Light-Meson Spectroscopy at Jefferson Lab

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PANDA Collaboration Meeting

Uppsala, Sweden

06/10/2015

Outline

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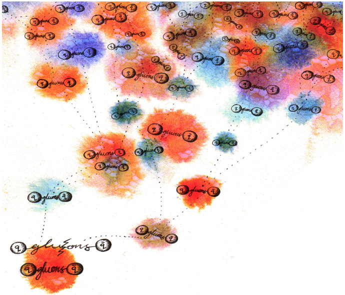
Non-Perturbative Quantum Chromodynamics (QCD)

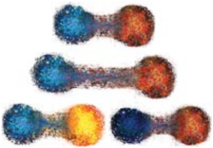


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

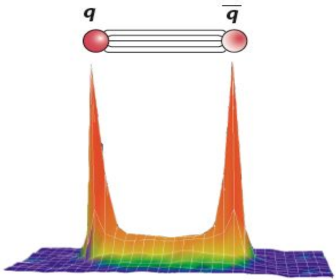
Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

Quarks are confined within hadrons.

Confinement of quarks and gluons within hadrons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of hadrons is still limited.



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?

Hadron Spectroscopy: (Baryons) What are the effective degrees of freedom inside the nucleon? (Mesons) What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.
Hybrid baryons are possible but do not carry “exotic” quantum numbers.

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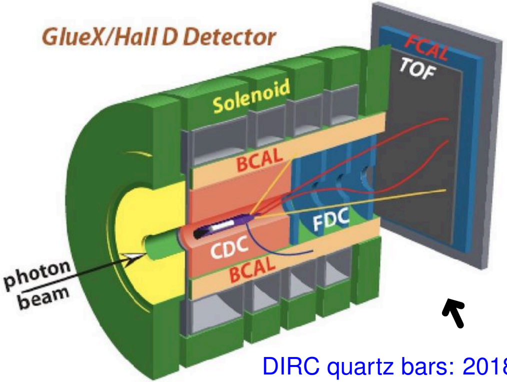
1. Introduction
2. The GlueX Experiment
   - Detector and Commissioning Status
   - Light-Meson Spectroscopy
3. Gluonic Excitations
   - Lattice QCD and Hybrid Mesons
   - Experimental Evidence
4. Other Physics (at GlueX)
5. Summary and Outlook

Hadron Spectroscopy

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



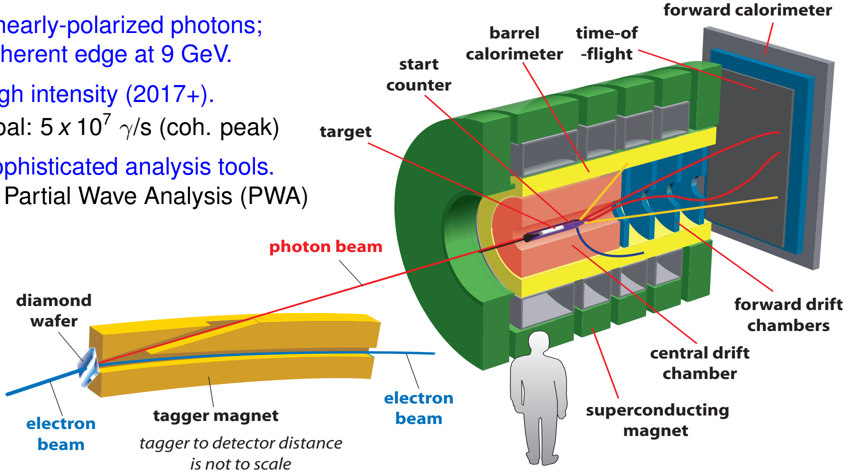
DIRC quartz bars: 2018+

The GlueX Collaboration

- 110 members, 21 institutions
  (USA, Canada, Chile, Armenia, Greece, Russia, UK)
- Commissioning in full swing
- First physics in 2016

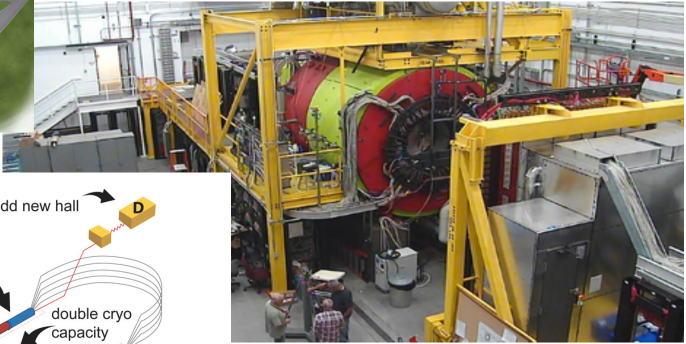
Search for exotic mesons:

- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity (2017+). Goal: $5 \, x \, 10^7 \, \gamma$/s (coh. peak)
- Sophisticated analysis tools. ➜ Partial Wave Analysis (PWA)

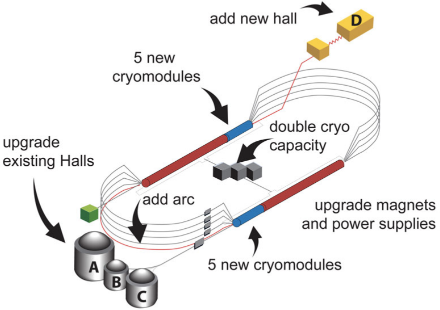


$\sim$ 75 m

May 2014



Hall D



Jefferson Lab Upgrade to 12 GeV

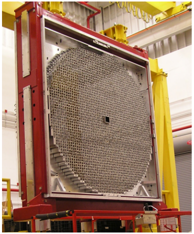
- 10.1 GeV achieved, Fall 2014
- Hall D complete

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

2.0 T superconducting solenoid

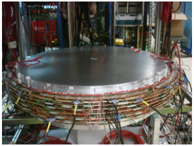
Coh. Peak: 8.4 - 9.0 GeV

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



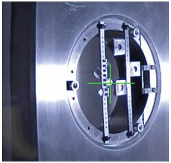
FCAL: 2800 lead glass blocks

CDC: 28-layer straw-tube chamber



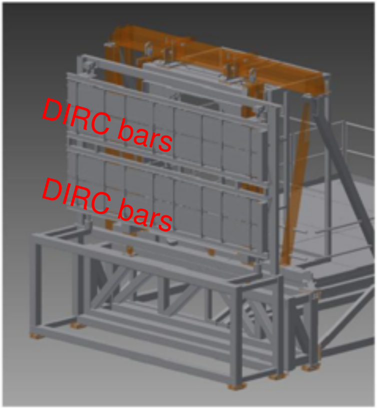
FDC: four six-plane forward drift chambers

Goniometer:
20 μm diamond



TOF: two planes of 2.5 cm scintillator bars

GlueX Upgrade: Focusing DIRC Detector

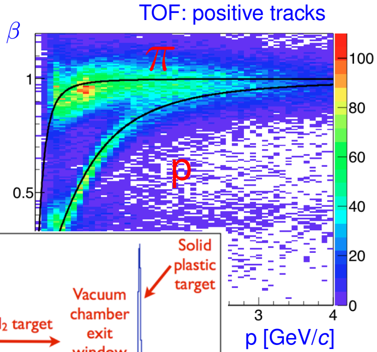


DIRC Detector

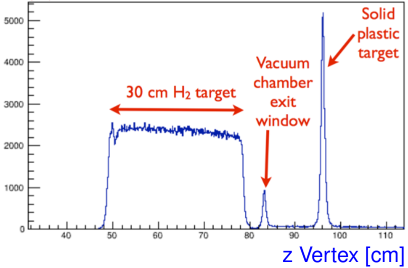
- Detection of Internally Reflected Cherenkov light
- Use 48 of BaBar DIRC quartz bars
- Separation of π/K up to 4 GeV
- Installation in FY 2018

Physics Motivation A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC. arXiv:1408.0215 [physics.ins-det].

Commissioning: Fall 2014 and Spring 2015

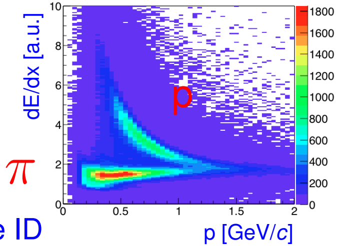


Vertex reconstruction from tracking



Data from all subsystems

Signal coincidence & hit correlation between detectors



Particle ID

Quark-Model Classification: Ordinary & Exotic Mesons

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

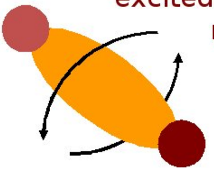
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0$:

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):

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

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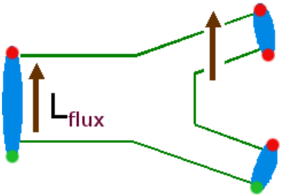
Hybrid Meson Decays and Interesting Channels

Ideas on Hybrid-Meson Decays:

(angular momentum in the flux tube stays in one of the daughter mesons)

Evidence for $J^{PC} = 1^{-+}$ wave
➜ Interpretation controversial ...



Lattice calculations:
(lightest hybrid) $M_{1^{-+}} \approx (1.9 \pm 0.2)$ GeV/c^2

0^{+-} $h_0 \rightarrow b_1\pi \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0;\ h_1\eta$
$b_0 \rightarrow \pi(1300)\pi;\ h_1\pi$

1^{-+} $\eta_1 \rightarrow a_1\pi \rightarrow 2\pi^+2\pi^-;\ \pi(1300)\pi$
$\pi_1 \rightarrow f_1\pi \rightarrow \eta\pi\pi\pi;\ b_1\pi,\ \pi\rho,\ \eta a_1$

2^{+-} $h_2 \rightarrow \rho\pi \rightarrow \pi\pi\pi;\ b_1\pi,\ \omega\eta$
$b_2 \rightarrow a_2\pi;\ a_1\pi,\ h_1\pi,\ \omega\pi$

➜ Multi-particle final states with neutral and charged particles!

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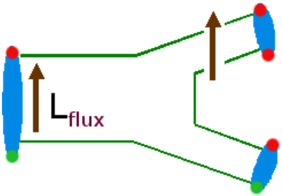

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$\quad b_0 \to \pi(1300)\pi;\ h_1\pi$

1^{-+} $\quad \eta_1 \to a_1\pi \to 2\pi^+2\pi^-;\ \pi(1300)\pi$

$\quad \pi_1 \to f_1\pi \to \eta\pi\pi\pi;\ b_1\pi,\ \pi\rho,\ \eta a_1$

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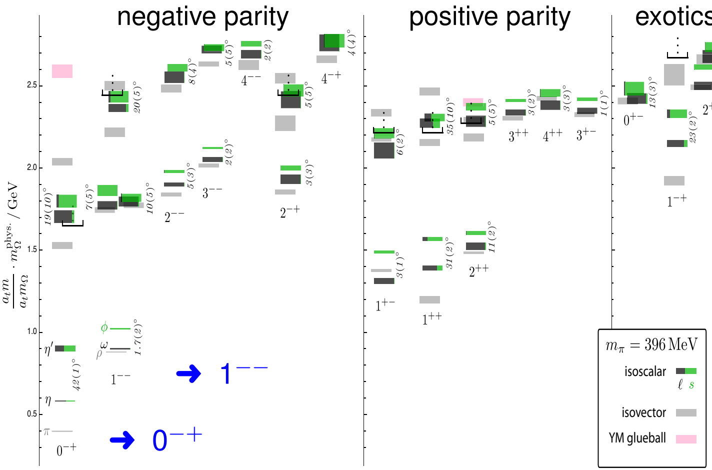
Meson Spectroscopy on the Lattice



$m_\pi = 396$ MeV

$\rightarrow$ isoscalar

$\rightarrow$ isovector

J. J. Dudek *et al.*, Phys. Rev. D **84**, 074023 (2011)

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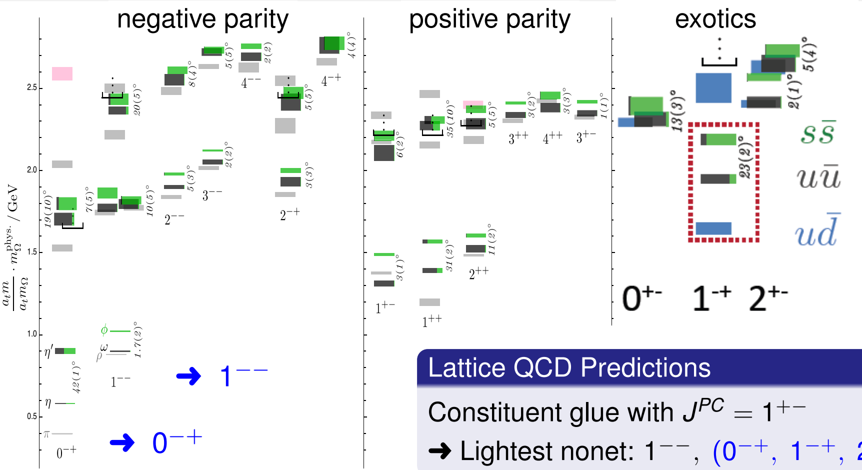


Lattice QCD Predictions

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

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

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

Experimental Searches for Hybrid Mesons

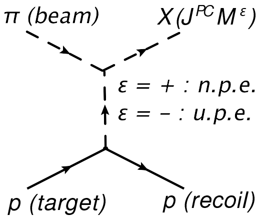
There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.
➜ The interpretation remains controversial.

Exotic waves are (all) observed in diffraction-like reactions.
➜ Observation of $\pi_1(1400) \to \eta\pi$ in $p\bar{p}$ remains exception.

1. $\pi_1(1400) \to \eta\pi$ ➜ Tetraquark? Nothing? (too low in mass for hybrid)
2. $\pi_1(1600)$ Appears to be robust signal.

Diffractive Production Process

- Natural parity exchange: $J^P = 0^+, 1^-, 2^+, \ldots$
  Unnatural parity exchange: $J^P = 0^-, 1^+, 2^-, \ldots$
- Same production mechanism, M^ϵ, expected for all decay modes.



Review: C. Meyer & Y. Van Haarlem, PRC **82**, 025208 (2010)

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.

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

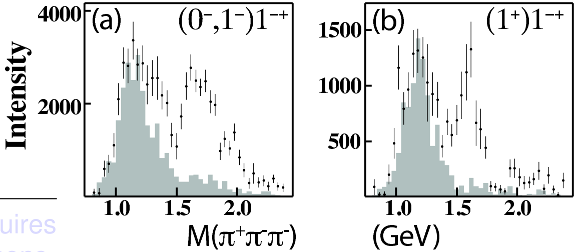
?

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

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

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

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



➜ Better understanding requires a spectrum of hybrid mesons.

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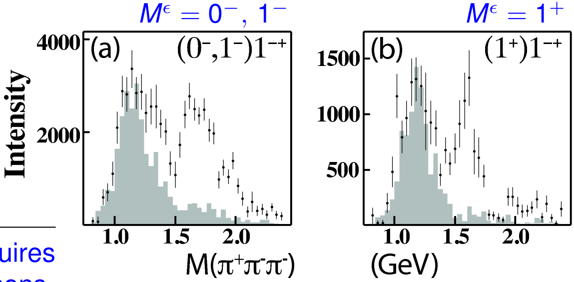
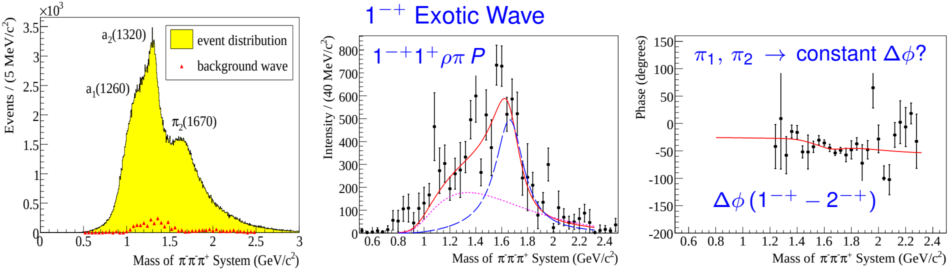


COMPASS Experiment (1): $\pi^- Pb \to \pi^-\pi^-\pi^+ (Pb)$

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



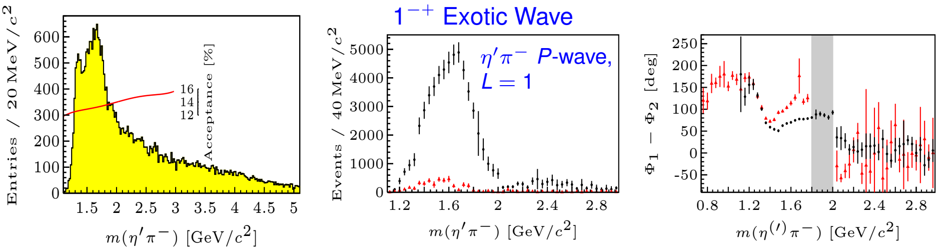
Based on $\sim 420,000$ events using a 180 GeV π beam:

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



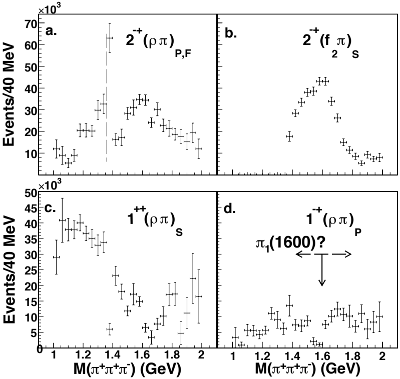
Collaboration refrains from proposing resonance parameters for exotic *P* wave.

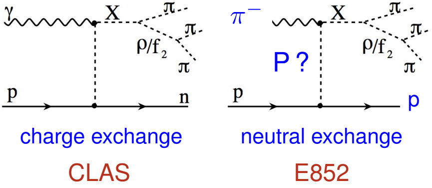
- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).
- Dominant $\mathbf{8} \otimes \mathbf{8}$ $(\eta\pi)$ & $\mathbf{1} \otimes \mathbf{8}$ $(\eta'\pi)$ nature of $SU(3)$ flavor configurations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

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))





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

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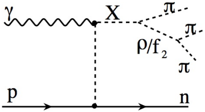
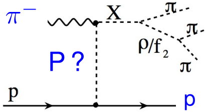
A $J^{PC} = 1^{-+}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.
(Close & Page, Phys. Rev. D **52**, 1706 (1995))



charge exchange

CLAS



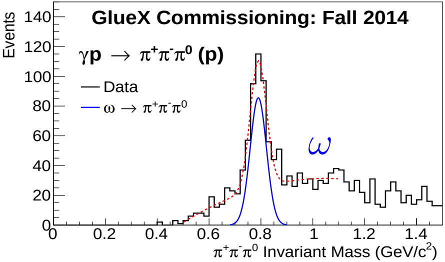
neutral exchange

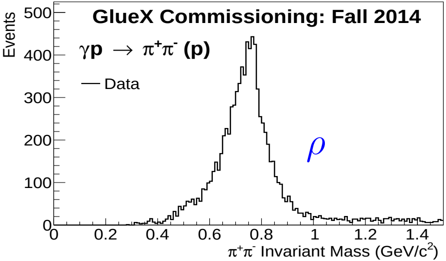
E852

- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2 % of the $a_2(1320)$.
- Recent CLAS-g12 data have an order of magnitude more statistics.

  ➜ e.g. $\gamma p \to n\pi^+\pi^+\pi^-$, $\gamma p \to p\pi^+\pi^-\pi^0$ ($J^{PC} = 1^{-+}$ isoscalar production?)

First GlueX "Physics": Observation of vector mesons



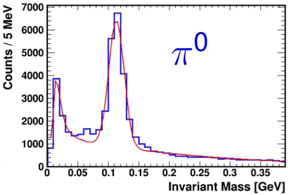


$\gamma\, p \rightarrow p\, \pi^+ \pi^- \pi^0$

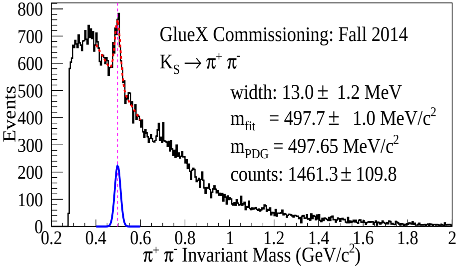
Proton PID based on dE/dx

Exclusive process (missing mass cut)

$\pi \rightarrow \gamma\gamma$: reconstructed from forward calorimeter ($\sigma \sim$ 11 MeV, calibration ongoing) ➜



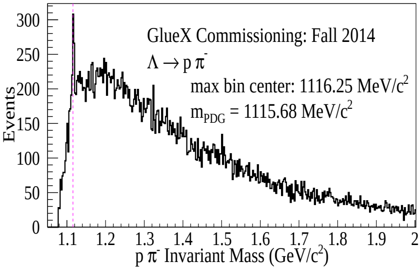
First GlueX "Physics": Observation of K_S and Λ



No direct $K^\pm$ meson ID, yet. But

- $K_S \to \pi^+\pi^-$
- $\Lambda \to p\pi^-$

clearly observed.



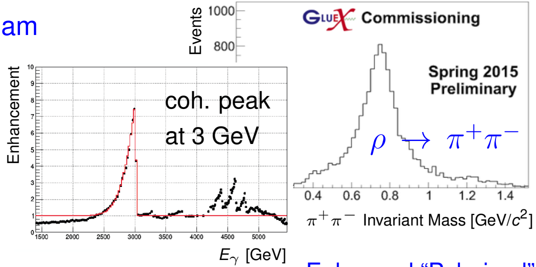
Reconstruction

- p & $\pi^\pm$ PID based on dE/dx, β
- Detached vertices

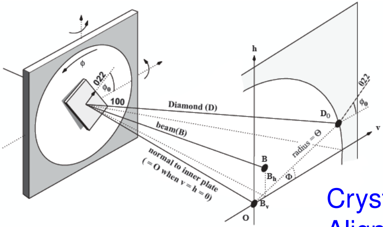
First GlueX "Physics": Polarized ρ Photoproduction

Studies of diamond radiator in beam confirmed understanding and control of photon polarization and diamond orientation.

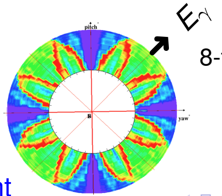
➜ 2.5h of pol. beam ($\sim$10 nA), $\mathcal{P}_{\text{max}} = 65\,\%$, $\mathcal{P}_{\text{ave}} = 47\,\%$



Enhanced "Polarized" Photon Spectrum



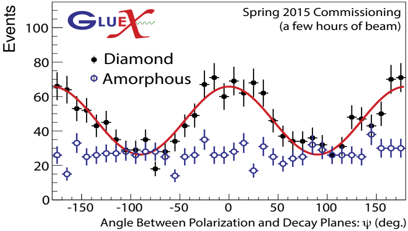
Crystal Alignment

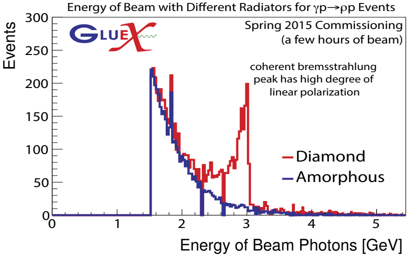


8-fold peaking (symmetries):

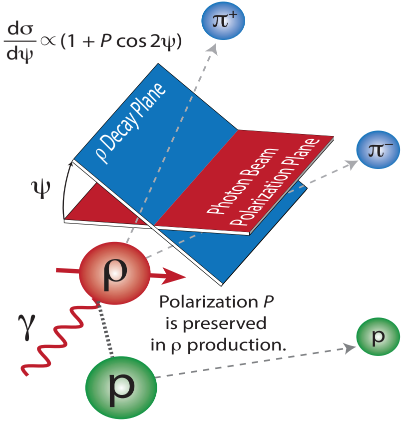
- Lattice planes: [022], [02$\bar{2}$], [004], [040]
- Each plane: ϕ, $\phi + \pi$

First GlueX "Physics": Polarized ρ Photoproduction

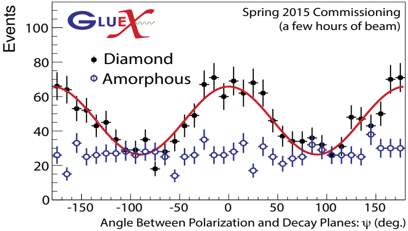




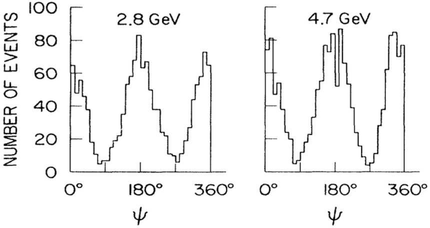
$$\gamma p \to \rho^0 p \to \pi^+ \pi^- p$$



First GlueX "Physics": Initial Analyses



SLAC: Phys. Rev. Lett. 24, 960 (1970)



← $\gamma p \to \rho^0 p \to \pi^+\pi^- p$

Detector Understanding:

- $\gamma p \to p\,\pi^0$
- $\gamma p \to p\,\eta$
- $\gamma p \to p\,\rho$
- $\gamma p \to p\,\omega$
- $\gamma p \to p\,\eta'$
- $\gamma p \to p\,\phi$

Initial Exotic Hybrid Searches

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

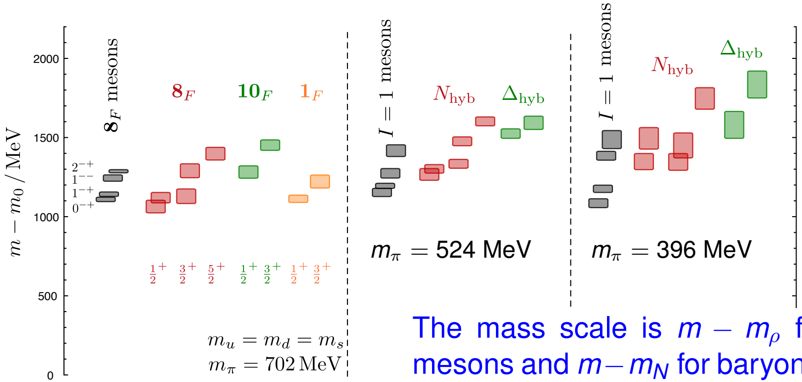
Strange Baryons: $\gamma p \to K^+\Lambda,\, K\,\Sigma,\, KK\,\Xi$

Outline

1. Introduction
2. The GlueX Experiment
   - Detector and Commissioning Status
   - Light-Meson Spectroscopy
3. Gluonic Excitations
   - Lattice QCD and Hybrid Mesons
   - Experimental Evidence
4. **Other Physics (at GlueX)**
5. Summary and Outlook

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.

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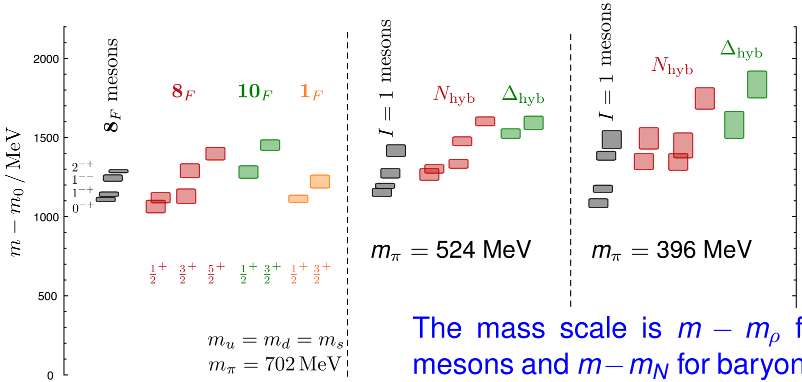
J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)



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Letter of Intent to JLab PAC 43

➜ Search for Hybrid Baryons with CLAS 12 in Hall B

Opportunities for Baryon Spectroscopy at GlueX

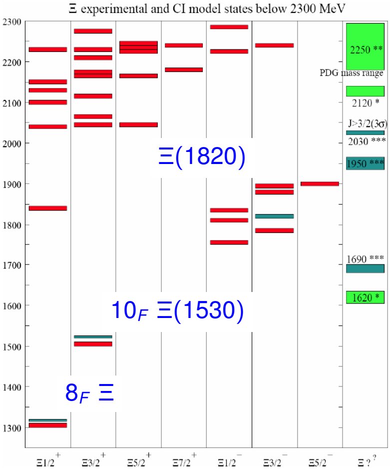
Spectroscopy of $|ssn\rangle$ Ξ baryons:

- Very few established states
- Hardly any J^P measured
- Possibly narrow resonances

The multi-strange baryons provide a missing link between light-flavor and heavy-flavor baryons.

Program on Cascades involves:

- Measurement of $\Xi^- - \Xi^0$ splittings.
- J^P measurements.
- Search for new states.



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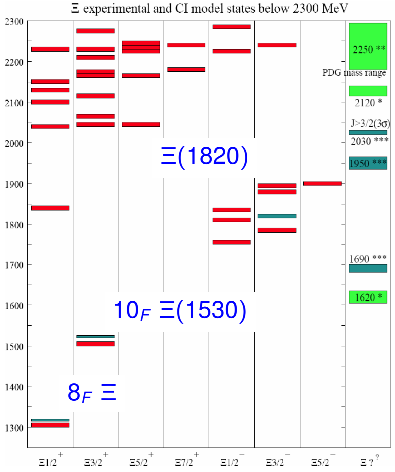

Planned Experiments at Jefferson Lab

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. (arXiv:)

  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 Polarizibility in the $\gamma\gamma \to \pi^+\pi^-$ Reaction.
- Symmetry Tests of Rare η Decays to All-Neutral Final States.

Spectroscopy Program in Hall B with CLAS 12:

- Search for hybrid mesons.
- Study of very (doubly) strange baryons; hybrid baryon program.

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Summary

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^{+-})
- 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.