Meson Spectroscopy at GlueX

- Exotic hybrid mesons
- GlueX Experiment
  - Detector systems
- Summary

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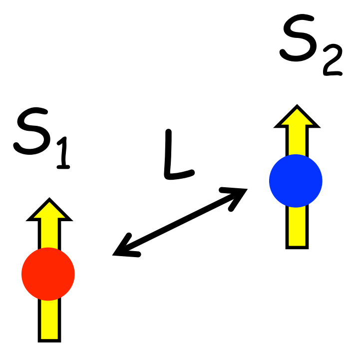
for the GlueX Collaboration

Normal Mesons – $q\bar{q}$ color singlet bound states

Spin/angular momentum configurations & radial excitations generate the known spectrum of light quark mesons.

Starting with u - d - s we expect to find mesons grouped in nonets - each characterized by a given J, P and C.

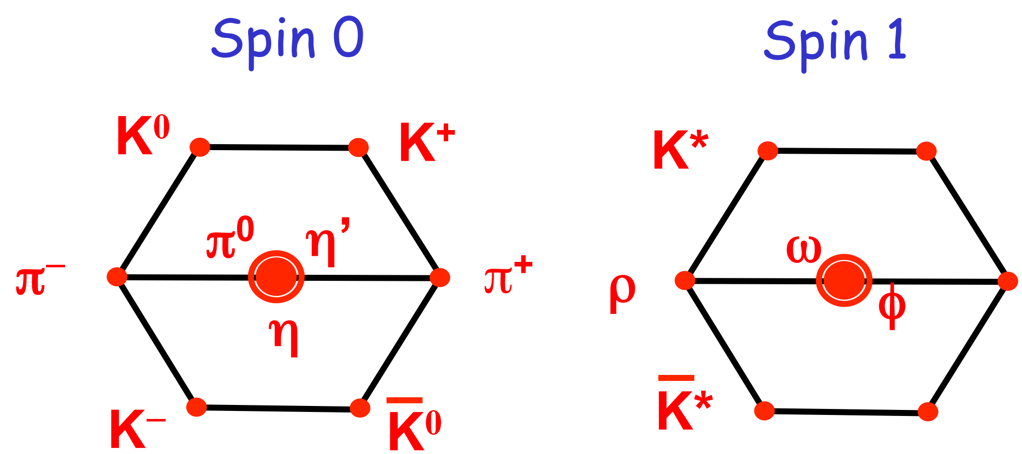


$S = S_1 + S_2$

$J = L + S$

$P = -(-1)^L$

$C = (-1)^{L+S}$



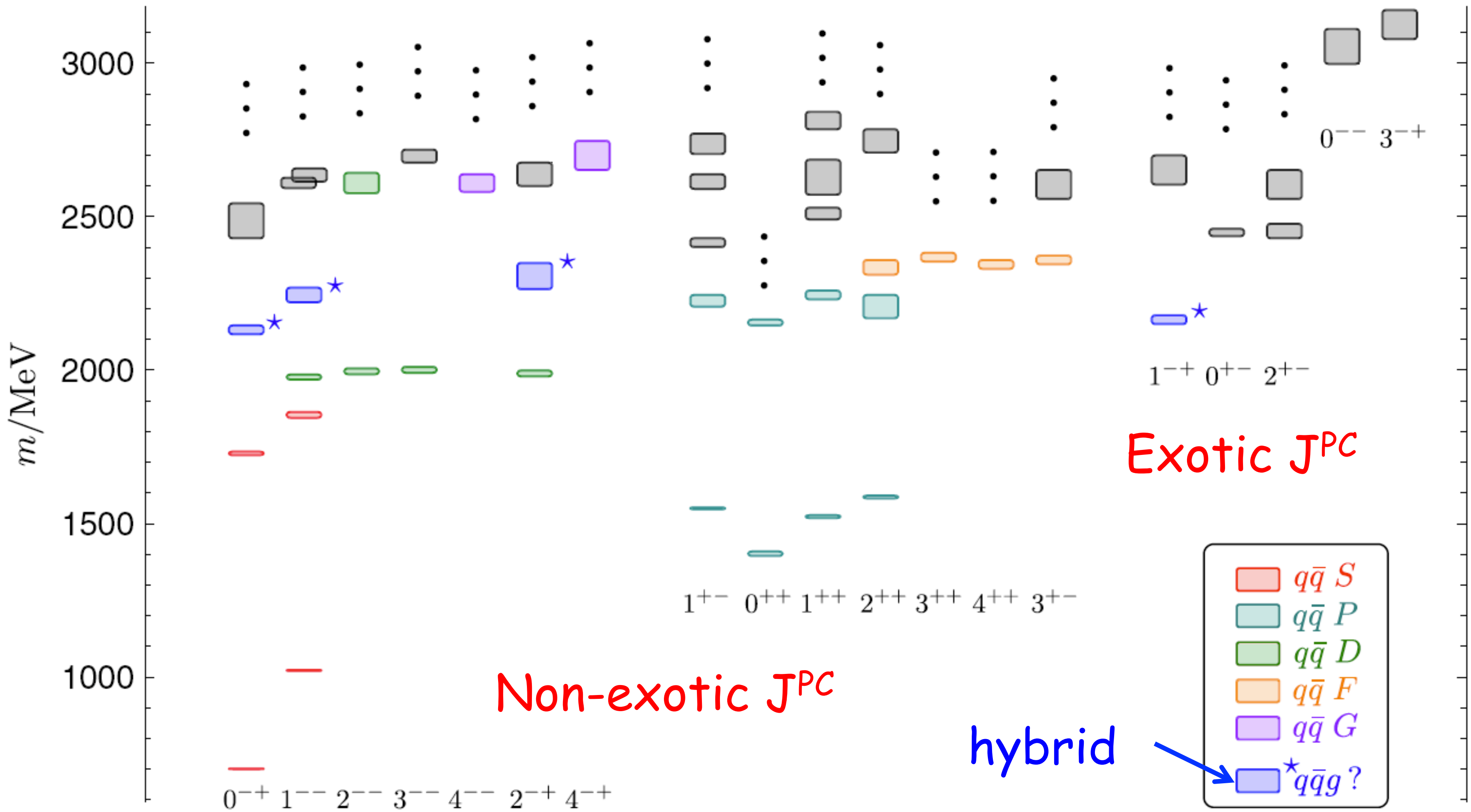
$J^{PC} = 0^{-+}\ 0^{++}\ 1^{--}\ 1^{+-}\ 2^{++} \ldots$

Allowed combinations

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

Not-allowed: exotic

Meson Spectroscopy from LQCD

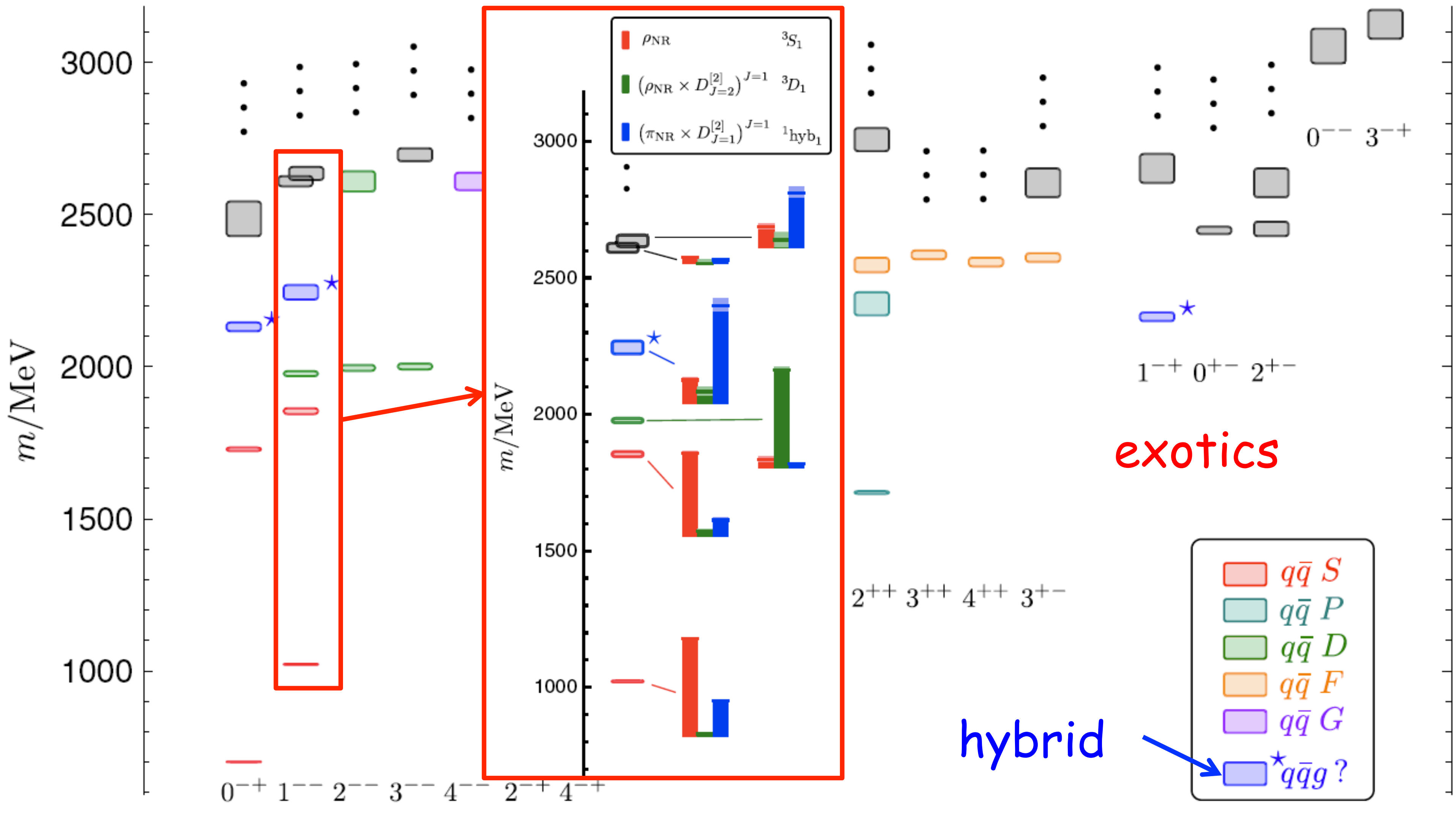


Isovector mesons, m_π~700 MeV

Dudek PRD 83 (2011) 111502

Dudek PRD 84 (2011) 074023

Meson Spectroscopy from LQCD

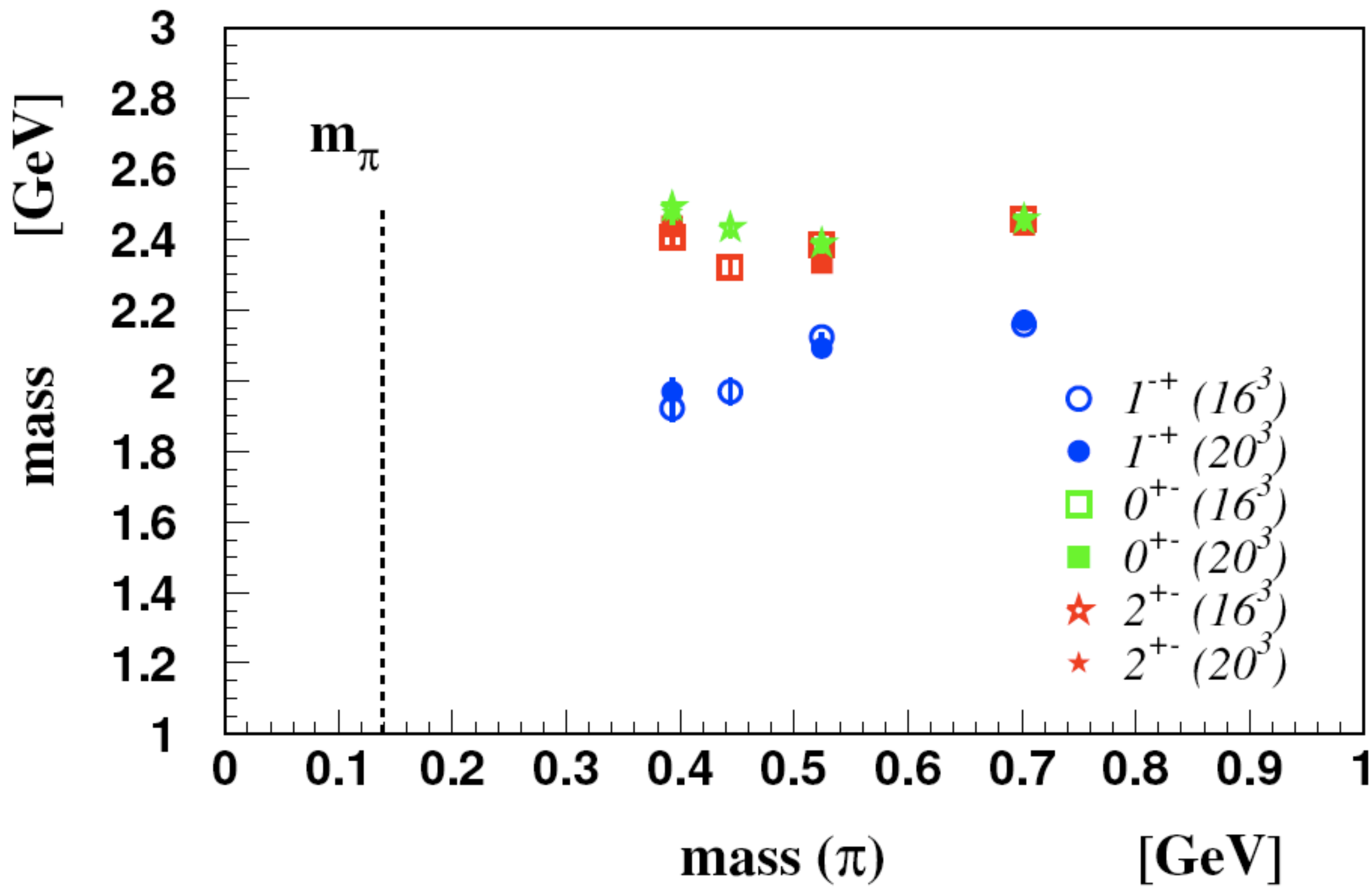


Isovector mesons, m_π~700 MeV

Dudek PRD 83 (2011) 111502
Dudek PRD 84 (2011) 074023

Extrapolation to physical mass

At m_π=400 MeV, mass (1^{-+}) ~ 1.9 GeV, mass (0^{+-}) ~ 2.5 GeV



Experimental evidence for 1^{-+} exotic hybrids

$\pi_1(1400)$

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

Unlikely Hybrid
Dynamical origin?

See also the mini-review under non-$q\overline{q}$ 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.			

$\pi_1(1600)$

$I^G(J^{PC})$

May be hybrid
Challenge in 3π
to separate exotic π_1 from π_2
Cleaner $\eta'\pi$ signal

$\pi_1(1600)$ MASS

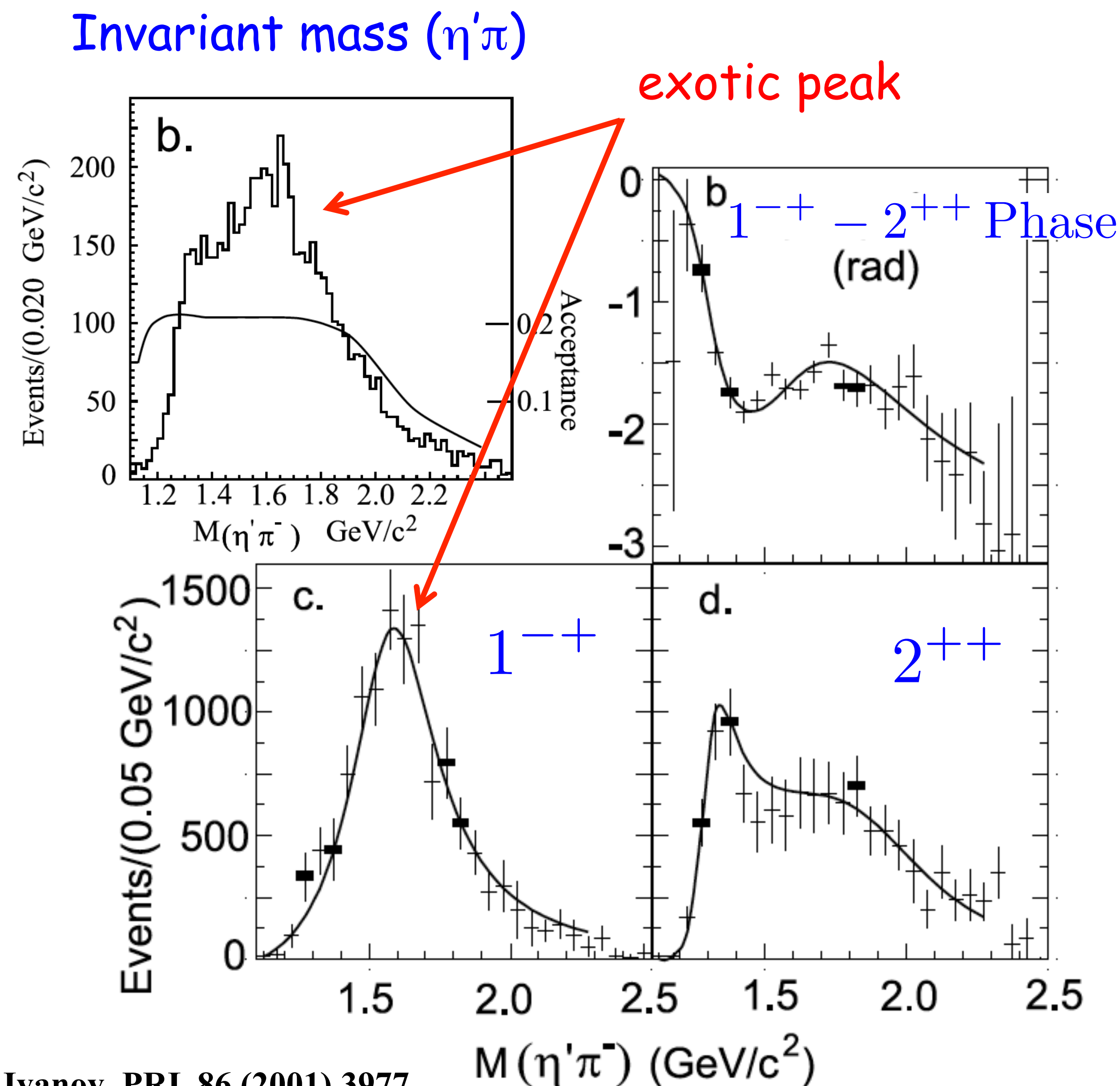
VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*
1662^{+8}_{-9}	**OUR AVERAGE**		

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

MASS (MeV)	*WIDTH* (MeV)	*EVTS*	*DOCUMENT IL*	
$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$	145k	LU	p
$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$	69k	KUHN	$\pi^- p$

Listed among
"further states"
Needs confirmation

Observation of $\pi_1(1600)\to\eta'\pi$



BNL E852

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

$\eta'\pi$ in P wave is exotic

Peak seen in raw data

Strongest evidence for $\pi_1(1600)$

Ivanov PRL 86 (2001) 3977

Photoproduction

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

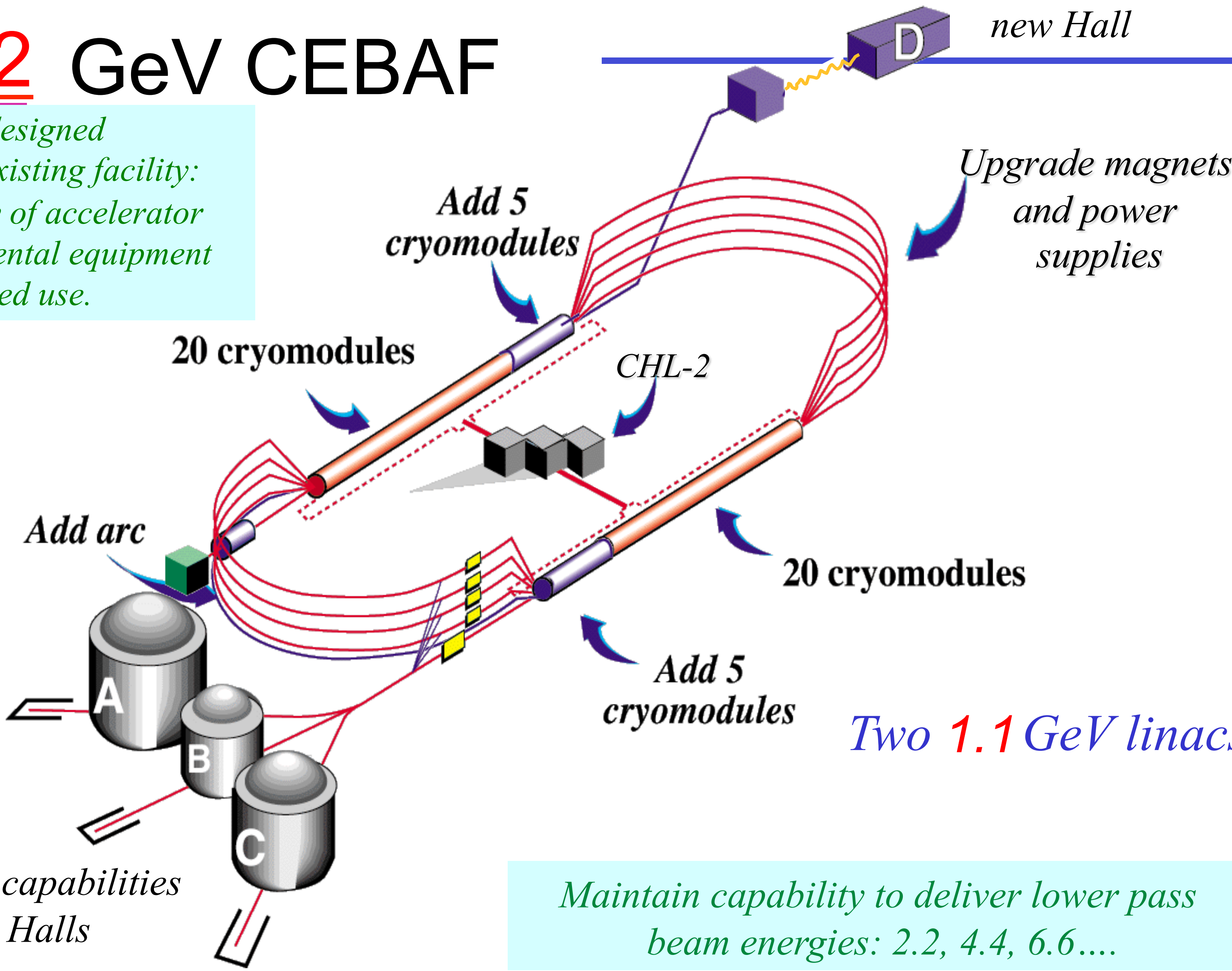
Approximately the 70% of total cross section in the energy region E_γ ~ 7-12 GeV has multiple neutrals and is completely unexplored

GlueX strategy for hybrid meson search

- Use 8.4–9 GeV linearly polarized photons (12 GeV electron beam)
  - Expect production of hybrids to be comparable to normal mesons
  - Dearth of experimental data
  - Sensitivity to masses up to ~ 2.8 GeV/c^2
- Use hermetic detector with large acceptance
  - Decay modes expected to have multiple particles
  - Hermetic coverage for charged and neutral particles
  - Medium resolution: momentum (~ 1-4%), energy (2-20%)
  - High data acquisition rate to enable amplitude analysis
- Perform amplitude analysis
  - Identify quantum numbers as a function of mass
  - Use linear polarization to help identify the J^{PC} of the final states
  - Check consistency of results in different decay modes

12 GeV CEBAF

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.

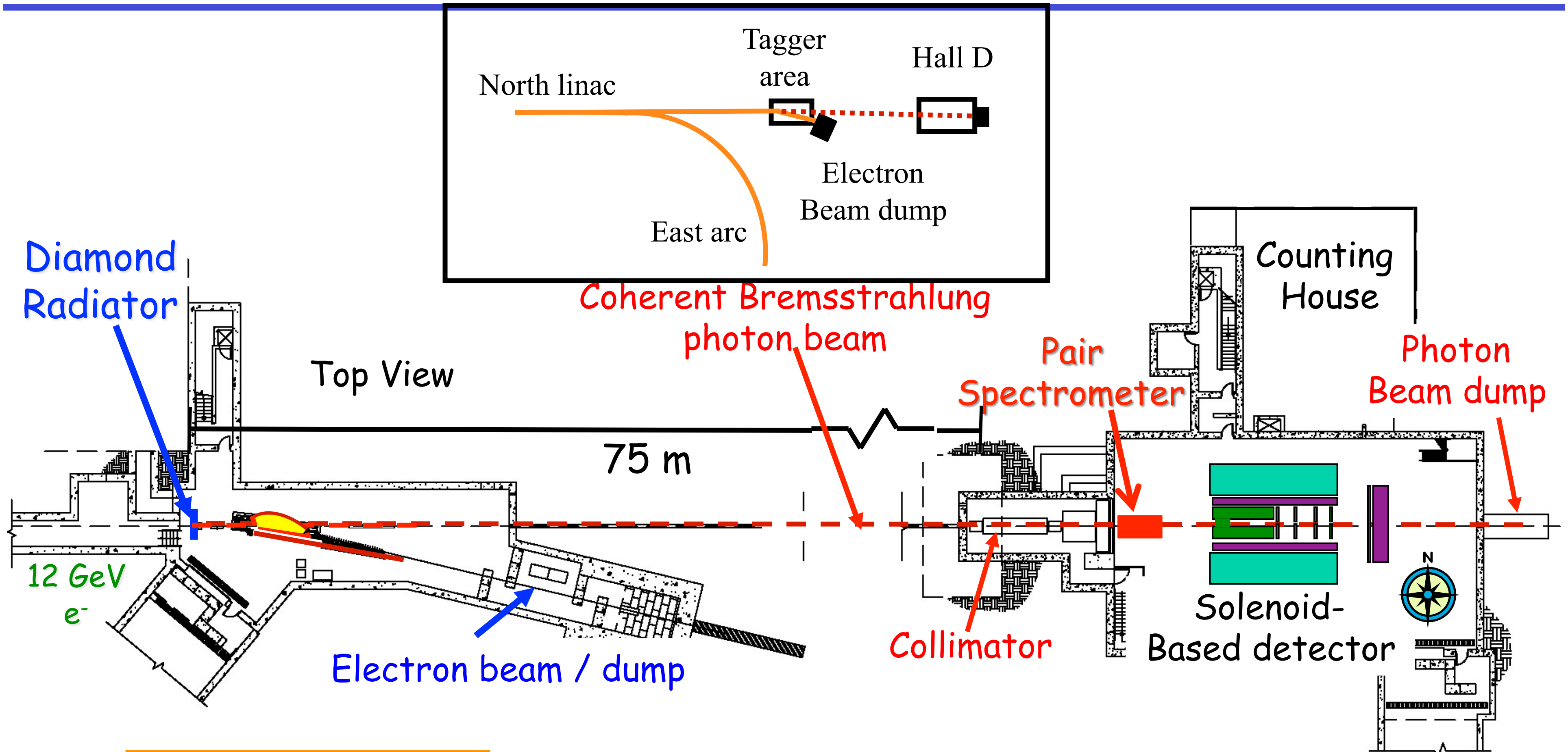


Two 1.1 GeV linacs

Enhanced capabilities in existing Halls

Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

Photon beam and experimental area



Tagger Area	Collimator Cave	Experimental Hall D
Radiation $e^- Z \rightarrow \gamma\, e^- Z$	Selection $\theta < 25\mu r$ polarized photons	Target, Spectrometer

Linearly Polarized Photon Beam

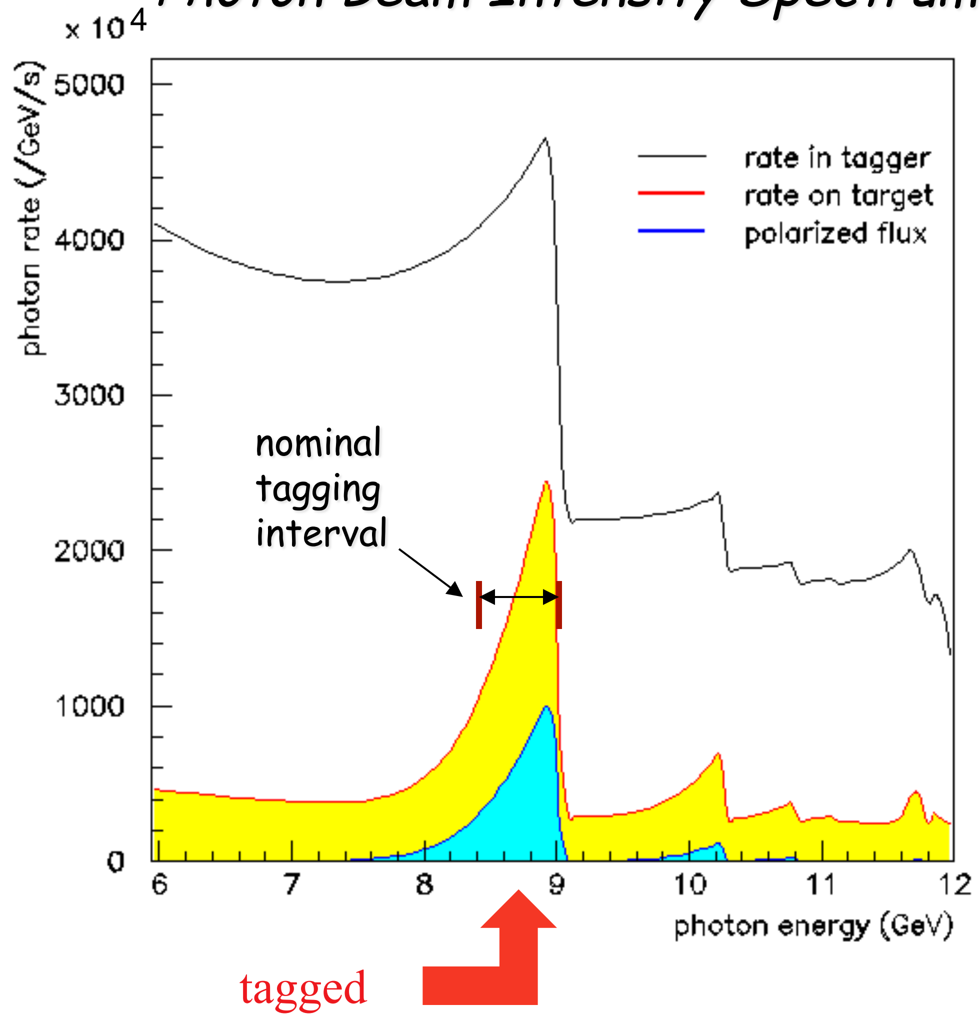
Rates are based on

- 12 GeV electron beam
- 20 μm diamond crystal
- 300 nA electron beam
- Rad-collimator: 76 m
- Collimator diameter: 3.5mm

Leads to $10^7\gamma$/s on target ($\Delta E\gamma$=8.4-9GeV)

Design is expandable to $10^8\gamma$/s

Photon Beam Intensity Spectrum

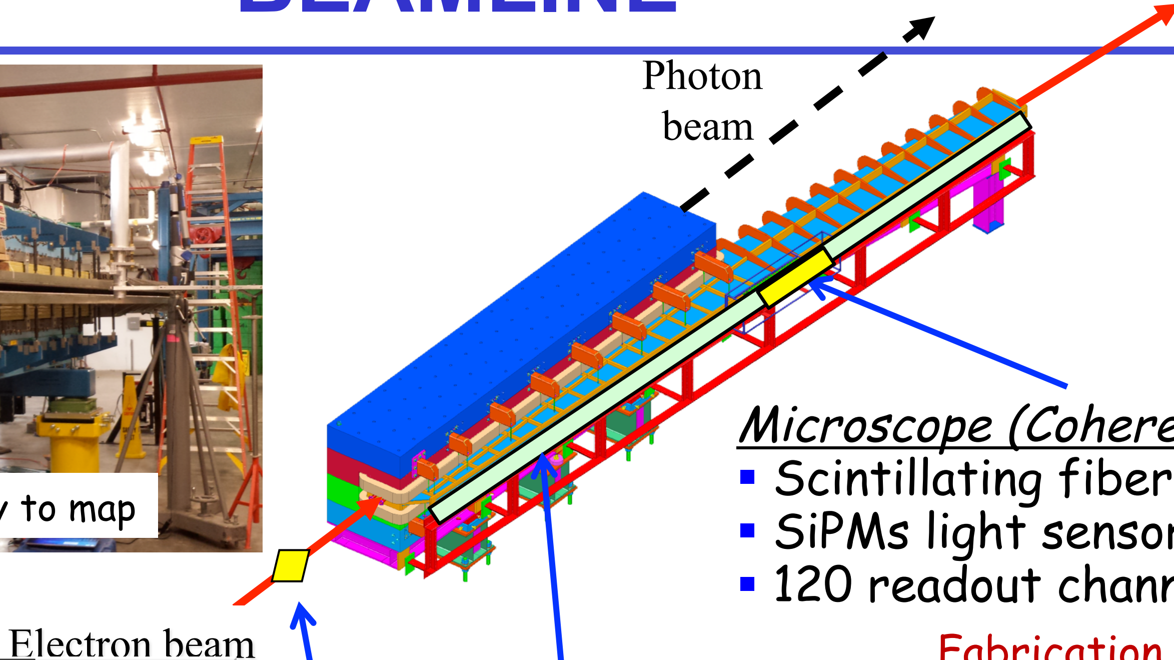


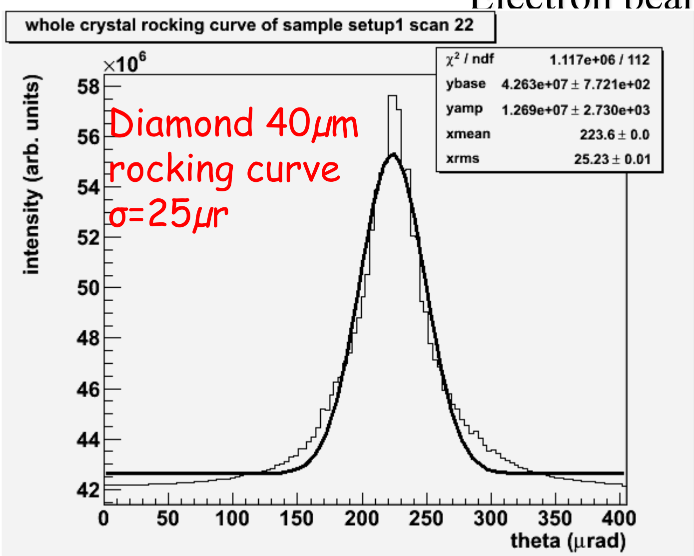
δE/E = 0.1%

Pol = 40%

photon energy (GeV)

BEAMLINE





Microscope (Coherent Peak)
- Scintillating fibers
- SiPMs light sensors
- 120 readout channels

Fabrication at UConn

Fixed Array (E_γ ~ 3-11.6 GeV)
- Small scintillators
- R9800 photomultipliers

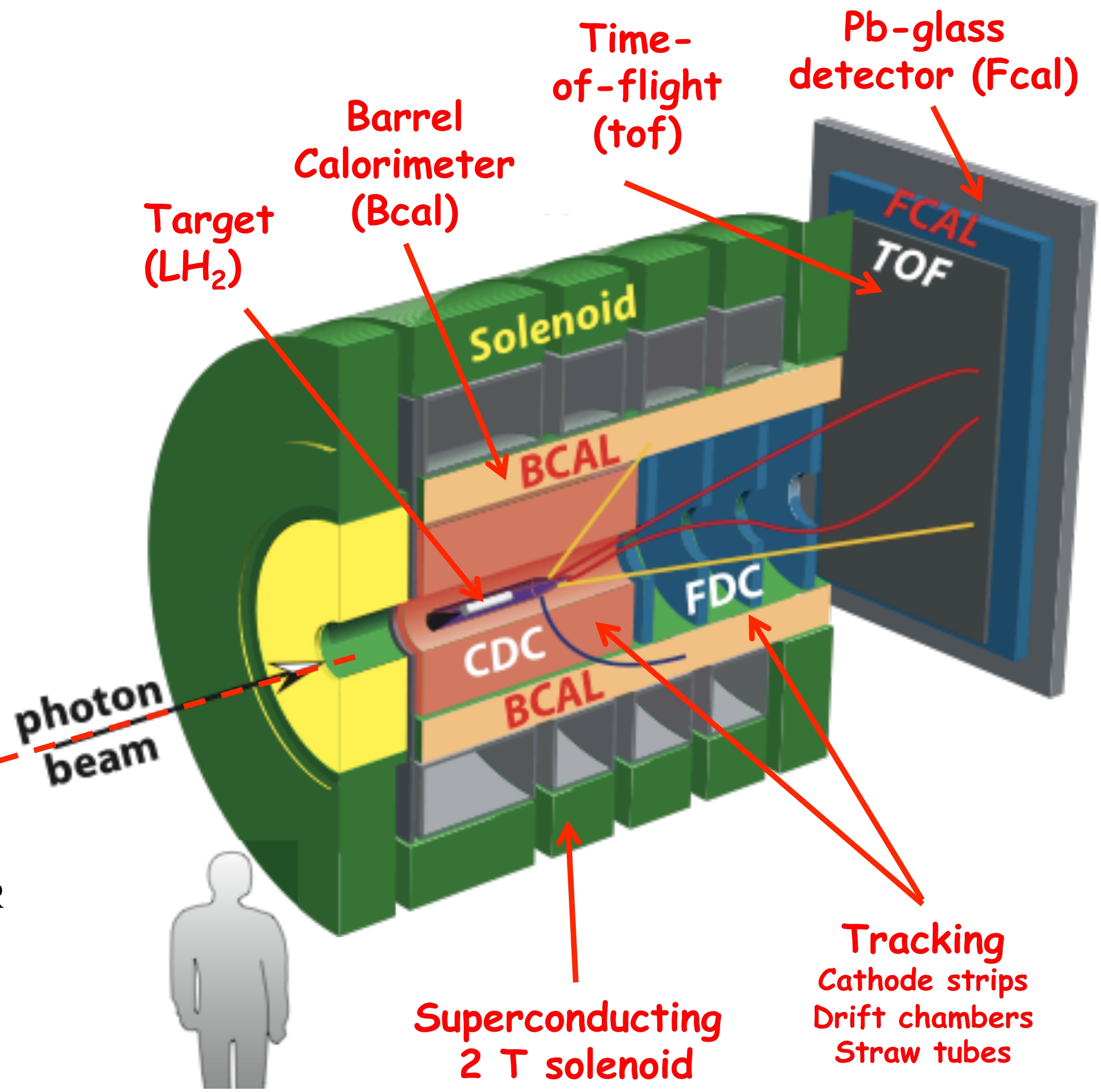
Fabrication at CUA

Thinning and testing of thin crystals
- UConn thinned a diamond to 40μm, ~25μr – good
- GlueX goal is 20μm

Hall D – GlueX detector

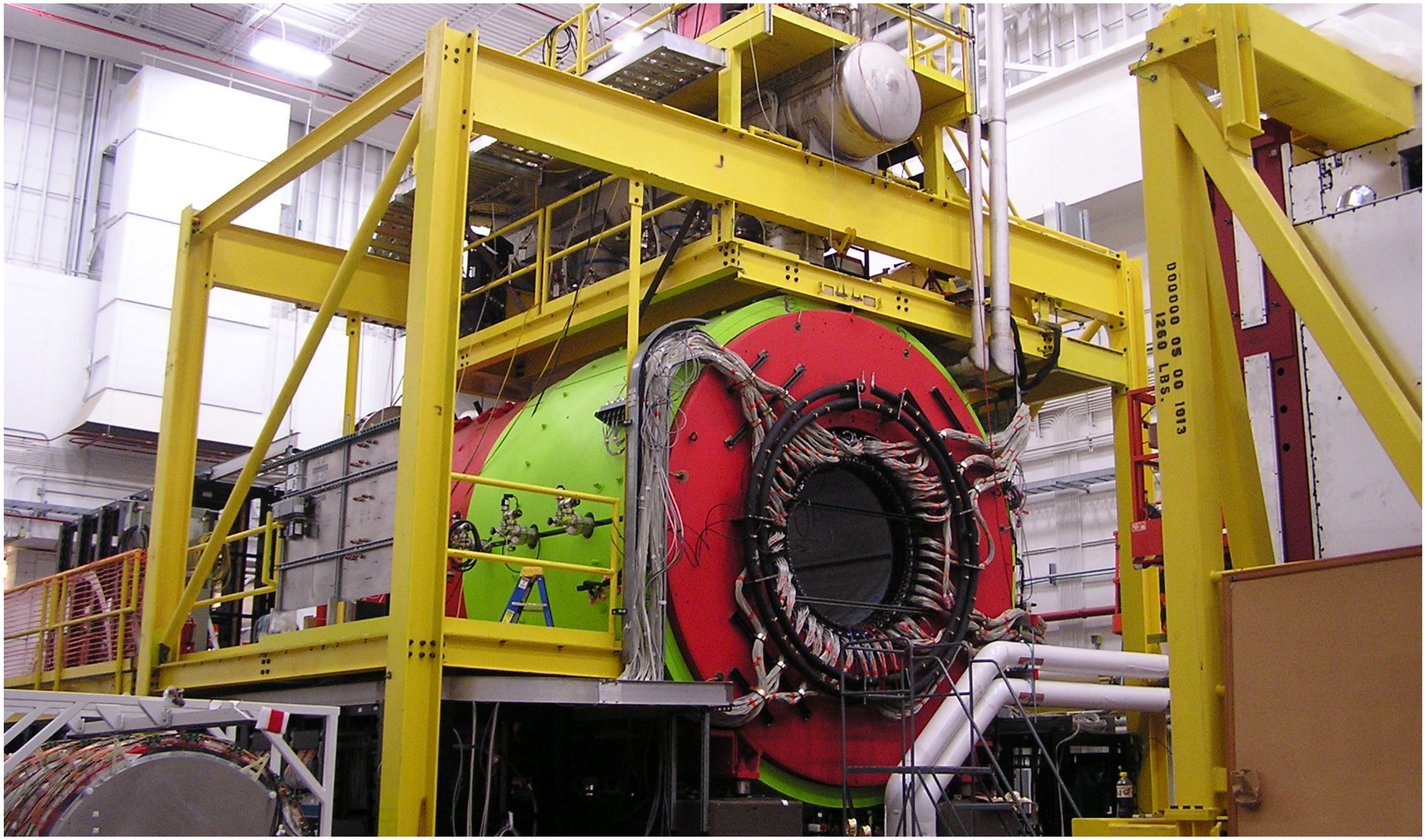
Hermetic detection of charged and neutral particles in solenoid magnet

Initial Flux 10^7 γ/s
18,000 FADCs
4,000 pipeline TDCs
20 KHz L1 trigger
300 MB/s to tape



TAGGER SPECTROMETER (UPSTREAM)

Solenoid: installed and field mapped



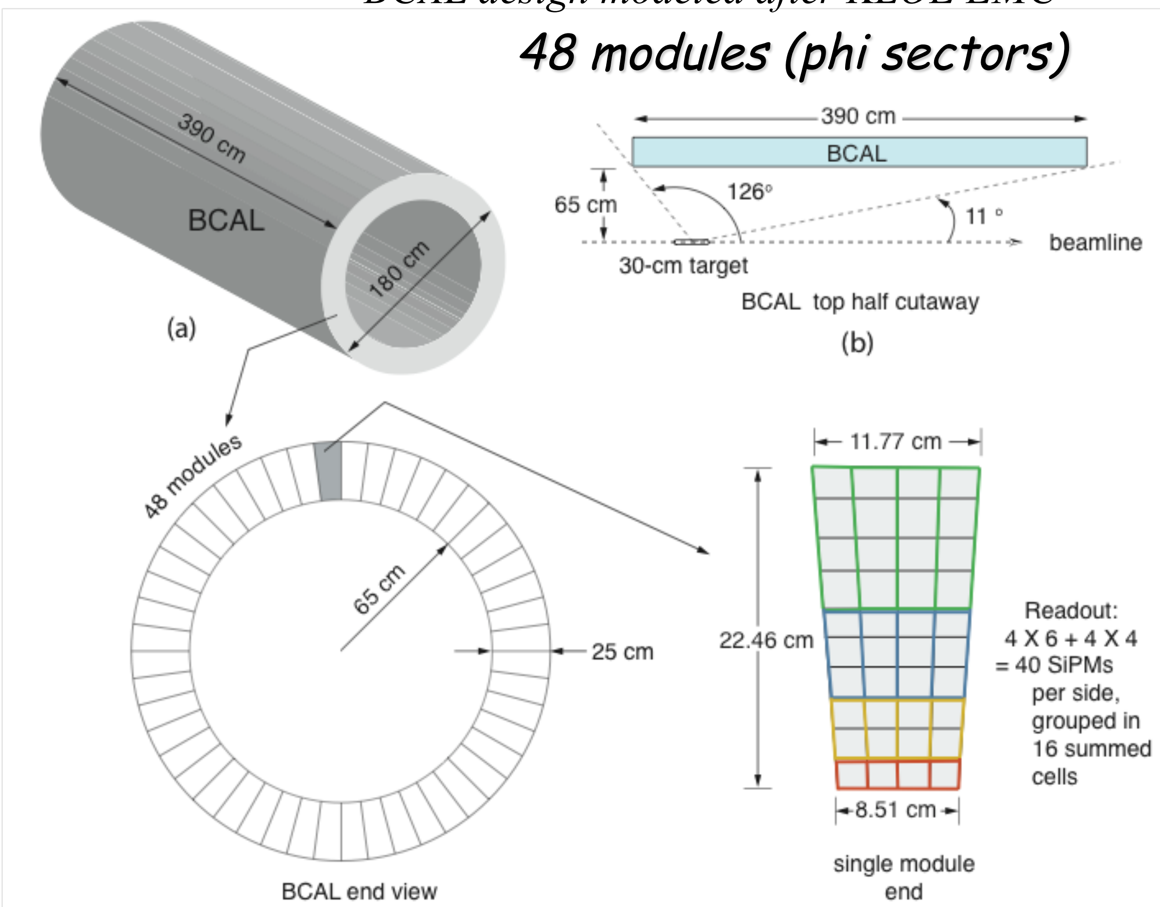
- Used for LASS at SLAC, for MEGA at Los Alamos, refurbished for GlueX
- Four separate coils, all different, "Cryo-stable" design
- Bore ID=185cm, length 400cm, Bmax=2.2T
- Full energy at 1500A is ~30 MJ
- Field strength increases toward the downstream end of the magnet

BCAL: Barrel Calorimeter

Fabricated at the University of Regina

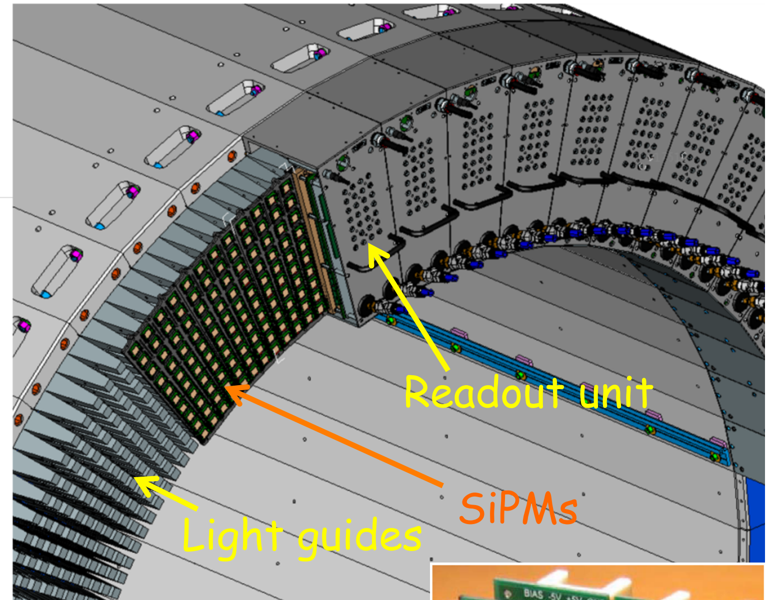
BCAL design modeled after KLOE EMC

48 modules (phi sectors)

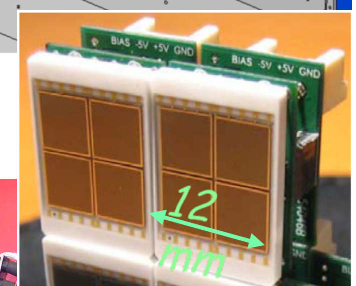


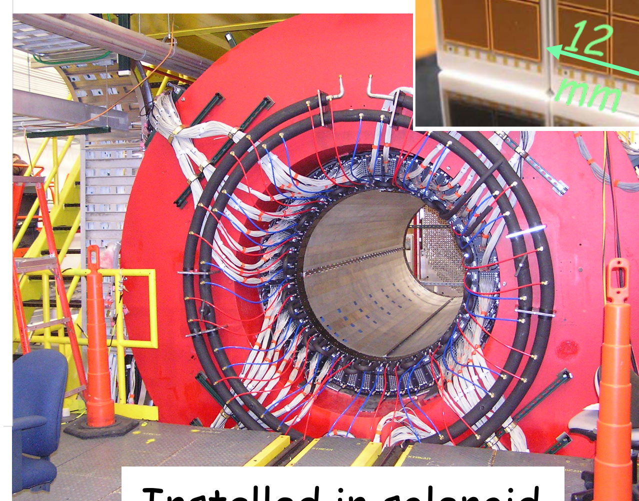
Module: 191 layers
Pb/Sc/Glue 37/49/14%

Readout tested at UTFSM



Immune to
magnetic fields!





Installed in solenoid

Forward Calorimeter

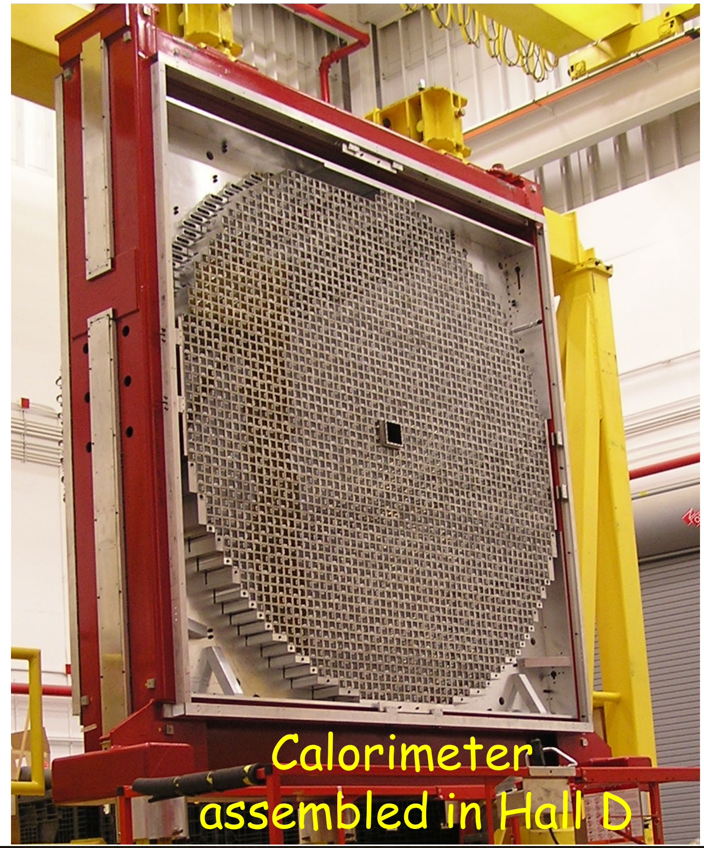
Lead Glass Calorimeter

- 2800 lead glass F8-00 blocks $4 \times 4 \times 45 cm^3$
- PMTs FEU84-3
- Cockroft-Walton bases

Fabricated at Indiana University

Beam test with e^- in Hall B, 2012

- σ_E/E=20% at 100 MeV – as expected



Calorimeter assembled in Hall D

Cockroft-Walton bases under test at IU

Single parts for module assembly

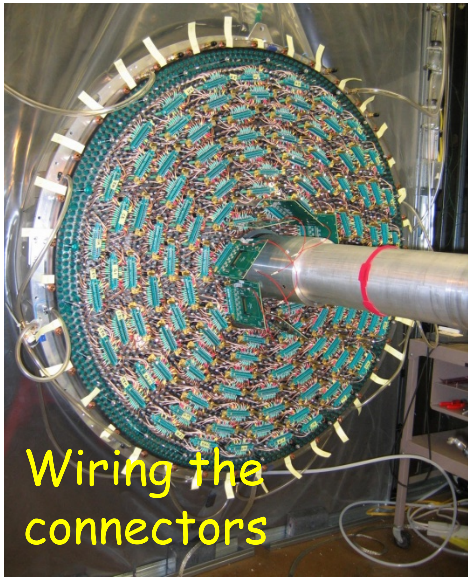
Central Drift Chambers

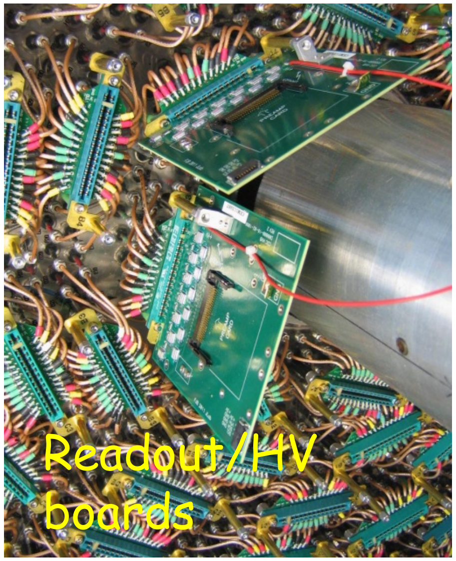
Straw Tube Chamber
surrounding the target
28 layers

Delivered to JLab

Fabricated at Carnegie Mellon

Angular Coverage: 6^o-155^o
3500 straw tubes r=8mm
+/- 6^0 stereo layers
dE/dx for p < 450 MeV/c
Gas mixture: ~60/40 Ar/CO_2
Readout: FADC-125MHz
Resolution: $\sigma_{r\phi}$ ~ 150 μm, σ_z~1.5 mm





Forward Drift Chamber

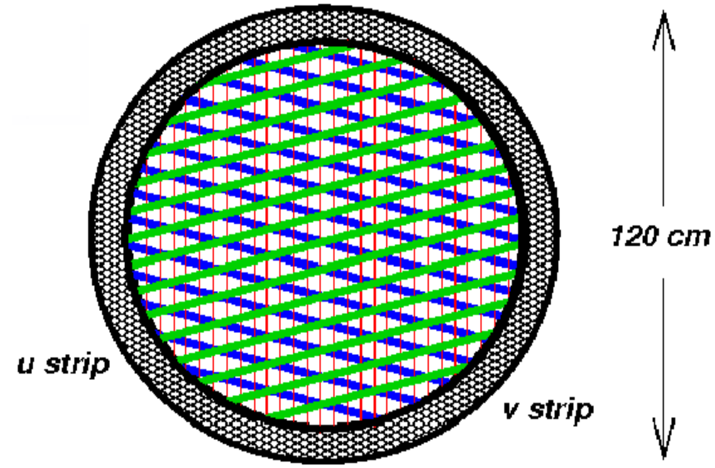
Round planar chambers
downstream of target
Cathode and wire readout

Fabricated at JLab

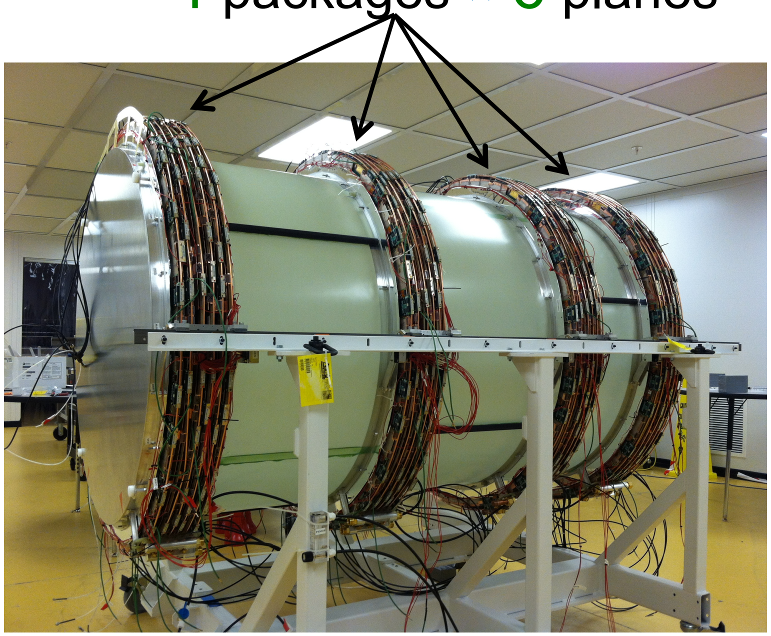
- Gas Mixture: 40/60 Ar/CO_2
- Angular Coverage: 1° – 30°
- Readout:
  - 2300 anode wires → F1TDC
  - 10200 cathode strips → FADC-125
  - *3 measured projections per plane*
- Resolution: 200μm wires, 200μm strips

The material affects photon detection in EM calorimeters: *minimize the RL*

- Cathodes: 25 μm Kapton, 2 μm Cu
- Frames: G10+Rohacell sandwich
- 6 planes: 0.3% RL in active area

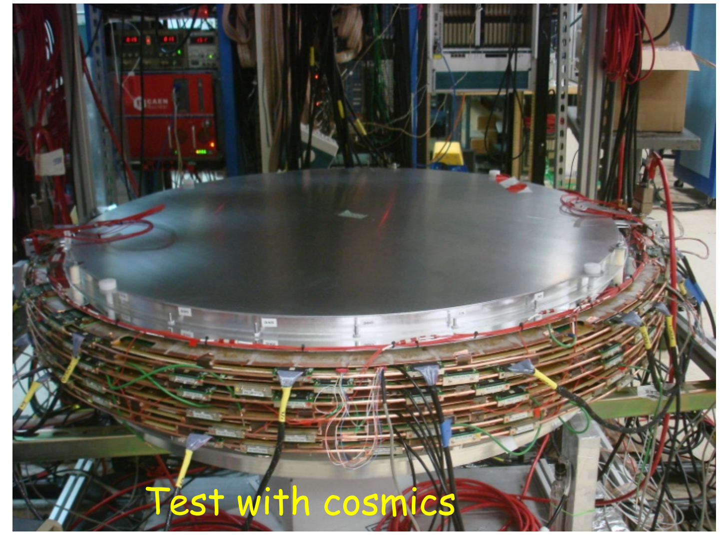


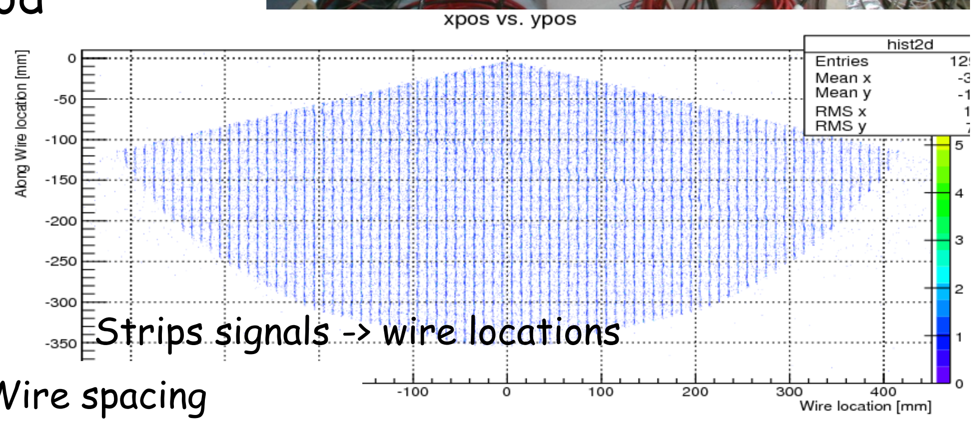
4 packages × 6 planes

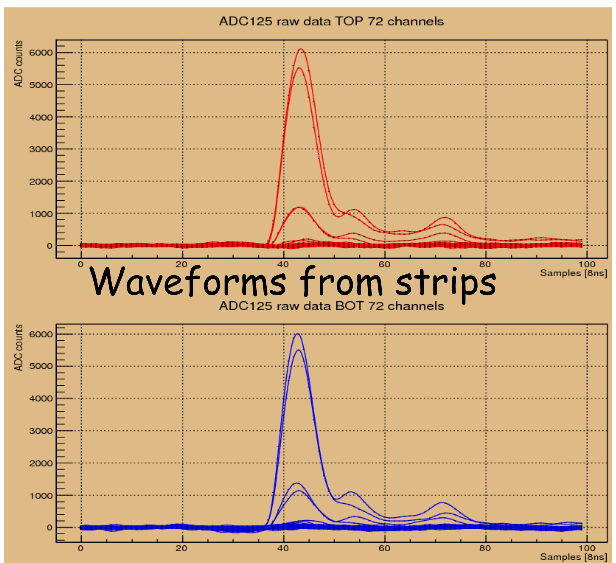


FDC construction

- All packages built
- All packages fully tested with cosmics
  - All wires and cathode strips - good signals
  - The noise level is low
  - The efficiency is >98%
  - The cathode coordinate resolution is 200μm per plane – as expected
  - Drift time resolution is 200μm as expected
  - The geometry of the chamber is good

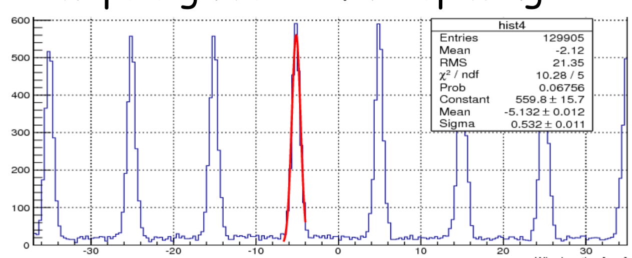






Waveforms from wires

Strips signals -> Wire spacing

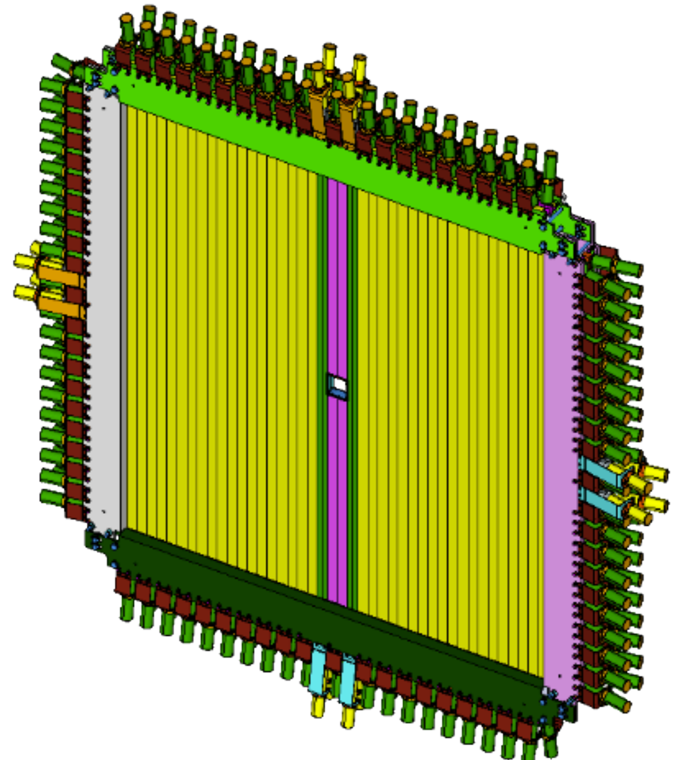


$\sigma \sim 200\ \mu m$

Time-of-flight system

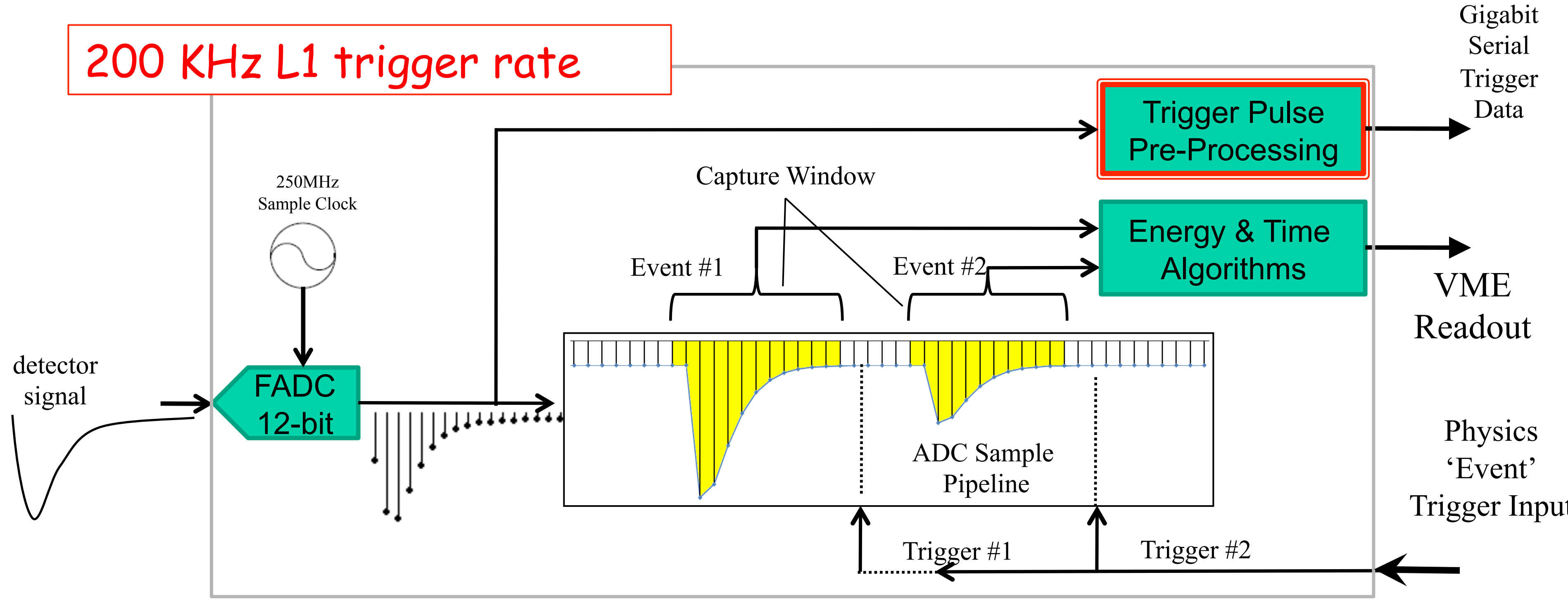
Scintillator hodoscope
Two independent planes

Fabricated at Florida State University



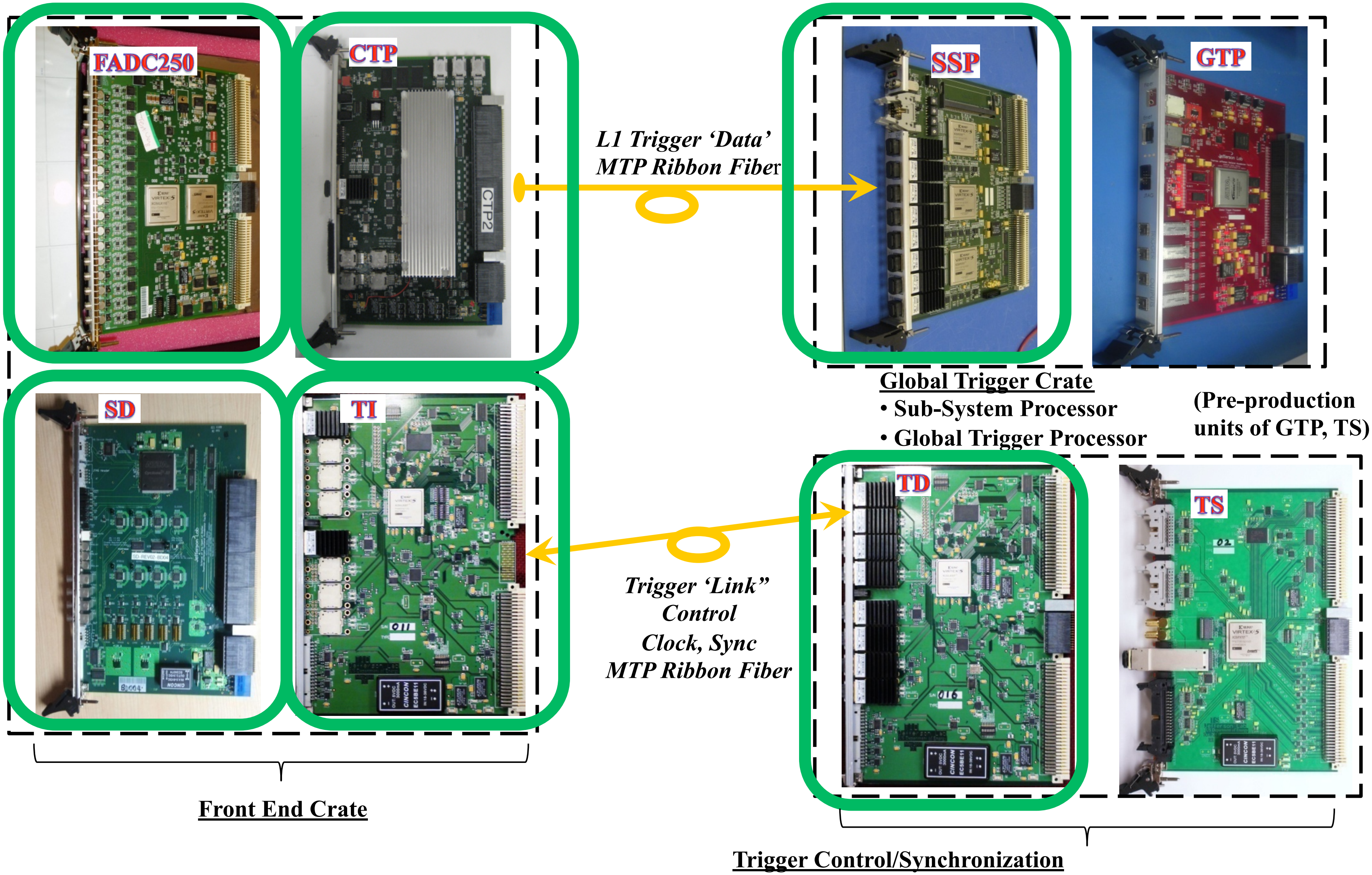
- Angular Coverage: 2^o – 11^o
- 92 scintillators (2.5x6x252 cm^3)
- Hamamatsu H10534 pmts
- Readout:
  - 176 channels CAEN V1290 TDCs
  - 176 channels 250 MHz fADCs
- Resolution: $80/\sqrt{2}$ ps
- π/K/p separation up to 2-3 GeV/c at 4σ

Modern method of signal capture: all pipeline



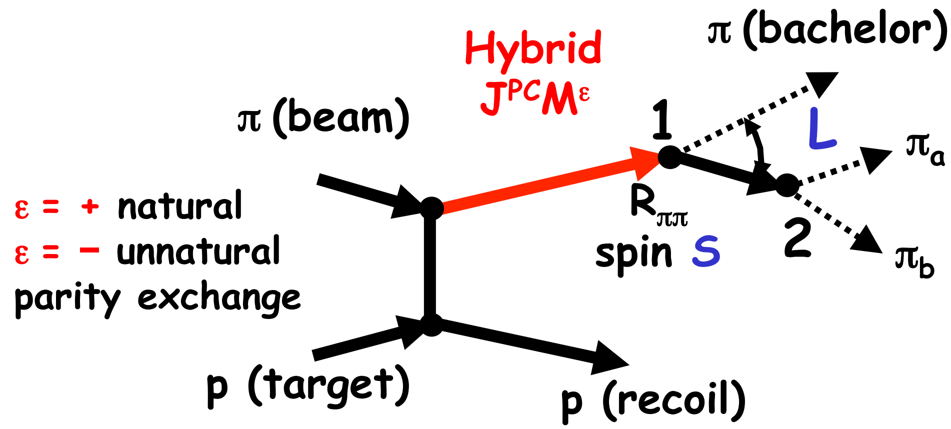
- 250MHz Flash ADC stores digitized signal in 8μs circular memory
- Trigger data contains detailed information useful for cluster finding, energy sum, etc.
- "Event" trigger extracts a window of the ADC data for pulse sum and time algorithms
- Hardware algorithms provide a huge data reduction by reporting only time & energy estimates for readout instead of raw samples

Readout and Trigger Modules (VXS based)



Tools for Amplitude Analysis (PWA)

Previous generation of amplitude analyses had many limitations, e.g. use of the isobar model.



Current generation of amplitude analyses

- Allow more flexibility when defining amplitudes
- Allow systematic studies of model dependencies
- Incorporate state of the art technology to increase fit speeds
  - Graphical Processor Units (GPUs)

There are no longer technological or experimental barriers to incorporating theoretical innovations into experimental analyses.

Amp Tools http://sourceforge.net/projects/amptools/

Sensitivity test using PWA tools

Expect hybrid signal to be large, but software tools can extract small signals

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

generated waves

$a_1(1260) \rightarrow \rho\pi$ (S – wave)

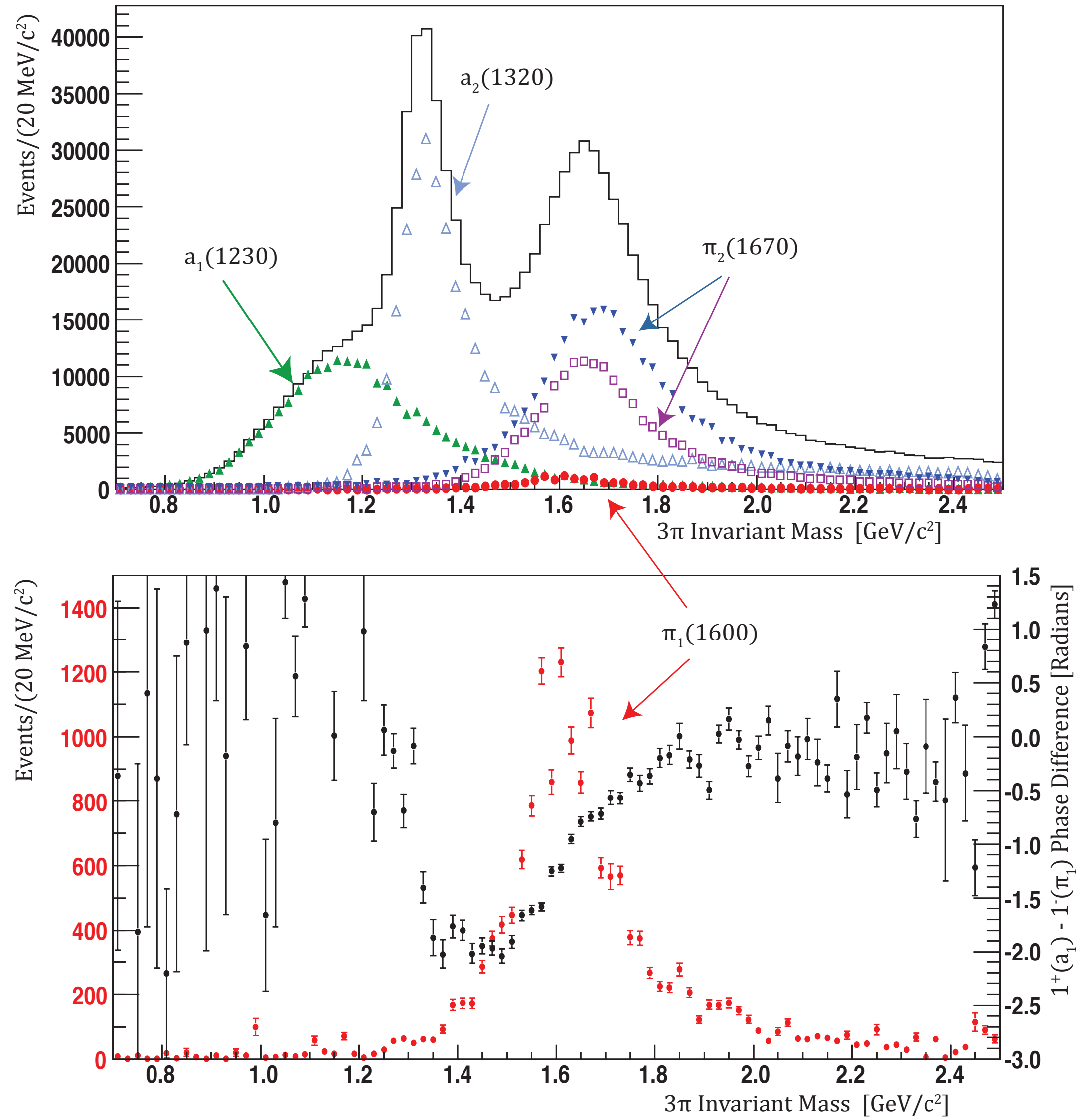
$a_2(1320) \rightarrow \rho\pi$ (D – wave)

$\pi_1(1600) \rightarrow \rho\pi$ (P – wave)

$\pi_2(1670) \rightarrow f_2\pi$ (S – wave)

$\pi_2(1670) \rightarrow \rho\pi$ (P – wave)

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



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

Summary

- GlueX
  - QCD allows for a rich spectrum of hadronic matter, as yet undiscovered.
  - New calculations on the lattice predict the excitation of gluonic fields and, in particular, exotic hybrid mesons.
  - GlueX will study the spectrum of mesons up to M ~ 2.8 GeV with a polarized photon beam and search for hybrid mesons with sensitivities of a few percent of the total cross section.
- Project status
  - The civil construction and accelerator are 90% complete
  - Hall D experimental equipment is > 75% complete.
  - Most GlueX detector systems are completed and being installed
  - Hall D commissioning is planned for Oct 2014

Backup Slides

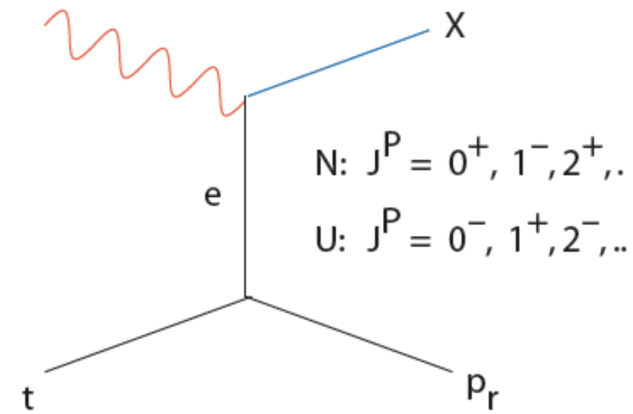
Photoproduction and linear polarization

- Production
  - The expectation from the flux tube model is that hybrids will be produced at a rate comparable to normal mesons.
  - This expectation is corroborated by recent lattice calculations that show that the strength of charmonium hybrid radiative decays are similar to normal mesons

$$\Gamma\left(\eta_{c1} \rightarrow J/\psi\,\gamma\right) \sim 100\,\mathrm{keV}$$

Dudek PRD 79 (2009) 094504

- Polarization
  - For a given produced resonance, linear polarization enables one to distinguish between naturalities of exchanged particles.
  - If the production mechanism is known, linear polarization enables one to filter resonances of different naturalities.



Filter on naturality

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

For review see
Meyer PRC 82 (2010) 025208

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

Analysis $\gamma p \to b_1^{\pm}\pi^{\pm}p$

I. Senderovich, Ph.D. Thesis, GlueX-doc 2096

- $b_1\pi$ is model-favored decay mode for exotics
  - challenging $5\pi p$ final state
  - $\omega\pi\pi$ cross-section is 200 nb; assume 40 nb exotic signal
- Two resonances in $b_1\pi$: a 1^{-+} state at 1.89 GeV and a 2^{+-} state at 2.00 GeV
  - isobar model; polarized beam
- Statistics: ~260 hours of beam
- Dominant "background" is kinematically-equivalent $\omega\pi\pi$ or 5π
  - emphasis on purity over efficiency
  - huge improvement from 3π: recoil proton, kinematic fitting
- Amplitude analysis extracts exotic signal