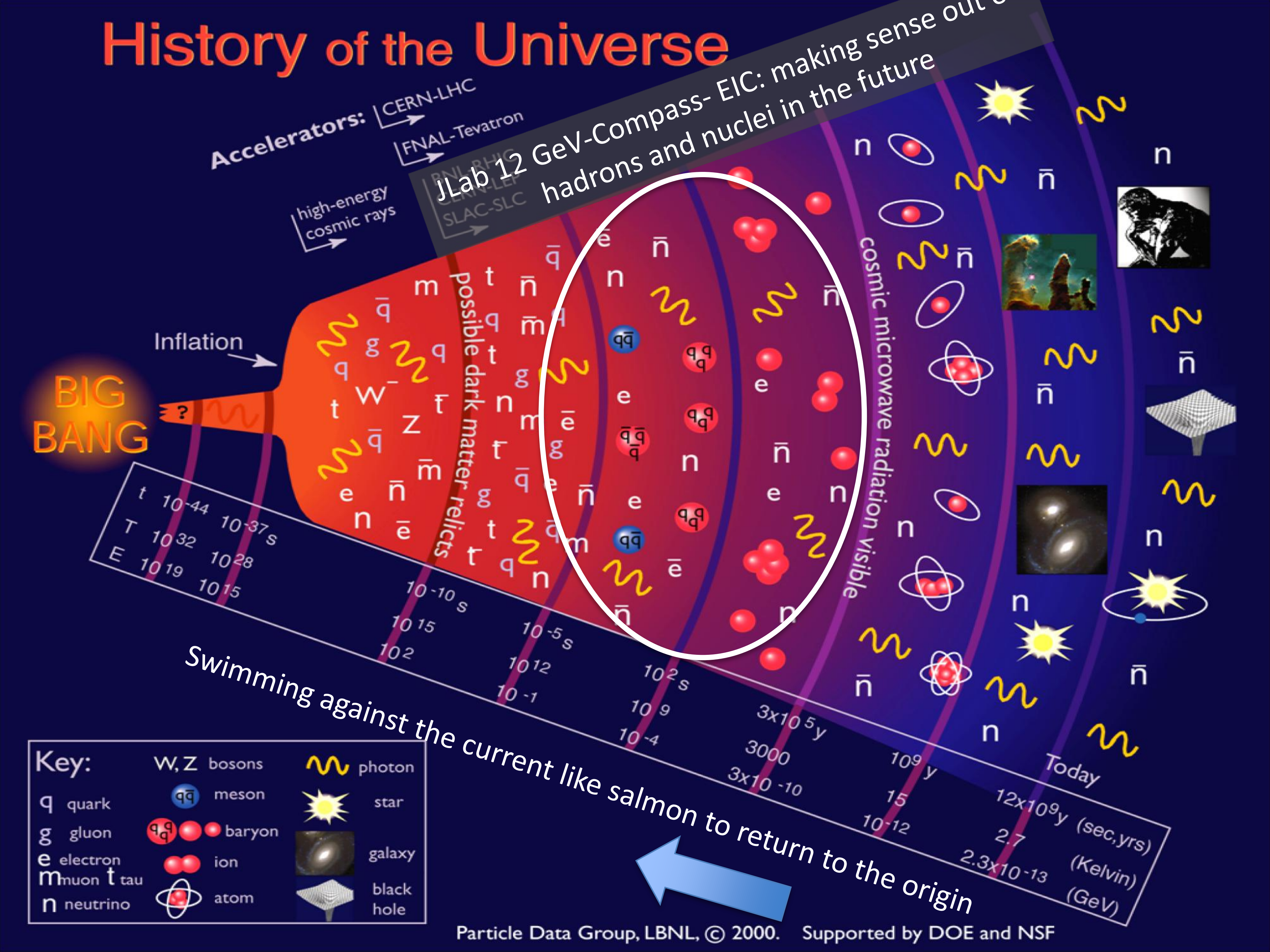
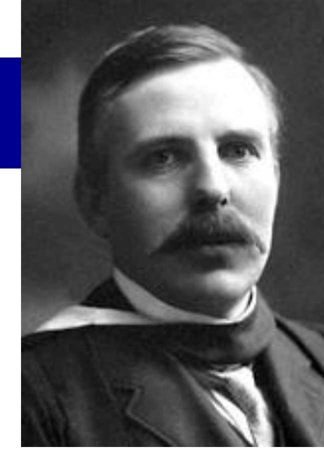
QCD at JLab 12 GeV

Zein-Eddine Meziani
Temple University


History of the Universe
JLab 12 GeV-Compass- EIC: making sense out of
hadrons and nuclei in the future
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10² s 3x10⁵ y 10⁹ y 12x10⁹ y (sec,yrs)
T 10³² 10²⁸ 10¹⁵ 10¹² 10⁹ 3000 15 2.7 (Kelvin)
E 10¹⁹ 10¹⁵ 10² 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Swimming against the current like salmon to return to the origin
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
galaxy
m muon t tau
ion
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

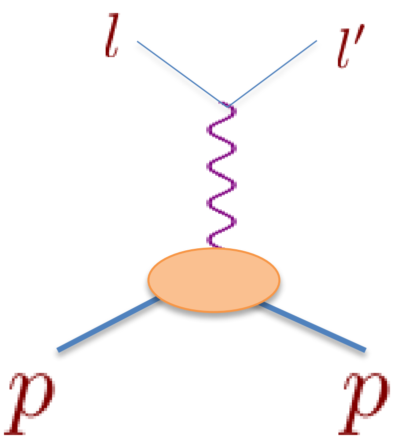
Experimental tools: Scattering

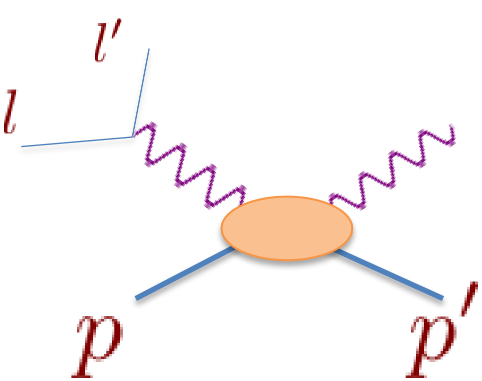


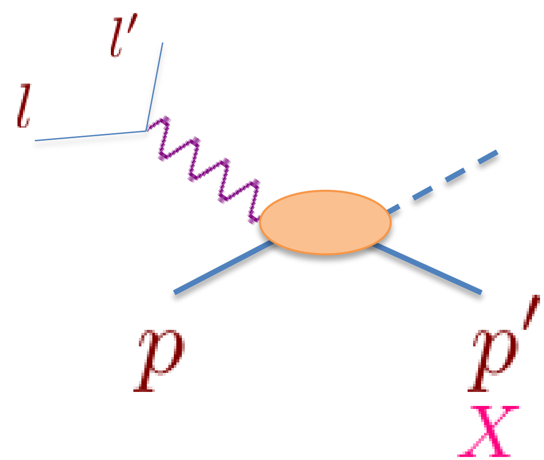
Rutherford, 1908, Chem. N.P.

- Use of lepton and hadron beams
  - Polarized beams of e-, e+, μ+, μ-, p
- Use of proton and nuclear targets
  - Targets in many cases are polarized (p, D, NH_3, ND_3, ^3He,…..)

- Electromagnetic probe: Compton scattering, real and virtual
  - Exclusive, semi-inclusive or inclusive (elastic scattering, inelastic scattering)







Compton, 1927, Phys. N.P.

The Tools

Spectroscopy

Generalized Parton Distributions

Since 1998

Inclusive

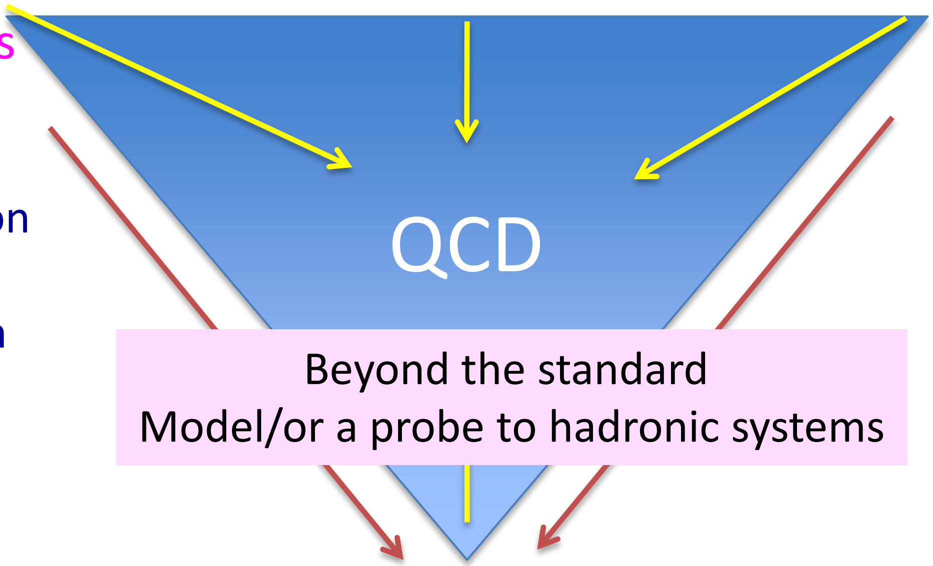
Sum rules and polarizabilities

Transverse Momentum Distributions

Since 2002

Exclusive reactions

Semi-Inclusive DIS



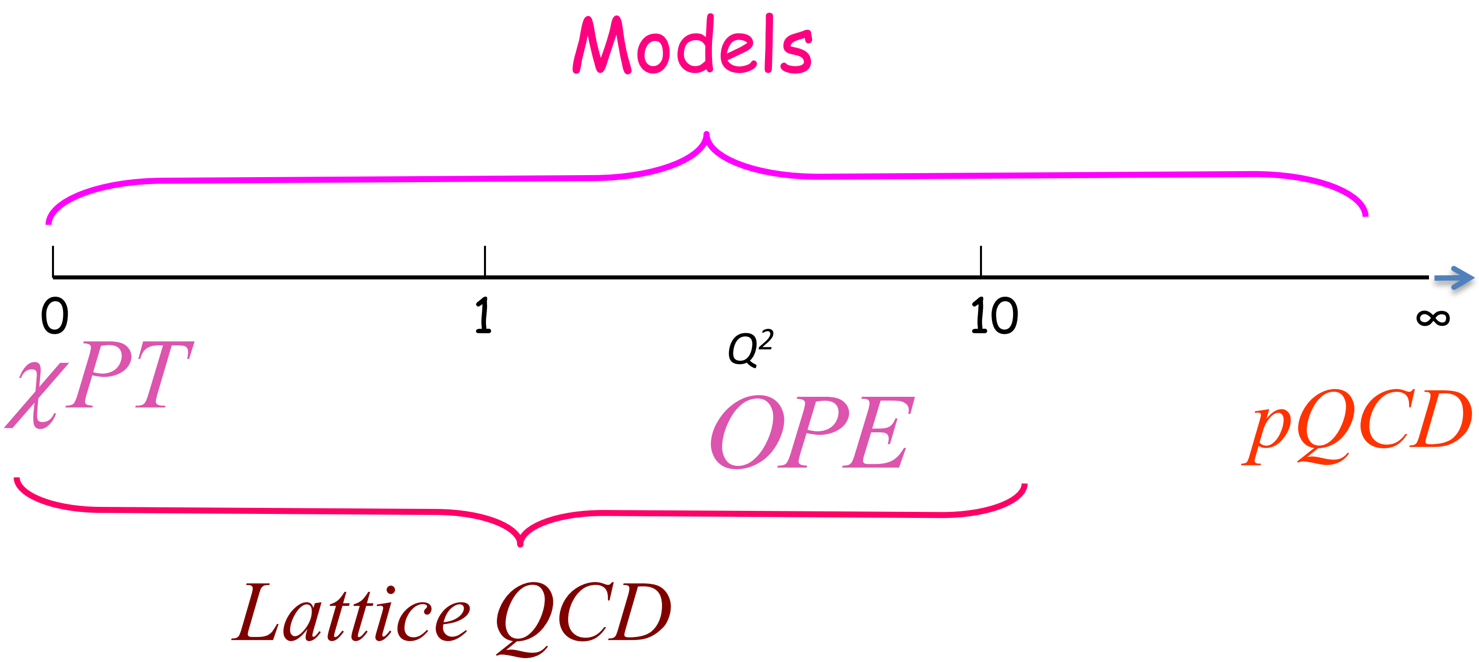
Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production

Distributions and
Fragmentation functions

Beyond the standard
Model/or a probe to hadronic systems

GPDs and TMDs in Nuclei
Exclusive
Semi-inclusive
Initial and final medium effects

Resolution of the probe and scale of theory tools



12 GeV Science Program

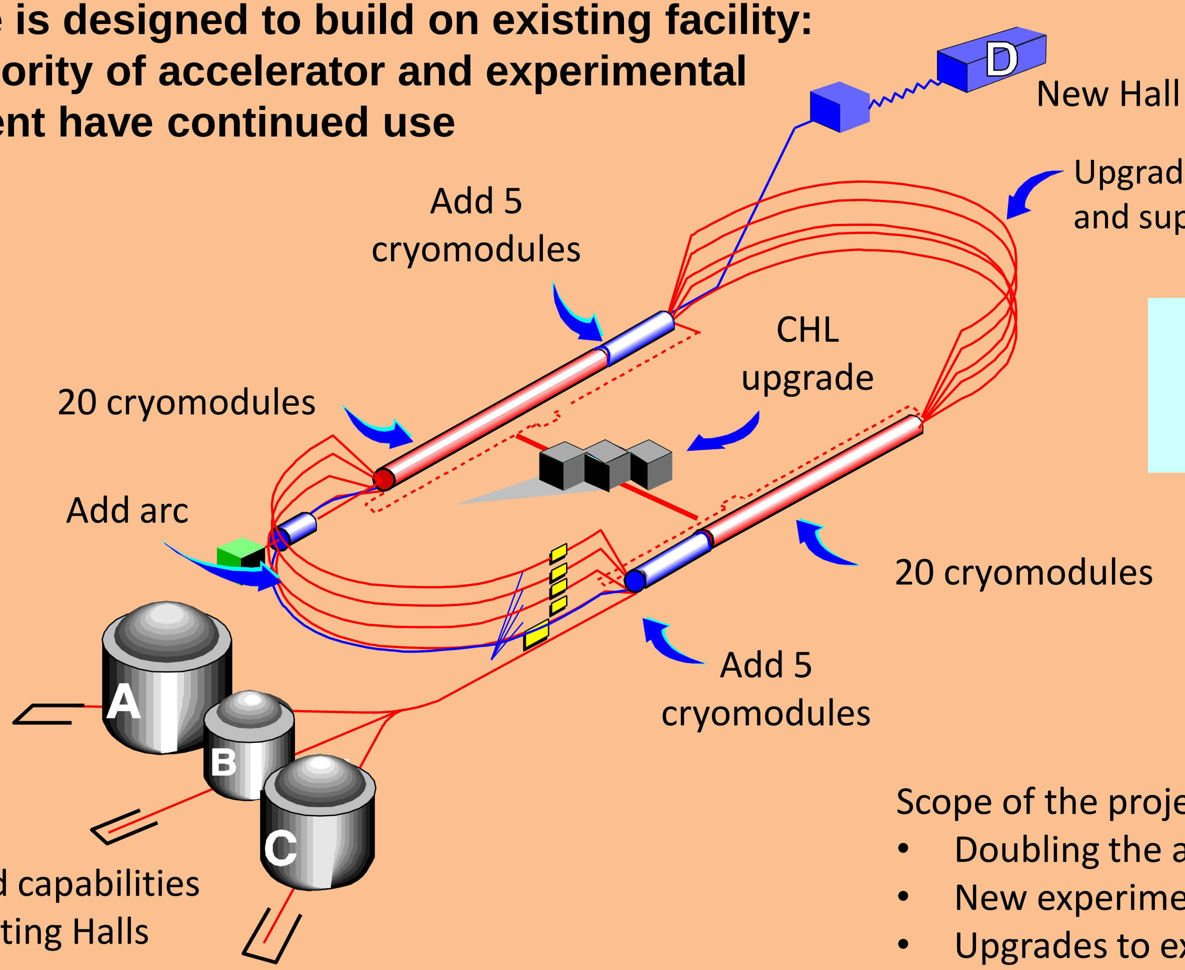
- The physical origins of quark confinement (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's…)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

- Defining the Science Program:
  - Six Reviews: Program Advisory Committees (PAC) 30, 32, 34, 35, 36, 37, 38
  - 2006 through 2011
  - Results: *48 experiments approved; 4 conditionally approved*

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

12 GeV Upgrade Project

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



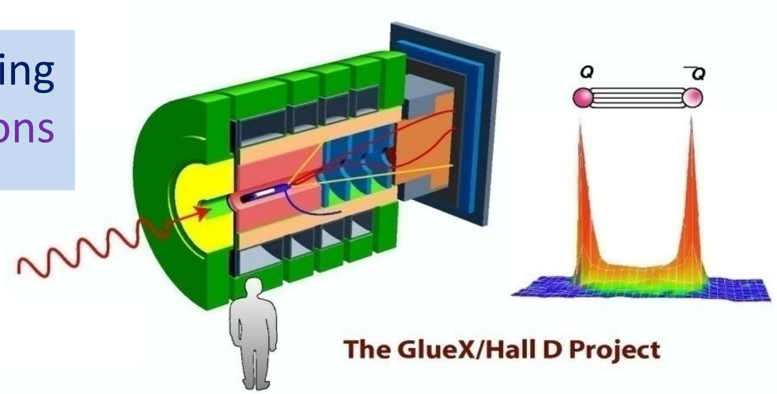
Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

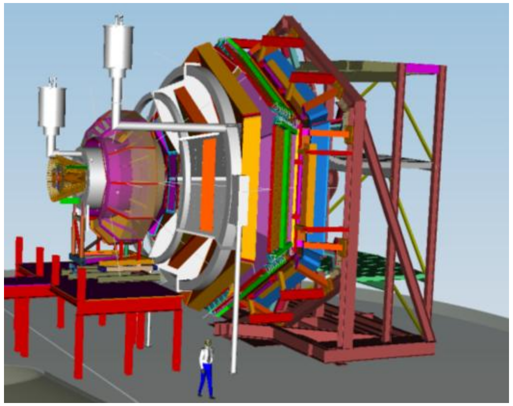
Scope of the project includes:

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

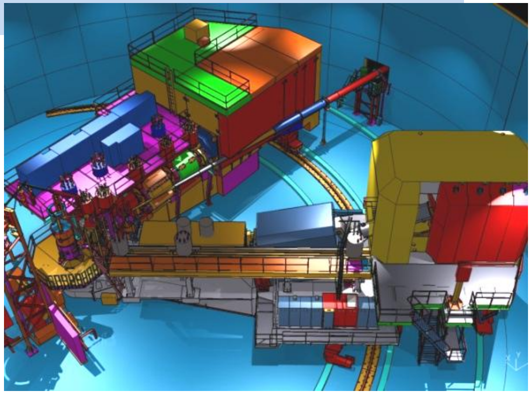
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

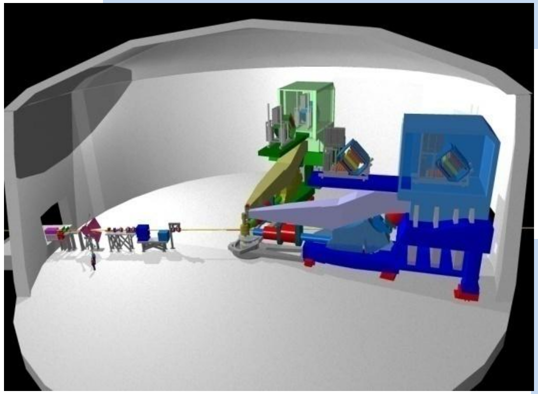




Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions

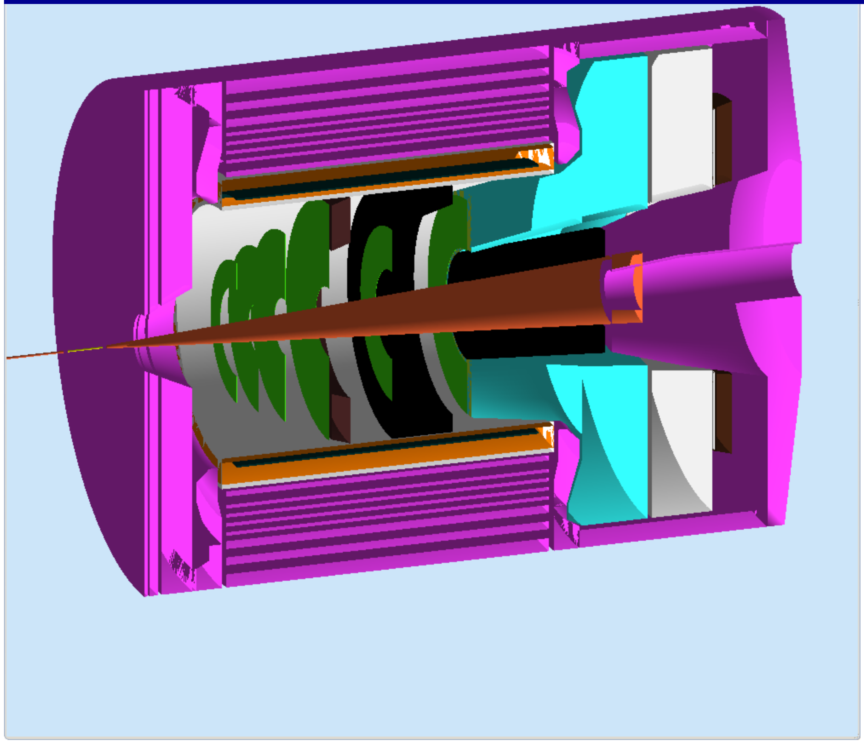


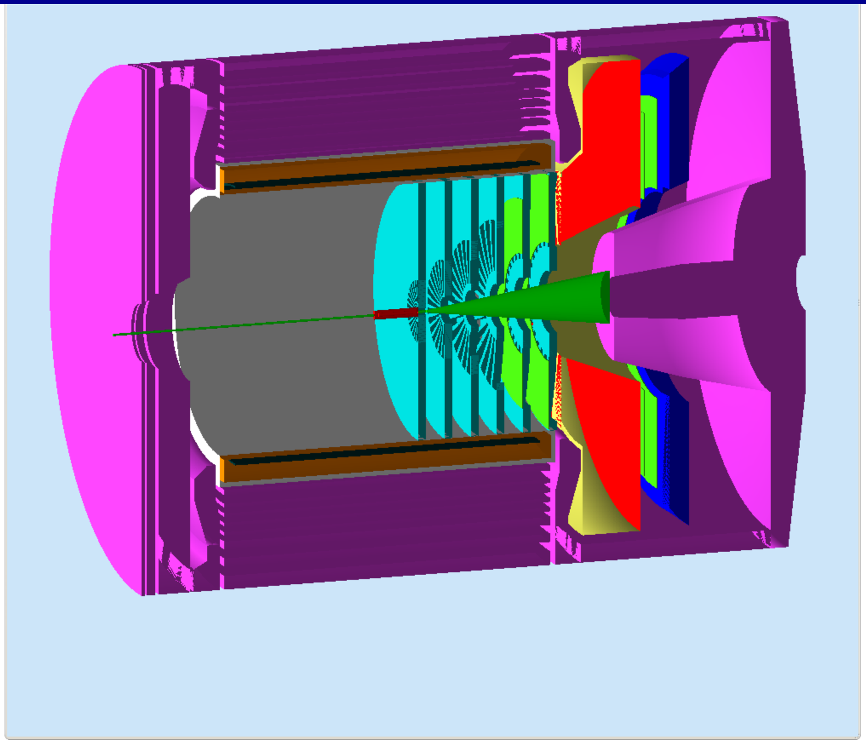
Hall C – precision determination of valence quark properties in nucleons and nuclei



Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., MOLLER, PVDIS, SIDIS)

Hall A (Additional Equipment Required)





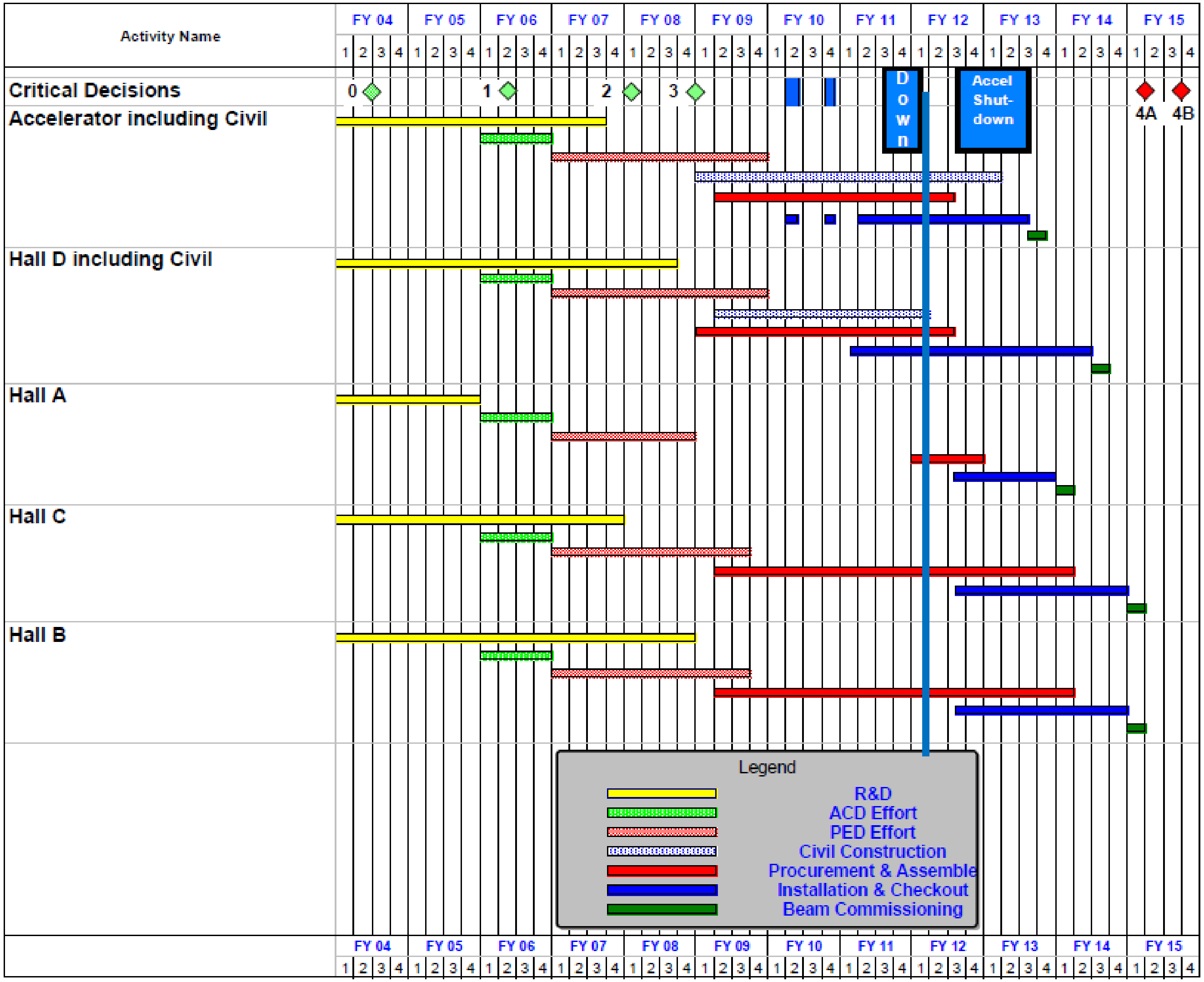
SOLID for SIDIS:

- High luminosity on polarized ^3He
- Better than 1% errors for small bins
- Large Q^2 coverage
- x-range 0.08-0.6
- W^2> 4 GeV^2

SOLID for PVDIS:

- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins
- Large Q^2 coverage
- x-range 0.25-0.75
- W^2> 4 GeV^2

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/C commissioning start October 2014

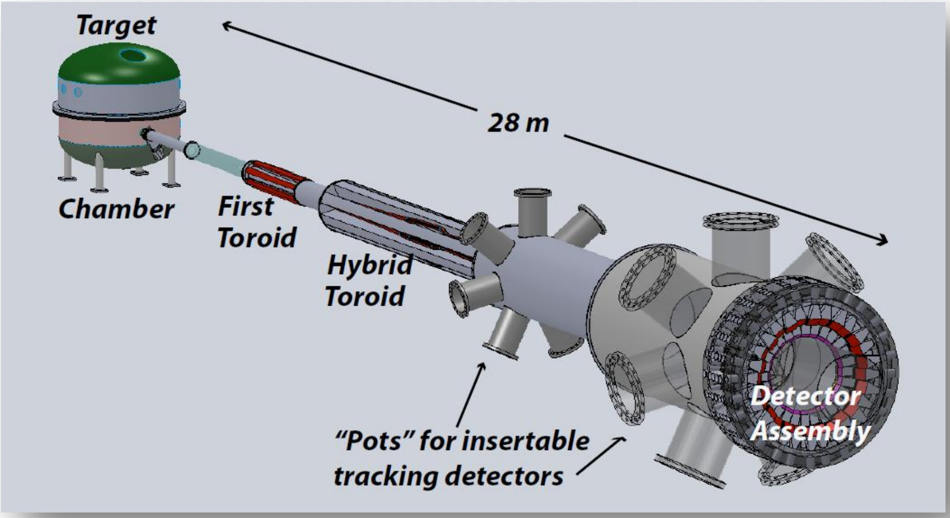
Project Completion June 2015

Hall D Status – July 2011

Ready For Equipment (RFE) Dec. 28, 2010

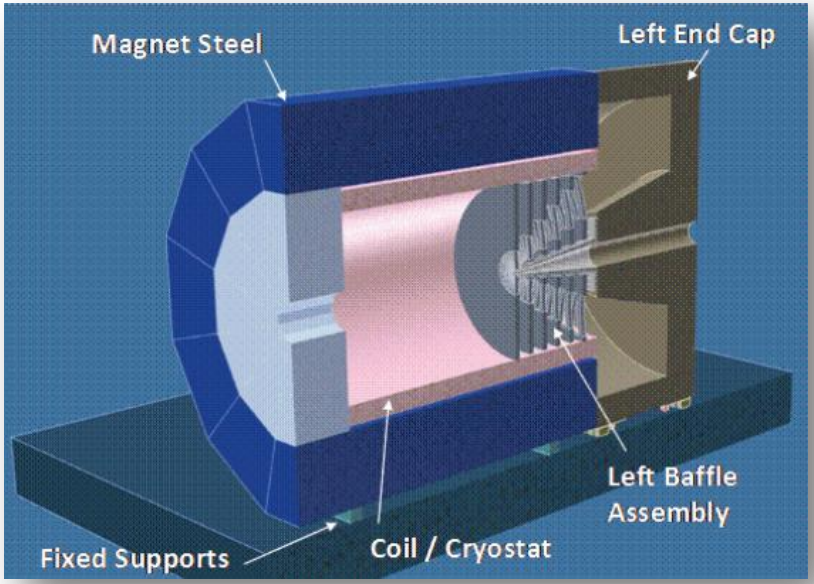
Arc Dipole Installation

New Projects in Hall A



- Dedicated MOLLER Experiment (successor to SLAC E158)
- DOE MIE proposal → CD-0

SoLID (solenoidal large intensity device):
general purpose deep inelastic scattering (PVDIS, SIDIS)

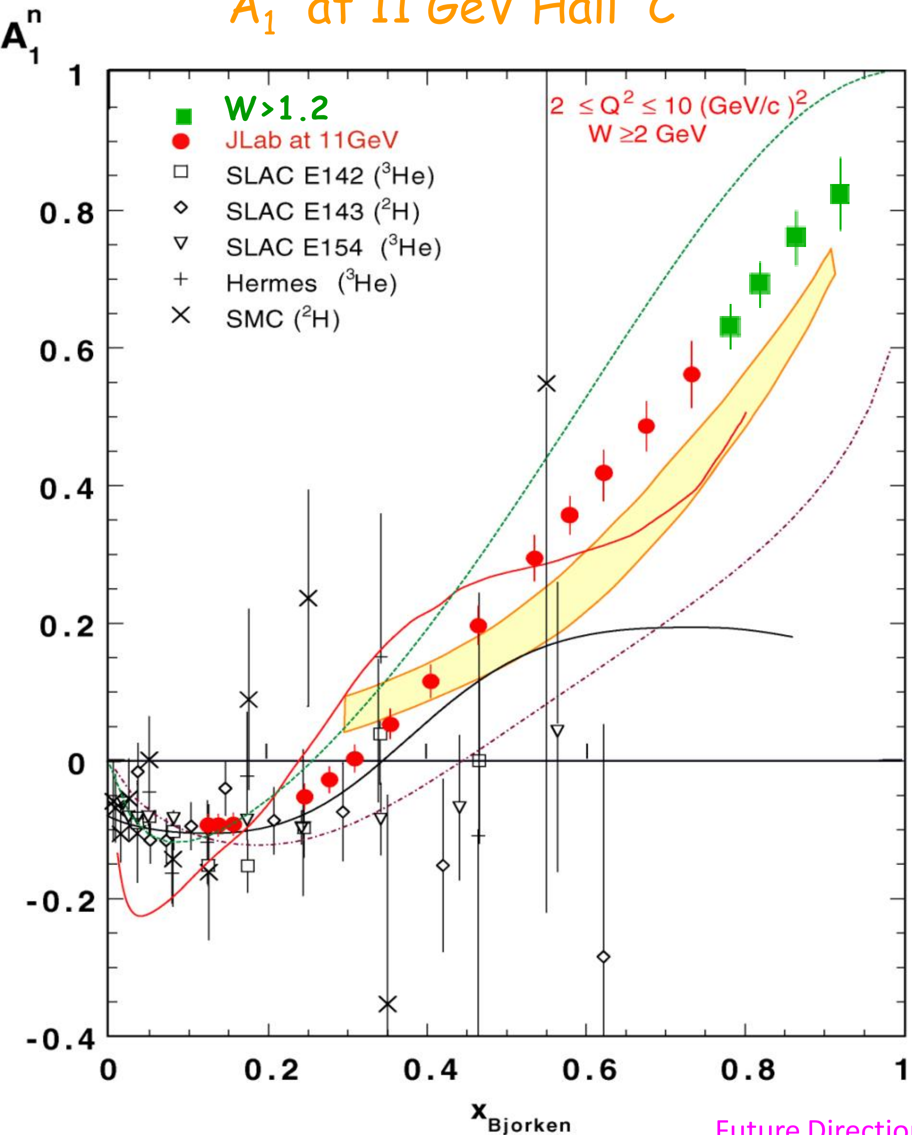


New Collaboration Opportunities

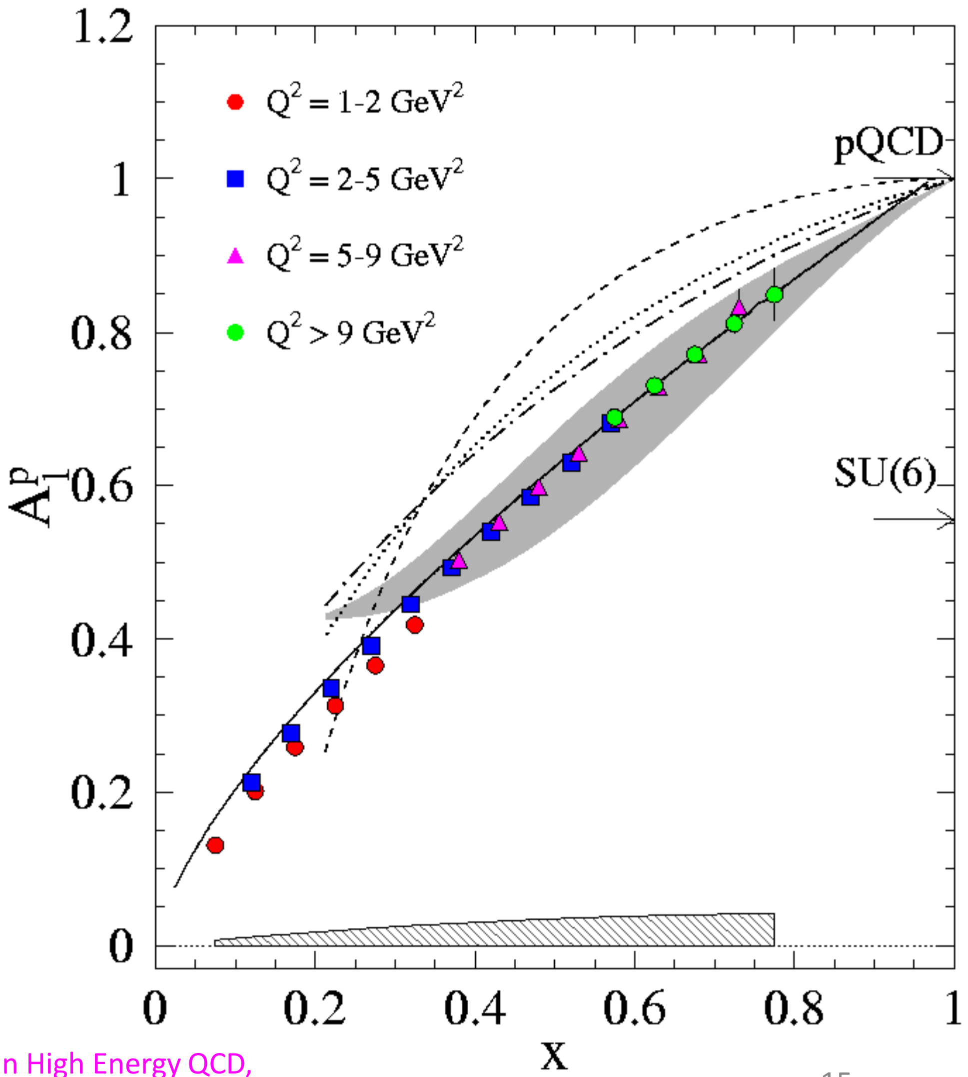
- MOLLER
- SoLID
- A' searches
- RICH detectors for CLAS12 and GlueX

Inclusive double spin asymmetries using 12 GeV

A_1^n at 11 GeV Hall C



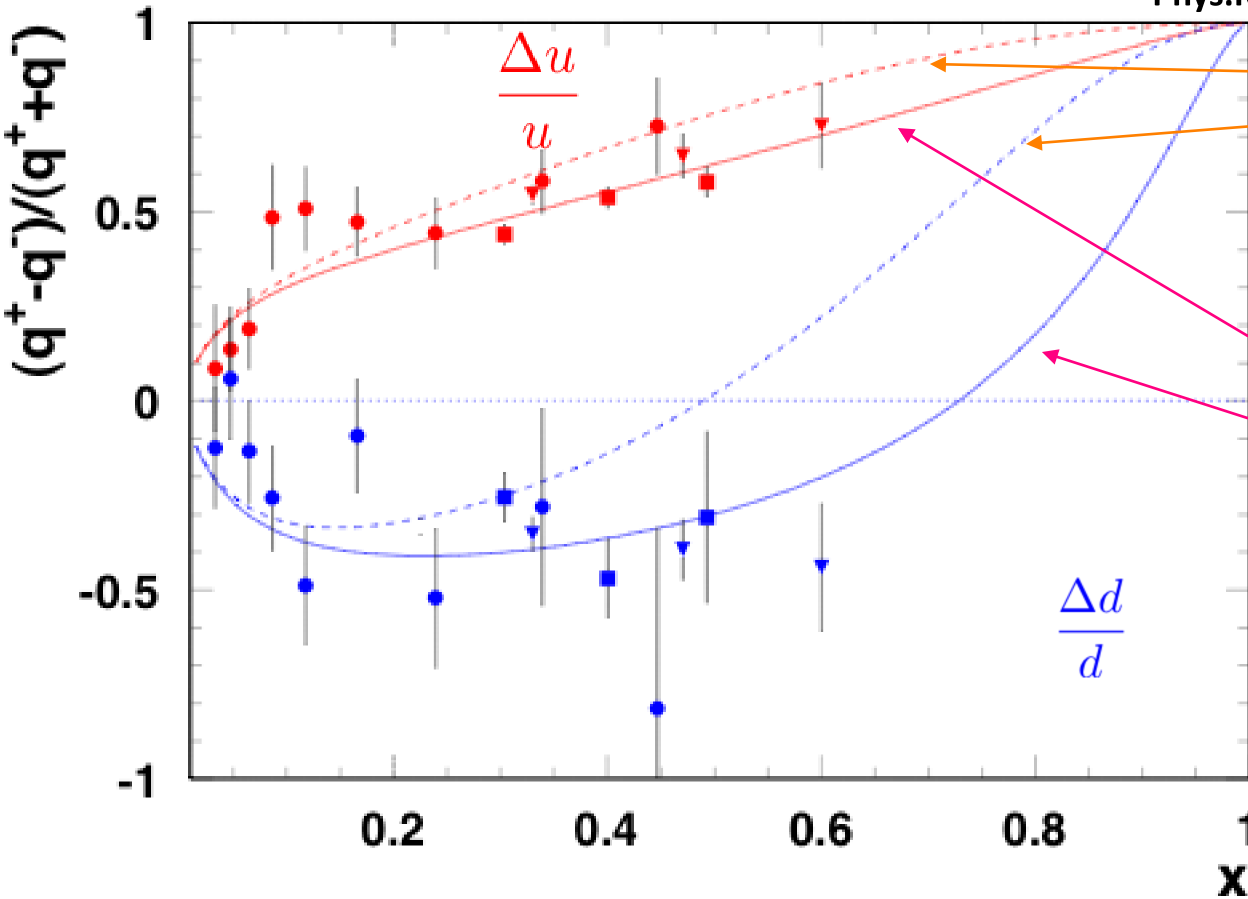
CLAS12 Proton



Effect of considering transverse momentum of quarks in the nucleon

Inclusive Hall A and B and Semi-Inclusive Hermes

Avakian, Brodsky, Deur and Yuan
Phys.Rev.Lett.99:082001,2007.



BBS

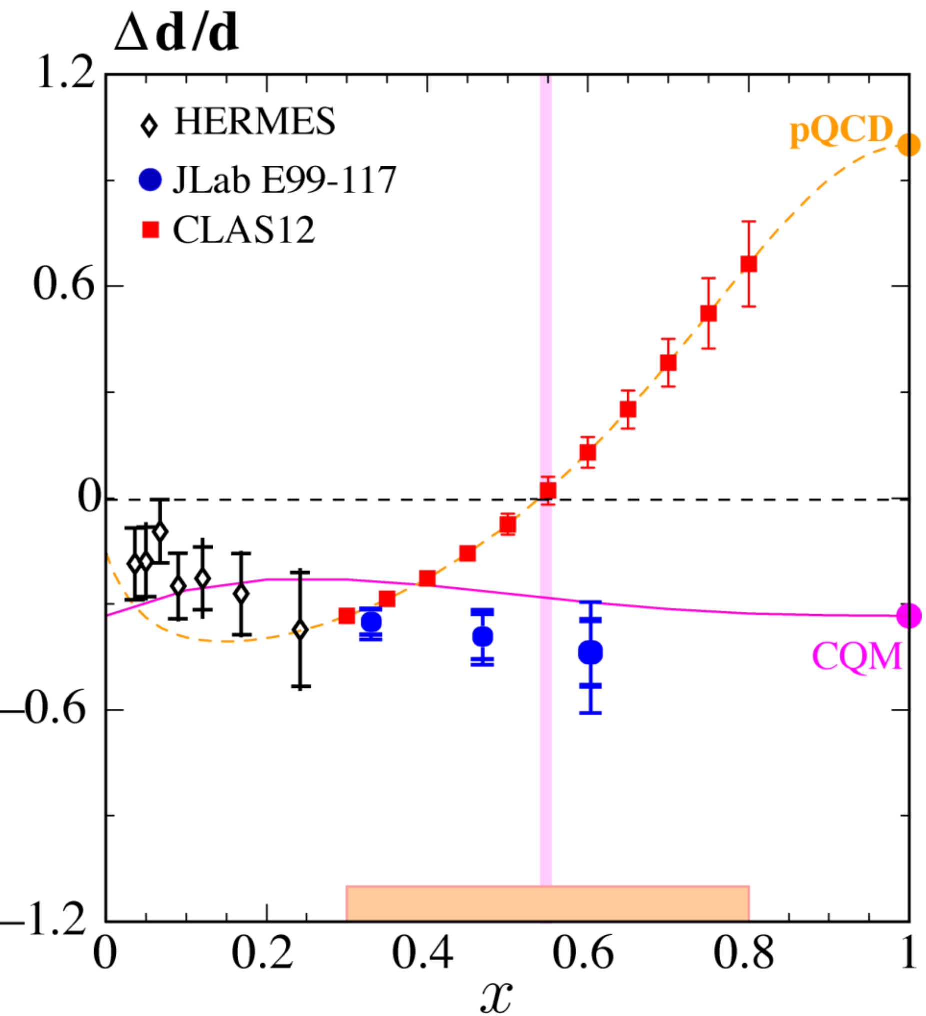
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

BBS+OAM

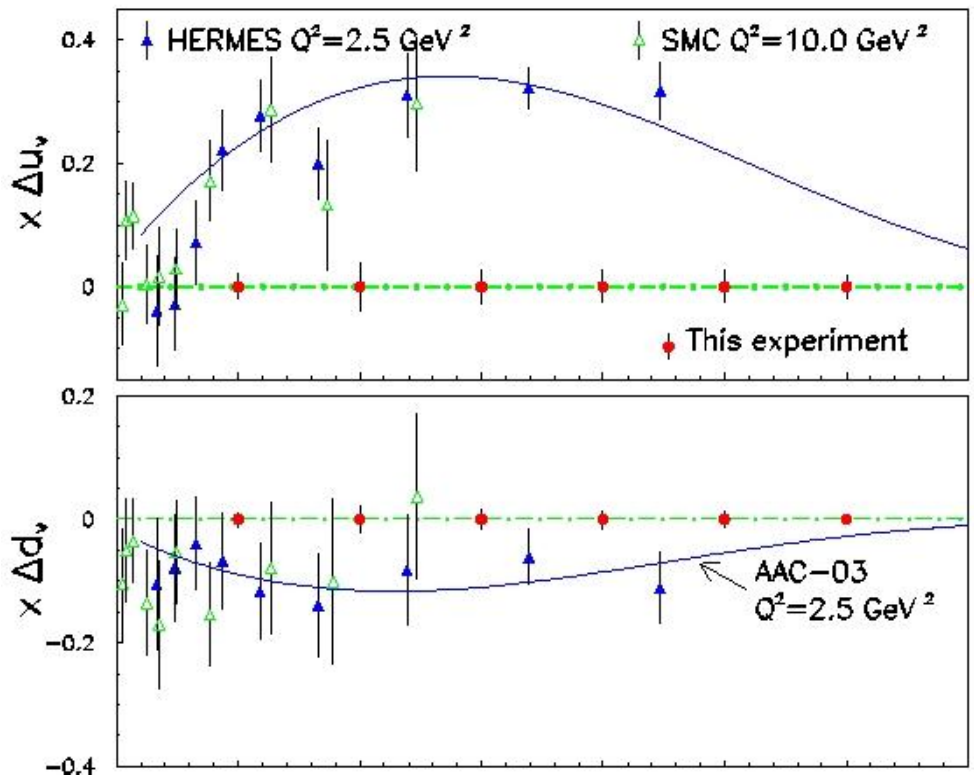
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Longitudinal Double Spin Asymmetry in SIDIS

At JLab 12 GeV with SIDIS

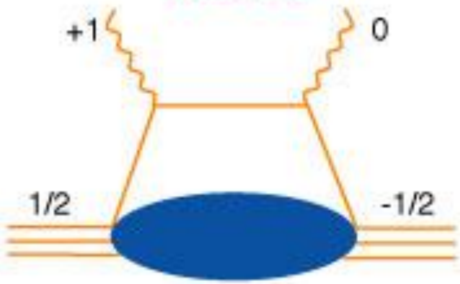


E_e =11 GeV **NH_3 and ^3He**

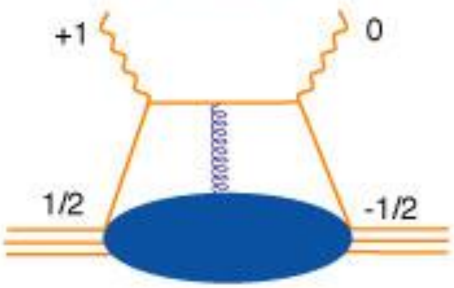


- Asymmetry measurements with different hadrons (π^+,π^-) and targets (p,n) allows for flavor separation

Quark Gluon Correlations



Carry one unit of orbital angular momentum



Couple to a gluon

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- a twist-2 term (Wandzura & Wilczek, 1977):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

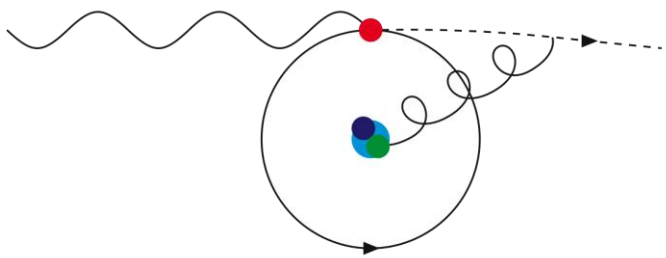
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

transversity

quark-gluon correlation

Average Color Lorentz Force (M. Burkardt)

$$\int dx x^2 \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \left\langle P, S \left| \bar{q}(0) g G^{+y}(0) \gamma^+ q(0) \right| P, S \right\rangle$$



$\hookrightarrow$ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

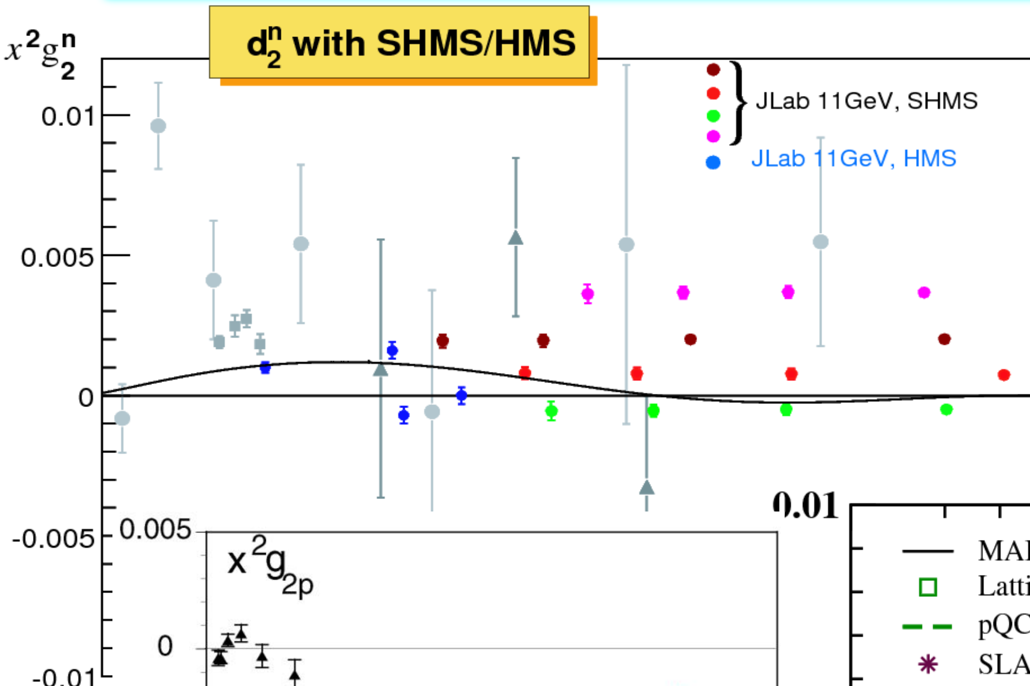
$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

- Interpretation of d_2 with the transverse FSI force in DIS also consistent with $\langle k_\perp^y \rangle \equiv \int_0^1 dx \int d^2k_\perp \, k_\perp^2 \, f_{1T}^\perp(x, k_\perp^2)$ in SIDIS (Qiu, Sterman)

$$\langle k_\perp^y \rangle = -\frac{1}{2p^+} \left\langle P, S \left| \bar{q}(0) \int_0^\infty dx^- g G^{+y}(x^-) \gamma^+ q(0) \right| P, S \right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

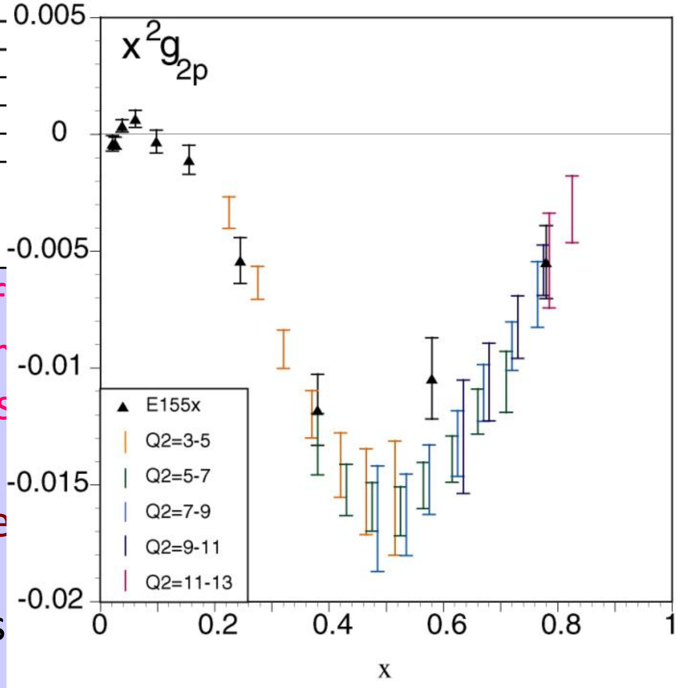
Projected results for g2n and d2n

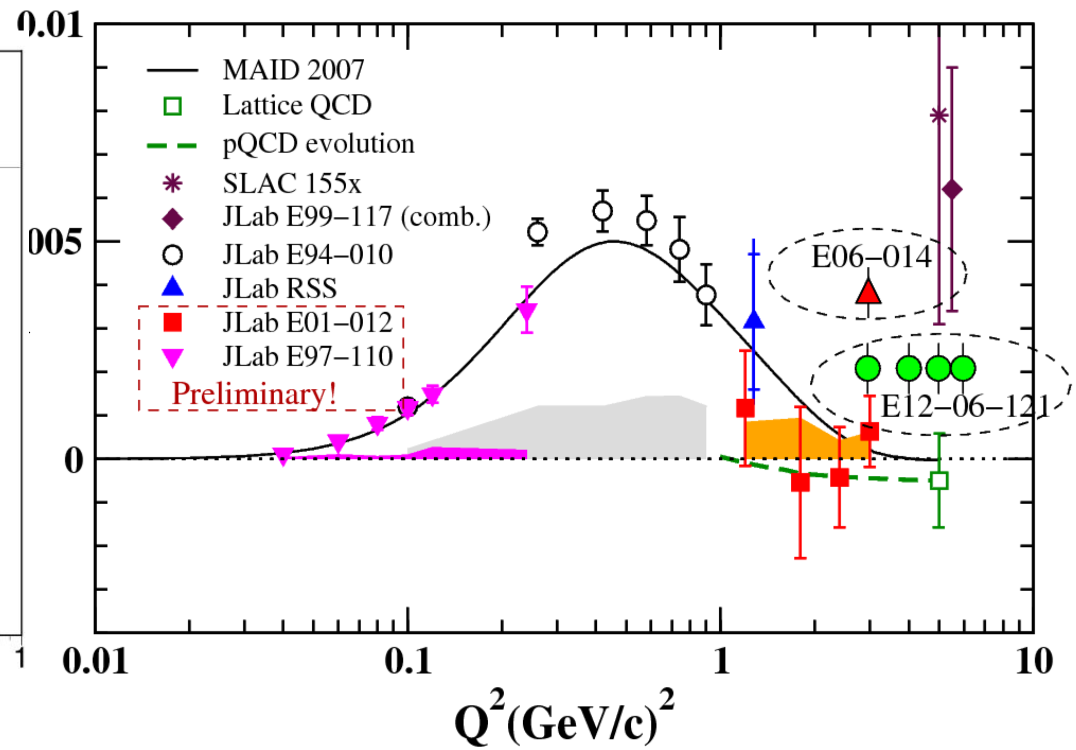


Projected g_2^n points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—7 GeV^2.

- g_2 f… fron… cros… the…
- Stre…

less…

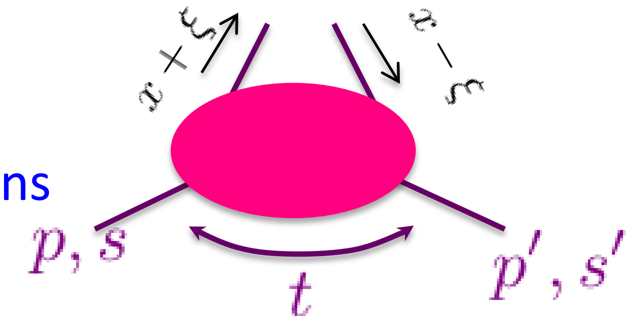




Theoretical Framework in QCD

- Generalized Parton Distributions
  - Matrix elements of non-local operators with quarks and gluon field

$$\langle p|\mathcal{O}|p\rangle$$



  - Depend on two longitudinal momentum fractions

$$x,\ \xi \text{ and } t = (p-p')^2$$

  - For unpolarized quarks we have two distributions:

H^q *conserves proton helicity*

E^q *flips proton helicity*

$$p = p' \Longrightarrow \quad H^q(x,0,0) = \begin{cases} q(x) & \text{for } x > 0 \\ -\bar{q}(x) & \text{for } x < 0 \end{cases}$$

$$\int dx\, x^n\, \mathrm{GPD}(x,\xi,t) \rightarrow \text{local operators} \rightarrow \text{form factors}$$

$$\sum_q e_q \int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1(t) \qquad \text{Dirac}$$

$$\sum_q e_q \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2(t) \qquad \text{Pauli}$$

Nucleon Angular Momentum Sum Rule

$$\frac{1}{2} = J^q(\mu) + J^g(\mu)$$

Ji Sum rule (1997)

$$J^q(\mu) = \frac{1}{2}\Delta\Sigma + L^q(\mu)$$

Spin of quarks contribution

Orbital angular momentum of quarks

$$J^q = \int dx x\,[H^q + E^q]$$

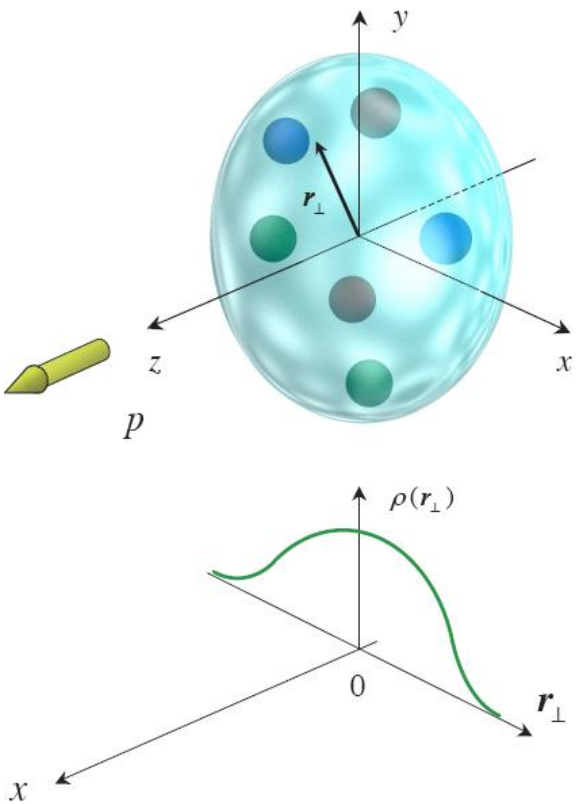
$$J^g = \int dx\,[H^g + E^g]$$

Total angular momentum of gluons

3D imaging of the nucleon

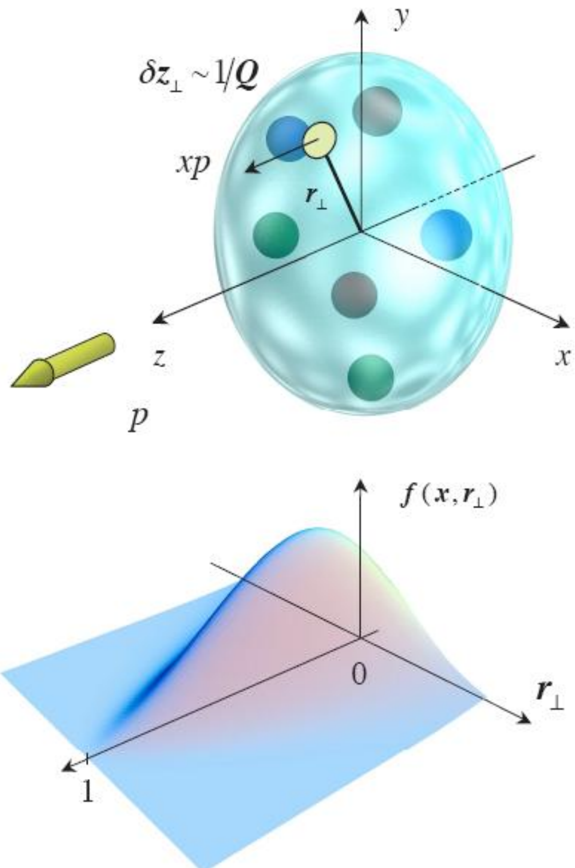
Tool: Generalised Parton Distributions

Form factors:



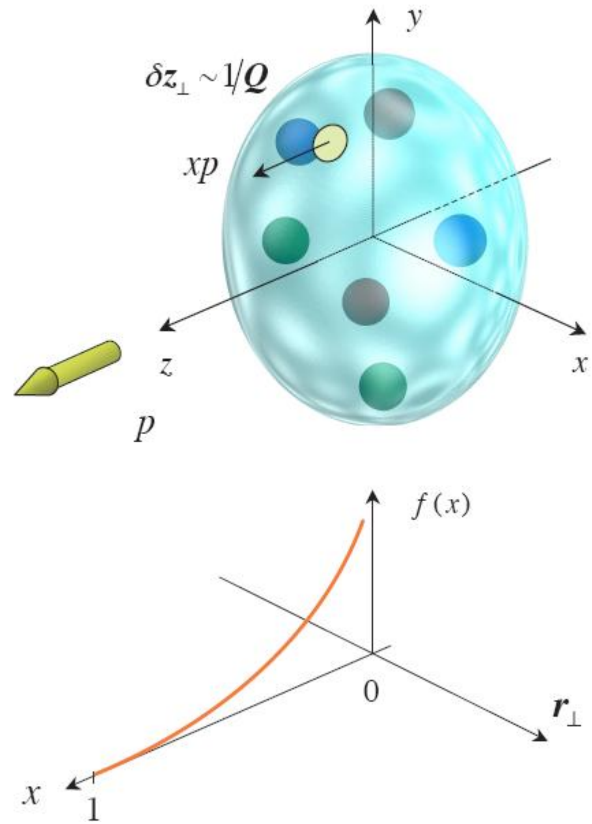
Fourier transform of e.g. a radial charge distribution

GPDs:



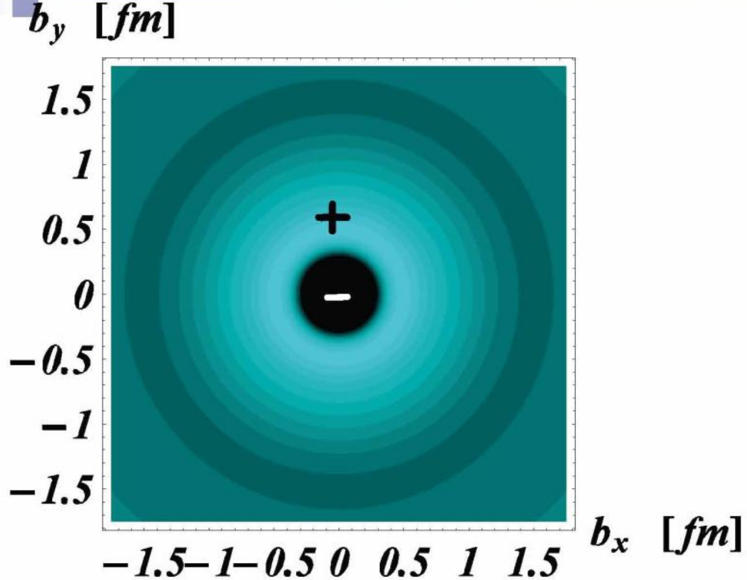
Generalized description in 2+ 1 dimensions

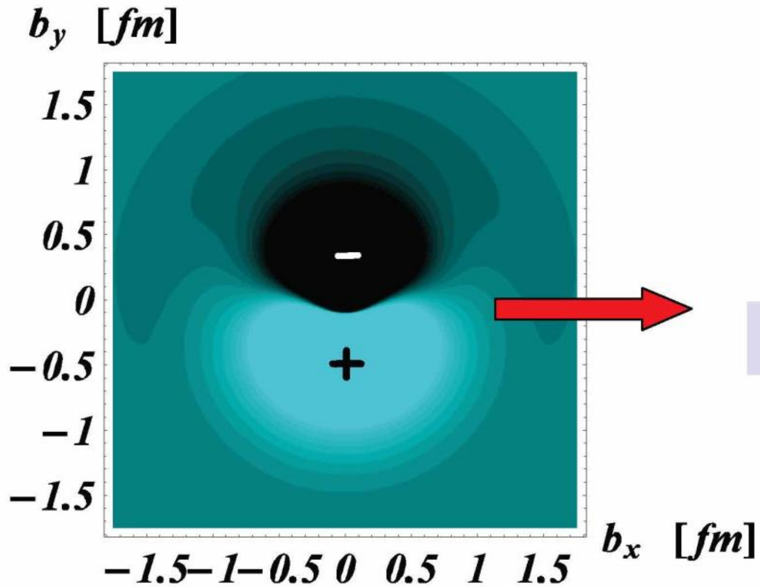
Parton Distrribution Functions:

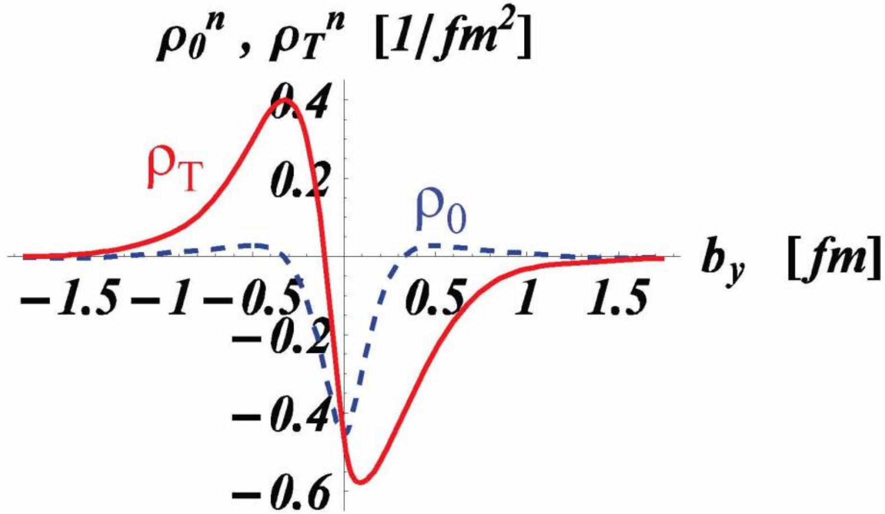


Number density of quarks with longitudinal momentum fraction x

empirical quark transverse densities in neutron





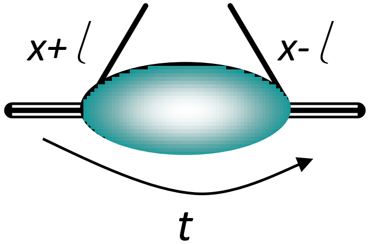


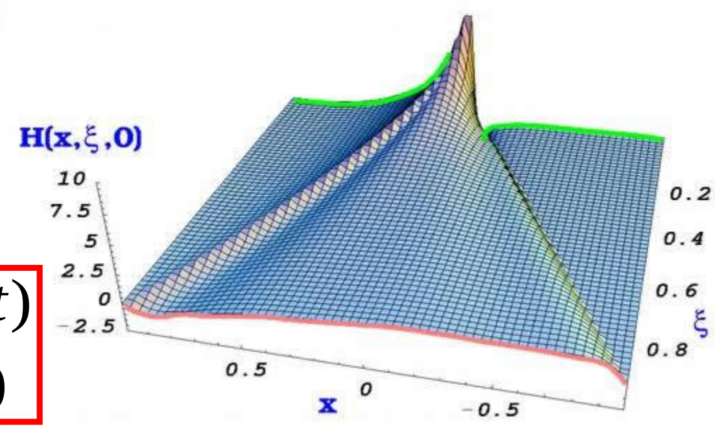
induced EDM : $d_y = F_{2n}(0) . e / (2 M_N)$

data: Bradford, Bodek, Budd, Arrington (2006)

densities : Miller (2007) ; Carlson, Vdh (2007)

Generalized Parton Distributions, Deeply Virtual Compton Scattering



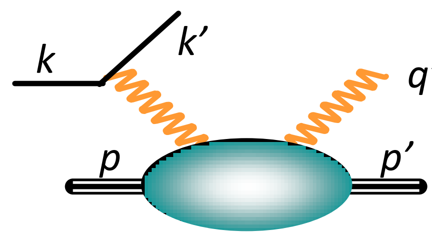


$$\langle p's' | \bar{\psi}(-y/2)\gamma^{\mu}\psi(y/2) | ps \rangle \rightarrow H,\ E(x,\xi,t)$$

$$\langle p's' | \bar{\psi}(-y/2)\gamma^{\mu}\gamma^{5}\psi(y/2) | ps \rangle \rightarrow \tilde{H},\tilde{E}(x,\xi,t)$$

Model by Goeke, Polyakov, Vanderhaeghen

Deeply Virtual Compton Scattering is the simplest hard exclusive process involving GPDs

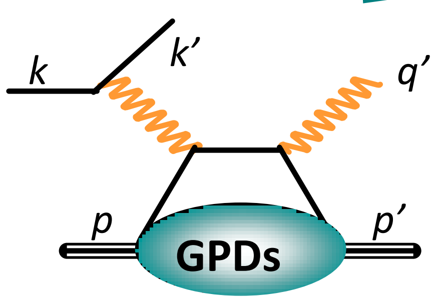


The handbag dominance:

$$Q^2 = -q^2 = -(k-k')^2 >> M^2$$

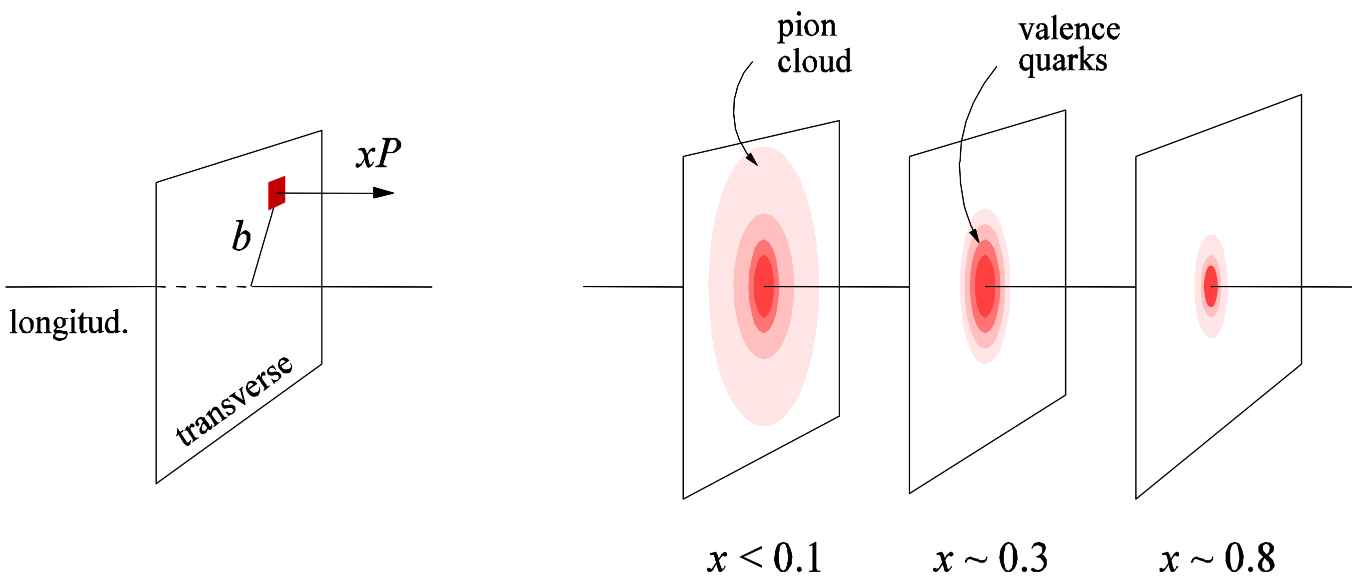
$$t = (p-p')^2 = \Delta^2 << Q^2$$

Factorization Theorem



$$\underset{\text{amplitude}}{DVCS} \approx \int \frac{dx}{x-\xi+i\varepsilon} GPD(x,\xi,t) + \cdots$$

GPDs : 3D quark/gluon imaging of nucleon



Fourier transform of GPDs :

simultaneous distributions of quarks w.r.t. longitudinal momentum x P and transverse position b

(M. Burkardt)

⇨ theoretical parametrization needed :

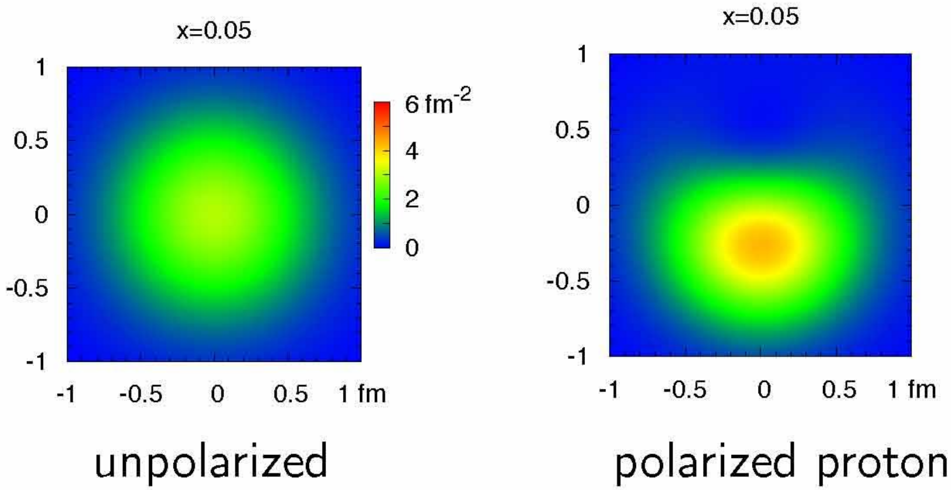
double distributions, dual param. (Guzey), conformal param. (Müller)

What can we do with the GPDs?

evaluate parton angular momenta from Ji's sum rule

$J^u = 0.25 \pm 0.03 \qquad J^d = 0.02 \pm 0.03 \qquad J^s = 0.02 \pm 0.03 \qquad J^g = 0.21 \pm 0.06$

work out transverse localization of partons



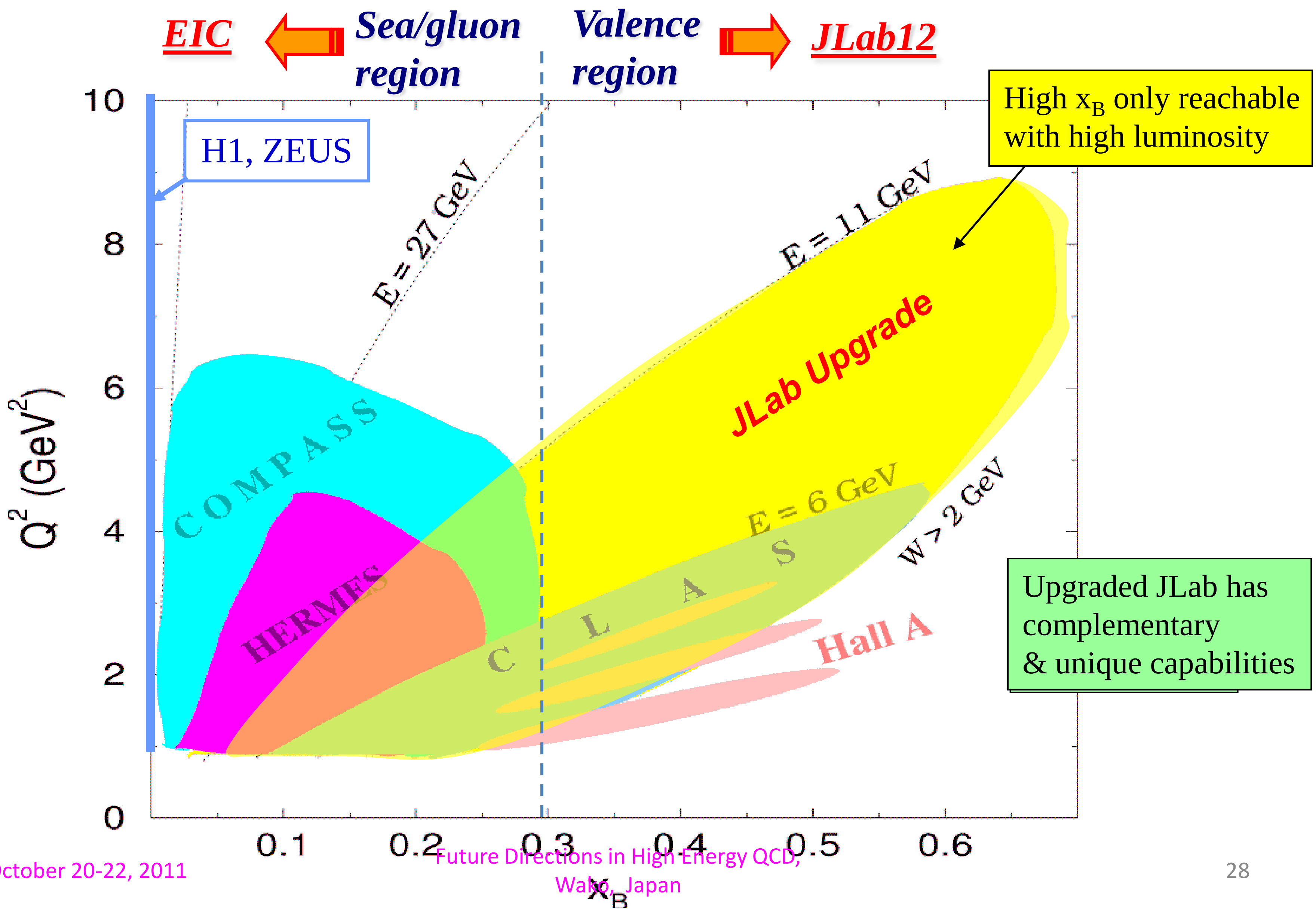
for d quarks

$$q_v^X(x,\mathbf{b}) = q_v(x,\mathbf{b}) - \frac{b^y}{m}\frac{\partial}{\partial \mathbf{b}^2} e_v^q(x,\mathbf{b})$$

PK 21

Peter Kroll

Large phase space (ξ,t,Q^2) and High luminosity required

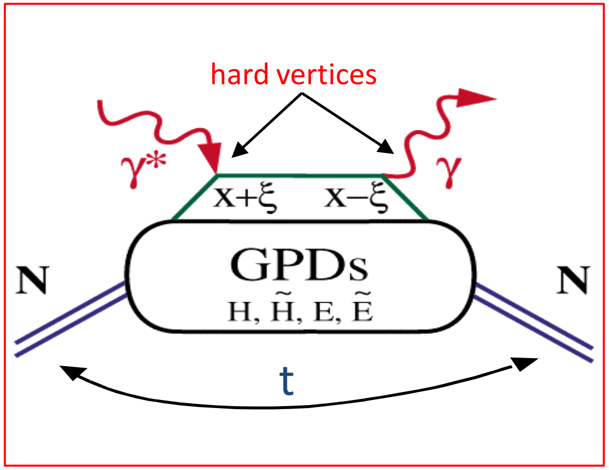


Extraction of GPD's

global analysis : cross sections, asymmetries, (p,n), (γ,M)

ep ⟶ ep©

Cleanest process: Deeply Virtual Compton Scattering



$$A = \frac{\int^{+} - \int^{-}}{\int^{+} + \int^{-}} = \frac{\otimes \int}{2 \int}$$

$\xi = x_B/(2-x_B)$

$k = -t/4M^2$

Polarized beam, unpolarized target:

$$\otimes \int_{LU} \sim \sin\rangle\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\rangle$$

⟹ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$$\otimes \int_{UL} \sim \sin\rangle\{F_1 \tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\rangle$$

⟹ $\tilde{H}(\xi,t)$

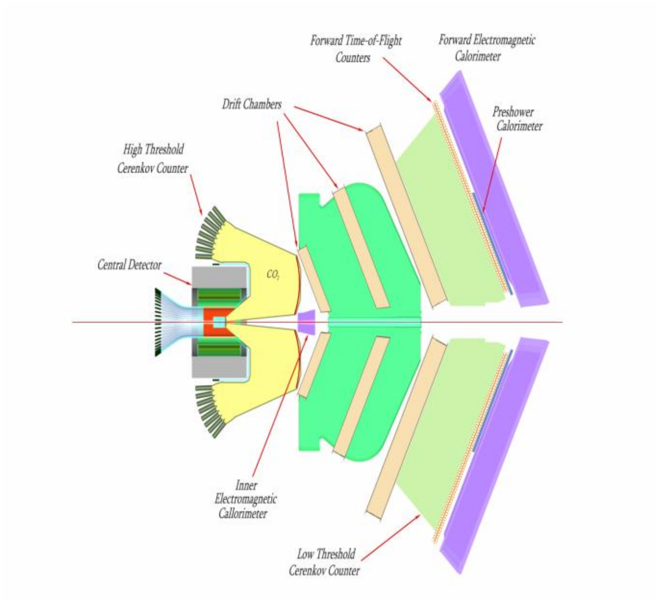
Unpolarized beam, transverse target:

$$\otimes \int_{UT} \sim \sin\rangle\{k(F_2 H - F_1 E)\}d\rangle$$

⟹ $E(\xi,t)$

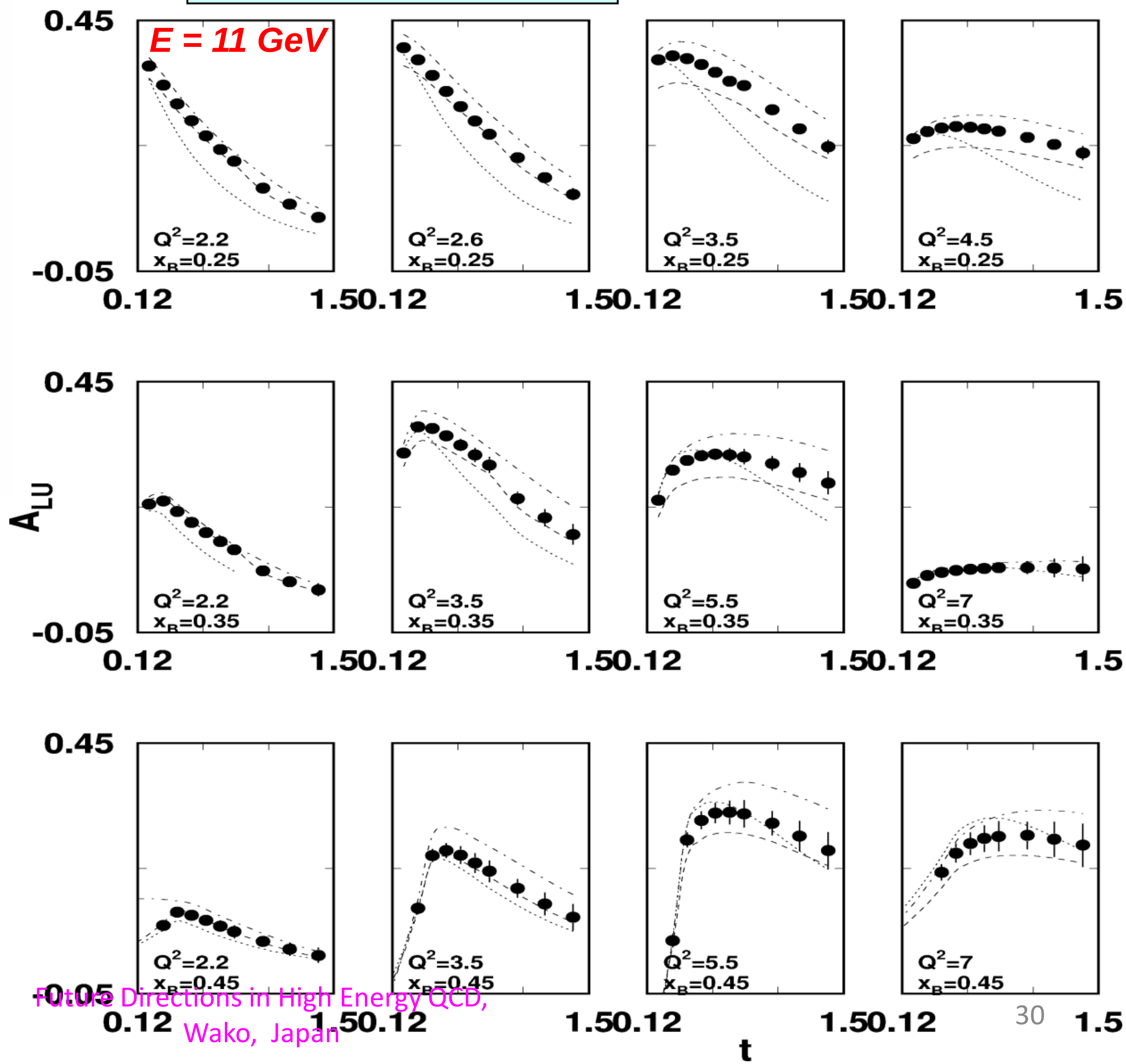
exclusive DVCS : BSA @ JLab 12 GeV

CLAS12



e p → ep©

Projected results



⊗ ʃ$_{LU}$~sin)Im{F_1H+. }d)

Selected Kinematics

L = 1x10^{35}
T = 2000 hrs
⊗Q^2 = 1 GeV^2
⊗x = 0.05

Avakian

Exclusive DVCS on *transverse* target @ JLab 12 GeV

e $p^{\uparrow} \longrightarrow$ ep©

E = 11 GeV

Transverse polarized target

$\otimes \int \sim \sin\Pi\,\mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\Pi$

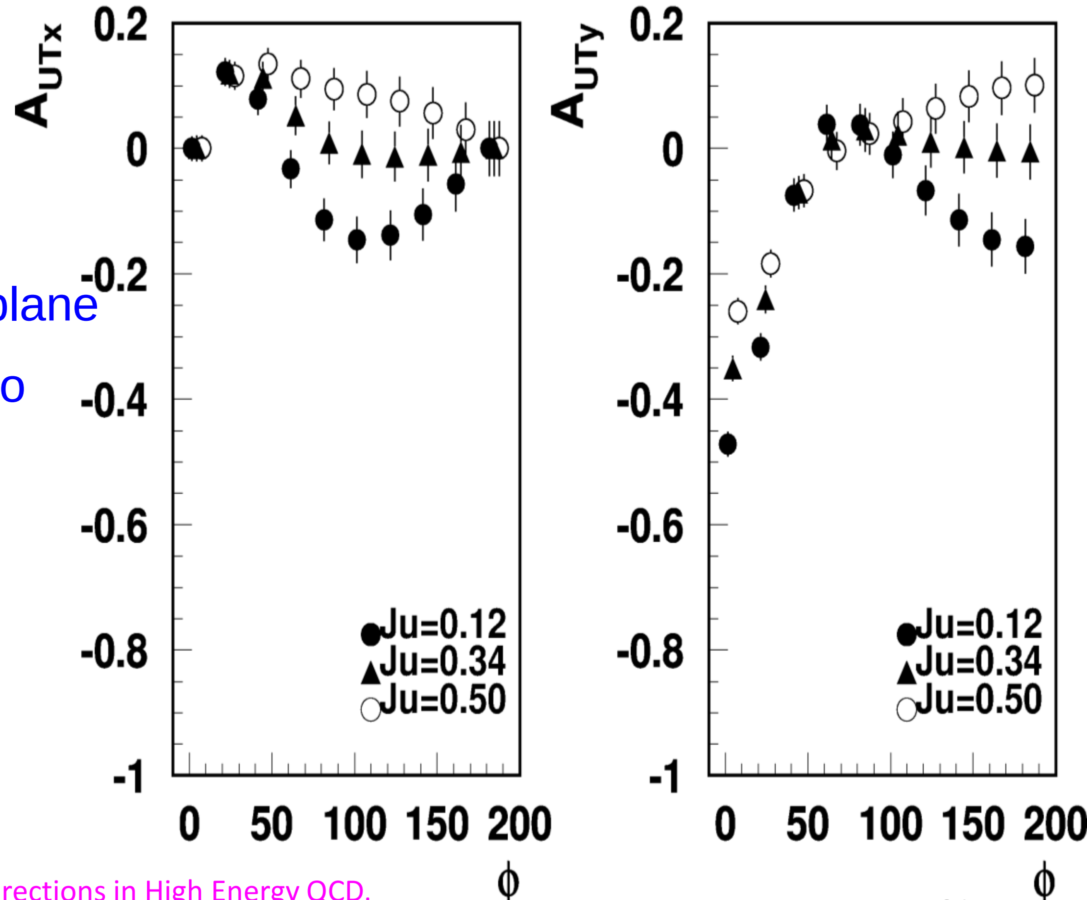
A_{UTx} Target polarization in scattering plane

A_{UTy} Target polarization perpedicular to scattering plane

- Asymmetry highly sensitive to the u-quark contributions to proton spin.

Projected results

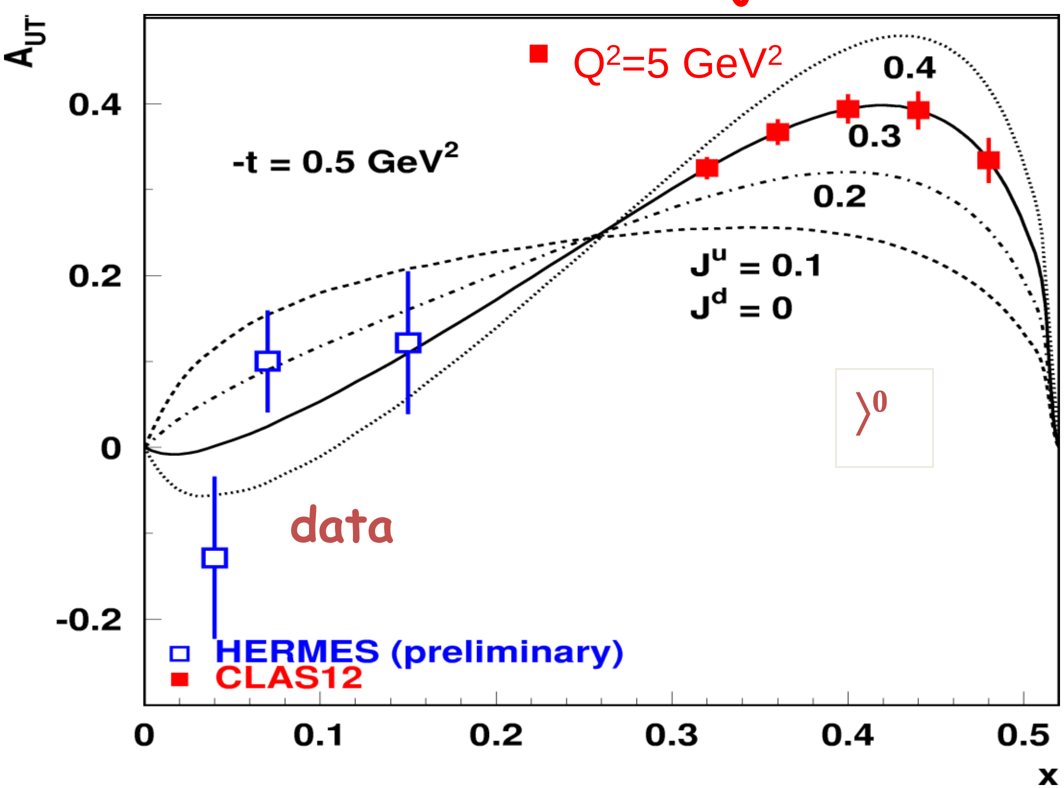
Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2



exclusive ρ^0 production on *transverse* target

$$A_{UT} = -\frac{2\otimes_{\perp} (\mathrm{Im}(AB^*))/\square}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

Projected results



$\rangle^0$

$A \sim 2H^u + H^d$

$B \sim 2E^u + E^d$

$\rangle^+$

$A \sim H^u - H^d$

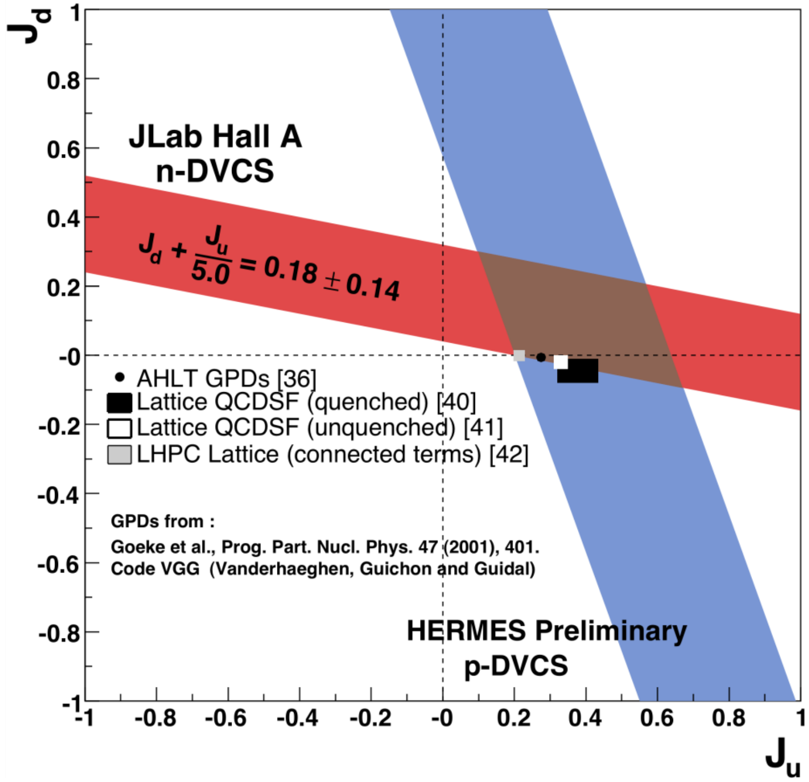
$B \sim E^u - E^d$

E^u, E^d needed for angular momentum sum rule.

Goeke, Polyakov, Vdh (2001)

Quark Angular Momentum

$$J^q(t) = \int_{-1}^{+1} dx x[H^q(x,\xi,t) + E^q(x,\xi,t)]$$



→ **Access to quark orbital angular momentum**

Total angular momentum of gluons

Transverse Spin Structure: Leading Twist TMDs

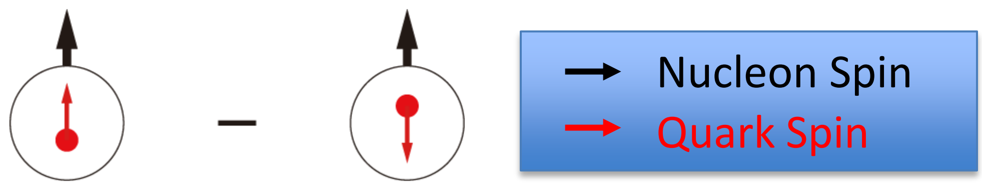
Nucleon Spin

Quark Spin

Quark /Nucleon		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ − **Boer-Mulder**
	L		$g_1 =$ − **Helicity**	$h_{1L}^\perp =$ −
	T	$f_{1T}^\perp =$ − **Sivers**	$g_{1T}^\perp =$ −	$h_{1T} =$ − **Transversity** $h_{1T}^\perp =$ − **Pretzelosity**

Transversity and the Tensor Charge

- Quark transverse polarization in a transversely polarized nucleon:

h_{1T} =


  - Can be probed in Semi-Inclusive DIS, Drell-Yan processes.
  - Does not mix with gluons, has valence like behavior.
  - Nucleon tensor charge can be extracted from the lowest moment of h_1 and compared to LQCD calculations

Tensor Charge

Intrinsic property
Like axial or vector charge

$$\langle PS\bar{\psi}\sigma^{\mu\nu}\psi PS\rangle = \int_0^1 dx\,[\delta q(x) - \delta\bar{q}(x)]$$

$$\int_{thr}^{\infty}\left[\frac{\sigma_{3/2}-\sigma_{1/2}}{\nu}\right] d\nu = \frac{2\pi^2\alpha}{M^2}\kappa^2$$

GDH sum rule

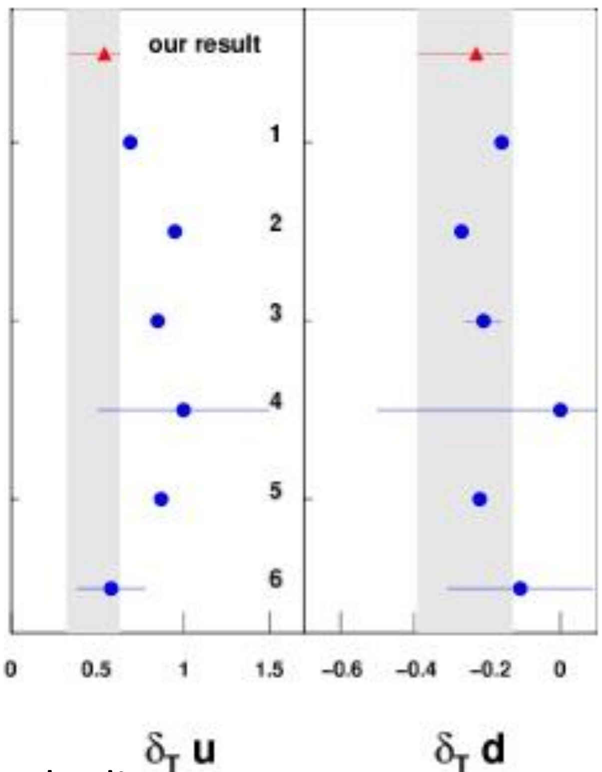
$$\int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] dx = \frac{1}{6}g_A$$

Bjorken Sum rule

Tensor charges

$$\delta_T q = \int_0^1 dx\,(h_{1q} - h_{1\bar{q}}) = \int_0^1 dx\, h_{1q}$$

$$\delta_T u = 0.54^{+0.09}_{-0.22},\ \delta_T d = -0.23^{+0.09}_{-0.16} \text{ at } Q^2 = 0.8\ \text{GeV}^2$$



Courtesy of Prokudin

1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB **653** (2007) 398.
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 ,
   $Q^2 = 4$ GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2
5. Constituent quark model:
   B. Pasquini, M. Pincetti, and S. Boffi,
   PRD72(2005)094029 and PRD76(2007)034020,
   $Q^2 \sim 0.8$ GeV^2
6. Spin-flavour SU(6) symmetry
   L. Gamberg, G. Goldstein,
   Phys.Rev.Lett.87:242001,2001 $Q^2 \sim 1$ GeV^2

Alexei Prokudin,

TMDs program @ 12 GeV in Hall B and Dynamical Imaging

PAC approved experiments & LoI

E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

E12-07-107: Pion SIDIS
E12-09-009: Kaon SIDIS

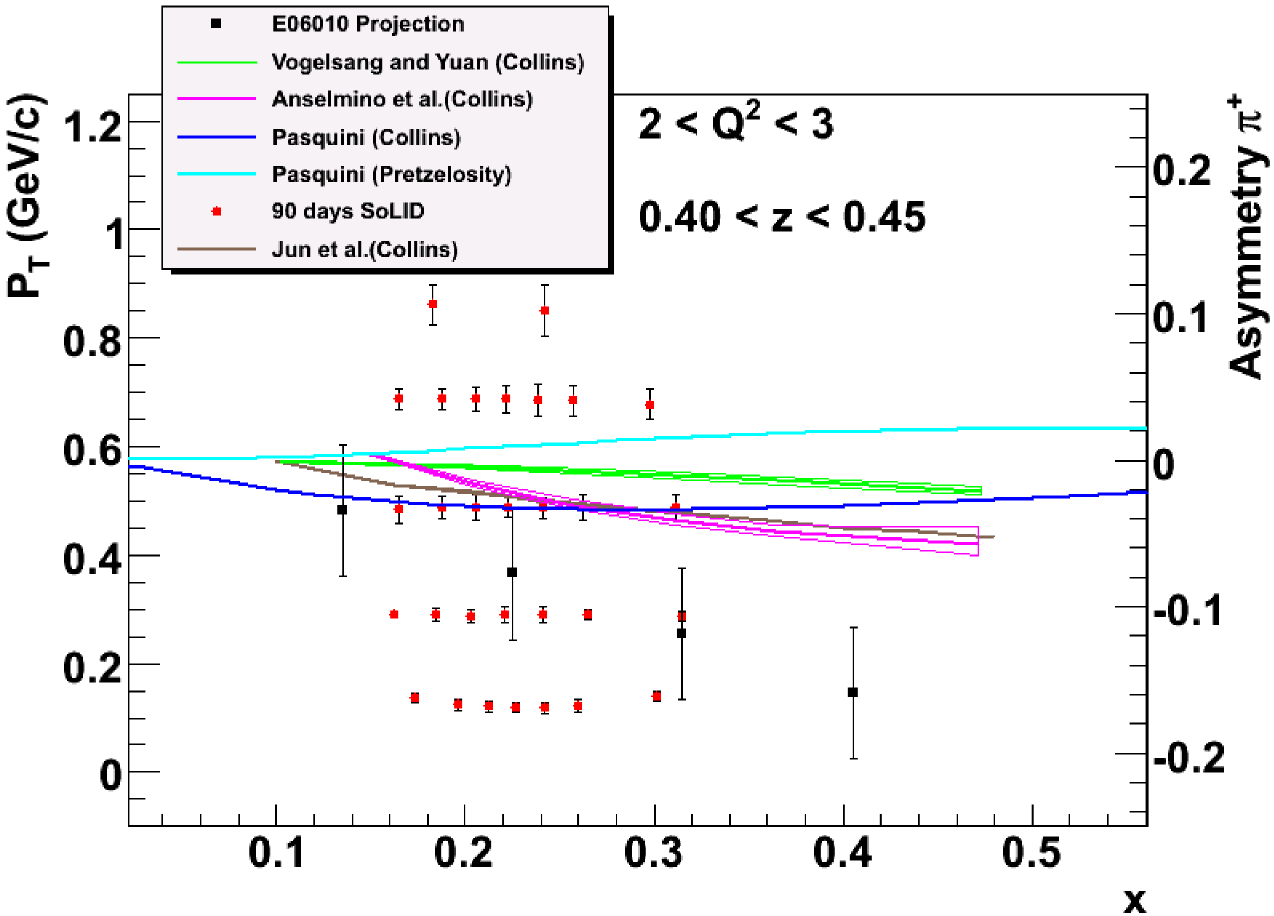
LOI12-06-108: Pion SIDIS
LOI12-09-004: Kaon SIDIS

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

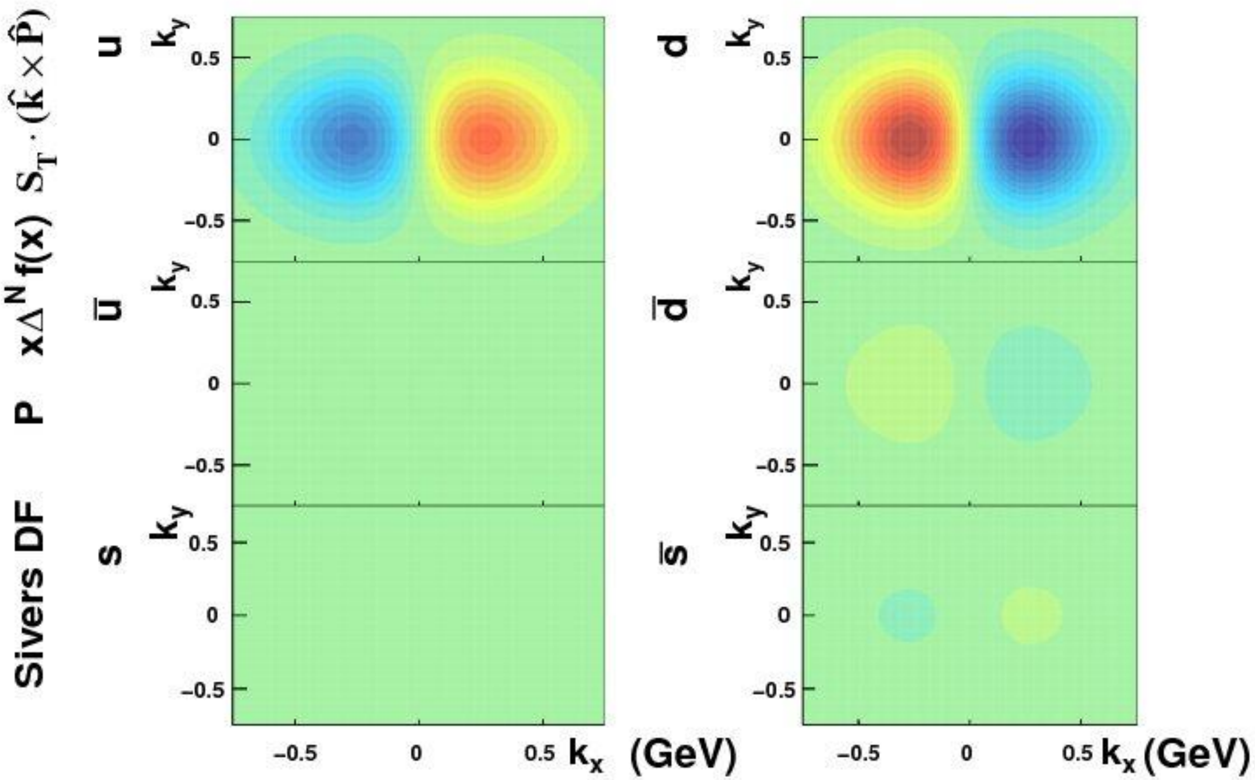
- Complete program of TMDs studies for pions and kaons
- Kaon measurements crucial for a better understanding of the TMDs "kaon puzzle"
- Kaon SIDIS program requires an upgrade of the CLAS12 detector PID
  RICH detector to replace LTCC
  Project under development

Neutron Collins Asymmetry Projected Data Using SOLID

- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^-.



3-D momentum structure the nucleon: Dipole pattern due to Sivers effect



(Plot from Prokudin; red: positive effect, blue: negative effect)

Summary

An exciting scientific opportunity

- Explore the physical origins of quark confinement (GlueX)
- New access to the spin and flavor structure of the proton and neutron
- Reveal the quark/gluon structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

Construction is well underway !

Opportunities

- MOLLER
- SoLID
- A' searches
- RICH detectors for CLAS12 and GlueX

New Proposals and collaborations are most welcome!