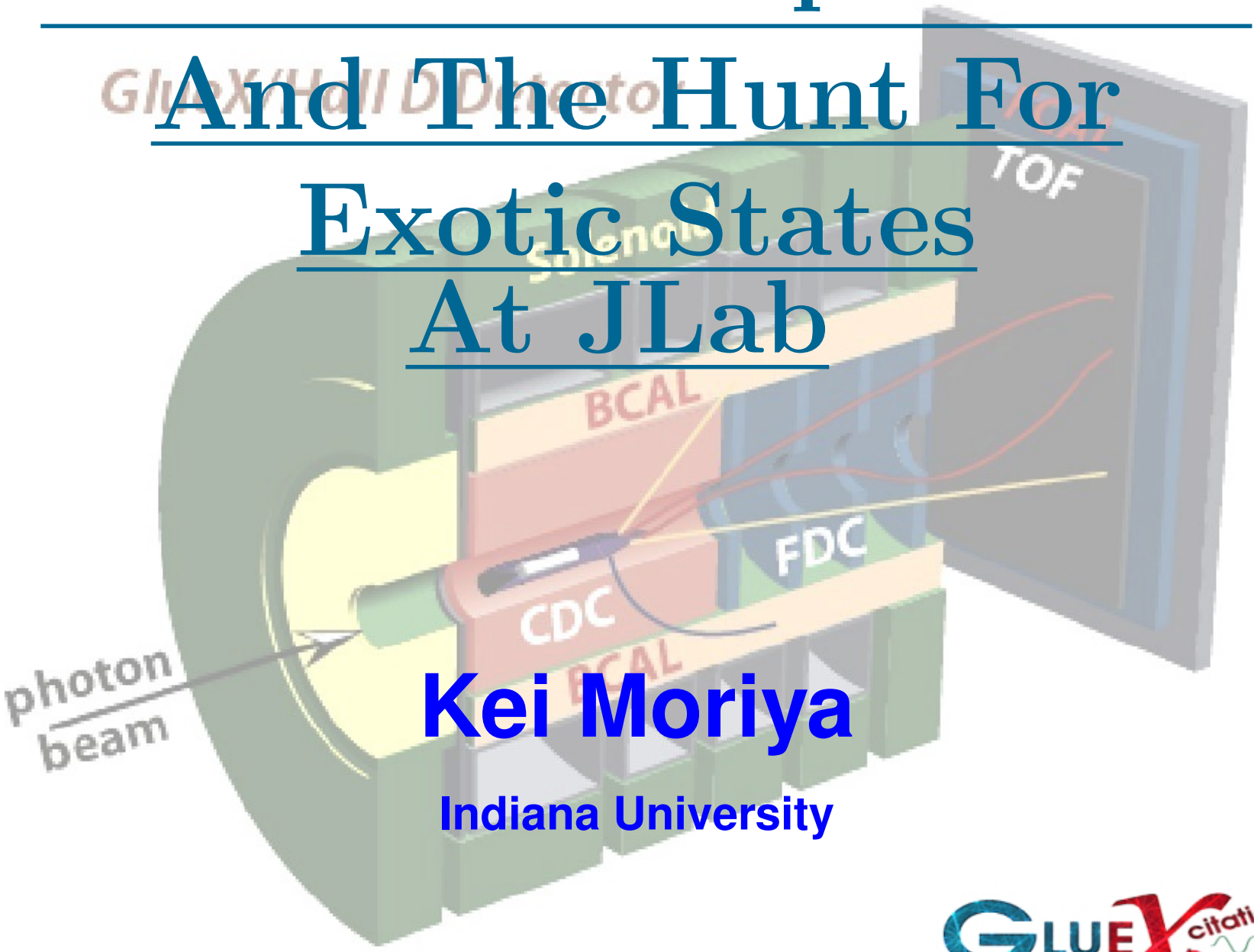
The GlueX Experiment And The Hunt For Exotic States At JLab



Kei Moriya

Indiana University

Outline

Meson Spectroscopy

- Quantum Chromodynamics (QCD) provides the theory of the strong force that acts on hadrons
- At low energies the nature of the strong force leads to confinement, and an abundance of states
- We can classify the meson states by spin (J), parity (P), and charge parity (C)
- "Conventional" $q\bar{q}$ states can have only specific J^{PC} combinations

Question

Can we find states with "exotic" quantum numbers, *i.e.*, states that do not fit into the conventional $q\bar{q}$ model?

The Case For Exotic States

	$S=0$		$S=1$	
L	L: even	L: odd	L: even	L: odd
PC	$-+$	$+-$	$--$	$++$
J	L (even)	L (odd)	$L \oplus 1$	$L \oplus 1$
examples of J^{PC}	0^{-+}			0^{++}
		1^{+-}	1^{--}	1^{++}
	2^{-+}		2^{--}	2^{++}
		3^{+-}	3^{--}	3^{++}
	4^{-+}		4^{--}	4^{++}
		5^{+-}	5^{--}	5^{++}
	6^{-+}		6^{--}	6^{++}

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examples of J^{PC}	0^{-+}	0^{+-}	0^{--}	0^{++}
	1^{-+}	1^{+-}	1^{--}	1^{++}
	2^{-+}	2^{+-}	2^{--}	2^{++}
	3^{-+}	3^{+-}	3^{--}	3^{++}
	4^{-+}	4^{+-}	4^{--}	4^{++}
	5^{-+}	5^{+-}	5^{--}	5^{++}
	6^{-+}	6^{+-}	6^{--}	6^{++}

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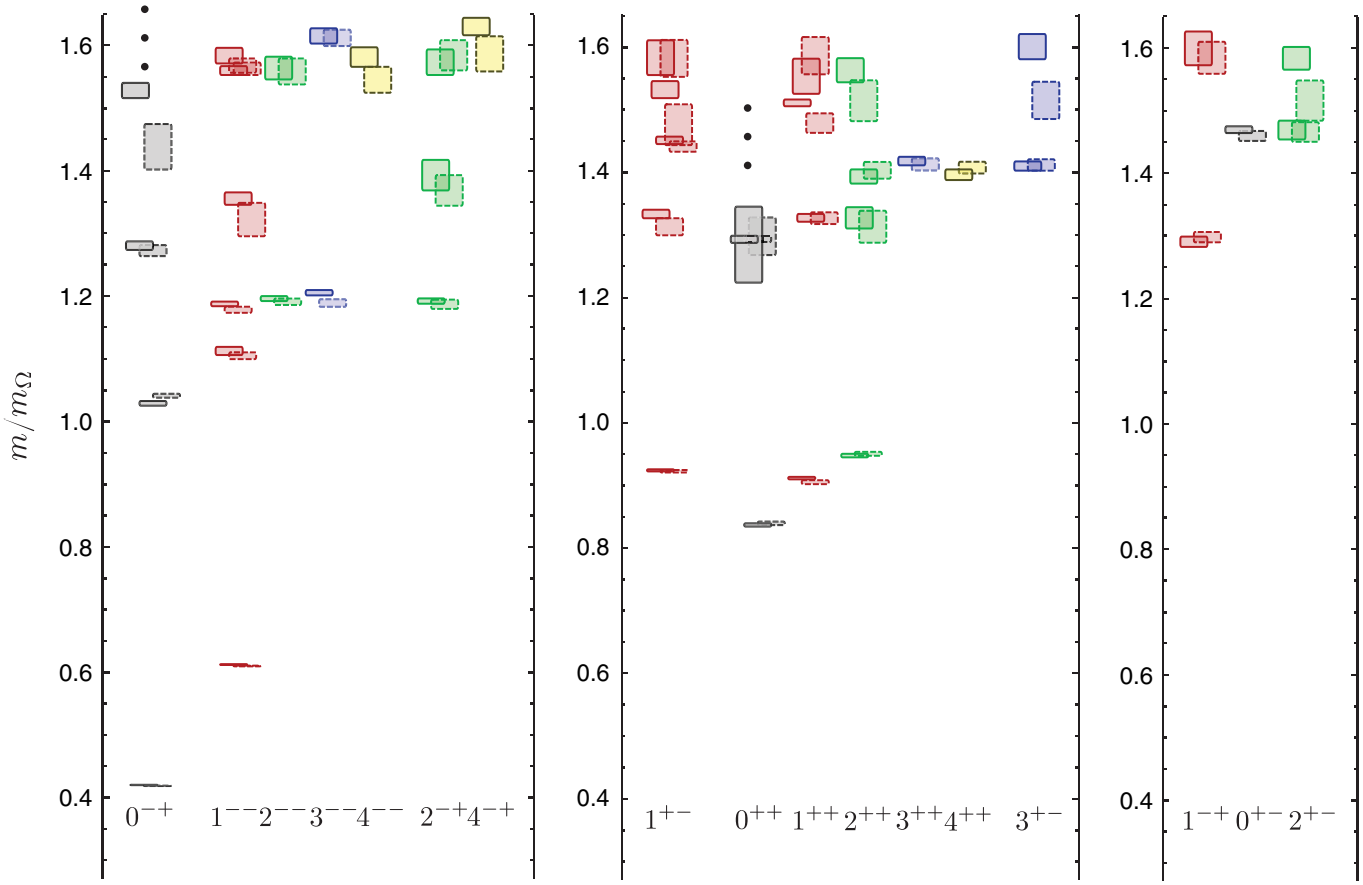
	5^{-+}	5^{+-}	5^{--}	5^{++}
	6^{-+}	6^{+-}	6^{--}	6^{++}

Goal

Observation of states with exotic quantum numbers would be a sure sign of physics not accounted for in the naive $q\bar{q}$ model, and would show the gluonic degrees of freedom in QCD.

Lattice QCD Calculations

- Lattice QCD calculations give support for exotic states with gluonic degrees of freedom
- Calculated spectrum, normalized to $m_\Omega = 1672\mathrm{MeV}$
- unquenched calculation, $m_u = m_d = m_s \sim 700\mathrm{MeV}$



J. Dudek *et al.* (Hadron Spectrum Collaboration), Phys. Rev. D82, 034508 (2010)

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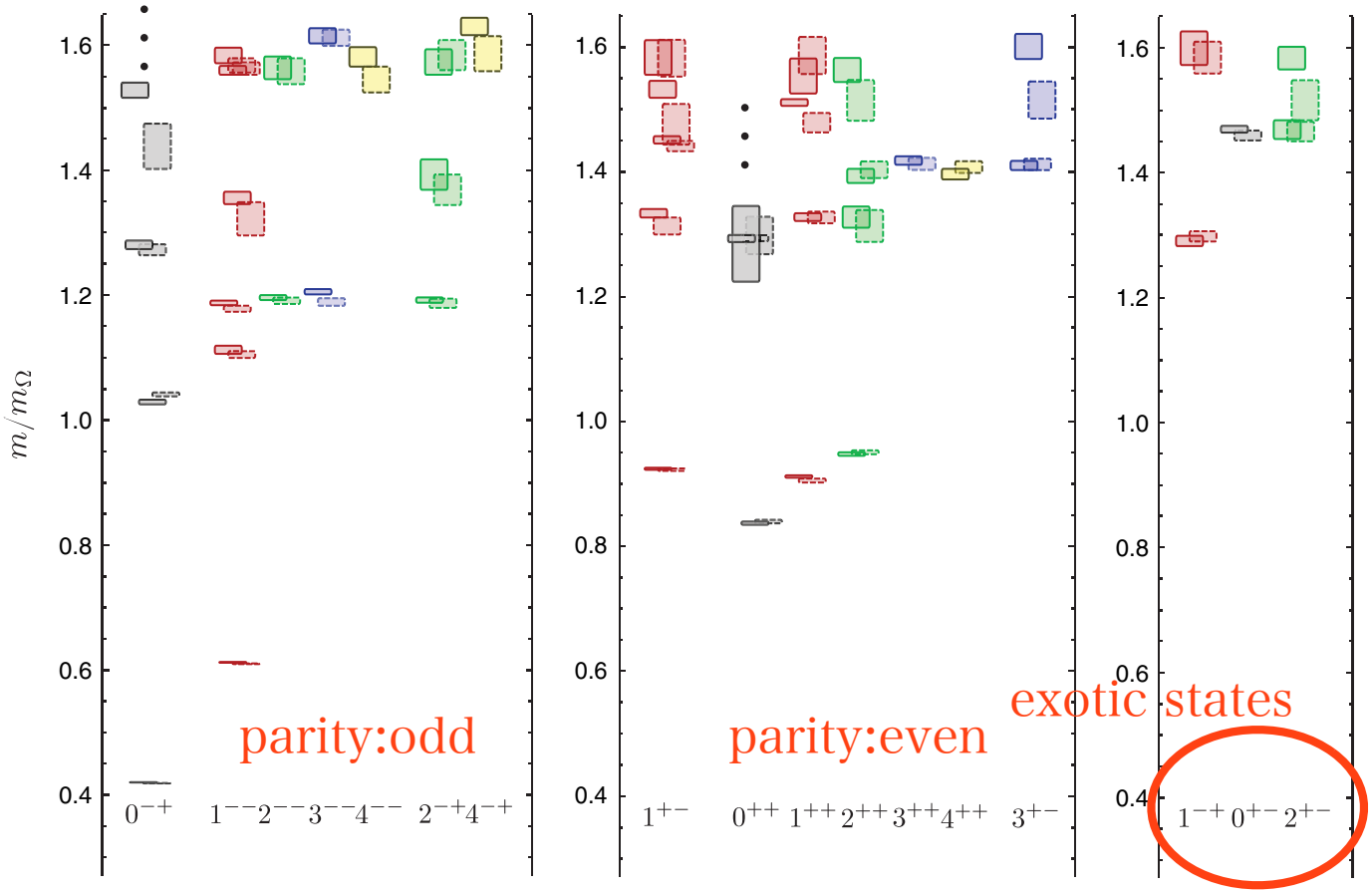
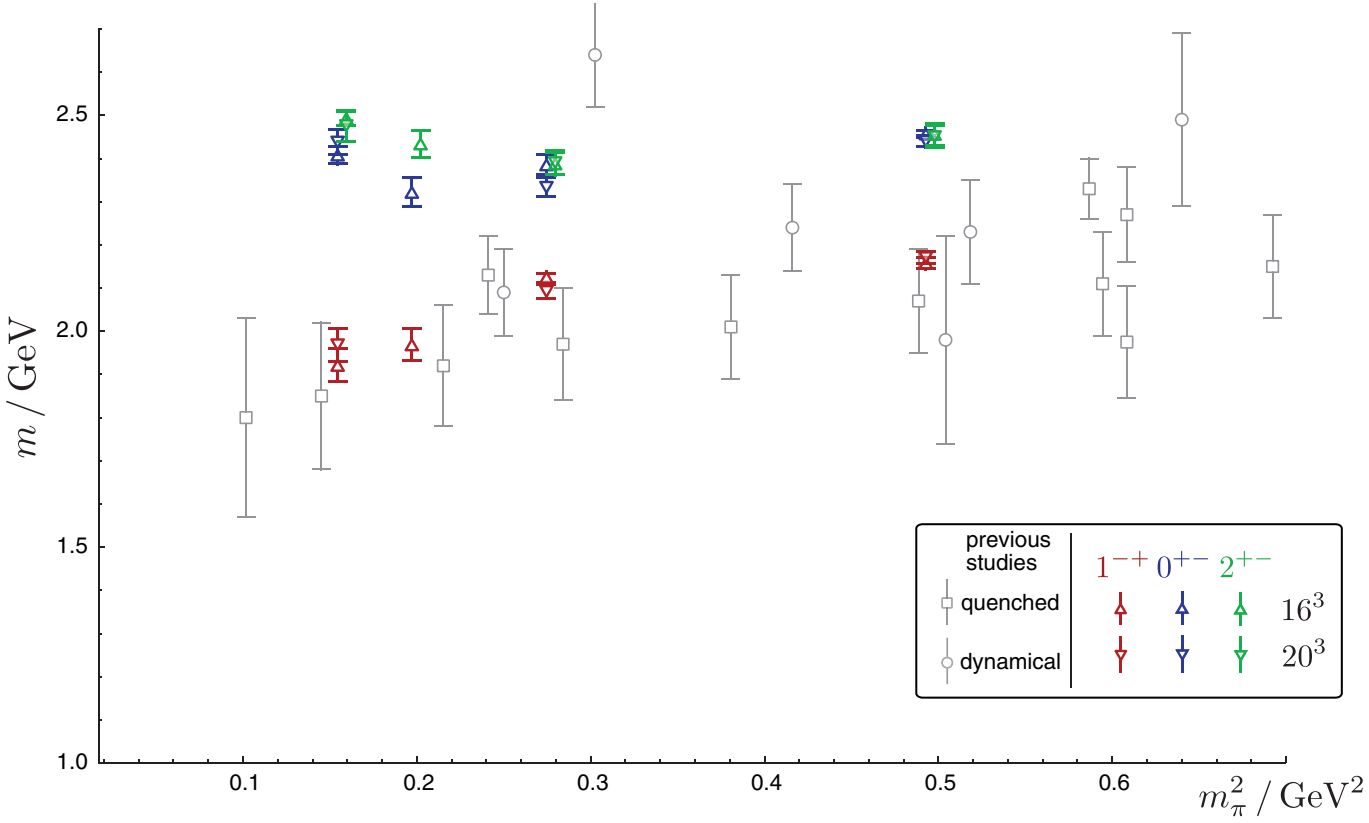


J. Dudek *et al.* (Hadron Spectrum Collaboration), Phys. Rev. D82, 034508 (2010)

Lattice QCD Calculations

- Lattice QCD calculations give support for exotic states with gluonic degrees of freedom
- Exotic 1^{-+} state mass as a function of m_π

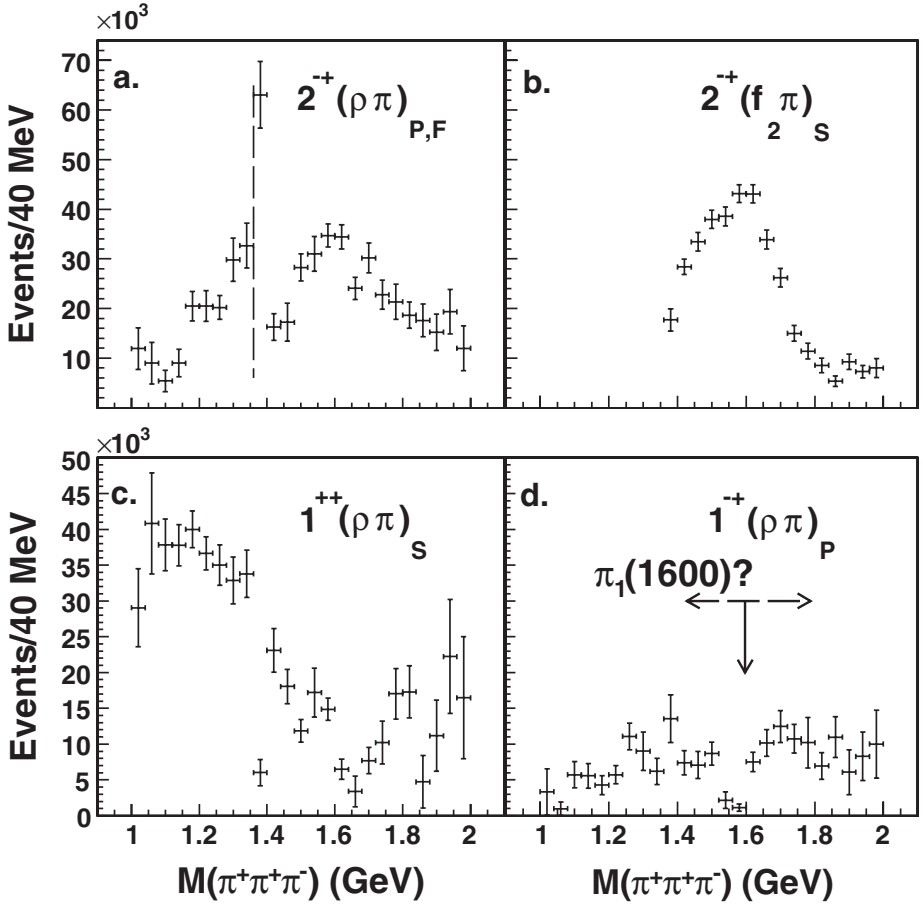


J. Dudek *et al.* (Hadron Spectrum Collaboration), Phys. Rev. D82, 034508 (2010)

For more details, see Jo Dudek's talk: April 29 (tomorrow) 15:10

Experimental Results on Exotic States

- $\pi_1(1600)$
- Strongest candidate for exotic quantum number state ($J^{PC} = 1^{-+}$)
- Seen by several experiments in several production/decay modes
- **not** seen by CLAS (JLab) in $\rho\pi$ P-wave
- 5.7 GeV photoproduction on hydrogen target



M. Nozar *et al.*(CLAS),

PRL 102, 102002 (2009)

Experimental Results on Exotic States

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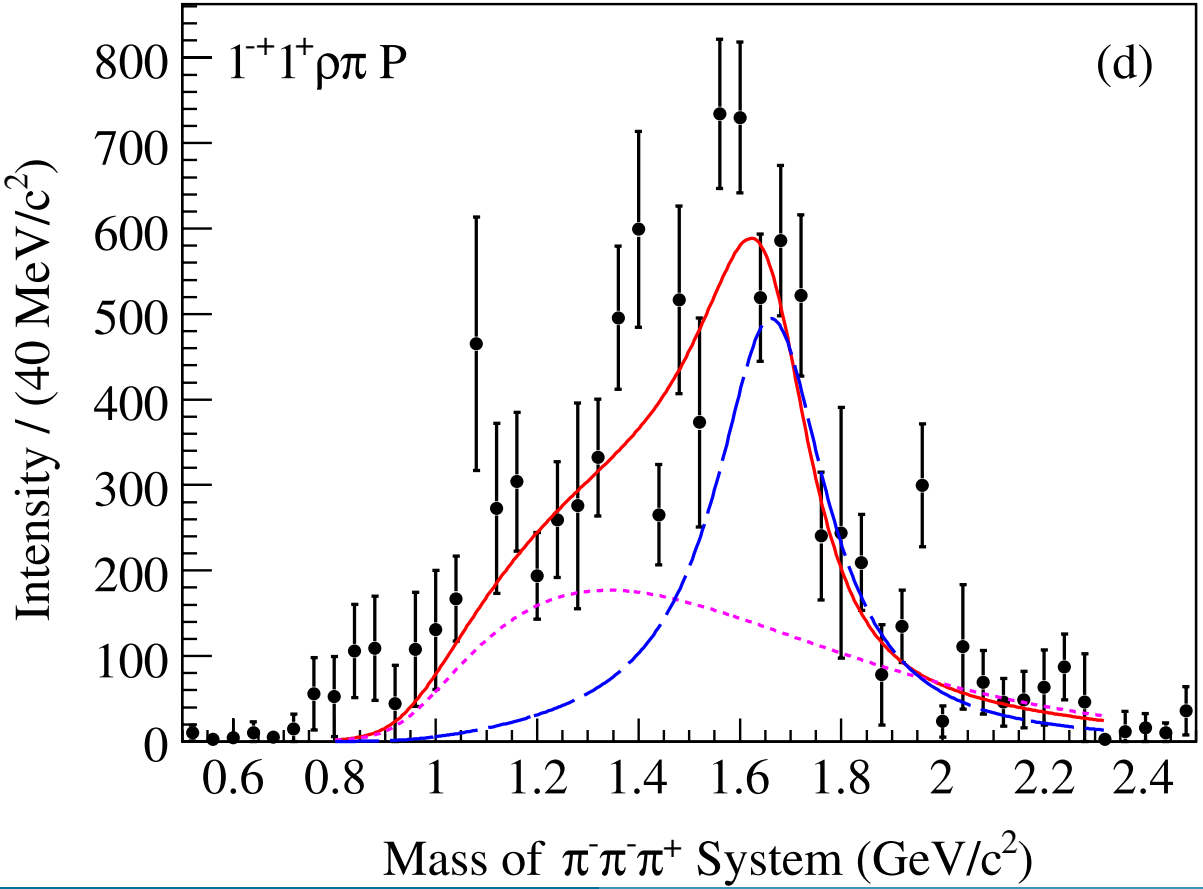
- Strongest candidate for exotic quantum number state ($J^{PC} = 1^{-+}$)
- Seen by several experiments in several production/decay modes
- Seen by COMPASS (CERN) in $\rho\pi$ P-wave
- 190 GeV$/c$ pion beam on a Pb target

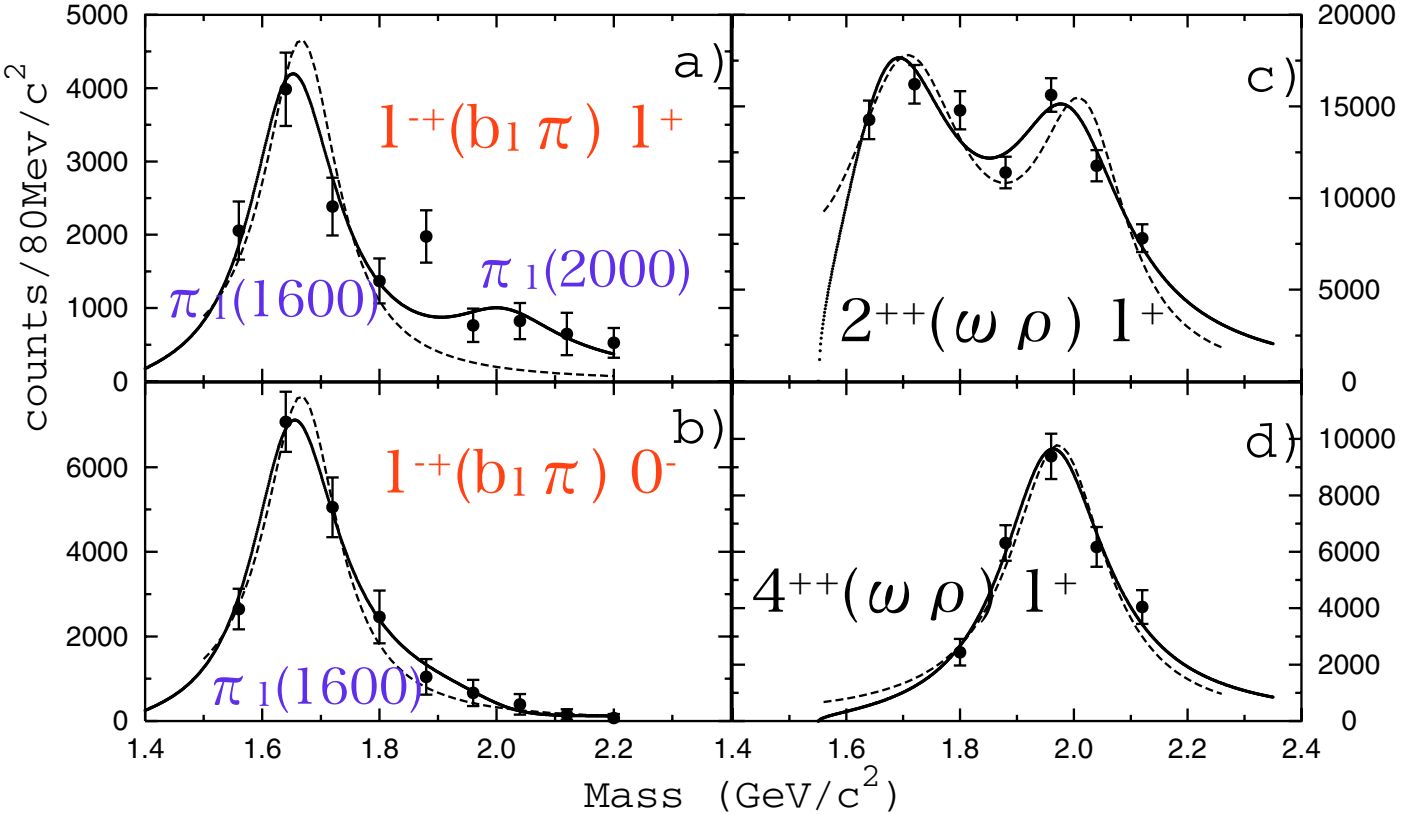


M. G. Alekseev *et al.*(COMPASS),

PRL 104, 241803 (2010)

Experimental Results on Exotic States

- $\pi_1(1400)$
  - Reported by several experiments
  - Mass is lower than that expected from theoretical models
- $\pi_1(2000)$
  - Reported by E852 only, for $f_1(1285)\pi$ and $b_1(1235)\pi$
  - No listing in PDG



M. Lu *et al.*(E852),

PRL 94, 032002 (2005)

Summary of Experimental Results

Some experimental evidence for exotic states, with varying degrees of confidence

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If there are exotic states, we would expect many more of them

- Partners within the same 1^{-+} nonet
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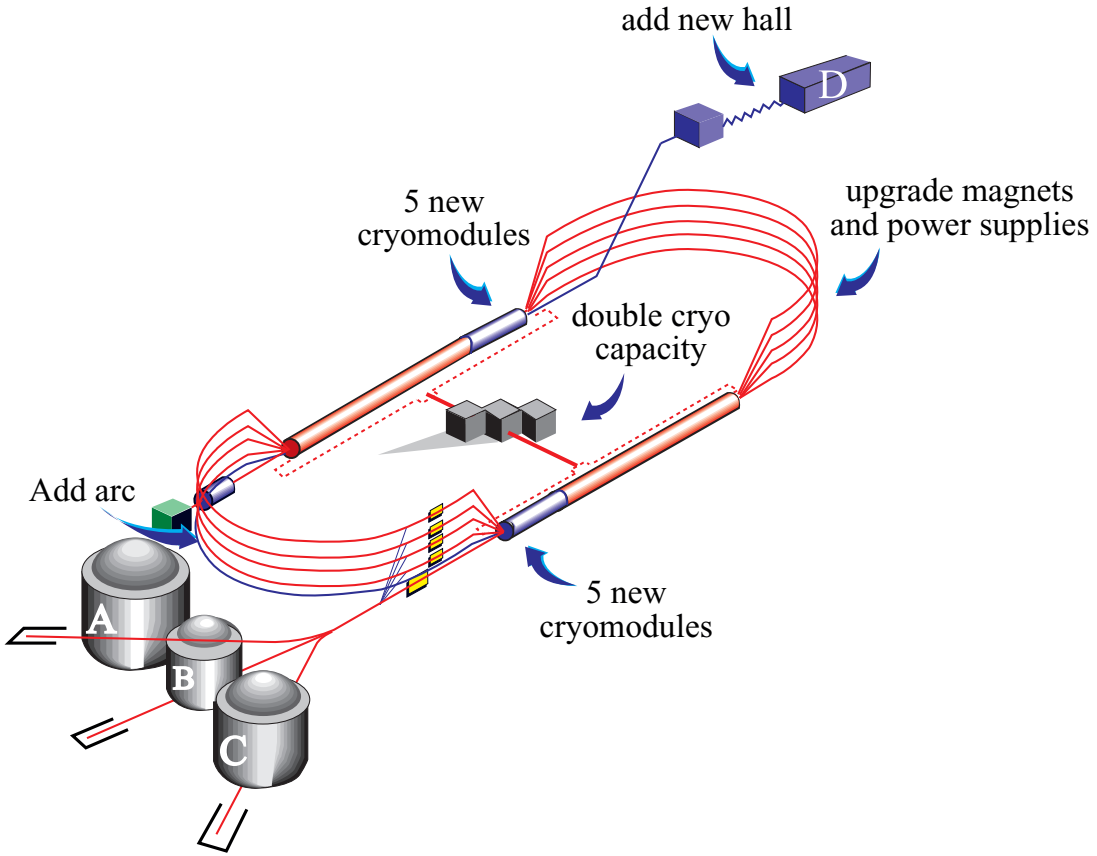
- Other exotic J^{PC} states

More experimental data needed to clarify the situation

GlueX will have extremely high statistics with good acceptance over the predicted range of exotic masses

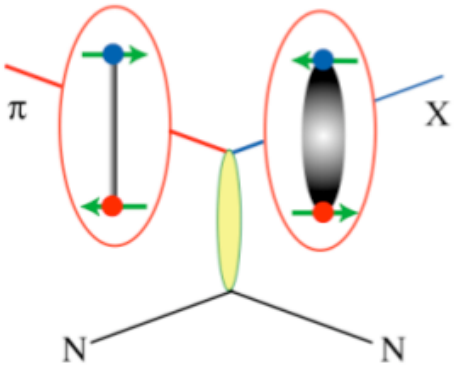
GlueX at JLab

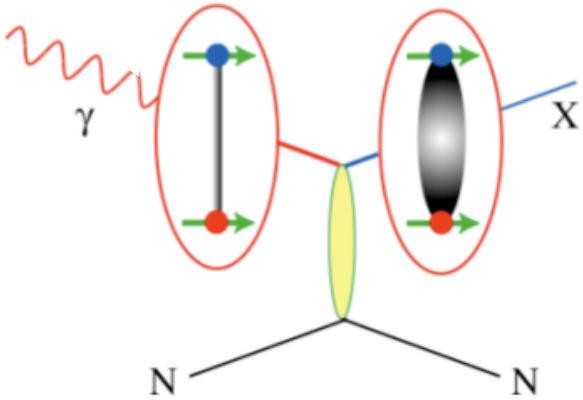
- The GlueX Experiment will be carried out in Hall D of Jefferson Lab, located in Newport News, VA
- Maximum 12 GeV electron beam, polarized
- 10^{7-8} photons/s, extremely high statistics
- High, uniform acceptance for multi-particle final states



Why Photoproduction?

- Phenomenological models predict that photon interactions will have much higher cross sections for hybrids than pion production
- Flux tube model





pion production – requires spin-flip of quark and excitation of flux tube
$\Rightarrow$ suppression $\sigma_{\text{exotic}} \ll \sigma_{\text{non-exotic}}$

photoproduction – photon can be regarded as virtual $q\bar{q}$ pair with spins aligned, so no need for spin-flip
$\Rightarrow \sigma_{\text{exotic}} \sim \sigma_{\text{non-exotic}}$?

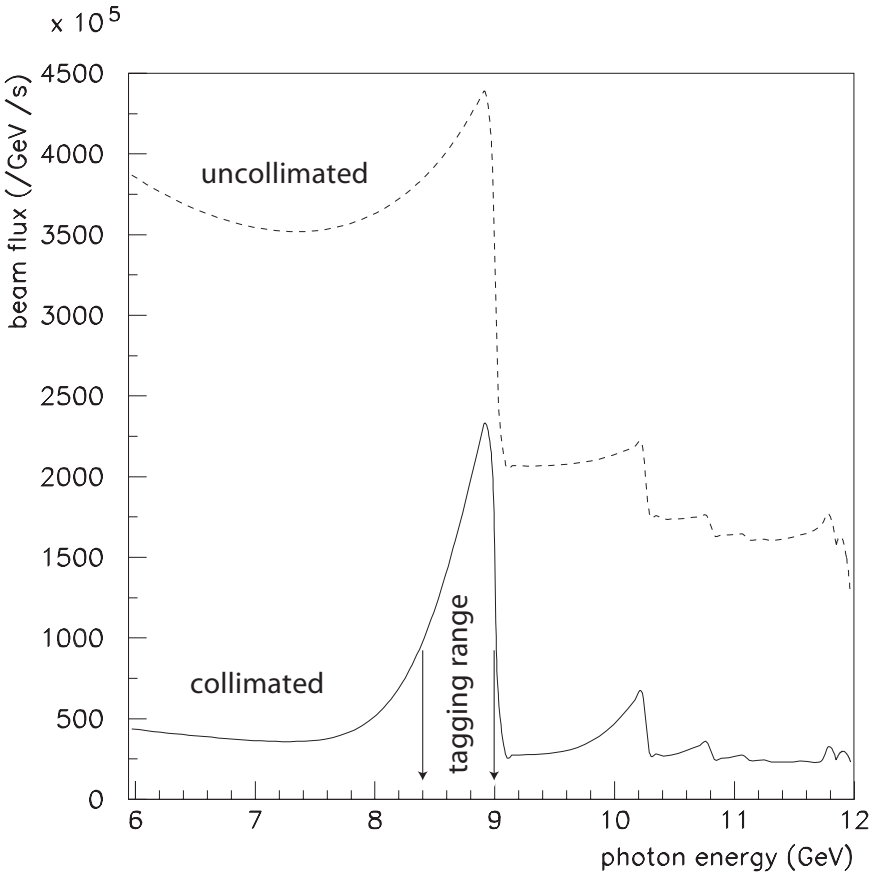
- More detailed Regge model calculations show that $\sigma_{\text{exotic}} \sim 0.50$–$1.00\ \sigma_{\text{non-exotic}}$ is possible

A. Szczepaniak Phys. Lett. B516, 72

The Photon Beam

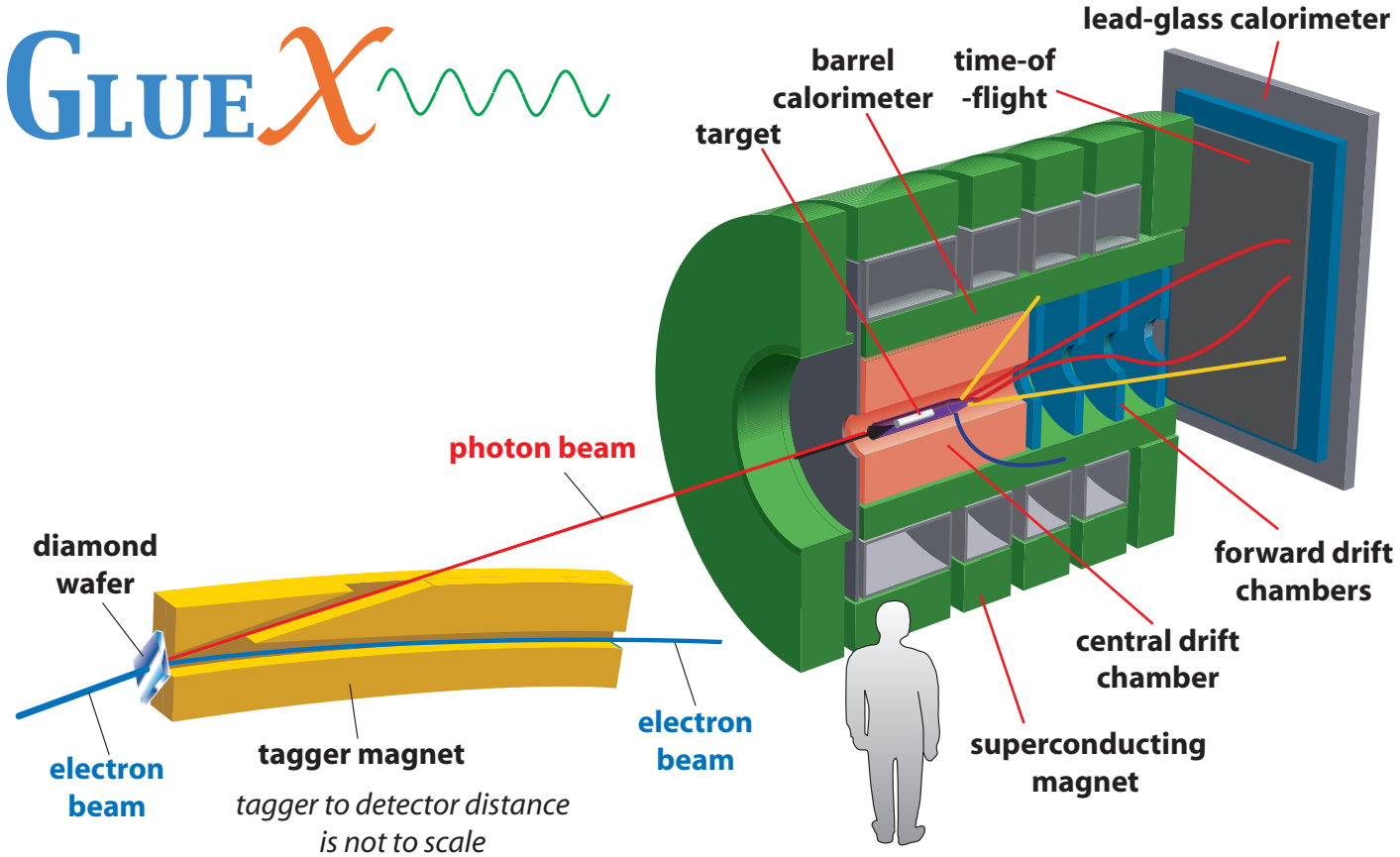
- GlueX will have a highly collimated, linearly polarized photon beam to allow an amplitude analysis
- Produced by coherent bremsstrahlung off of thin diamond wafer radiator
- Maximize kinematic coverage in region of interest

- Expected photon energy spectrum
- Centered at 9 GeV
- Linear polarization $\sim 40\%$



Detector Components

- 2.2 T solenoid magnet
- Tracking with Central Drift Chamber (CDC), Forward Drift Chamber (FDC)
- Timing with Barrel Calorimeter (BCAL), Time of Flight (TOF)
- Calorimetry with BCAL and Forward Calorimeter (FCAL)



Current Hall Status

- Experimental Hall currently under construction
- Data taking to begin in 2014

within the Hall, February 2011

Progress in CDC Construction

- CDC (Central Drift Chamber)
  - 1.5 m long, 1.2 m diameter
  - Coverage of $6°$-$165°$
  - $3,500$ Al-layer mylar straw tubes, 20μm Au-plated tungsten wires
  - Provide hit information with $\sigma_{r\phi} \sim 150\mu\mathrm{m}$, $\sigma_z \sim 1.5\mathrm{mm}$
  - Provide $\mathrm{d}E/\mathrm{d}x$ measurements

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- CDC developed at Carnegie Mellon
- tested with prototype NIM A622, 142 (2010)

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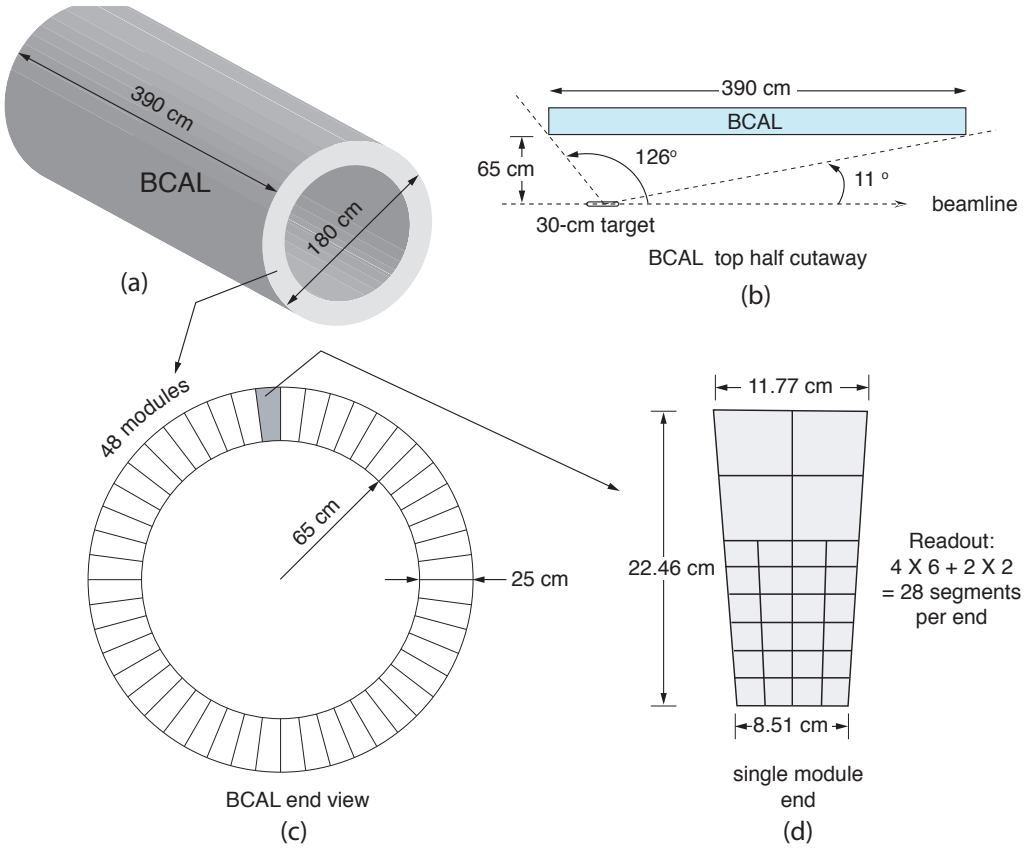
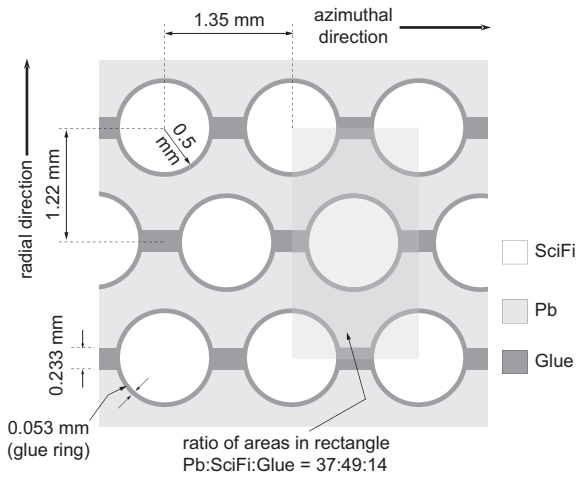
- Half of straw tubes are in place
- Stringing to start this year

Progress in BCAL Construction

- BCAL (Barrel Calorimeter)
  - 3.9 m long, $65/90$ cm inner/outer diameter
  - Coverage of $11°$-$126°$
  - Pb and scintillating fibers
  - Provide timing information and photon detection





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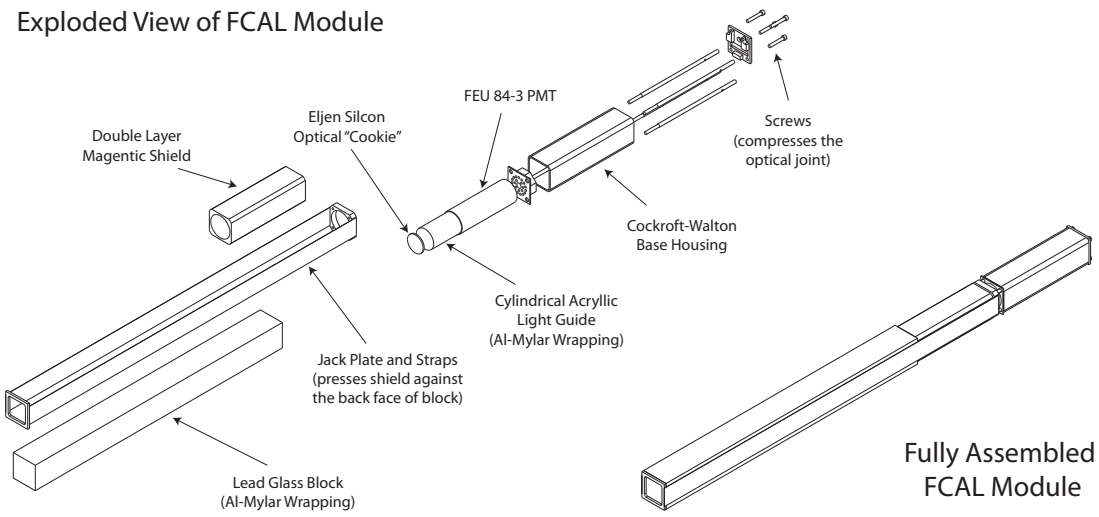
  - Provide timing information and photon detection

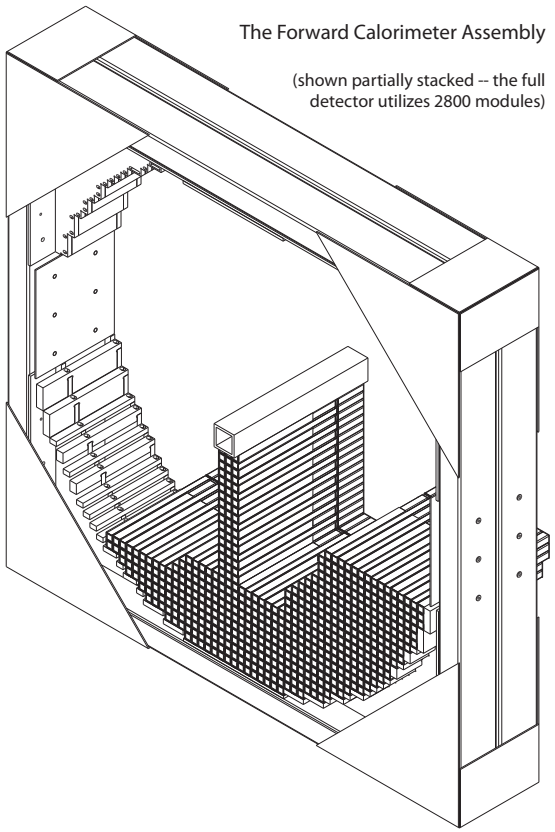
- Being built at University of Regina
- $\sigma_E/E = \frac{5.5\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 2.4\%$
- $\sigma_{\Delta T/2} = \frac{70}{\sqrt{E[\mathrm{GeV}]}}\mathrm{ps}$

  NIM A596, 327 (2008)
- More than half of 48 modules completed
- Magnetic field-insensitive SiPM readouts

Progress in FCAL Construction

- FCAL (Forward Calorimeter)
  - 2.4 m diameter
  - Coverage of $\sim 0.6°$-$12°$
  - Array of $2,800$ $(4 \times 4 \times 45)$ cm lead glass blocks
  - Provide photon detection and timing information
  - flash ADC for fast readout





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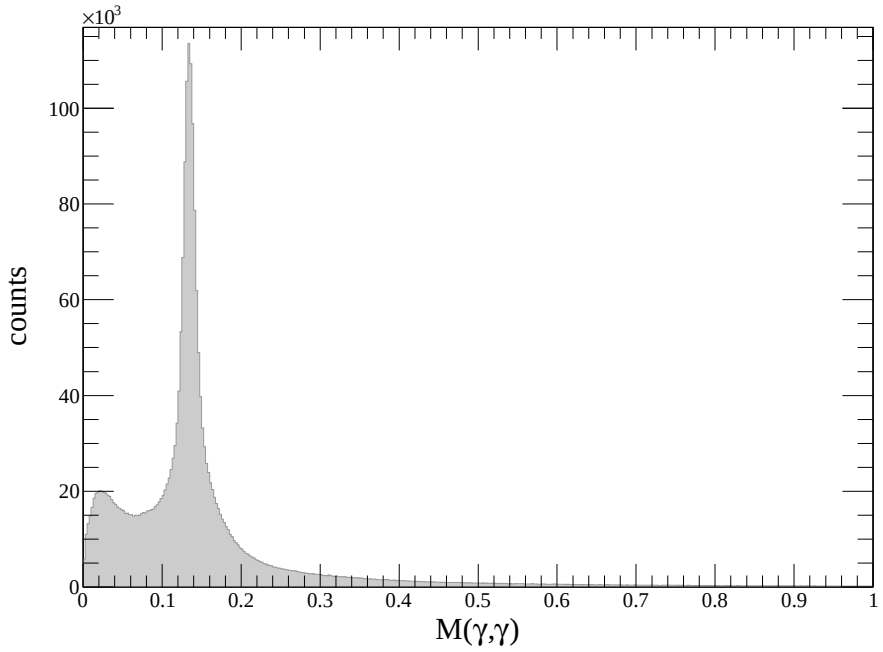
- Being developed at Indiana University
- $\sigma_E/E = \frac{6\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 2\%$
- Preparing for beamtest



reconstructed π^0 mass distribution summed over various angles (MC)

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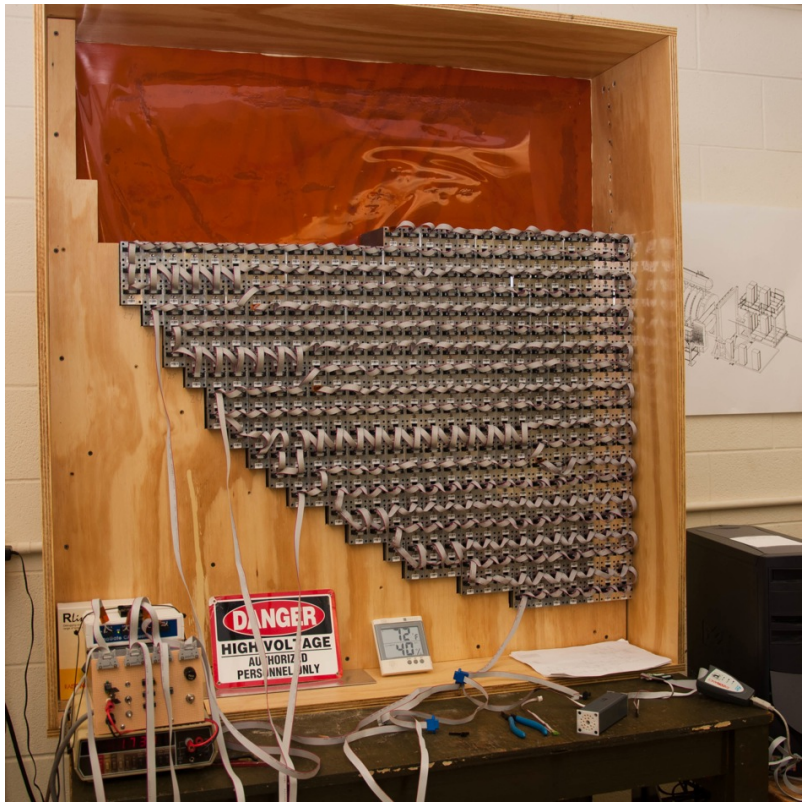
- Timing resolution studied

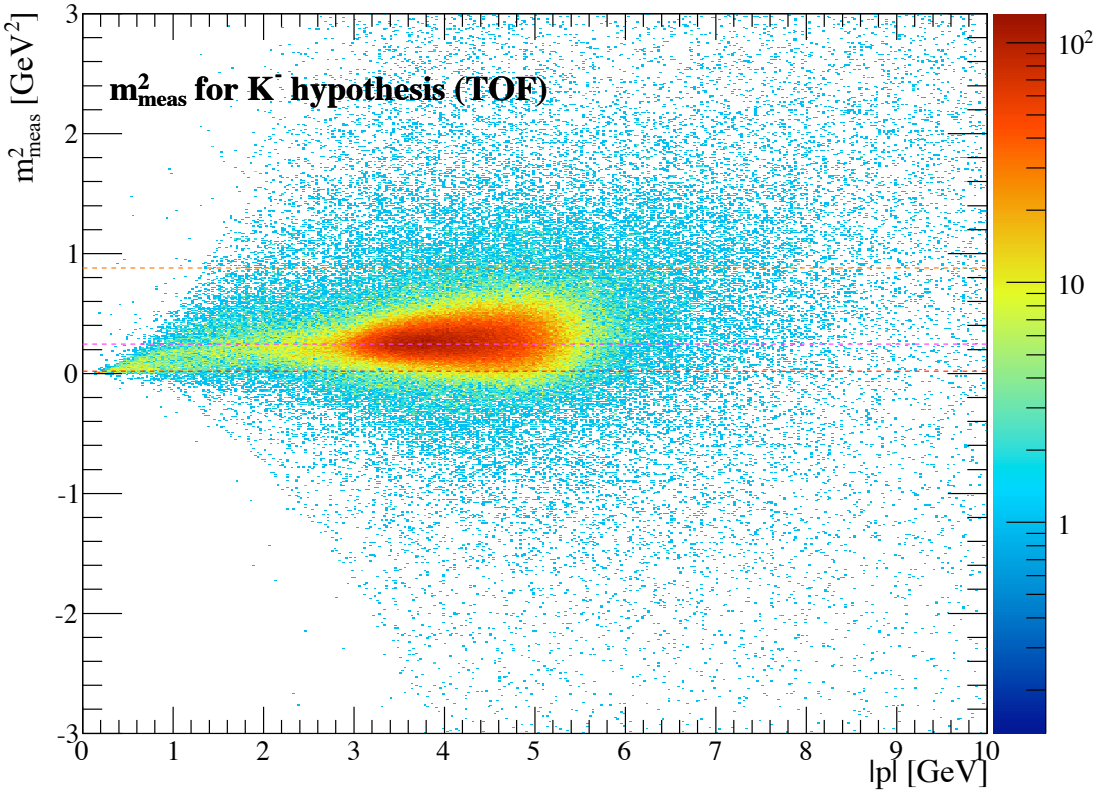
  NIM A622, 225 (2010)
- Radiation damage studies done

  to be submitted to NIM
- Testing and monitoring 500 HV Cockcroft-Walton bases



Analysis Tools

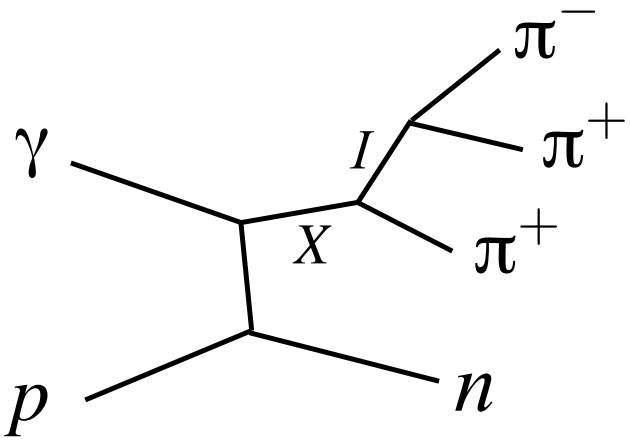
- GlueX will accumulate large statistics on various physics channels
- Need many (new) computational tools to handle requirements
- Full GEANT Simulation
  - Hit level full GEANT-based simulation
  - Currently working on improving PID, tracking errors



Amplitude Tools

- GlueX will accumulate large statistics on various physics channels
- Need many (new) computational tools to handle requirements
- Amplitude Tools
  - To extract exotic amplitudes, a full Partial Wave Analysis is required
  - Analyses will be done at the amplitude level
  - Development of tools to allow writing of amplitudes

$$\begin{aligned}\mathcal{A} \propto & BW_X(M_X, k) \\ & \times BW_I(M_I, q) \\ & \times F_{x,y}(\theta_x, \phi_x, \theta_I, \phi_I, \alpha, k, q)\end{aligned}$$



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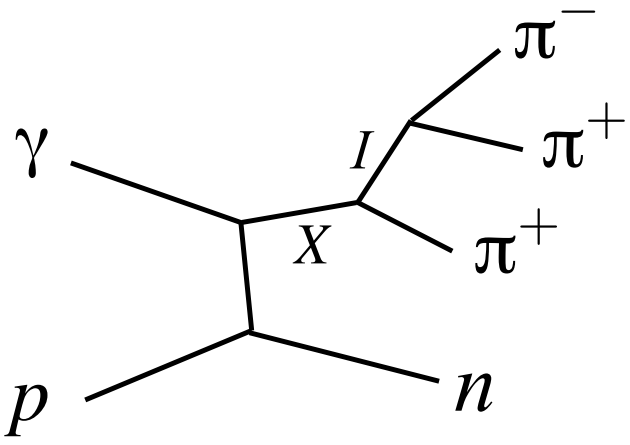

$$\mathcal{A} \propto BW_X(M_X, k) \times BW_I(M_I, q) \times F_{x,y}(\theta_x, \phi_x, \theta_I, \phi_I, \alpha, k, q)$$

Breit-Wigner for resonance

Breit-Wigner for isobar

polarization, angular decays

Computational Tools

- GlueX will accumulate large statistics on various physics channels
- Need many (new) computational tools to handle requirements
- GPUs
  - Graphics Processing Unit — process events in parallel
  - Preliminary tests show improvements in process time of several orders of magnitude
  - Enormous increase in speed of calculating log likelihoods for amplitude analyses

Nvidia TESLA C2070 (448 CUDA cores)

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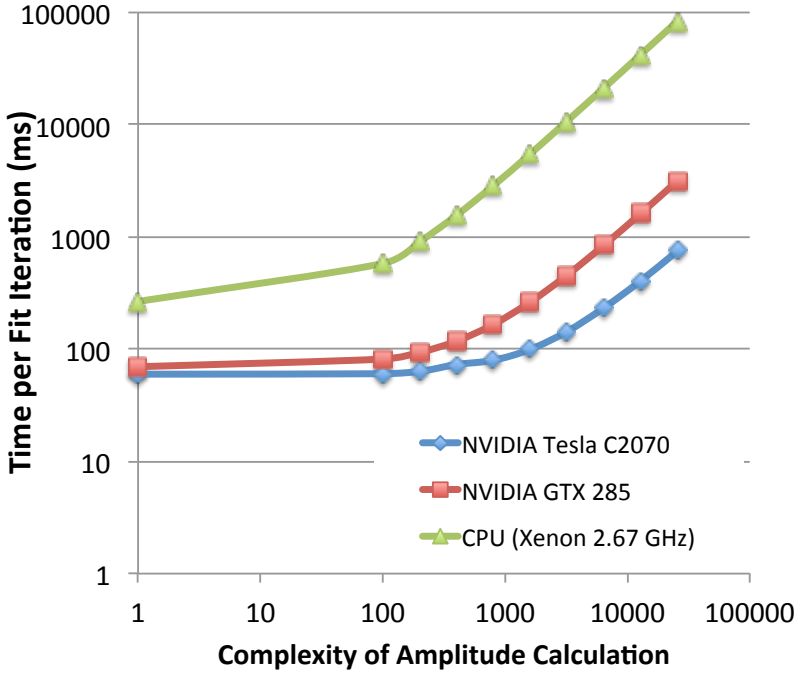
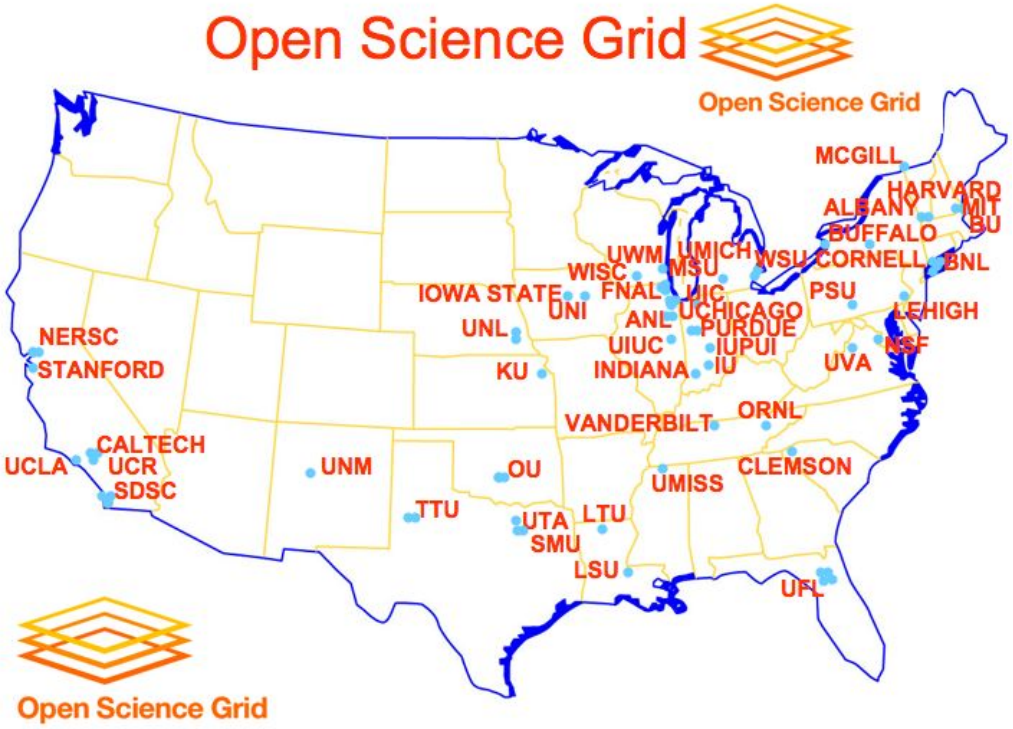


Result of amplitude-level fit using extremely computation-intensive amplitudes

$\Rightarrow$ Real two orders of magnitude speed gain!!

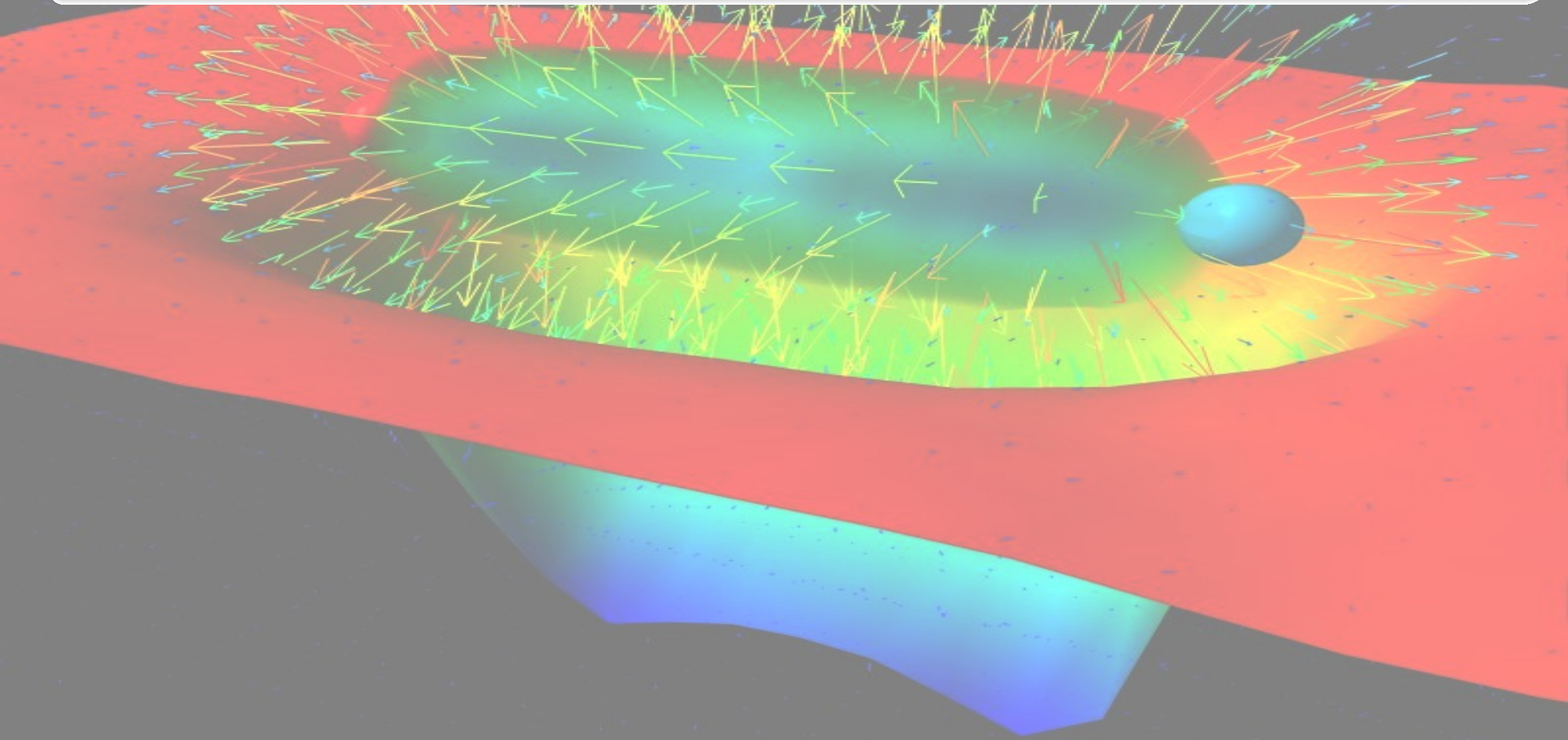
Computational Tools

- GlueX will accumulate large statistics on various physics channels
- Need many (new) computational tools to handle requirements
- Grid Computing
  - Collaborators involved in Open Science Grid (OSG)
  - Now testing with GlueX software
  - Will use to calculate and store background events
  - Necessary to handle large data/background



Conclusion

GlueX will be the first dedicated experiment to search for exotic mesons using photoproduction



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GlueX will provide a rich physics program, with the potential of mapping out not only the spectrum of exotic states, but also other states:

- strange meson/baryon, strangeonium production
- charm meson/baryon production

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- charm meson/baryon production

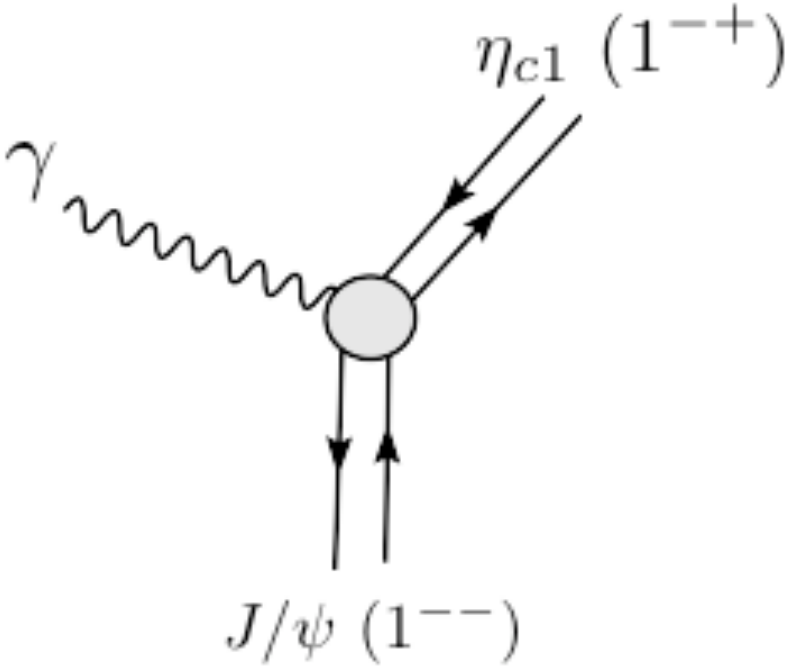
Various hardware and analysis tools are being implemented, so that datataking can start in 2014

References and Links for GlueX

- Websites:
  - Jefferson Lab: http://www.jlab.org/
  - GlueX main webpage: http://www.jlab.org/Hall-D/
- Project Overviews:
  - 2010 PAC update
  - 2006 PAC proposal
- Meson Review Articles:
  - "The Status of Exotic-quantum-number Mesons" C. A. Meyer and Y. Van Haarlem, Phys. Rev. C 82, 025208 (2010) http://link.aps.org/doi/10.1103/PhysRevC.82.025208
  - "The Experimental Status of Glueballs" V. Crede and C. A. Meyer, Prog. Part. Nucl. Phys. 63, 74, (2009) http://dx.doi.org/10.1016/j.ppnp.2009.03.001

Further Lattice QCD Results on Exotics

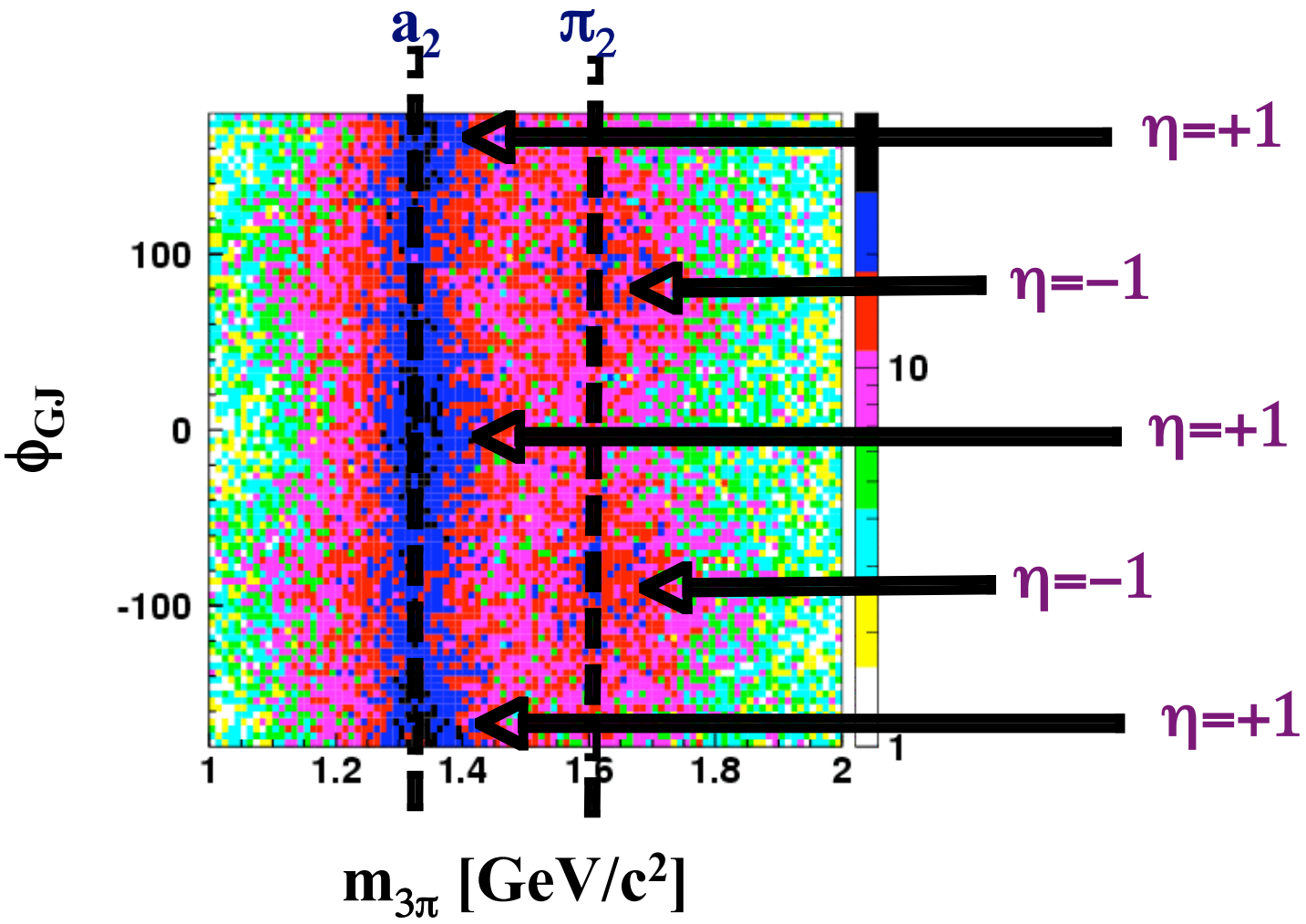
- Lattice Calculations show that
  $\Gamma(\eta_{c1} \to \gamma J/\psi) = 115\text{keV} \gg \Gamma(J/\psi \to \gamma\eta_c) = 2.51\text{keV}$
- Suggests stronger coupling of exotic states to photons
- Extensions to light quarks in progress



J. Dudek *et al.*, PRD79, 094504 (2009)

Effect of Linear Polarization

- Linear polarization of photon beam appears in azimuthal distributions



Expected Statistics of GlueX (1/2)

- Target is 30 cm long $\Rightarrow 1.26[\mathrm{b}^{-1}]$ scattering centers/area
- Assume cross section for wanted reaction is $\sigma[\mu\mathrm{b}]$
- Assume 26 weeks of datataking in 1st year
- Assume $1/3$ efficiency for accelerator/beam/tagger
- Assume rate of 10^7 photons/s
- Raw counts:

$$\begin{aligned} N &= \sigma[\mu\mathrm{b}] \times 1.26[\mathrm{b}^{-1}] \times (5 \times 10^6[\mathrm{sec}]) \times 10^7[\mathrm{s}^{-1}] \\ &= \sigma[\mu\mathrm{b}] \times 6 \times 10^7[\text{raw events/year}] \end{aligned}$$

- In later phases of the experiment, photon flux should increase to 10^8 photons/sec

Expected Statistics of GlueX (2/2)

- Assume trigger is set to reaction of interest
- Assume $\sim 75\%$ acceptance for events (depends strongly on event topology)
- Assume BR of 1 (again depends strongly on channel)
- Reconstructed events:

$$\begin{aligned} n &= N \times \epsilon_{\text{acceptance}} \times BR \\ &= \sigma[\mu\text{b}] \times 6 \times 10^7 \times 0.75 \times 1 \\ &= \sigma[\mu\text{b}] \times 4.5 \times 10^7 \text{events/year} \end{aligned}$$

- $\sigma = 2[\mu\text{b}]$ measured at SLAC for $\gamma p \to \omega p$
  $\Rightarrow \sim 90$M events expected in 1st year of GlueX
- $\gamma p \to (3\pi)^+ n$ has $\sigma \sim 10[\mu\text{b}]$ $\Leftarrow$ primary channel for exotics
  $\Rightarrow \sim \mathcal{O}(100\text{M})$ events expected in 1st year of GlueX

  acceptance will be lower than ωp