Hadron Spectroscopy at the GlueX Experiment and the Search for Gluonic Excitations

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Reimei Workshop
Hadronic Resonances and Dense Nuclear Matter

J-PARC, Tokai, Japan

12/11/2017

Outline

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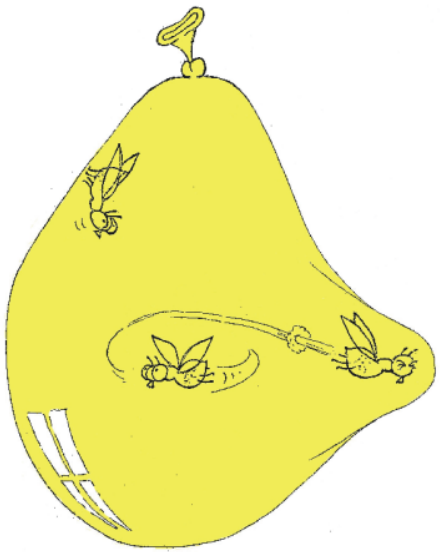
Strong-Coupling Quantum Chromodynamics (QCD)

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

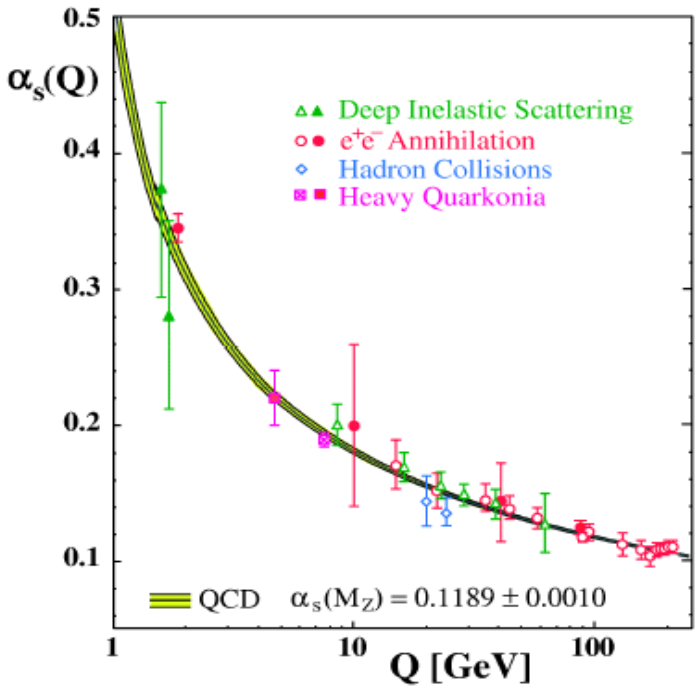
QCD = Theory of the strong nuclear force

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

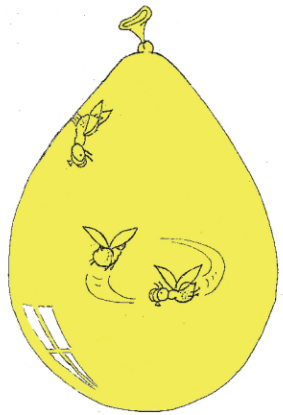


Confinement & Strong QCD

"World of Hadrons"



"pQCD"



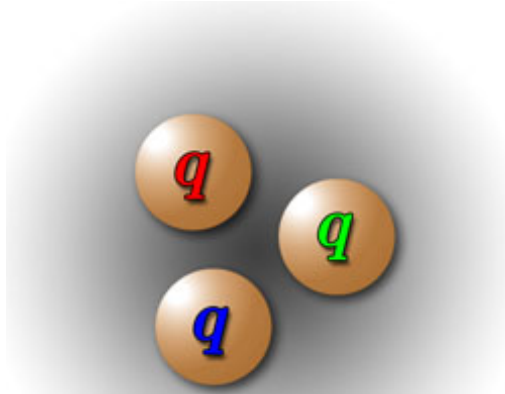
Asymptotic Freedom

Hadrons: Baryons & Mesons

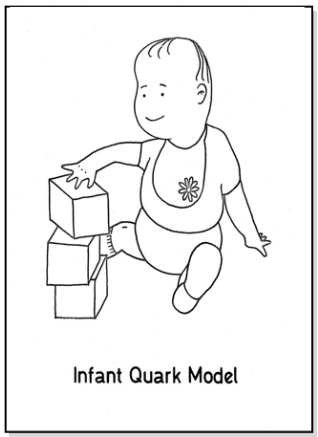
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

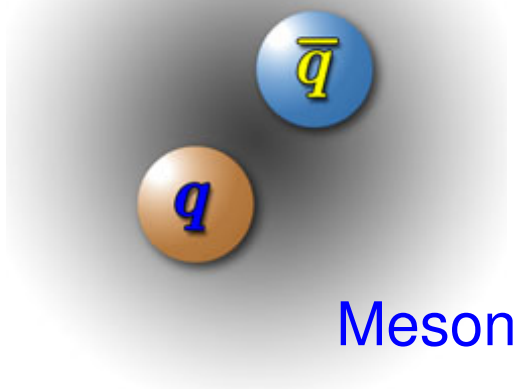
- Their structure is most obviously related to the color degree of freedom, e. g. $|\Delta^{++}\rangle = |u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$.
- they are the stuff of which our world is made.



Baryons

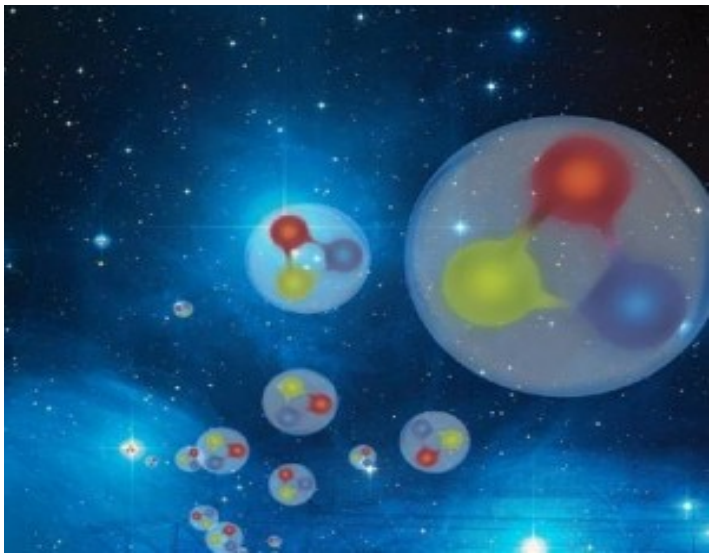


Strong Coupling QCD



Mesons

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?

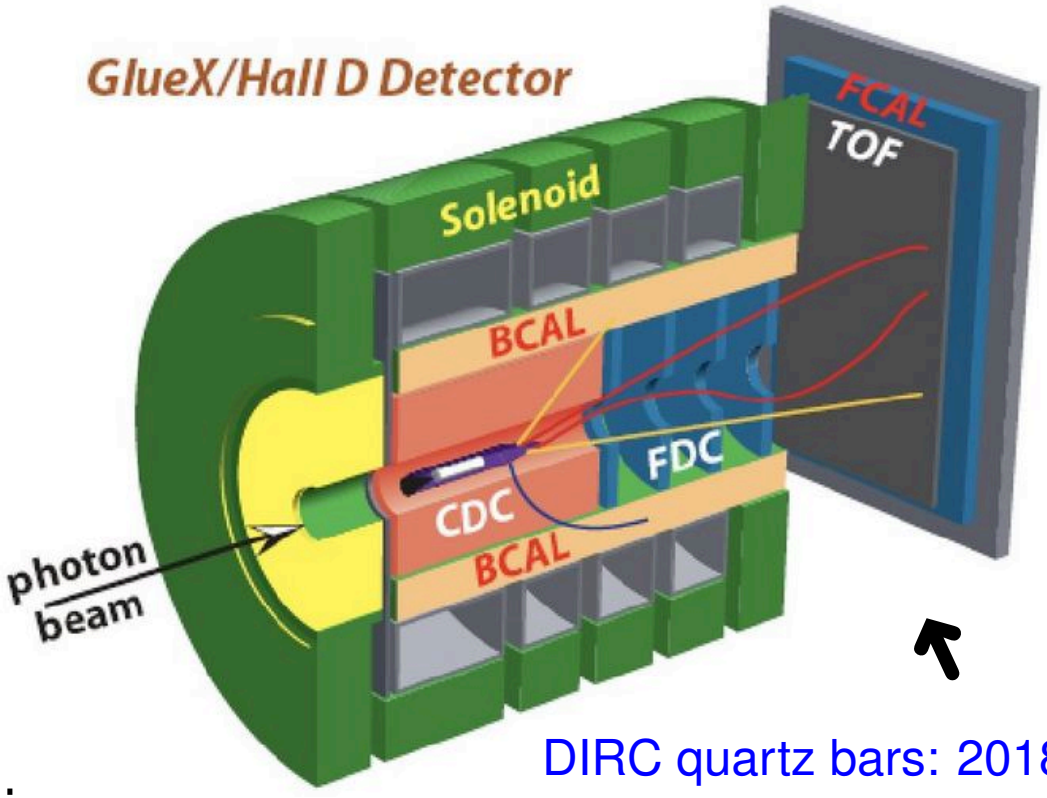
Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, tetraquarks, ...)?

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

Hybrid baryons are also possible ...

Hadron Spectroscopy

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



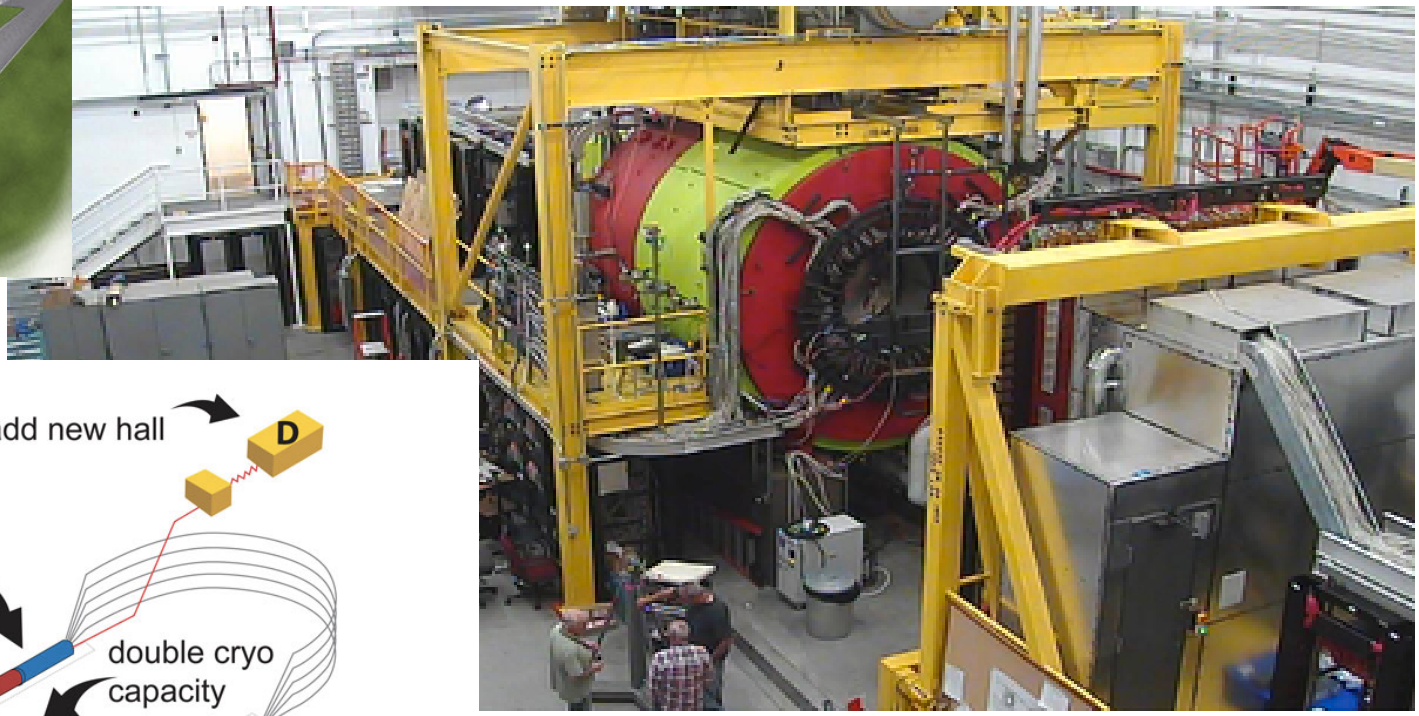
DIRC quartz bars: 2018+

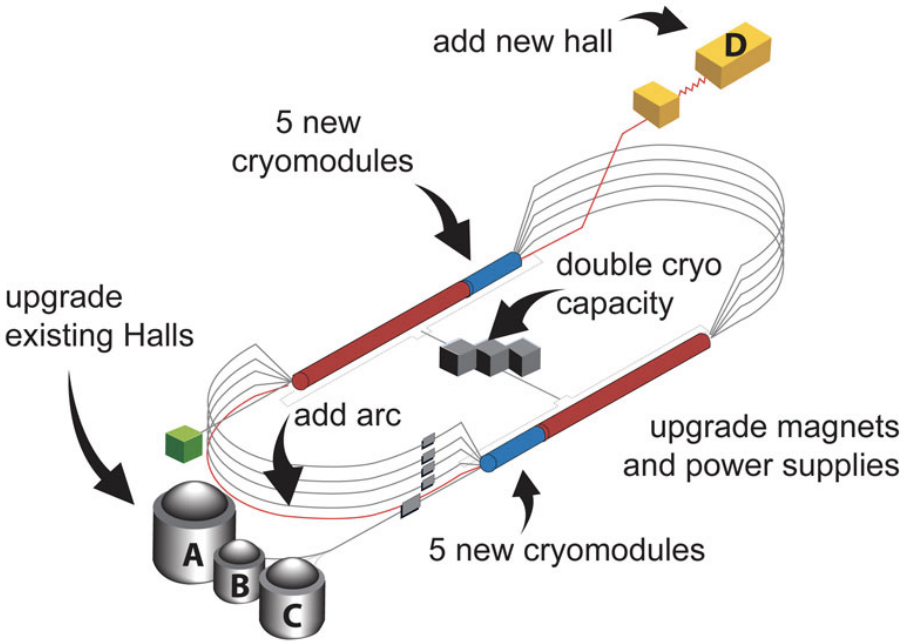
The GlueX Collaboration

- $\sim$130 members, 28 institutions
  (USA, Chile, China, Armenia, Greece, Russia, UK)
- Production data-taking in full swing
- First physics published in 2017

Hall D

May 2014



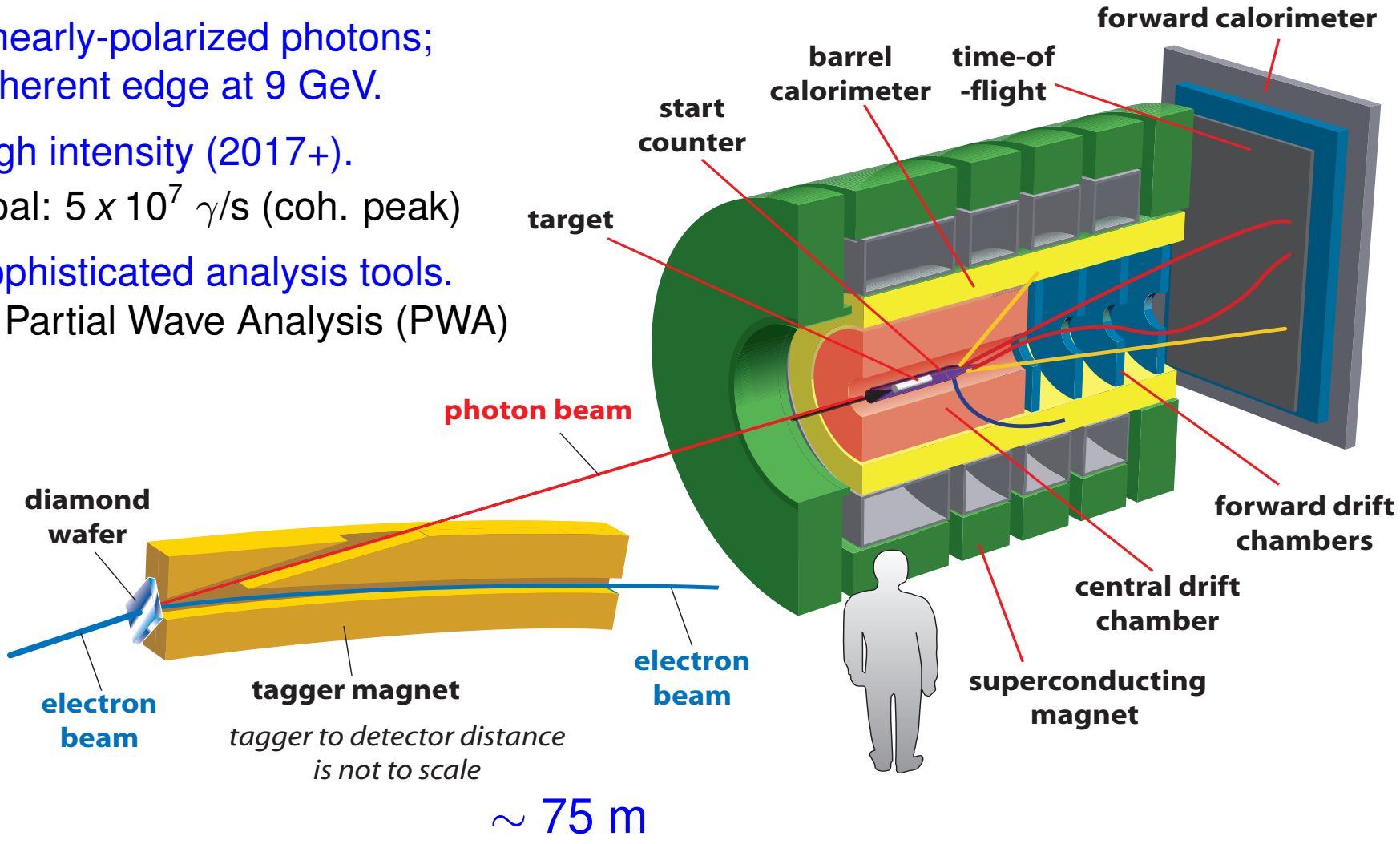


Jefferson Lab Upgrade to 12 GeV

- 10.1 GeV achieved, Fall 2014
- Hall D project complete

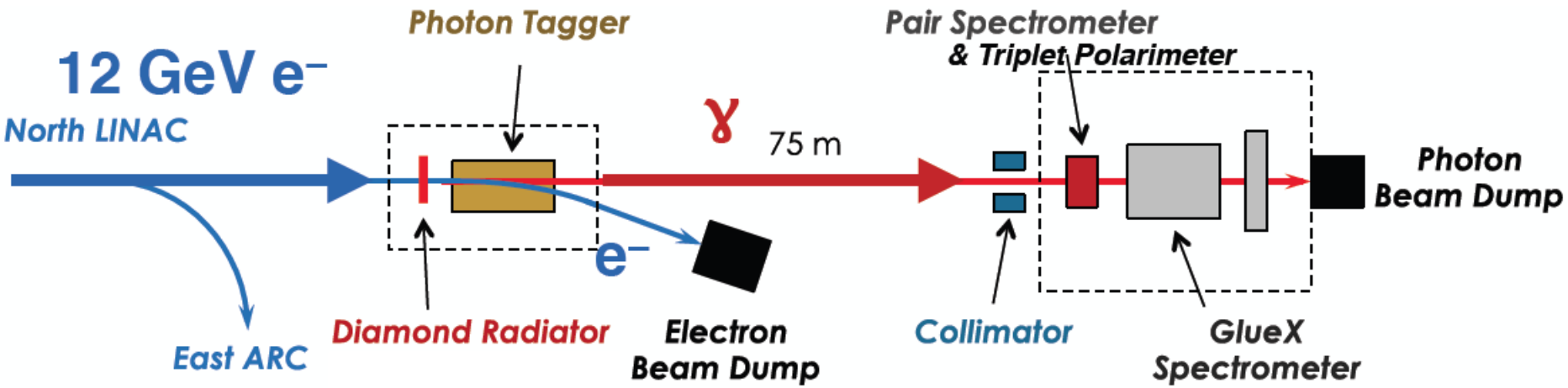
Study of light-flavor (hybrid) mesons and baryons:

- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity (2017+).
  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.

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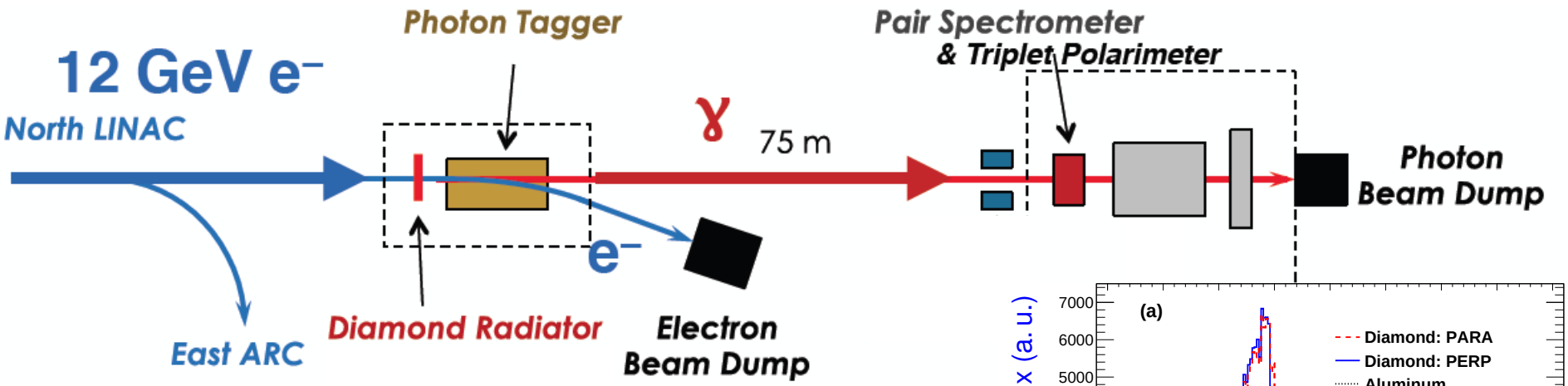

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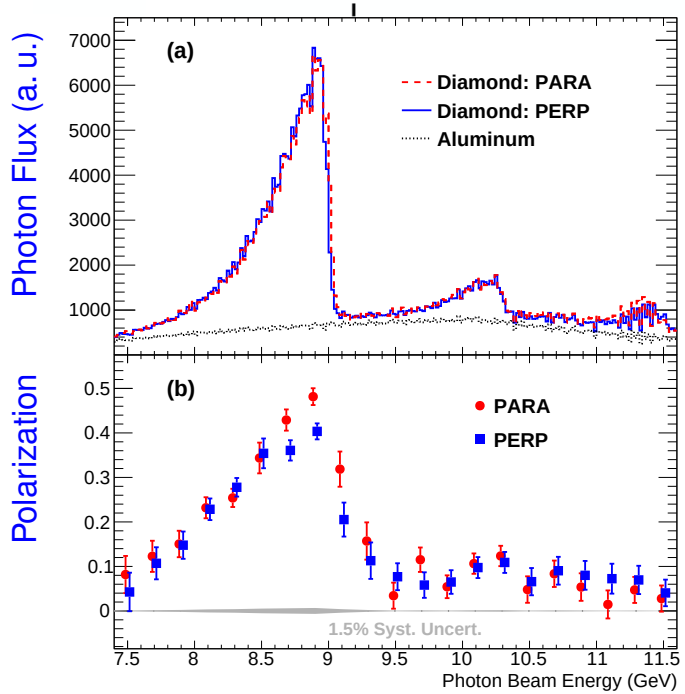


Outline

Quark-Model Classification: Ordinary & Exotic Mesons

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

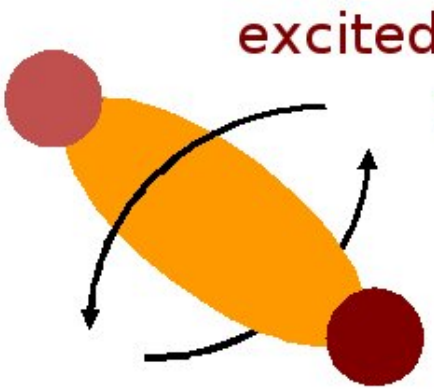
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^{I}$

$L = 0,\ S = 0$:

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

$L = 0,\ S = 1$:

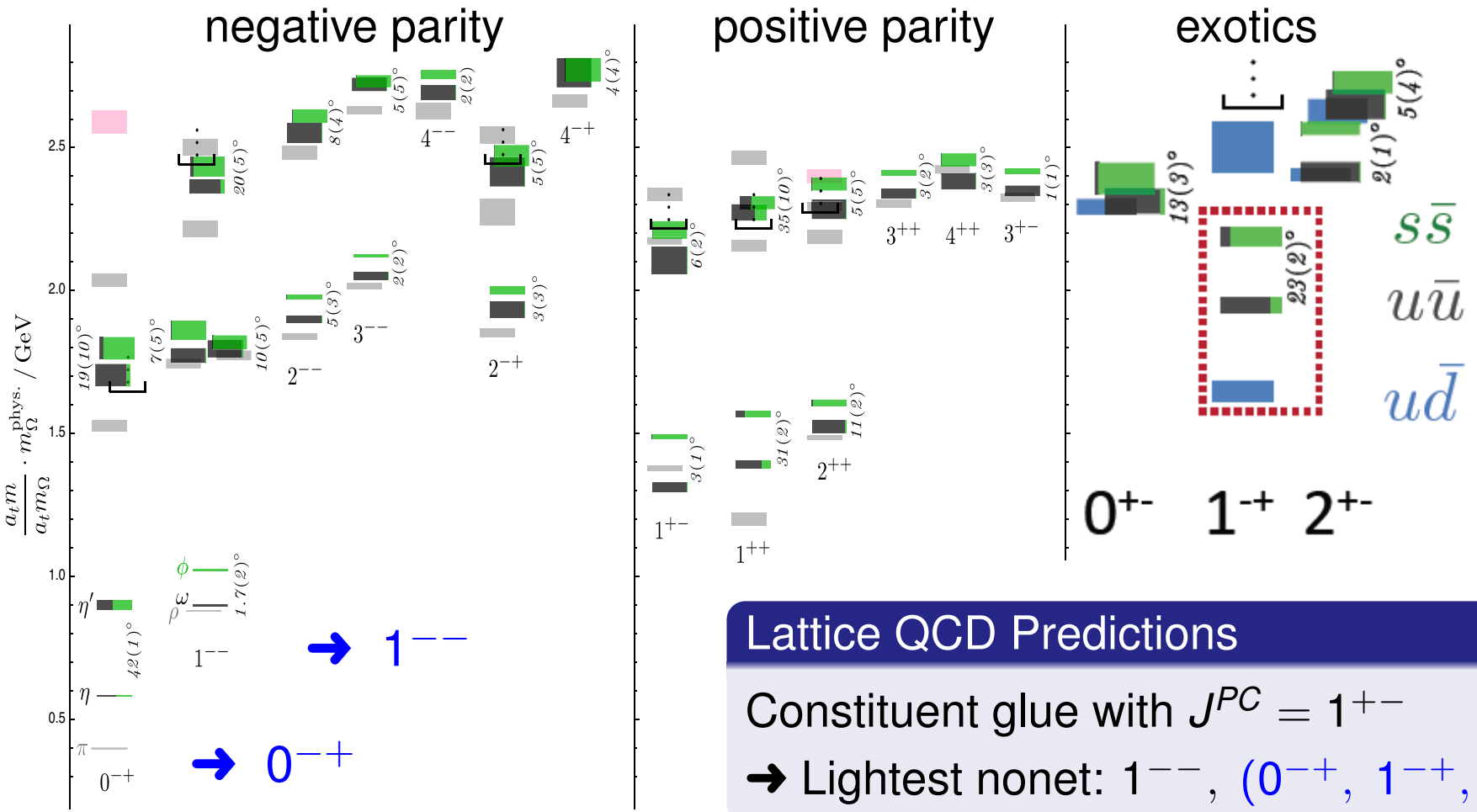
e.g. $\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$



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

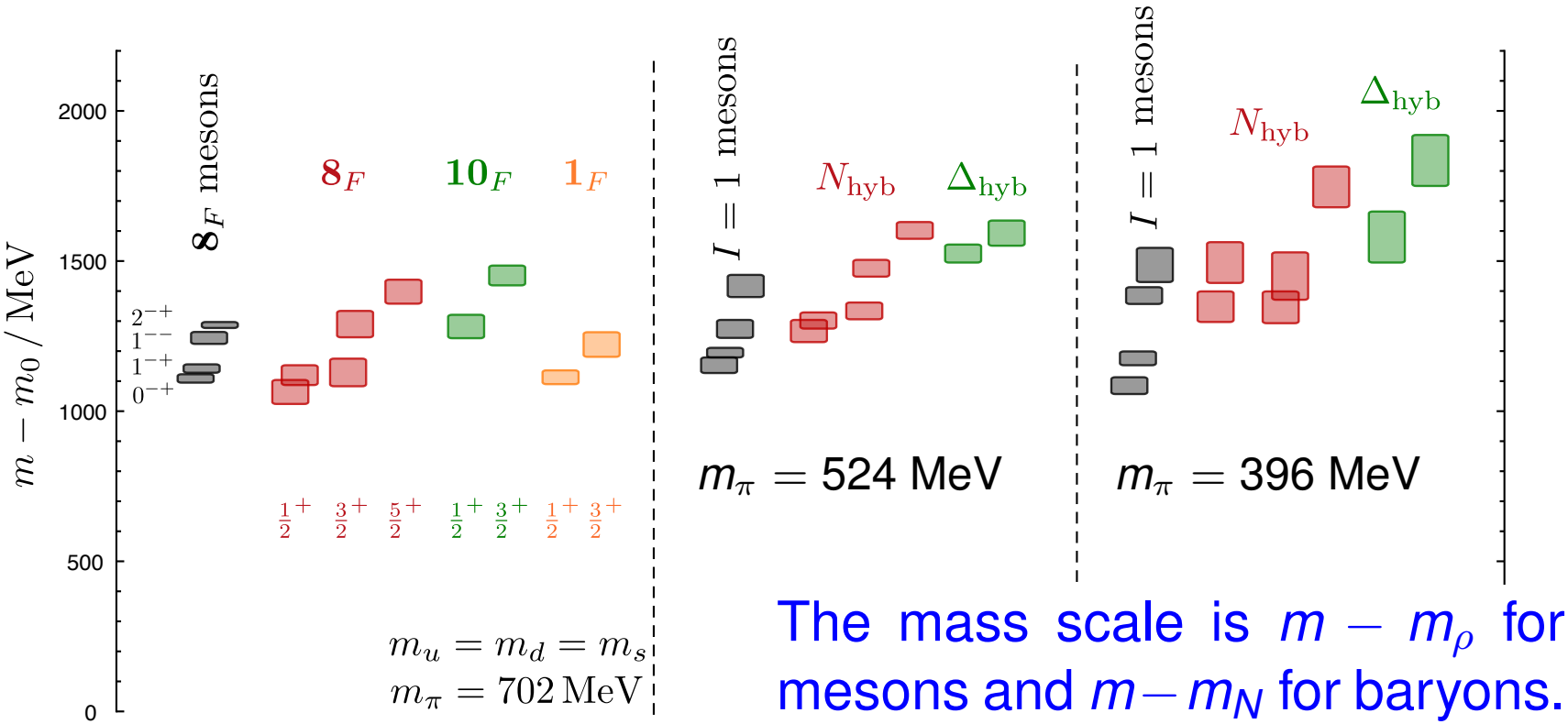
Constituent glue with $J^{PC} = 1^{+-}$

➜ 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)

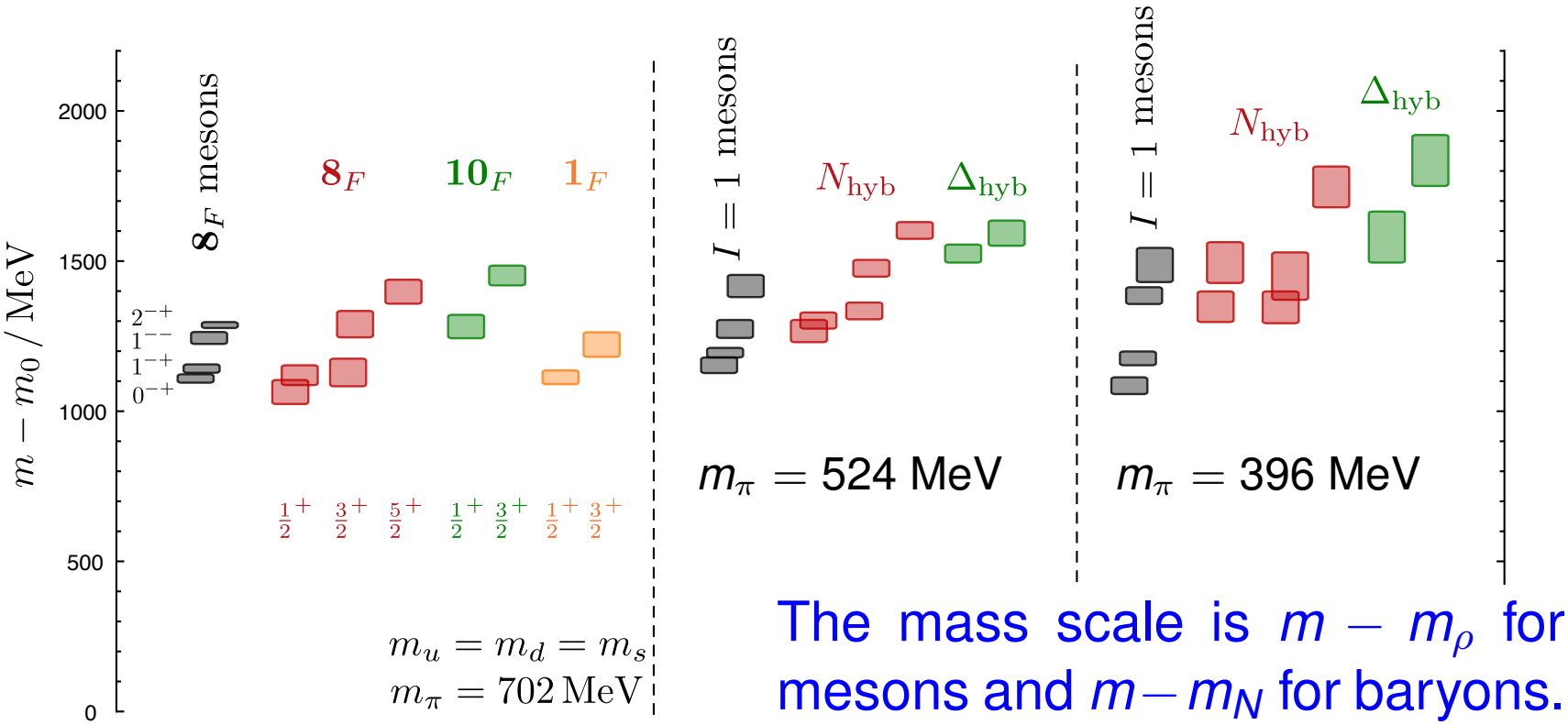


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

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

Gluonic Excitations on the Lattice

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

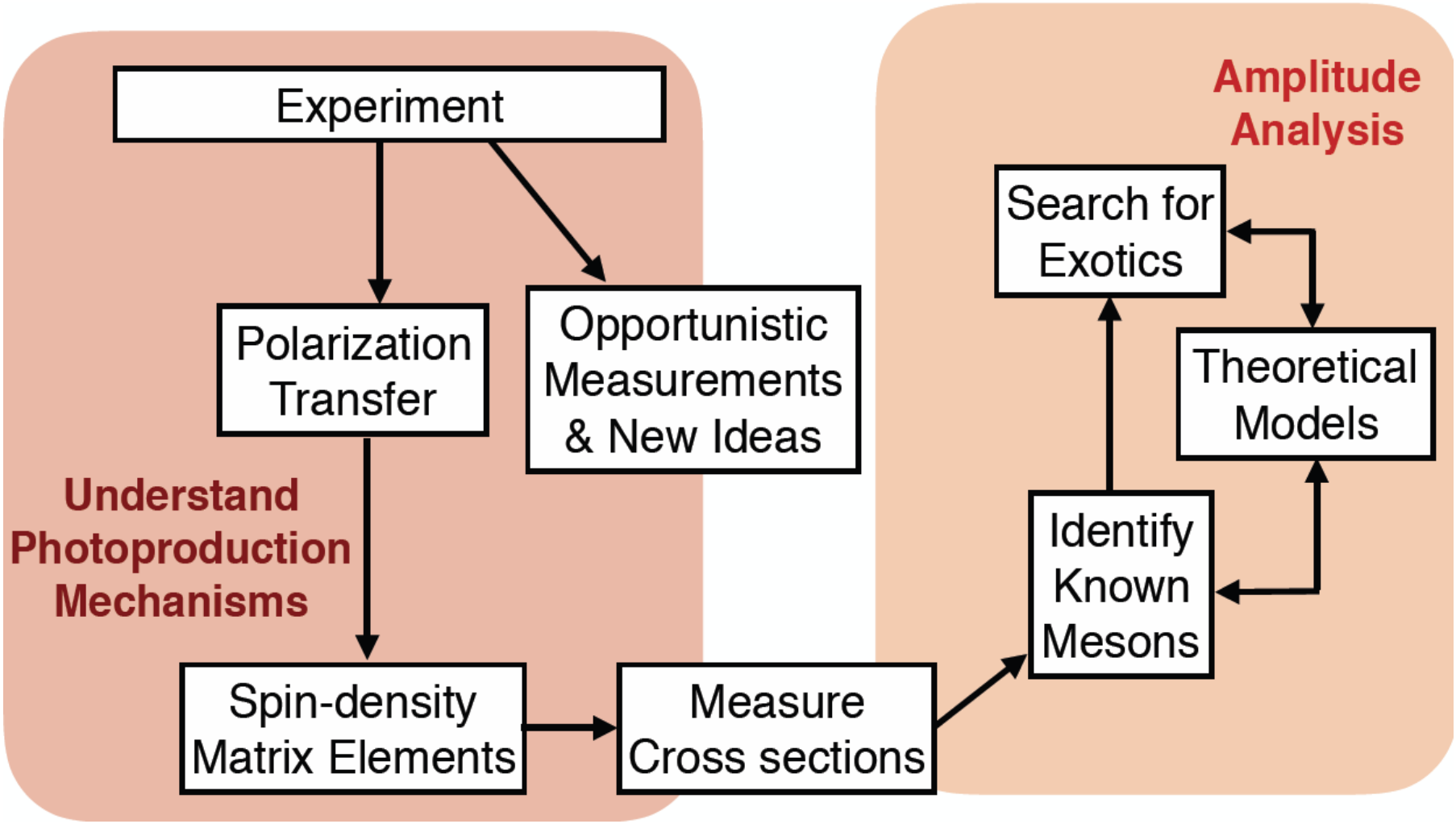


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

Letter of Intent to JLab PAC 43

➜ Search for Hybrid Baryons with CLAS 12 in Hall B

Spectroscopy and Amplitude Analysis



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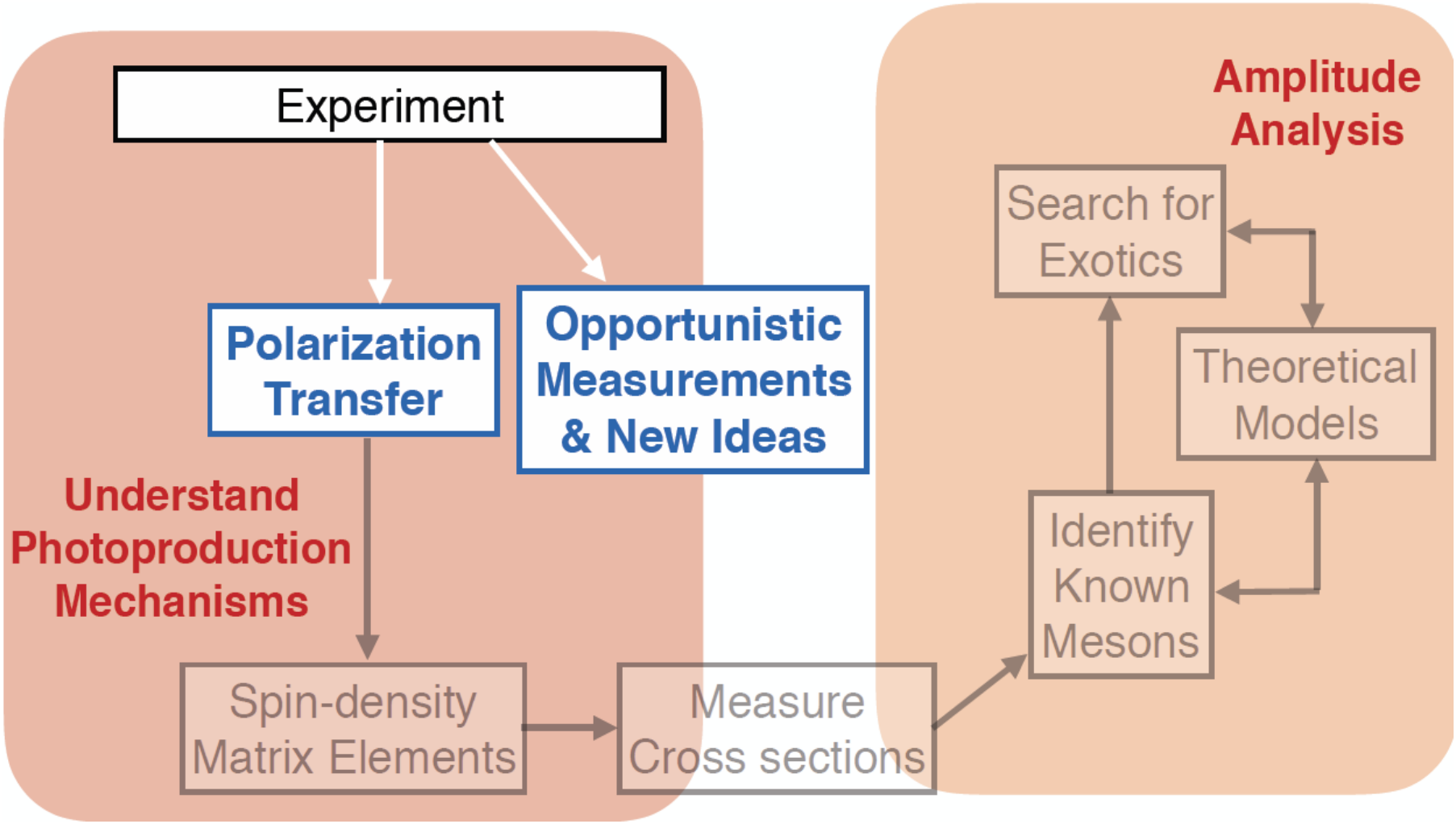
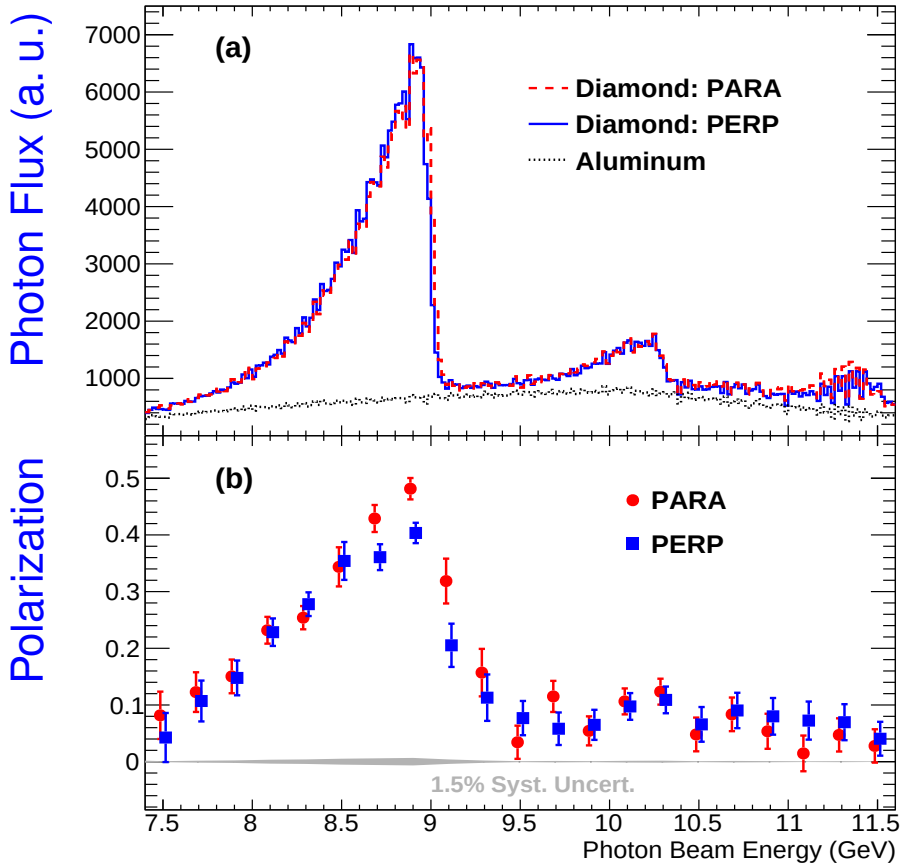


First GlueX "Physics:" Initial Analyses



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

Detector Understanding:

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

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

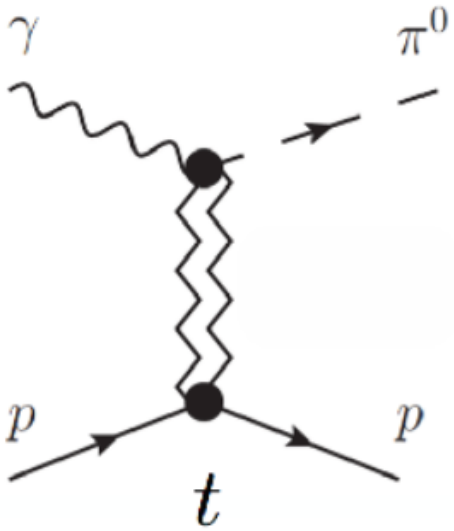
Initial Exotic Hybrid Searches

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

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

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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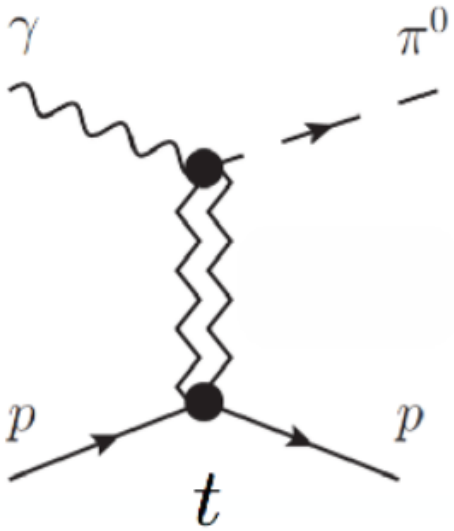

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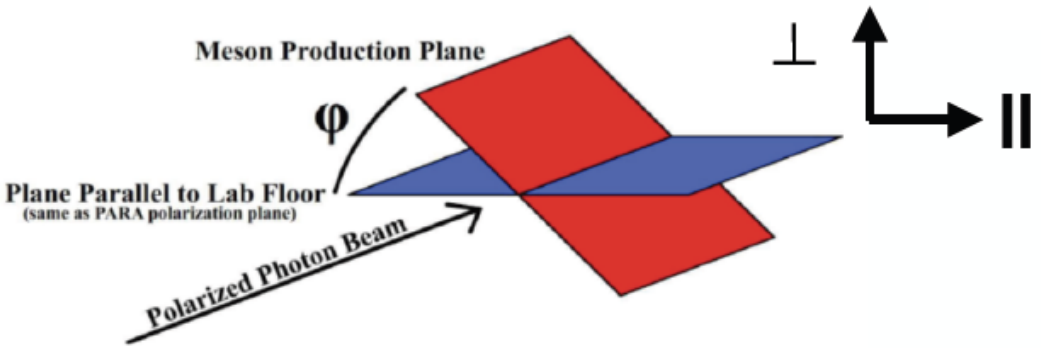
1^{--} : $\omega,\ \rho$

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

Experimentally:

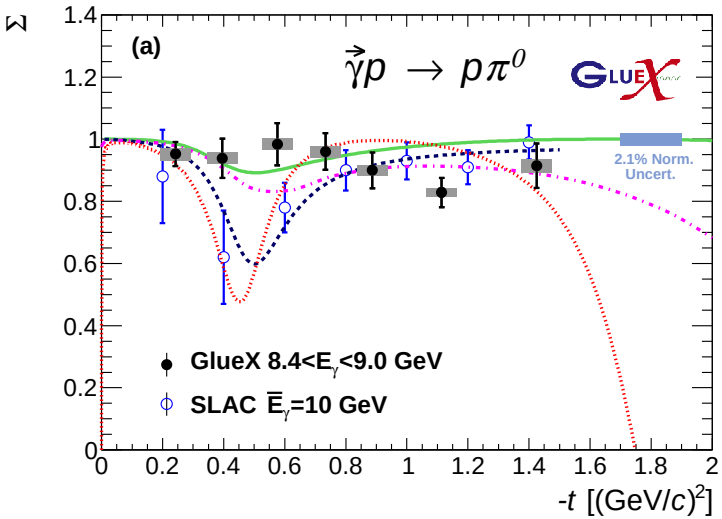
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

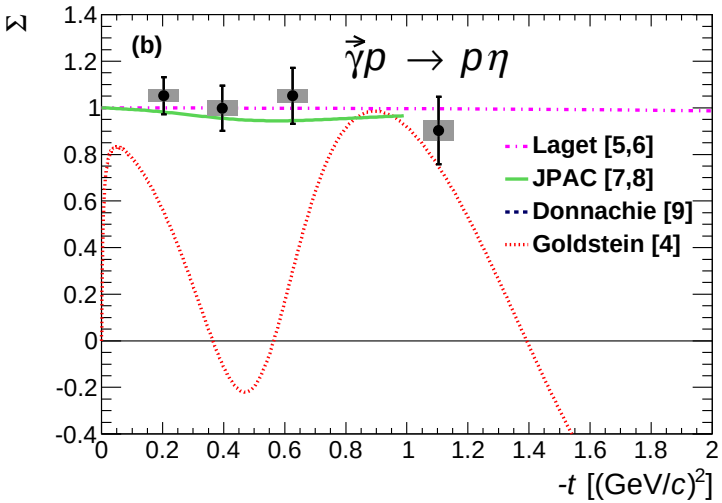
$$\Sigma = \frac{|\omega + \rho| - |h + b|}{|\omega + \rho| + |h + b|}$$



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-time measurement of the η beam asymmetry for $8.4 < E_\gamma < 9.0$ GeV.
- Beam asymmetry close to unity: $\Sigma \approx 1$
  ➜ Dominance of vector-meson exchange.
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction at high energies.
  ➜ Step toward search for exotic mesons.

Opportunities for Baryon Spectroscopy at GlueX

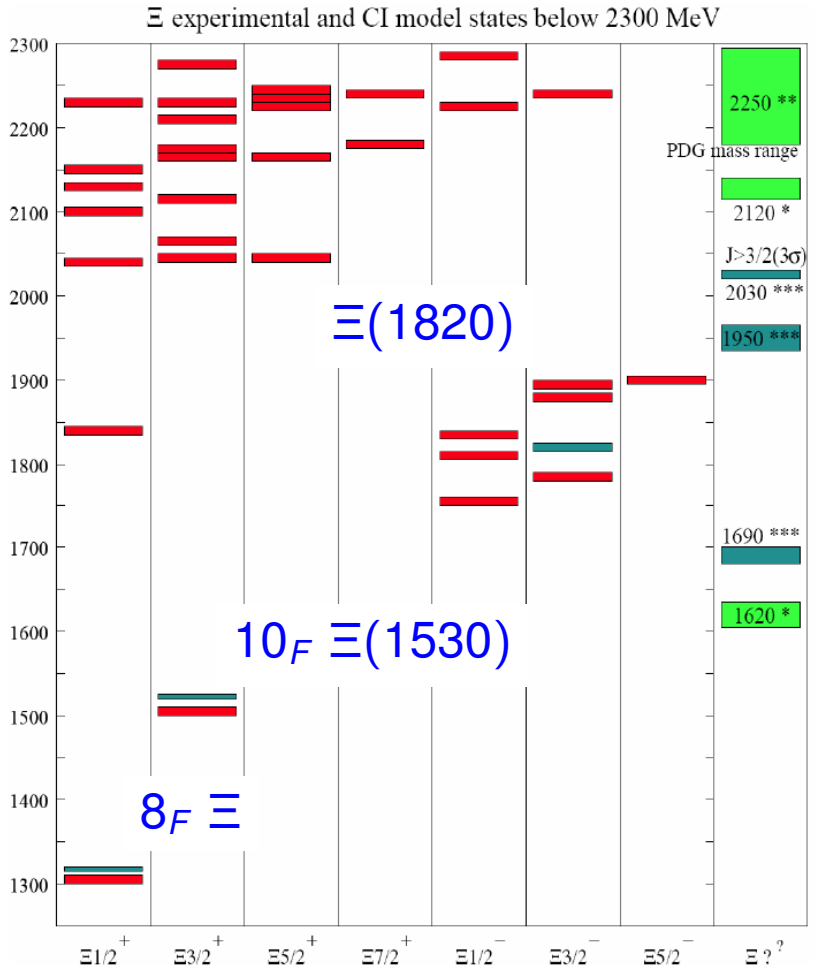
Spectroscopy of $|ssn\rangle$ Ξ baryons:

- 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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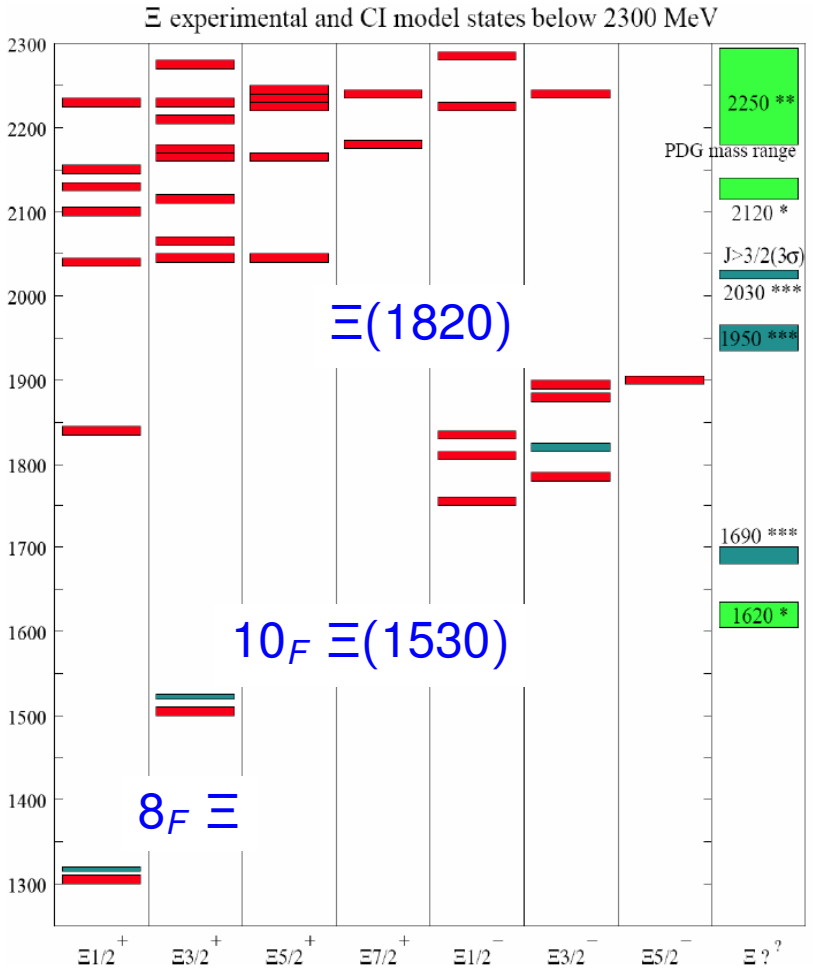
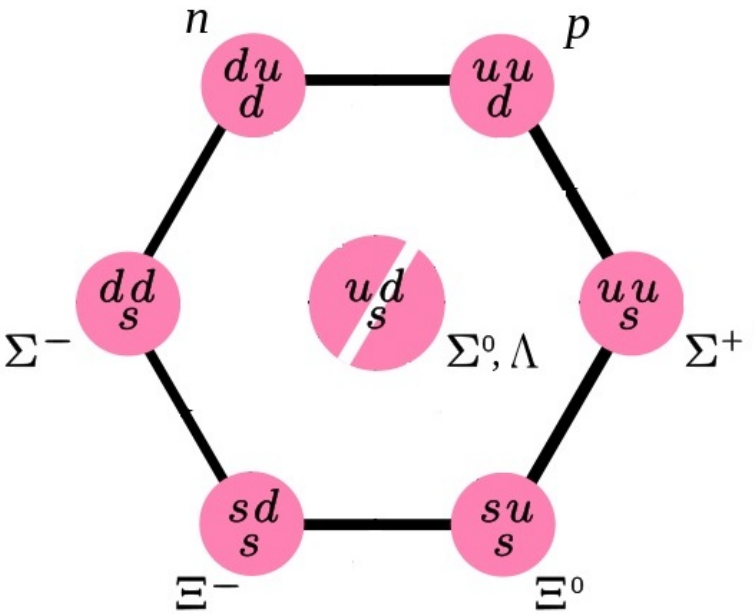
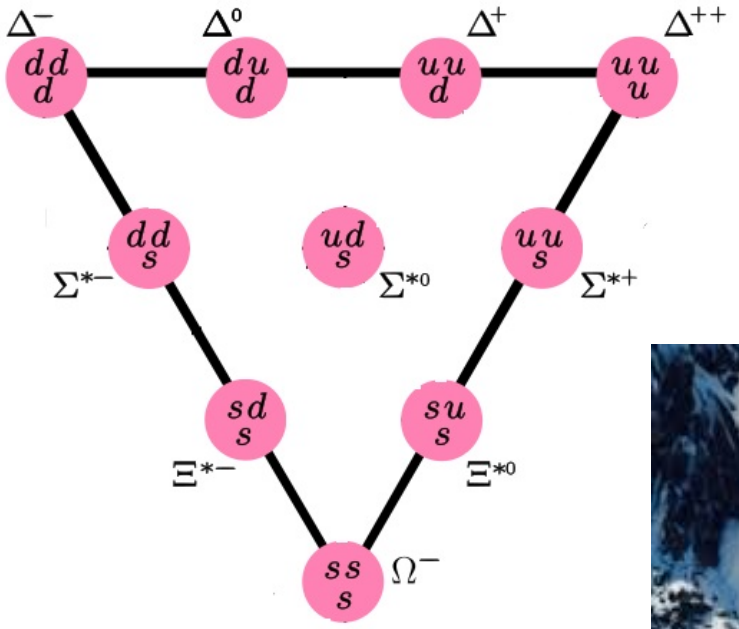


Cascade Spectrum and Multiplets



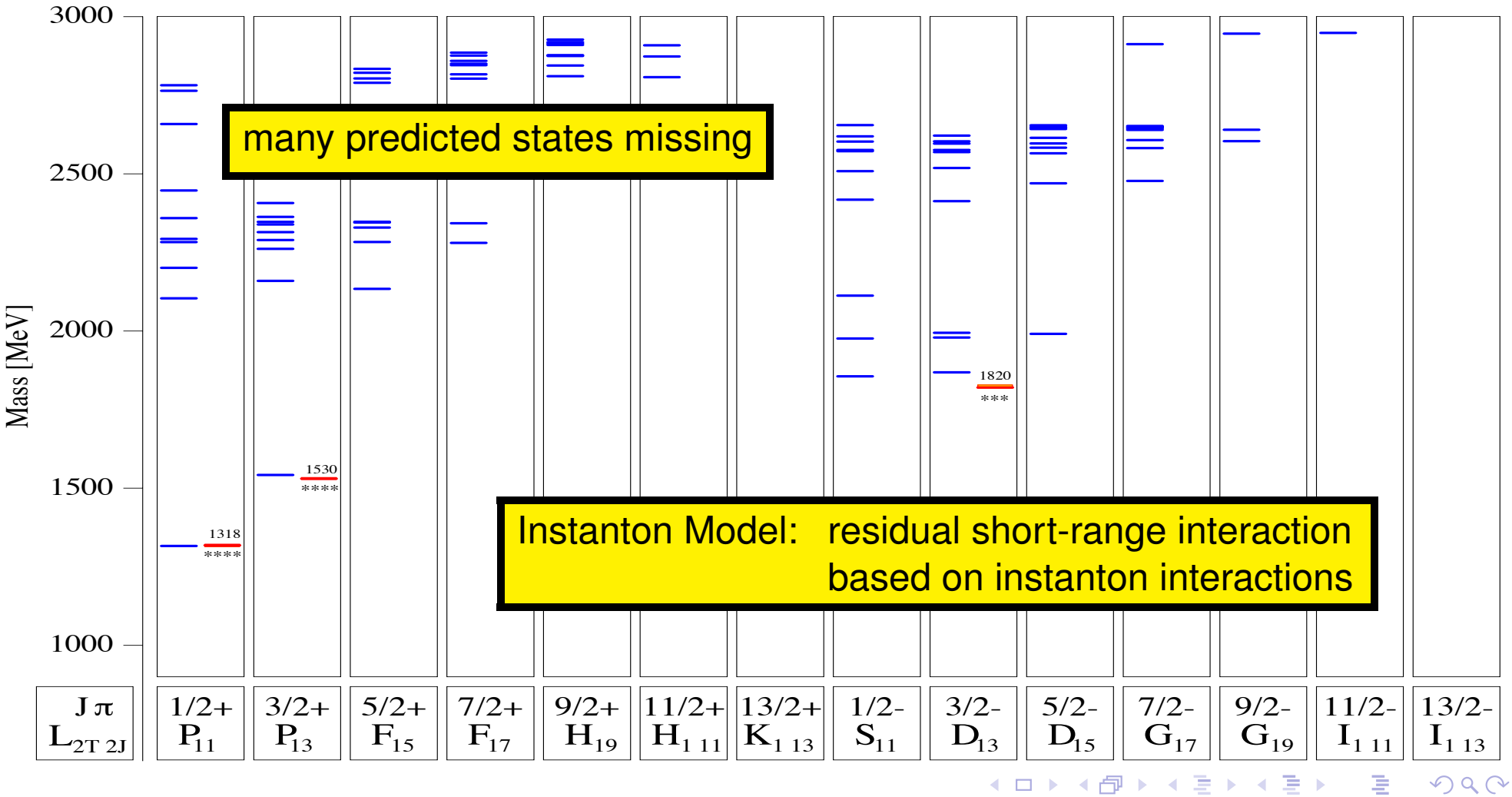


The decuplets consist of Δ^*, Σ^*, Ξ^*, and Ω^* resonances, but also the octets consist of an Ξ^* state.

➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Cascade Resonances: Status as of 2016

U. Loering, B. Ch. Metsch, H. R. Petry, Eur. Phys. J. **A10** (2001) 447-486



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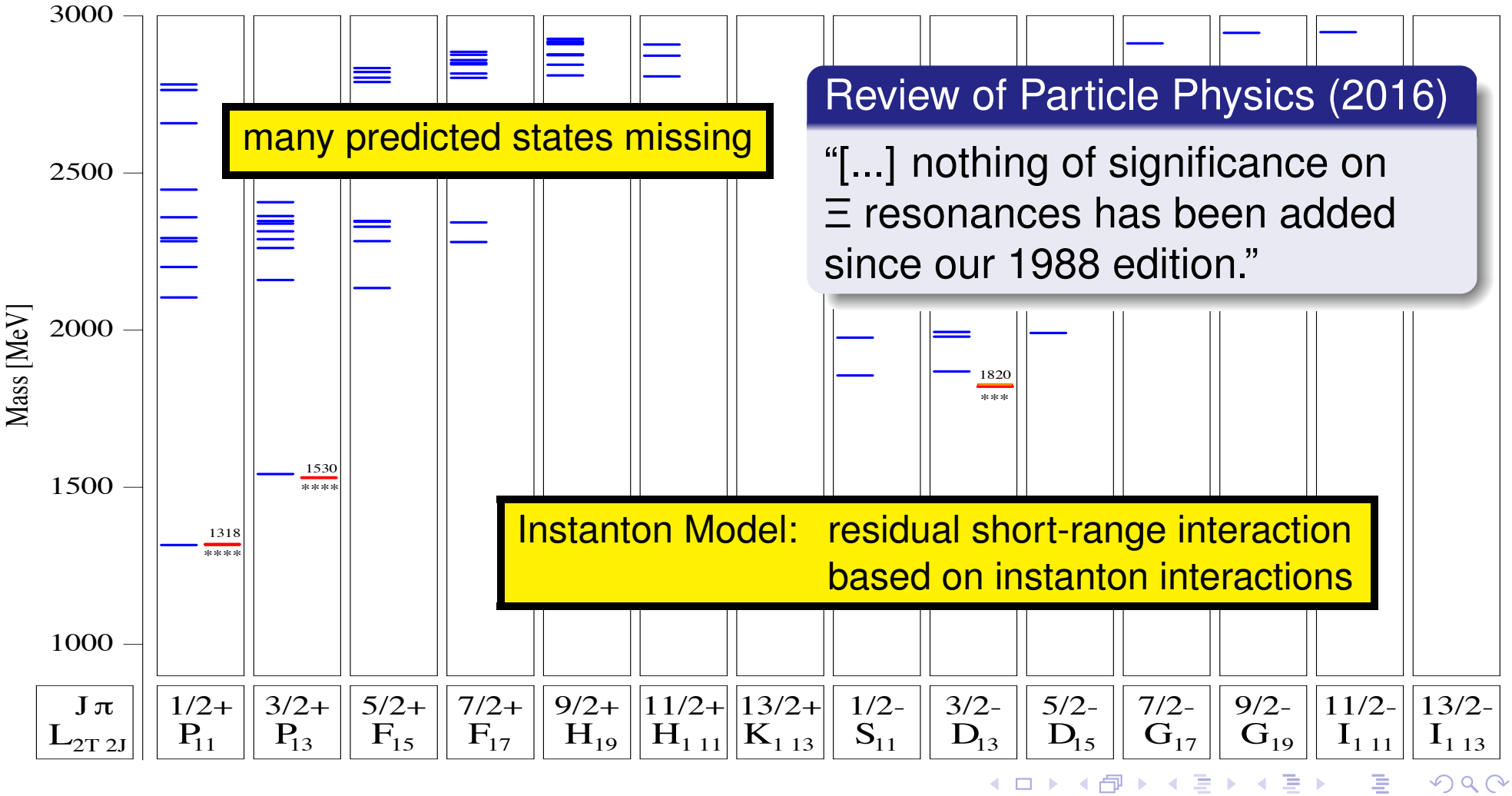


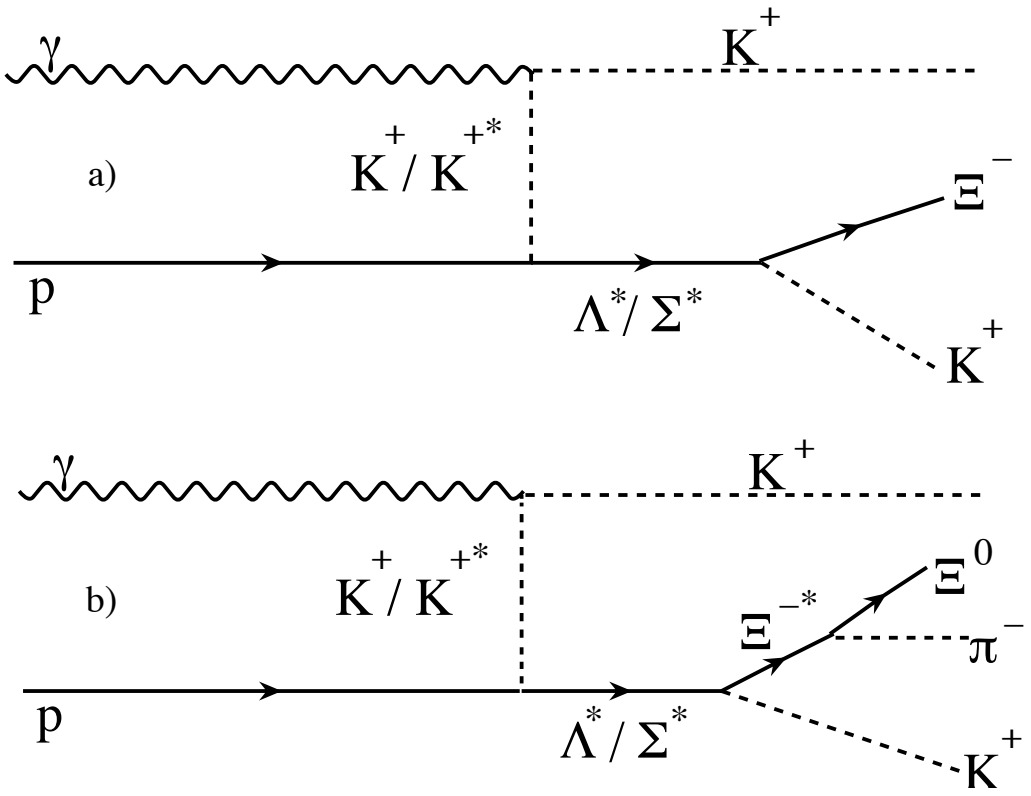
many predicted states missing

Review of Particle Physics (2016)

"[...] nothing of significance on Ξ resonances has been added since our 1988 edition."

Instanton Model: residual short-range interaction based on instanton interactions

Possible Production Mechanisms



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

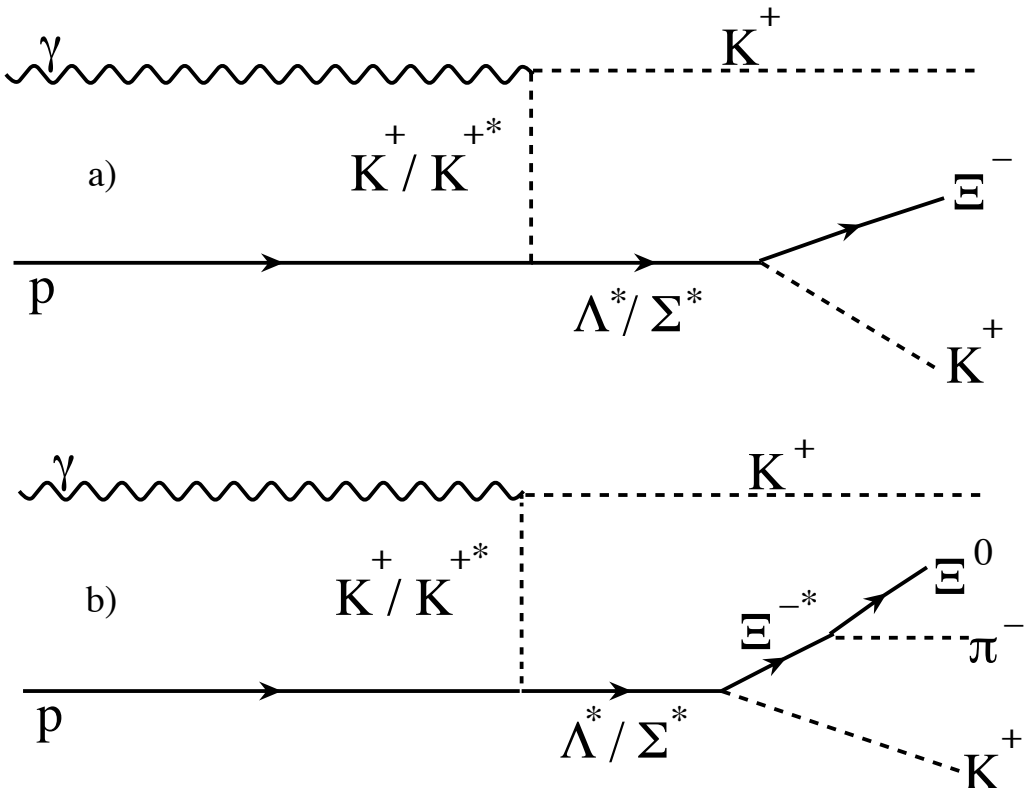
➜ Cross sections, beam asymmetries
(similar to $p\pi\pi$ & pKK^*)

Production of excited states via a

1. forward-going K^0 meson
   ➜ $K^0\,(\,\Xi^-\,\pi^+\,)\,K^+$, etc.
2. forward-going K^+ meson
   ➜ $K^+\,(\,\Xi^-\,\pi^+\,)\,K^0$,
   $K^+\,(\,\Xi^0\,\pi^-\,)\,K^+$, etc.

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

Possible Production Mechanisms



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

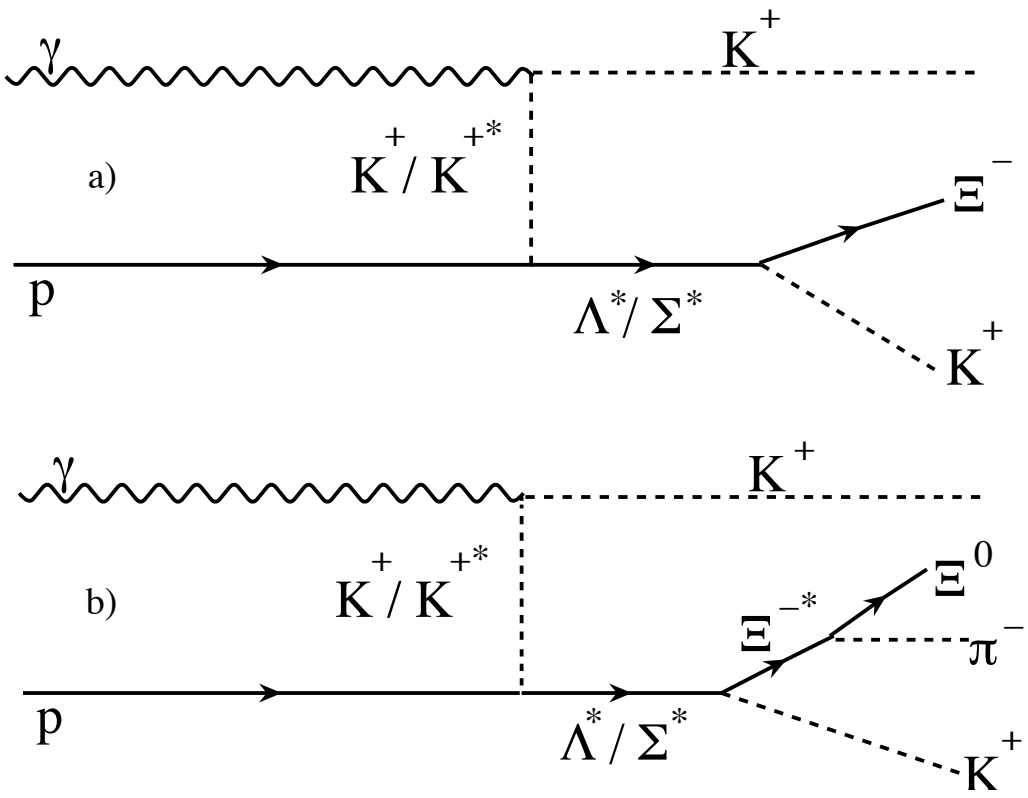
➜ Cross sections, beam asymmetries
(similar to $p\pi\pi$ & pKK^*)

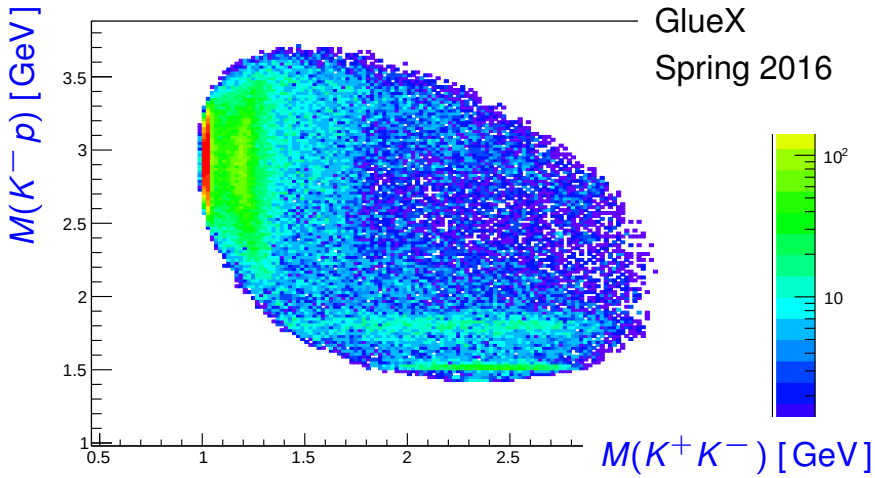
At other facilities (for comparison):

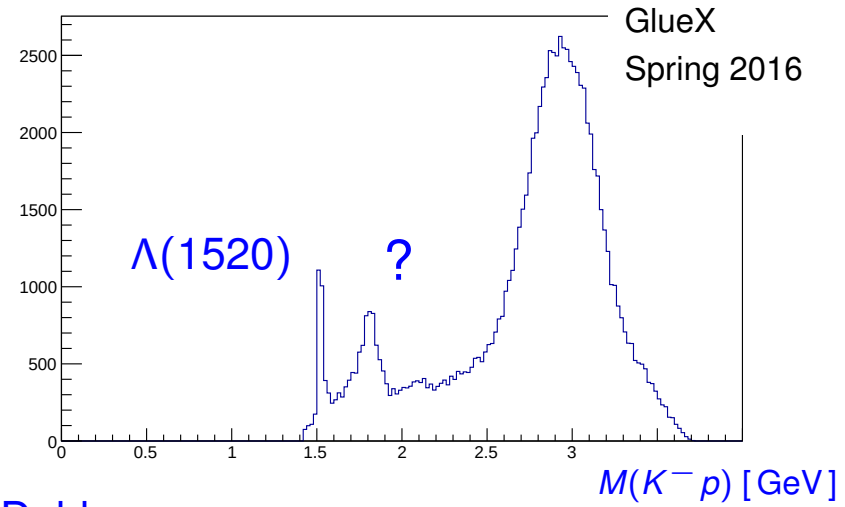
$K^- p \to K^+ \Xi^{*-}$	J-PARC
$K_L p \to K^+ \Xi^{*0}$	Hall D ?
$p p \to \Xi^* X$	LHCb
$\bar{p} p \to \Xi^* \bar{\Xi}$	$\bar{\text{P}}$ANDA
$e^+ e^- \to \Xi^* X$	Belle II, BES III

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

Possible Production Mechanisms

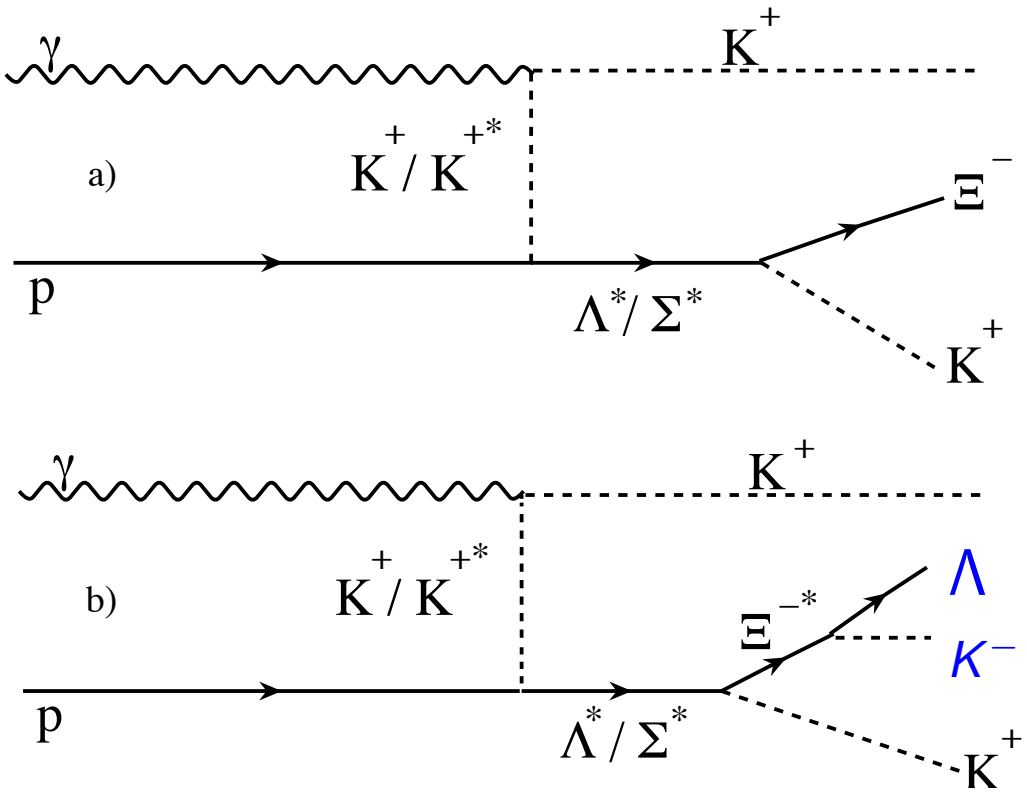




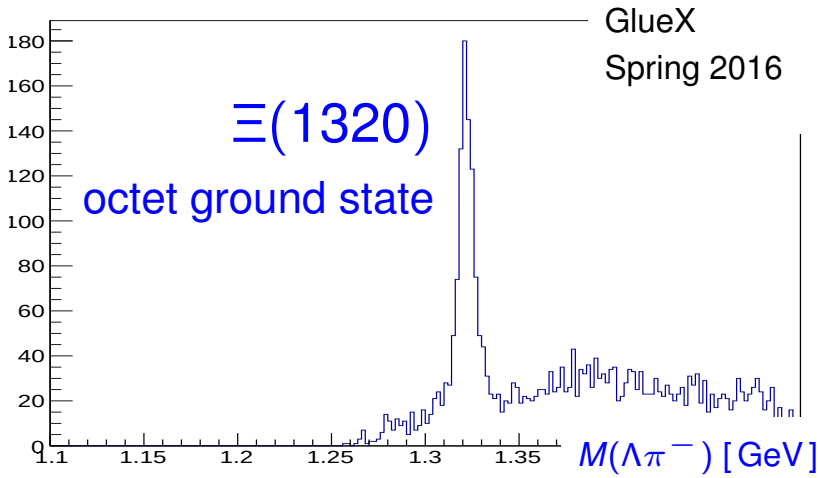


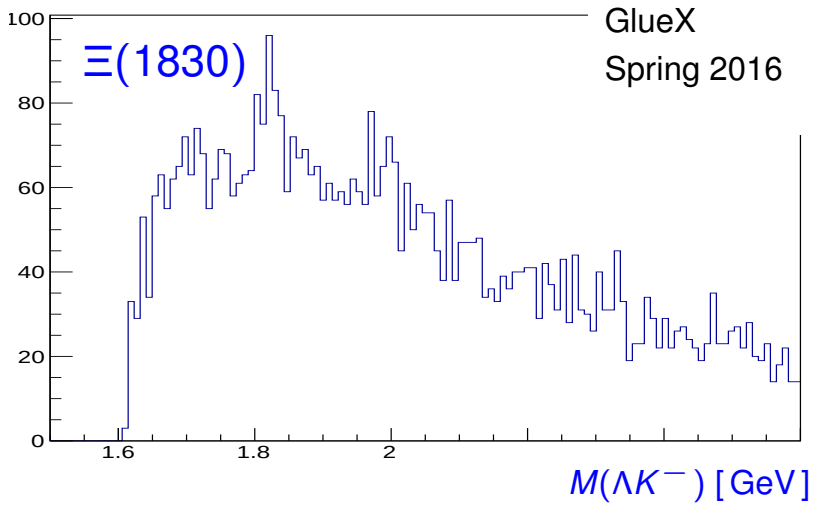
Courtesy of Sean Dobbs

Possible Production Mechanisms



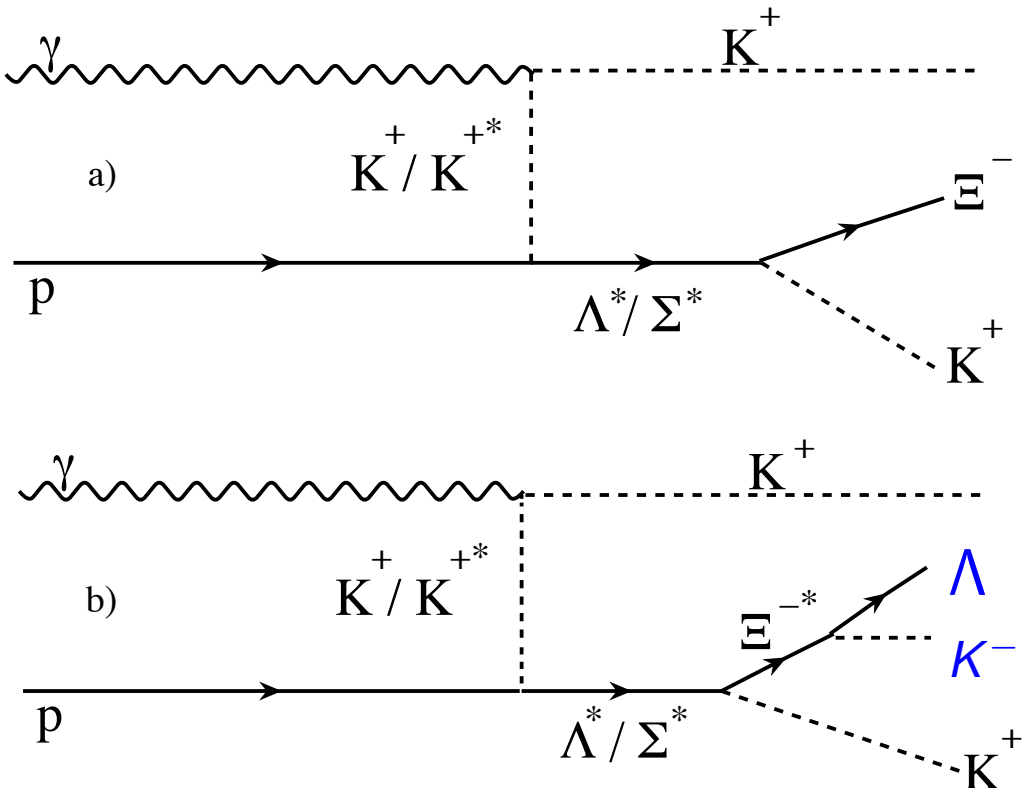
$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$





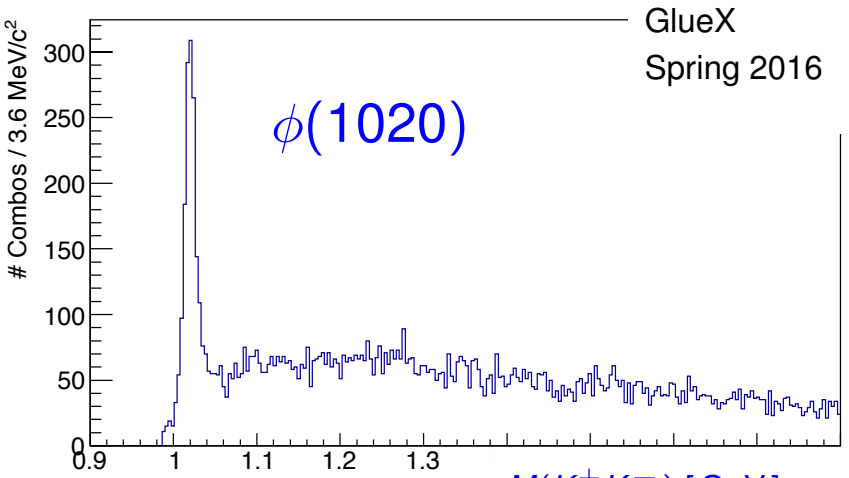
Courtesy of Ashley Ernst (FSU)

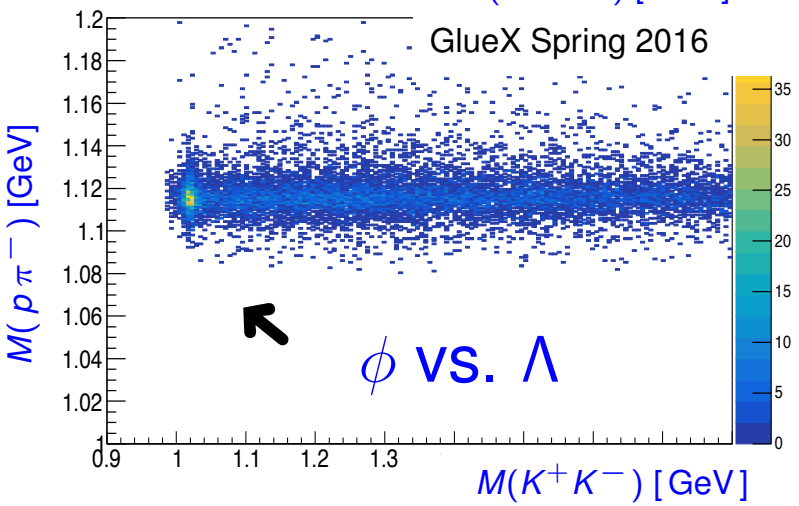
Possible Production Mechanisms



$\gamma p \to K^+ (\Lambda K^+ K^-)$

1) $K^+ (\Xi^{-*} K^+)$, 2) $K^+ (\Lambda \phi)$





Courtesy of Ashley Ernst (FSU)

J/ψ Photoproduction Near Threshold

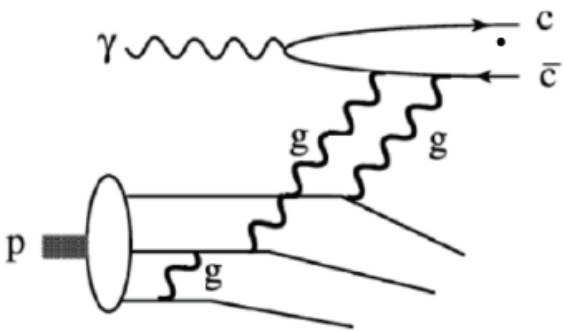
Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton

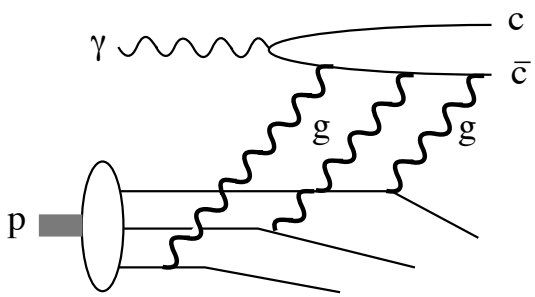
  (D. Kharzeev *et al.*, Nucl. Phys. A **661**, 568 (1999))

- Sensitive to multi-quark correlations

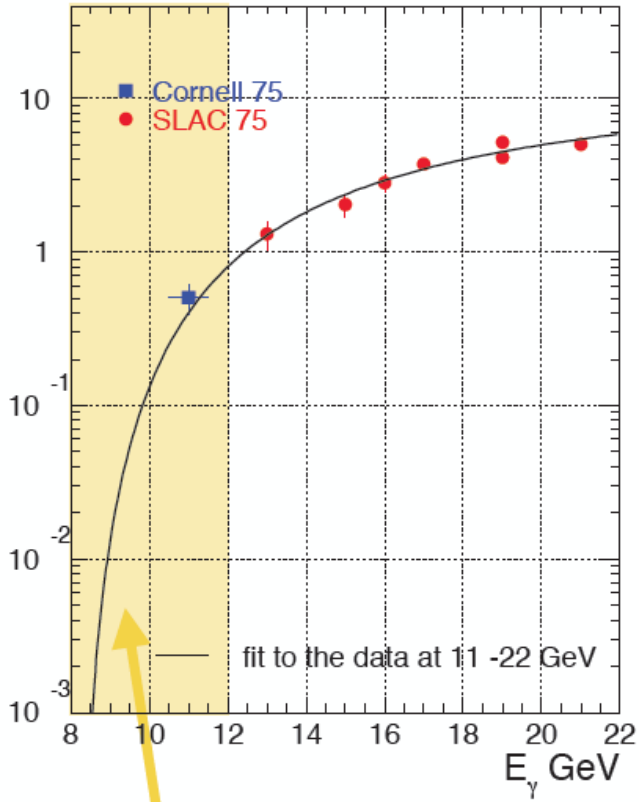
  (S. Brodsky *et al.*, Phys. Lett. B **498**, 23 (2001))



leading twist



higher twist



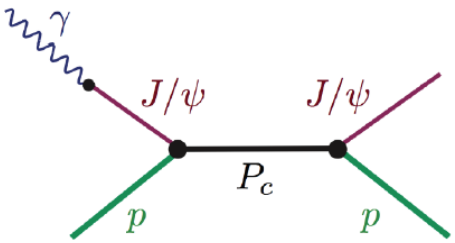
GlueX energy range

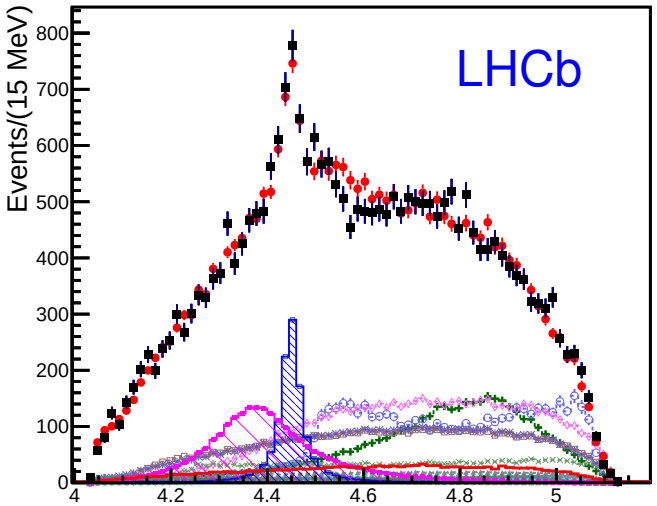
J/ψ Photoproduction Near Threshold

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

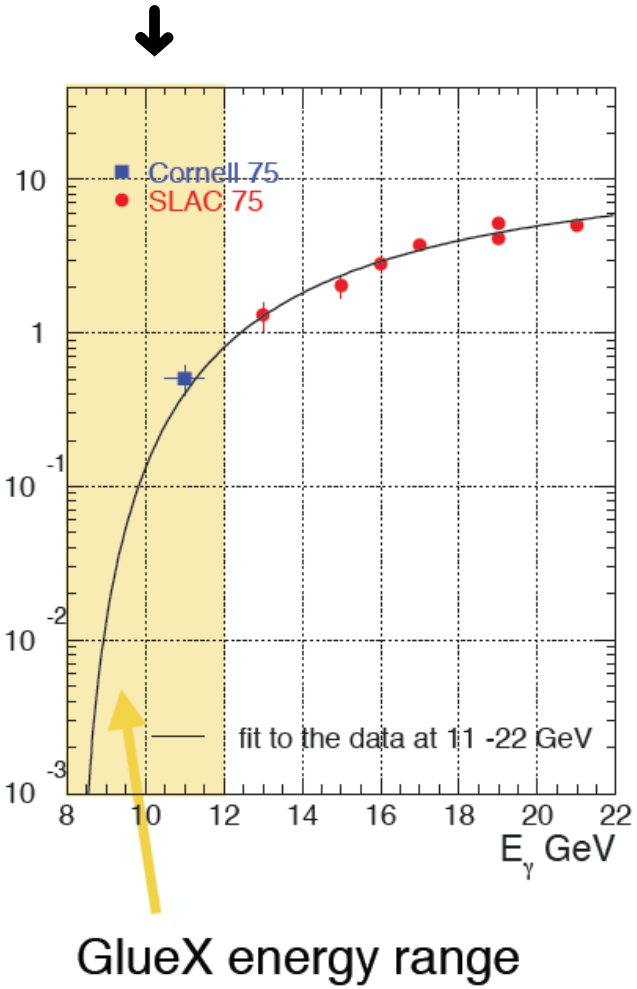
- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction

$P_c(4450)$

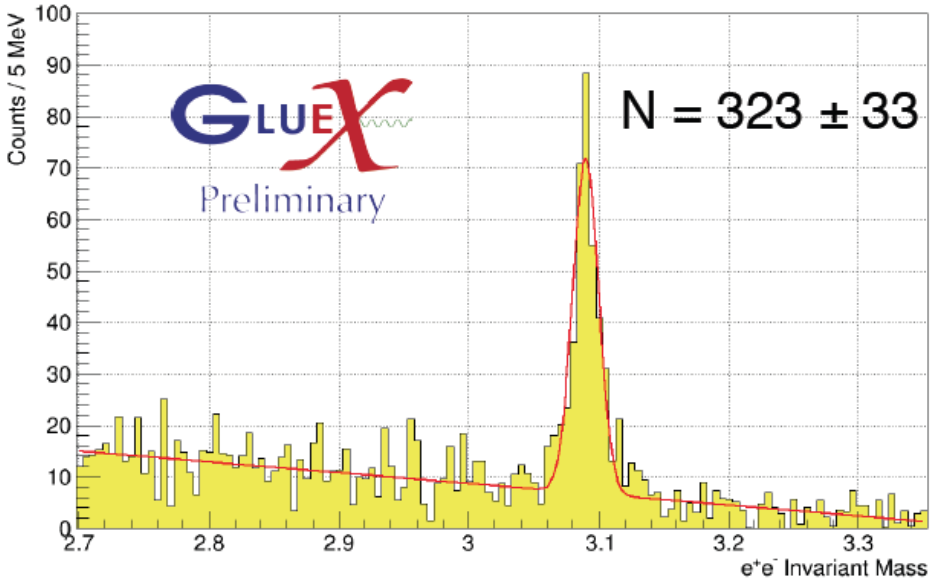


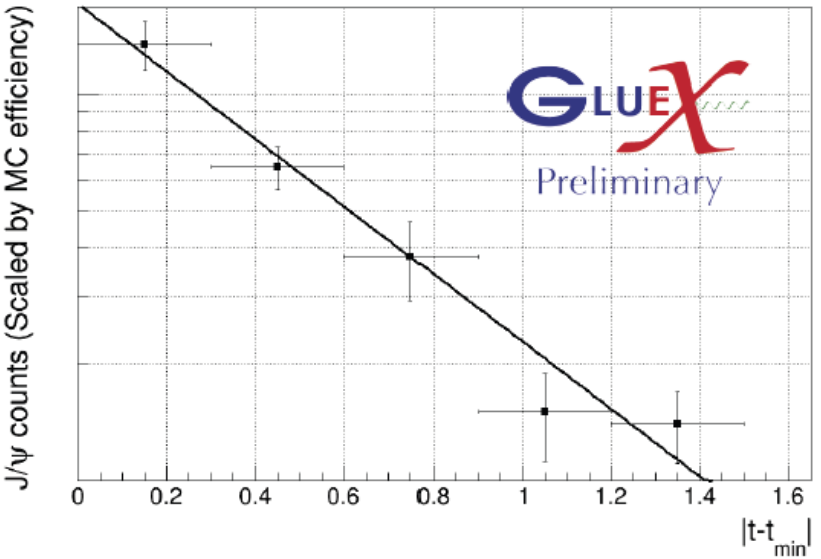


R. Aaij *et al.*, PRL **115**, 072001 (2015)



Observation of J/ψ at GlueX





Using 2016 + 2017 Data

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 (8.2 - 12 GeV): $(2.01 \pm 0.36_{\text{stat.}})$ 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. (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.

- 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:

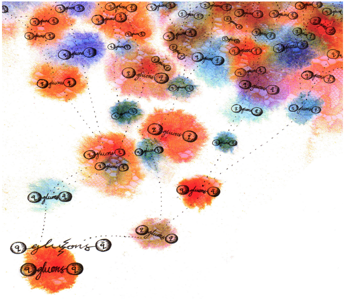
- It is important to establish the existence and the nonet nature of the 1^{-+} state (and of 0^{+-}, 2^{+-})
- For a given produced resonance, linear polarization will allows us to distinguish between naturalities of exchanged particles.
- About 70 % of the photoproduction cross section in the energy 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

Non-Perturbative Quantum Chromodynamics (QCD)

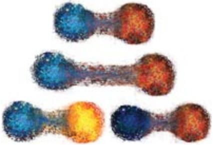


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

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

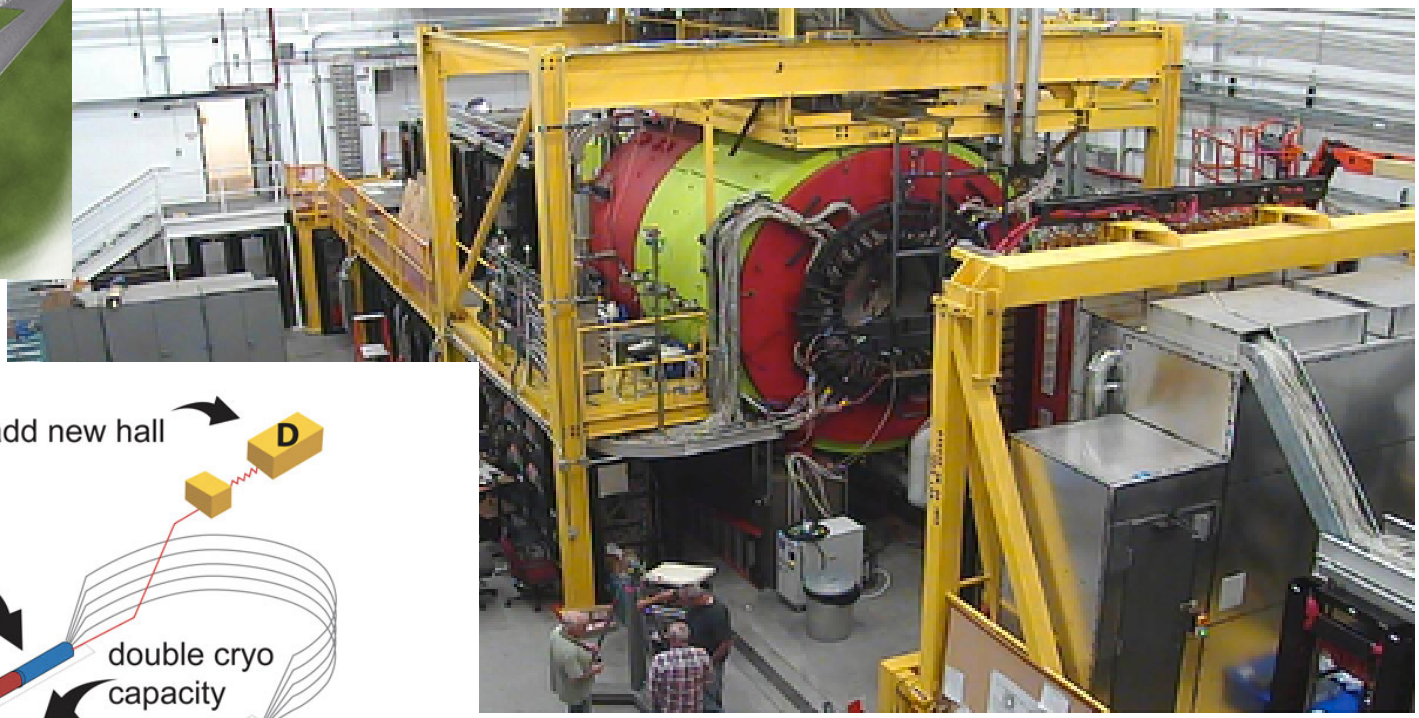
Quarks are confined within hadrons.

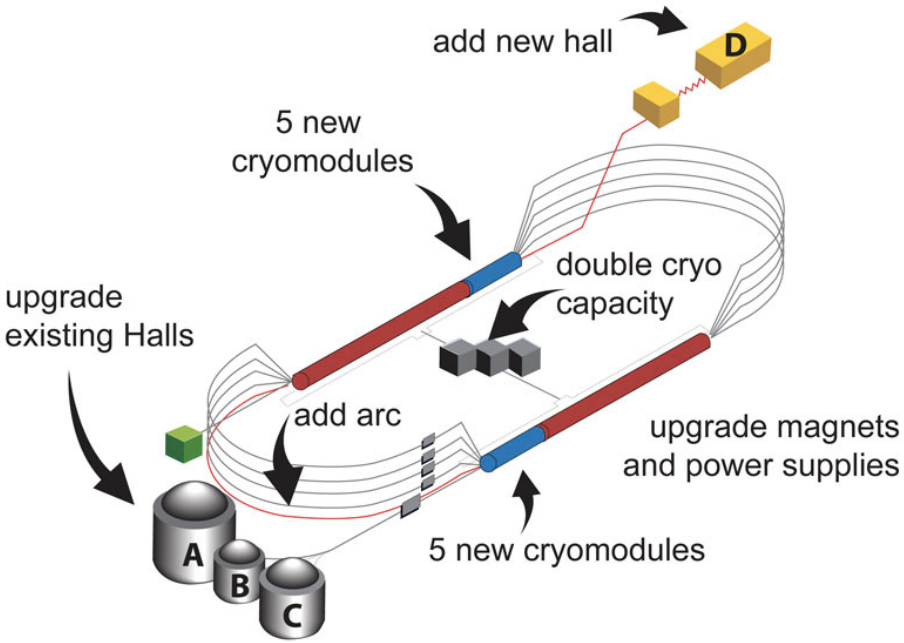
Confinement of quarks and gluons within hadrons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of hadrons is still limited.



Hall D

May 2014



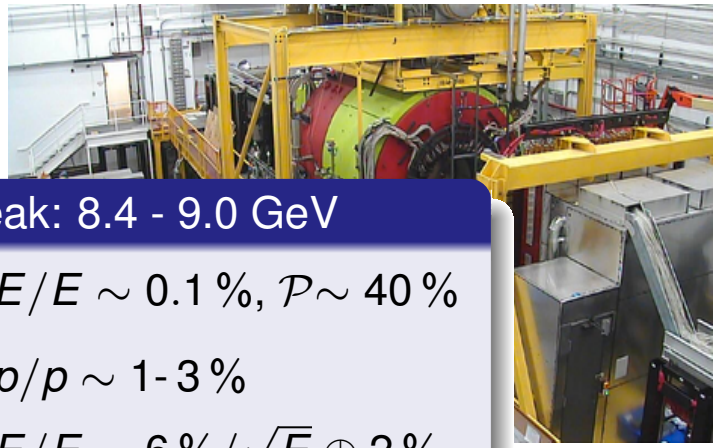


Jefferson Lab Upgrade to 12 GeV

- 10.1 GeV achieved, Fall 2014
- Hall D complete

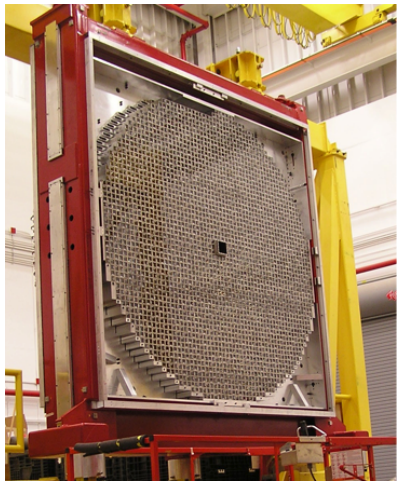
Barrel CALorimeter (BCAL):
48 4-m long modules

2.0 T superconducting solenoid



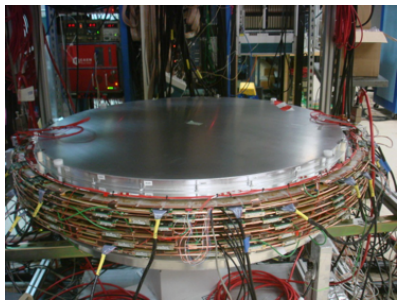
Coh. Peak: 8.4 - 9.0 GeV

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



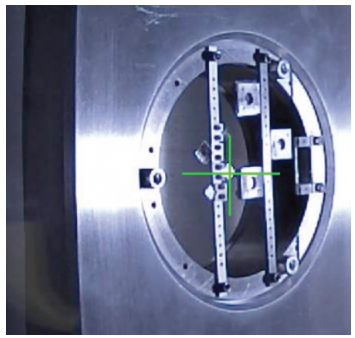
FCAL: 2800 lead glass blocks

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

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.

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

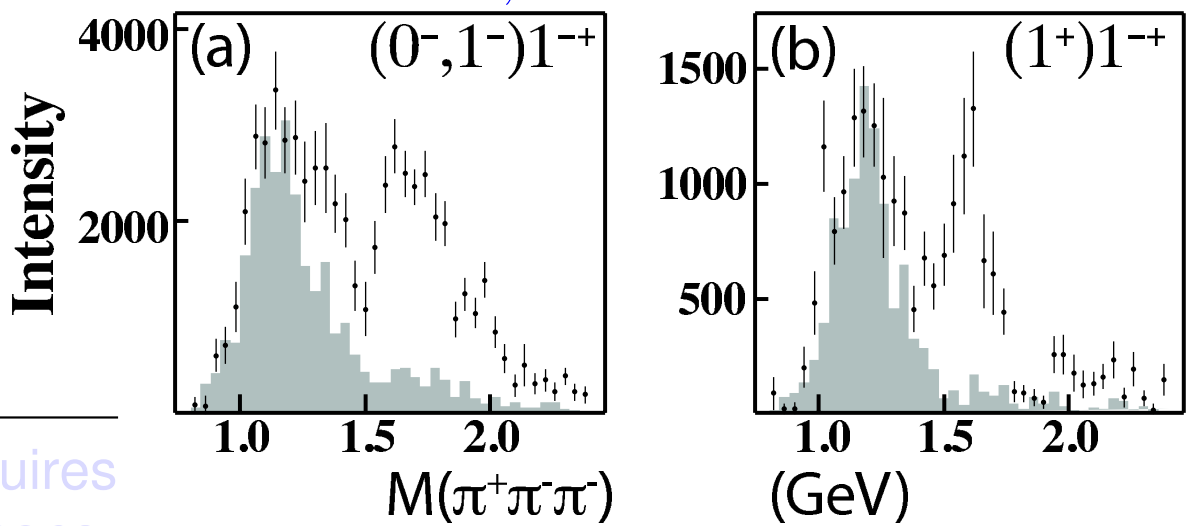
$\pi(1600) \to \rho\pi$
$(\text{E852} : \pi^- p \to \pi^+ 2\pi^- p)$

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

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

➜ Better understanding requires a spectrum of hybrid mesons.

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



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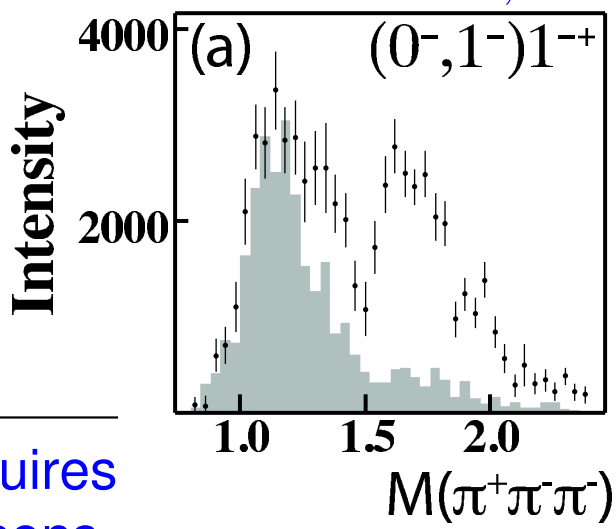
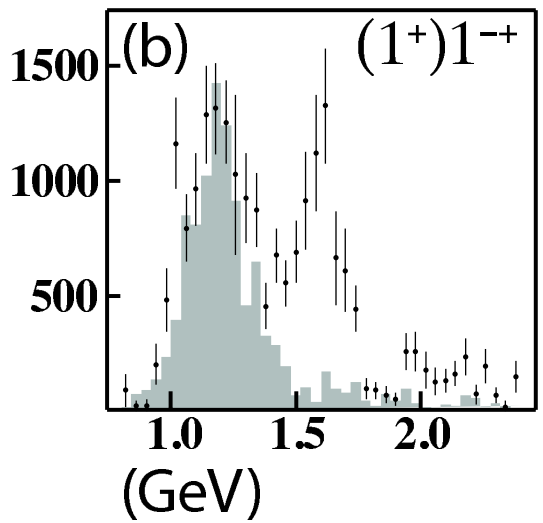
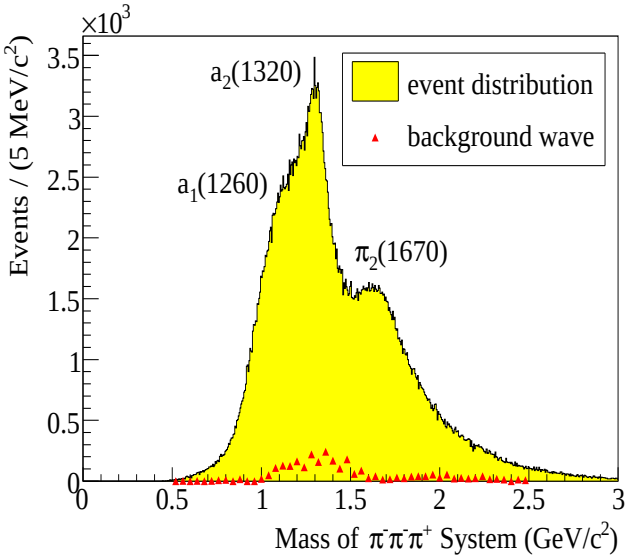


$M^\epsilon = 1^+$

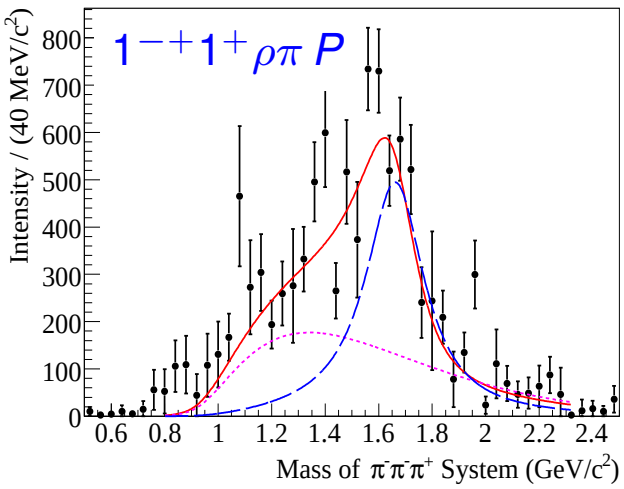


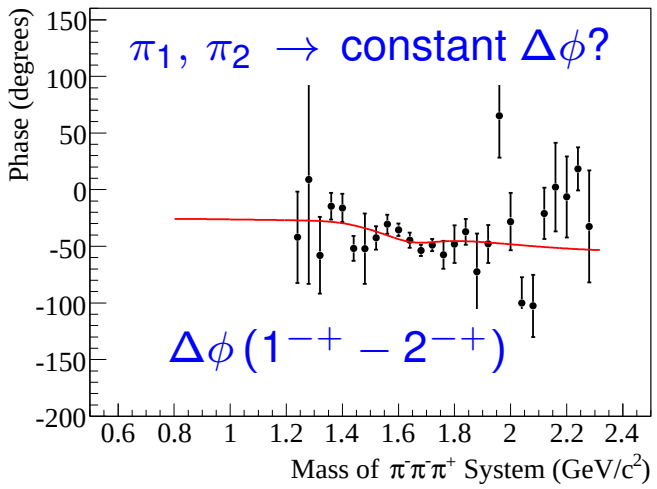
COMPASS Experiment (1): $\pi^- Pb \to \pi^-\pi^-\pi^+ (Pb)$

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



1^{-+} Exotic Wave





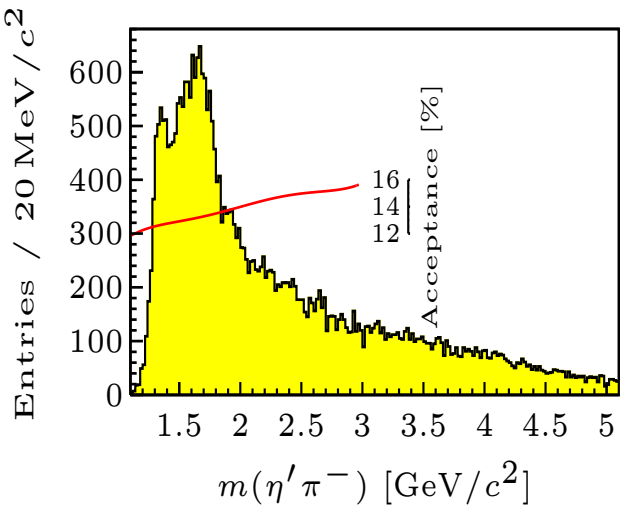
Based on $\sim 420,000$ events using a 180 GeV π beam:

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

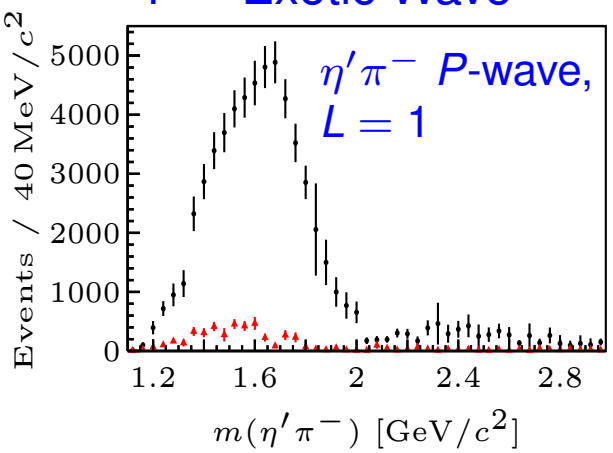
➜ Exotic 1^{-+} wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.

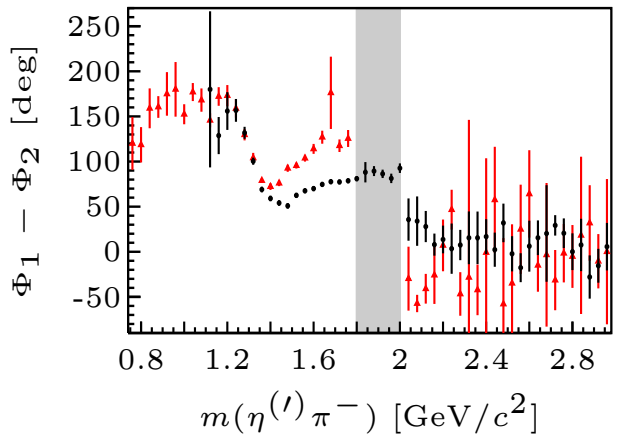
COMPASS Experiment (2): $\pi^- p \to \eta^{(\prime)} \pi^- (p)$

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



1^{-+} Exotic Wave





Collaboration refrains from proposing resonance parameters for exotic P wave.

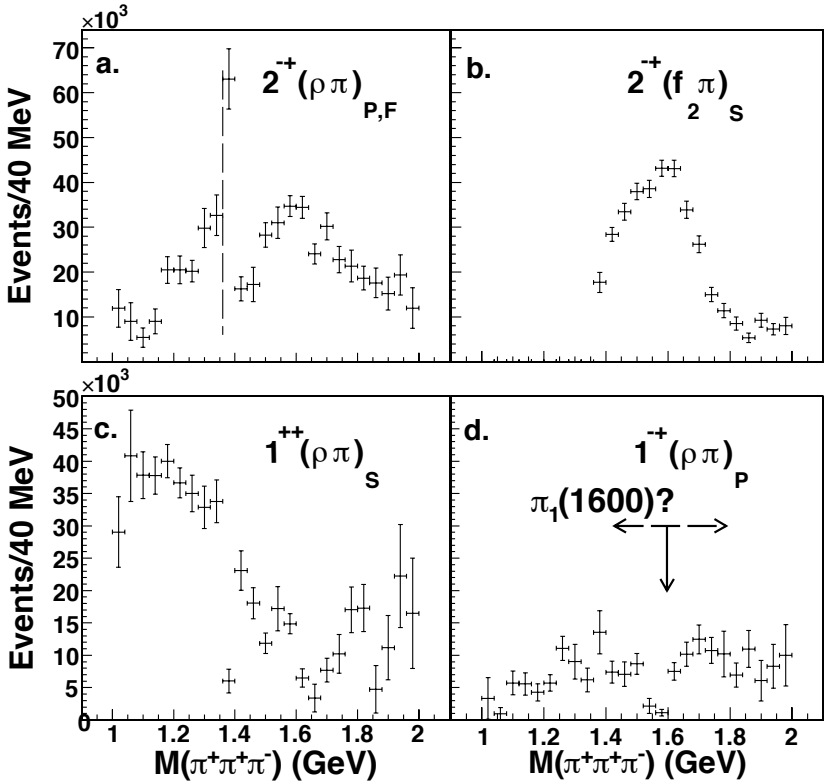
- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).
- Dominant **8** $\otimes$ **8** $(\eta\pi)$ & **1** $\otimes$ **8** $(\eta'\pi)$ nature of $SU(3)$ flavor configurations
  ➜ $gq\bar{q}$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

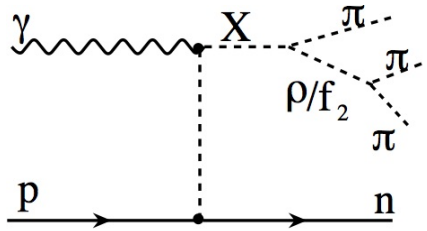
Meson Spectroscopy in Photoproduction: CLAS

Results on light mesons from CLAS at Jefferson Lab

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

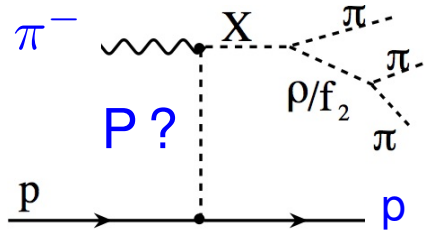
(M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))





charge exchange

CLAS



neutral exchange

E852

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