Physics Program at Jefferson Lab and a Future Electron-Ion Collider

J. P. Chen, Jefferson Lab, Virginia, USA

BCVSPIN, Hue, Vietnam, July 26, 2011

- Introduction
- JLab 6 GeV Facility and 12 GeV Upgrade
- A Future Electron-Ion Collider (EIC)
- Highlights of JLab 6 GeV Results and 12 GeV Program
  - Form Factors, Spin Structure
  - Transverse Momentum Dependent Structure (TMDs)
  - Generalized Parton Distributions (GPDs)
  - Test Standard Model with Parity-Violation Electron Scattering
  - Hadron Spectroscopy
- Physics Program with EIC
  - Study the quark-gluon structure of the sea: TMDs, GPDs of the sea/gluons
  - Gluon saturation,…

Standard Model

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

What are the challenges?

- Success of the Standard Model

  Electro-Weak theory tested to very good level of precision

  QCD tested in the high energy (short distance) region

- Major challenges:

  Test QCD in the strong interaction region (distance of the nucleon size)

  Understand quark-gluon structure of the nucleon

  Confinement

- Beyond Standard Model

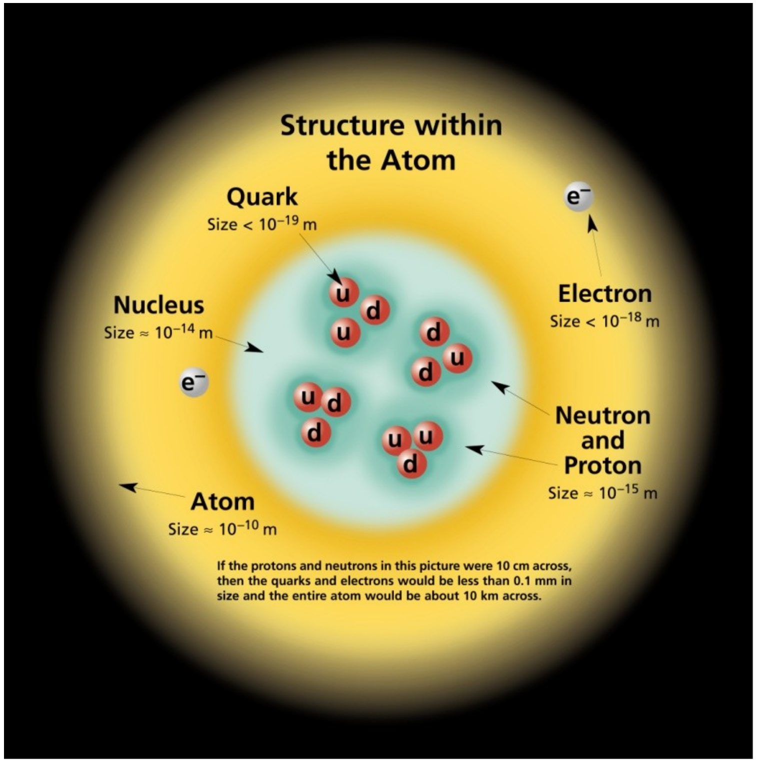
  Energy frontier: LHC search

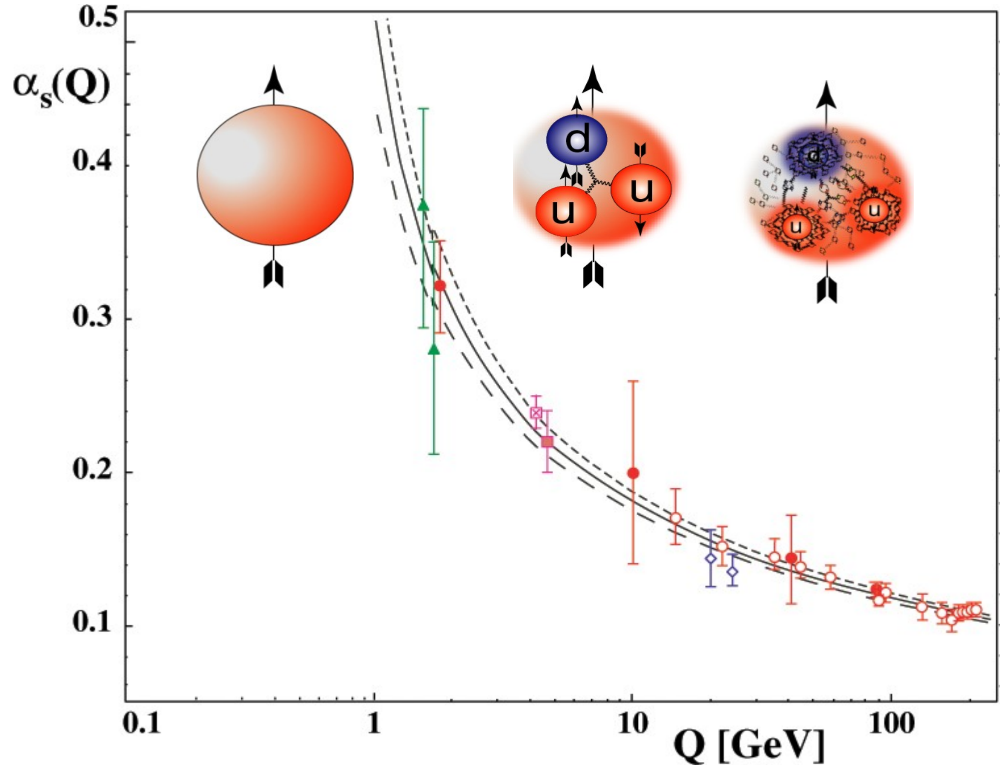
  Higgs? Supersymmetry? …

  Search for dark matter, dark energy, …

  Precision: test Standard Model at low energy

QCD: still unsolved in non-perturbative region





- *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*

Nucleon Structure

- Nucleon: proton =(uud) ,   neutron=(udd)
  + sea + gluons

- Global properties and structure: full of suprises
  - Mass: 99% of the visible mass in universe
    ~1 GeV, but u/d quark mass only a few MeV each!
  - Charge and magnetic distributions: different!
  - Proton charge radius: muonic hydrogen Lamb shift result! **(Nature 466, 213 (2010))**
  - Momentum: quarks carry ~ 50%
  - Spin: ½, but total quarks contribution only ~30%! — Spin Sum Rule
  - Magnetic moment: large part is anomalous, >150%! — GDH Sum Rule
  - Axial charge — Bjorken Sum Rule
  - Tensor charge
  - Orbital angular momentum
  - …

Electron Scattering and Nucleon Structure

- Clean probe to study nucleon structure
  only electro-weak interaction, well understood

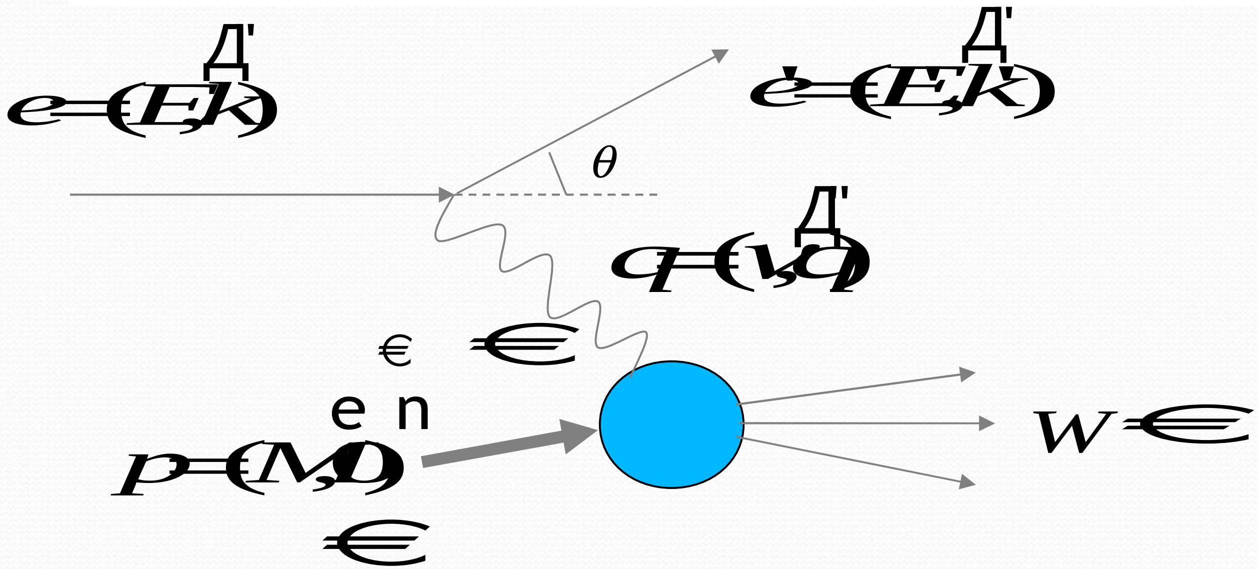
- Elastic Electron Scattering: Form Factors
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions

- Resonance Excitations

  → internal structure, rich spectroscopy (new particle search)
  constituent quark models

- Deep Inelastic Scattering
  → 70s: established quark-parton picture (Nobel Prize)
  parton distribution functions (PDFs)
  polarized PDFs : Spin Structure

Inclusive Electron Scattering



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

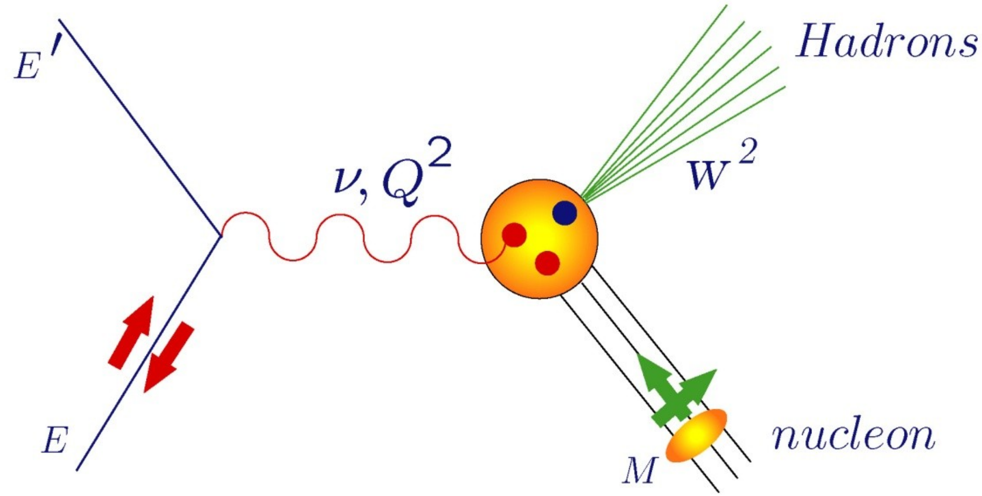
Unpolarized:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[\frac{1}{\nu} F_2(\nu, Q^2) + \frac{2}{M} F_1(\nu, Q^2) \tan^2\frac{\theta}{2} \right]$$

$$\sigma_M = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}$$

F_1 and F_2: information on the nucleon/nuclear structure

Polarized Deep Inelastic Electron Scattering



$x = \dfrac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Quark-Parton Model

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 f_i(x) \qquad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$f_i(x) = \quad q_i^{\uparrow}(x) + q_i^{\downarrow}(x)$$

$$\Delta q_i(x) = \quad q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

$q_i(x)$ quark momentum distributions of flavor i

$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

$F_2 = 2xF_1$ $\qquad$ $g_2 = 0$

$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\Sigma\,\Delta q_i(x)}{\Sigma\,f_i(x)}$$

JLab Facility

6 GeV CEBAF, 3 Experimental Halls

Thomas Jefferson National Accelerator Facility

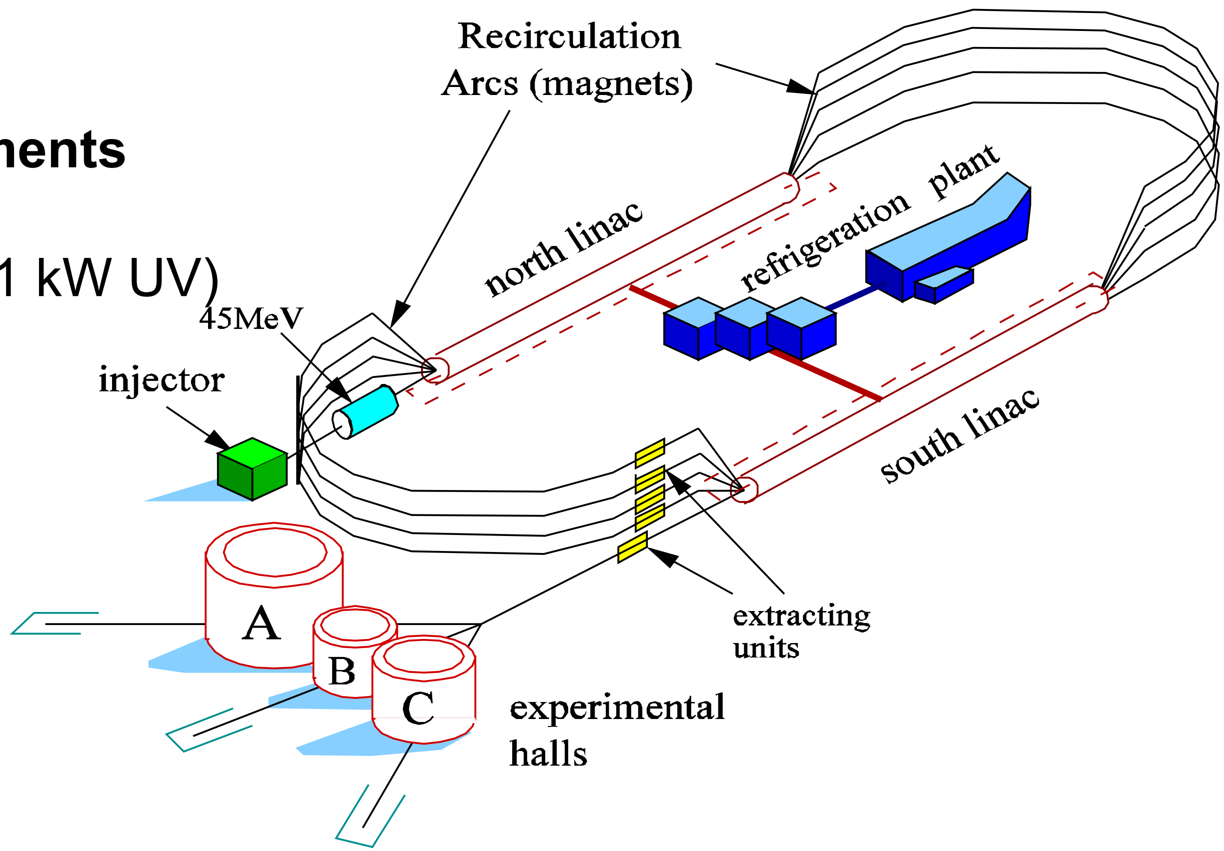
Newport News, Virginia, USA

One of two primary DOE nuclear/hadronic physics laboratories

6 GeV polarized CW electron beam
(P = 85%, I = 180 μ A)

3 halls for fixed-target experiments

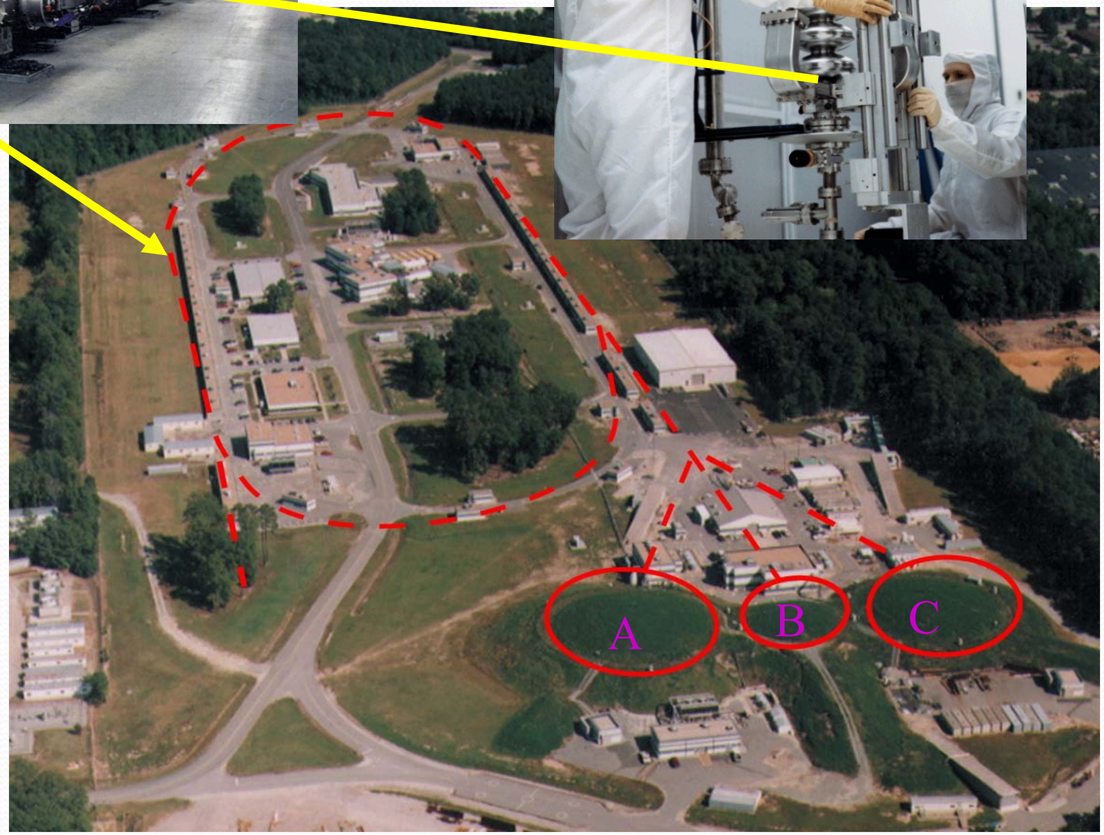
Free Electron Laser (10kW IR, 1 kW UV) for material research



Unique Forefront Capabilities for Science

Cryomodules in the accelerator tunnel

Superconducting radiofrequency (SRF) cavities undergo vertical testing.

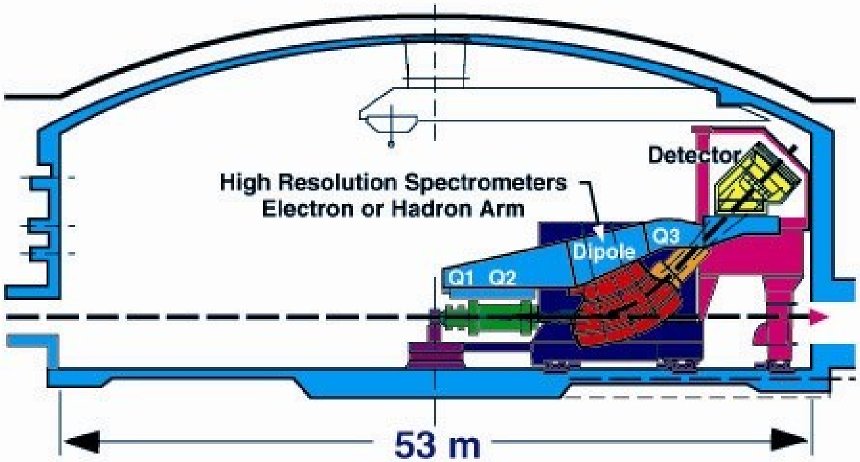


An aerial view of the recirculating linear accelerator and 3 experimental halls.

CEBAF @ JLab Today

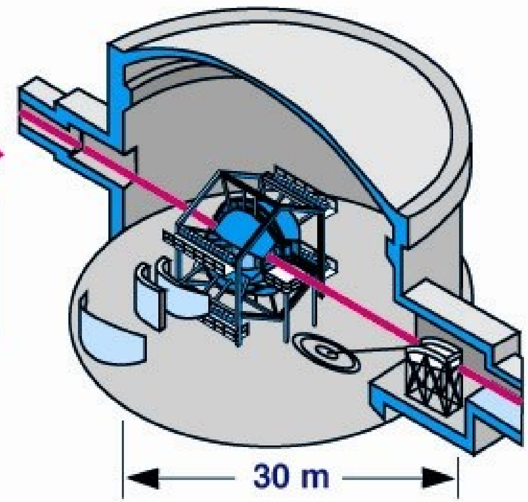
- Superconducting recirculating electron accelerator
  - maximum energy 6 GeV
  - maximum current 200 μ A
  - electron polarization 85%
- Equipment in 3 halls (simultaneous operation) $L[cm^{-2}s^{-1}]$ (pol)
  - A: 2 High Resolution Spectrometers 10^{39} (10^{36})
  - B: Large Acceptance Spectrometer 10^{34} (10^{34})
  - C: 2 spectrometers and dedicated devices 10^{39} (10^{35})
- JLab and User Community
  - ~600 JLab employees
  - ~2000 users from ~300 institutions, ~40 countries
  - ~ 1/4-1/3 of the nuclear physics PhDs in US
  - Experiment scale: ~100 collaborators (10-20 core), ~run for few months

SIMULTANEOUS COMPLEMENTARY EXPERIMENTS



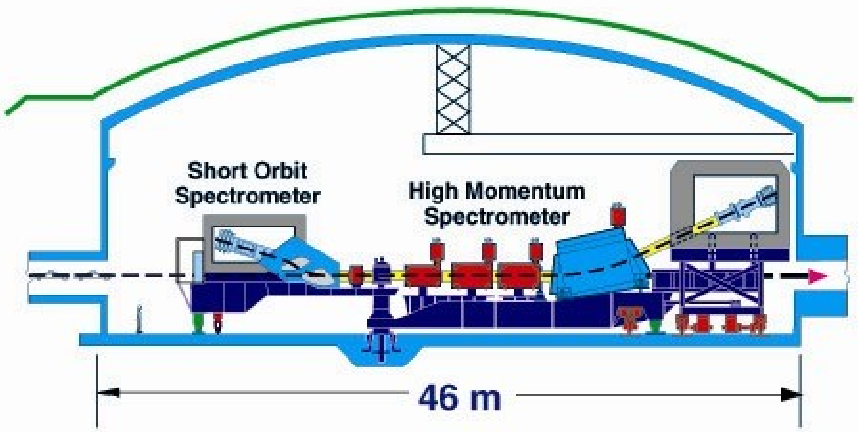
HALL A

Pair of identical High Resolution Spectrometers (HRS^2)



HALL B

CEBAF's Large Acceptance Spectrometer (CLAS) and Bremsstrahlung Photon Tagger



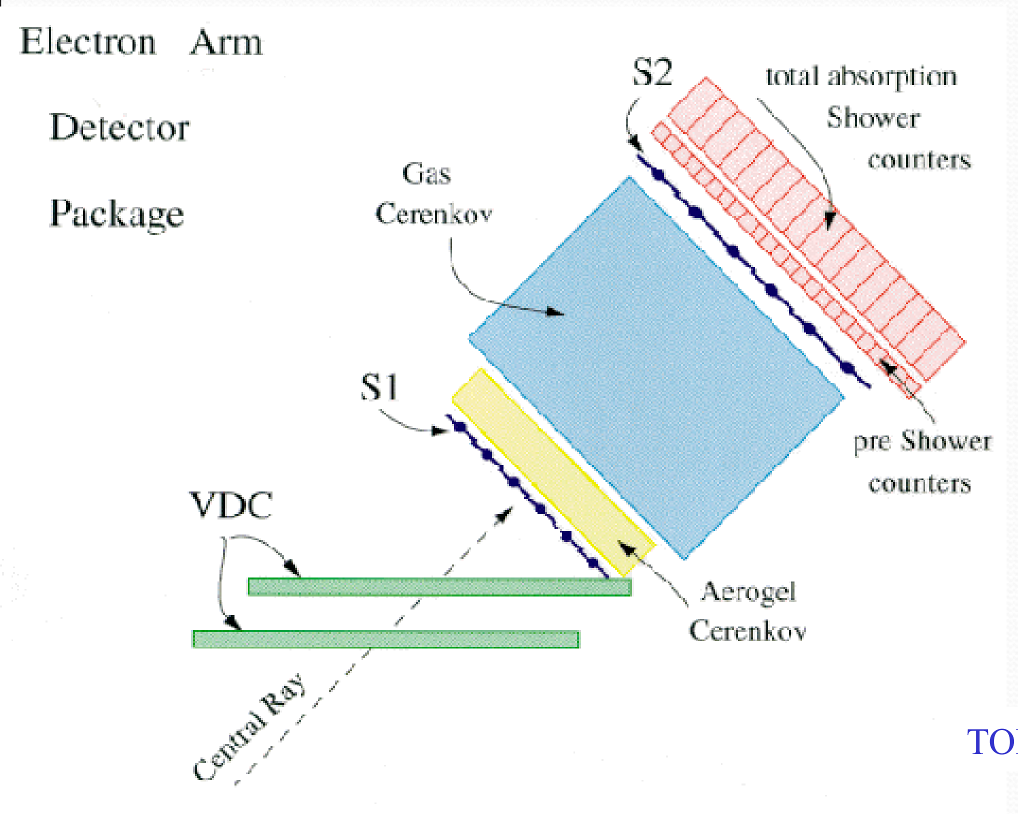
HALL C

High Momentum Spectrometer (HMS) and Short Orbit Spectrometer (SOS)

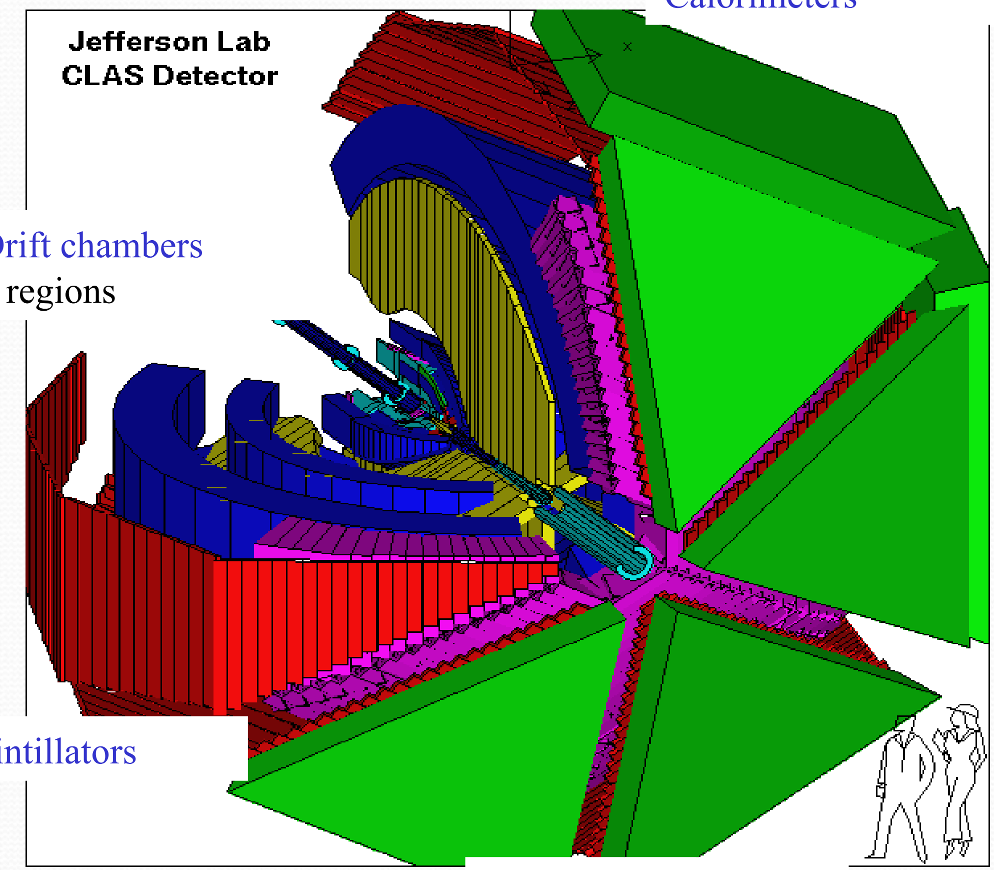
Jefferson Lab

Detector Packages

Hall A Detectors



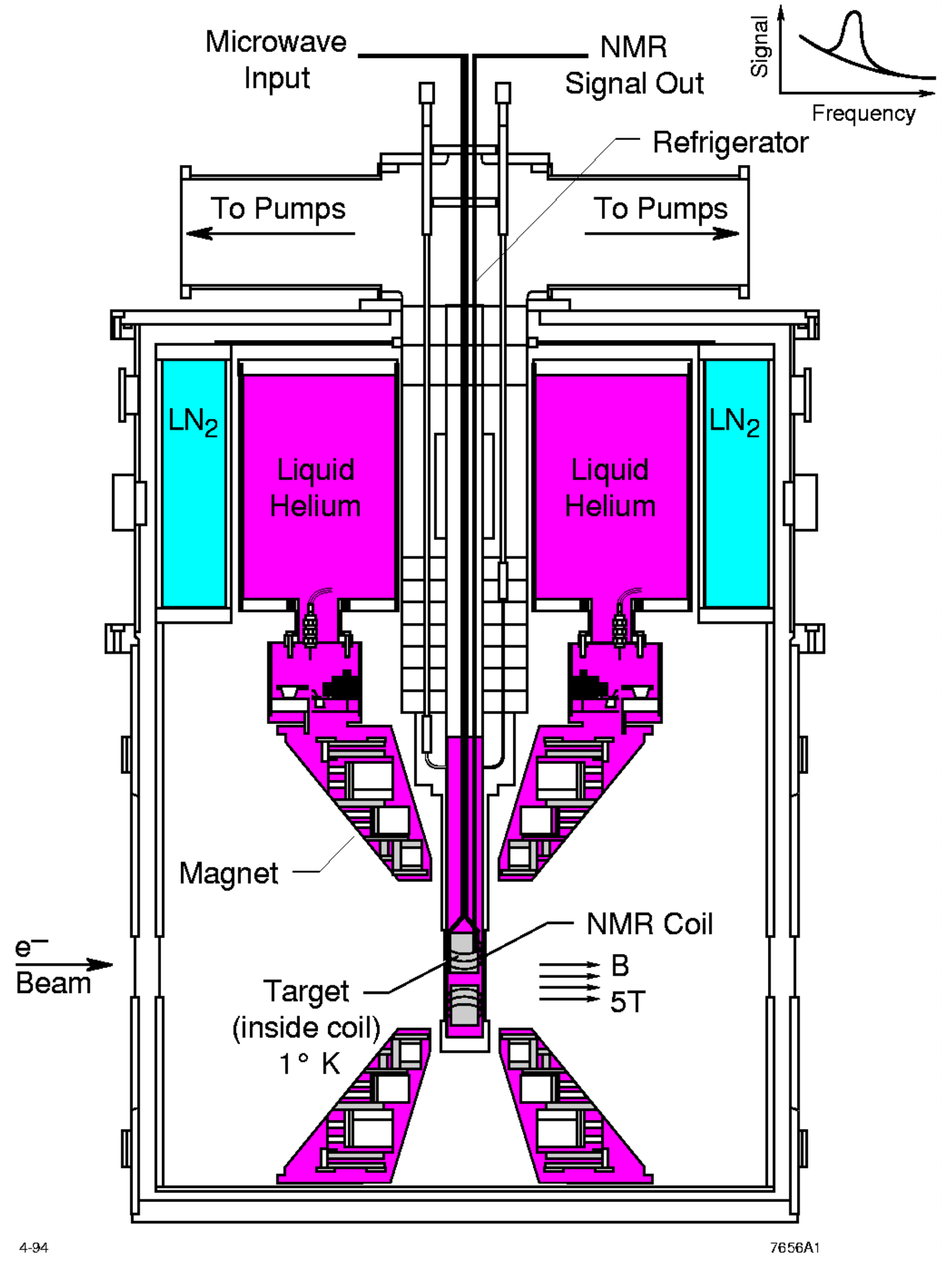
Hall B Detectors



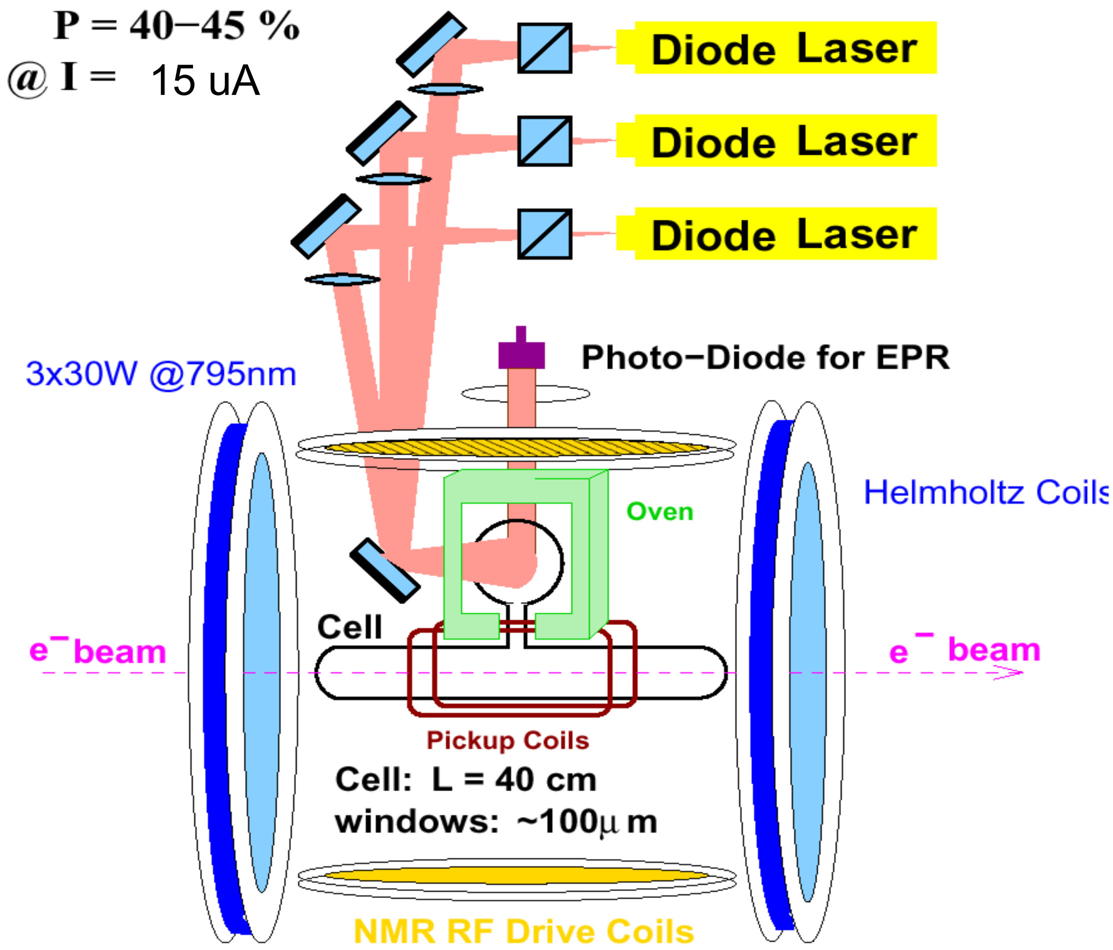
Polarized proton/deuteron target

- Polarized NH_3/ND_3 targets
- Used in Hall B and Hall C (also at SLAC)
- Dynamical Nuclear Polarization

- ~ 90% for p
  ~ 40% for d
- Luminosity ~ 10^{35}



JLab polarized ^{3}He target

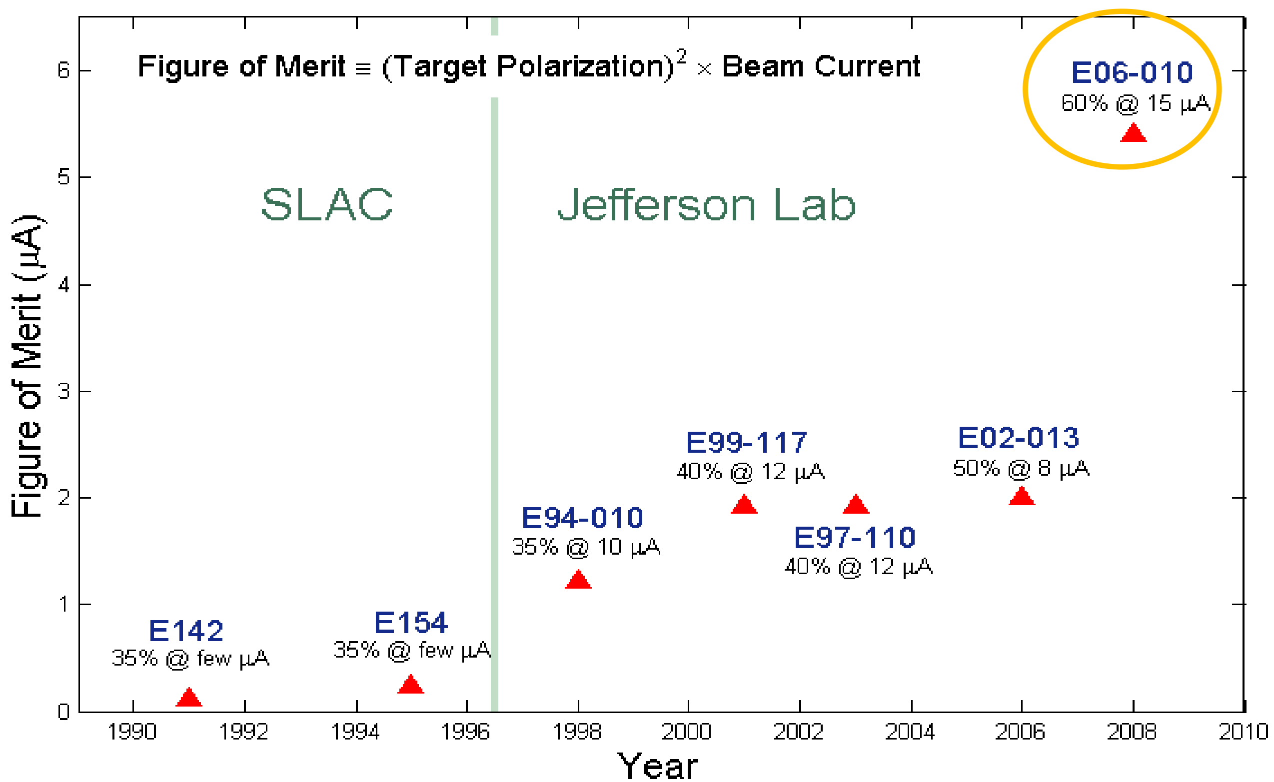


- ✓longitudinal, transverse and vertical
- ✓Luminosity=10^{36} (1/s) (highest in the world)
- ✓High in-beam polarization ~ 60%
- ✓Effective polarized neutron target
- ✓13 completed experiments
  7 approved with 12 GeV (A/C)

Performance of ^{3}He Target

- High luminosity: $L(n) = 10^{36}$ cm^{-2} s^{-1}
- Polarization in all 3 directions (L, T, V)
- **Record high in-beam ~ 60% polarization**
- Fast spin flip (every 20 minutes)

History of Figure of Merit of Polarized ^{3}He Target



JLab Physics Program

JLab's Scientific Mission

- How are the hadrons constructed from the quarks and gluons of QCD?
- Where are the limits of our understanding of nuclear structure?
- Is the "Standard Model" complete?

Critical issues in "strong QCD":

- What is the mechanism of confinement?
- How and where does the dynamics of the q-g and q-q interactions make a transition from the strong (confinement) to the perturbative QCD regime?
- What is the multi-dimensional structure of the nucleon?

JLab 6 GeV Program

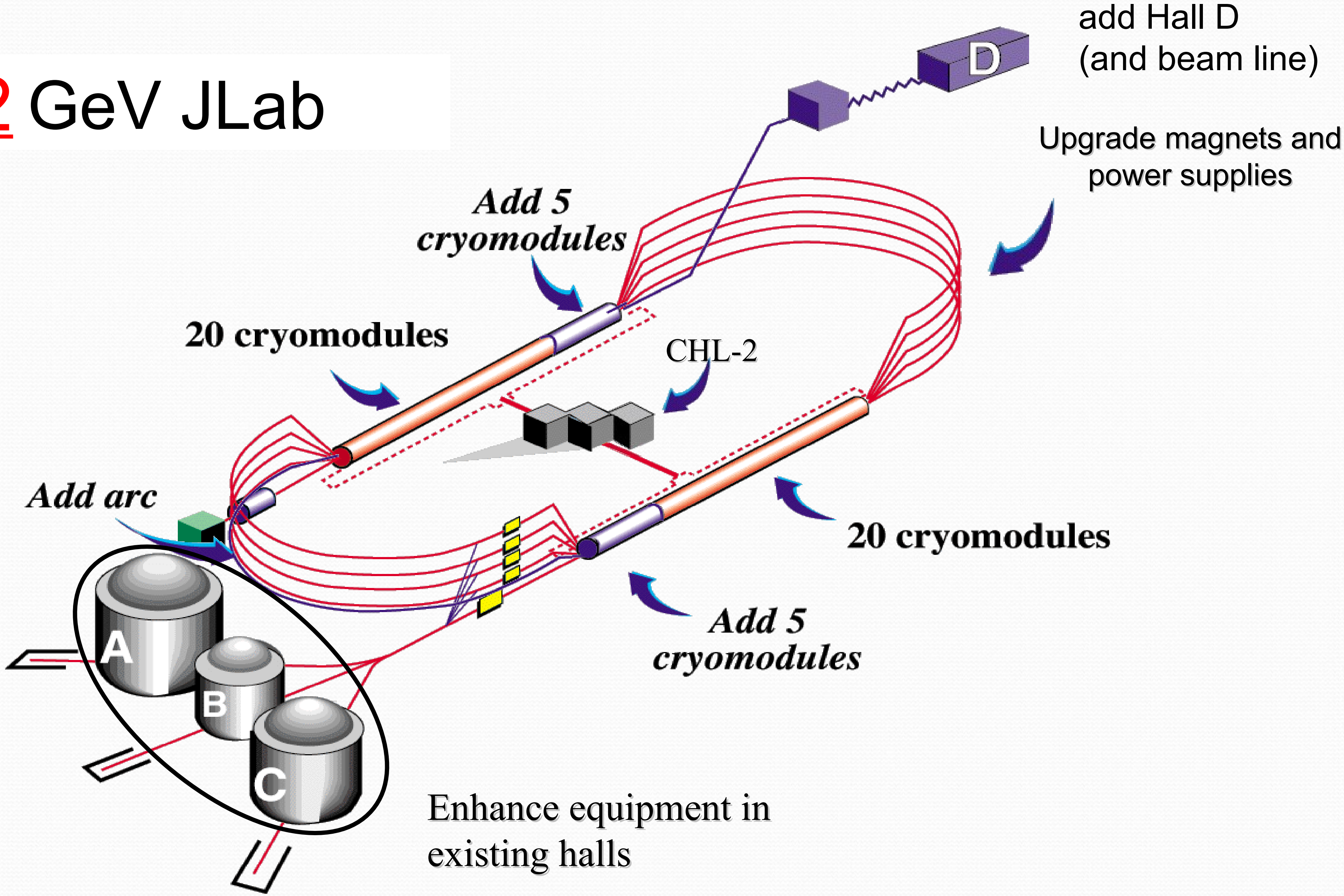
- Main physics programs
  - nucleon electromagnetic form factors
  - N $\rightarrow$ N* electromagnetic transition form factors
  - longitunidal spin structure of the nucleon
  - Transverse spin and transverse structure
  - exclusive reactions
  - parity violation
  - form factors and structure of light nuclei
  - nuclear medium effects
  - hypernuclear physics
  - exotic states search

  …….

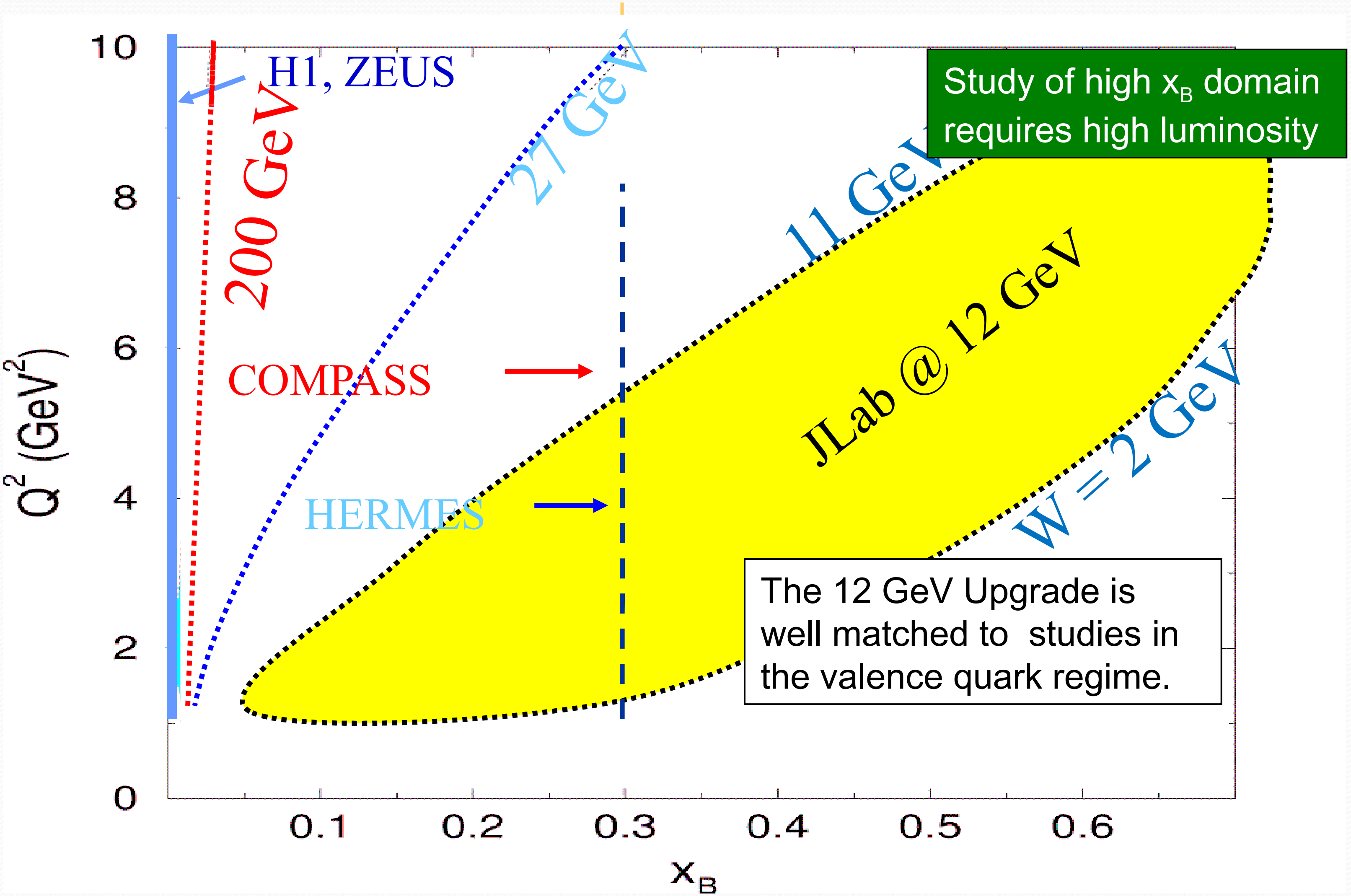
JLab 12 GeV Upgrade

and beyond

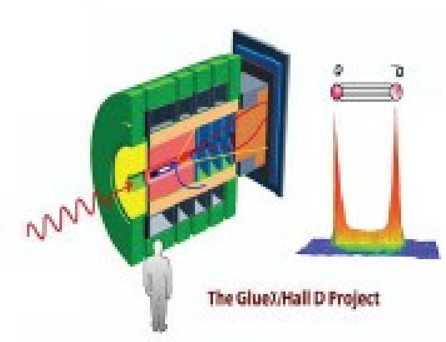
12 GeV JLab

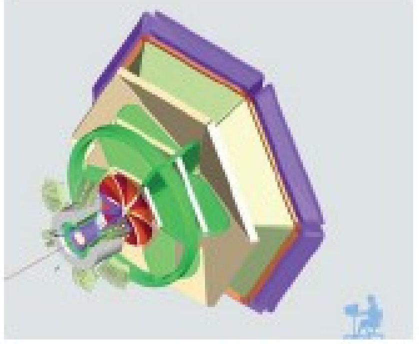
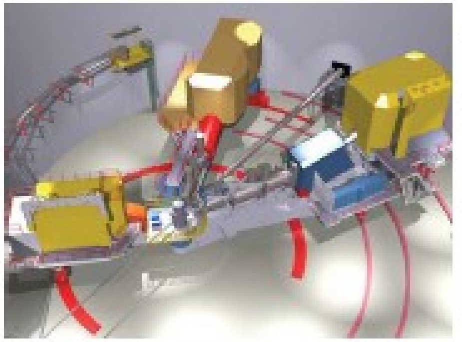
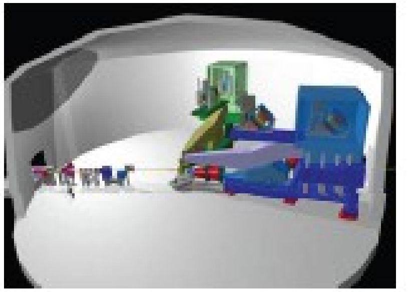

add Hall D
(and beam line)
D
Upgrade magnets and
power supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment in
existing halls

Kinematics Coverage of the 12 GeV Upgrade



Experimental Halls



- **(new) Hall D: linear polarized photon beam, Selonoid detetcor**
  - *GluoX* collaboration: exotic meson spectroscopy
    gluon-quark hybrid, confinement
- Hall B: CLAS12
  - GPDs, TMDs, …
- Hall C: Super HMS + existing HMS
  - Form factors, structure functions, …
- Hall A: Dedicated devices + existing spectrometers
  - Super BigBite, Solenoid, Moller Spectrometer
  - SIDIS, PVDIS, …

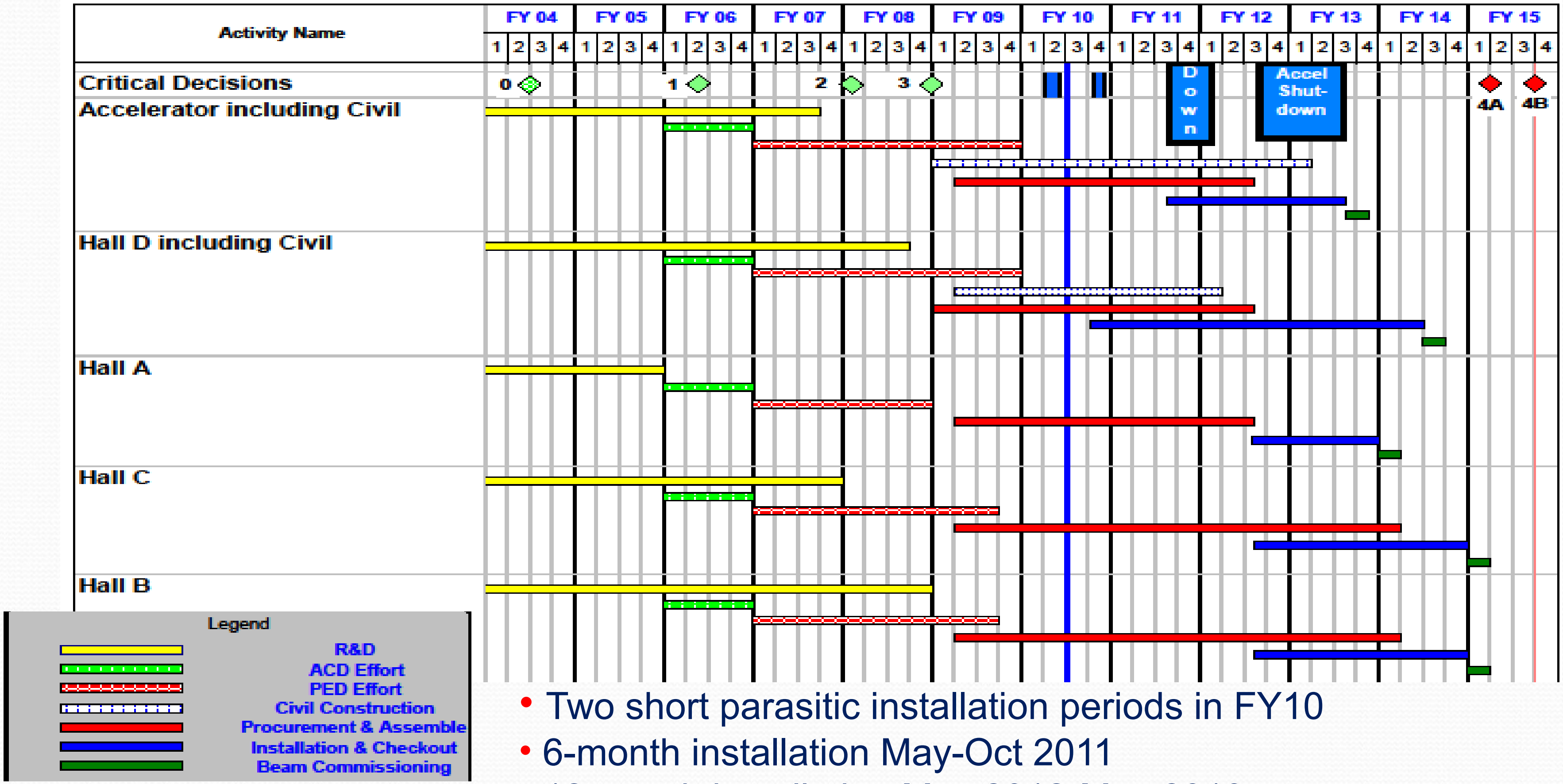
12 GeV Science Program

- The physical origins of quark confinement
  (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's…)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

- Defining the Science Program:
  - Six Reviews: Program Advisory Committees (PAC) 30, 32, 34, 35, 36, 37
  - 2006 through 2011
  - Results: *45 experiments approved; 14 conditionally approved*
  - PAC38 scheduled August 2011: consider new proposals, continue rankings

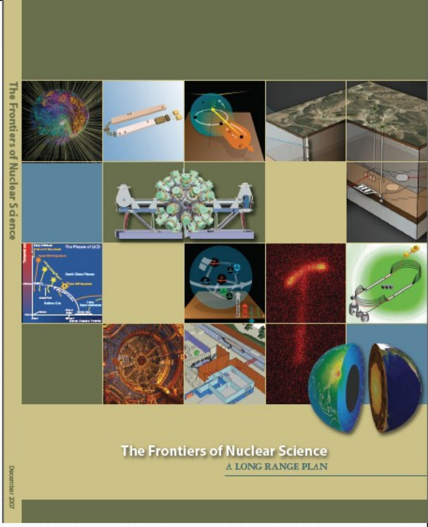
Exciting slate of experiments for 4 Halls planned for initial five years of operation!

12 GeV Upgrade Schedule



- Two short parasitic installation periods in FY10
- 6-month installation May-Oct 2011
- 12-month installation May 2012-May 2013
- Hall A commissioning start October 2013
- Hall D commissioning start April 2014
- Halls B and C commissioning start October 2014
- Project Completion June 2015

Beyond 12 GeV: ELIC: Science Motivation



A High Luminosity, High Energy Electron-Ion Collider:
A New Experimental Quest to Study the Sea and Glue
How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

Precisely image the sea-quarks and gluons in the nucleon:

- How do the gluons and sea-quarks contribute to the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do hadronic final-states form in QCD?

Explore the new QCD frontier: strong color fields in nuclei:

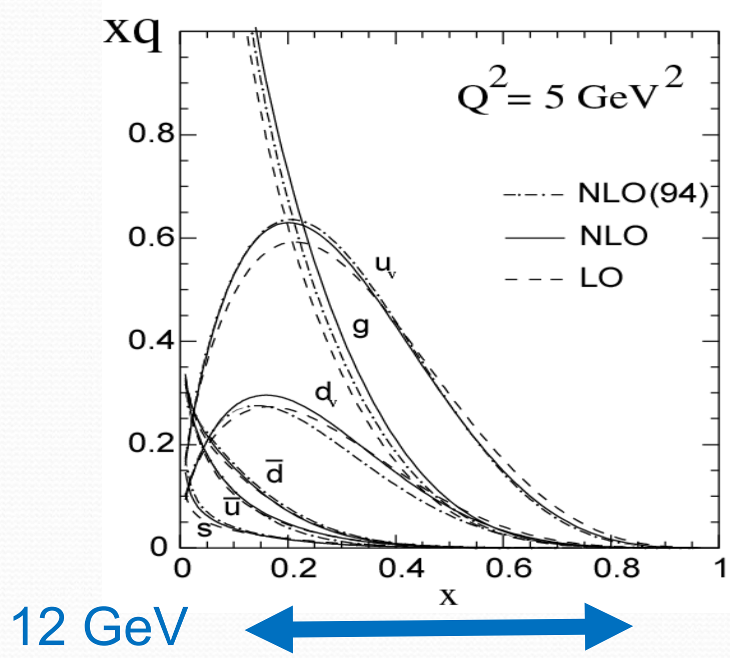
- How do the gluons contribute to the structure of the nucleus?
- What are the properties of high density gluon matter?
- How do fast quarks or gluons interact as they traverse nuclear matter?

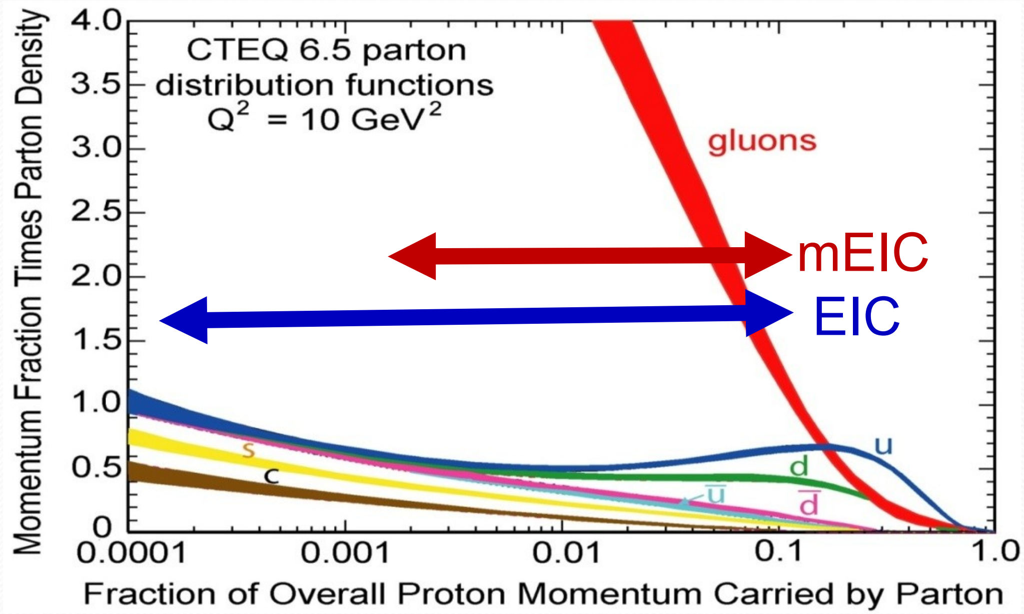
Into the "Sea": A Future Electron-Ion Collider

- Hadrons in QCD are relativistic many-body systems, with a fluctuating number of elementary quark/gluon constituents and a very rich structure of the wave function.

- With 12 GeV we study mostly the <u>valence quark component</u>, which can be described with methods of nuclear physics (fixed number of particles).

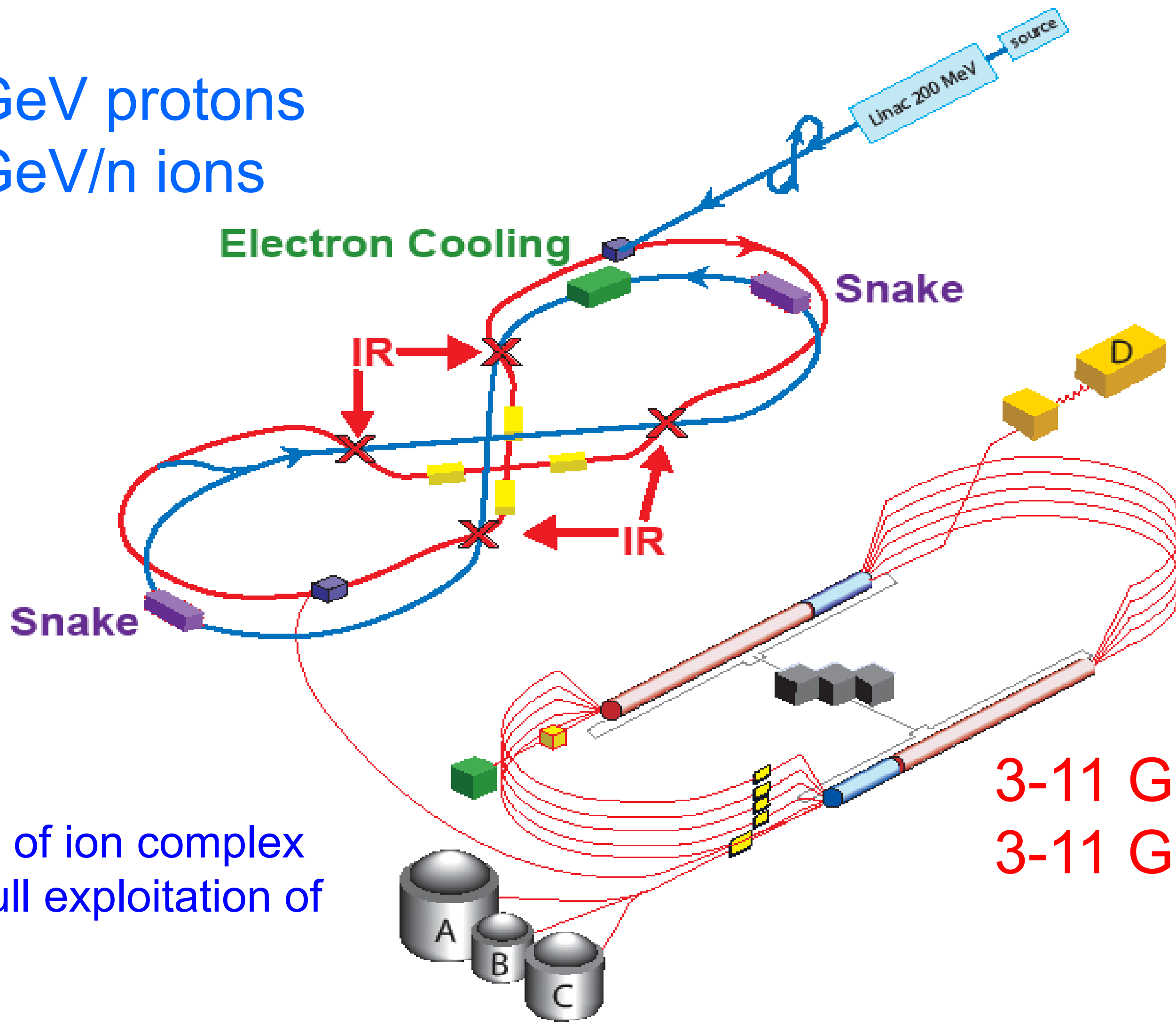
- With an (M)EIC we enter the region where the many-body nature of hadrons, coupling to vacuum excitations, etc., become manifest and the theoretical methods are those of quantum field theory. An EIC aims to study the <u>sea quarks, gluons, and scale (Q^2) dependence</u>.





ELIC at $L \sim 10^{35}$ $cm^{-2}s^{-1}$

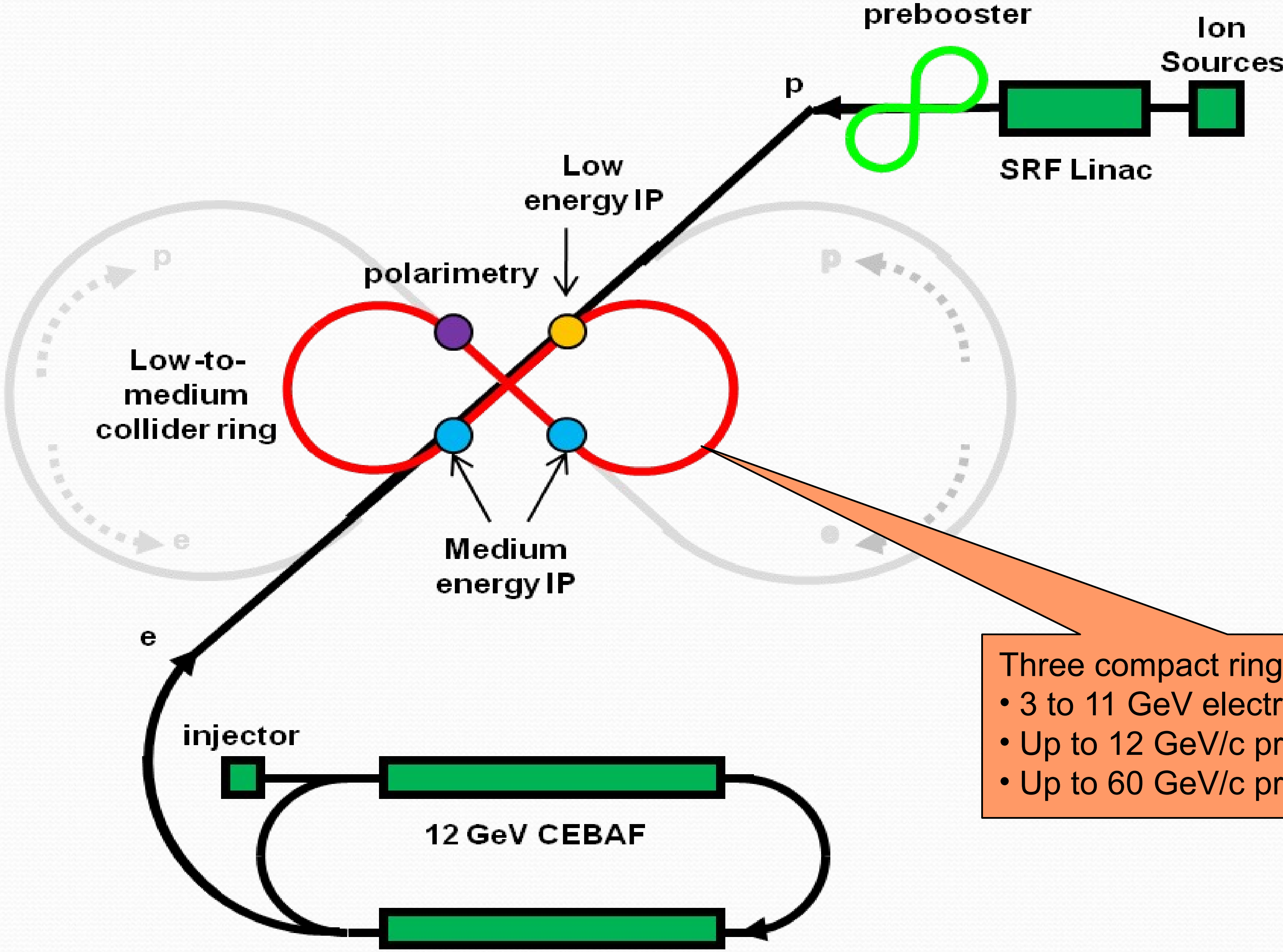
30-225 GeV protons
30-100 GeV/n ions



3-11 GeV electrons
3-11 GeV positrons

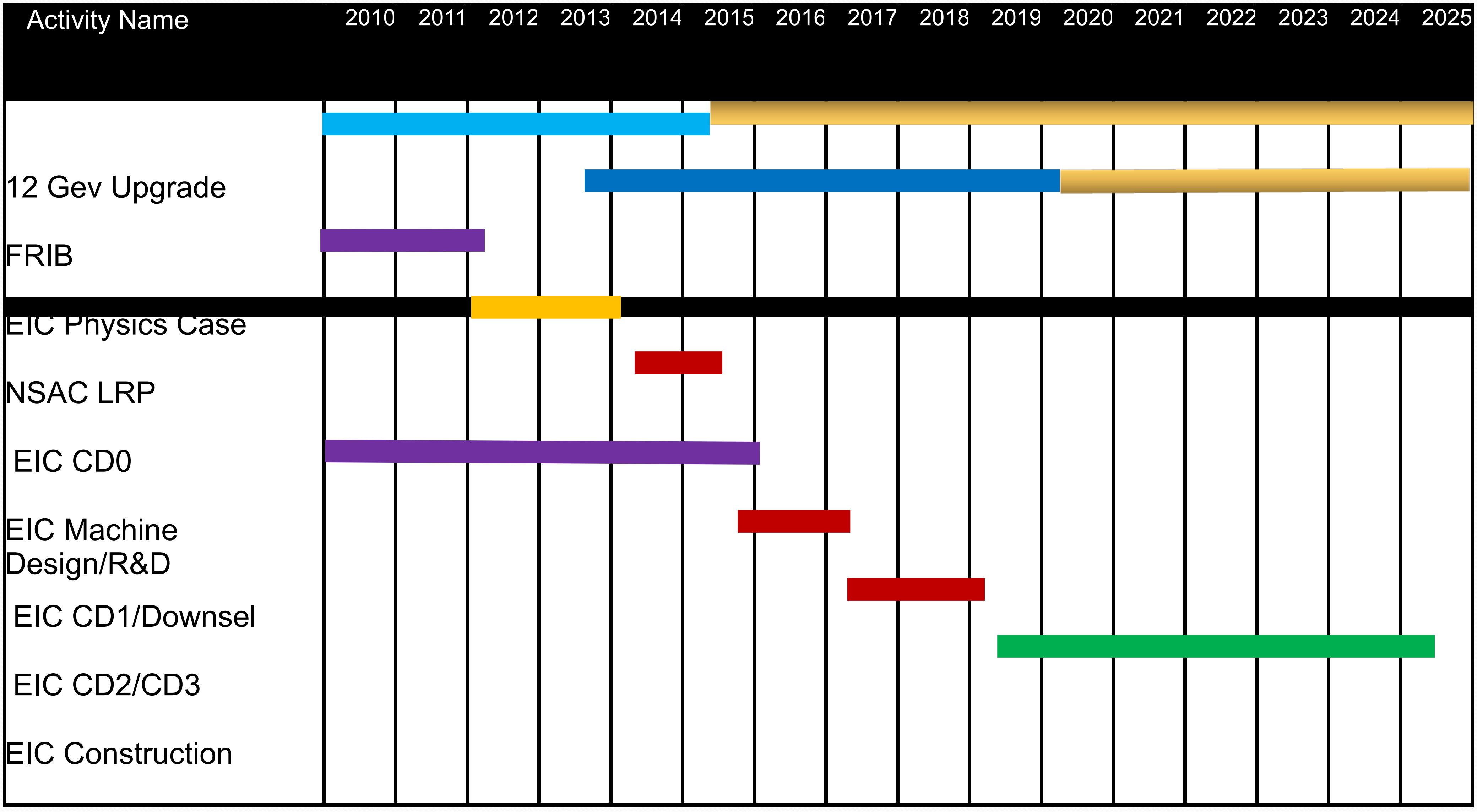
Green-field design of ion complex directly aimed at full exploitation of science program.

Medium Energy EIC@JLab



Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)

EIC Realization Imagined



Highlights of 6 GeV Program
Example of 12 GeV Program

Form Factors

Longitudinal Spin Structure,

Transverse Spin structure,

PVES test Standard Model

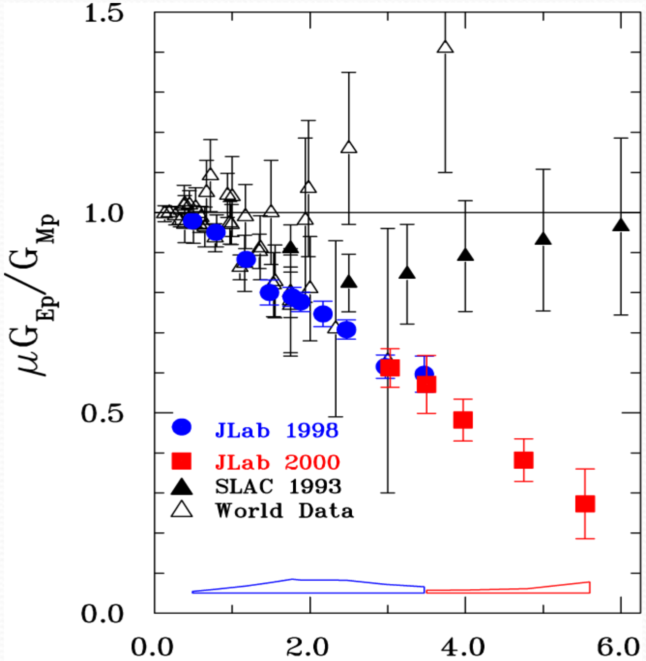
JLab Data on EM Form Factors

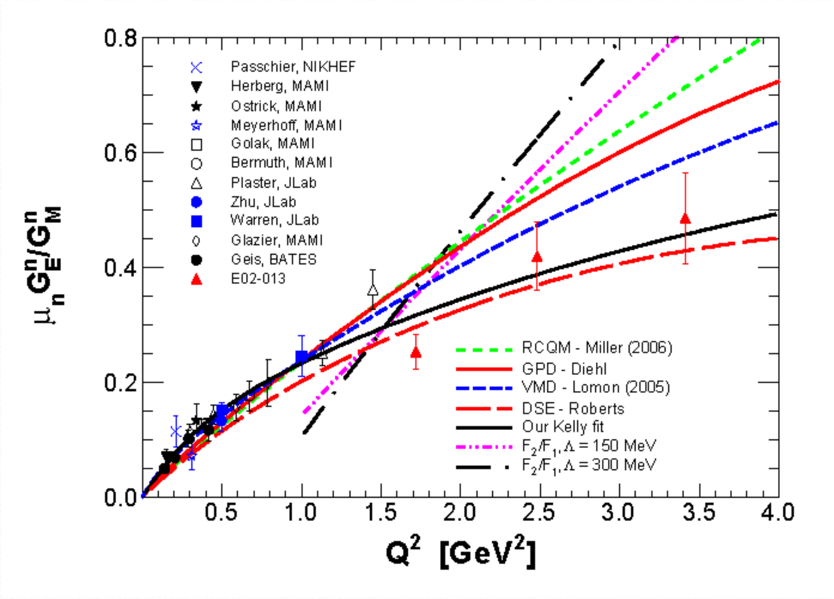
Testing Ground for Theories of Nucleon Structure

Proton

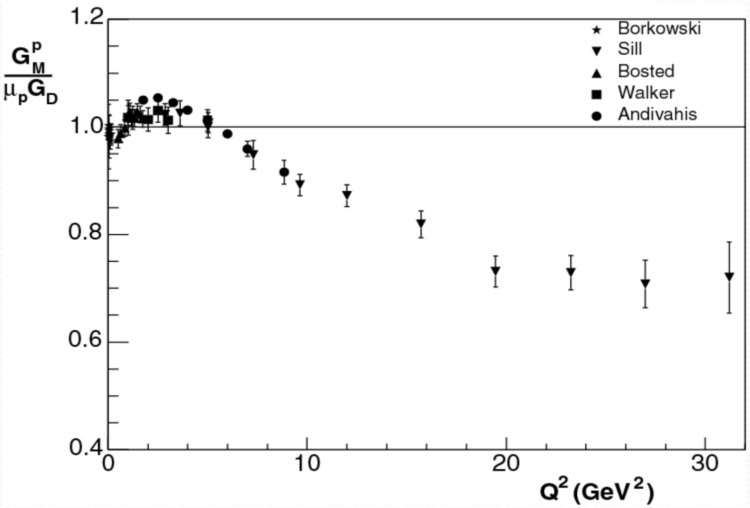
Neutron

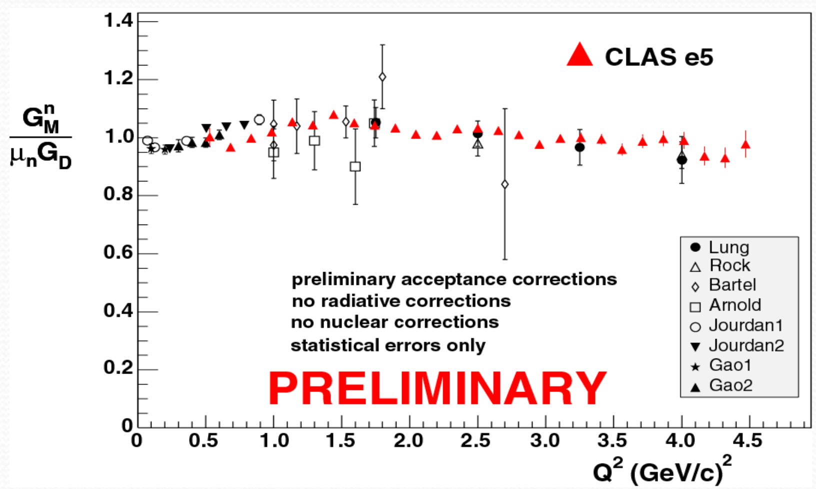
Electric





Magnetic





Form Factors: JLab Polarization-Transfer Data

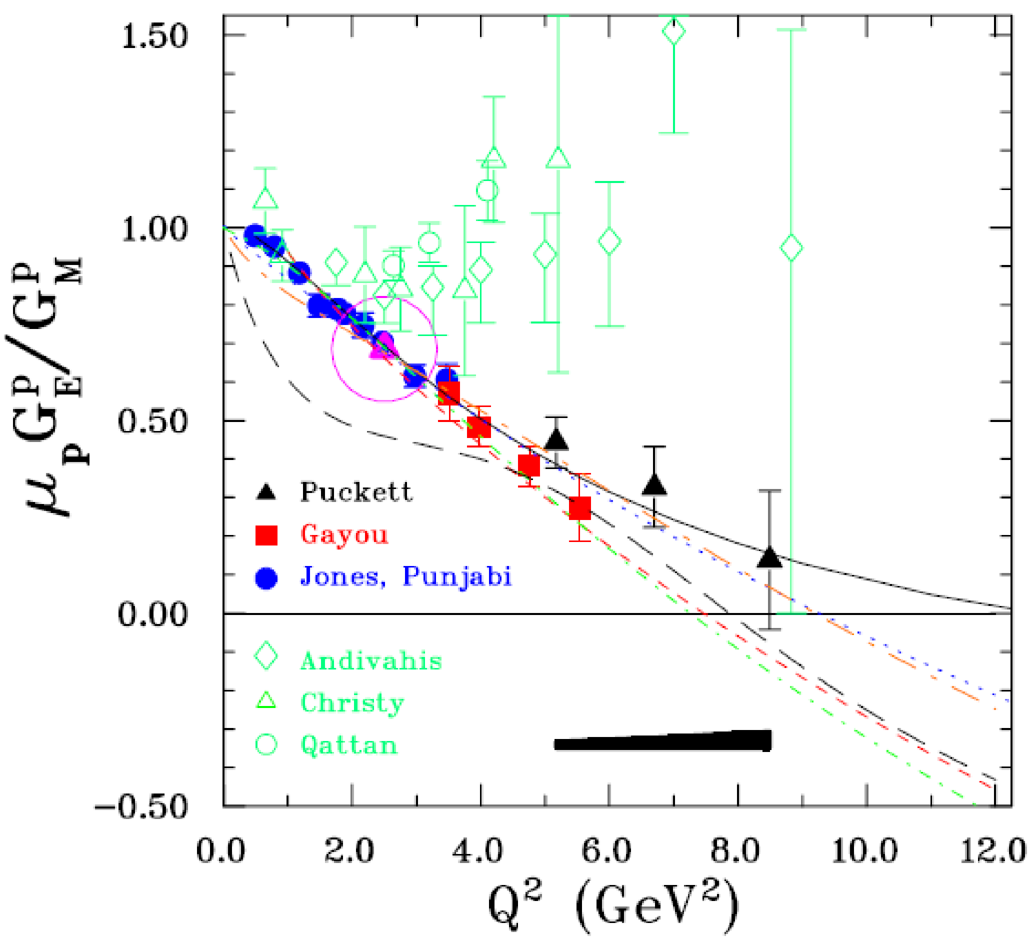
Using Focal Plane Polarimeter in Hall A

- E93-027 PRL 84, 1398 (2000)
- E99-007 PRL 88, 092301 (2002)
- E04-108, arXiv:1005.3419v2 (2010)

Clear discrepancy between polarization transfer and Rosenbluth data

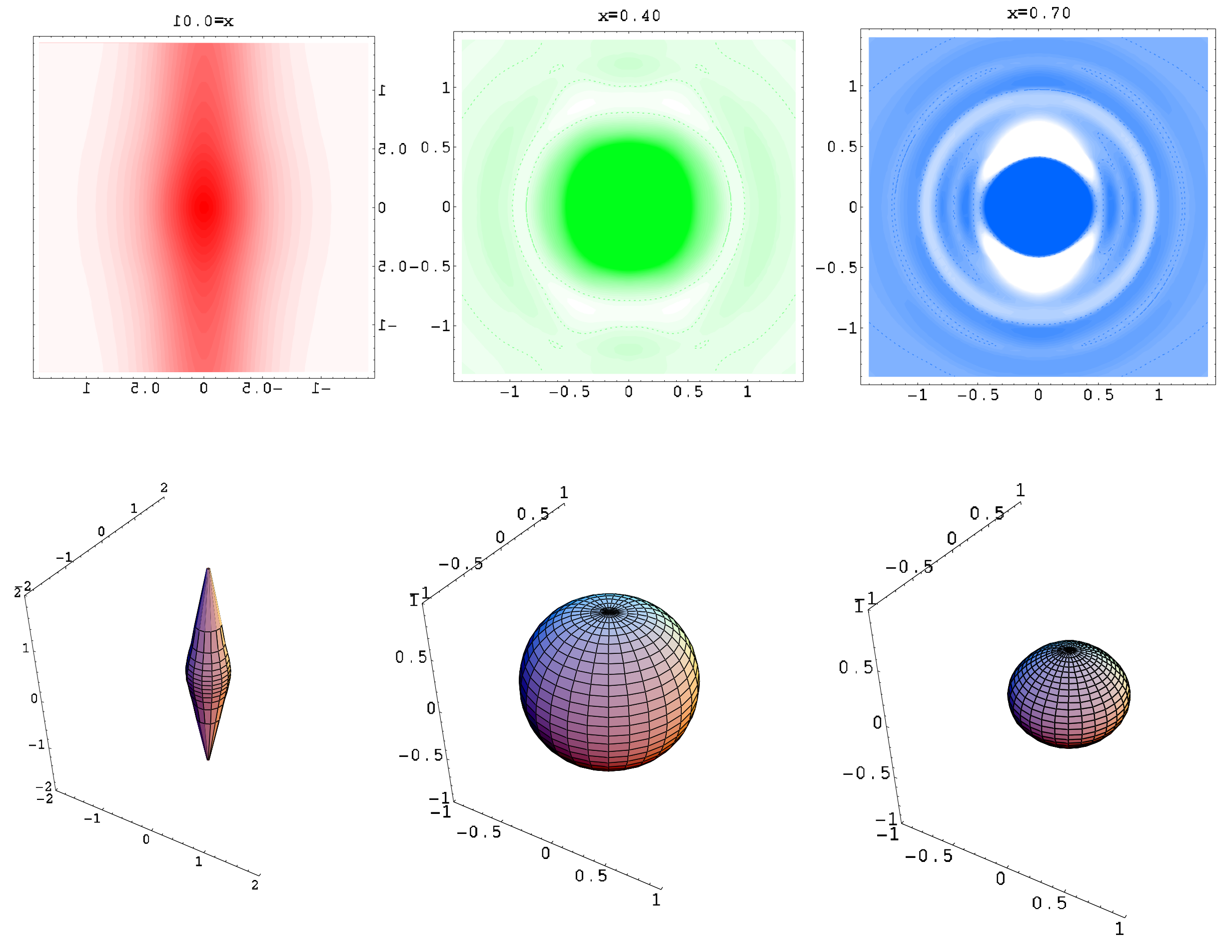
- Investigate possible theoretical sources for discrepancy
  → two-photon contributions

Information on the shape of the proton and the orbital angular momentum.



The Proton’s Shape

Belitsky, Ji and Yuan: PRD 69, 074014(04)



It’s a Ball. No, It’s a Pretzel. Must Be a Proton.
(K. Chang, NYT, May 6, 2003)

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: Breakthrough in nucleon spin physics?
- 2000s: Application of nucleon spin physics?

Pauli and Bohr watch a spinning top

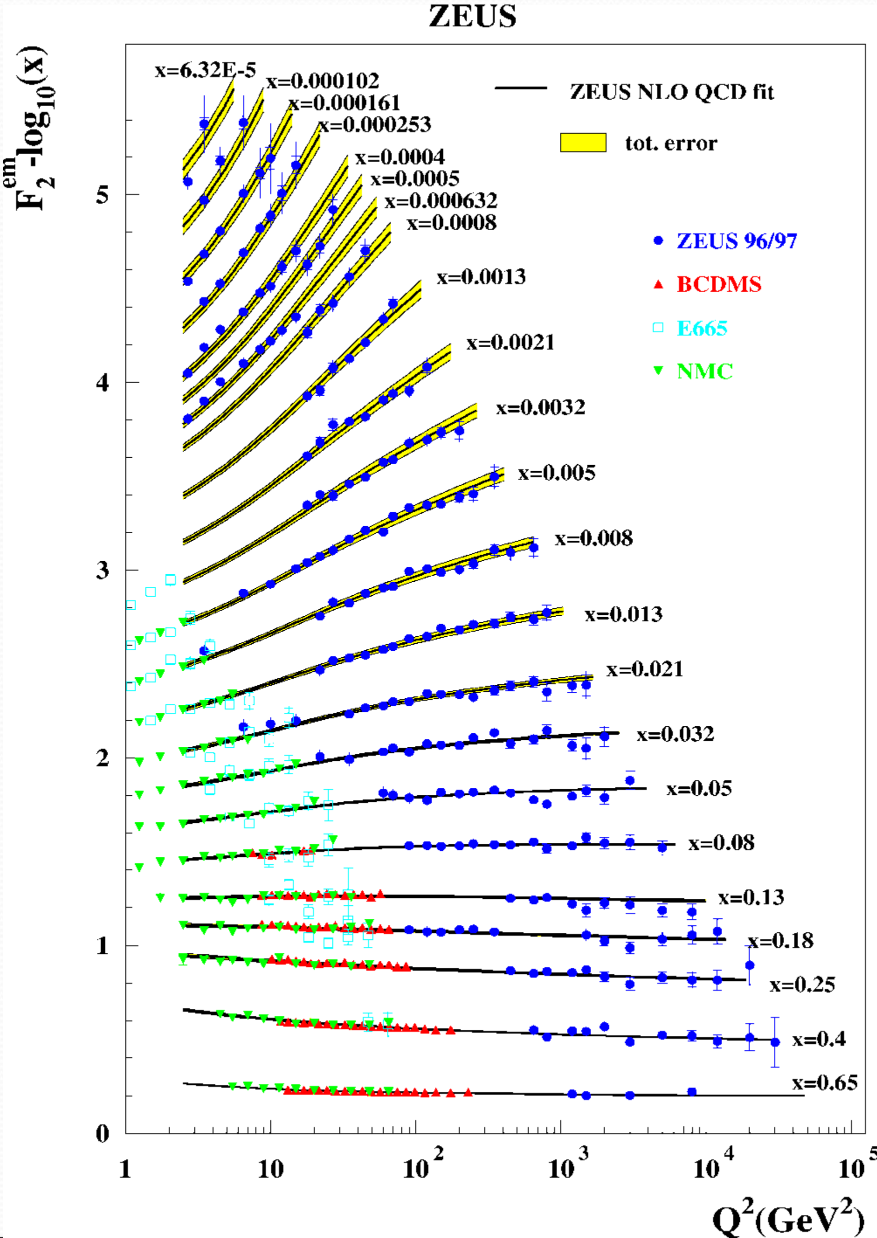
Three Decades of Nucleon Spin Structure Study

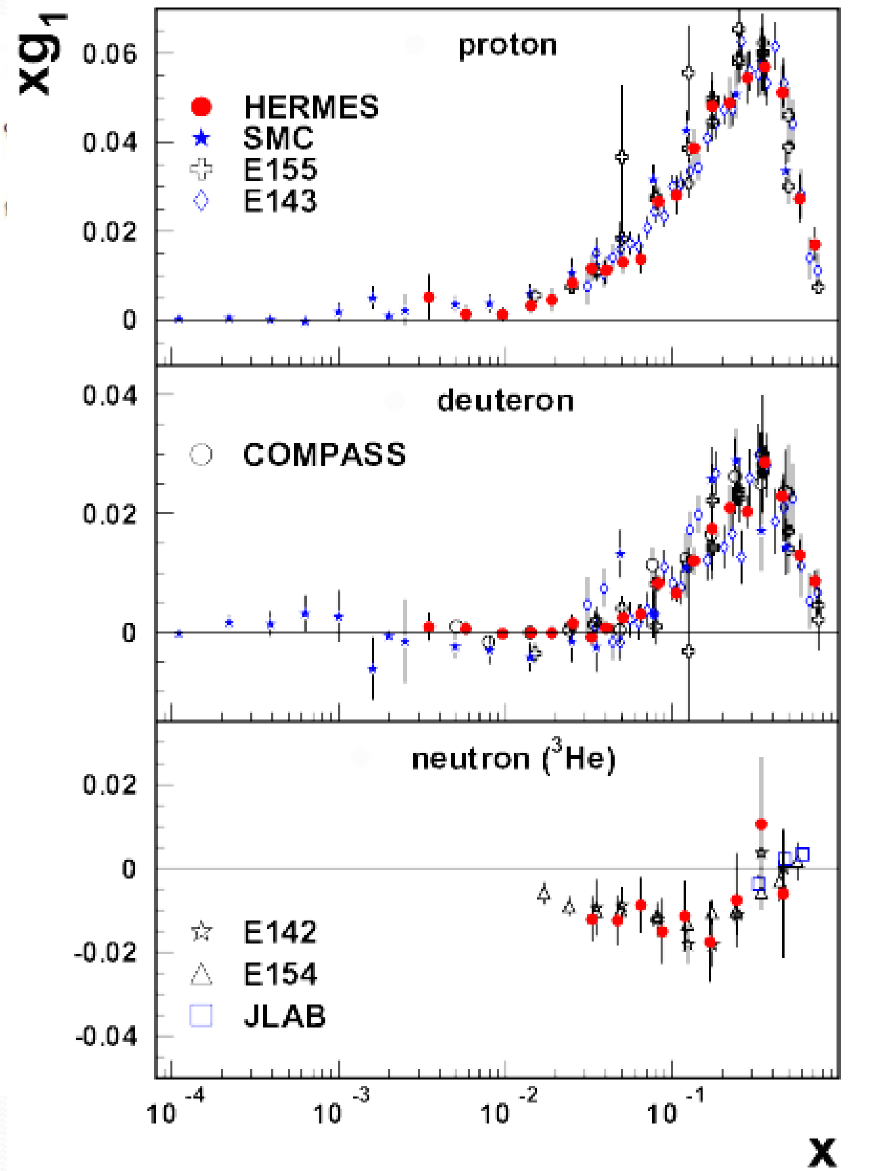
- 1980s: EMC (CERN) + early SLAC
  quark contribution to proton spin is very small
  $\Delta\Sigma$ = (12+-9+-14)% !   'spin crisis'

- 1990s: SLAC, SMC (CERN), HERMES (DESY)
  $\Delta\Sigma$ = 20-30%
  the rest: gluon and quark orbital angular momentum
  gauge invariant $(½)\Delta\Sigma + L_q + J_G = 1/2$ (X. Ji)
  Bjorken Sum Rule verified to <10% level

- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :
  $\Delta\Sigma$ ~ 30%; ΔG probably small, orbital angular momentum significant
  Valence quark structure
  Transversity, Transverse-Momentum Dependent Distributions

Unpolarized and Polarized Structure functions

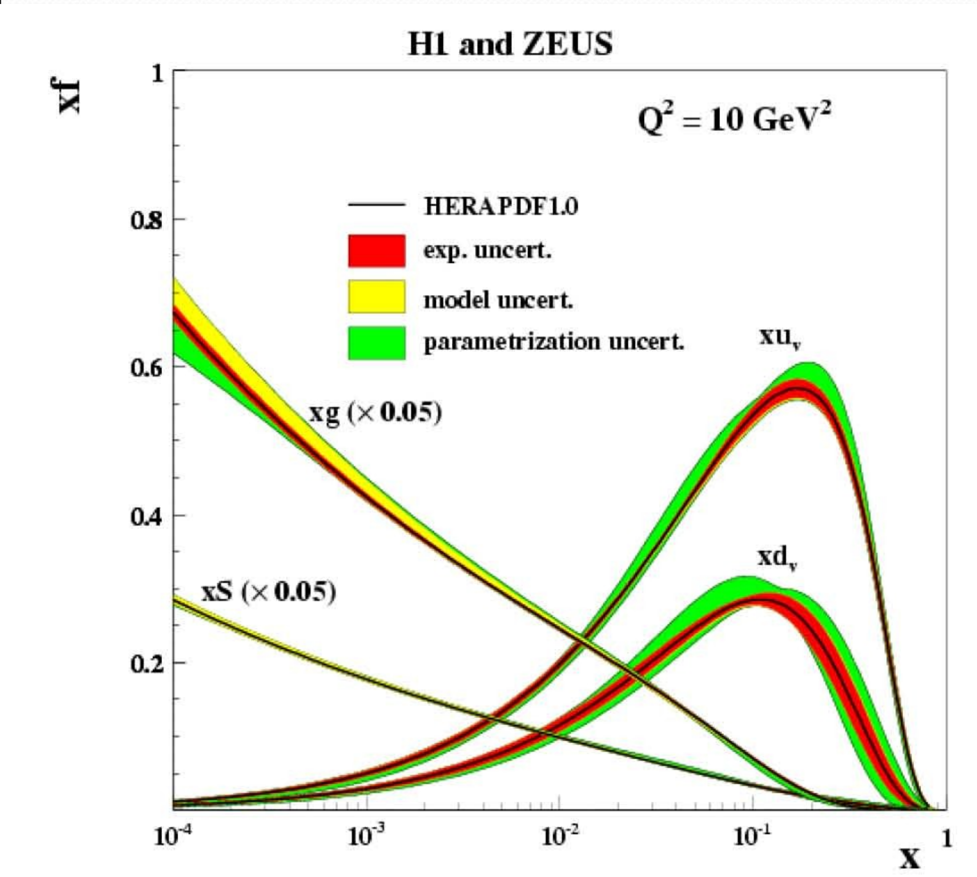


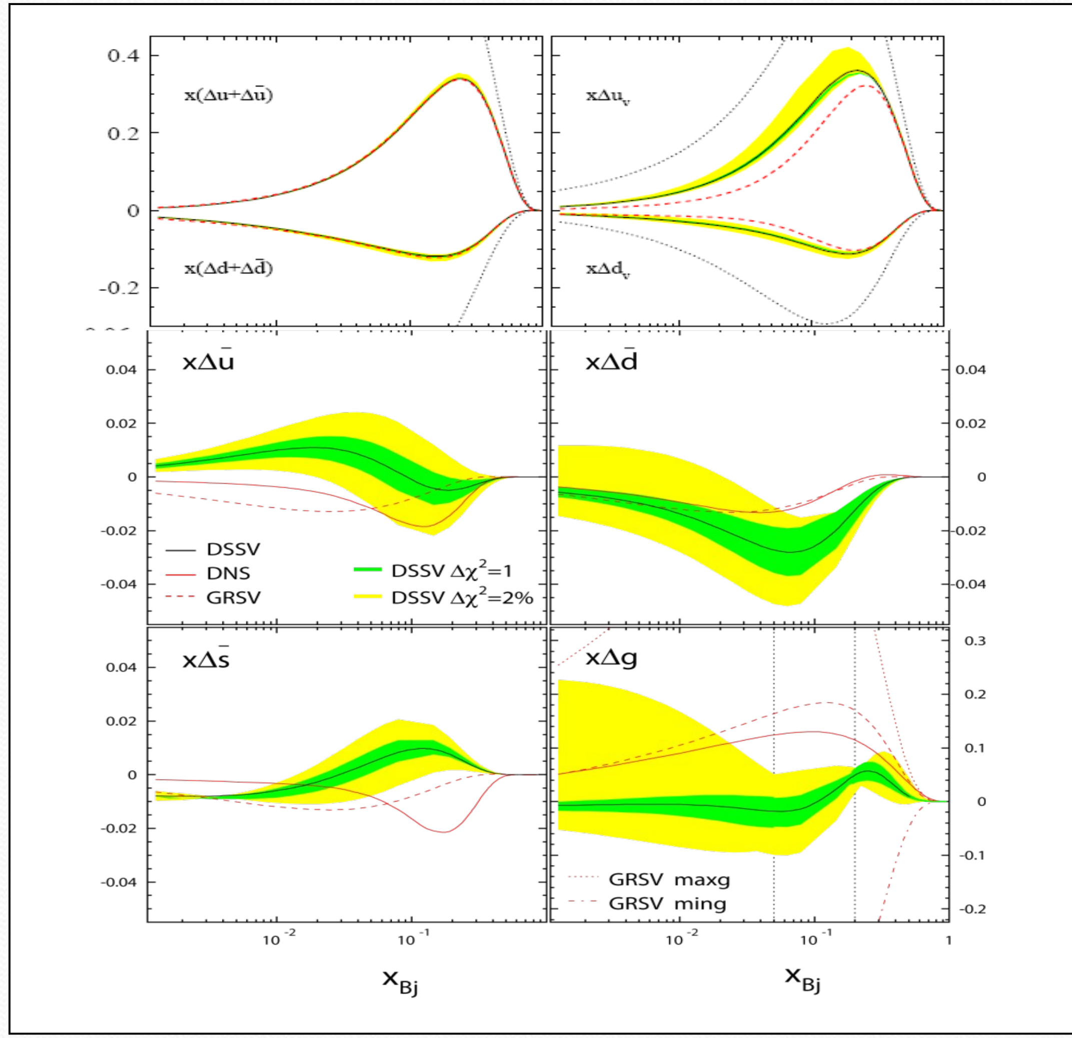


Parton Distributions (CTEQ6 and DSSV)

Unpolarized PDFs

Polarized PDFs



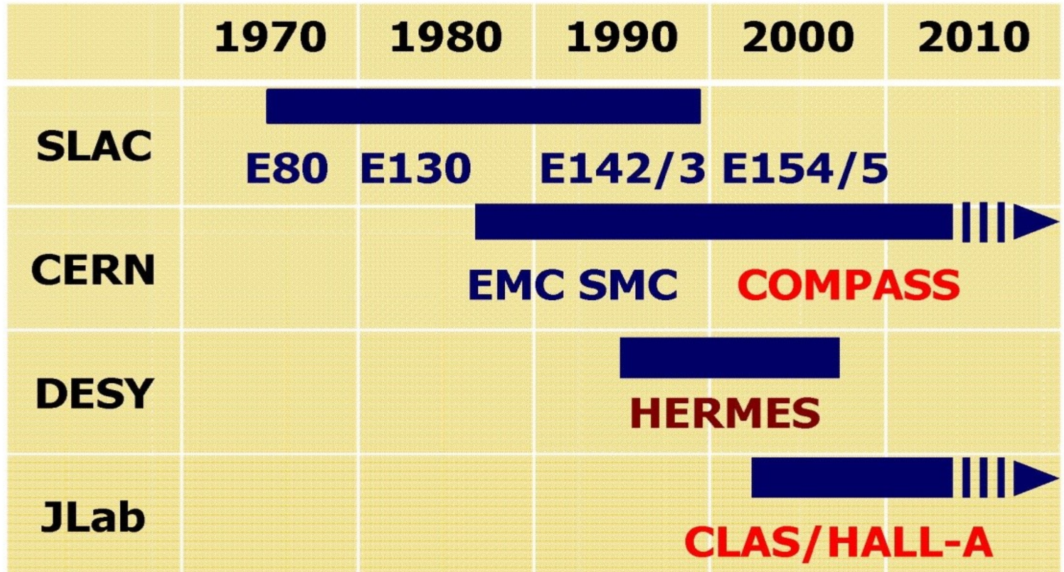


JHEP 1001: 109 (2010)

DSSV, PRL101, 072001 (2008)

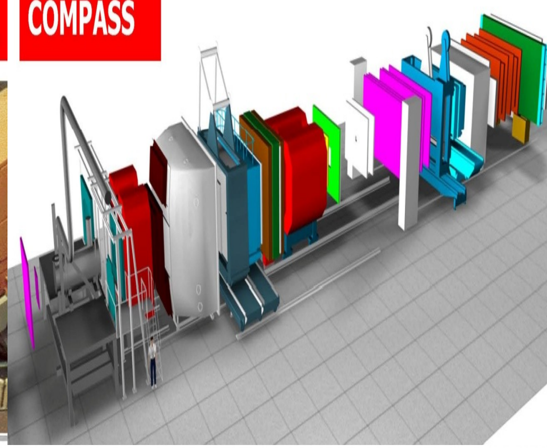
Experiments

E80, E130	$\vec{e}\ \vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\ \vec{p}$	100–200 GeV
E142, 143	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\ \vec{p}, \vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\ \vec{p}, \vec{d}$	160 GeV
HALL A	$\vec{e}\ \vec{n}$	6 GeV
CLAS	$\vec{e}\ \vec{p}, \vec{d}$	6 GeV

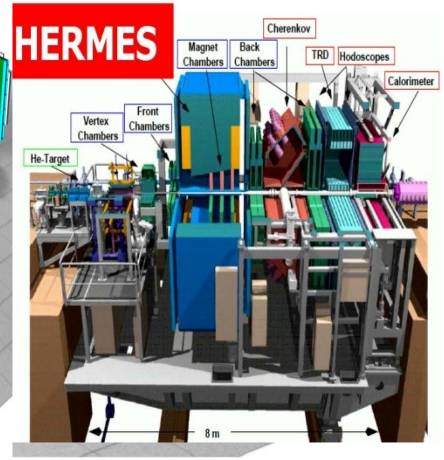


SLAC - End Station A

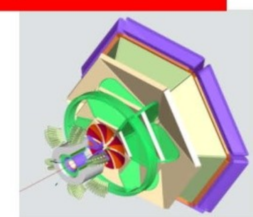
COMPASS

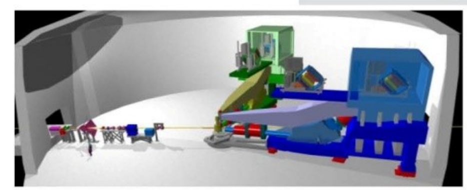


HERMES



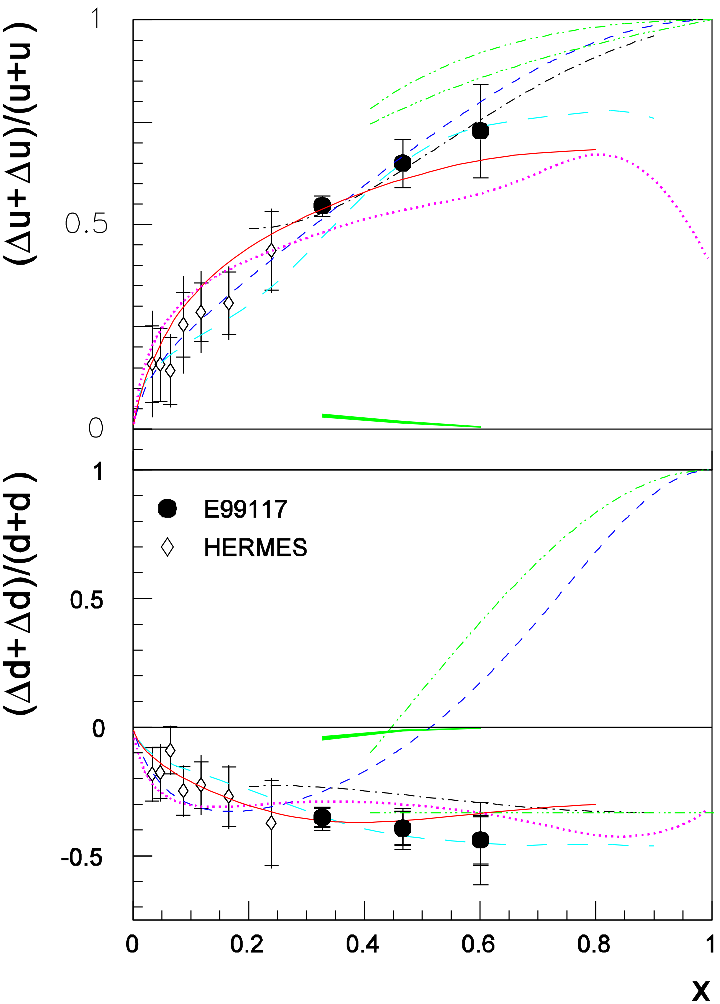
Jlab - CLAS, Hall A

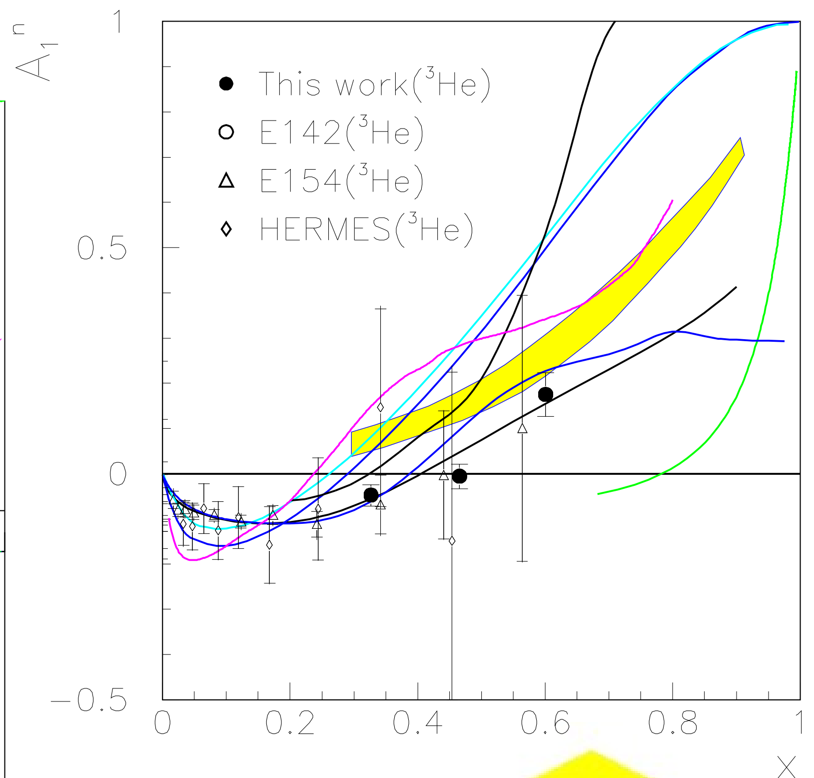


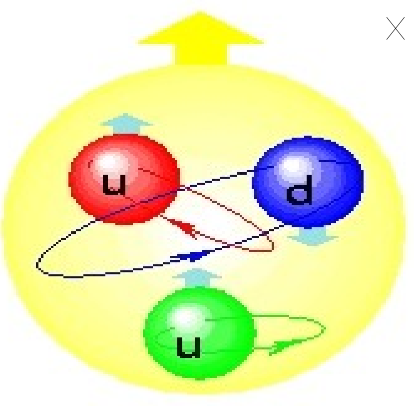


Valence (high-x) A_1^n results

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

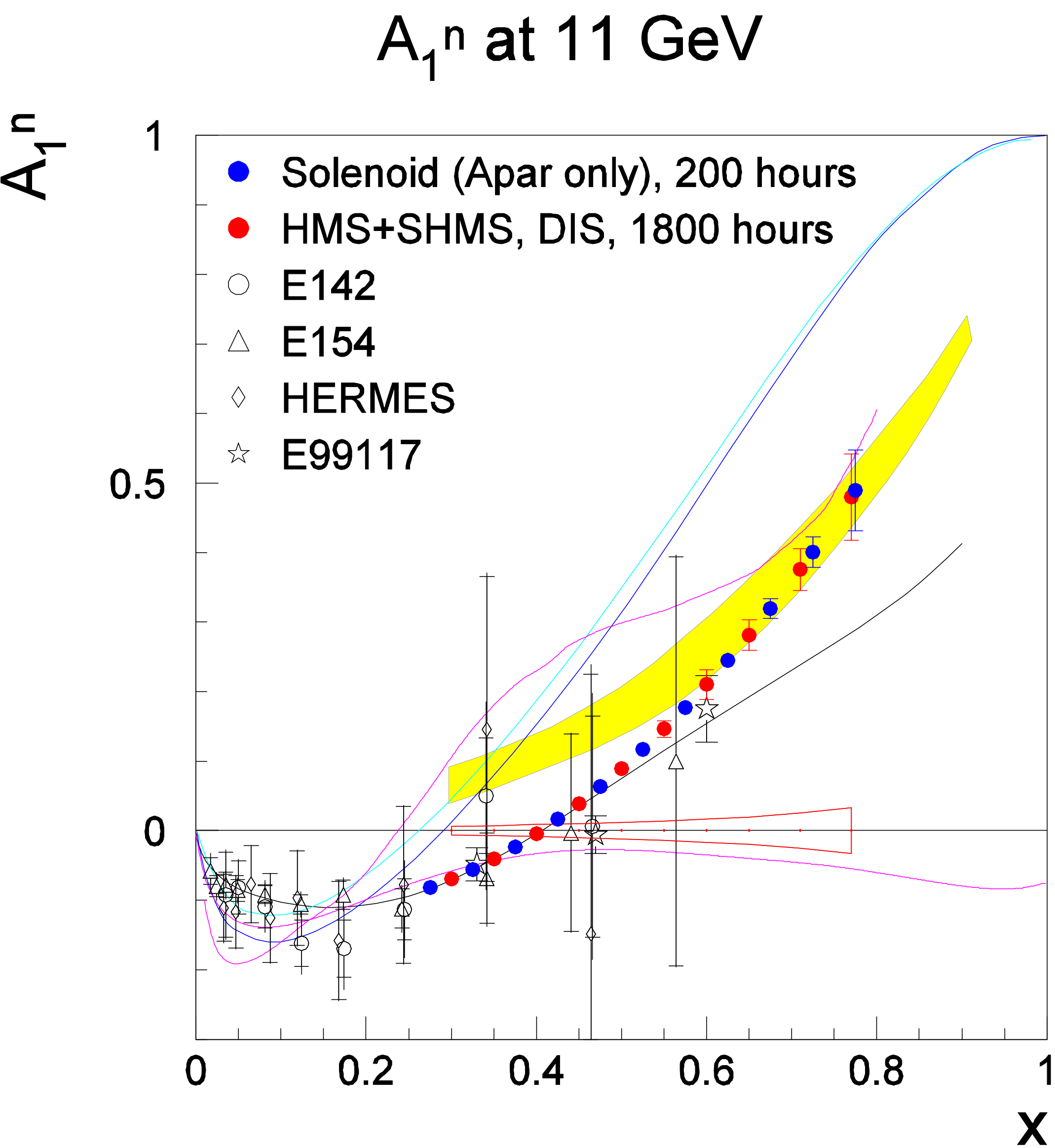


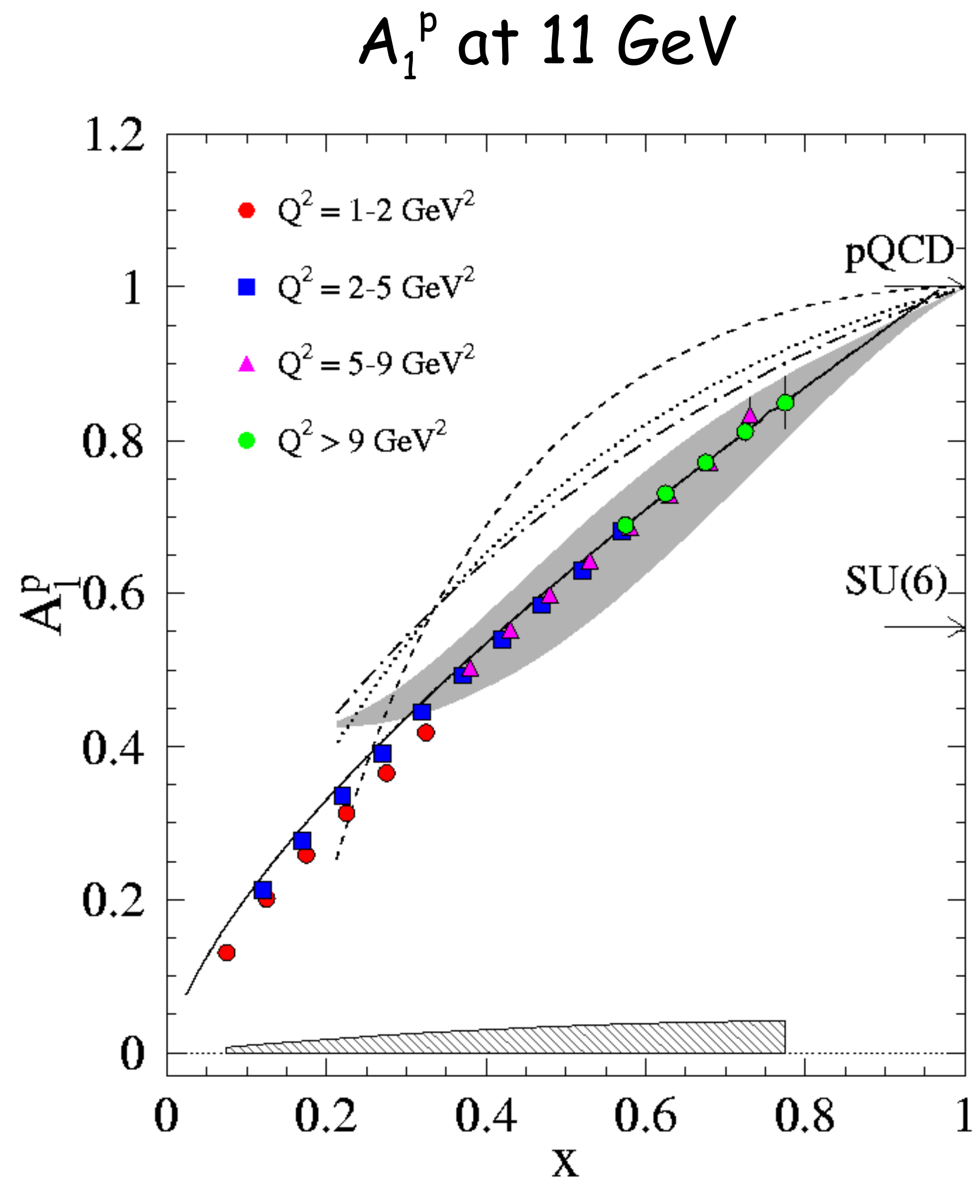




- Physics News Update, 12/18/2003 'Bringing the Nucleon into Sharper Focus'
- Science Now , 12/23/2003 'Quarks in a Surprising Spin'
- Science News, 1/3/2004 'Topsy Turvy'
- Physics Today Update, 2/2004 'Spinning the Nucleon into Sharper Focus'

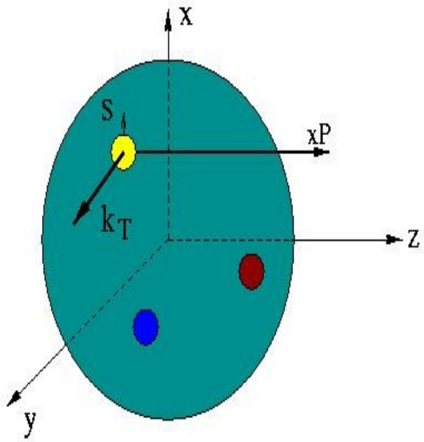
Projections for JLab at 11 GeV





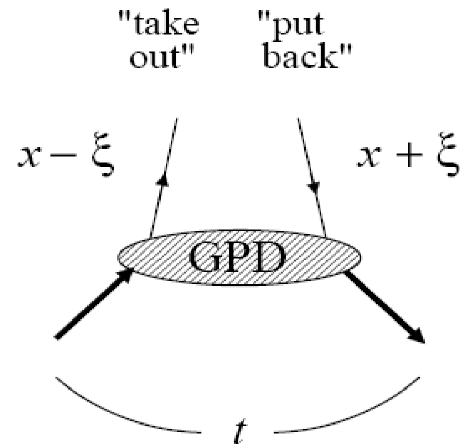
Unified View of Nucleon Structure

$W_p^u(x, k_T, r)$ Wigner distributions (X. Ji) **6D Dist.**



d^3r → TMD PDFs: $f_1^u(x, k_T)$, .. $h_1^u(x, k_T)$

$d^2k_T\, dr_z$ → GPDs/IPDs



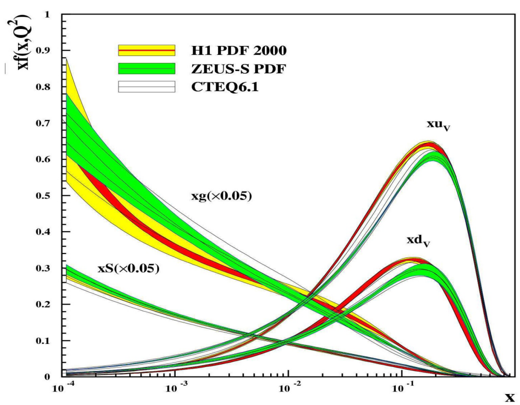
3D imaging

d^2k_T (from TMD PDFs) → PDFs

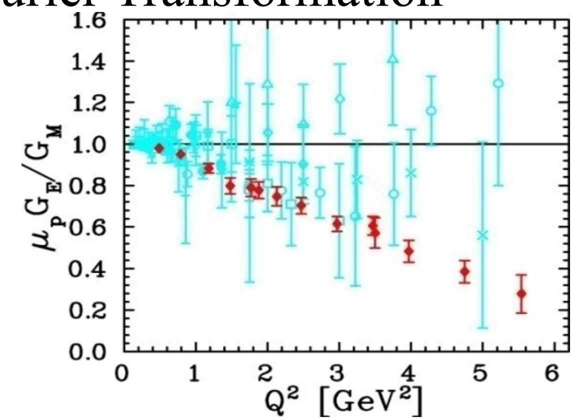
d^2r_T (from GPDs/IPDs) → PDFs

PDFs: $f_1^u(x)$, .. $h_1^u(x)$

1D

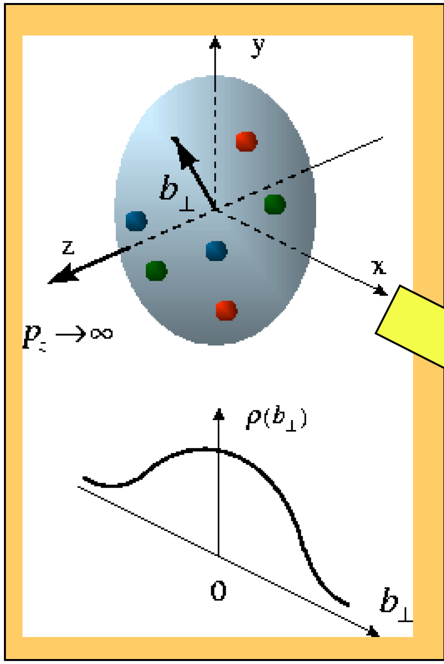


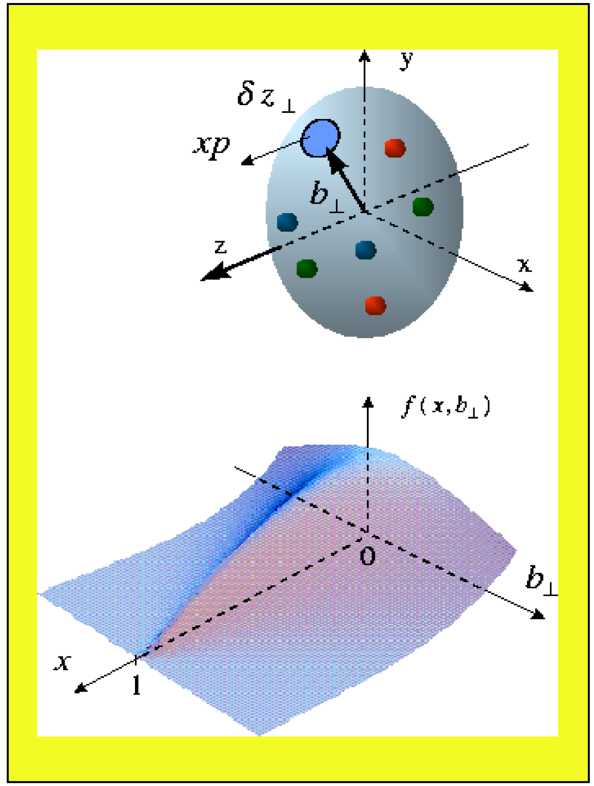
dx & Fourier Transformation (from GPDs/IPDs) → Form Factors $G_E(Q^2)$, $G_M(Q^2)$

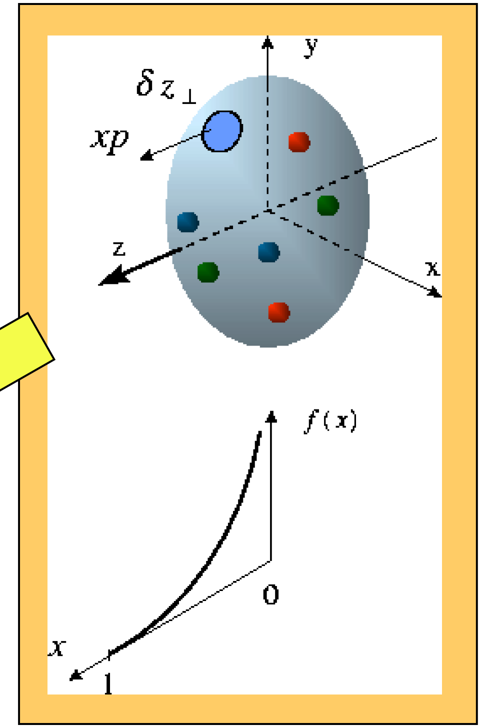


Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997)







Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

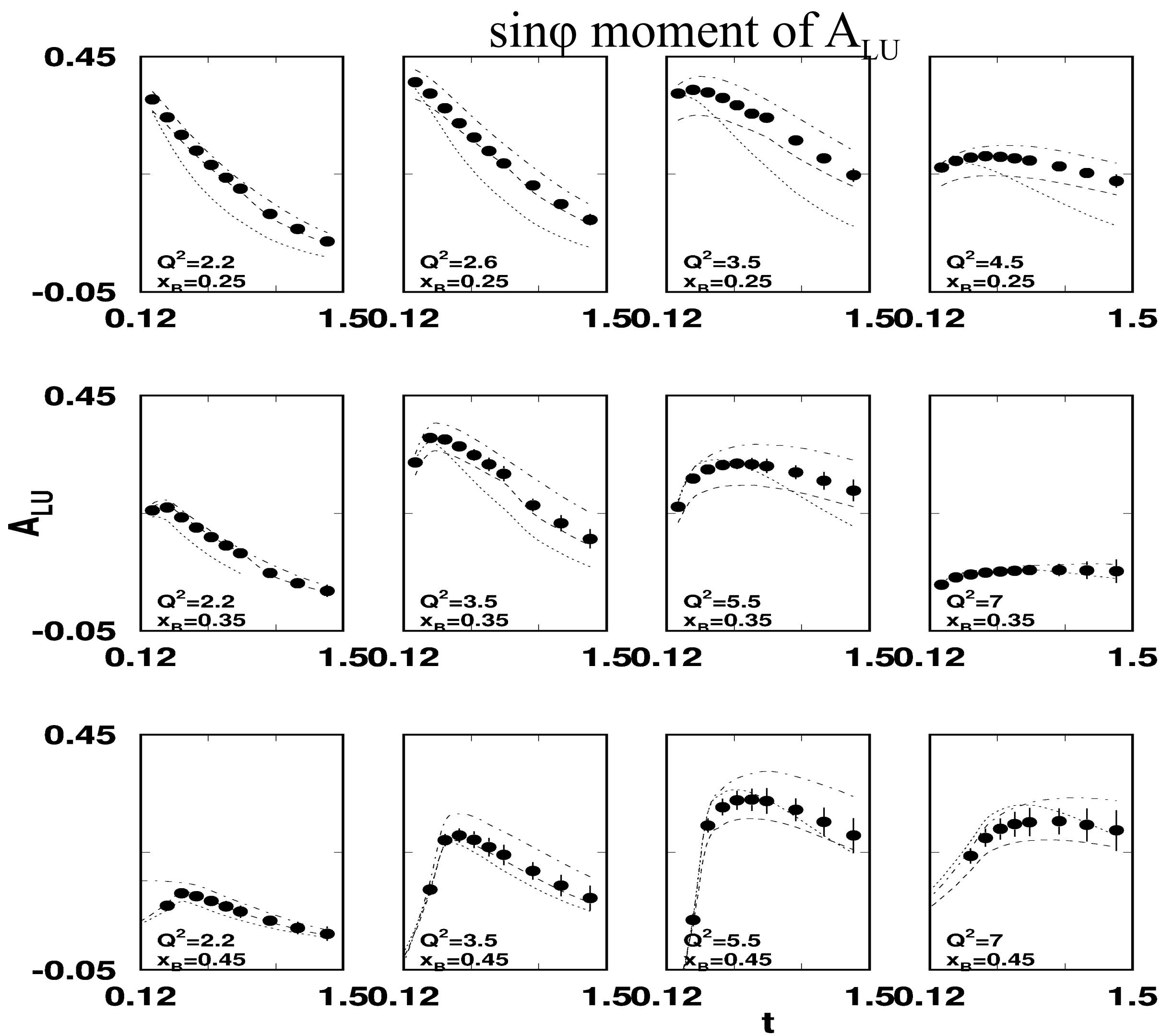
DVCS beam asymmetry at 12 GeV

CLAS12

Experimental DVCS program E12-06-119 was approved for the 12 GeV upgrade using polarized beam and polarized targets.

$\vec{e}p \longrightarrow ep\gamma$

High luminosity and large acceptance allows wide coverage
in $Q^2 < 8$ GeV^2, $x_B < 0.65$,
and
$t < 1.5$GeV^2



Transverse Spin: Transversity

- Three twist-2 quark distributions:
  - Momentum distributions: $q(x,Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$
  - Longitudinal spin distributions: $\Delta q(x,Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$
  - Transversity distributions: $\delta q(x,Q^2) = q^{\perp}(x) - q_{\top}(x)$
- It takes two chiral-odd objects to measure transversity
  - Semi-inclusive DIS

    Chiral-odd distributions function (transversity)

    Chiral-odd fragmentation function (Collins function)
- TMDs: (without integrating over P_T)
  - Distribution functions depends on x, $k_\perp$ and Q^2 : δq, $f_{1T}^{\perp}(x,k_\perp,Q^2)$, …
  - Fragmentation functions depends on z, $p_\perp$ and Q^2 : D, $H_1(x,p_\perp,Q^2)$
  - Measured asymmetries depends on x, z, $P_\perp$ and Q^2 : *Collins, Sivers, …*

    ($k_\perp$, $p_\perp$ and $P_\perp$ are related)

Leading-Twist TMD PDFs

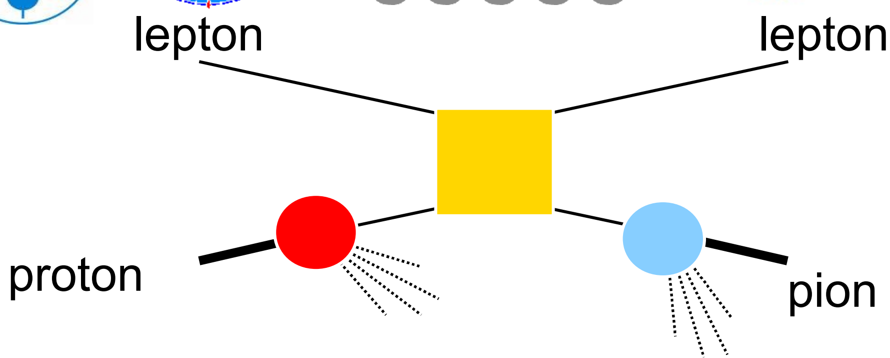
Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} =$ Boer-Mulders
L		$g_1 =$ Helicity	$h_{1L}^{\perp} =$ Worm Gear (Kotzinian-Mulders)
T	$f_{1T}^{\perp} =$ Sivers	$g_{1T} =$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

Nucleon Spin

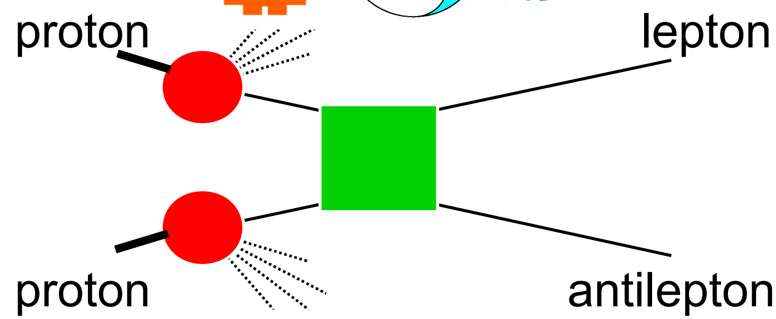
Quark Spin

: Probed by E06-010

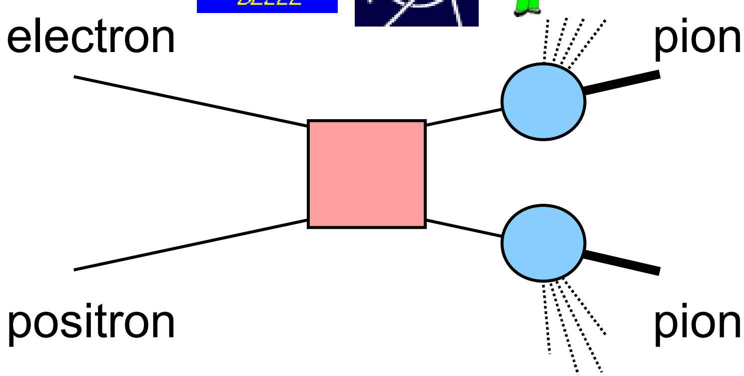
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

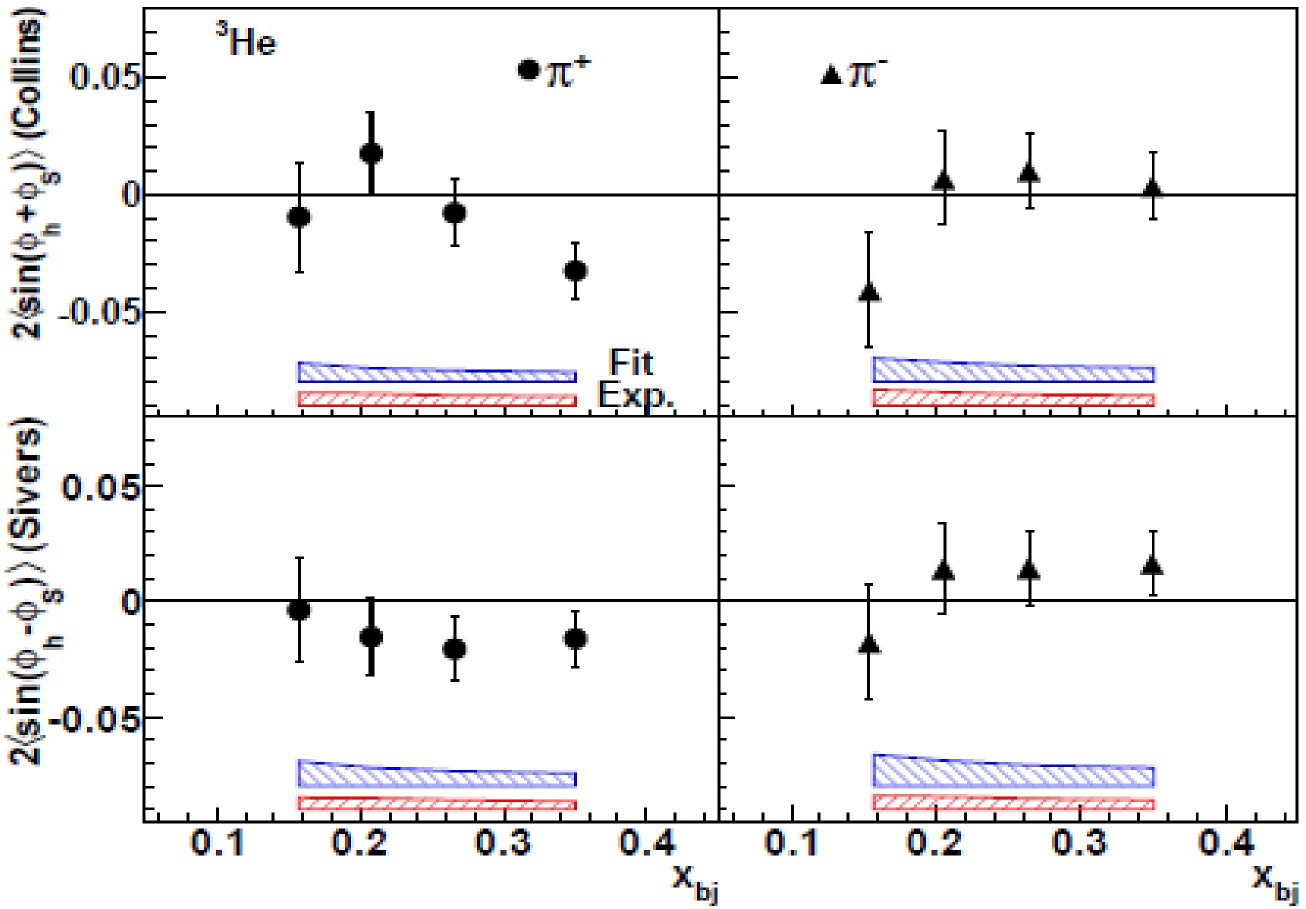
- Gauge invariant definition (Belitsky,Ji,Yuan 2003)
- Universality of k_T-dependent PDFs (Collins,Metz 2003)
- Factorization for small k_T (Ji,Ma,Yuan 2005)

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

Asymmetry in SIDIS

arXiv: 1106.0363, accepted to PRL

$$^{3}\mathrm{He}^{\uparrow}(e, e'h),\ \ h = \pi^{+}, \pi^{-}$$

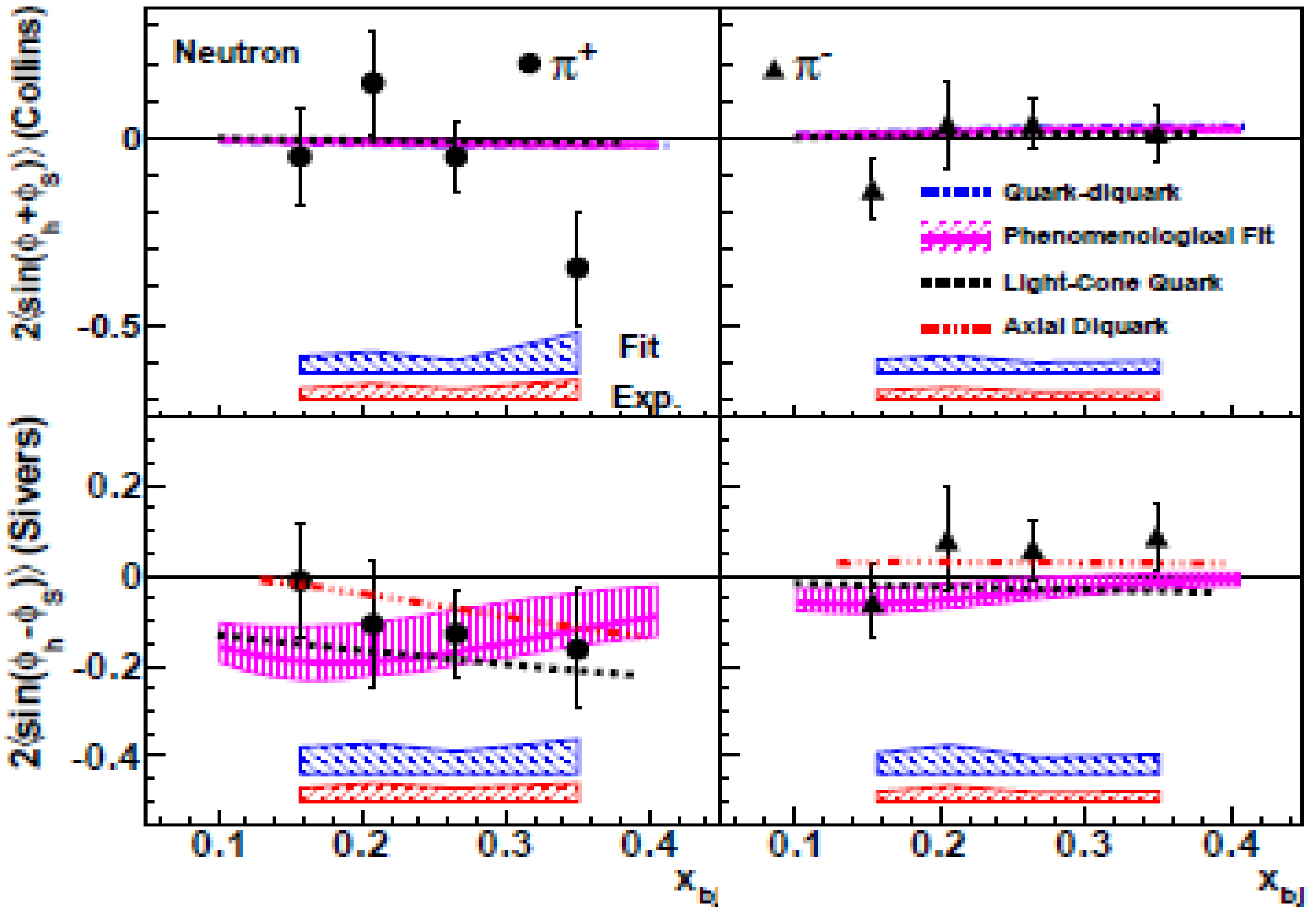


^{3}He Collins SSA small
Non-zero at highest x for π^+

^{3}He Sivers SSA:
negative for π^+,

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

Results on Neutron Collins/Sivers



Collins

asymmetries are not large, except at x=0.34

Sivers

$\pi^+ (u\bar{d})$ negative

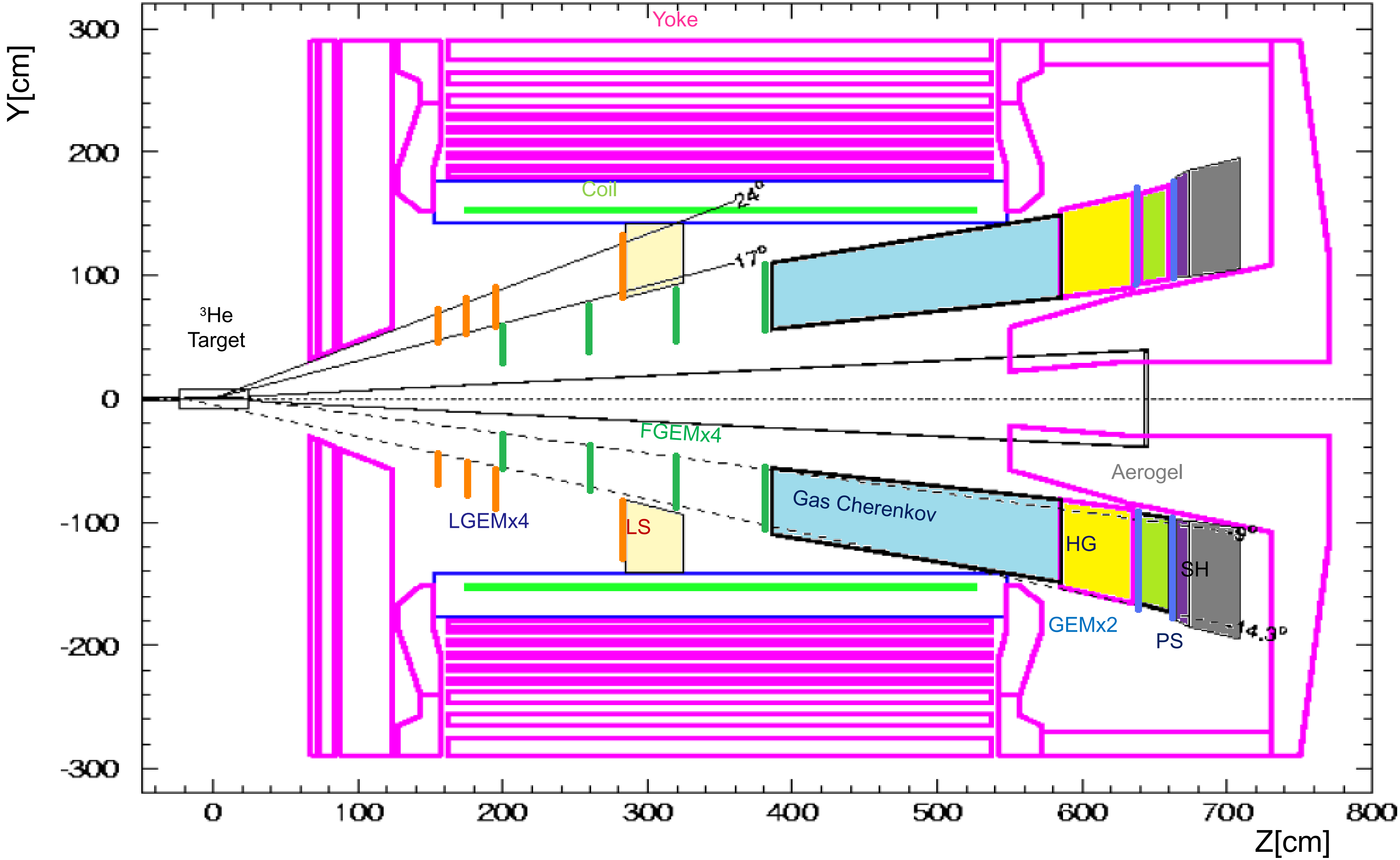
Blue band: model (fitting) uncertainties

Red band: other systematic uncertainties

Precision Study of Transversity and *TMDs*

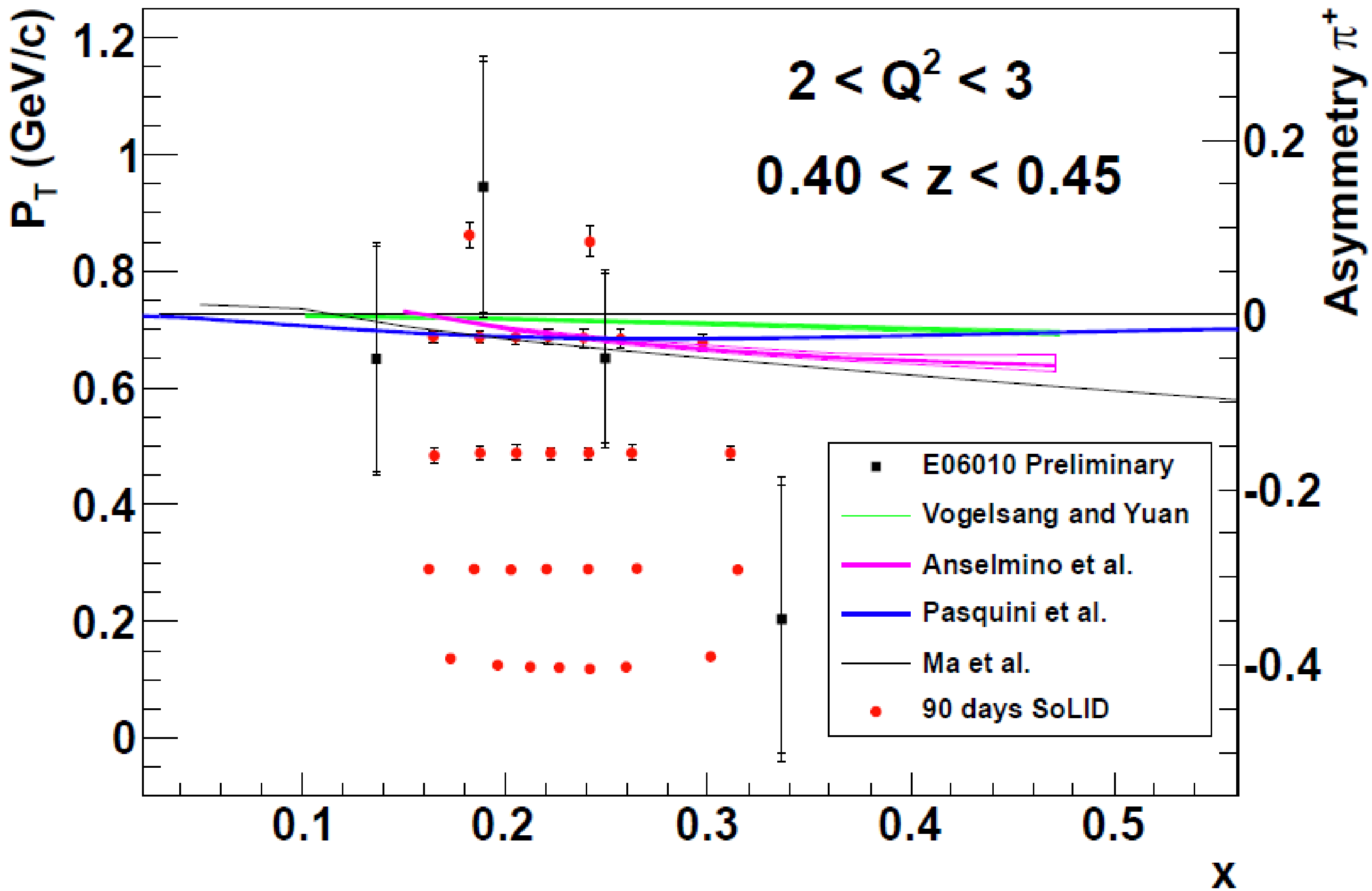
- From exploration to precision study
- Transversity: fundamental *PDFs*, tensor charge
- *TMDs* provide multi-d structure information of the nucleon
- Spin-orbit correlations: quark orbital angular momentum
- Multi-parton correlations: QCD dynamics
- Multi-dimensional mapping of *TMDs*
  - 4-d ($x, z, P_{\perp}, Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

A Solenoid Spectrometer for SIDIS with 12 GeV JLab

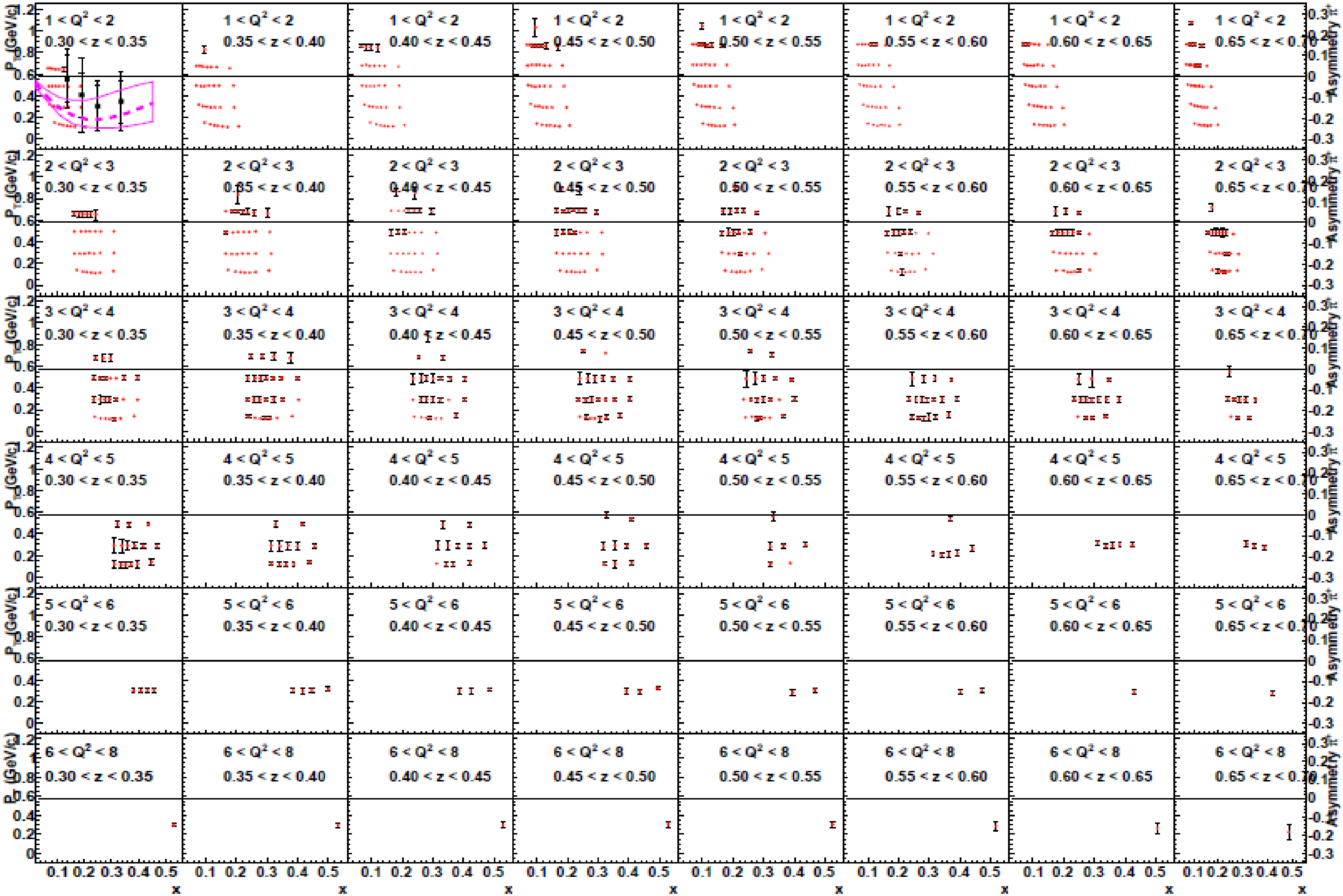


12 GeV: Mapping of Collins/Siver Asymmetries with SoLID

- Both π + and π -
- For one z bin (0.4-0.45)
- Will obtain many z bins (0.3-0.7)
- Upgraded PID for K+ and K-



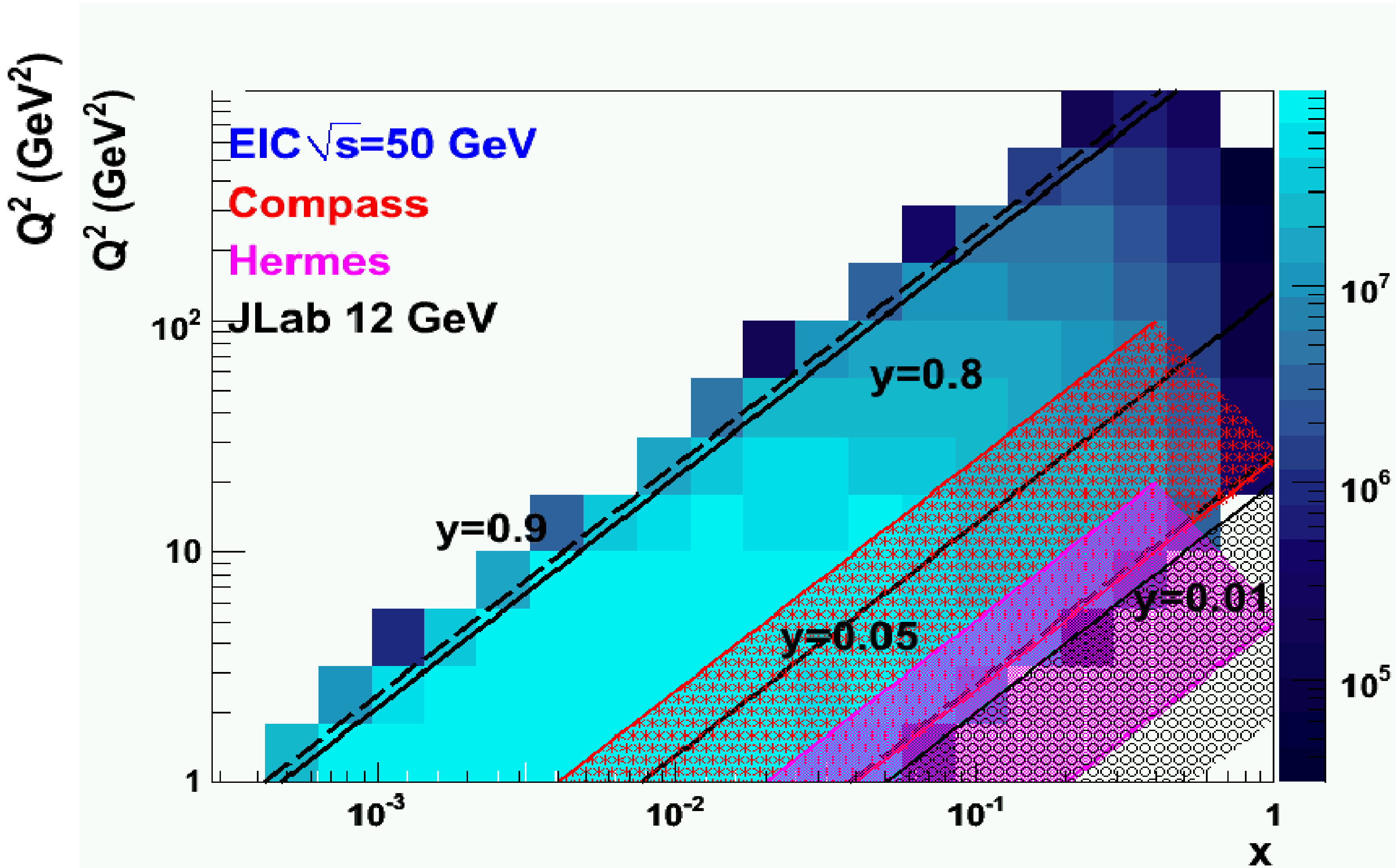
Map Collins and Sivers asymmetries in 4-D (x, z, Q^2, P_T)



Discussion

- Unprecedented precision *4-d* mapping of SSA
  - Collins, Sivers, other TMDs
  - π^+, π^- and K^+, K^-
- Study factorization with *x* and *z*-dependences
- Study P_T dependence
- On both proton and neutron and combine with world data (e+e-)
  - extract transversity and fragmentation functions for both *u* and *d* quarks
  - determine tensor charge
  - study TMDs for both valence and sea quarks
  - study quark orbital angular momentum
- Combining with world data from high energy facilities
  - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of multi-d nucleon structure and QCD

Phase Space Coverage



Proton π⁺ (z = 0.3-0.7)

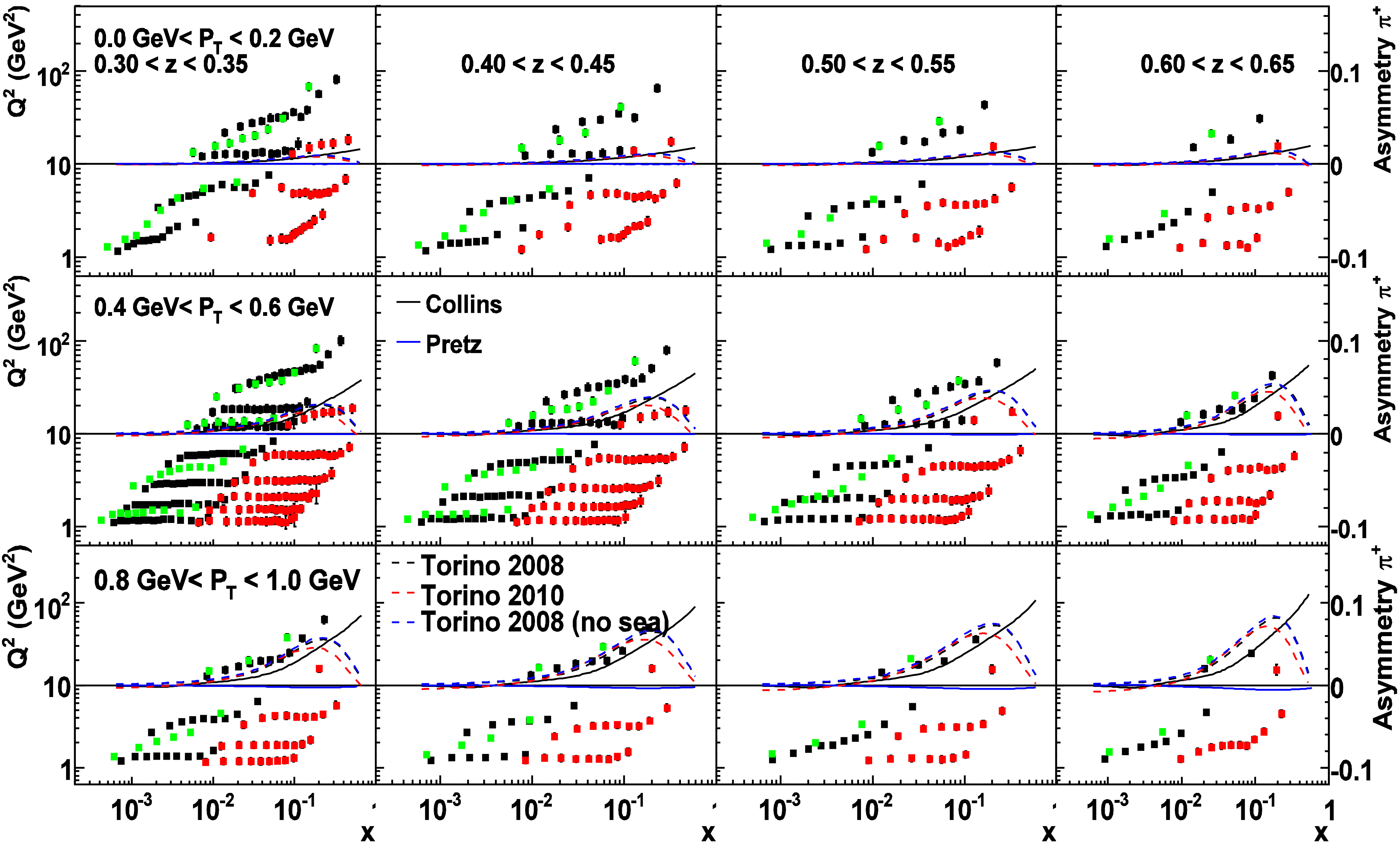
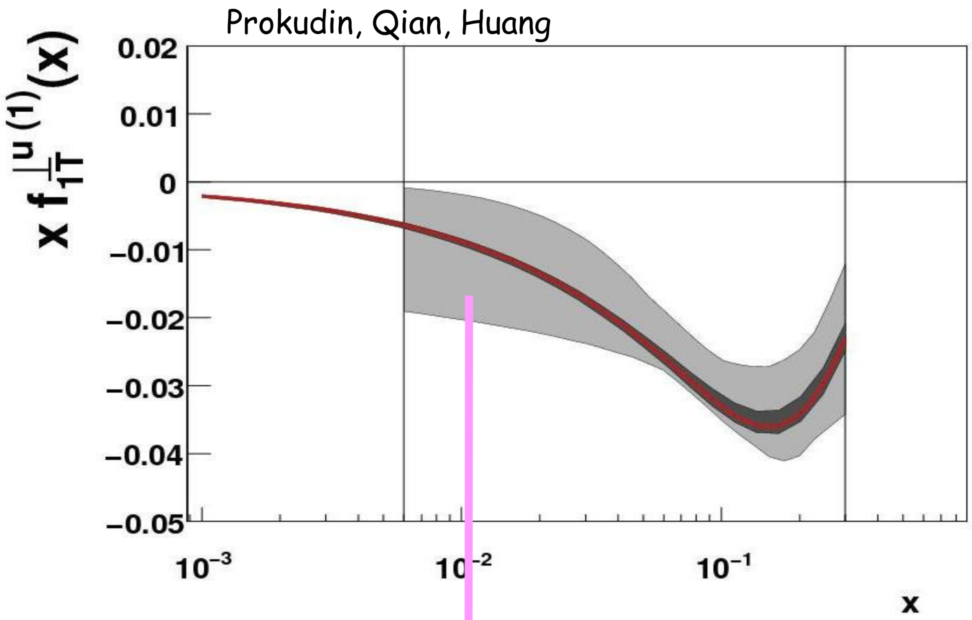
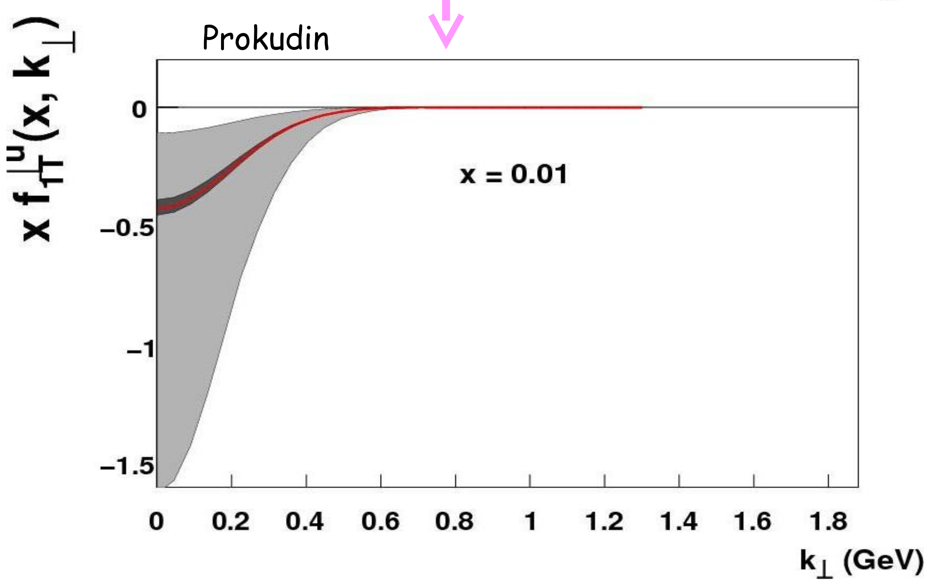


Image the Transverse Momentum of the Quarks





Only a small subset of the (x,Q^2) landscape has been mapped here:

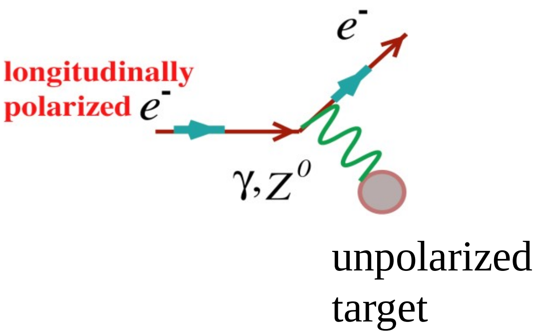
terra incognita

Gray band: present "knowledge"
Red band: EIC (1σ)
(dark gray band: EIC (2σ))

Exact k_T distribution presently essentially unknown!
"Knowledge" of k_T distribution at large k_T is artificial!
(but also perturbative calculable limit at large k_T)

An EIC with good luminosity & high transverse polarization is the optimal tool to to study this!

Parity-Violating (PV) Electron Scattering



$$\sigma \;\alpha\; |A_\gamma + A_{weak}|^2 \sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\, g$$

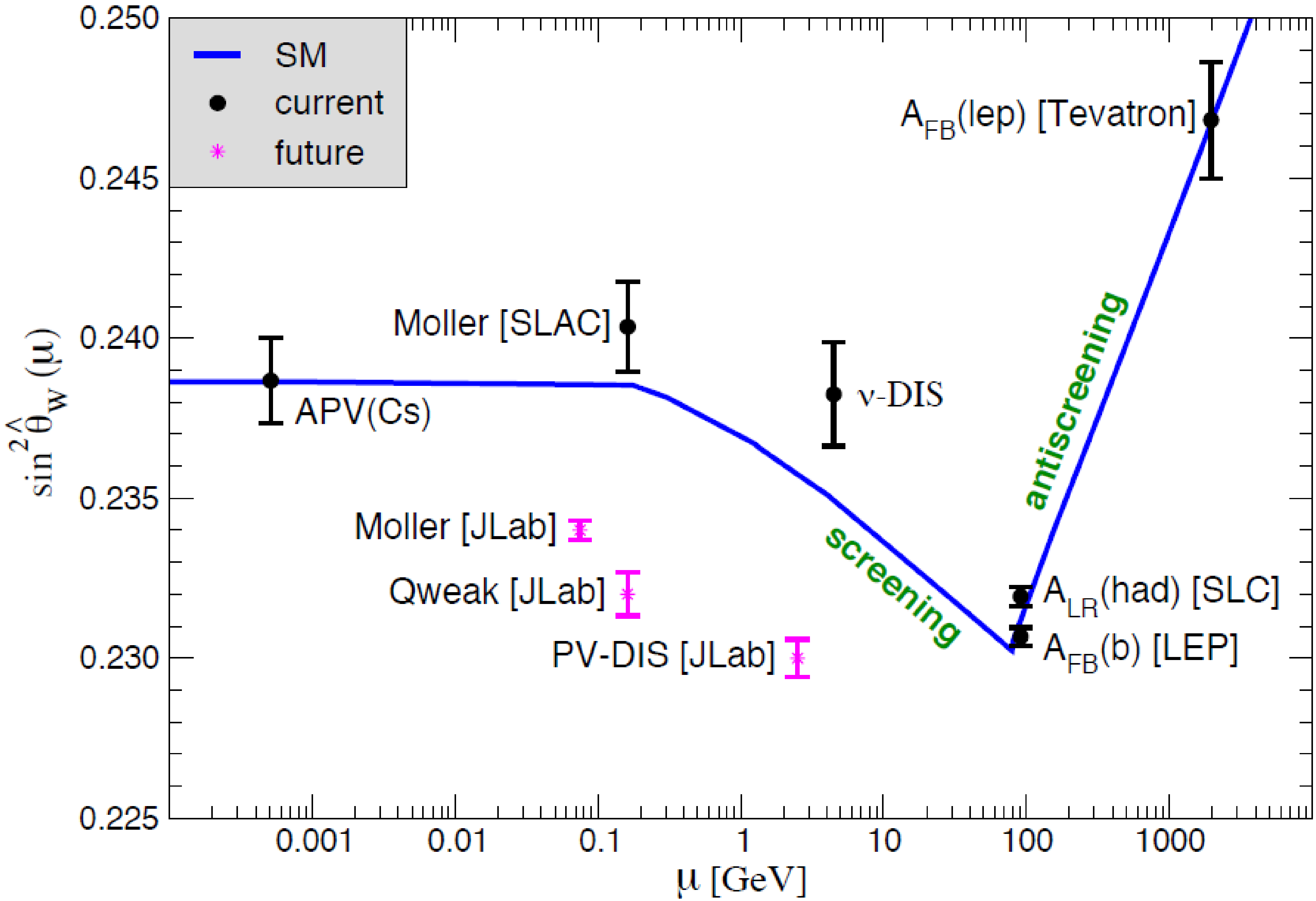
Leading contribution to parity-violating scattering asymmetry from interference of EM and weak amplitudes

$$g = g_A^e g_V^T + \beta\, g_V^e g_A^T$$

$A \sim \cdot Q$ to $\cdot Q^4 \cdot Q^2$

- g_V^e and g_A^e are function of $\sin^2\theta_W$
- β is a kinematic factor
- g^T: nucleon structure (QCD)

Low Energy Tests of the Standard Model



Summary

- Electron Scattering: A clean tool to study nucleon structure and QCD
- JLab facility and 12 GeV upgrade
- A Future Electron-Ion Collider
- Highlights of 6 GeV results and examples of 12 GeV program
    - Precision EM form factors
    - Nucleon spin structure (valence quark)
    - GPDs
    - Transversity and TMDs
    - Parity violating electron scattering to test the Standard Model
- EIC goes into new region: understand sea quarks and gluons

Exciting new opportunities → lead to breakthroughs?