The 12 GeV JLab Program

Including excerpts from
a presentation by R. McKeown in December 2018 and

The Science and Experimental Equipment
for
The 12 GeV Upgrade of CEBAF

Updated from the Document Originally Prepared for
the April 2005 DOE Science Review

Jefferson Lab

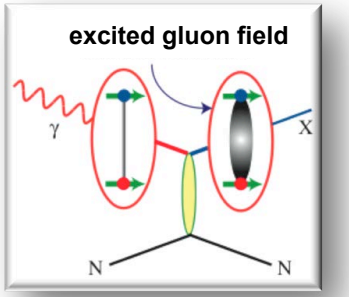
January 10, 2005

Planned Science “Thrusts”

- The experimental study of gluonic excitations in order to understand the fundamentally new dynamics that underpins all of nuclear physics: the confinement of quarks.
- The Fundamental Structure of the Nuclear Building Blocks
- The Physics of Nuclei
  - The emergence of nuclei from QCD
  - Fundamental QCD processes in the nuclear arena
  - Neutron Skins
- Tests of the Standard Model of electro-weak interactions and the determination of fundamental parameters of this model

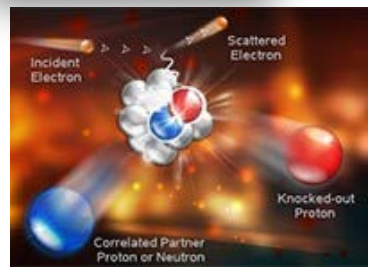
Jefferson Lab @ 12 GeV Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons?

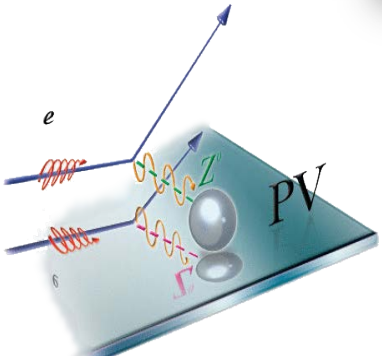


- Where is the missing spin in the nucleon? Role of orbital angular momentum?

- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- 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?



Robert McKeown

QNP 2018

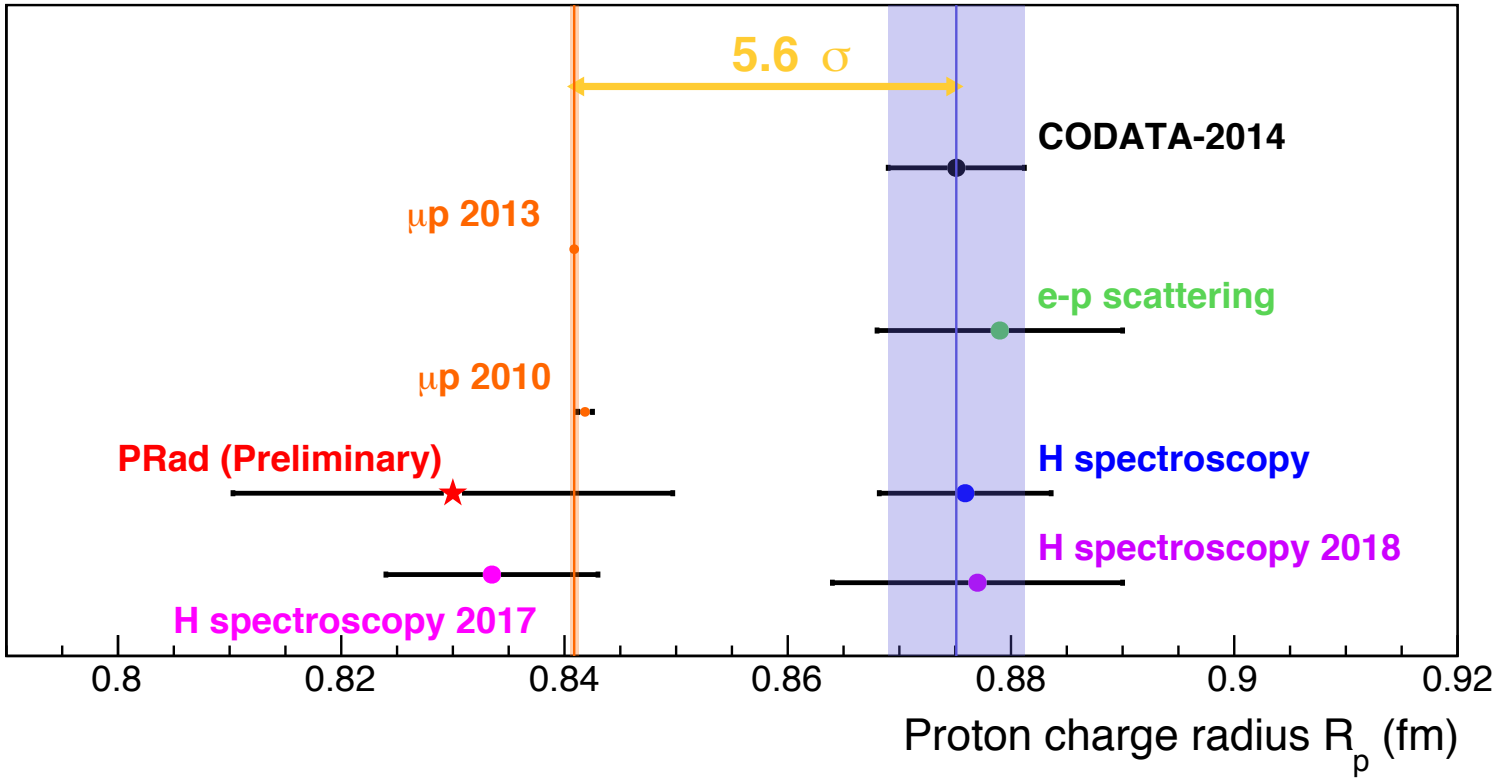
Program Status

12 GeV Approved Experiments by Physics Topics

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	2	1	3	0	**6**
The transverse structure of the hadrons	6	3	3	1	0	**13**
The longitudinal structure of the hadrons	2	3	6	0	0	**11**
The 3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**23**	**5**	**3**	**78**
Total Experiments Completed	**4.6**	**2.7**	**2.1**	**0.8**	**0**	**10.2**
Total Experiments Remaining	**19.4**	**20.3**	**20.9**	**4.2**	**2.0**	**67.8**

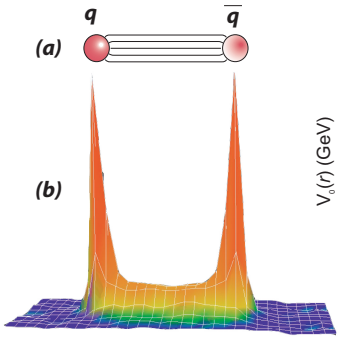
Note: Hall B includes Prad and HPS experiments

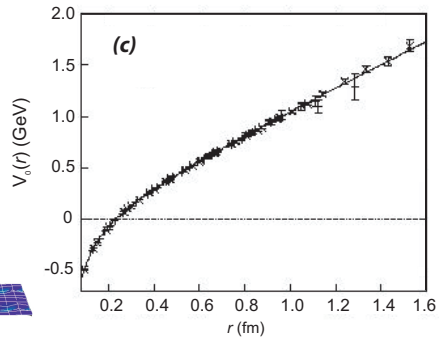
First or preliminary results exist from several experiments, including HPS and PRad

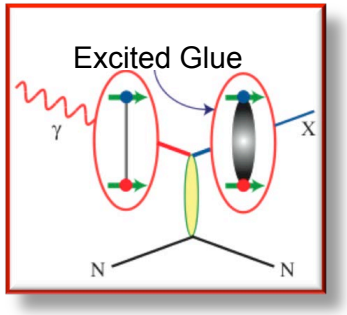


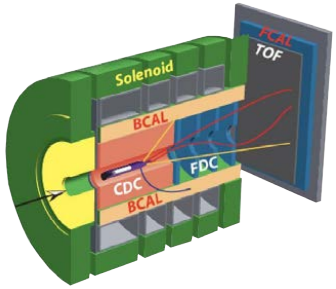
PRad Preliminary result:
R_p = 0.830 ± 0.008 (stat.) ± 0.018 (syst.) fm

1.A Mapping Gluonic Excitations and Understanding Confinement



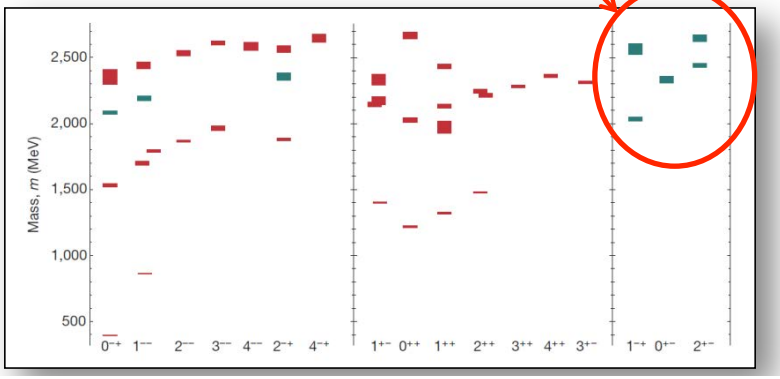






GLUEX CITATIONS PERIMENT
Hall D@JLab

States with Exotic Quantum Numbers



Additional projects:

- Eta factory (Chiral dynamics)
- K_{long} factory?
- GDH sum rule?

nature International weekly journal of science

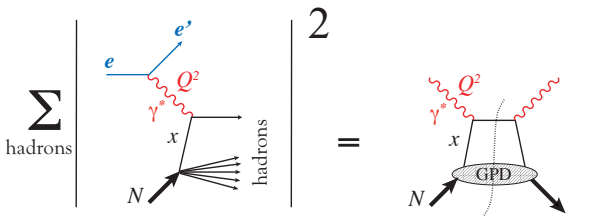
Searching for the rules that govern hadron construction

M. R. Sheperd, J. J. Dudek, R. E. Mitchell

1.B The Fundamental Structure of the Nuclear Building Blocks

Nuclear Femtography

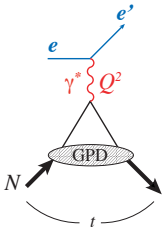
a)



Inclusive Deep–Inelastic Scattering (DIS)

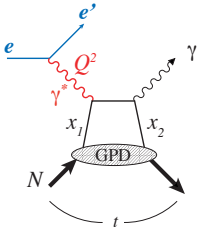
Forward Compton Scattering Amplitude

b)



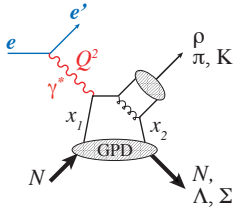
Elastic form factors

c)

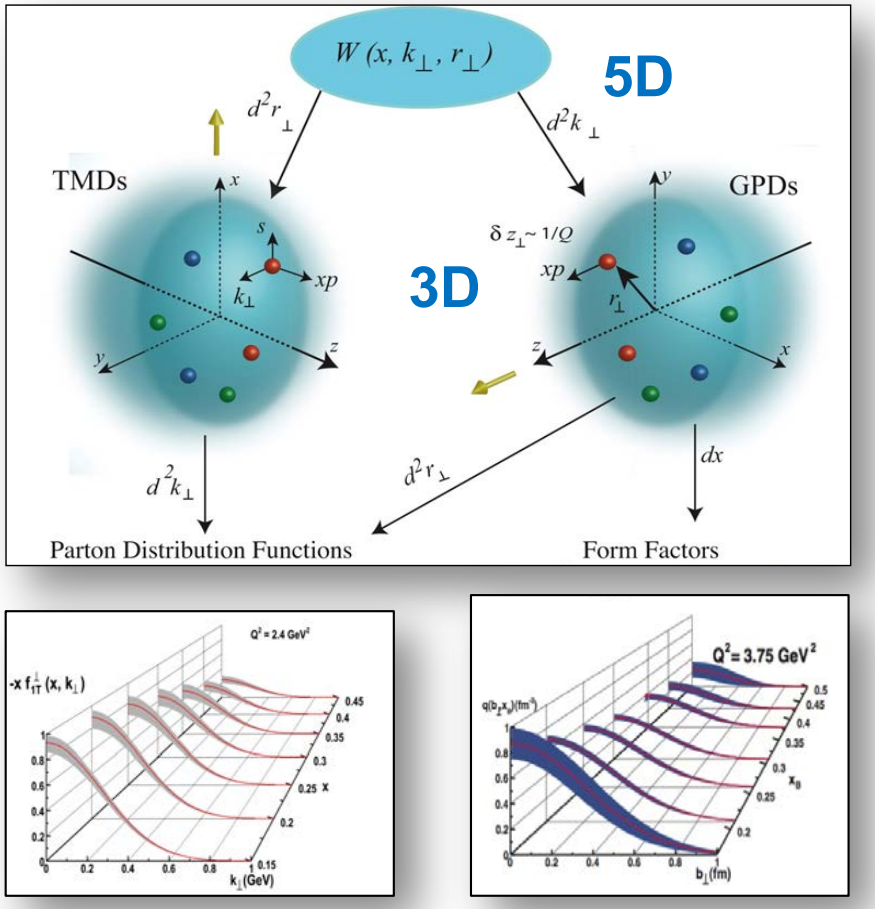


Deeply Virtual Compton Scattering (DVCS)

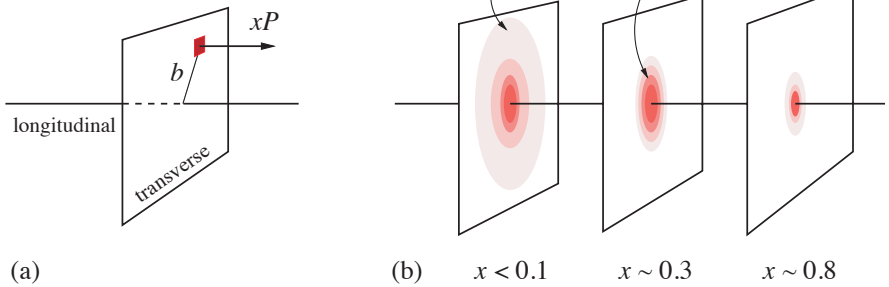
d)

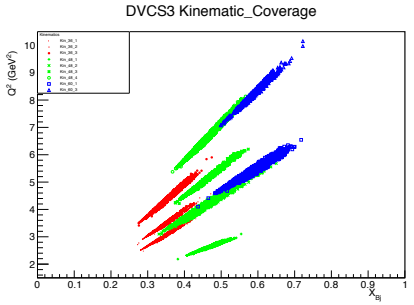


Deeply Virtual Meson Production (DVMP)



GPDs





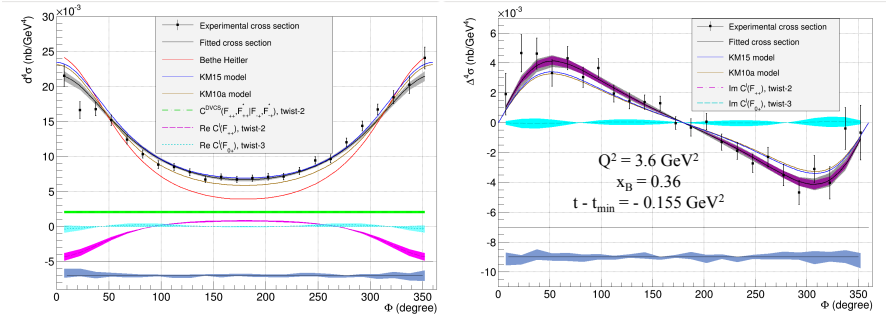
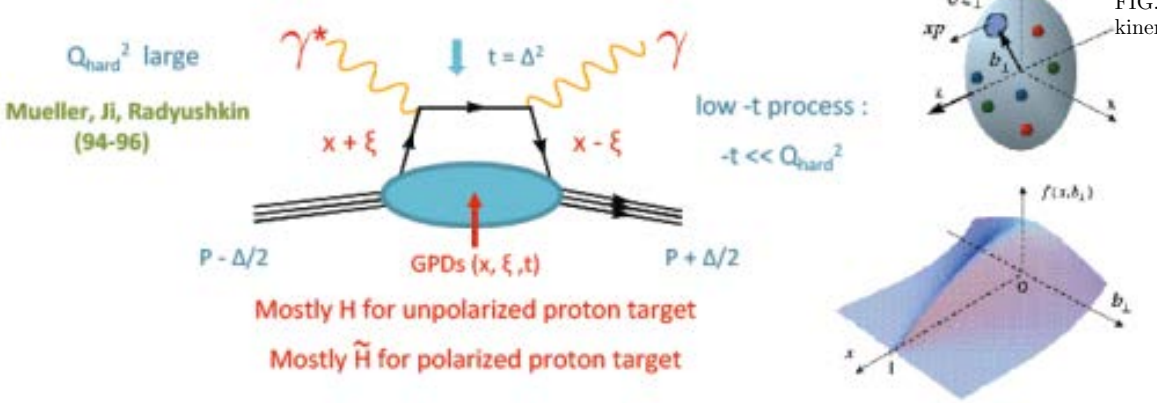
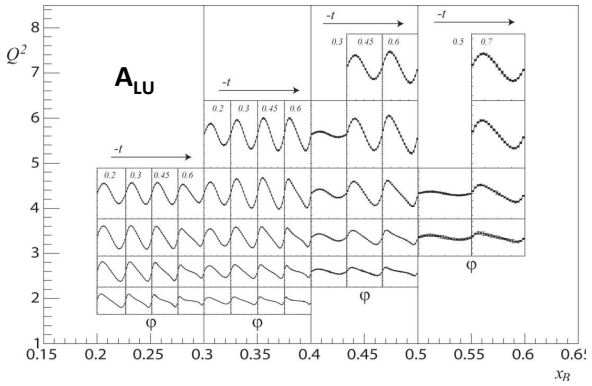


FIG. 6. DVCS cross section (Left: unpolarized, Right: electron-helicity dependent) in one kinematic setting from Fig. 5, and one bin in $t = (q - q')^2$.





Form Factors

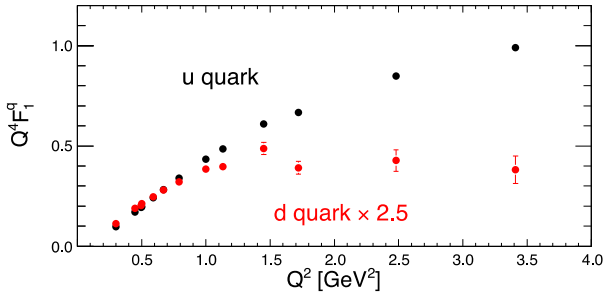


Figure 2.1: *The u- and d-quark contributions to the nucleon form factors and their surprising difference. The extraction of these quantities was made possible by measuring the neutron form factors to high values of momentum transfer. The range will be tripled with JLab's 12-GeV Upgrade.*

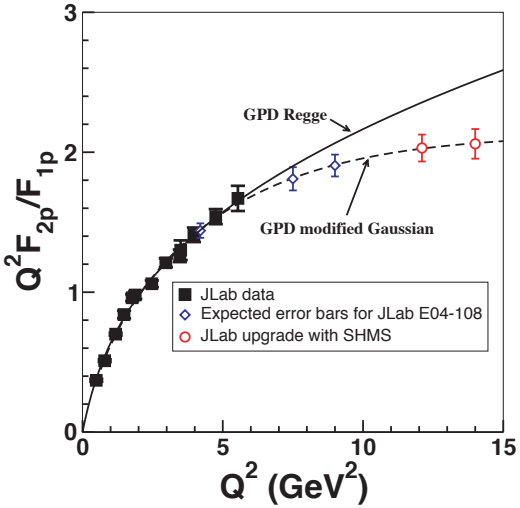
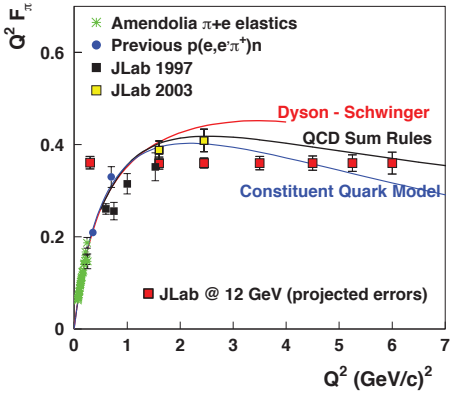


Figure 6: The JLab 6 GeV data on the ratio of proton form factors, F_2^p/F_1^p, and the projected measurements at 12 GeV. Perturbative QCD implies that $F_2^p/F_1^p \sim 1/Q^2$ for $Q^2 \to \infty$. The graph illustrates the potential of form factor measurements at 12 GeV to discriminate between GPD models. Shown are the predictions of a Regge–based GPD model [Gu04] and a model based on soft Gaussian nucleon wavefunctions modified by a short–range interaction [St03d].



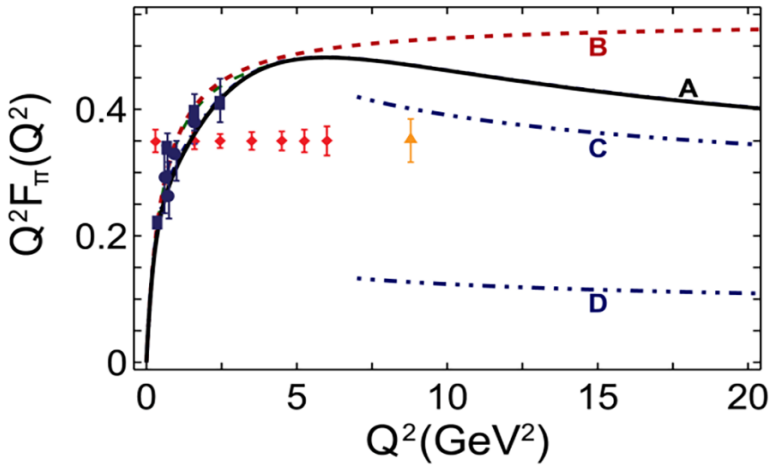
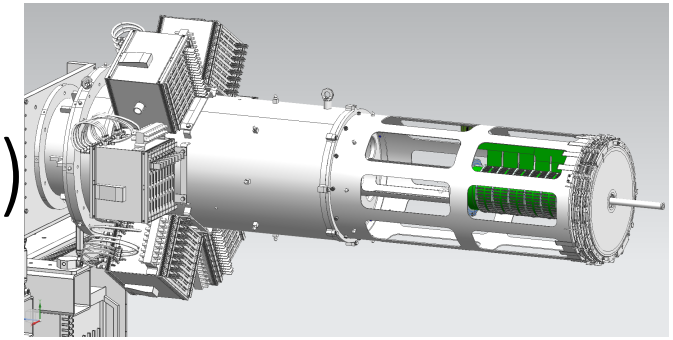
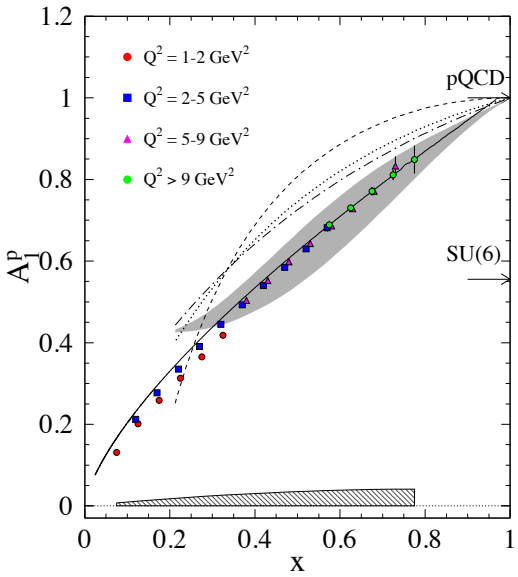
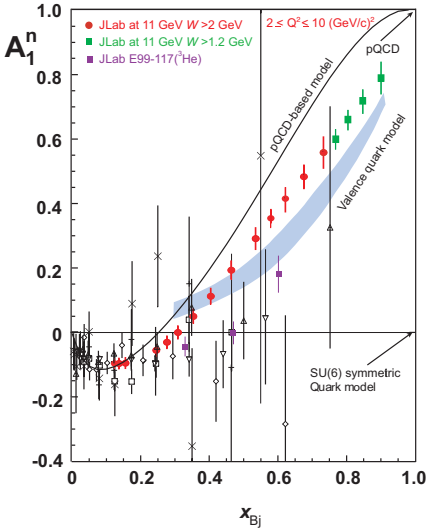


Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

Valence Quark Structure (large *x*)







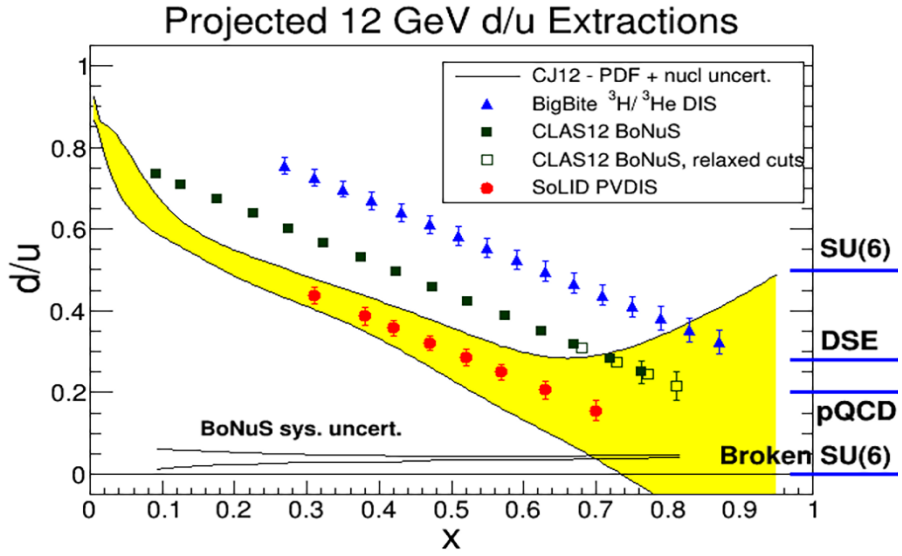


Figure 2.3: *Projected uncertainties (offset for display) for JLab 12-GeV measurements of the ratios of the PDFs for the d and u quarks at large momentum fraction x. The yellow band represents the uncertainty in the existing measurements under several theoretical assumptions. Various predictions for this ratio in the limit of x = 1 are given by the blue lines.*

TMDs

$$\nu = E - E' = |\vec{k}| - |\vec{k}'|$$

$$\vec{q} = \vec{k} - \vec{k}'; \quad q^\mu = (\nu, \vec{q}) = k^\mu - k'^\mu$$

$$Q^2 = -(k - k')^2 = \vec{q}^2 - \nu^2 \approx 4EE' \sin\frac{\theta_e}{2}$$

$$y = \frac{q^\mu P_\mu}{k^\mu P_\mu} = \frac{\nu}{E}; \quad x = \frac{Q^2}{2q^\mu P_\mu} = \frac{Q^2}{2M\nu}$$

$$W = \sqrt{(P_\mu + q^\mu)^2} = \sqrt{M^2 + (1/x - 1)Q^2}$$

Lepton variables

Inclusive

Semi-Inclusive

Hadron variables

$$P^\mu_{had} = \left(z\nu, \sqrt{z^2\nu^2 - m_h^2 - P_{hT}^2}, \vec{P}_{hT}\right)$$

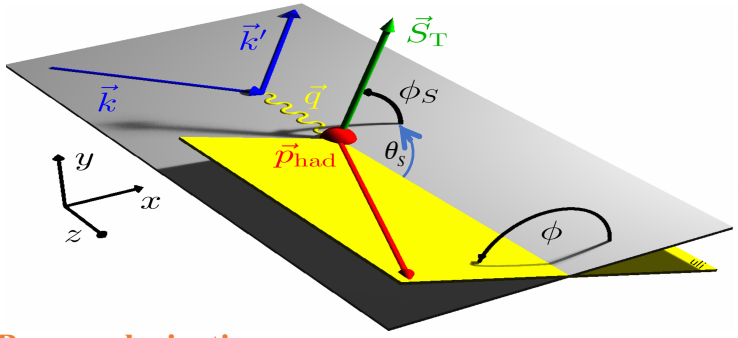
$$z = E_h / \nu$$

$$\vec{P}_{hT} = |\vec{P}_{hT}|(\sin\theta_h \cos\phi_h, \sin\theta_h \sin\phi_h)$$

$$x_F = \frac{\vec{P}_h^{c.m.} \cdot \hat{q}}{|\vec{P}_h^{c.m.}|(\max)}$$

Rapidity $\quad \operatorname{artanh}\frac{|\mathbf{p}|c}{E} = \frac{1}{2}\ln\frac{E + |\mathbf{p}|c}{E - |\mathbf{p}|c}$

Pseudo-Rapidity $\quad \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$



P_b, P_t

- **U** unpolarized
- **L** long.polarized
- **T** trans.polarized

Target polarization

Beam polarization

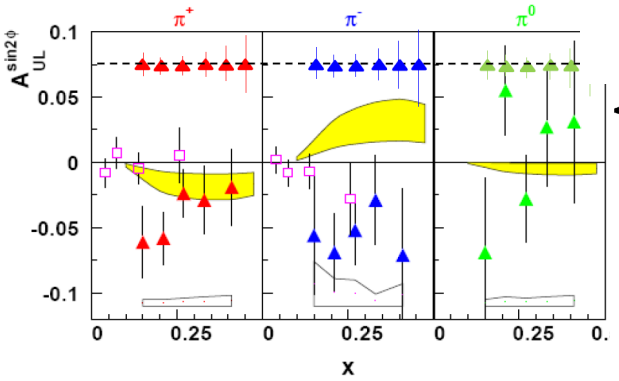
$$\sigma = \sigma_{UU} + P_t \sigma_{UT} \sin(\phi - \phi_S) + P_b P_t \sigma_{LT} \cos(\phi - \phi_S) \ldots$$

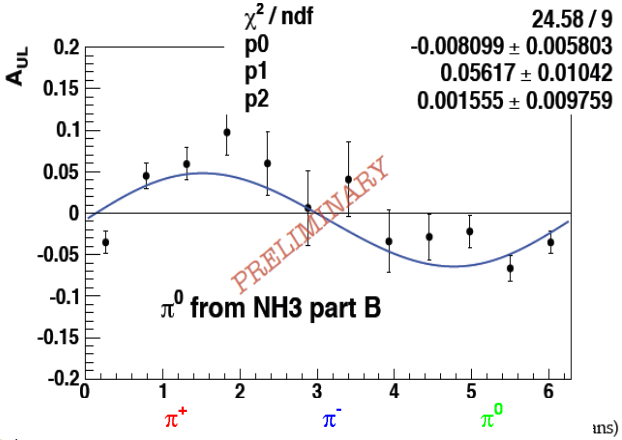
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sigma_{UT}}{\sigma_{UU}} \longrightarrow$$

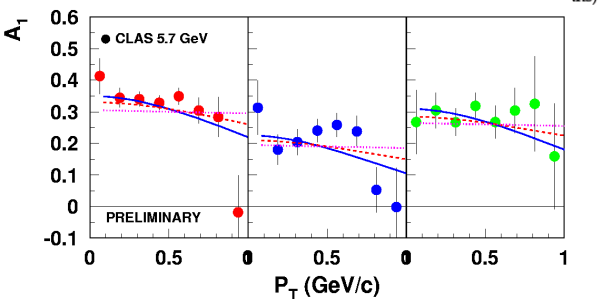
$\sin(\phi-\phi_S)$ moment of the cross section for unpolarized beam and transverse target

TMDs

- Target and Beam Polarization
  - Can use similar methods (Møller/Compton scattering, NMR, inclusive and exclusive scattering)
- Backgrounds
  - Same as DIS…
  - + misidentified hadrons (π^+ vs. K^+ vs. p)
  - + combinatorial background ($\pi^0 \rightarrow \gamma\gamma$)
  - + accidental coincidences
- Radiative Corrections
  - More complicated but less pronounced than for inclusive scattering
  - POLRAD, HAPRAD and various generators…
- Extract moments (sinϕ, cosϕ, sin2ϕ, cos2ϕ,…)
  - Fine binning and fit
  - Moments; correct for acceptance
- Monte Carlo simulations for acceptance etc.
- Models ⇒ TMDs, GPDs,…
- Final results,
  publications,
  talks,…







TMDs

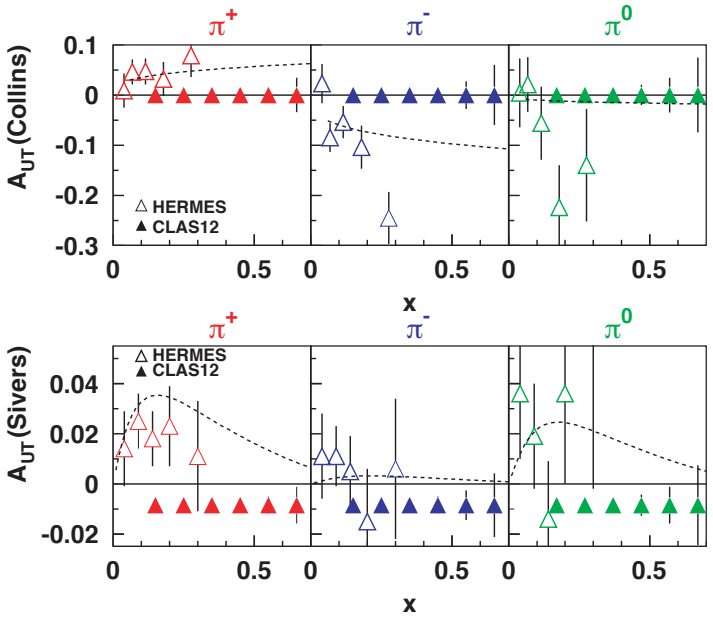
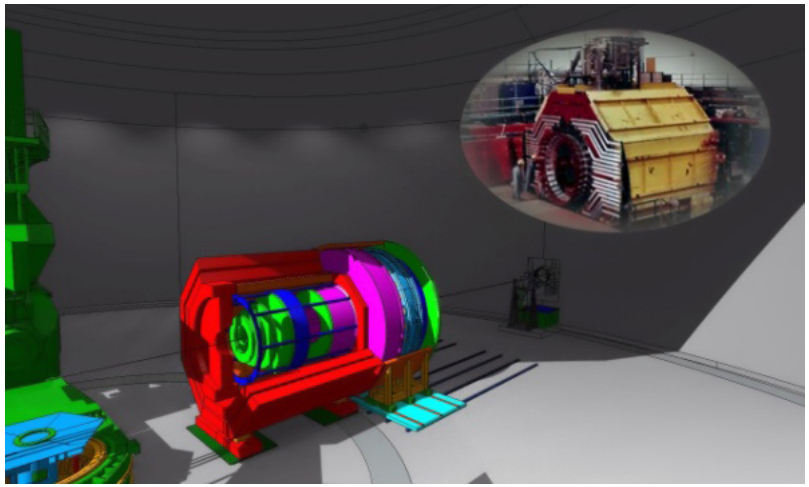


Figure 15: Projected measurements of the Collins and Sivers transverse single–spin asymmetries in semi-inclusive pion production at 12 GeV. The HERMES data are shown for comparison. The curves represent the phenomenological parameterizations of Ref. [Ef04].



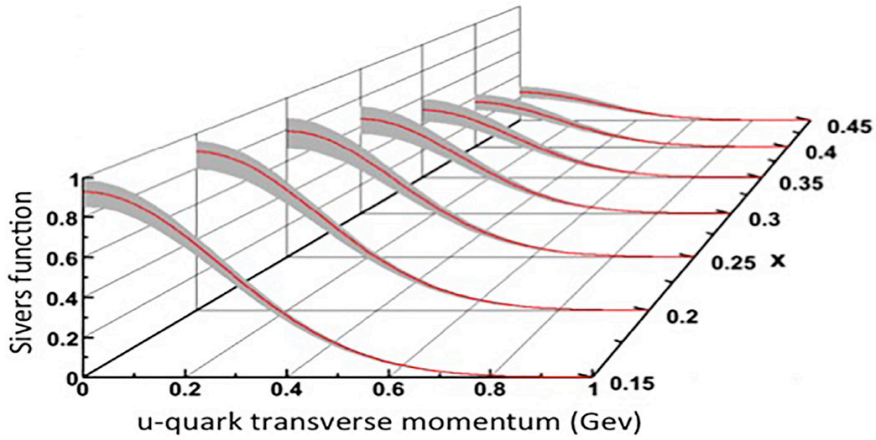
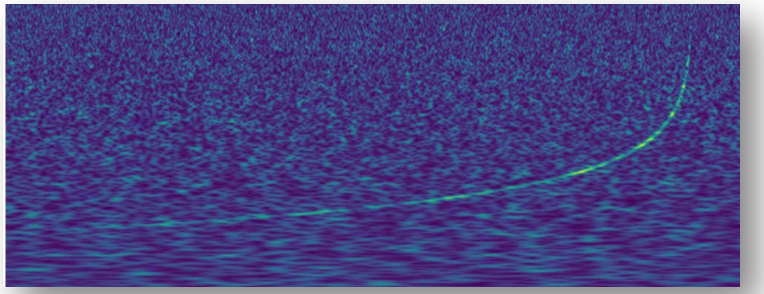


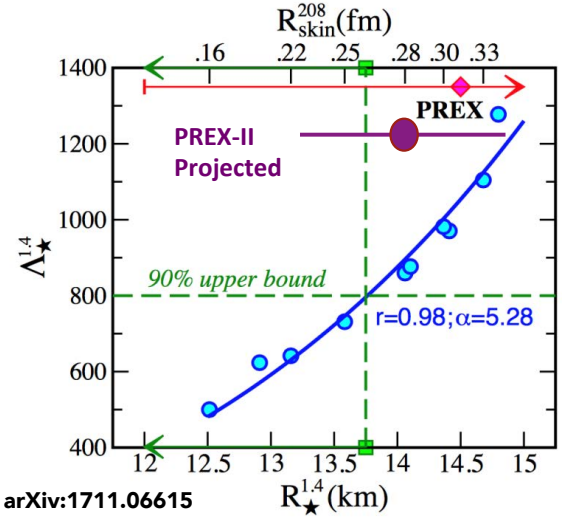
Figure 2.5: *Maps of the Sivers function for up quarks as a function of transverse momentum and at different values of the longitudinal momentum fraction x, as projected for 12-GeV JLab data.*

Nuclear Physics and Neutron Stars

Courtesy of NASA/Goddard Space Flight Center

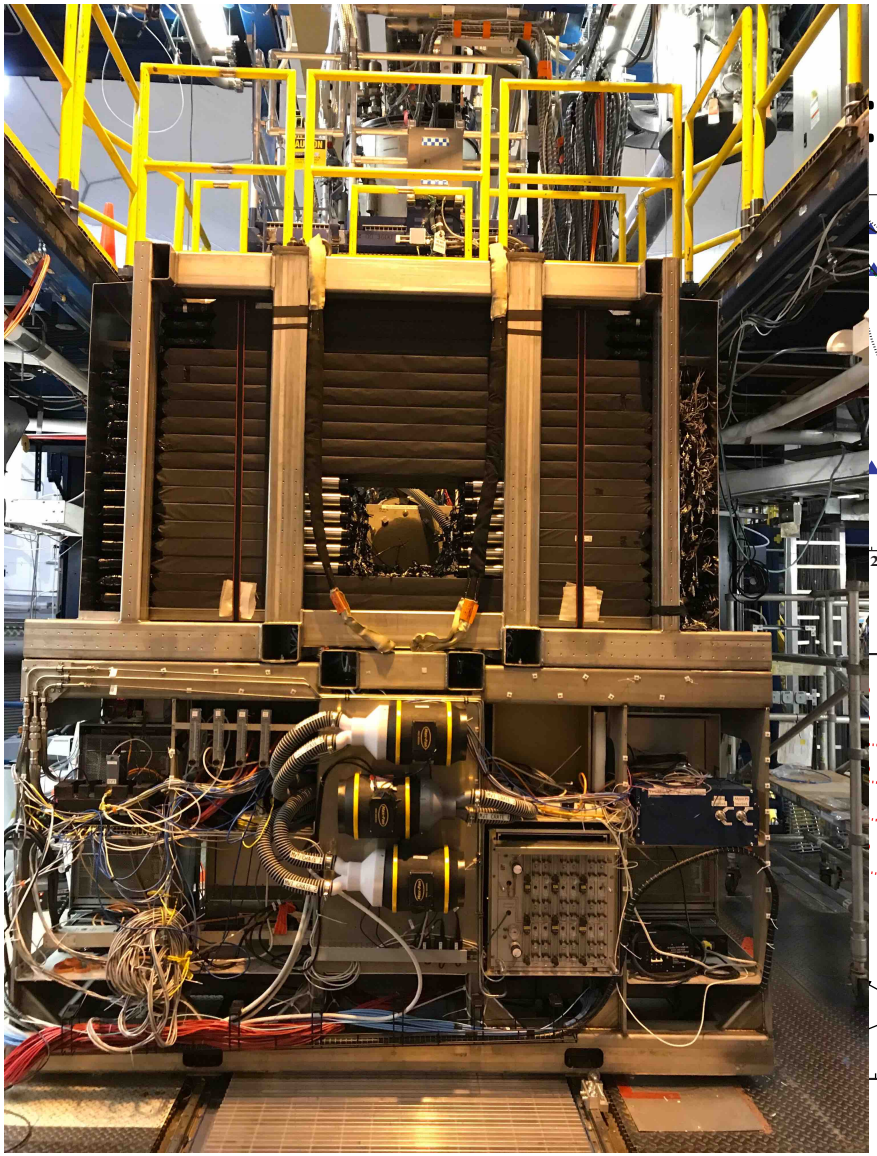
Measurement of neutron skin at JLab constrains tidal polarizability of neutron stars

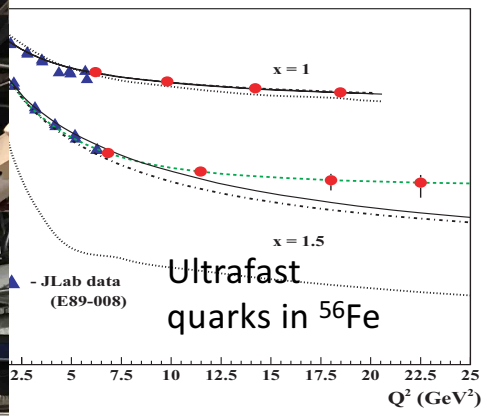


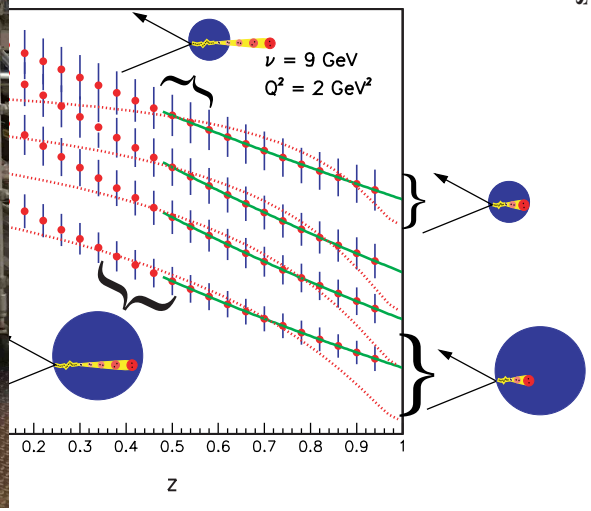


arXiv:1711.06615

: SRC, EMC, Hadronization, CT







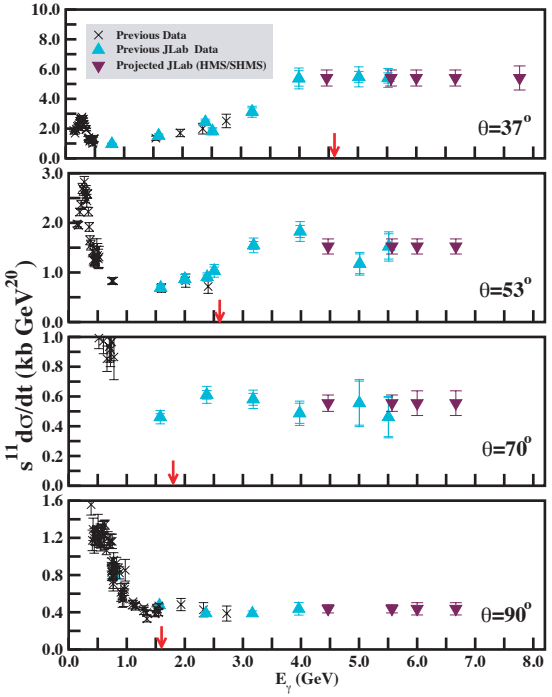
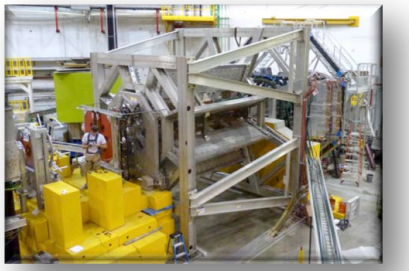
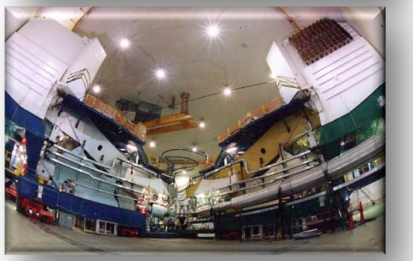
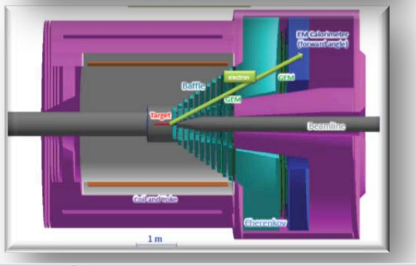


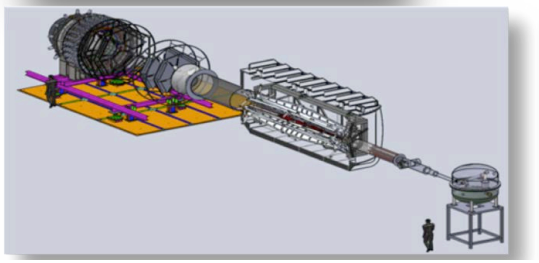
Figure 20: Available data and projected results for a differential cross-section measurement of deuteron photodisintegration. The arrow indicates a transverse momentum of 1.6 GeV in each plot.

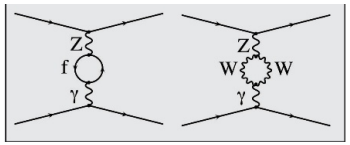
Precision Tests of the Standard Model at JLab



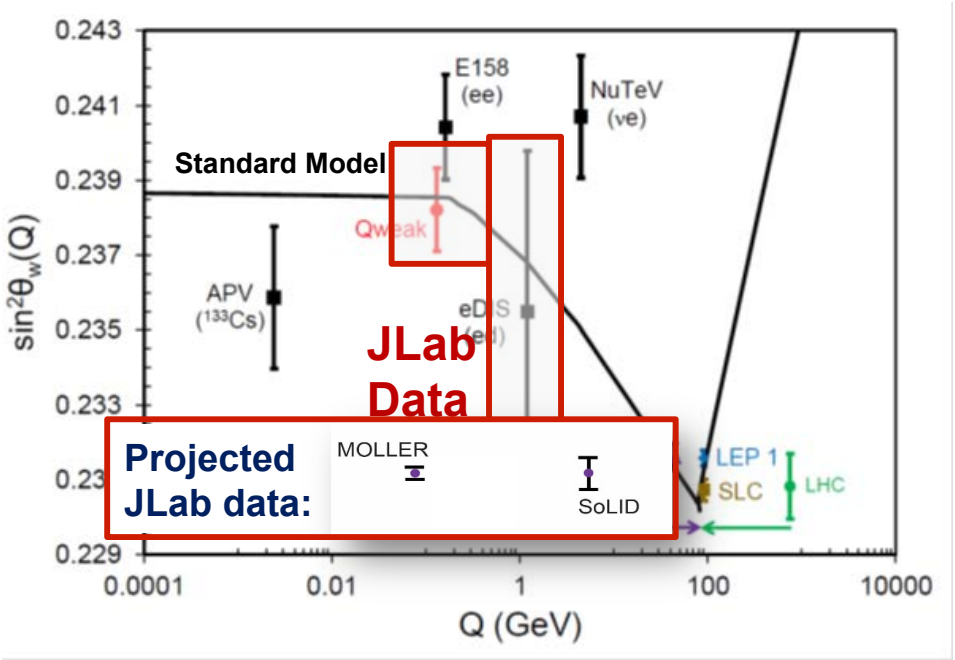








- EW Radiative Corrections
- +New Physics?



- Parity violating electron scattering provides a high precision test of the standard model.
- Complementary to measurements at CERN's Large Hadron Collider

.. Plus: Dark photons, precision measurements needed as input for neutrino experiments,

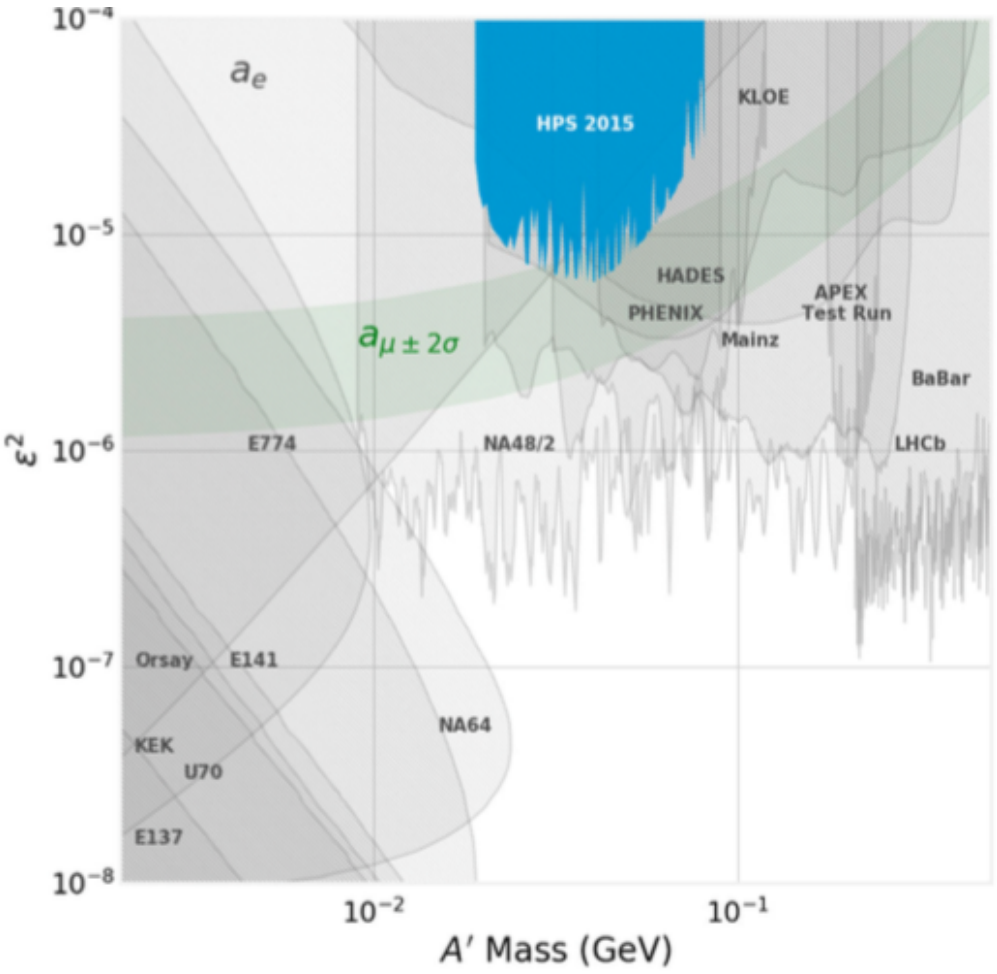
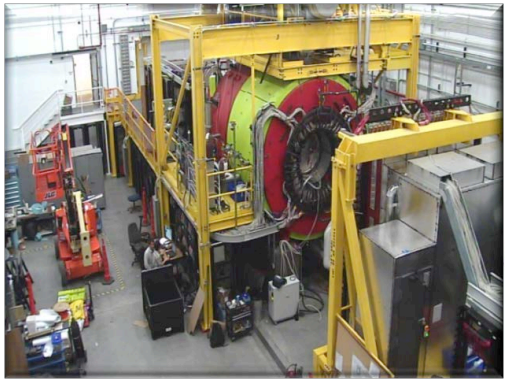


FIG. 15. The 95% C.L. power-constrained upper limits on ϵ^2 versus A' mass obtained in this analysis. A limit at the level of 6×10^6 is set. Existing limits from beam dump, collider and fixed target experiments are also shown. The region labeled a_e is an exclusion based on the electron $g2$. The green band labeled $a_\mu \pm 2\sigma$ represents the region that an A' can be used to explain the discrepancy between the measured and calculated muon anomalous magnetic moment. See Ref. [32] for details.

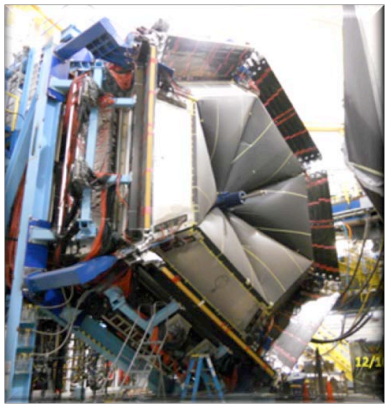
High Impact Experiments To run in the "first 5 years"

Exp#	Exp Name	Hall	Run Group/Days	PAC Days	PAC Grade	Comments
			TOPIC 1: SPECTROSCOPY			
E12-06-102	**GlueX:** Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	**D**		(120) approved **★90**	A	GlueX - assumed half commissioning/half physics **★plus (30) commissioning days**
E12-16-007	A Search for the LHCb Charmed "Pentaquark" using Photoproduction of J/Psi at Threshold in Hall C at Jefferson Lab	**C**		**11**	A	
			TOPIC 2: FORM FACTORS			
E12-06-101	Measurement of the Charged **Pion Form Factor** to High Q2	**C**		**52**	A	Requires fully commissioned SHMS
E12-07-109	**GEp/GMp**: Large Acceptance Proton Form Factor Ratio Meas's at 13 and 15 (GeV/c)2 Using Recoil Polarization Method	**A**		**45**	A-	Requires SBS and high power cryo target
E12-11-106	High Precision Measurement of the **Proton Charge Radius**	**B**		**15**	A	Non-CLAS12 experiment, Prad
			TOPIC 3: PDFs			
E12-06-113	**BONuS**: The Structure of the Free Neutron at Large x-Bjorken	**B**	F/40	(40) approved ★21 ↓	A	Requires BONuS Radial TPC upgrade **★42 days High Impact for the experiment**
E12-10-103	**MARATHON**: Measurement of the F2n/F2p, d/u Ratios and A=3 EMC Effect in DIS off the Tritium and Helium Mirror Nuclei	**A**	Tritium target group/61	↑ **★21** (42) approved	A	**that runs first; experiments are equally important & both are essential**
E12-06-110	**A1n HallC–3He**: Meas of Neutron Spin Asymmetry A1n in the Valence Quark Region Using an 11 GeV Beam and a Polarized 3He Target in Hall C	**C**		**36**	A	Requires high luminosity 3He
			TOPIC 4T: TMDs			
C12-11-111	**TMD CLAS–HDIce**: SIDIS on Transverse polarized target	**B**	G/110	**110** concurrent	A	Requires transversely polarized HDIce with electron beam
C12-12-009	**Dihadron CLAS-HDIce**: Measurement of transversity with dihadron production in SIDIS with transversely polarized target	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-06-112	**TMD CLAS-H(Unpol)**: Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV	**B**	A/139	(60) approved **★10**	A	Hall B commissioning + 10 days **★plus (50) commissioning days**
			TOPIC 4G: GPDs			
E12-06-114	**DVCS HallA–H(UU,LU)**: Measurements of Electron-Helicity Dependent Cross Sections of DVCS with CEBAF at 12 GeV	**A**	Early: DVCS & GMp/62	(100) approved **★70**	A	Hall A commissioning
C12-12-010	**DVCS CLAS–HDIce**: DVCS at 11 GeV with transversely polarized target using the CLAS12 Detector	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-11-003	**DVCS CLAS–D(UU,LU)**: DVCS on the Neutron with CLAS12 at 11 GeV	B	B/90	(90) approved	A	Requires D target; central neutron detector ready in 2016 ★Backup GPD-E meas if HDIce delayed
			TOPIC 5: NUCLEAR			
E12-13-005	**Bubble Chamber**: Measurement of 16O(^{3},±)12C with a bubblechamber and a bremsstrahlung beam	**INJ**		14	A-	Our guess: 2017
E12-11-101	**PREx-II**: Precision Parity-Violating Measurement of the Neutron Skin of Lead	**A**		35	A	Requires septum, Pb target, 1% Moller polarimetry
E12-06-105	**SRC–hiX**: Inclusive Scattering from Nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes	**C**		32	A-	
E12-11-112	**SRC–Tritium**: Precision measurement of the isospin dependence in the 2N and 3N short range correlation region	**A**	Tritium target group/61	19	A-	
E12-17-003	Determining the Unknown Lambda-n Interaction by Investigating the Lambda-nn Resonance	**A**		**12**	A-	
			TOPIC 6: FUNDAMENTAL SYMMETRIES			
E12-11-006	**HPS**: Status of the Heavy Photon Search Experiment at Jefferson Laboratory (Update on PR12_11_006)	**B**	H/180	(155) approved **★39**	A	Non-CLAS12 experiment, HPS **★25 pre-CLAS engr + 14 physics @ 4.4 GeV**
E12-10-009	**APEX**: Search for new Vector Boson A1 Decaying to e+e-	**A**		**34**	A	

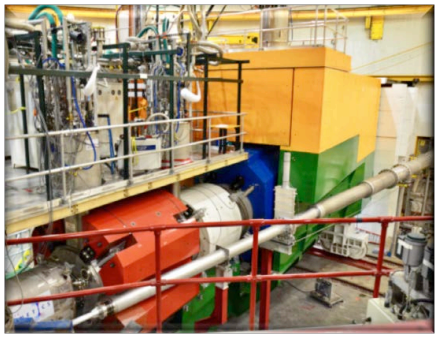
12 GeV Scientific Capabilities



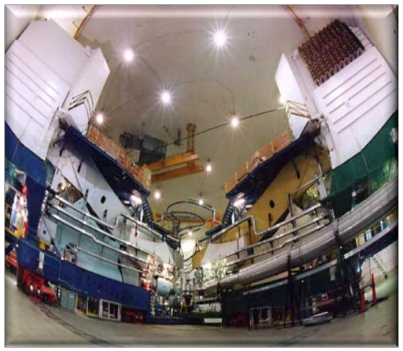
Hall D – exploring origin of **confinement** by studying **exotic mesons**



Hall B – understanding **nucleon structure** via **generalized parton distributions** and **transverse momentum distributions**



Hall C – precision determination of **valence quark** properties in nucleons and nuclei



Hall A – short range correlations, form factors (SBS), hyper-nuclear physics, **future new experiments (e.g., SoLID and MOLLER)**

HALL A

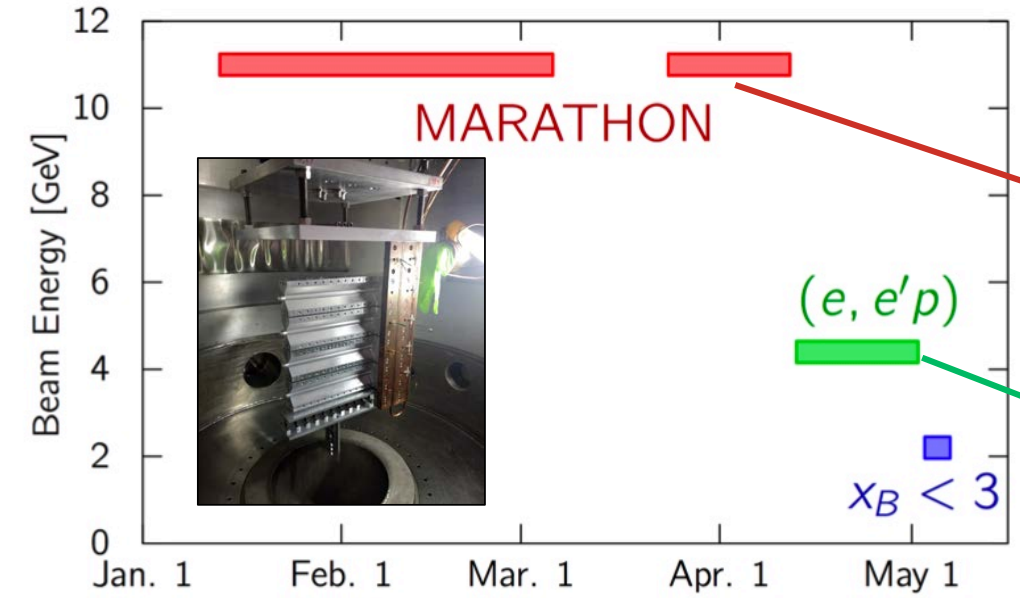
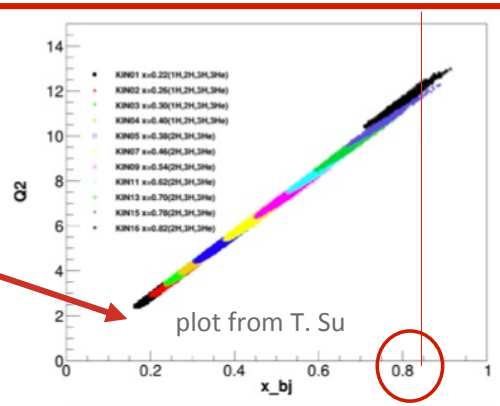
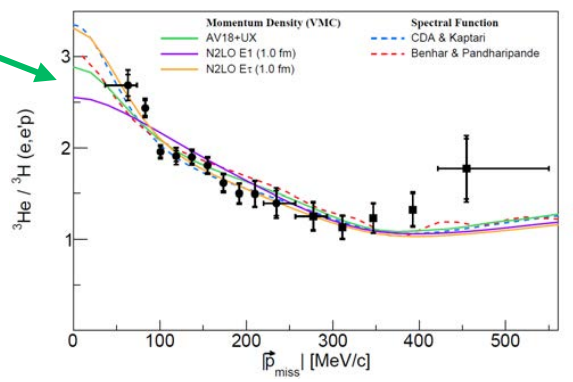


Figure by A.Schmidt





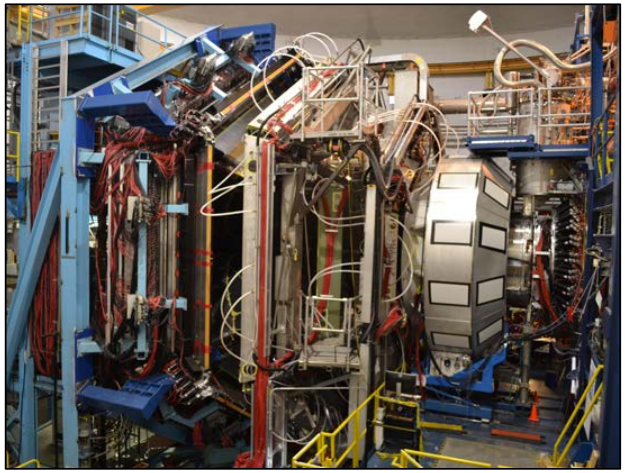
- Running tritium family of experiments in 2018 – 3 complete!
- Continue to publication results of previous 12 GeV experiments

Published in Phys. Rev. C98 (2018) no.1, 014617

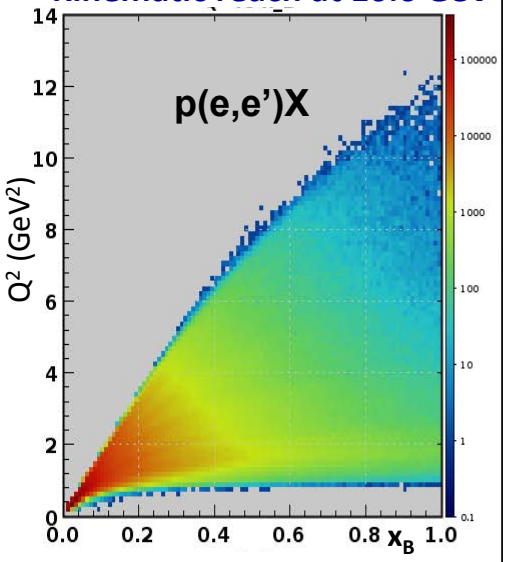
First Measurement of the Ti(e, e')X Cross Section at Jefferson Lab

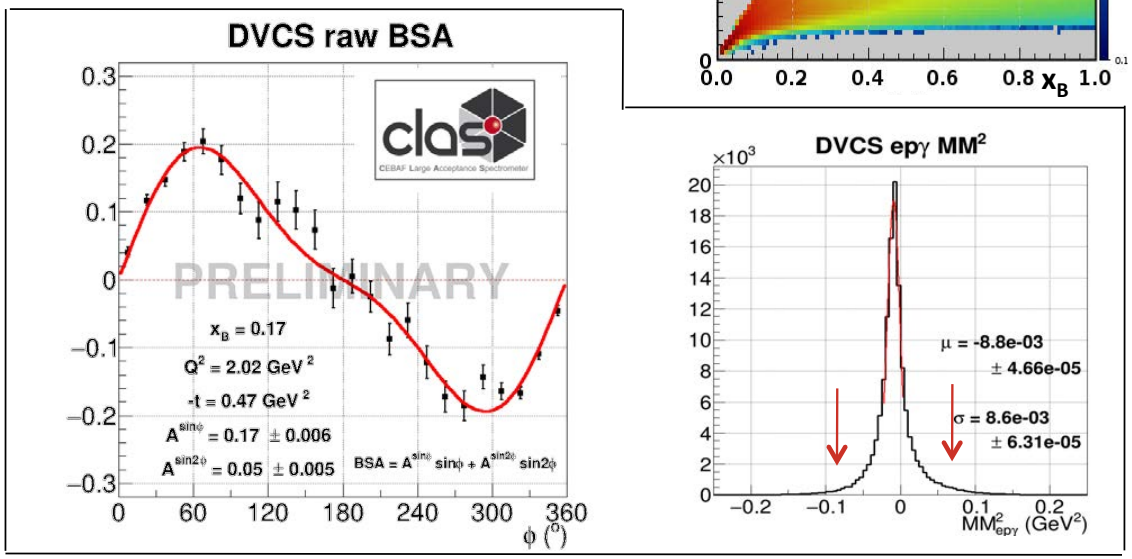
H. Dai,[1] M. Murphy,[1] V. Pandey,[1,*] D. Abrams,[2] D. Nguyen,[2] B. Aljawrneh,[3] S. Alsalmi,[4] A. M. Ankowski,[1,5,†] J. Bane,[6] S. Barcus,[7] O. Benhar,[8] V. Bellini,[9] J. Bericic,[10] D. Biswas,[11] A. Camsonne,[10] J. Castellanos,[12] J.-P. Chen,[10] M. E. Christy,[11] K. Craycraft,[6] R. Cruz-Torres,[13] D. Day,[2] S.-C. Dusa,[10] E. Fuchey,[14] T. Gautam,[11] C. Giusti,[15] J. Gomez,[10] C. Gu,[2] T. Hague,[4] J.-O. Hansen,[10] F. Hauenstein,[16] D. W. Higinbotham,[10] C. Hyde,[16] C. M. Jen,[1] C. Keppel,[10] S. Li,[17] R. Lindgren,[18] H. Liu,[19] C. Mariani,[1] R. E. McClellan,[10] D. Meekins,[10] R. Michaels,[10] M. Mihovilovic,[20] M. Nycz,[4] L. Ou,[13] B. Pandey,[11] K. Park,[10] G. Perera,[18] A.J.R. Puckett,[14] S. Širca,[21,20] T. Su,[4] L. Tang,[11] Y. Tian,[22] N. Ton,[18] B. Wojtsekhowski,[10] S. Wood,[10] Z. Ye,[23] and J. Zhang[18]
(The Jefferson Lab Hall A Collaboration)

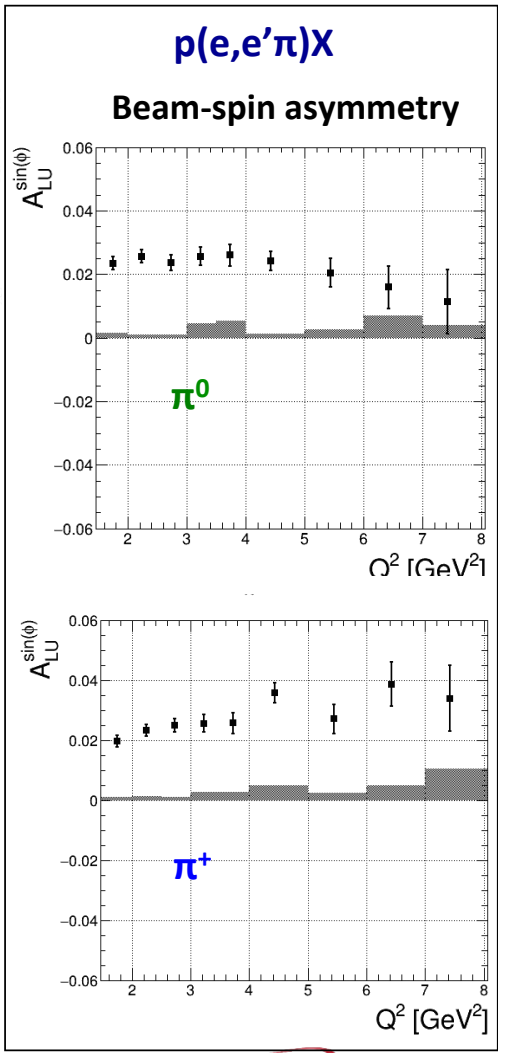
HALL B – CLAS12: TOWARD HIGH IMPACT SCIENCE



Kinematic reach at 10.6 GeV



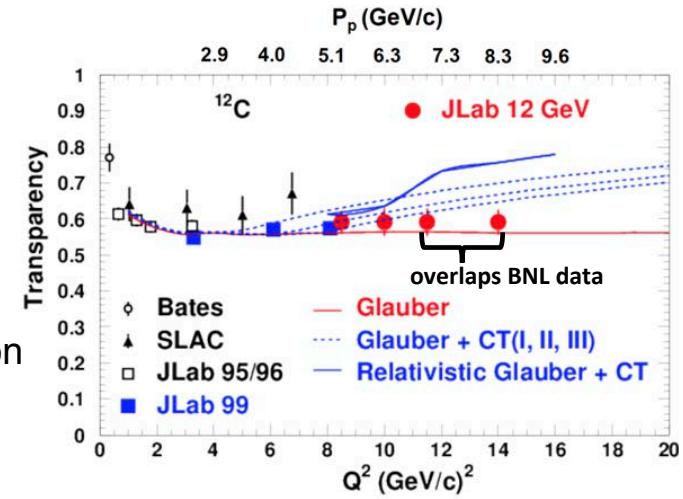


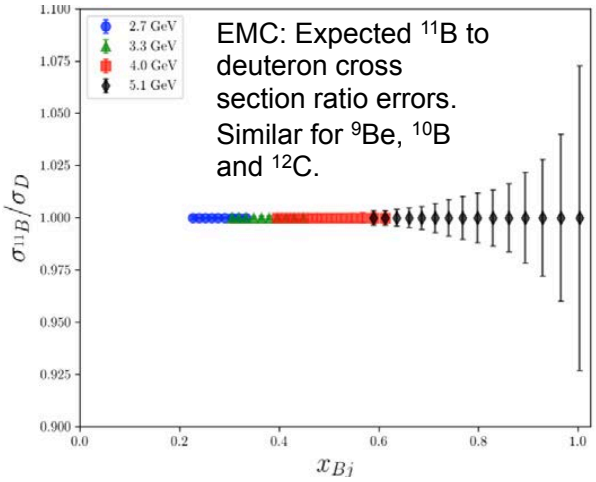


HALL C

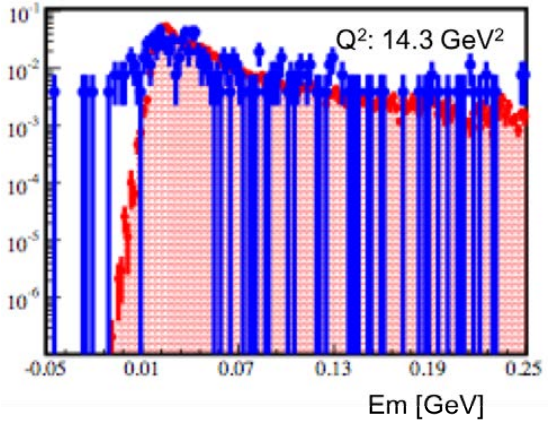
- SHMS calibration initial physics data acquired
  - $F_2^{H,D}$ structure functions, EMC effect
  - D(e,e'p) at high missing momentum
  - Color Transparency (CT) – ^{12}C(e,e'p)
    - Data for 3 points acquired.
    - Highest Q^2 is where BNL A(p,2p) saw rise in transparency
  - TMD studies (SIDIS) and Kaon electroproduction scaling measurement underway
- Analyses of CT, F2, D(e,e'p), EMC underway

Projected Color Transparency errors





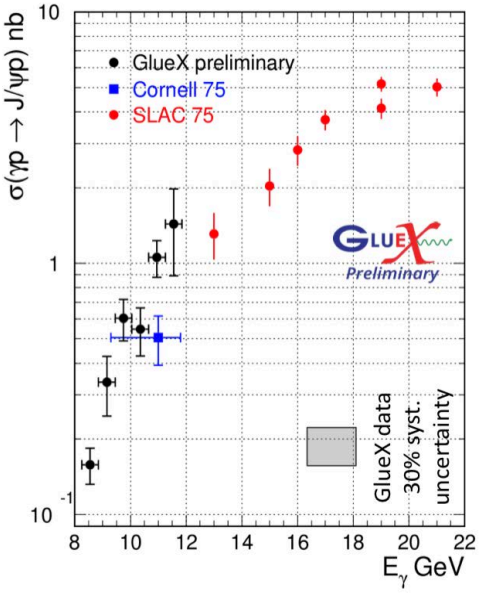
EMC: Expected ^{11}B to deuteron cross section ratio errors. Similar for ^{9}Be, ^{10}B and ^{12}C.



CT: Good agreement between data and simulation even at the highest Q^2. Will improve as SHMS optics model is optimized.

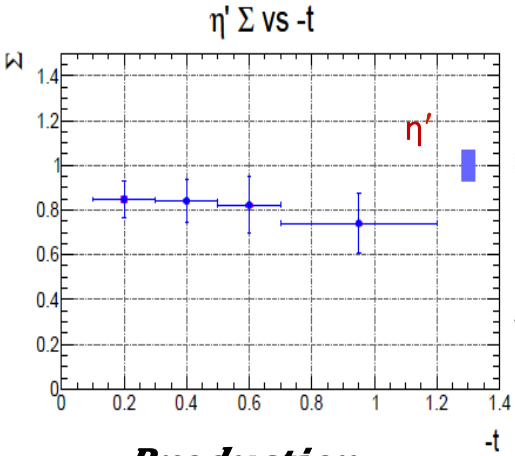
HALL D: ANALYSIS AS OF FALL 2018

J/ψ production at threshold



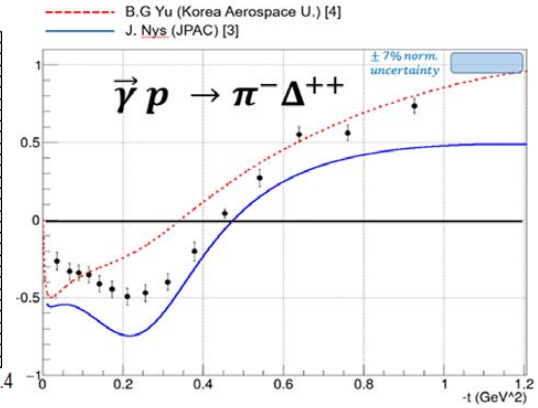
J/ψ cross section at threshold and limit on charm pentaquark photoproduction *(manuscript in preparation)*

Production Asymmetries



Production asymmetry of the reaction γp → p η'

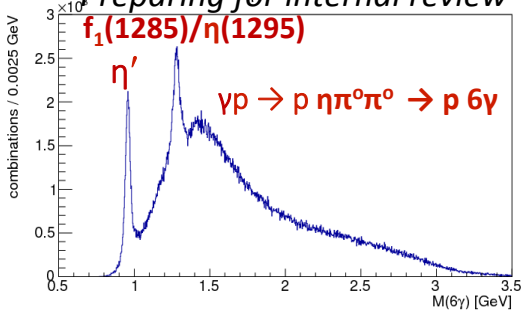
Preparing for internal review



Production asymmetry of the reaction γp → π⁻ Δ⁺⁺

Preparing for internal review

- GlueX-I has 80% of data
- GlueX-I is scheduled to collect all data by FY19 FQ2
- 25% of data analyzed
- 3 papers in preparation
- Getting ready for Primex-η and GlueX-II (with DIRC)



Theory at Jefferson Lab

- Focus on 3 of the 5 Research Areas identified in 2015 NSAC LRP Document:

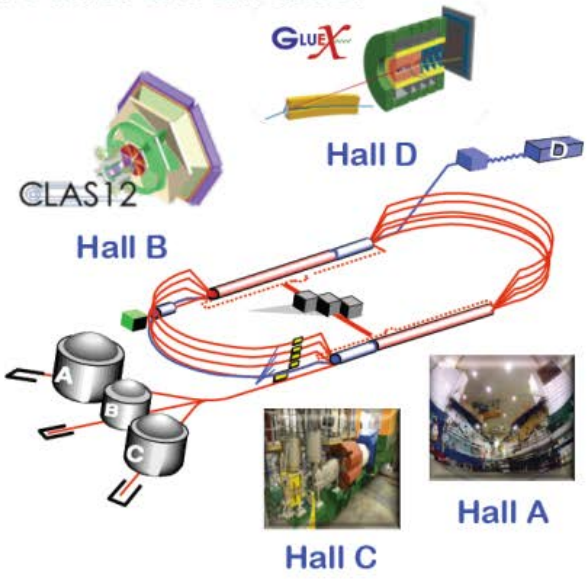
  Area 1 – QCD and the structure of hadrons and nuclei
  Area 3 – Nuclear structure and reactions
  Area 5 – Fundamental symmetries and neutrinos

- Support JLab12 with six coherent thrusts:

Hadron spectroscopy – LQCD: Edwards, Dudek, Orginos, Richards

Hadron spectroscopy – JPAC: Doring, Passimar, Szczepaniak

Nuclear structure & Low energy EFTs: Goity, Melnitchouk, Schiavilla, Van Orden, Weiss



3D hadron structure – LQCD: Edwards, Orginos, Richards, Shanahan

3D hadron structure – Global analyses: Accardi, Melnitchouk, Prokudin, Rogers

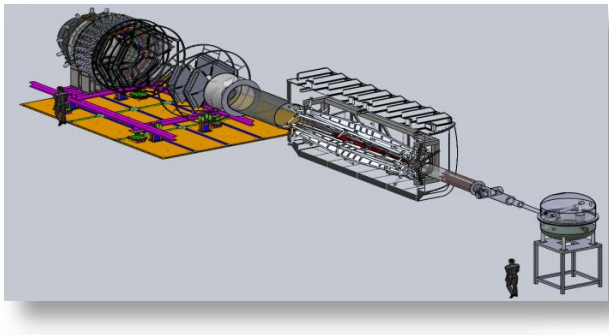
3D hadron structure – QCD & EFTs: Accardi, Balitsky, Melnitchouk, Prokudin, Qiu, Radyushkin, Rogers, Weiss

- Research with high performance computing:

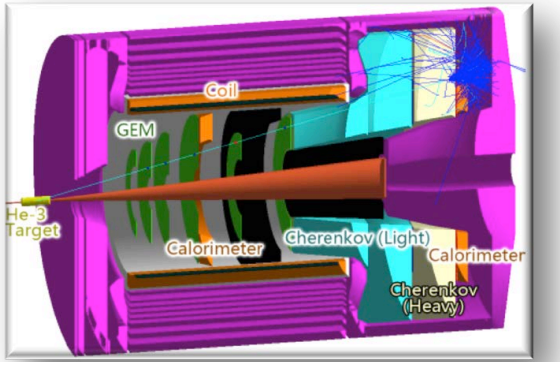
  Lattice QCD, SciDAC4, Exascale computing, software supporting experiments, …

Future Projects

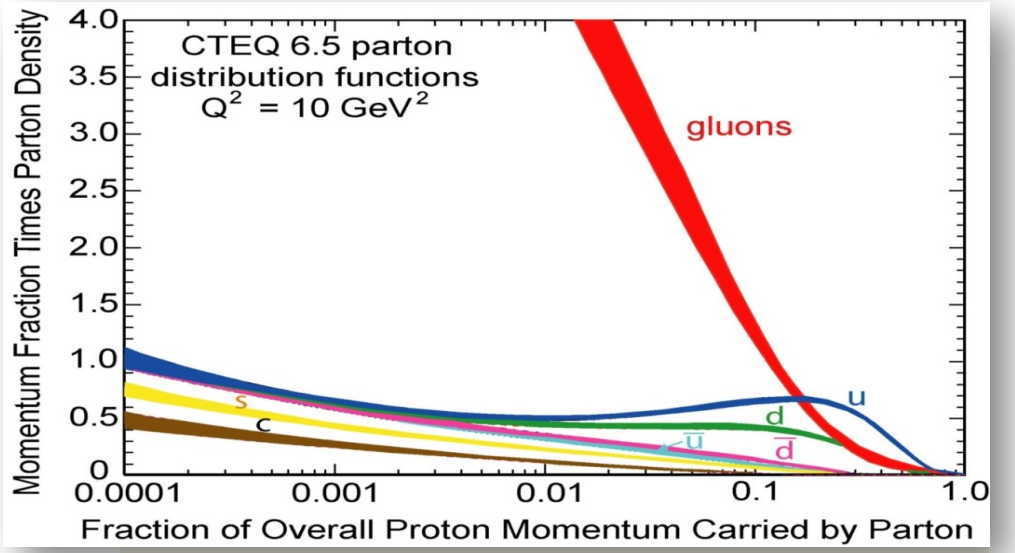
- MOLLER experiment
  - DOE science review (Sept. 2014) – strong endorsement
  - Director's Cost, Schedule and Technical review held Dec. 2016
  - CD-0 approved, Dec. 2016
    (project paused due to budget)
  - Developing project structure in
    preparation for FY19 Director's Review

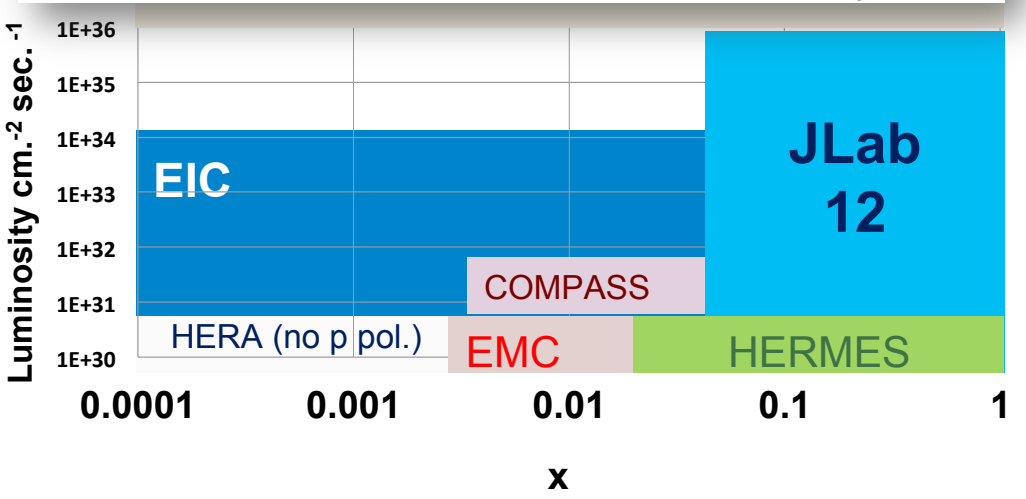


- SoLID
  - New pre-CDR completed
  - Briefed ONP, Pre-R&D request
  - Awaiting science review from ONP



FROM JLAB12 TO EIC





- High Luminosity
  → 10^{34} cm^{-2}s^{-1}
- Low x regime
  x → 0.0001
- High Polarization
  → 70%

Discovery Potential!