First Round of Experiments in Hall D

V. Credé

Florida State University, Tallahassee, Florida

JLab Users Group Workshop

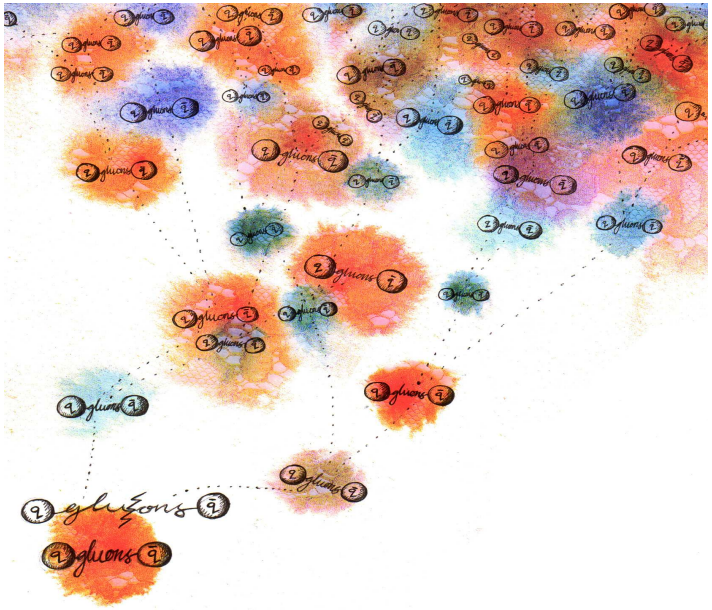
Jefferson Lab

05/31/2013

Outline

Outline

Non-Perturbative Quantum Chromodynamics (QCD)

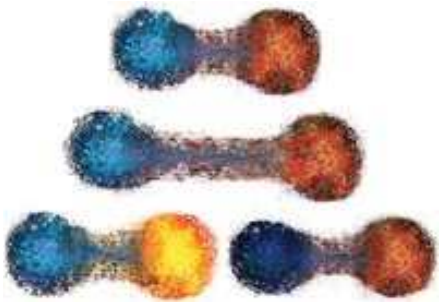


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

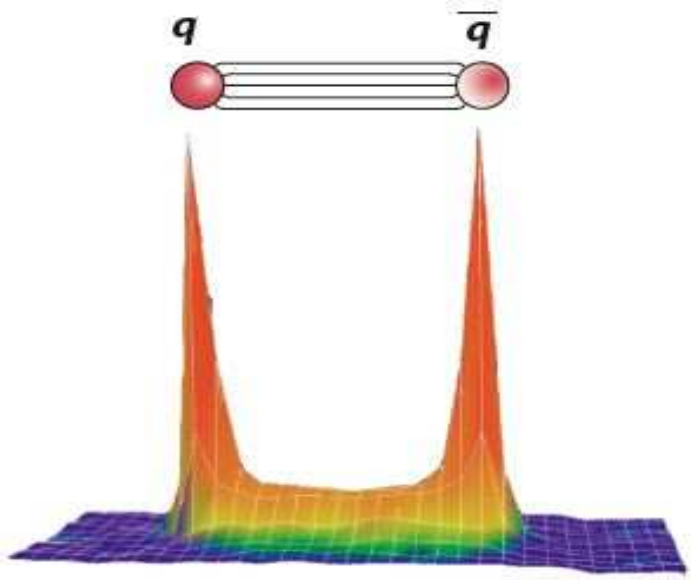
Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

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?

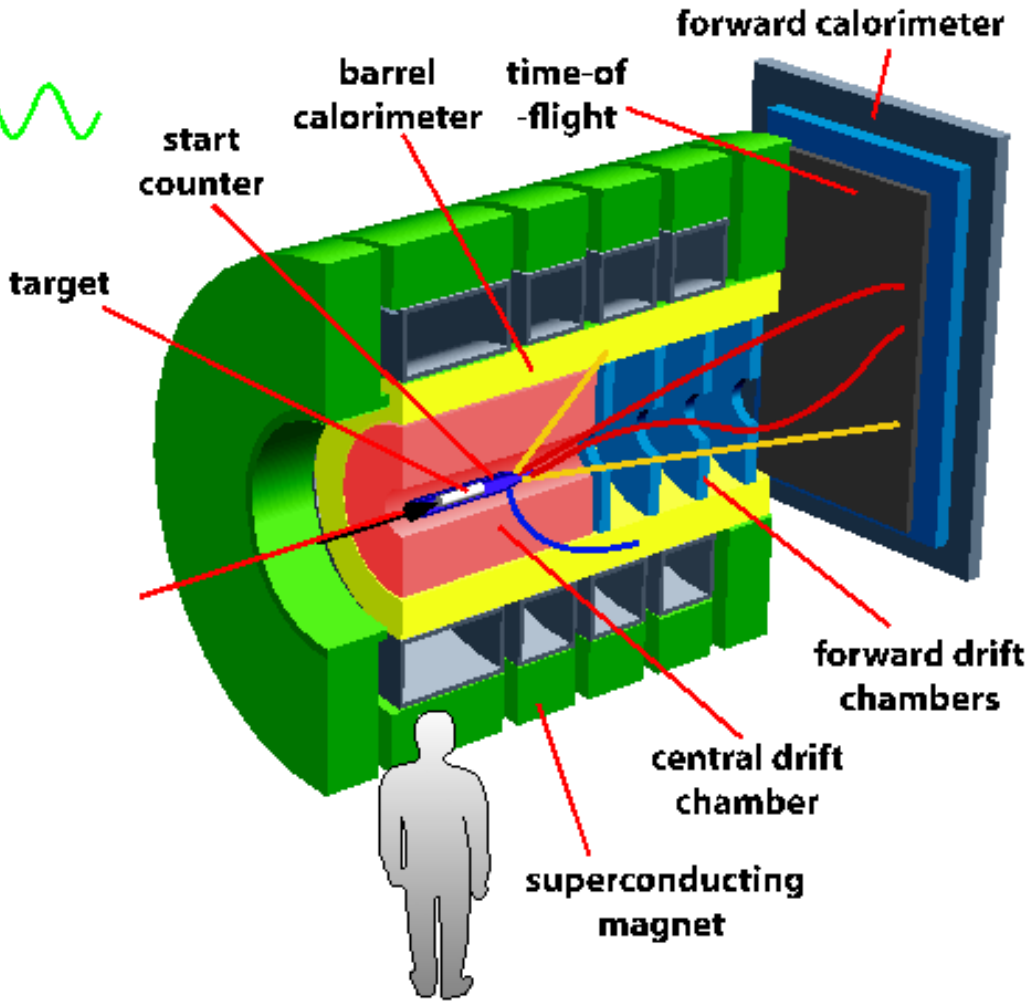
Hadron Spectroscopy: (Baryons) What are the fundamental degrees of freedom inside the nucleon? (Mesons) What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

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

Outline

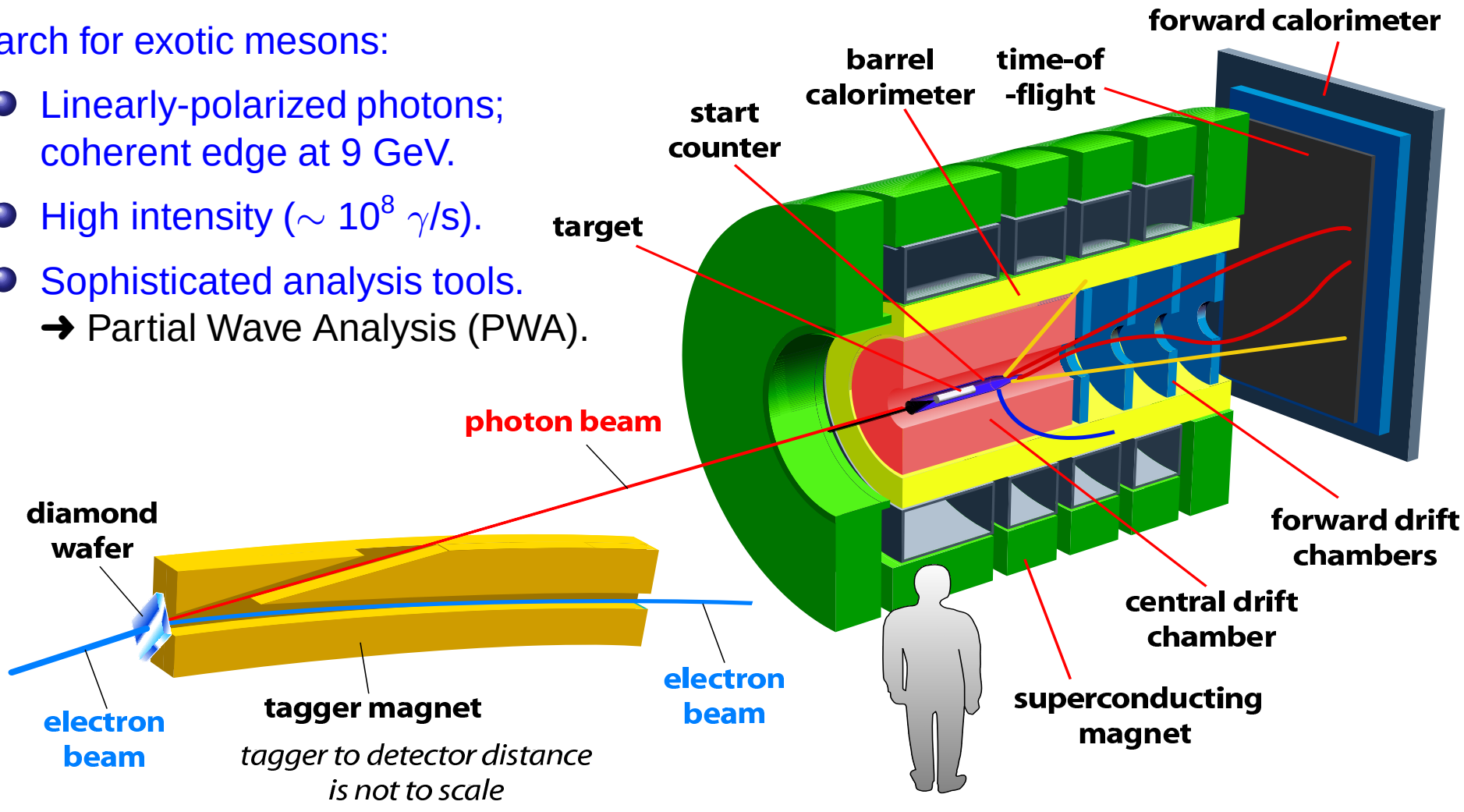
The GlueX Collaboration

Acadia University, Arizona State U, Athens University, Carnegie Mellon University, Catholic University, Christopher Newport University, University of Connecticut, Florida International University, Florida State U, University of Glasgow, Indiana U, University of Massachusetts Amherst, MIT, MEPHI, Norfolk State U, North Carolina A&T State University, University of North Carolina Wilmington, Northwestern U, Old Dominion University, University of Oxford, University of Pittsburgh, Universidad Técnica Federico Santa María, University of Regina, and Jefferson Lab.

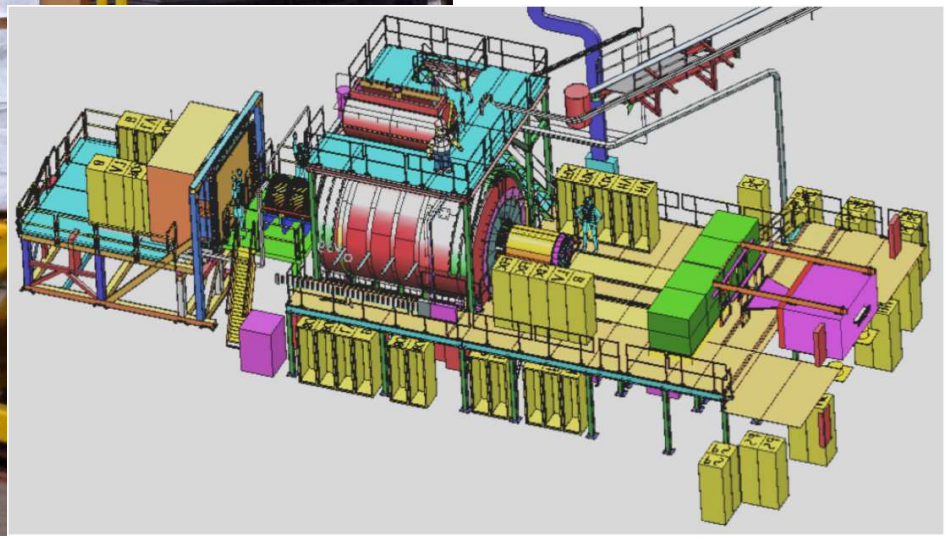


Search for exotic mesons:

- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity ($\sim 10^8$ γ/s).
- Sophisticated analysis tools.
  ➜ Partial Wave Analysis (PWA).



February 2013



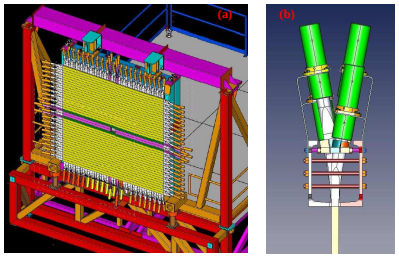
BCAL: all 48 4-m long modules at JLab

2.2 T superconducting solenoid

FCAL: 2800 lead glass blocks

CDC: 28-layer straw-tup chamber

FDC: four six-plane forward drift chambers

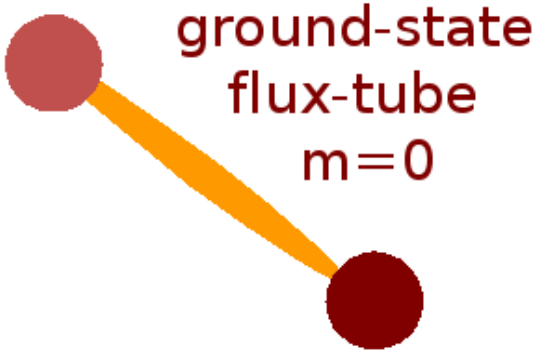


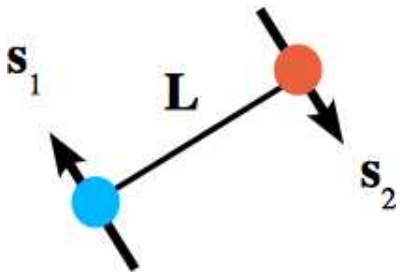
TOF: two planes of 2.5 cm scintillator bars

Quark-Model Classification: Ordinary 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. $\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 1,\ S = 0$:

e.g. $h_1,\ b_1\ (J^{PC} = 1^{+-})$

Quark-Model Classification: Ordinary & Exotic Mesons

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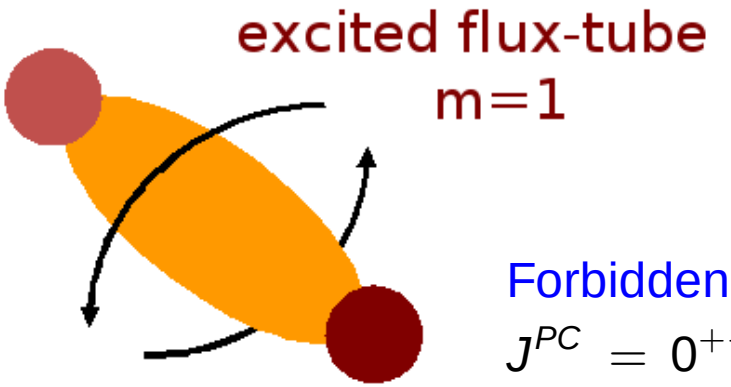


12 GeV CEBAF upgrade has high priority
(DOE Office of Science, Long Range Plan)
"[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Forbidden States (Exotics):

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

Outline

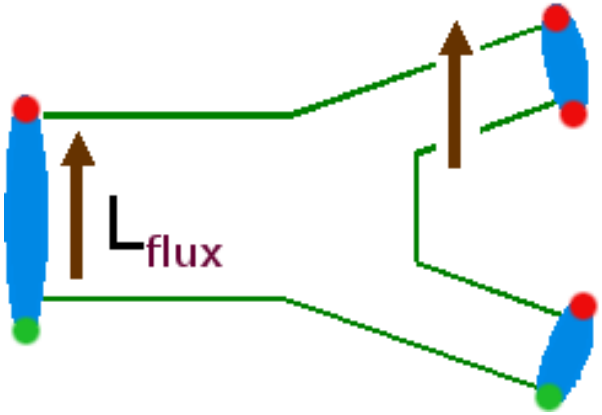
Hybrid Meson Decays and Interesting Channels

Hybrid-Meson Decays:

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

Evidence for $J^{PC} = 1^{-+}$ wave

➜ Interpretation controversial



$L = 1$

$L = 0$

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

0^{+-} $h_0 \to b_1\pi \to \pi^+\pi^-\pi^0\pi^0\pi^0$; $h_1\eta$

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

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

$\pi_1 \to f_1\pi \to \eta\pi\pi\pi$; $b_1\pi$, $\pi\rho$, ηa_1

2^{+-} $h_2 \to \rho\pi \to \pi\pi\pi$; $b_1\pi$, $\omega\eta$

$b_2 \to a_2\pi$; $a_1\pi$, $h_1\pi$, $\omega\pi$

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

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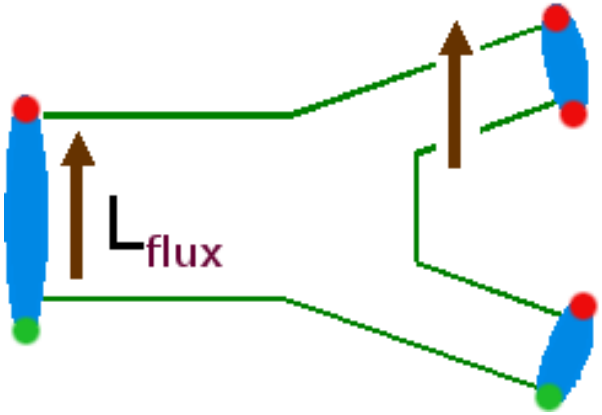

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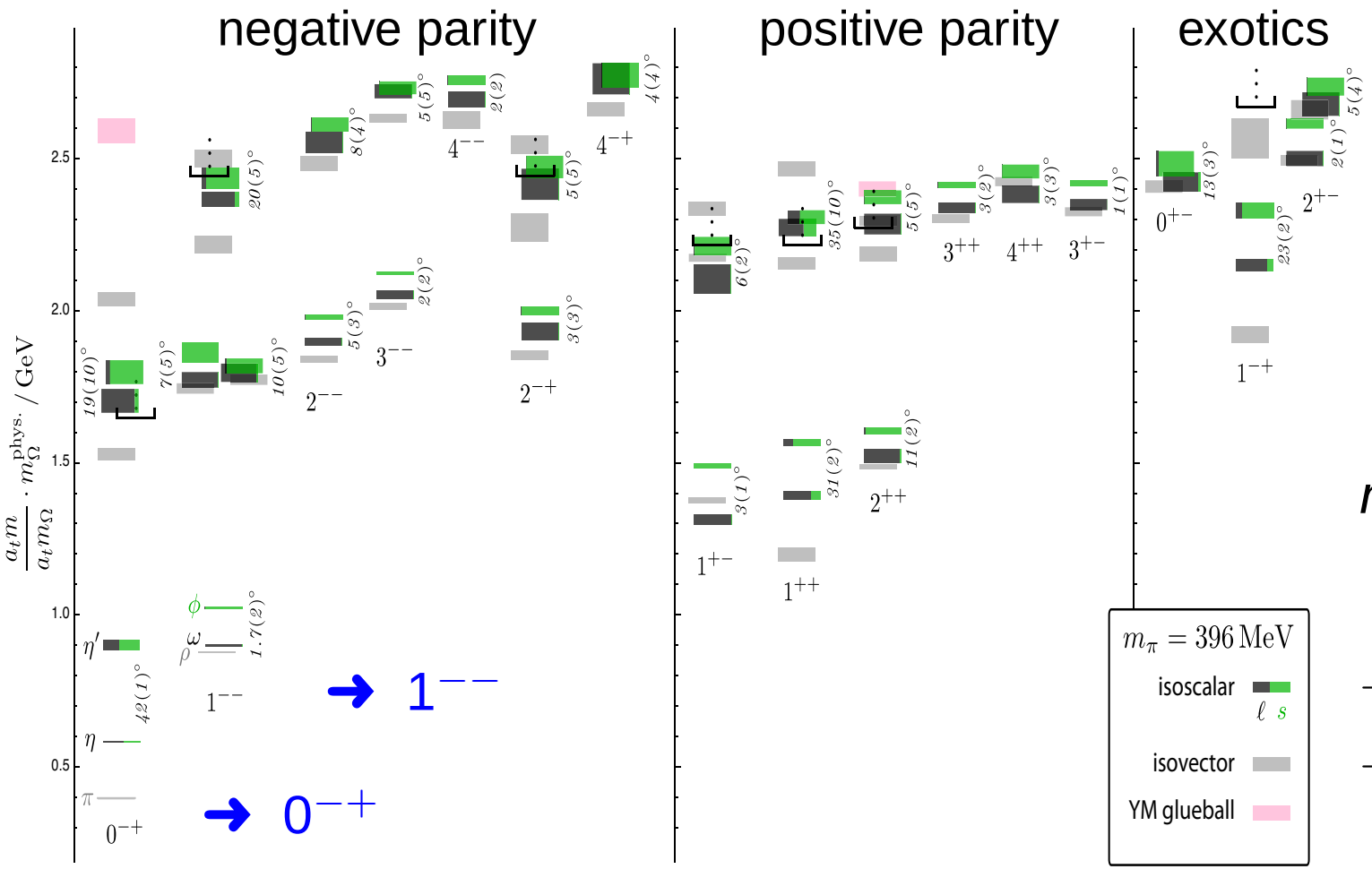
$b_2 \to a_2\pi$; $a_1\pi$, $h_1\pi$, $\omega\pi$

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

Meson Spectroscopy on the Lattice



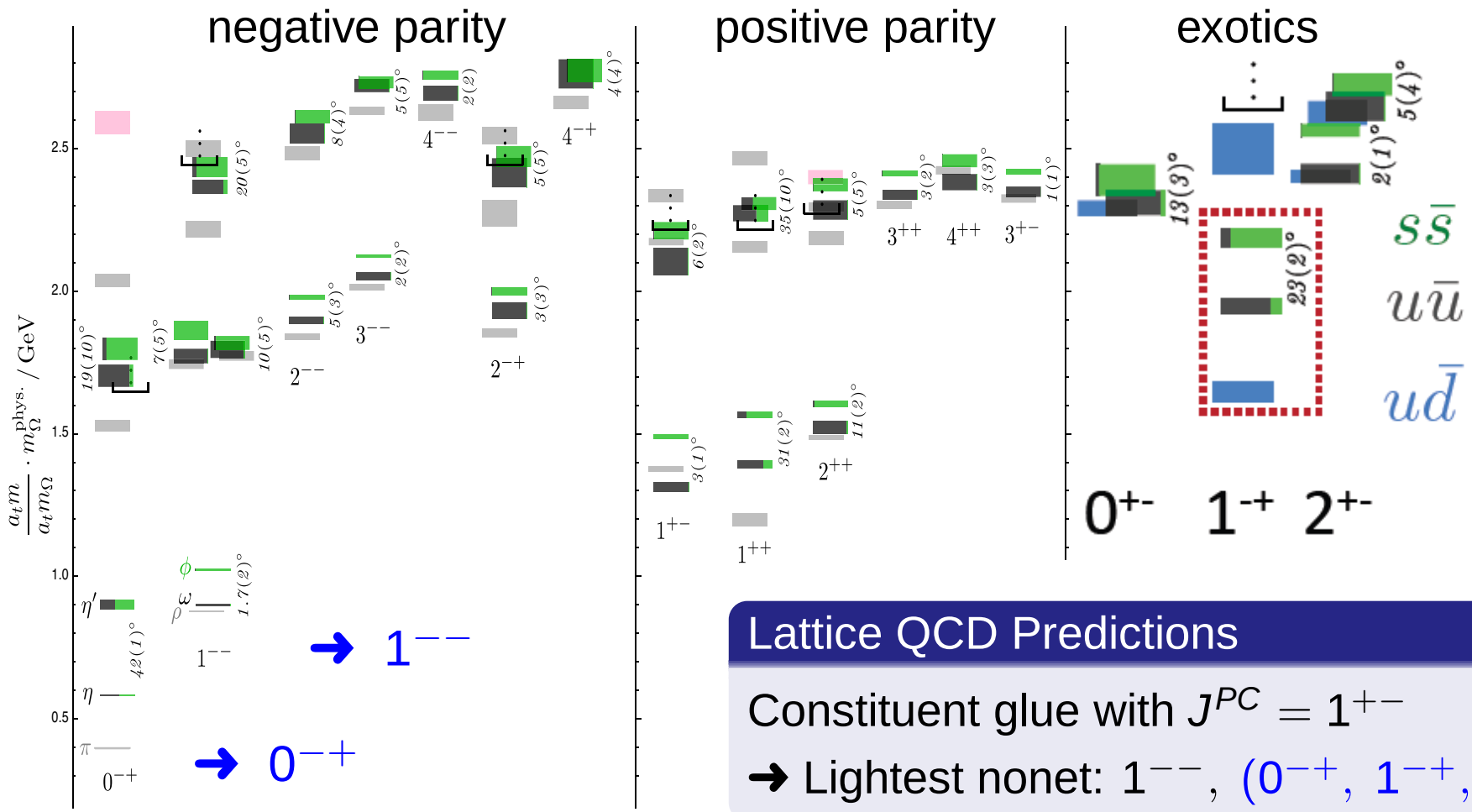
$m_\pi = 396$ MeV

→ isoscalar

→ isovector

J. J. Dudek *et al.*, Phys. Rev. D **83**, 111502 (2011)

Meson Spectroscopy on the Lattice



J. J. Dudek *et al.*, PRD **83**, 111502 (2011)

Lattice QCD Predictions

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

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

Experimental Evidence: $J^{PC} = 1^{-+}$ Exotic Wave

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)

$\pi_1(1400) \to \eta\pi$

Resonant Interpretation
- E852, Phys. Rev. D 60 (1999) 092001.
- VES, Phys. Atom. Nuc. D 68 (2005) 3.
- Crystal Barrel, Phys. Lett. B 423 (1998) 175.

Nonresonant Interpretation
- E852 (IU), Phys. Rev. Lett. 91 (2003) 092002. (includes background phase)

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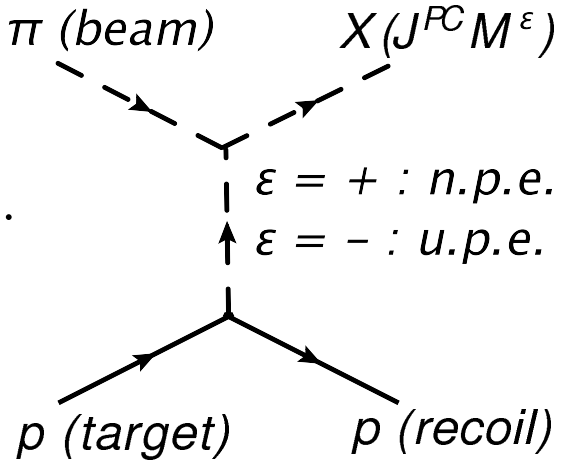
Diffractive Production Process

- 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.



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

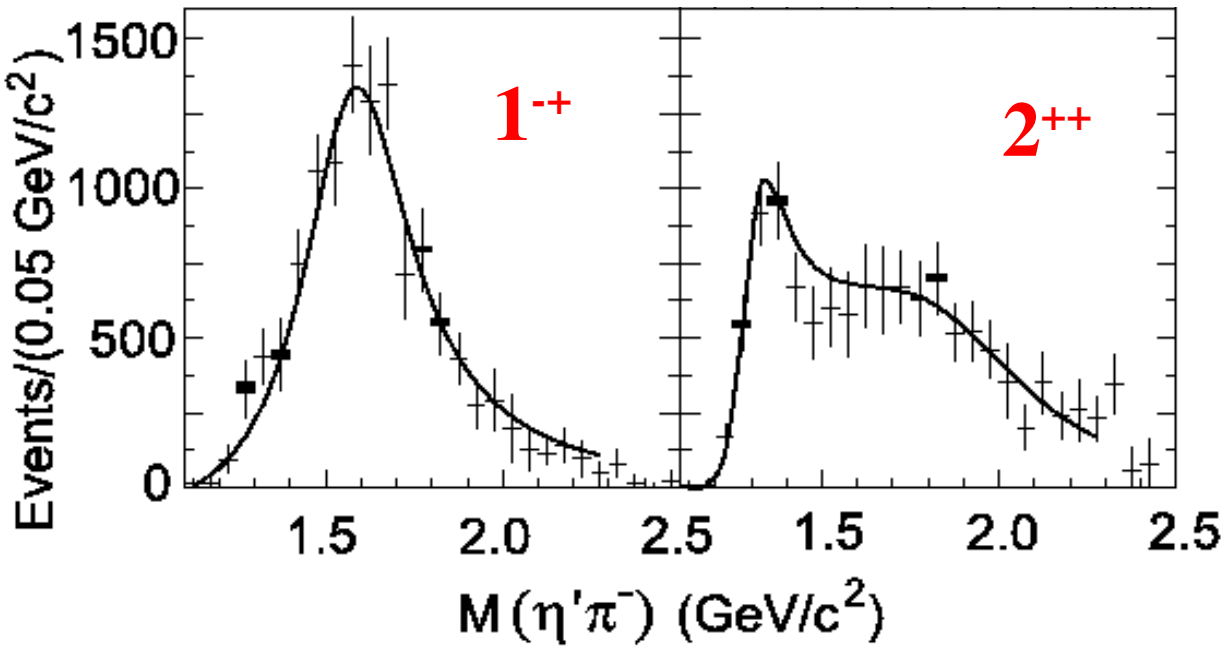
There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.

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

$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV

$\Gamma = 340 \pm 40 \pm 50$ MeV



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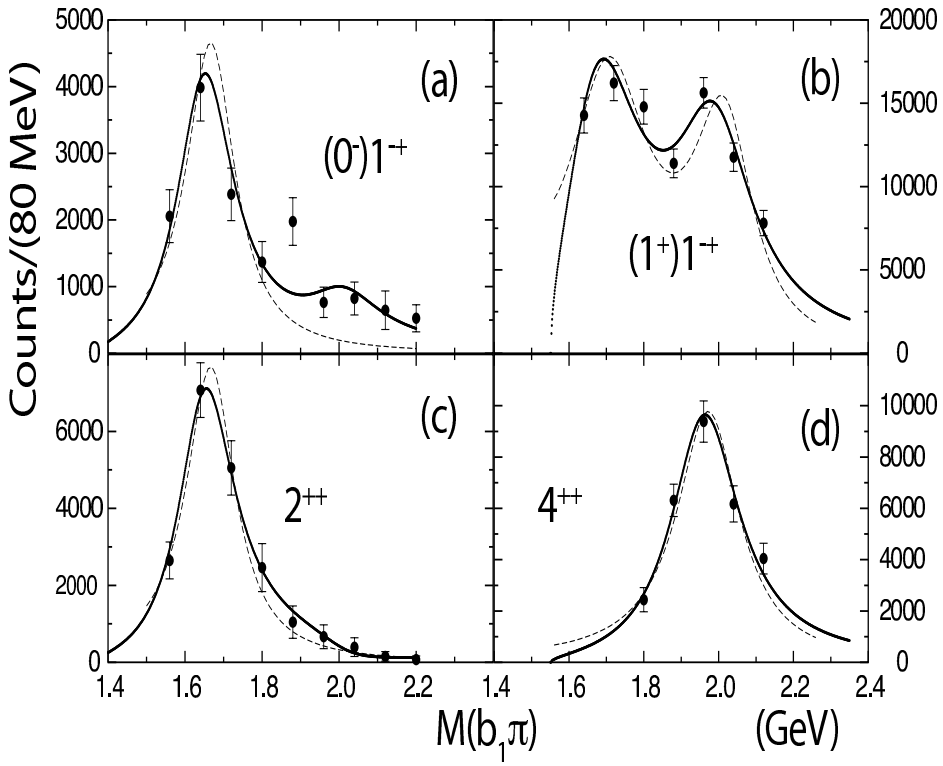
   $\pi_1(1600) \to b_1\pi$
   ➜ Unnatural-parity dominates.

$\pi(1600) \to b_1\pi$
$(\mathrm{E852}: \pi^- p \to \omega\pi^0\pi^- p)$

$M = 1664 \pm 8 \pm 10$ MeV

$\Gamma = 185 \pm 25 \pm 38$ MeV

$\sim 145,000$ events



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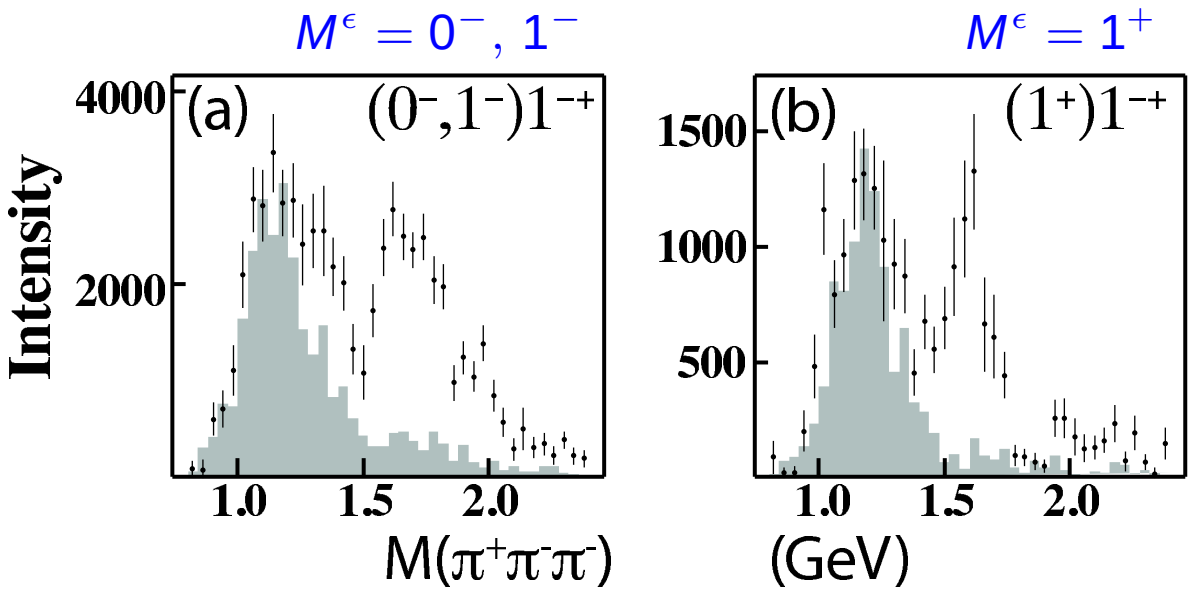
$M = 1598 \pm 8^{+29}_{-47}$ MeV

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



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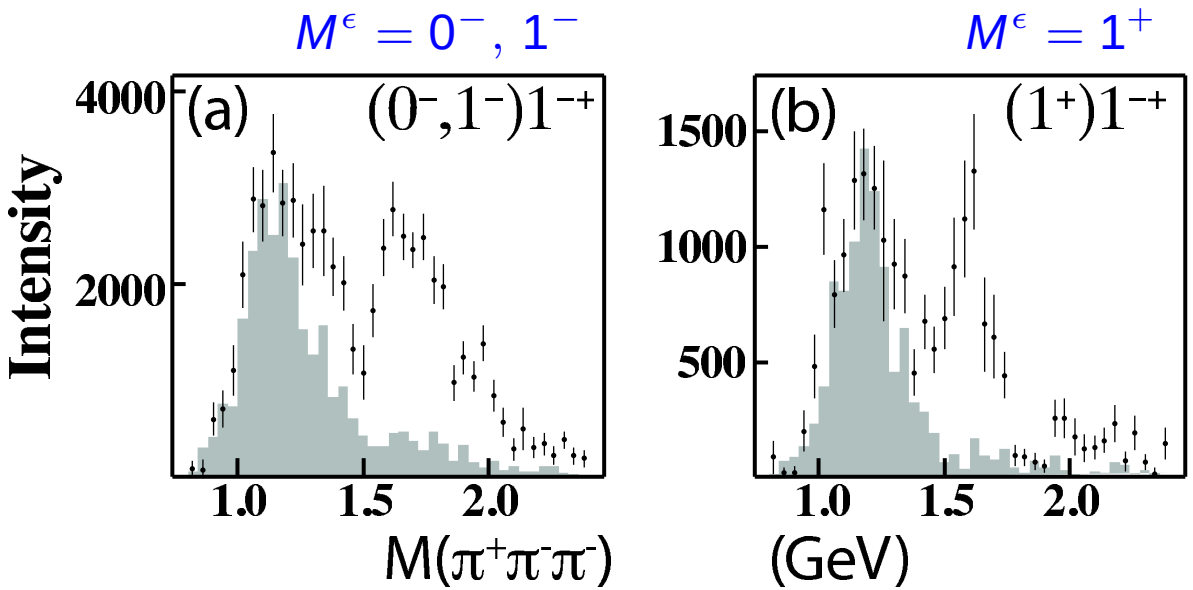
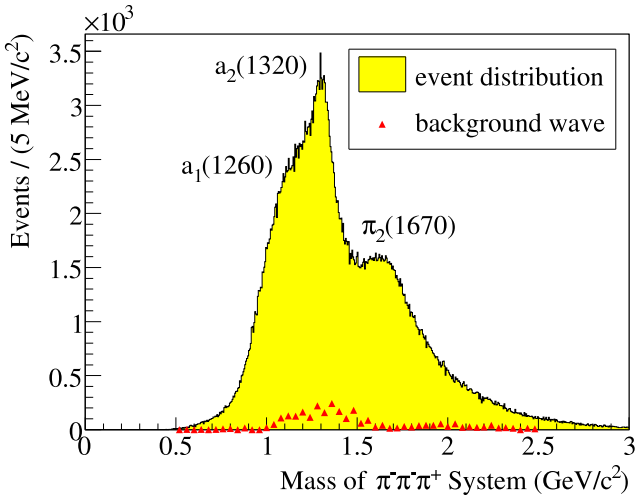
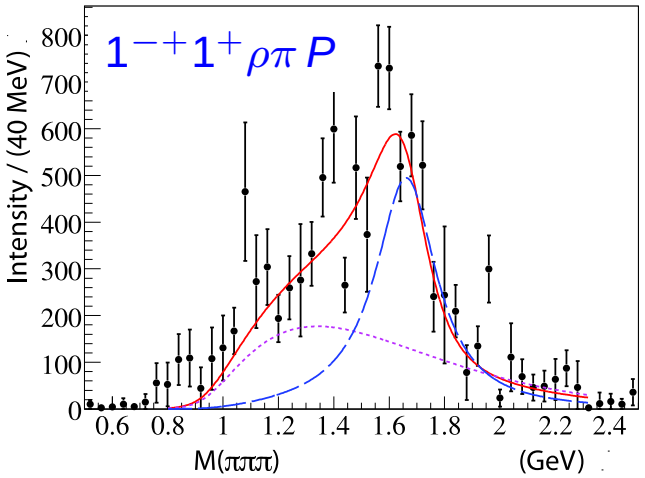


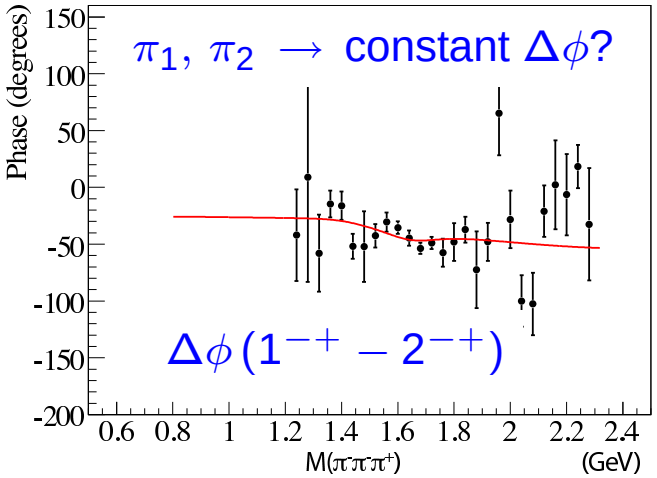
COMPASS Experiment: $\pi^- Pb \to \pi^-\pi^-\pi^+ (Pb)$

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



1^{-+} Exotic Wave





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

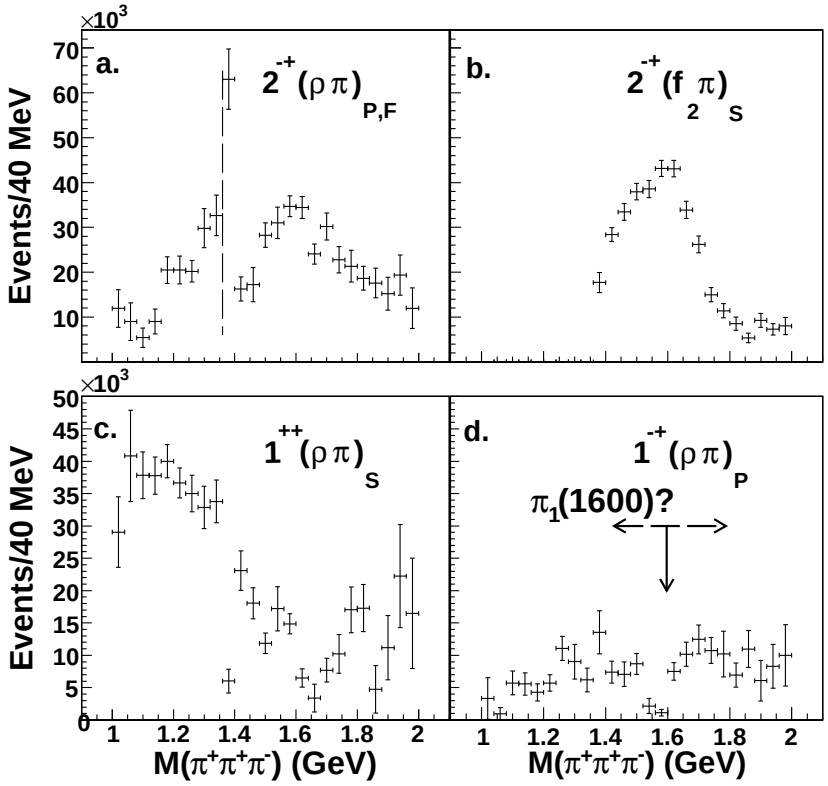
➜ Exotic 1^{-+} wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.

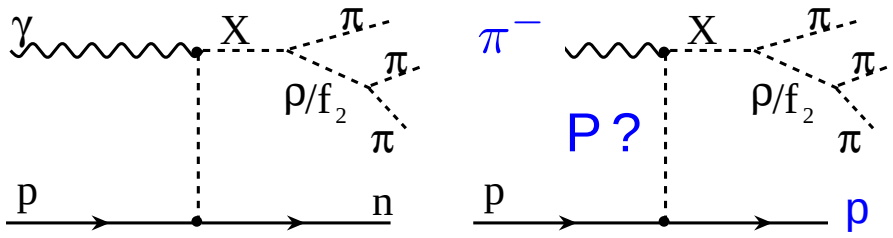
Meson Spectroscopy in Photoproduction: CLAS

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.

Meson Spectroscopy in Photoinduced Reactions

Results on light mesons from CLAS at Jefferson Lab

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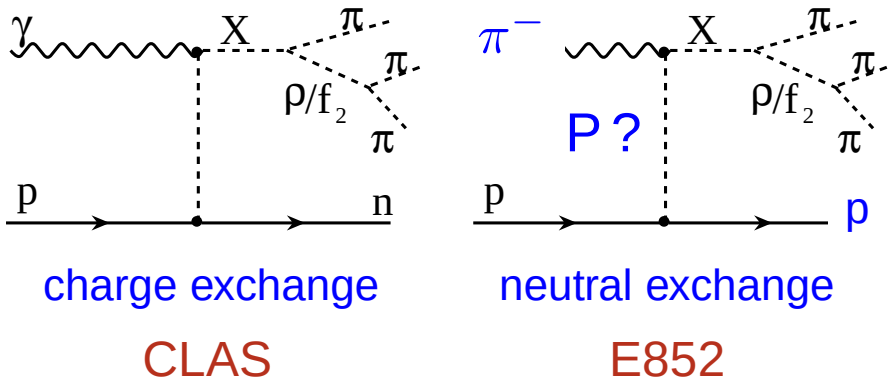


A $J^{PC} = 1^{-+}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.

(Close & Page, Phys. Rev. D **52**, 1706 (1995))

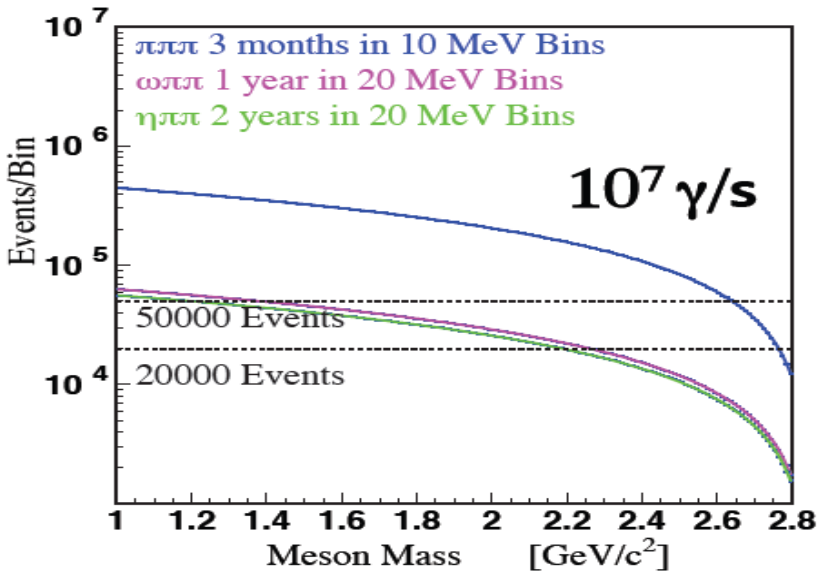
- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2 % of the $a_2(1320)$.
- New CLAS-g12 data have an order of magnitude more statistics.
  ➜ e.g. $\gamma p \to n\,\pi^+\pi^+\pi^-$, $\gamma p \to p\,\pi^+\pi^-\pi^0$ ($J^{PC} = 1^{-+}$ isoscalar production?)

Sample GlueX Amplitude Analysis

Analyses of mock data:

- $\gamma p \to \pi^+\pi^-\pi^+ n$ ($\rho\pi$ Exotic)
- $\gamma p \to \omega\pi^+\pi^- p$ ($b_1\pi$ Exotic)

Assume exotic meson production with a 2 nb cross section, then we expect about 30,000 events per year or about 1000 events per anticipated mass bin of 20 MeV.



$\rho\pi$	$\to \pi\pi\pi$	5-10 μb
$b_1\pi$	$\to \omega\pi\pi$	0.2 μb
$a_2\pi$	$\to \eta\pi\pi$	0.2 μb
$f_1\pi$, $\eta'\pi$		0.1 μb

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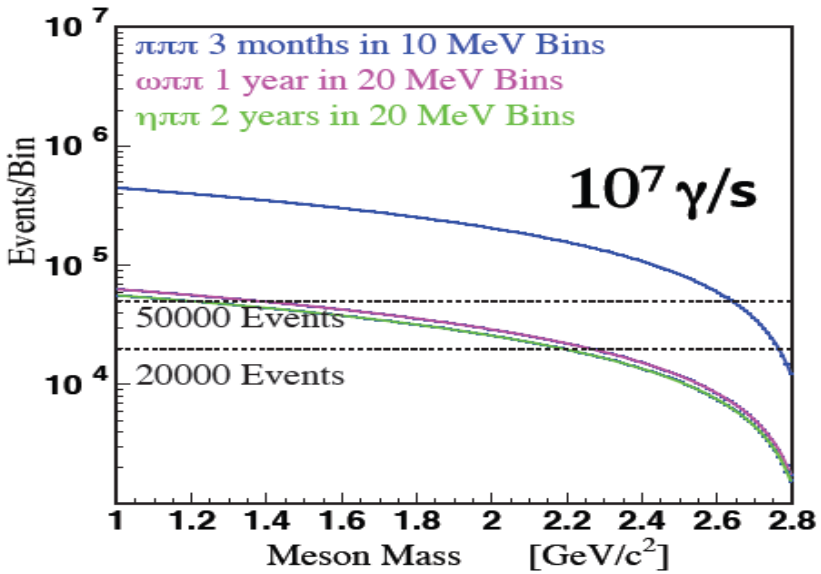

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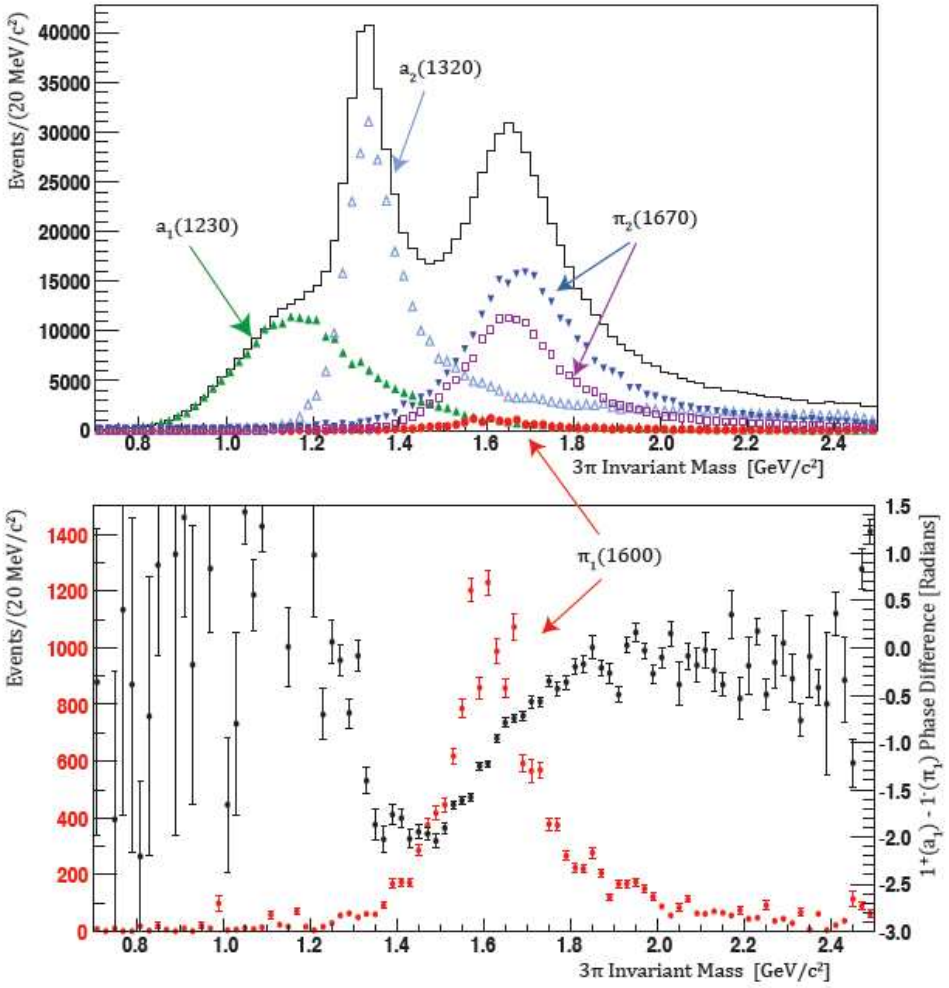
J^{PC} exotic wave has been generated with 1.6 % relative strength:

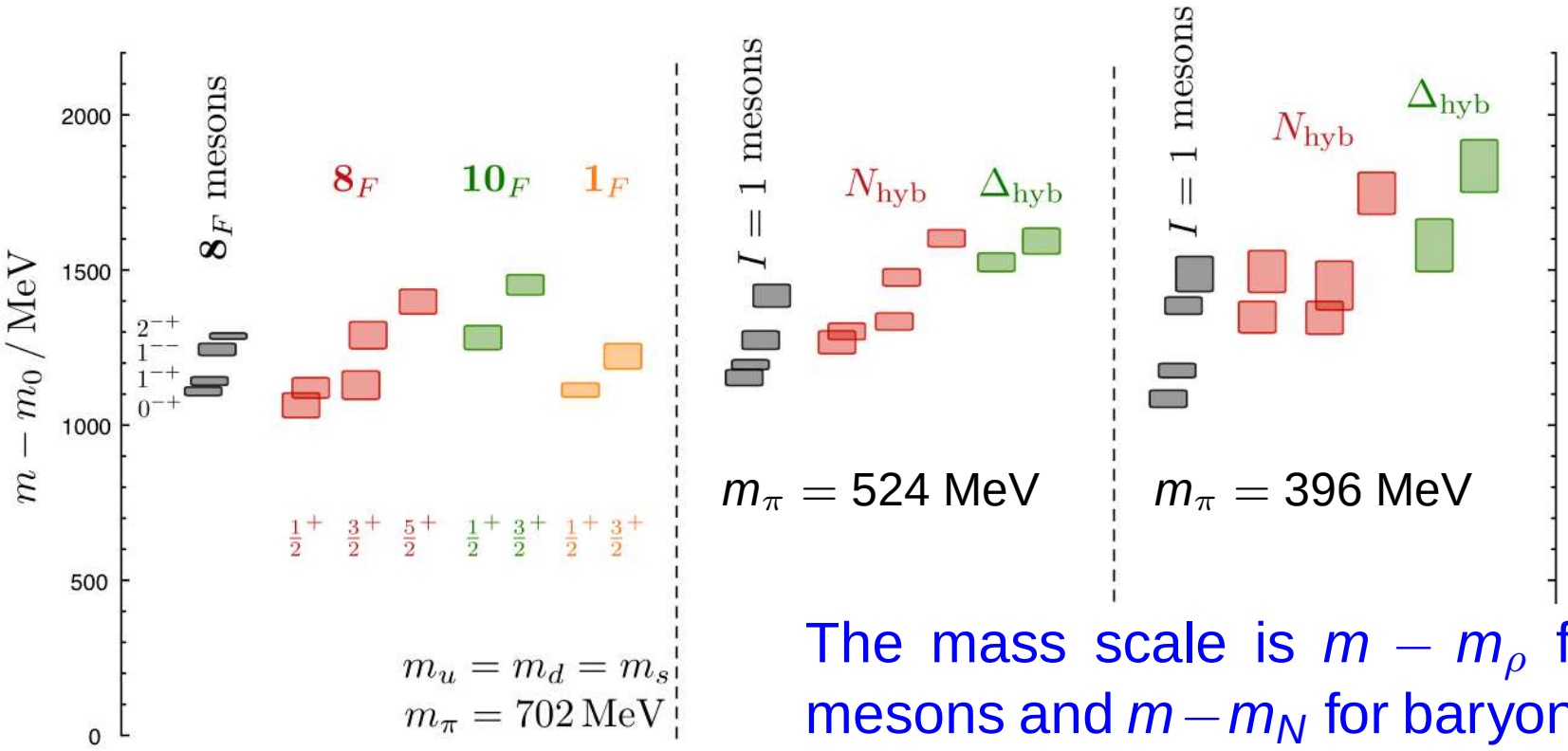
- $\approx$ 3 hrs of GlueX data
- Valid test of GlueX acceptance.
  - ➜ Full detector simulation and reconstruction.
- Isobar model; single-π exchange; full and partial photon polarization.



Outline

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, but hybrid baryons are difficult to identify experimentally.

Opportunities for Baryon Spectroscopy at GlueX

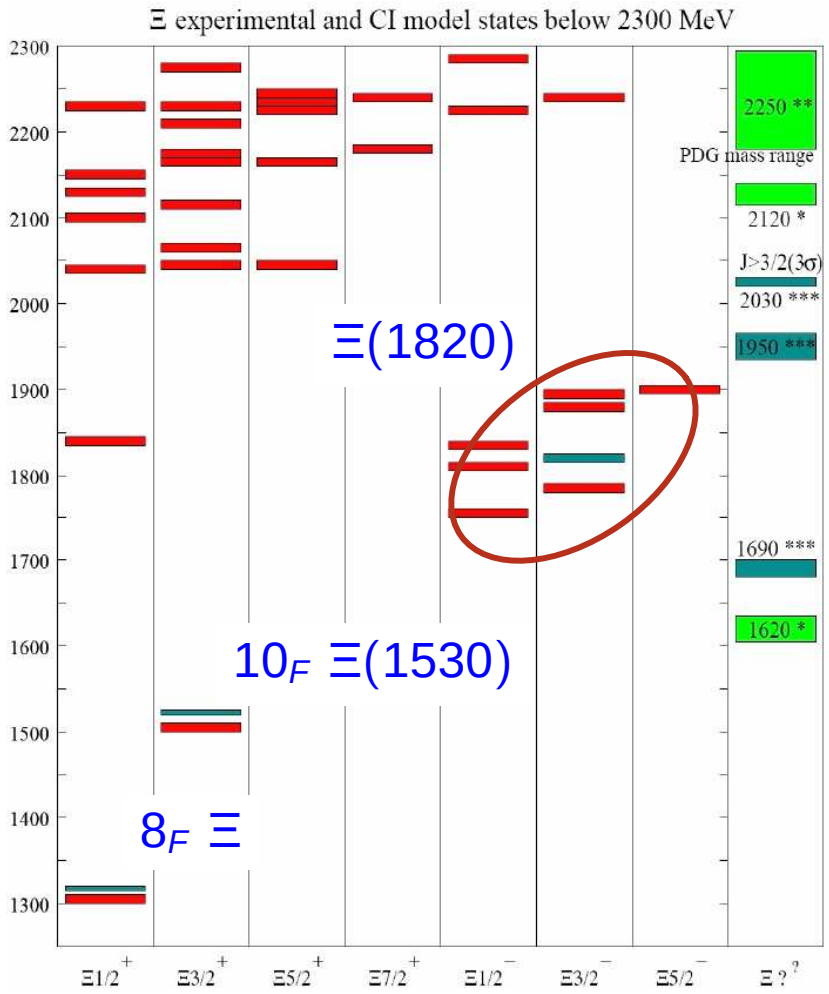
Spectroscopy of $|ssn\rangle$ Ξ baryons:

- Very few established states
- None of the 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.



Opportunities for Baryon Spectroscopy at GlueX

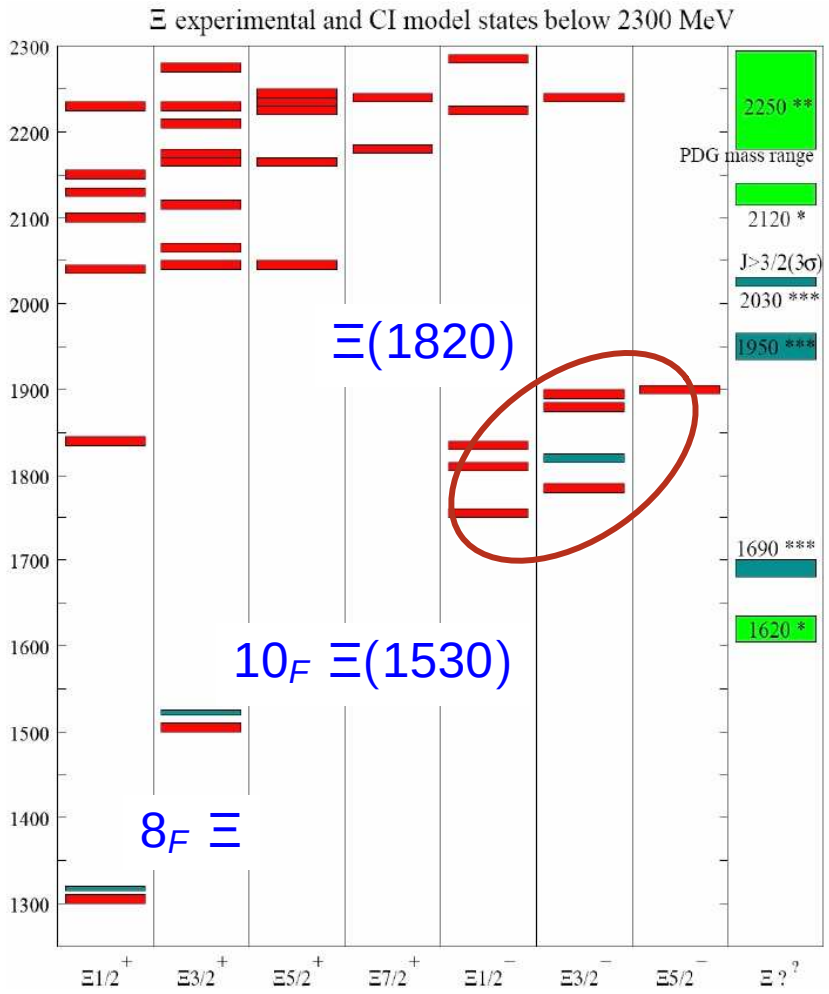
Spectroscopy of $|ssn\rangle$ Ξ baryons:

- Very few established states
- None of the 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.



Opportunities for Baryon Spectroscopy at GlueX

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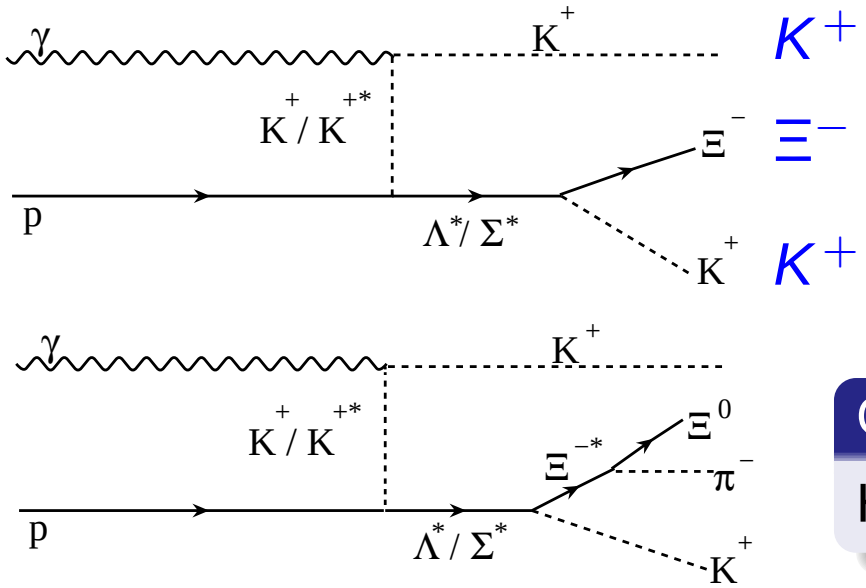
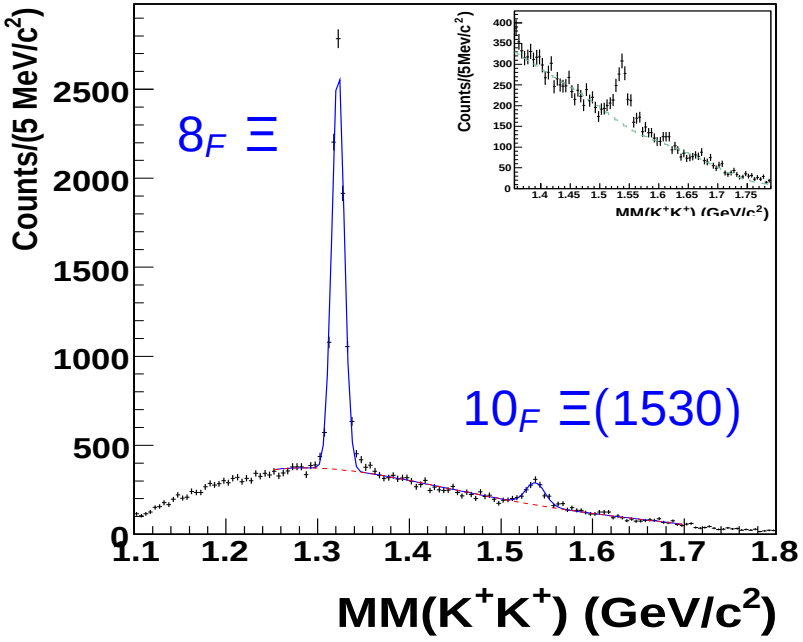
Production via excited hyperons:



K^+ Ξ^- K^+

L. Guo *al.* [CLAS], PRC **76**, 025208 (2007)



GlueX Proposal, PAC 40 (arXiv:1305.1523)

Higher energies, $\sim 100\times$ more statistics, ...

Approved and Pending Experiments in Hall D

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

- Mapping the Spectrum of Light-Quark Mesons and Gluonic Excitations with Linearly Polarized Photons.
- A Precision Measurement of η Radiative Decay Width via the Primakoff Effect.

Recent submissions to Jefferson Lab PAC 40:

- An initial study of mesons and baryons containing strange quarks with GlueX (arXiv:1305.1523).
- Measuring the Charged-π Polarizibility in the $\gamma\gamma \to \pi^+\pi^-$ Reaction.
- Symmetry Tests of Rare η Decays to All-Neutral Final States: The JLab η Factory (JEF) Experiment.

Outline

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.