Early Results from GlueX Experiment

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[1]JLab

Presented at

Second Workshop on the Proton Mass

ECT, Trento, 3-7 April 2017*


Outline

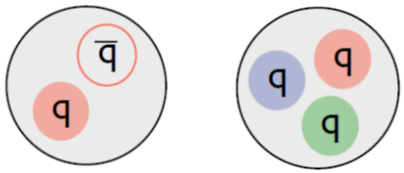
1. Physics motivation
   - QCD and Spectroscopy
   - Search for hybrid mesons
2. Experiment GlueX in Hall D at JLab
   - Apparatus
   - First runs: performance and early results
     - Photoproduction by linearly polarized photons
     - J/ψ Photoproduction near threshold
     - Observations of various known mesonic resonances
3. Outlook

Masses of Hadrons

- Quark Model was a big success!
  - Flavor SU(3) symmetry for “constituent” quarks
  - Postulated observables: $(q\bar{q})$ & (qqq)
- QCD: exact color SU(3) symmetry
  - Asymptotic freedom; Confinement
  - The masses are generated dynamically. Challenges - the topic of the Workshop!

Initial anzatz

based on flavor SU(3)



color SU(3) singlets

Further Insights from Spectroscopy?

QCD does not limit the bound states to $(q\bar{q})$ & (qqq).
Do others exist?

- LQCD predicts states like “hybrids”
- Probing our understanding of the mass scale and the binding energy

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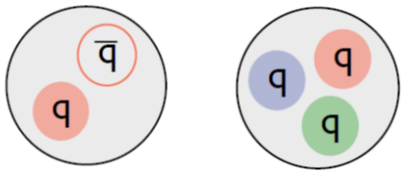

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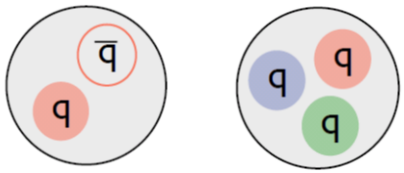

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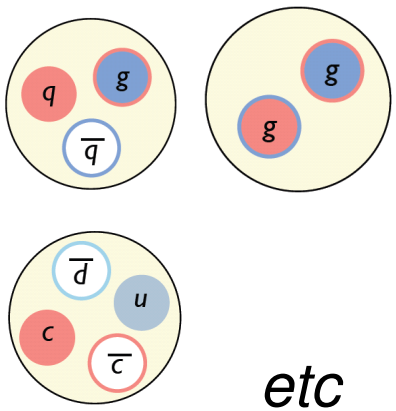
QCD-possible

but not established

"exotic" hadrons



etc

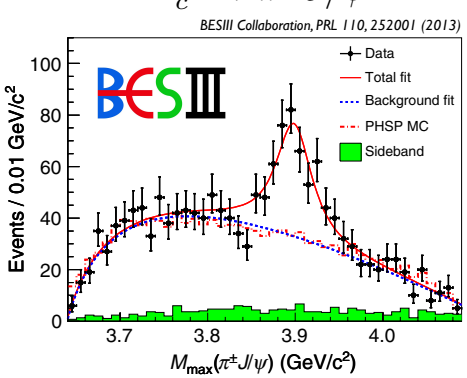
Jefferson Lab

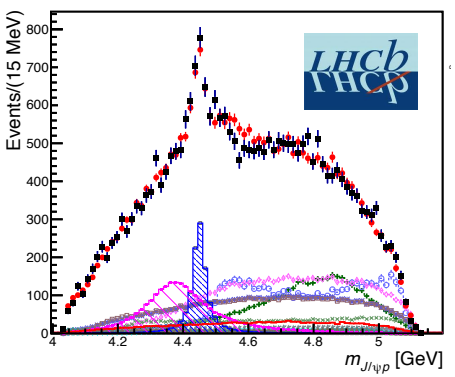
Experimental evidence for "Exotic" hadrons

Multi-quark candidates

- Numerous narrow signals
  $X, Y, Z \to J/\psi$ or Υ
- Experimentally well established:
  Belle, BaBar, CDF, BES, LHCb etc
- Interpretation?
  - Threshold cusps
  - "Molecules" of color singlets
  - Color multiplets $\quad P \to pJ/\psi$

$Z_c^{\pm} \to \pi^{\pm} J/\psi$

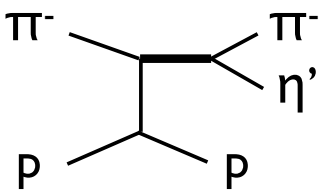


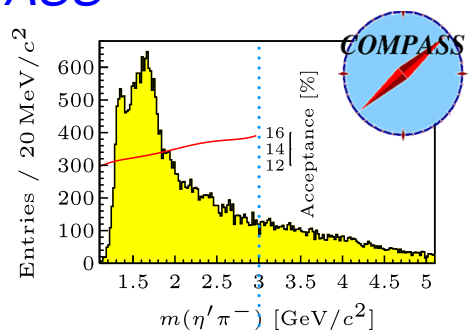


Hybrid candidates

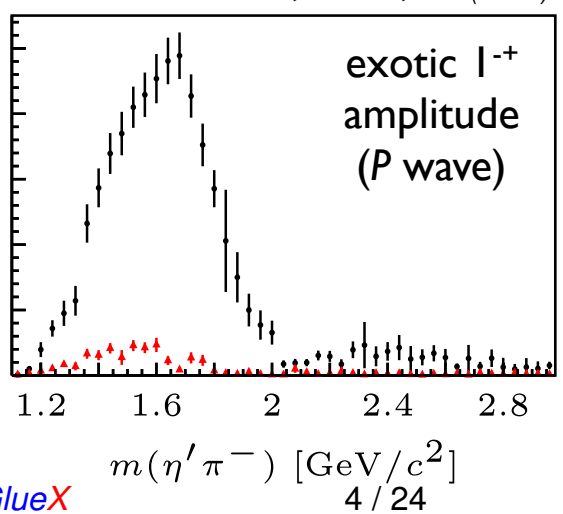
- Relatively weak evidence
- Experiments: LEAR, E852, VES, COMPASS etc $p\bar{p}, \pi^- p$

COMPASS



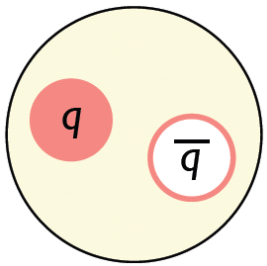


COMPASS Collab., PLB 740, 303 (2015)



Meson spectroscopy

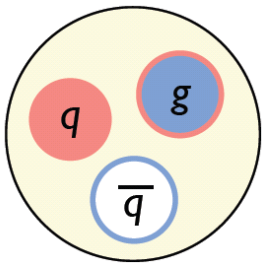
Constituent quark model



- No gluonic degrees of freedom
- Restrictions on the quantum numbers: J^{PC}:
  $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

J	$--$	$++$	$-+$	$+-$
0		0^{++}	0^{-+}	
1	1^{--}	1^{++}		1^{+-}
2	2^{--}	2^{++}	2^{-+}	
3	3^{--}	3^{++}		3^{+-}
	$q\overline{q}$ QN	"exotic" QN		

Gluonic excitations $\Rightarrow$ hybrid mesons ?



g - color octet

- Predicted by models, LQCD
- "Constituent gluon":
  LQCD: 1^{+-}, 1-1.5 GeV
- Exotic QN: excellent signature of a new degree of freedom
  no mixing with the regular $\overline{q}q$ states

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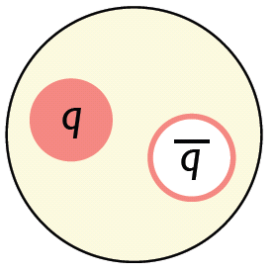

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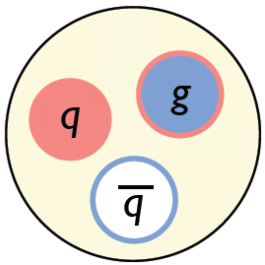

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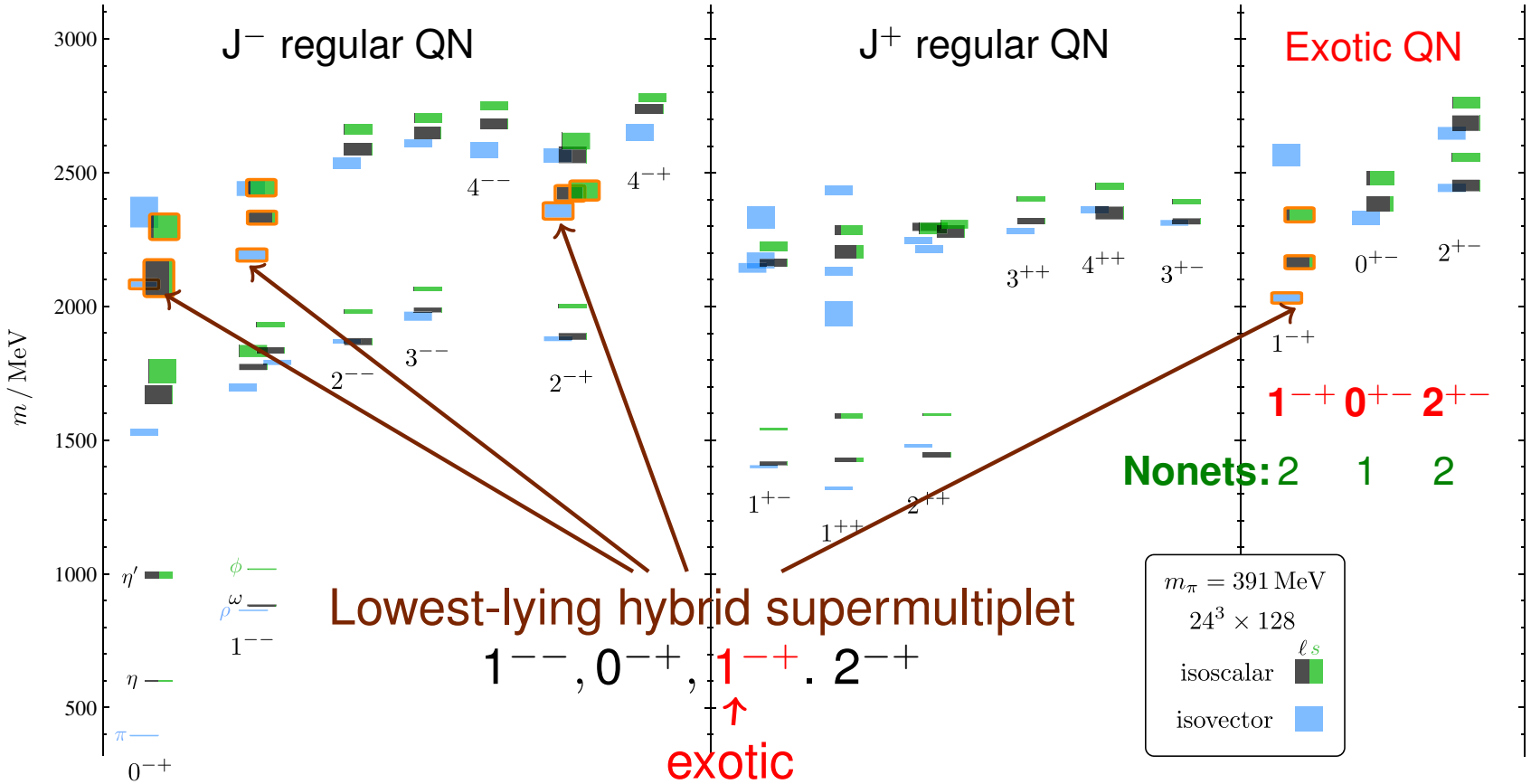
Lattice QCD - the Meson Spectra

J.Dudek et al PRD 83 (2011); PRD 84 (2011), PRD 88 (2013)

Hybrids identified: States with non-trivial gluonic fields



Calculations for $m_\pi \sim 400 MeV$

Orange frames - lightest hybrids

Hybrids: expected features and ways to detect

LQCD: Masses

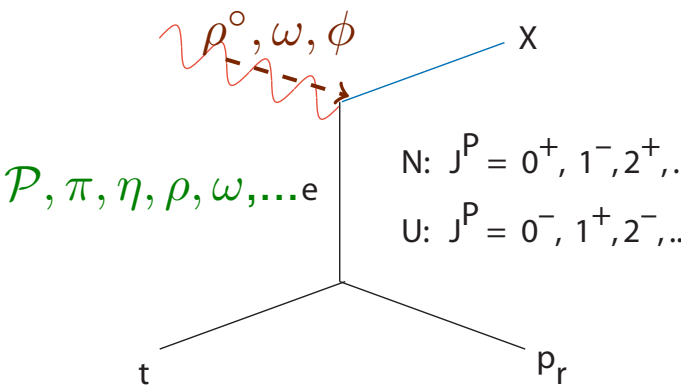
- 1^{-+} π_1, η_1... $\sim$2.0 – 2.4 GeV/c^2
  0^{+-} $b_\circ, h_\circ$... $\sim$2.3 – 2.5 GeV/c^2
  2^{+-} b_2, h_2... $\sim$2.4 – 2.6 GeV/c^2

Models: Decays

- $\Gamma_{tot} \sim 0.1 - 0.5$ GeV/c^2
- Final states: multiple $\pi^\pm$ and γ

No calculations for the decay widths, couplings or cross sections so far.

Photoproduction by linearly polarized photons



Exchange particle		Final states	
$\mathcal{P}$	0^{++}	$2^{+-}, 0^{+-}$	b°, h, h'
π°	0^{-+}	2^{+-}	b_2°, h_2, h_2'
$\pi^\pm$	0^{-+}	1^{-+}	$\pi_1^\pm$
ω	1^{--}	1^{-+}	π_1, η_1, η_1'

Can couple to all 3 exotic nonets

How to detect the hybrids?

- Detect the final states (exclusive reactions)
- Identify the QN using the Partial Wave Analysis (PWA)
  Photon linear polarization - a filter on *naturality* - helps

GlueX Experiment

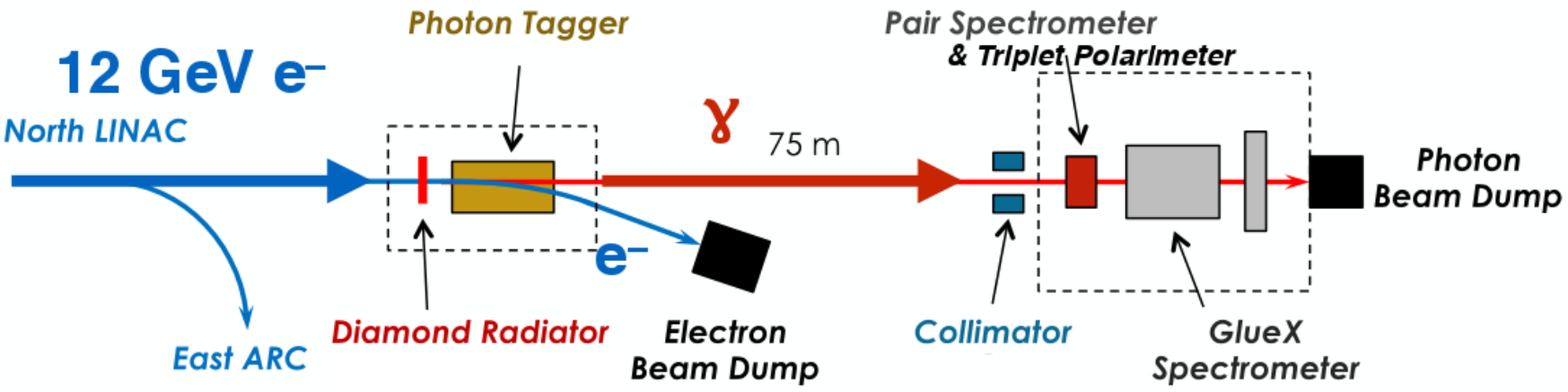
- GlueX Features
  - Hermeticity and uniform acceptance
  - High statistics
  - Beam: Coherent Bremsstrahlung $\Rightarrow$ linearly polarized photons in coherent peak
- Considerable theoretical support for the PWA (JPAC)
- Approved beam time
  - *GlueX-I* 120 days at $\sim$10 MHz γ/peak , $\mathcal{L}_{int} \sim 0.1$ fb^{-1}
  - *GlueX-II,III* 220 days at $\sim$50 MHz γ/peak with DIRC $\mathcal{L}_{int} \sim 1$ fb^{-1}

The GlueX Collaboration

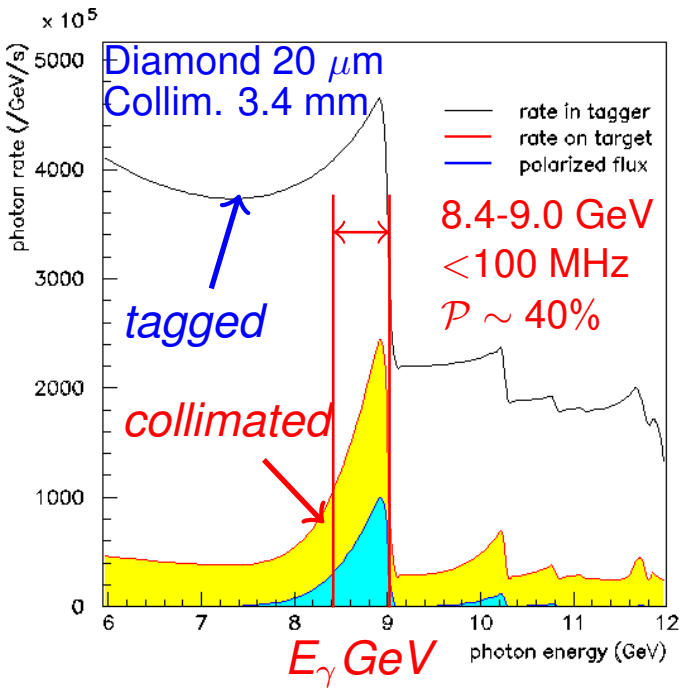
Arizona State, Athens, Carnegie Mellon, Catholic University, Univ. of Connecticut, Florida International, Florida State, George Washington, Glasgow, GSI, Indiana University, ITEP, Jefferson Lab, U. Mass. Amherst, MIT, MEPhi, Norfolk State, North Carolina A&T, Univ. North Carolina Wilmington, Northwestern, Santa Maria, University of Regina, W&M, Wuhan, and Yerevan Physics Institute.

Over 120 collaborators from 25 institutions.

Hall D/GlueX Photon beam line



- 12 GeV e^- beam $0.05 - 2.2$ μA
- Coherent Bremsstrahlung on diamond crystal
- $20 - 50$ μm diamond: coherent <25 μrad
- Collimation to suppress the incoherent part
- Coherent peak $8.4 - 9.0$ GeV $\quad \mathcal{P} \sim 40\%$
  Photon flux 10-100 MHz in the peak
- Energy/polarization measured:
  - Tagger spectrometer σ_E/E ~0.1%
  - Triplet polarimeter $\gamma e^- \to e^- e^+ e^- \Rightarrow$ $\sigma_{\mathcal{P}}/\mathcal{P}$ ~2%



Hall D/GlueX Spectrometer and DAQ

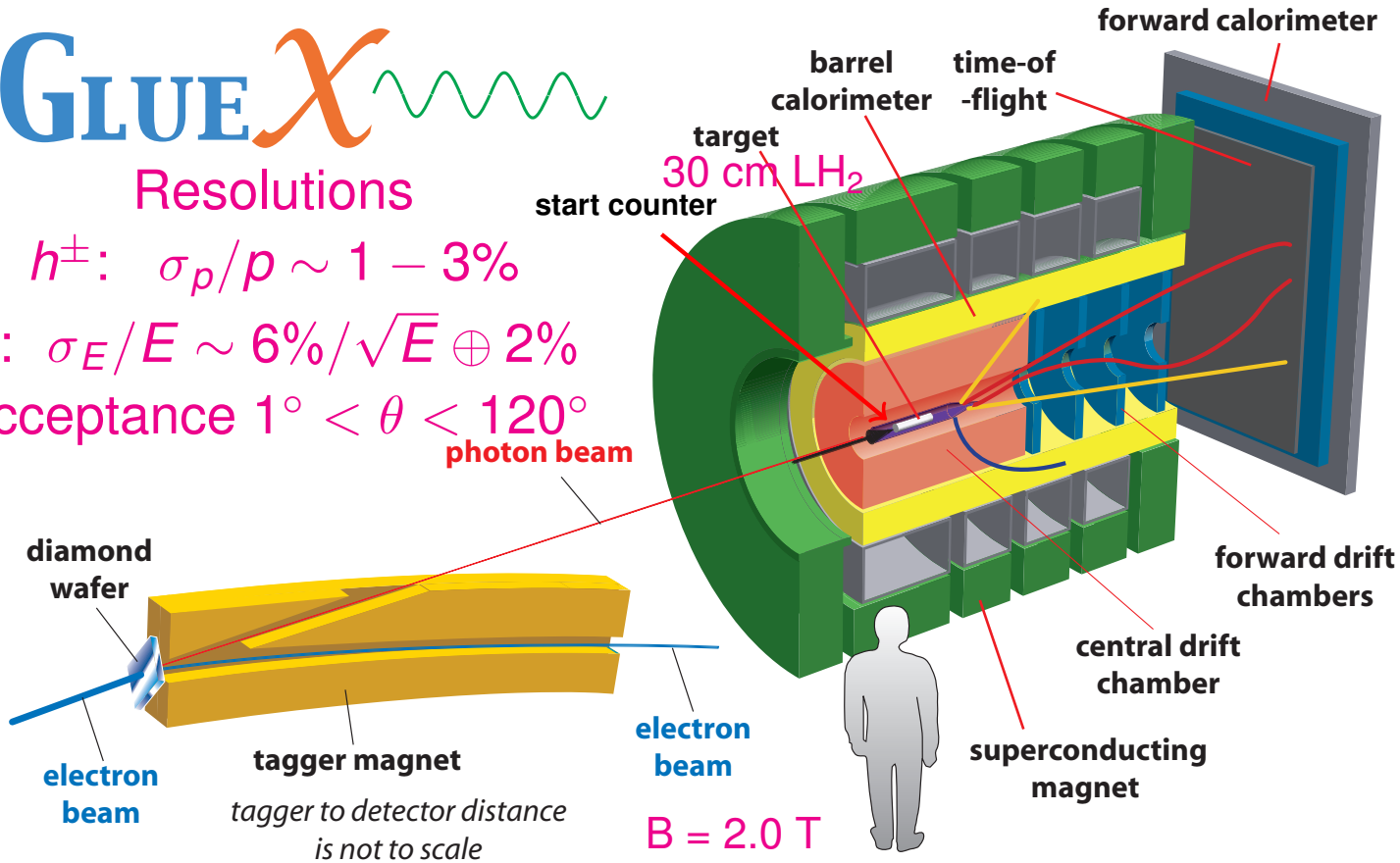
GLUEX

Resolutions

$h^{\pm}$: $\sigma_p/p \sim 1-3\%$

γ: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$

Acceptance $1^\circ < \theta < 120^\circ$



Detectors

- CDC, FDC
- BCAL, FCAL
- TOF, ST

Plans to add

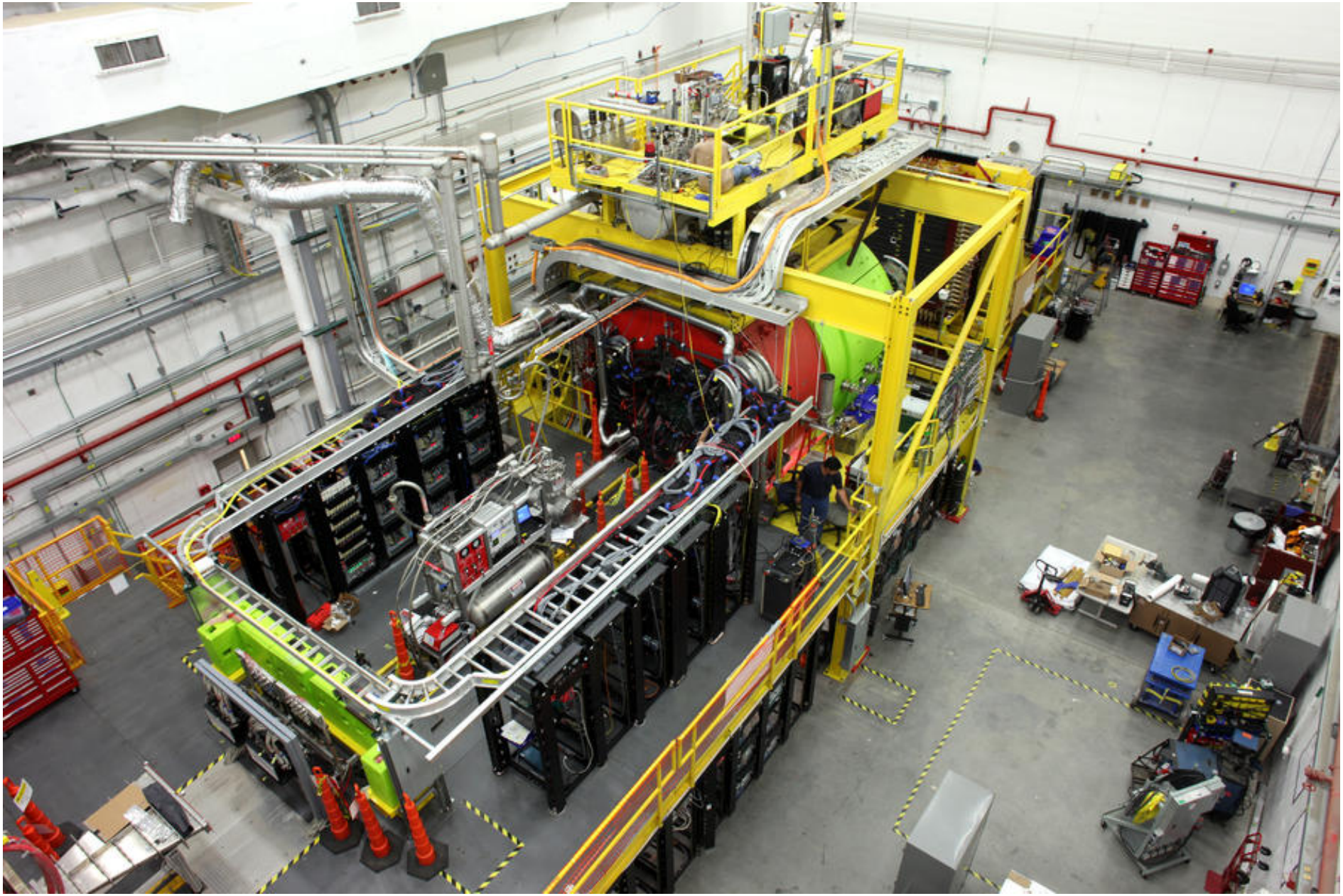
- 2018 L3
- 2019 DIRC

Photoproduction γp 15 kHz for a 100 MHz beam

Beam 10 MHz/GeV: inclusive trigger 20 kHz $\Rightarrow$ DAQ $\Rightarrow$ tape

Beam 50 MHz/GeV: inclusive trigger 100 kHz $\Rightarrow$ DAQ $\Rightarrow$ L3 farm $\Rightarrow$ tape

Hall D

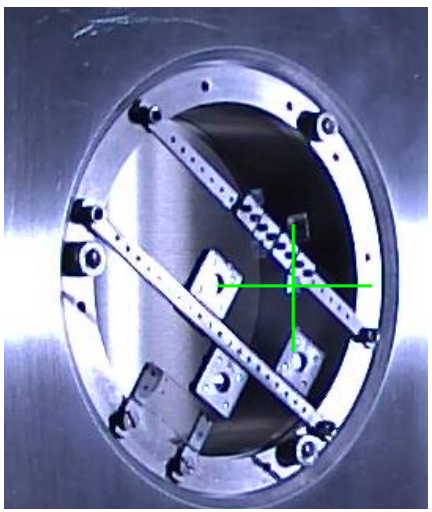


Hall D/GlueX Data taking Status

- Fall 2014 - Spring 2015: commissioning
- Spring 2016 12 GeV Engineering run
  - Commissioning is complete
  - Data for early physics results
    $\sim$ 22 G events recorded, 7 G events fully meet the specs
- Spring 2017 11.65 GeV Physics run
  - 50 G events, $\mathcal{L}_{int} \sim 20$ pb^{-1}/peak (20% of GlueX-I)
  - Plans to finish the data processing by mid-July

Hall D/GlueX Beam: Coherent Bremsstrahlung

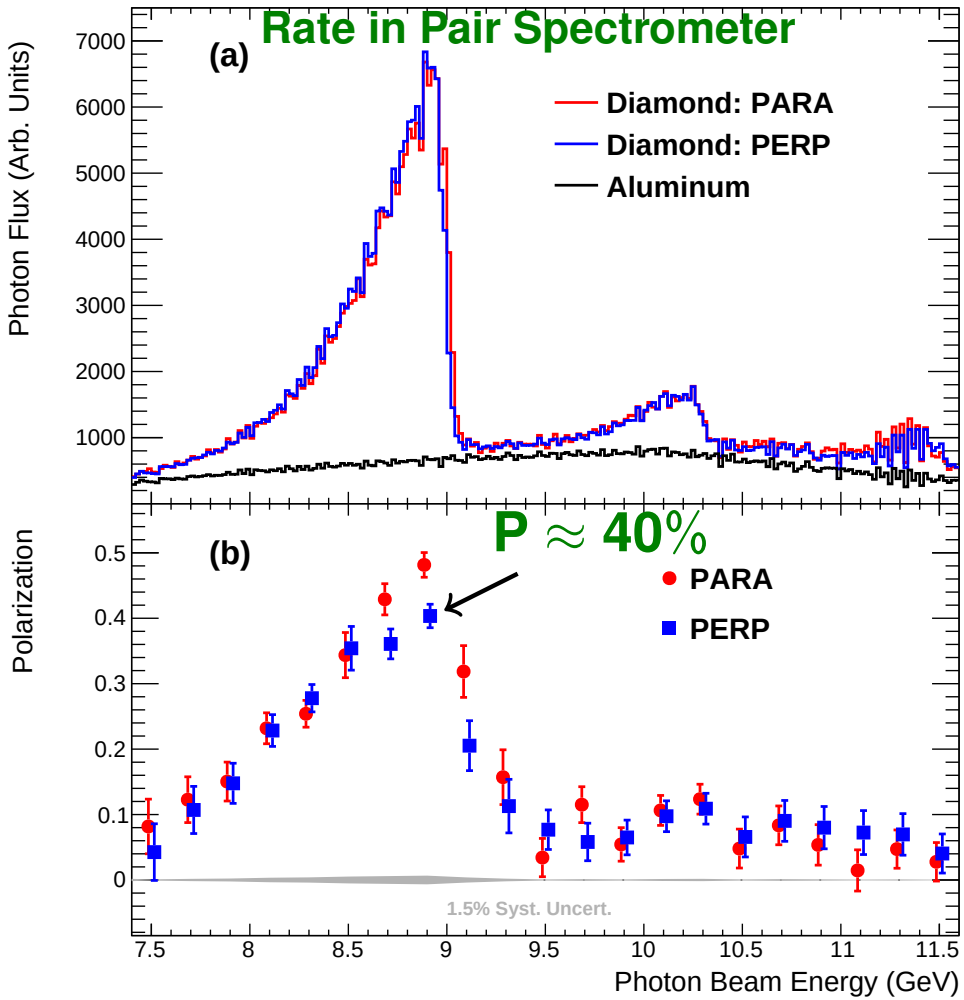
- 20-50 μm thick diamond radiators
- Precision alignment using a goniometer



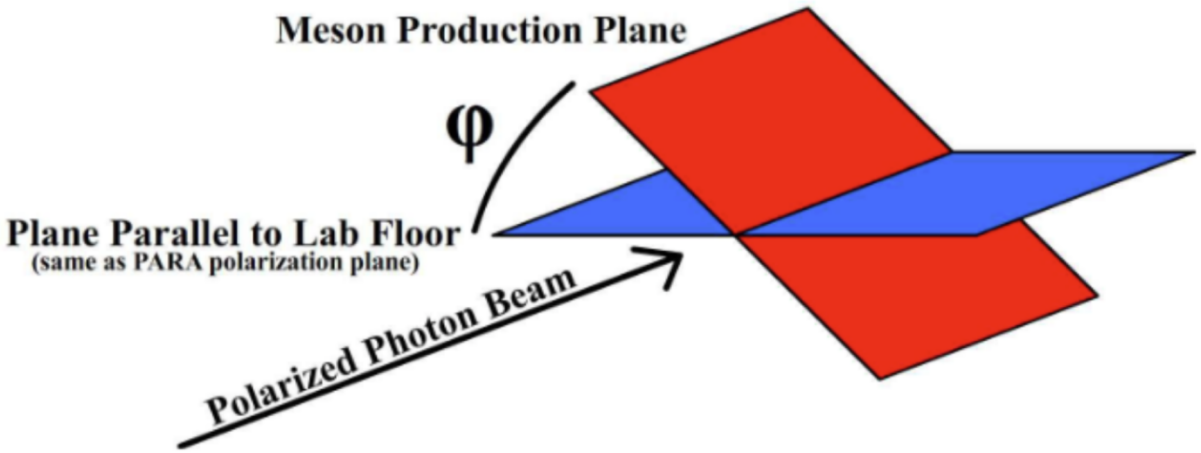
Polarization measurements

- Derived from the spectrum
- Triple polarimeter $\gamma e^- \to e^+ e^- e^-$
- Processes like $\gamma p \to \rho^\circ p$

Rotating polarization plane:
Two diamond orientations at 90°:
Reduces asymmetries of the apparatus!



Pseudoscalar Beam Asymmetries



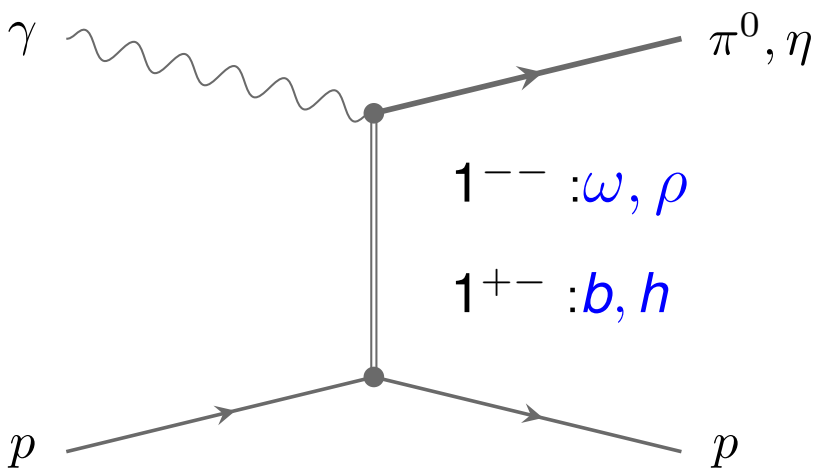
Polarization $\parallel$ $\quad \frac{d\sigma}{d\varphi_{\parallel}} \quad \propto \quad (1 - P\Sigma\cos(2\varphi))$

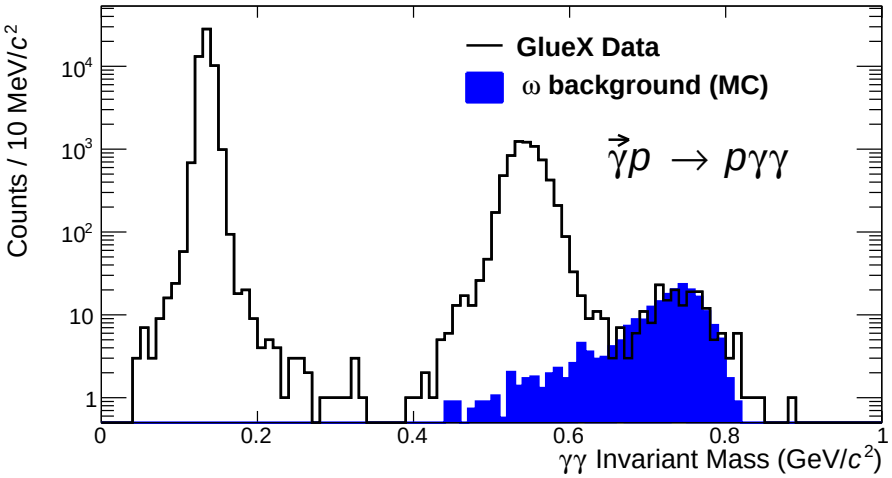
Polarization $\perp$ $\quad \frac{d\sigma}{d\varphi_{\perp}} \quad \propto \quad (1 - P\Sigma\cos(2\varphi - \pi))$

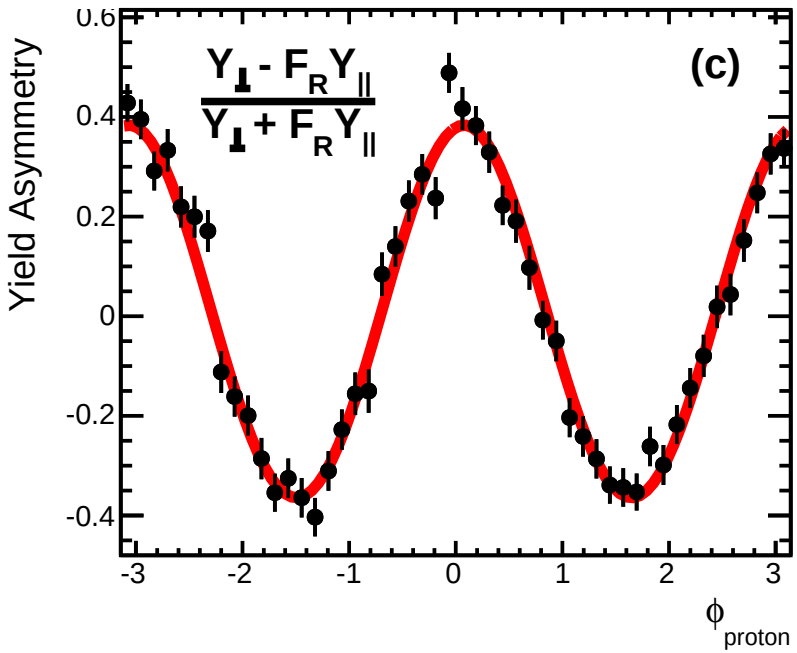
Cancel systematic effects by measuring the asymmetry:

$$A(\varphi) = \frac{\frac{d\sigma}{d\varphi_{\perp}} - \frac{d\sigma}{d\varphi_{\parallel}}}{\frac{d\sigma}{d\varphi_{\perp}} + \frac{d\sigma}{d\varphi_{\parallel}}} \approx P\Sigma\cos(2\varphi)$$

Beam Asymmetries of π^0, η







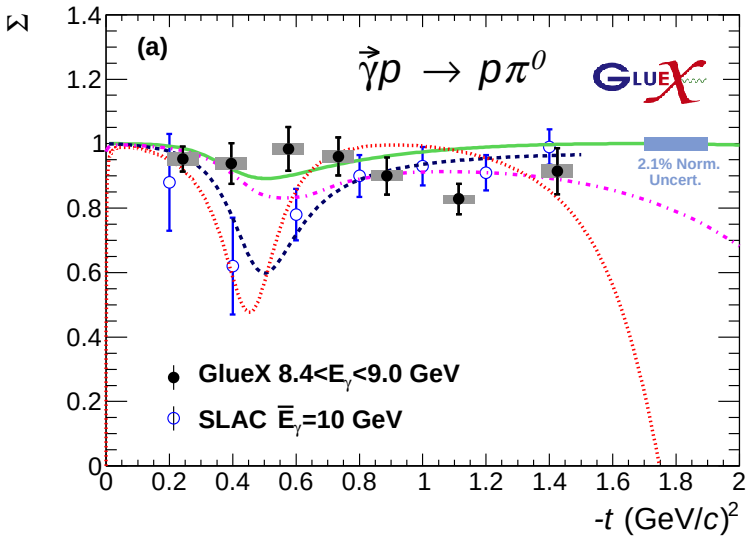
Σ sensitive to exchanged J^{PC}

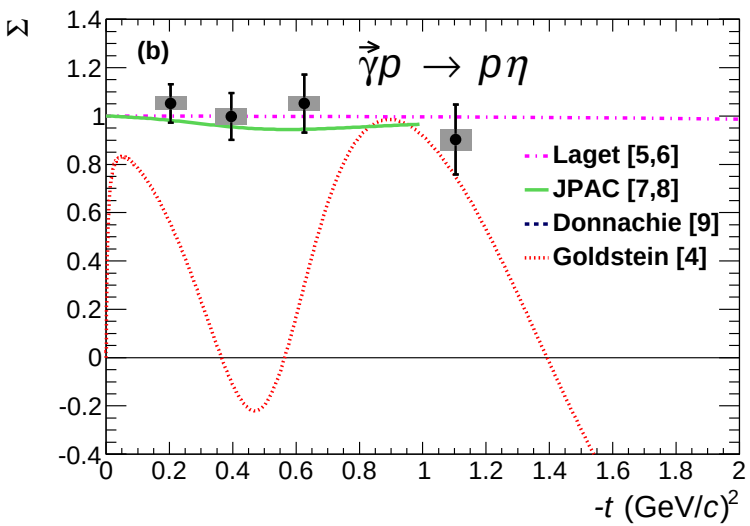
$$\Sigma = \frac{|\omega+\rho|^2 - |h+b|^2}{|\omega+\rho|^2 + |h+b|^2}$$ [PRD 92 (2015) 074013]

$\Sigma \approx +1$ for 1^{--} exchange
$\Sigma \approx -1$ for 1^{+-} exchange

$$A = P\Sigma \cos 2\phi$$

Beam Asymmetries of π^0, η





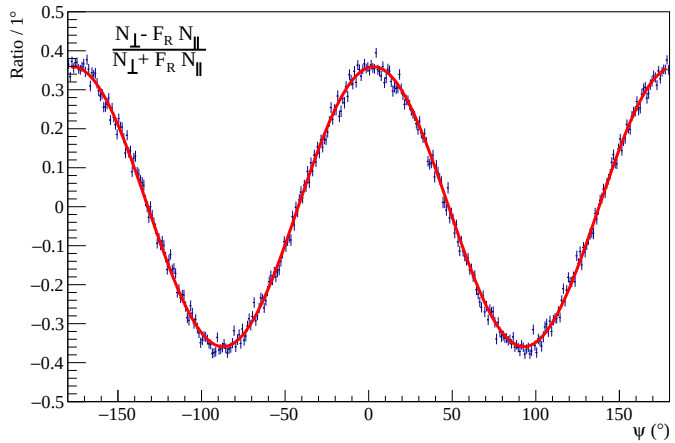
- The results: $\Sigma \approx +1$
- Vector exchange dominates
- No observed dip at $-t = 0.5$ (GeV$/c)^2$
- Comparison with several models
- First measurement for η at this energy
- Accepted in PRC [arXiv:1701.08123]

- Planned:
  Measurement for η' with 2017 data

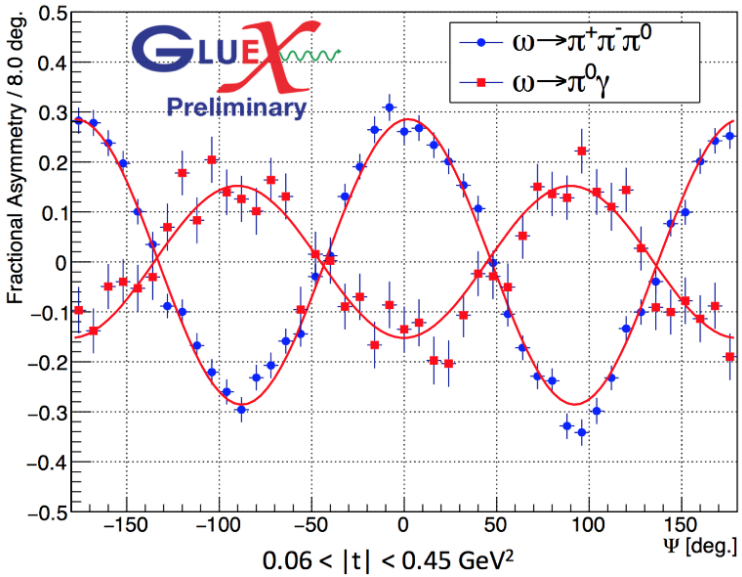
Beam Asymmetries of Vectors

- ω 2 decays modes: $\pi^+\pi^-\pi^0$ and $\pi^0\gamma$:
  - Expectations: $\Sigma_{3\pi}/\Sigma_{\pi^0\gamma} = -2$
  - Measurement: $\Sigma_{3\pi}/\Sigma_{\pi^0\gamma} = -1.88 \pm 0.13$
- High statistics for ρ, ω: plans to measure the Spin-Density Matrix elements

Preliminary: ρ Asymmetry



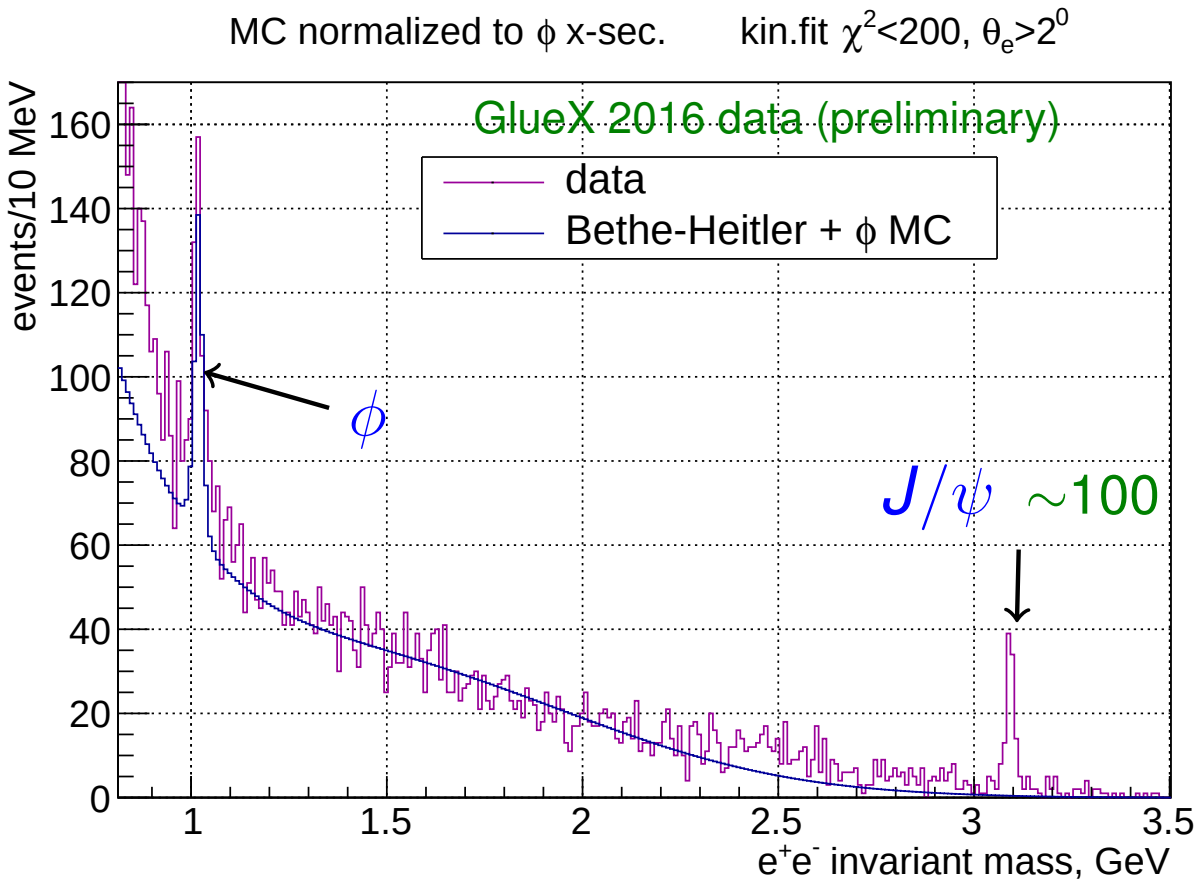
Preliminary: ω Asymmetry



Photoproduction of J/ψ close to threshold

$$\gamma + p \to J/\psi + p, \quad J/\psi \to e^+e^-$$

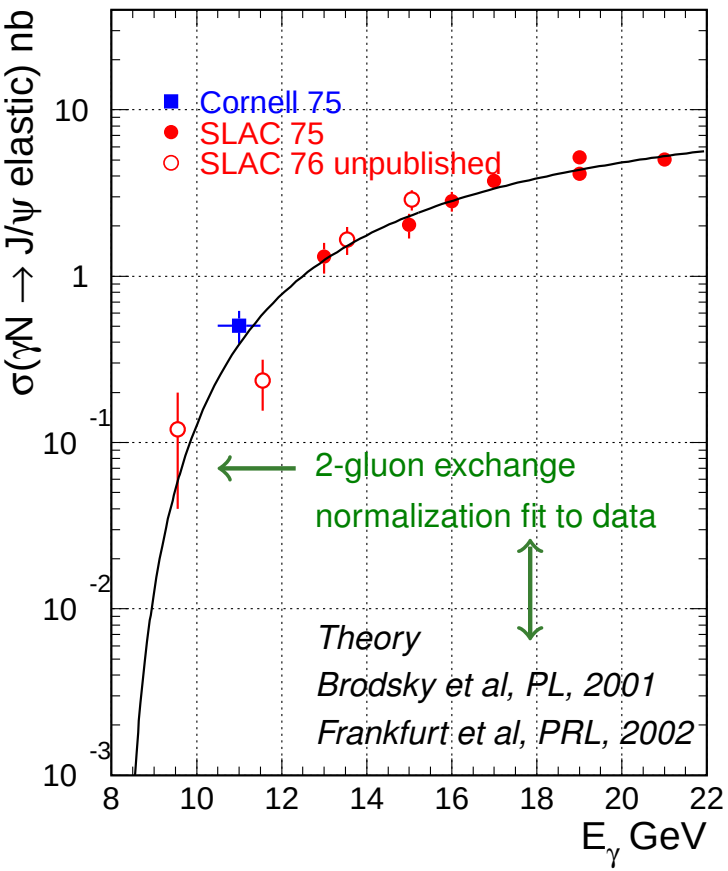
- All 2016 data: exclusive events $p + e^+e^-$
- e^+e^- PID using the electromagnetic calorimeters BCAL and FCAL
- Kinematic fit with the beam energy from the tagger

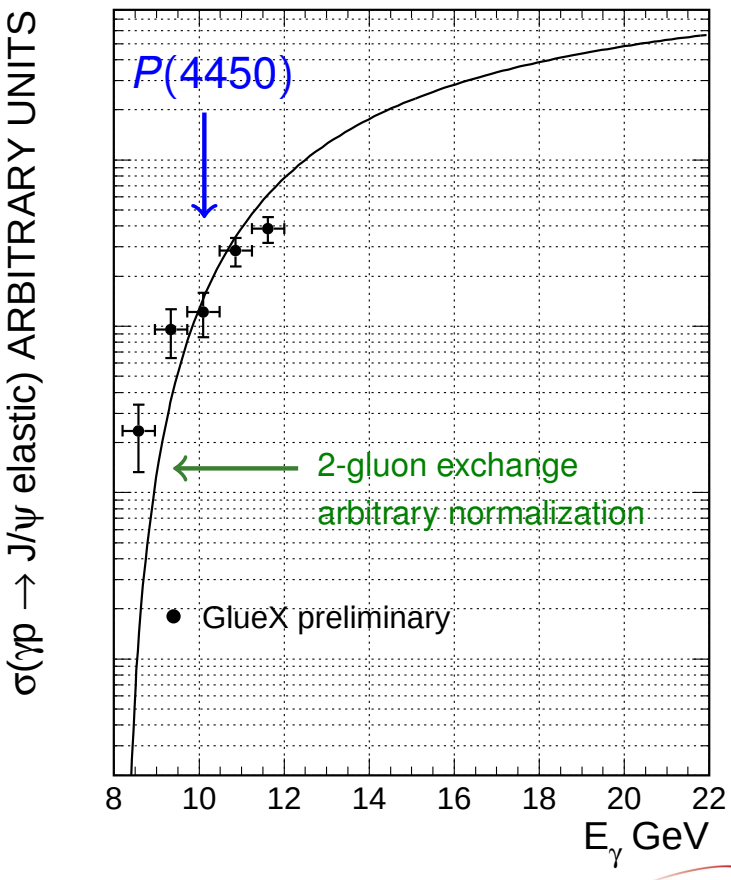


Photoproduction of J/ψ close to threshold

Planned measurements, after adding the 2017 Spring data:

- $\sigma(E)$ - sensitive to gluons at high x
- t-slope
- Limits on the pentaquark yield (the mass resolution $\sim$6 MeV/c^2)





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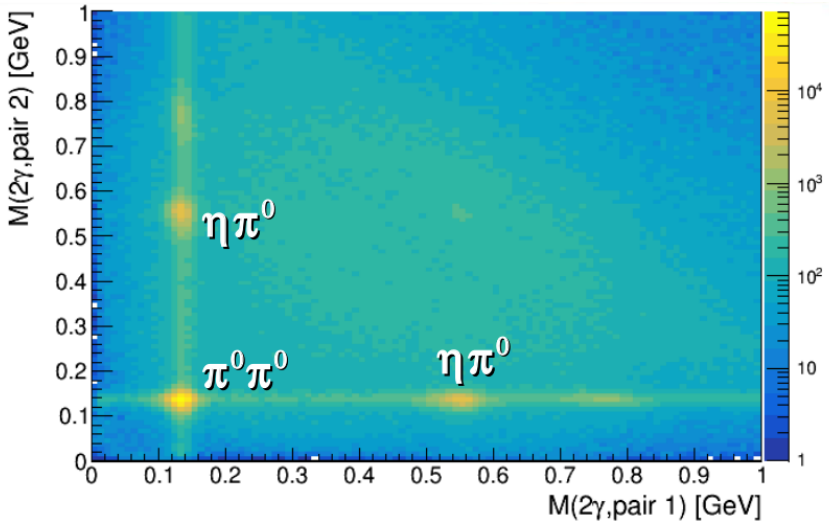
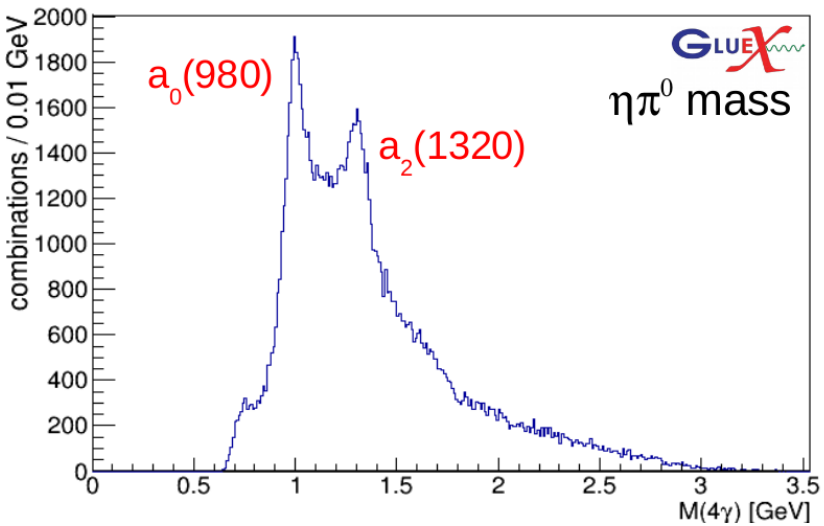
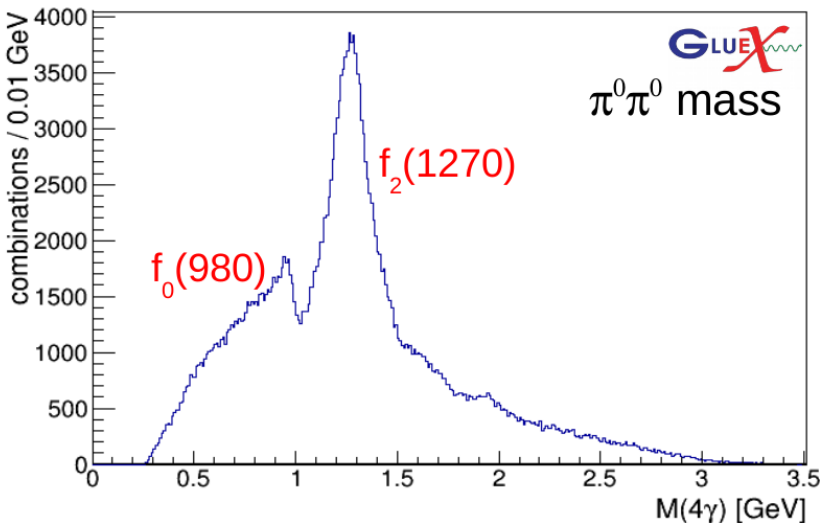
Event Reconstruction and Signals Observed

From 2016 data: $\gamma p \to 4\gamma\, p$

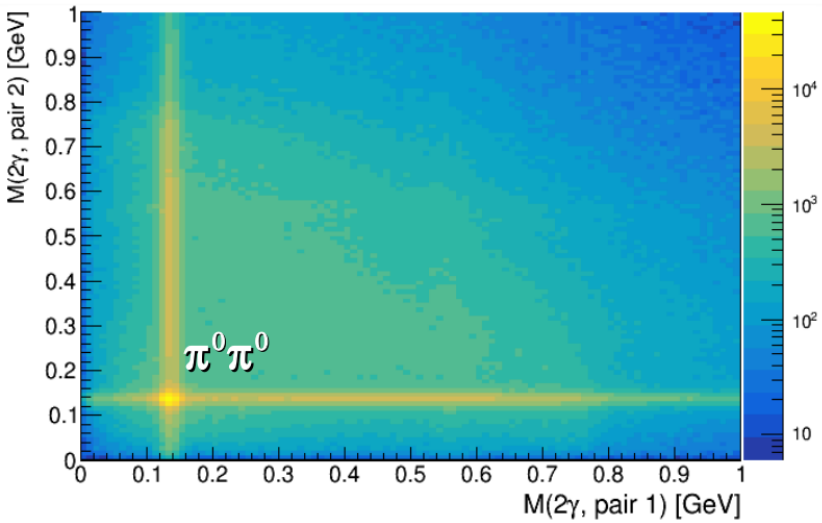


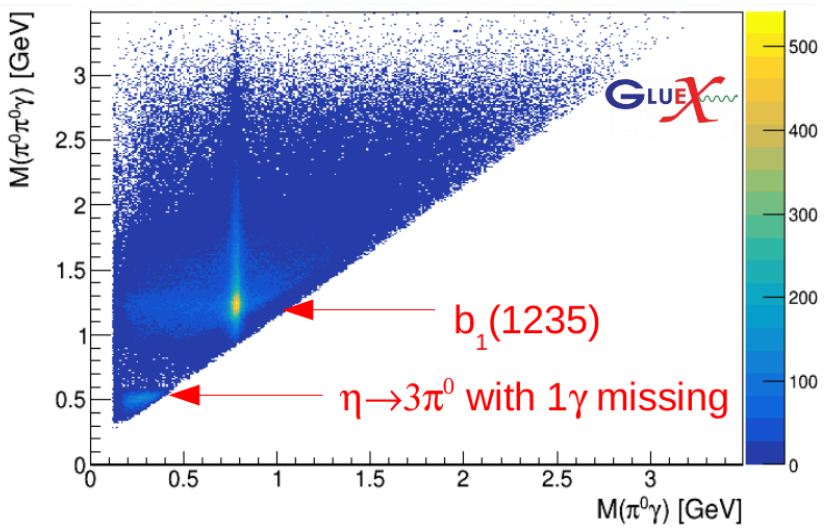


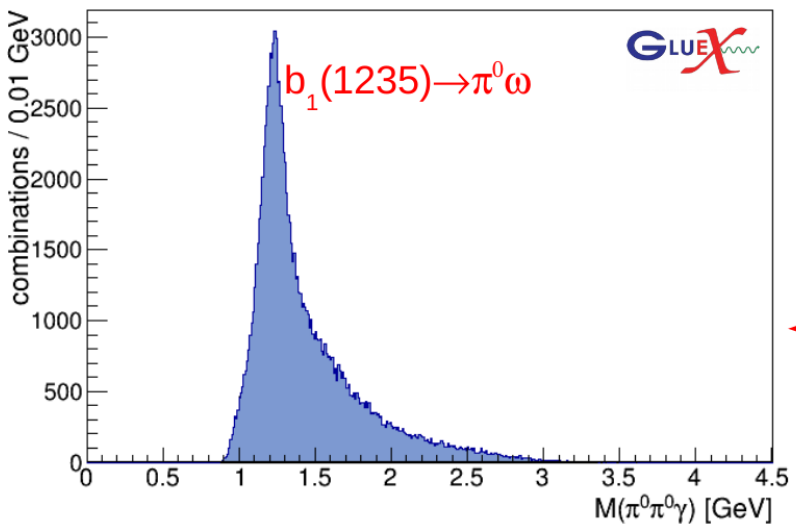


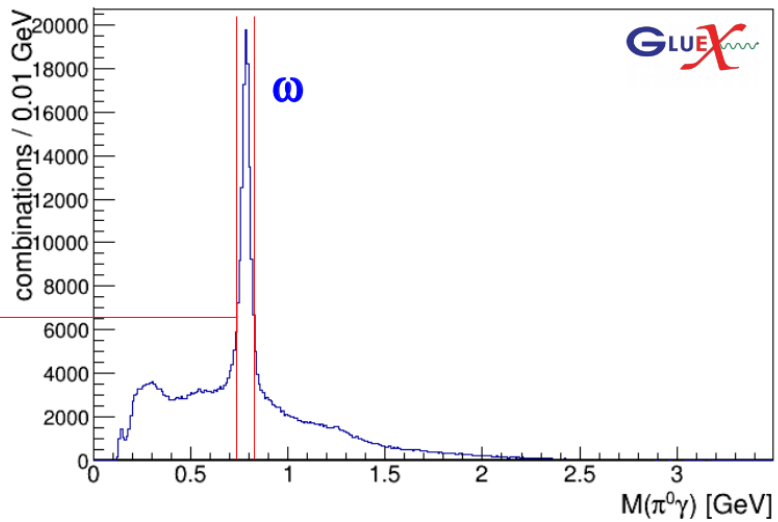
Event Reconstruction and Signals Observed

From 2016 data: $\gamma p \to 5\gamma\, p$









Outlook

- Analysis of the Spring 2017 data:
  - Measurements of various beam asymmetries
  - Measurement of the J/ψ cross section
  - Measurements of the Spin Density Matrix for the lower vectors
  - PWA of the known lower resonances (1.0 - 1.5 GeV/c^2)
- Next run is scheduled for the Fall 2017 (some uncertainty)
- 2019-2022 GlueX at "high" intensity 50 MHz in the peak
  focus on hidden strangeness and hyperon resonances
- Other approved experiments:
  - η Radiative Decay Width via Primakoff effect
  - Charged pion polarizability via Primakoff effect
- More Proposals and Letters of Intent are on the way

APPENDIX

Hall D Physics Program

Proposal/ experiment	Sta- tus	Title	Beam days	PAC #
E12-06-102	A	Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	120	30
E12-10-011	A-	A Precision Measurement of the η Radiative Decay Width via the Primakoff Effect	79	35
E12-13-003	A	An initial study of hadron decays to strange final states with GlueX in Hall D	200	40
E12-13-008	A-	Measuring the Charged Pion Polarizability in the $\gamma\gamma \to \pi^+\pi^-$ Reaction	25	40
E12-12-002	A	A study of meson and baryon decays to strange final states with GlueX in Hall D	220	42
C12-14-004	C2	Eta Decays with Emphasis on Rare Neutral Modes: The JLab Eta Factory Experiment (JEF) *partly concurrent with GlueX* ($\eta \to 3\pi$)	(130)	42
LOI12-15-001		Physics with secondary K_L° beam		43
LOI12-15-006		ω-production on nuclei		43

Experimental Evidence for Exotic Hybrids 1^{-+}

mass	reaction	experiment	mass	width
1400	$\pi^- p \to \eta\pi^\circ n$	GAMS, 100 GeV 1988	1406±20	180± 20
	$\pi^- p \to \eta\pi^- p$	BKEI, 6 GeV 1993	1320± 5	140± 10
	$\pi^- p \to \eta\pi^- p$	MPS, 18 GeV 1997	1370±60	380±100
	$\pi^- p \to \eta\pi^\circ n$	E-852, 18 GeV 2007	1260±40	350± 60
	$\bar{p}p \to \eta\pi^\circ\pi^\circ$	CBAR, 0 GeV 1999	1360±25	360± 80
	$\bar{p}n \to \eta\pi^\circ\pi^-$	CBAR, 0 GeV 1998	1400±30	220± 90
1600	$\pi^- A \to \pi^+\pi^-\pi^- A$	VES, 37 GeV 2000	1610±20	290± 30
		VES, 37 GeV 2005	*none*	
		COMPASS, 190 GeV 2009	1660±60	270± 60
	$\pi^- p \to \pi^+\pi^-\pi^- p$	E-852, 18 GeV 2002	1590±40	170± 60
		E-852, 18 GeV 2006	*none*	
		COMPASS, 190 GeV 2015	*in progress*	
	$\gamma p \to \pi^+\pi^+\pi^- n$	CLAS, 5. GeV 2008	*none*	
	$\pi^- p \to \pi^-\pi^\circ\pi^\circ p$	E-852, 18 GeV 2006	*none*	
		COMPASS, 190 GeV 2015	*in progress*	
	$\pi^- p \to \eta'\pi^- p$	E-852, 18 GeV 2001	1600±40	340± 50
		COMPASS, 190 GeV 2015	*in progress*	
	$\pi^- A \to \eta'\pi^- A$	VES, 37 GeV 2005	1600	300
		GAMS, 100 GeV 2005	1600	300
	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$	E-852, 18 GeV 2004	1710±60	400± 90
	$\pi^- p \to \omega\pi^-\pi^\circ p$	E-852, 18 GeV 2005	1660±10	190± 30
	$\pi^- A \to \omega\pi^-\pi^\circ A$	VES, 18 GeV 2005	1600	300
2000	$\pi^- p \to b_1\pi, f_1\pi$	E-852, 18 GeV 2005	2010±25	230± 80

Experimental Evidence for Exotic Hybrids 1^{-+}

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	$\pi^- p \to \eta\pi^- p$	[illegible]	[illegible]	[illegible]
	$\pi^- p \to \eta\pi^\circ n$			
	$\bar{p}p \to \eta\pi^\circ\pi^\circ$			
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Signal: solid, seen by several experiments
Interpretation: unclear, but not a hybrid:
1400 dynamic origin; 4-quark state

Experimental Evidence for Exotic Hybrids 1^{-+}

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1400	$\pi^- p \to \eta\pi^\circ n$	GAMS, 100 GeV 1988	1406±20	180± 20
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	$\pi^- p \to \pi^+\pi^-\pi^- p$			
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	$\pi^- p \to \eta'\pi^- p$	E-852, 18 GeV 2001	1600±40	340± 50
		COMPASS, 190 GeV 2015	*in progress*	
	$\pi^- A \to \eta'\pi^- A$	VES, 37 GeV 2005	1600	300
		GAMS, 100 GeV 2005	1600	300
	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$	E-852, 18 GeV 2004	1710±60	400± 90
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Signal: solid, seen by several experiments
Interpretation: unclear, but not a hybrid:
1400 dynamic origin; 4-quark state

Signal: 3π - controversial - leakage from 2^{-+}
COMPASS: confirmation in $\pi^- A$
COMPASS: in progress $\pi^- p$
$\eta'\pi^-$ - promising
Interpretation: may be a hybrid
1600 needs more analysis and data

Experimental Evidence for Exotic Hybrids 1^{-+}

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		VES, 37 GeV 2005	*none*	
		COMPASS, 190 GeV 2009	1660±60	270± 60
	$\pi^- p \to \pi^+\pi^-\pi^- p$	E-852, 18 GeV 2001	1500±40	170± 60
	$\gamma p \to \pi^+\pi^+\pi^- n$			
	$\pi^- p \to \pi^-\pi^\circ\pi^\circ p$			
	$\pi^- p \to \eta'\pi^- p$	E-852, 18 GeV 2001	1600±40	340± 50
		COMPASS, 190 GeV 2015	*in progress*	
	$\pi^- A \to \eta'\pi^- A$	VES, 37 GeV 2005	1600	300
		GAMS, 100 GeV 2005	1600	300
	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$	E-852, 18 GeV 2001	1665±10	210± 90
	$\pi^- p \to \omega\pi^-\pi^\circ p$	VES, 37 GeV 2005	1650	230± 30
	$\pi^- A \to \omega\pi^-\pi^\circ A$	VES, 37 GeV 2005	1650	230
2000	$\pi^- p \to b_1\pi, f_1\pi$	E-852, 18 GeV 2001	1960±30	270± 80

Signal: solid, seen by several experiments
Interpretation: unclear, but not a hybrid:
1400 dynamic origin; 4-quark state

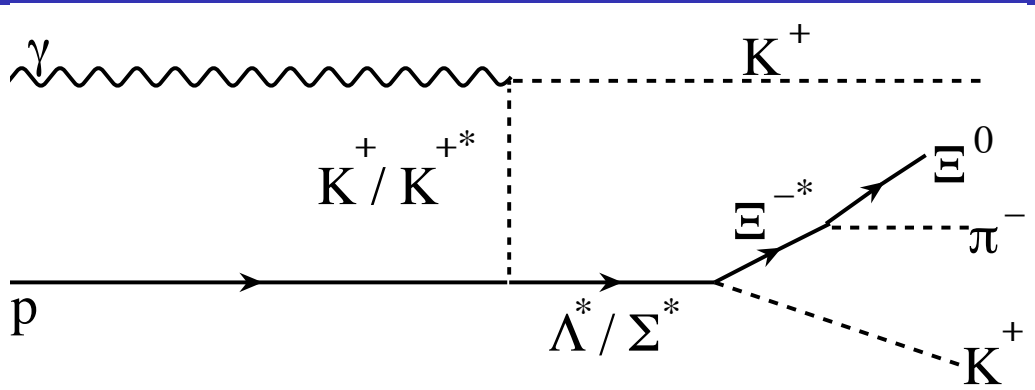
Signal: 3π - controversial - leakage from 2^{-+}
COMPASS: confirmation in $\pi^- A$
COMPASS: in progress $\pi^- p$
$\eta'\pi^-$ - promising
Interpretation: may be a hybrid
1600 needs more analysis and data

Signal: weak - one experiment only
Interpretation: may be a hybrid
expected decay modes
2000 needs more data

Hyperon Spectroscopy in Photoproduction

GlueX 2-nd stage: 2019-..

- With DIRC
- High beam intensity
  50 MHz in peak
- QN of hyperons/cascades
  Like CLAS ($\Lambda(1405)$: $\frac{1}{2}^-$)



Baryon 2016: discussed by A.Gillitzer on Tuesday

State	Status	J^P	Width (MeV)
Ξ	****	$1/2^+$	0
$\Xi(1530)$	****	$3/2^+$	9
$\Xi(1620)$	*	$?^?$	22
$\Xi(1690)$	***	$?^?$	<30
$\Xi(1820)$	***	$3/2^-$	24
$\Xi(1950)$	***	$?^?$	60 ± 20
$\Xi(2030)$	***	$\geq 5/2^?$	20^{+15}_{-5}
$\Xi(2120)$	*	$?^?$	<20
$\Xi(2250)$	**	$?^?$	<30
$\Xi(2370)$	**	$?^?$	80
$\Xi(2500)$	*	$?^?$	150