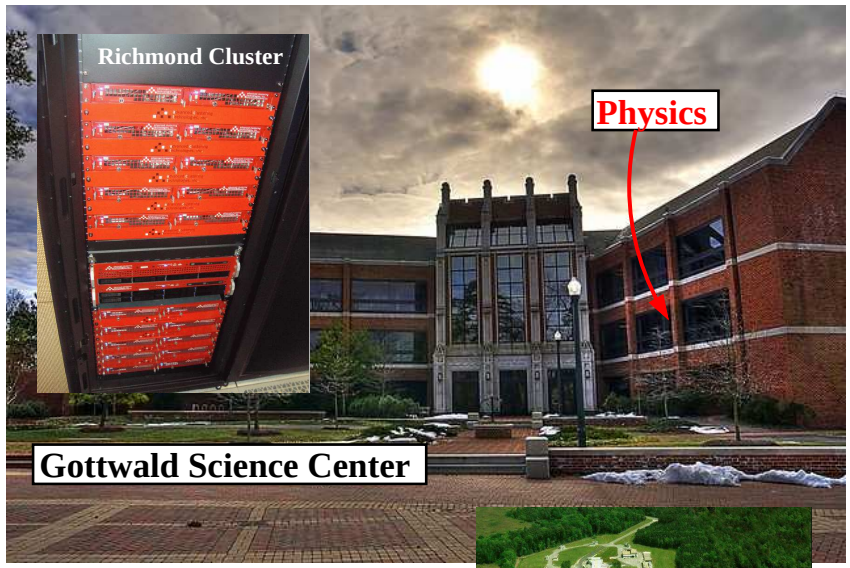
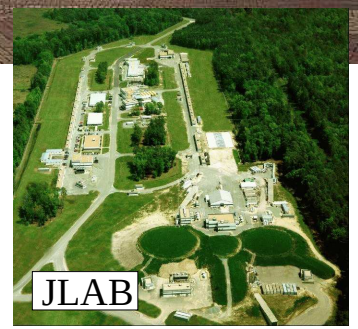
Nuclear and Particle Physics at the University of Richmond

G.P. Gilfoyle (PI)

Outline

1. The University of Richmond
2. Scientific Motivation
3. Recent Progress
4. The Future
5. Funding and Facilities





The Group

1. Jerry Gilfoyle (PI)
2. Alex Colvill (Surrey masters student)
3. Justin Ruger, Liam Murray, Keegan Sherman (undergrads)

Physics at the University of Richmond

1. Richmond is a small (2,800 undergraduates), primarily undergraduate, liberal arts institution; no grad programs in Physics.
2. The Physics Department consists of seven tenure-line faculty, one instructor, one laboratory manager, and an administrative assistant.
3. One other faculty member is in low-energy nuclear structure physics (Con Beausang).
4. The Department graduates 10-14 physics majors per year.
5. Our focus is on the program in Hall B at Jefferson Lab (CLAS6/CLAS12).
6. Richmond is 75 miles from JLab.
7. Partnership with the University of Surrey in the U.K. - masters students spend a research year at JLab with support from DOE.

Richmond students at JLab

Scientific Motivation

- Hadron Structure and Its Emergence from QCD

> A new frontier: “understanding precisely how quarks and gluons are assembled”- NSAC Long-Range Plan.

- Few-body physics and the transition from the hadronic model to the quark-gluon picture.

> “Can few-body systems be understood in terms of a *standard model* for nuclear physics.” - JLab PAC Few-Body Workshop.

- Computing and Software for CLAS12 and the 12 GeV Upgrade.

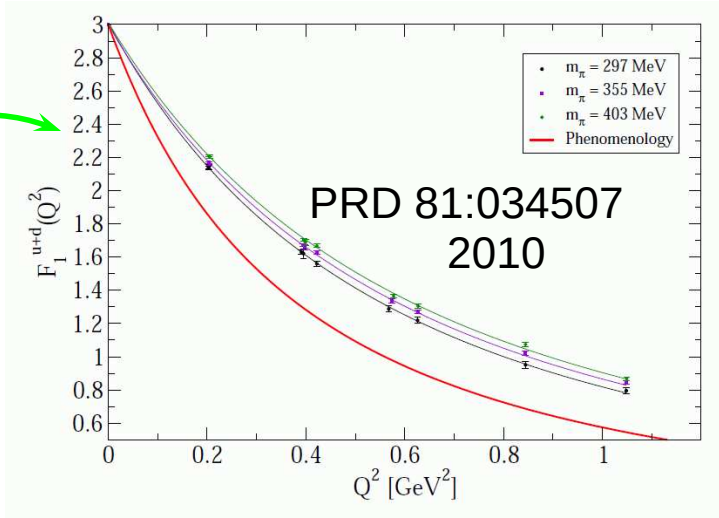
> “it is the desire of the laboratory to have all computing systems and software ready, so that the time from beam on target to physics journal articles is as short as possible.” - 2011 Review of Information Technology for the 12 GeV Era, JLab, 2011.

Hadron Structure - Elastic Electromagnetic Form Factors (EEFFs)

- Nucleon EEFFs map the charge and magnetization in the nucleon.
- Large JLab EEFF program after the 12 GeV Upgrade.
  - Six experiments in the first five years.
  - 224 days of running in Halls A, B, and C.
- What we can learn?
  - Early test for lattice QCD.
  - Constrain generalized parton distributions.
  - Quark decomposition.
  - Medium modifications to form factors.
- Gilfoyle is spokesperson for E12-07-104 to measure the neutron magnetic form factor G_M^n.
- Use the ratio method on deuterium.
- We are analyzing existing CLAS6 data to extract G_M^n with the ratio method.

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left(\frac{(G_E^n)^2 + \tau(G_M^n)^2}{1+\tau} + 2\tau \tan^2\frac{\theta_e}{2}(G_M^n)^2\right)$$

$$\tau = Q^2/M_n^2$$



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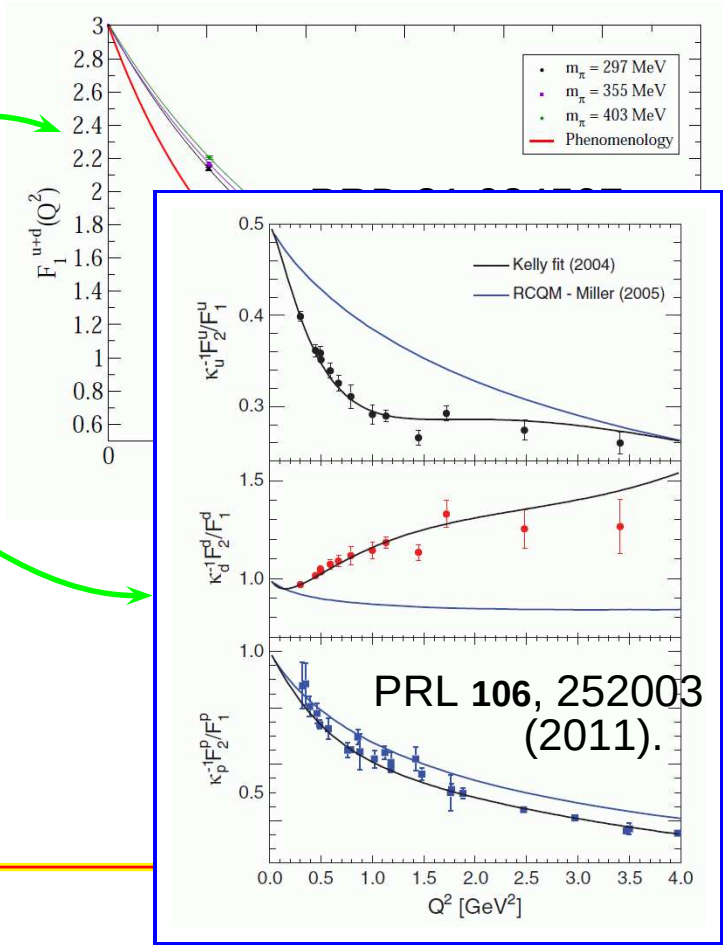
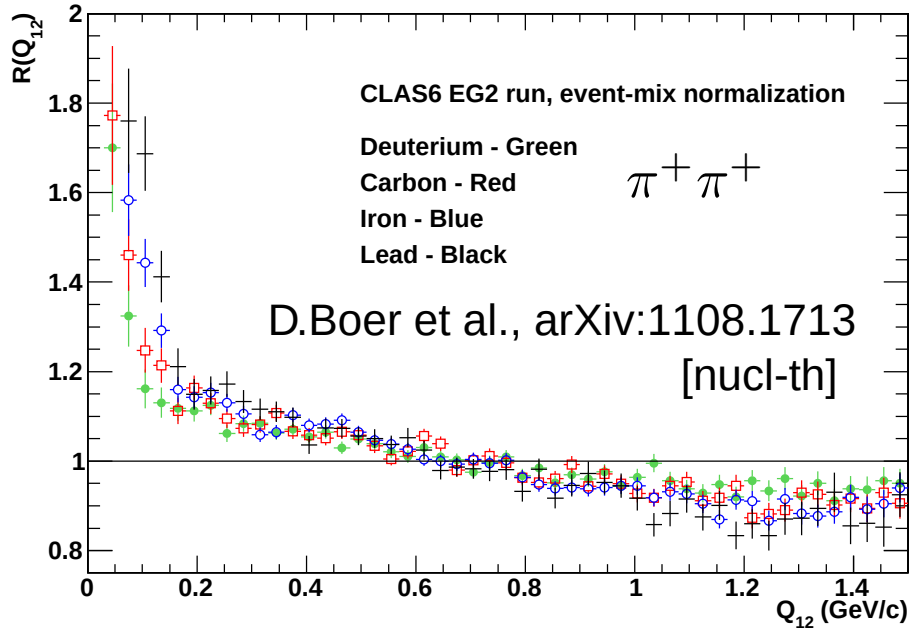


Hadron Structure - Quark propagation and hadron formation

- Nuclear deep inelastic scattering (DIS) opens a window to observe the nature of confinement in QCD.
- Study space-time structure of hadron production and formation.
- Nuclei used as spatial filters with known properties.
- What we can learn?
  Correlations between identical particles probe the space-time extent of hadron sources; *i.e.* fragmentation of the gluon 'string'.
- Gilfoyle is a collaborator on JLab experiment E12-06-117.



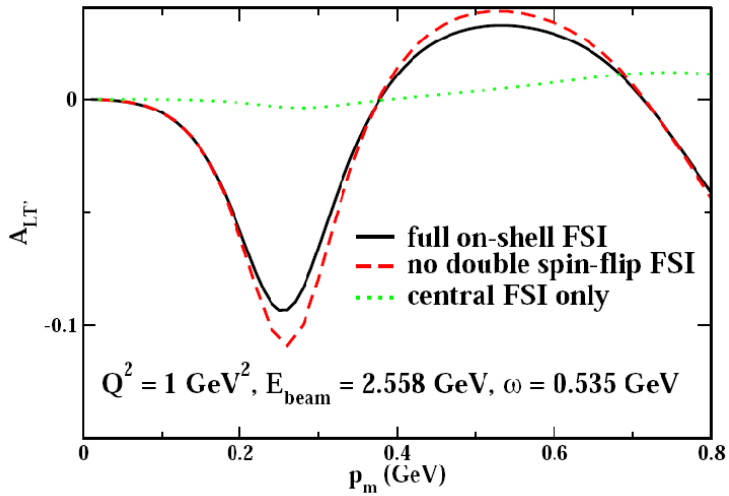
$$R(Q_{12}) = \frac{dN/dQ_{12}}{dN_{ref}/dQ_{12}}$$

$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

Few-body physics

- A precise understanding of the transition from the hadronic picture of nuclei to one based on QCD remains a challenge theoretically and experimentally.
- Goal: Establish a baseline for the hadronic model to more clearly see the transition to quark-gluon degrees of freedom.
- The deuteron is a test bench for the NN force.
- What can we learn?

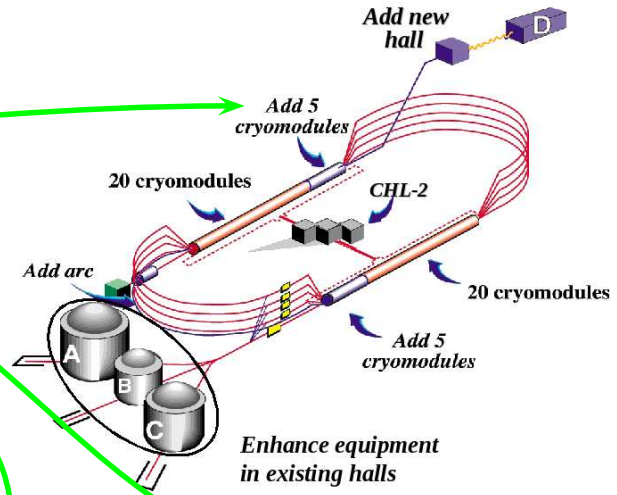
  The helicity asymmetry for quasielastic $^2\mathrm{H}(\vec{e}, e'p)n$ connects to the imaginary part of the LT interference.
- Draft analysis note of CLAS6 results under internal review.

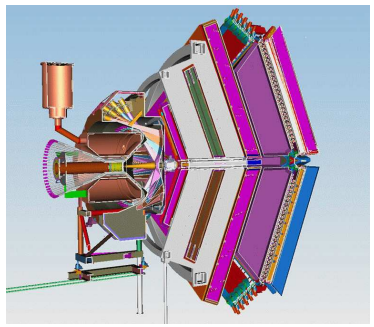


Jeschonnek and Van Orden,
PRC 78:014007, 2008

CLAS12 Computing and Software

- The JLab 12 GeV Upgrade will double the beam energy.
- New detector in Hall B (CLAS12).
- The CLAS12 luminosity will be ten times higher than CLAS6 and we will collect ≈ 5 TBytes/day.
- New, modern software is essential to keep up with the data and produce physics results in a timely manner.
- The Richmond group is part of the team developing new technologies in software (*e.g.* service-oriented architecture) and hardware (*e.g.* Many-Integrated-Coprocessors (MICs) from Intel).



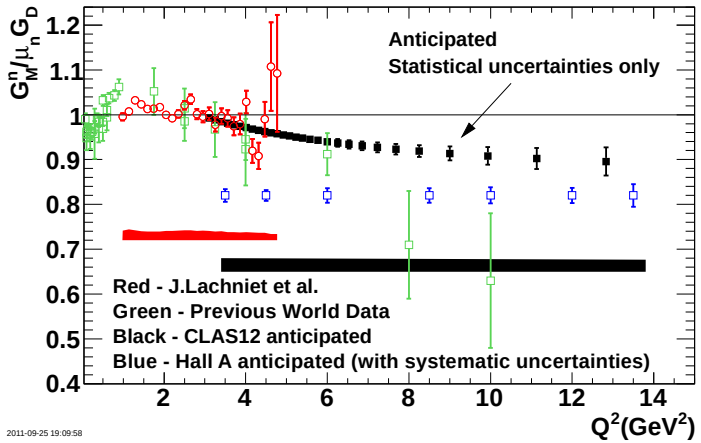


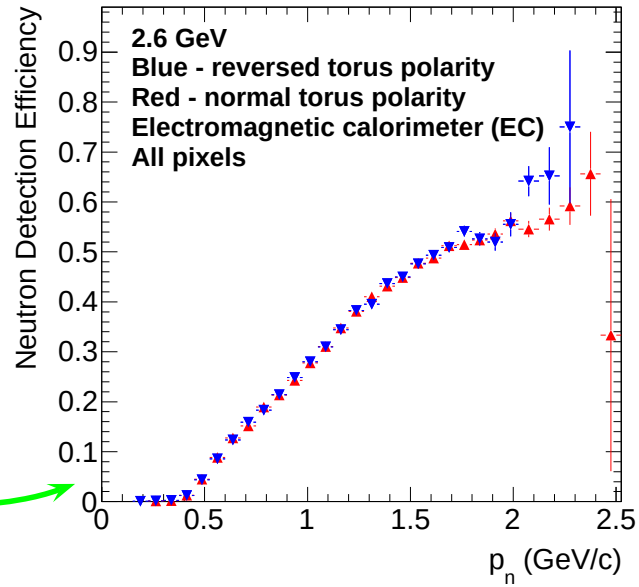
Item	Quantity
Cores	12,500
Disk	2 PByte
Tape	8 PByte

CLAS12 Computing Requirements

Recent Progress - G_M^n

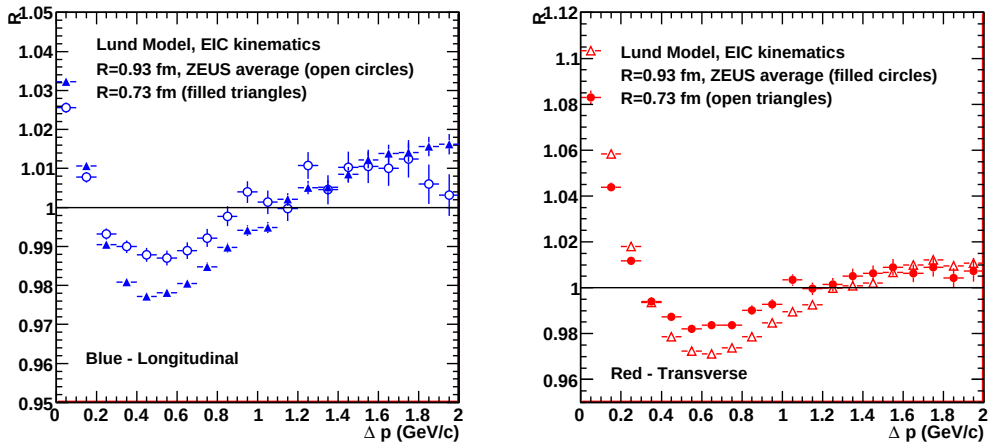
- The CLAS12 G_M^n measurement (E12-07-104) was approved in 2007 and reassessed by JLab PAC35 in 2010. A scientific rating of A^- was awarded with 30 days of beamtime.
- Gilfoyle is a collaborator on E12-09-119 to measure G_M^n in Hall A. PAC35 awarded this experiment a B^+ and allocated 25 days of beamtime.
- Computing preparations done for E12-07-104 (see next pages).
- Target simulation developed by undergrad and presented at 2011 DNP meeting.
- The neutron magnetic form factor G_M^n was measured with CLAS6 during the E5 running period for three sets of running conditions.
  1. Results for two sets of running conditions published - PRL 102, (2009) 192001.
  2. Third set at low Q^2 - reversed torus polarity.
  3. Started analyzing this final set.





Recent Progress - Quark propagation and hadron formation

- JLab experiment E12-06-117 is a program of measurements and analyses using DIS to determine the mechanisms of confinement in forming systems - atomic nuclei are used as filters to study the hadronization process.
- Much work has already been done with CLAS6 data from the EG2 run period.
- The original proposal was approved in 2006 and then reassessed in 2011. PAC36 awarded the proposal a scientific rating of A^- and allocated 60 days of running.
- We have studied $\pi^+\pi^+$ correlations in preparation for the Electron-Ion Collider.
  1. Studied the sensitivity of the $\pi^+\pi^+$ correlations to the source size.
  2. Used longitudinal center-of-mass system (LCMS).
  3. Observed a significant dependence on the source size.



D.Boer et al., arXiv:1108.1713 [nucl-th]

$$R(\Delta p_{L,T}) = \frac{dN/dp_{L,T}}{dN_{ref}/dp_{L,T}}$$

L, T - longitudinal, transverse

Recent Progress - Extracting the Fifth Structure Function of $^2\mathrm{H}(\vec{e}, e'p)n$

- The cross section for quasielastic (QE) scattering is

$$\frac{d^3\sigma}{d\omega d\Omega_e d\Omega_p} = \sigma^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})$$

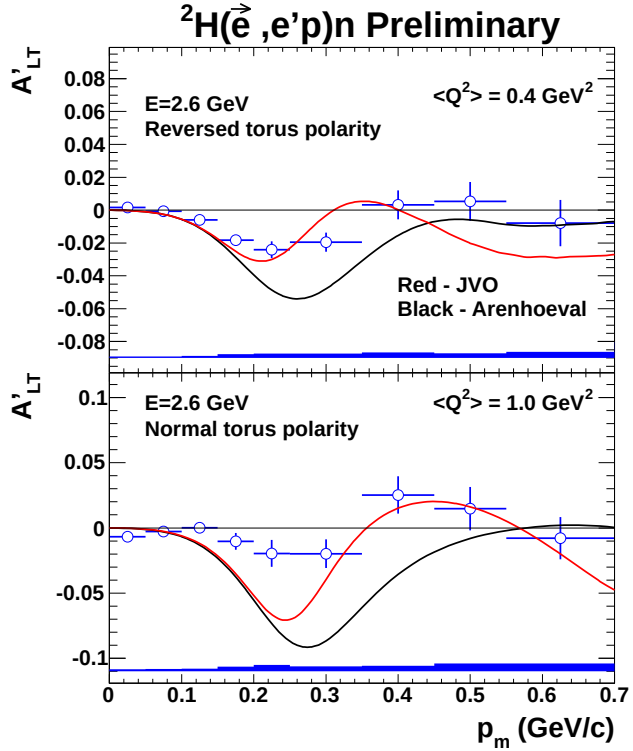
  where $\pm$ and $h = \pm 1$ refer to beam helicities.

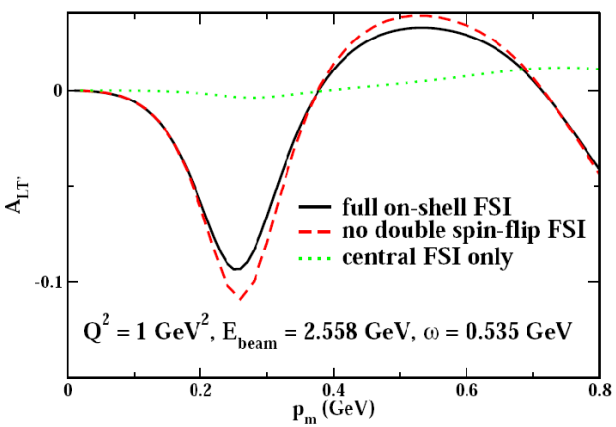
- Construct a helicity asymmetry A'_{LT} to isolate σ'_{LT} and use the $\sin\phi_{pq}$-dependent moments.

$$A'_{LT} = \frac{\sigma'_{LT}}{\sigma_L + \sigma_T} = \langle \sin\phi_{pq}\rangle_+ - \langle \sin\phi_{pq}\rangle_-$$

$$\langle \sin\phi_{pq}\rangle_{\pm} = \frac{\int_{-\pi}^{\pi} \sigma^{\pm}\sin\phi_{pq} d\phi_{pq}}{\int_{-\pi}^{\pi} \sigma^{\pm} d\phi_{pq}} = \pm\frac{A'_{LT}}{2}$$

- Analysis done on CLAS6 E5 data set; same as G_M^n measurement.
- Analysis note submitted for internal review.
- Undergrad poster presented at 2012 DNP meeting.

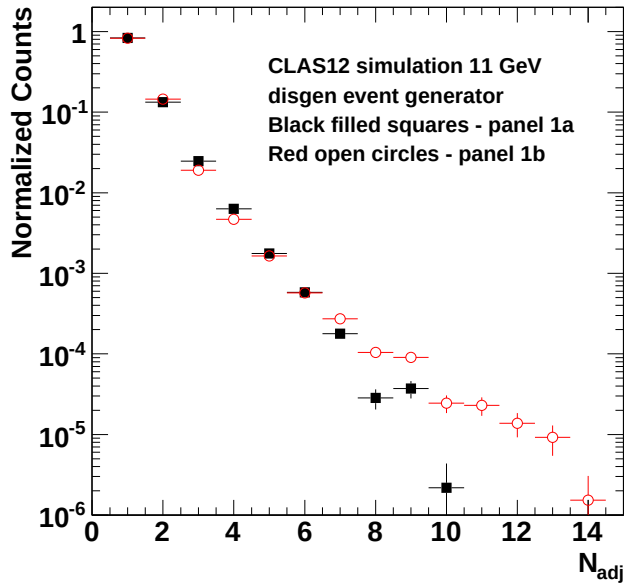




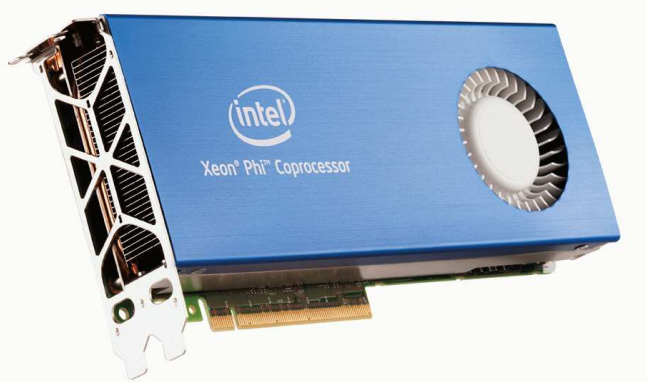
JVO, PRC 78:014007, 2008

Recent Progress - CLAS12 Computing and Software - 1

- Focus on projects that support the CLAS12 software effort and prepare for the CLAS12 G_M^n experiment.
- CLAS12 Forward Time-of-Flight (FTOF) reconstruction now part of third generation CLAS12 reconstruction framework (Clara).
  1. FTOF is essential for neutron detection in G_M^n experiment (E12-07-104).
  2. Clara uses service-oriented architecture.
  3. Used in 'stress test'.
  4. Masters thesis project for Alex Colvill from the University of Surrey mentored by Gilfoyle.

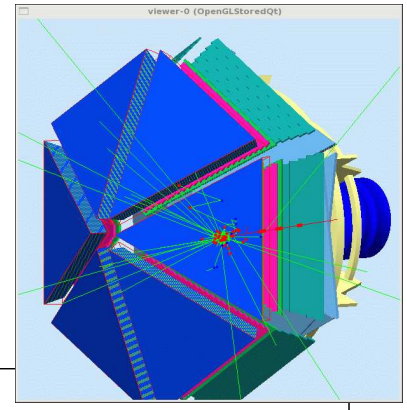


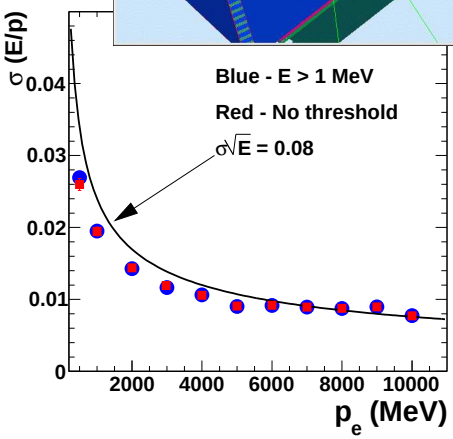
- Use of Intel Many Integrated Coprocessors (MICs) for CLAS12 reconstruction and analysis.
  1. Has many parallel processors (like GPUs), but uses well-developed tools to write code.
  2. Have written first codes on JLab machine; comparing API's; profiling; undergrad project.

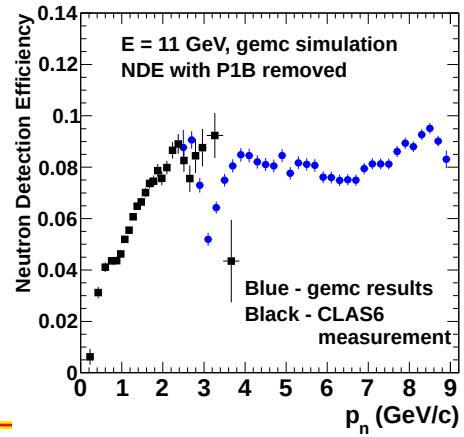


Recent Progress - CLAS12 Computing and Software - 2

- The G_M^n experiment requires neutron detection in the electromagnetic calorimeter (EC) and the forward Time-of-Flight system (FTOF).
- Added EC to CLAS12 simulation (*gemc*).
  1. CLAS12 will re-use the EC from CLAS6.
  2. *gemc* uses Geant4, factory methods.
  3. Results agree with CLAS6 simulations (CLAS-NOTE 2011-019).
  4. Undergrad posters presented at 2010 and 2012 DNP meetings.
- Test *gemc* neutron simulation in FTOF using first generation reconstruction code.
  1. CLAS12 will re-use the CLAS6 TOF sub-system.
  2. Studied neutron detection efficiency (NDE) in CLAS6.
  3. Obtained good agreement between *gemc* and CLAS6 measured NDE (CLAS-NOTE 2011-015).
  4. Undergrad poster presented at 2010 DNP meeting.



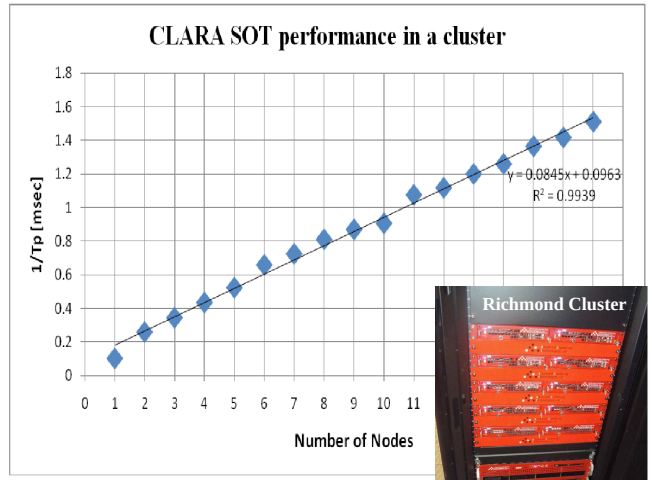




Recent Progress - CLAS12 Computing and Software - 3

- Service-oriented architecture (SOA) for the CLAS12 software.
  1. Software services are pieces of code containing data and/or algorithms that are weakly coupled to other services.
  2. CLAS12 calibration and reconstruction codes use SOA developed in-house called Clara.
  3. Primary test bench for development of Clara has been the Richmond Physics cluster obtained with an NSF MRI grant.
  4. FTOF reconstruction service (Colvill).
  5. Undergrad poster presented at 2010 DNP meeting.

Gyurjyan et al., J.Phys.Conf. 331 (2011) 032013



- Software Planning
  1. Gilfoyle presented CLAS12 software overview at internal JLab review (May, 2011).
  2. Estimated CLAS12 computing requirements for external software review (June, 2012).
  3. Organized CLAS12 software workshop in 2010 at the University of Richmond.

Future Plans (next 1-2 years)

- Hadron Structure
  1. Preparations for G_M^n.
     (a) Target design.
     (b) Update event simulations of calibration, quasielastic, and inelastic reactions.
  2. E5 G_M^n analysis
     (a) Shares many features of the upcoming G_M^n experiment
     (b) Extract and compare neutron/proton detection efficiency with overlapping normal and reversed torus polarity data sets at 2.6 GeV.
     (c) Fermi correction, ... (see PRL, 102, (2009) 192001 and J. D. Lachniet, Ph.D. thesis, Carnegie-Mellon University, (2005)).
- CLAS12 software.
  1. Study clustering within and between FTOF panels, effect of missing information (*e.g.* PMT signal on one side).
  2. Study reconstruction of other particles including neutrons (relevant to G_M^n experiment), effects of magnetic field on charged particle signals.
  3. Write reconstruction code for TOF in CLAS12 Central Detector.
- Few-Body Physics - complete analysis note on fifth structure function.

Funding and Facilities

1. DOE Nuclear Physics support since 2010($K):

	FY10	FY11	FY12	FY13*
Salaries, Wages, Fringe Benefits	$25	$26	$27	$51
Travel	$6	$6	$3	$9
Other Direct Costs	$2	$2	$2	$2
Total Direct Costs	$33	$34	$32	$69
Indirect Costs	$13	$14	$14	$20
Total Budget	$46	$48	$46	$89

2. National Science Foundation Major Research Instrumentation (MRI) support.
   (a) 32, dual 6-core Westmere nodes, 6.2 TByte of space, $162K (2009-2011).
   (b) Development platform for Clara.
3. SURA/JSA Sabbatical support (2009-2010).
4. University of Richmond support.
   (a) Routine travel to JLab, faculty and student travel to conferences - ≈$7,000/year.
   (b) Student summer stipends - $4,500/student-year for 1-2 students.
   (c) Commitment to maintain the computational power of the Physics cluster.

* Includes supplemental funds for joint Richmond/Surrey masters student.

Additional Slides

Recent Progress - Extracting G_M^n - 1

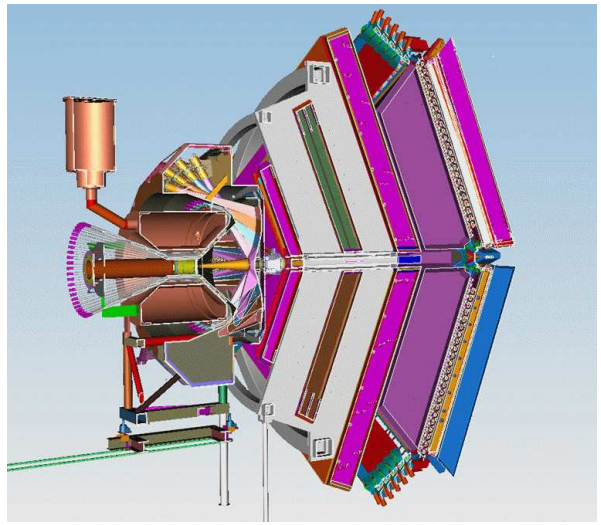
- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium ($^2\mathrm{H}(e,e'p)n$ and $^2\mathrm{H}(e,e'n)p$) in quasielastic (QE) kinematics:

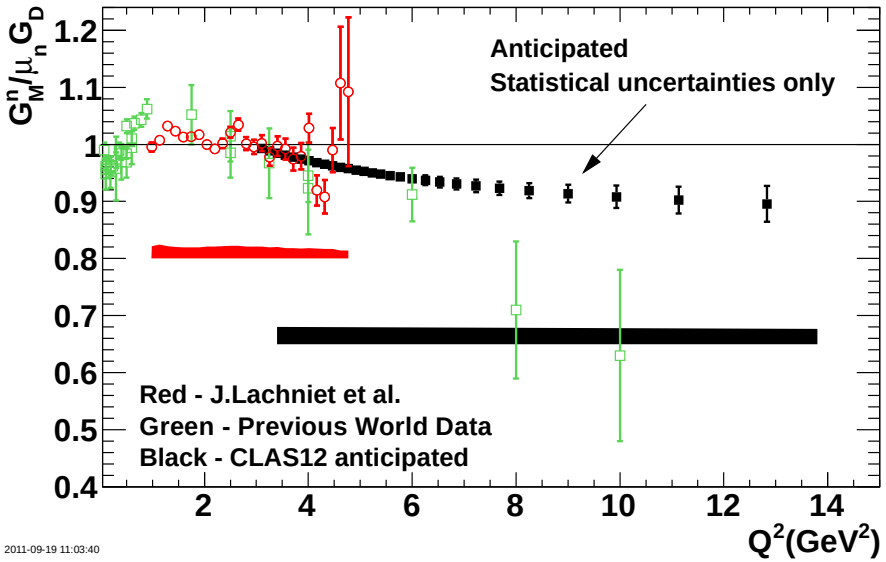
$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]} \qquad \tau = \frac{Q^2}{4M_n^2}$$

$$= a \times \frac{\sigma_{Mott}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau\tan^2\frac{\theta_e}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}[^1\mathrm{H}(e,e')p]}$$

where a is nuclear correction.

- Extends CLAS6 measurement (PRL 102, 192001 (2009)).
- Precise neutron detection efficiency needed to keep systematics low.
  - tagged neutrons from $p(e,e'\pi^+n)$.
  - Dual $LD_2 - LH_2$ target for *in situ* calibrations.
- 30 days of beam; $\mathrm{Q}^2 = 3.5 - 13.0\ (\mathrm{GeV/c})^2$.



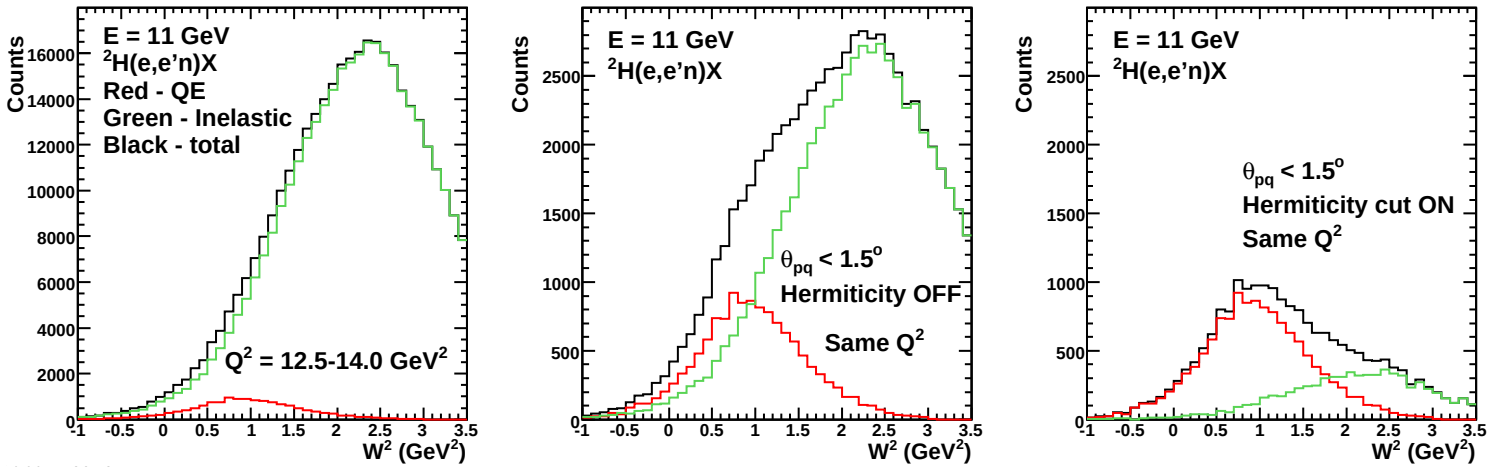


Recent Progress - Extracting G_M^n - 2

- Challenge: Separate QE events from high-Q^2, inelastic background.
  1. θ_{pq} **cut:** QE neutrons/protons emitted in a narrow cone along $\vec{q}$.
  2. **Hermiticity cut:** No additional particles in the event.

Effect of θ_{pq} and hermiticity cuts.

Worst-case (high-Q^2) simulation.



- Internal consistency check for $e - n$: electromagnetic calorimeter and time-of-flight separately measure neutrons.
- Simultaneous, *in situ* calibrations with dual hydrogen-deuterium target.
  - Use $\mathrm{H}(e, e'\pi^+ n)$ to produce tagged neutrons.
  - Elastic scattering off hydrogen target for tagged protons.

Goal is 3% systematic uncertainties and smaller statistical ones.

Summary of prominent refereed papers

- H. Egiyan et al. CLAS Collaboration, “Upper limits for the photoproduction cross section for the $\Phi^{--}(1860)$ pentaquark state off the deuteron”, Phys. Rev. C85 (2012) 015205.
  Searched for the Φ^{--}(1860) pentaquark in photoproduction on the deuteron in the $\Xi^-\pi^-$ decay channel using CLAS. The invariant-mass spectrum of the $\Xi^-\pi^-$ system does not indicate any statistically significant enhancement.
- V. Gyurjyan, D. Abbott, J. Carbonneau, G. Gilfoyle, D. Heddle, G. Heyes, S. Paul, C. Timmer, D. Weygand, E. Wolin, “CLARA: A contemporary approach to physics data processing”, J. Phys. Conf. Ser. 331 (2011) 032013.
  CLARA is the CLAS12 physics data processing application development framework based on a service oriented architecture. The framework uses weakly coupled software services to improve maintenance, scalability and quality of physics data analysis.
- A. Daniel et al. CLAS Collaboration, “Measurement of the nuclear multiplicity ratio for K^0_s hadronization at CLAS”, Phys.Lett. B706 (2011) 26-31.
  For the first time the multiplicity ratios for K^0_s have been extracted using semi-inclusive deep inelastic scattering with detection of the K^0_s using CLAS with a 5.0-GeV electron beam incident on deuterium and nuclear targets. A variety of models can explain these data which are consistent with measurements (at different kinematics) at HERMES.

Undergraduate research assistants since 2010.

year	name	funding source	year	name	funding source
2013	Murray	UR	2012	Murray	DOE
2013	Sherman	DOE	2012	Sherman	UR
2013	Ruger	DOE	2012	Bialt	DOE
2011	Moog	DOE	2010	Moog	UR
2011	Sherman*	volunteer	2010	Musalo	DOE
2011	Carbonneau	UR+DOE	2010	Carbonneau	DOE
2011	Musalo	UR	2010	Barker	DOE
			2010	Sherman*	volunteer

* - high school student

Some facts:

- Eight students, four have graduated.
- Two now in PhD programs in nuclear physics (Moog - UNC, Barker - ODU).
- One (Carbonneau) is a programmer at NASA Langley.
- One (Musalo) is a health care analyst.
- Six poster presentations at fall DNP meeting; three more coming this fall.
- No grad students in Physics at Richmond.

Student DNP Posters since 2010

1. L.Murray and G.P.Gilfoyle, “Extracting the Fifth Structure Function of the 2H(e,e’p)n Reaction”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00114 (2012), poster.
2. K.Sherman and G.P.Gilfoyle, “Simulation of the Scintillator Geometry in the Electromagnetic Calorimeter in the CLAS12 Detector”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00115 (2012), poster.
3. C. Musalo, and G.P.Gilfoyle, “Simulation of the CLAS12 dual hydrogen-deuterium target”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00102 (2011).
4. M.Moog, J.Carbonneau, and G.P.Gilfoyle, “Simulating the Neutron Detection of the CLAS12 Detector”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00073 (2010).
5. C. Musalo, J.Carbonneau, and G.P.Gilfoyle, “Simulation of the CLAS12 Forward Electromagnetic Calorimeter”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00077 (2010).
6. J.Carbonneau and G.P.Gilfoyle, “Development of a Computing Cluster At the University of Richmond”, Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00018 (2010).

All invited talks since 2010

1. “Hunting for Quarks” presented at UVa, Jan 20, 2012.
2. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation” presented at UVa, Jan 20, 2012.
3. “Future Measurements of Elastic Electromagnetic Form Factors at Jefferson Lab” presented at PINAN11 in Marrakech, Morocco September 26, 2011.
4. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation” presented at Jefferson Lab, June 29, 2011.
5. Presentation for the CLAS12 Software Group on the CLAS12 Information Technology Readiness Review, Jefferson Lab, May 20, 2011.
6. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation” presented at the University of Richmond, April 13, 2011.
7. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation” presented at Catholic University, April 6, 2011.
8. Combined research introduction on nuclear physics, non-proliferation, and science careers presented at the University of Richmond, Nov. 10, 2010.
9. “Bose-Einstein Correlations at the Electron-Ion Collider”, Institute for Nuclear Theory, University of Washington, Seattle, Washington, October 12, 2010.
10. “Few Body Physics with CLAS” presented at the 21st European Conference on Few-Body Problems in Physics, Salamanca, Spain, Aug 30, 2010.
11. “Measuring the Magnetic Form Factor of the Neutron in CLAS12” presented at the Workshop on Exclusive Reactions at High Momentum Transfer, Jefferson Lab, May 19, 2010.
12. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation” presented at the Joint Meeting of the New England Section and the New York State Section of the American Physical Society, Modern Nuclear Applications, Union College, April 24, 2010.
13. “Update for E12-07-104: Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on Deuterium”, presented at Jefferson Laboratory PAC35, January, 2010.

CLAS12 Run Groups

Proposal	Physics	Contact	Rating	Days	Group	New equipment	Energy	Group	Target
E12-06-108	Hard exclusive electro-production of π^0, η	P. Stoler	B	80	119	RICH IC Forward tagger	11	RG-A F. Sabatié	liquid H_2
E12-06-112	Proton's quark dynamics in SIDIS pion production	H. Avakian	A	60					
E12-06-119	Deeply Virtual Compton Scattering	F. Sabatie	A	80					
E12-09-103	Excitation of nucleon resonances at high Q^2	R. Gothe	B+	40					
E11-005	Hadron spectroscopy with forward tagger	M. Battaglieri	A-	119					
PR12-11-103	DVMP of ρ, ω, φ	M. Guidal		D					
E12-07-104	Neutron magnetic form factor	G. Gilfoyle	A-	30	90	Neutron detector RICH IC	11	RG-B K. Hafidi	liquid D_2 target
PR12-11-109 (a)	Dihadron DIS production	Avakian		D					
E12-09-007a	Study of partonic distributions in SIDIS kaon production	K. Hafidi	A-	56					
E12-09-008	Boer-Mulders asymmetry in K SIDIS w/ H and D targets	M. Contalbrigo	A-	TBA					
11-003	DVCS on neutron target	S. Niccolai	A	90					
E12-06-109	Longitudinal Spin Structure of the Nucleon	S. Kuhn	A	80	170	Polarized target RICH IC	11	RG-C S. Kuhn	NH_3 ND_3
E12-06- 119(b)	DVCS on longitudinally polarized proton target	F. Sabatie	A	120					
E12-07-107	Spin-Orbit Correl. with Longitudinally polarized target	H. Avakian	A-	103					
PR12-11-109 (b)	Dihadron studies on long. polarized target	H. Avakian		D					
E12-09-007(b)	Study of partonic distributions using SIDIS K production	K. Hafidi	A-	110					
E12-09-009	Spin-Orbit correlations in K production w/ pol. targets	H. Avakian	B+	103					
E12-06-106	Color transparency in exclusive vector meson production	K. Hafidi	B+	60	60		11	RG-D	Nuclear
E12-06-117	Quark propagation and hadron formation	W. Brooks	A-	60	60		11	RG-E	Nuclear
E12-10-102	Free Neutron structure at large x	S. Bueltman	A	40	40	Radial TPC	11	RG-F	Gas D_2
PR12-11-109	SIDIS on transverse polarized target	M. Contalbrigo		C2		Transverse target	11	RG-G	HD
TOTAL run time				1231	539				