Hadron Spectroscopy at GlueX and the Search for Gluonic Excitations

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Int. Workshop on Hadron Structure and Spectroscopy

Trieste, Italy

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Outline

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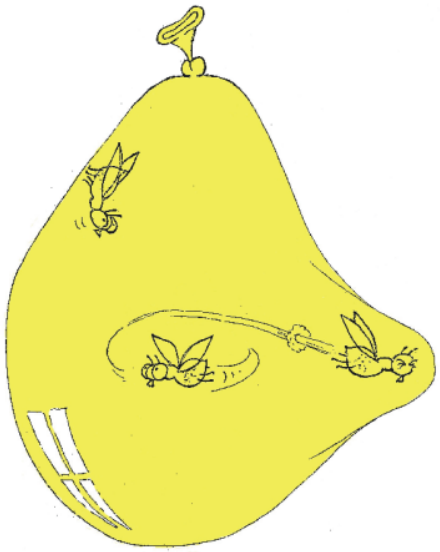
Strong-Coupling Quantum Chromodynamics (QCD)

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\left(i\gamma_\mu D^\mu - m_q\right) q - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

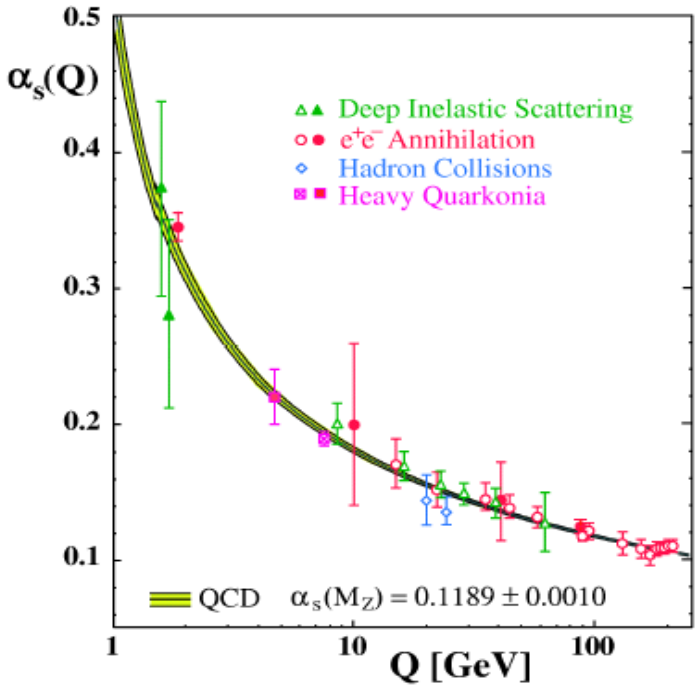
QCD = Theory of the strong nuclear force

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

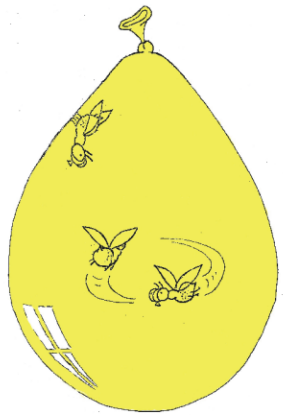


Confinement & Strong QCD

"World of Hadrons"

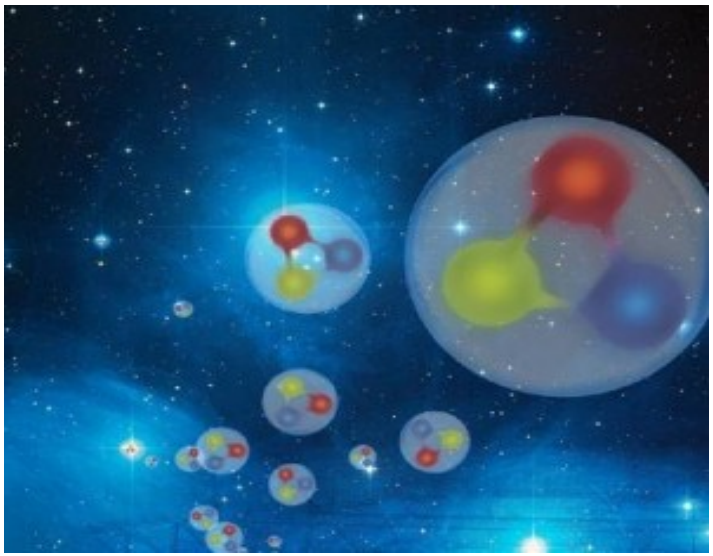


"pQCD"



Asymptotic Freedom

Non-Perturbative QCD



How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do the degrees change with varying quark masses?

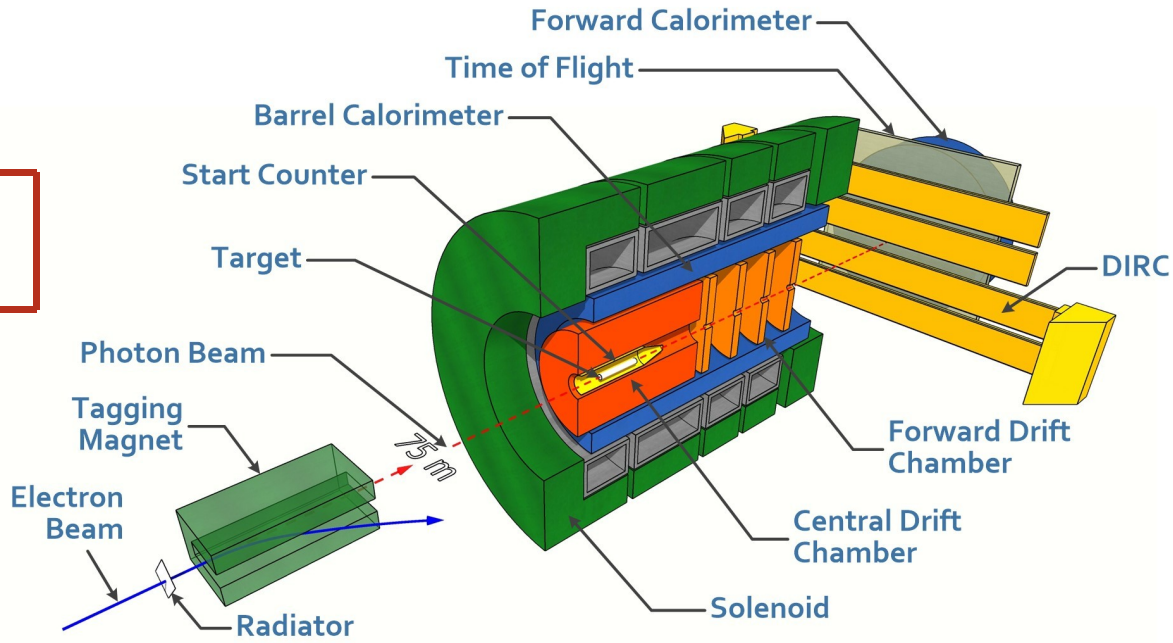
Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, tetraquarks, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are also possible ...

Hadron Spectroscopy

- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+\, e^-$
- $\bar{p}\, p$

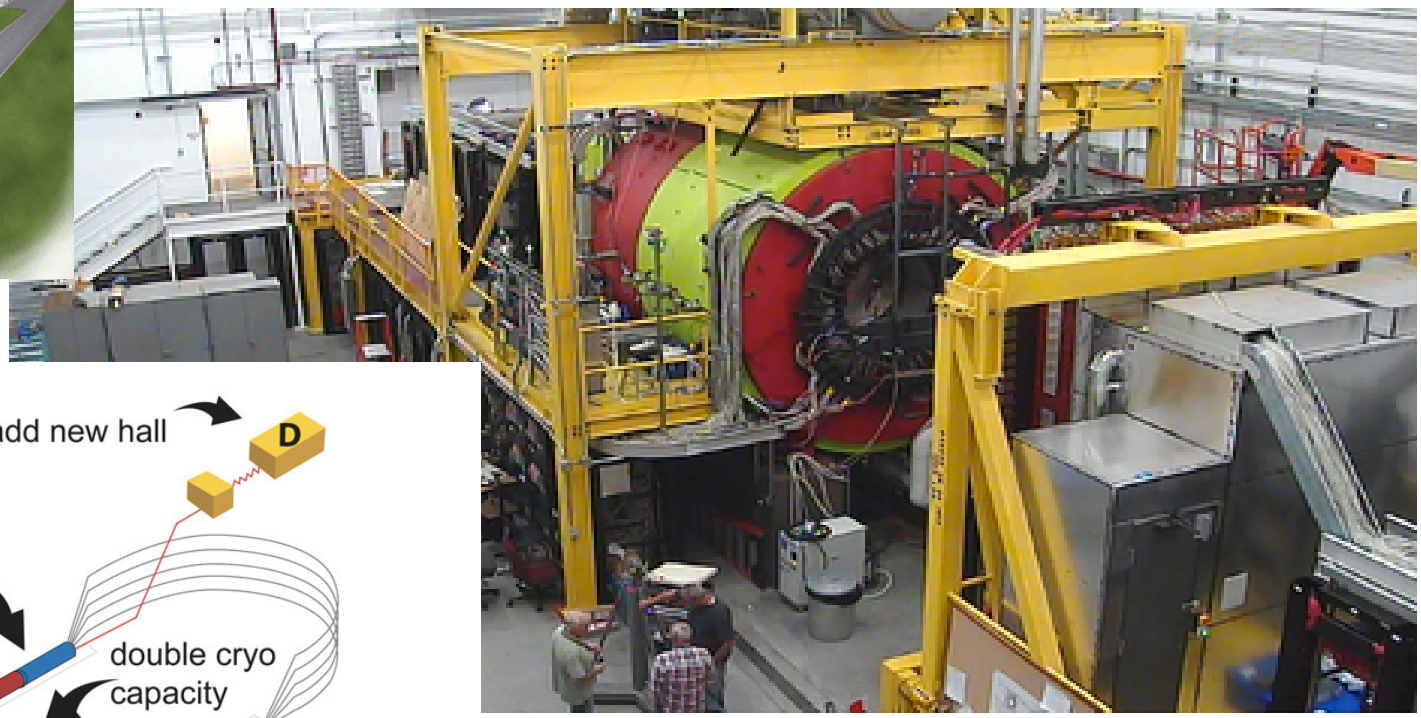


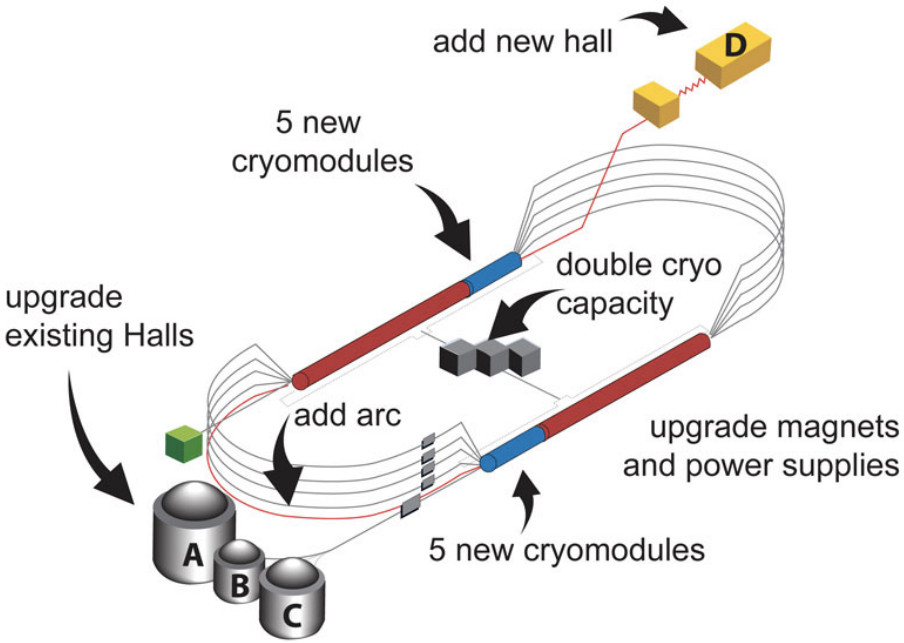
The GlueX Collaboration

- $\sim$135 members, 29 institutions
  (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017

Hall D

May 2014



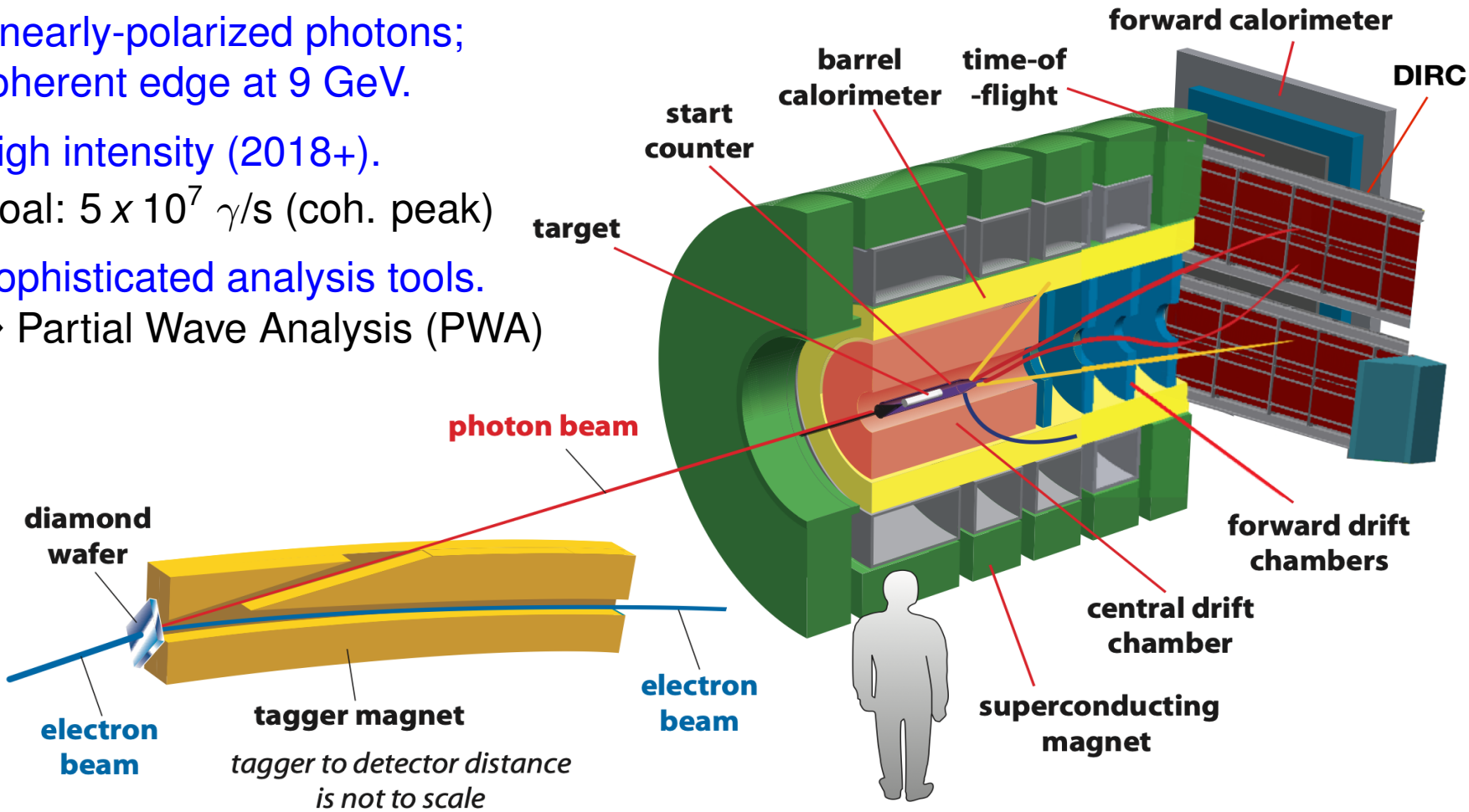


Jefferson Lab Upgrade to 12 GeV

- 10.1 GeV achieved, Fall 2014
- GlueX commissioning in 2015

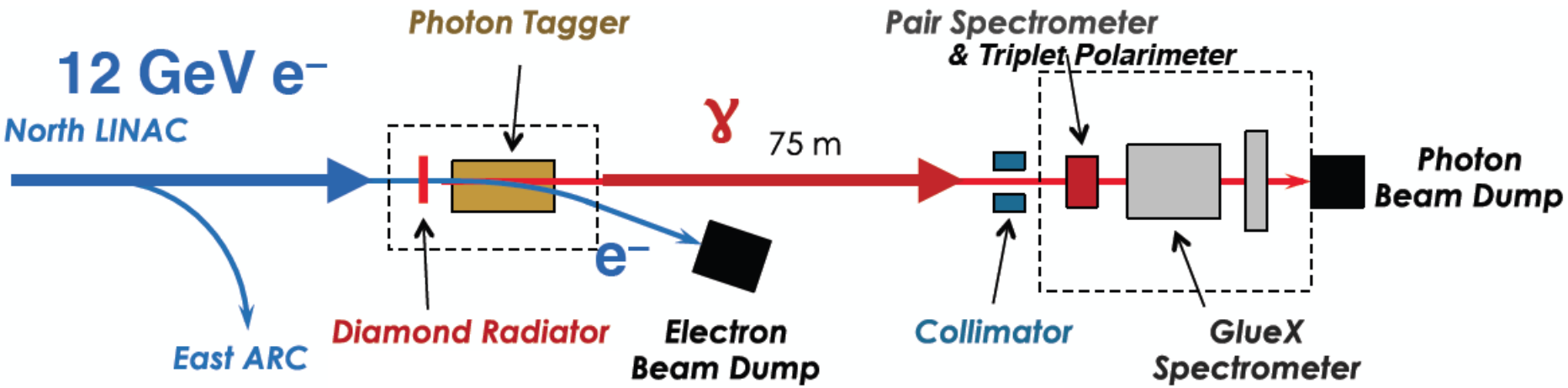
Study of light-flavor (hybrid) mesons and baryons:

- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity (2018+).
  Goal: $5\,x\,10^7$ γ/s (coh. peak)
- Sophisticated analysis tools.
  ➜ Partial Wave Analysis (PWA)



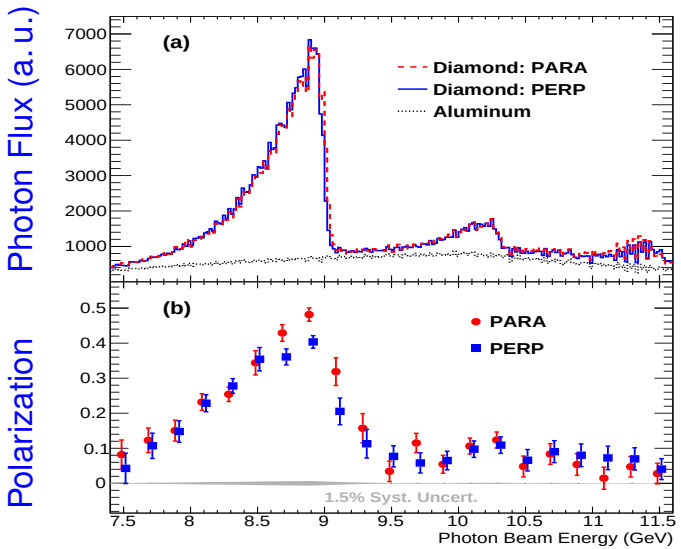
~ 75 m

The GlueX Experiment: Photon Beamline



Polarized photon beam produced via coherent bremsstrahlung off thin diamond radiator:

- Tagging system with $\Delta E < 25$ MeV.
- Linear photon polarization of $P_\gamma \approx 40\,\%$ in the coherent peak.
- Design intensity of 10^8 γ/s in peak.



Outline

Quark-Model Classification: Ordinary & Exotic Mesons

Quantum Numbers $J^{PC} \equiv {}^{2S+1}L_J$

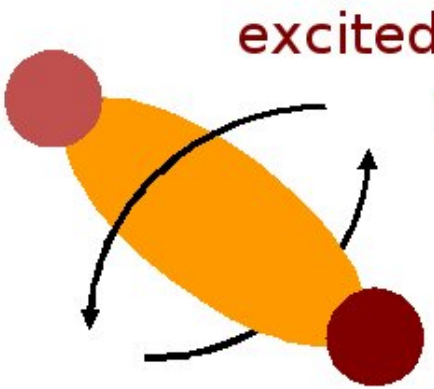
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^{I}$

$L = 0,\ S = 0$:

e.g. $\pi,\ \eta\ (J^{PC} = 0^{-+})$

$L = 0,\ S = 1$:

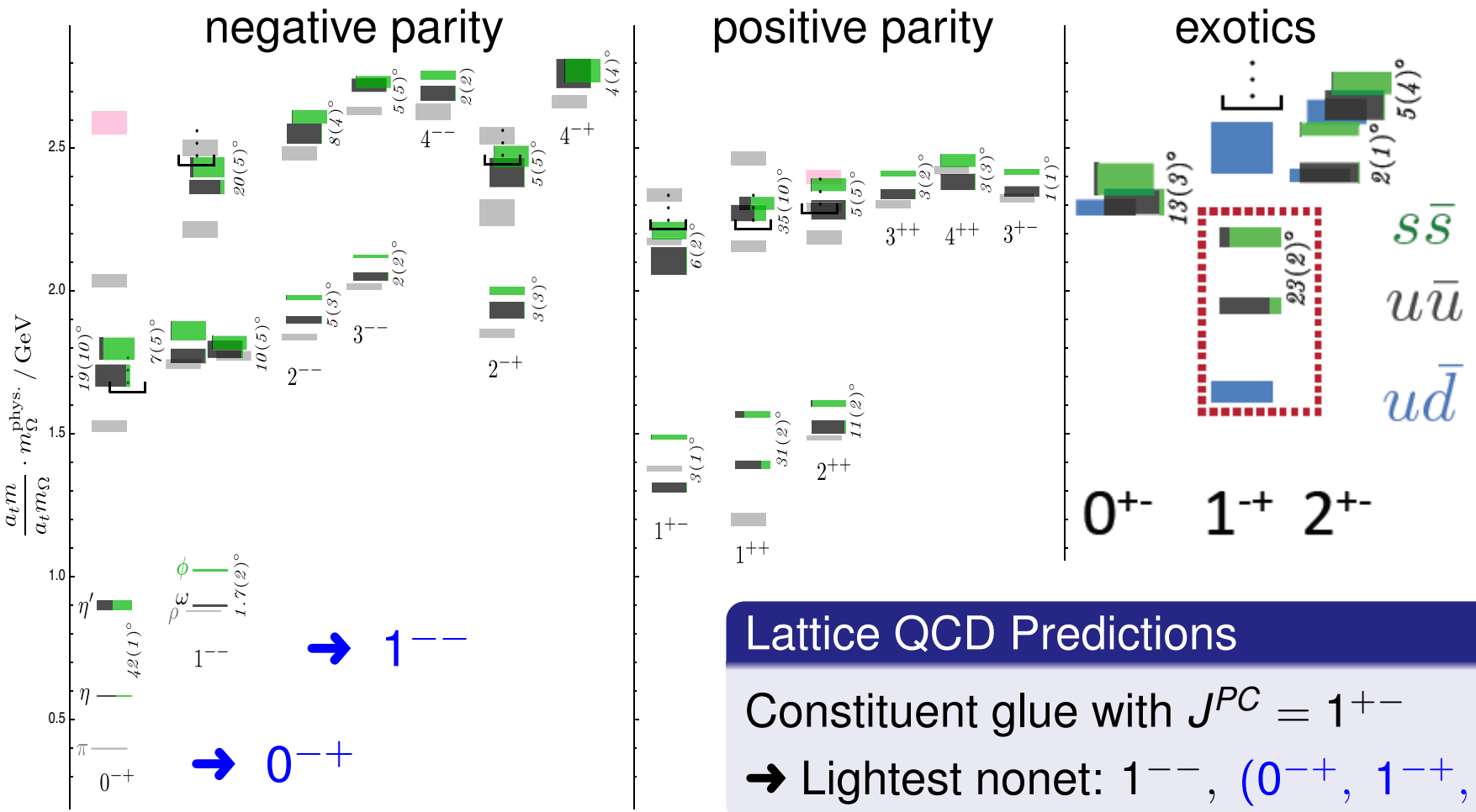
e.g. $\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$



12 GeV CEBAF upgrade has high priority
(DOE Office of Science, Long Range Plan)
"[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Forbidden States (Exotics): $J^{PC} = 0^{+-},\ 0^{--},\ 1^{-+},\ 2^{+-},\ \cdots$
(hybrid kaons do not have exotic QNs)

Meson Spectroscopy on the Lattice



➜ 1^{--}

➜ 0^{-+}

Lattice QCD Predictions

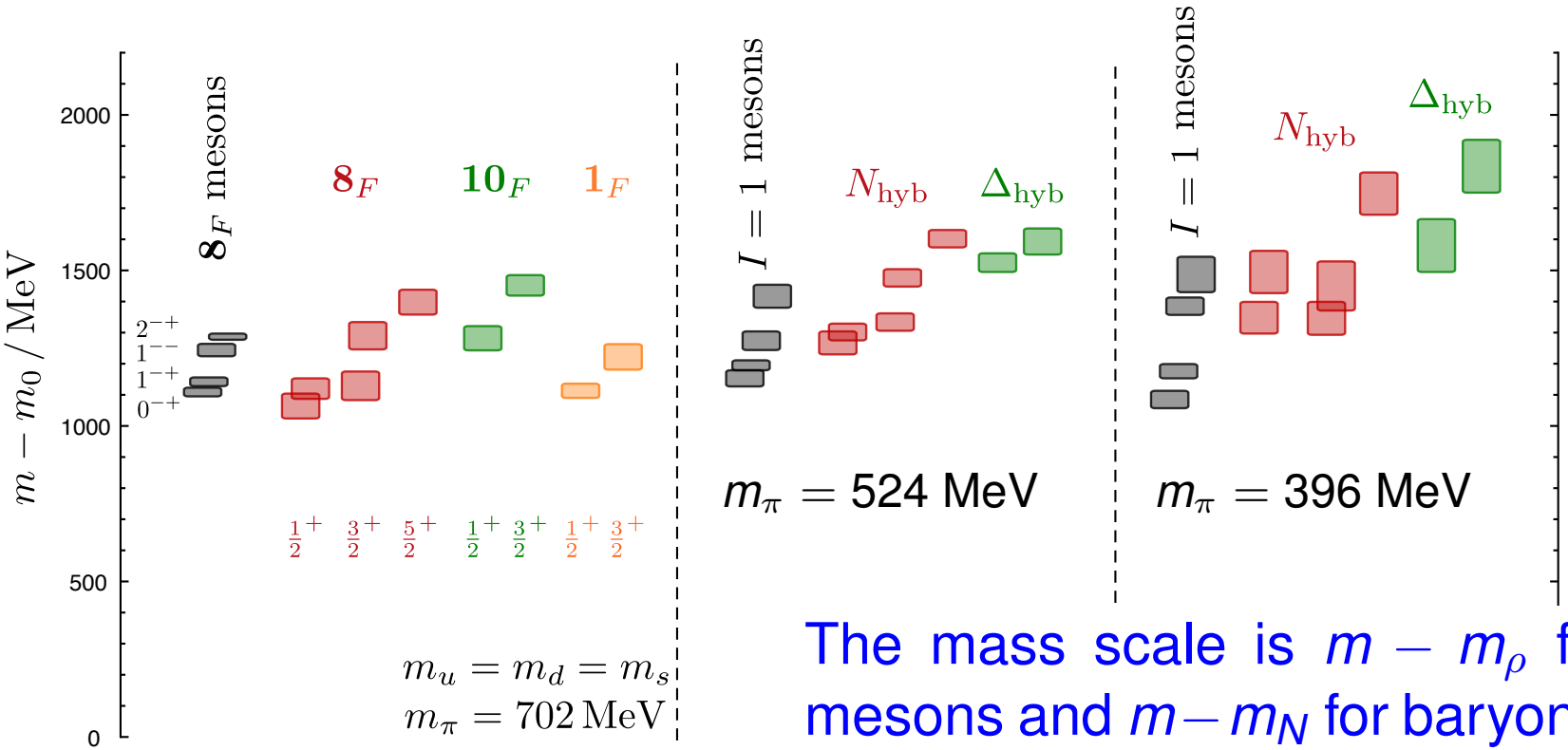
Constituent glue with $J^{PC} = 1^{+-}$

➜ Lightest nonet: 1^{--}, $(0^{-+}, 1^{-+}, 2^{-+})$

J. J. Dudek *et al.*, PRD **84**, 074023 (2011)

Gluonic Excitations on the Lattice

J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)

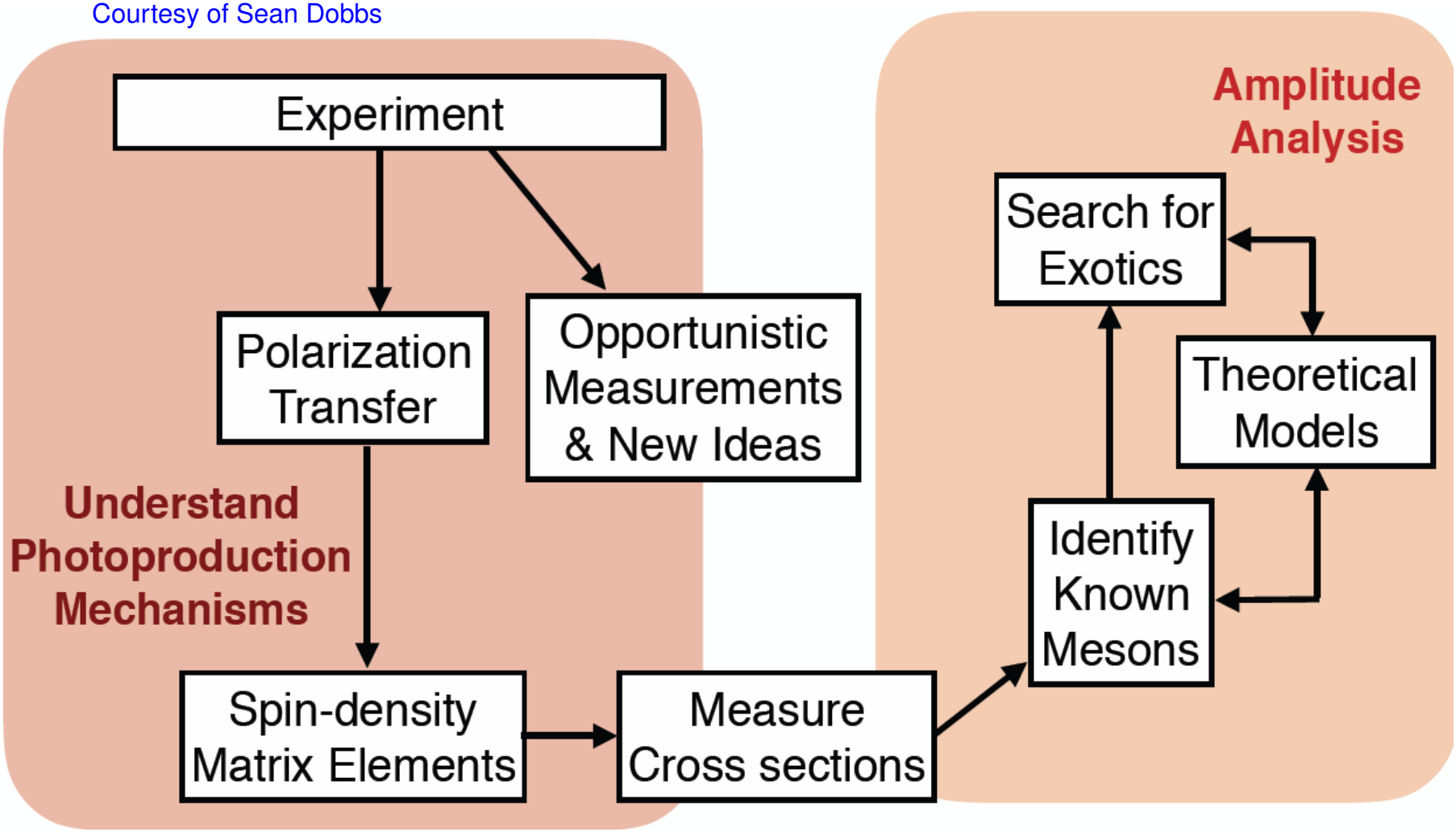


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

Common scale of $\sim$ 1.3 GeV for gluonic excitation.

Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs



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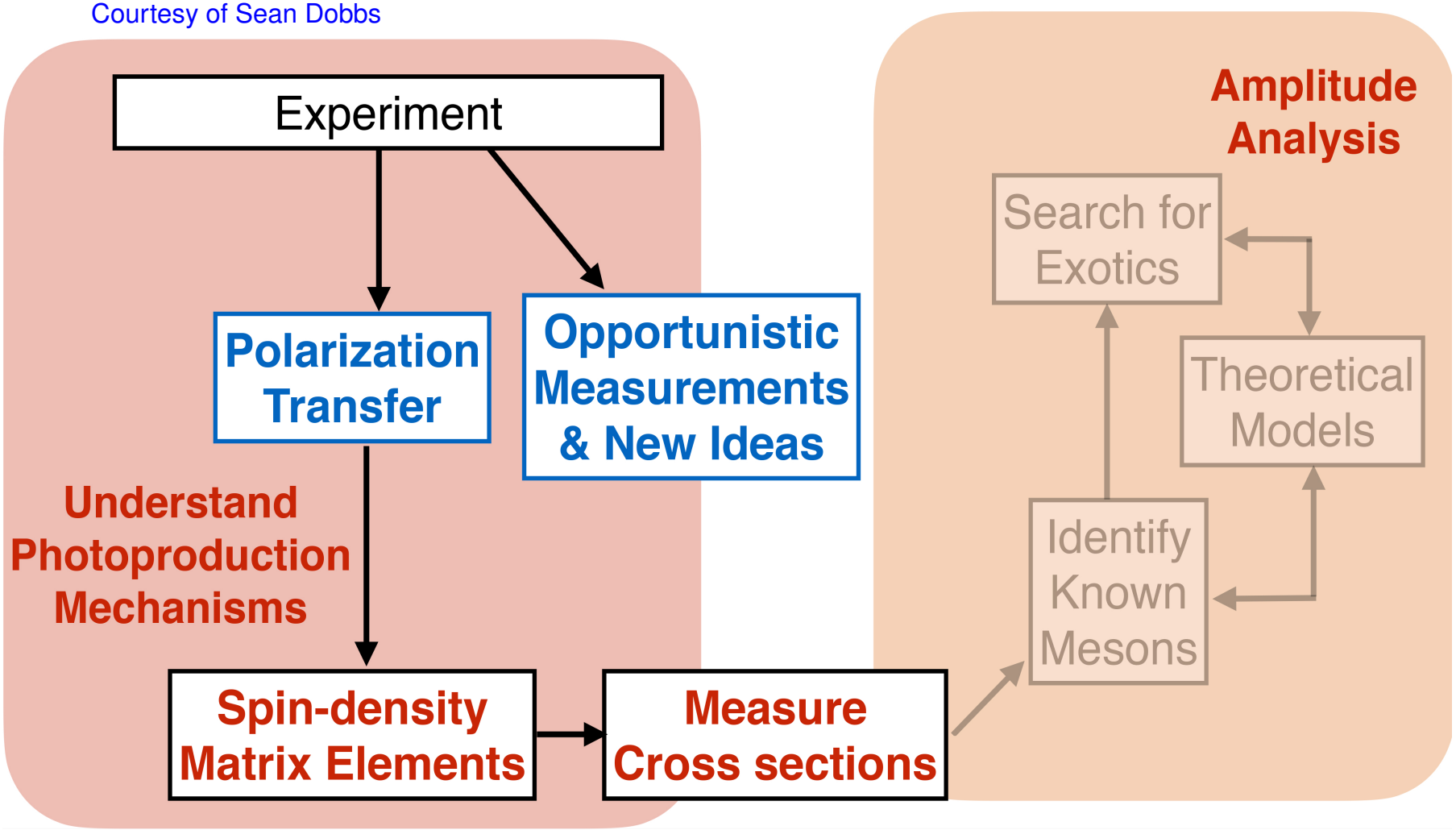
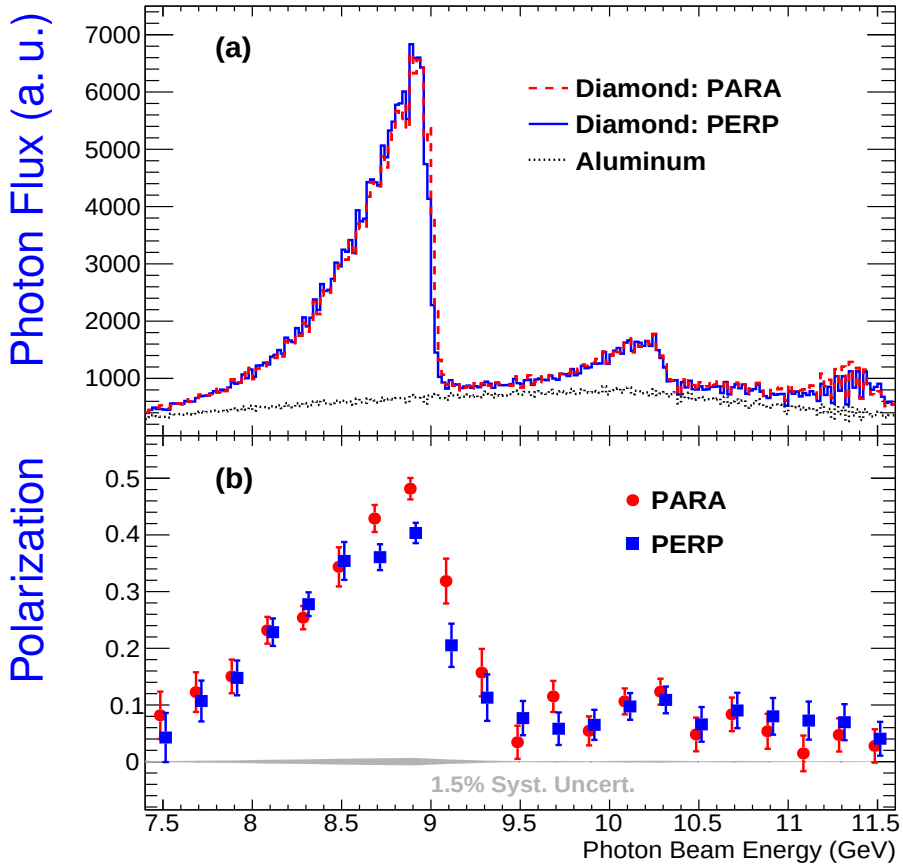


First GlueX "Physics:" Initial Analyses



← H. Al Ghoul *et al.*, PRC **95**, 042201 (2017)

Detector Understanding:

$\gamma p \to p\,\pi^0$
$\gamma p \to p\,\eta$ ➜ Beam Asymmetries

$\gamma p \to p\,\eta'$
$\gamma p \to K^+\,\Sigma^0$
$\gamma p \to \pi^-\,\Delta^{++}$

$\gamma p \to p\,\rho$
$\gamma p \to p\,\omega$
$\gamma p \to p\,\phi$

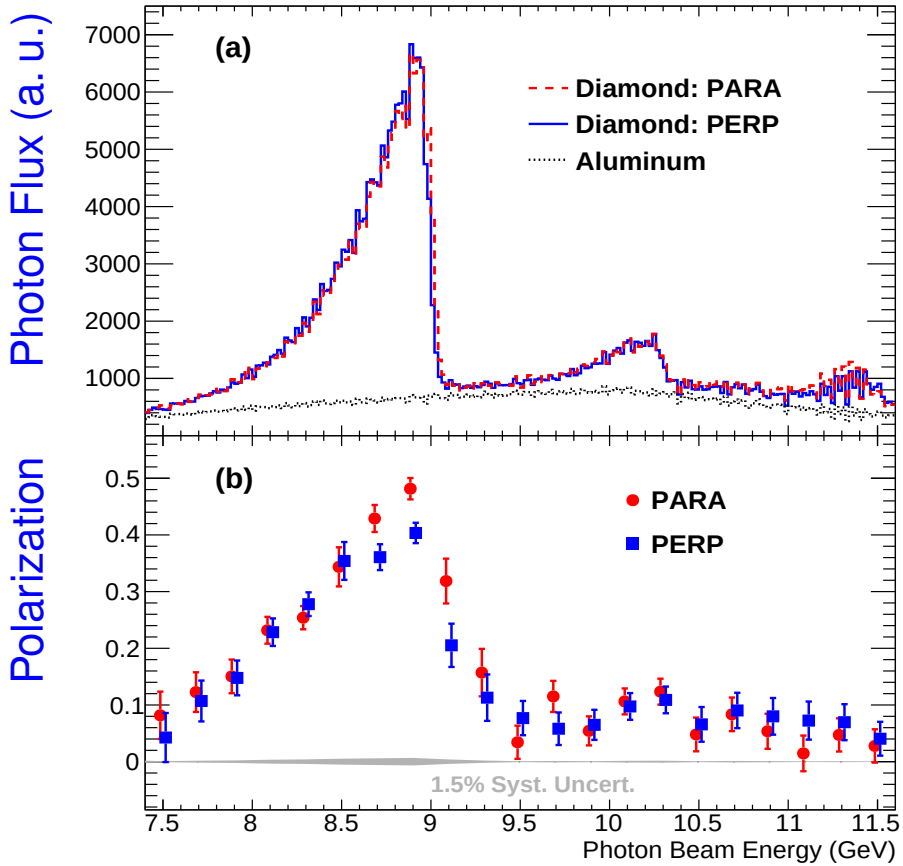
↓

cross sections
SDMEs

Initial Exotic Hybrid Searches

$\gamma p \to \eta\pi\,(p, \Delta^{++})$
$\gamma p \to \eta'\pi\,(p, \Delta^{++})$
$\gamma p \to \rho\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\pi\,(p, \Delta^{++})$
$\gamma p \to \eta\pi\pi\,(p, \Delta^{++})$

First GlueX "Physics:" Initial Analyses



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Detector Understanding:

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$\gamma p \to p\eta'$
$\gamma p \to K^+\Sigma^0$
$\gamma p \to \pi^-\Delta^{++}$

$\gamma p \to p\rho$
$\gamma p \to p\omega$
$\gamma p \to p\phi$

$\gamma p \to pJ/\psi$
$\gamma p \to pB\overline{B}$

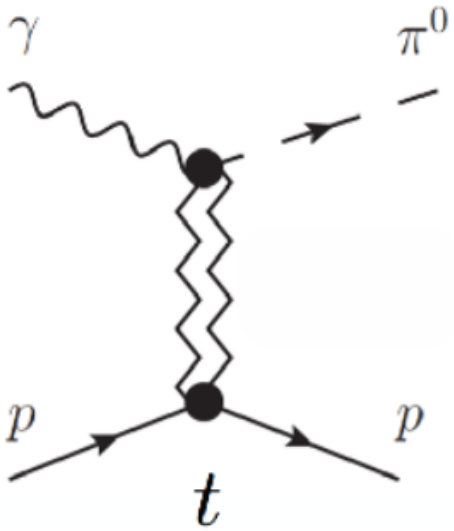
Initial Exotic Hybrid Searches

$\gamma p \to \eta\pi\,(p, \Delta^{++})$
$\gamma p \to \eta'\pi\,(p, \Delta^{++})$
$\gamma p \to \rho\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\pi\,(p, \Delta^{++})$
$\gamma p \to \eta\pi\pi\,(p, \Delta^{++})$

Strange Baryons: $\gamma p \to K^+\Lambda,\ K\Sigma,\ KK\Xi$

Measurement of Beam Asymmetries: $\gamma p \to p\pi^0$

Beam Asymmetry, Σ, yields information on production mechanism



Exchange of J^{PC}

1^{--} : $\omega,\ \rho$

1^{+-} : $b,\ h$

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

V. Mathieu *et al.*, Phys. Rev. D **92**, no. 7, 074004 (2015)

Measurement of Beam Asymmetries: $\gamma p \to p\pi^0$

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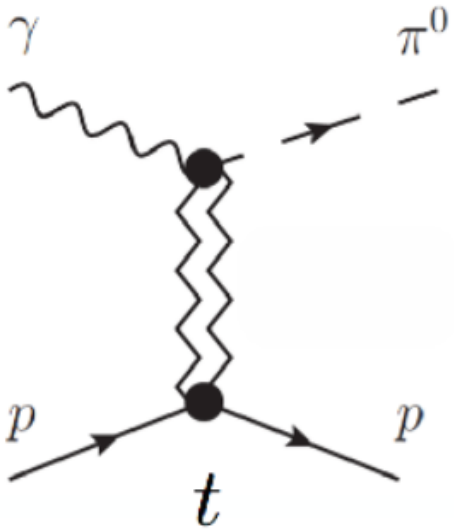


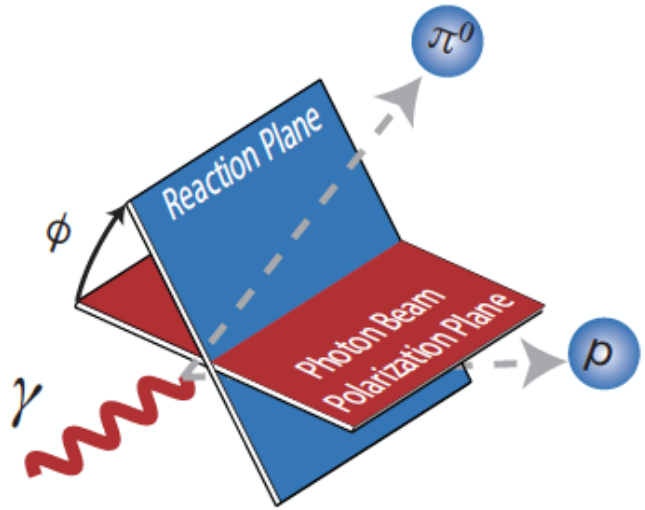
Exchange of J^{PC}

1^{--} : $\omega,\ \rho$

1^{+-} : $b,\ h$

Experimentally:

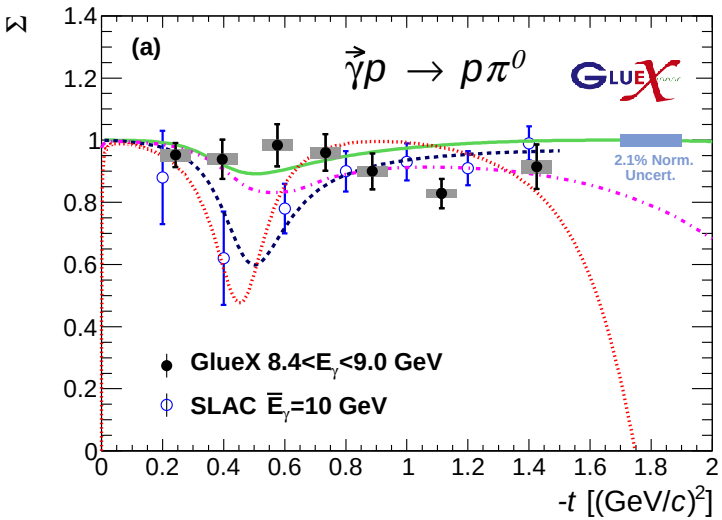
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

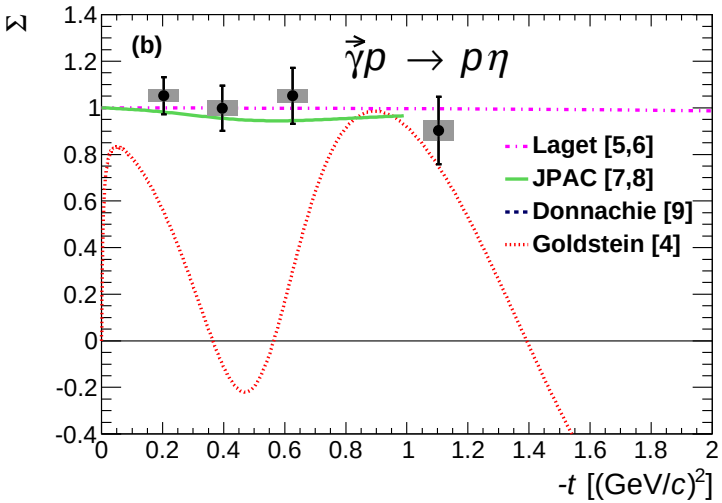


$$\Sigma = \frac{|\omega + \rho| - |h + b|}{|\omega + \rho| + |h + b|}$$

V. Mathieu *et al.*, Phys. Rev. D **92**, no. 7, 074004 (2015)

Measurement of Beam Asymmetries: $\gamma p \to p\pi^0/\eta$



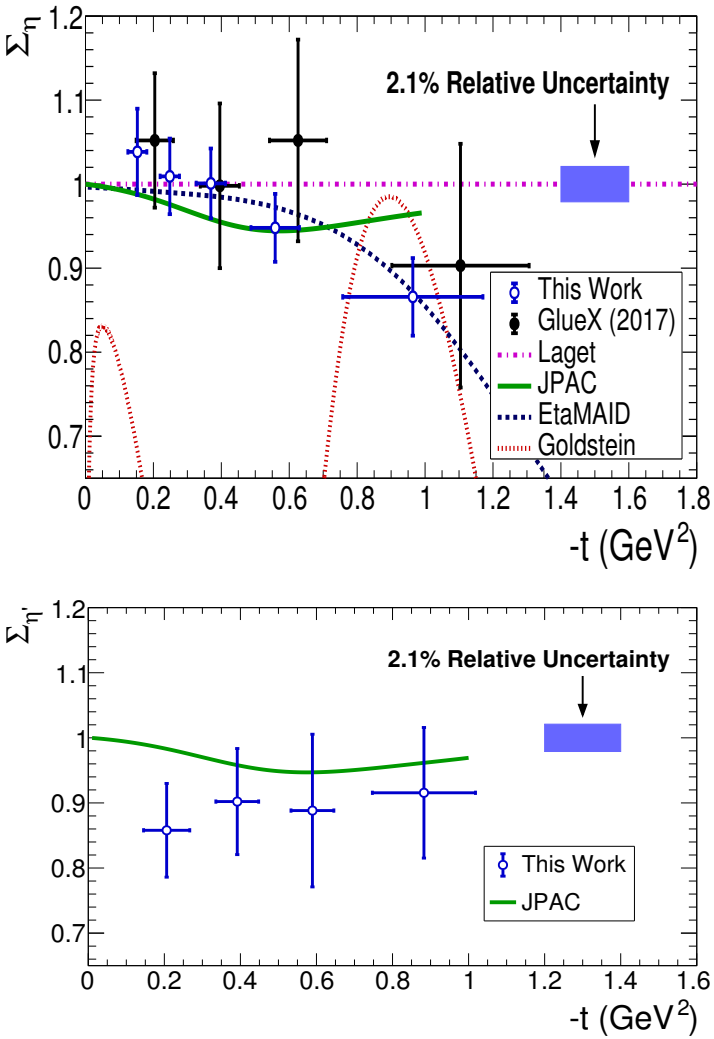


H. Al Ghoul *et al.*, Phys. Rev. C **95**, no. 4, 042201 (2017)

Significantly improved data quality

- First measurement of the η beam asymmetry for $8.4 < E_\gamma < 9.0$ GeV.
- Beam asymmetries close to unity: $\Sigma \approx 1$
  ➜ Dominance of vector-meson exchange
  No dip around $-t = 0.5$ GeV^2 for π^0
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
  ➜ Step toward search for exotic mesons.

Measurement of Beam Asymmetries: $\gamma p \to p\eta/\eta'$



S. Adhikari *et al.*, Phys. Rev. C **100**, no.5, 052201 (2019)

Significantly improved data quality

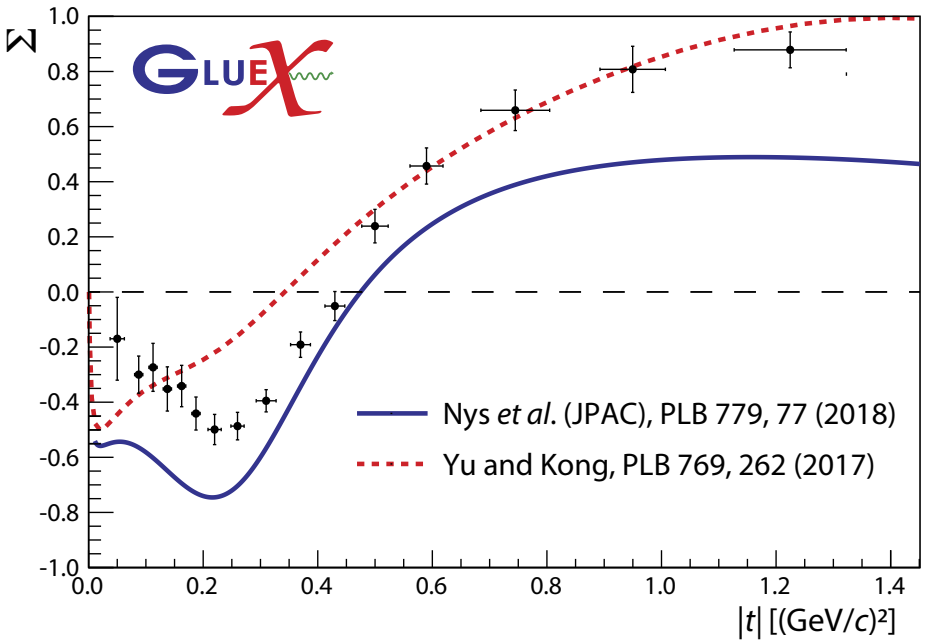
- First measurement of the $(\eta)/\eta'$ beam asymmetries for $8.2 < E_\gamma < 8.8$ GeV.
- Beam asymmetry close to unity: $\Sigma_\eta \approx 1$
  ➜ Dominance of vector-meson exchange
  No indication for 2^{--} exchange
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
  ➜ Step toward search for exotic mesons.

Measurement of Beam Asymmetries

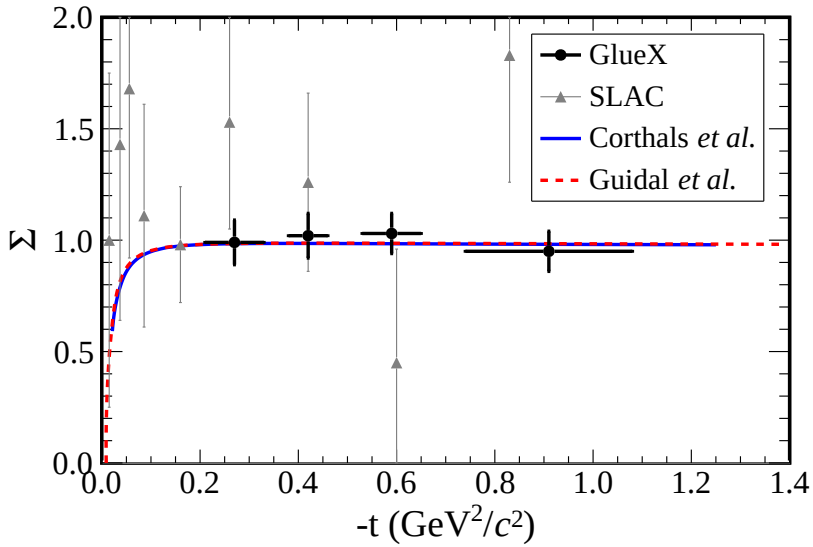
S. Adhikari *et al.*, [arXiv:2009.07326 [nucl-ex]]

- Charge exchange process
- Dominated by π exchange at low |t|

$\gamma p \to \pi^- \Delta^{++}$



$\gamma p \to K^+ \Sigma^0$



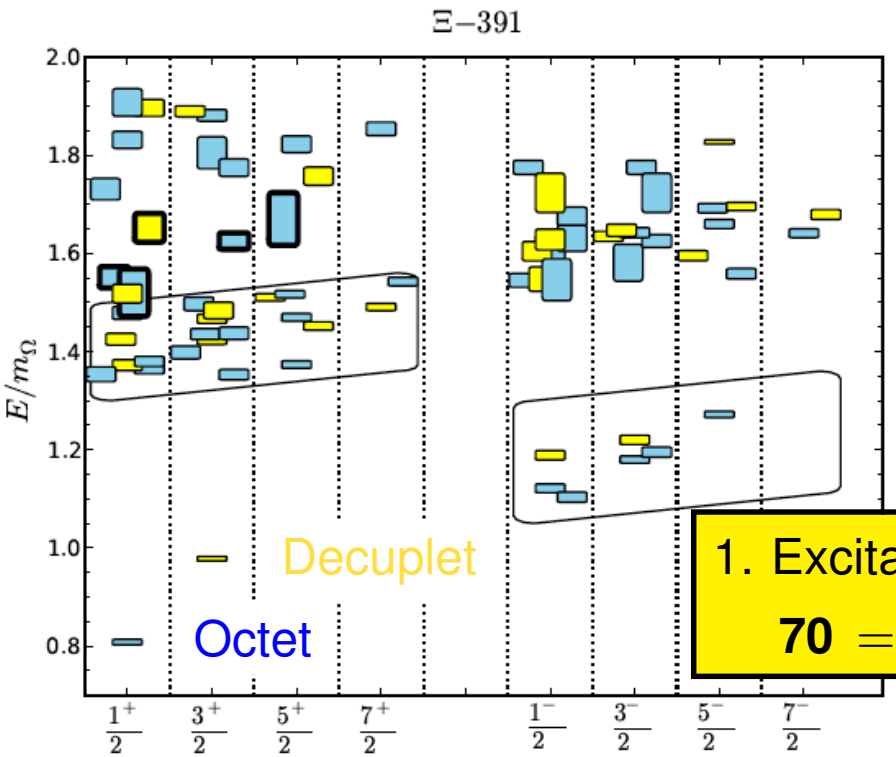
Phys. Rev. C **101**, no.6, 065206 (2020)

- Consistent with unity

  ➜ Dominant natural parity exchange

The Ξ^* Resonance Spectrum from Lattice QCD

R. Edwards *et al.*, PRD **87**, 054506 (2013)



$\Xi(1320)$	****	$\to \Lambda\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
$\Xi(1530)$	****	$\to \Xi\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
$\Xi(1620)$	*	$\to \Xi\pi$?	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+ \text{ or } \frac{1}{2}^-\right)$
$\Xi(1690)$	***		$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^-?\right)$
$\Xi(1820)$	***	$\to \Lambda\overline{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^-\right)$
$\Xi(1950)$	***		$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^-?\right)$
$\Xi(2030)$	***	$\to Y\overline{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\geq \frac{5}{2}^?\right)$

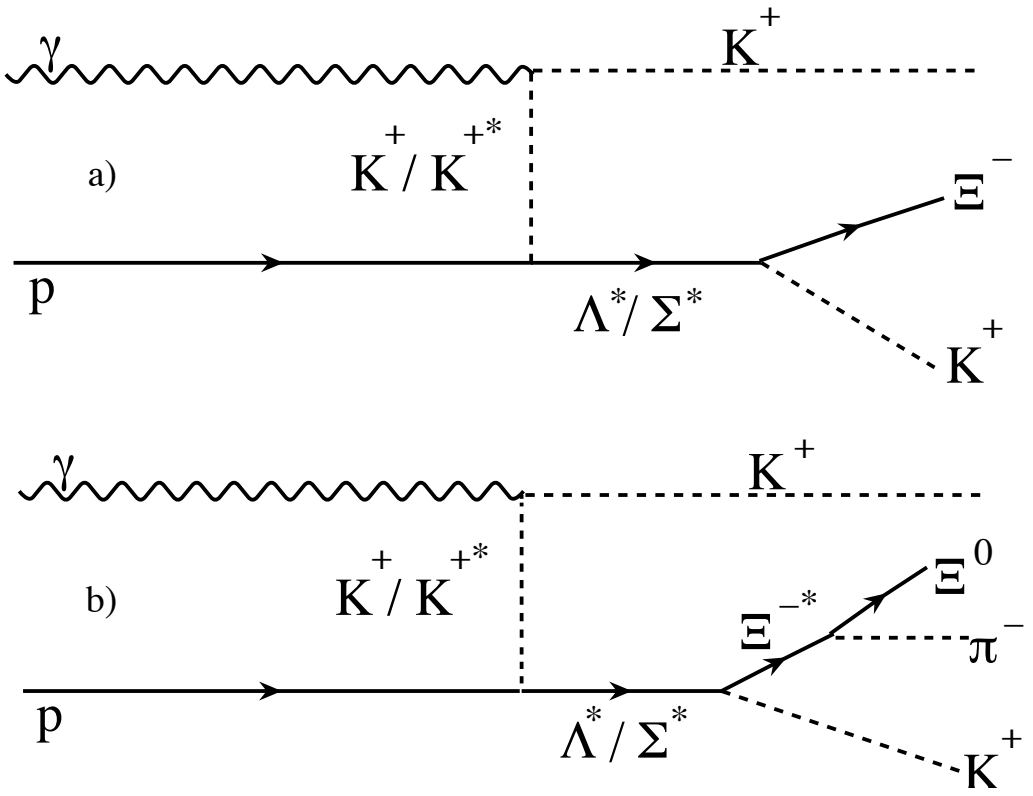
1. Excitation Band: $(\mathbf{70}, 1^-_1)$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.

Possible Production Mechanisms



$K^+(\Xi^- K^+)$, $K^+(\Xi^0 K^0)$, $K^0(\Xi^0 K^+)$

➜ Cross sections, beam asymmetries
(similar to $p\pi\pi$ & pKK^*)

At other facilities (for comparison):

$K^- p \to K^+ \Xi^{*-}$	J-PARC
$K_L p \to K^+ \Xi^{*0}$	Hall D
$p p \to \Xi^* X$	LHCb
$\bar{p} p \to \Xi^* \bar{\Xi}$	$\bar{\text{P}}$ANDA
$e^+ e^- \to \Xi^* X$	Belle II, BES III

* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

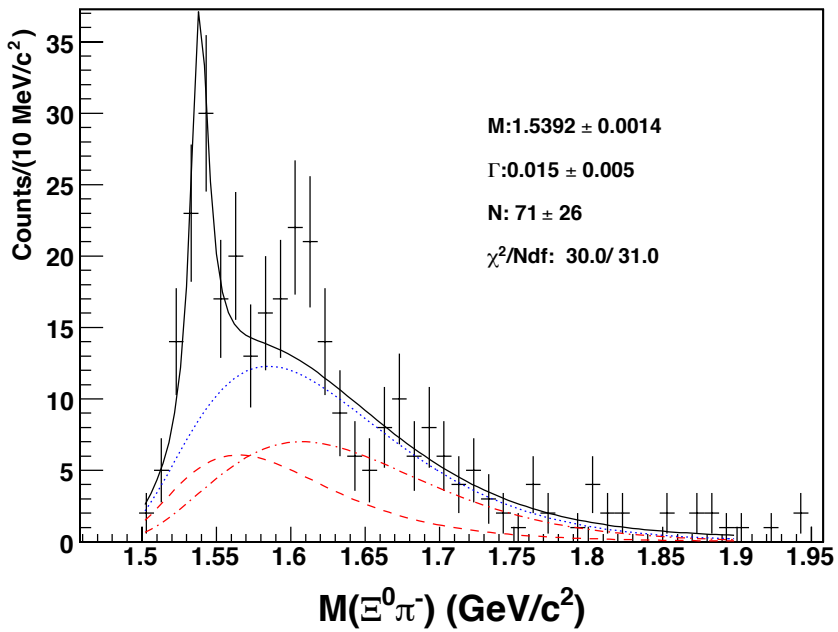
CLAS g11a: Excited States in $\gamma p \to K^+K^+\pi^-(X)$

From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*
Phys. Rev. C **76**, 025208 (2007)

Need high-statistics, high-energy data from an experiment designed to see Ξ states:

- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors

➜ CLAS 12 and GlueX at Jefferson Lab



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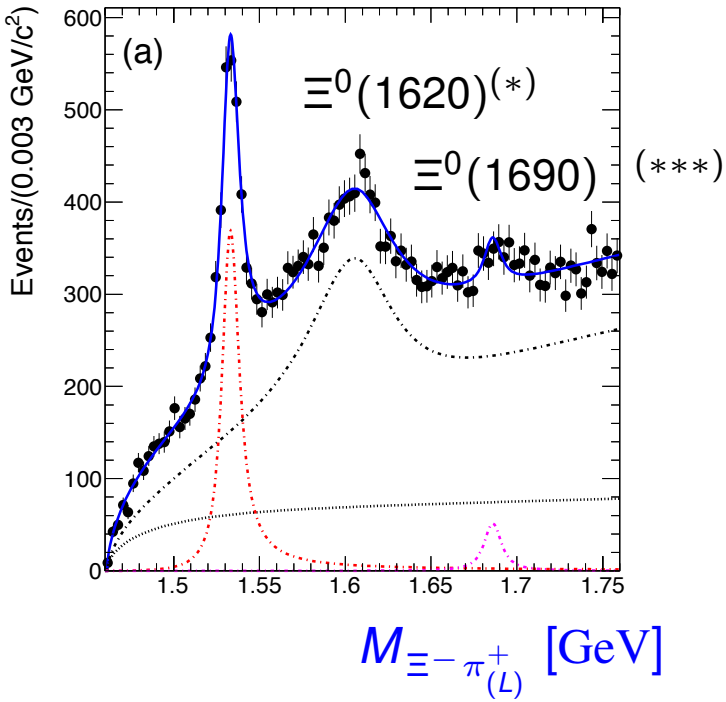
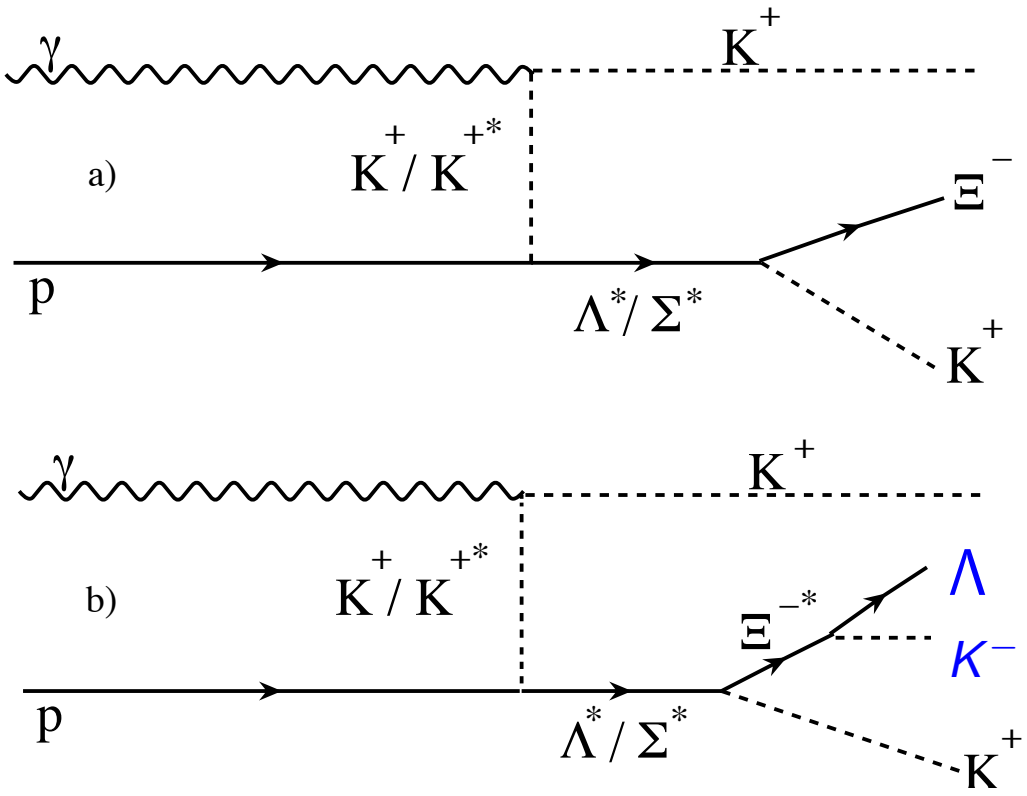
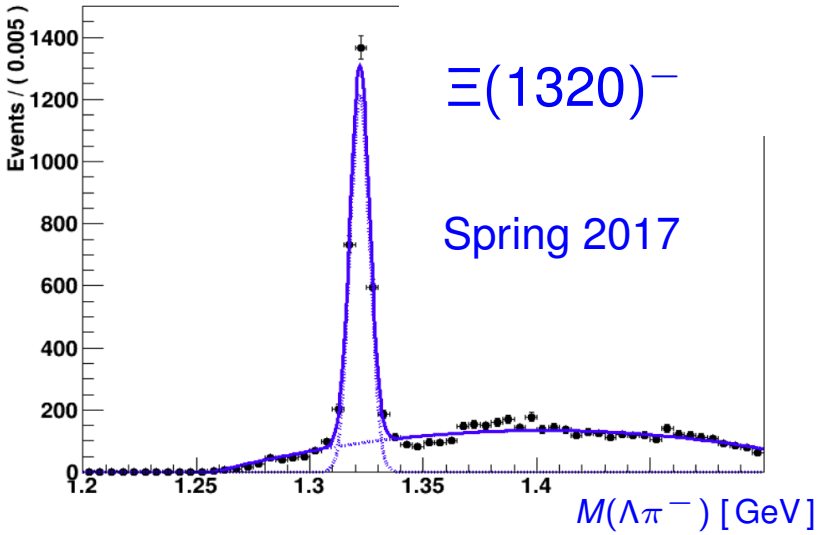
Belle: PRL **122**, 072501 (2019)



Possible Production Mechanisms





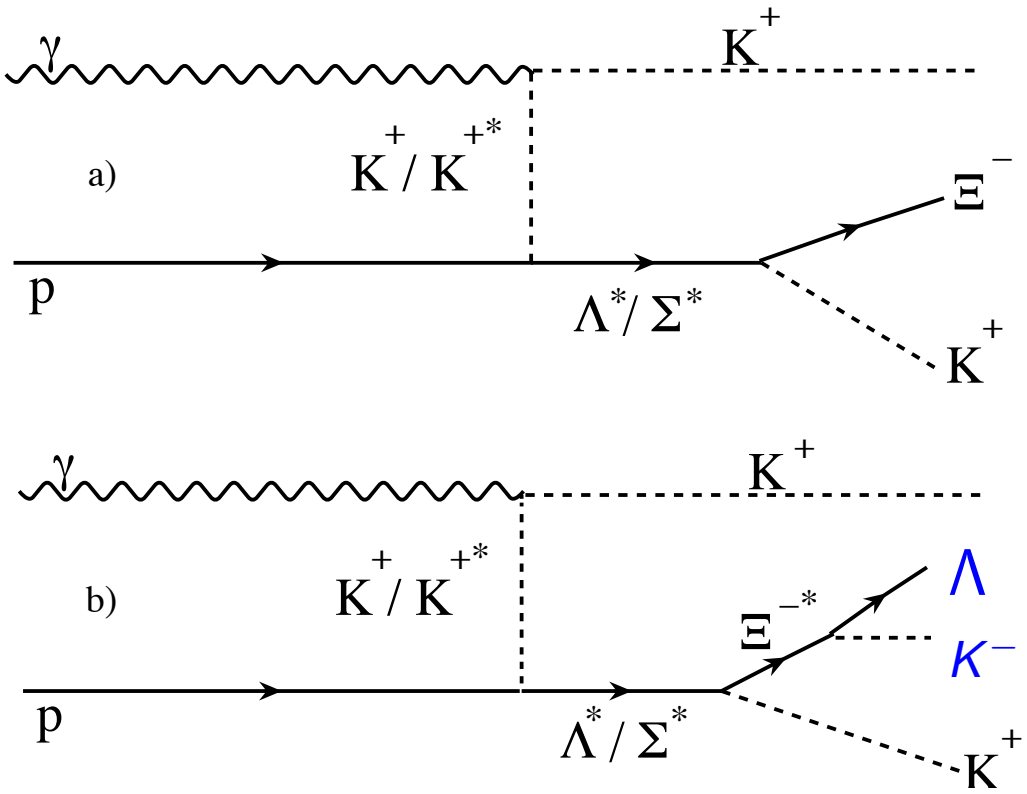
$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$

Study and Measurement of

- Cross sections
- Beam asymmetry
- $\Xi^- - \Xi^0$ mass splitting

Ashley Ernst, Dissertation (2020), Florida State University

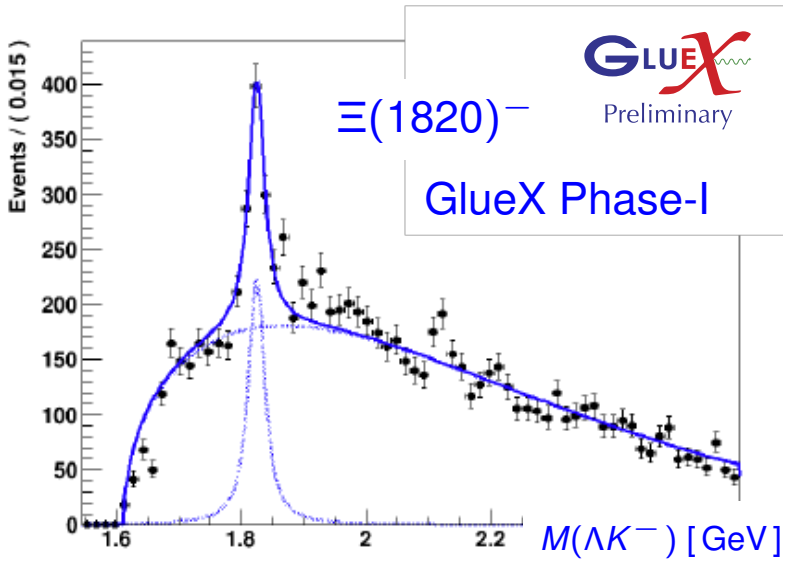
Possible Production Mechanisms



$$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$$

First observation of excited Ξ^* state in photoproduction with

- ≈ 700 $\Xi(1820)^-$ signal events
- Peak significance $> 10\sigma$



Ashley Ernst, Dissertation (2020), Florida State University

J/ψ Photoproduction Near Threshold

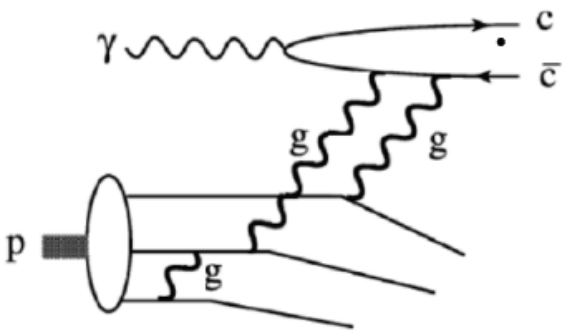
Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton

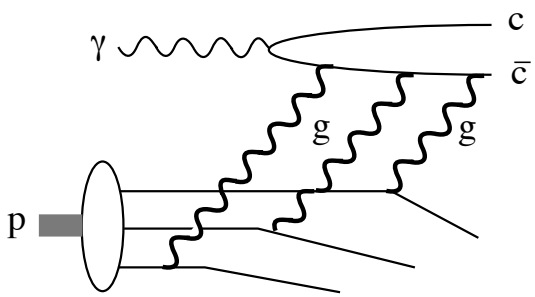
  (D. Kharzeev *et al.*, Nucl. Phys. A **661**, 568 (1999))

- Sensitive to multi-quark correlations

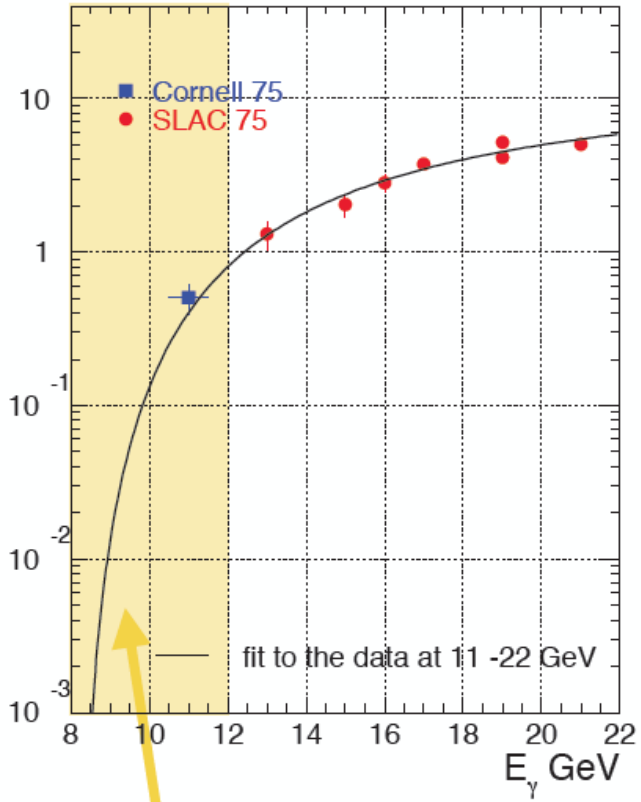
  (S. Brodsky *et al.*, Phys. Lett. B **498**, 23 (2001))



leading twist



higher twist



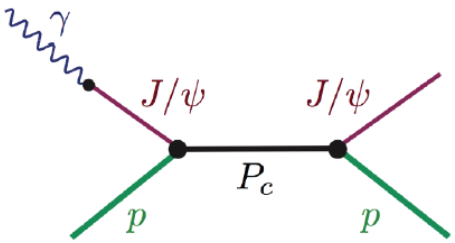
GlueX energy range

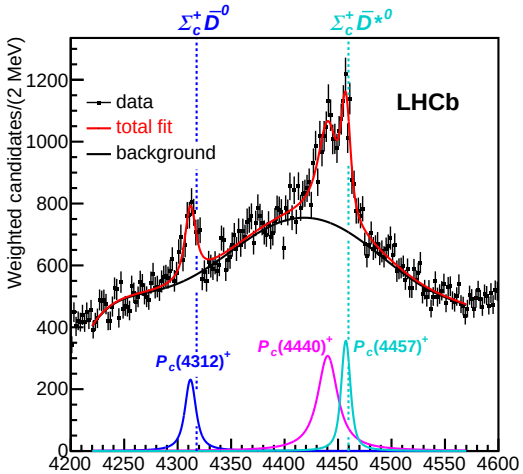
J/ψ Photoproduction Near Threshold

Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

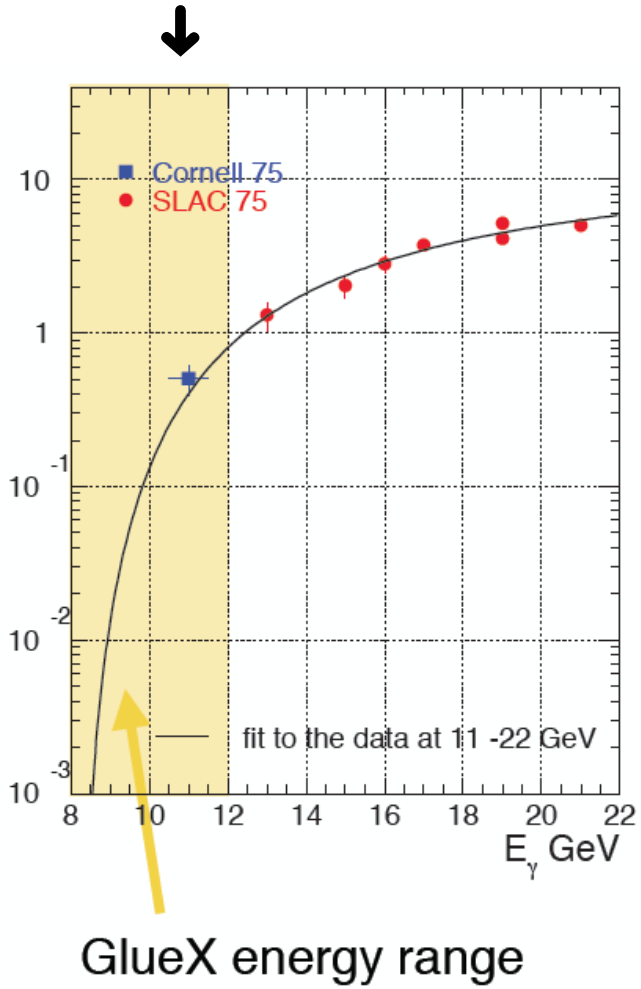
- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction

$P_c(4450)$



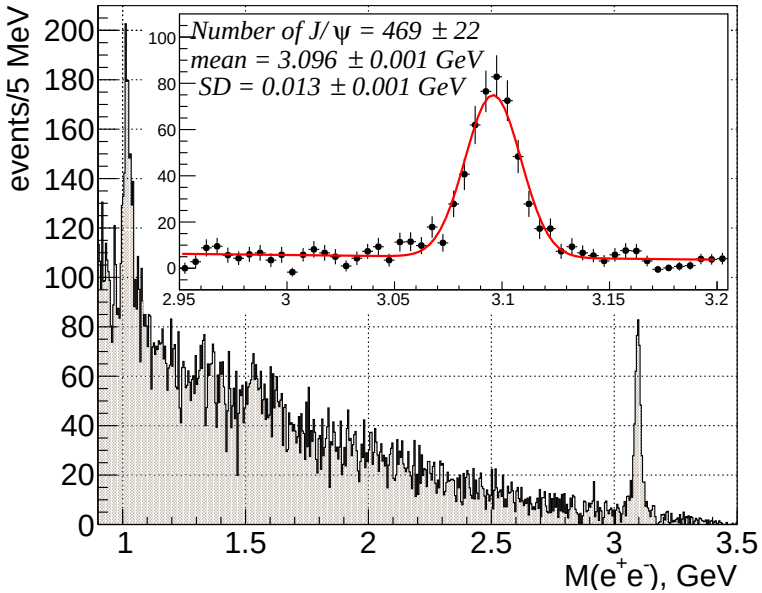


R. Aaij *et al.*, PRL **122**, 222001 (2019)



Observation of J/ψ at GlueX

A. Ali *et al.* [GlueX], Phys. Rev. Lett. **123**, no.7, 072001 (2019)



First observation of J/ψ at Jefferson Lab in $\gamma p \to p\, J/\psi \to p\, e^+ e^-$

- First detailed look at cross section near threshold

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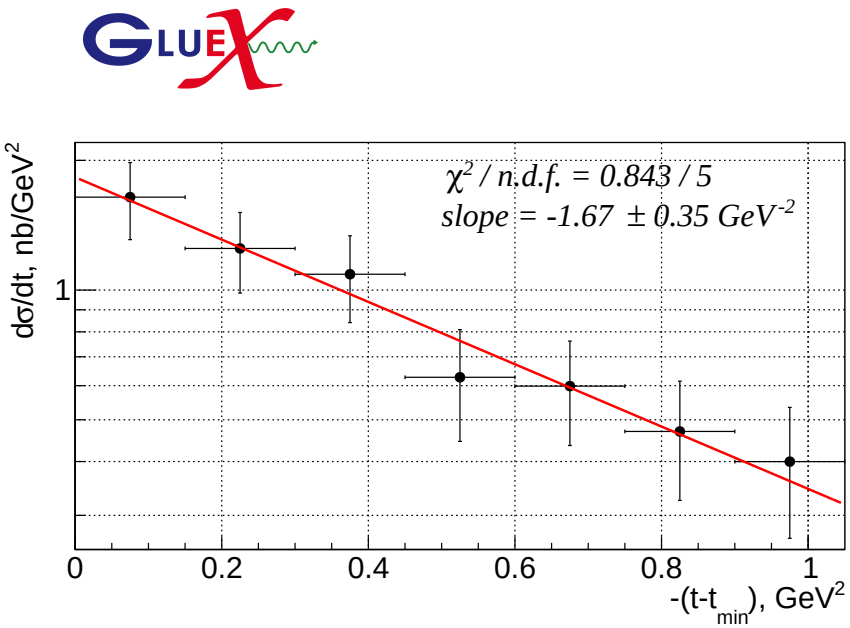

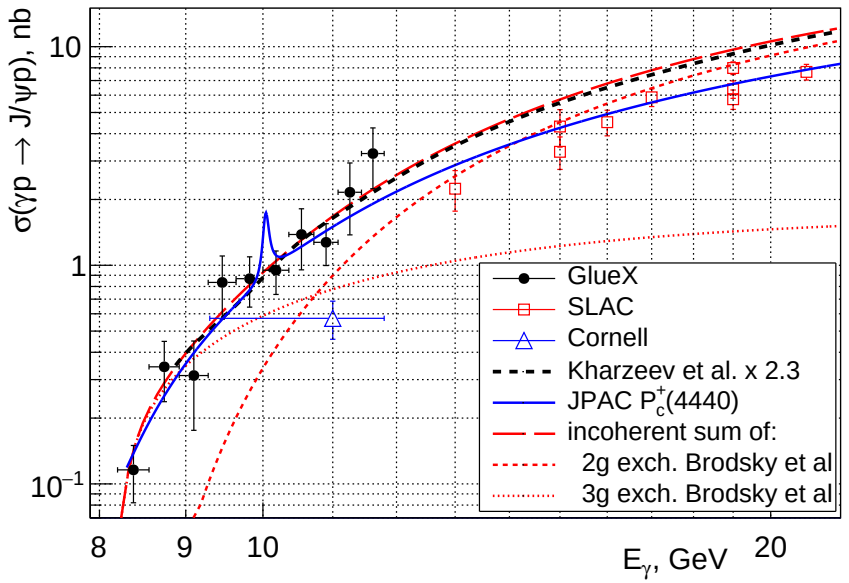

First observation of J/ψ at Jefferson Lab in $\gamma p \to p\, J/\psi \to p\, e^+ e^-$

- First detailed look at cross section near threshold
- Measurement of t slope (at 10.7 GeV avg. E_γ): (-1.67 ± 0.39) GeV^{-2}
- Limits on pentaquark production

Outline

Planned Experiments at Jefferson Lab

Broad and rich physics program in Hall D using the GlueX detector:

- Mapping the Spectrum of Light-Quark Mesons and Gluonic Excitations with Linearly-Polarized Photons. (GlueX Phase-I)

  A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC. (arXiv:1408.0215)
- Precision Measurement of η Radiative Decay Width via Primakoff Effect.
- Measuring the Charged-π/(π^0) Polarizibility in the $\gamma\gamma \to \pi^+\pi^-$ Reaction.
- Symmetry Tests of Rare η Decays to All-Neutral Final States.

- Probing QCD in the nuclear medium with real photons and nuclear targets at GlueX
- Photoproduction of vector mesons on nuclei with GlueX

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Outline

Summary

Early GlueX data show rich prospects for hadron spectroscopy:

➜ High-luminosity running (+ BaBar DIRC detectors) will extend the program to strange-quark states.

First observation of Charmonium at JLab!!

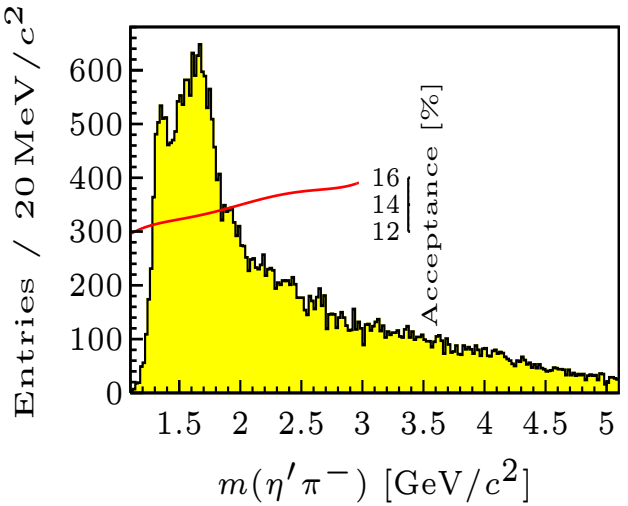
Outlook

The GlueX experiment is ideally suited to study the spectrum of light-flavor mesons up to $M \approx 2.8$ GeV and – if existing – the pattern of the gluonic excitations produced in γp collisions:

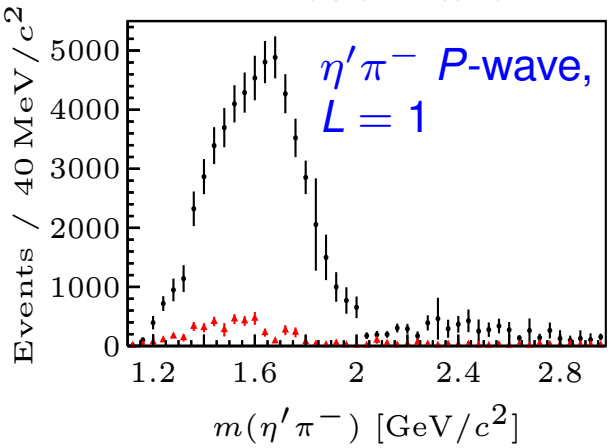
- It is important to establish the existence and the nonet nature of the 1^{-+} state (and of 0^{+-}, 2^{+-})

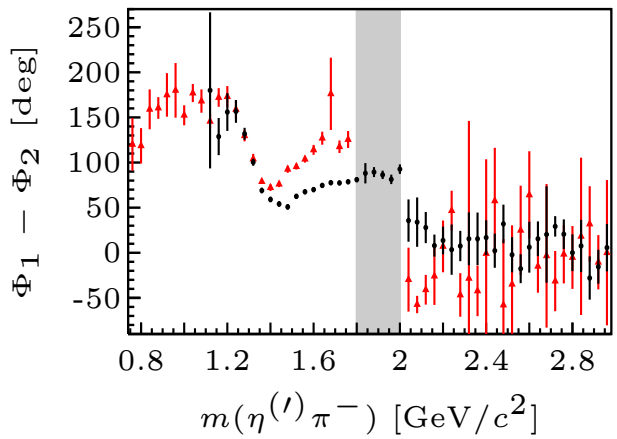
COMPASS Experiment: $\pi^- p \to \eta^{(\prime)} \pi^- (p)$

C. Adolph *et al.*, PLB **740**, 303 (2015)



1^{-+} Exotic Wave





Collaboration refrains from proposing resonance parameters for exotic P wave.

- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).
- Dominant **8** $\otimes$ **8** $(\eta\pi)$ & **1** $\otimes$ **8** $(\eta'\pi)$ nature of $SU(3)$ flavor configurations
  ➜ $gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have **1** $\otimes$ **8** character.

Outlook

The GlueX experiment is ideally suited to study the spectrum of light-flavor mesons up to $M \approx 2.8$ GeV and – if existing – the pattern of the gluonic excitations produced in γp collisions:

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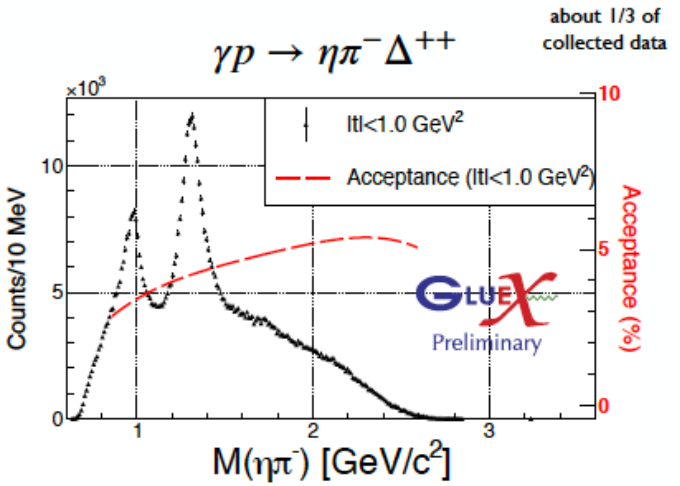
- For a given produced resonance, linear polarization will allows us to distinguish between naturalities of exchanged particles.



Analysis of $\vec{\gamma}p \to \eta^{(\prime)}\,\pi^-\,(p)$ priority for GlueX

- Sufficient data available to explore the $\eta\pi$ and $\eta'\pi$ systems with competitive statistics
- Multiple charge combinations and decay modes accessible
- Close collaboration with JPAC

Outlook

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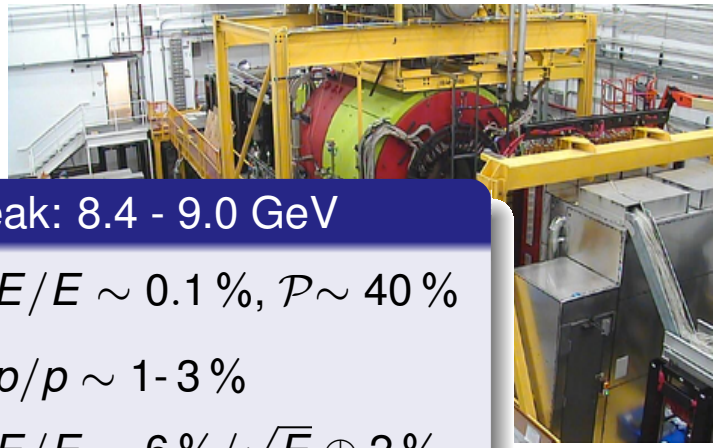
- For a given produced resonance, linear polarization will allows us to distinguish between naturalities of exchanged particles.
- About 70 % of the photoproduction cross section in the energy region $E_\gamma \sim 7 - 12$ GeV has multiple neutrals and is completely unexplored.
  - ➜ Many opportunities for GlueX to make key experimental advances in our knowledge of excited mesons and baryons.

Advances in both theory and experiment will allow us to finally understand QCD and confinement.

Backup Slides

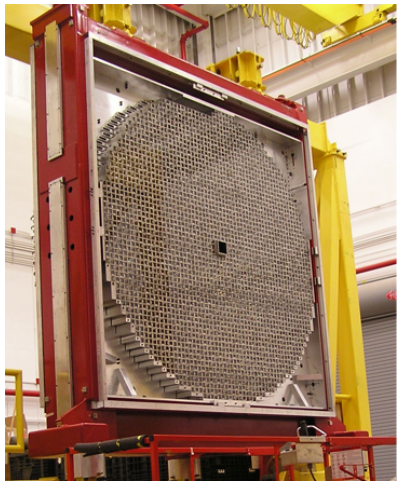
Barrel CALorimeter (BCAL):
48 4-m long modules

2.0 T superconducting solenoid



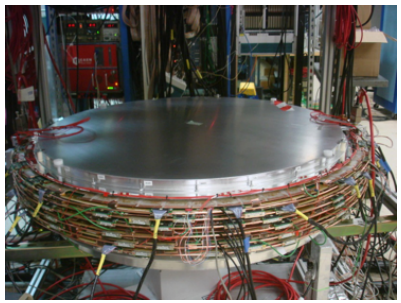
Coh. Peak: 8.4 - 9.0 GeV

$\vec{\gamma}$	$\sigma E/E \sim 0.1\,\%$, $\mathcal{P} \sim 40\,\%$
$h^{\pm}$	$\sigma p/p \sim 1\text{-}3\,\%$
γ	$\sigma E/E \sim 6\,\%/\sqrt{E} \oplus 2\,\%$



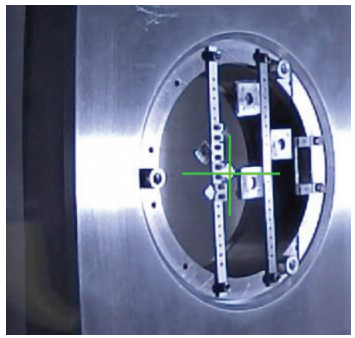
FCAL: 2800 lead glass blocks

CDC: 28-layer straw-tube chamber



FDC: four six-plane forward drift chambers

Goniometer:
20 μm diamond



TOF: two planes of 2.5 cm scintillator bars

The $J^{PC} = 1^{-+}$ Exotic Wave: E852 Experiment

There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.

1. $\pi_1(1400) \to \eta\pi$
2. $\pi_1(1600) \to \eta'\pi;\ f_1(1285)\pi$ ➜ Natural-parity exchange.

$\pi_1(1600) \to b_1\pi$ ➜ Unnatural-parity exchange dominates.

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

?

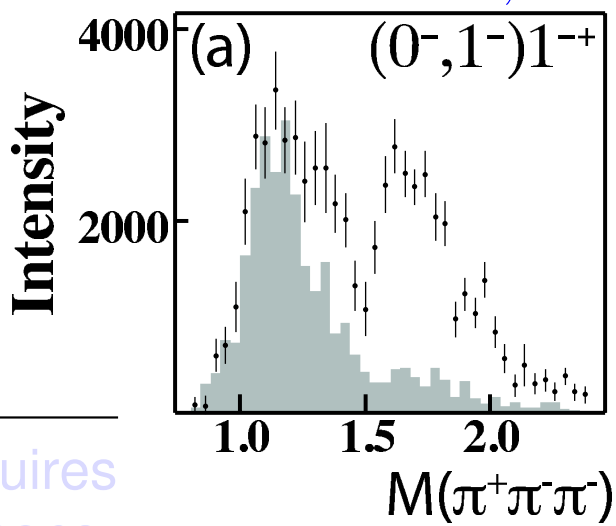
$\pi(1600) \to \rho\pi$
$(\text{E852} : \pi^- p \to \pi^+ 2\pi^- p)$

$M = 1598 \pm 8^{+29}_{-47}$ MeV

$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV

➜ Better understanding requires a spectrum of hybrid mesons.

$M^\epsilon = 0^-, 1^-$



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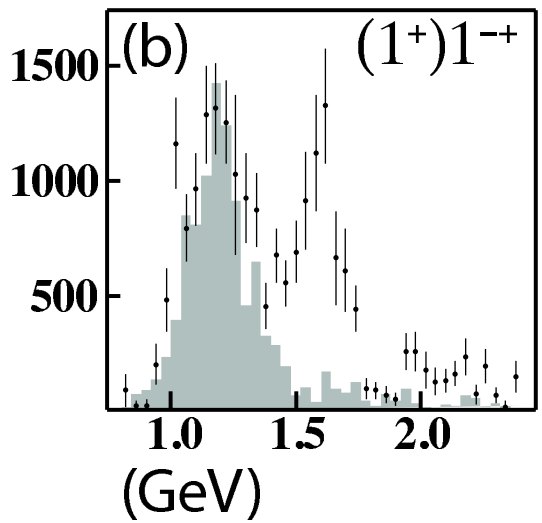

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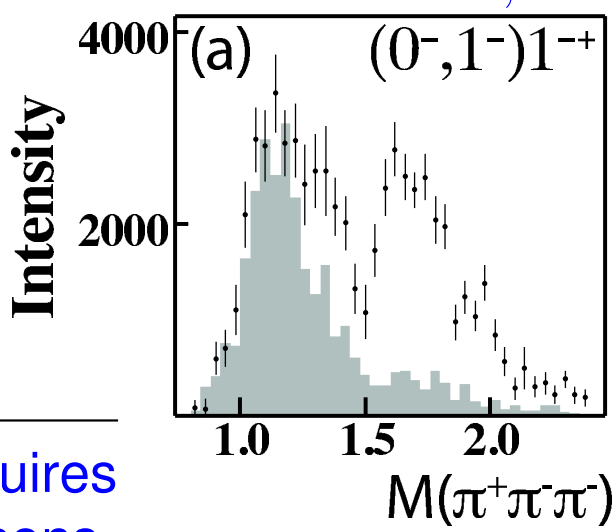

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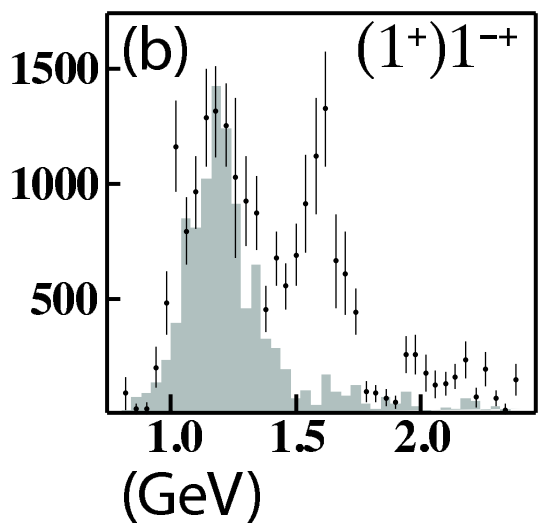
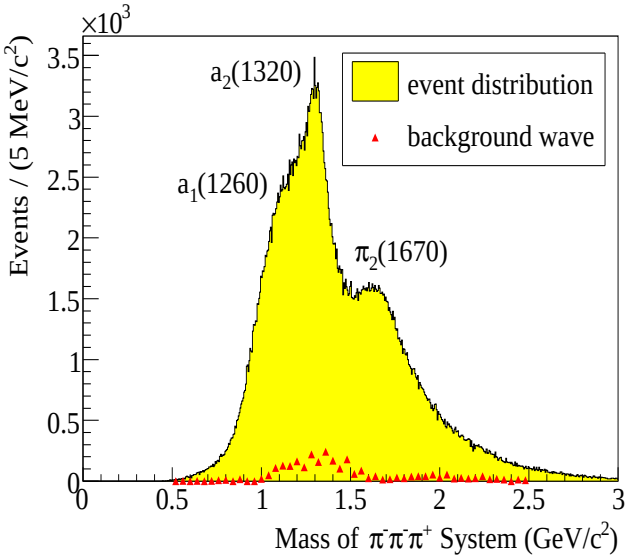


COMPASS Experiment (1): $\pi^- Pb \to \pi^-\pi^-\pi^+ (Pb)$

M. Alekseev *et al.*, PRL **104**, 241803 (2010)



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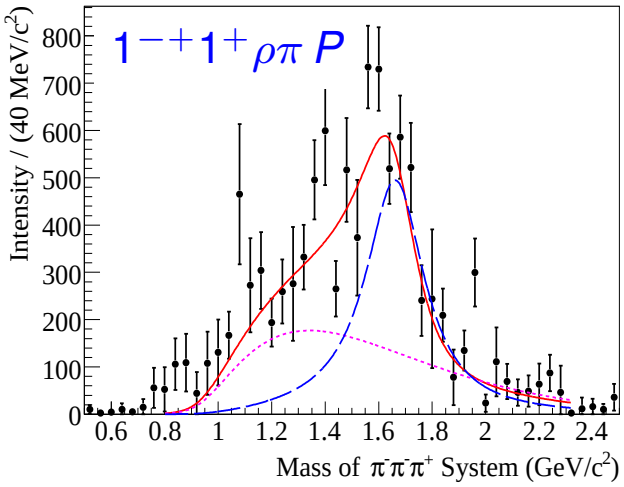
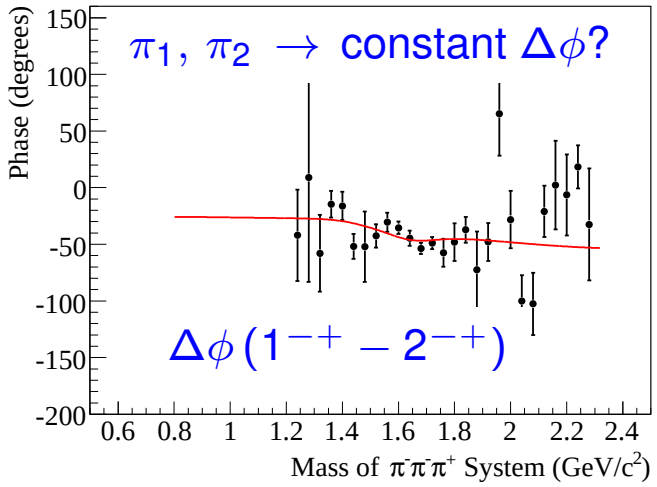




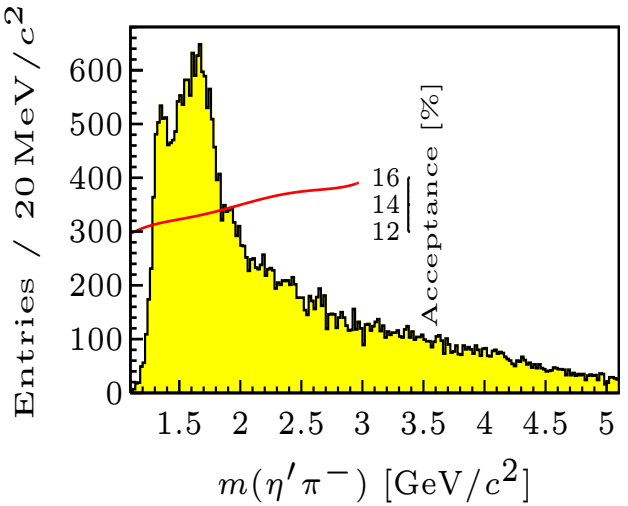
Based on $\sim 420,000$ events using a 180 GeV π beam:

$\pi_1(1600)$: $M = 1660$ MeV, $\Gamma = 269$ MeV	$\pi_2(1670)$: $M = 1658$ MeV, $\Gamma = 271$ MeV

➜ Exotic 1^{-+} wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.

COMPASS Experiment (2): $\pi^- p \to \eta^{(\prime)} \pi^- (p)$

C. Adolph *et al.*, PLB **740**, 303 (2015)



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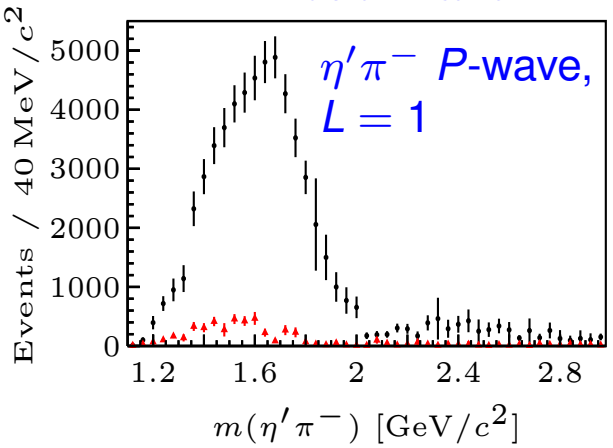

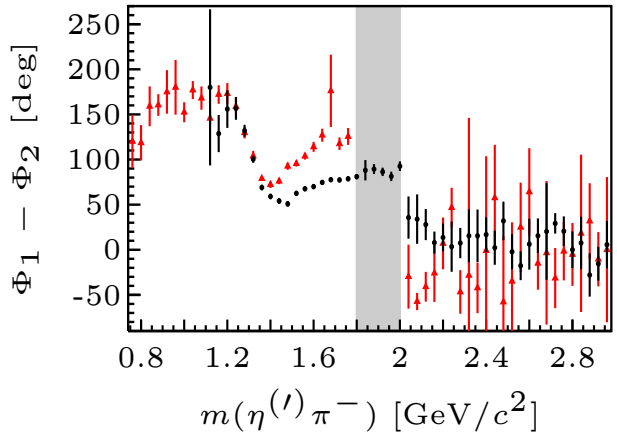

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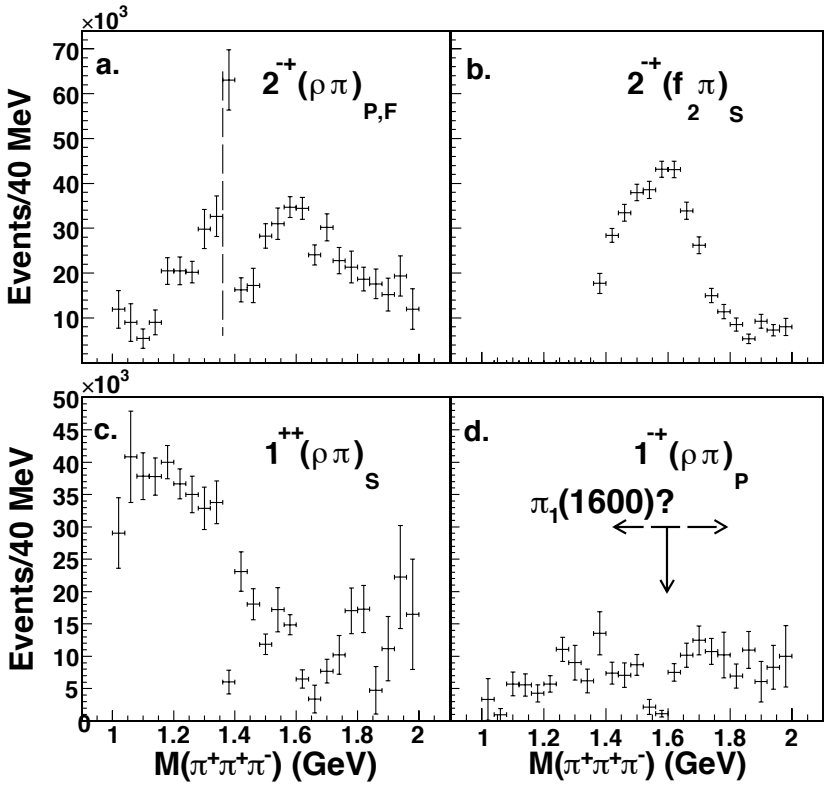
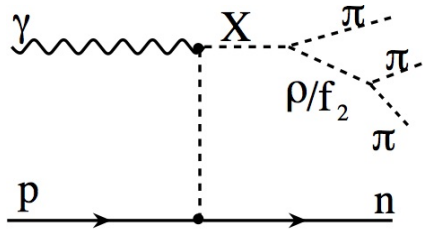
Meson Spectroscopy in Photoproduction: CLAS

Results on light mesons from CLAS at Jefferson Lab

Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system:

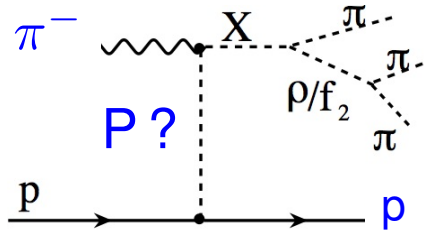
(M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))





charge exchange

CLAS



neutral exchange

E852

CLAS does not observe a resonant structure in the $1^{-+}\,(\rho\pi)_P$ partial wave.