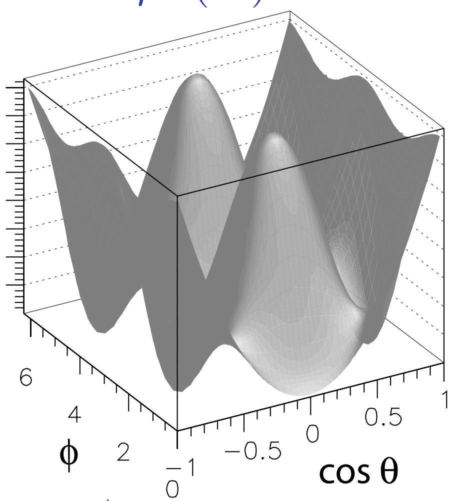
Decay angles

Correlated angular distributions for representative partial waves

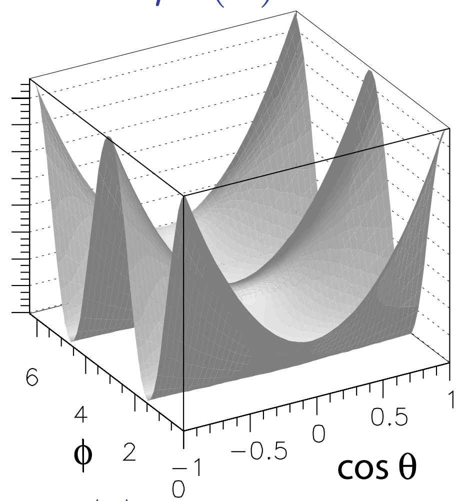


$X \to D_{\pi\pi}$ *Gottfried-Jackson frame*

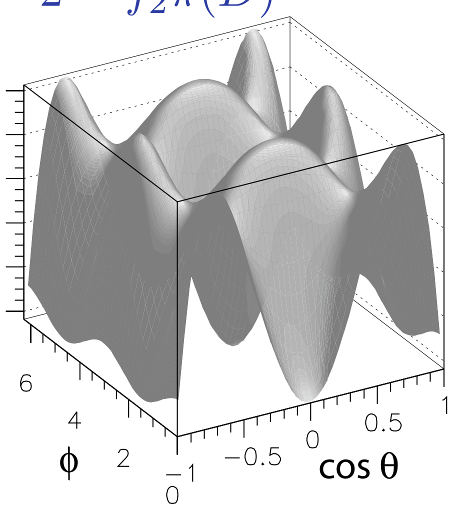
$2^{++}\rho\pi(D)$



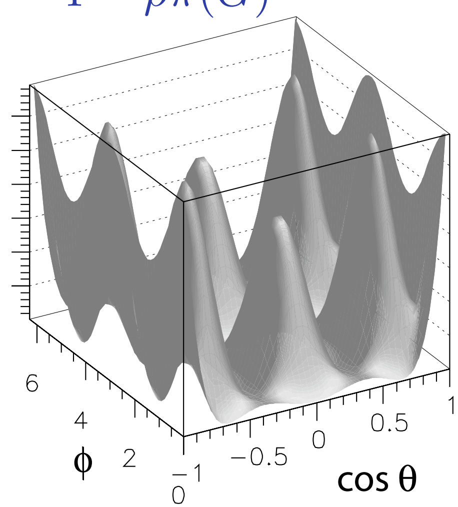
$1^{++}\rho\pi(S)$



$2^{-+}f_2\pi(D)$

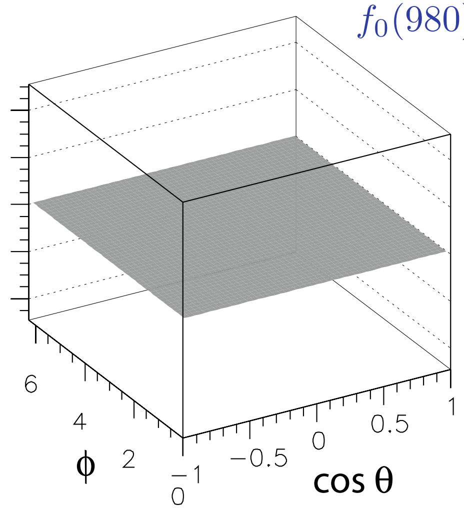


$4^{++}\rho\pi(G)$

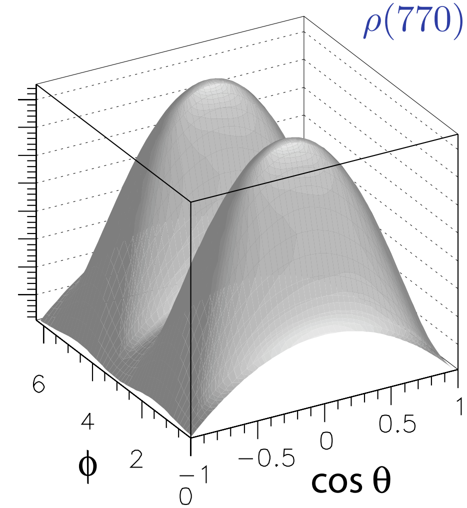


$D_{\pi\pi} \to \pi\pi$ *Helicity frame*

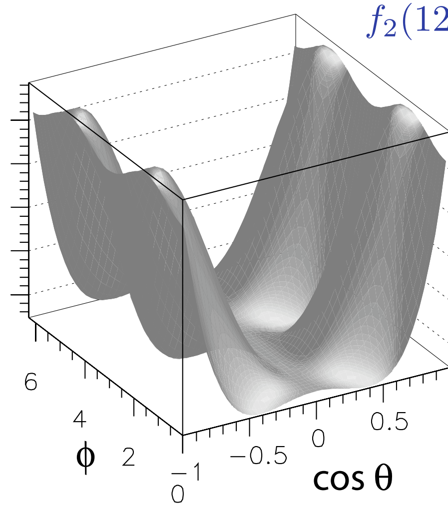
$f_0(980)$



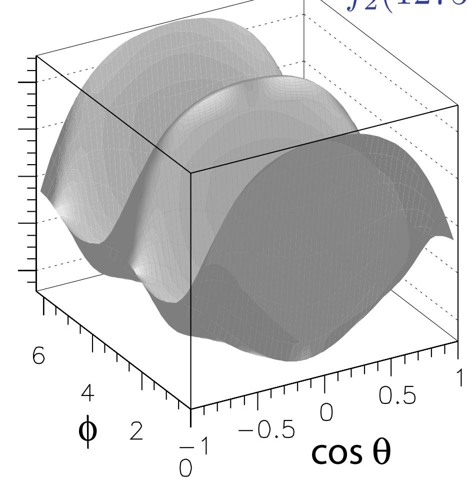
$\rho(770)$



$f_2(1275)$

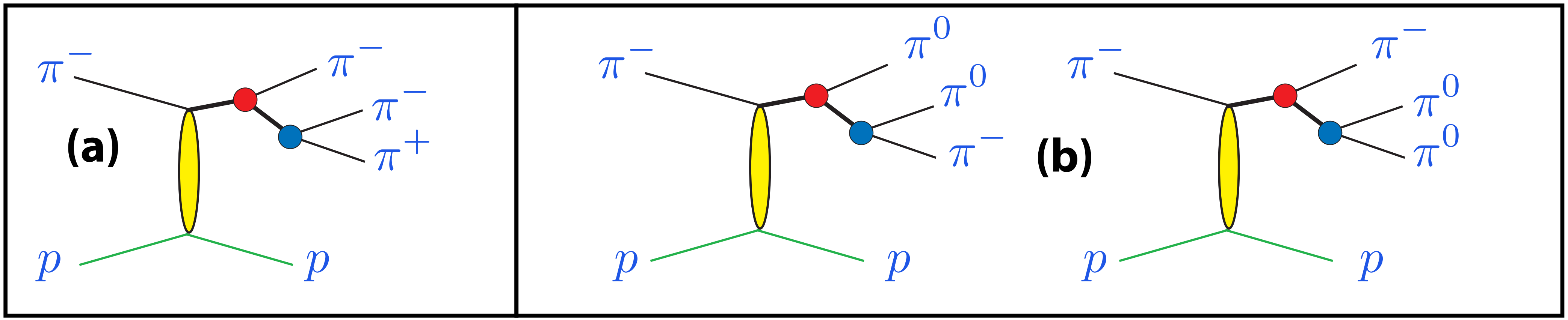


$f_2(1275)$



New Analysis

The 1998 analysis based on 250K events of reaction (a). New analysis is based on 3M events each of reactions (a) and (b). The two modes provide important cross-checks.



PWA shows:

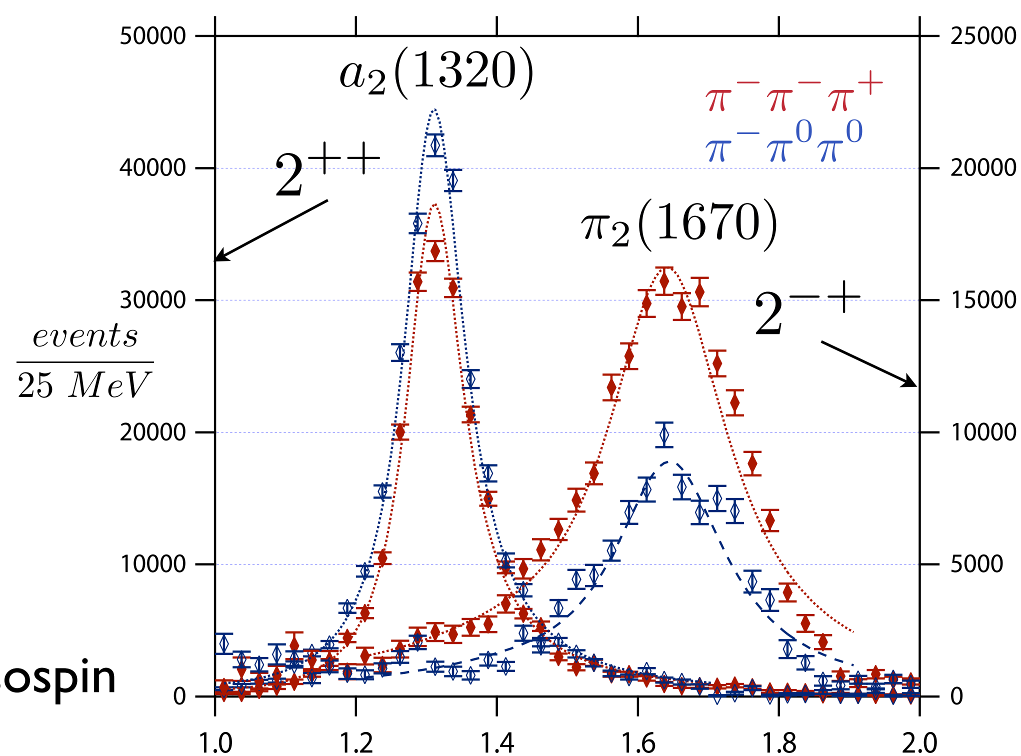
$a_2 \to \rho\pi$

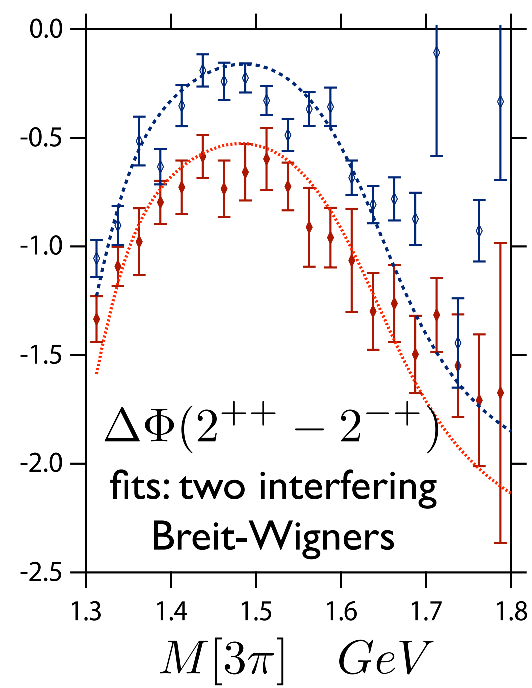
$$\frac{\pi^-\pi^-\pi^+}{\pi^-\pi^0\pi^0} \approx 1$$

$\pi_2 \to f_2\pi$

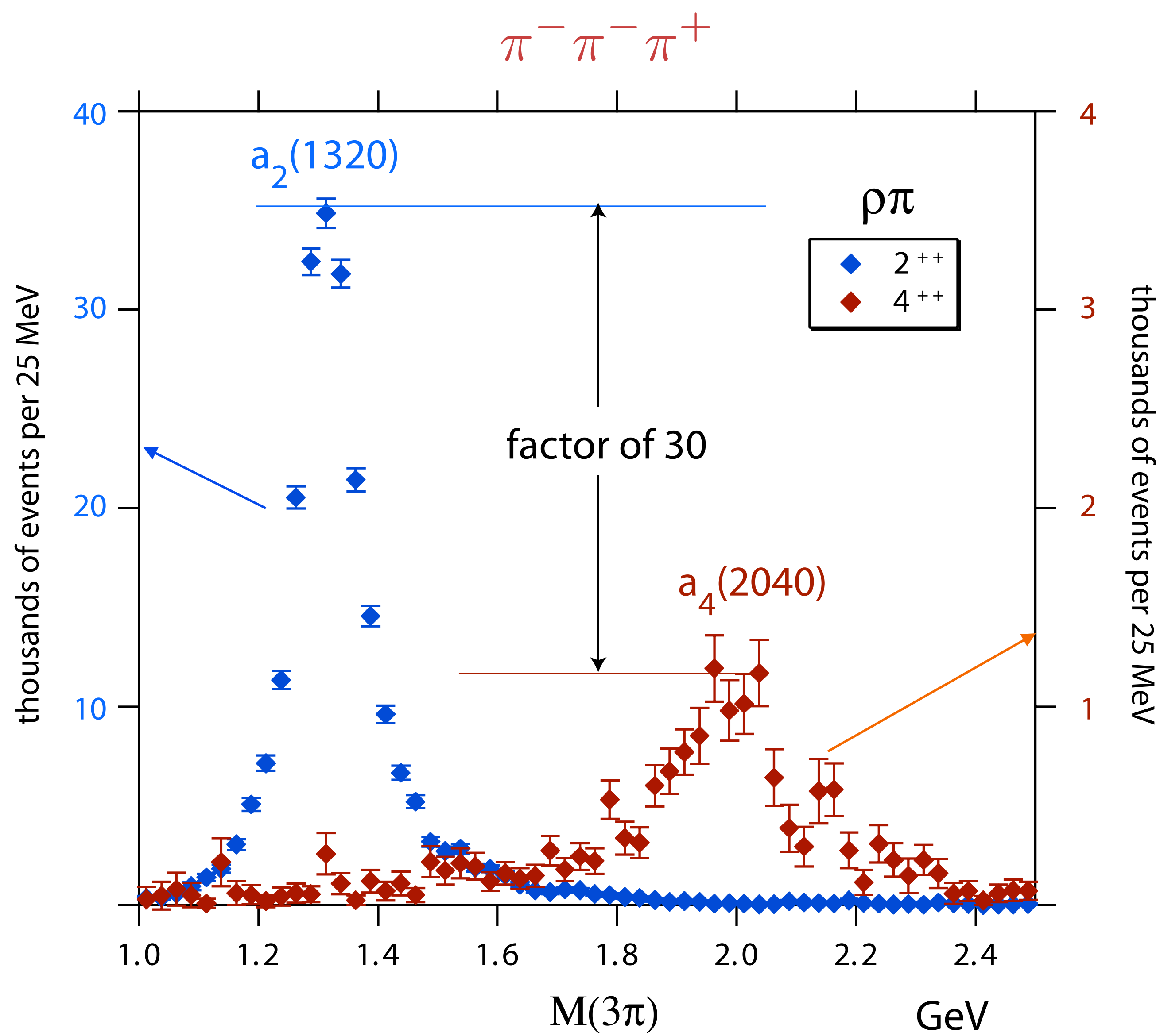
$$\frac{\pi^-\pi^-\pi^+}{\pi^-\pi^0\pi^0} \approx 2$$

as expected from isospin





PWA Has A Large Dynamic Range



Moments and PWA

Moments provide an arbiter for wave set sufficiency

$$H(LMN) = \int I(\Omega) D^{L}_{MN}(\Omega) d\Omega$$

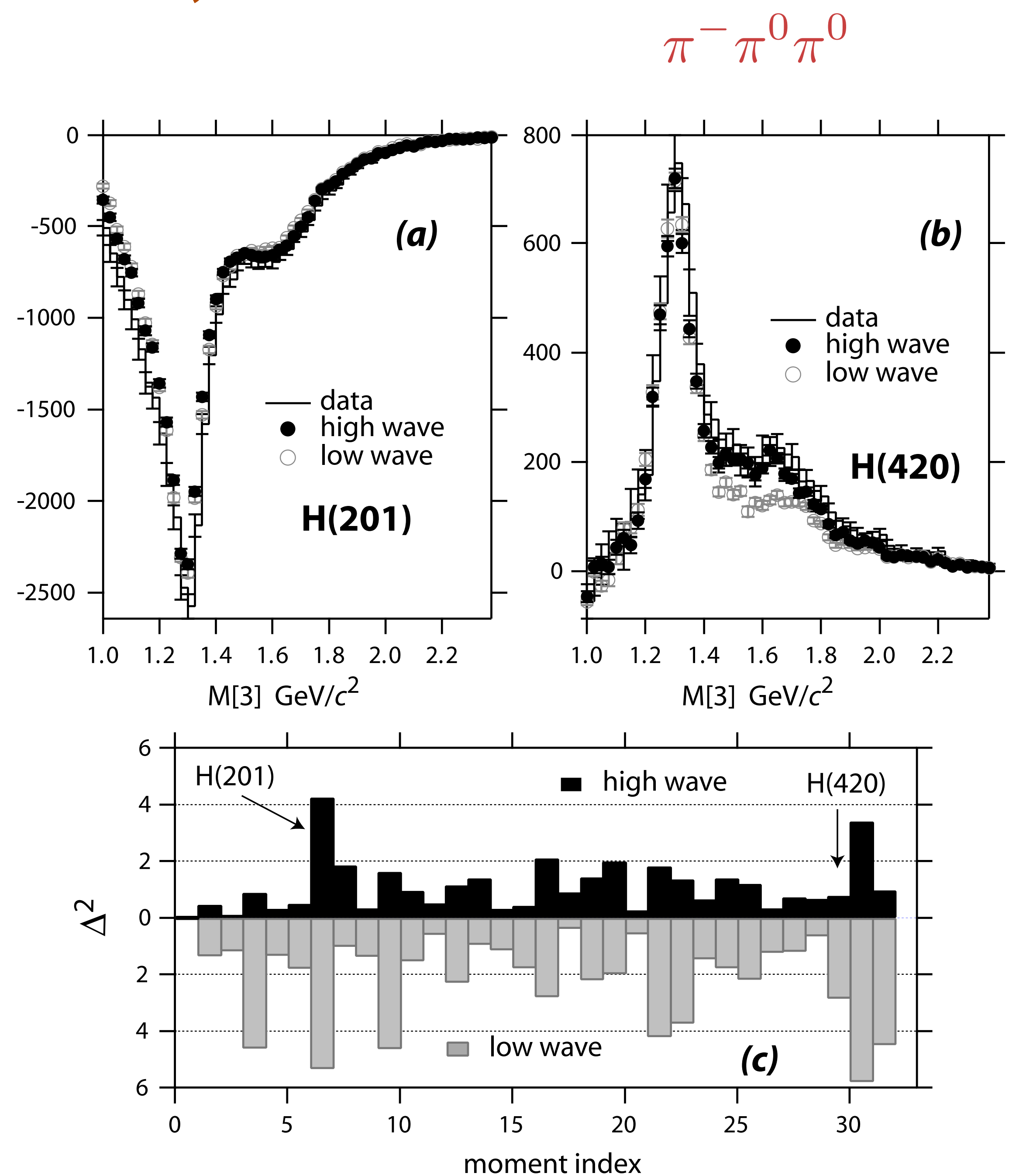
compare moments calculated from data and from PWA

$$\Delta^2 = \frac{1}{n} \sum_{i}^{n} \frac{(H_D - H_P)^2}{\sigma_D^2 + \sigma_P^2}$$

Number of waves used in old analysis - 21 waves (low-wave set)

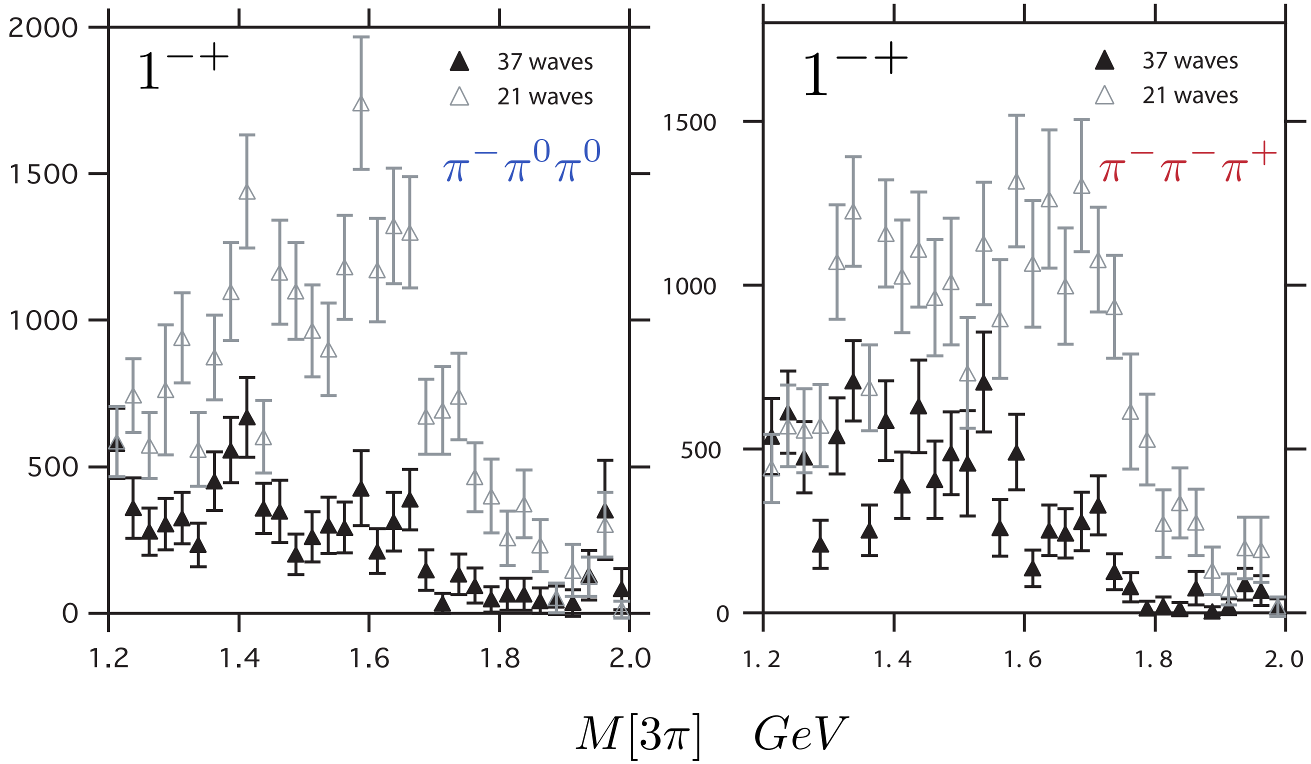
Number of waves used in new analysis - 35 waves (high-wave set)

Agreement with moments better with high wave set.



Results of the New Analysis

- **Wave set that has a better agreement with moments does not show evidence for the exotic meson.**



What Have We Learned From E852?

- **The PWA reliably extracts resonances with cross sections that differ by factors of 50 to 100. Line shapes and relative phases are understood.**

- **High statistics and cross checks provided by different decay modes are important in establishing states with lower cross sections - as with the recent higher statistics analysis of the 3π system in two modes.**

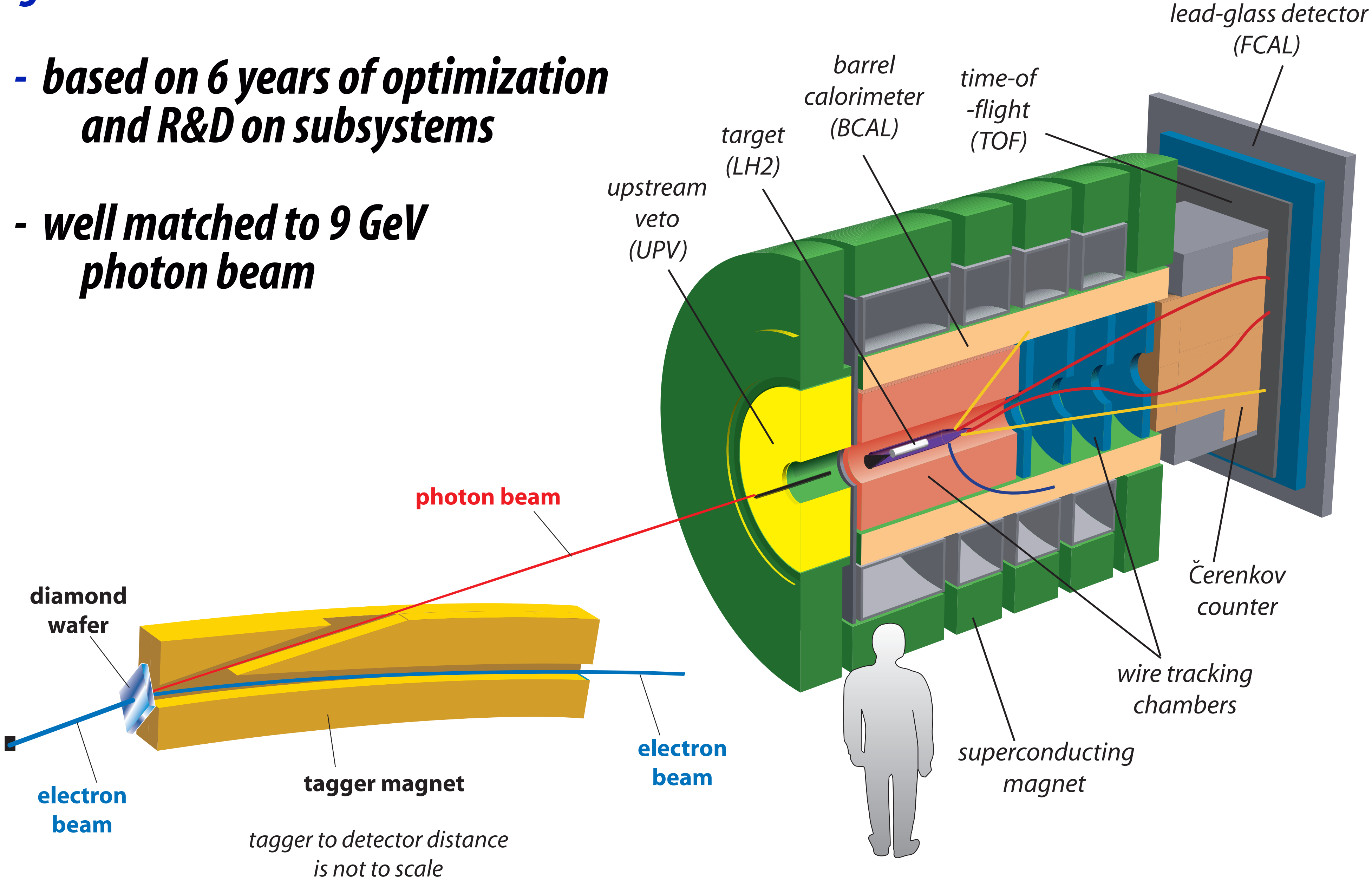
- **E852 data are providing an important test bed for understanding the PWA and its phenomenological underpinnings.**

- ***GlueX will have:***
  - superior acceptance and resolution
  - a probe (photon) expected to yield exotic hybrids
  - statistics that exceed E852 by several orders of magnitude

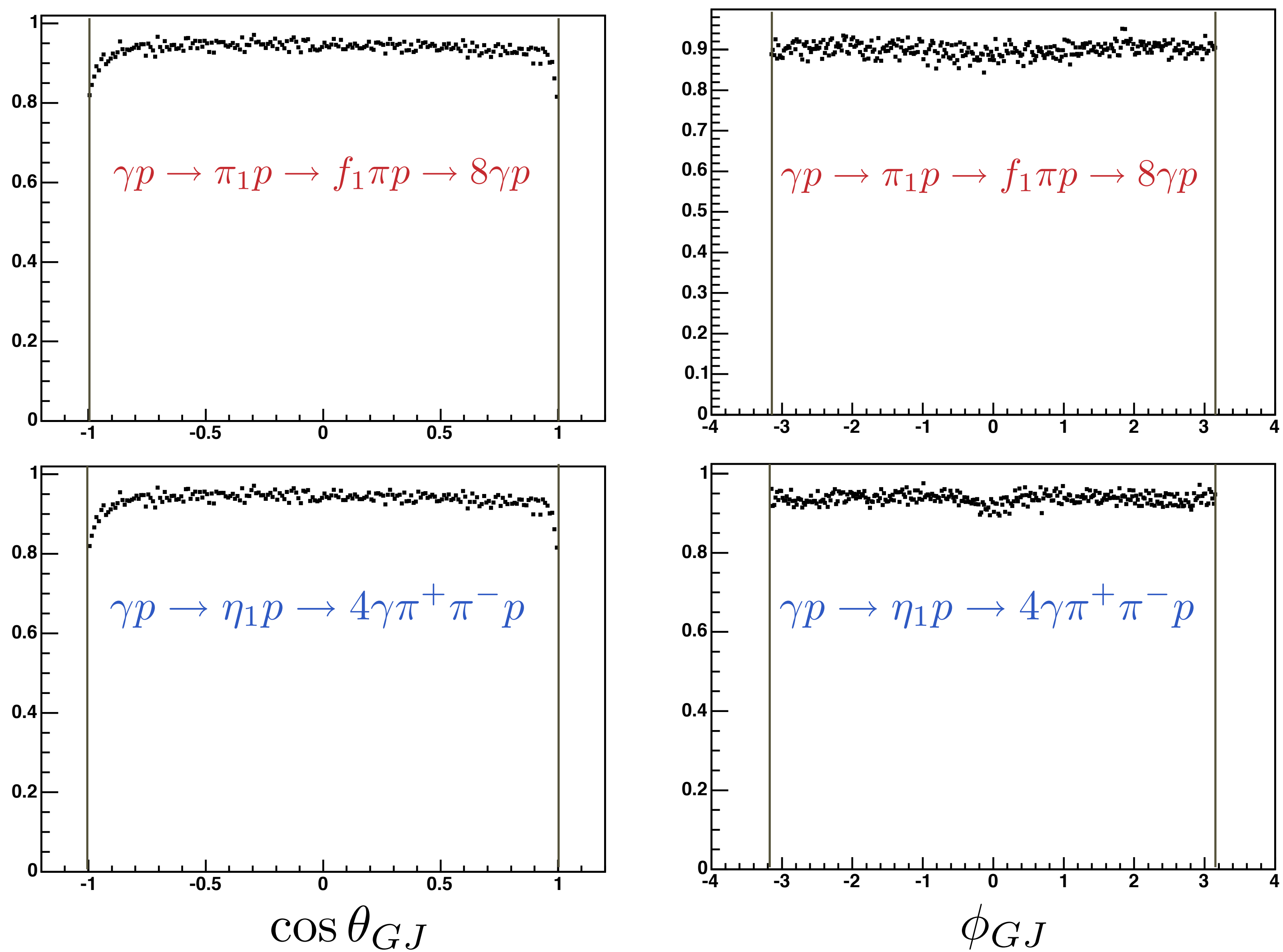
GlueX Detector

Design is mature:

- ***based on 6 years of optimization and R&D on subsystems***
- ***well matched to 9 GeV photon beam***



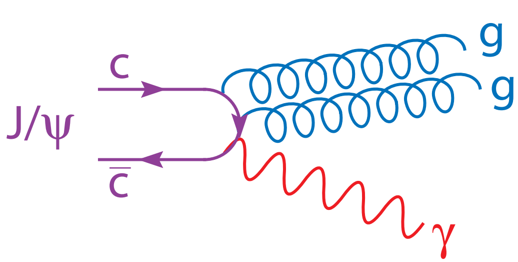
Acceptance in Decay Angles

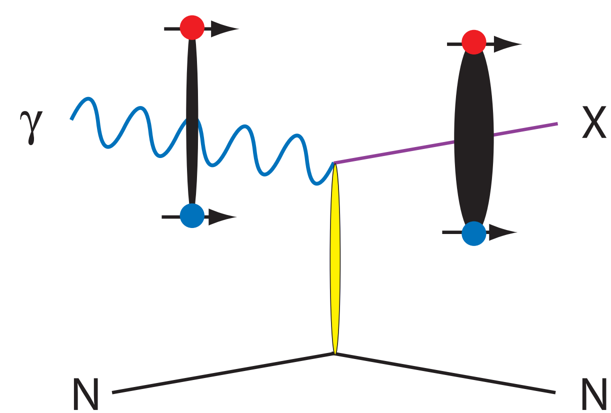


Recall the rich structure in these angles for various partial waves

Data and Analysis Plans

- GlueX will collect about 1 PetaByte/year.
- After 3-4 years of initial running GlueX will collect statistics that will exceed existing data on light-meson production by several orders of magnitude.
- Software tools to handle these data sets are being developed. We will make extensive use of GRID-based tools as they become available.
- We are also working closely with physicists at CLEO-c (searching for glueballs in J/ψ radiative decays) - to develop techniques to unambiguously identify gluonic excitations. A white paper is in preparation.





In the first 5 years....

- GlueX will establish the existence of a $\mathrm{J^{PC}} = 1^{-+}$ or 2^{+-} exotic in several modes if it is present at a level of a few % of conventional mesons. If exotics are not present - the few % level will be the exclusion limit - enough to present problems for QCD as we know it.

- GlueX will measure branching modes for established exotic states to validate QCD predictions.

- GlueX will also add to the knowledge of conventional meson spectroscopy especially strangeonium states that straddle the light and heavy quark sectors.

In the next 5 years....

- GlueX will establish other exotic hybrid states and nonets along with non-exotic hybrids.

Conclusions

- Mapping the spectrum of hybrid mesons provides the critical experimental information needed to answer a fundamental question: **the nature of confinement in QCD.**

- **Advances in science follow advances in technology** and the recent advances in detectors/readout, computational power, diamond wafers (for coherent bremsstrahlung) put us in a position to achieve the experimental goals.

- With the upgrade of CEBAF to 12 GeV - coupled with the superb electron beam characteristics - **JLab will be in a unique position to discover and map the spectrum of hybrid mesons.**