Jefferson Lab Report

E.Chudakov

JLab

Presented at

11th International workshop on e^+e^- collisions from ϕ to ψ

PhiPsi17, Mainz, 26-29 June 2017

Jefferson Lab

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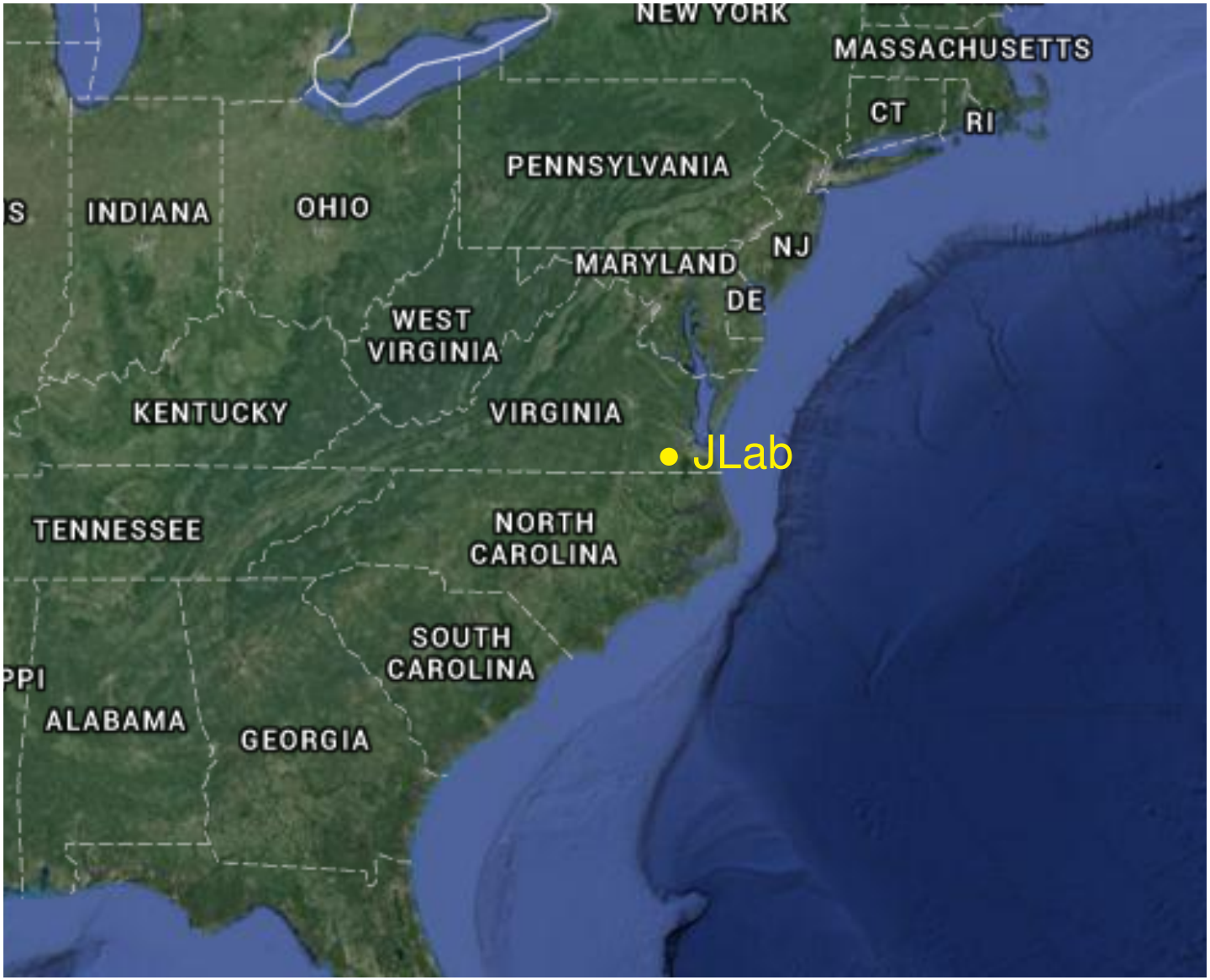

Jefferson Lab

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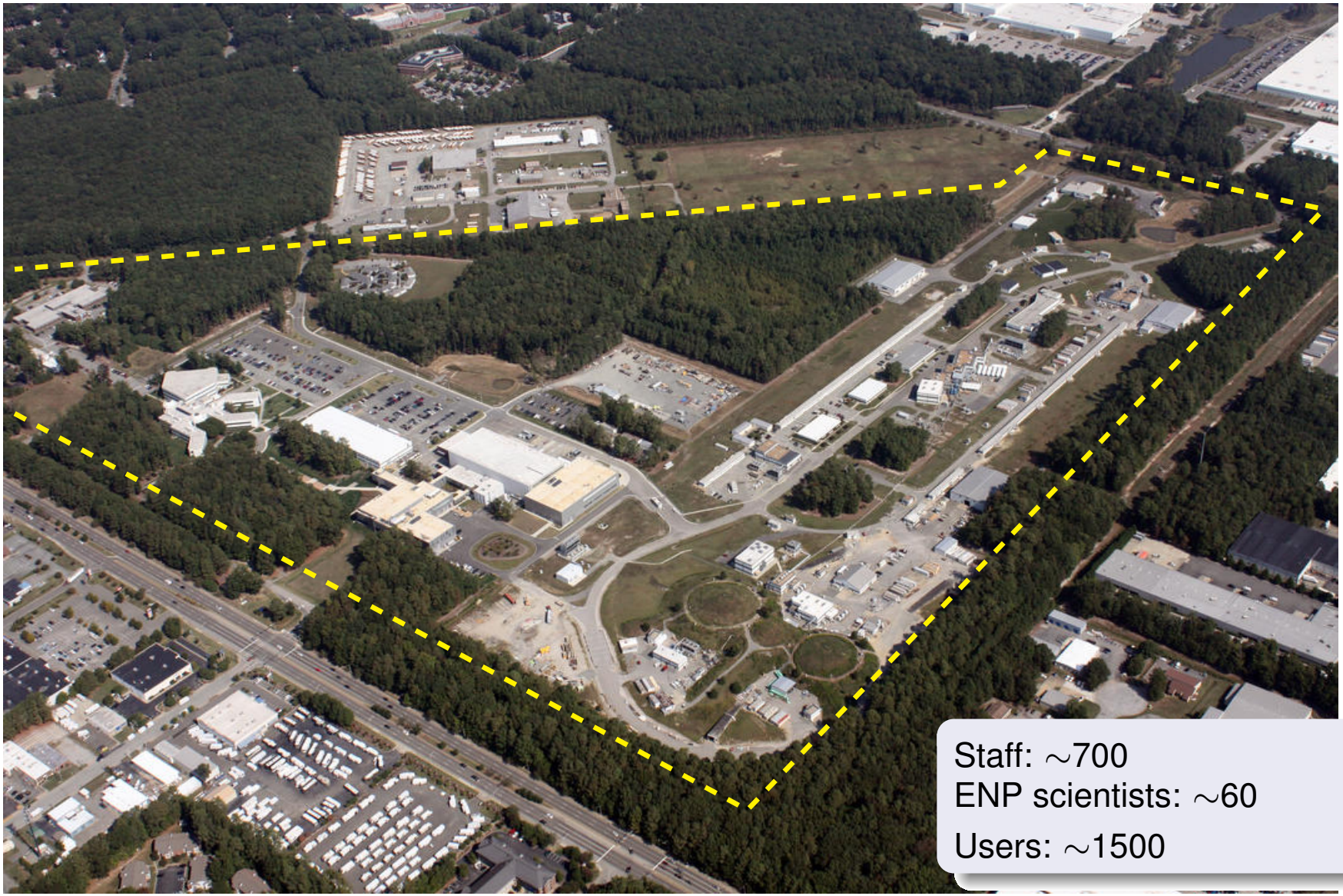
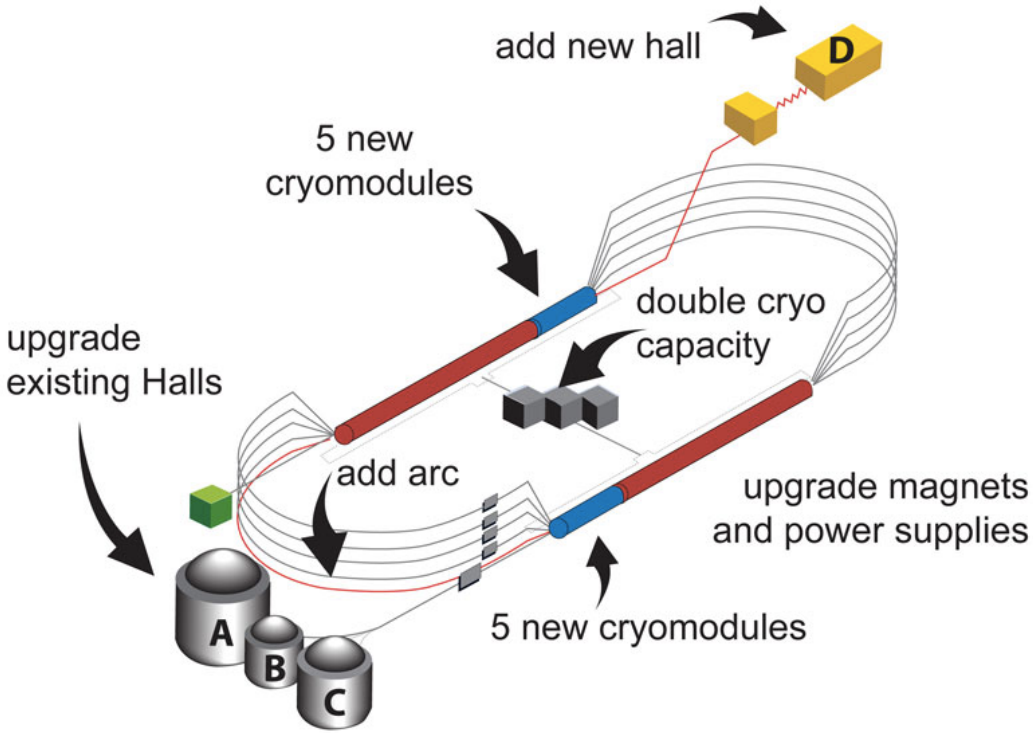


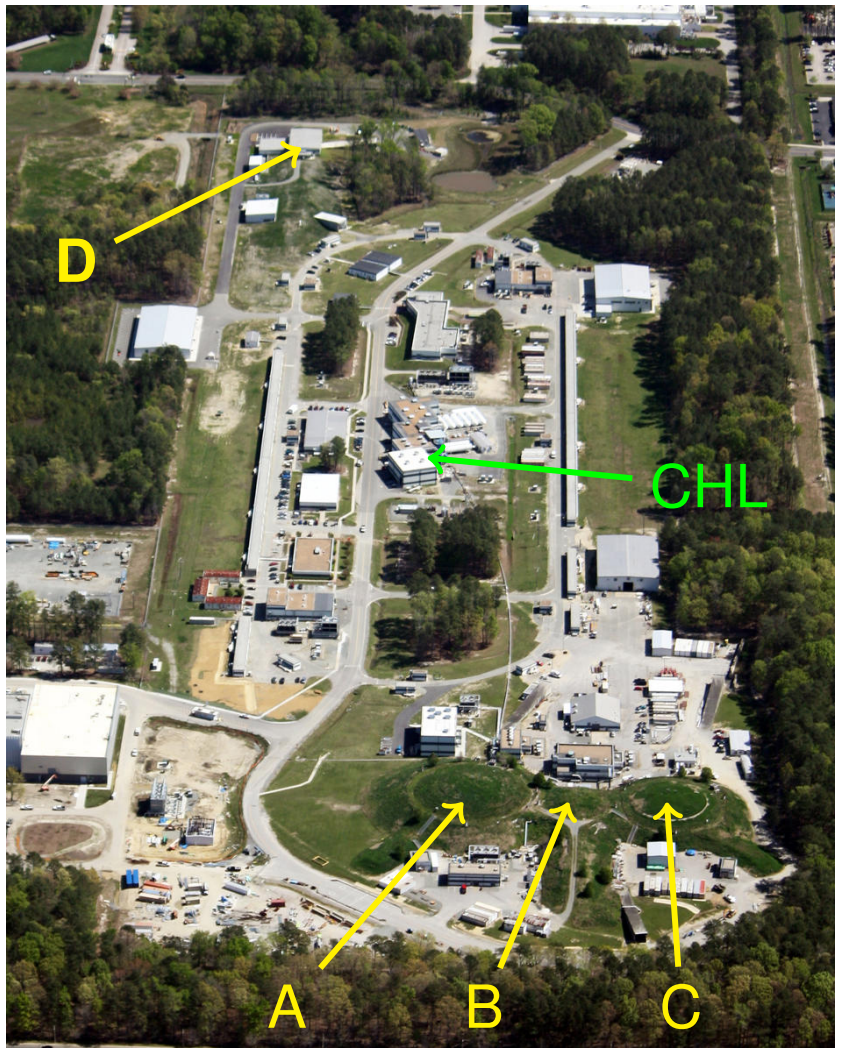
Staff: ∼700
ENP scientists: ∼60
Users: ∼1500

Outline

1. JLab at 12 GeV
   - Accelerator
   - Experimental halls
   - Running
2. Main Physics Goals
3. Selected topics and early results
   - Hall D early results
   - Parity violation
   - Heavy photon search
   - Proton radius

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

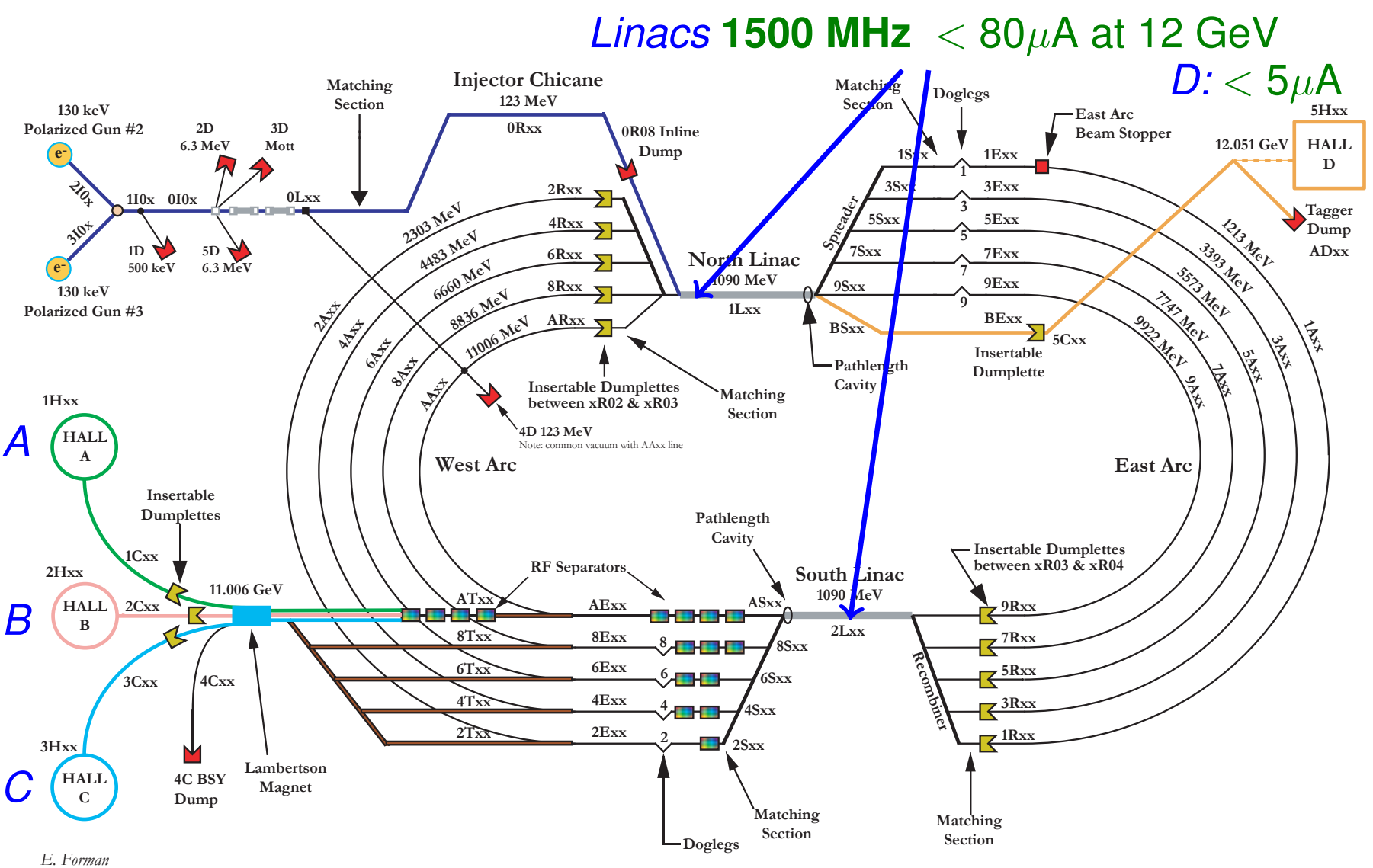
Upgrade Status

- 12 GeV started in Feb 2016
- Halls A,D,B(~~CLAS12~~): running
- Halls B,C: 12 GeV KPP Spring 2017

Remaining scope

- Hall B SC solenoid installation
- Upgrade completion: Sept 2017

Beam extraction



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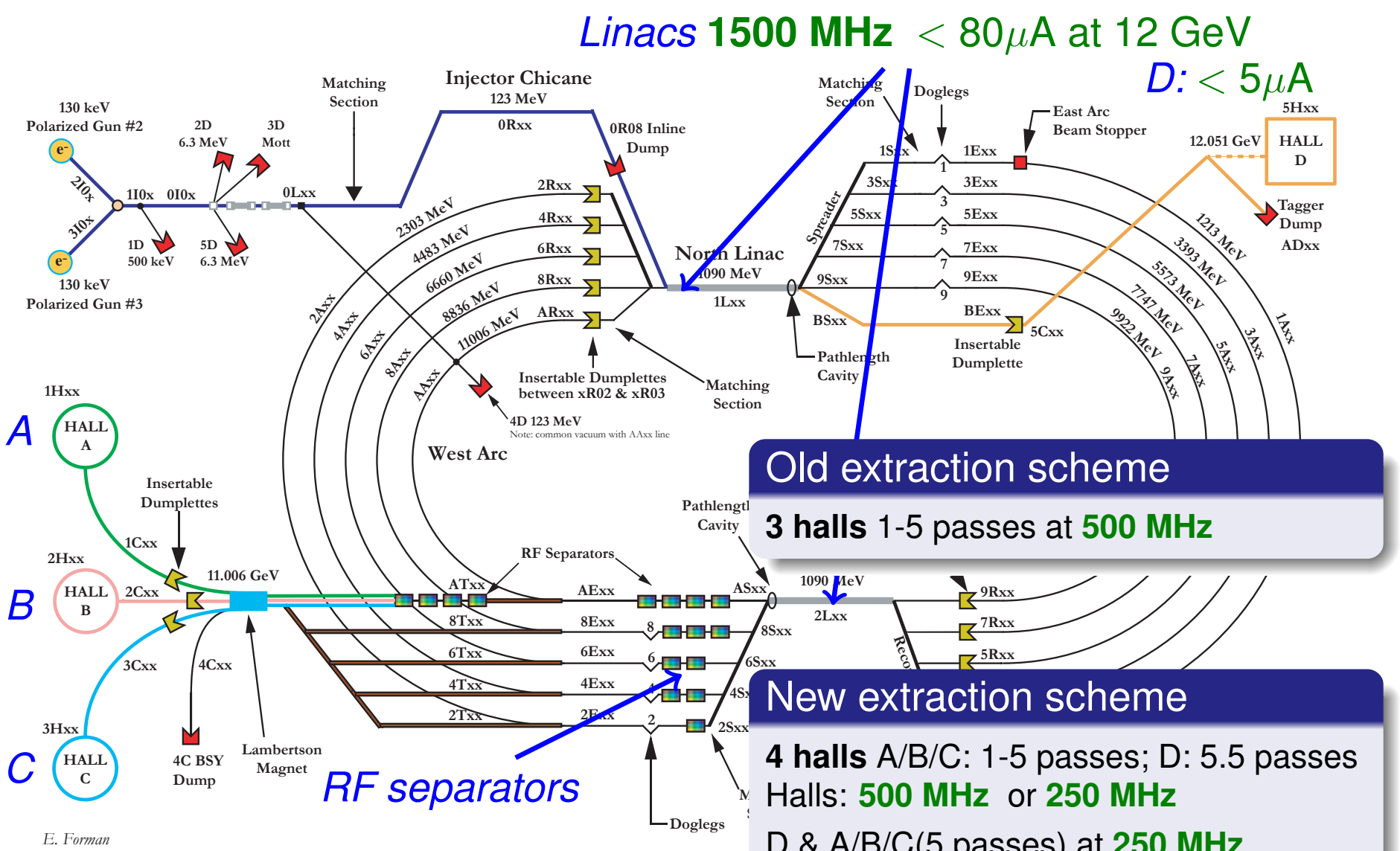


Old extraction scheme

3 halls 1-5 passes at **500 MHz**

New extraction scheme

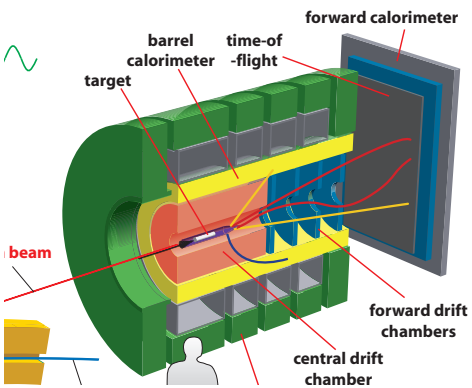
4 halls A/B/C: 1-5 passes; D: 5.5 passes

Halls: **500 MHz** or **250 MHz**

D & A/B/C(5 passes) at **250 MHz**

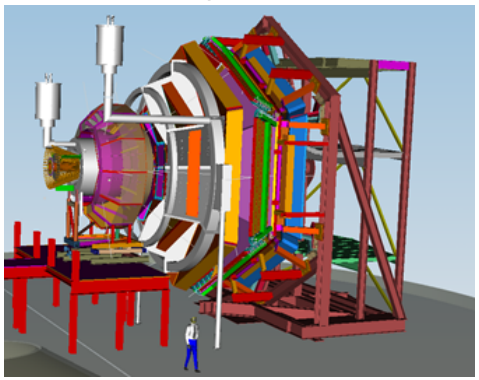
JLab Experimental Halls

Hall D



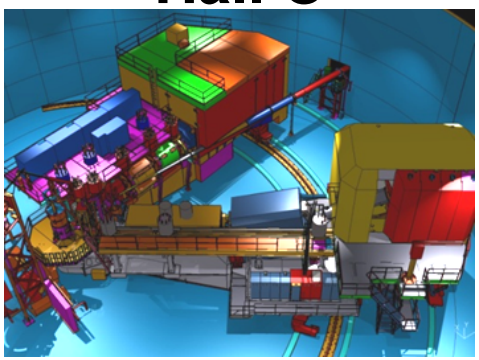
Spectroscopy
Search for:
exotic hybrid mesons

Hall B



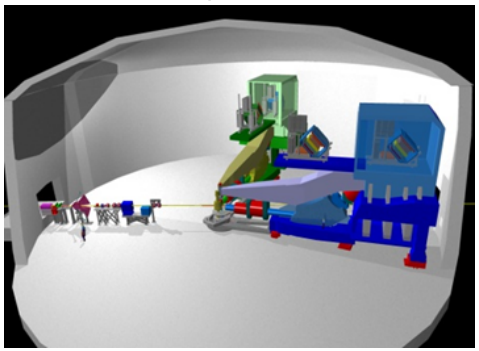
Nucleon Structure
GPD, TMD

Hall C



Nucleon Structure
Valence quarks

Hall A



Diverse program
Formfactors, PDF
SM tests (PV)
Future installations

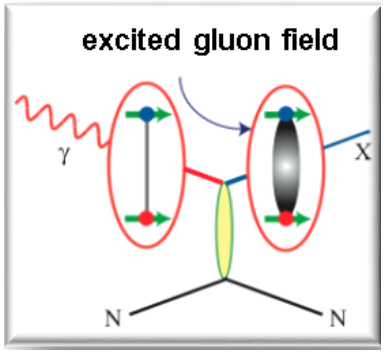
hermeticity	large acceptance	high resolution	custom installations
12 GeV $e^- \Rightarrow \gamma$	e^- 2.2–11 GeV		
γ linear polariz.	e^- longitudinal polarization		
GlueX spectrometer	CLAS12	HMS, SHMS	HRS, SBS
target LH	LH, LD; ammon. $\parallel, \perp$	any, polar. ^{3}He $\parallel, \perp$	any, polar. ^{3}He $\parallel, \perp$
<100 MHz/GeV	10^{35} cm^{-2}s^{-1}	10^{38} cm^{-2}s^{-1}	
$\sigma(p)/p \sim 1-3\%$	$\sigma(p)/p \sim 0.5\%$	$\sigma(p)/p \sim 0.1\%$	$\sigma(p)/p \sim 0.02\%$

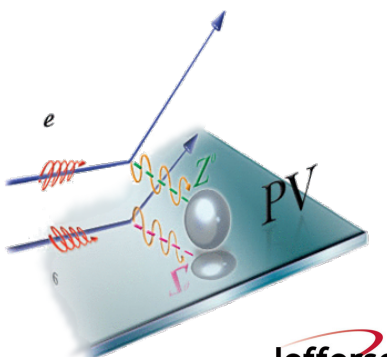
12 GeV runs

- Fall 2014 - Spring 2015: 10 GeV, 5 GeV:
  - Hall A DVCS
  - Hall B (~~CLAS12~~) HPS - heavy photon search
  - Hall D/GlueX commissioning
- Spring 2016 12 GeV
  - Hall A DVCS, Form Factors
  - Hall B (~~CLAS12~~) HPS (heavy photon search)
  - Hall D/GlueX engineering run
- Spring 2017 11.65 GeV
  - Hall A DVCS, GMP (G_M^p)
  - Hall B (~~CLAS12~~) HPS (heavy photon search); PRAD (proton radius)
  - Hall B CLAS12 KPP (Key Performance Parameters)
  - Hall C SHMS KPP
  - Hall D/GlueX 1-st physics run ($\sim$20% of GlueX-I)
- Fall 2017 11.65 GeV Planning
  - 4 halls to run

JLab at 12 GeV: Scientific Questions

- What is the role of gluonic excitation in the spectroscopy of light mesons?
- Where is the missing spin in the nucleon? Is there a significant contribution from orbital angular momentum of valence quarks?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?



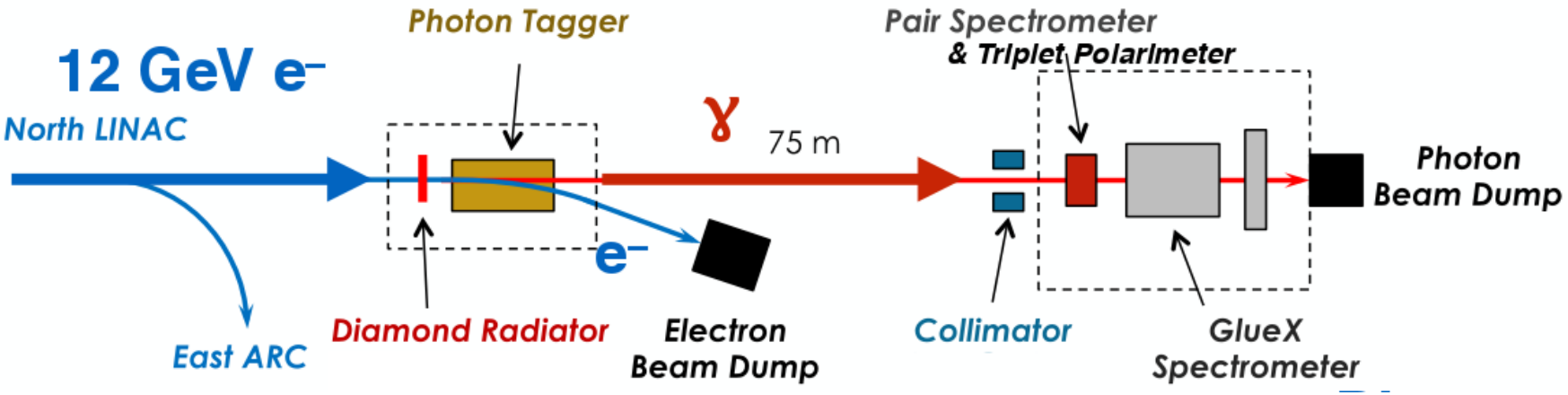


12 GeV Approved Experiments by Physics Topic

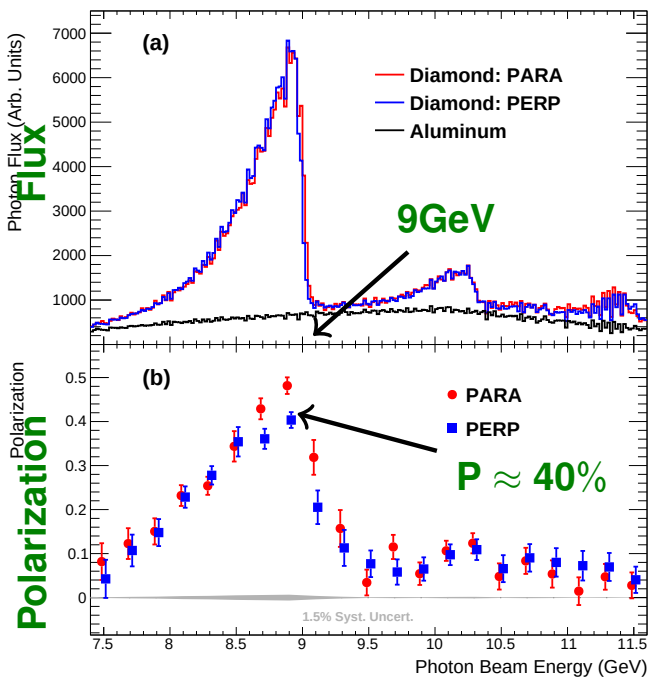
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	3	1	3	0	**7**
Transverse structure of the hadrons	5	4	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	6	0	0	**11**
3D structure of the hadrons	5	9	7	0	0	**21**
Hadrons and cold nuclear matter	7	3	7	0	1	**18**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	1	**6**
Total	**22**	**23**	**24**	**5**	**2**	**76**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**19.5**	**22**	**24**	**4.6**	**2**	**72.0**

Remaining: 2400 days

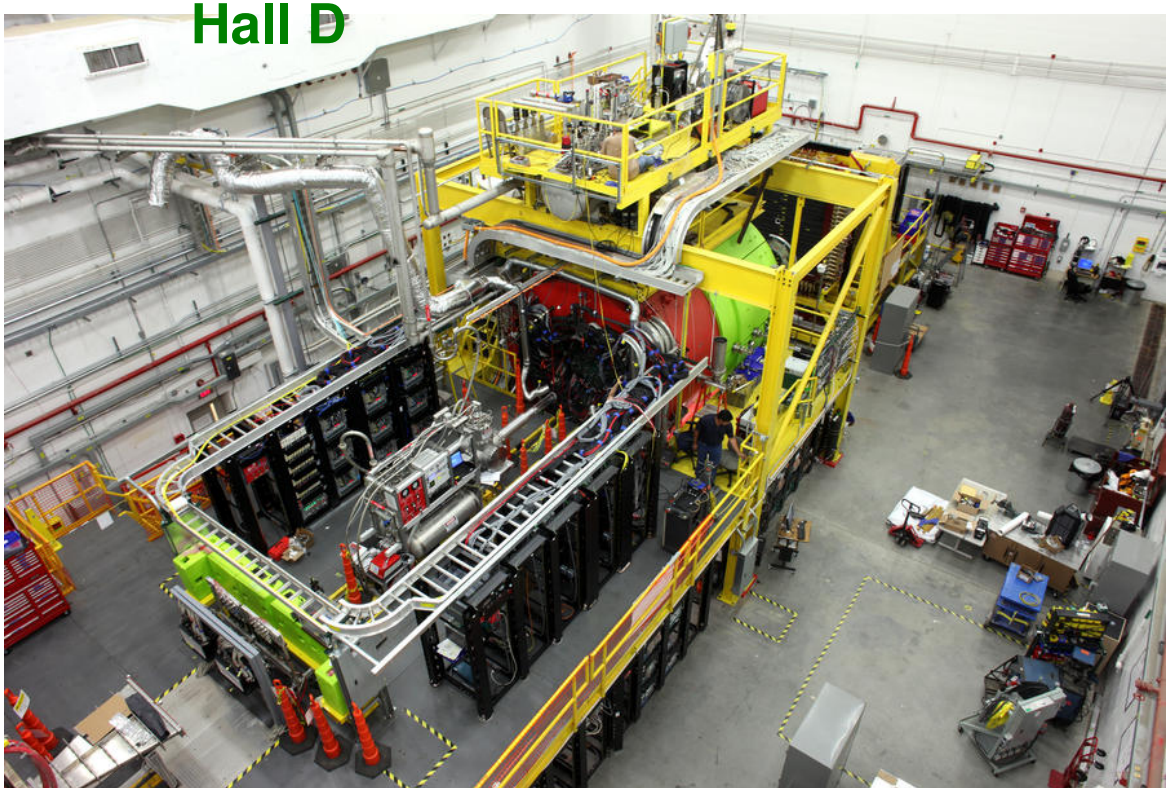
Hall D/GlueX Meson Spectroscopy In Photoproduction



Photon Beam Spectrum



Hall D



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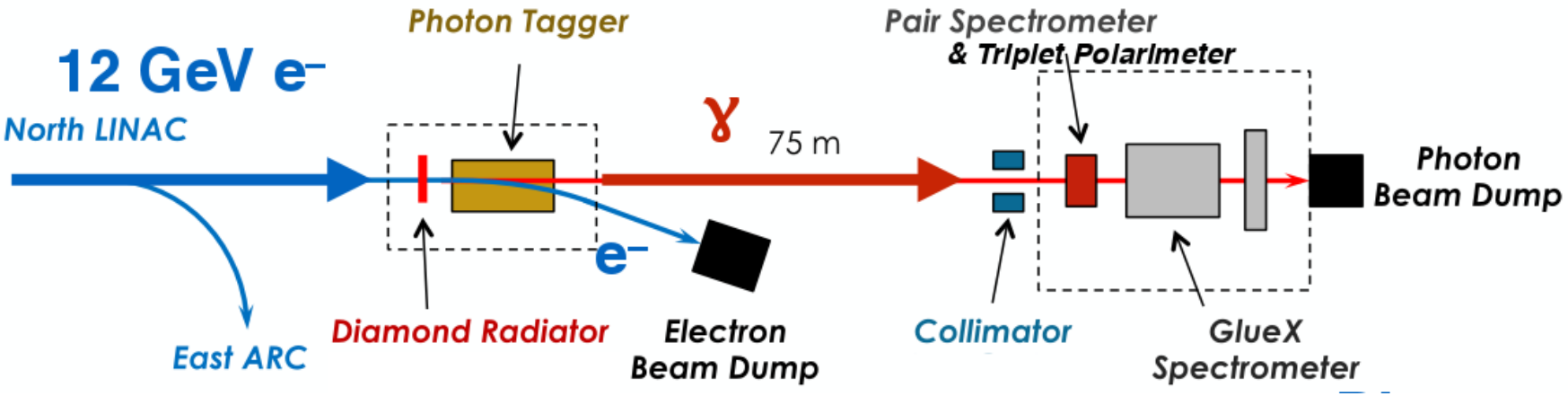
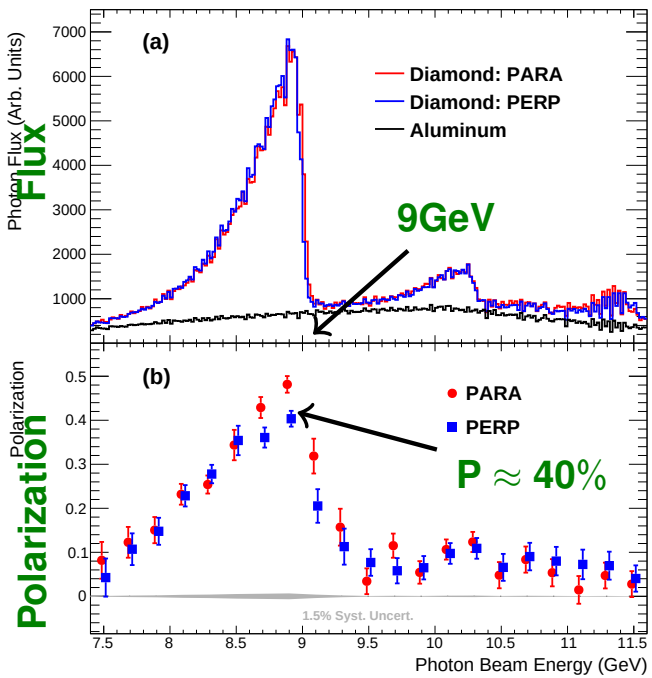


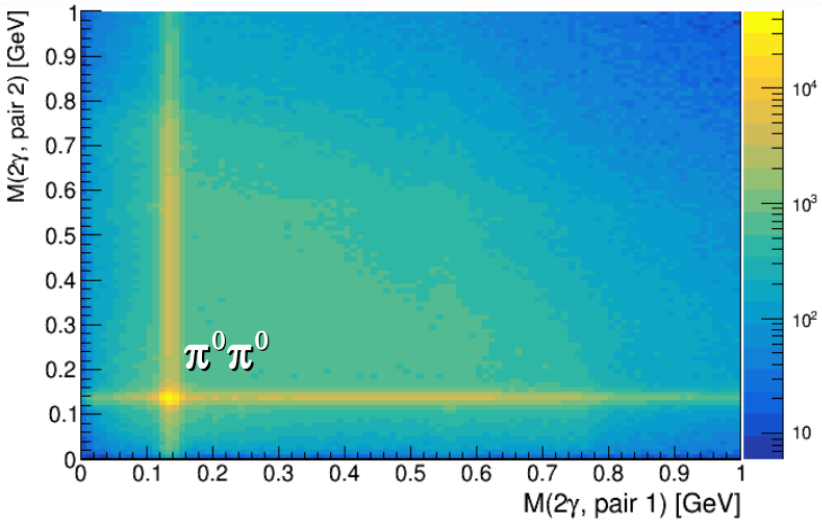
Photon Beam Spectrum

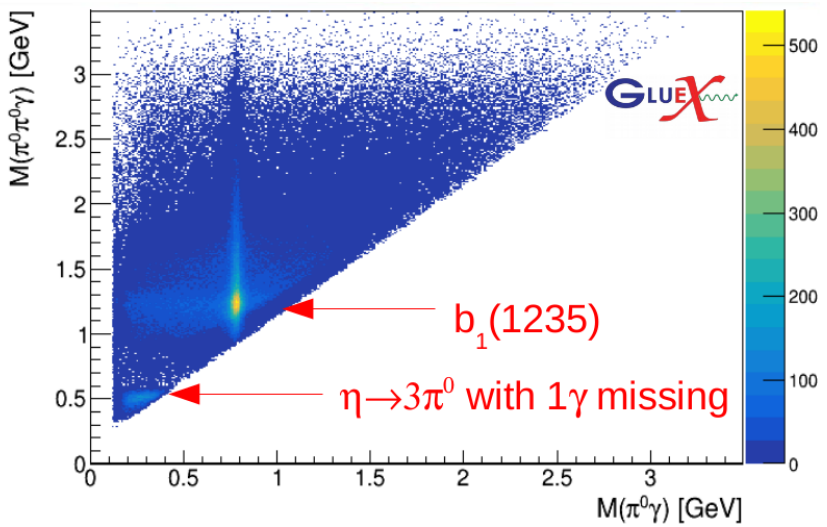


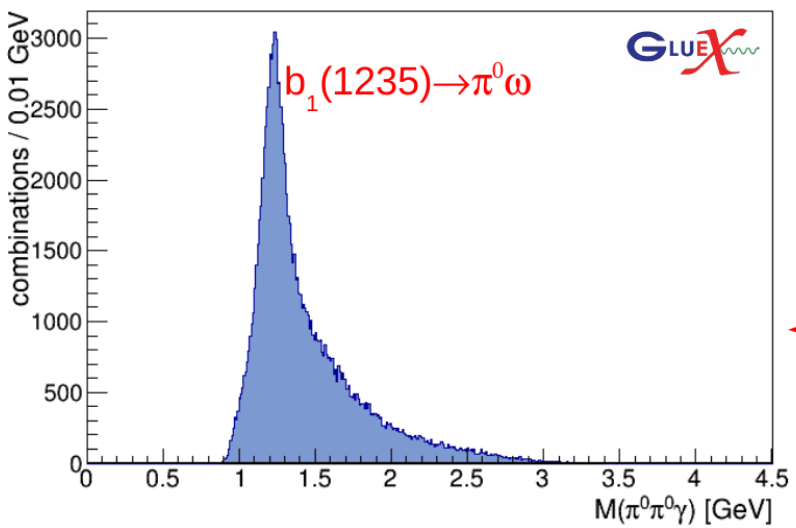
- Acceptance: $1^\circ < \theta < 120^\circ$
- Resolutions:
  $h^\pm$: $\sigma_p/p \sim 1 - 3\%$
  γ: $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$
- Trigger takes all the photoproduction at $E_{BEAM} > 8$ GeV
  in 2017: 55 kHz
- Luminosity for $E_{BEAM} > 8$ GeV:
  2016: $\sim$ 5 pb^{-1} of "physics quality"
  2017: $\sim$ 30 pb^{-1} analysis in progress

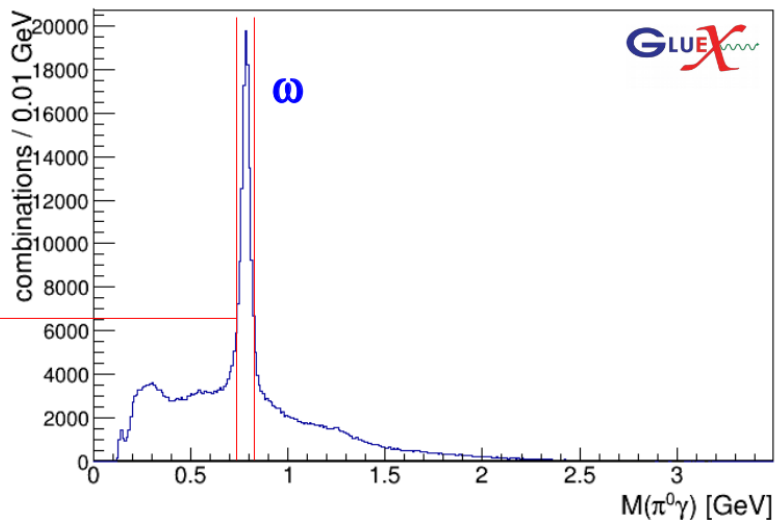
GlueX: Event Reconstruction and Signals Observed

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





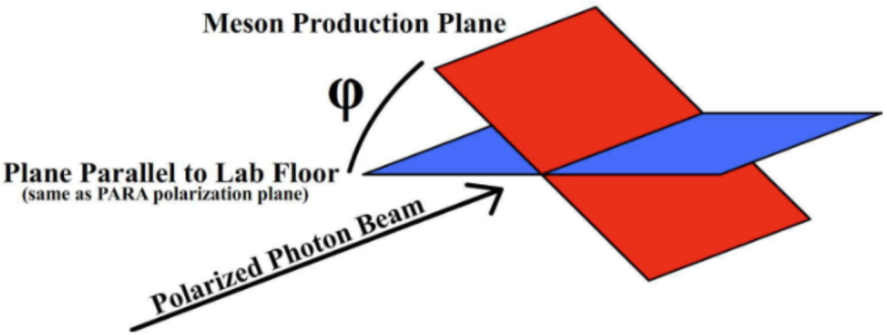




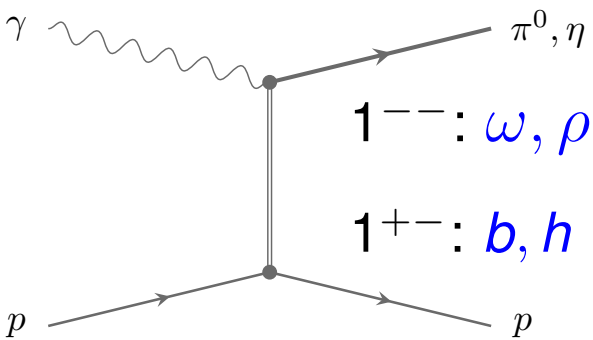
GlueX: Beam Asymmetries of π^0, η

Properties of Photoproduction

Phys.Rev. C95, 042207(R), 2017

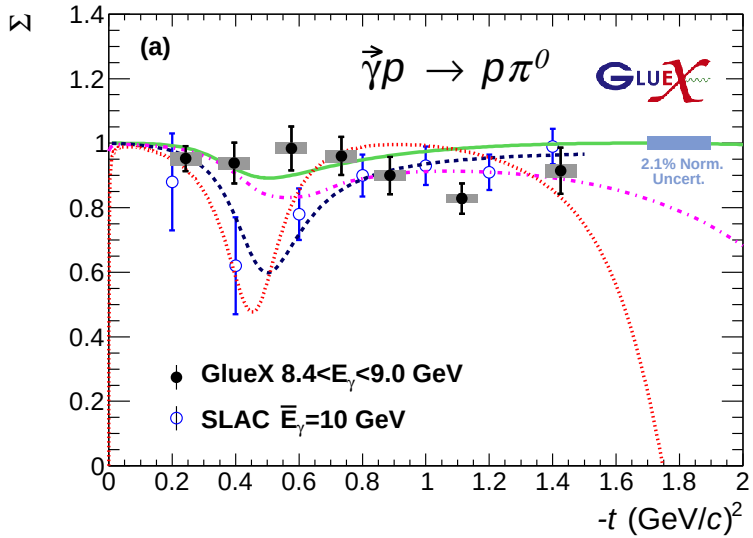


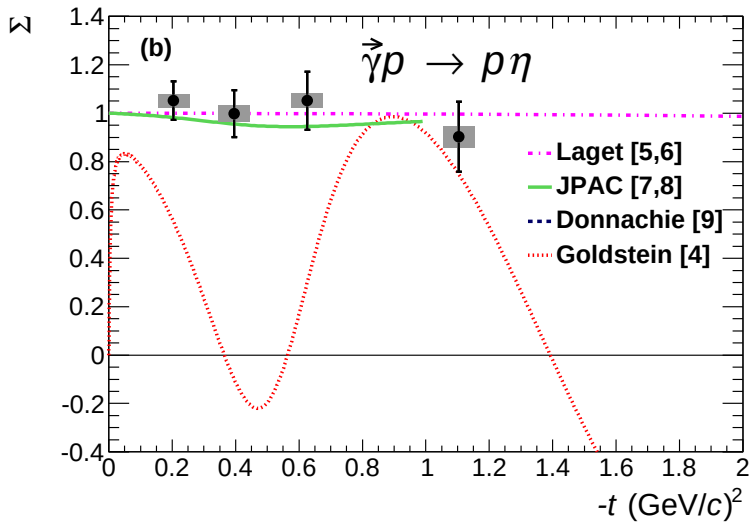
$$A(\varphi) = \frac{\frac{d\sigma}{d\varphi_\perp} - \frac{d\sigma}{d\varphi_\parallel}}{\frac{d\sigma}{d\varphi_\perp} + \frac{d\sigma}{d\varphi_\parallel}} \approx P\Sigma\cos(2\varphi)$$



1^{--}: ω, ρ $\quad \Sigma \approx +1$

1^{+-}: b, h $\quad \Sigma \approx -1$





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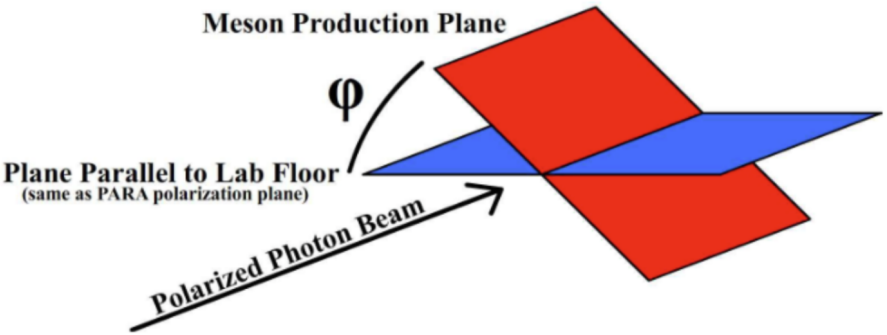

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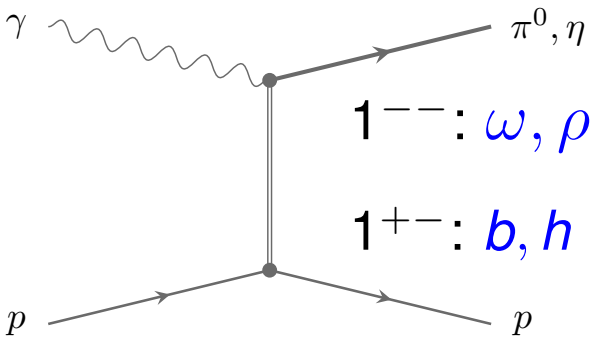

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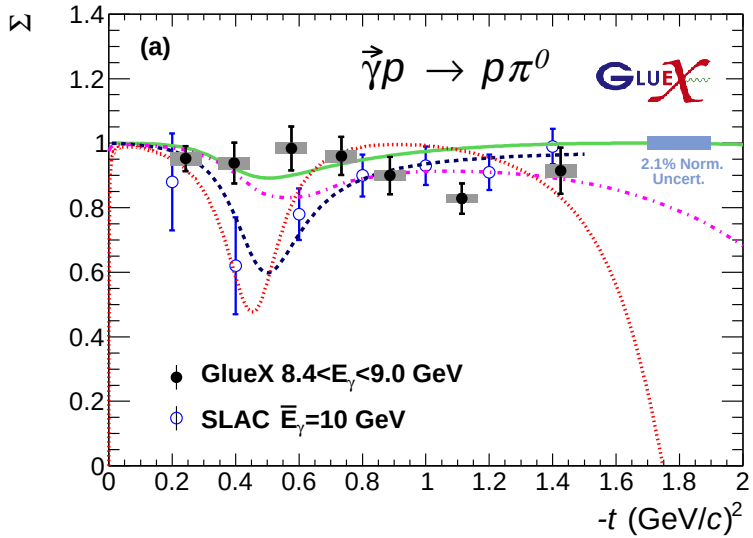

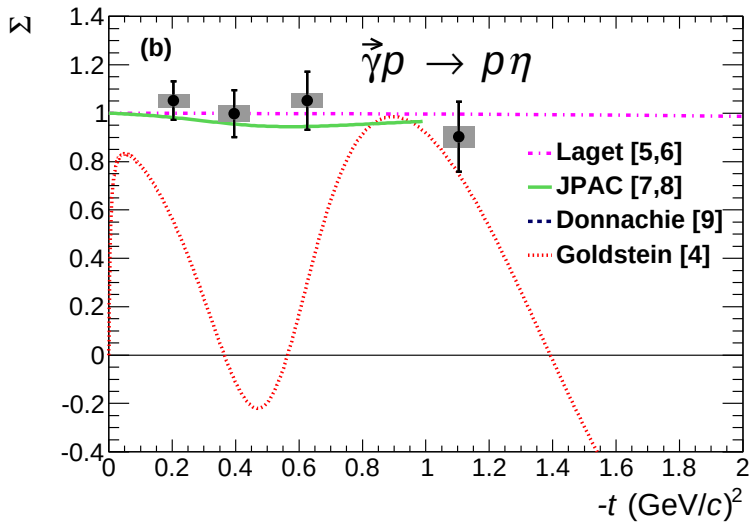

- Vector exchange dominates
- No observed dip at $-t = 0.5$ (GeV/c)^2

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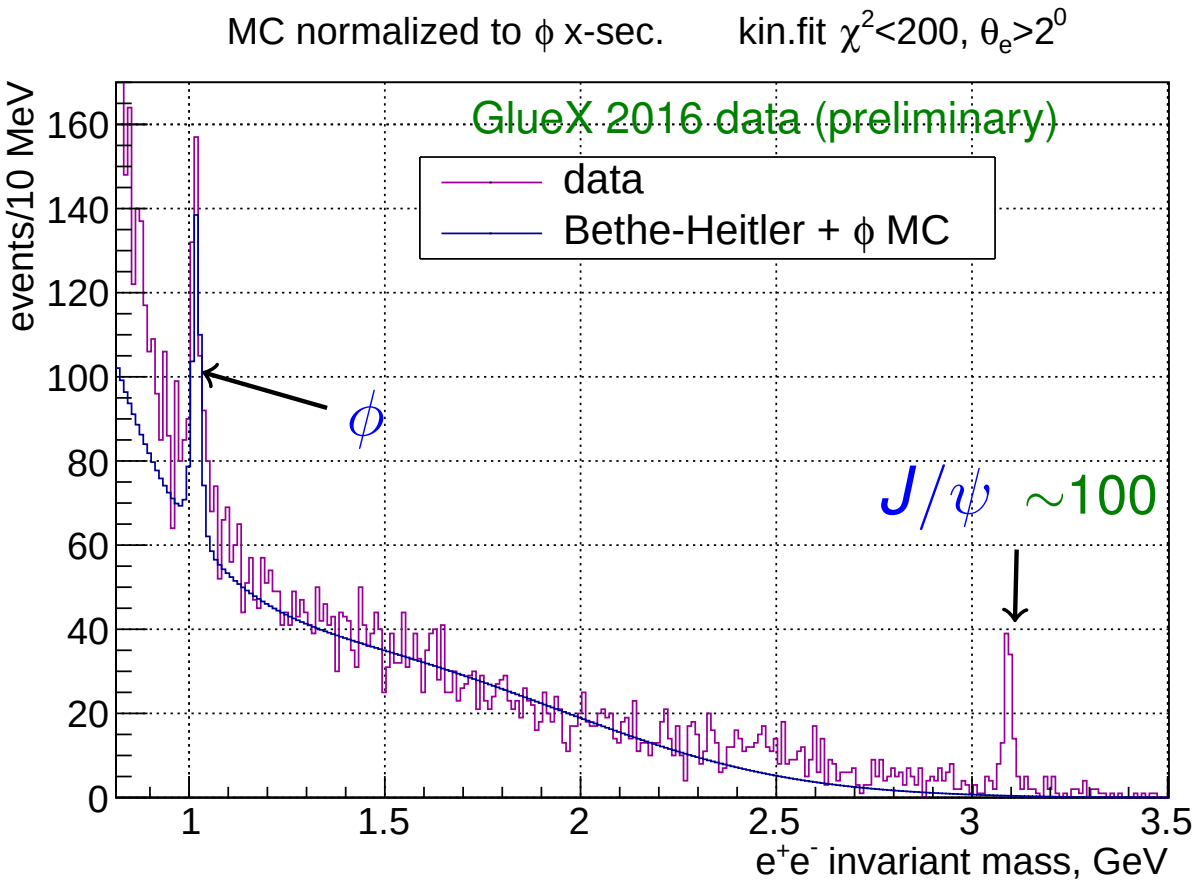
GlueX: Photoproduction of J/ψ close to threshold

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

- 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



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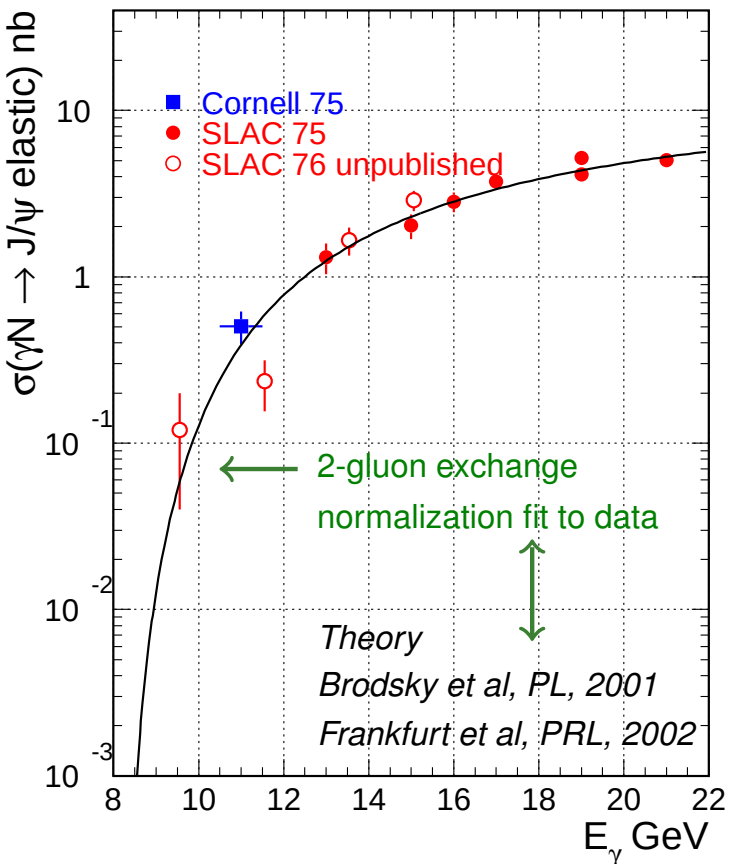
GlueX: Photoproduction of J/ψ close to threshold

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)
  $\gamma p \to P(4450) \to J/\psi p$ predictions $\propto B^2(P \to J/\psi p)$



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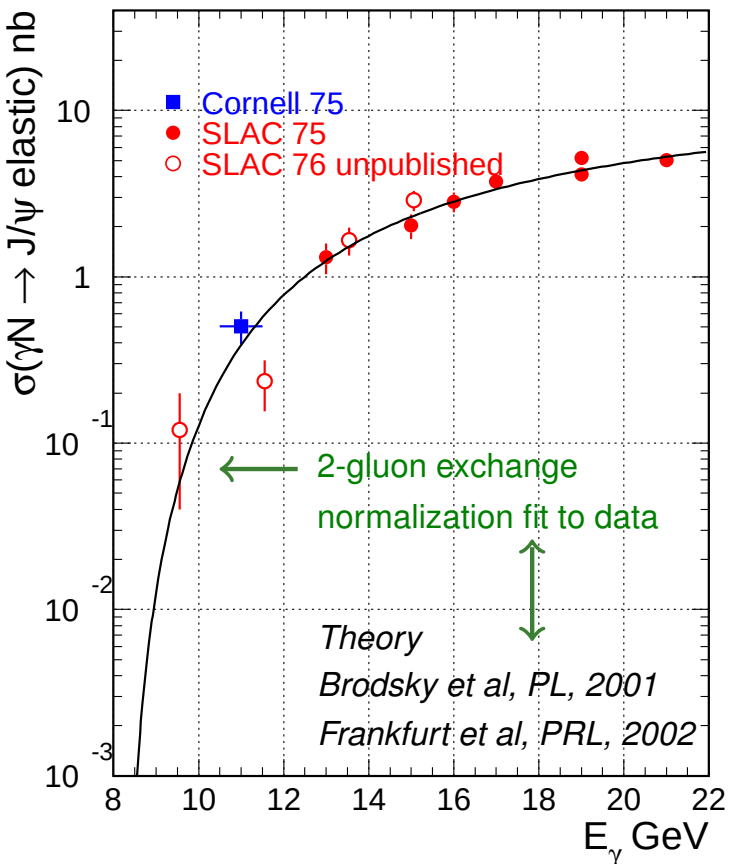
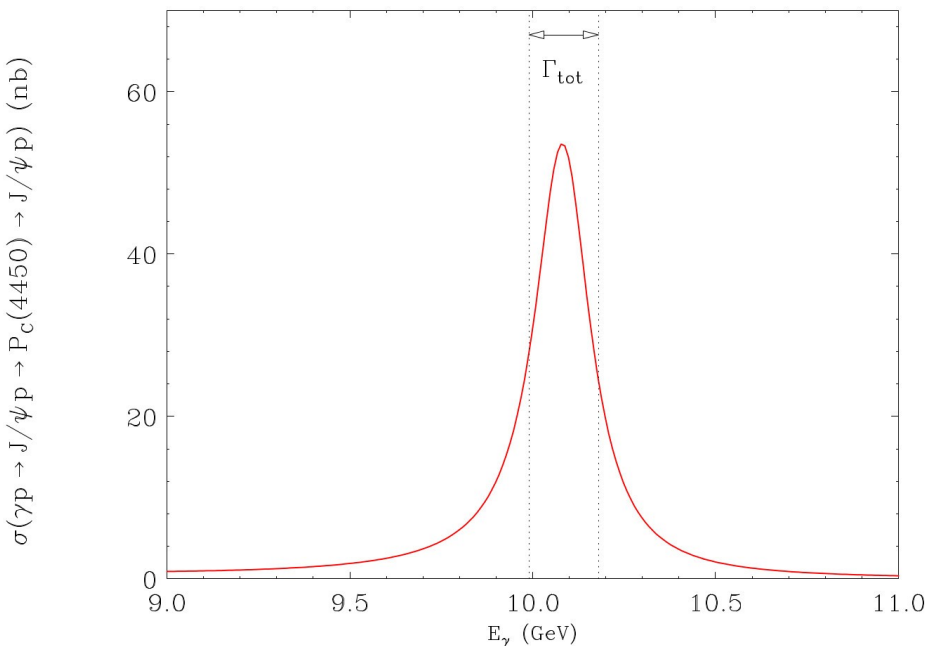


M.Karliner, Phi2Psi 2017: $B(P \to J/\psi p) = 10\%$



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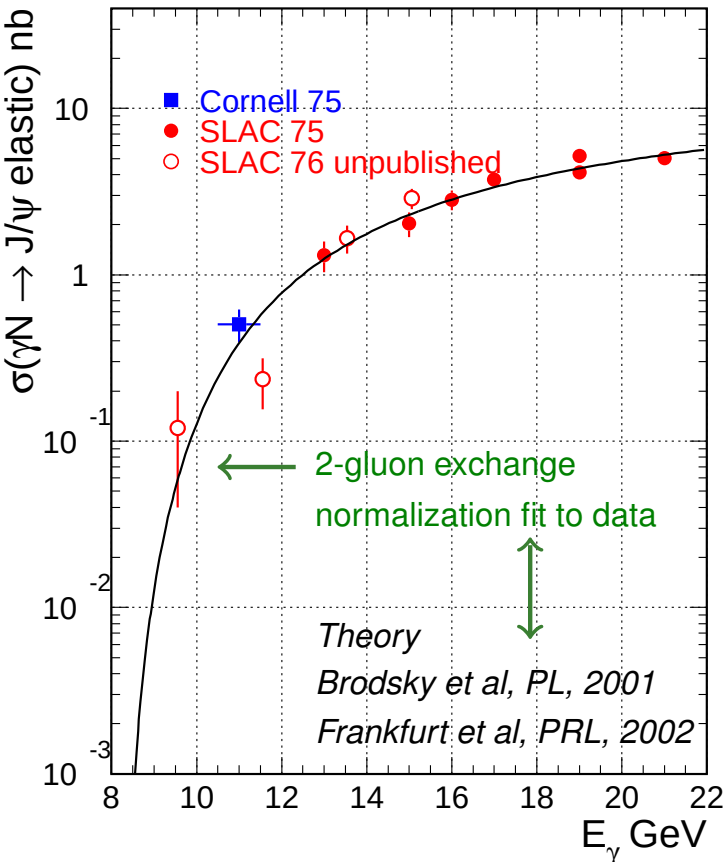
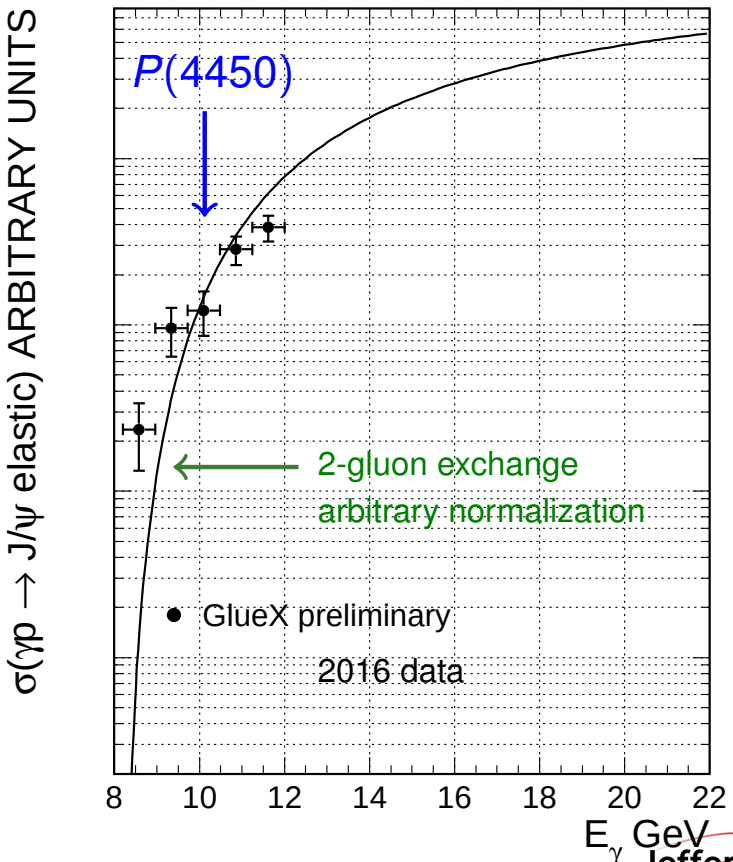
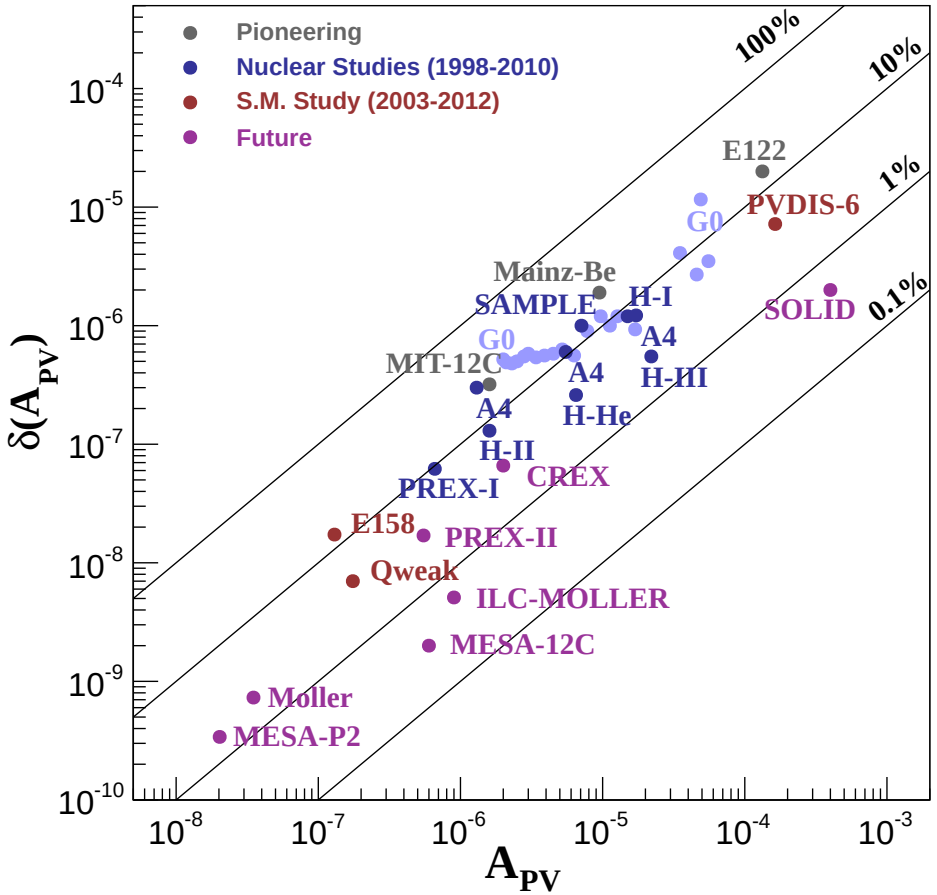


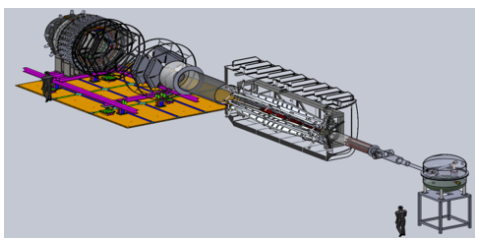


Parity Violation at JLab

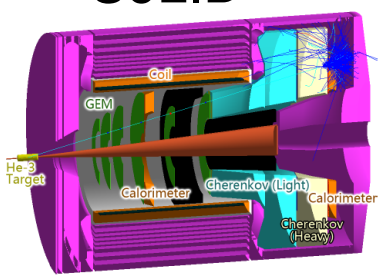
- Nucleon Strangeness Formfactors *complete*
  - HAPPEX Hall A
  - G0 Hall C
- Neutron skin
  - PREX, CREX Hall A
- Precision tests of Standard Model
  - PVDIS Hall A *published*
  - Qweak Hall C *to publish soon*
  - MOLLER, SOLID (Hall A, future)



MOLLER



SoLID



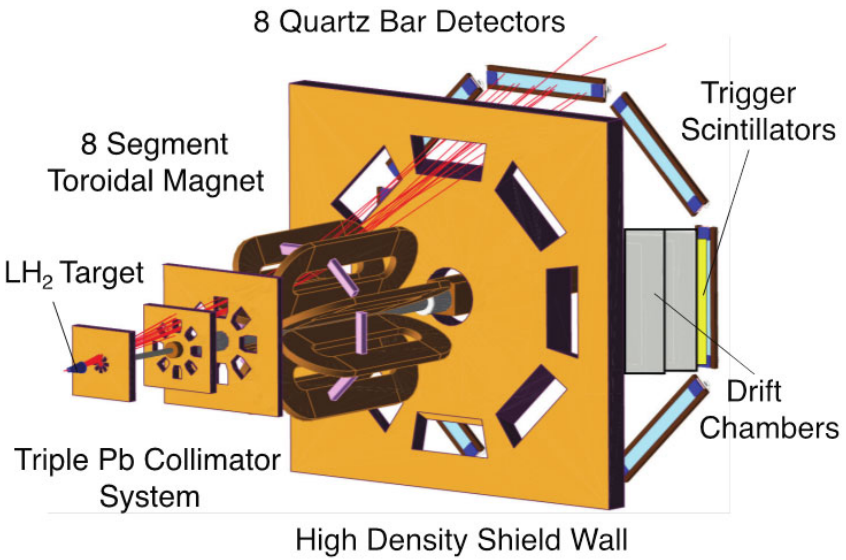
e^- on Unpolarized target

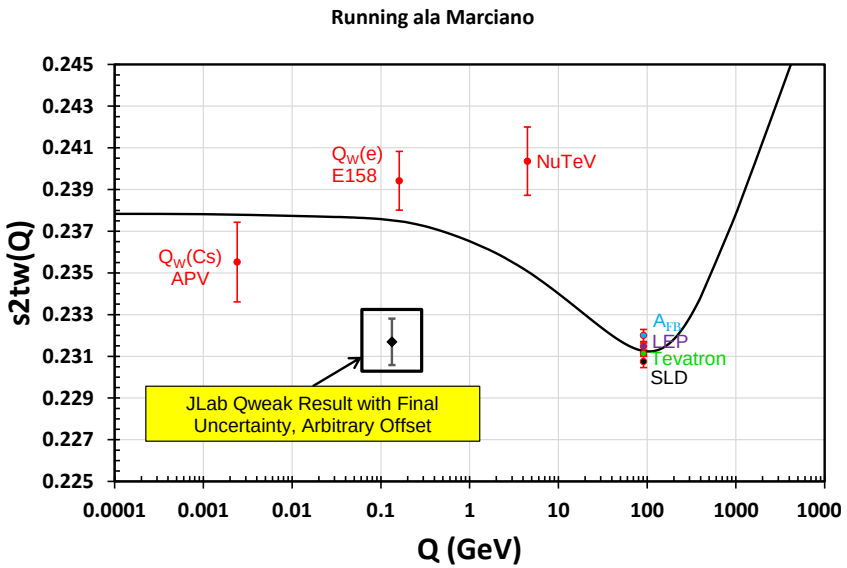
$$\sigma \propto |A_\gamma + A_{weak}|^2 \sim |A_\gamma|^2 + 2A_\gamma A^*_{weak} + \ldots$$

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A_{weak}}{A_\gamma} \propto \frac{G_F Q^2}{4\pi\alpha} \mathbf{g}$$

Qweak: PV Elastic e^-p Scattering

$$Q_W^p = (1 - 4\sin^2\theta_W)$$

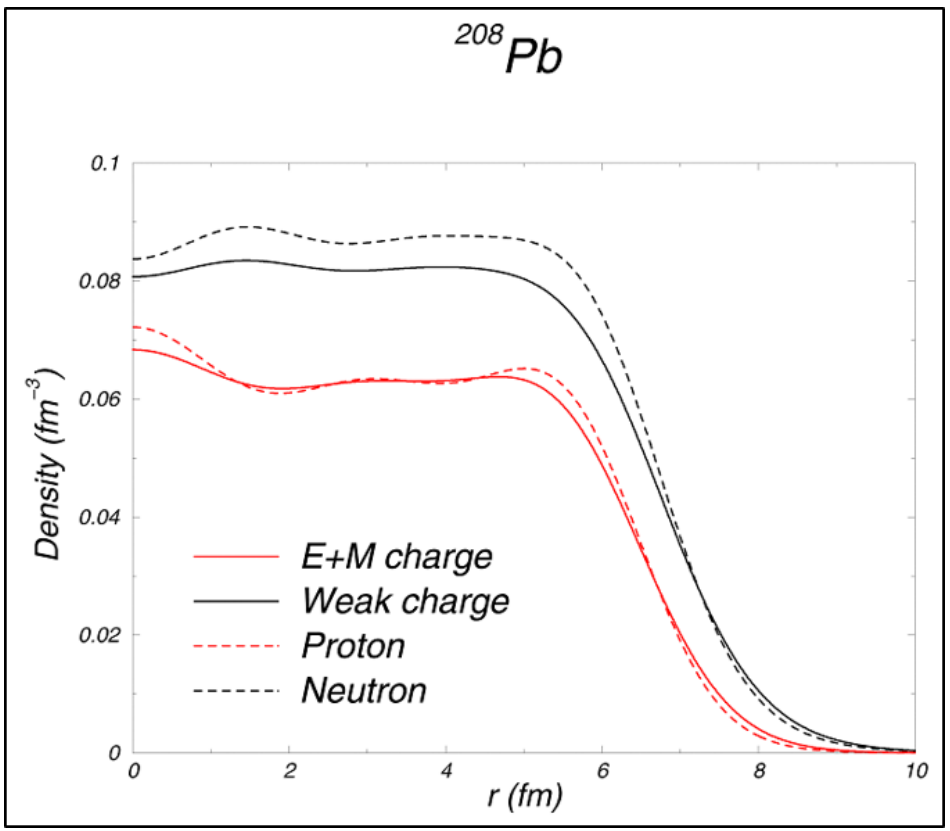


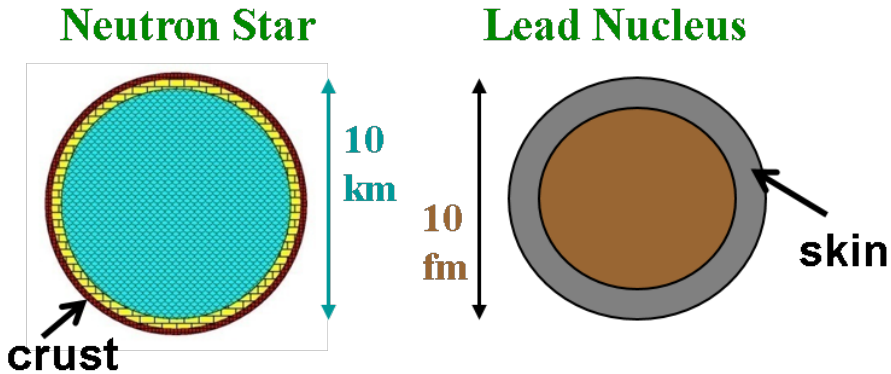


PREX/CREX Measuring the “Neutron skin” of Pb, Ca

PV elastic scattering off nuclei: sensitive to the “neutron size”

$$Q_W^p = (1 - 4\sin^2\theta_W) < 0.1$$
$$Q_W^n = -1$$



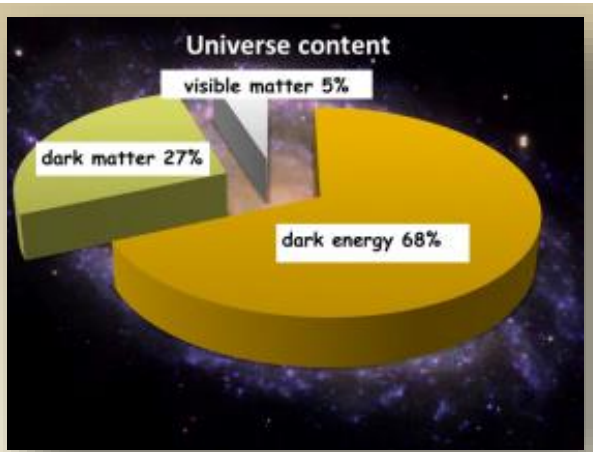


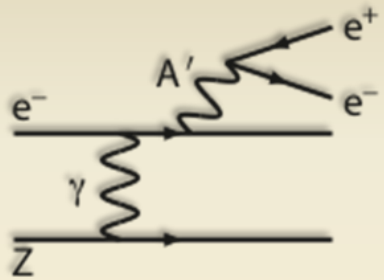
- PREX: ^{208}Pb
  pilot experiment published
- CREX: ^{48}Ca

Applications: Nuclear Physics, Neutron Stars, Atomic Parity, Heavy Ion Collisions

Heavy Photon Search - First Results

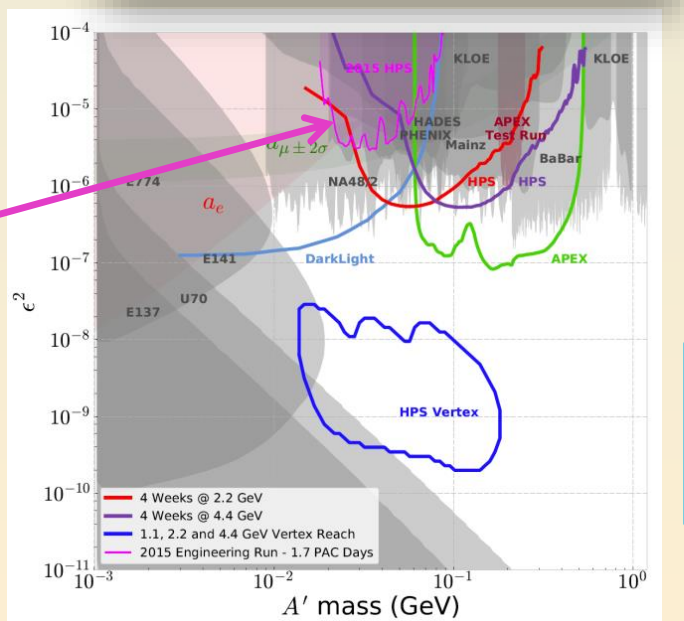
- NP-HEP Collaboration

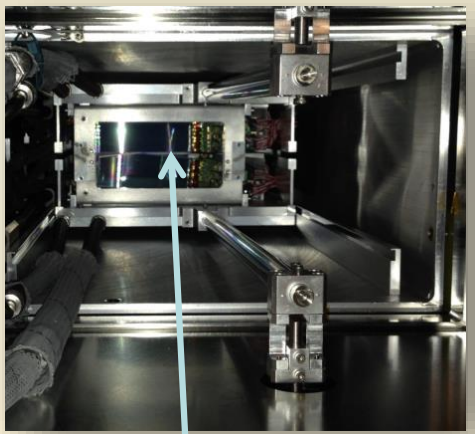




2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2 GeV data taken in 2016, under analysis





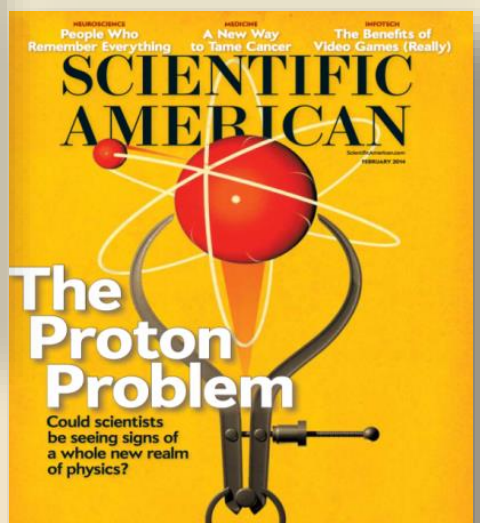
1 mm gap between Si tracker detectors for passage of electron beam

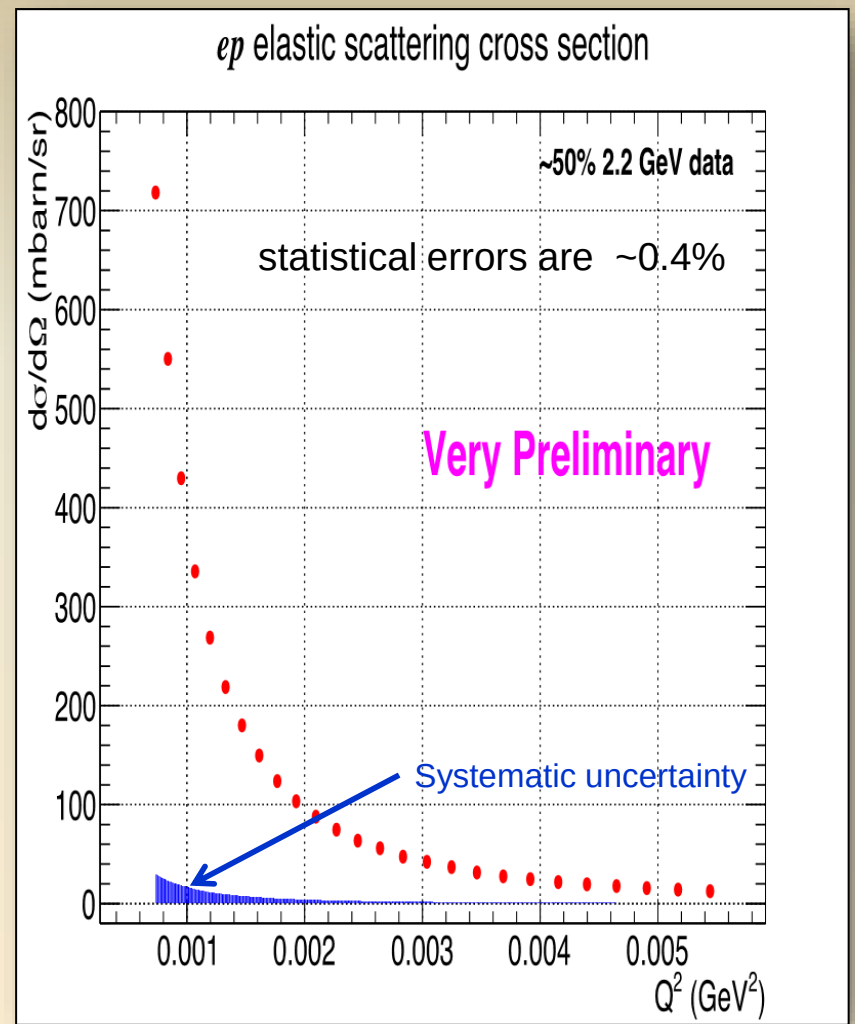
Future program: more HPS, APEX, DarkLIGHT

Courtesy to B.McKeown

PRAD - Proton Radius

- PRad: new experiment to address proton radius @ JLab
- NSF MRI: H_2 gas target
- DOE GEM tracking detectors
- Successful run in summer 2016





Final results expected by the end of 2018

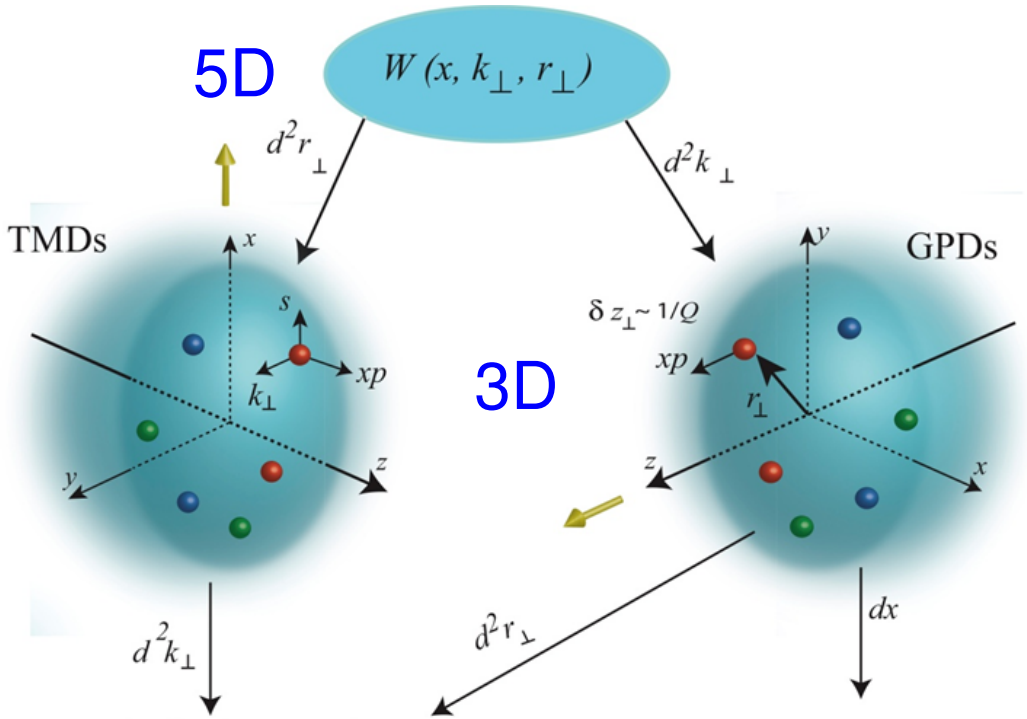
Courtesy to B.McKeown

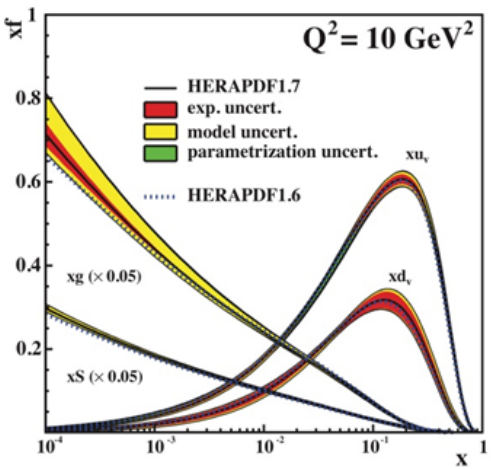
Outlook

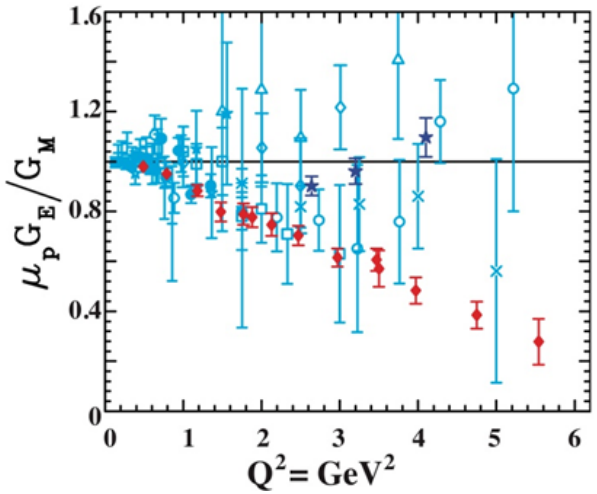
- The 12 GeV operations of JLab have begun
  - Hall A: running
  - Hall B: CLAS12 started commissioning; other experiments have run
  - Hall C: started commissioning
  - Hall D: running, 1-st paper published
- Next large projects planned:
  - MOLLER: SM test in PV
  - SoLID: broad program: PV; nucleon imaging
- At least a decade of excellent opportunities for discovery
  - New QCD vistas
  - Growing program Beyond the Standard Model
- Beyond 12 GeV: EIC is moving forward

APPENDIX

Imaging the Nucleon

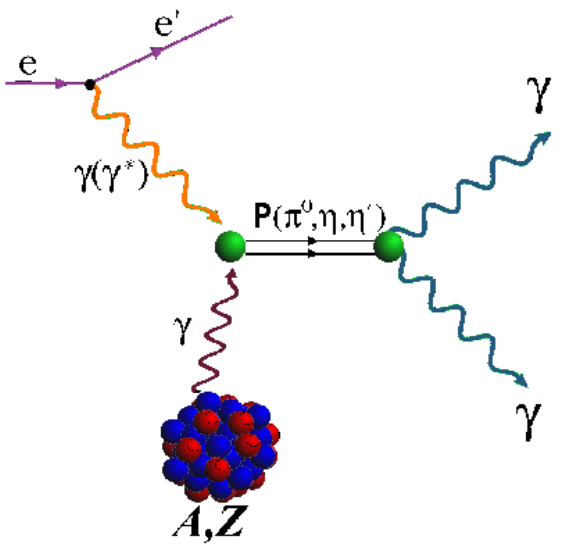






- TMD
  Transverse Momentum Dist.
  Confined motion in a nucleon
  (semi-inclusive DIS: SIDIS)
- GPD
  Generalized Parton Dist.
  Spatial Imaging
  (exclusive DIS: for ex. DVCS)
- Requires
  – High luminosity.
  – Polarized beams & targets
  – Sophisticated detectors

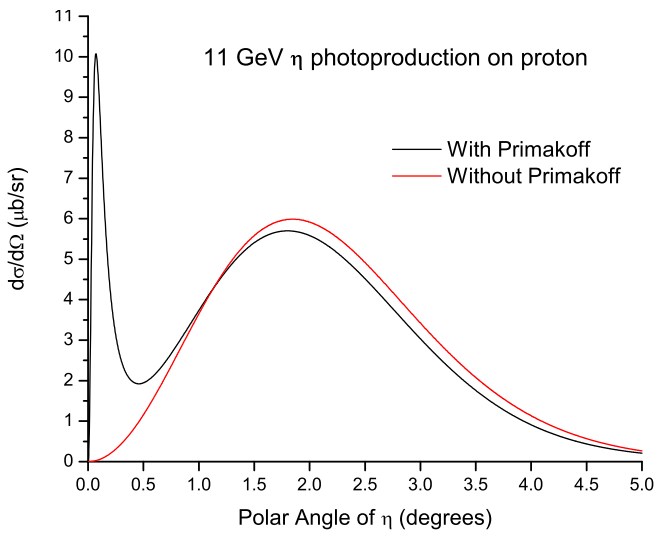
$\pi^\circ, \eta, \eta' \to \gamma\gamma$ coupling in Primakoff reaction



- $\Gamma(\pi^\circ \to \gamma\gamma)$
  test of Chiral symmetry/anomalies
  6 GeV E-02-103 in Hall B
- $\Gamma(\eta \to \gamma\gamma)$
  light quark mass ratio,
  $\eta - \eta'$ mixing angle
  12 GeV PR12-10-011 in Hall D

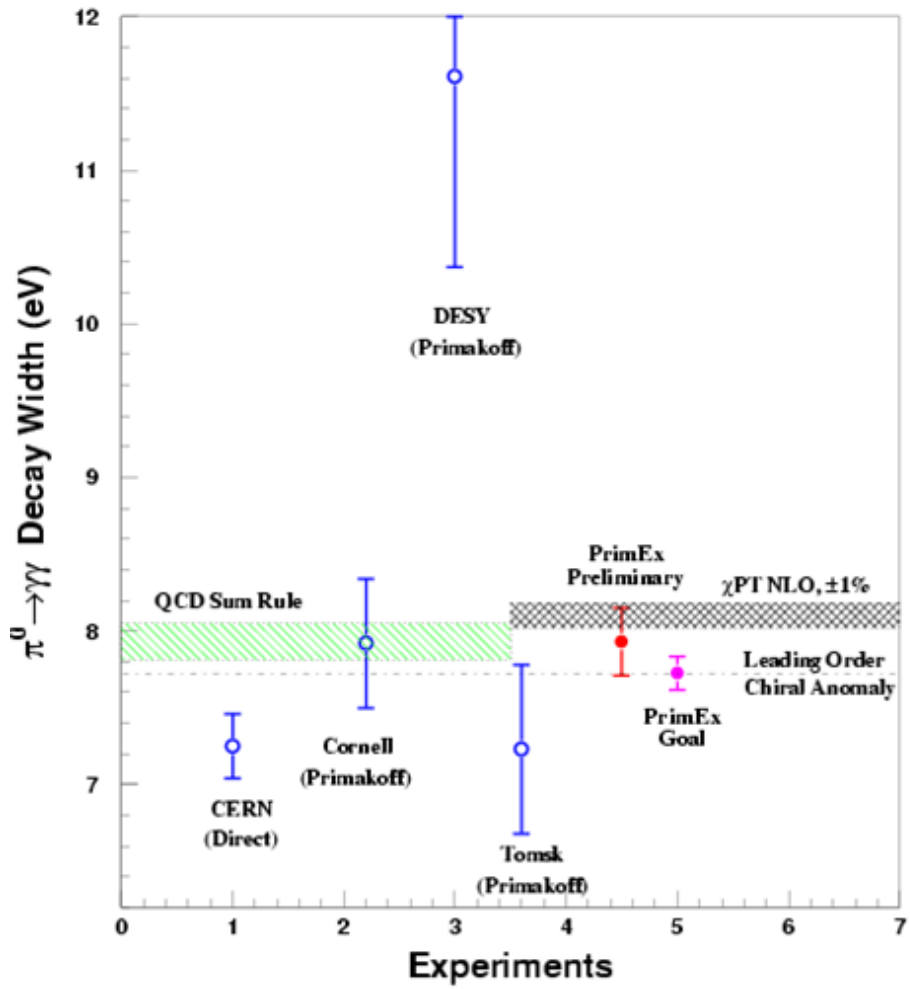
$$\frac{d\sigma}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2 \beta^3 E^4}{m^3 Q^4} |F_{e.m.}(Q)|^2 \cdot \sin^2\theta$$

- Primakoff $\theta < 0.5^\circ$
- Primakoff-Nuclear interference
  $\Rightarrow \theta < 5^\circ$
- Fit to $\frac{d\sigma}{d\Omega}(\theta)$

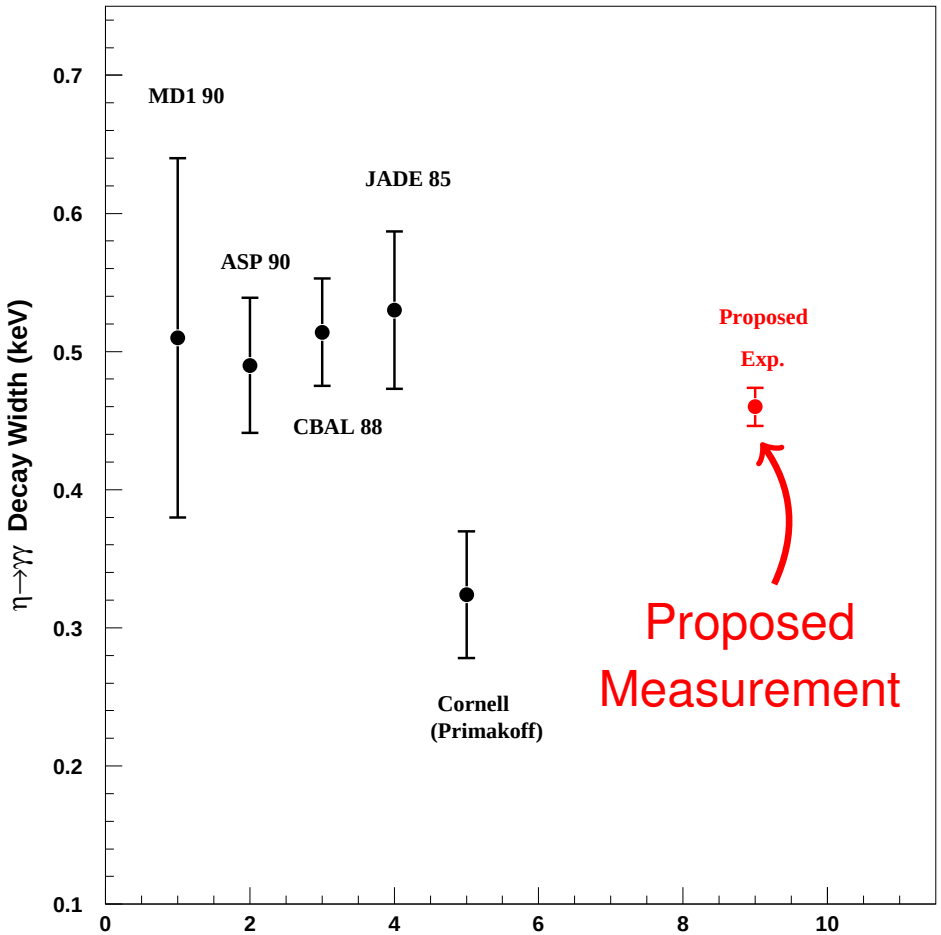


PRIMEX Projected Results

$\Gamma(\pi^\circ \to \gamma\gamma)$ *Hall B*



$\Gamma(\eta \to \gamma\gamma)$ *Hall D projection*

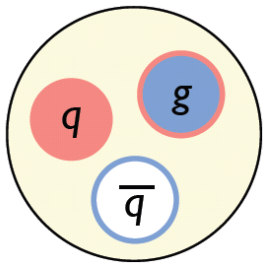


Calculations of the backgrounds

Jefferson Lab

Meson spectroscopy

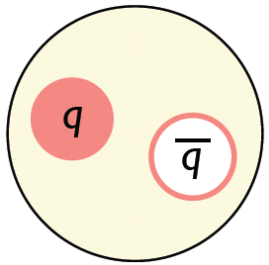
Gluonic excitations ⇒ hybrid mesons ?



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

Constituent quark model

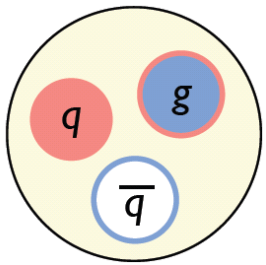


- No gluonic degrees of freedom
- Restrictions on the quantum numbers: J^{PC}:
  $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

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

Meson spectroscopy

Gluonic excitations ⇒ hybrid mesons ?



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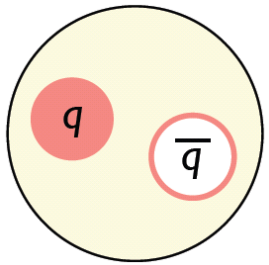

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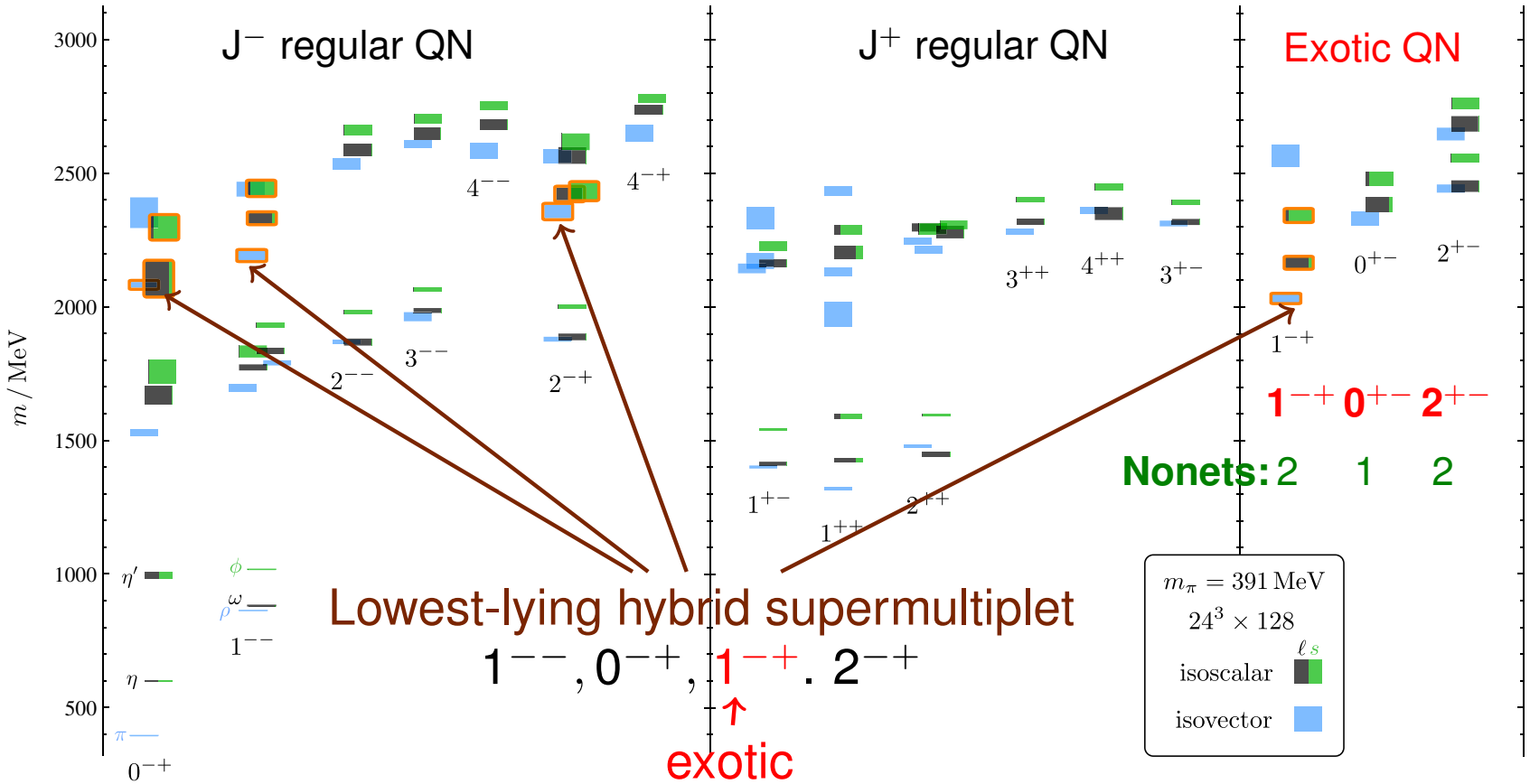
J	$--$	$++$	$-+$	$+-$
0	$\mathbf{0^{--}}$	0^{++}	0^{-+}	$\mathbf{0^{+-}}$
1	1^{--}	1^{++}	$\mathbf{1^{-+}}$	1^{+-}
2	2^{--}	2^{++}	2^{-+}	$\mathbf{2^{+-}}$
3	3^{--}	3^{++}	$\mathbf{3^{-+}}$	3^{+-}
	$q\overline{q}$ QN		"exotic" QN	

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

Jefferson Lab

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

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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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COMPASS: confirmation in $\pi^- A$
COMPASS: in progress $\pi^- p$
$\eta'\pi^-$ - promising
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1600 needs more analysis and data

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		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
	$\pi^- A \to \omega\pi^-\pi^\circ A$	GAMS, 100 GeV 2005	1650	230
2000	$\pi^- p \to b_1\pi, f_1\pi$	E-852, 18 GeV 2001	1960±30	230± 80

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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

Hybrids: expected features and ways to detect

LQCD: Masses

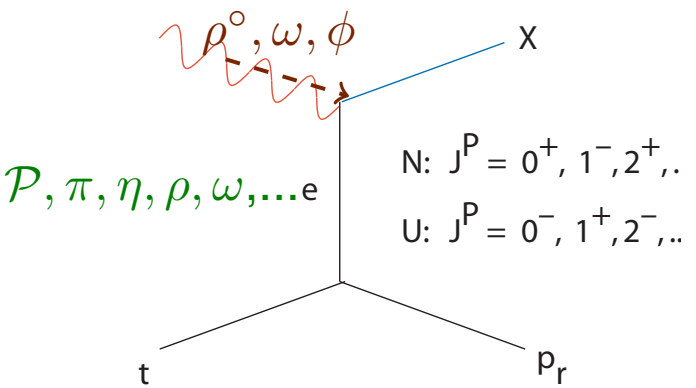
- 1^{-+} π_1, η_1... $\sim$2.0 – 2.4 GeV/c^2
  0^{+-} $b_\circ, h_\circ$... $\sim$2.3 – 2.5 GeV/c^2
  2^{+-} b_2, h_2... $\sim$2.4 – 2.6 GeV/c^2

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

Hall D/GlueX Spectrometer and DAQ

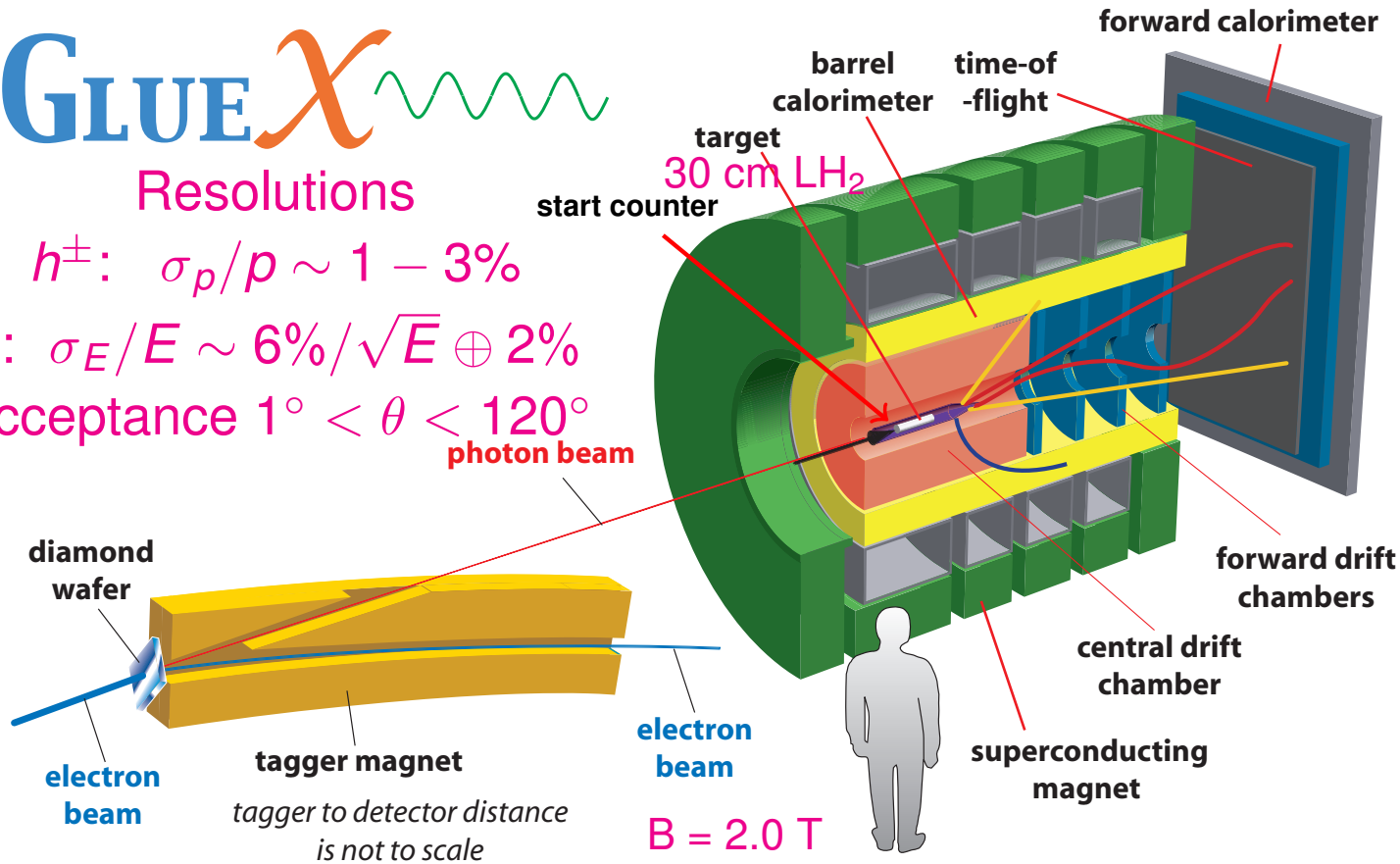
GLUEX

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