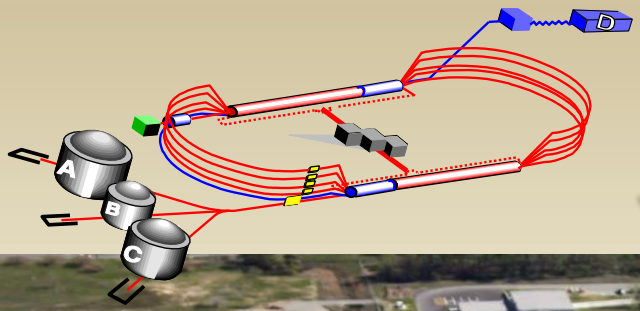
U.S. DEPARTMENT OF ENERGY | Office of Science | JSA



Jefferson Lab
Nuclear Science Program

R. D. McKeown

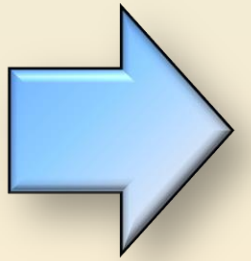
Quark Nuclear Physics
March 2, 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- JLab context in Nuclear Physics
- 12 GeV CEBAF
  - Upgrade status
  - Science Program:

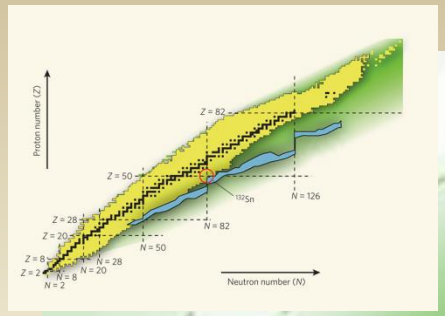
New
Phenomenology
Techniques (theory+exp)
Standard model tests



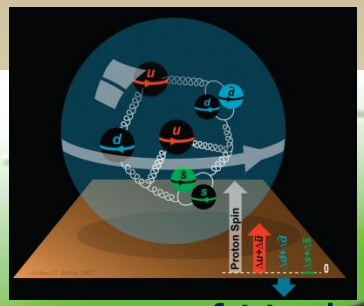
Discovery Potential

- Future new capability: MEIC
- Outlook

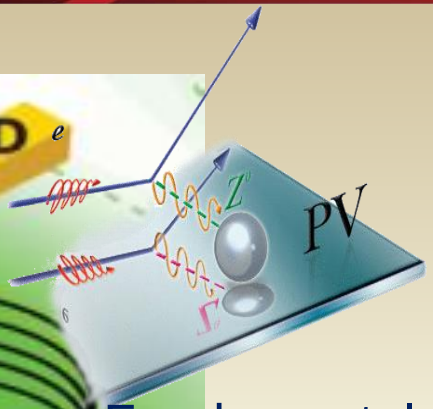
A Laboratory for Nuclear Science



Nuclear Structure



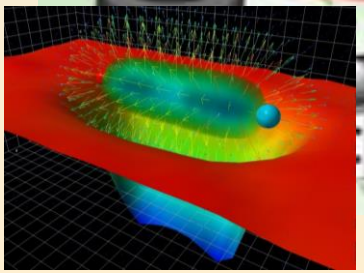
Structure of Hadrons



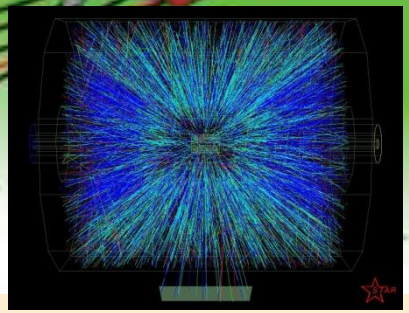
Fundamental
Forces & Symmetries

Medical Imaging

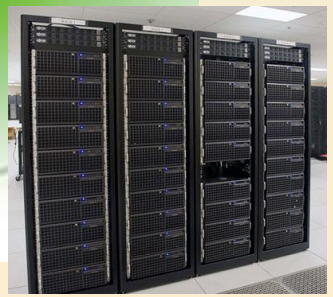
Accelerator S&T



Quark Confinement



Hadrons from Quarks

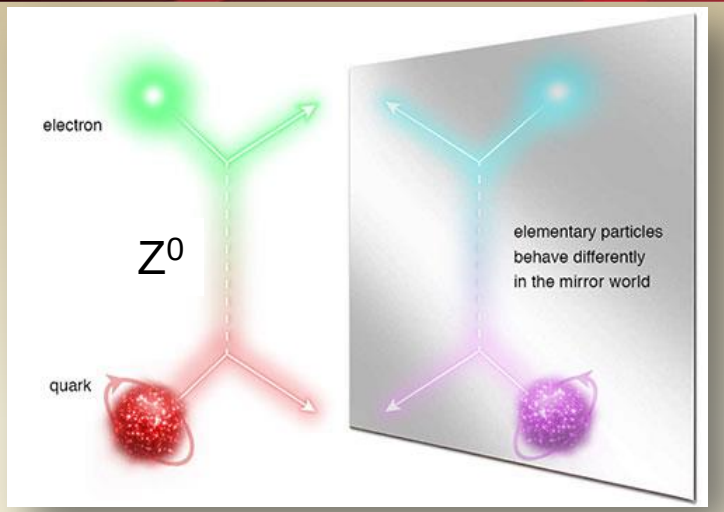


Theory and Computation

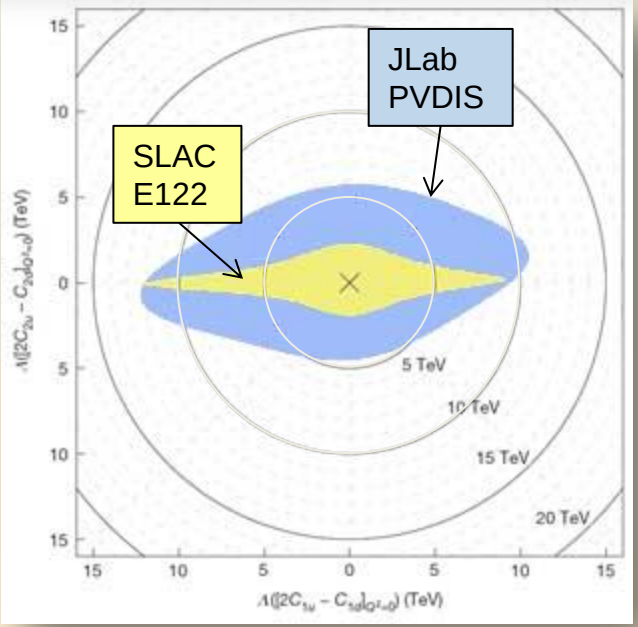
Measurement of the Parity-Violating Asymmetry in eD Deep Inelastic Scattering

Nature 506, 67–70 (06 February 2014)
The Jefferson Lab PVDIS Collaboration
See also News & Views, *Nature* 506, 43–44 (06 February 2014)

Longitudinally Polarized Electron Scattering from Unpolarized Deuterium



- Precise determination of the effective electron-quark weak coupling combination $2C_{2u} - C_{2d}$, five times more precise than previous measurement.
- Combined with previous experiments like Qweak, first non-zero C_{2q} (at 95% confidence level).
- Provides a mass exclusion limit (Λ) on the electron and quark compositeness and contact interactions of ~5 TeV.

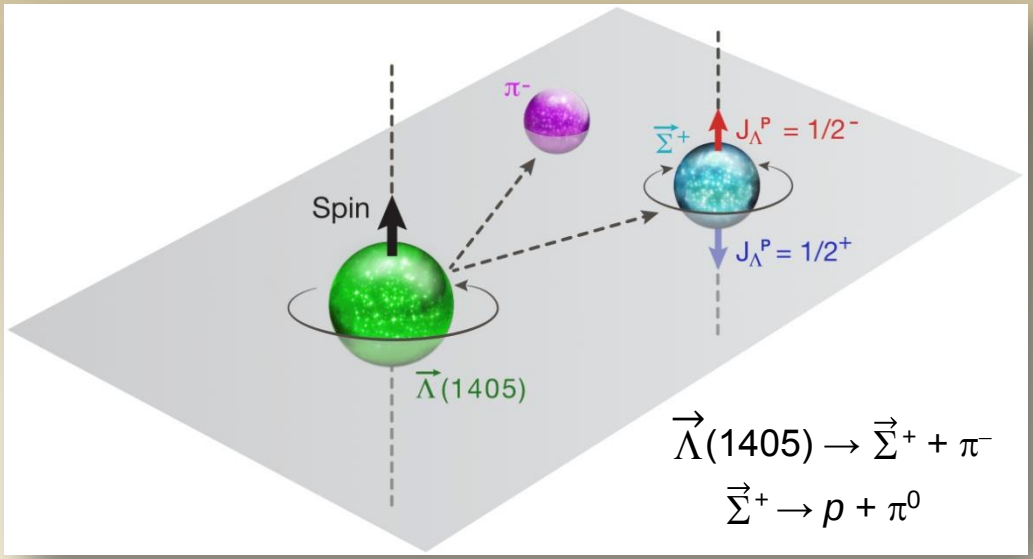


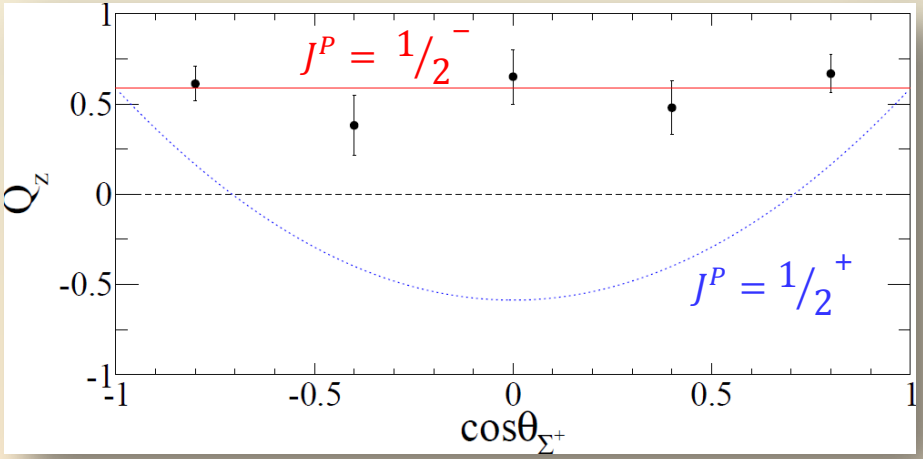
Spin and Parity of the Λ(1405) Baryon

- Λ(1405) is a well-known hyperon (PDG Status: ★★★★)
- Spin-Parity, J^P, has never been definitively measured
- Λ(1405) created polarized via photoproduction in liquid hydrogen & detected in CLAS

$$\gamma + p \rightarrow K^+ + \vec{\Lambda}(1405),$$

$$\vec{\Lambda}(1405) \rightarrow \vec{\Sigma}^+ + \pi^-$$





- Isotropic decay of Λ(1405) is consistent with spin $J = 1/2$
- Polarization transfer to Σ^+ direction reveals $J^P = 1/2^-$ vs. $J^P = 1/2^+$
- Quark model expectation confirmed
- Higher spins are disfavored by the data and by theoretical expectations

- K. Moriya, R. A. Schumacher *et al.* (CLAS Collaboration), Phys. Rev. Lett. **112** 082004 (2014).
- Selected as an "Editors' Suggestion" by PRL

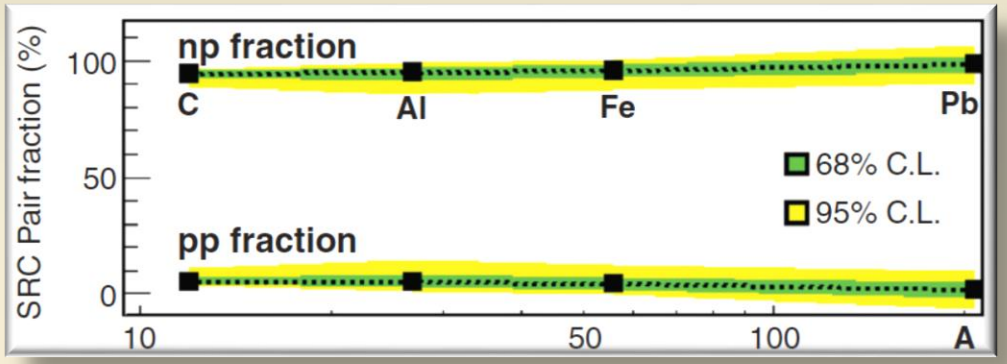
Momentum Sharing in Imbalanced Fermi Systems

O. Hen *et al.,* Science **346** (2014) 614, *doi:10.1126/science.1256785*

The Jefferson Lab CLAS Collaboration

Selected for Science Express (16 October 2014)

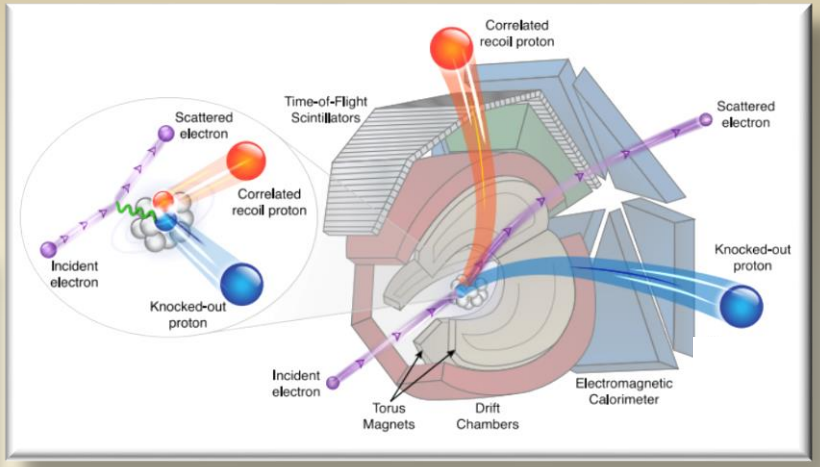
For momenta greater than the Fermi momentum (k_f), proton-neutron pairs dominate over proton-proton and by inference neutron-neutron pairs, **even in neutron-rich heavy nuclei.**

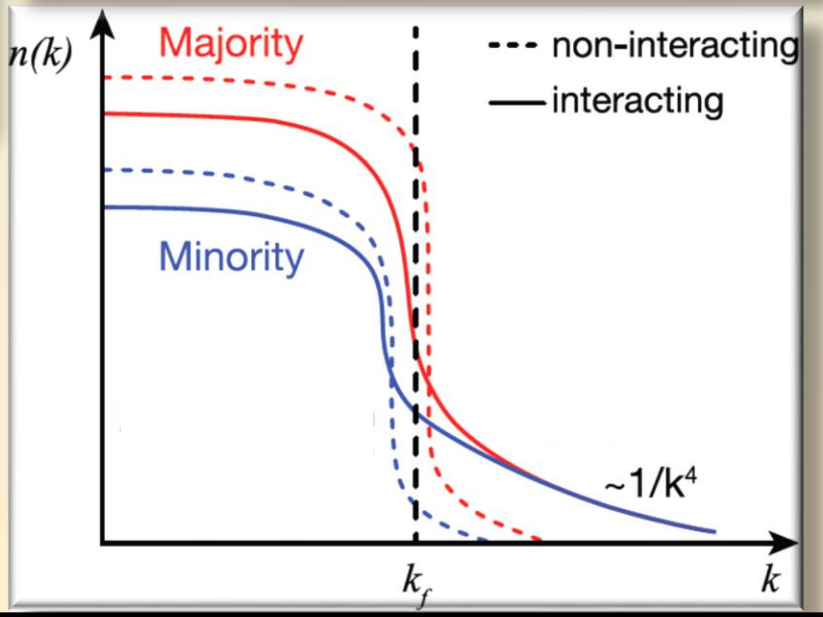


The average proton momentum is increased by this pairing more than the average neutron momentum, completely unlike the effects of non-interacting Fermions in a mean field.

This type of momentum sharing in an imbalanced Fermi system has implications for the equations of state of neutron stars and atomic interactions in ultra-cold atomic gases and can be studied not only in nuclei but also in atomic systems

The data were analyzed by the CLAS Data Mining Initiative.



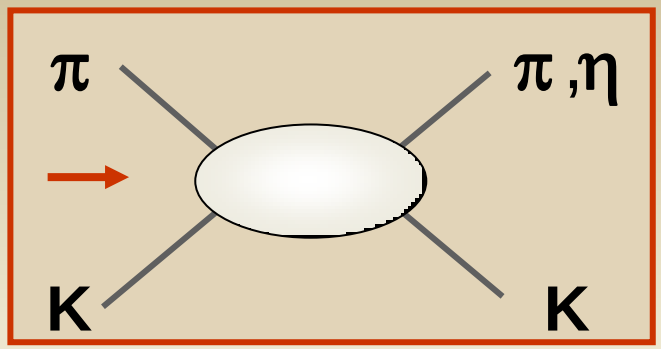


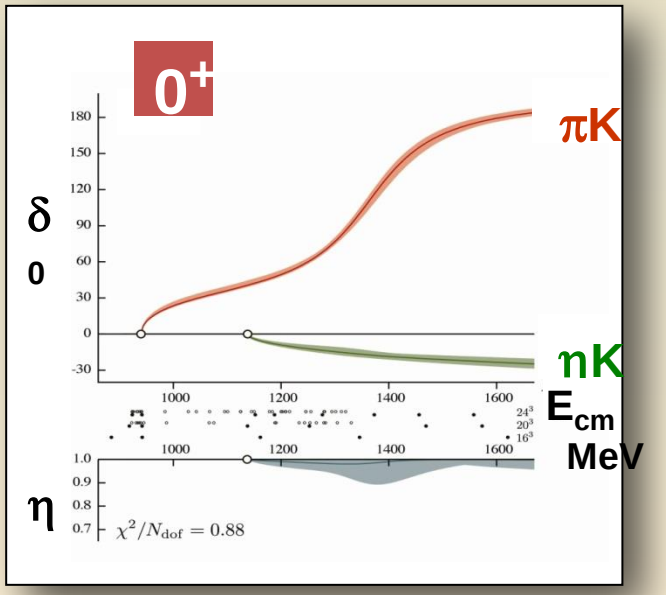
Theory and Computation Highlight

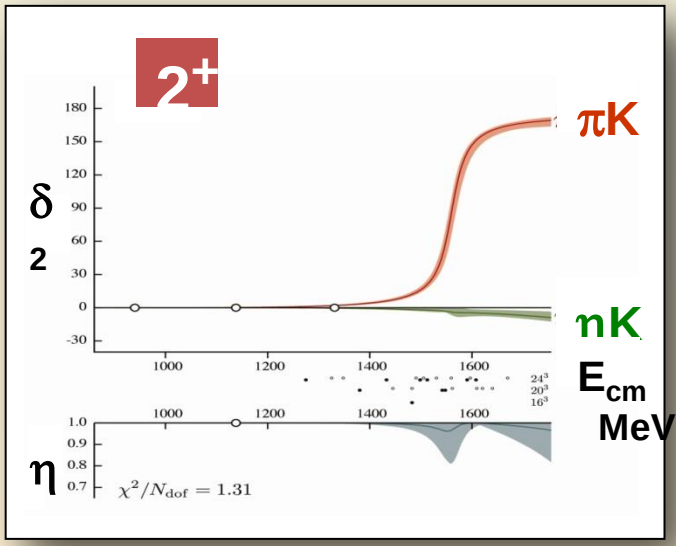
New Technology + Innovative Techniques

Lattice QCD Advance:
First scattering calculation of
Inelastic channels

Now published in PRL







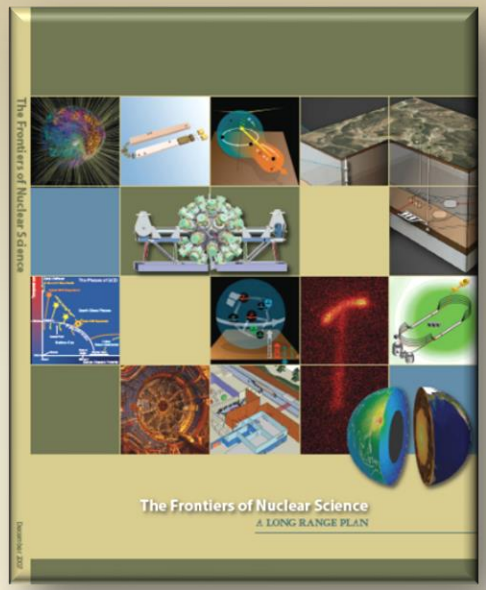
Work on leadership GPU systems
such as DOE Titan (ORNL) and
NSF Blue Waters (NCSA - University of Illinois)

Large ASCR Computing Challenge Award in May 2014: 250M core hours

JLab: 21st Century Science Questions

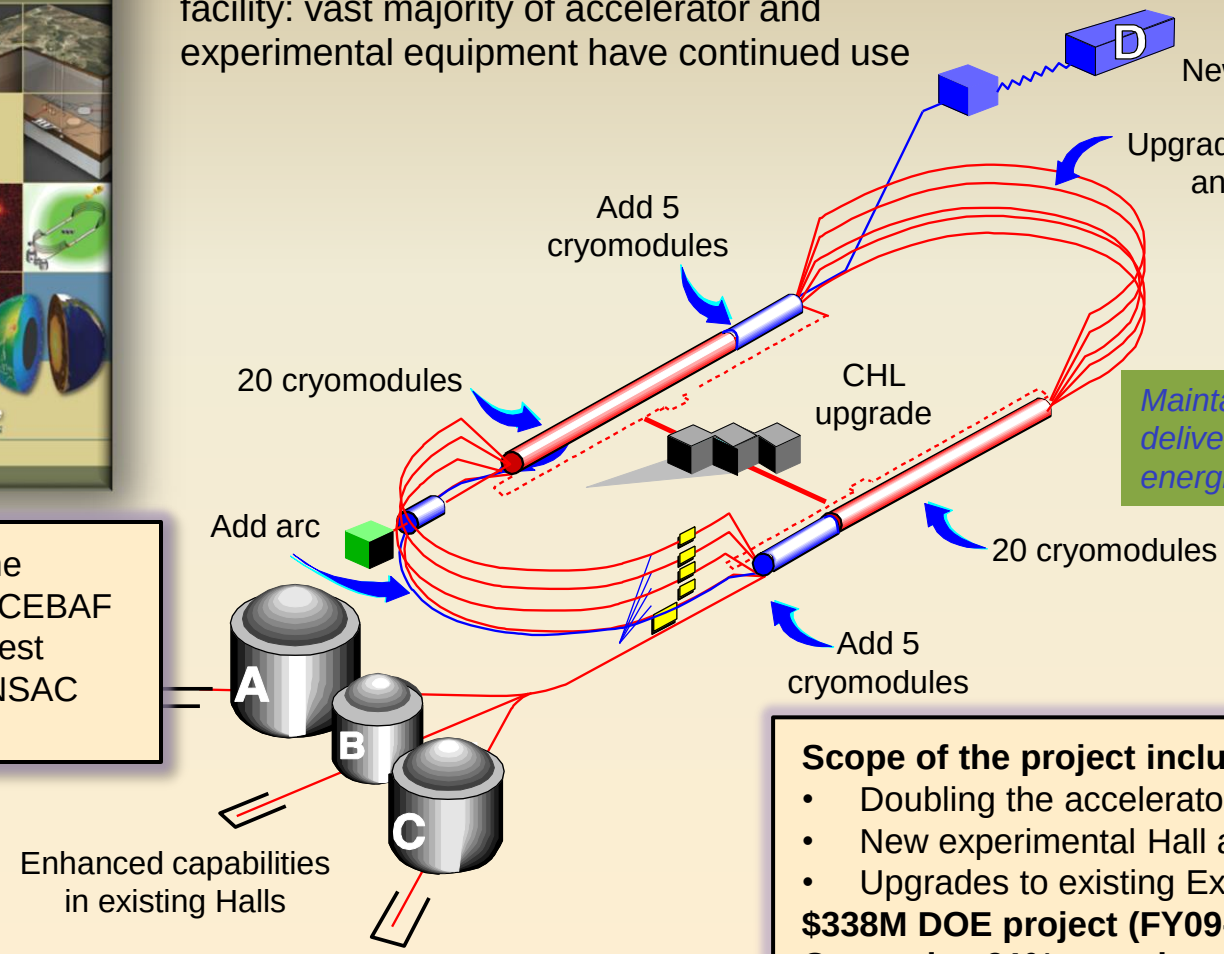
- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape 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 Upgrade Project



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

Scope of the project includes:

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

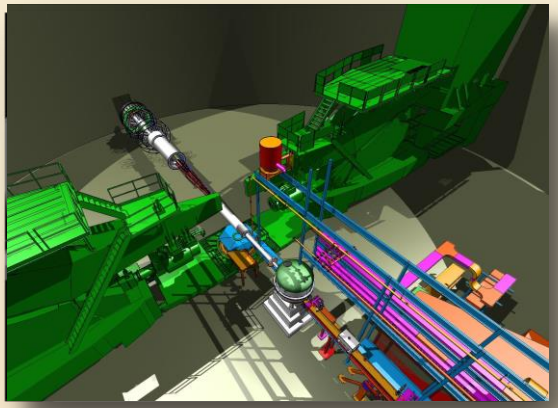
$338M DOE project (FY09-17)
Currently ~91% complete
Beam Commissioning in progress

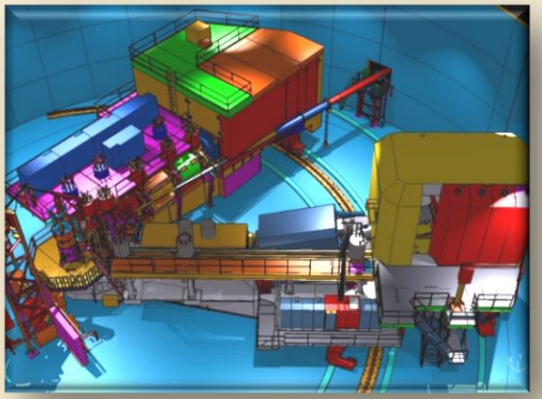
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

Hall B – understanding nucleon structure via generalized parton distributions

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

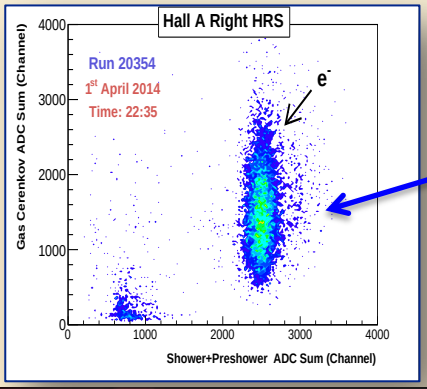


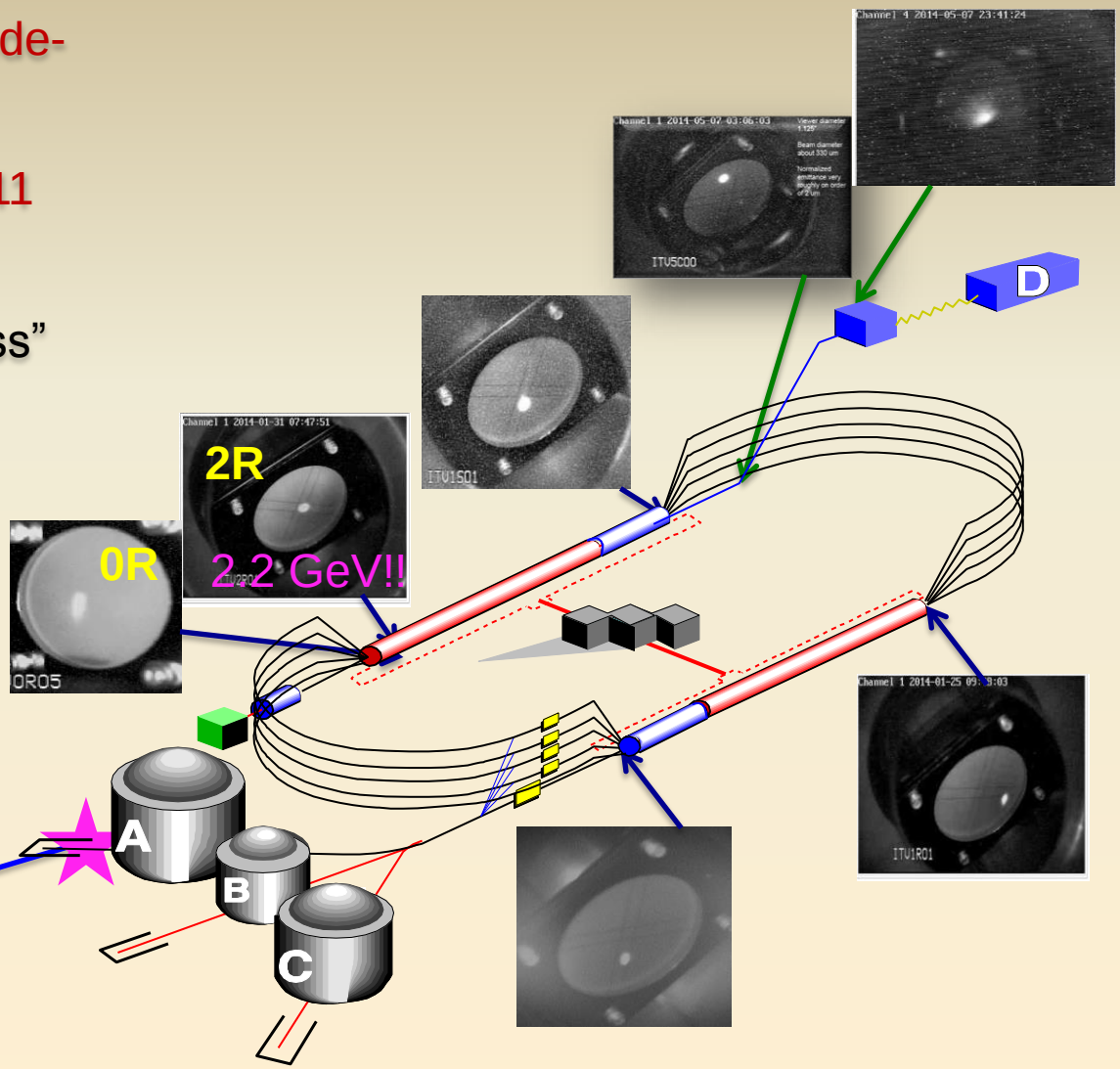


Hall A –form factors, future new experiments (e.g., SoLID and MOLLER)

Accelerator Commissioning & First Beam to Halls

- ★ Feb 5, 2014 achieved full upgrade-energy of 2.2 GeV in one pass.
- ★ April 1, 2014 "3-pass" beam, 6.11 GeV electrons @ 2 nA in Hall A
- ★ May 7, 2014 10.5 GeV ("5.5 pass" beam) to Hall-D Tagger dump
- ★ November 2014 beam to Hall D (GlueX engineering run), Hall A (DVCS/G_M^P exp.), Hall B (non-CLAS12 exp.)

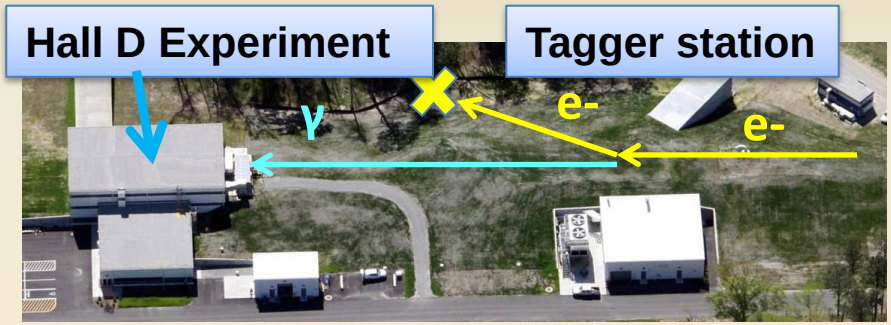


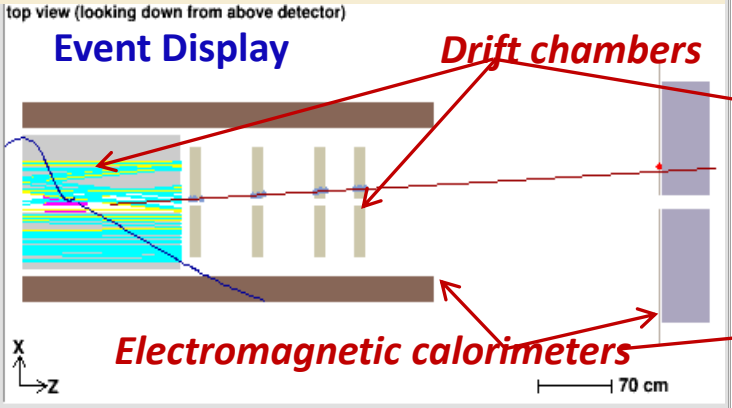


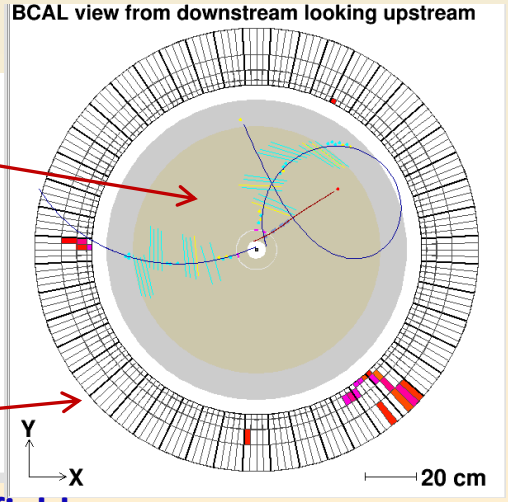
Beam on Carbon Target

Jefferson Lab: Hall D Commissioning

- Hall D complex: facility for experiments with linearly polarized photon beam
- Main goal: search for gluonic excitations in light meson spectra (experiment GlueX)
- Photon beam line + large acceptance spectrometer for charged particles & photons
- Commissioning with beam Nov. & Dec. 2014: KPP have been demonstrated

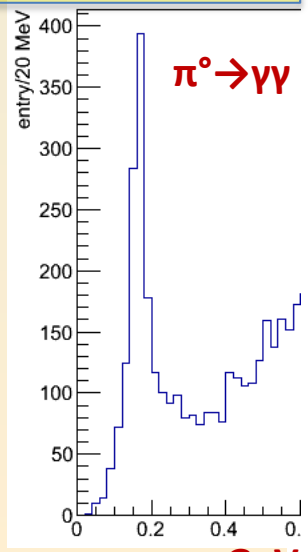




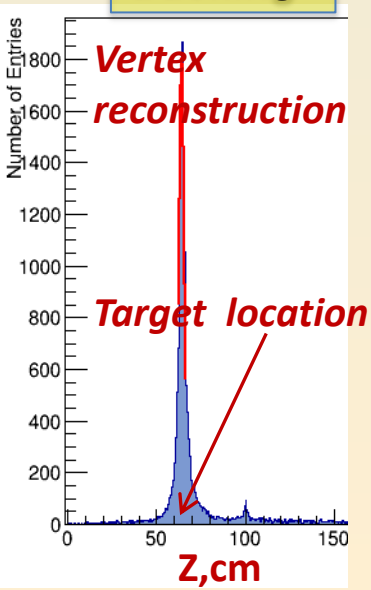


Spectrometer in solenoidal magnetic field

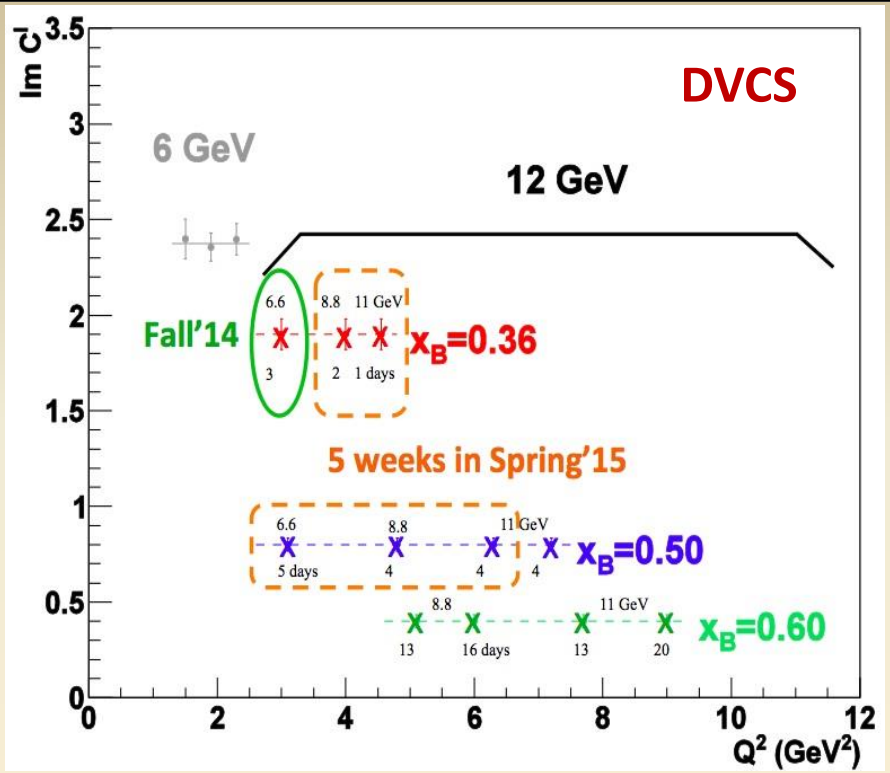
Neutral particles reconstruction



Charged particles tracking



Early Science of 12 GeV Era in Halls A and B



DVCS: A High impact experiment for 3D nucleon imaging

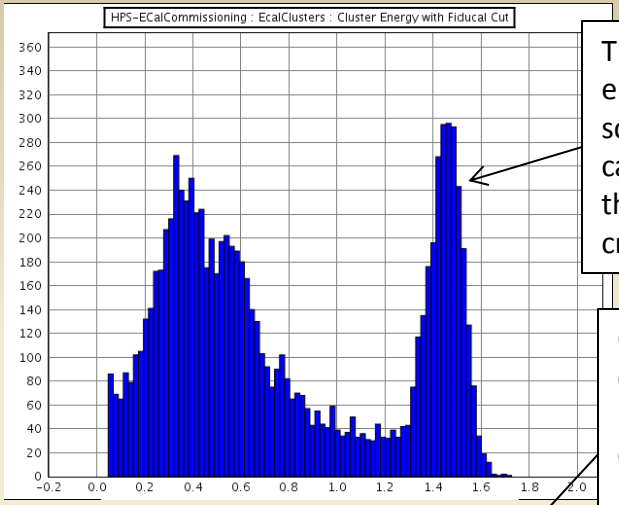
- Deeply Virtual Compton Scattering (DVCS) provides access to Generalized Parton Distributions (GPDs)
- Demonstration of scaling critical to full JLab 12 GeV GPD program

Runs concurrently with a high Q^2 Form Factor G_M^p experiment

- Enabling experiment for High Impact Super BigBite program

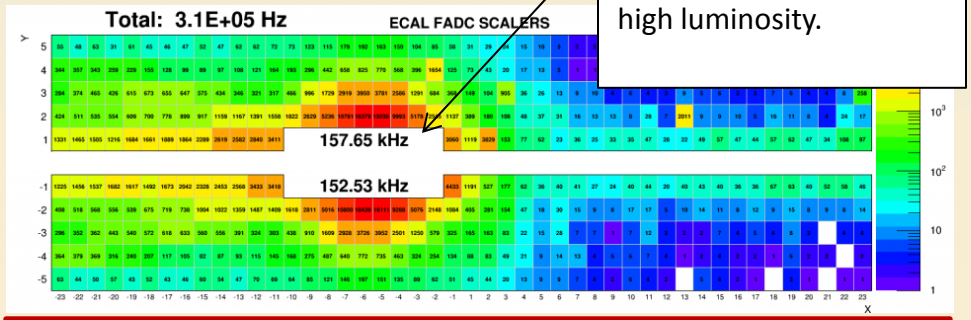
7 graduate thesis students on site taking data

Heavy Photon Search (HPS)



The peak from elastic electron-platinum scattering is used to calibrate the response of the 420 lead-tungstate crystals.

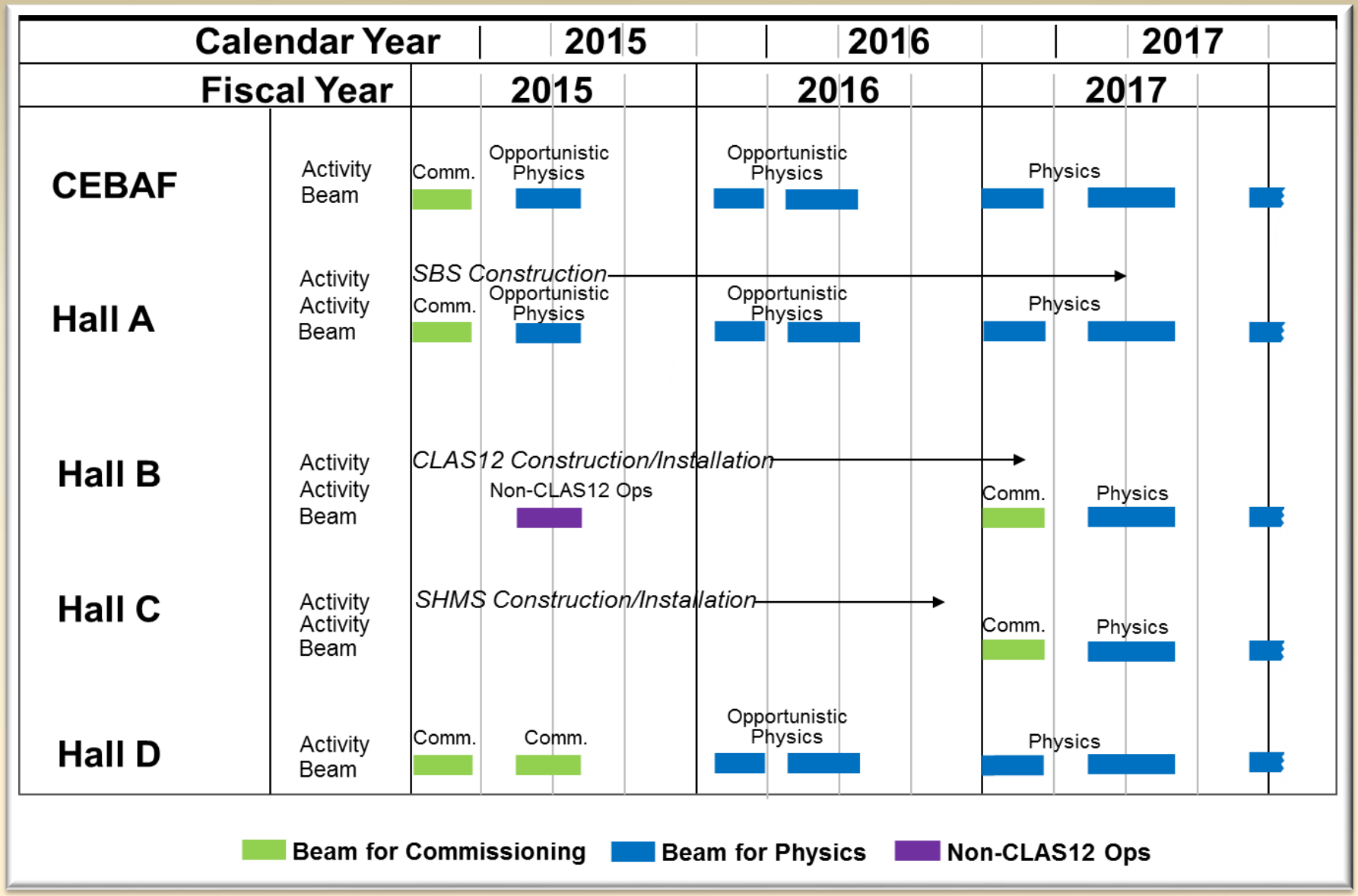
Count rate in individual crystals located near the beam (below) shows the experiment can achieve its objective to run at high luminosity.



HPS: High impact experiment to search for the proposed carrier of Dark Matter interacting with Light Matter.
Test Run in December 2014 successfully completed.
Commissioned beam line and the e.m. calorimeter

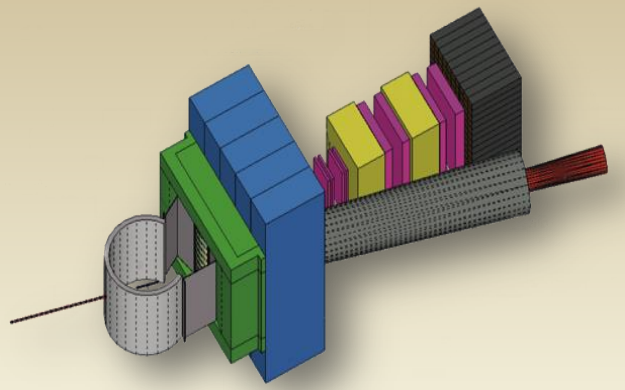
Funded by DOE HEP and NP.

Jefferson Lab 3 Year Schedule

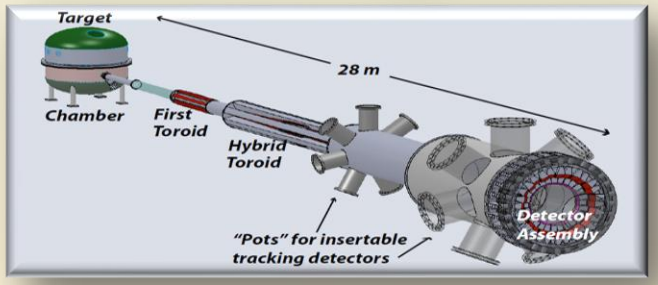


Additional Experimental Equipment

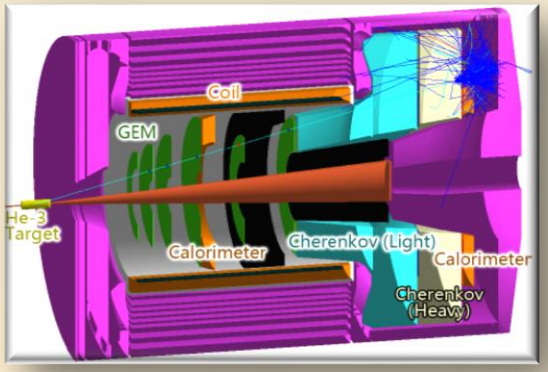
- Super BigBite Spectrometer (FY13-17 construction)
  - High Q^2 form factors
  - SIDIS



- MOLLER experiment (MIE – FY17-19?)
  - Standard Model Test
  - Successful Science Review



- SoLID
  - SIDIS and PVDIS
  - Chinese collaboration
  - CLEO Solenoid



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 (GlueX and heavy baryon and meson spectroscopy)		1		3		4
The transverse structure of the hadrons (Elastic and transition Form Factors)	5	3	2	1		11
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	3	6			11
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	9	7			21
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	6	3	7		1	17
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1		1	1	6
TOTAL	21	20	22	5	2	70

A Decade of Experiments

12 GeV Approved Experiments by PAC Days

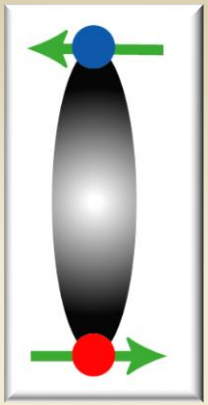
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GlueX and heavy baryon and meson spectroscopy)		119		540		695
The transverse structure of the hadrons (Elastic and transition Form Factors)	145.5	85	102	25		357.5
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	65	230	165			460
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	409	872	212			1493
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	180	175	201		14	570
Low-energy tests of the Standard Model and Fundamental Symmetries	547	205		79	60	891
TOTAL	1346.5	1686	680	644	74	4430.5

Quantum Numbers of Hybrid Mesons

Quarks ⊕ **Excited Gluon Field** → **Hybrid Meson**

$S = 0$
$L = 0$
$J^{PC} = 0^{-+}$

like π, K

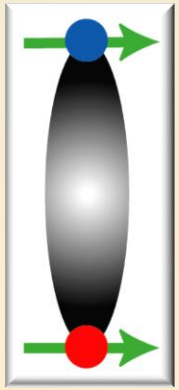


$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$

$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$

$S = 1$
$L = 0$
$J^{PC} = 1^{--}$

like γ, ρ



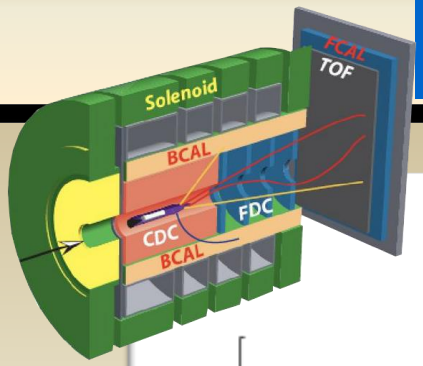
$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$

Exotic

$J^{PC} = \begin{cases} 0^{-+} & 1^{-+} & 2^{-+} \\ 0^{+-} & 1^{+-} & 2^{+-} \end{cases}$

Gluonic excitation (and parallel quark spins) lead to exotic J^{PC}

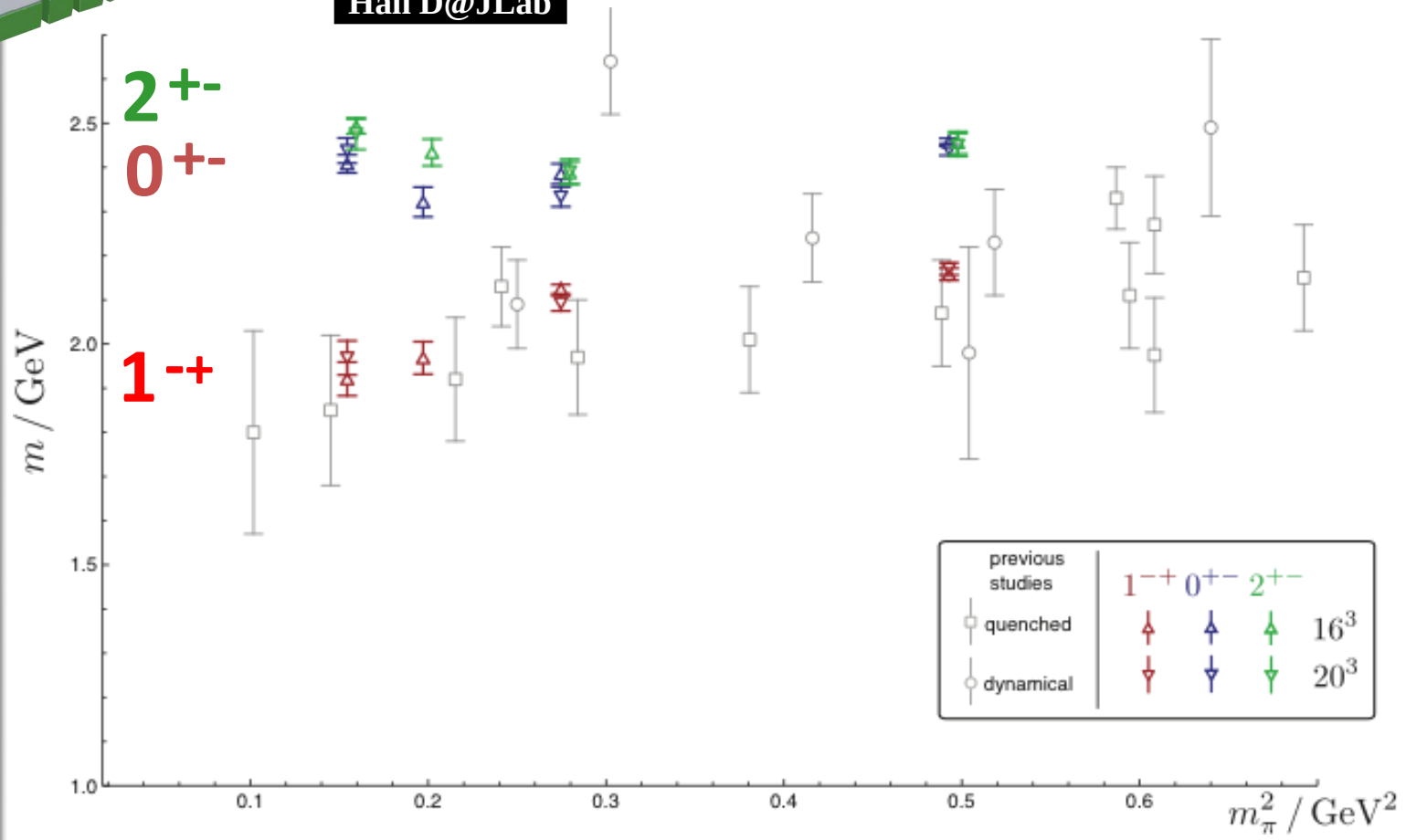
Isovector Meson Spectrum



GlueX Experiment
Hall D@JLab

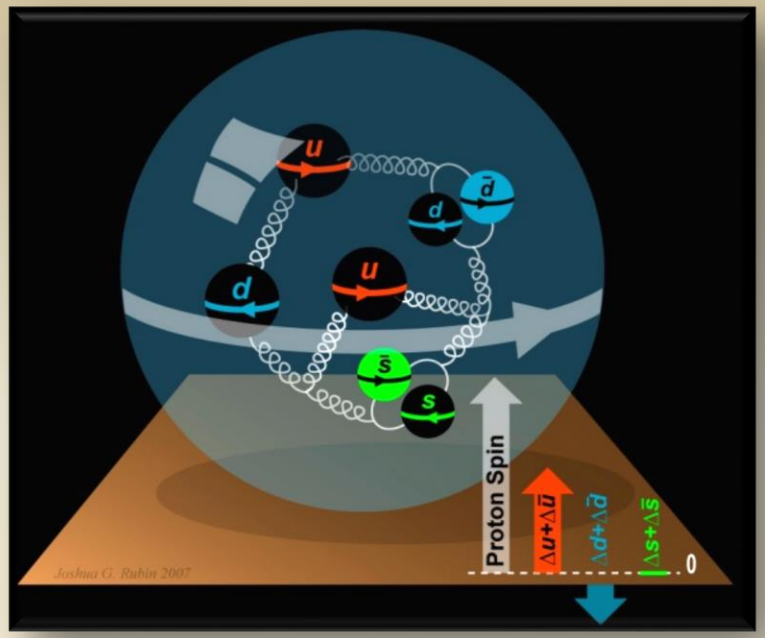
States with Exotic Quantum Numbers

2^{+-}
0^{+-}
1^{-+}



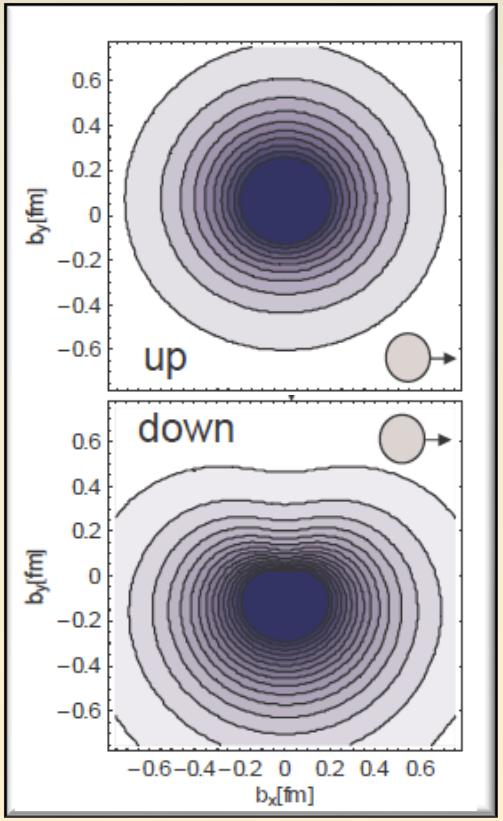
Dudek et al.

The Incomplete Nucleon: Spin Puzzle



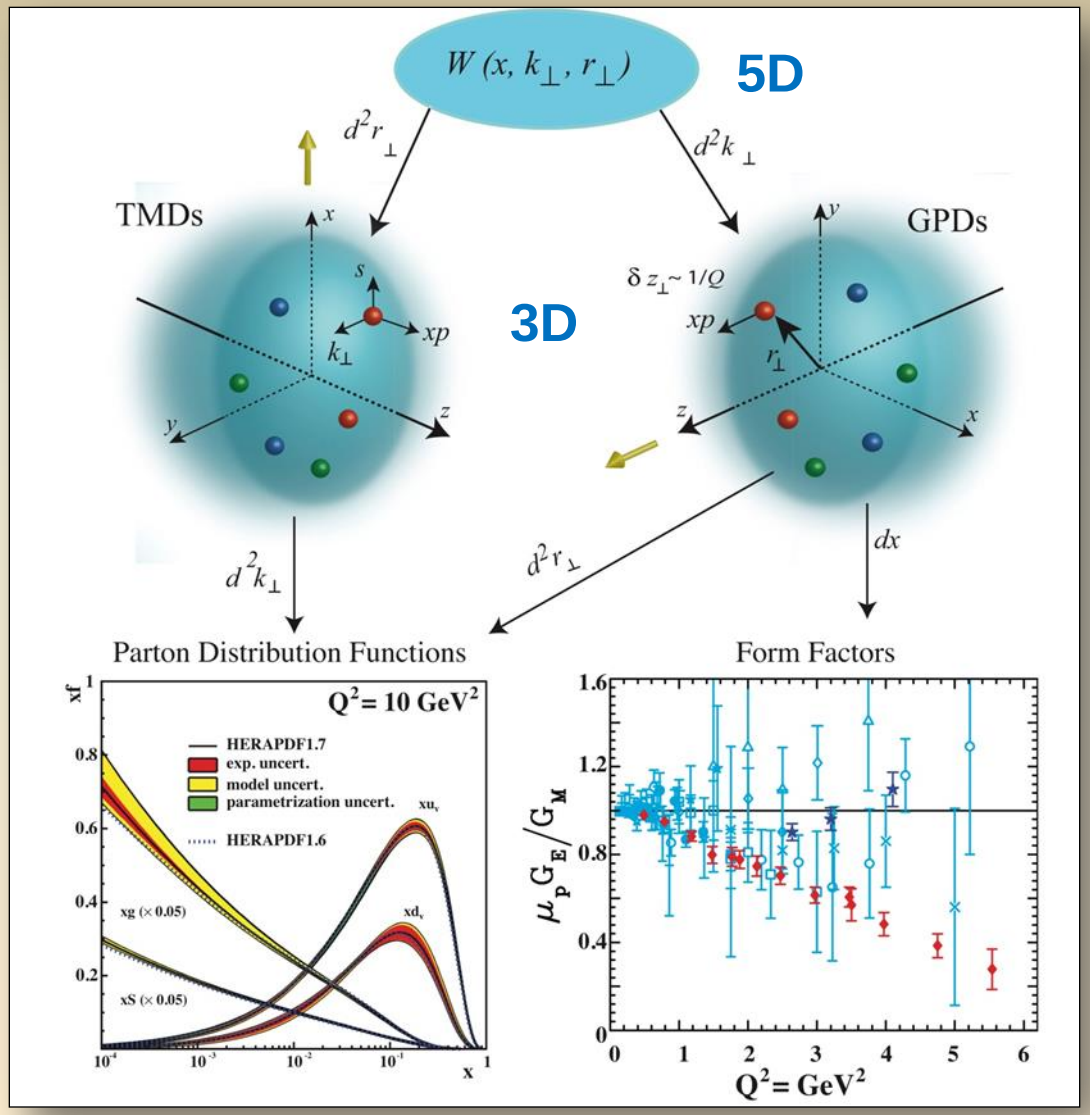
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

[X. Ji, 1997]



- **DIS → $\Delta\Sigma \cong 0.25$**
- **RHIC + DIS → $\Delta G \sim 0.2$**
- **→ L_q**

New Paradigm for Nucleon Structure



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

Major new capability with JLab12

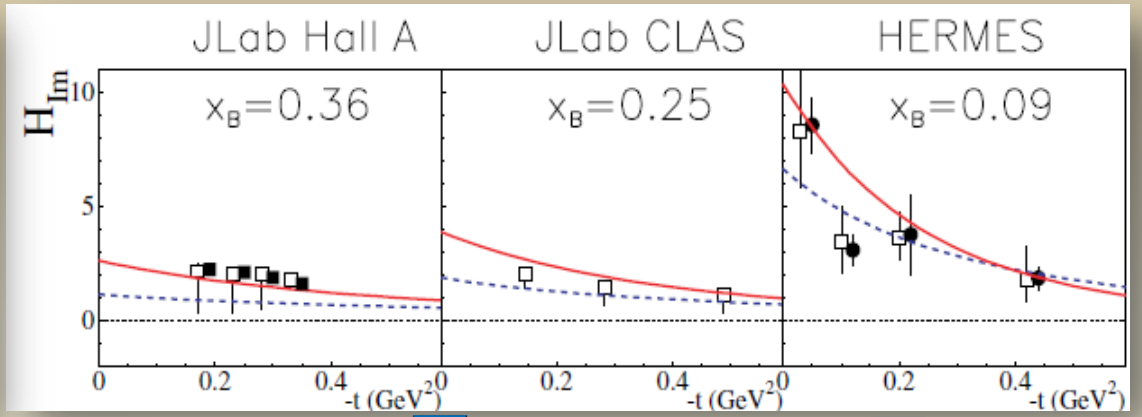
The First Crude Images

the GPD H in *Im* DVCS

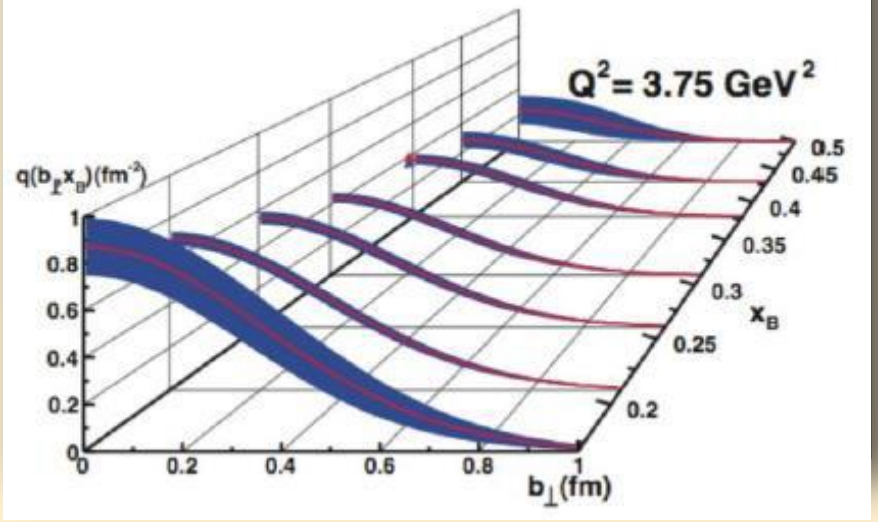
●○■□ Different local fits

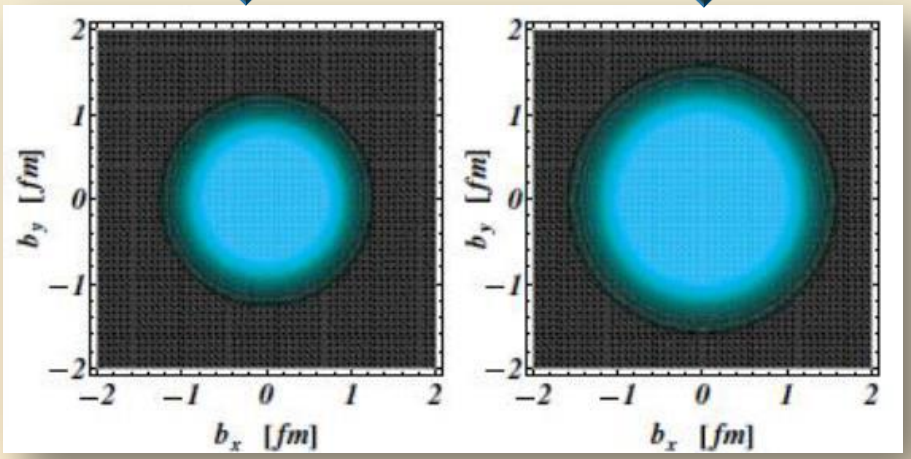
VGG model

KM10 global fit on the world data ranging from H1,ZEUS to HERMES, JLab



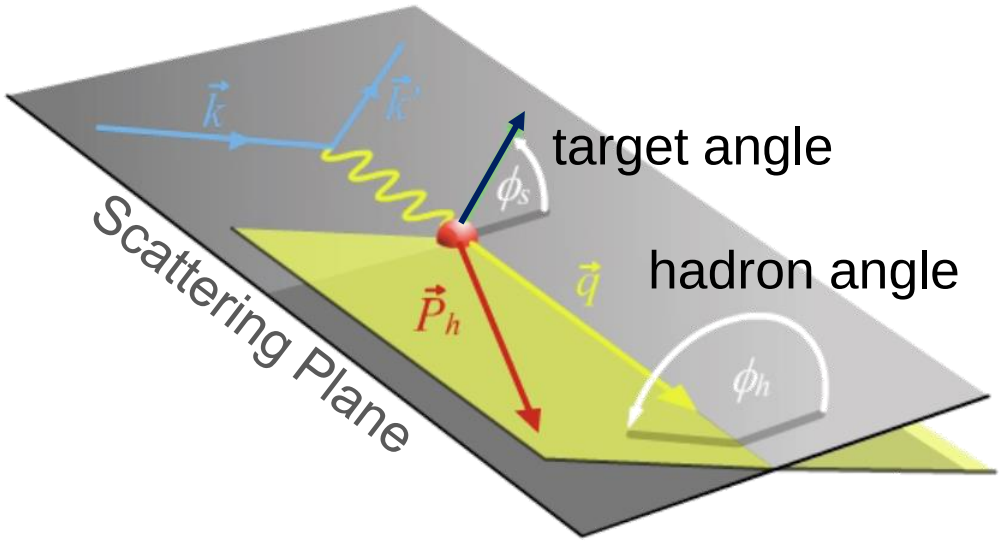
Projection for JLab 12 GeV



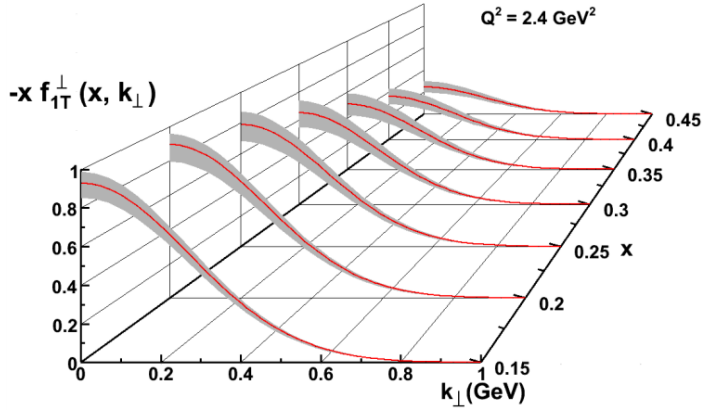


SIDIS Electroproduction of Pions

- Separate Sivers and Collins effects



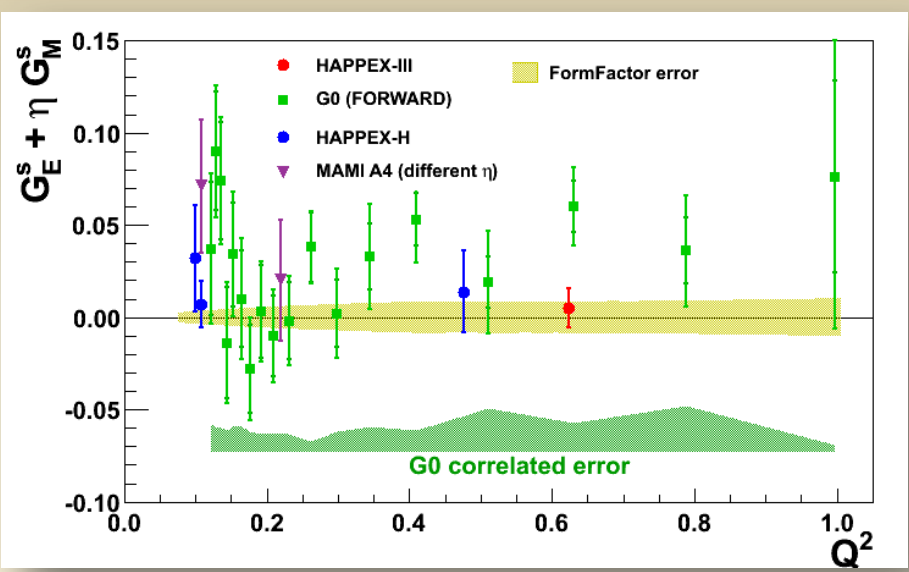
- Previous data from HERMES,COMPASS
- New landscape of TMD distributions
- Access to orbital angular momentum



- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$

Parity Violation at JLab

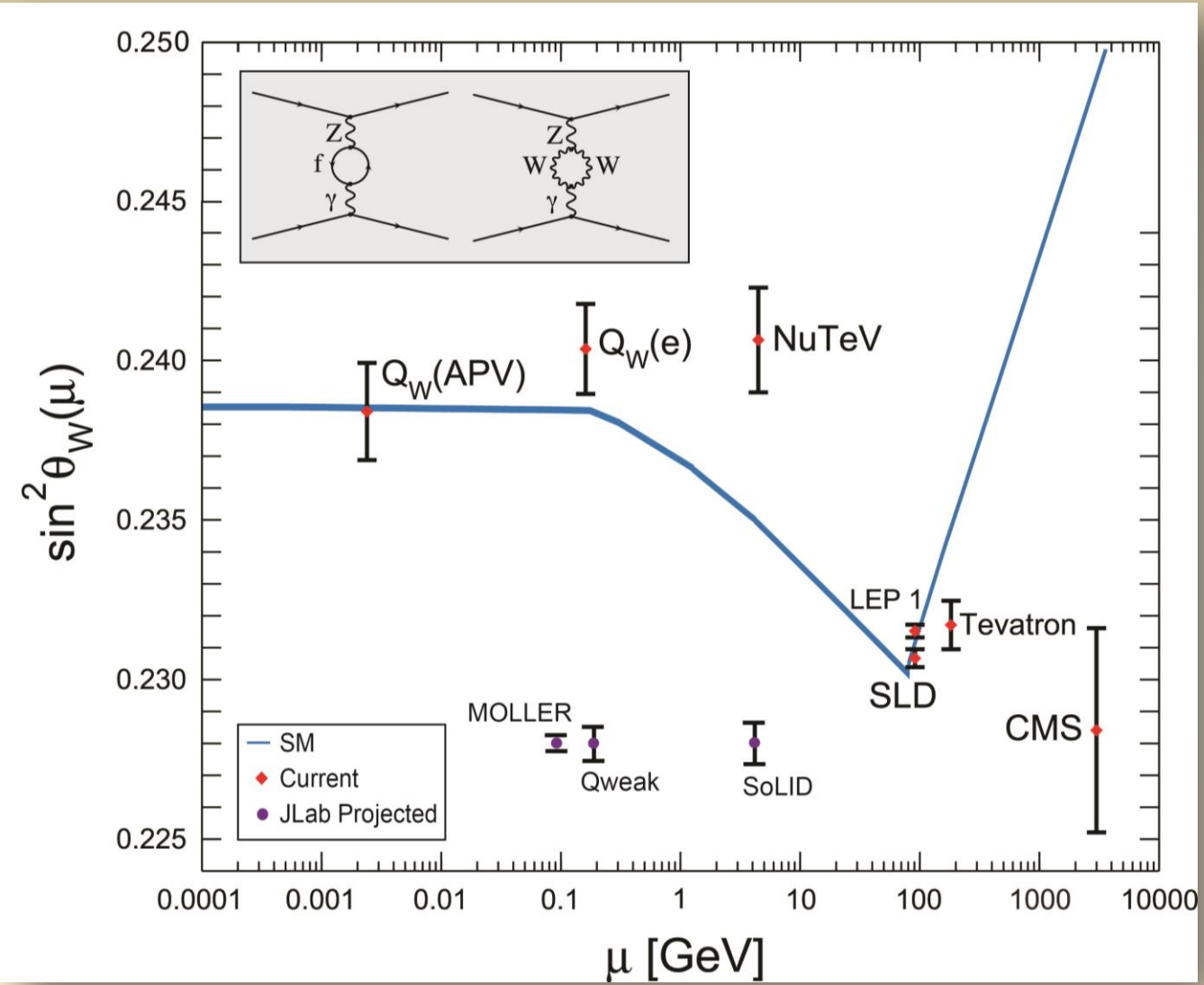
- Nucleon Strangeness Form Factors (complete)
  - HAPPEX (Hall A)
  - G0 (Hall C)



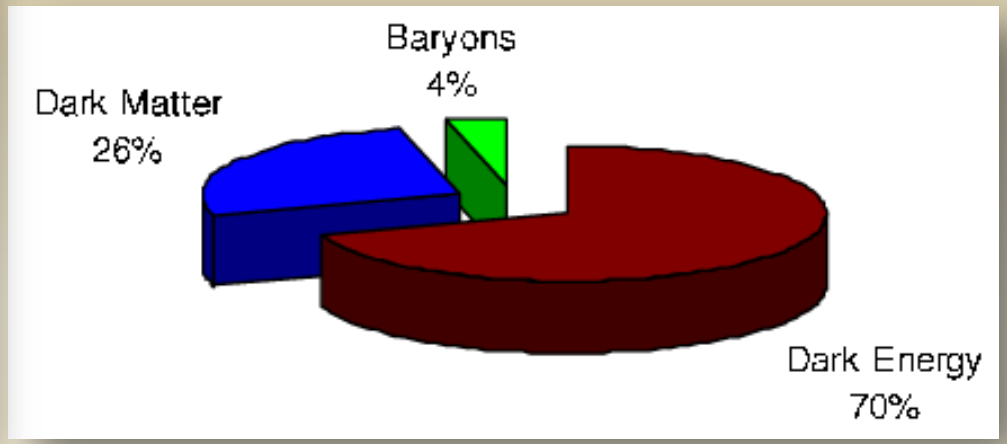
- Neutron Skin
  - PREX
  - CREX

- Precision Tests of Standard Model
  - Qweak (Under analysis)
  - MOLLER
  - SoLID

Projected Results

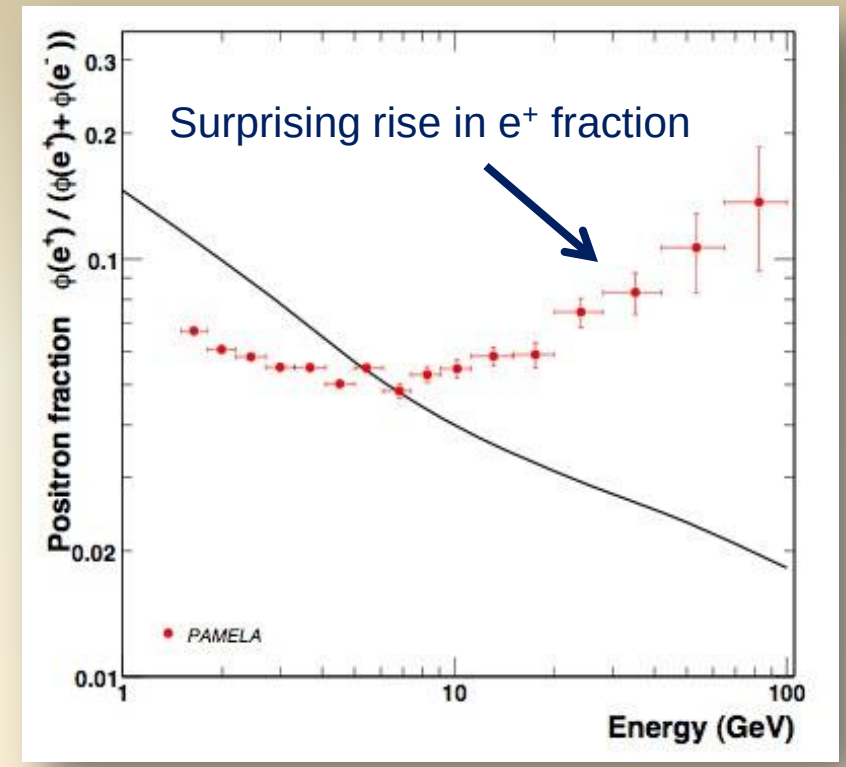


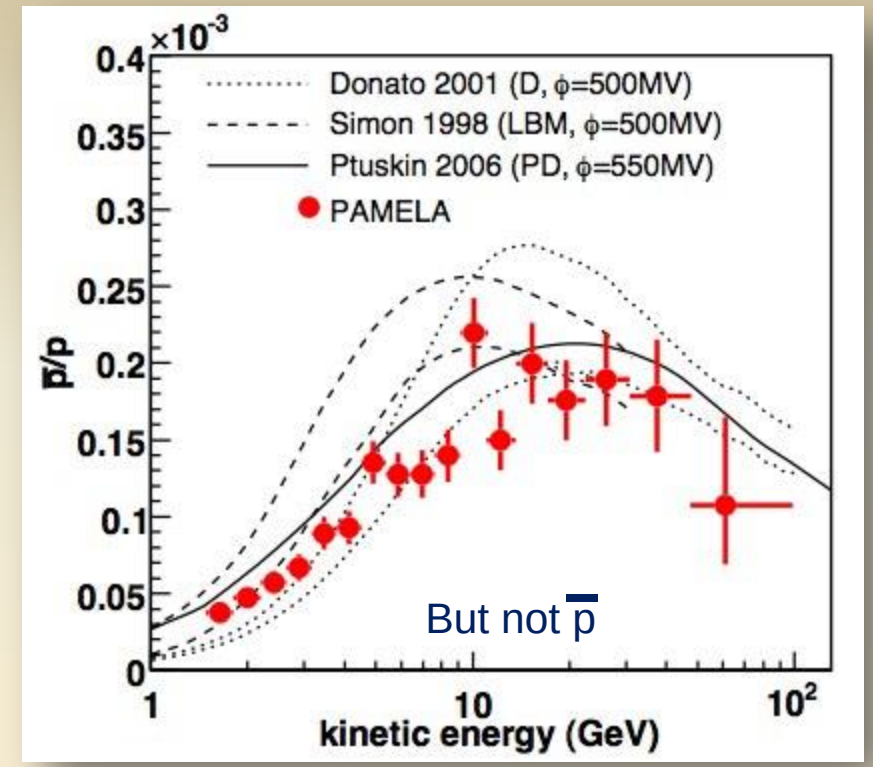
Cosmology and Dark Matter



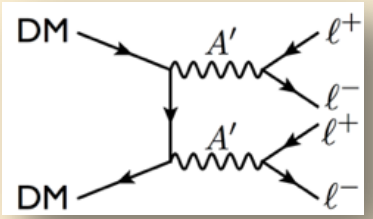
- *Dark sector is new physics, beyond the standard model*
- *Many direct searches for dark matter interacting with sensitive detectors (hints, no established signal yet…)*
- *Controversial evidence for excess astrophysical positrons…*

PAMELA Data on Cosmic Radiation

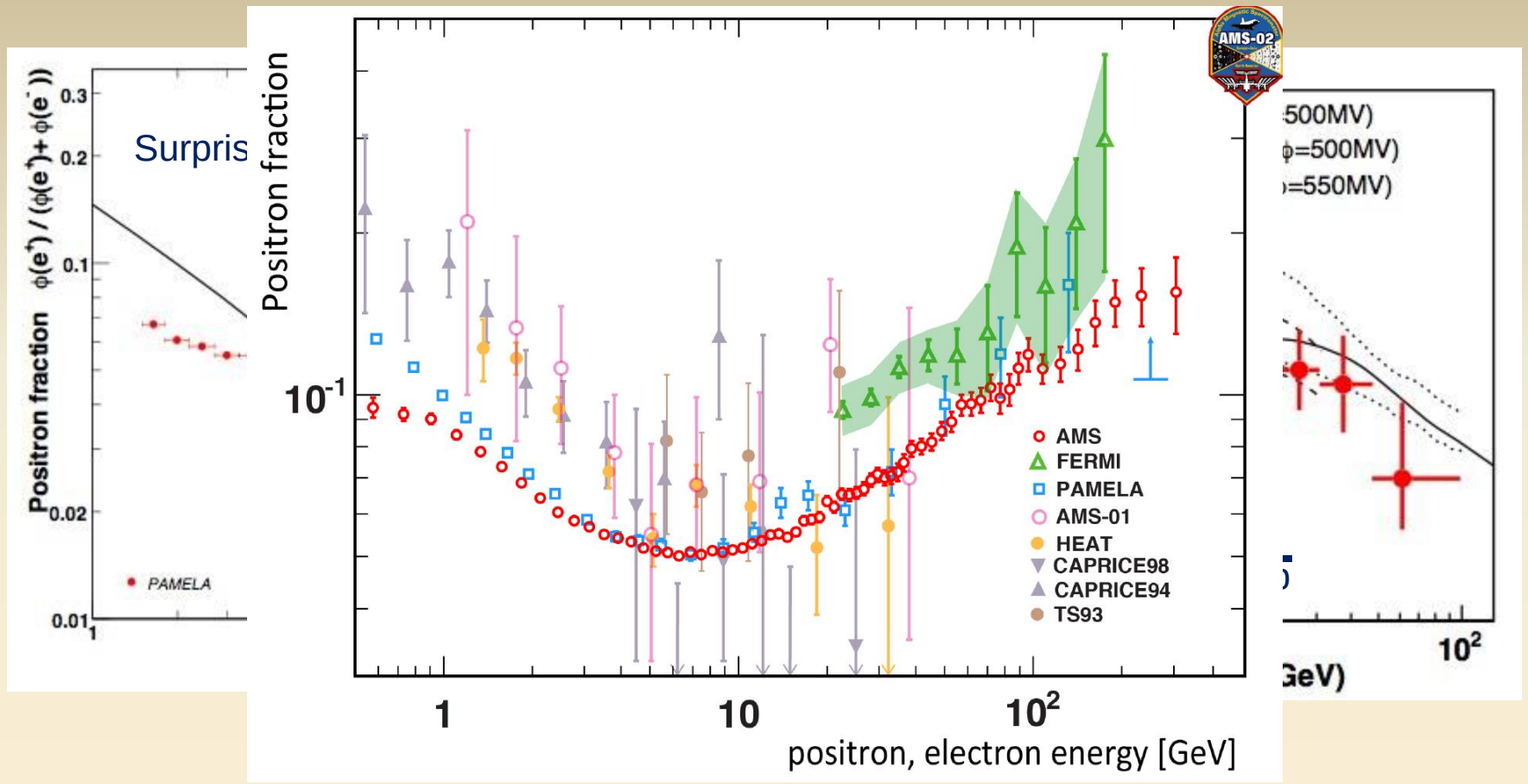




- Could indicate low mass A' ($M_{A'} < 1$ GeV)
- Or local astrophysical origin??



PAMELA Data on Cosmic Radiation



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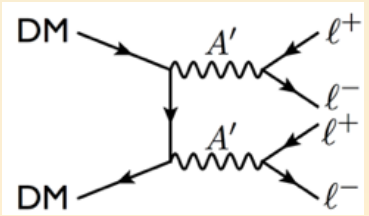
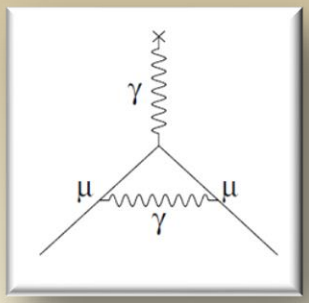
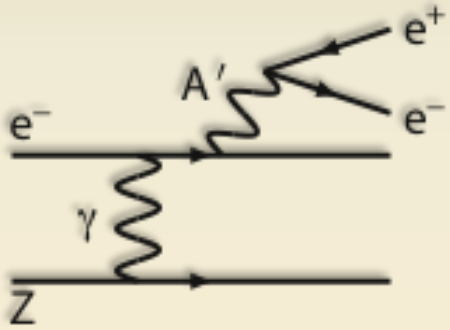


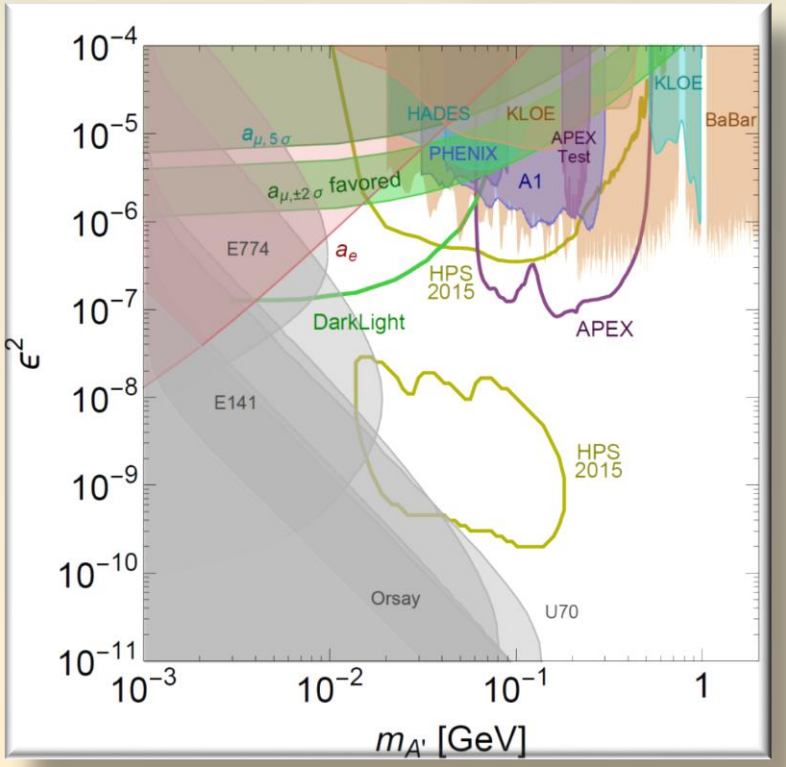
New Opportunity: Search for A' at Jefferson Lab

- BNL "g-2" expt: Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)
- No evidence for SUSY at LHC (yet)
- Another solution: A', a massive neutral vector boson





  - Also useful for dark matter models

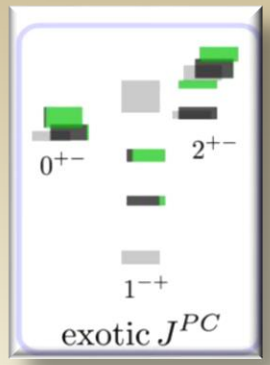


- 3 Jefferson Lab proposals:

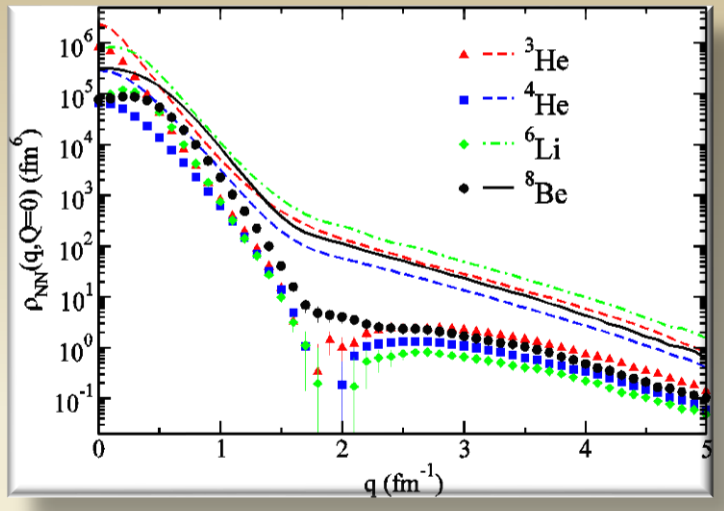
- APEX test run (Hall A) – published PRL 107, 191804 (2011)
- HPS (Hall B) – installed for FY15 run
- DarkLight (FEL) – NSF-MRI funds

Jefferson Lab Nuclear Theory

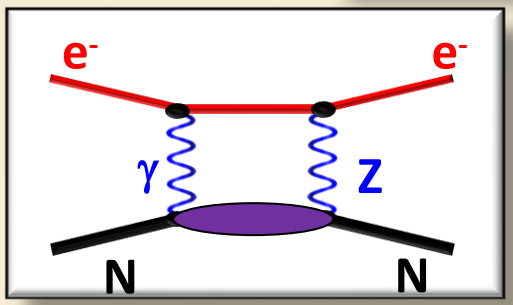
- Lattice QCD



- Phenomenology
  → Physics Analysis Center



- Nuclear Structure
- Electroweak



- **Strong support for experimental program**
- **An intellectual center for a global theory effort**

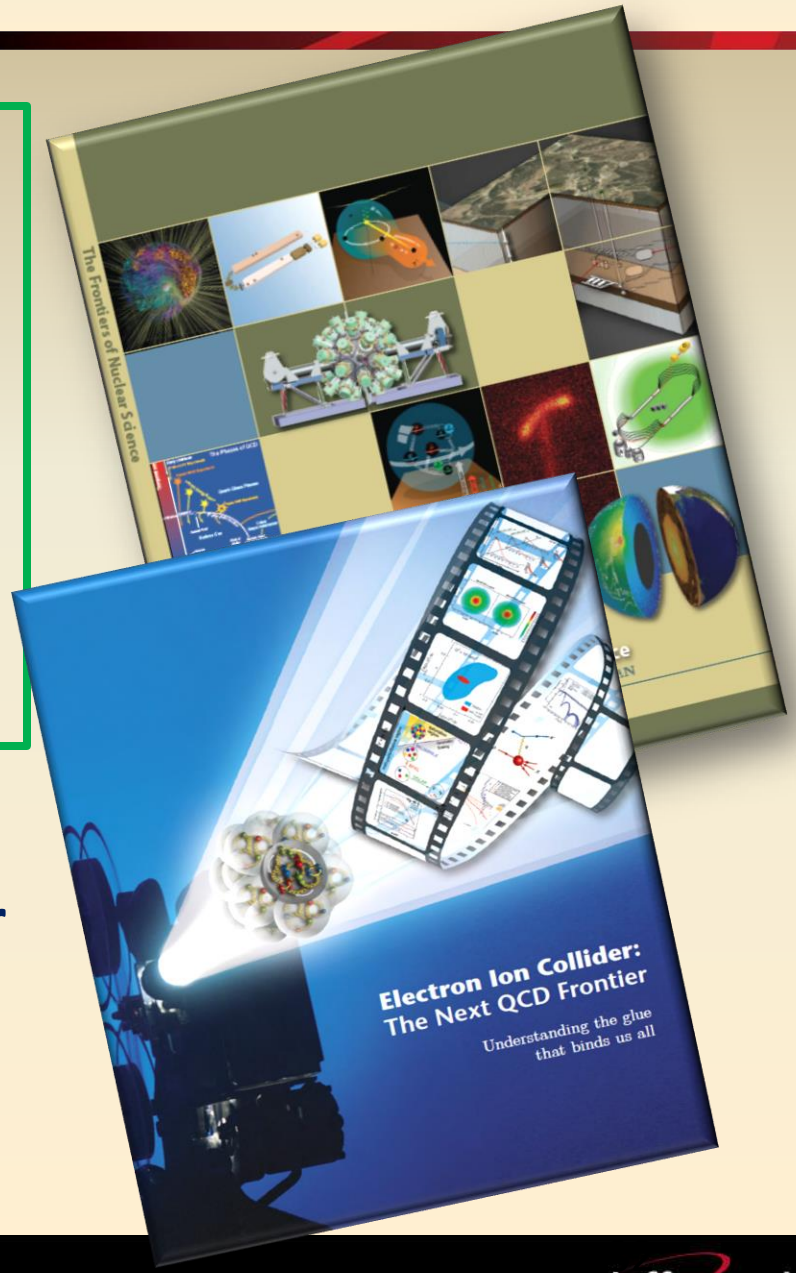
12 GeV JLab – The Potential

- Opportunity to discover and study new exotic mesons to elucidate the mechanism of confinement.
- Open a new landscape of nucleon tomography, with potential to identify the missing angular momentum.
- Establish the quantitative foundation for the short-distance behavior in nuclei, underpinning the development of precision nuclear structure studies.
- Provide stringent new tests of the standard model and extensions, complementing the information obtained at LHC.
- Establish a firm basis for higher energy studies with a future **Electron Ion Collider**

Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

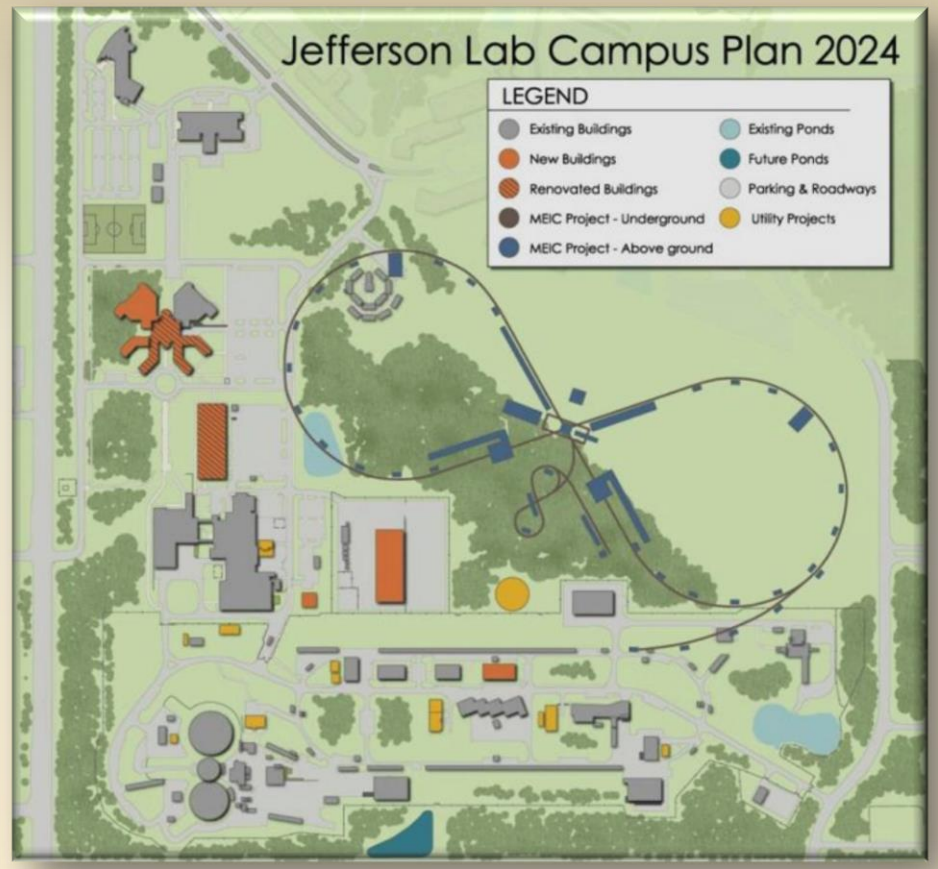


EIC Community White Paper
arXiv:1212.1701

Medium Energy EIC@JLab

JLab Figure 8 Concept

- Initial configuration (MEIC):
  - 3-12 GeV on 20-100 GeV ep/eA collider
  - Fully-polarized, longitudinal and transverse
  - Luminosity:
    up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Upgradable to higher energies
  250 GeV protons + 20 GeV electrons
- Construction compatible with normal CEBAF operation
- Cost estimate in progress



→ **Fulfills White Paper Requirements**

A Laboratory for Nuclear Science

- The Jefferson Lab electron accelerator is a unique world-leading facility for nuclear physics research

- These are exciting times at Jefferson Lab
  - Upgraded accelerator operational, commissioning underway
  - Ready to begin physics program
  - Construction of Halls B,C continue through FY17

- 12 GeV program ensures at least a decade of excellent opportunities for discovery
  - New vistas in QCD
  - Growing program Beyond the Standard Model
  - Budget for 30 weeks operation presented
  - Additional equipment: MOLLER, SoLID

- EIC moving forward:
  - JLab design well developed – time scale following 12 GeV program is "natural"