Physics Program at Jefferson Lab Hall-D

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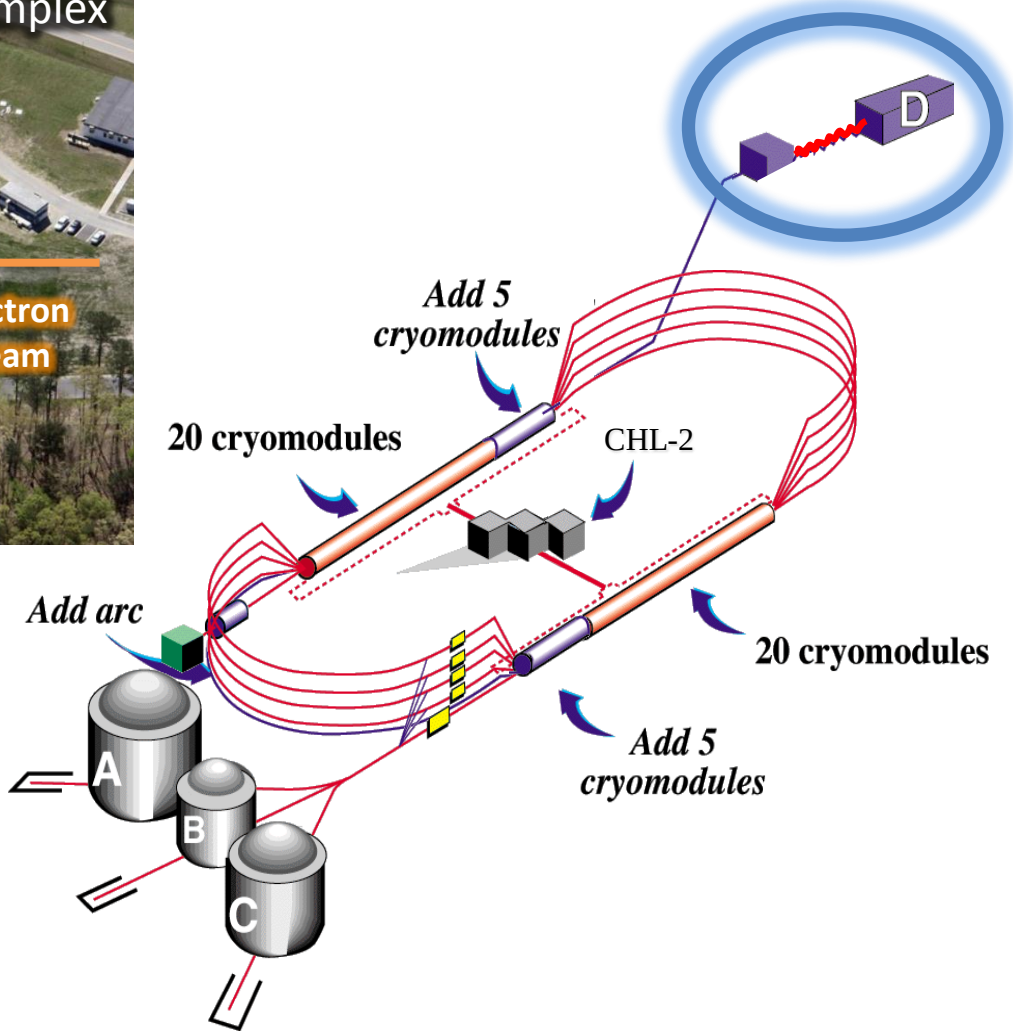
Jefferson Lab

for the GlueX Collaboration

July 3, 2013

Jefferson Lab 12 GeV Upgrade



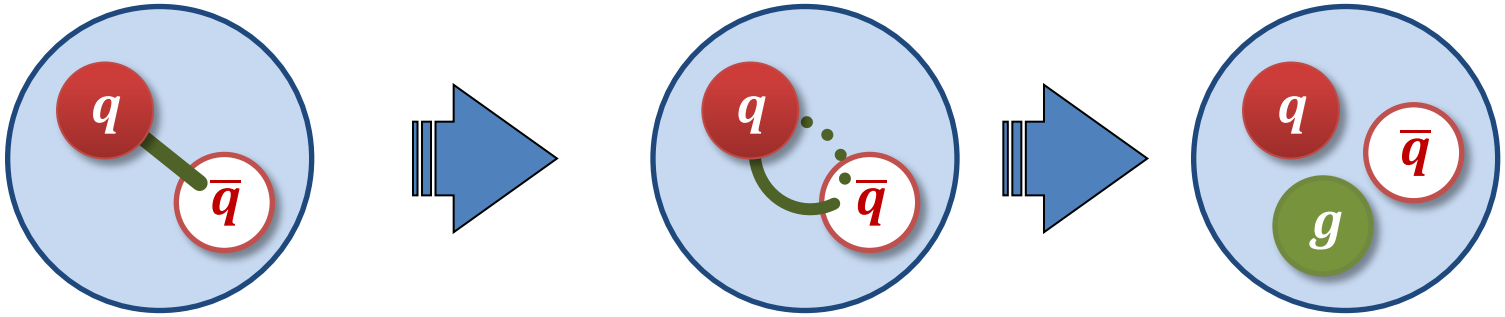
- JLab 12 GeV Upgrade
  - New experimental Hall-D
  - Enhanced capabilities in existing Halls
  - Max beam energy: 12 GeV to Hall-D, 11 GeV to Hall-A/B/C

GlueX Program

Gluon Interactions in QCD

- QCD has interesting properties
  - Confinement: force is strong at large distances
  - Gluon-gluon interactions
- How do these properties exhibit themselves in experimental data?
  - What role do gluons play in the structure of matter?
  - Does QCD predict experimentally observable gluonic excitations?
  - Can we observe evidence for gluonic degrees of freedom in the spectrum of meson states?

Hall-D's Flagship: GlueX Program



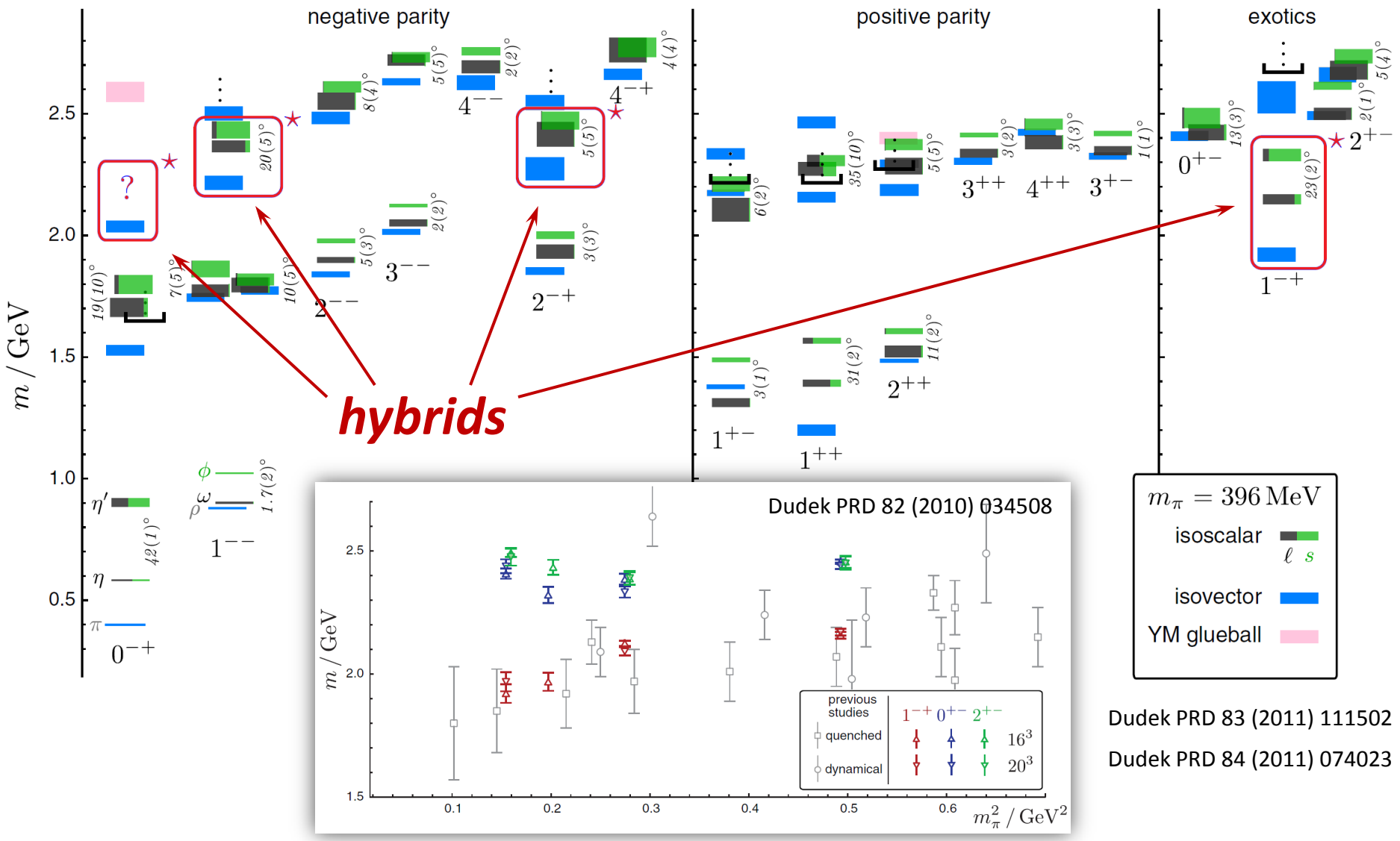
- Conventional meson has quantum numbers determined only by constituent quarks:

$$S = S_1 + S_2$$
$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

- Possible J^{PC}s: 0^{-+}, 0^{++}, 1^{++}, 1^{+-}, 2^{-+}, 2^{++}

- Gluon excitation introduces additional degrees of freedom
- Hybrid meson has excited gluons as constituent particles
- Multiplets of states expected
- More J^{PC} combinations allowed: 0^{-+}, 0^{++}, $\mathbf{0^{+-}}$, 1^{++}, $\mathbf{1^{-+}}$, 1^{+-}, 2^{-+}, 2^{++}, $\mathbf{2^{+-}}$
- Unique signature: **exotic** states

Lattice QCD Calculations



Dudek PRD 83 (2011) 111502

Dudek PRD 84 (2011) 074023

Lattice QCD Calculations (cont.)

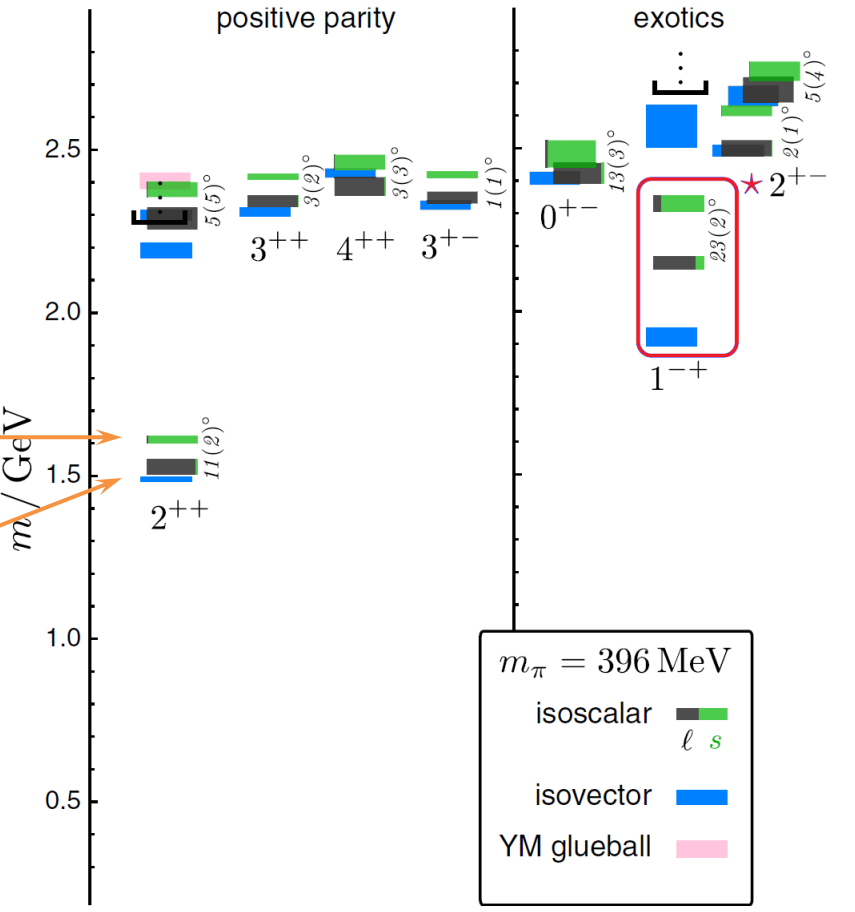
- Lattice QCD predicts quark flavor mixing angles for isoscalar hybrids
- Experimentally, internal quark structure can be inferred by comparing decay modes, for example:

$$\frac{\mathcal{B}(f_2'(1525) \to \pi\pi)}{\mathcal{B}(f_2'(1525) \to KK)} \approx 0.009$$

$$\frac{\mathcal{B}(f_2(1270) \to KK)}{\mathcal{B}(f_2(1270) \to \pi\pi)} \approx 0.05$$

(measured values)

- By studying many decay modes, GlueX may be able to qualitatively validate LQCD predictions



Dudek PRD 83 (2011) 111502

Dudek PRD 84 (2011) 074023

Experimental Evidence for 1^{-+} Exotic Hybrids

$\pi_1(1400)$

$I^G(J^{PC}) = 1^-(1^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates in PDG 06, Journal of Physics, G **33** 1 (2006).

$\pi_1(1400)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1354 ±25 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			

Unlikely hybrid
Dynamical origin, FSI?

$\pi_1(1600)$

$I^G(J^{PC}) = 1^-(1^{-+})$

$\pi_1(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1662^{+8}_{-9} OUR AVERAGE				

May be hybrid
Challenge in 3π from π_2 background
Cleaner η'π signal

$\pi_1(2015)$ $I^G(J^{PC}) = 1^-(1^{-+})$

MASS (MeV)	WIDTH (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$	145k	LU	05	B852	18 $\pi^- p \to \omega \pi^- \pi^0 p$
$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$	69k	KUHN	04	B852	18 $\pi^- p \to \eta \pi^+ \pi^- \pi^- p$

Among "further states"
Needs confirmation

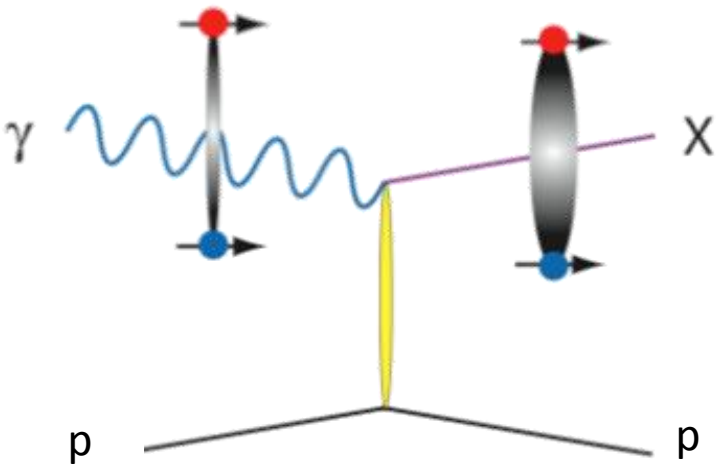
Photo-production of Exotic Hybrids

➢ Photo-production

- The expectation from the flux tube model is that hybrids will be produced at a rate comparable to normal mesons
- Photons have spin-1, allow easier production of exotics compared to pion beams where a spin flip must occur

➢ Photon Polarization

- Polarized photon beam helps determine production mechanism
- Linear polarization put additional constraints on particle quantum numbers through partial wave analysis (PWA)



NPE: $J^P = 0^+, 1^-, 2^+ \ldots$

UPE: $J^P = 0^-, 1^+, 2^- \ldots$

Key Decay Modes of Exotics

	Approximate Mass (MeV)	J^{PC}	Total Width (MeV)		Relevant Decays	Final States
			PSS	IKP		
$\boldsymbol{\pi_1}$	1900	1^{-+}	80 – 170	120	$b_1\pi^\dagger, \rho\pi^\dagger, f_1\pi^\dagger, a_1\eta, \eta'\pi^\dagger$	$\boldsymbol{\omega\pi\pi^\dagger}, \boldsymbol{3\pi^\dagger}, 5\pi, \eta 3\pi^\dagger, \boldsymbol{\eta'\pi^\dagger}$
$\boldsymbol{\eta_1}$	2100	1^{-+}	60 – 160	110	$a_1\pi, f_1\eta^\dagger, \pi(1300)\pi$	$4\pi, \eta 4\pi, \eta\eta\pi\pi^\dagger$
$\boldsymbol{\eta_1'}$	2300	1^{-+}	100 – 220	170	$K_1(1400)K^\dagger, K_1(1270)K^\dagger, K^*K^\dagger$	$KK\pi\pi^\dagger, KK\pi^\dagger, KK\omega^\dagger$
$\boldsymbol{b_0}$	2400	0^{+-}	250 – 430	670	$\pi(1300)\pi, h_1\pi$	4π
$\boldsymbol{h_0}$	2400	0^{+-}	60 – 260	90	$b_1\pi, h_1\eta, K(1460)K$	$\boldsymbol{\omega\pi\pi^\dagger}, \eta 3\pi, KK\pi\pi$
$\boldsymbol{h_0'}$	2500	0^{+-}	260 – 490	430	$K(1460)K, K_1(1270)K, h_1\eta$	$KK\pi\pi^\dagger, \eta 3\pi$
$\boldsymbol{b_2}$	2500	2^{+-}	10	250	$a_2\pi, a_1\pi, h_1\pi$	$4\pi, \eta\pi\pi^\dagger$
$\boldsymbol{h_2}$	2500	2^{+-}	10	170	$b_1\pi, \rho\pi$	$\boldsymbol{\omega\pi\pi^\dagger}, \boldsymbol{3\pi^\dagger}$
$\boldsymbol{h_2'}$	2600	2^{+-}	10 – 20	80	$K_1(1400)K, K_1(1270)K, K_2^*K$	$KK\pi\pi^\dagger, KK\pi^\dagger$

† experimentally promising: few particles or narrow isobars

High priority exotic search channels in initial running

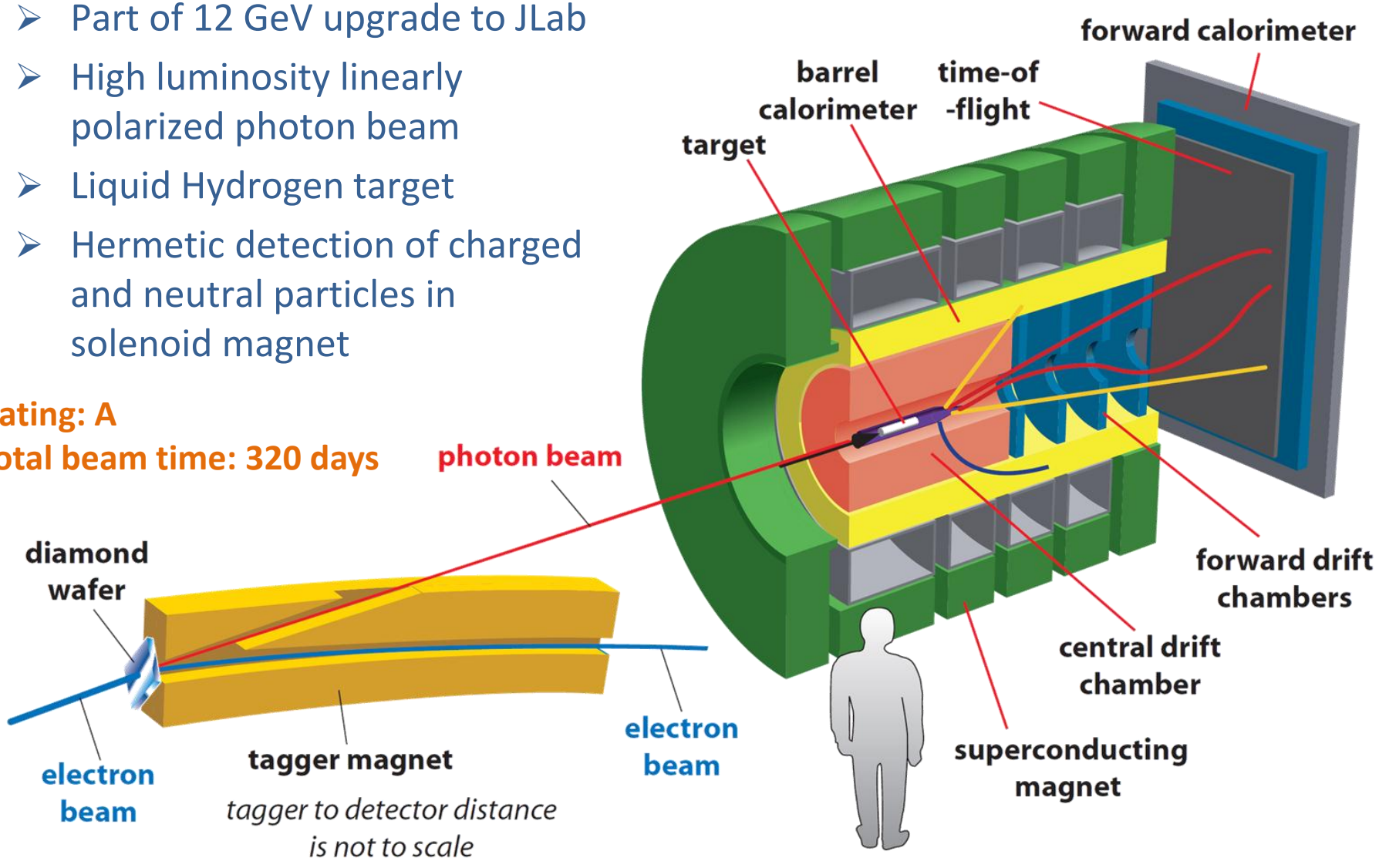
➢ Experiment requirements

- Ability to identify multiparticle final states: charged particles and photons
- High statistics and hermetic detection system
- K/π separation is helpful to identify whole hybrid family

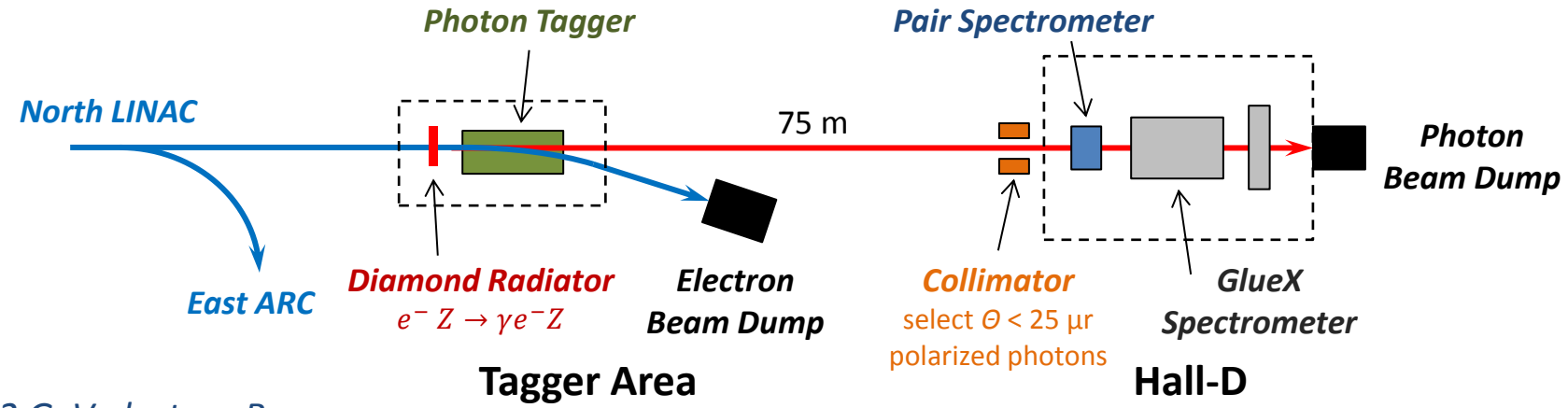
GlueX Experimental Setup

- Part of 12 GeV upgrade to JLab
- High luminosity linearly polarized photon beam
- Liquid Hydrogen target
- Hermetic detection of charged and neutral particles in solenoid magnet

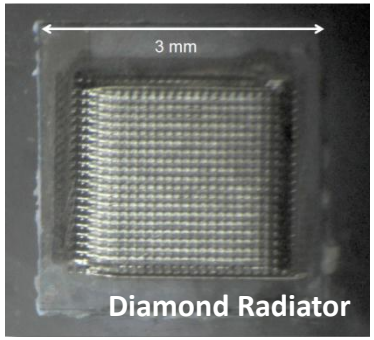
Rating: A
Total beam time: 320 days

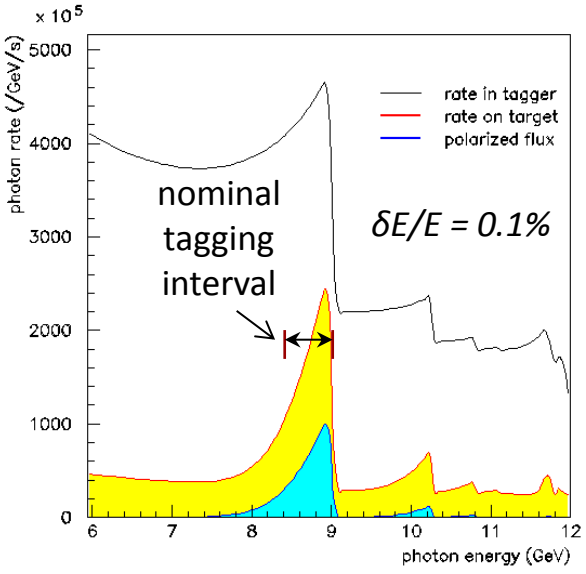


Photon Beam and Tagger



- *12 GeV electron Beam*
- *Coherent Peak @ 9 GeV*
- *M_X up to 2.8 GeV*
- *20 μm diamond radiator*
- *Polarization: 40%*



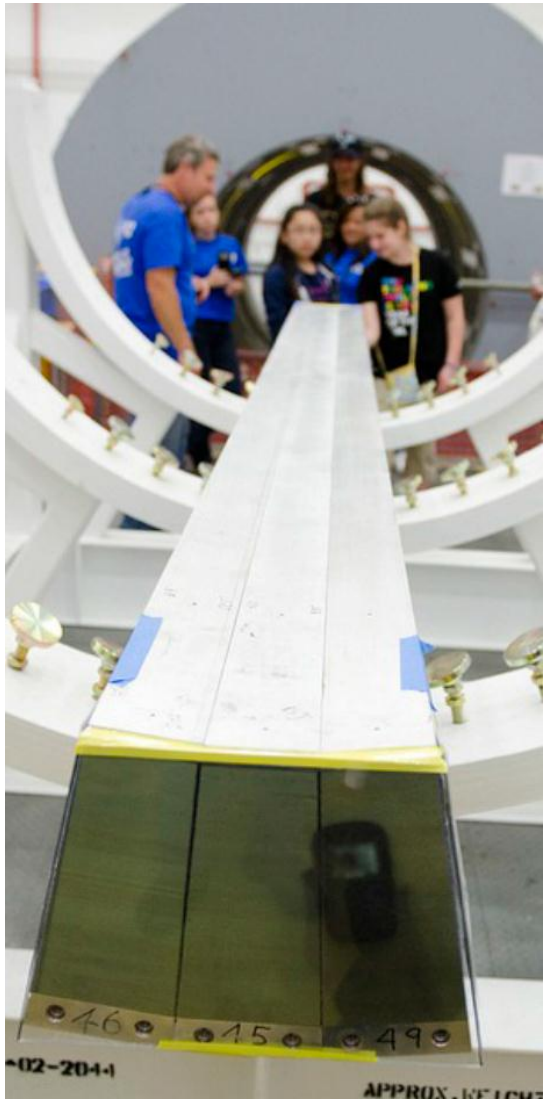


- *Initial photon flux: 10^7γ/s on Target (ΔEγ= 8.4 – 9 GeV)*
- *Design expandable to 10^8γ/s*

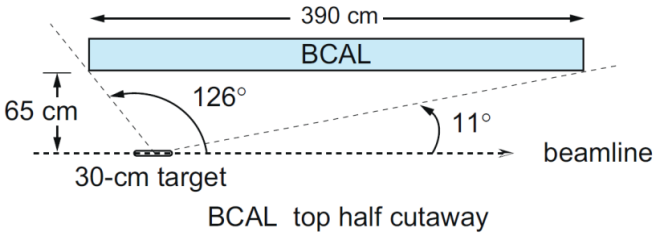
Solenoid: Testing in Progress

- Used for LASS at SLAC, for MEGA at Los Alamos, refurbished for Hall-D
- Bore inner diameter 1.85 m, length 4 m, B_{MAX} 2.2 T @ 1500 A

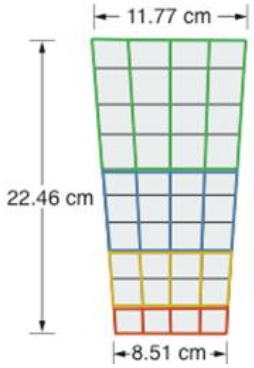
Barrel Calorimeter (BCAL)

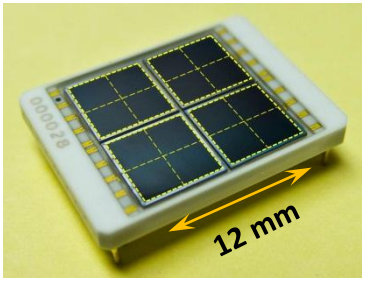


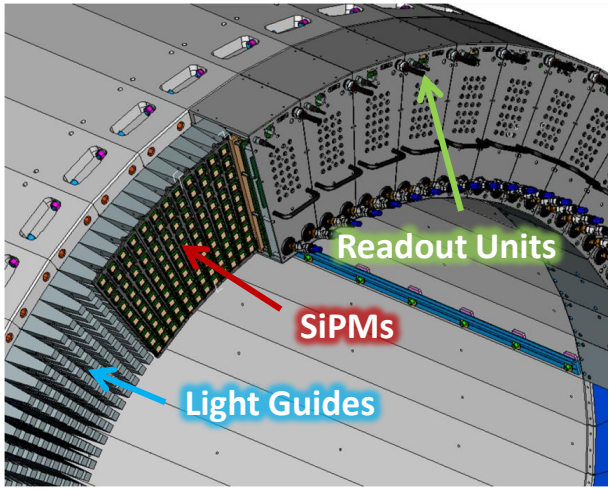
- SciFi calorimeter modules
  - Fabricated by Univ. of Regina
  - 48 Modules (φ sectors)
  - 191 layers
  - Pb/Scint./glue = 37/49/14%
- Photon readout
  - Readout from both sides
  - 3840 Silicon Photo Multiplier (SiPM) arrays from Hamamatsu: 1.2×1.2 cm^2
  - Immune to magnetic fields
  - Temperature control: 5°C



BCAL top half cutaway

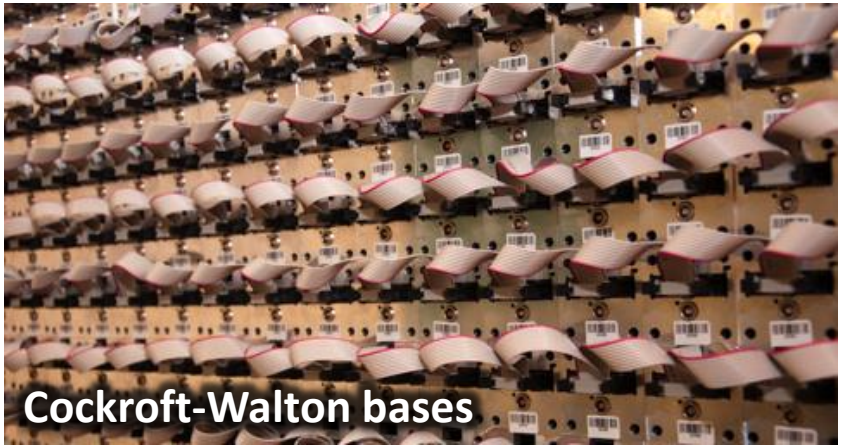






Forward Calorimeter (FCAL)

- Lead Glass Calorimeter
  - Fabricated at Indiana University
  - 2800 lead glass F8-00 blocks 4×4×45 cm^3
  - FEU84-3 PMTs and Cockroft-Walton bases
- Prototype test at Hall-B, 2012
  - δE/E = 20% with 100 MeV electrons, as expected



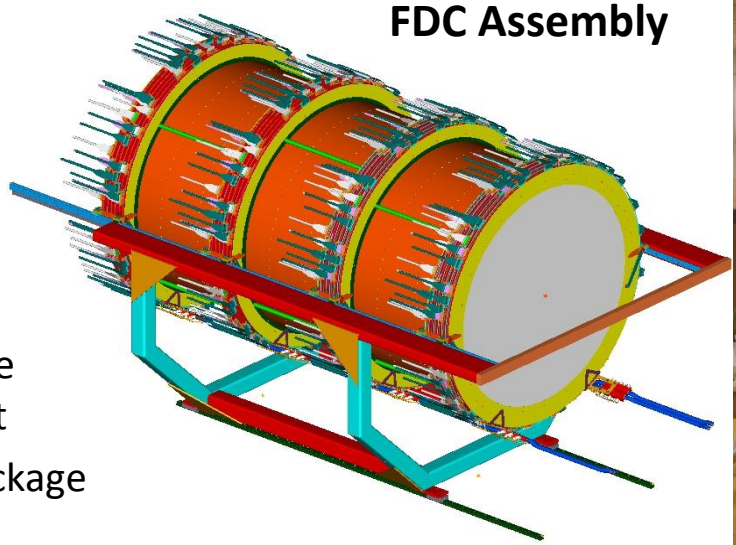
Charged Particle Tracking

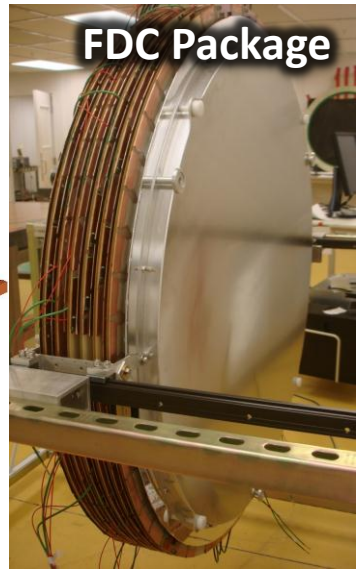
➢ Central Drift Chamber (CDC)

- ❑ Fabricated at Carnegie Mellon University
- ❑ Straw chamber: 3500 straw tubes
- ❑ Resolution: $\sigma_{r\varphi}$ = 150 μm, σ_z = 1.5 mm
- ❑ dE/dx for proton identification (<450 MeV)
- ❑ Fully wired, being tested

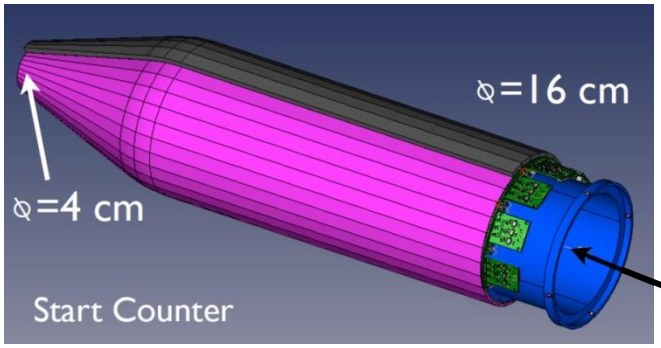
➢ Forward Drift Chamber (FDC)

- ❑ Built and tested at JLab
- ❑ Round planar chambers with cathode strips (U/V) and anode wires readout
- ❑ 4 packages, 6 readout planes per package
- ❑ Resolution: σ = 150 μm

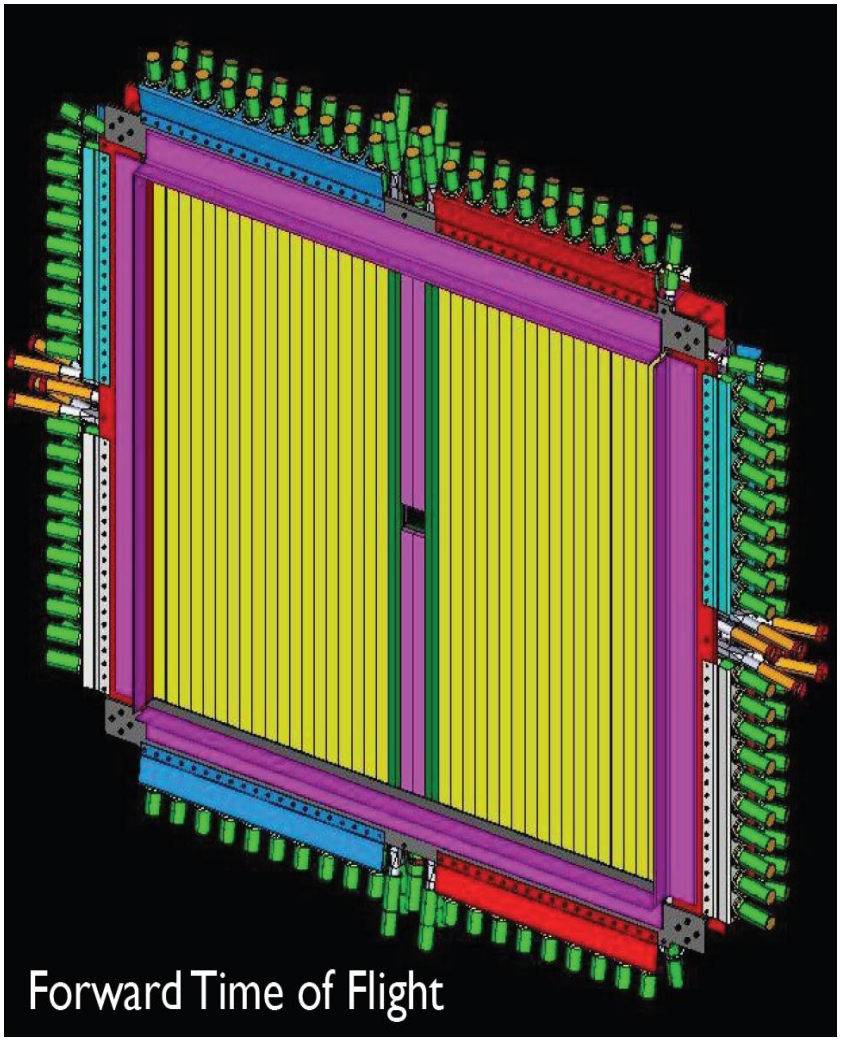




Particle ID and Timing



beam on LH_2 target



- Start Counter (SC)
  - Being fabricated at Florida International University
  - Thin scintillator to tag accelerator beam bunch
  - Readout by SiPMs
- Forward TOF (TOF)
  - Being fabricated at Florida State University
  - Two scintillator planes: 70 ps resolution, 4σ K/π separation up to 2 GeV

Electronics and Trigger

- Fully pipelined payload modules (VME64-VXS)
  - F1-TDC (60 ps, 32 ch. or 115 ps 48 ch.)
  - 125 MHz flash ADC (12 bit, 72 ch.)
  - 250 MHz flash ADC (12 bit, 16 ch.)
- Versatile trigger setup on FPGAs
  - Energy sum, pattern match or combination every 4 ns
  - Initial L1 trigger: simple algorithm on total energy sum
  - L3-farm: reduce L1 trigger rate by a factor of 10
- Trigger/Data Rate
  - 200 kHz, 3 GB/s readout from front end ($10^8\gamma$/s)
  - 300 MB/s to tape

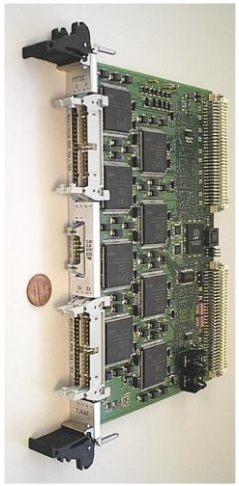
Sub-System Processor

Global Trigger Processor

Crate Trigger Processor

Signal Distribution Board

F1TDC



250MHz Flash ADC

Trigger Interface

Reconstruction and Analysis

- Reconstruction
  - Multi-threaded framework: JANA
  - Working libraries for all sub-systems, improvement ongoing
- Particle identification
  - Kinematic fitting
  - Boosted decision tree
- PWA analysis
  - AmpTool: flexible, take advantages from GPUs
- Data challenges
  - Finished first round, 5.6 B events (30 days of initial running) generated and analyzed
  - Successfully utilized Open Science Grid (OSC)

Roadmap of GlueX Program

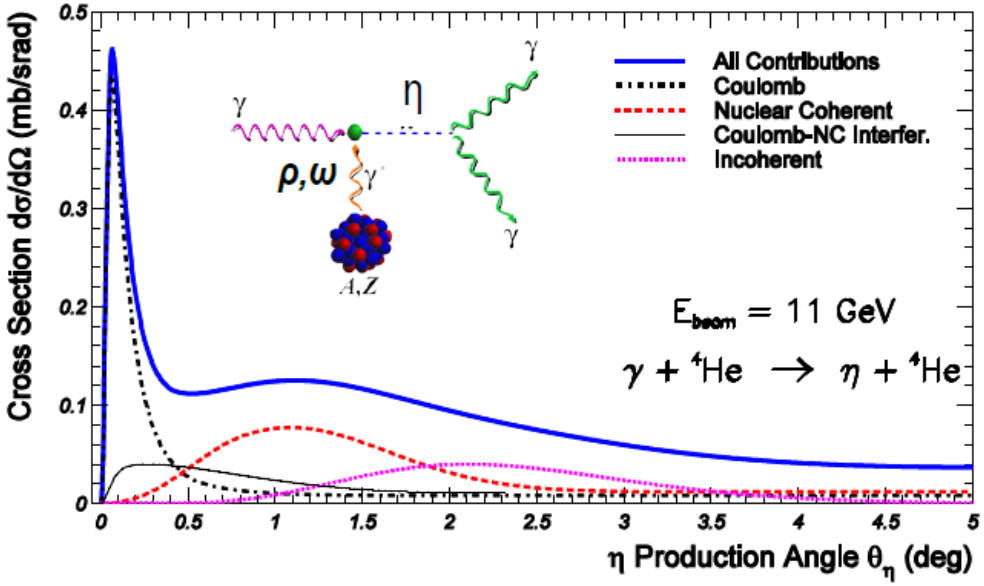
	Low-intensity			High-intensity
	Phase I	Phase II	Phase III	Phase IV
Duration (PAC days)	30	30	60	300
Expected Date	2015	2016	2017	2018+
Electron Energy (GeV)	<10	11	12	12
Beam Current (nA)	50 – 200	220	220	1100
Photon Flux 8.4-9 GeV (γ/s)	10^6	10^7	10^7	5×10^7
Max Beam Emittance (mm-μr)	50	20	10	10
Level-1 Trigger Rate (kHz)	2	20	20	200
Level-3 Farm	No	No	No	Yes
Raw Data Volume (TB)	60	600	1200	2300

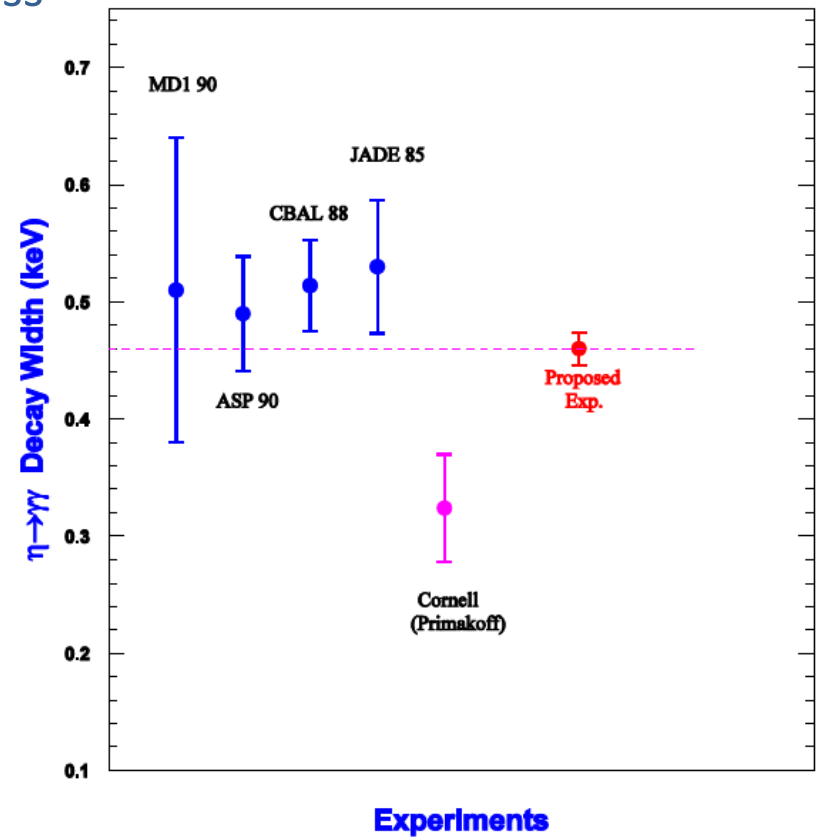
- Initial "low-intensity" runs will provide incredible statistics in some channels
  - 3×10^8 events: $\gamma p \to \pi^+\pi^+\pi^- n$
  - 5×10^6 events: $\gamma p \to \omega\pi^+\pi^- p$
  - 10^5 - 10^6 events: $\gamma p \to \eta'\pi^+ n$
- Approved high-intensity running Phase IV: more decay channels, kaons, cascades

Other Approved Experiments

η Radiative Decay Width

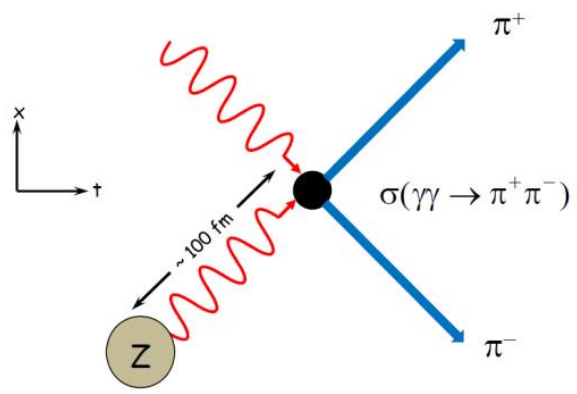
- Measure $\Gamma(\eta \to \gamma\gamma)$ through Primakoff process
  - Precision tests of Chiral symmetry in QCD
  - Potentially solve collider/Primakoff discrepancy
  - Significantly improve $(\eta - \eta')$ mixing angle measurement
- Experimental Setup
  - GlueX detector + LH2/LHe target
  - Addition Calorimeter for cross-section calibration





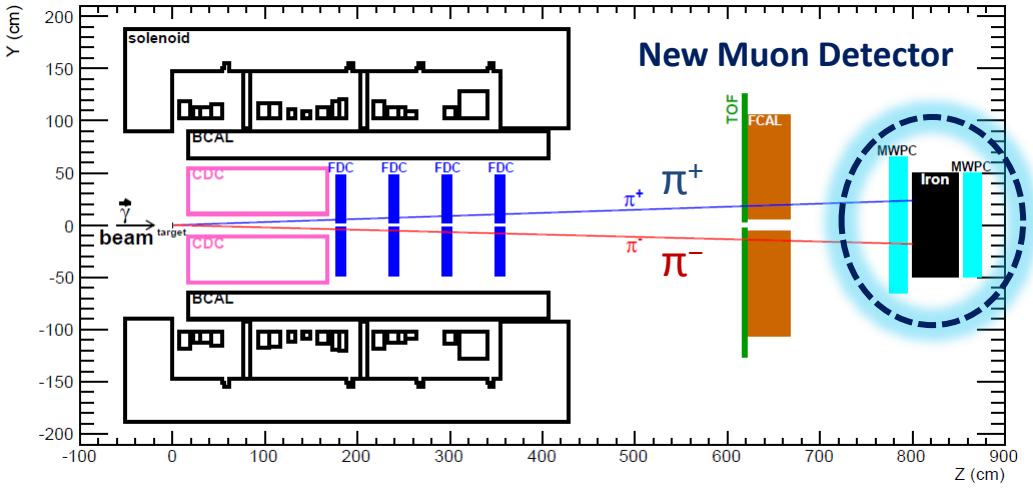
Rating: A⁻ Beam time: 79 days
Spokespersons: Liping Gan (UNCW), Ashot Gasparian (NCAT)

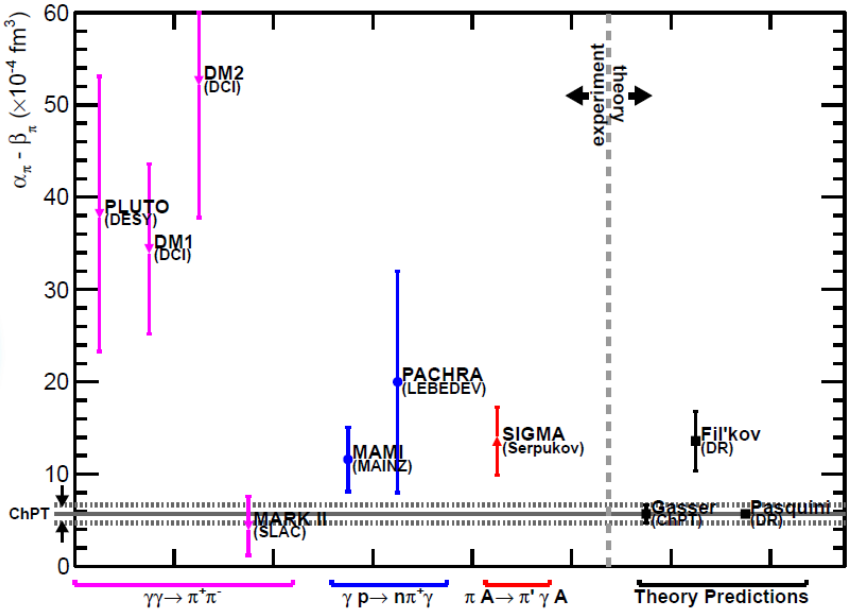
Charged Pion Polarizability



- **Pion Polarizability**
  - Important test of low-energy QCD unresolved by experiment
  - Predicted value directly from $L_{QCD}(p^4)$, NLO corrections are small
- **Experimental Setup**
  - Primakoff process, near threshold region
  - GlueX Spectrometer + ^{112}Sn target + muon detector
  - 10 % measurement, similar precision to the best theory prediction

Rating: A⁻, Beam time: 25 days
Spokespersons: David Lawrence (JLab), Rory Miskimen (UMass), Elton Smith (JLab)





Future Plan and Summary

Opportunities and Future Projects

- Tasks need attention
  - BCAL photon reconstruction
  - Detector commissioning and calibration
  - Data analysis: PID and PWA
- Plans for detector upgrades
  - PID upgrade for kaon identification: requirements and options being evaluated – threshold Cherenkov counter, DIRC and RICH
  - Fine granularity forward calorimetry: better energy resolution and π^0 PID
- Physics under discussion
  - Well developed: Rare eta decay
  - Early stage: charm photoproduction, time-like Compton scattering
  - New ideas are welcome: http://www.jlab.org/exp_prog/PACpage/
- Contacts
  - Yi Qiang (yqiang@jlab.org)
  - Hall-D leader: Eugene Chudakov (gen@jlab.org)
  - GlueX spokesperson: Curtis Meyer (cmeyer@ernest.phys.cmu.edu)
  - GlueX wiki: https://halldweb1.jlab.org/wiki

Summary

- GlueX: search for exotic mesons
  - GlueX will study the spectrum of mesons with a polarized photon beam up to 2.8 GeV with sensitivities of a few percent of the total cross section
  - Unique study of QCD in gluonic degrees of freedom
- Other approved experiments
  - Radiative decays of $\eta \rightarrow \gamma\gamma$
  - Charged pion polarizability
  - Study of Cascade baryons
- 12 GeV schedule
  - Hall-D detectors are 80% complete, installation in progress
  - Accelerator commissioning is planned for Jan. 2014
  - Hall-D detector commissioning starts in late 2014
  - GlueX phase I data taking starts in 2015

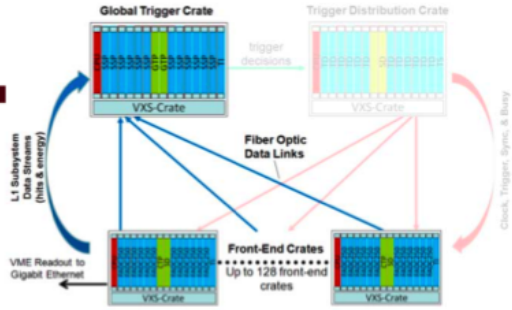
BACKUP SLIDES

GlueX Detector Design Parameters

Capability	Quantity	Range
Charged particles	Coverage	$1° < \theta < 160°$
	Momentum Resolution ($5° - 140°$)	$\sigma_p/p = 1 - 3\%$
	Position resolution	$\sigma \sim 150 - 200\ \mu m$
	CDC dE/dx measurements	$20° < \theta < 160°$
	Time-of-flight measurements	$\sigma_{TOF} \sim 60$ ps; $\sigma_{BCAL} \sim 200$ ps
	BCAL time resolution	$\sigma_t^\gamma < (74/\sqrt{E} \oplus 33)$ ps
Photon detection	Energy measurements	$2° < \theta < 120°$
	FCAL energy resolution ($E > 60$ MeV)	$\sigma_E/E = (5.7/\sqrt{E} \oplus 2.0)\%$
	BCAL energy resolution ($E > 60$ MeV)	$\sigma_E/E = (5.54/\sqrt{E} \oplus 1.6)\%$
	FCAL position resolution	$\sigma_{x,y} = (0.64/\sqrt{E})$ cm
	BCAL position resolution	$\sigma_z = (0.5/\sqrt{E})$ cm
DAQ/trigger	Level 1	< 200 kHz
	Level 3 event rate to tape	~ 15 kHz
	Data rate	300 MB/s
Electronics	Fully pipelined	250/125 MHz fADCs, TDCs
Photon flux	Initial/Final	$10^7/10^8\ \gamma/s$

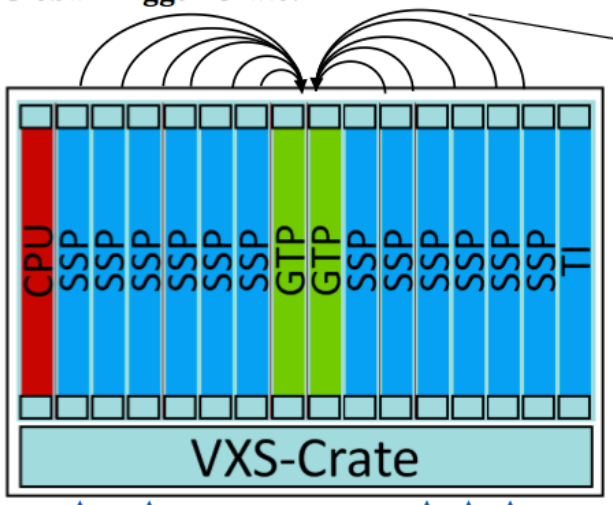
L1 Trigger System

Subsystem Processor: L1



Global Trigger Crate:

Subsystem Energy Sum & Hit Pattern (10Gbps to GTP)

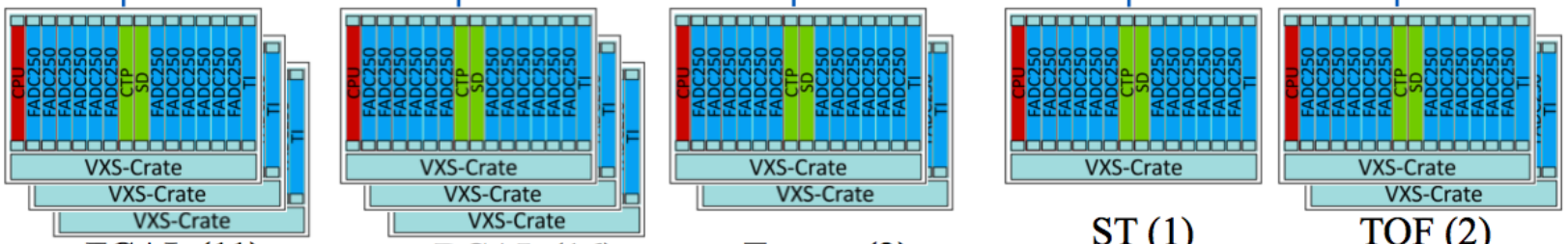


- Sub-System-Processor (SSP) consolidates multiple crate subsystems & report final subsystem quantity to Global-Trigger-Processor (GTP)
- 32bit quantity every 4ns

Hit Pattern

10Gbps fiber optics

Energy

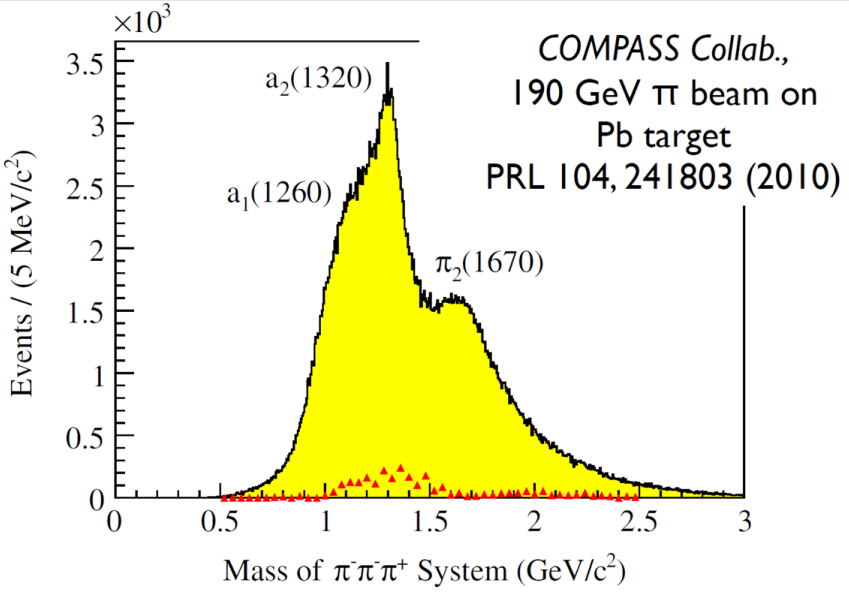


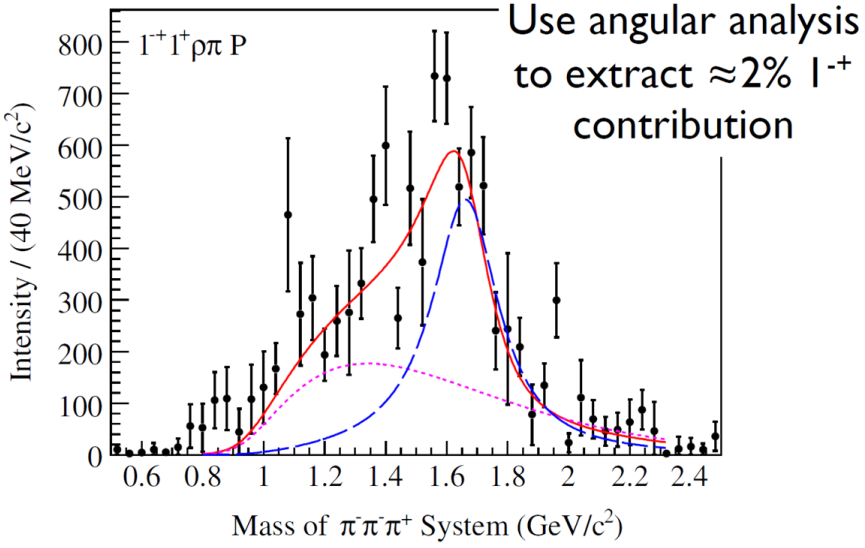
L1 Subsystems (# Crates)

9

Experimental Evidence for 1^{-+} Exotic Hybrids

- Several candidates for the $\pi_1(1^{-+})$ in the literature at 1400, 1600 and 2000 MeV: some reported by multiple experiments
  - Interpretation of data has received much discussion in community
  - Recent review: Meyer and Van Haarlem, arXiv:1004.5516 (PRC 82, 025208)
- $\pi_1(1600)$ appears to be most robust: multiple decay modes and experiments
  - Reported by COMPASS in $\rho\pi$
  - Handling π_2 background in $\rho\pi$ was a contentious issue in E852
  - Dominant signal in $\pi p \to \eta'\pi n$ (E852); needed to fit $\chi_c \to \eta'\pi\pi$ (CLEO-c)
- Understanding is not likely to come from studying this state alone: find neighboring exotics and non-exotic hybrids





Decomposition of Total Cross Section

- E_γ = 9.3 GeV

Topology	σ (μb)	% of σ with neutrals
1-prong	8.5 ± 1.1	100
3-prong	64.1 ± 1.5	76 ± 3
5-prong	34.2 ± 0.9	86 ± 4
7-prong	6.8 ± 0.3	86 ± 6
9-prong	0.61 ± 0.08	87 ± 21
With visible strange decay	9.8 ± 0.4	-
Total	124.0 ± 2.5	82 ± 4

Approximately the 70% of total cross section in the energy region E_γ = 7 – 12 GeV has multiple neutrals and is completely unexplored

Sensitivity Test using PWA Tools

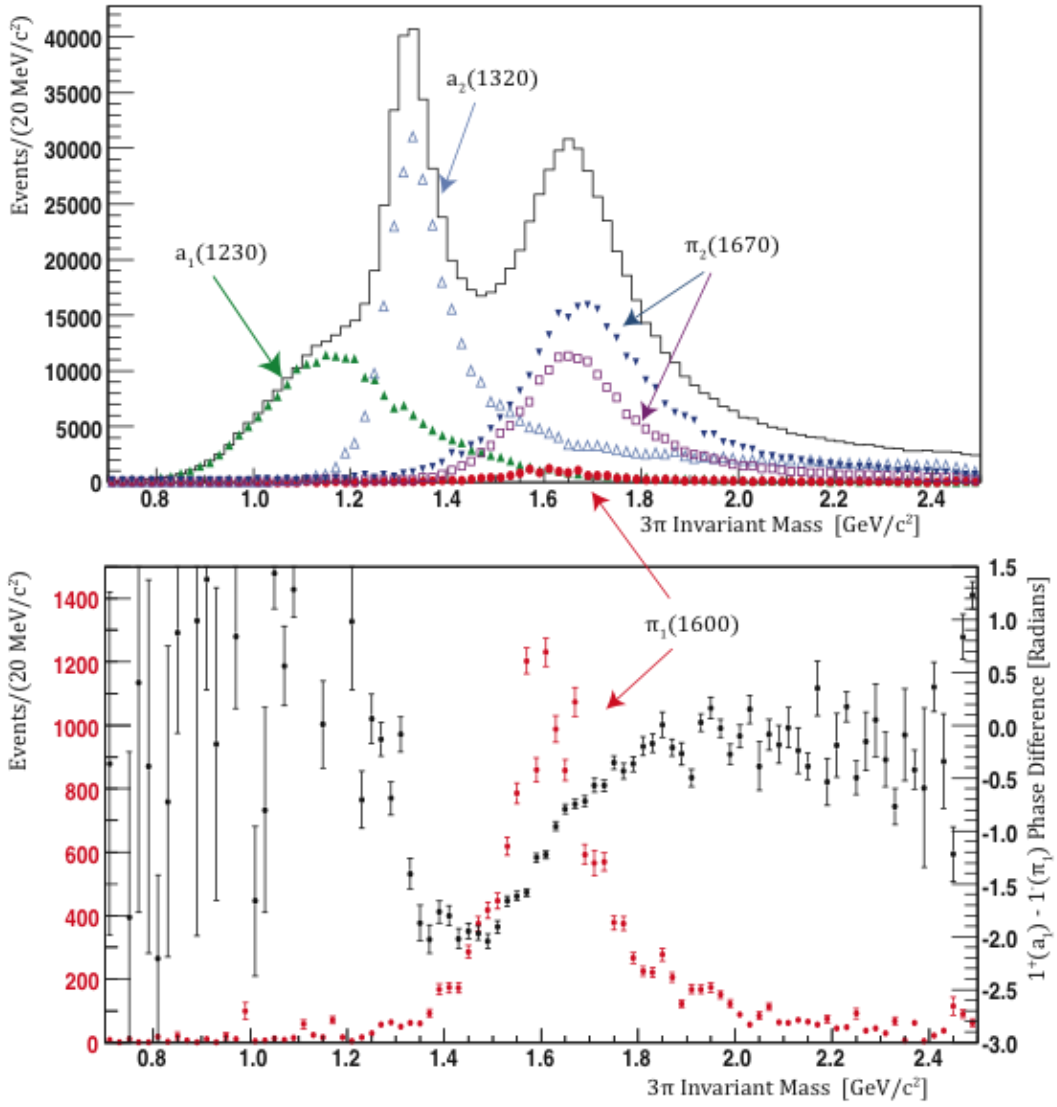
$$\gamma p \rightarrow \pi^+\pi^+\pi^- n$$

generated waves

$$a_1(1260) \rightarrow \rho\pi \quad (\mathrm{S-wave})$$
$$a_2(1320) \rightarrow \rho\pi \quad (\mathrm{D-wave})$$
$$\pi_1(1600) \rightarrow \rho\pi \quad (\mathrm{P-wave})$$
$$\pi_2(1670) \rightarrow f_2\pi \quad (\mathrm{S-wave})$$
$$\pi_2(1670) \rightarrow \rho\pi \quad (\mathrm{P-wave})$$

1^{-+} exotic wave generated with 1.6% relative strength

Corresponds to 3.5 hours GlueX data, full detector simulation and reconstruction



Event Rates

Use track reconstruction efficiency based on software performance and final states coupled with estimated cross sections.

Final State	Cross Section (μb)	Phase I-III (x 10^6)	Phase IV (x 10^6)	
$\pi^+\pi^-\pi^0$	10	**300**	**3000**	Phase III
$\pi^+\pi^-\pi^+$	4	**120**	**1200**	
$\omega_{3\pi}\pi\pi$	0.2	**4**	**40**	
Estimates: $\omega_{\gamma\pi}\pi\pi$	0.2	0.6	**6**	Higher statistics
$\eta_{\gamma\gamma}\pi\pi$	0.2	**3**	**30**	
$\eta_{\gamma\gamma}\pi\pi\pi$	0.2	2	**20**	
$\eta'_{\pi\pi\pi}pp$	0.1	0.3	**3**	
$KK\pi\pi$	0.5	**4**	**40**	Kaons
$KK\pi$	0.1	1	**10**	

A factor 10 increase in statistics allows access to small signals from initial running.

GlueX Data Rates

		Front End DAQ Rate	Event Size	L1 Trigger Rate	Bandwidth to mass Storage	
JLab	GlueX	3 GB/s	15 kB	200 kHz	300 MB/s	private comm.
	CLAS12	0.1 GB/s	20 kB	10 kHz	100 MB/s	
LHC	ALICE	500 GB/s	2,500 kB	200 kHz	200 MB/s	CHEP2007 talk Sylvain Chapelin
	ATLAS	113 GB/s	1,500 kB	75 kHz	300 MB/s	
	CMS	200 GB/s	1,000 kB	100 kHz	100 MB/s	
	LHCb	40 GB/s	40 kB	1000 kHz	100 MB/s	
BNL	STAR	50 GB/s	1,000 kB	0.6 kHz	450 MB/s	*
	PHENIX	0.9 GB/s	~60 kB	~ 15 kHz	450 MB/s	**

* Jeff Landgraf Private Comm. 2/11/2010

** CHEP2006 talk Martin L. Purschke. current capability is 800MB/s peak, 500MB/s sustained (priv. comm. 2/14/2010)

Experimental status of exotic 1^{-+} $\pi(1600)$

For review see
Meyer PRC 82 (2010) 025208

VES	$\pi^- A$	$\rightarrow$	$\pi^- b_1 A$ $\pi^- f_1 A$ $\pi^- \eta' A$
E852	$\pi^- p$	$\rightarrow$	$\rho\pi^- p$ $b_1\pi^- p$ $f_1\pi^- p$ $\eta'\pi^- p$
Crystal Barrel	$\bar{p}n$	$\rightarrow$	$b_1\pi^-$
E852-IU	$\pi^- p$	$\not\rightarrow$	$(\rho\pi^-)_{\pi_1} p$ $(\rho^-\pi^0)_{\pi_1} p$
CLAS	γp	$\not\rightarrow$	$(\rho\pi^+)_{\pi_1} n$
COMPASS	$\pi^- A$	$\rightarrow$	$\rho\pi^- A$
CLEO-c	$\psi(2S)$	$\rightarrow$	$\gamma\chi_{c1}, \quad \chi_{c1} \rightarrow \eta'\pi^+\pi^-$

Only one photo-production search

Cascade Spectroscopy

- Information is limited
  - J^P is only known for 3 states
  - PDG: Nothing of significance has been added since 1988
  - Expectations that many are narrow
- Experimentally challenging
  - Produced through hyperon decay
  - Many-particle final states including kaons
  - Small cross sections
- GlueX acceptance and rates are ideal
  - Parasitic to the main GlueX project
  - The baseline GlueX detector can provide pure kaonic event samples with good efficiency for some channels

PDG 2012

$\Xi(1320)$	$J^P = (1/2)^{+?}$	****
$\Xi^*(1530)$	$J^P = (3/2)^{+}$	****
$\Xi^*(1620)$	$J^P = (?/2)^{?}$	*
$\Xi^*(1690)$	$J^P = (?/2)^{?}$	***
$\Xi^*(1820)$	$J^P = (3/2)^{-}$	***
$\Xi^*(1950)$	$J^P = (?/2)^{?}$	***
$\Xi^*(2030)$	$J^P = (?/2)^{?}$	***
$\Xi^*(2120)$	$J^P = (?/2)^{?}$	*
$\Xi^*(2250)$	$J^P = (?/2)^{?}$	**
$\Xi^*(2370)$	$J^P = (?/2)^{?}$	**
$\Xi^*(2500)$	$J^P = (?/2)^{?}$	*