Future Spectroscopy Studies at Jefferson Lab

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[1]JLab, Hall D

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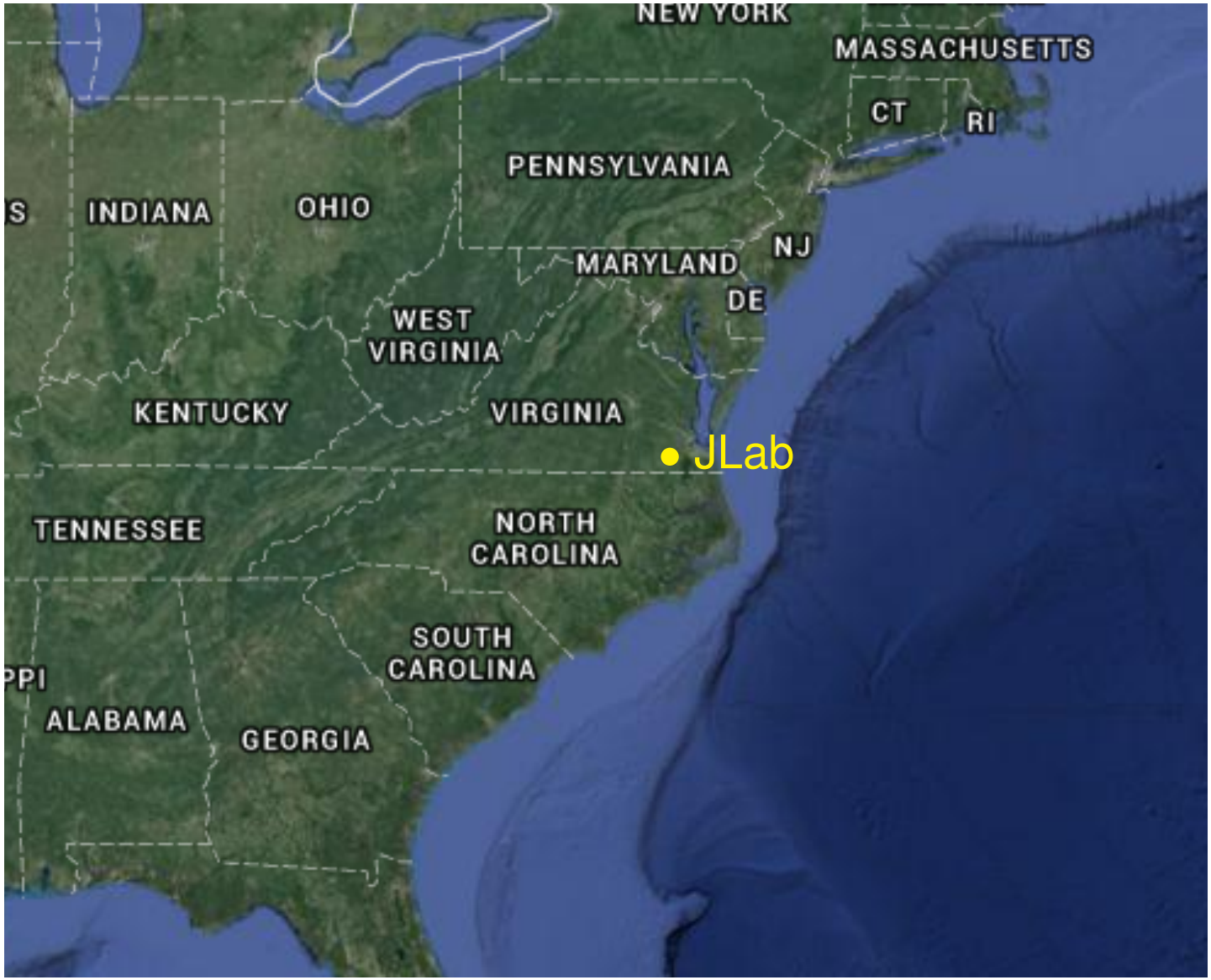
COMPASS beyond 2020
CERN, 21-22 Mar 2016

Outline

1. JLab at 12 GeV
2. Physics motivation for JLab spectroscopy program
3. Experiments at JLab: GlueX in Hall D and CLAS12 in Hall B
   - Apparatus
   - Performance of GlueX during commissioning
4. Experimental schedule

Jefferson Lab



Jefferson Lab

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Jefferson Lab History

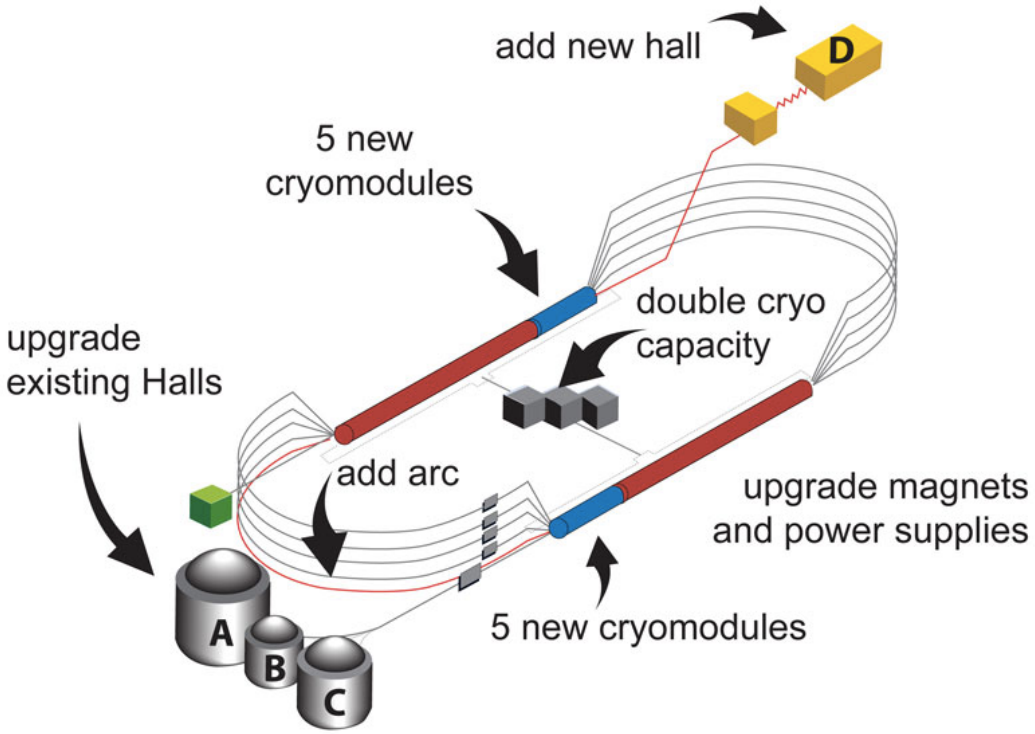
Continuous **E**lectron **B**eam **A**ccelerator (CEBAF)

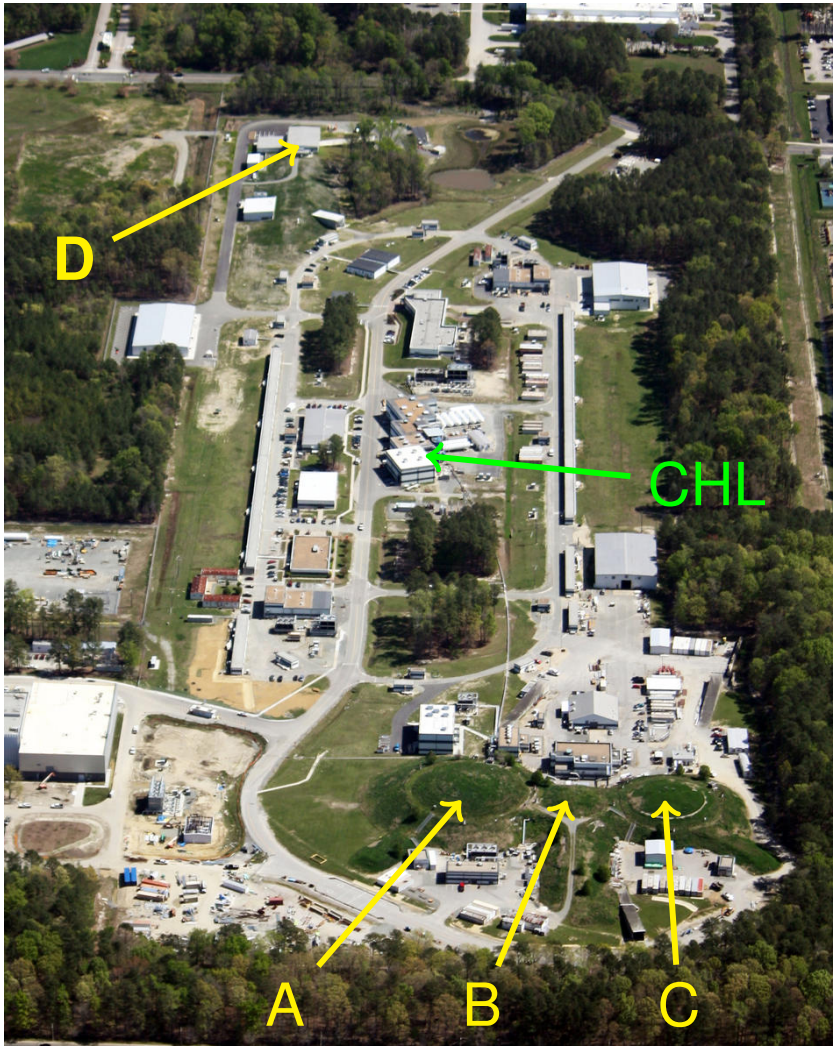
- Up to 5 passes through 2 superconducting linacs ($\sim$1500 MHz at 2°K)
- Injector: 3 independent 500 MHz beams
- Parallel delivery of 1-5 passes beams to 3 Halls
- Electron beam polarization

History:

- 1995 4 GeV CEBAF and Hall C started
- 1997 4 GeV 3 hall operations started
- 1999-2012 6 GeV operations
- 2007-2017 12 GeV Upgrade (includes a new Hall D)
- 2016 12 GeV operations started for Hall D and Hall A

CEBAF Upgrade to 12 GeV





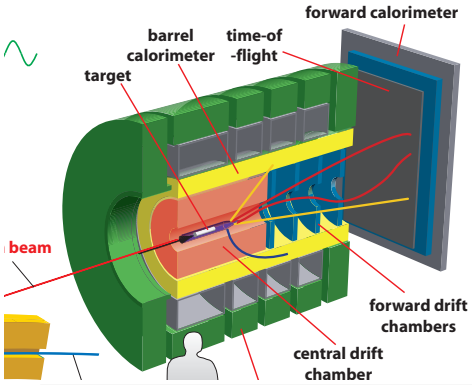
- Accelerator: 2.2 GeV/pass
- Halls A,B,C: e^- 1-5 passes $\leq$11 GeV
- Hall D: e^- 5.5 passes 12 GeV $\Rightarrow$ γ-beam
- Beam separation to 4 Halls at 250 MHz

Upgrade Status

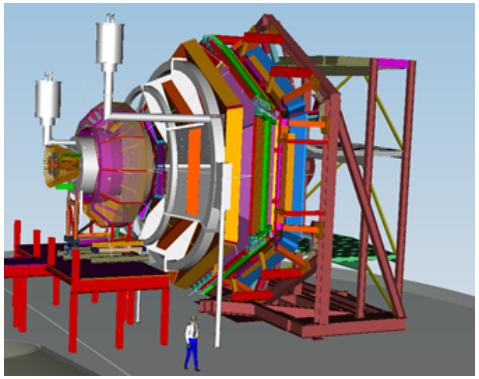
- 12 GeV started in Feb 2016
- Halls A,D: running; B,C: start in 2017

JLab Experimental Halls

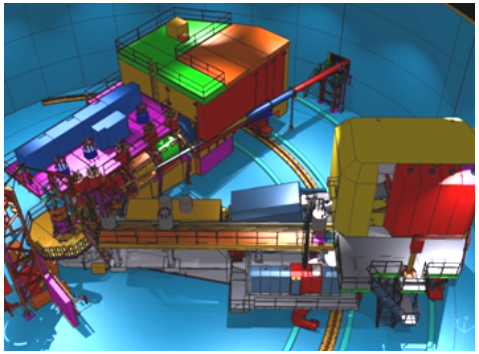
Hall D



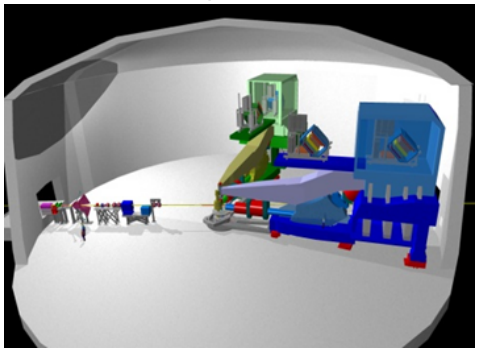
Hall B



Hall C



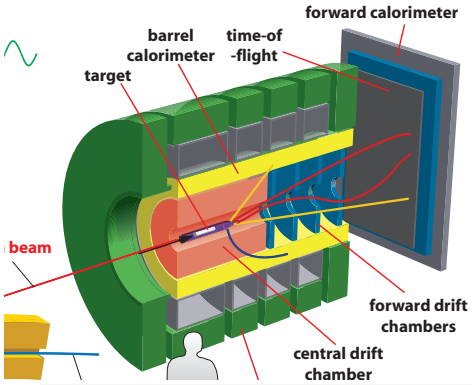
Hall A



hermeticity	large acceptance	high resolution	custom installations
12 GeV e^- $\Rightarrow$ γ	e^- 2.2–11 GeV		
γ linear polariz.	e^- longitudinal polarization		
<100 MHz/GeV	10^{35} cm^{-2}s^{-1}	10^{38} cm^{-2}s^{-1}	
$\sigma(p)/p \sim 1-3\%$	$\sigma(p)/p \sim 0.5\%$	$\sigma(p)/p \sim 0.1\%$	$\sigma(p)/p \sim 0.02\%$
spectroscopy program			

JLab Experimental Halls

Hall D



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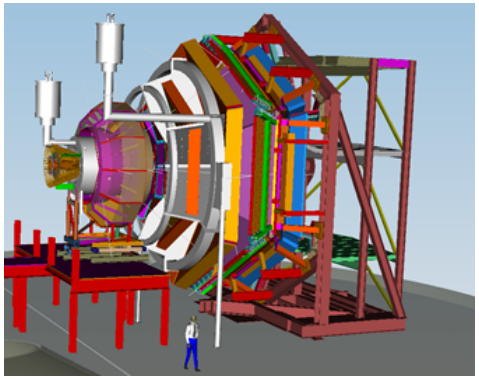

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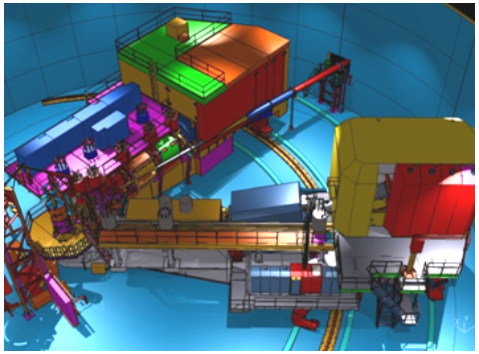

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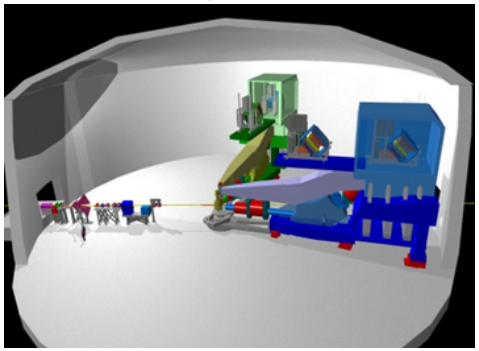

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spectroscopy program			

- Hall D: photoproduction by tagged real photons
- Hall B: photoproduction by tagged virtual photons at low Q^2

Spectroscopy of Hadrons - Highlights

Important Historic Role

- Structure - the Quark Model was motivated by hadron spectroscopy
- Forces - QCD forces were derived from the spectra of charmonium

Present Highlights

- Observation of the predicted states and identification of the observed non-exotic states
- Are there multi-quark states? Interpretation of the observed X,Y,Z stated: are they multi-quark states, or threshold effects, or something else?
- Is there a glueball?
- Are there hybrid states made of quarks and “constituent” gluons?

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The focus of the spectroscopy program at JLab for 2016-2022

Complimentary to the current COMPASS research

- a different beam will be used

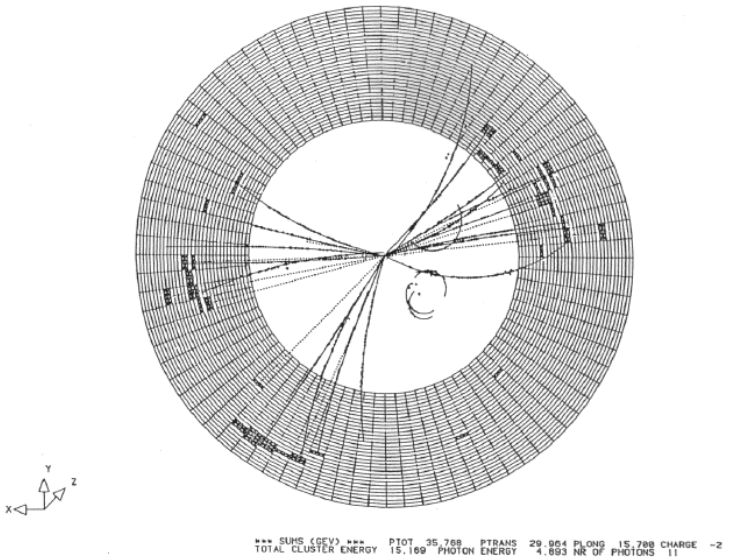
Gluons in QCD

Asymptotic Freedom

High Energy $\Longleftrightarrow$ Small Distance
Gluons self-interaction is weak

- Perturbative QCD - calculable
- Gluon Jets observed

3-jet event, JADE 1980



Confinement

Low Energy $\Longleftrightarrow$ Large Distance
Gluons self-interaction is strong

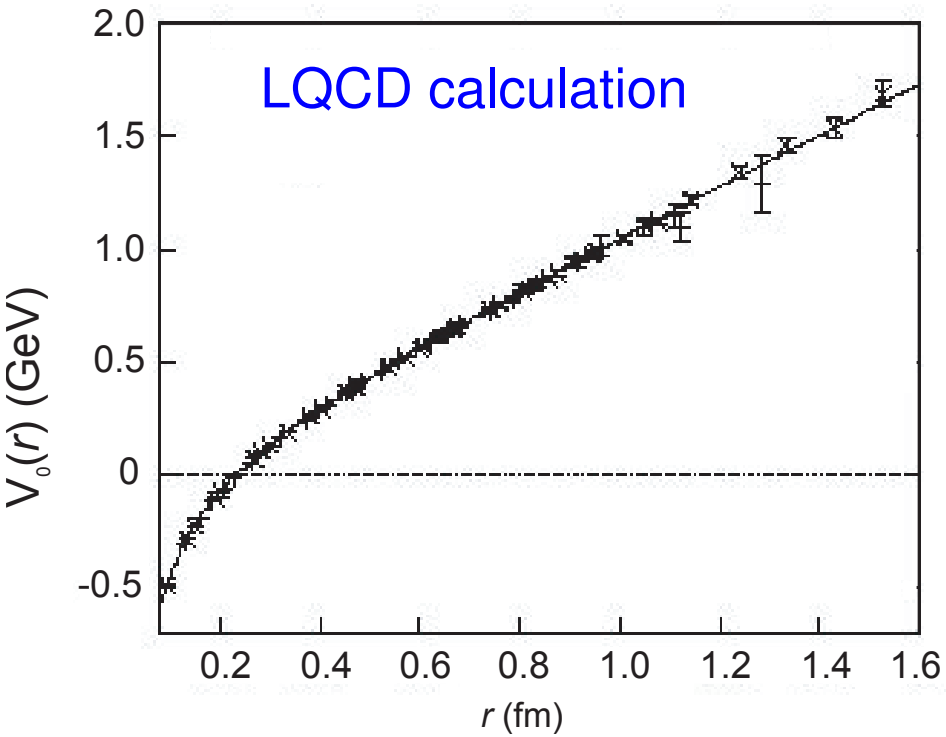
- Lattice QCD calculations
  ChP theory
- The field makes most of the hadron's mass
- *No explicit manifestation of gluons has been observed so far*

Gluonic field in a $\overline{q}q$ pair

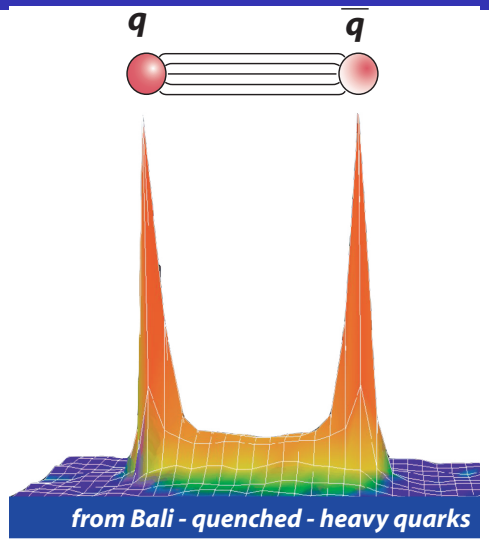
$\overline{c}c$ spectra suggested a QCD potential:

$$V(r) \propto -\frac{a}{r} + \kappa r$$

Linear term $\Rightarrow$ *confinement*



LQCD quenched and unquenched reproduce the shape of the potential



Quenched LQCD, heavy quarks

- Flux tube model (*Nambu 1970*)
- Lattice QCD Calculations

The models and the LQCD predict gluonic excitations which may be observable in the mass spectra

"Constituent gluon":

LQCD: 1^{+-}, mass 1.3 GeV/c^2

Meson spectroscopy

Naive quark model:

- Mesons are $\overline{q}q$, constituent quarks are $S = 1/2$ fermions
- 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		

Glue and spectroscopy

Gluonic excitations ⇒ hybrid mesons

- Exotic QN: an excellent signature of a new degree of freedom
  no mixing with the regular $\overline{q}q$ states

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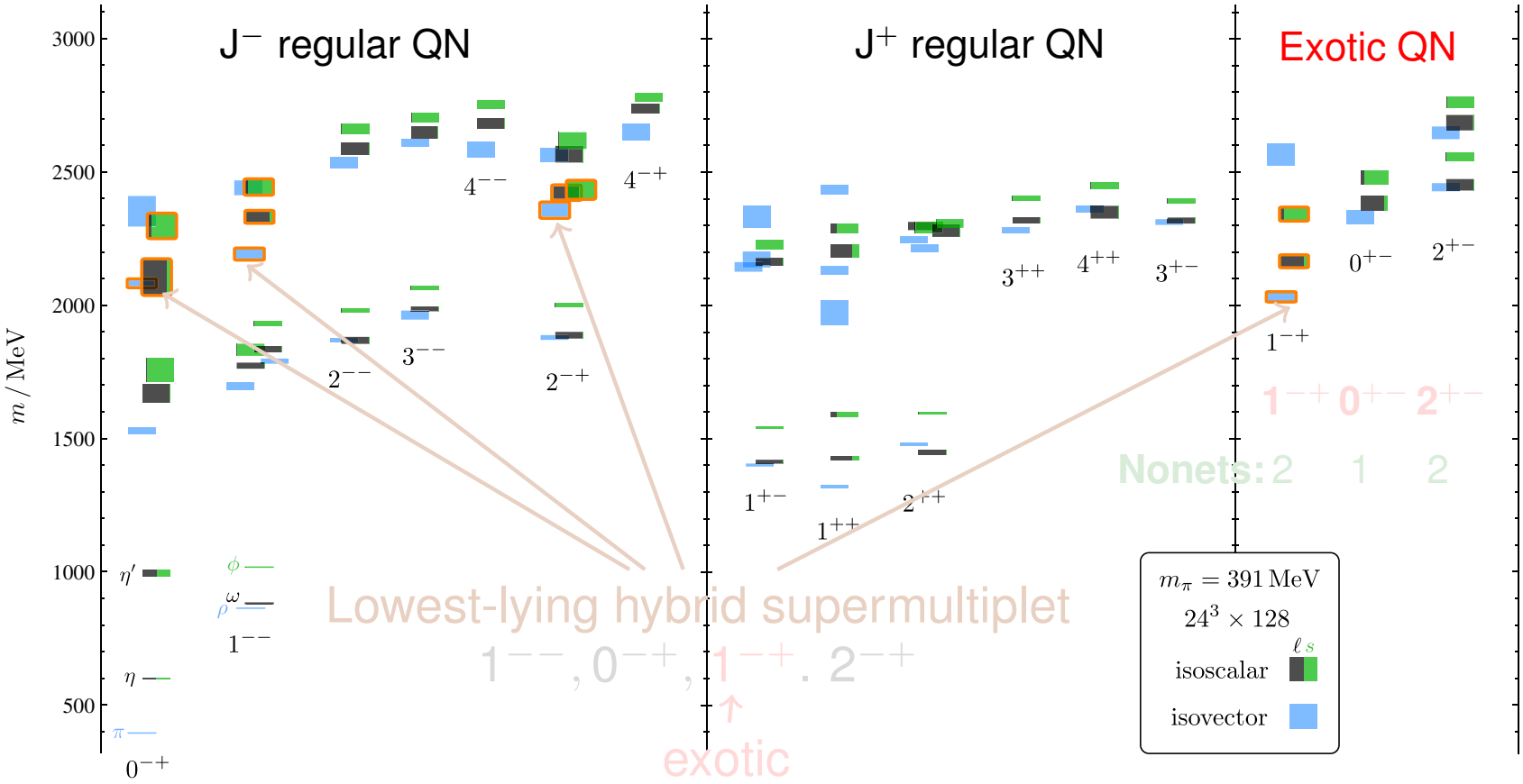
Lattice QCD - the Meson Spectra

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

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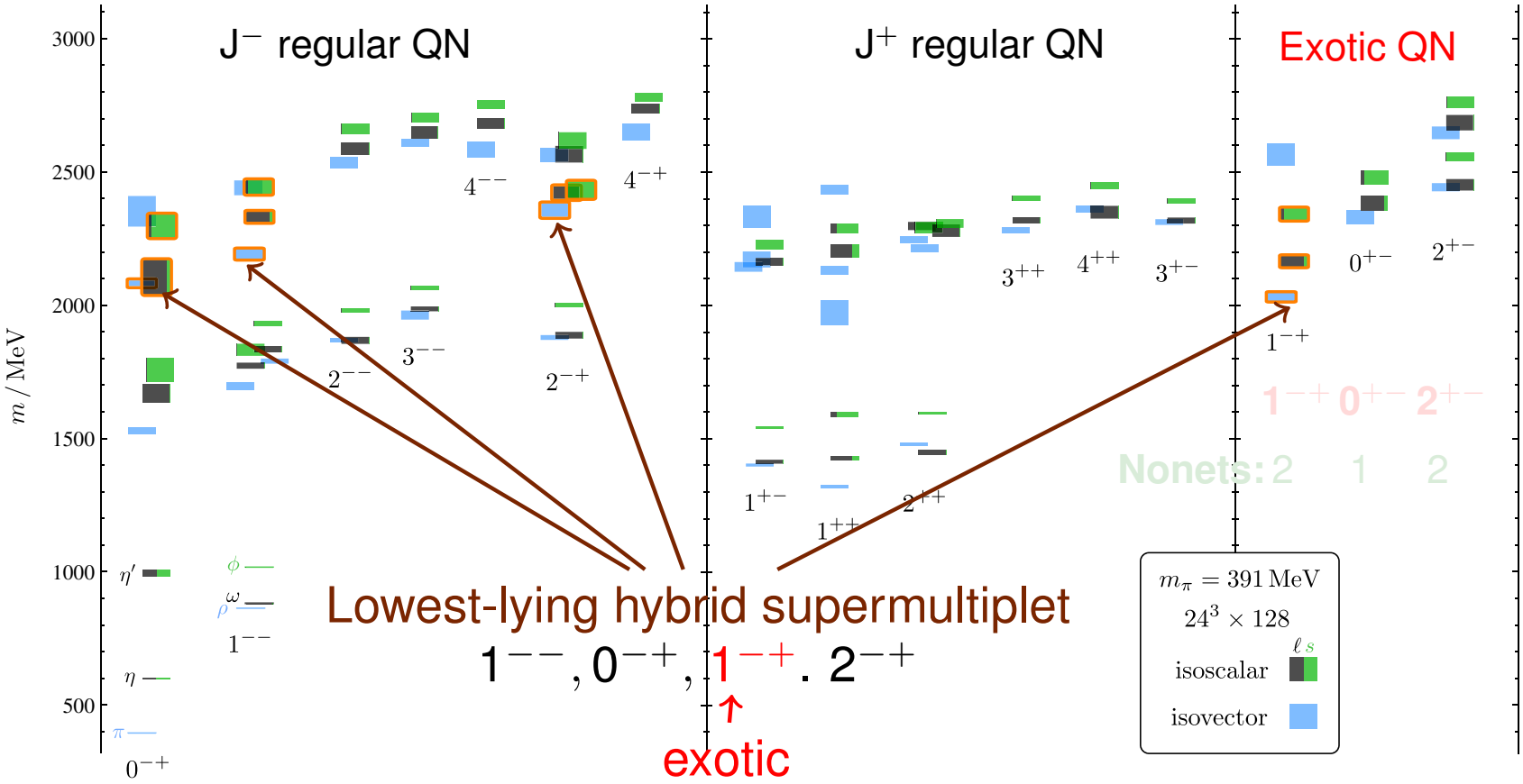

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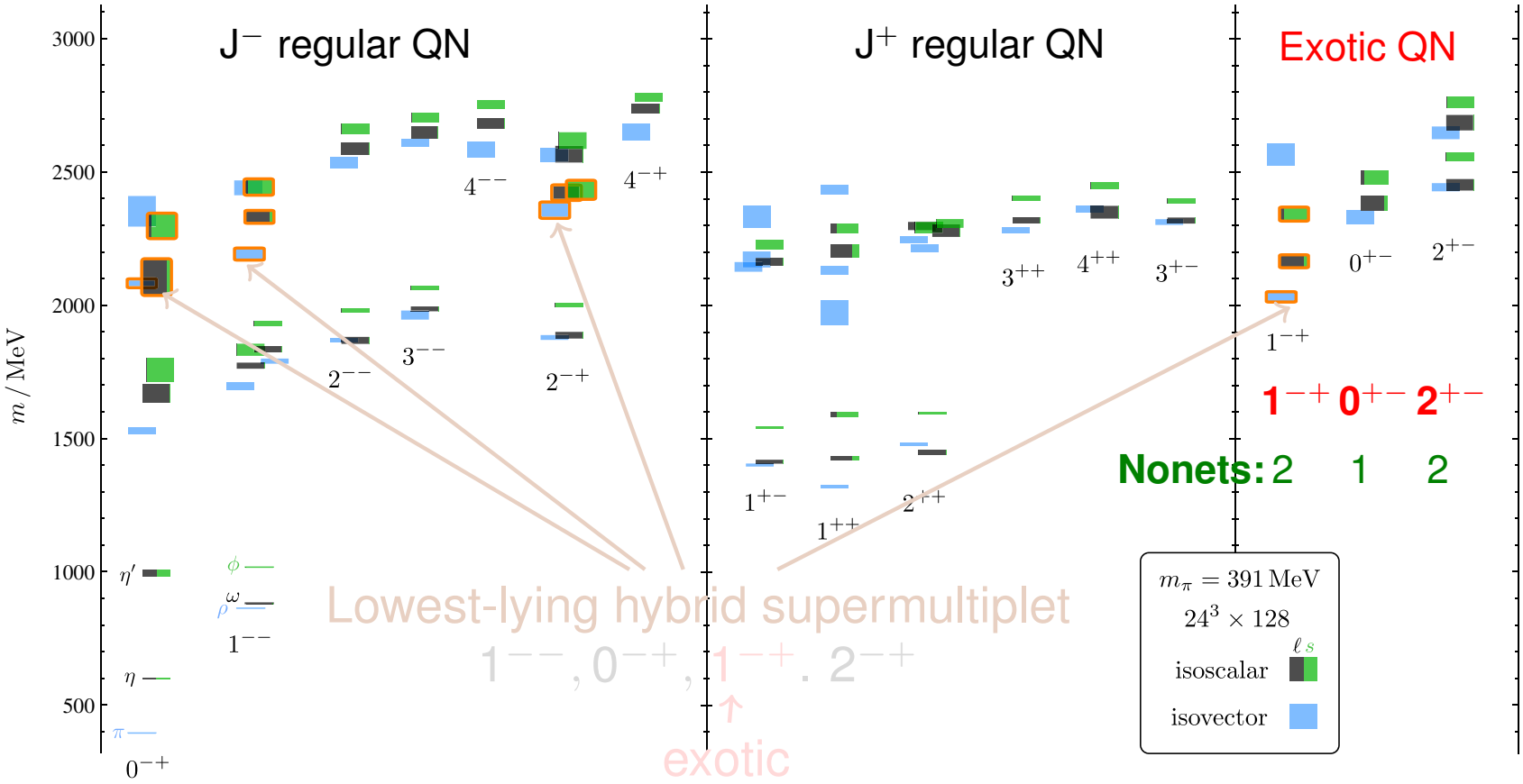

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Lower-lying exotic hybrids: masses, widths, decays

LQCD: masses

1^{-+} $\sim$2.0 – 2.4 GeV/c^2
0^{+-} $\sim$2.3 – 2.5 GeV/c^2
2^{+-} $\sim$2.4 – 2.6 GeV/c^2

Models: widths and decays

$\Gamma \sim$0.1-0.5 GeV/c^2,
$\Gamma(1^{-+}) \sim \Gamma(2^{+-}) < \Gamma(0^{+-})$

easy $\Rightarrow$ *statistics* $\Rightarrow$ *hard*
reach *needed*

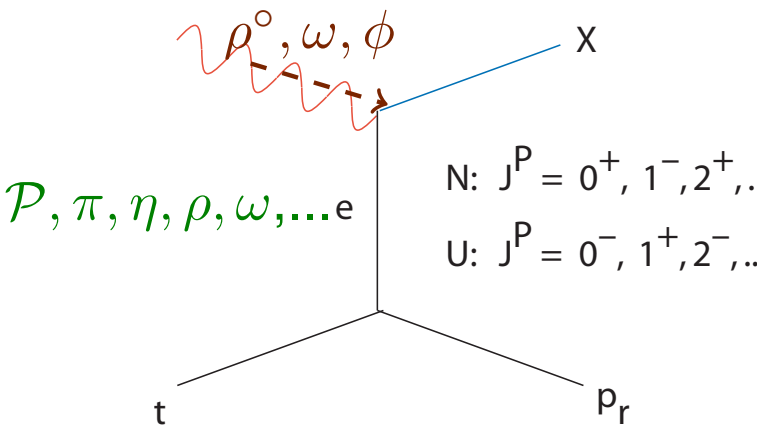
1^{-+}
$\pi_1 \to \rho\pi$, $b_1\pi$, $f_1\pi$, $\eta'\pi$, $a_1\eta$
$\eta_1 \to f_2\eta$, $a_2\pi$, $f_1\eta$, $\eta'\eta$, $\pi(1300)\pi$, $a_1\pi$
$\eta'_1 \to K^*\overline{K}$, $K(1270)\overline{K}$, $K(1410)\overline{K}$, $\eta'\eta$,

2^{+-}
$b_2 \to \omega\pi$, $a_2\pi$, $\rho\eta$, $f_1\rho$, $a_1\pi$, $h_1\pi$, $b_1\eta$
$h_2 \to \rho\pi$, $b_1\pi$, $\omega\eta$, $f_1\omega$
$h'_2 \to K_1(1270)\overline{K}$, $K(1410)\overline{K}$, $K_2\overline{K}$, $\phi\eta$, $f_1\phi$

0^{+-}
$b_\circ \to \pi(1300)\pi$, $h_1\pi$, $f_1\rho$, $b_1\eta$
$h_\circ \to b_1\pi$, $h_1\eta$
$h'_\circ \to K_1(1270)\overline{K}$, $K(1410)\overline{K}$, $h_1\eta$

Final states:
$(p,n)+3\pi$, 4π, $3\pi\eta$, $4\pi\eta$...
70% $\geq 1\pi^\circ$
50% $\geq 2\pi^\circ$

Photoproduction Mechanisms



Allowed Processes
vector meson + exchange particle

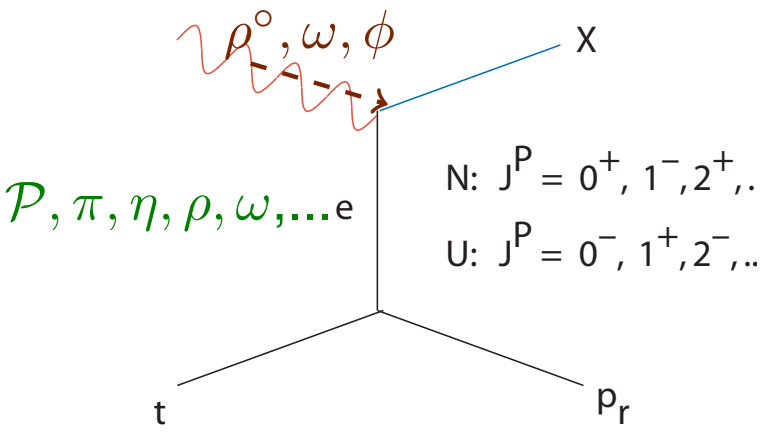
Exchange particle		Final states	
$\mathcal{P}$	0^{++}	$2^{+-}, 0^{+-}$	b°, h, h'
π°	0^{-+}	2^{+-}	b_2°, h_2, h_2'
$\pi^\pm$	0^{-+}	1^{-+}	$\pi_1^\pm$
ω	1^{--}	1^{-+}	π_1, η_1, η_1'

Can couple to all the lightest exotic hybrid nonets through photoproduction and VMD

Photon Polarization at JLab

- Coherent Bremsstrahlung at $E_e = 12$ GeV provides $\mathcal{P} \sim 40\%$ at $E_\gamma \sim 9$ GeV

Photoproduction Mechanisms



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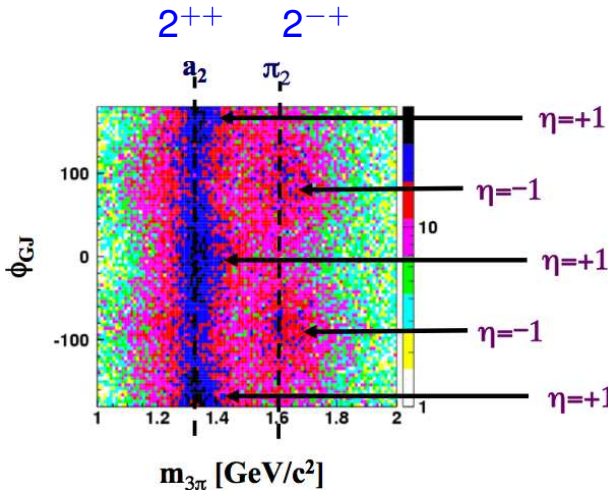
Effect of Beam Linear Polarization

Filter on the *naturality*
MC simulation $\gamma p \to 3\pi p$:



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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
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		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*	
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	$\pi^- p \to \eta'\pi^- p$	E-852, 18 GeV 2001	1600±40	340± 50
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		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
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Signal: solid, seen by several experiments
Interpretation: unclear, but not a hybrid:
1400 dynamic origin; 4-quark state

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

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^{-+}

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
	$\pi^- p \to \eta\pi^\circ n$			
	$\bar{p}p \to \eta\pi^\circ\pi^\circ$			
	$\bar{p}n \to \eta\pi^\circ\pi^-$	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	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
	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$			0± 90
	$\pi^- p \to \omega\pi^-\pi^\circ p$			0± 30
	$\pi^- A \to \omega\pi^-\pi^\circ A$			0
2000	$\pi^- p \to b_1\pi, f_1\pi$			0± 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

JLab approved program for spectroscopy

	Program	CLAS12 Hall B	GlueX Hall D
1	Search for hybrid mesons	yes	yes
2	Search for hybrid baryons: regular QN, identification through electrocouplings	yes	–
3	Measure missing QN for excited hyperons	yes	yes

Features:

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community

JLab approved program for spectroscopy

	Program	CLAS12	GlueX
1	Search for hybrid mesons	y	
2	Search for hybrid baryons: regular QN, identification through electrocouplings	yes	–
3	Measure missing QN for excited hyperons	yes	yes

$\Lambda(1405)$: $\frac{1}{2}^-$
from CLAS
PRL 112 (2014)

Features:

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community

JLab approved program for spectroscopy

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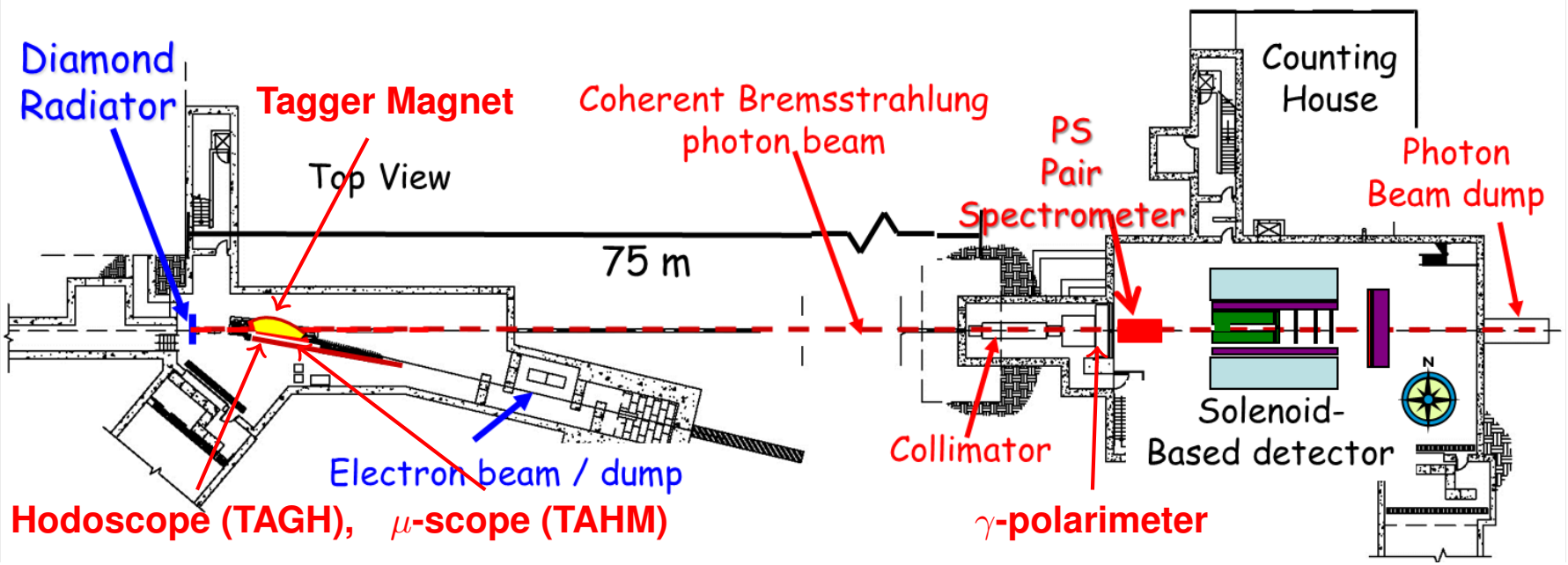
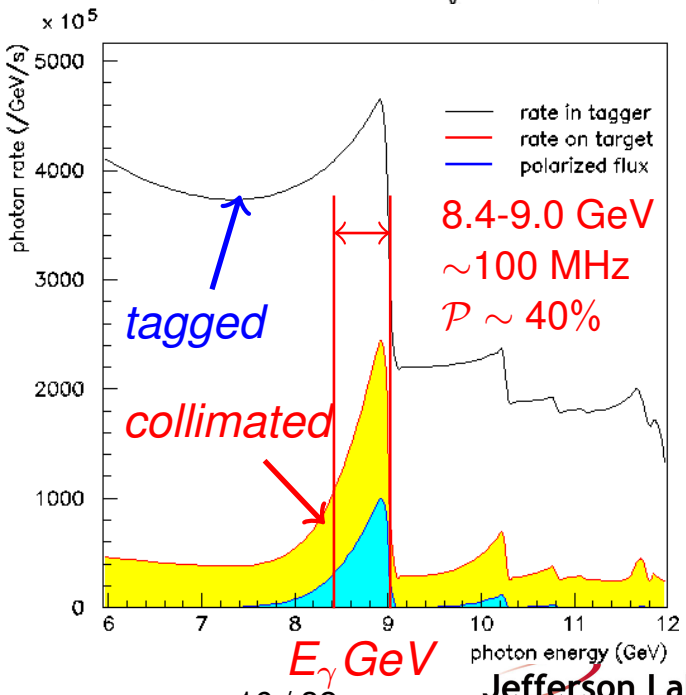
Features:

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community

Hall D/GlueX Beamline



- 12 GeV e^- beam $0.05 - 2.2\ \mu$A
- 20 μm diamond: coherent $<$25 μrad
- Collimation $r <$1.8 mm at $\sim$ 80 m
- Coherent peak 8.4 – 9.0 GeV $\quad \mathcal{P} \sim 40\%$
  2.2 μA $\Rightarrow$ 100 MHz γ
- Energy/polarization measured:
  - Tagger spectrometer $\sigma_E/E \sim$0.1%
  - Pair spectrometer: spectrum $\Rightarrow \sigma_{\mathcal{P}}/\mathcal{P} \sim$5%



Hall D/GlueX Spectrometer and DAQ

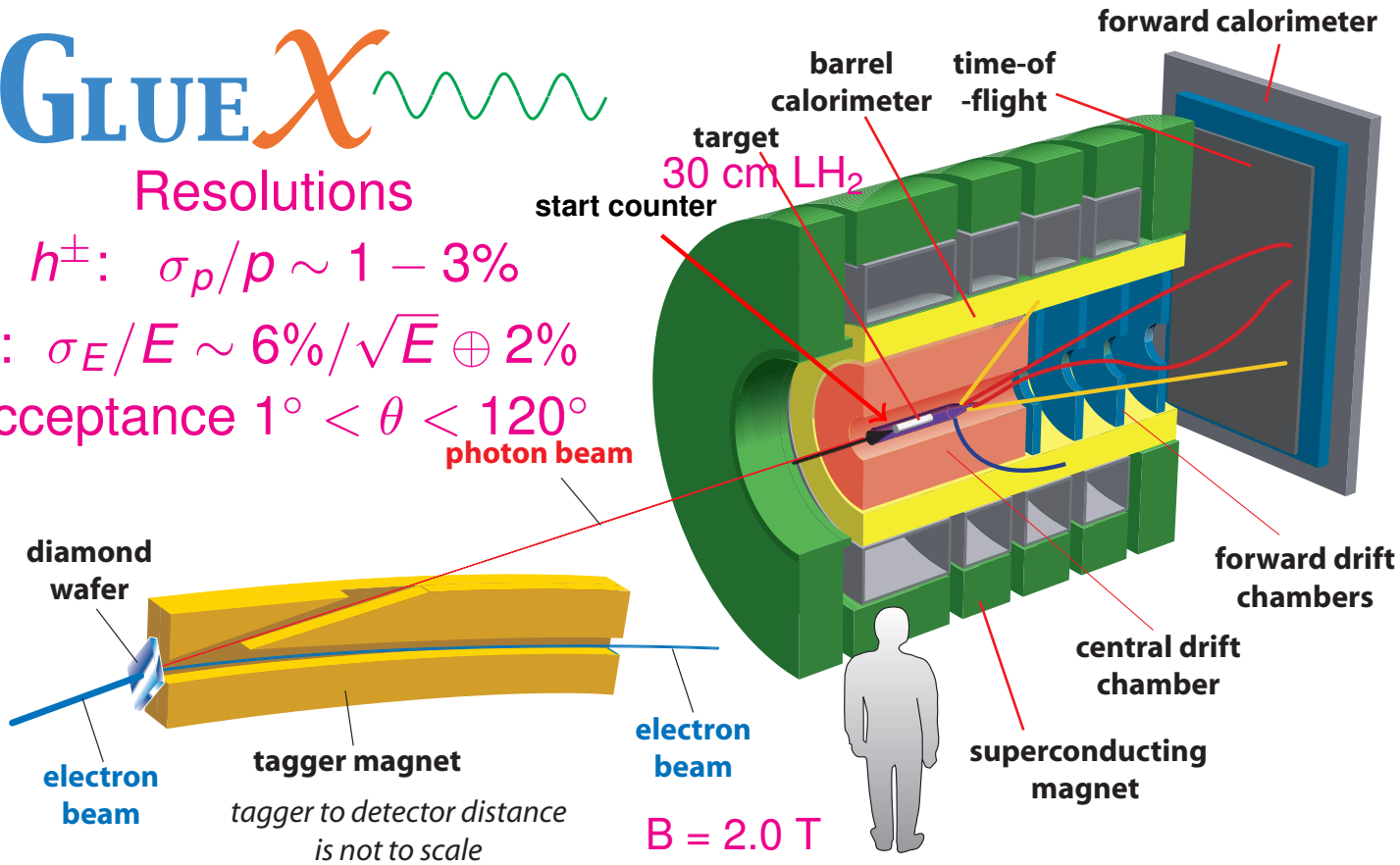
GlueX

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

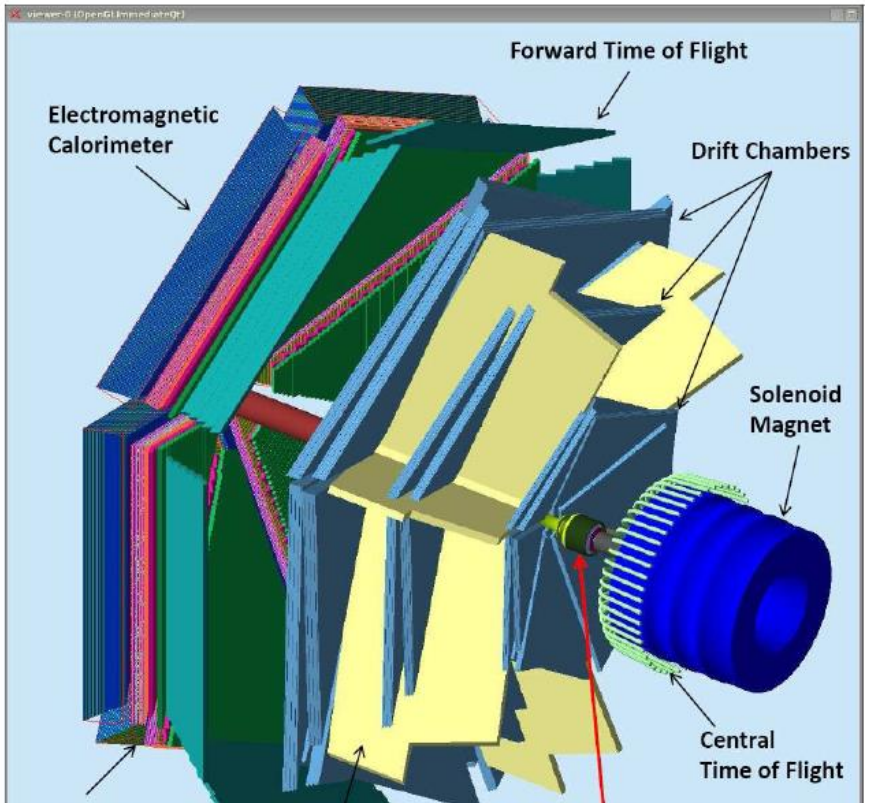
- 2017 L3
- 2018 Cherenkov

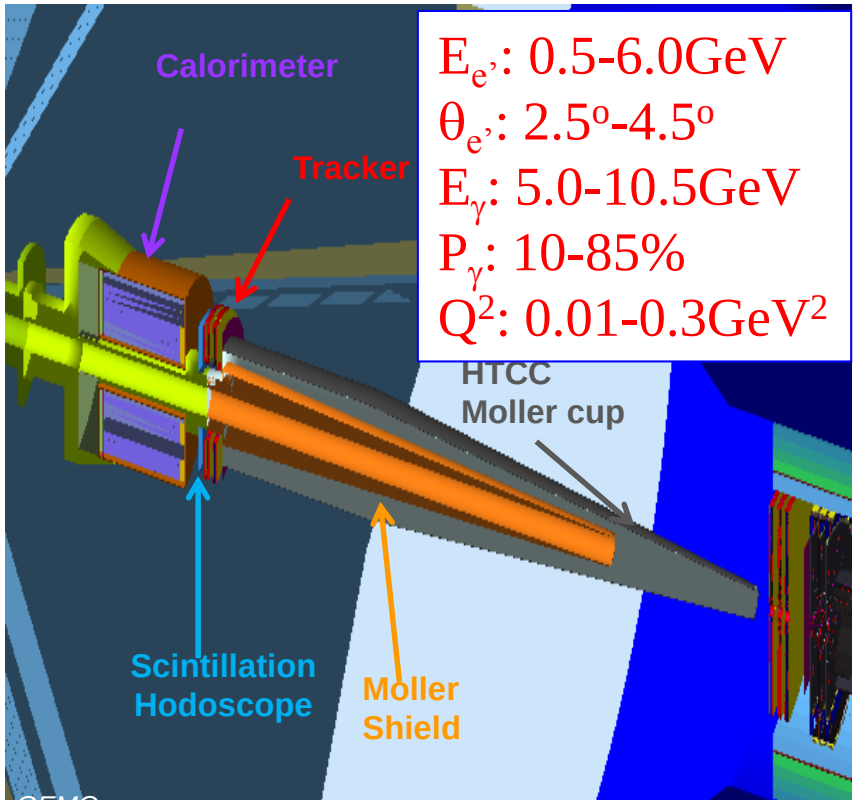
Photoproduction γp 15 kHz for a 100 MHz beam

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

Beam 100 MHz/GeV: inclusive trigger 200 kHz $\Rightarrow$ DAQ $\Rightarrow$ L3 farm $\Rightarrow$ tape

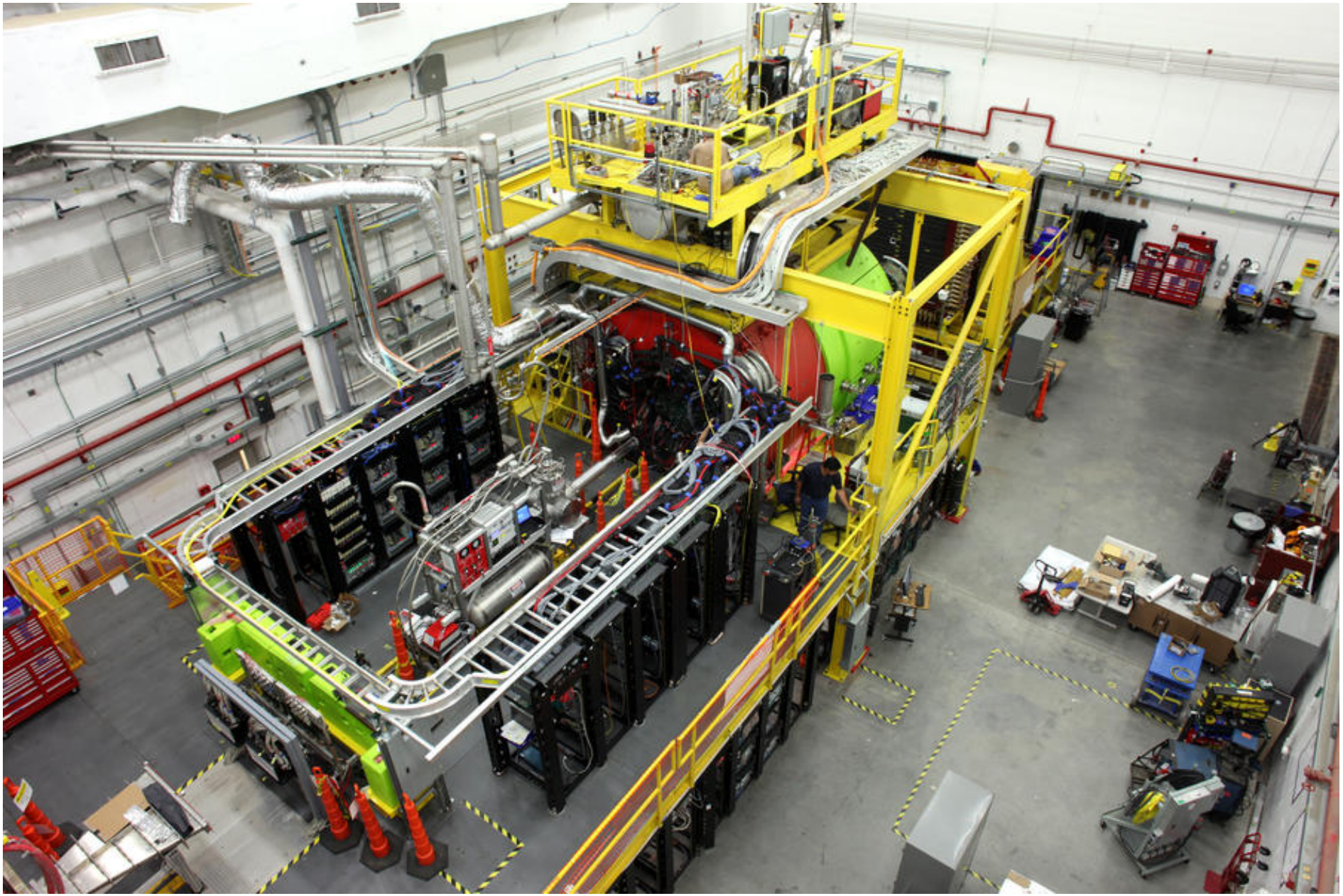
Hall B/CLAS12 Forward Tagger



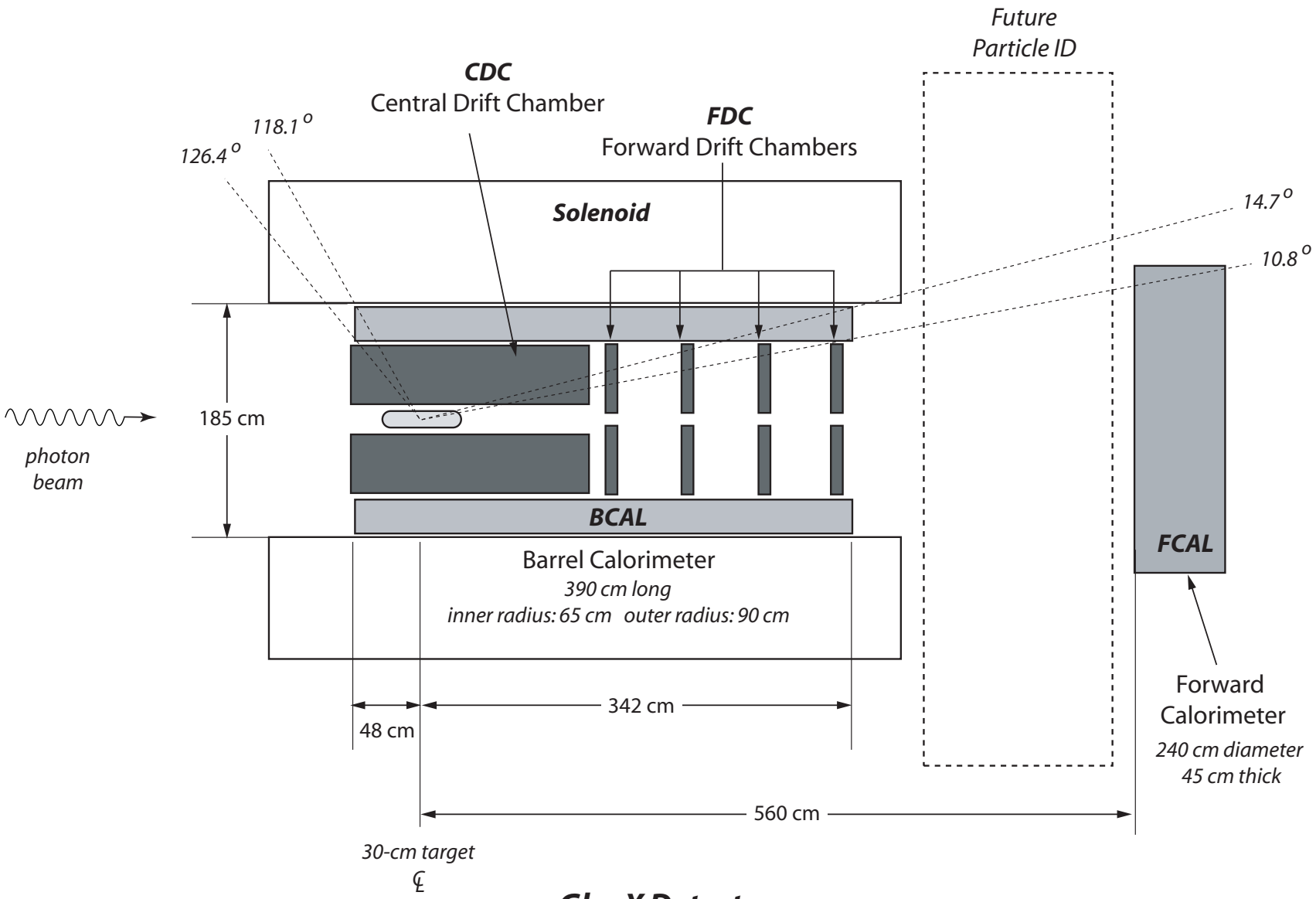


- CLAS12 acceptance $5^\circ < \theta$
- CLAS12 max $e^- p$ –luminosity 10^{35} cm^{-2}s^{-1}
- Tagged photon rate 50 MHz
- Advantage for very thin targets
- Linear polarization $\sim (1 + \nu^2/2EE')^{-1}$

Hall D

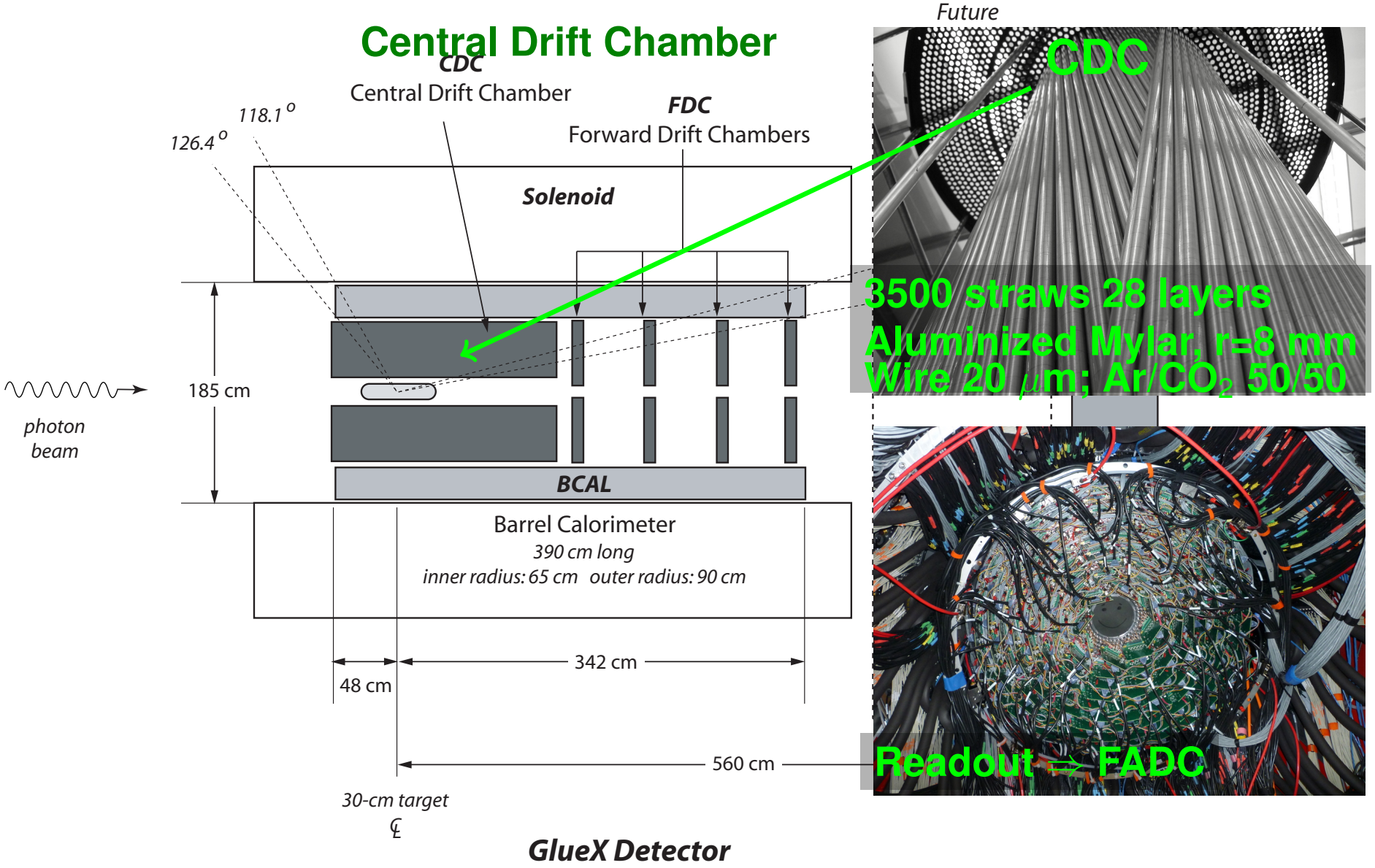


Spectrometer, Detectors and Dimensions



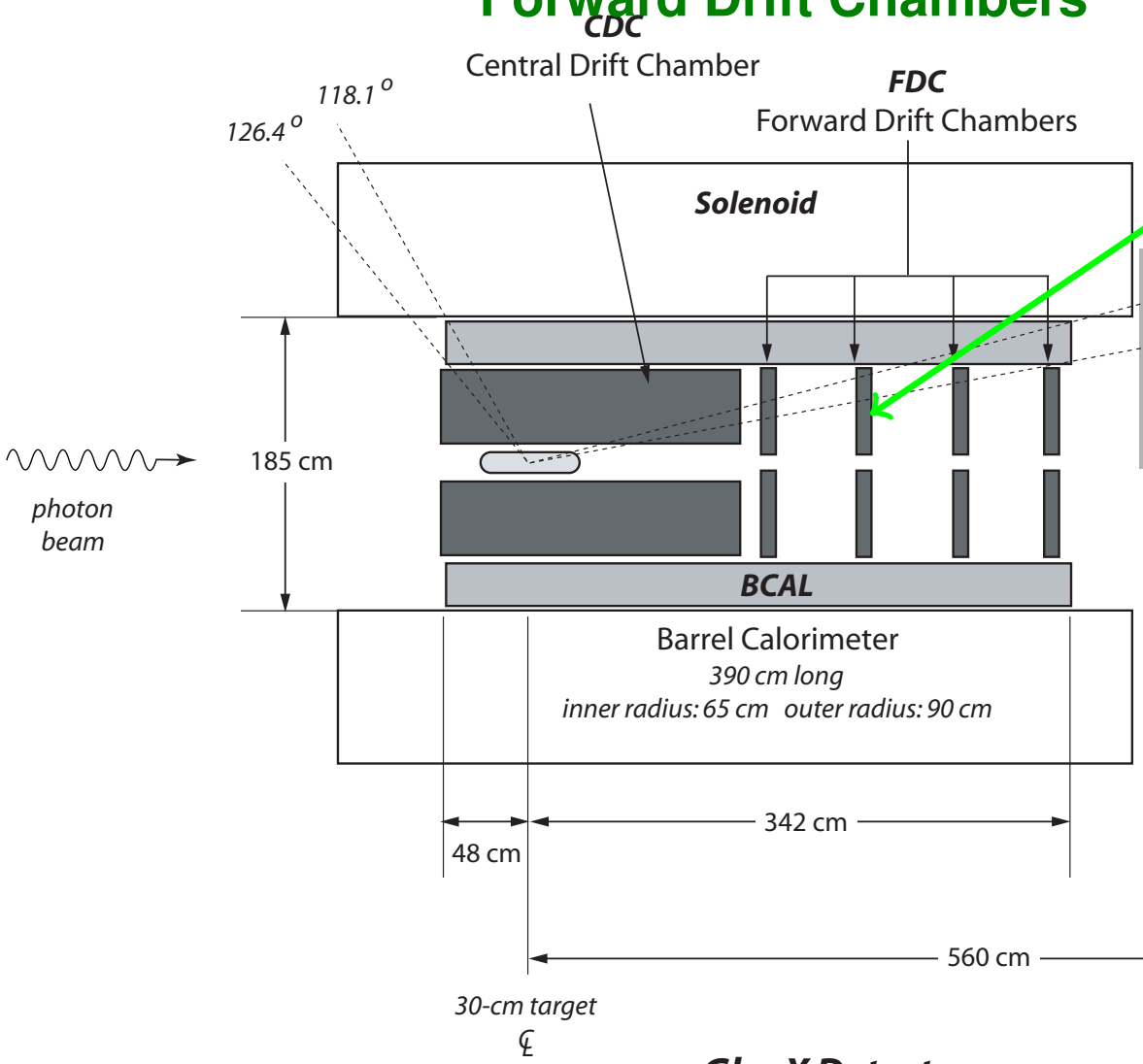
GlueX Detector

Spectrometer, Detectors and Dimensions

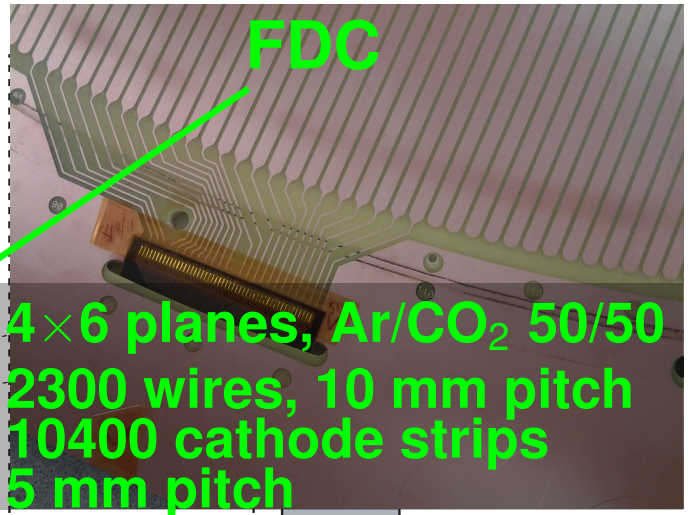


Spectrometer, Detectors and Dimensions

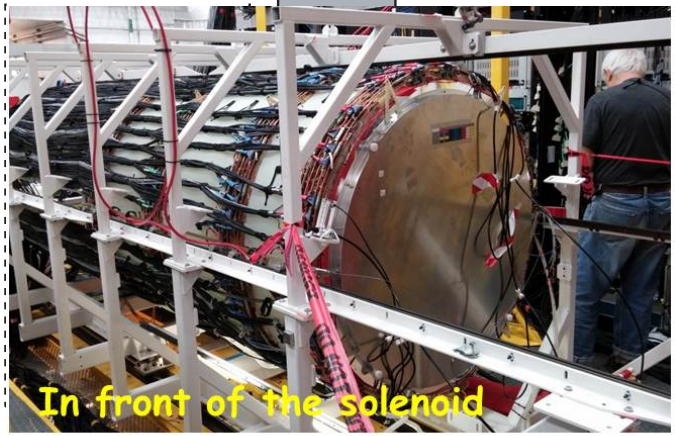
Forward Drift Chambers



Future

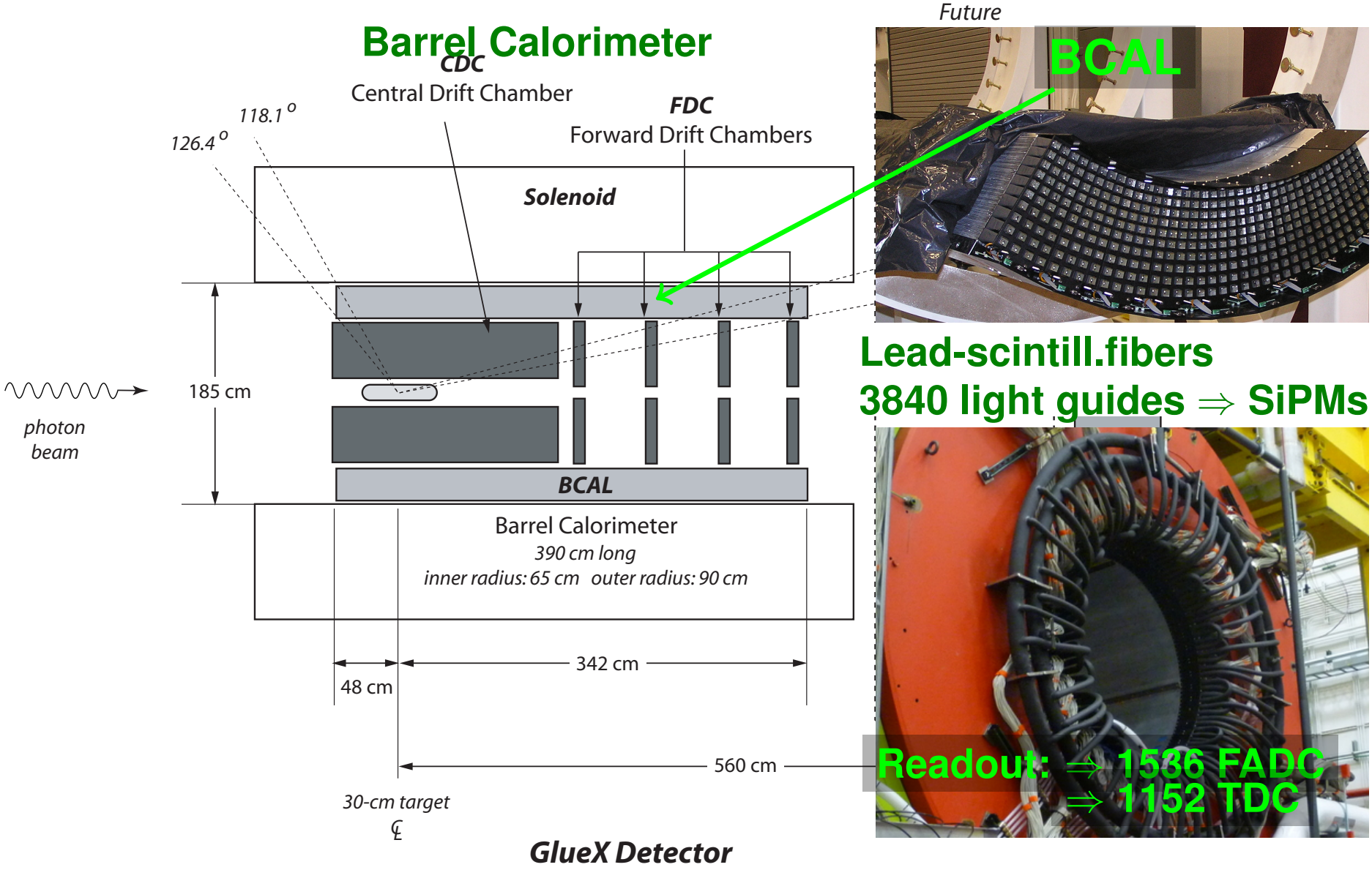


4×6 planes, Ar/CO_2 50/50
2300 wires, 10 mm pitch
10400 cathode strips
5 mm pitch

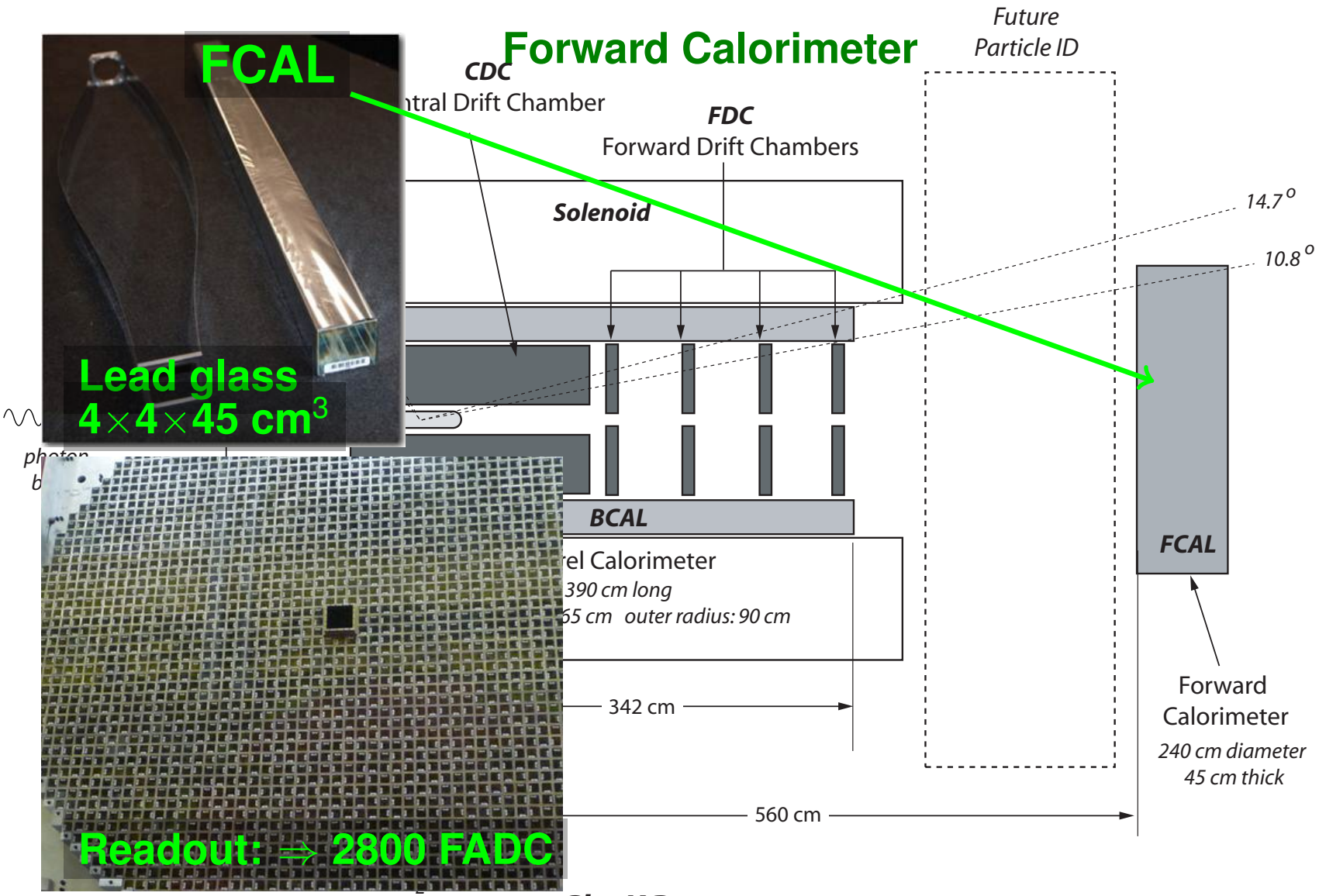


Readout: strips ⇒ FADC
Readout: wires ⇒ TDC

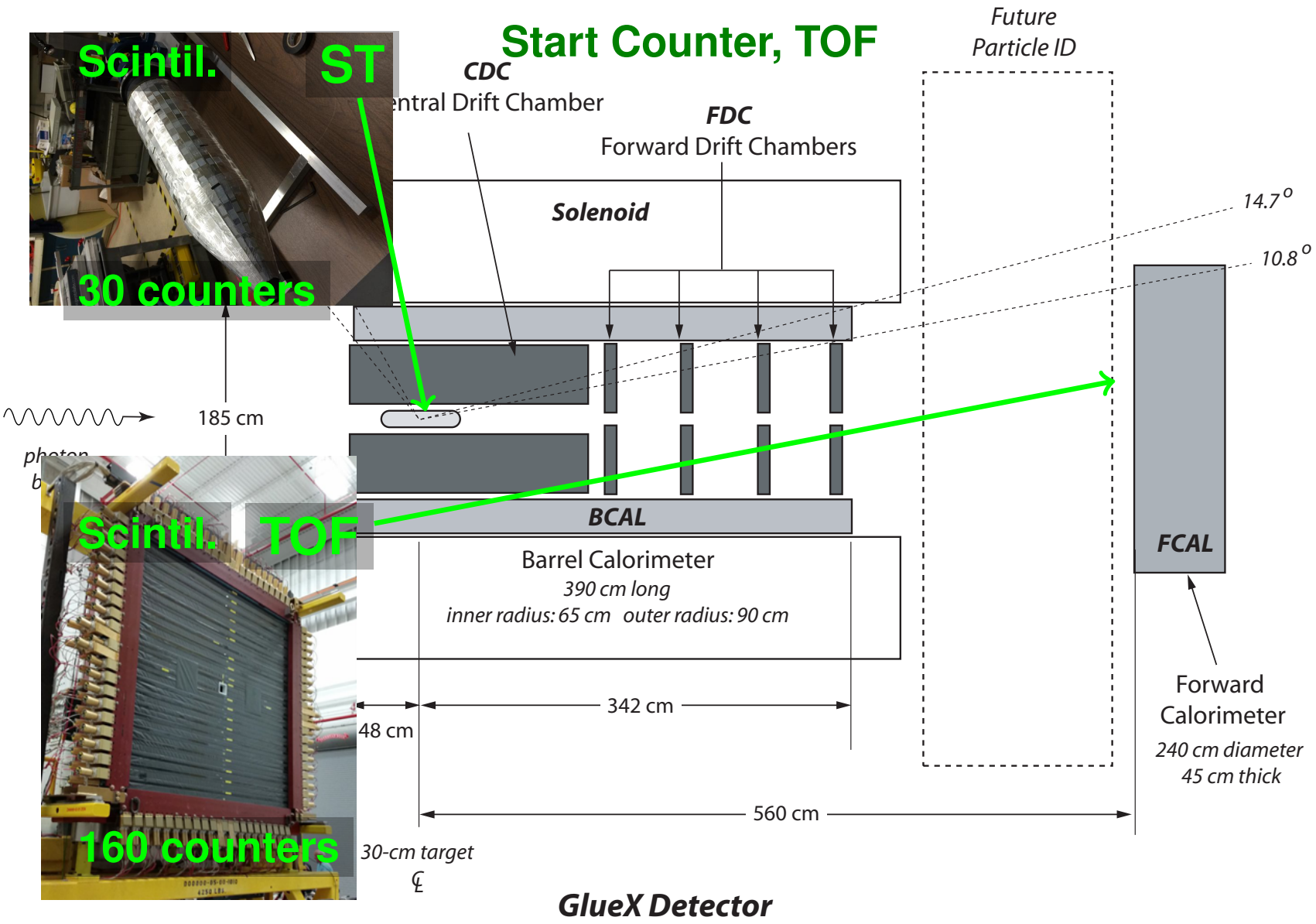
Spectrometer, Detectors and Dimensions



Spectrometer, Detectors and Dimensions



Spectrometer, Detectors and Dimensions



Jefferson Lab

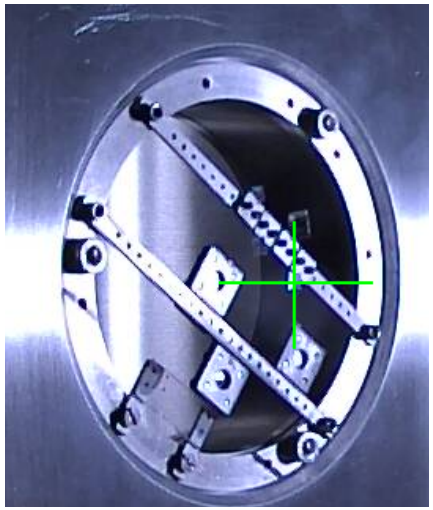
Hall D/GlueX Commissioning Status

Runs with beam:

- Fall 2014 10.0 GeV beam: beam commissioning and detector checkout
  - Unpolarized beam and nuclear target
  - 120 TB of data collected, 0.9 G events
- Spring 2015 5.5 GeV beam: 1 week of beam - commissioning
  - Commissioning of the linearly polarized beam
  - Commissioning of the Liquid Hydrogen target
  - 70 TB of data collected, 1.3 G events
- Spring 2016 12 GeV beam (started Feb 10, ongoing)
  - Finish the commissioning of all the systems
  - Data for early physics results
  - $\sim$ 8 G events recorded up to now

Hall D/GlueX Beam: Coherent Bremsstrahlung

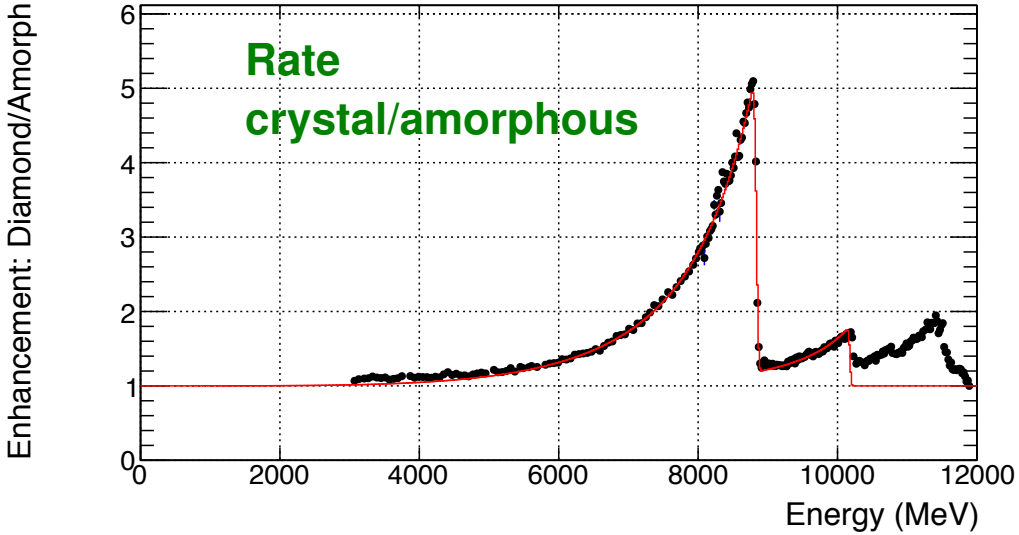
- 20-50 μm thick diamond radiators
- Precision alignment using a goniometer

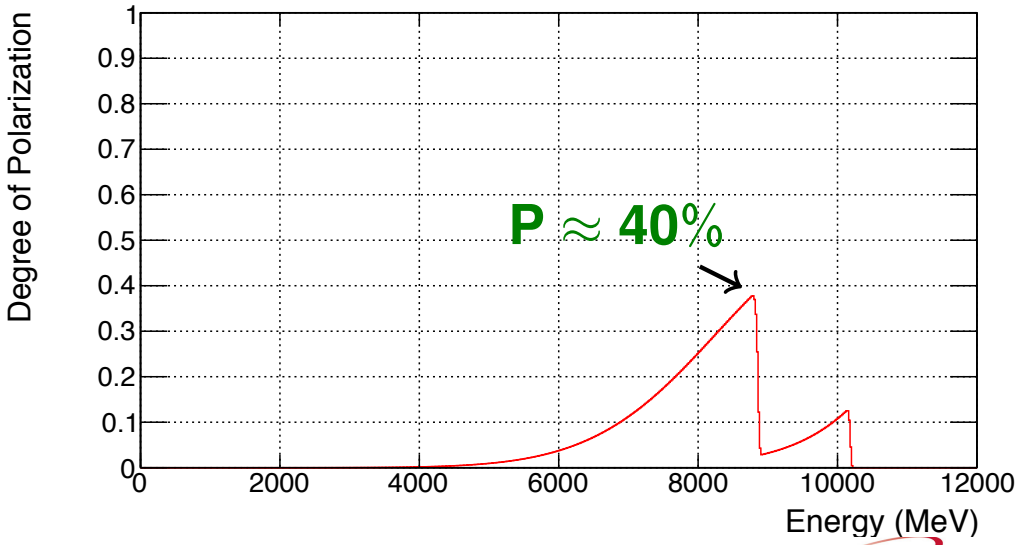


Polarization measurements

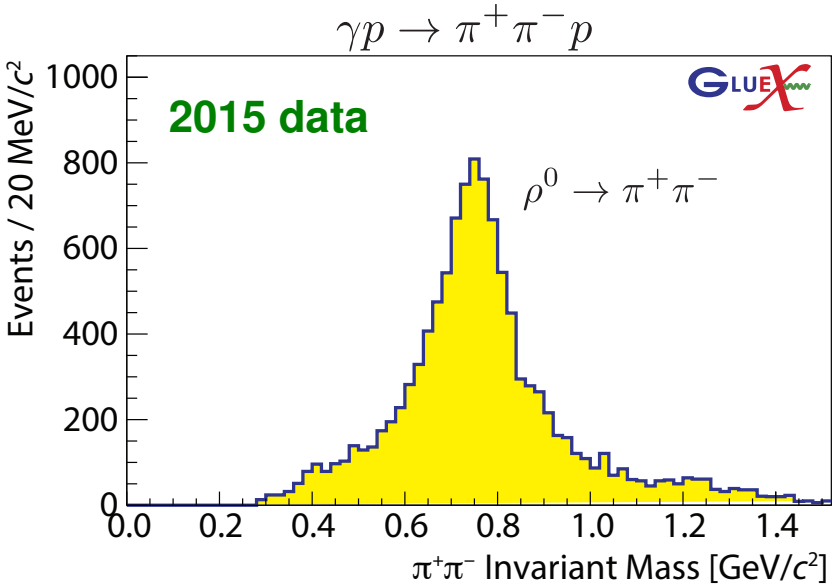
- Derived from the spectrum
- Triple polarimeter $\gamma e^- \to e^+ e^- e^-$
- Processes like $\gamma p \to \rho^\circ p$

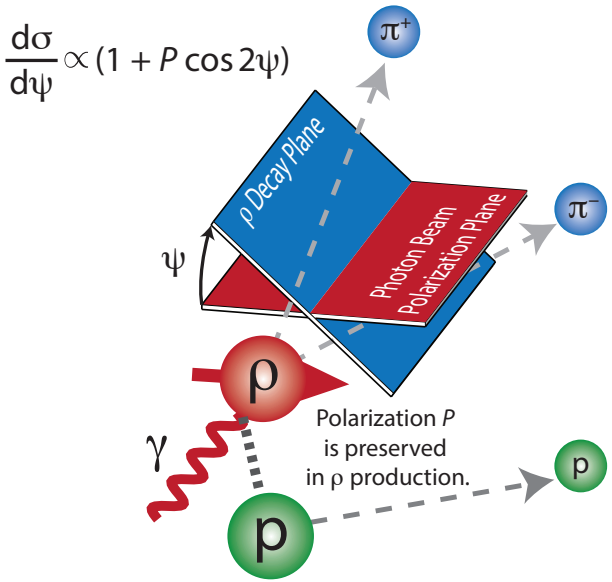
Run 10492: 50 µm diamond





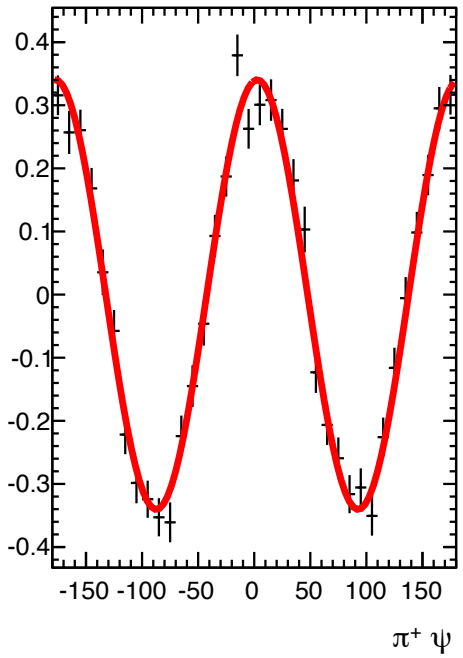
Physics With Linearly Polarized Beam





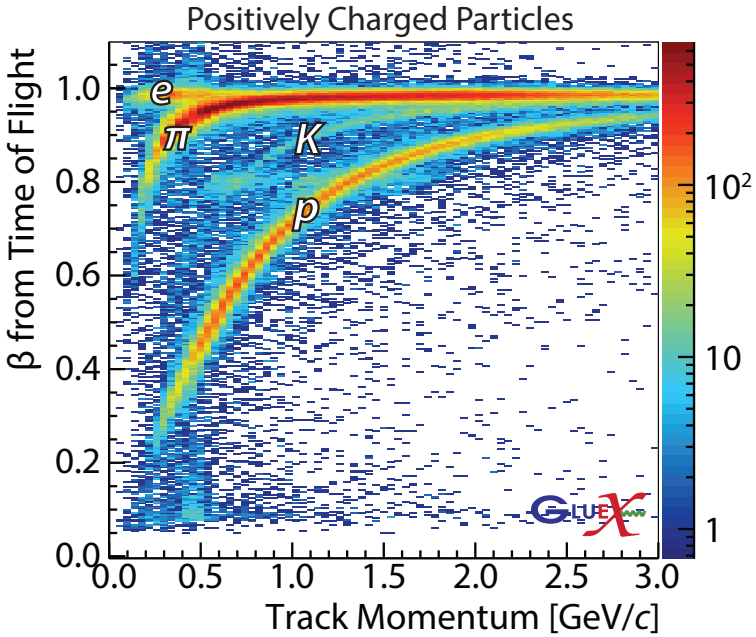
from 2016 data

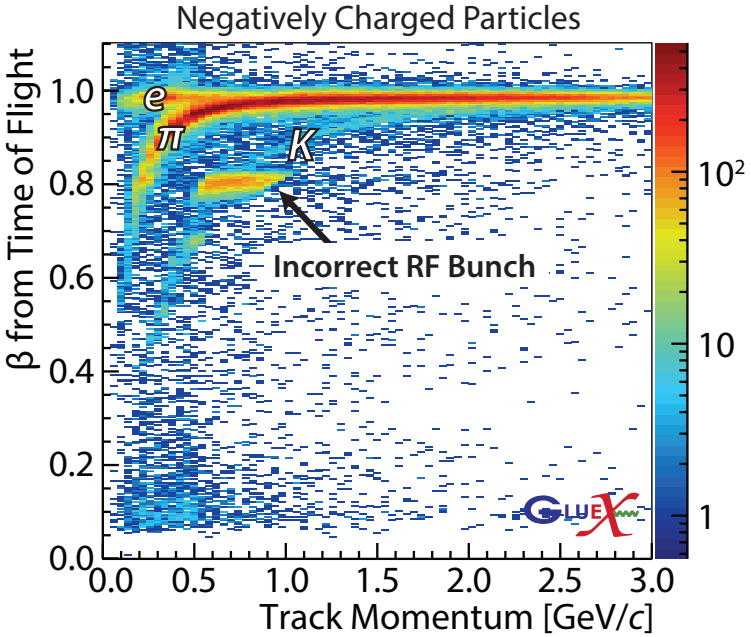
- 38k $\gamma p \to \rho^\circ p$ in $8.4 < E_\gamma < 9.0$ GeV
- 2 crystal orientations at 90°
- $\frac{N_0 - N_{90}}{N_0 + N_{90}} = P\Sigma \cos 2\psi$

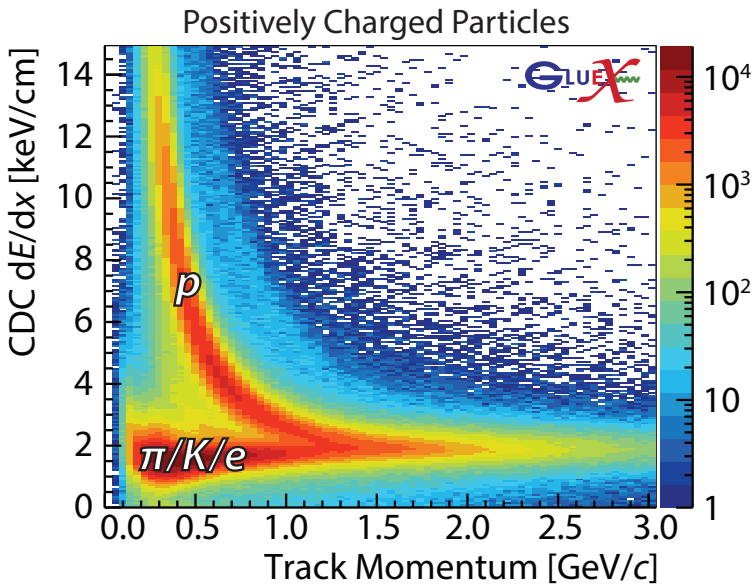


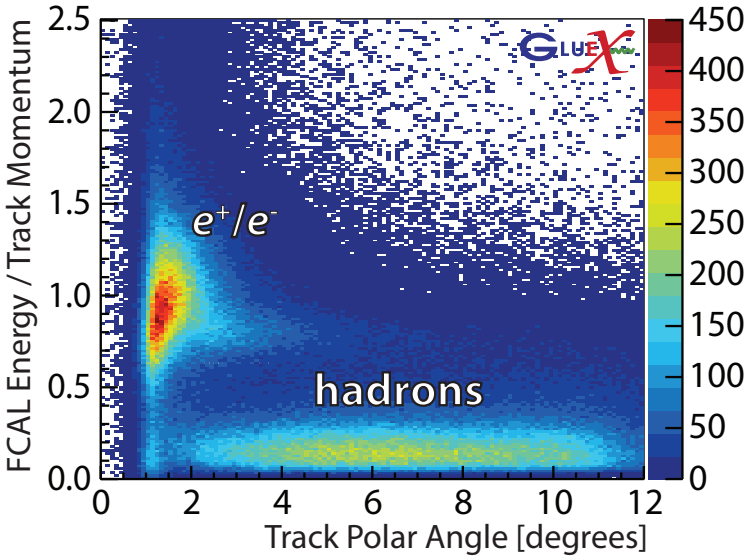
$P\Sigma = \mathbf{0.341 \pm 0.007\%}$

PID


Positively Charged Particles
β from Time of Flight
Track Momentum [GeV/c]
e
π
K
p
GlueX

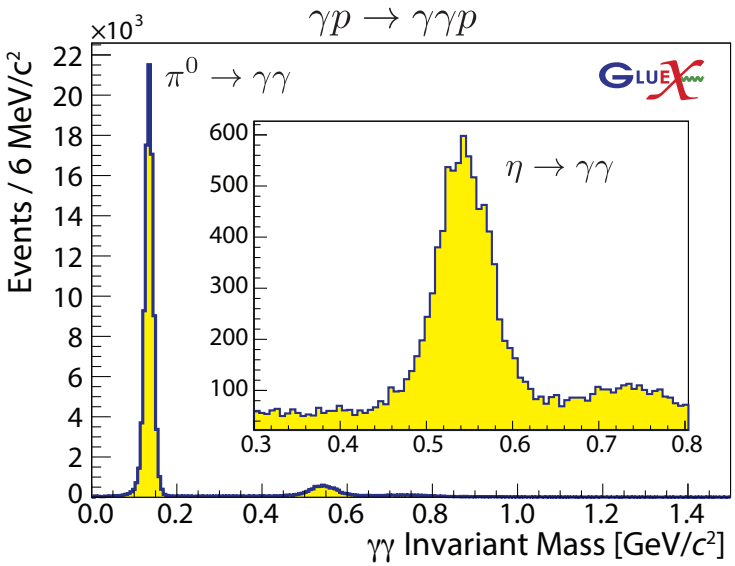

Negatively Charged Particles
β from Time of Flight
Track Momentum [GeV/c]
e
π
K
Incorrect RF Bunch
GlueX

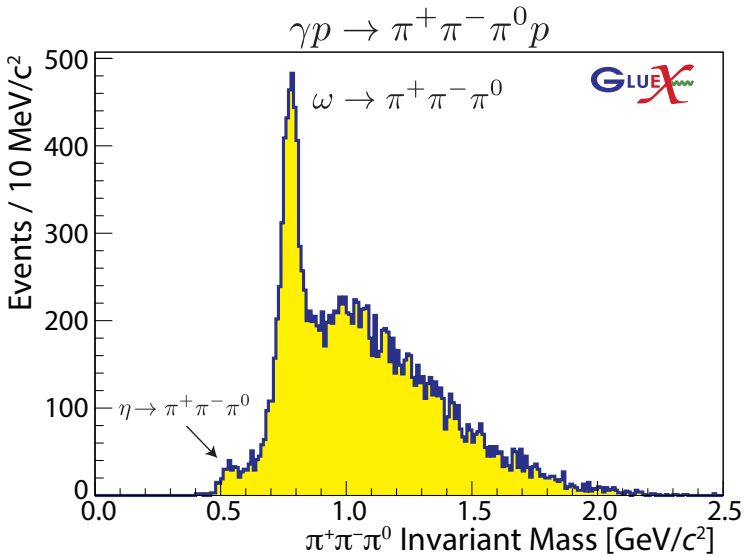

Positively Charged Particles
CDC dE/dx [keV/cm]
Track Momentum [GeV/c]
p
π/K/e
GlueX


FCAL Energy / Track Momentum
Track Polar Angle [degrees]
e+/e-
hadrons
GlueX

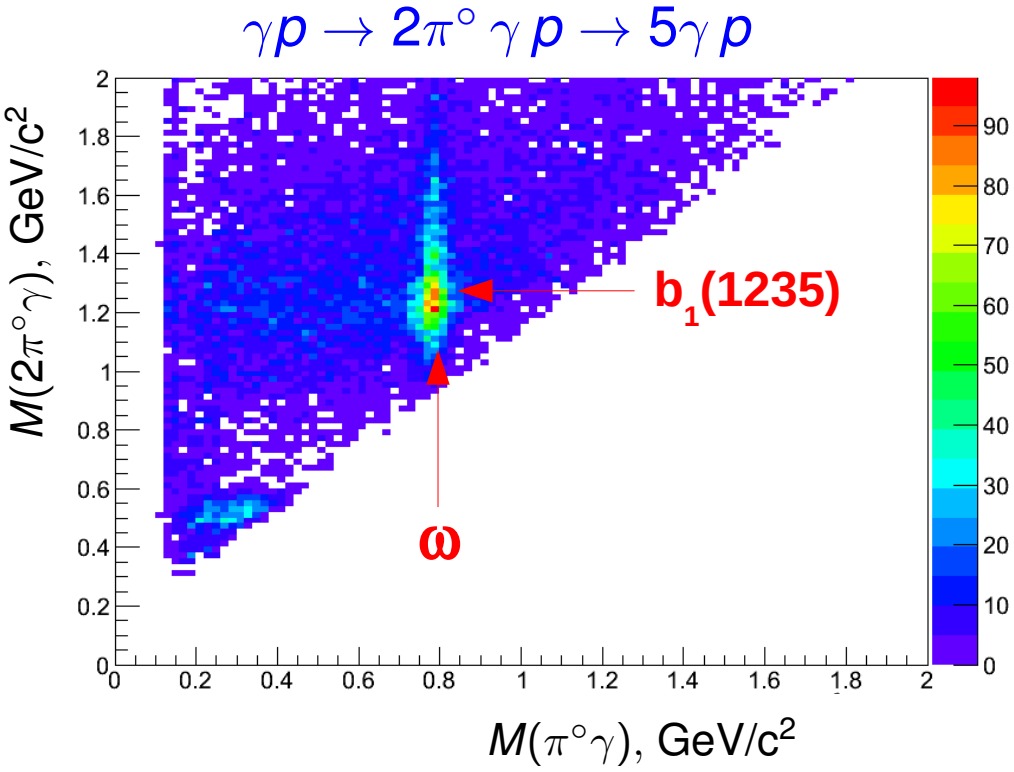
Event Reconstruction and Signals Observed

2015 data





from 2016 data

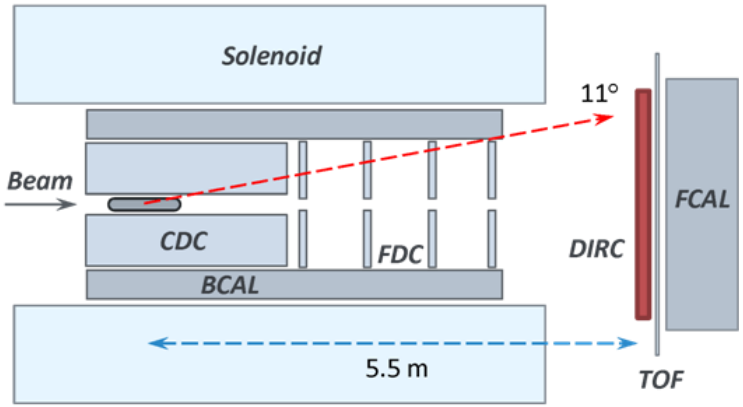


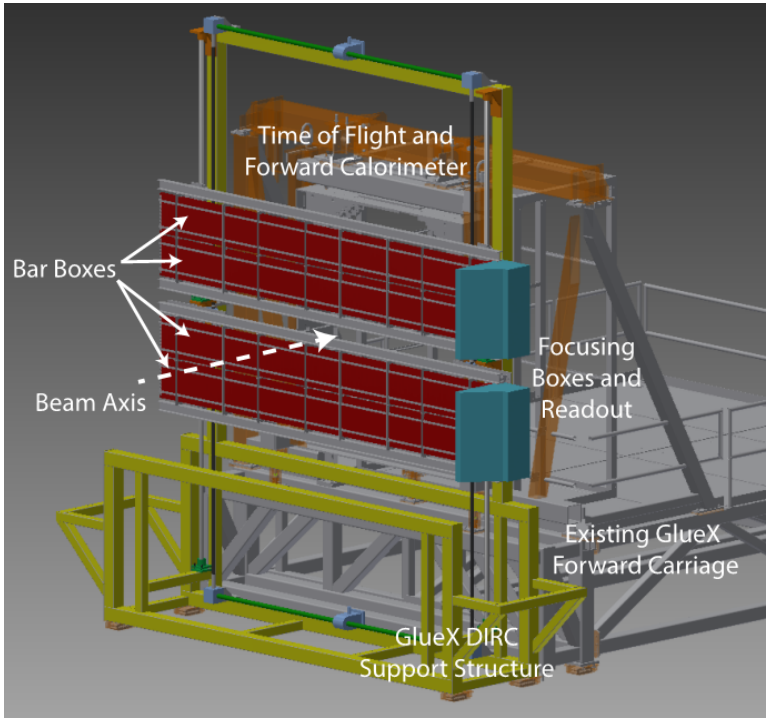
Forward Kaon Identification

Present PID: TOF, dE/dx, Kinematics

Upgrade

- 4 of the BaBar DIRC bar boxes
- New readout system
- Allows to study:
  - Strangeonium and hybrids
  - Hyperons
- Installation planned for 2018





Hall D Preliminary Running Schedule

- 2016-2018 GlueX at “low” intensity of 10 MHz in the peak
- 2018 PRIMEX (Primakoff) experiment
- 2018 DIRC installation
- 2019-2022 GlueX at “high” intensity 5×10 MHz in the peak
  focus on hidden strangeness and hyperon resonances

Summary

- Spectroscopy is big part of the JLab program for 2016-2022
  the main focus is on the search for hybrid mesons
- GlueX (Hall D) and CLAS12 (Hall B) are of comparable capabilities,
  but have different acceptances, tagging methods etc.
- GlueX is finishing the commissioning phase
- By the Fall 2016 GlueX is planning to be ready to start the main program
  - the search for exotic mesons

APPENDIX

Hall D Physics Program

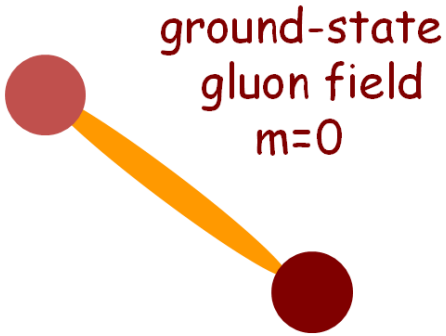
Proposal/ experiment	Status	Title	Beam days	PAC #
E12-06-102	A	Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	120	30
E12-10-011	A-	A Precision Measurement of the η Radiative Decay Width via the Primakoff Effect	79	35
E12-13-003	A	An initial study of 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

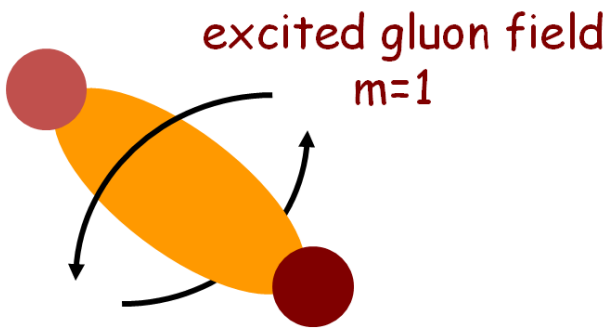
The GlueX Collaboration

Arizona State, Athens, Carnegie Mellon, Catholic University, Univ. of Connecticut, Florida International, Florida State, George Washington, Glasgow, 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, and Yerevan Physics Institute.

Over 100 collaborators from 22 institutions. Others are planning to join and more are welcome.

Regular and hybrid multiplets





J^{PC}

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

The lowest excitation $L = 1$:

J^{PC} : 1^{+-} or 1^{-+}

Conventional mesons

Regular quantum numbers:

0^{-+}	$S = 0, L = 0$	π, η, K
1^{--}	$S = 1, L = 0$	ρ, ω, ϕ, K^*
1^{+-}	$S = 0, L = 1$	b_1, h_1, K_1..
0^{++}	$S = 1, L = 1$	$a_\circ, f_\circ, K^*_\circ$
1^{++}	$S = 1, L = 1$	a_1, f_1, K^*_{1A}
2^{++}	$S = 1, L = 1$	a_2, f_2, K^*_2

etc.

Lower hybrid mesons

Regular quantum numbers:

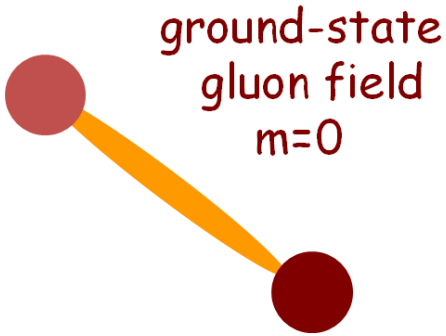
1^{--}	...
1^{++}	...

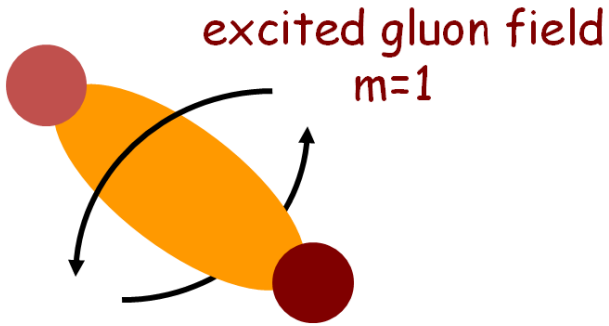
Exotic quantum numbers:

1^{-+}	π_1, η_1...
2^{+-}	b_2, h_2...
0^{+-}	$b_\circ, h_\circ$...

etc.

Regular and hybrid multiplets





J^{PC}

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

The lowest excitation $L = 1$:

J^{PC} : 1^{+-} or 1^{-+} Flux tube

Conventional mesons

Regular quantum numbers:

0^{-+}	$S = 0, L = 0$	π, η, K
1^{--}	$S = 1, L = 0$	ρ, ω, ϕ, K^*
1^{+-}	$S = 0, L = 1$	b_1, h_1, K_1..
0^{++}	$S = 1, L = 1$	$a_\circ, f_\circ, K^*_\circ$
1^{++}	$S = 1, L = 1$	a_1, f_1, K^*_{1A}
2^{++}	$S = 1, L = 1$	a_2, f_2, K^*_2

etc.

Lower hybrid mesons

Regular quantum numbers:

1^{--} ...

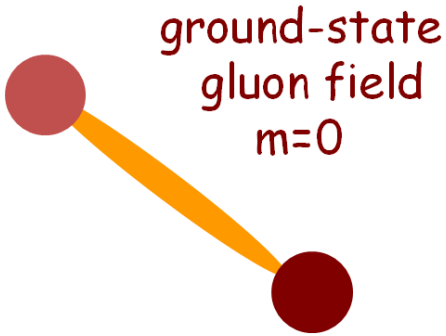
1^{++} ...

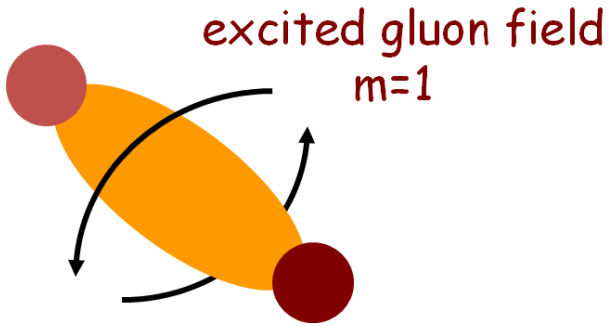
Exotic quantum numbers:

1^{-+}	π_1, η_1...
2^{+-}	b_2, h_2...
0^{+-}	$b_\circ, h_\circ$...

etc.

Regular and hybrid multiplets





J^{PC}

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

The lowest excitation $L = 1$:

J^{PC} : 1^{+-} or 1^{-+} **LQCD**

Conventional mesons

Regular quantum numbers:

0^{-+}	$S = 0, L = 0$	π, η, K
1^{--}	$S = 1, L = 0$	ρ, ω, ϕ, K^*
1^{+-}	$S = 0, L = 1$	b_1, h_1, K_1..
0^{++}	$S = 1, L = 1$	$a_\circ, f_\circ, K^*_\circ$
1^{++}	$S = 1, L = 1$	a_1, f_1, K^*_{1A}
2^{++}	$S = 1, L = 1$	a_2, f_2, K^*_2

etc.

Lower hybrid mesons

Regular quantum numbers:

1^{--} ...

1^{++} ...

Exotic quantum numbers:

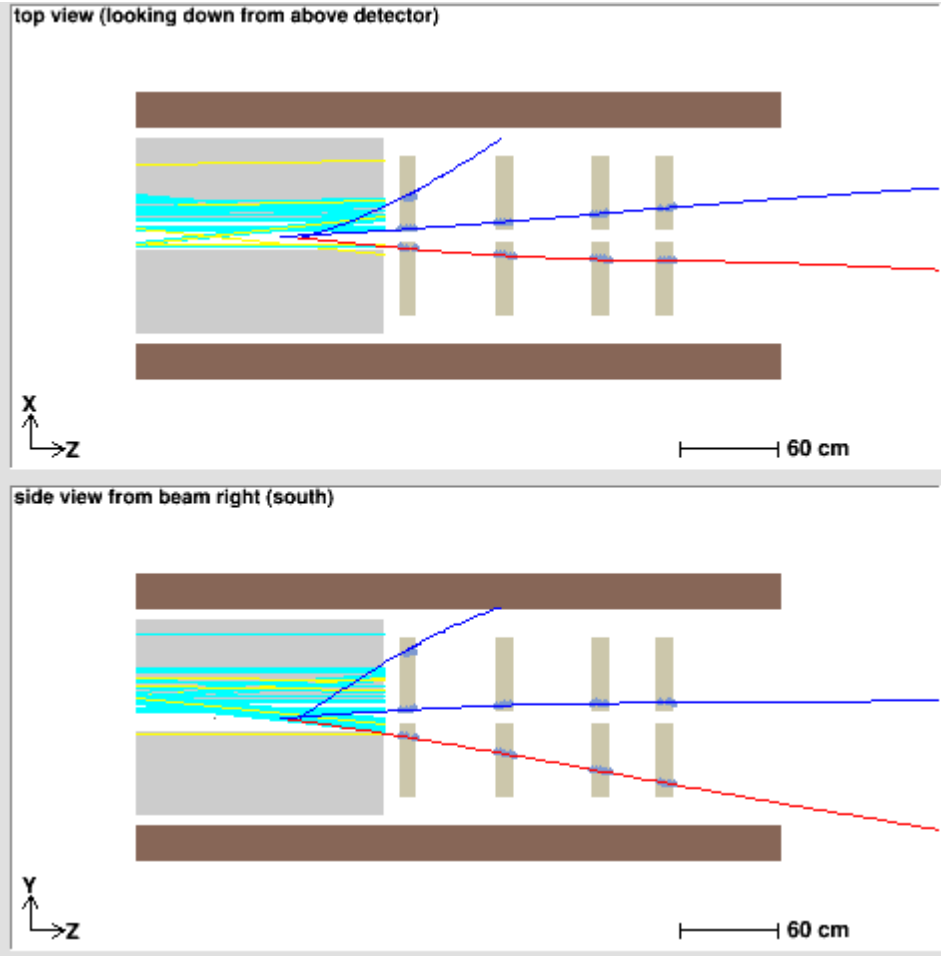
1^{-+} π_1, η_1...

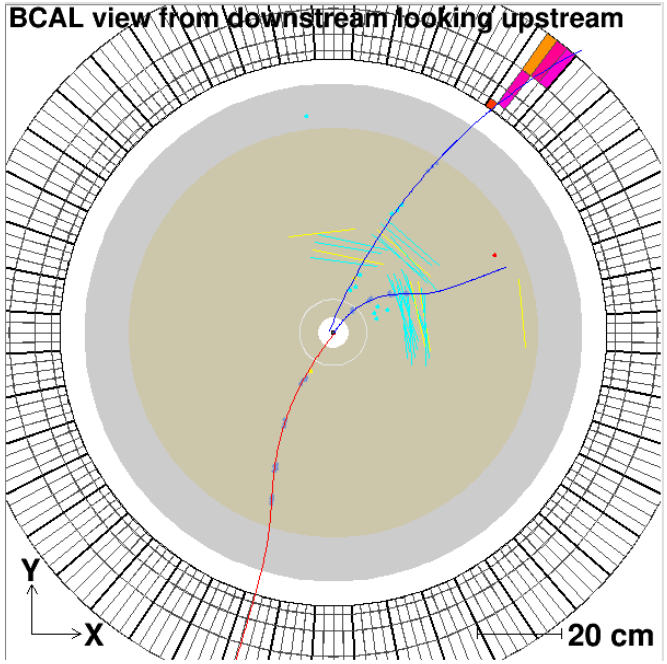
2^{+-} b_2, h_2...

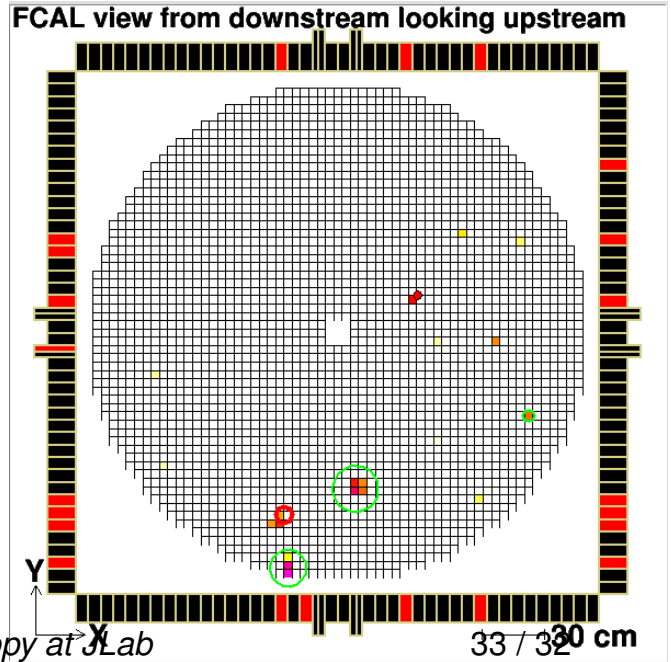
0^{+-} $b_\circ, h_\circ$...

etc.

Event Display







- 2 positive tracks
- 1 negative track
- Hits in FDC, CDC, BCAL, FCAL. TOF

Jefferson Lab

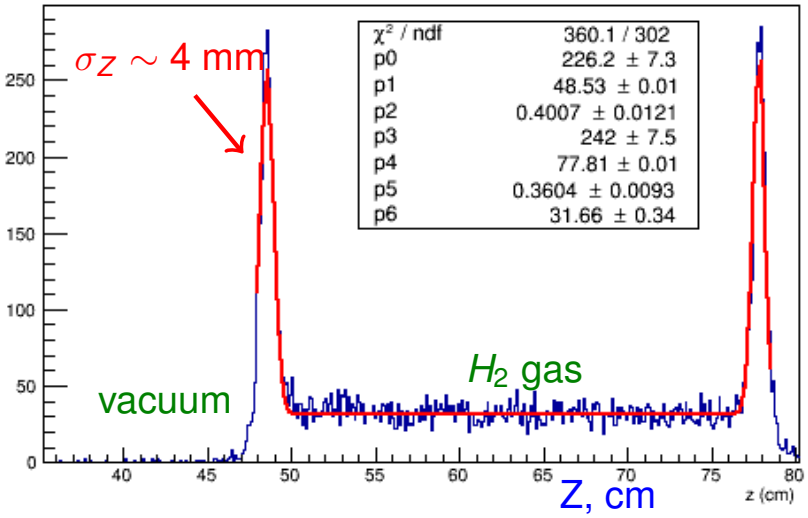
Track Reconstruction in Drift Chambers

Alignment, calibration: in progress

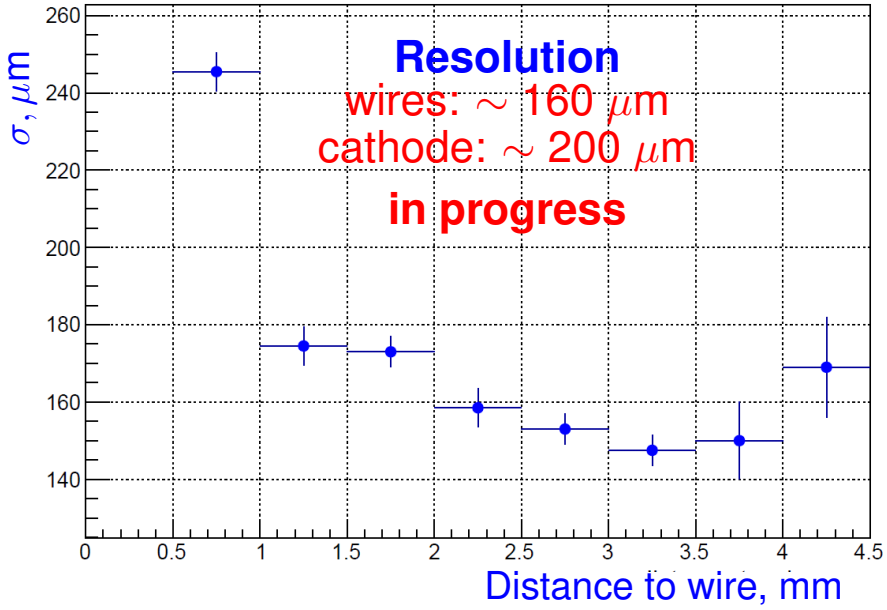
Field-off alignment

- FDC - tracks from the target
- CDC - cosmics

Empty LH_2 Target: thin windows



FDC: Resolution



CDC efficiency