The 11th ICFA Seminar on Future Perspectives in High-Energy Physics

Institute of High Energy Physics, CAS, October 27-30, 2014

Spin Physics and Nucleon Structure

11th The International Committee for Future Accelerators (ICFA) Seminar

Oct 27-30, 2014

Haiyan Gao

Duke University and Tsinghua U

Spin as a knob （自旋在物理学中的重要性）

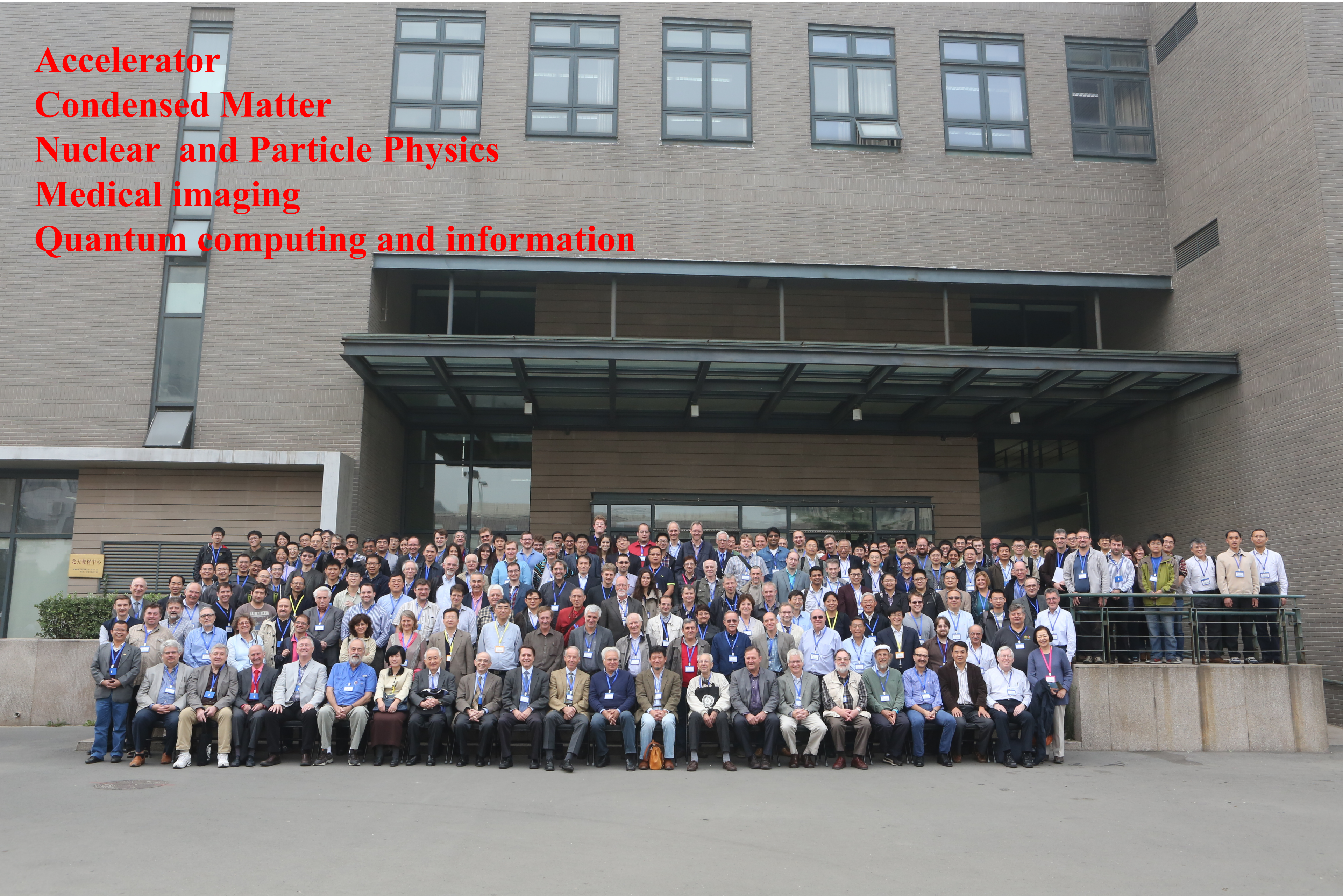
- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - 1980s: "Proton spin crisis"
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: "New breakthrough in spin physics"?

Pauli and Bohr watch a spinning top

topological insulator, quantum anomalous Hall effect, etc..

Nature: http://www.nature.com/milestones/milespin/index.html

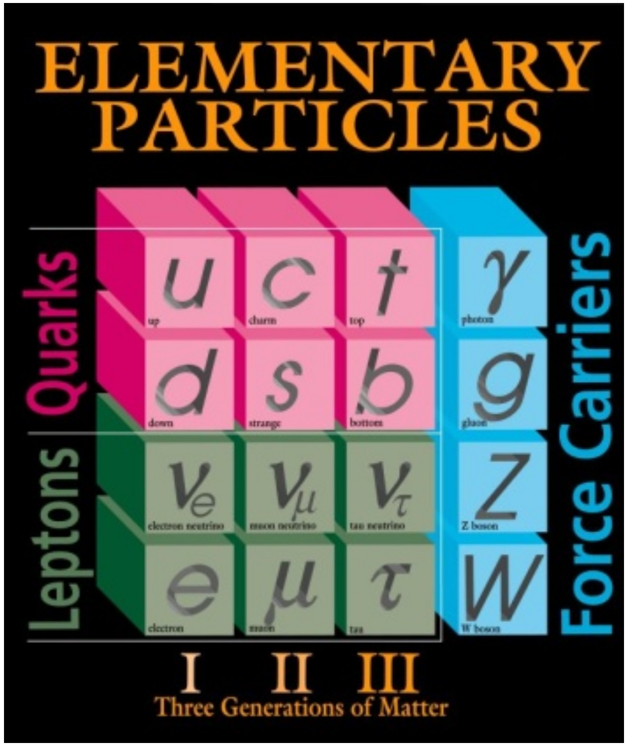
21st International Symposium on Spin Physics, Oct 20-24, 2014, Peking University

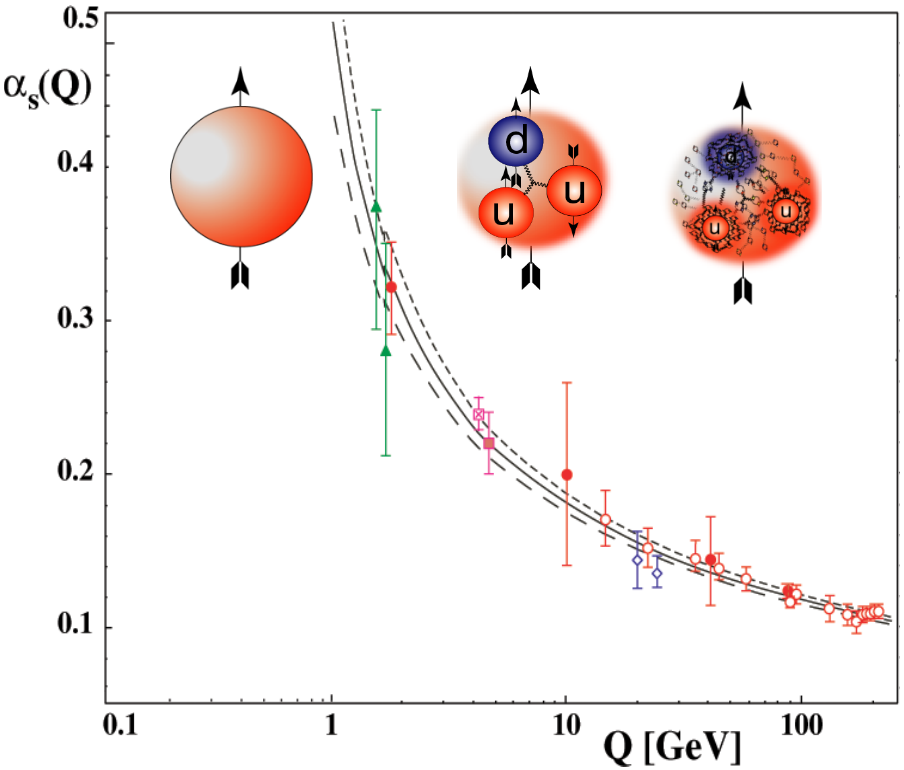


Outline

- ***Introduction***
- ***Few selected examples***
  - ***Nucleon Form factors and Proton charge radius puzzle***
  - ***Proton spin puzzle and tomography***
  - ***Parity-violating electron scattering***
- ***Future outlook and Summary***

QCD: still unsolved in non-perturbative region



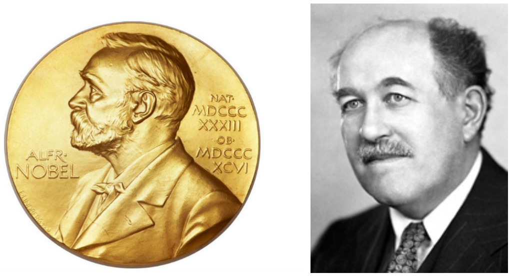


Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom"*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

What is inside the proton/neutron?

1933: Proton's magnetic moment



Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic mor
of the proton".

$$g \neq 2$$

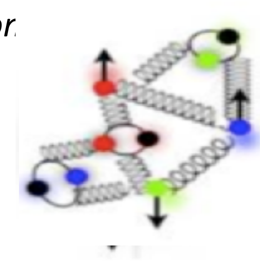
1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

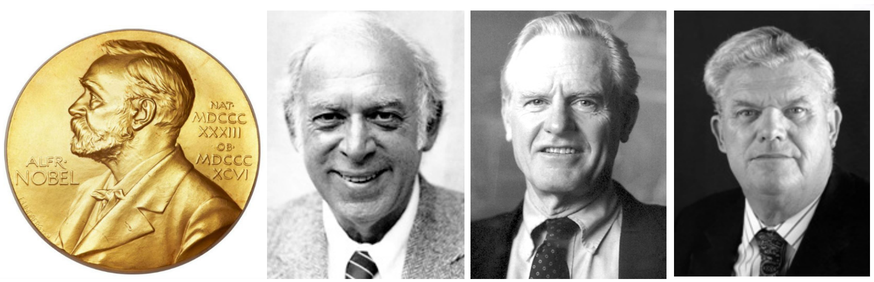
Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

$$\text{Form factors} \rightarrow \text{Charge distributions}$$



1969: Deep inelastic e-p scattering



Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

1974: QCD Asymptotic Freedom

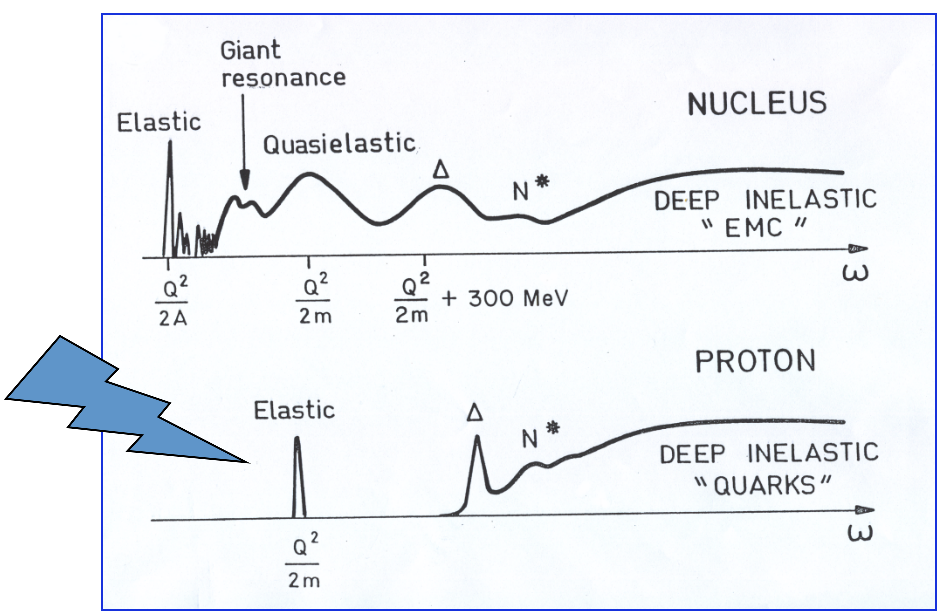
Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***One can vary the wave-length of the probe to view deeper inside the hadron***

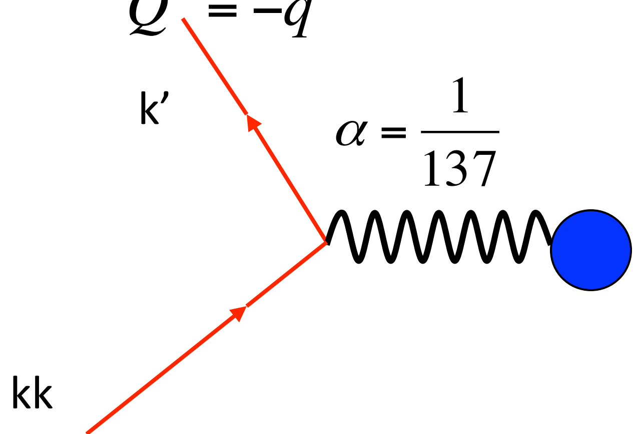


Virtual photon 4-momentum

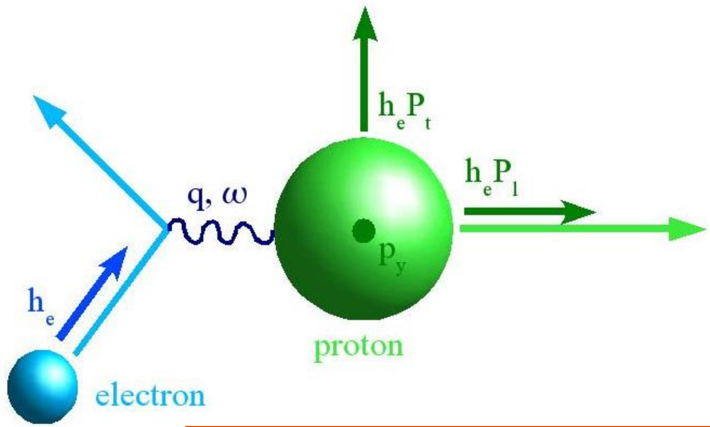
$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$

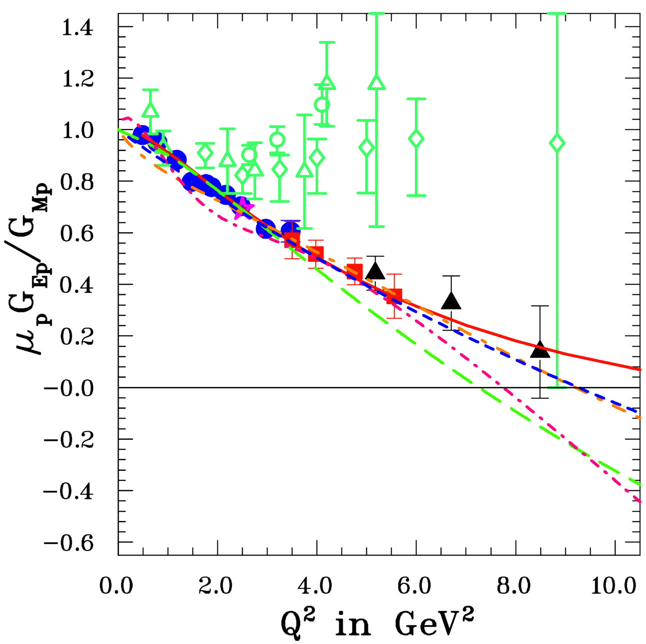
$$\alpha = \frac{1}{137}$$



Tremendous advances in electron scattering

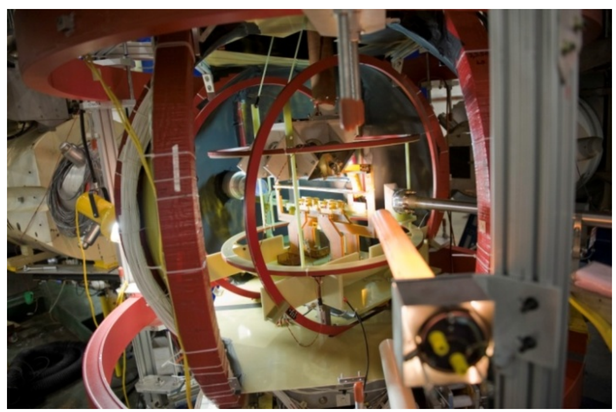


$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

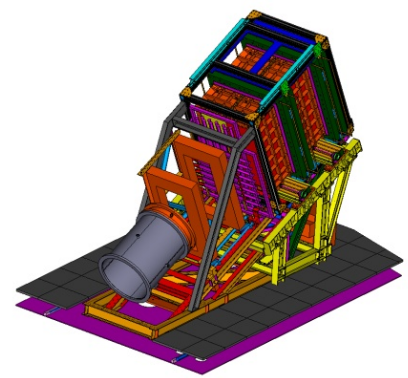


Unprecedented capabilities:

- High Intensity
- High Duty Factor
- High Polarization- M. Poelker (2012 Lawrence Award)
- Parity Quality Beams
- Large acceptance detectors
- State-of-the-art polarimetry, polarized targets



Polarized ^{3}He target



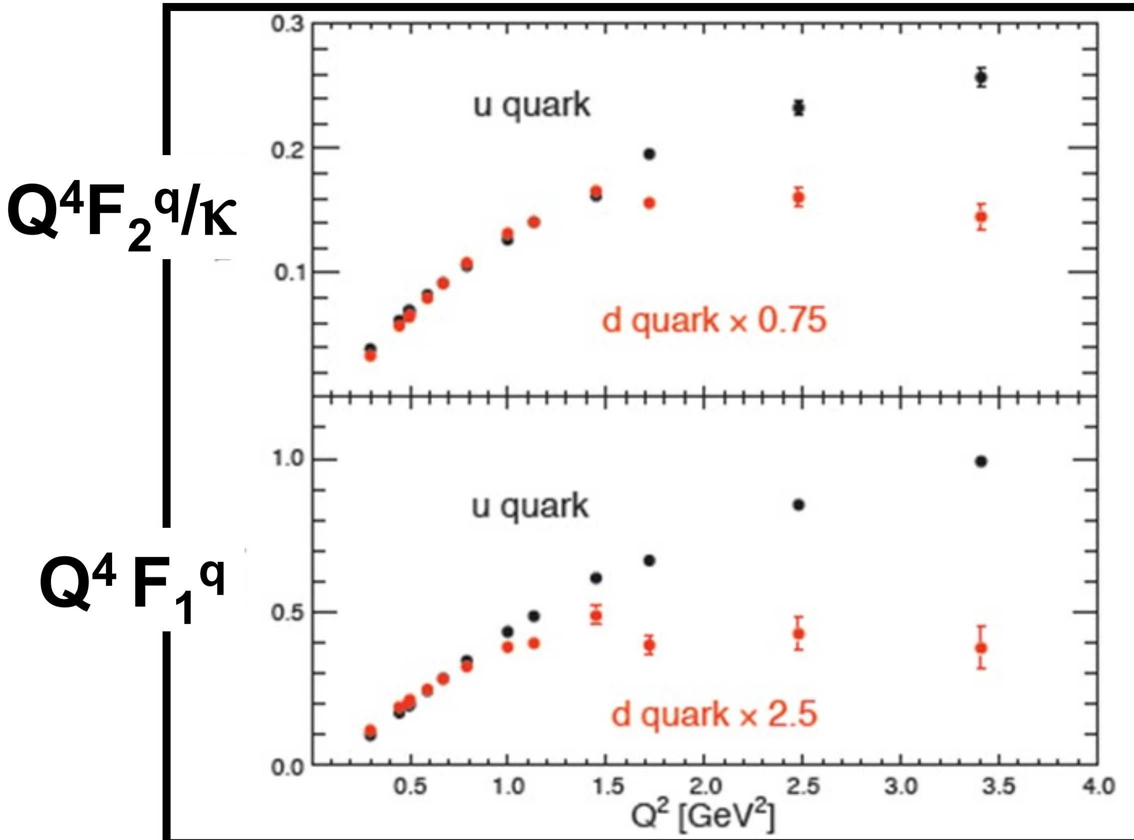
Focal plane polarimeter – Jefferson Lab

Flavor separation of nucleon form factors

HAPPEx, G0, A4 →
$G_E^s = G_M^s = 0$

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)}$$
$$F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

Cates, de Jager,
Riordan, Wojtsekhowski,
PRL 106 (2011) 252003



- **Very different behavior for *u* and *d* quarks**
- ***Evidence for diquark correlations – axial diquark -> soft f.f.***
- ***Six 12-GeV experiments to extend Q^2 range***

Thanks to Craig Roberts

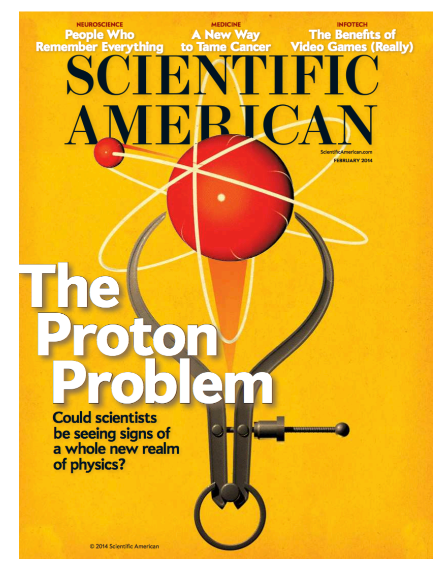
Proton charge radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  - An important physics input to the bound state QED calculations, affects muonic H Lamb shift $(2S_{1/2} - 2P_{1/2})$ by as much as 2%

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

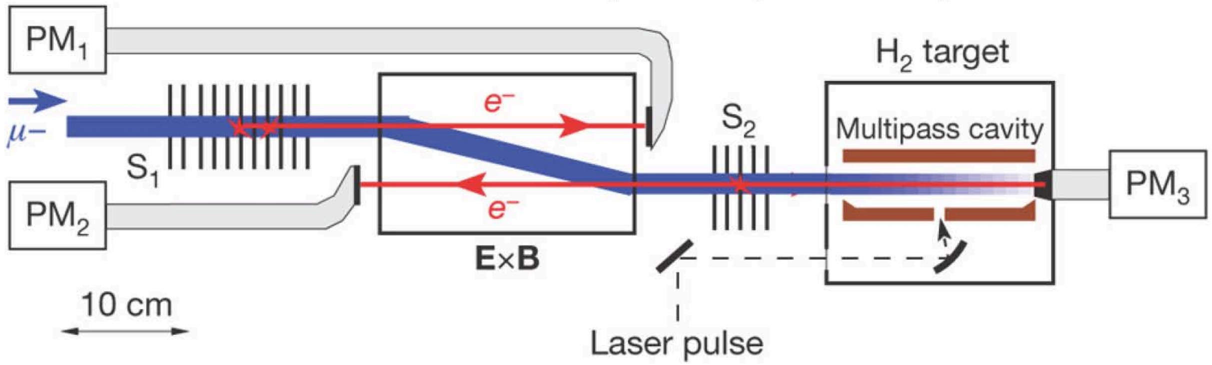
$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}\Big|_{q^2=0}}$$

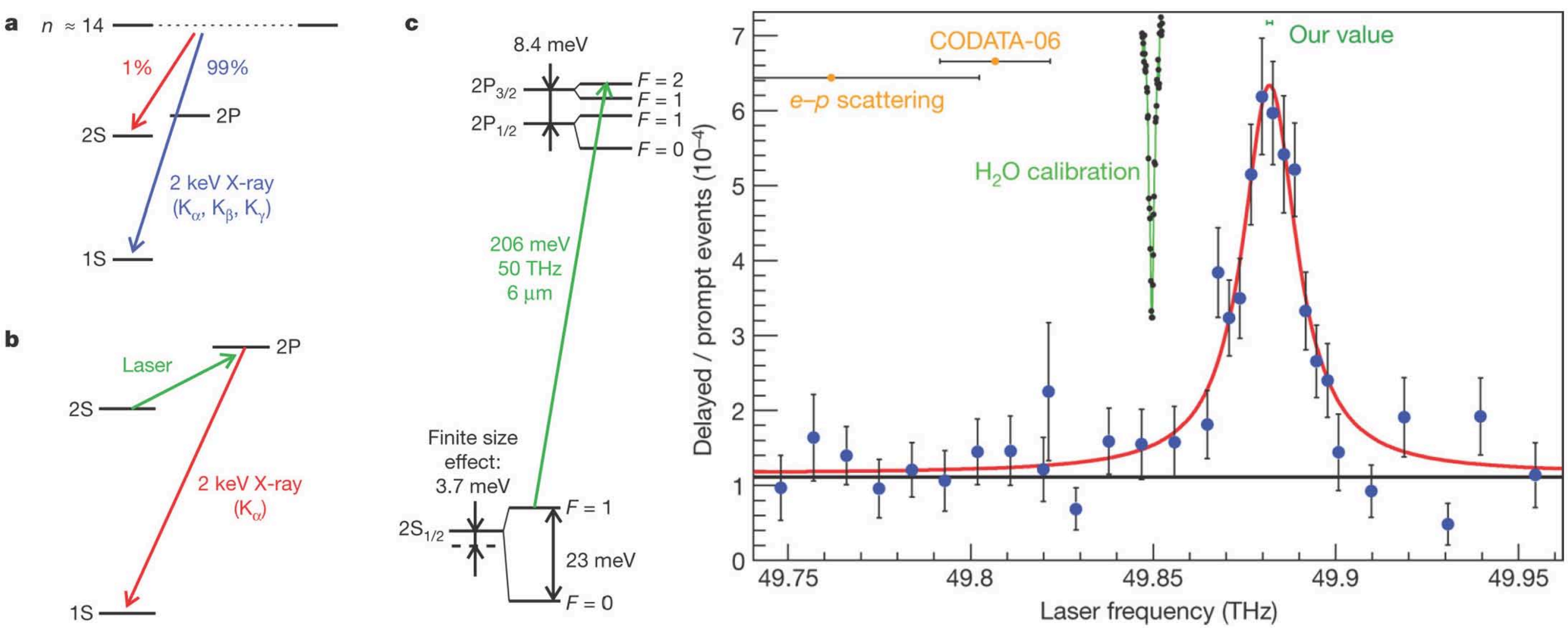
- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift



Muonic hydrogen Lamb shift experiment at PSI

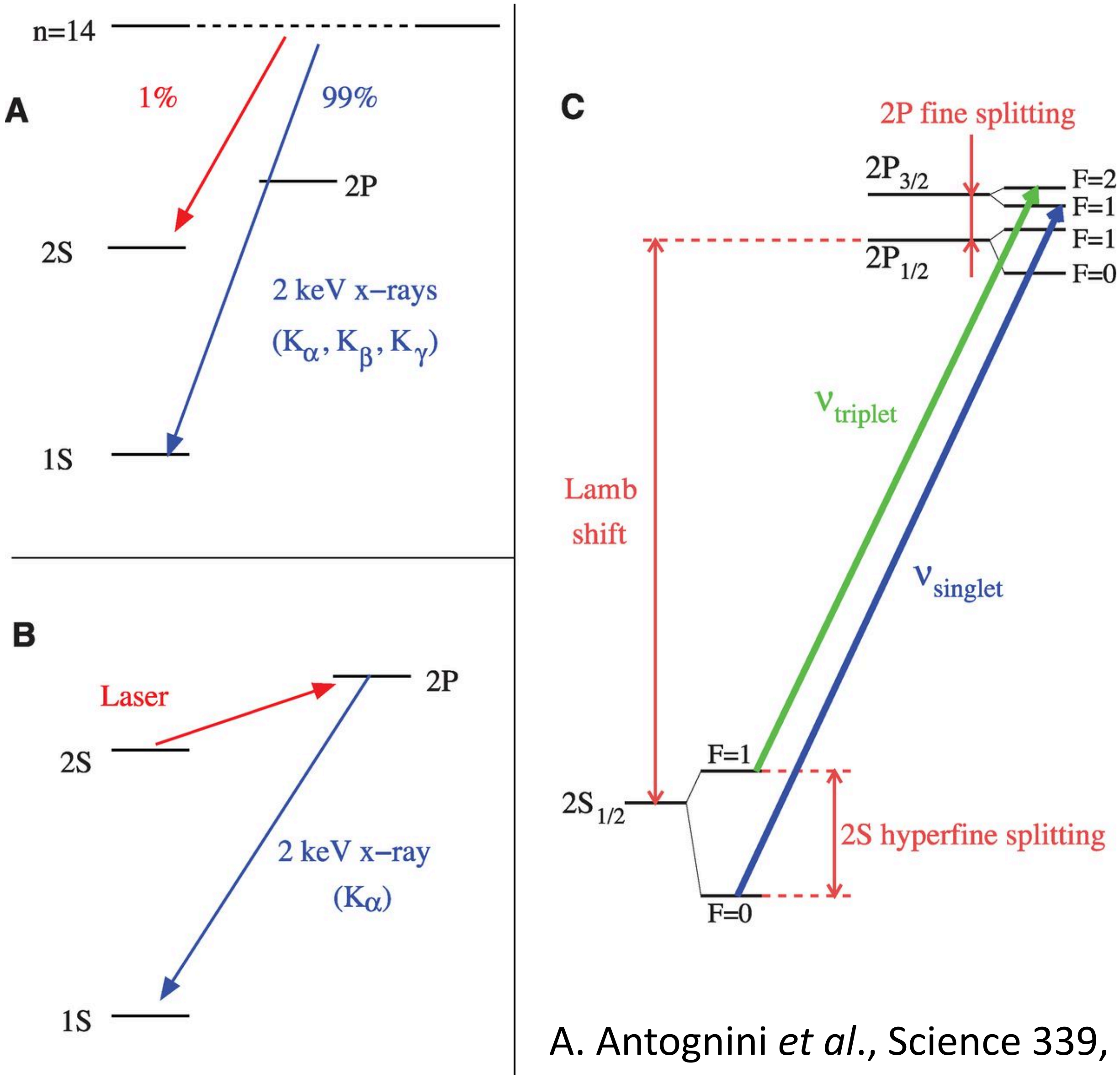
Nature **466**, 213-216 (8 July 2010)





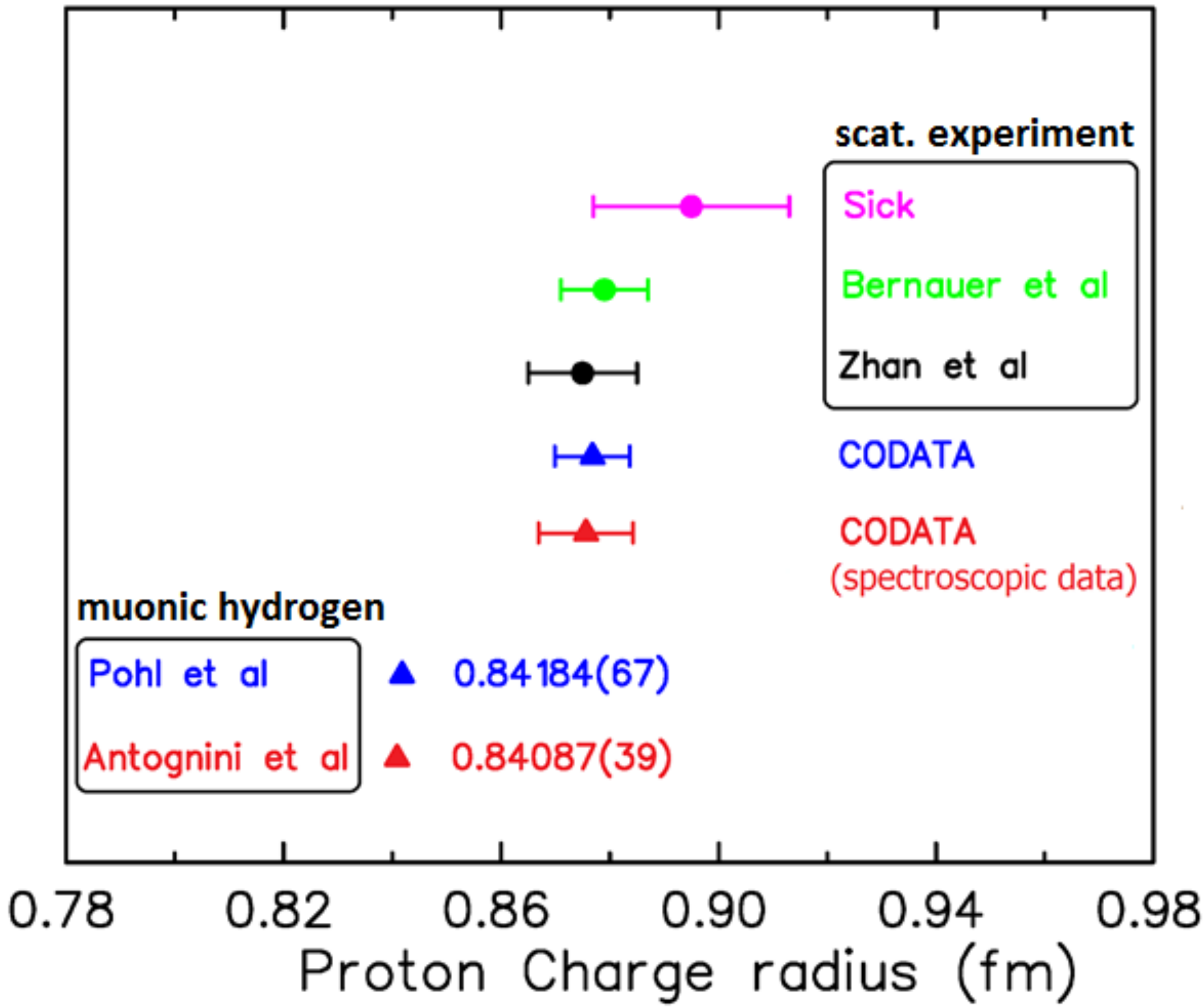
2010: new value is r_p = 0.84184(67) fm

New PSI results reported in Science 2013

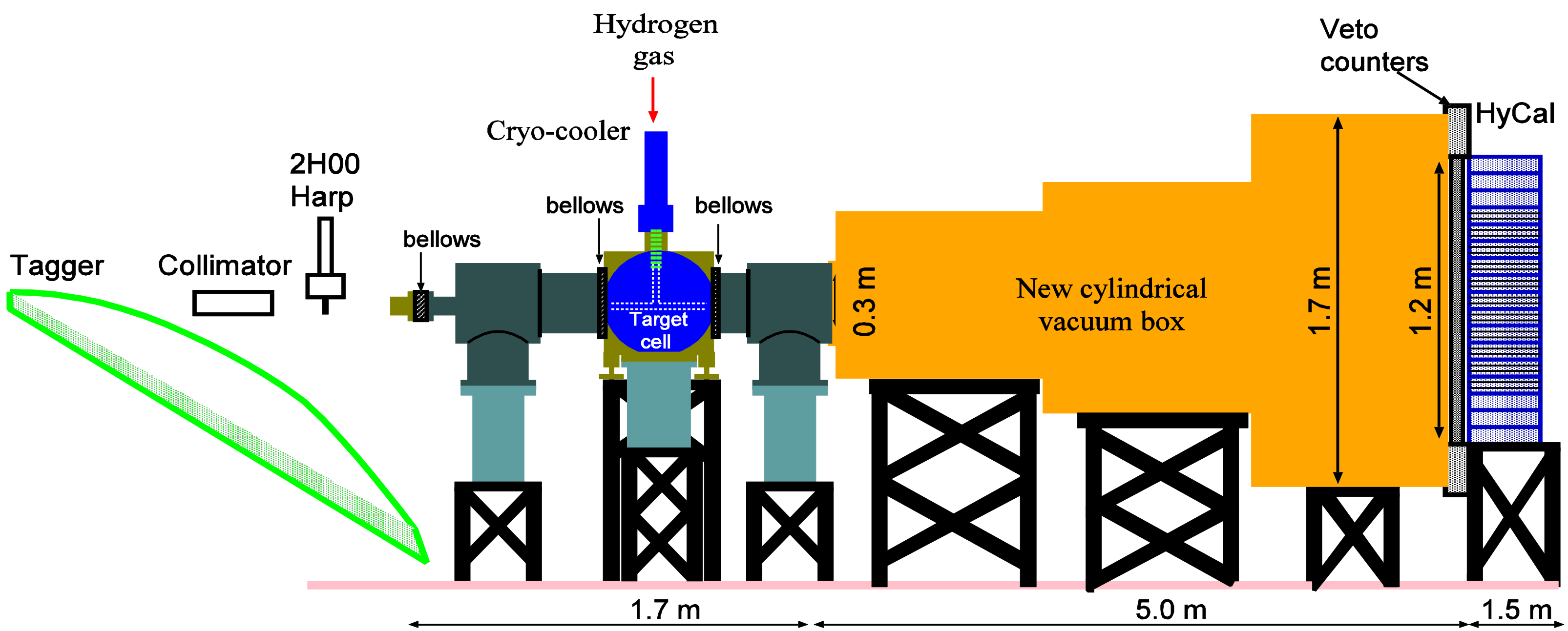


A. Antognini *et al.*, Science 339, 417 (2013)

The proton radius puzzle intensified, more intrigued by muonic helium results



PRad Experimental Setup in Hall B at JLab



- **High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2x10^{-4}$ – $0.14\ GeV^2$**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

Spokespersons: A. Gasparian, D. Dutta, H. Gao, M. Khandaker

Future sub 1% measurements:

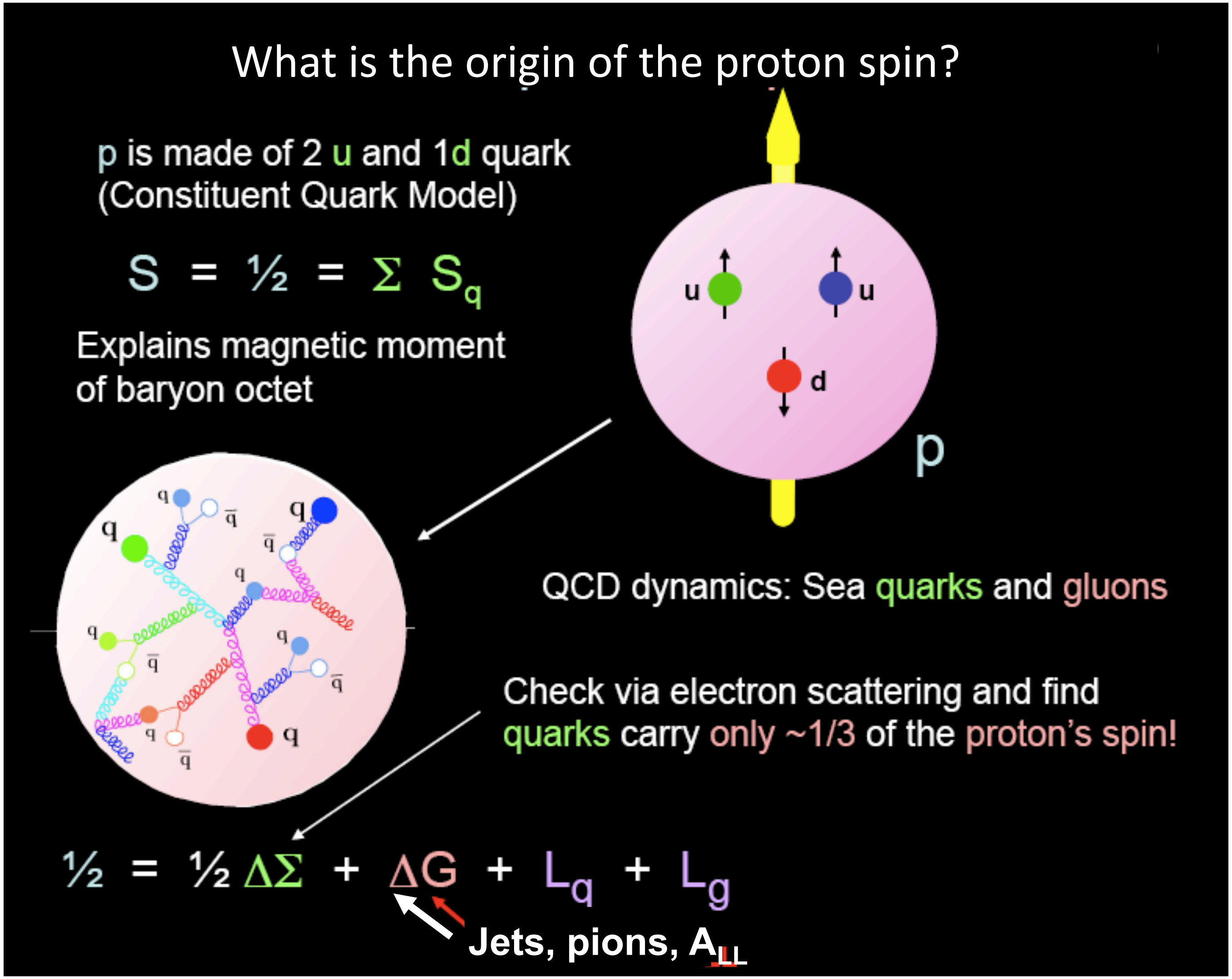
(1) ep elastic scattering at Jlab (PRad)

(2) µp elastic scattering at PSI - 16 U.S. institutions! (MUSE)

(3) ISR experiments at Mainz

Ongoing H spectroscope experiments

Worldwide quest: spin structure of the nucleon



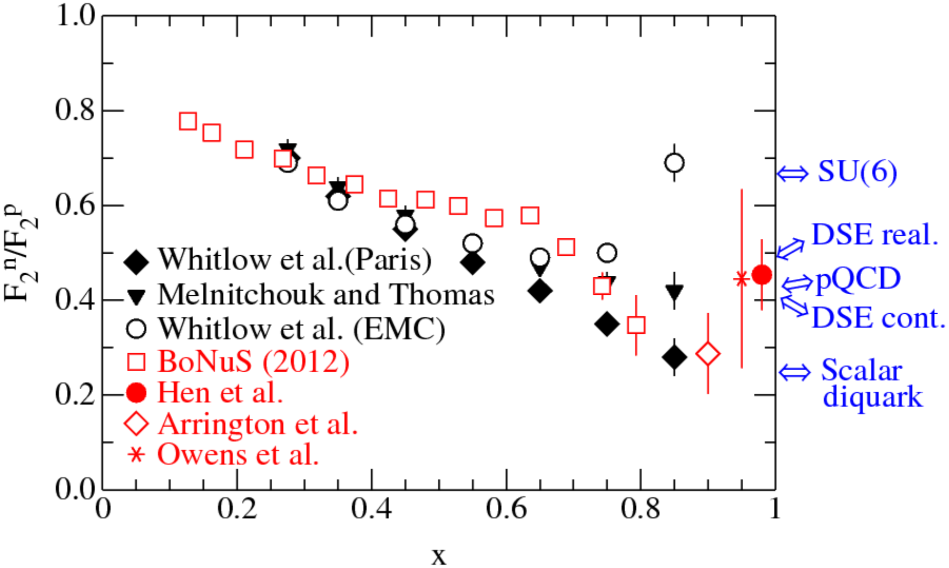
Unpolarized and Longitudinally Polarized Structure Functions

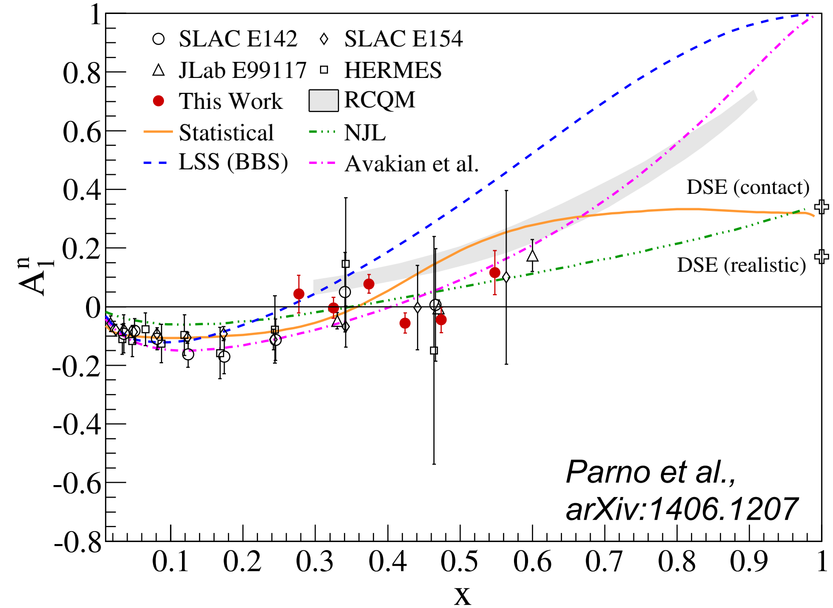
Parton model ->

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1}$$

$$\frac{F_2^n}{F_2^p} = \frac{[1+4(d/u)]}{[4+(d/u)]}$$

$$= \frac{\sum_q e_q^2\, \Delta q(x,Q^2)}{\sum_q e_q^2\, q(x,Q^2)}$$

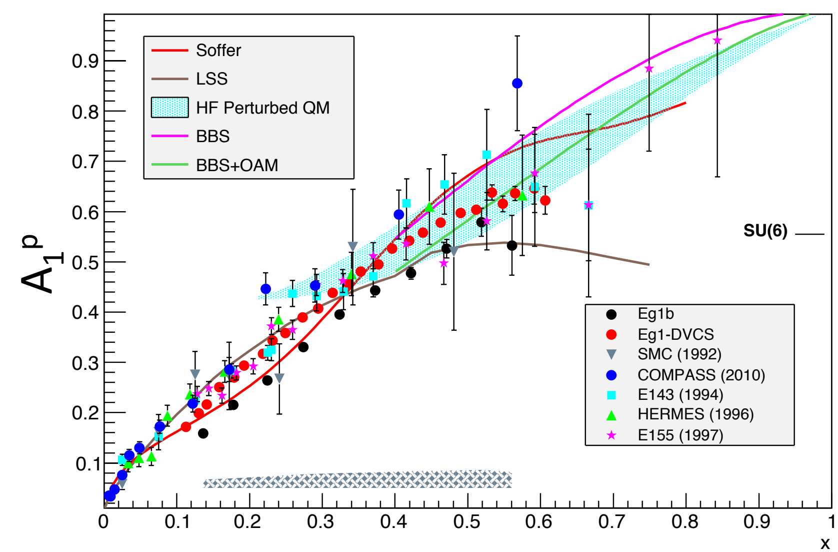




NSAC milestone HP6 (2011) completed, steps toward HP14 (2018)

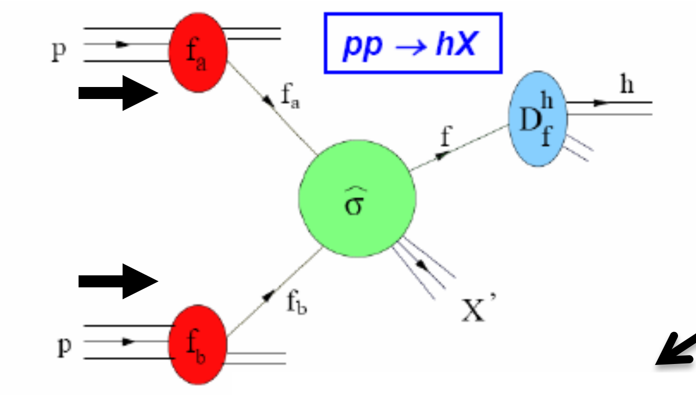
6 JLab 12-GeV experiments

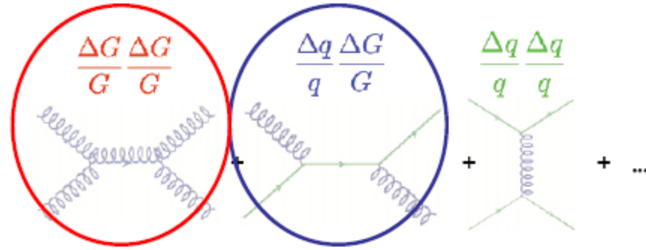
Upgraded JLab has unique capability to define the **valence region**



Thanks to C. Keppel, K. Kumar, G. Petratos, C. D. Roberts, S. Kuhn, Z.-E. Meziani

Measurement of the gluon polarization Δg at RHIC



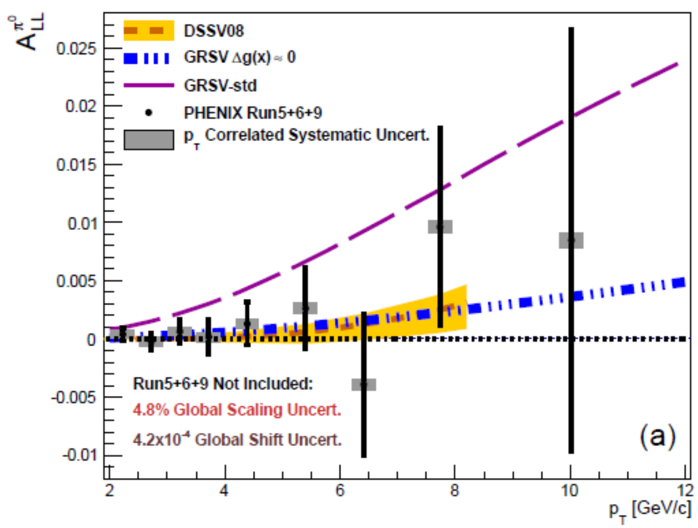


Dominates at low p_T

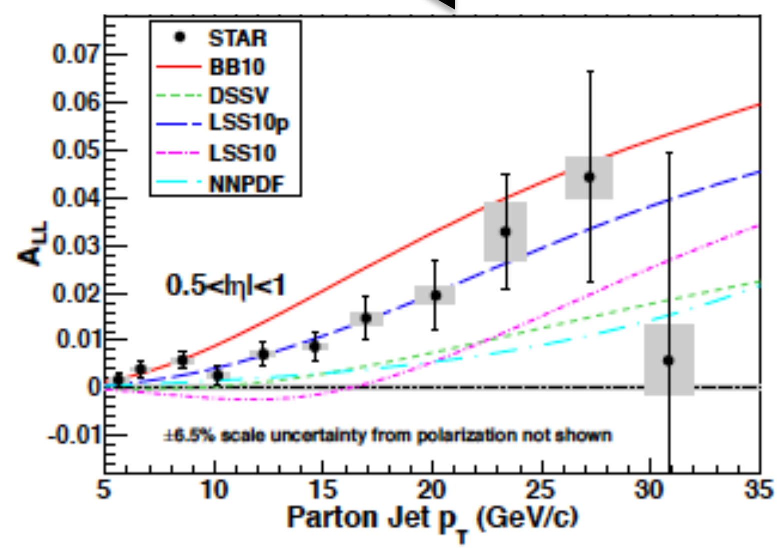
Dominates at high p_T

D. de Florian *et al*, **PRL 113 (2014) 01200**

E. Nocera et al, arXiv 1406.5539



PRD 90 (2014) 012007



arXiv:1405.5134

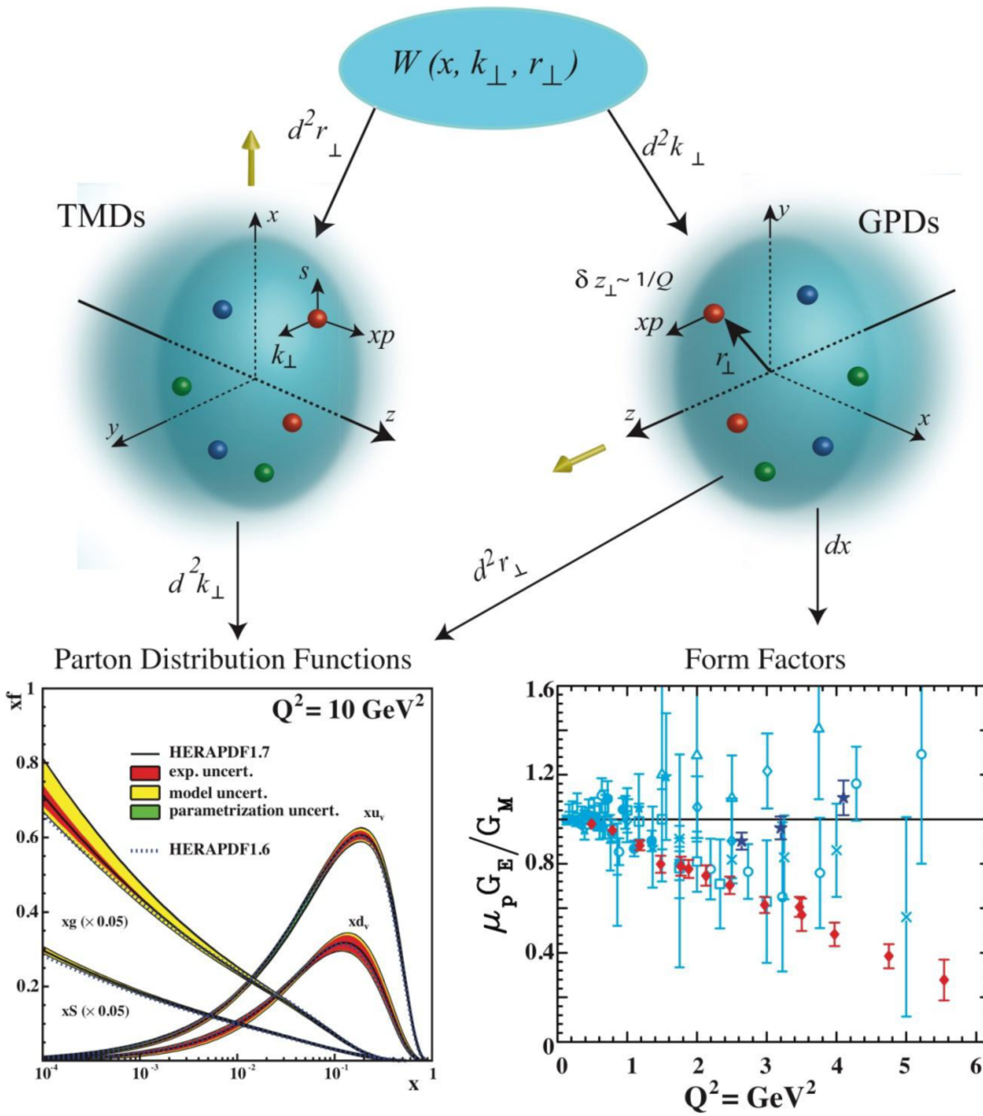
$$\int_{0.05}^{1} dx\Delta g(x,Q^2=10\text{GeV}^2) = 0.20^{+.06}_{-.07} \quad \text{DSSV++}$$

$$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10\text{GeV}^2) = 0.17 +\!- 0.06 \quad \text{NNPDFpol1.1}$$

Multidimensional parton distribution functions

Transverse momentum distribution functions

eg., Sivers distribution



Generalized parton distribution functions

Leading-Twist TMD PDFs

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Long-Transversity
T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Trans-Helicity	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

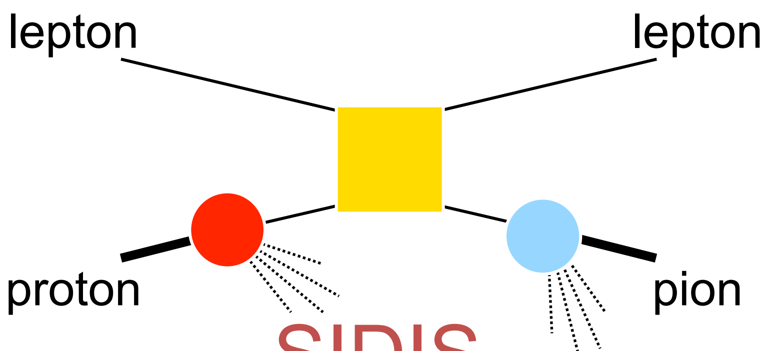
Leading-Twist TMD PDFs

Nucleon Spin

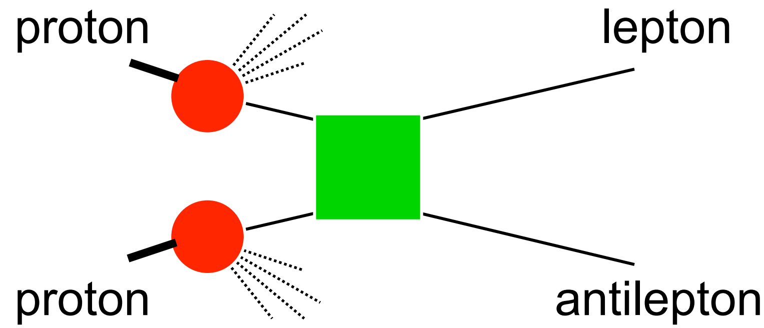
Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Long-Transversity
T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Trans-Helicity	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

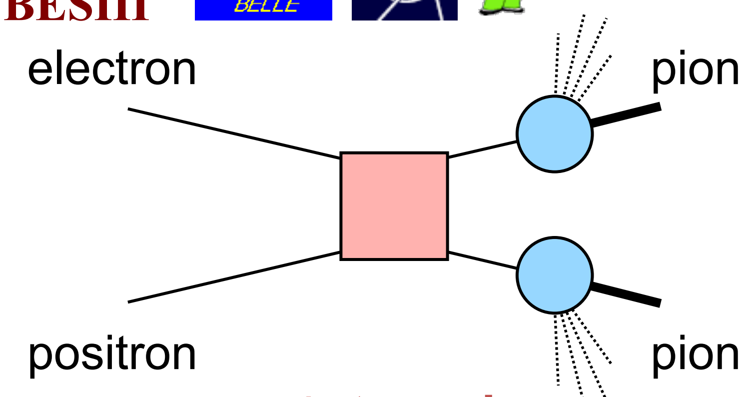
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

- Partonic scattering amplitude (yellow square)
- Fragmentation amplitude (light blue circle)
- Distribution amplitude (red circle)

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

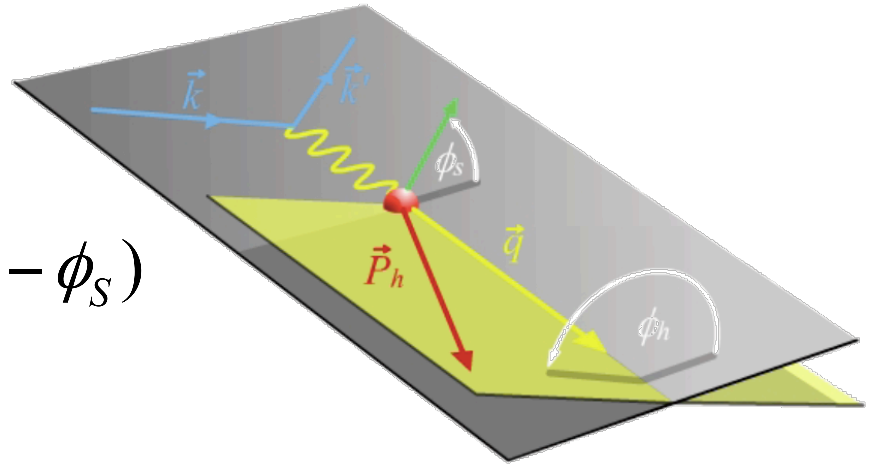
$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

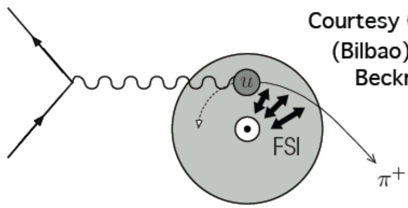
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

The Sivers function

Indication of orbital motion

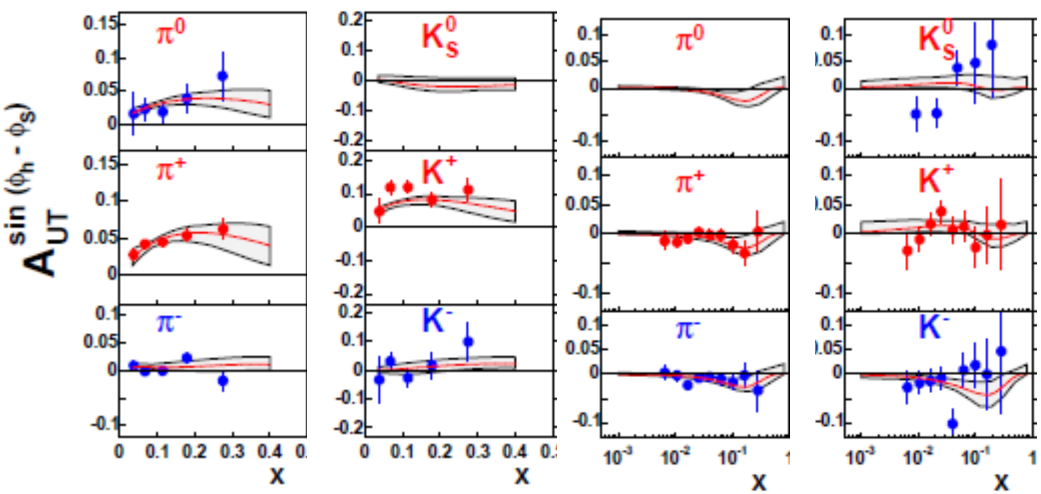


Courtesy G. Schnell (Bilbao) and U. Beckmann

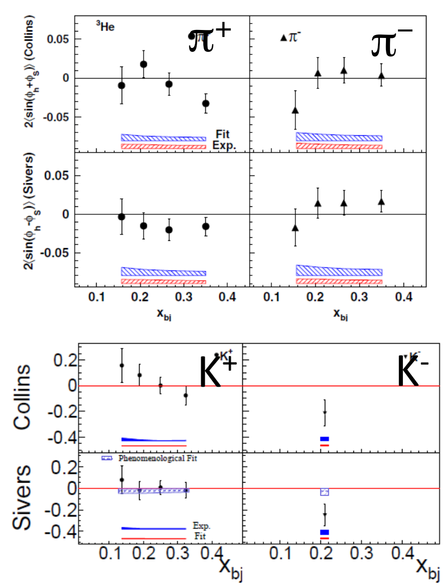
$L_z^u > 0$

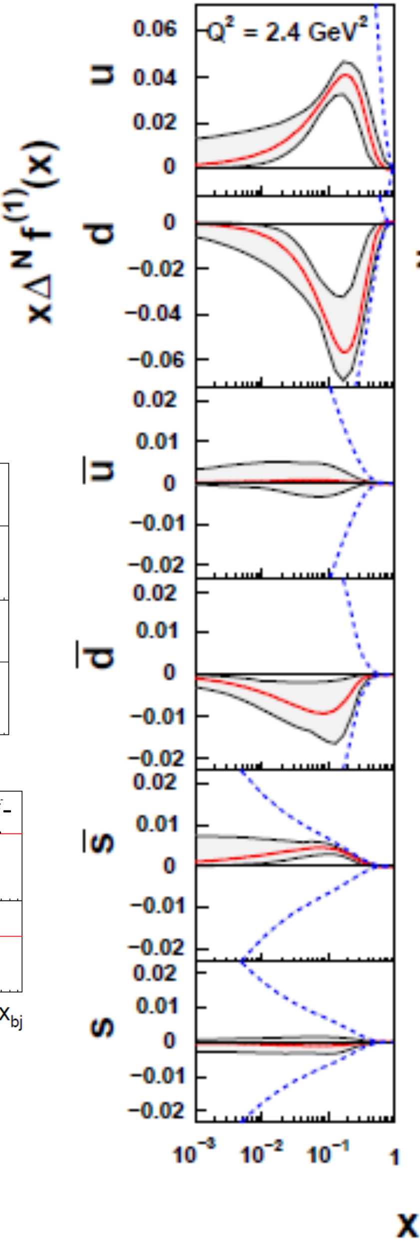
X. Qian et al., PRL 39 (2011) 89
Y. Zhao, et al., arXiv 1404.7204

HERMES COMPASS



JLab



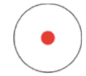


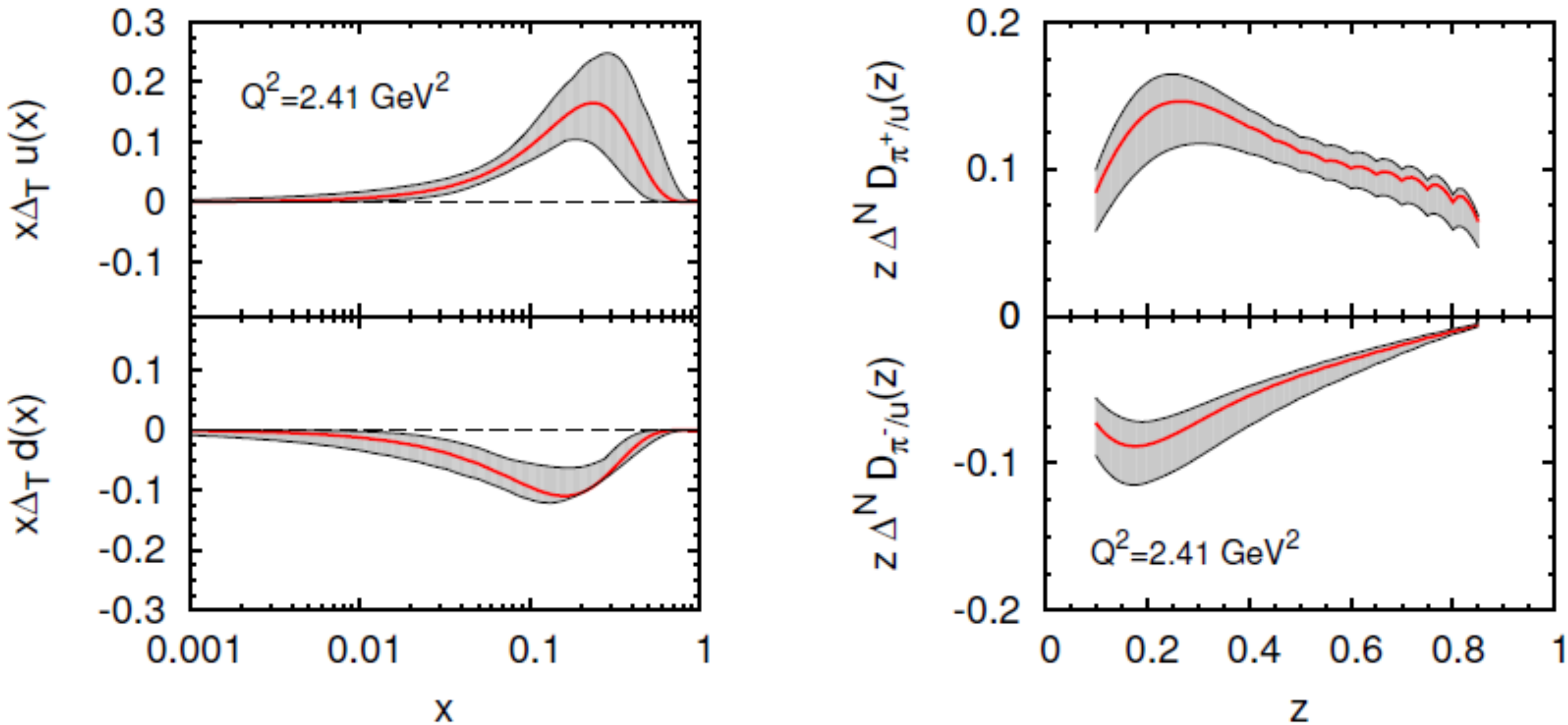
- u and d quark Sivers functions are opposite in sign.
  - L. Gamberg et al, PRD 77 (2008) 094016 → axial diquarks
- Sea quark Sivers functions are non-zero.

Anselmino et al., Eur. Phys. J. A39 (2009) 89

Transversity

h_{1T} = 

- The third PDFs in addition to f_1  and g_{1L} 



$$\Delta_T = h_{1T}$$

A global fit to the HERMES, COMPASS and BELLE e+e- data
Anselmino et al., arXiv:1303.3822

Transversity

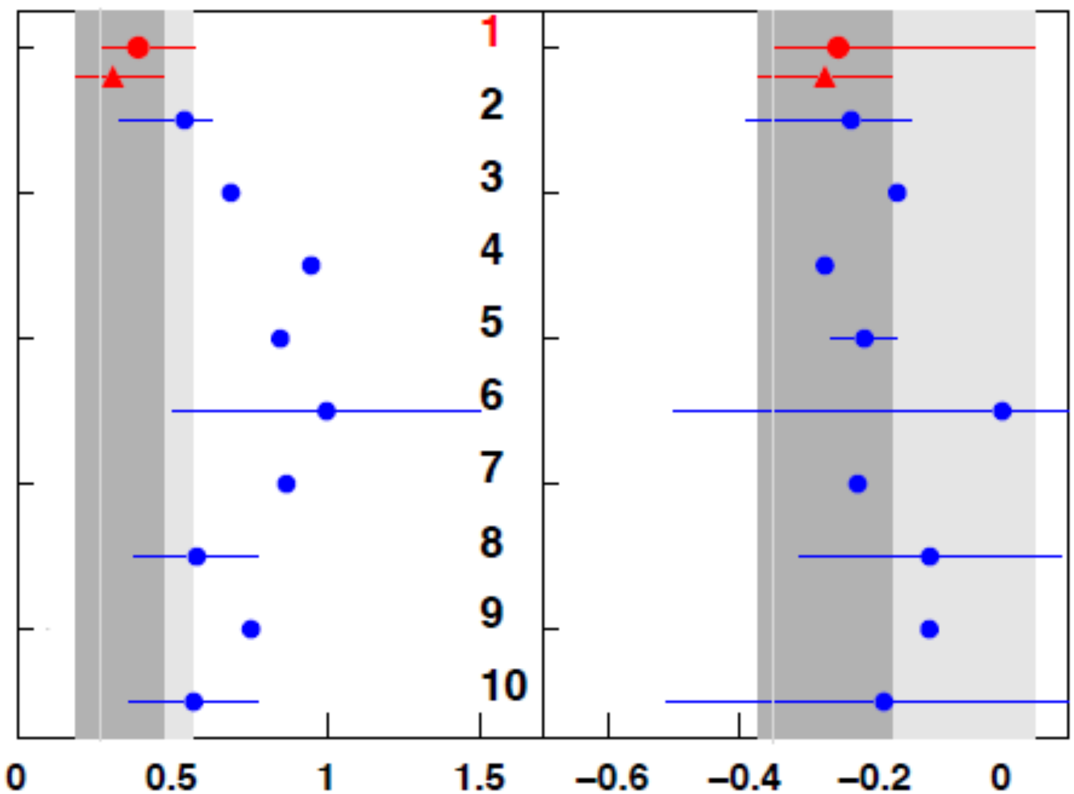
h_{1T} = 

- Lowest moment gives tensor charge
  - Fundamental property, benchmark test of Lattice QCD

$$\delta q^a = \int_0^1 (h_{1T}^a(x) - h_{1T}^{\bar{a}}(x))dx$$

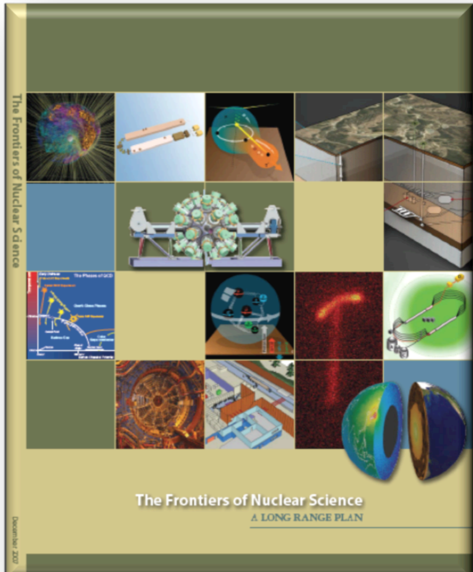
● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$

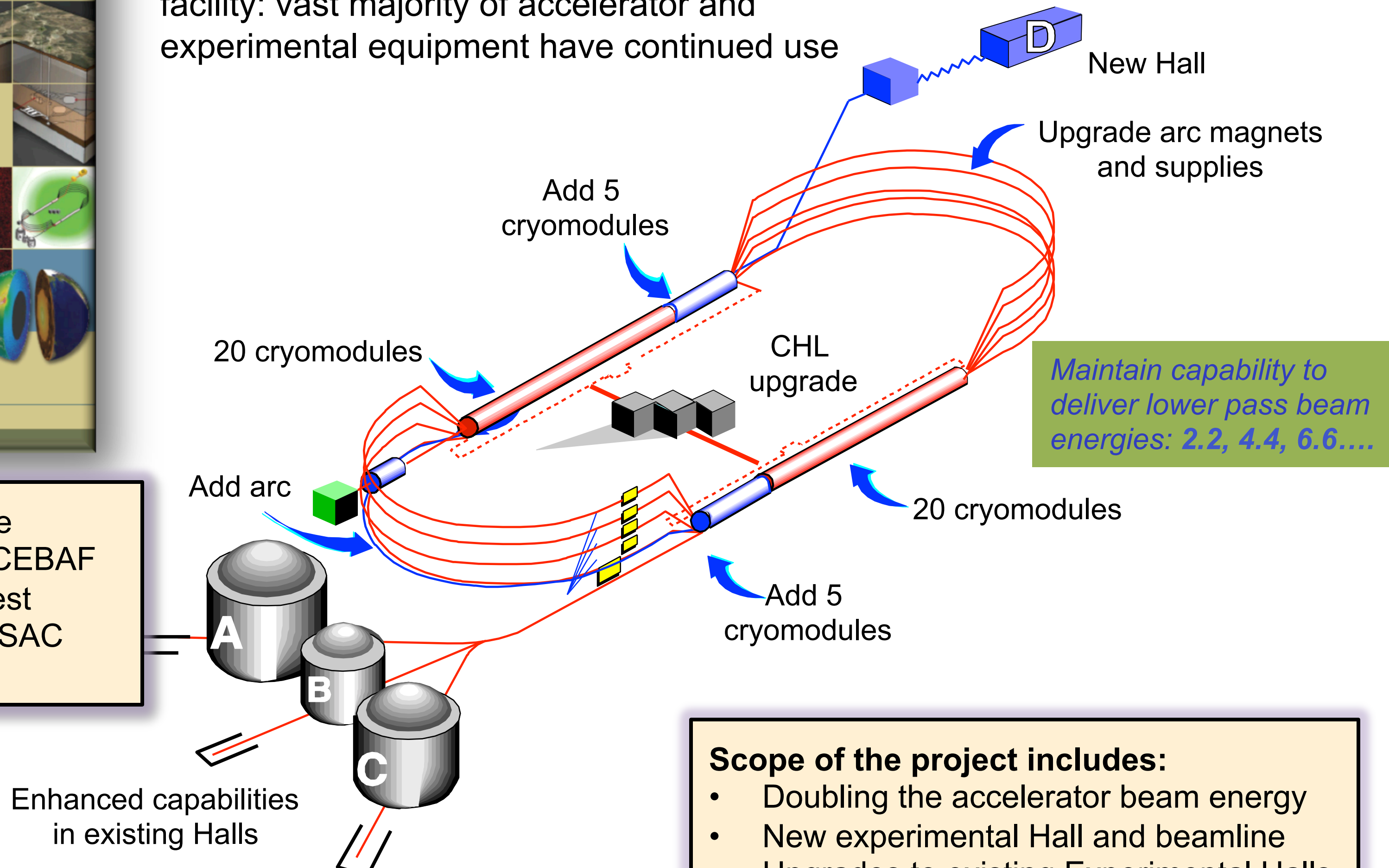


Anselmino et al., arXiv:1303.3822

12 GeV Upgrade Project



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

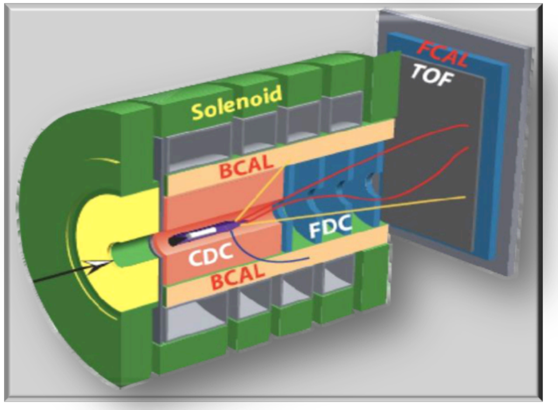


The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

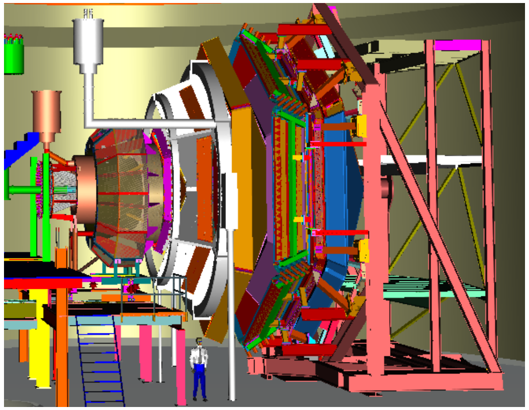
Scope of the project includes:

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

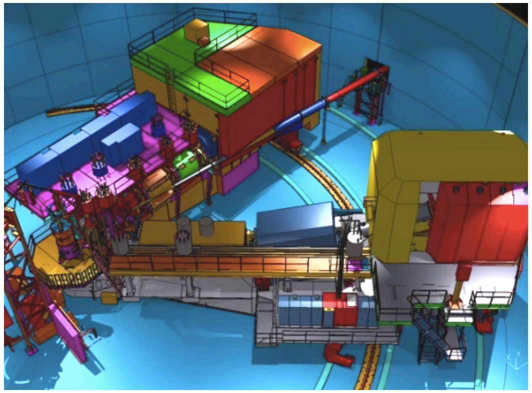
12 GeV Upgrade Physics Instrumentation



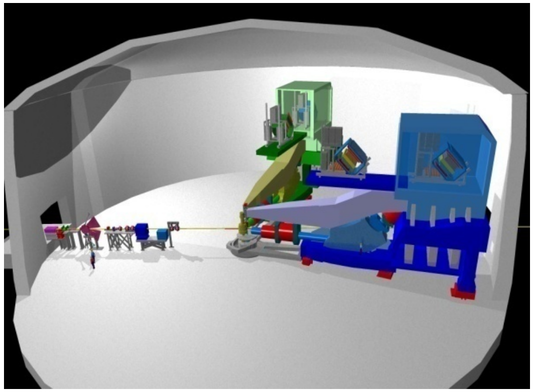
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**



CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**



SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**



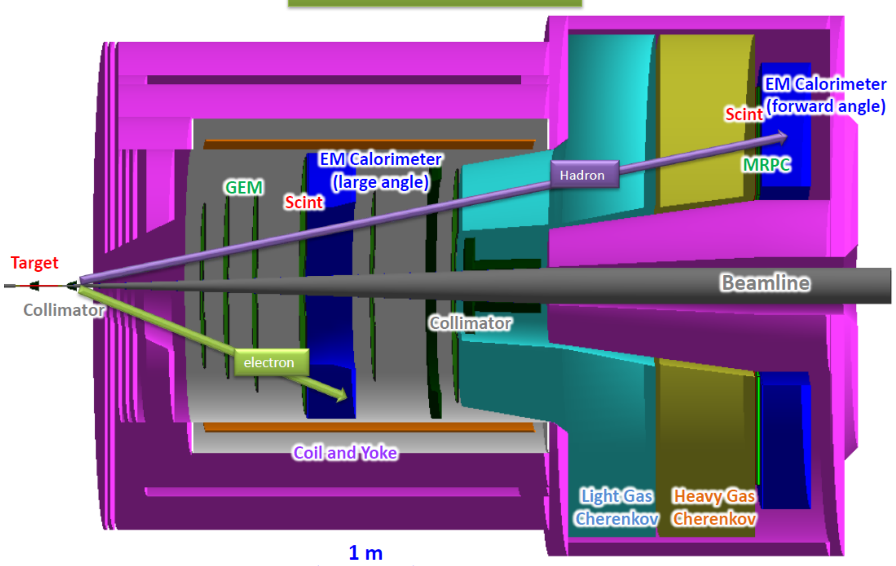
Hall A: **nucleon form factors,**
& future new experiments like Moller & SOLID

Overview of SoLID

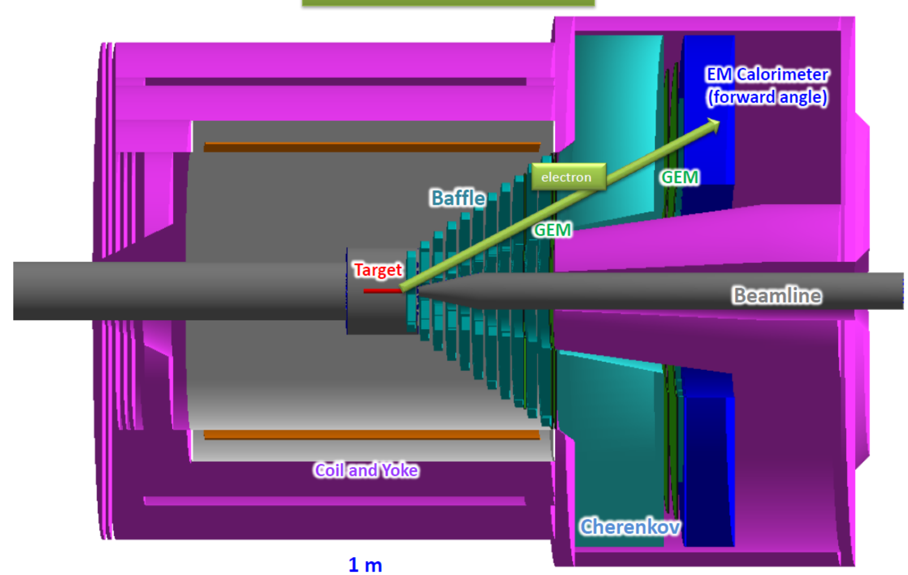
Solenoidal **L**arge **I**ntensity **D**evice

- **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
  Bonus: di-hadron, Inclusive-SSA, and much more …
- **Strong collaboration** (200+ collaborators from 50+ institutes, 11 countries)
  Significant international contributions

SoLID (SIDIS & J/ψ)



SoLID (PVDIS)



Collaboration Institutions from China

中国原子能科学研究院
China Institute of Atomic Energy

中国科学技术大学
University of Science and Technology of China

黄山學院
Huang Shan XueYuan

蘭州大學

華中科技大學
HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

北京大學
PEKING UNIVERSITY

中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

清華大學
Tsinghua University

Chinese Academy of Sciences
IMP
www.impcas.ac.cn

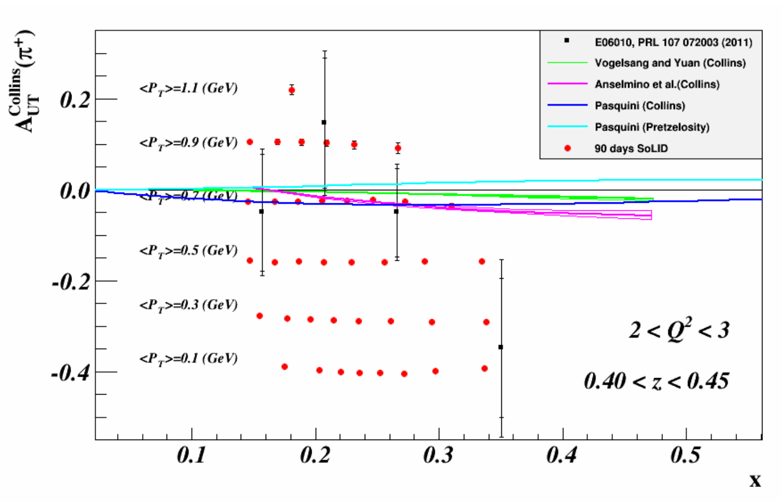
中国科学院近代物理研究所
...titute of Modern Physics,Chinese Academy of Sciences

山东大学
SHANDONG UNIVERSITY

Transversity and Tensor Charge

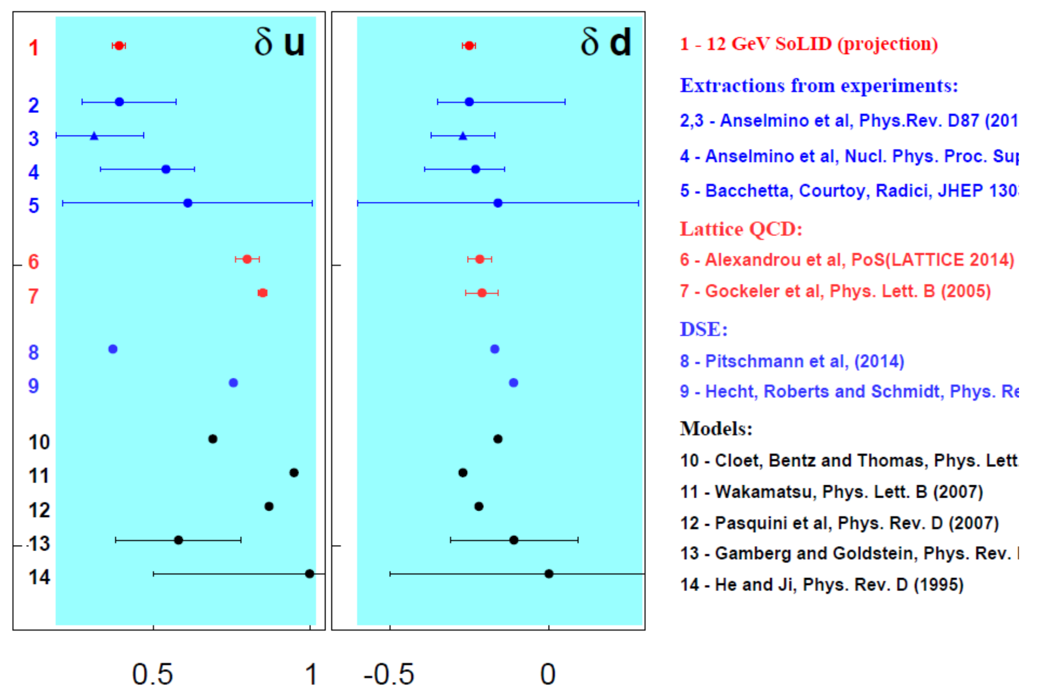
- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , Light-cone Quark Models, …
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → determination of tensor charges for **d & u**

Collins Asymmetries



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

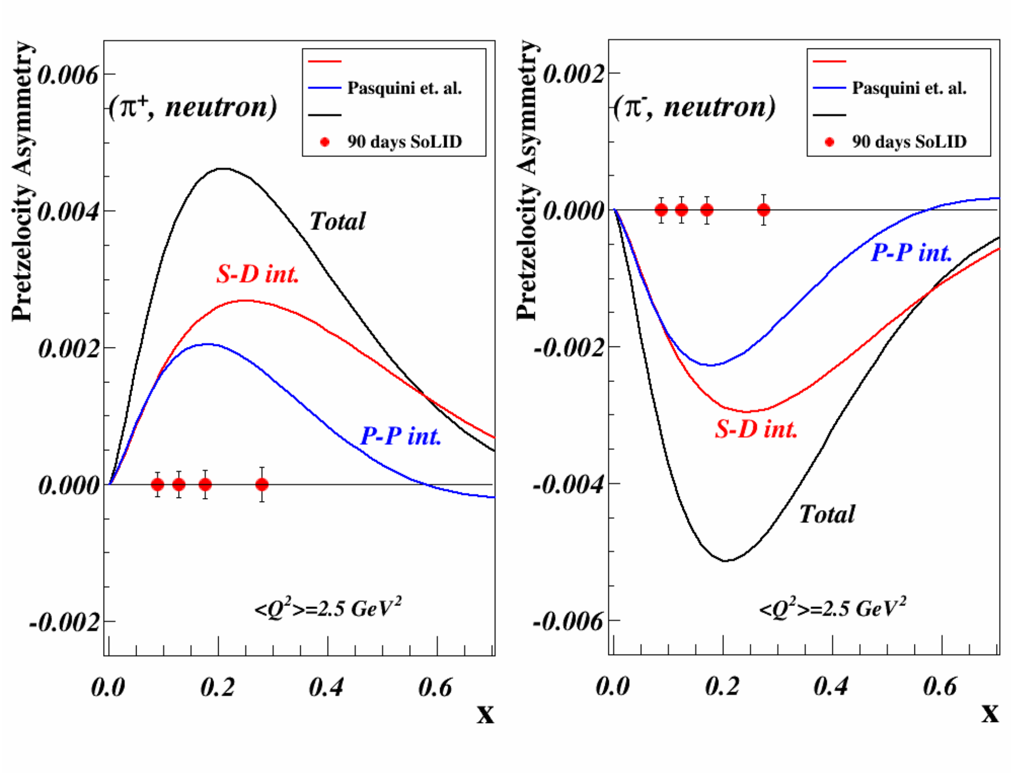
Tensor Charges



- *Projections with a model*
- *There are un-measured regions*
- *QCD evolutions being worked*

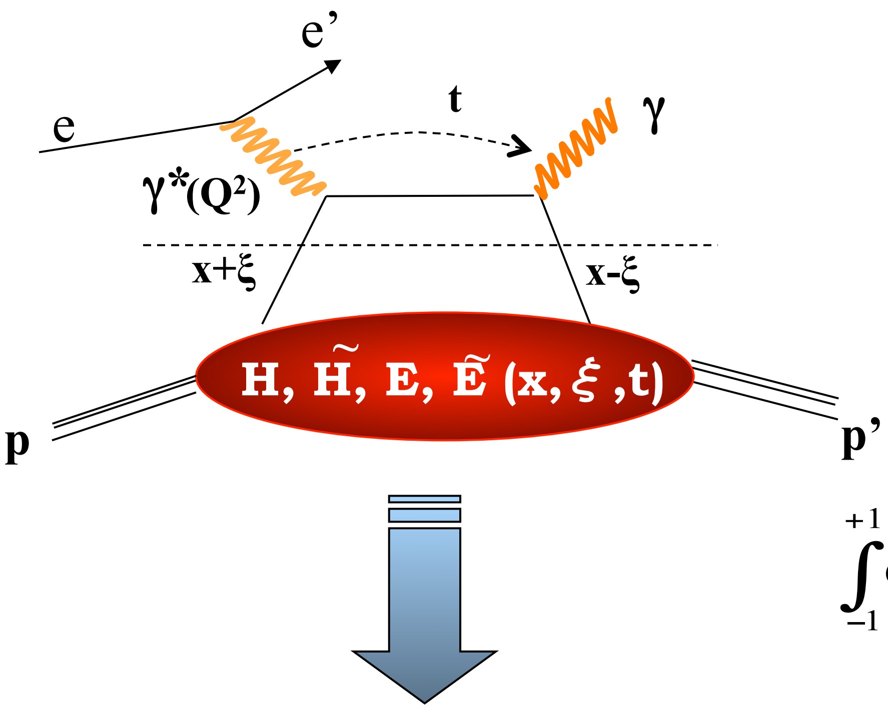
TMDs: 3-d Structure, Quark Orbital Motion

- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0,**
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: ΔL=1 (L=0 and L=1 interference)
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**



Pretzelosity

Generalized parton distributions and DVCS



Vector: **H (x,ξ,t)** **Axial-Vector:** $\widetilde{\mathbf{H}}$ **(x,ξ,t)**

Tensor: **E (x,ξ,t)** **Pseudoscalar:** $\widetilde{\mathbf{E}}$ **(x,ξ,t)**

Forward limit (t →0, ξ→0)

$H^q(x,0,0) = q(x)$ $\quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

Sum rules

$$\int_{-1}^{+1} dx \; H^q(x,\xi,t) = F^q_1(t) \qquad \int_{-1}^{+1} dx \; E^q(x,\xi,t) = F^q_2(t)$$

Quark angular momentum (Ji's sum rule)

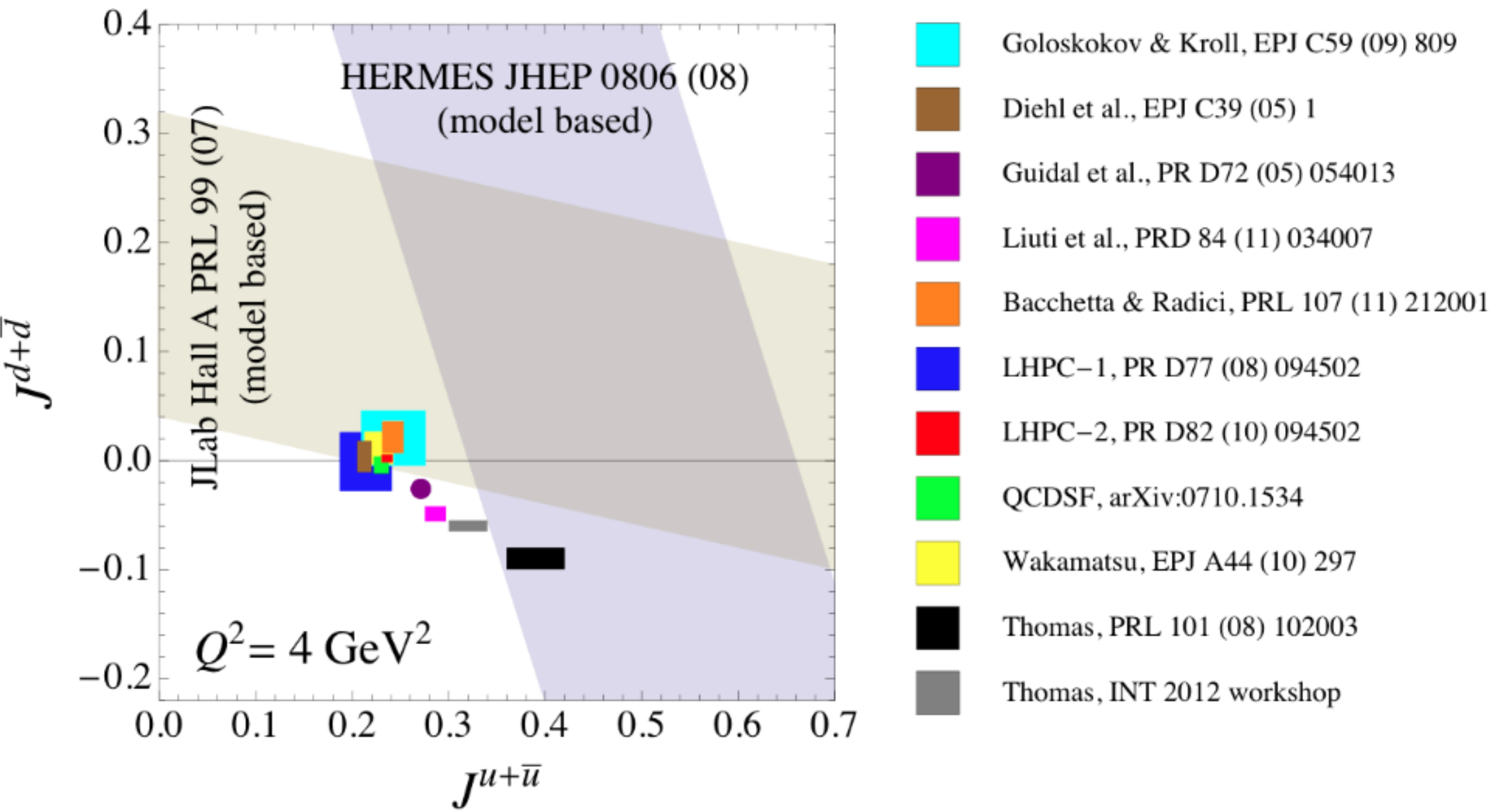
$$\int_{-1}^{1} (\, H(x,\xi,t=0) + E(x,\xi,t=0)\,)\; x\, dx = J_{quark} = 1/2\, \Delta\Sigma + \Delta L_z$$

X. Ji, Phy.Rev.Lett.78,610(1997)

A. Radyushkin, PRD **56** (1996) 5524

C. Munoz Comacho *et al*, PRL **97** (2006) 262002 ; F. X. Girod *et al*, PRL **100** (2008)162002.

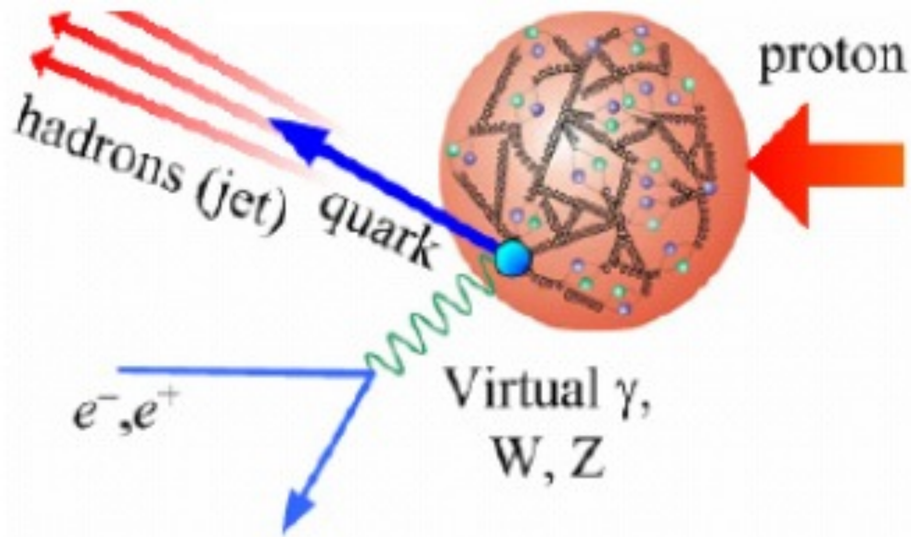
Extraction of quark total angular momentum

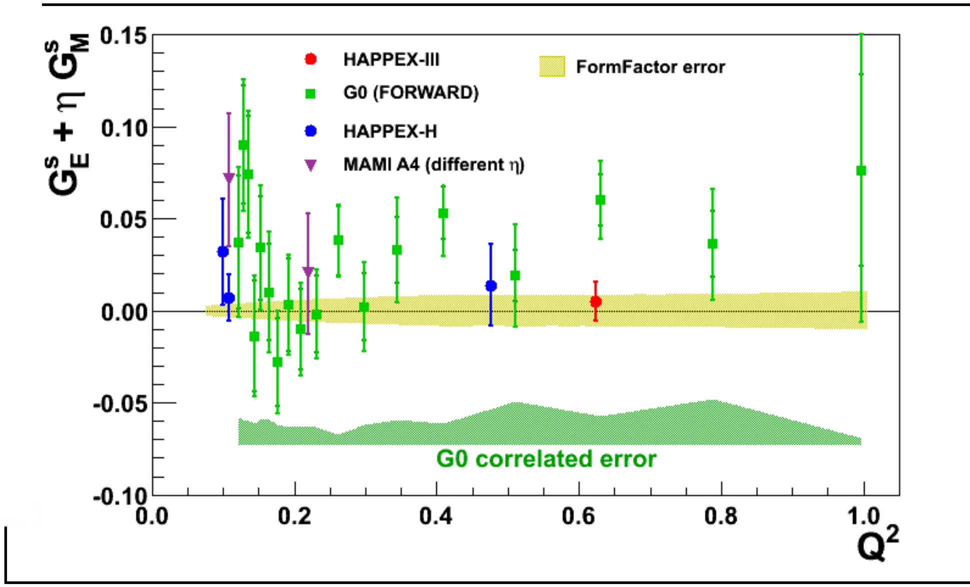


Plot credit: JLab whitepaper

- **DVCS is the "golden channel":**
  γ^* + N -> γ + N'
- **"Lattice + experiment** provides a much greater constraint on GPDs than from either alone." - J. Negele
- Major program for JLab 12 GeV, COMPASS-II, EIC

Parity Violating Electron Scattering





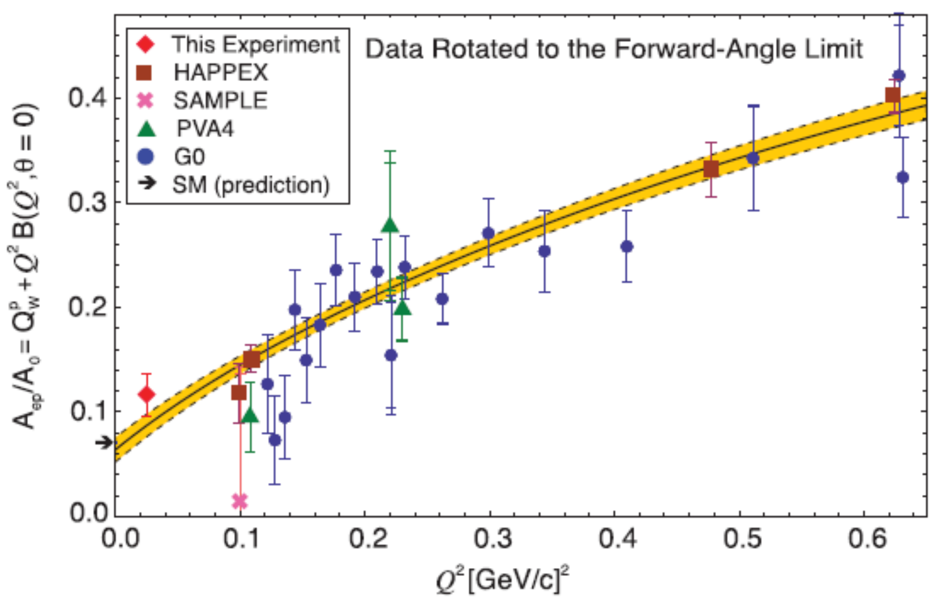
- **Nucleon Strangeness Form Factors**
- **Weak charge of the proton**
- **Precision Tests of Standard Model**
- **Neutron skin**

Parity-violating electron scattering

$$\sigma \sim |M_\gamma + M_Z|^2 = |M_\gamma|^2 + |M_Z|^2 + 2\,\mathrm{Re}(M_\gamma^*)(M_Z)$$

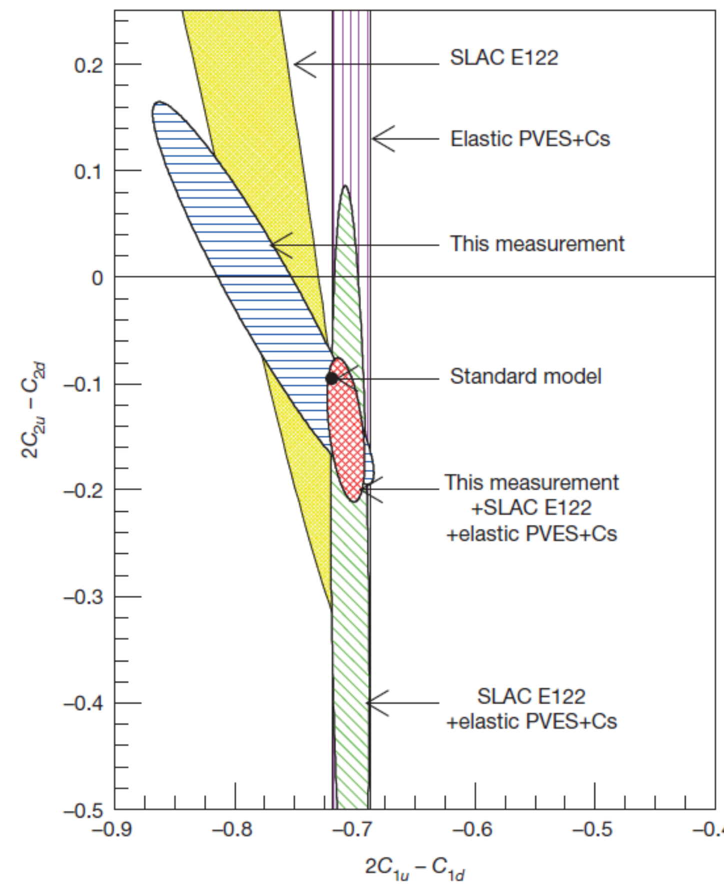
$$APV = (\sigma_R - \sigma_L)/(\sigma_R - \sigma_L)$$

First determination of proton's weak charge



D. Androic et al, PRL 111 (2014) 141803

First indication of non-zero
Electron-vector and quark-axial-vector
coupling

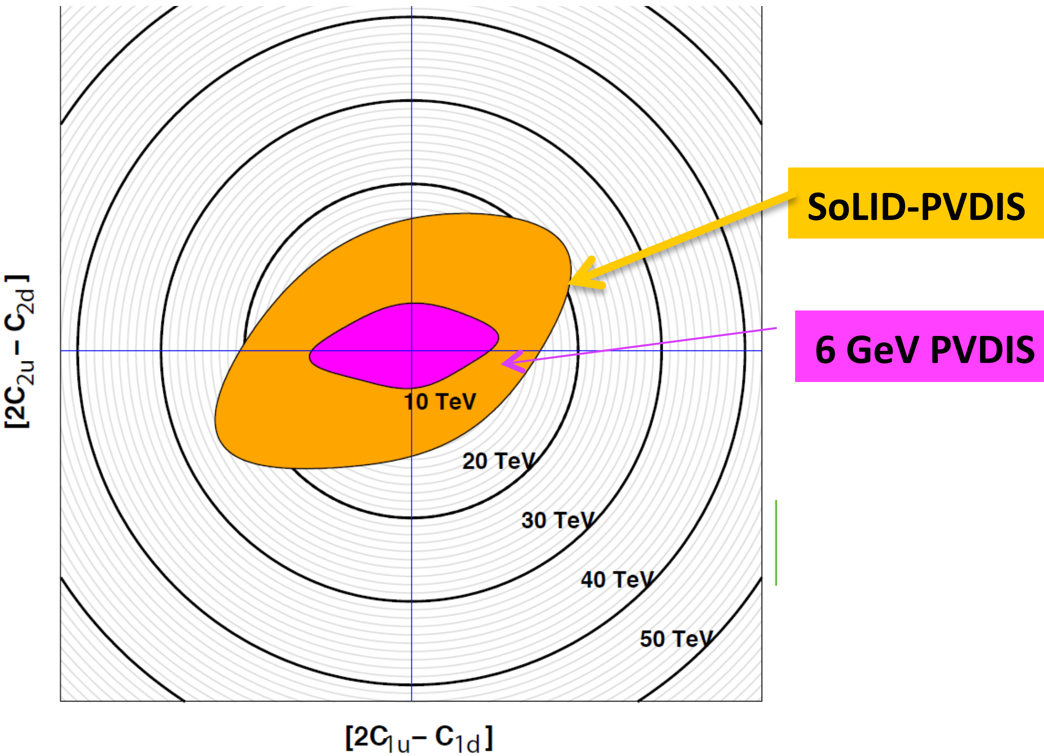


D. Wang et al, Nature 506 (2014) 7486

Parity Violation with SoLID

Parity-violating Deep Inelastic Scattering:

- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - **charge symmetry violation**
  - **d/u at large x**
  - **quark-gluon correlations**

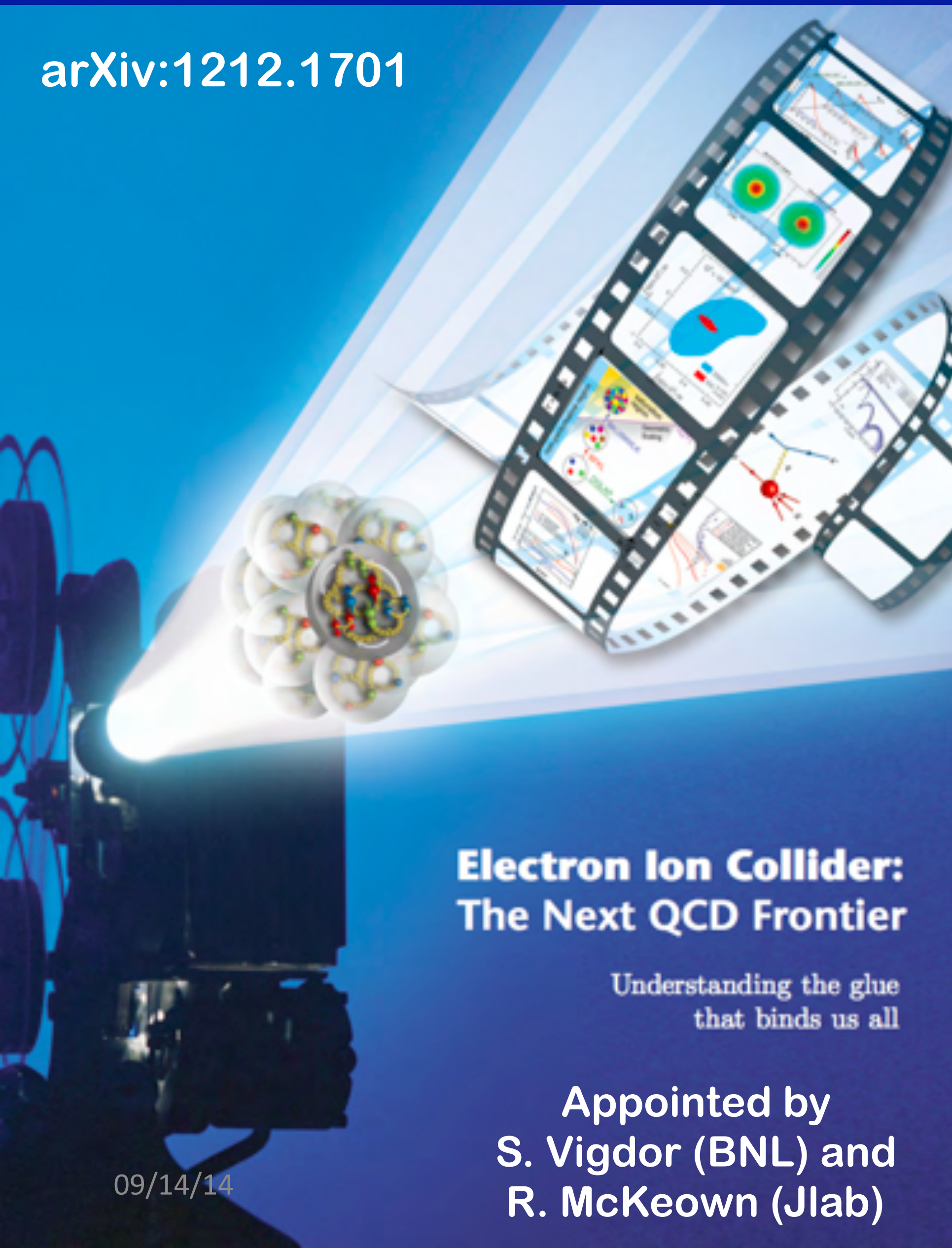


PVDIS asymmetry has two terms:
1) C_{2q} weak couplings, test of Standard Model
2) Unique precision **quark structure information**

Mass reach in a composite model
SoLID-PVDIS ~ 20 TeV (LHC scale)

U.S.-based EICs – the White Paper

arXiv:1212.1701



Appointed by
S. Vigdor (BNL) and
R. McKeown (Jlab)

Overall Editors:
A. Deshpande (Stony Brook), Z-E. Meziani (Temple), J. Qiu (BNL)

Gluon Saturation in e+A:
T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
E. Sichtermann (LBNL) and W. Vogelsang (Tübingen)

GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and F. Yuan (LBNL)

Parton Propagation in Nuclear Medium:
W. Brooks (TSFM) and J. Qiu(BNL)

Electroweak physics:
K. Kumar (U Mass) and M. Ramsey-Musolf (Wisconsin)

Accelerator design and challenges:
A. Hutton (JLab) and T. Roser (BNL)

Detector design and challenges:
E. Aschenauer (BNL) and T. Horn (CUA)

Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

Successful thanks to many other co-authors and contributions

Science Questions

- What is the transverse spatial and momentum structure of the gluons and sea quarks? Are there non-perturbative structures and can one image them?

- How much do the gluons contribute to the nucleon spin? Is there significant orbital angular momentum?

- How is the gluon distribution in nuclei different than in the nucleon? How does this relate to nuclear binding or short range nucleon-nucleon correlations?

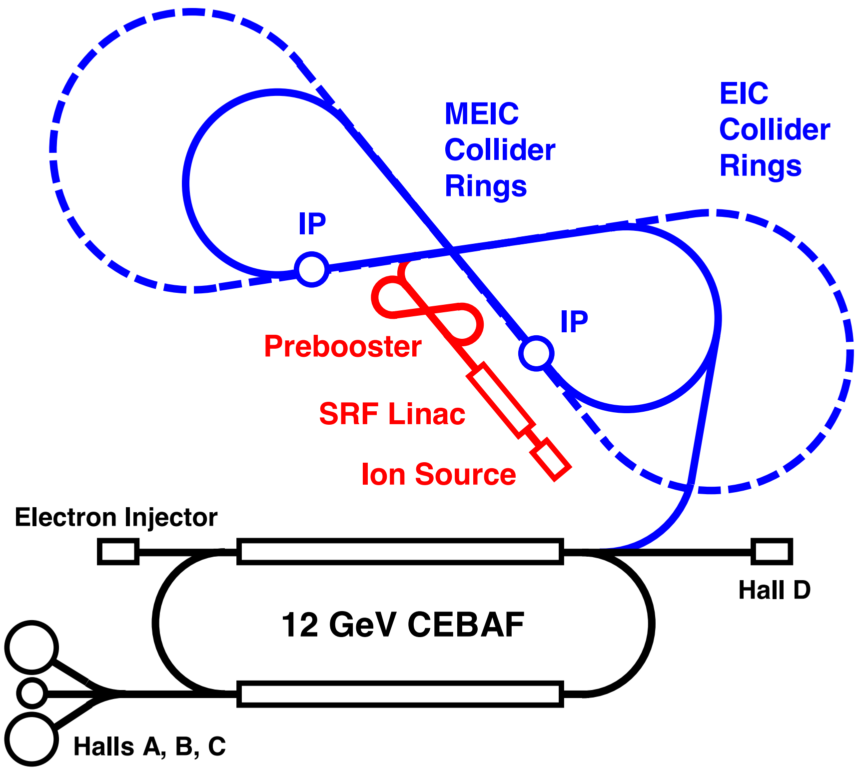
- Can one find evidence for saturation of the gluon density?

- How do quarks and gluons propagate in nuclear matter and join together to form hadrons?

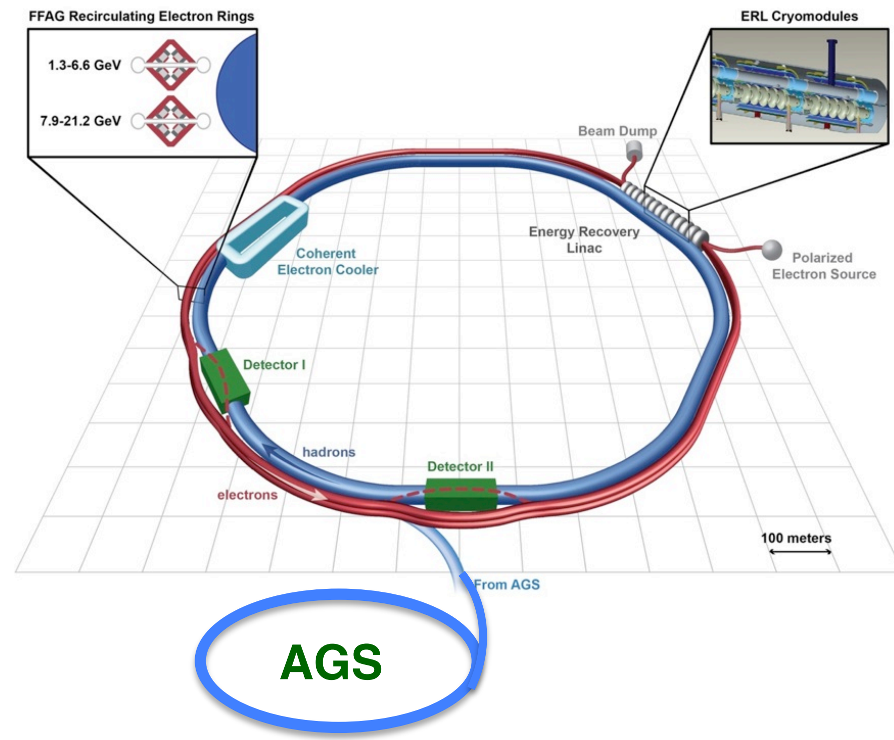
R.D. McKeown, Joint QCD town Meetings, September, 2014

U.S.-based EICs – the Machines

MEIC (JLab)



eRHIC (BNL)



- ✧ First polarized electron-proton/light ions collider in the world
- ✧ First electron-nucleus (various species) collider in the world
- ✧ Both cases make use of existing facilities (H. Montgomery, Oct 29)

Summary

- Lepton scattering is a powerful tool to probe the rich internal structure of the nucleon
- Spin remains to be important and puzzling in the case of the nucleon
- Proton charge radius puzzle prompts intensive theoretical and experimental efforts
- Three-dimensional imaging of nucleon helps solve remaining puzzle to the proton spin, and uncovers the rich dynamics of QCD
- PV electron scattering probes internal structure of the nucleon, provides tests of SM and searches for new physics
- Electron Ion Collider – A new QCD frontier that US NP QCD community is hoping for (ongoing US NP LRP)

Thanks to E. Aschenaur, J.-P Chen, A. Deshpande, R. Ent, R. Gilman, R. Holt, J. Huang, X. D. Ji, R.D. McKeown, M. Meziane, Z.-E. Meziani, H. Montgomery, A. Prokudin, J.W. Qiu, C. Roberts, P. Souder, Z. Ye, F. Yuan, Z. Zhao, X. Zheng

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231