Highlights and Opportunities in Nuclear/Hadron Physics

Jian-ping Chen (陈剑平), Jefferson Lab, Virginia, USA

iHIC2018, Tsinghua University, August 8-10, 2018

- Introduction: Medium Energy Nuclear/Hadron Physics, Electron Scattering, JLab
- Nucleon Structure study at JLab:
  - highlights: spin, 3-d (TMDs/GPDs)
  - 12GeV/SoLID program
- Nuclear physics program at JLab
  - nucleon properties in nuclear medium
    EMC, Coulomb Sum Rule, Short-Range Correlations
  - N-N interaction, few-body, relativistic effects,
    spin/polarization in few-body, tensor force, hypernuclear physics
  - PVES to study neutron skin : PREX/CREX
- Intermediate Energy Nuclear Physics at HIAF:
  - polarization, 3-body force
- Future: EIC in US (JLEIC, e-RHIC), EIC in China (EicC)

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Introduction

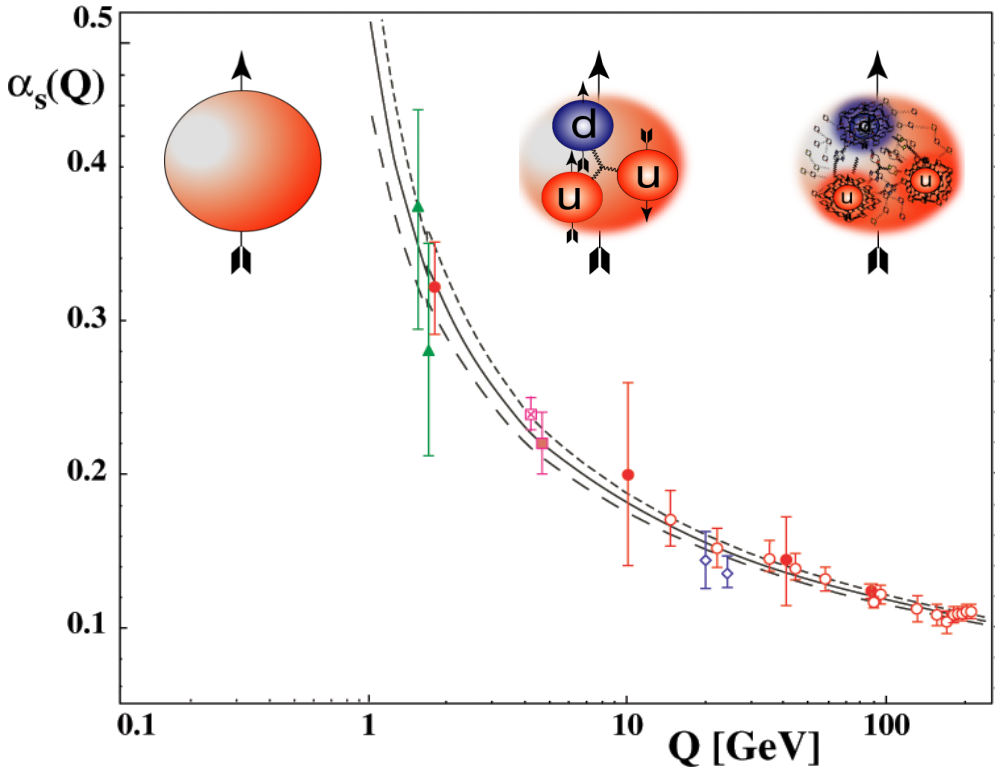
Nucleon/Nuclear Structure and Strong Interaction

Electron Scattering/JLab/12 GeV/SoLID

Last Frontier in SM: QCD in Nonperturbative Region

- ***Non-perturbative regime QCD***
  Color Confinement
- ***One of the top 10 challenges for physics!***
- ***Nucleon: stable lab to study QCD***
  Nucleon 3-d structure
- ***How hadron and nuclei emerge from QCD/q-g degrees of freedom***
- ***N-N interactions***
  - ***Residual strong interaction***
  - ***3-body force, …***
- ***QCD phase and QCD under extreme conditions (QGP)***

running coupling "constant"

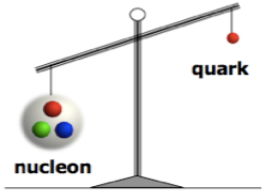


Nucleon Structure: A Universe Inside

- Nucleon: proton =(uud) , neutron=(udd) ***+ sea quarks + gluons (QCD vacuum)***
- Nucleon: ***99% of the visible mass in universe***

➢ **Proton mass "puzzle":**

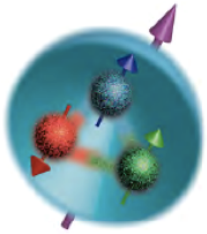
Quarks carry $\sim 1\%$? of proton's mass



m_q ~ 10 MeV

m_N ~ 1000 MeV

How does glue dynamics generate the energy for nucleon mass?



➢ **Proton spin "puzzle":**

Quarks carry $\sim 30\%$ of proton's spin

How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon: 3D in momentum or (2D space +1 in momentum)**

Color Confinement — Asymptotic freedom

Q (GeV)

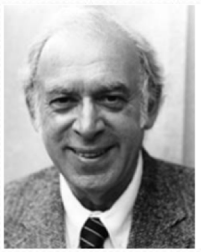
200 MeV (1 fm) — 2 GeV (1/10) — Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?
Can we scan the nucleon to reveal its 3D structure?

Electron Scattering and Nucleon Structure

- **Lepton vs hadron probe:**
  Lepton: clean probe to study nucleon structure
  only electro-weak interaction, well understood
  Probe scale(s) and size of object structure
- **Elastic Electron Scattering: Form Factors**
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions
- Resonance Excitations
  → internal structure, rich spectroscopy (new particle search)
  constituent quark models
- **Deep Inelastic Scattering (DIS)**
  → 70s: established quark-parton picture (Nobel Prize)
  parton distribution functions (PDFs)
  polarized PDFs : Spin Structure
- **Semi-inclusive DIS, Deep Exclusive Processes**
  → 3D nucleon structure (TMDs, GPDs)

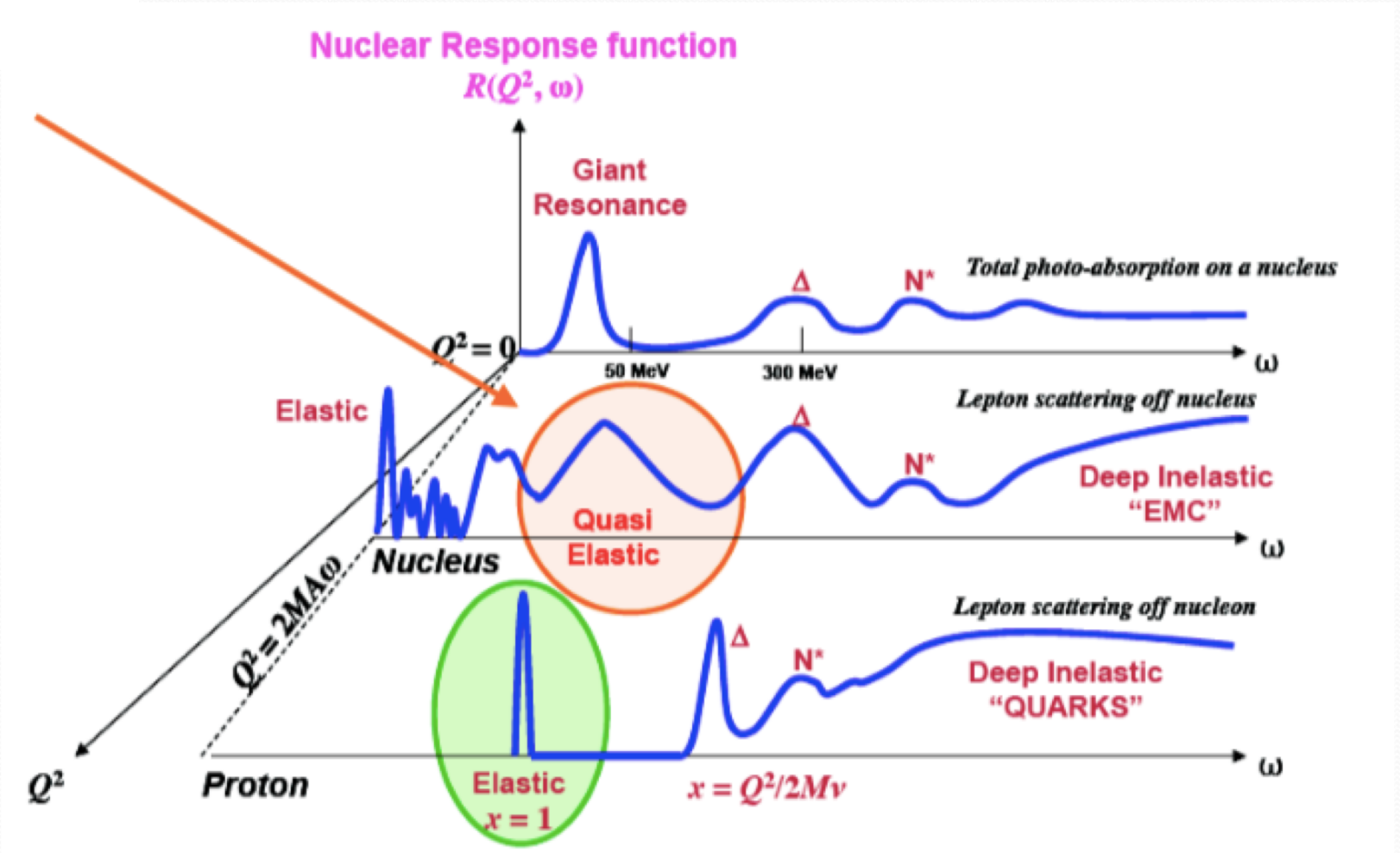
Robert Hofstadter,
Nobel Prize 1961



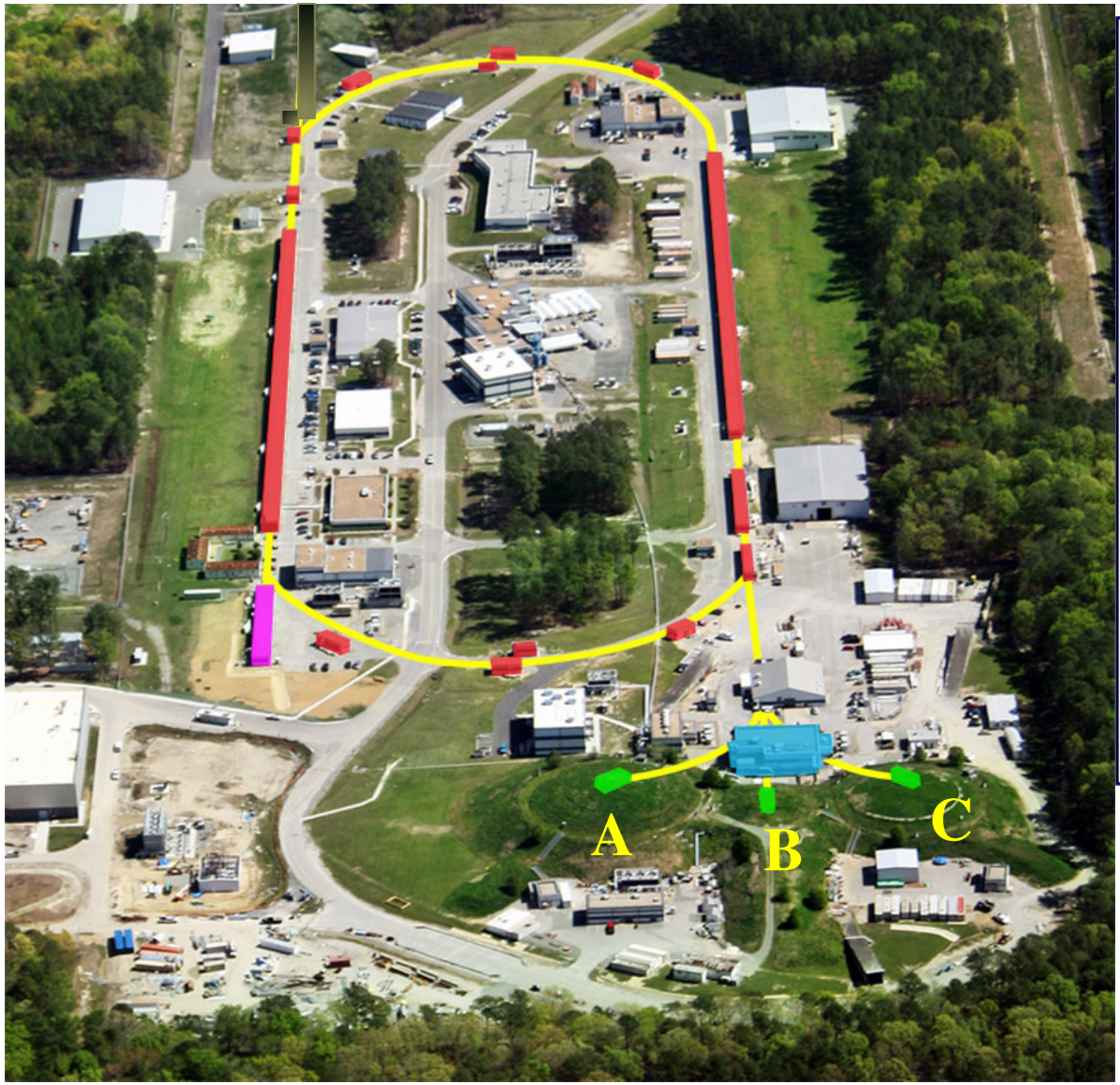
J.T. Friedman ***R. Taylor*** ***H.W. Kendall***

Nobel Prize 1990

Nuclear Responses for e-p, e-A and γ–A



Jefferson Lab Newport News, Virginia, USA

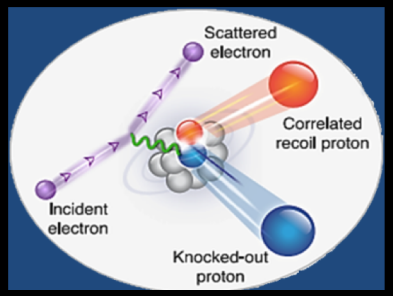


CEBAF

- **High-intensity** electron accelerator based on **CW SRF** technology (1984-1994)
- **I_{max} = 200 μA**
- **Pol_{max} = 90%**
- **E_{max} = 6 GeV: 1995-2012**
- **Energy Upgrading to 12 GeV (2012-2017)**
- **12 GeV data taking started**

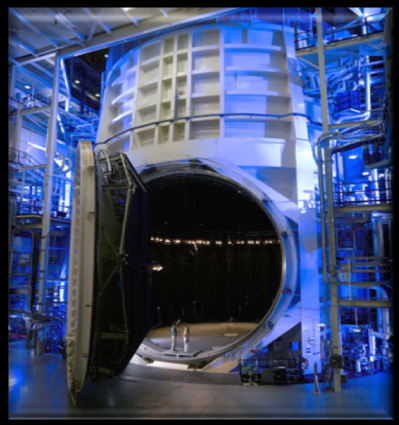
- **~ 1400** Active Users
- Produces **~1/3** of US PhDs in Nuclear Physics

JLab: A Laboratory for Nuclear Science

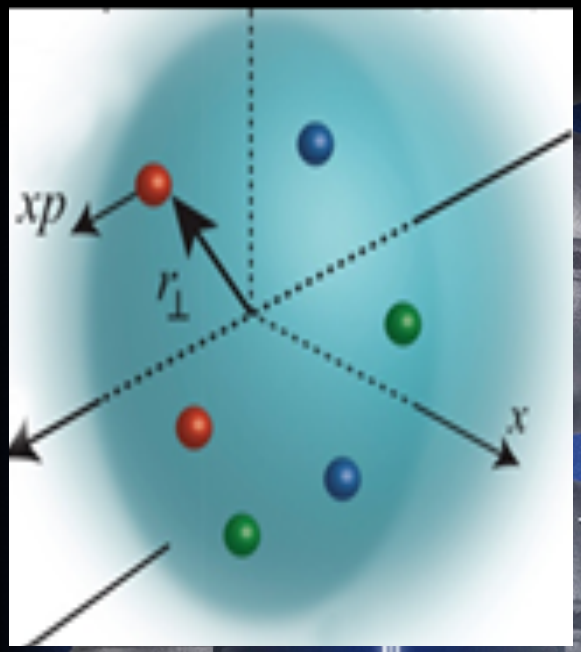


Nuclear Structure

Medical Imaging

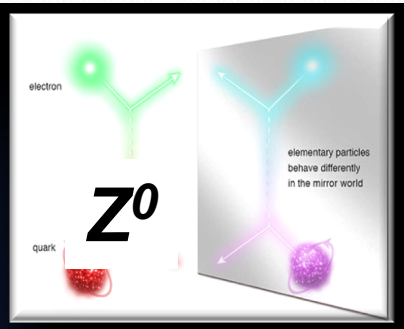


Cryogenics

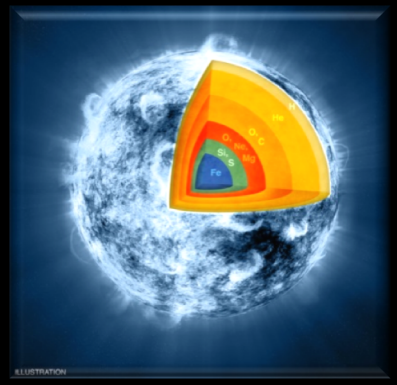


Structure of Hadrons

Accelerator S&T



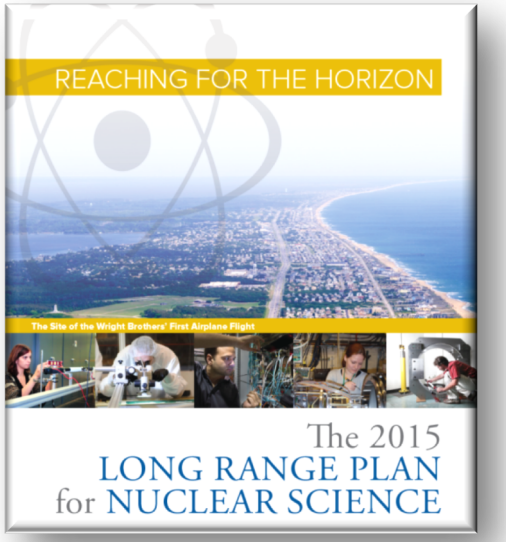
Fundamental Forces & Symmetries



Nuclear Astrophysics

Theory &

Jefferson Lab is an Integral Part of the NSAC Long Range Plan



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.* ***→ Operate 12 GeV CEBAF***

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

→Jefferson Lab EIC (JLEIC) development

RECOMMENDATION IV

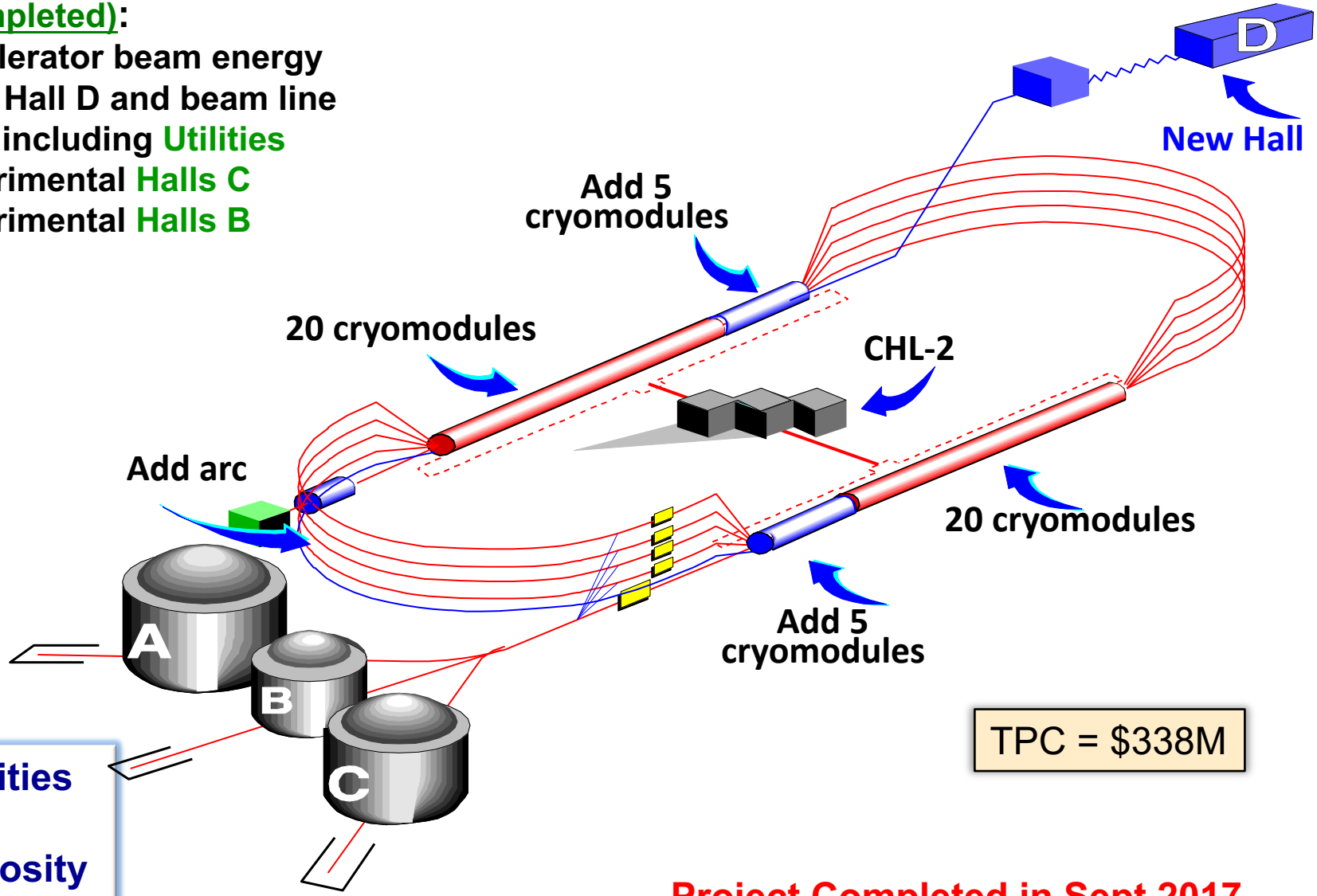
We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

→ SoLID,MOLLER

12 GeV Upgrade Project

Project Scope (completed):

- Doubling the accelerator beam energy
- New experimental Hall D and beam line
- Civil construction including Utilities
- Upgrades to Experimental Halls C
- Upgrades to Experimental Halls B



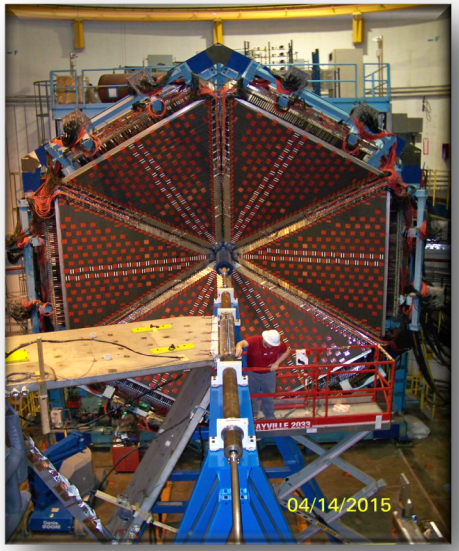
TPC = $338M

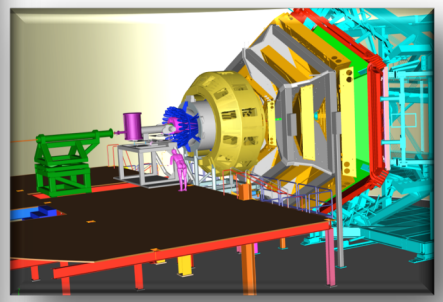
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

Project Completed in Sept 2017

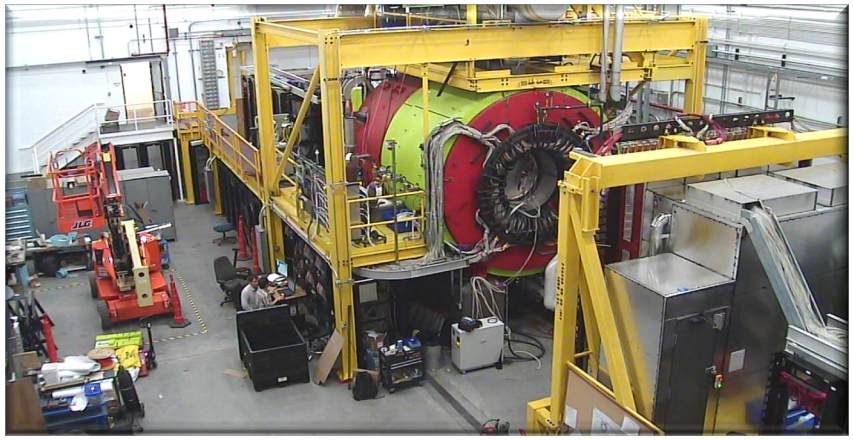
12 GeV Scientific Capabilities

Hall B – understanding nucleon structure via generalized parton distributions

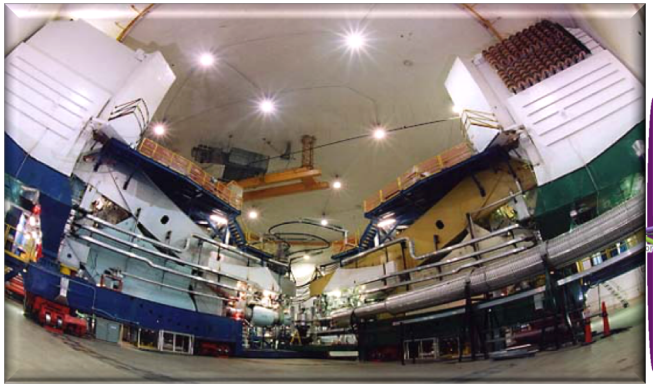


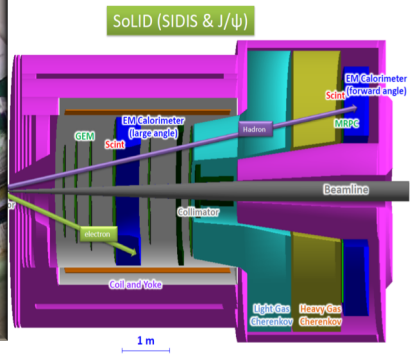


Hall D – exploring origin of confinement by studying exotic mesons



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





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

12 GeV Science Era has Begun!

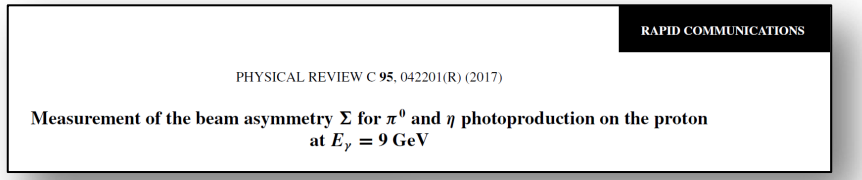
- ***Quark confinement:*** *Hall D (GlueX) started physics operations*
  - *Engineering Run Complete: Basis for > dozen papers at APS DNP Fall 2016 Meeting*
  - *First 12 GeV era publication: 24 April, 2017!*
  - *Physics run since spring 2017*

- ***Nucleon Structure(I):*** *Hall A in physics operations*
  - *GMp experiment completed in Fall 2016*
  - *First phase of DVCS experiment completed*
  - *Marathon: d/u@high-x completing data taking*

- ***Nuclear Structure:*** *First experiment completed*
  - *Argon Spectral Function experiment completed in Hall A in Spring 2017, results published*
  - *Short-Range-Correlations run starting*

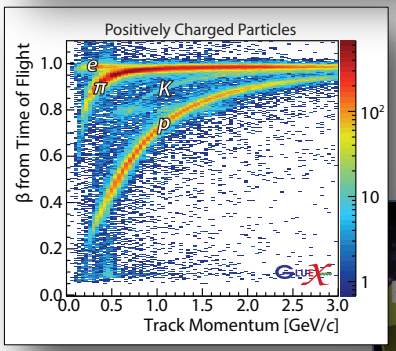
- ***Fundamental Symmetries:*** *Hall B Heavy Photon Search*
  - *First results of 2015 engineering run presented*

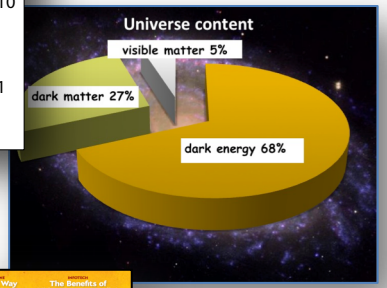
- ***Nucleon Structure (II):*** *Hall B Proton Radius (PRad)*
  - *Experiment run and completed Summer 2016*


RAPID COMMUNICATIONS

PHYSICAL REVIEW C **95**, 042201(R) (2017)

Measurement of the beam asymmetry Σ for π^0 and η photoproduction on the proton at $E_\gamma = 9$ GeV





All 4 halls running to exploit the Upgrade for Physics

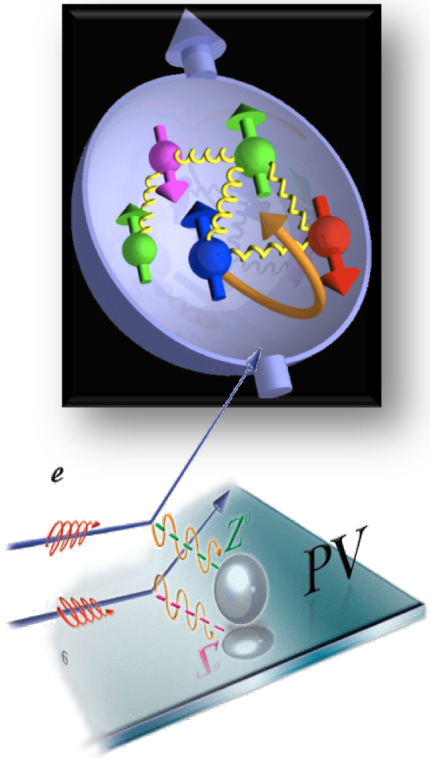
Jefferson Lab @ 12 GeV Science Questions

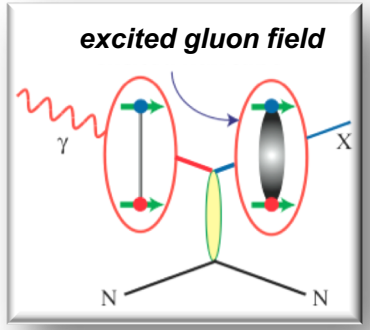
- How does the valence quark behave in the nucleon?
  Where is the missing spin in the nucleon?
  Role of orbital angular momentum?

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

- Can we discover evidence for physics beyond the standard model of particle physics?

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





Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**

  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})

  Take advantage of latest development in detectors , data acquisitions and simulations

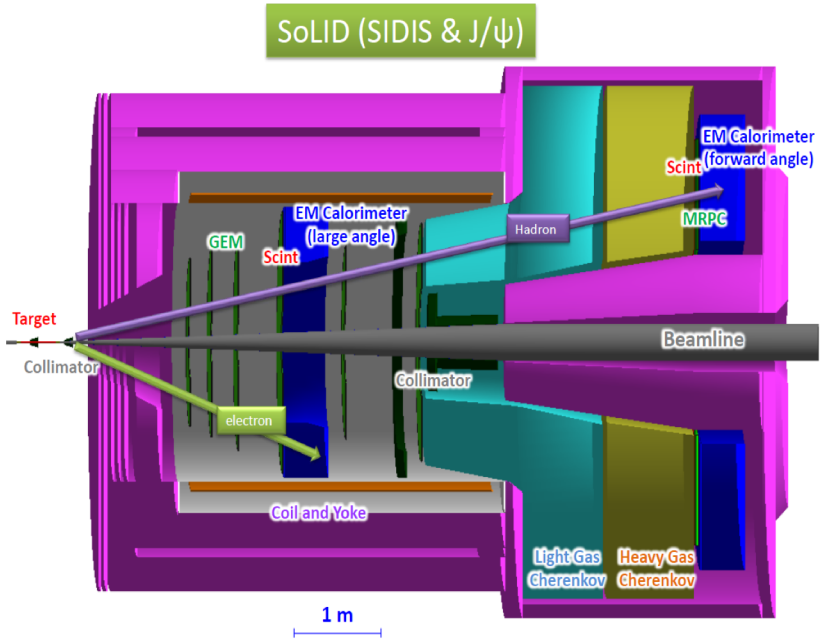
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ

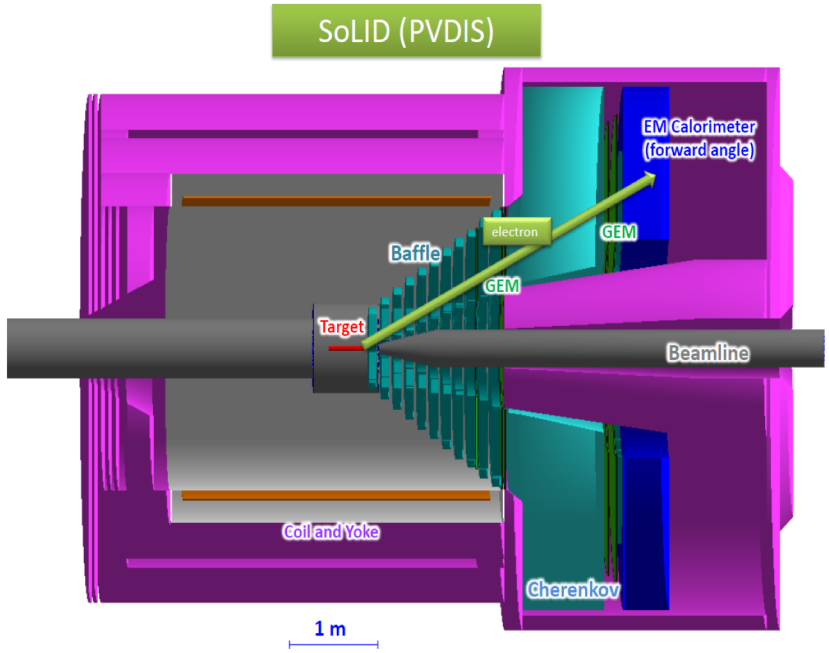
- **5 highly rated experiments approved**

  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 4 run group experiments)

- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)

  International collaborations (significant Chinese contributions)





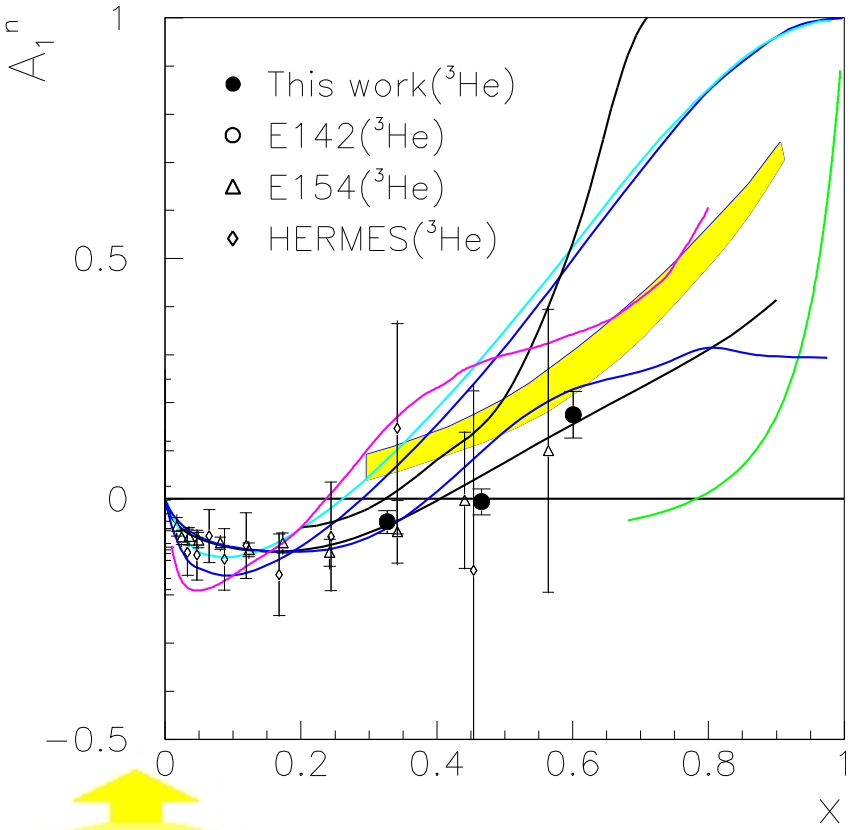
Nucleon Structure Study at JLab/SoLID

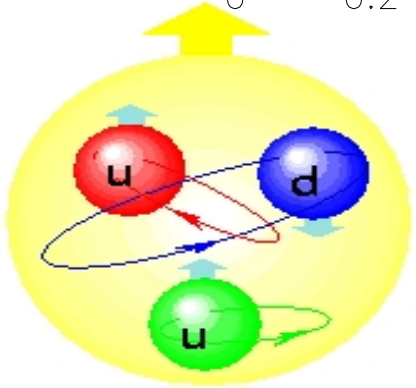
Spin, TMDs, proton mass, Parity Violation

JLab E99117: *Precision Measurement of A_1^n at High-x*

PRL 92, 012004 (2004) , PRC 70, 065207 (2004)

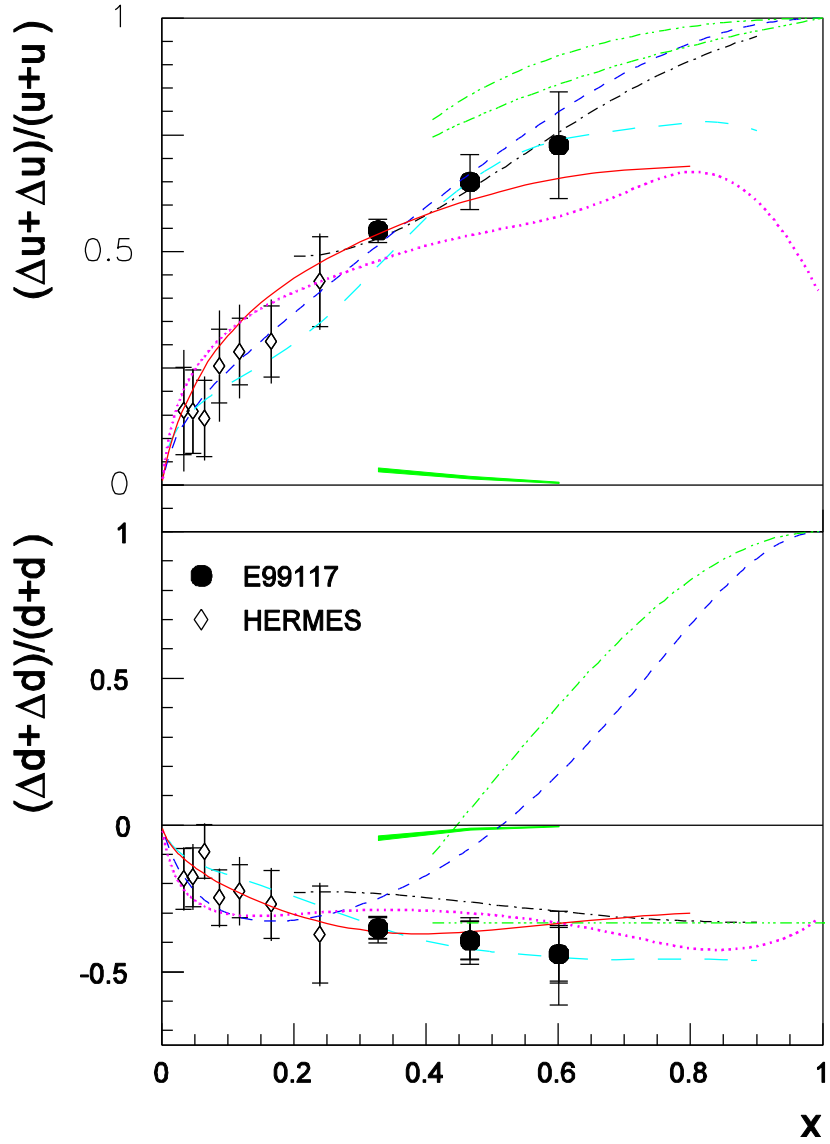
Physics News Update, Science Now
Science News, Physics Today Update





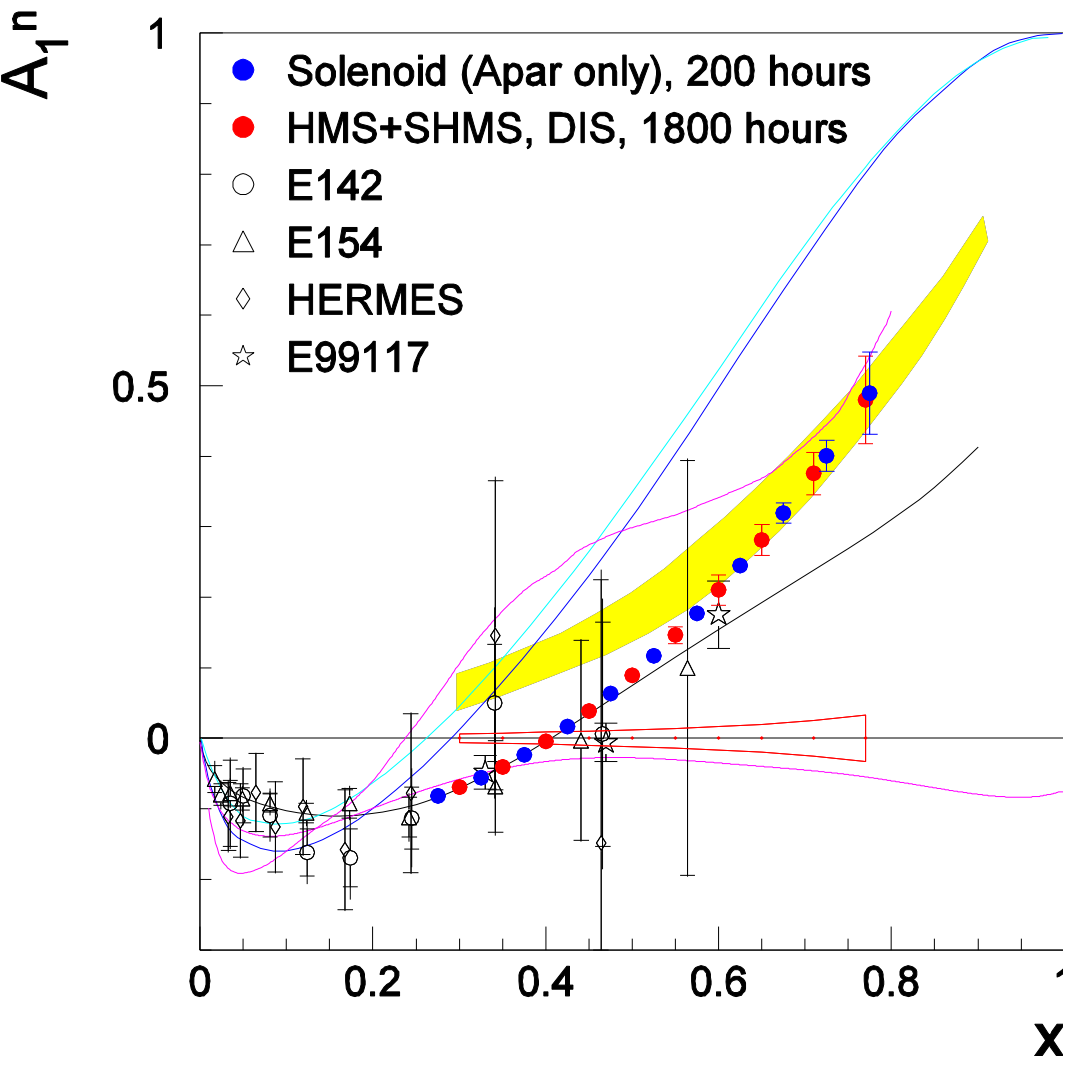
Indirect evidence for quark orbital angular momentum

Perturbative vs non-pertubative

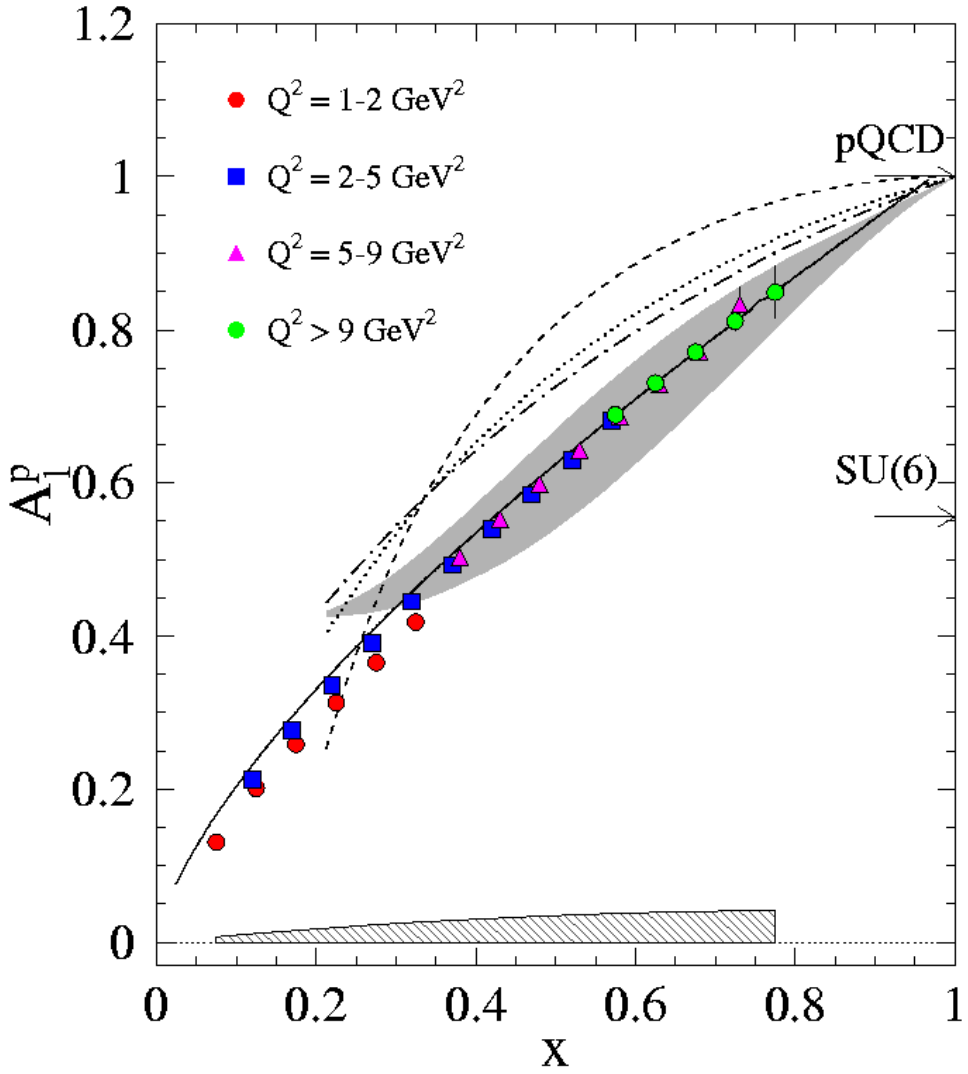


Polarized DIS: JLab12 Projections

A_1^n at 11 GeV



A_1^p at 11 GeV



Bjorken Sum: Γ_1 of *p-n*

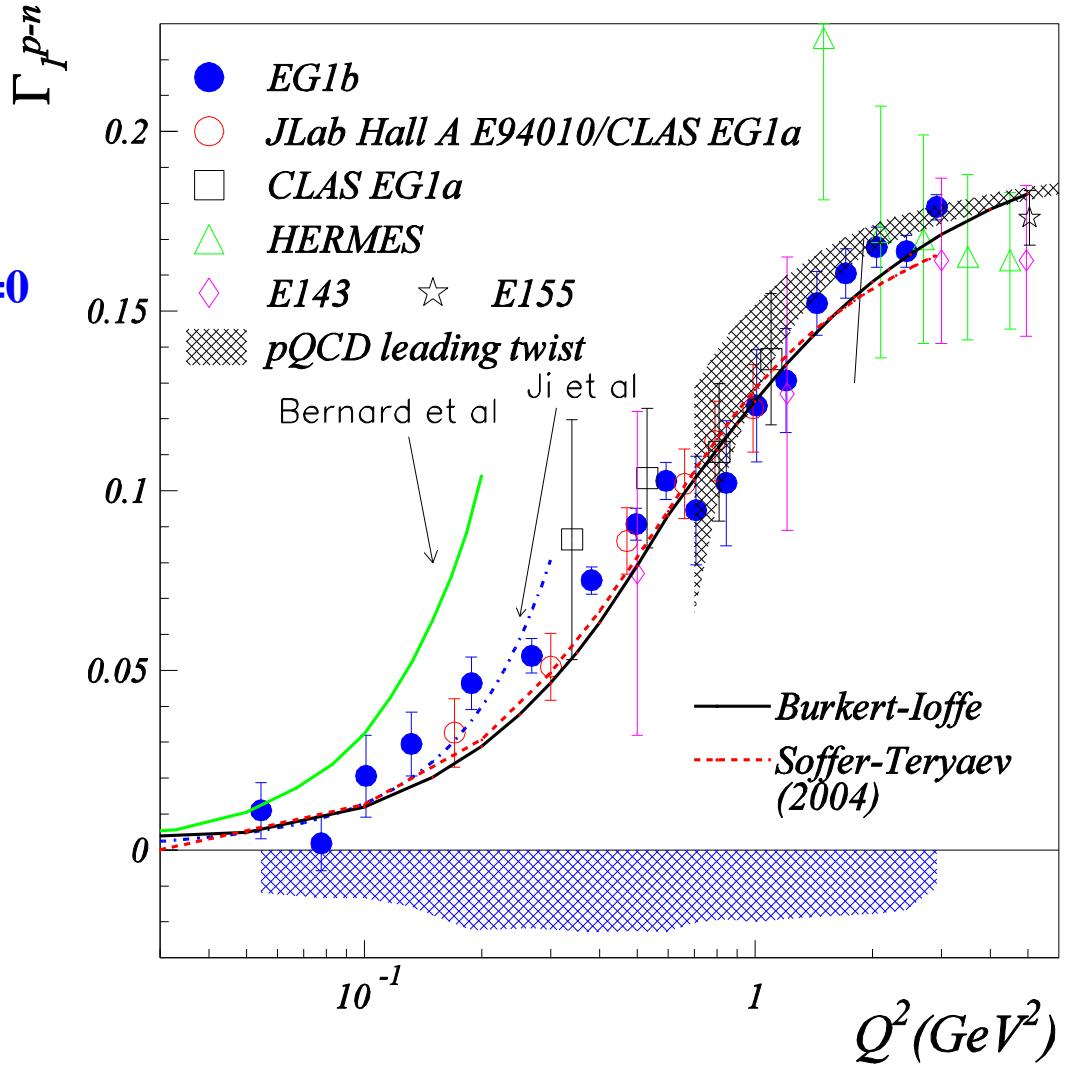
First moment of spin structure function

Spin sum rules relate it to
axial charge at large Q^2 limit
anomalous magnetic moment at Q^2=0

Spin sum rules from low Q2 to high Q2 bridge pQCD to non-pQCD

Spin sum rules and spin polarizabilities provide extensive data to test theoretical calculations from ChPT, LQCD and pQCD

EG1b, PRD 78, 032001 (2008)
E94-010 + EG1a: PRL 93 (2004) 212001



Effective Coupling Extracted from Bjorken Sum

A. Deur, V. Burkert, J. P. Chen and W. Korsch

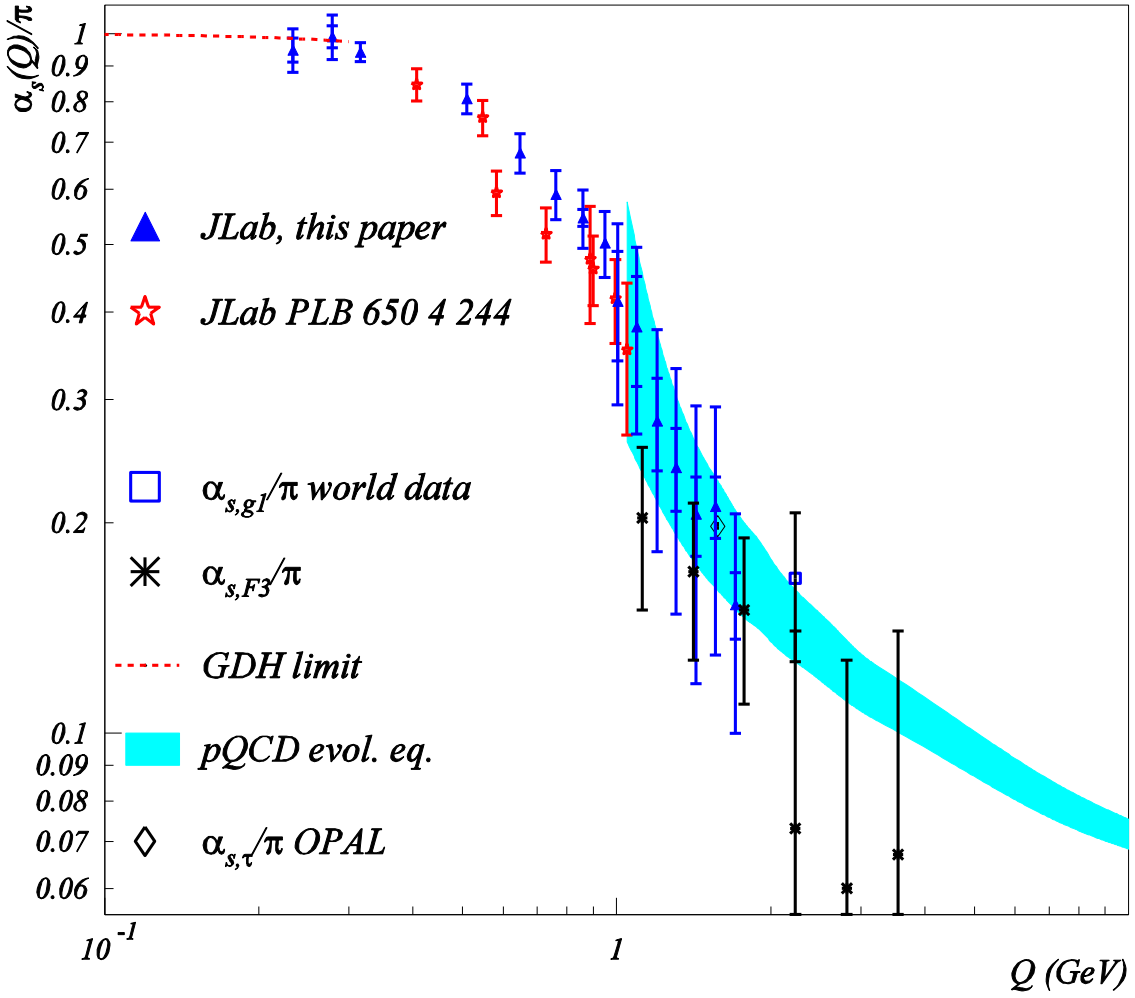
PLB 650, 244 (2007) and PLB 665, 349 (2008)

α_s/π

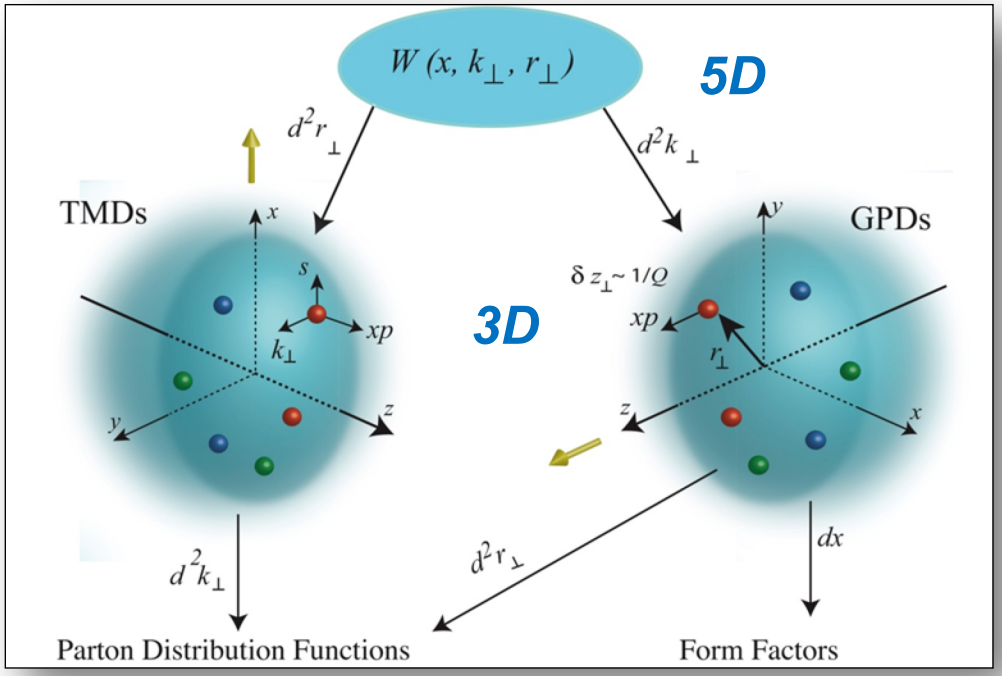
An attempt to study non-perturbative QCD

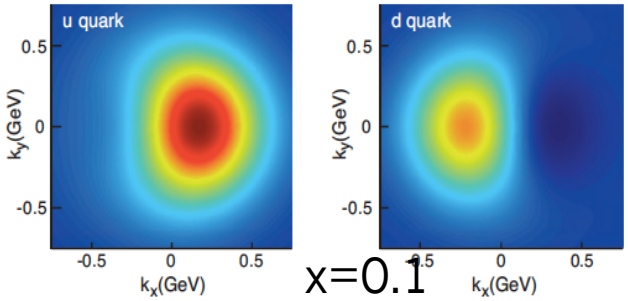
LQCD and S-D approach shows similar behavior

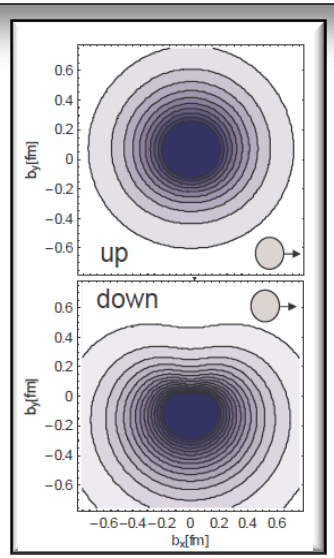
Infrared Comformal behavior, base for ADS/CFT Holographic QCD



Imaging the Nucleon - Femtography



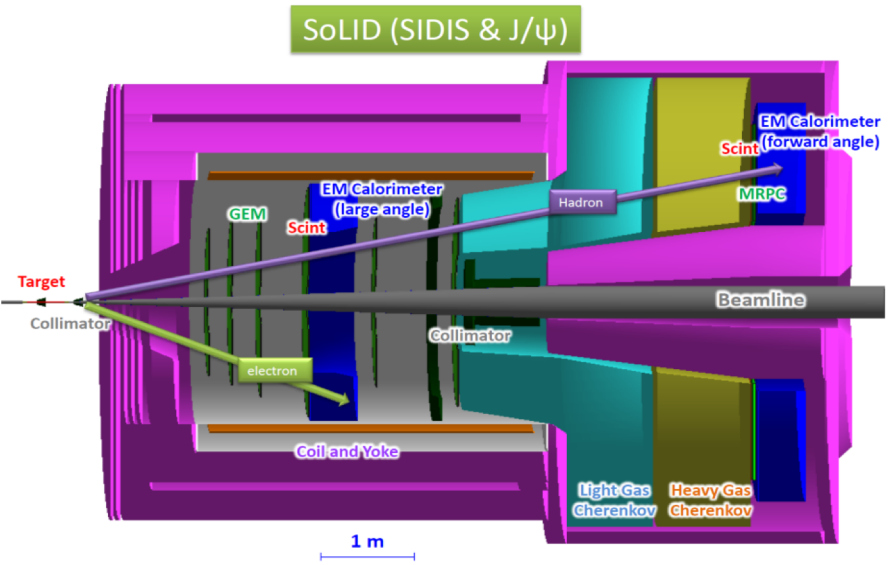




- *Transverse Momentum Dist. (TMD)*
  - *Confined motion in a nucleon (semi-inclusive DIS)*
- *Generalized Parton Dist. (GPD)*
  - *Spatial imaging (exclusive DIS)*
- *Requires*
  - *High luminosity*
  - *Polarized beams and targets*
  - *Sophisticated detector systems*

Major new capability with JLab @ 12 GeV

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV



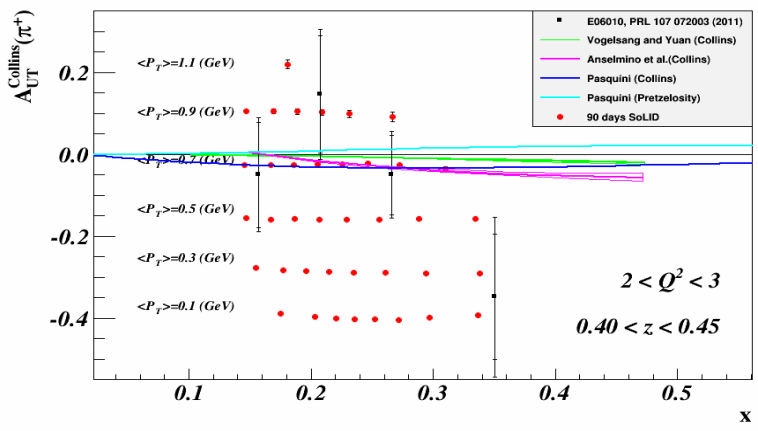
E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, rating A

E12-11-007: Single and Double Spin Asymmetries on ^{3}He, rating A

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, rating A

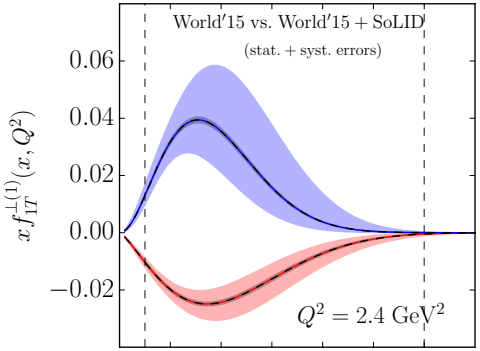
Two run group experiments DiHadron and Ay

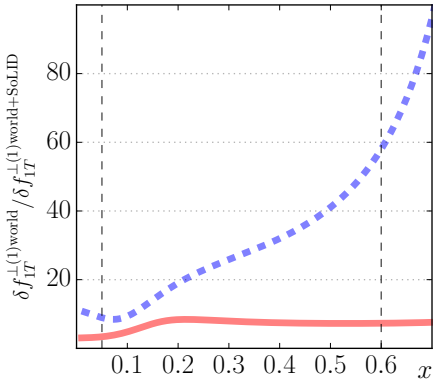
Sivers Asymmetries



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ **Tensor charge**, TMDs …
→**Lattice QCD**, QCD Dynamics,
Quark Orbital Angular Momentum,
Imaging in 3-D momentum space.





SoLID-J/ψ: Study Non-Perturbative Gluons

J/ψ: ideal probe of non-perturbative gluon

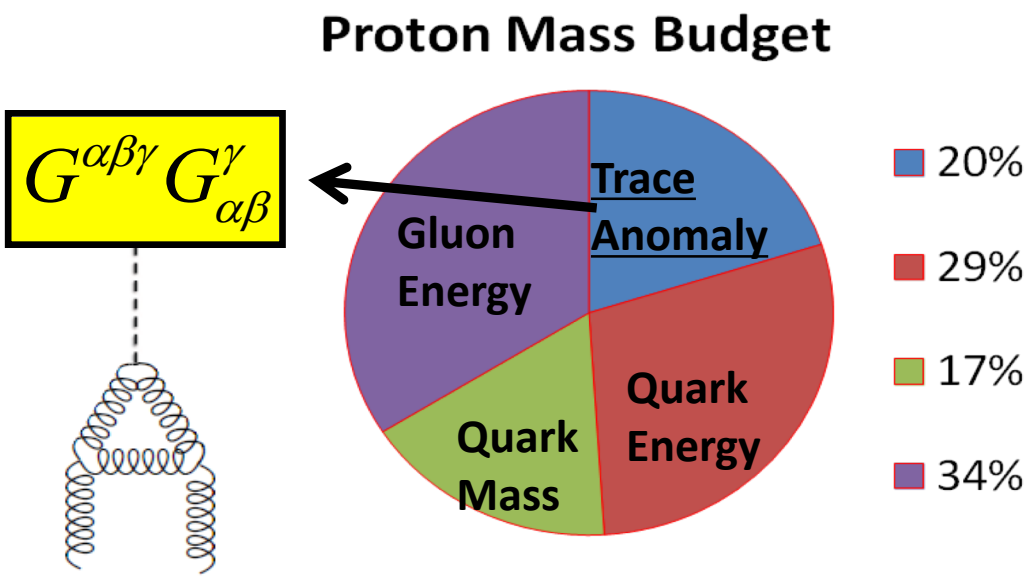
The high luminosity & large acceptance capability of SoLID enables a unique "precision" measurement near threshold

- **Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force)**
- **Shed light on the 'conformal anomaly' an important piece in the proton mass budget:**

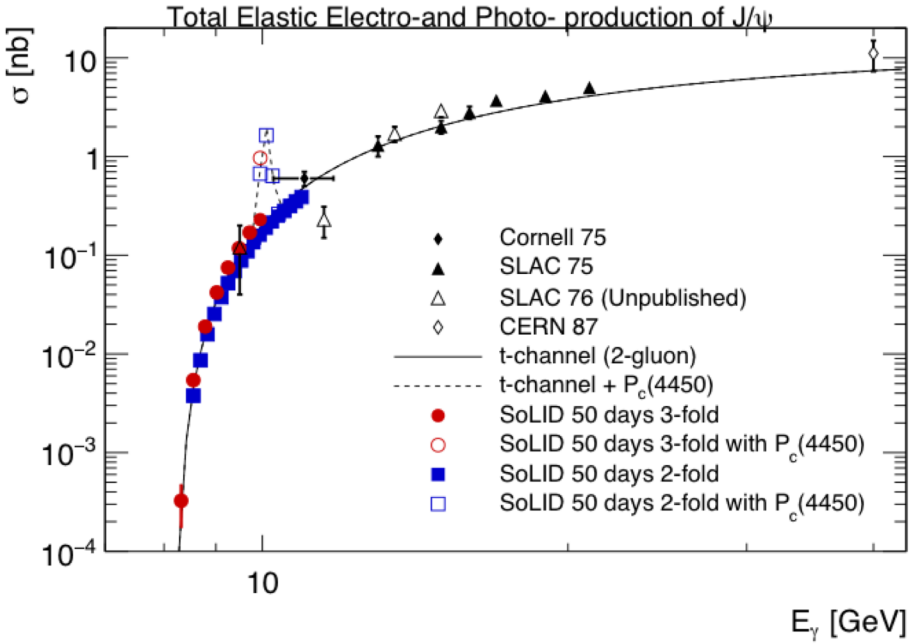
Models relate J/ψ enhancement to trace anomaly

- **Study charm-pentaquark**

$$\gamma^* + N \rightarrow N + J/\psi$$

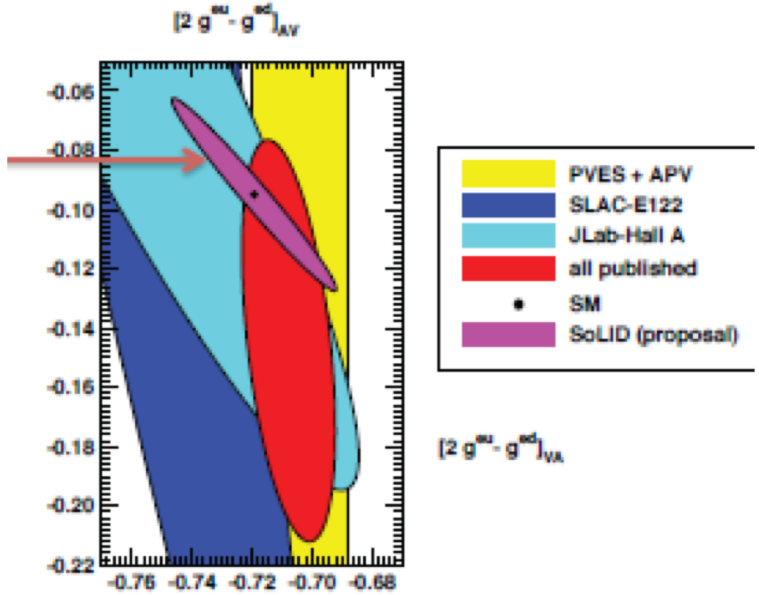


X. Ji PRL 74 1071 (1995)



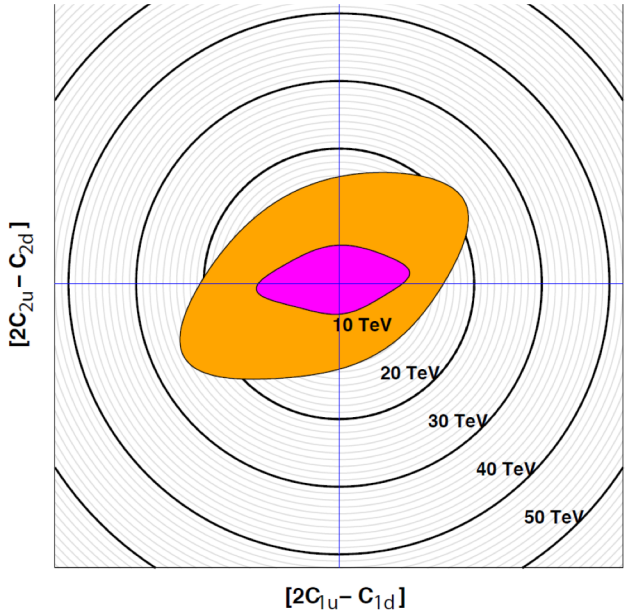
Parity Violation at JLab

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



- Neutron Skin
  - PREX
  - CREX

- Precision Tests of Standard Model
  - PVDIS@6 GeV **(Nature, 506 (2014) 67)**
  - Qweak (final results submitted to Nature)
  - MOLLER
  - SoLID



Quark-gluon Structure of Nuclei

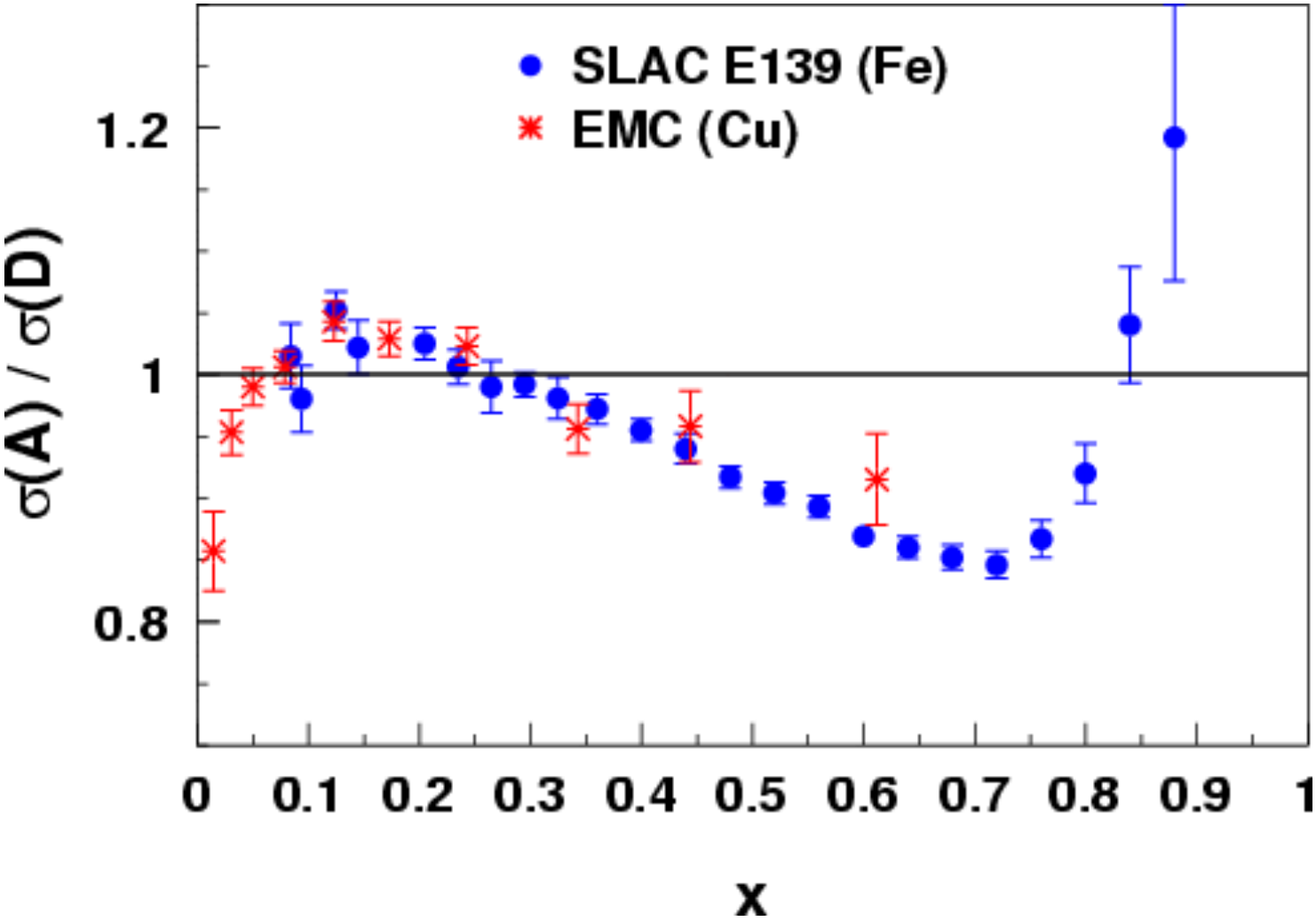
Nuclear Medium as a Laboratory to Study QCD

QCD and Nuclei

- **Most of the strong interaction confined in nucleon, only residual strong interaction remains among nucleons in a nucleus**
  - **Effective N-N interaction with meson exchanges**
- **Study QCD with nuclei**
  - **Short range not well understood**
  - **Nuclei at extreme conditions: QGP, CGC (gluon saturation)**
  - **Nuclear medium effects**
    - **EMC effect**
    - **Nucleon Property in Nuclear medium**
    - **Short range correlations**
    - **Quark propagation in cold nuclear matter**

Nuclear Medium Effects: EMC Effects

- **EMC effects, shadowing and anti-shadowing**

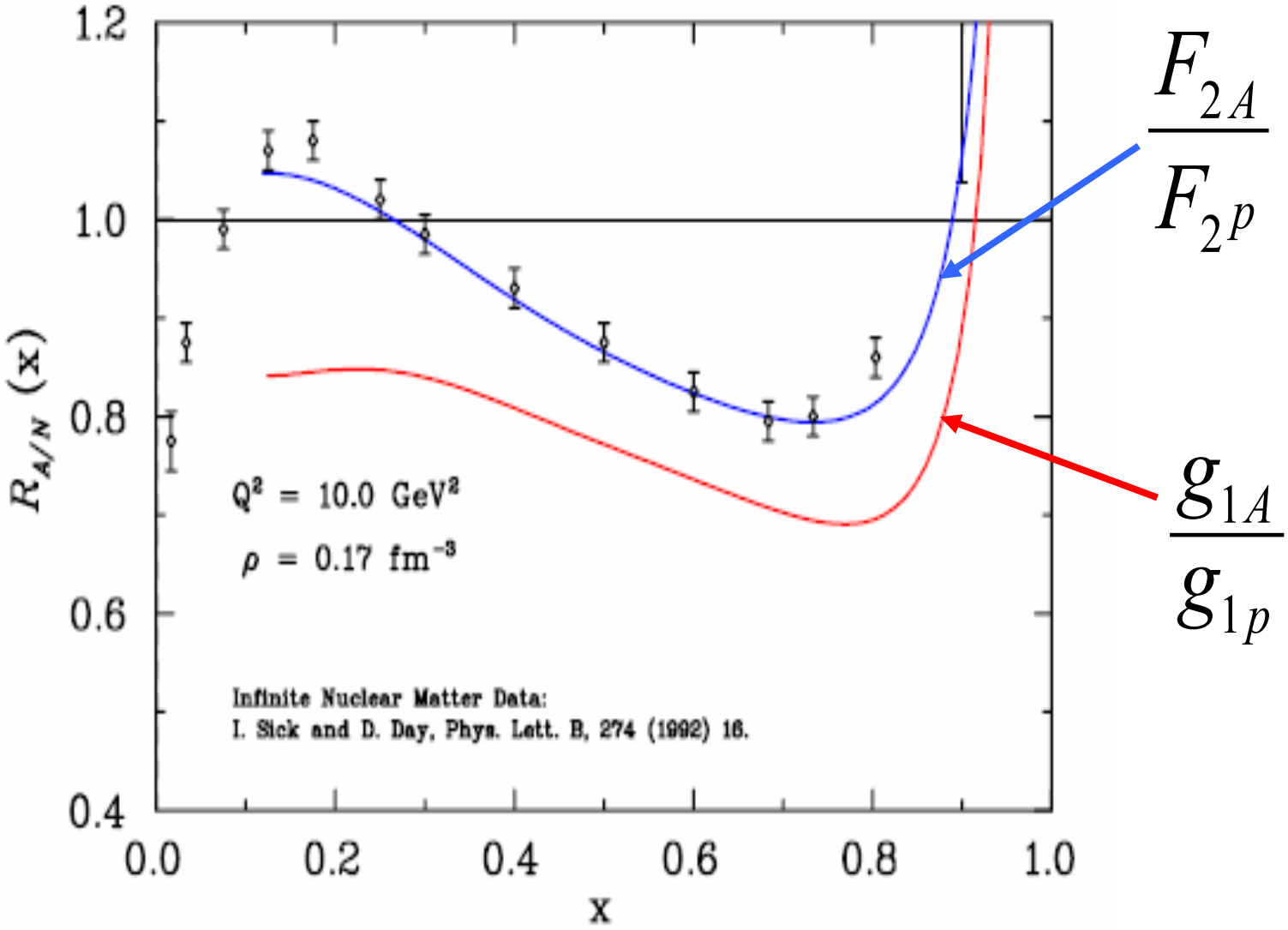


J. Ashman *et al.*, Z. Phys. **C57**, 211 (1993)

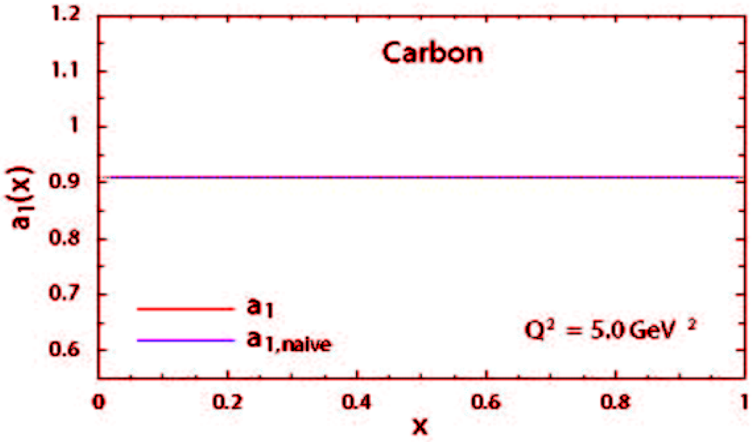
J. Gomez *et al.*, Phys. Rev. **D49**, 4348 (1994)

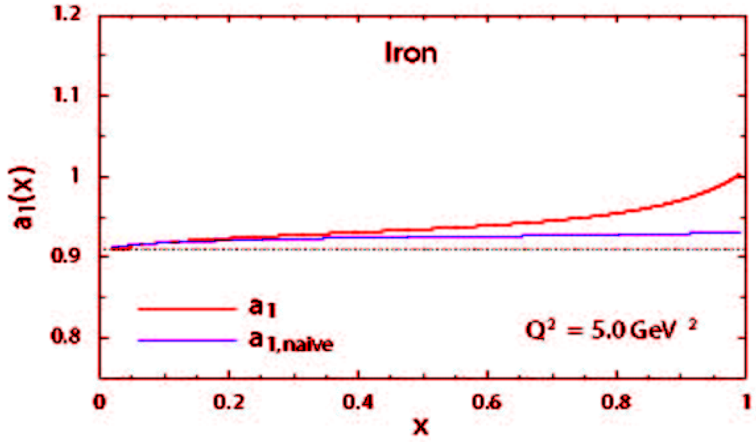
Polarized EMC effect

(Ian Cloet,
Wolfgang Bentz,
Tony Thomas)

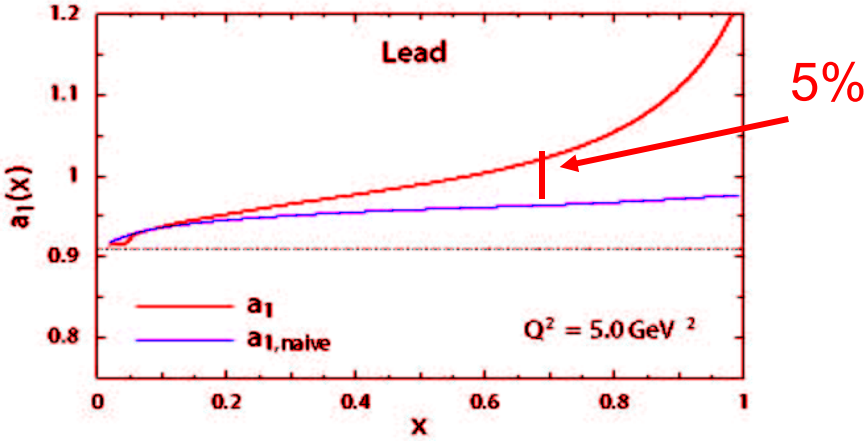


EMC Effect in PVDIS: CSV in Heavy Nuclei





Can be measured with SoLID

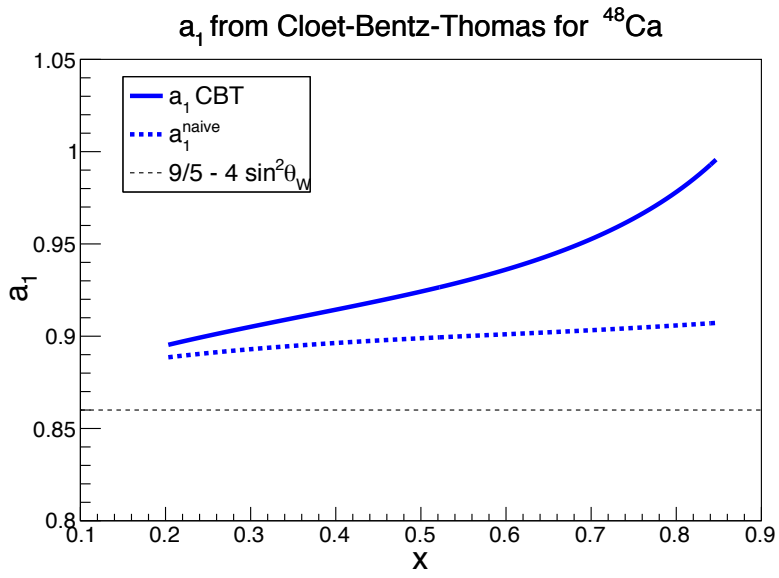


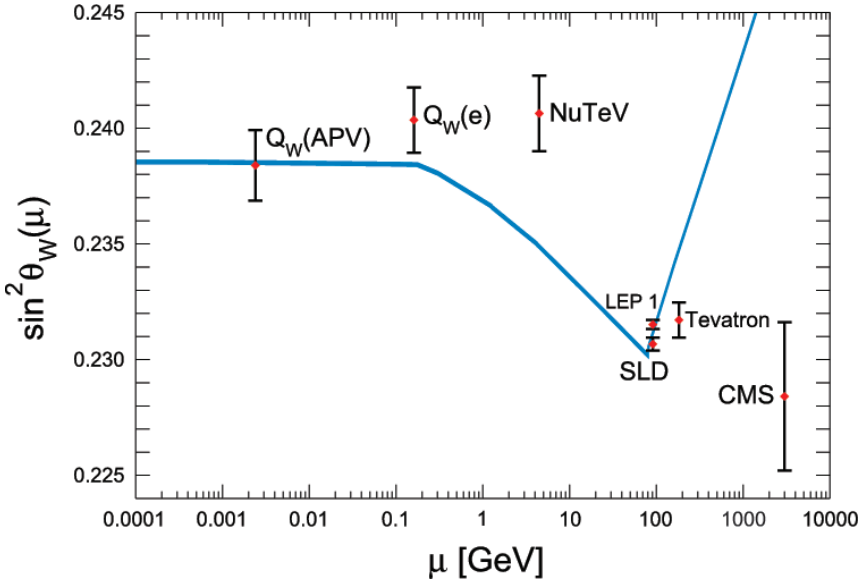
(Cloet, Bentz, and Thomas)

EMC Effect Flavor Dependence

S. Riordan, et al., new proposal - 48Ca PVDIS

- Flavor dependence of EMC effect and be probed with PVDIS
- Relevant for nuclear modification, short-range correlations, neutrinos, BSM, ...



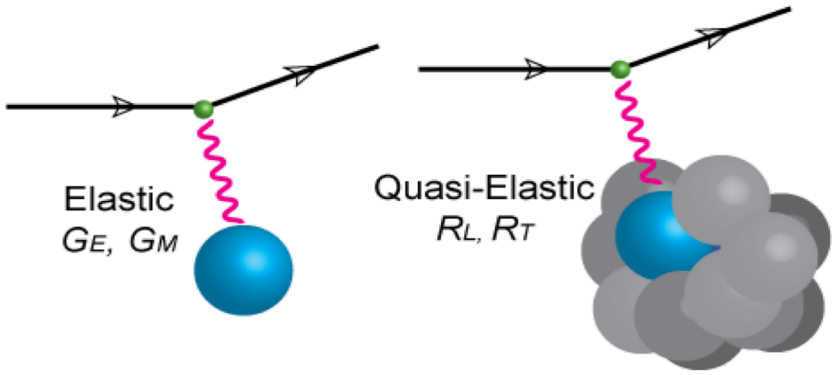


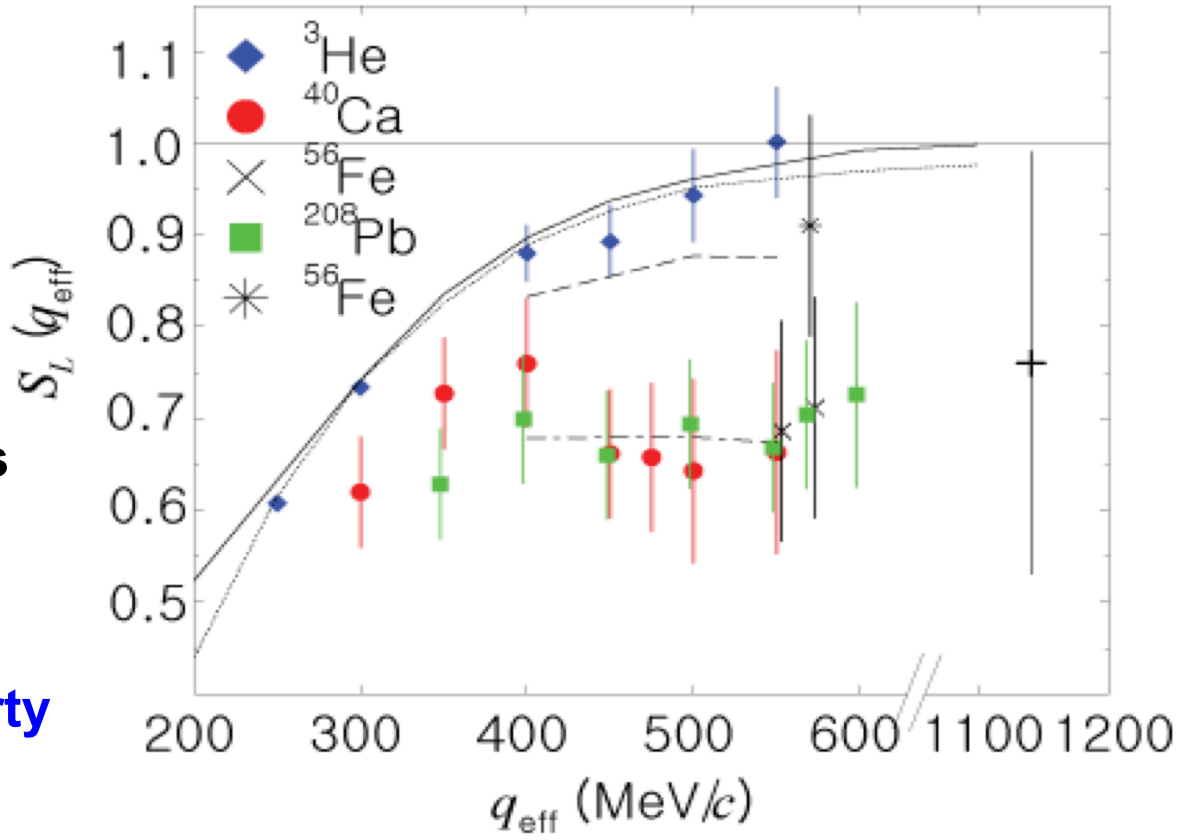
Symmetric nucleus limit

$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$

Nuclear Medium Effects: Coulomb Sum Rule

$$S_L(q) = \frac{1}{Z}\int_{0+}^{\infty} \frac{R_L(q,\omega)}{[(G_E^p + N/ZG_E^n)\zeta]^2} d\omega \;=\; 1\,?$$





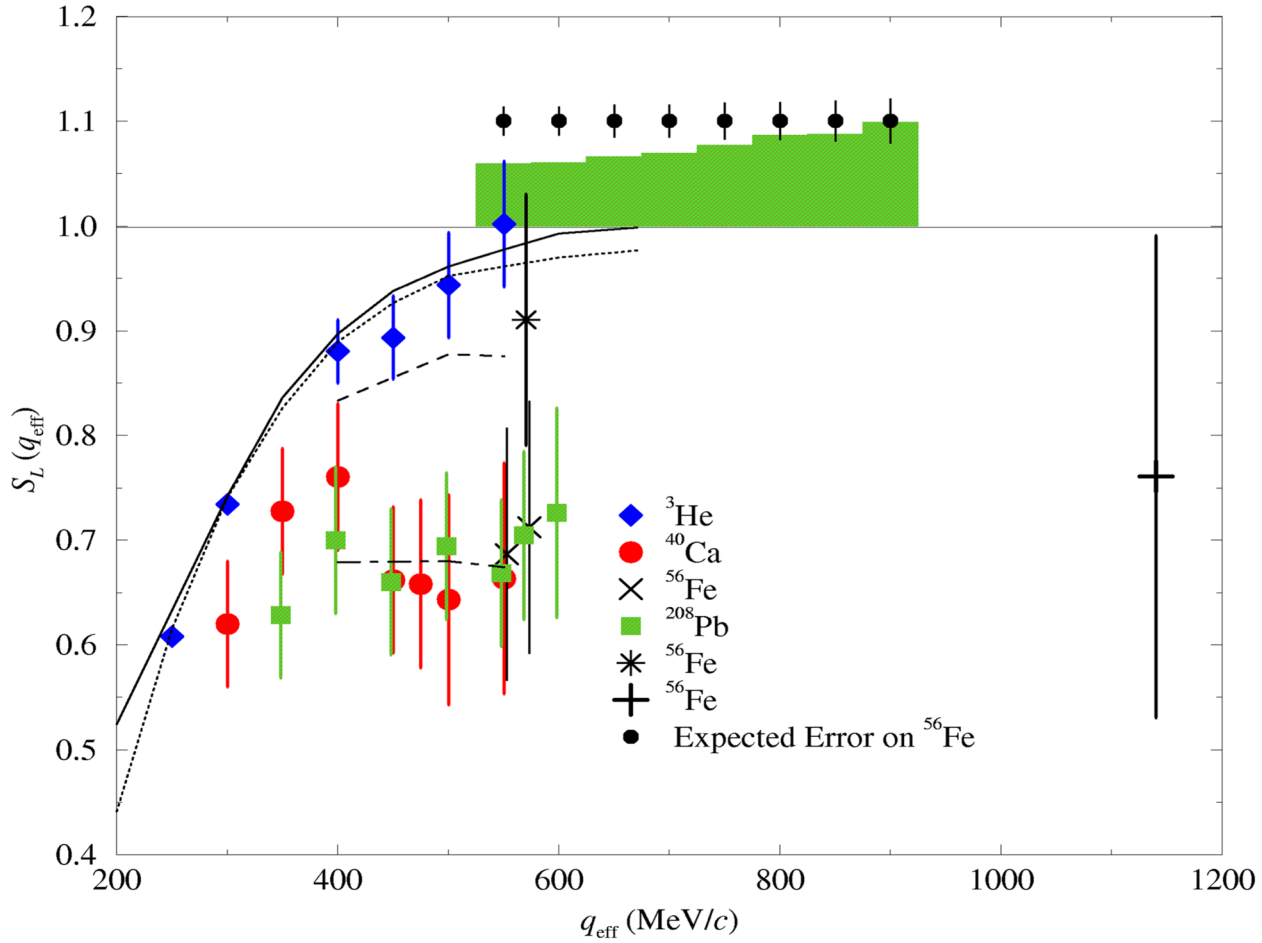
Probing a nucleon inside a nucleus

N-N correlations

Modification of the nucleon property inside nuclei

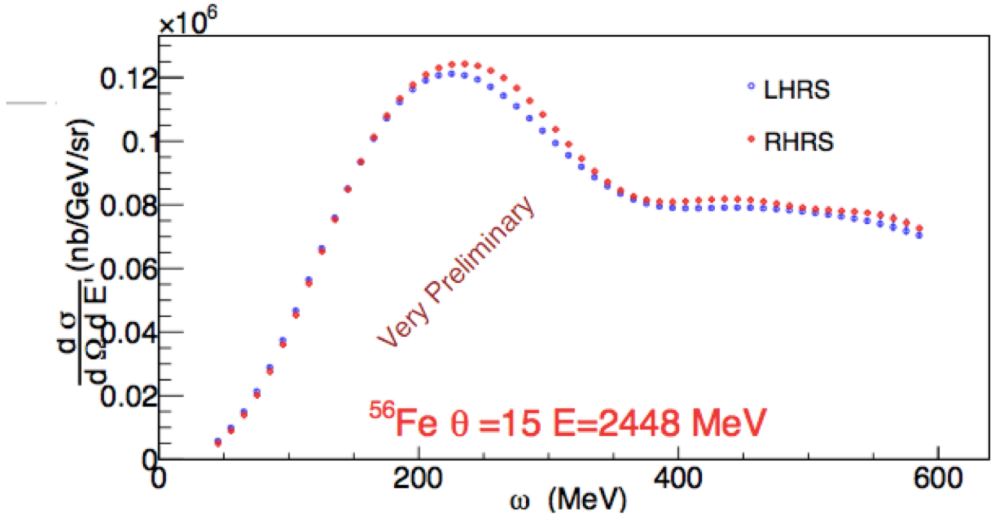
JLab E01-015
Precision Measurement of Coulomb Sum at q=0.5-1 GeV/c on ^{4}He, ^{12}C, ^{56}Fe and ^{208}Pb

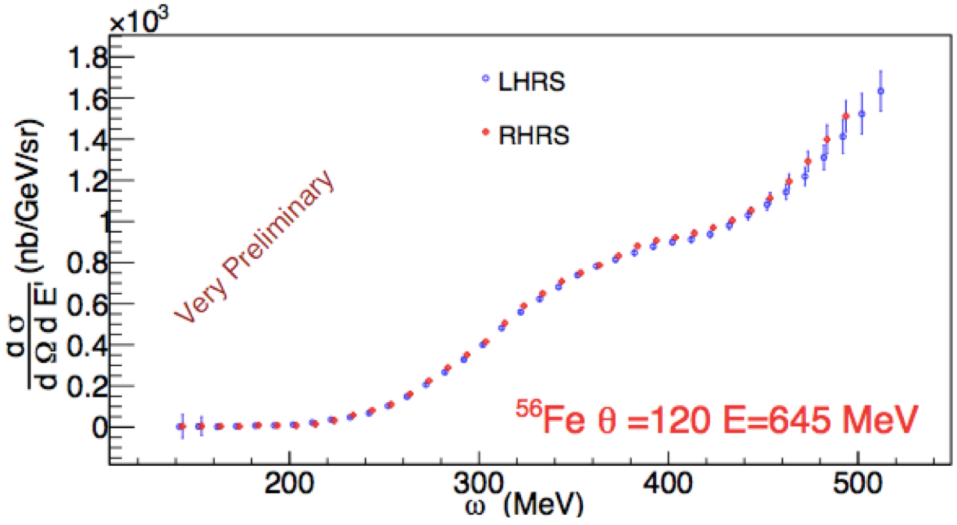
- High precision, good control of systematics
- New NaI detector for background control
- Analysis nearly complete



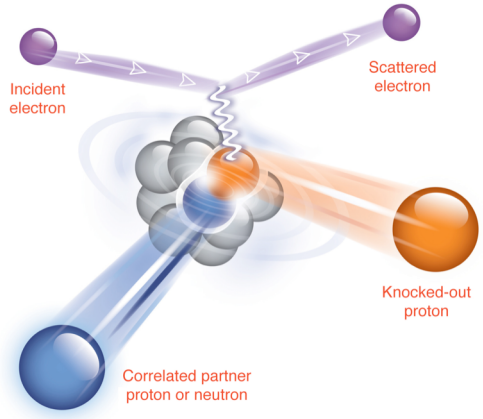
Preliminary Cross Sections

- Comparison of left and right spectrometer data
- Final Acceptance and other corrections
- Expect 1st results in a few months



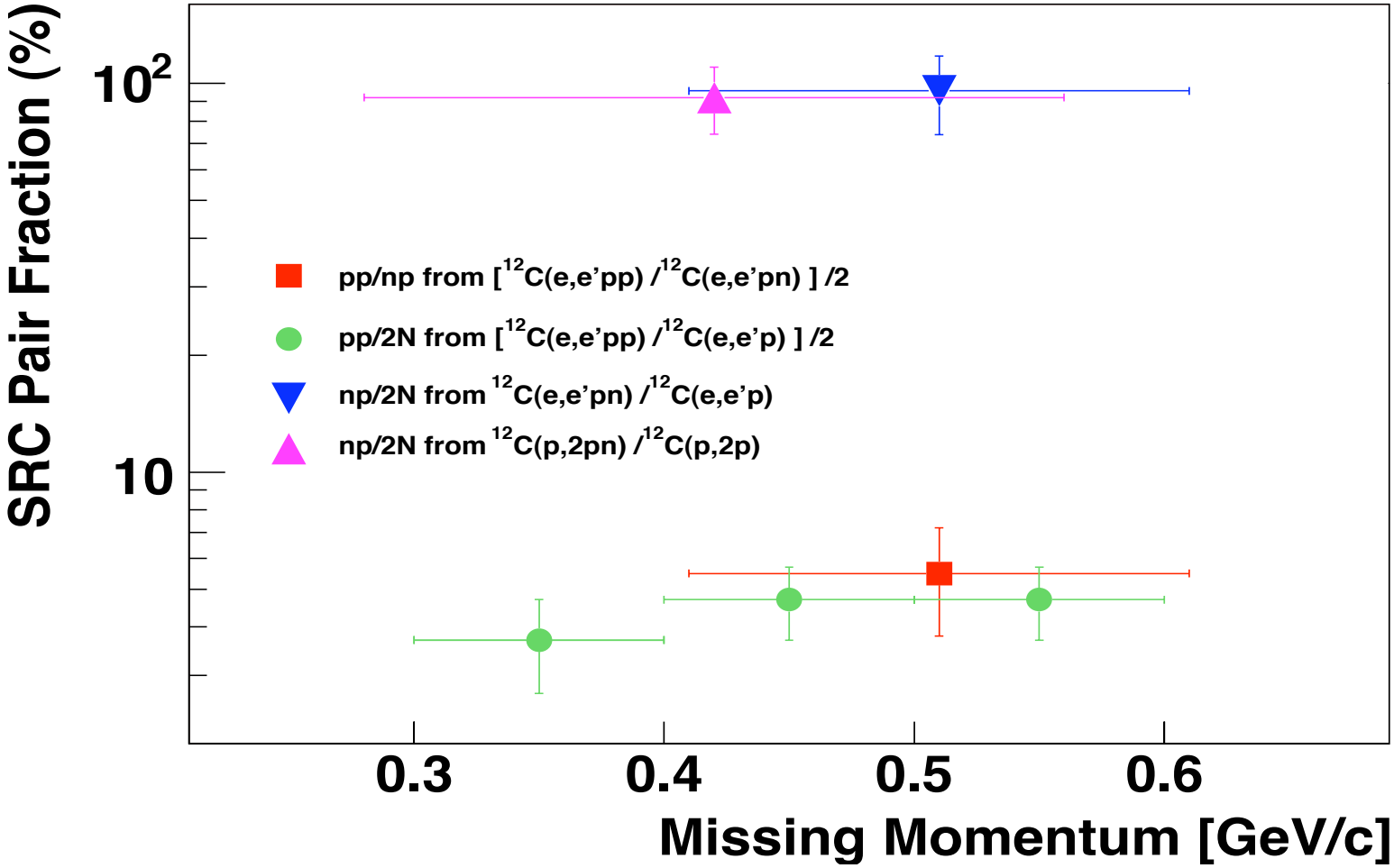


Short-Range Correlation Pair Factions



R. Subedi *et al.*, Science **320** (2008) 1476.

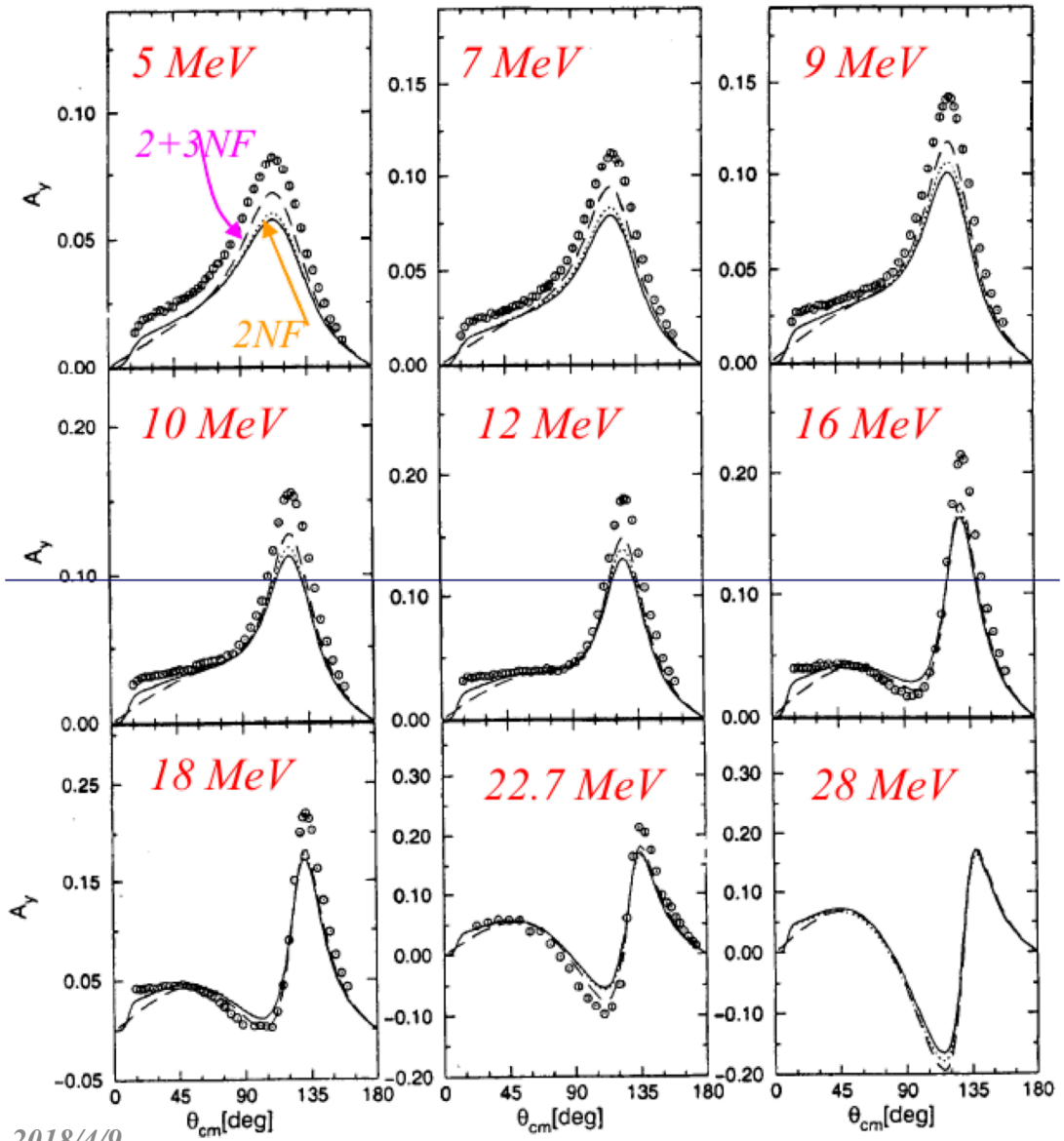
O. Hen et al., Science, 346 (2014) 614



Spin dependence Few-body Physics at CSR and HIAF

proton on polarized ^{3}He to study 3-body force

$$\vec{p} + d \rightarrow p + d$$



Spin-1/2 particle

$$\sigma(\theta,\phi) = \sigma_0(\theta)\left[1 + p_y A_y(\theta)\cos\phi\right]$$

$$A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Inclusion of 3-body force reduces the disagreement between data and theory, but disagreement persists

→ A_y puzzle

Rep. Prog. Phys. 75 (2012) 016301

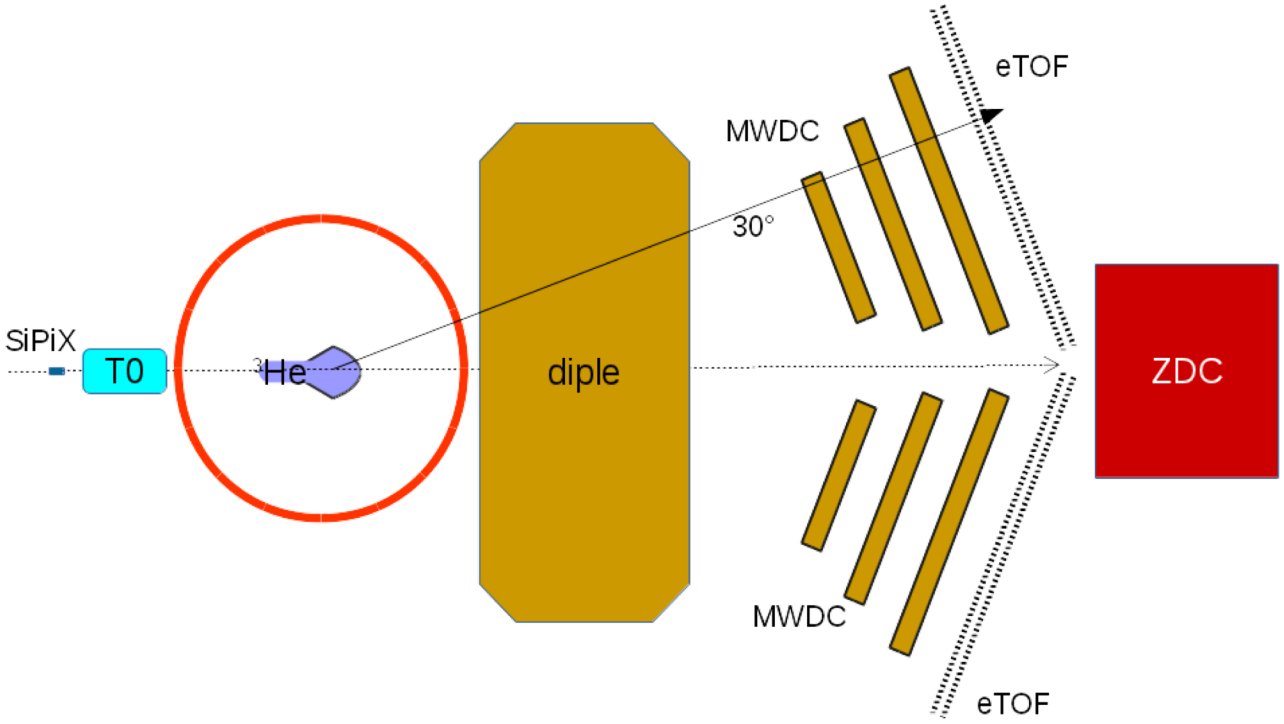
Polarized ^{3}He target with CEE

Yi Zhang

- A possible first experiment: A_y in elastic proton on pol ^{3}He at CSR@IMP

  Study polarization dependence of 3-body force

- A rich program to study spin dependent few-body physics at HIAF



Future: Electron Ion Collider

EIC in US: JLEIC and e-RHIC

EIC@HIAF in China: EicC

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."

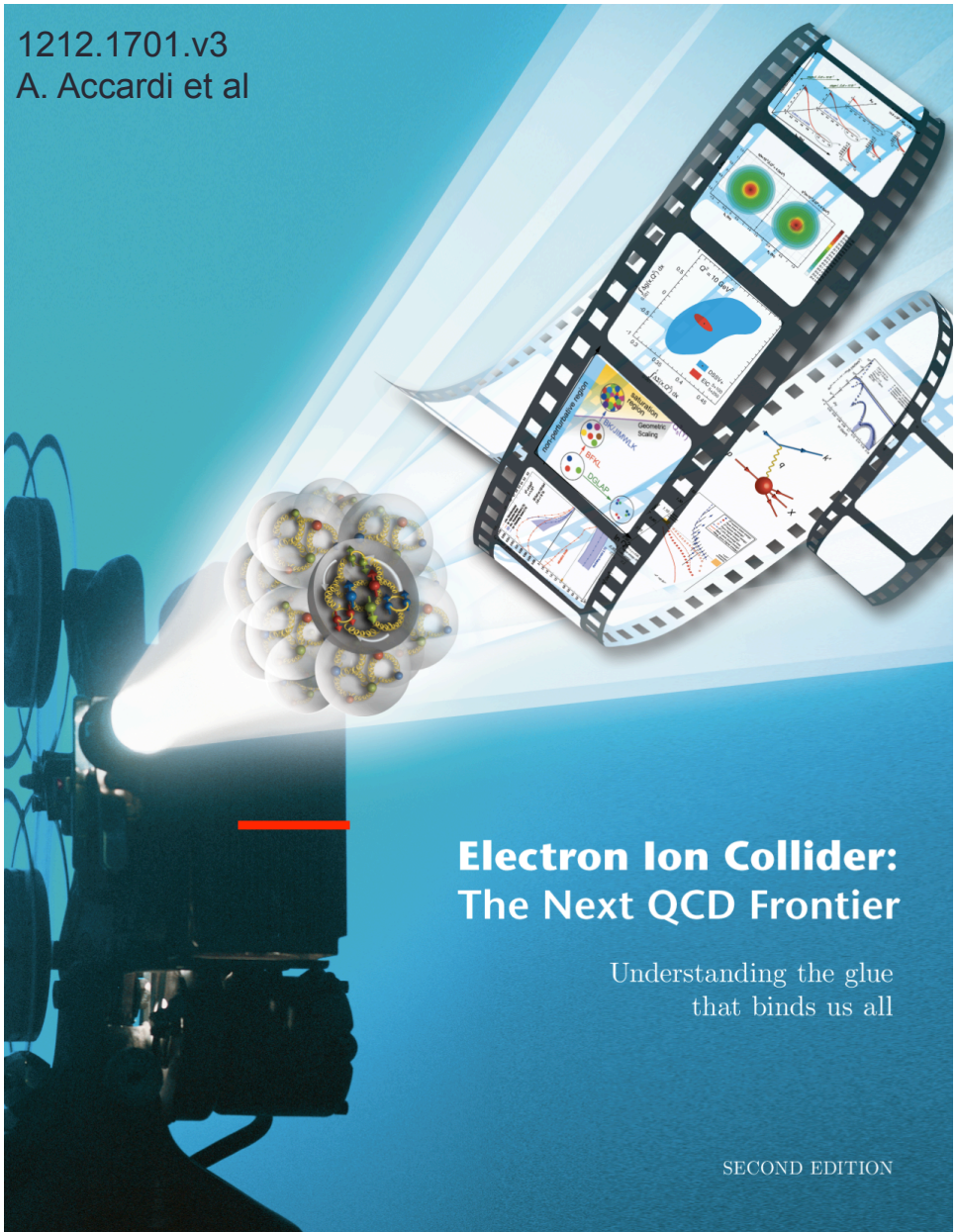
NSAC 2015 Long-Range Plan:

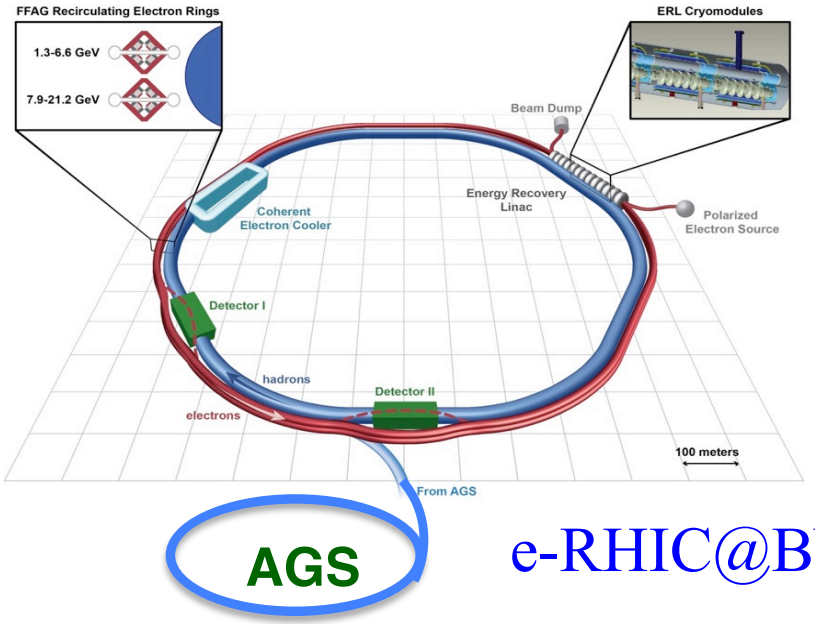
We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility construction** following the completion of FRIB.

EIC Community White Paper arXiv:1212.1701v2

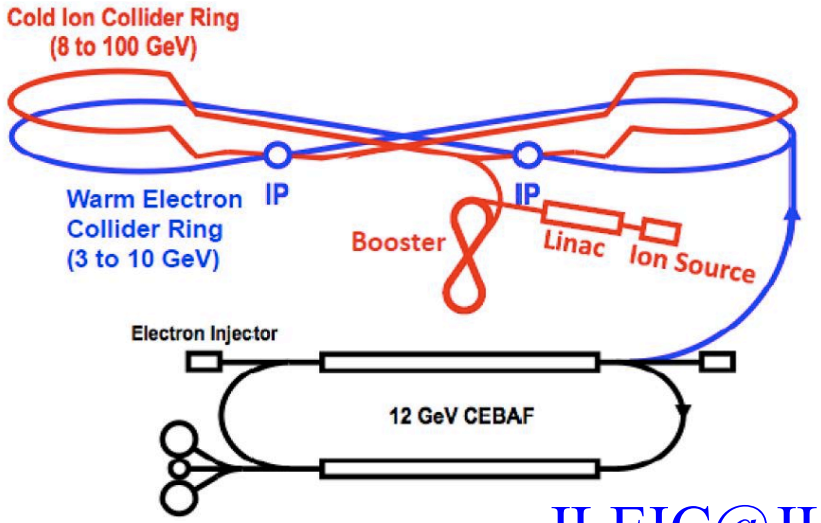
The Electron Ion Collider

Two proposals for realization of the Science Case



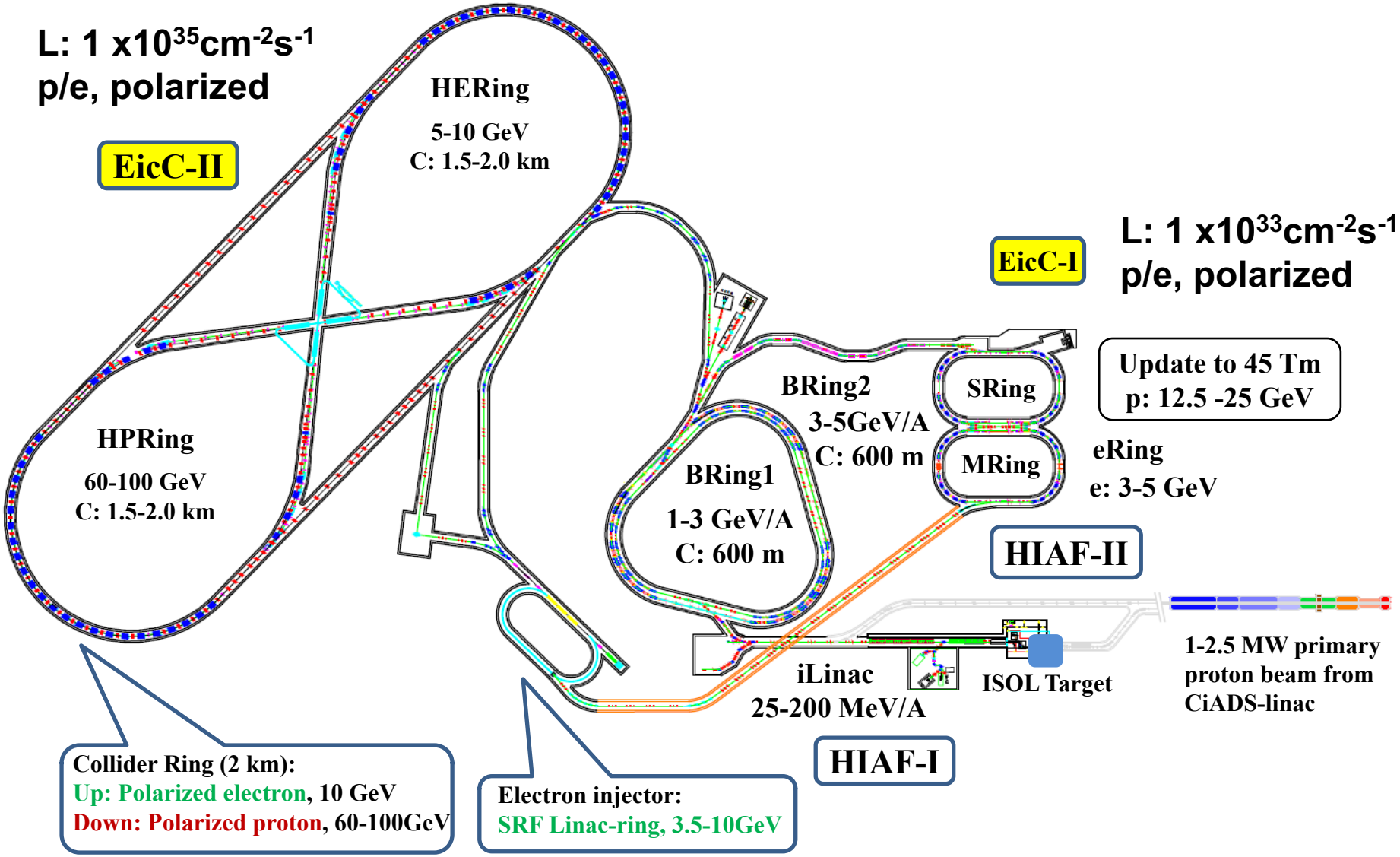


e-RHIC@BNL



JLEIC@JLab

HIAF- EicC-I and EicC-II



Overview of EIC Experiments

A Key Question for EIC:

"How are the sea quarks and gluons, and their spins distributed in space and momentum inside the nucleon?"

- Spin and Flavor Structure of the Nucleon
- 3-d Structure in Momentum Space and Confined Motion of Partons inside the Nucleon
- 3-d Structure in Coordinator Space and Tomography of the Nucleon

Other Important Questions:

"Where does the saturation of gluon densities set in?

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?"

Opportunity for Low Energy Search of Physics Beyond SM

- Parity Violating e-N

Summary

- Selected highlights and future program at JLab/SoLID

  Nucleon structure: spin, 3-d (TMDs), femtography;

  Nucleon modifications: EMC, Coulomb Sum Rule, SRC
- Spin dependent few-body physics: 3-body force study @ HIAF
- Future – EIC in US and in China (EicC)