National Nuclear Physics Summer School 2012

Spin Structure of the Nucleon?

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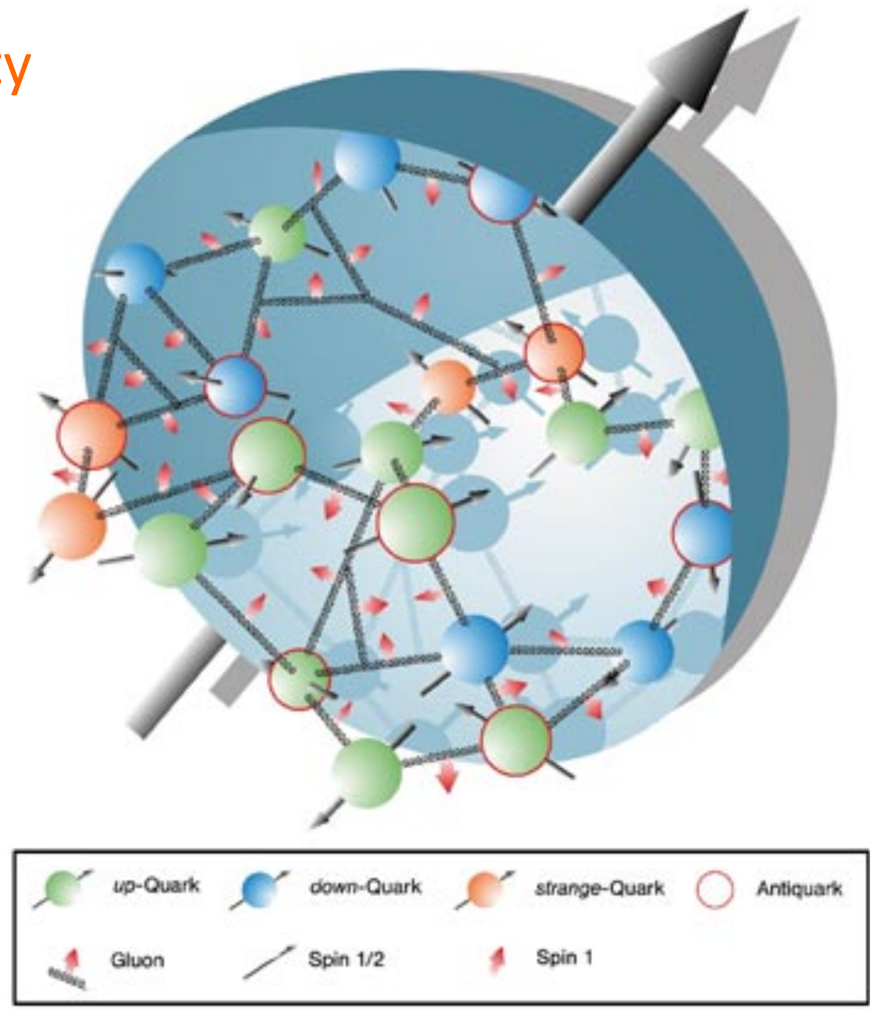

Lecture # 3

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Coutesy of CERN Courier

Jefferson Lab 12 GeV Science Program

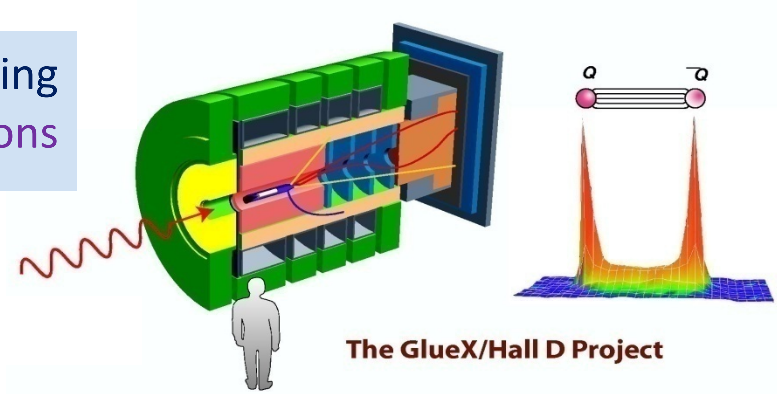
- The physical origins of quark confinement (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's…)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

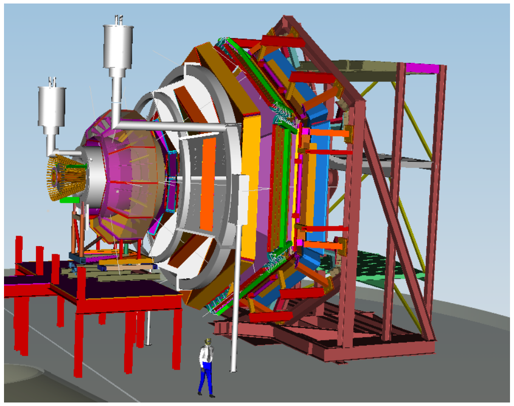
- Defining the Science Program:
  - Six Reviews: Program Advisory Committees (PAC) 30, 32, 34, 35, 36, 37, 38
  - 2006 through 2011
  - Results: *48 experiments approved; 4 conditionally approved*

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

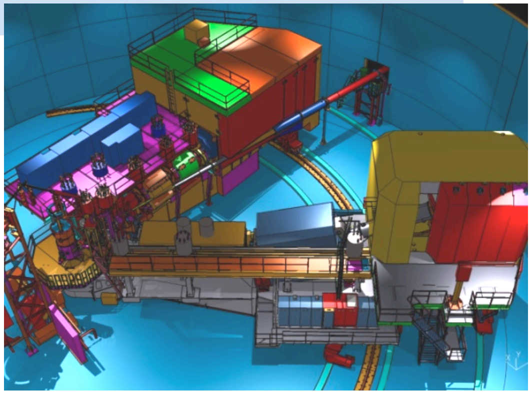
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

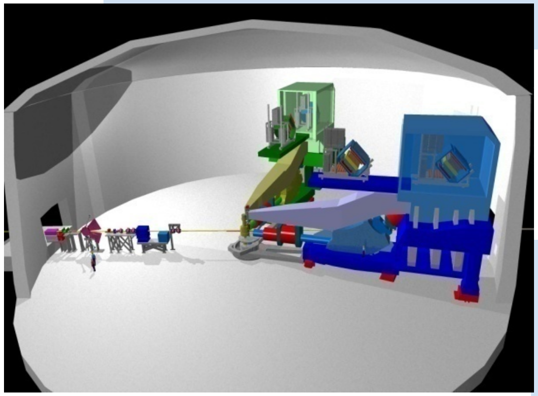




Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions



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)

Spin Structure in the Valence Region :
Helicity Dependent Parton Distributions at Large x

Parton Distributions Functions at Large x

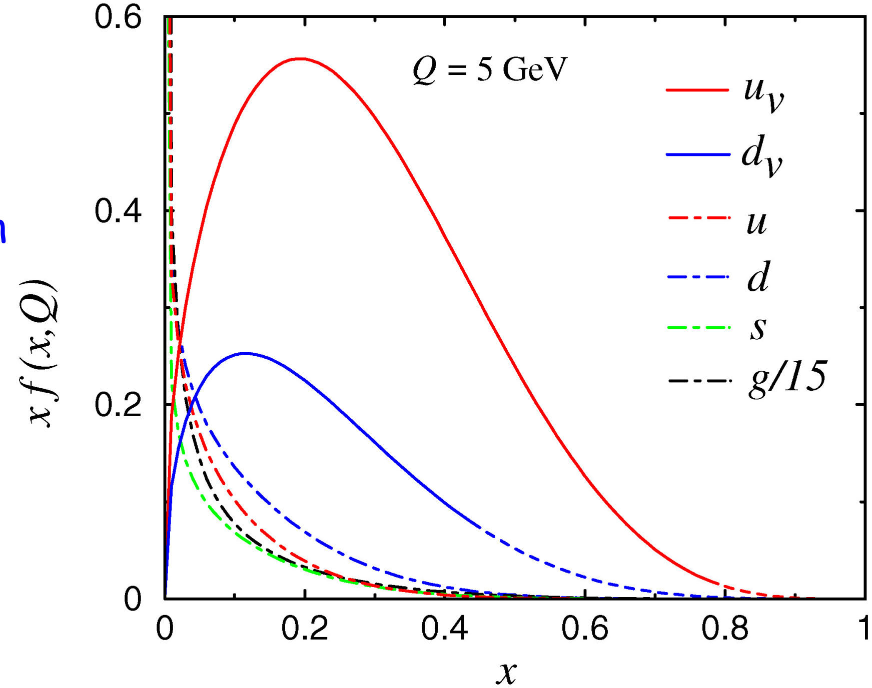
Understand the nucleon structure in the valence quark region

⦿ What is required?

- Complete knowledge of parton distribution functions (PDFs).

At Large x

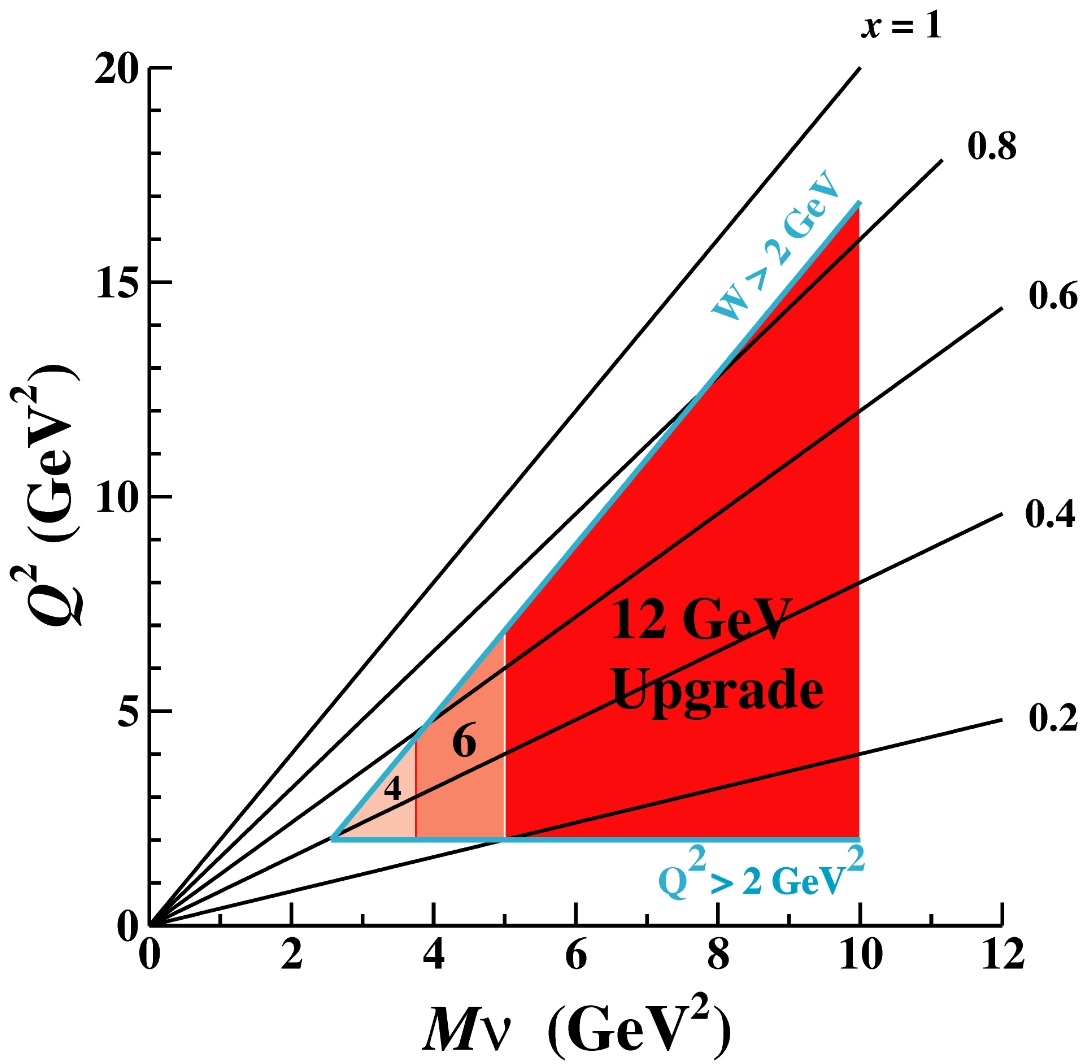
- large x exposes valence quarks
  - free of sea effects
- no explicit hard gluons to be included
- x->1 behavior – sensitive test of spin-flavor symmetry breaking
- important for higher moments of PDFs - compare with lattice QCD
- intimately related with resonances, quark-hadron duality



$$M_n(Q^2) = \int_0^1 dx\; x^{n-2}\, F_2(x, Q^2) \qquad n = 2,4,...$$

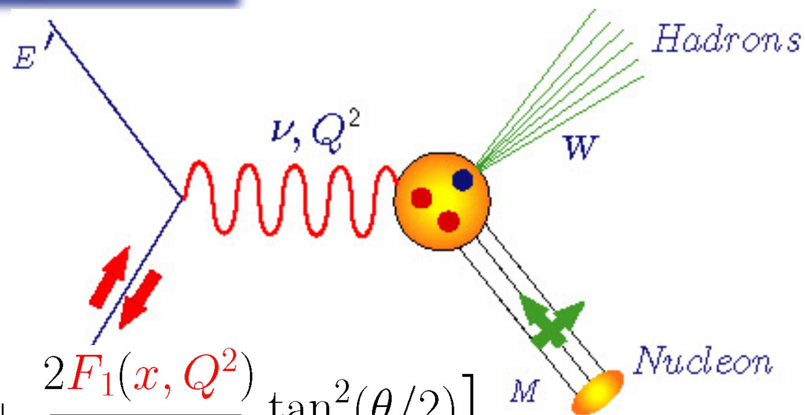
$$M_n(Q^2) = \int_0^1 dx\; x^{n-1}\, g_1(x, Q^2), \qquad n = 1,3,5...$$

Kinematical reach at JLab



Inclusive DIS

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$
  - Proton & neutron measurements provide d/u distributions ratio



U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$
  - Proton & neutron measurements combined with d/u provide the spin-flavor distributions $\Delta u/u$ & $\Delta d/d$

Q^2 :Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

Virtual photon-nucleon asymmetries

Longitudinal

$$\frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}} = A_{\parallel} = D(A_1 + \eta A_2)$$

Transverse

$$\frac{\sigma^{\downarrow\Leftarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\downarrow\Leftarrow} + \sigma^{\uparrow\Leftarrow}} = A_{\perp} = d(A_1 - \xi A_2)$$

D, d, η and ξ are kinematic factors

D depends on $R(x,Q^2) = \sigma_L/\sigma_T$

$$A_1 = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

$$A_2 = \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

where $\gamma = \sqrt{Q^2}/\nu$

- Positivity constraints

$|A_1| \leq 1$ and $|A_2| \leq \sqrt{R(1+A_1)/2}$

In the quark-parton model:

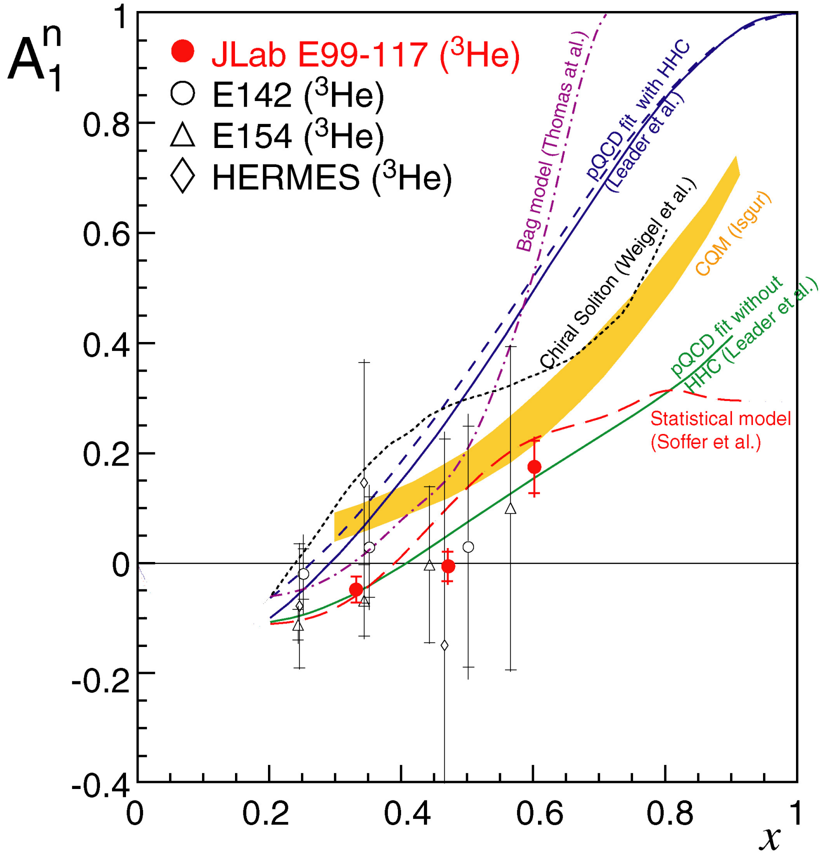
$$F_1(x,Q^2) = \tfrac{1}{2}\sum_f e^2 q_f(x,Q^2) \qquad g_1(x,Q^2) = \tfrac{1}{2}\sum_f e^2 \Delta q_f(x,Q^2)$$

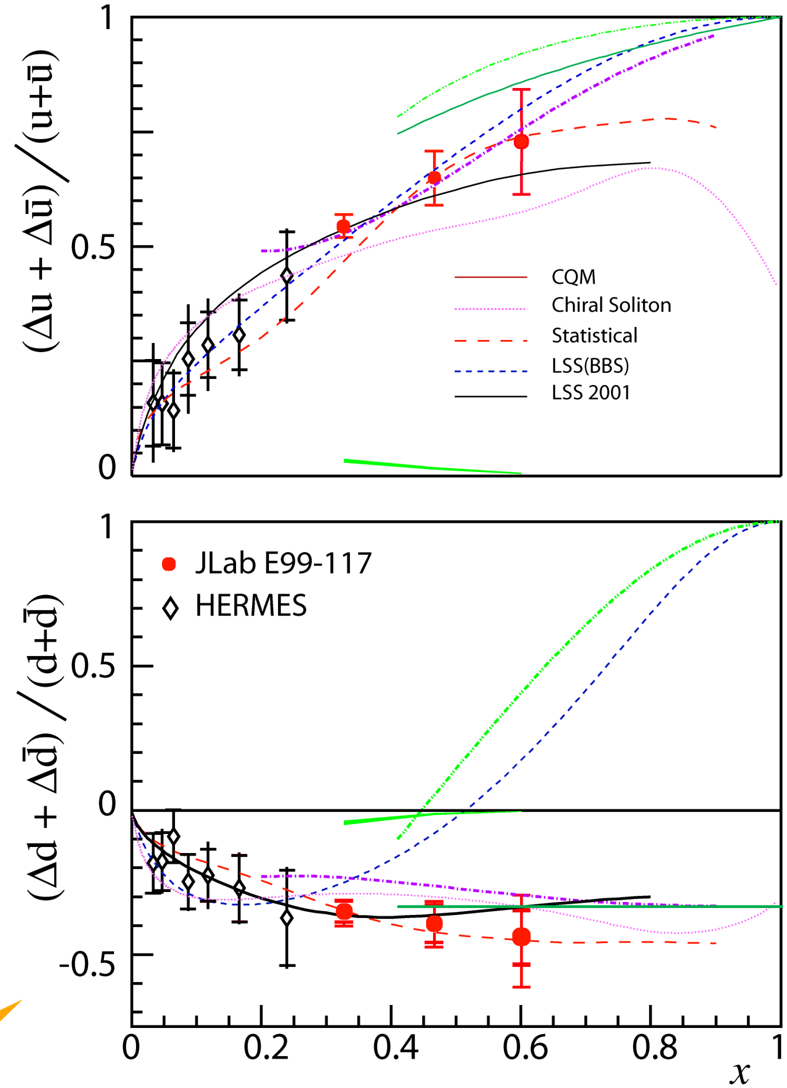
$$q_f(x) = q_f^{\uparrow}(x) + q_f^{\downarrow}(x) \qquad \Delta q_f(x) = q_f^{\uparrow}(x) - q_f^{\downarrow}(x)$$

$q_f(x)$ quark momentum distributions of flavor f

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

A_1^n and Helicity-Flavor Decomposition





$$\frac{\Delta u + \Delta\bar{u}}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

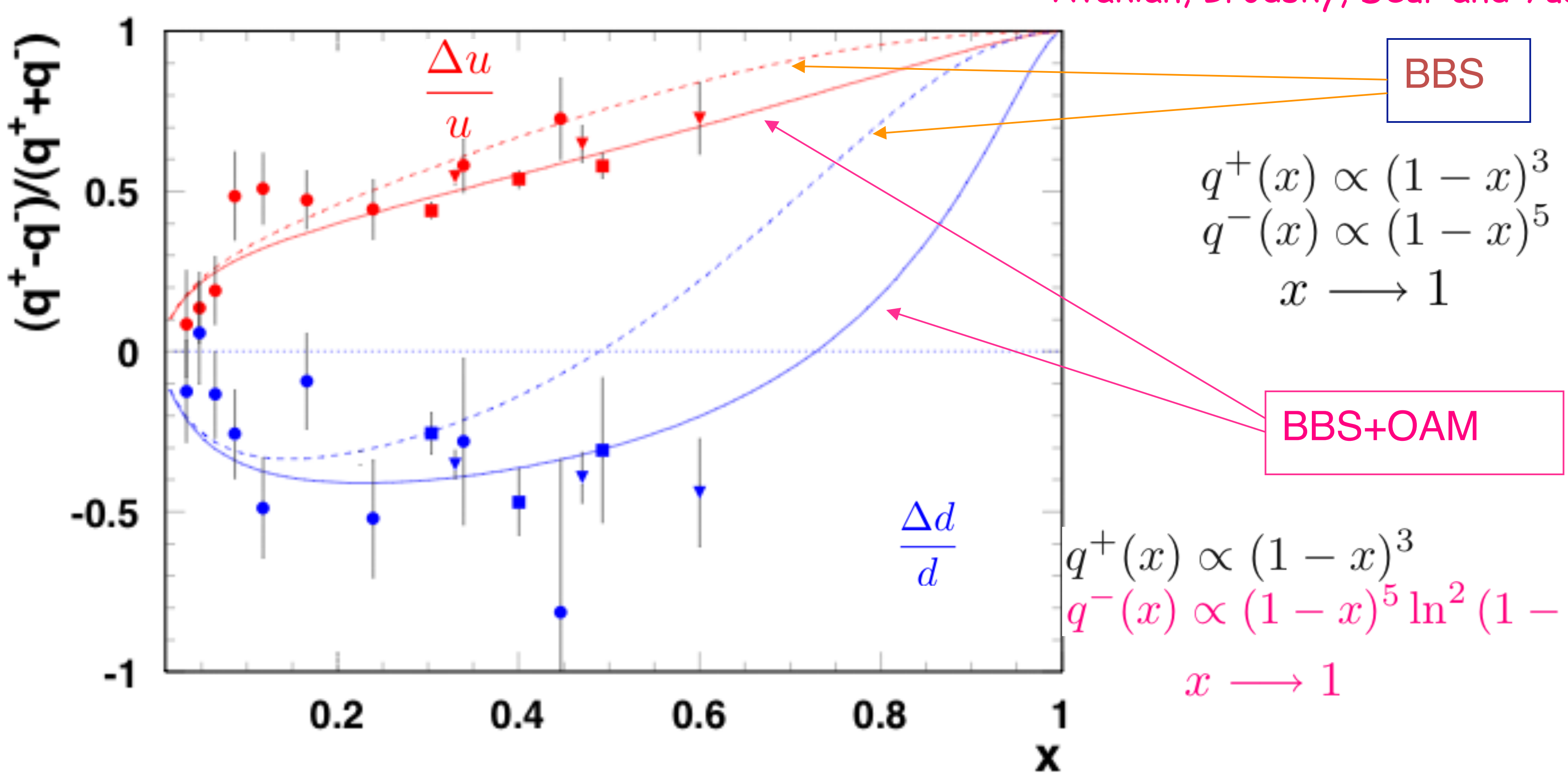
$$\frac{\Delta d + \Delta\bar{d}}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{1}{R^{du}}\right)$$

$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}}$$

Effect of quark orbital angular momentum

Inclusive Hall A and B and Semi-Inclusive Hermes

Avakian, Brodsky, Deur and Yuan

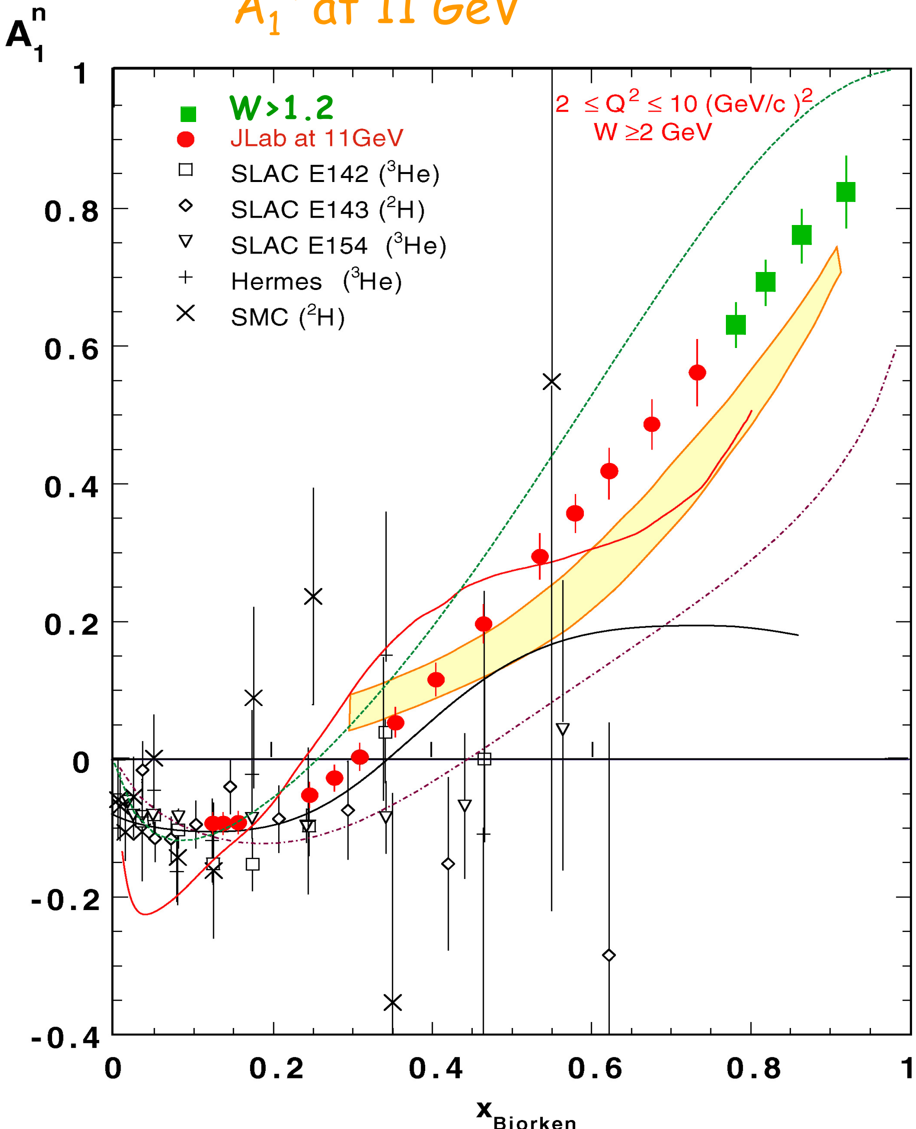


$q^+(x) \propto (1-x)^3$
$q^-(x) \propto (1-x)^5$
$x \longrightarrow 1$

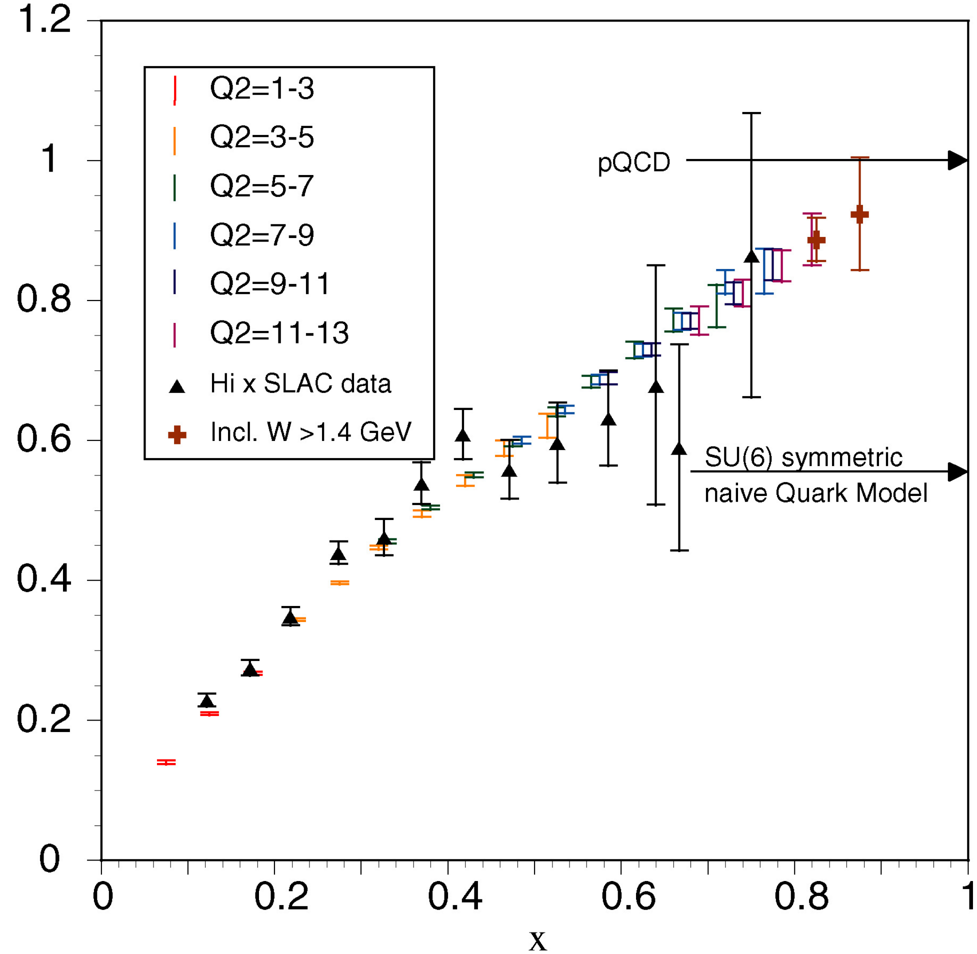
$q^+(x) \propto (1-x)^3$
$q^-(x) \propto (1-x)^5 \ln^2(1-x)$
$x \longrightarrow 1$

Inclusive measurements of asymmetries

A_1^n at 11 GeV

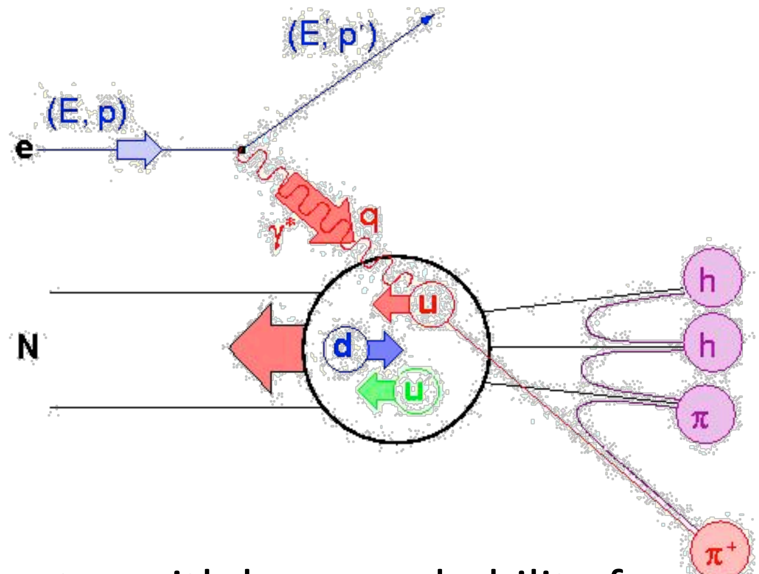


A_1^p at 11 GeV



Quark helicity distributions from Semi-Inclusive DIS

- Spin-flavor decomposition of valence and sea quarks by tagging hadron (e.g. π, K) in current fragmentation region



Leading hadron originates with large probability from struck quark

$D_q^h(z)$:= Fragmentation function (FF)

$z = E_h/\nu$

Measure hadron asymmetries

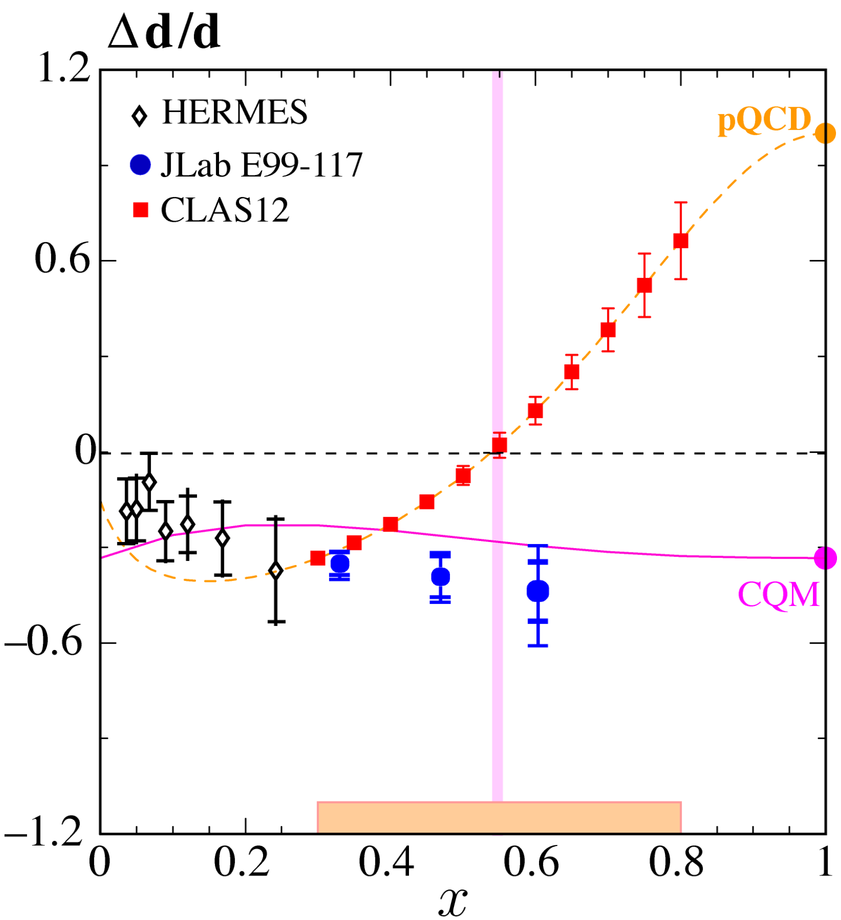
$$A_1^h(x,z) = \frac{\sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\sum_q e_q^2\, q(x)\, D_q^h(z)}$$

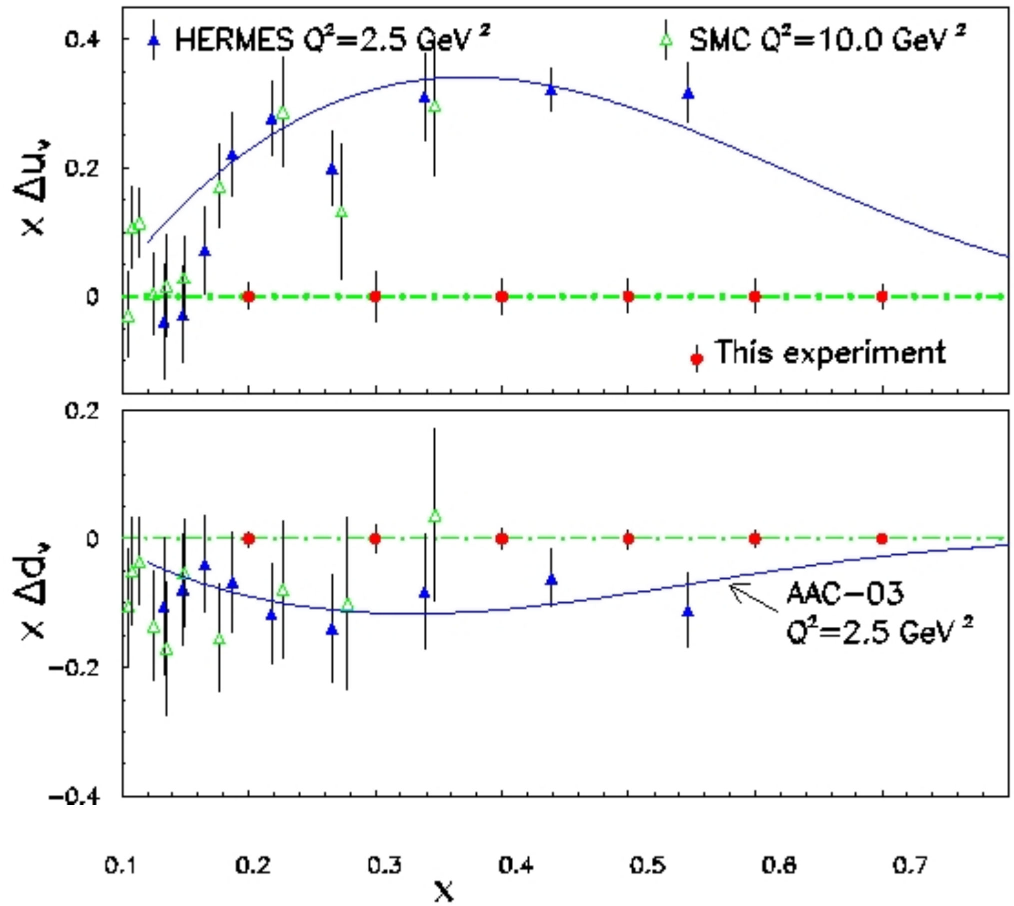
Targets: $\vec{H}$, $\vec{D}$; h =$\pi^\pm$, $K^\pm$,p

Flavor decomposition

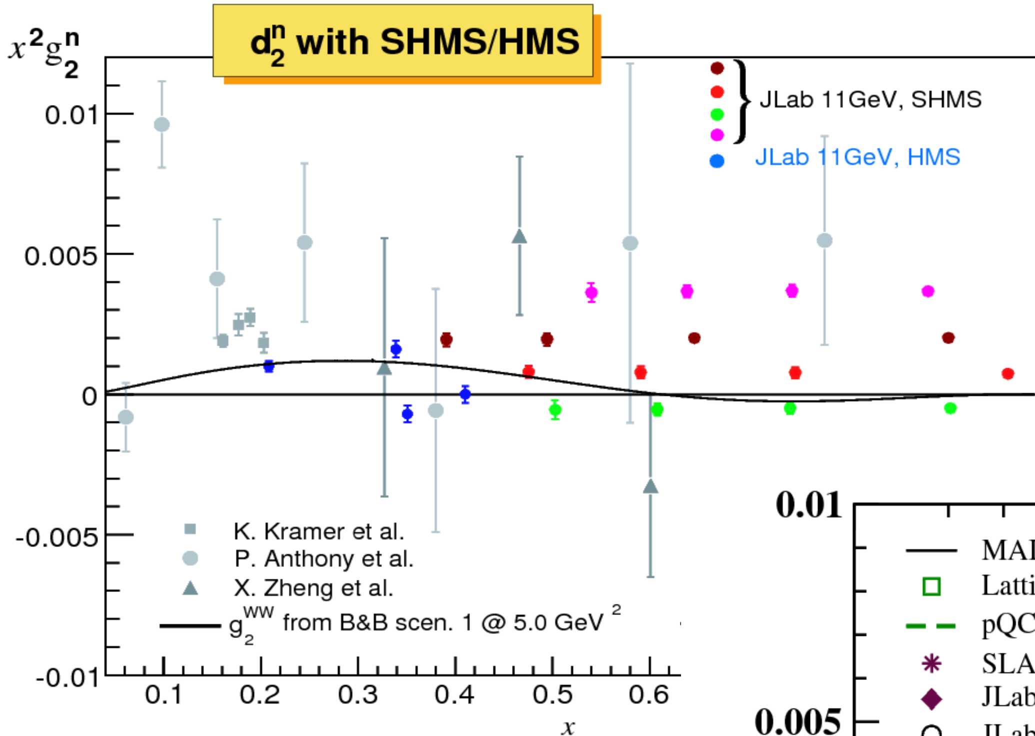
- Asymmetry measurements with different hadrons ($\pi+$,$\pi-$) and targets (p,n) allow flavor separation

E_e =11 GeV NH$_3$ and ^{3}He



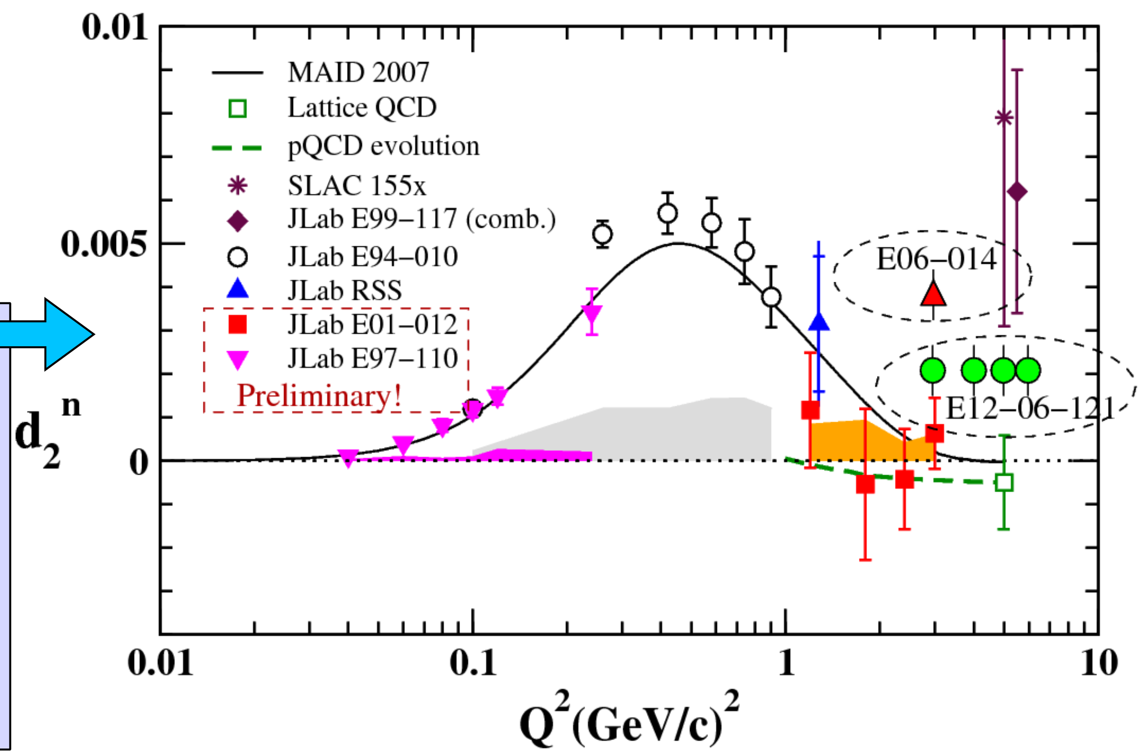


12 GeV Projected results for g2n and d2n



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 for ^3He is extracted directly from L and T spin-dependent cross sections measured within the same experiment.
- Strength of SHMS/HMS: nearly constant Q^2 (but less coverage for x < 0.3)

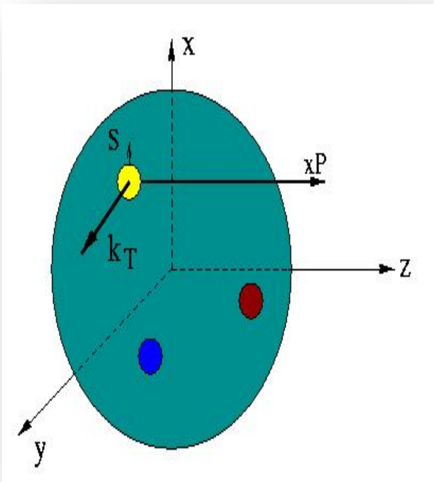


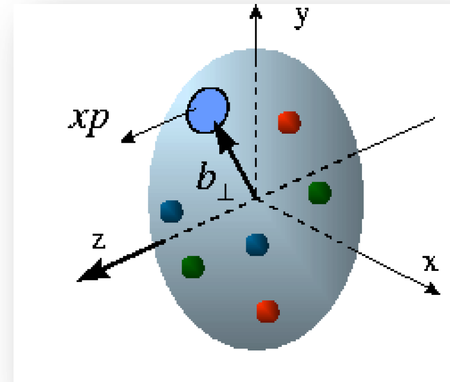
Beyond one dimensional View

Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r})$ Wigner distributions

6D Dist.





$d^3\boldsymbol{r}$

$d^2k_T\, dr_z$

TMD PDFs $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

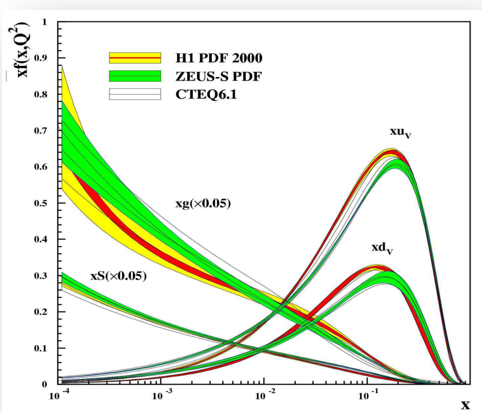
GPDs

3D imaging

d^2k_T

d^2r_T

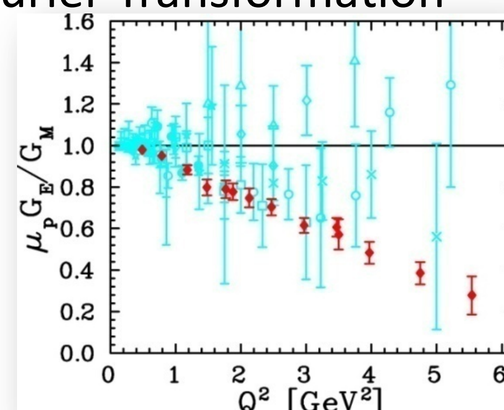
dx &
Fourier Transformation



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

1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

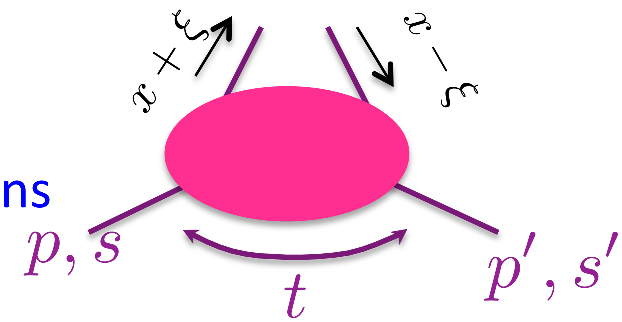


3-Dimensional view of the nucleon

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*

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

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

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

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

Nucleon Angular Momentum Sum Rule

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

Ji Sum rule (1997)

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

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

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

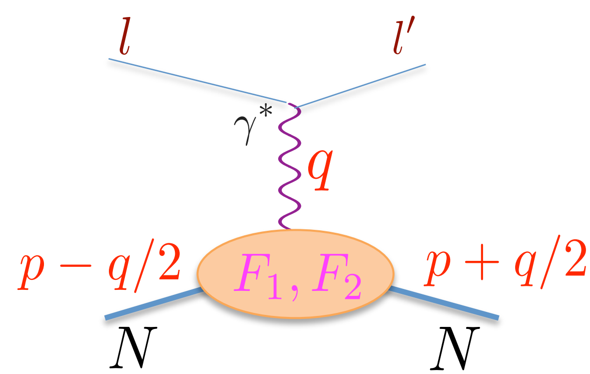
Spin of quarks contribution

Orbital angular momentum of quarks

Total angular momentum of gluons

Elastic Electron Scattering

- Elastic e p → e p scattering is like an electron microscope to investigate nucleon structure



- In 1-photon exchange approximation: nucleon structure parameterized by two form factors

$$A^{\mu}_{\lambda\lambda'} = \langle p+\frac{1}{2}q,\lambda' \mid J^{\mu}(0) \mid p-\frac{1}{2}q,\lambda\rangle$$
$$= \bar{u}(p+\frac{1}{2}q,\lambda')\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i}{2m}\sigma^{\mu\nu}q_{\nu}\right]u(p-\frac{1}{2}q,\lambda)$$

Dirac Pauli

F_1 helicity conserving, F_2 helicity flip form factors

- In experiments we measure the Sachs form factors

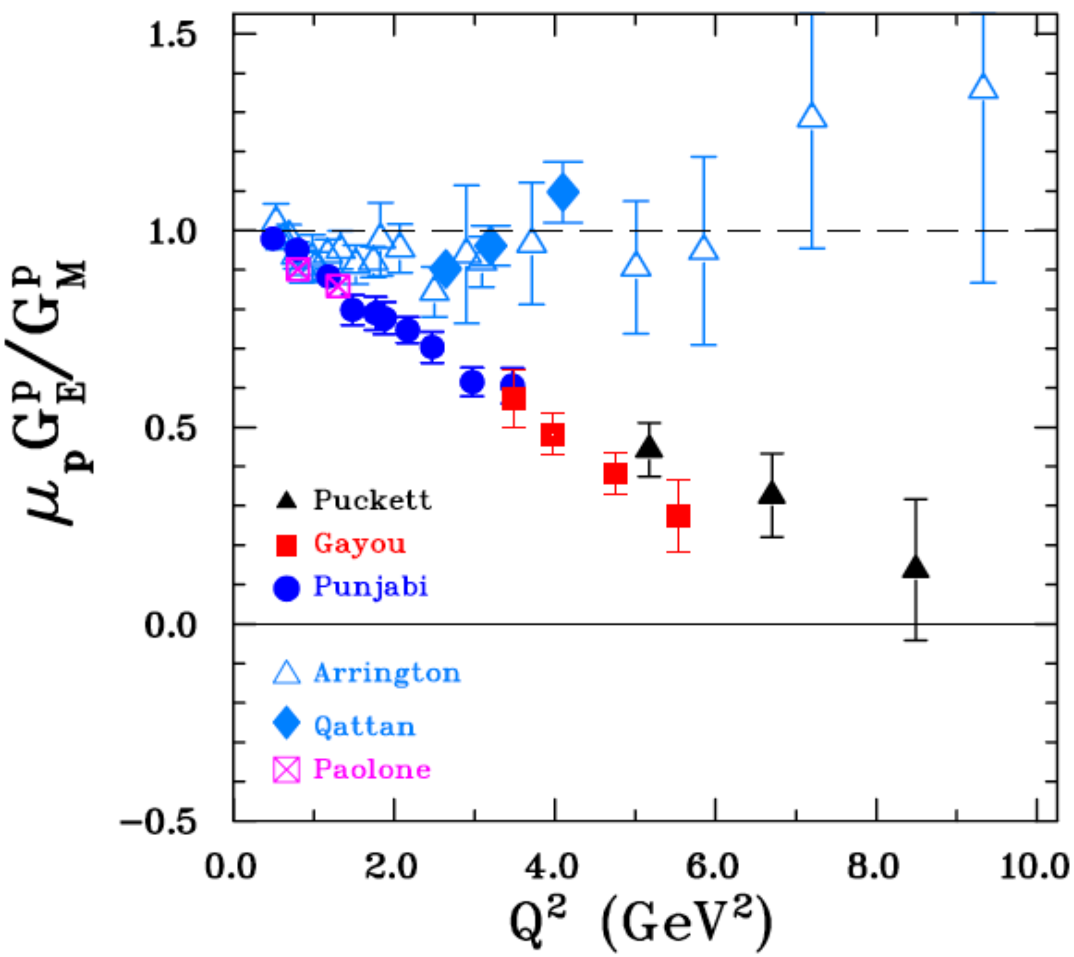
$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M\left[\frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\frac{\theta}{2})\right]$$

$$\tau = \frac{Q^2}{2M} \qquad \sigma_M = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}$$

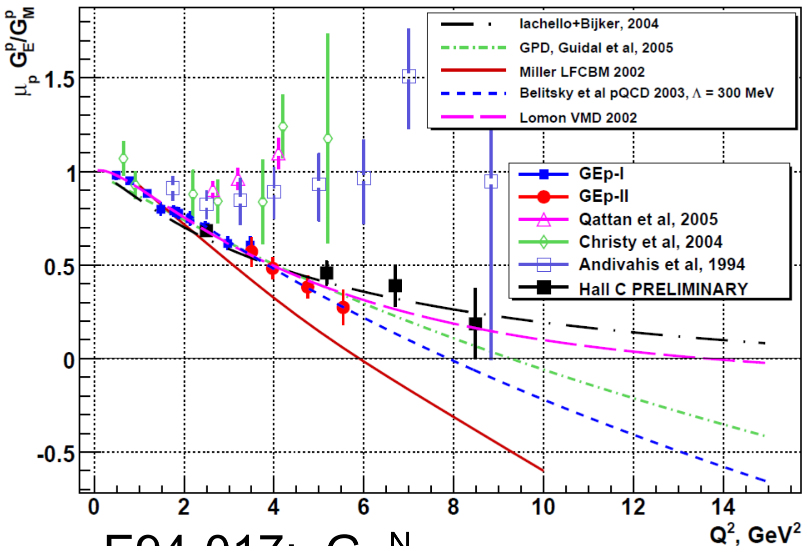
Rosenbluth Formula

Proton electric form factor

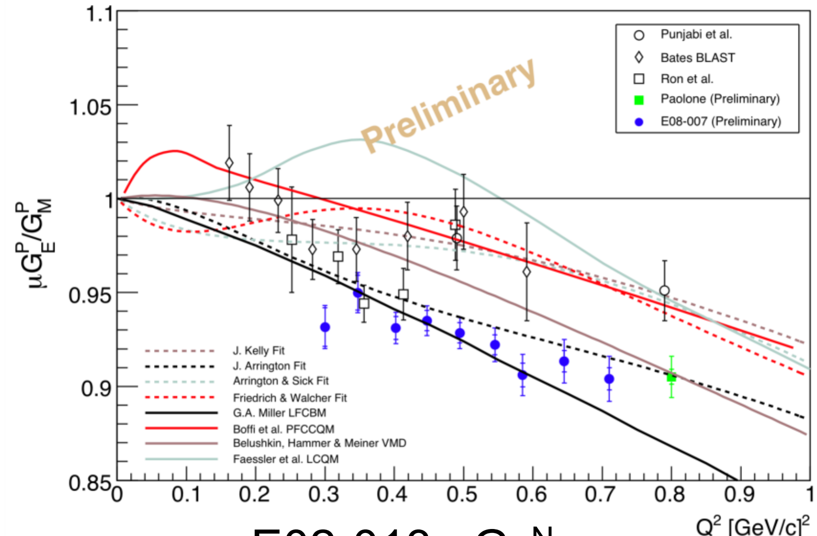


Progress on the Nucleon EM Form Factors

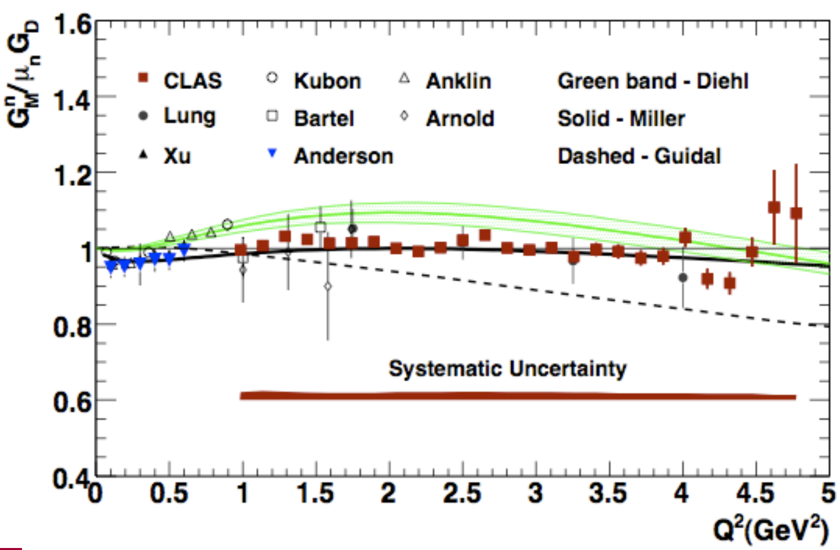
E04-108 G_E^P-III



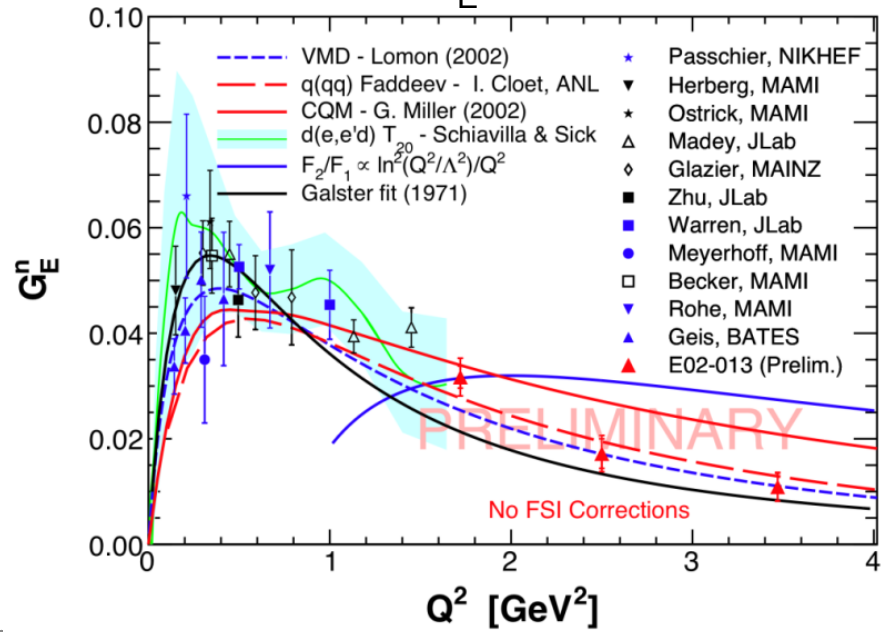
E08-007: High Precision Low Q^2 G_E^P



E94-017: G_M^N

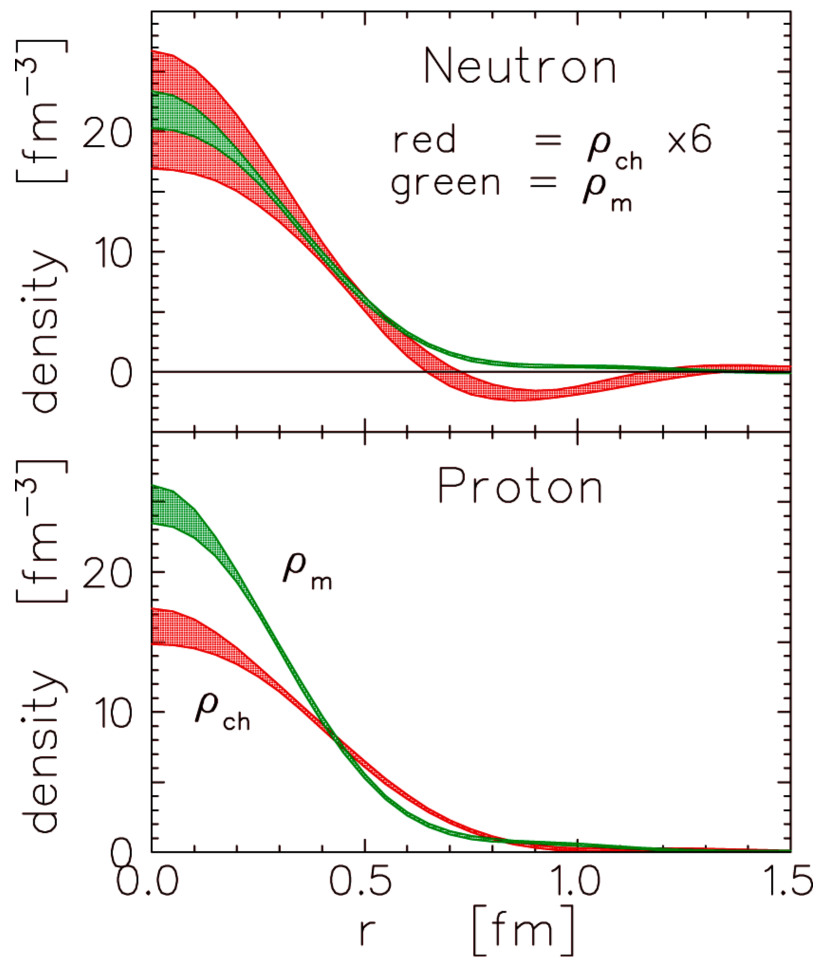


E02-013: G_E^N

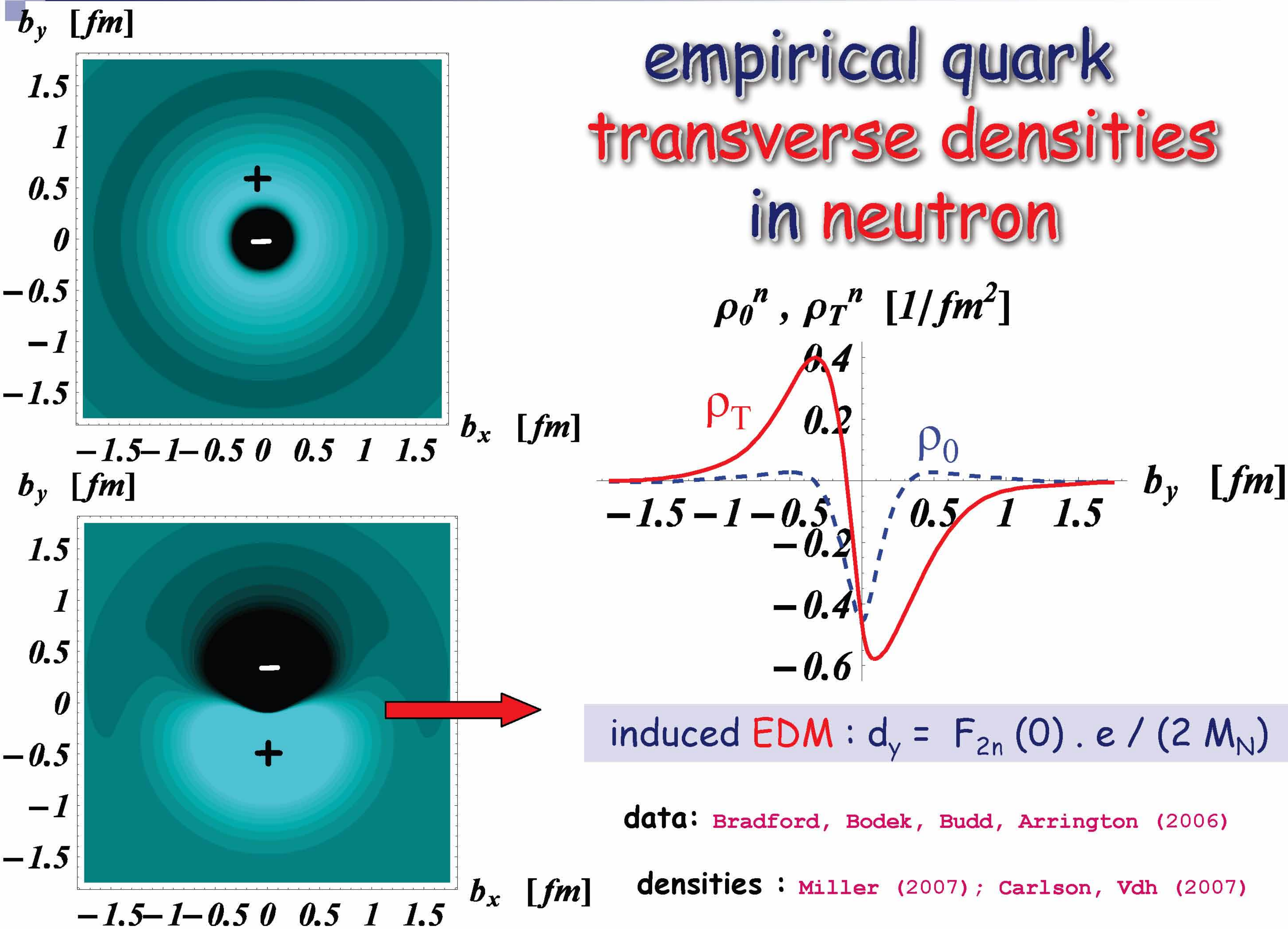


Charge and magnetization distribution

- Charge and magnetization distribution as Fourier transform of form factors
- Extracted using the Breit (center of mass) frame
- At large momentum transfer the method of extraction has been be revisited using light cone formalism
- The framework uses the Generalized Parton Distributions



empirical quark transverse densities in neutron



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

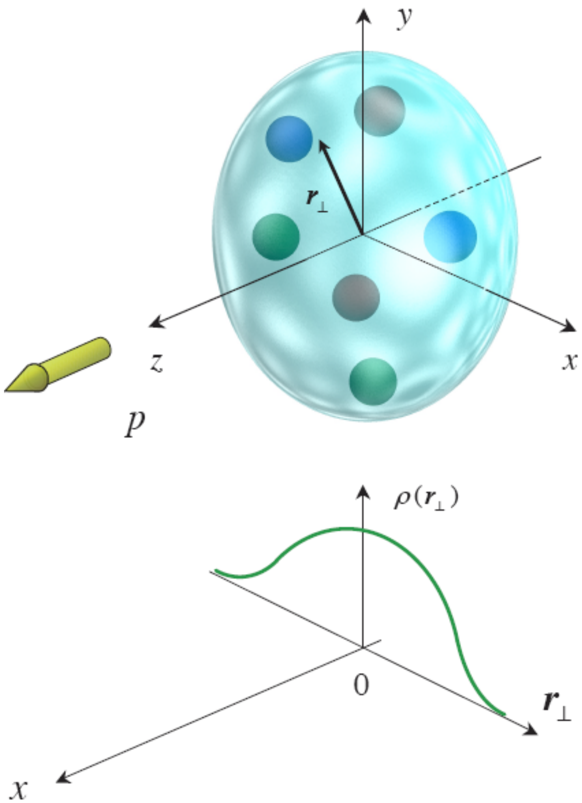
data: Bradford, Bodek, Budd, Arrington (2006)

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

3D imaging of the nucleon

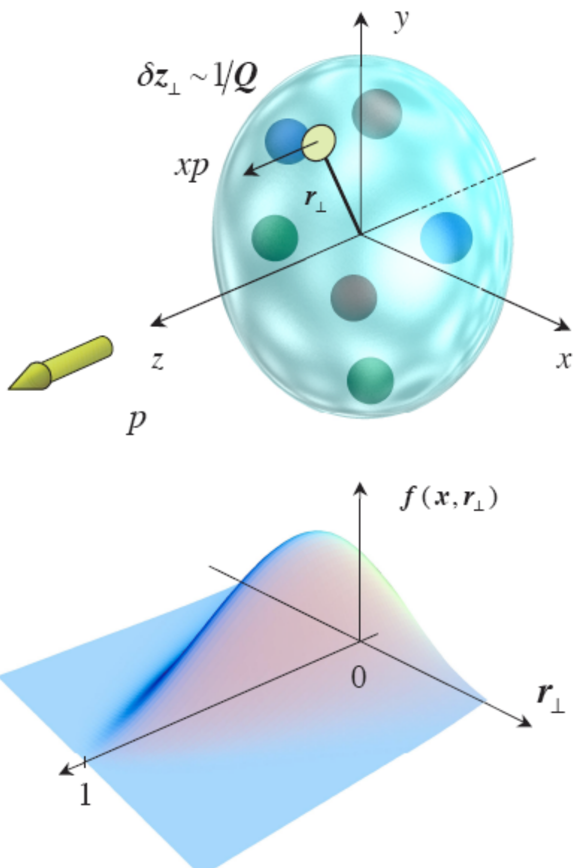
Tool: Generalised Parton Distributions

Form factors:



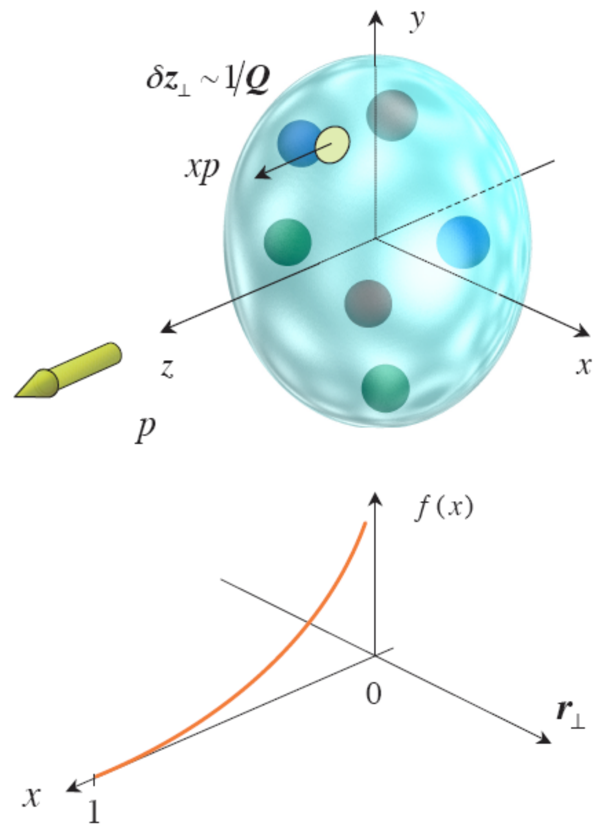
Fourier transform of e.g. a radial charge distribution

GPDs:



Generalized description in 2+ 1 dimensions

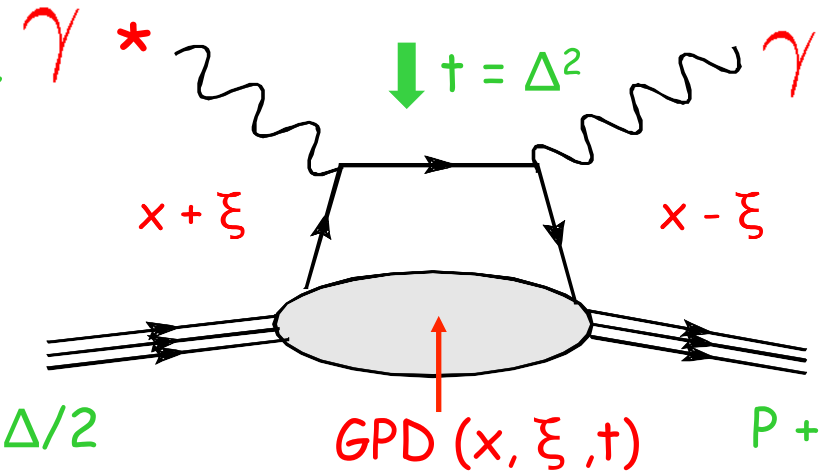
Parton Distrribution Functions:



Number density of quarks with longitudinal momentum fraction x

Generalized Parton Distributions

- Q_{hard}^2 large



Ji , Radyushkin (1996)

low −t process : $-t \ll Q_{hard}^2$

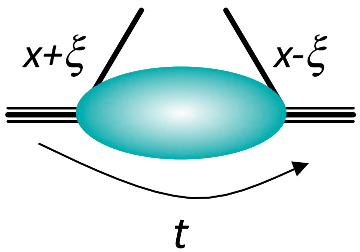
(x + ξ) and (x - ξ) : longitudinal momentum fractions of quarks

- at large Q^2 : QCD factorization theorem → hard exclusive process can be described by 4 transitions (GPDs) :

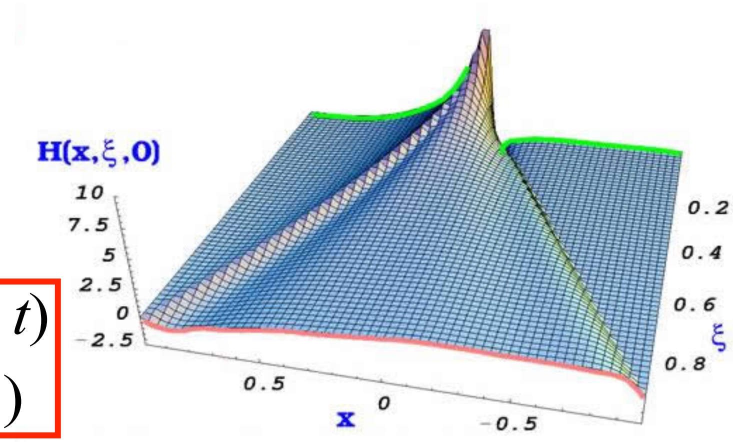
$H(x, \xi, t)$ $\qquad$ $\tilde{H}(x, \xi, t)$

$E(x, \xi, t)$ $\qquad$ $\tilde{E}(x, \xi, t)$

Generalized Parton Distributions, Deeply Virtual Compton Scattering

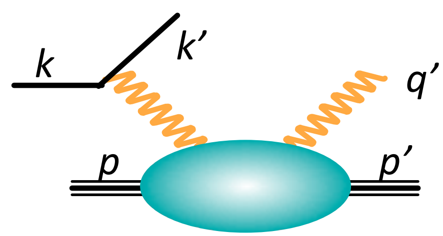


$$\langle p's'|\overline{\psi}(-y/2)\gamma^{\mu}\psi(y/2)|ps\rangle \rightarrow H,\ E(x,\xi,t)$$
$$\langle p's'|\overline{\psi}(-y/2)\gamma^{\mu}\gamma^{5}\psi(y/2)|ps\rangle \rightarrow \widetilde{H},\widetilde{E}(x,\xi,t)$$



Model by Goeke, Polyakov, Vanderhaeghen

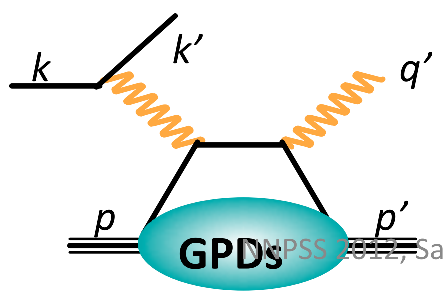
Deeply Virtual Compton Scattering is the simplest hard exclusive process involving GPDs



The handbag dominance:

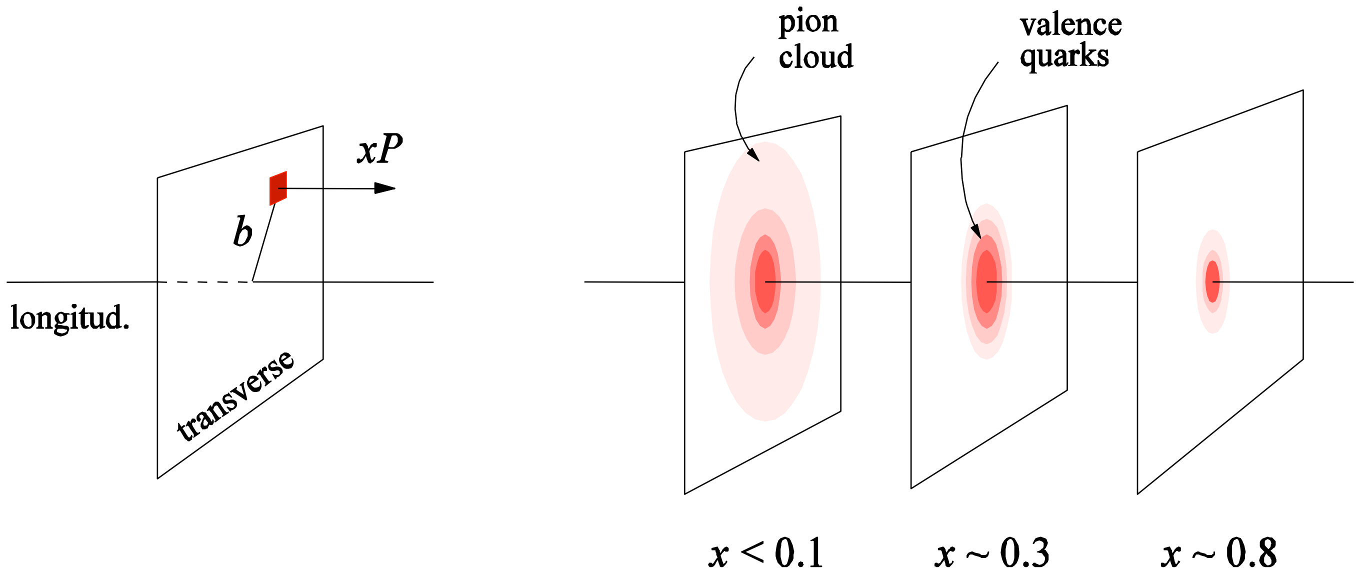
$$Q^2 = -q^2 = -(k-k')^2 >> M^2$$
$$t = (p-p')^2 = \Delta^2 << Q^2$$

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 :

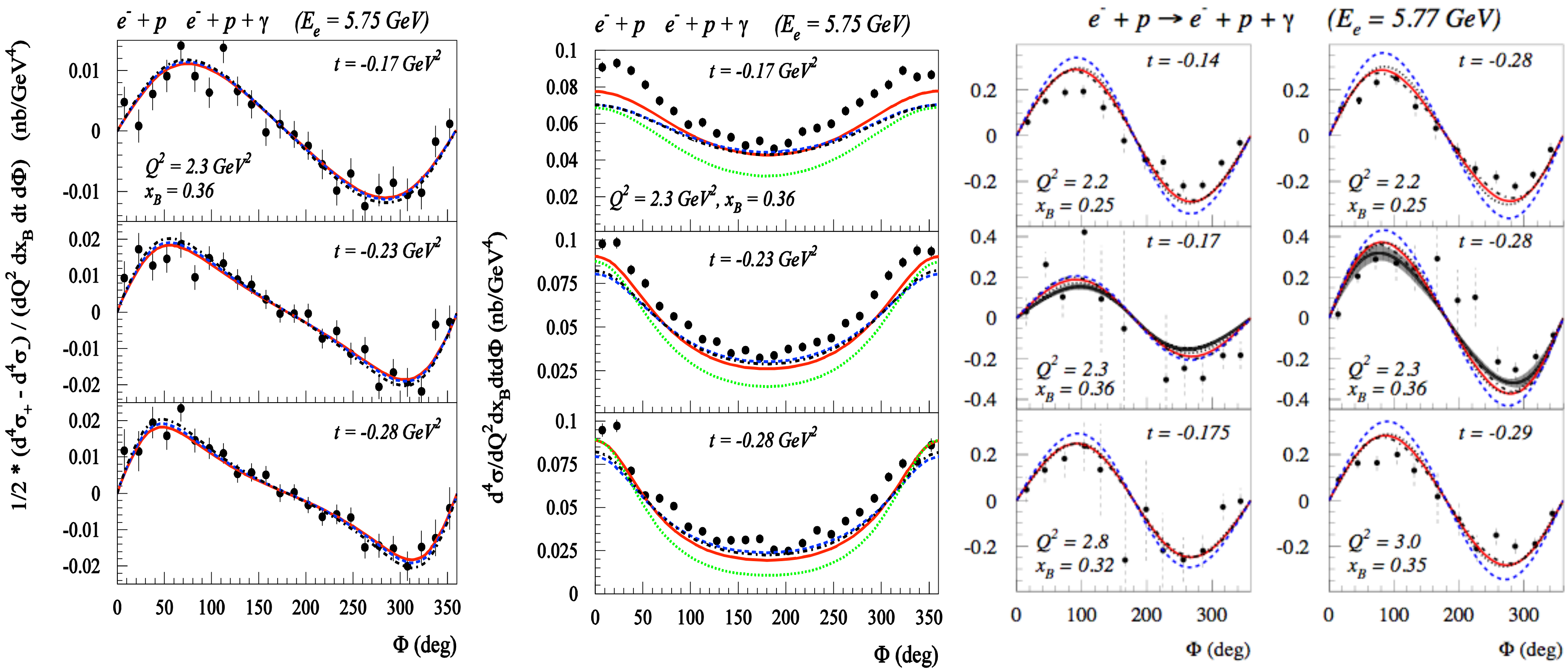
simultaneous distributions of quarks w.r.t. longitudinal momentum x P and transverse position b

(M. Burkardt)

⇨ theoretical parametrization needed :

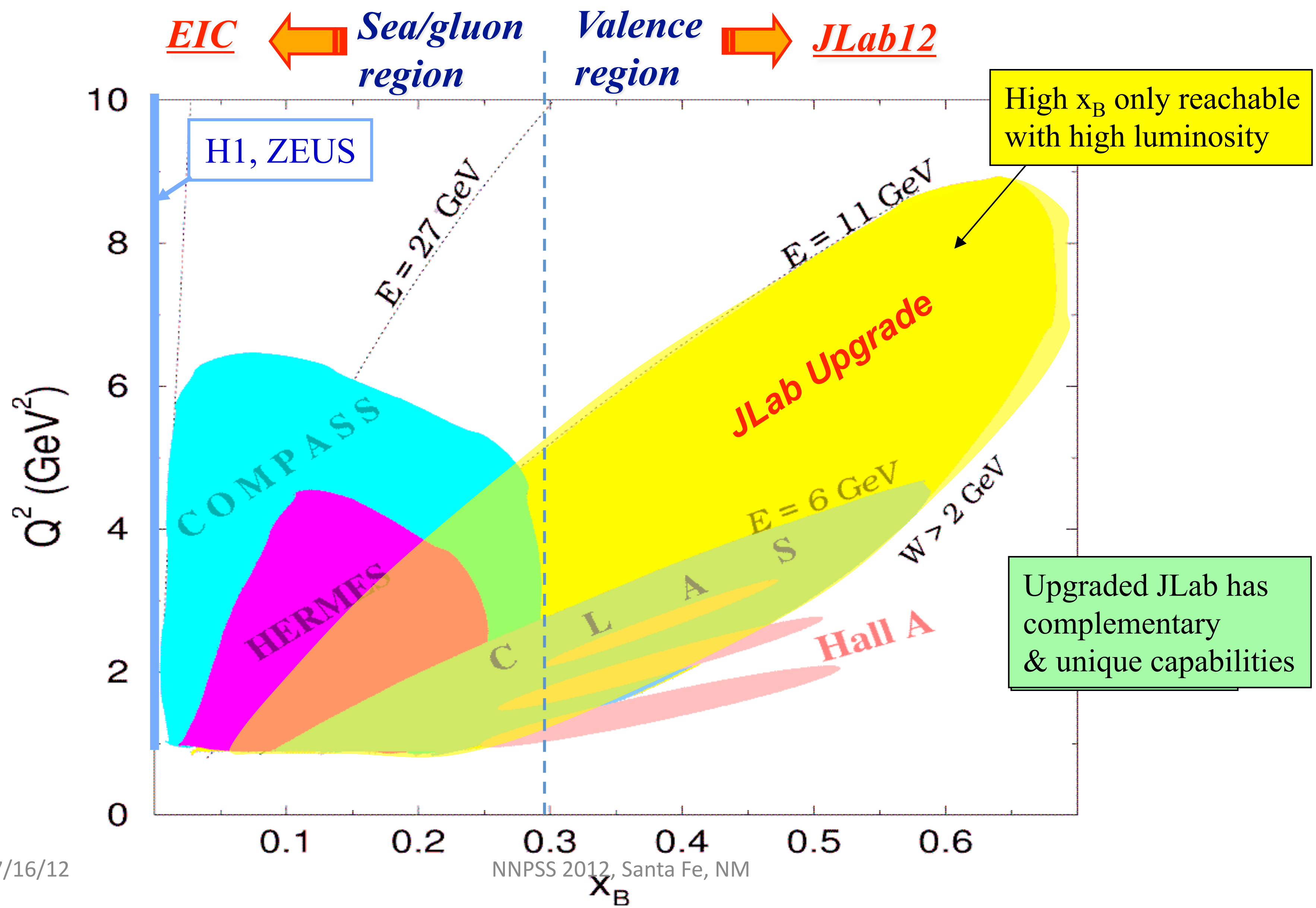
double distributions, dual param. (Guzey), conformal param. (Müller)

Generalized Parton Distributions (GPDs)



Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Halls A and B and more to come

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



DVCS program at JLab 12GeV upgrade

Nucleon polarization	Sensitivity to GPDs	Experiments
U	$H, \tilde{H}, E$	E12-06-114 : (A) proton E12-06-119 : (B) proton E12-11-003: **(B)** neutron
L	$\tilde{H}, H, E$	E12-06-119 : **(NH_3)** (B) proton
T	E, H	E12-11-105 : **(HD)** (B) proton

The JLab DVCS program will be carried out in two experimental Halls: **A & B (CLAS12)**

Extraction of GPD's

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

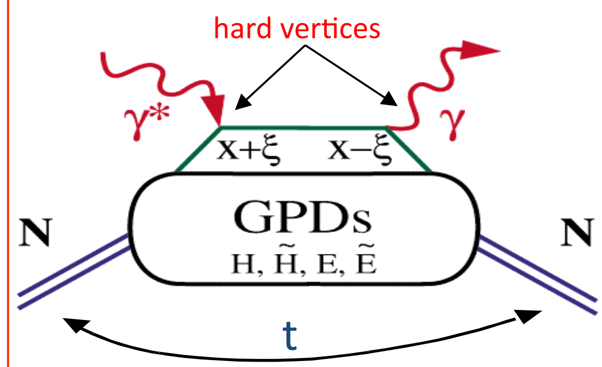
$ep \longrightarrow ep\gamma$

Cleanest process: Deeply Virtual Compton Scattering

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

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

$k = -t/4M^2$



Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

$\Rightarrow$ $H(x,t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1 \tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$$

$\Rightarrow$ $\tilde{H}(x,t)$

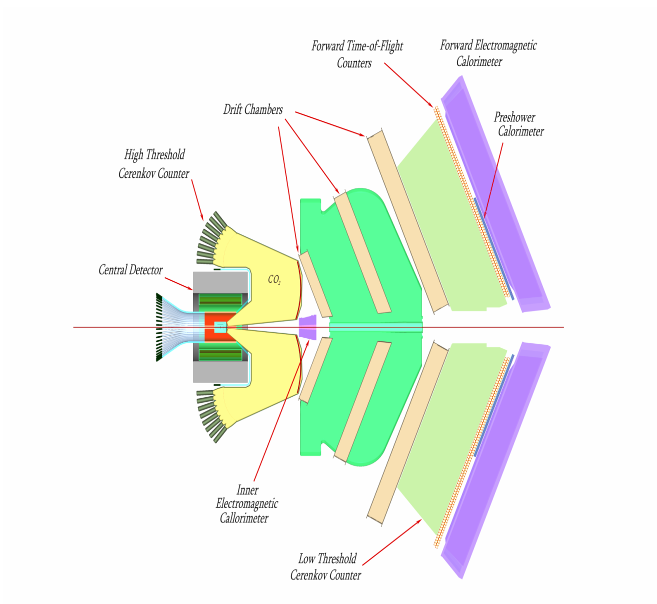
Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E)\}d\phi$$

$\Rightarrow$ $E(x,t)$

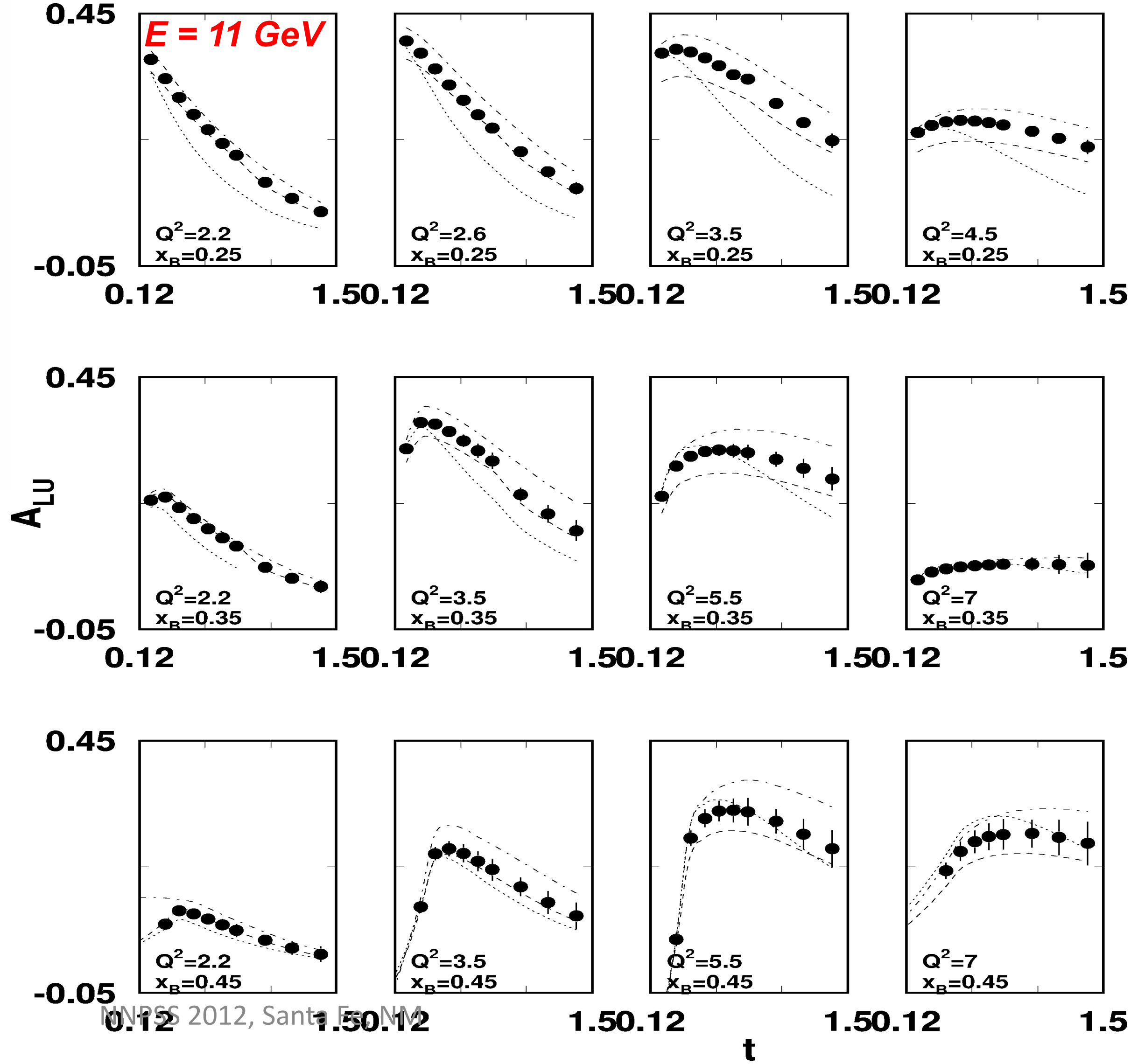
exclusive DVCS : BSA @ JLab 12 GeV

CLAS12



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

Projected results

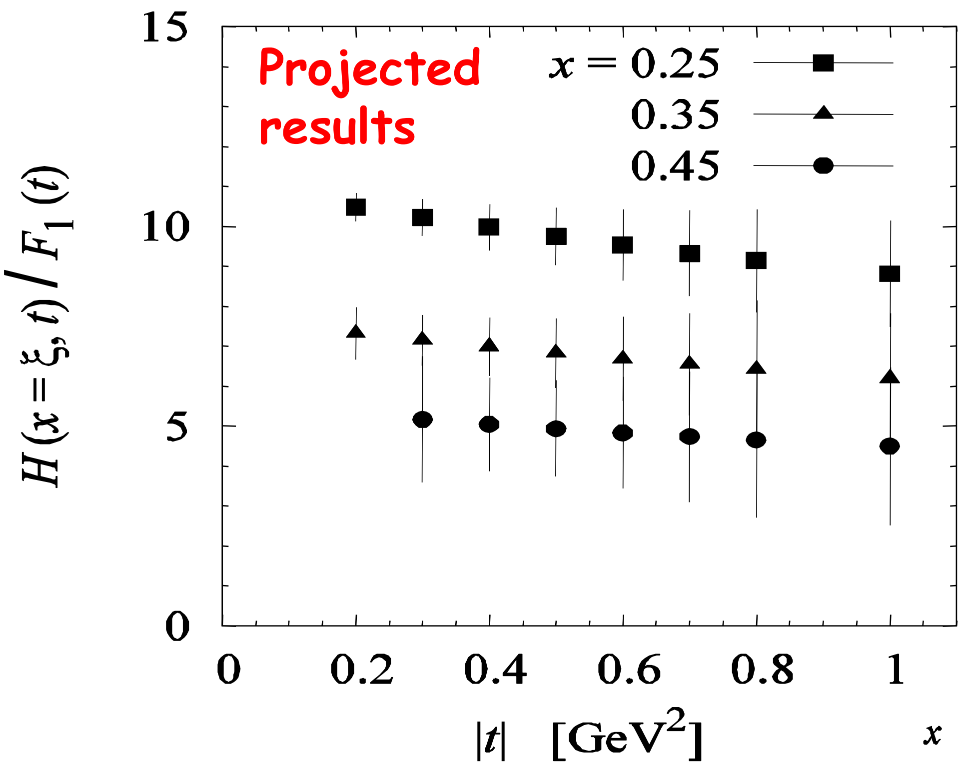


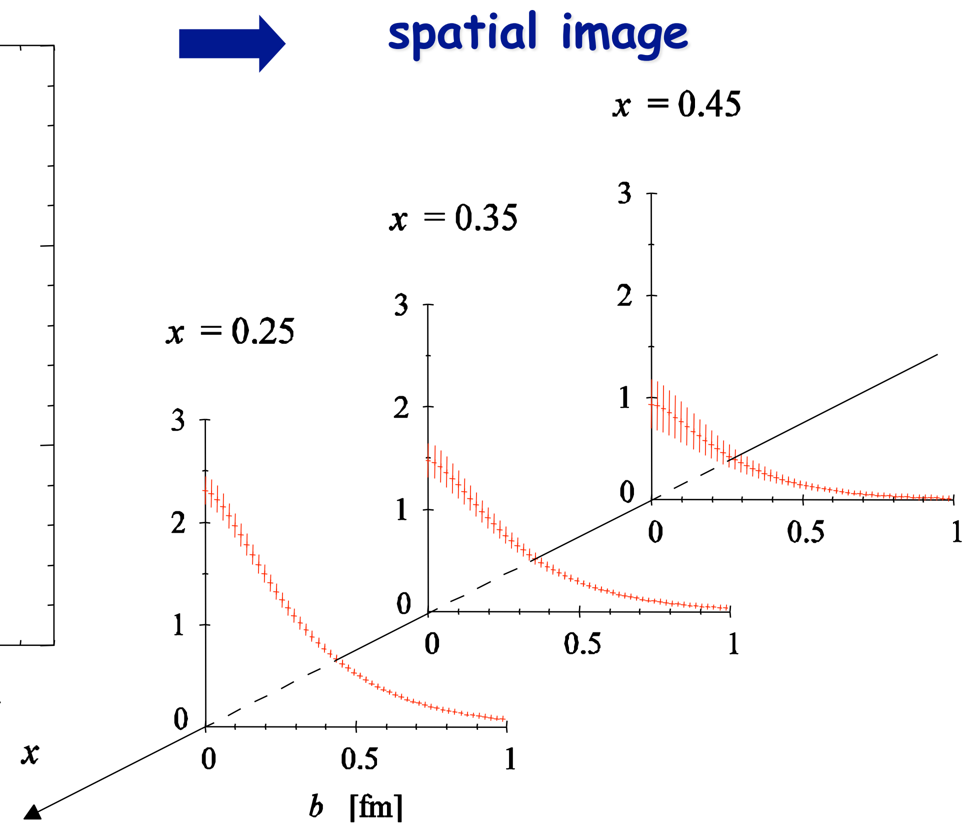
$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + ..\} d\phi$

Selected Kinematics

$L = 1\text{x}10^{35}$
T = 2000 hrs
$\Delta Q^2 = 1\ GeV^2$
$\Delta x = 0.05$

Projected precision in extraction of GPD H at $x = \xi$

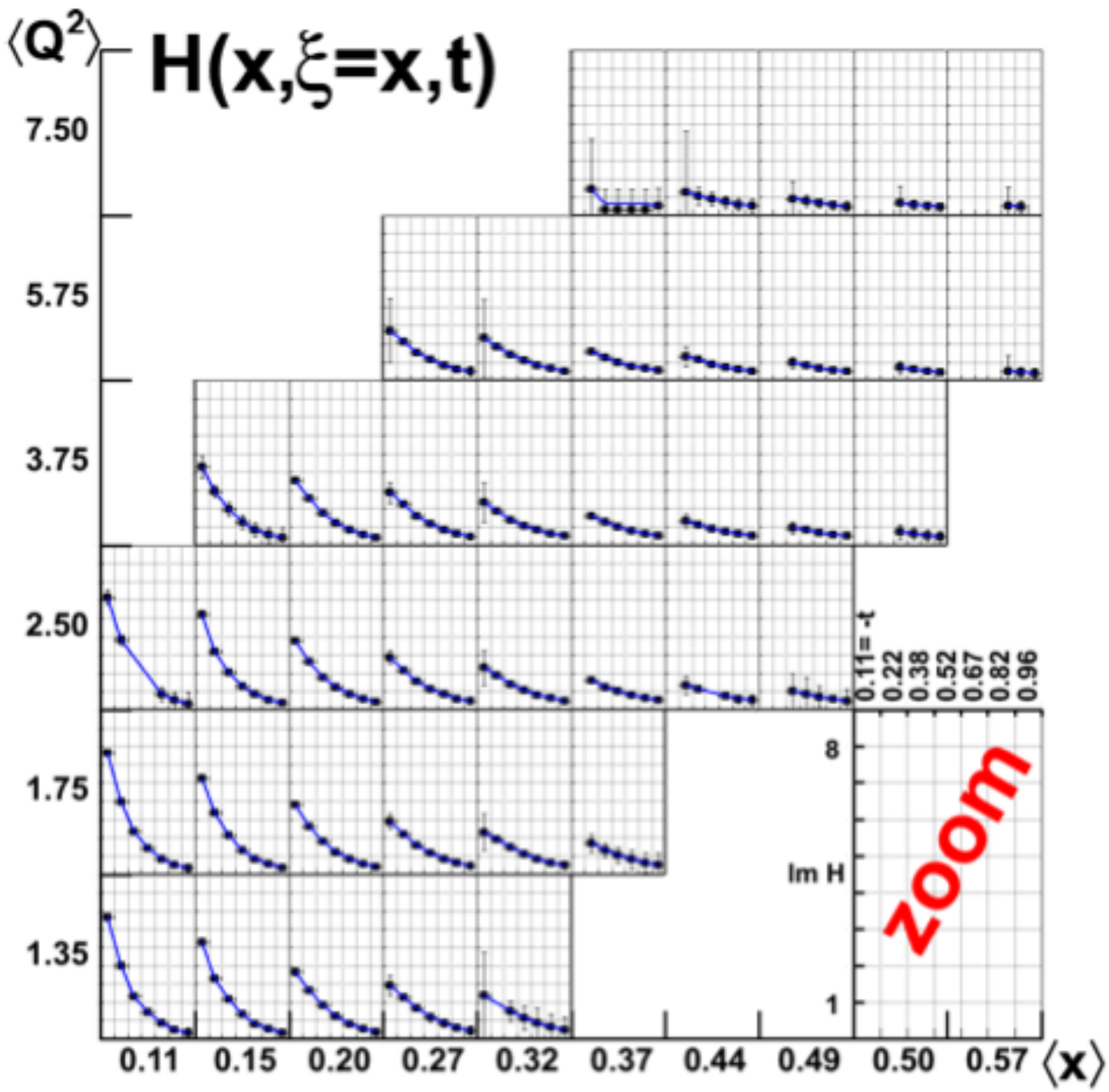




upgraded CLAS @ JLab12GeV

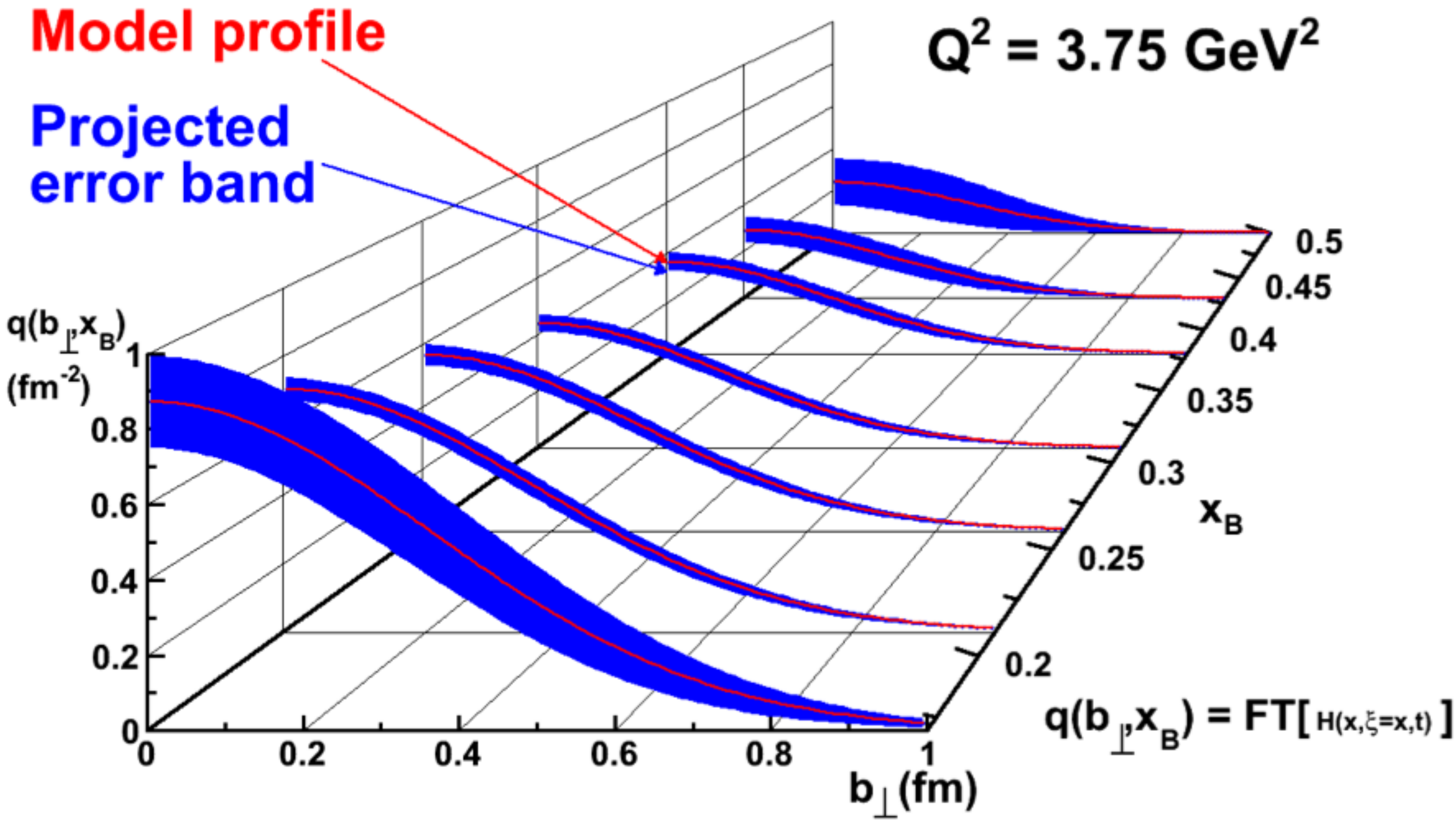
Avakian, Weiss

Projected impact on GPD extraction methods



Using simulated data based on VGG model. Input GPD H extracted with good accuracy

Nucleon Transverse Profile: Projections



Exclusive DVCS on *longitudinal* target @ JLab 12 GeV

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

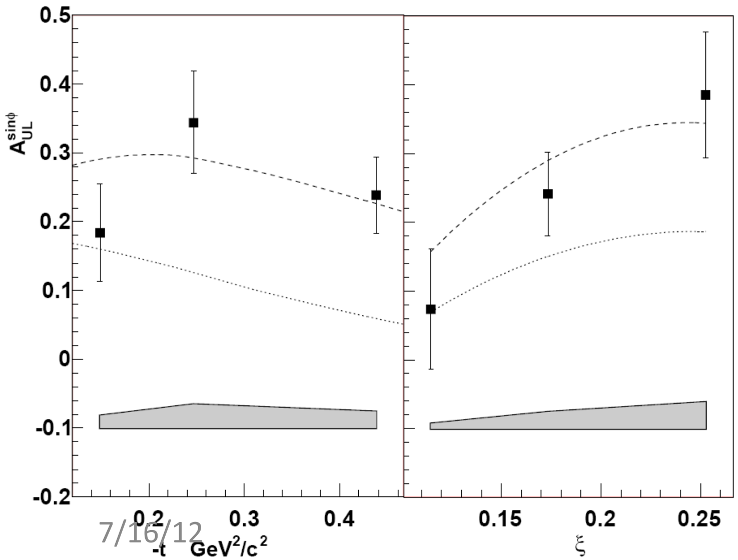
L = 2×10^{35} $cm^{-2}s^{-1}$
T = 1000 hrs
ΔQ^2 = 1GeV^2
Δx = 0.05

Longitudinally polarized target

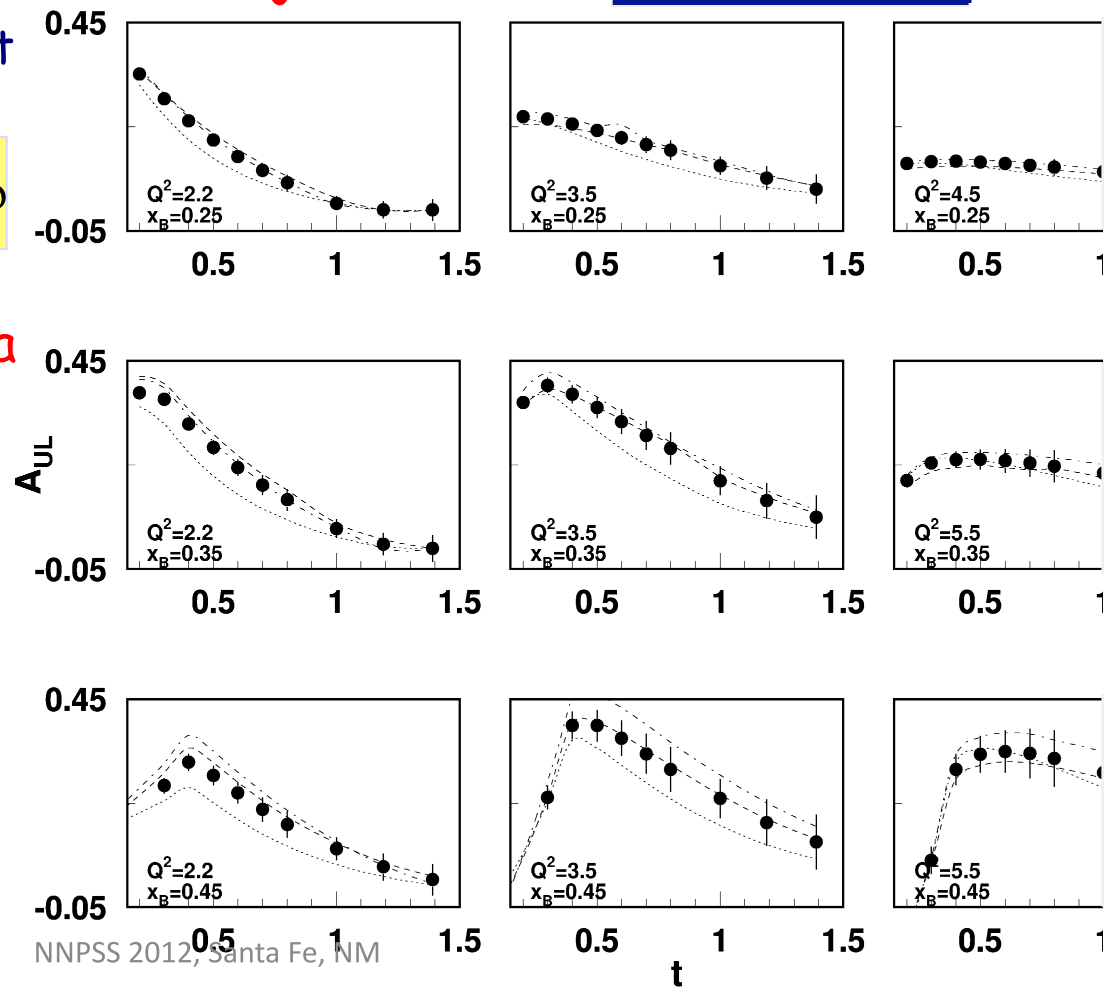
$\Delta\sigma \sim \sin\varphi\, \mathrm{Im}\{F_1\tilde{H} + x(F_1+F_2)H\ldots\}d\varphi$

CLAS exclusive DVCS data

PRL97, 072002 (2006)



Projected results



Exclusive DVCS on *transverse* target @ JLab 12 GeV

$e\, p^{\uparrow} \longrightarrow e p \gamma$

E = 11 GeV

Transverse polarized target

$\Delta\sigma \sim \sin\varphi \, \mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\varphi$

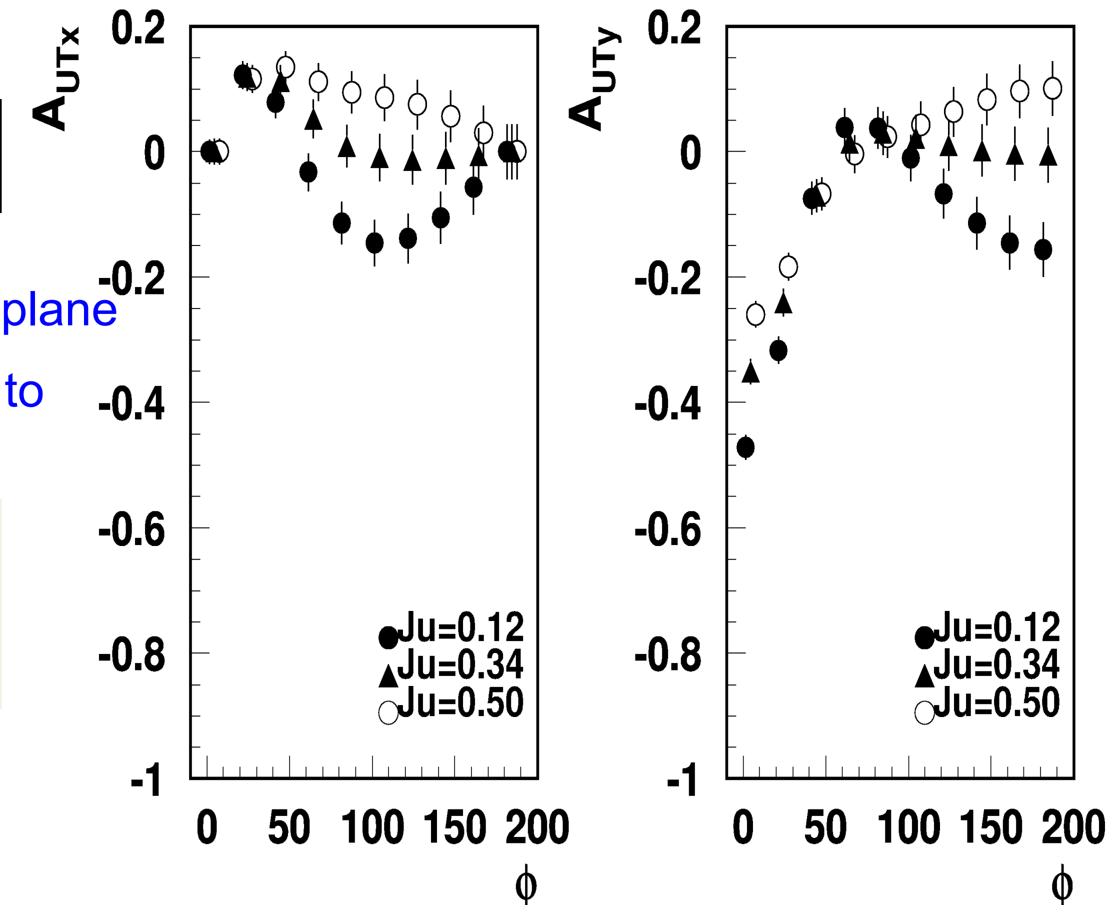
A_{UTx} Target polarization in scattering plane

A_{UTy} Target polarization perpedicular to scattering plane

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

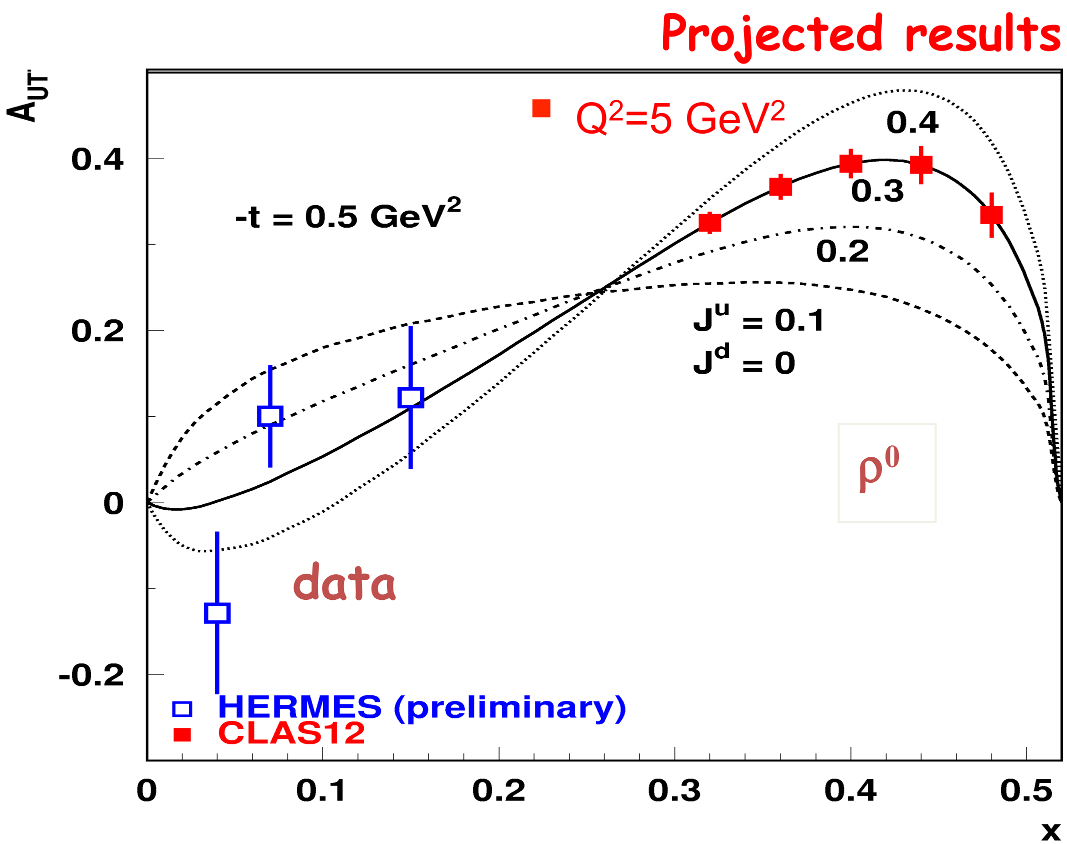
Projected results

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



exclusive ρ^0 production on *transverse* target

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



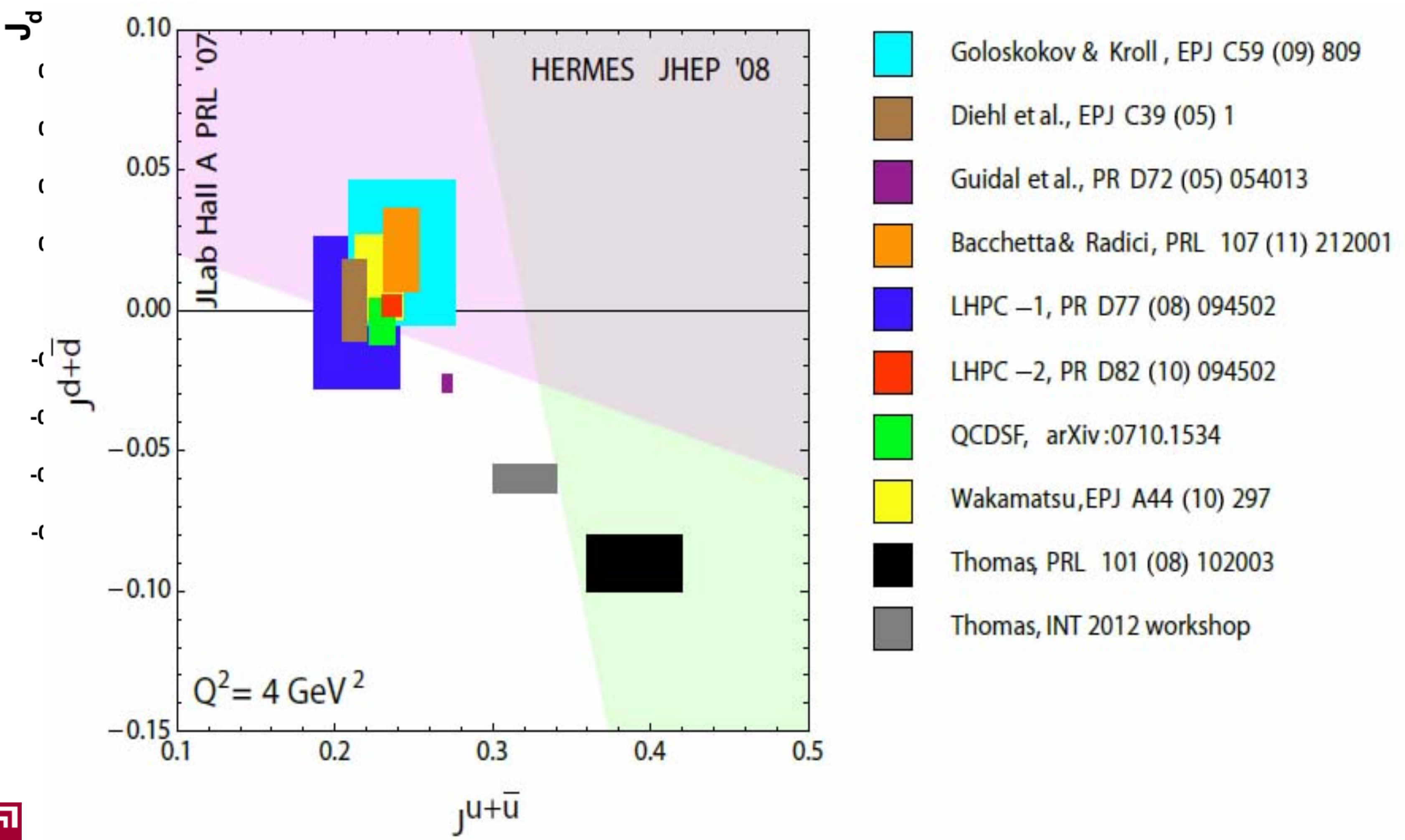
ρ^0	$A \sim 2H^u + H^d$ $B \sim 2E^u + E^d$
ρ^+	$A \sim H^u - H^d$ $B \sim E^u - E^d$

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

Goeke, Polyakov, Vdh (2001)

Quark Angular Momentum

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

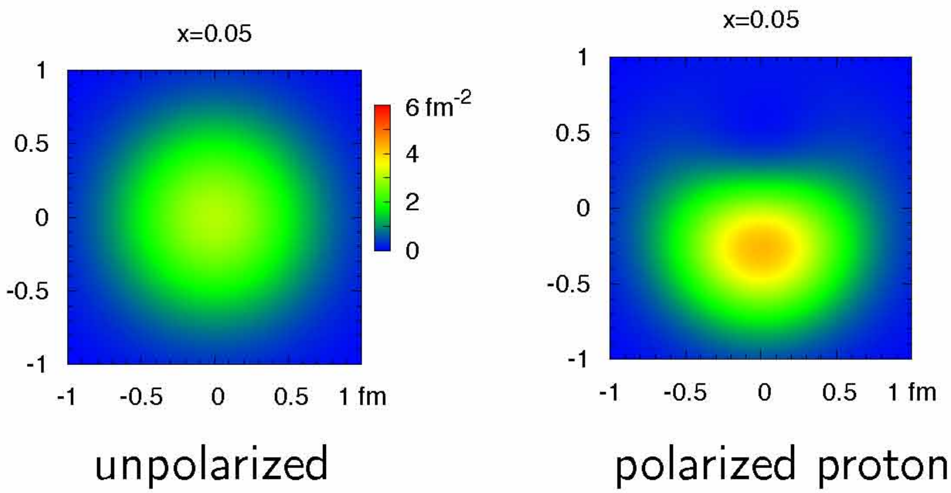


What can we do with the GPDs?

evaluate parton angular momenta from Ji's sum rule

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

work out transverse localization of partons

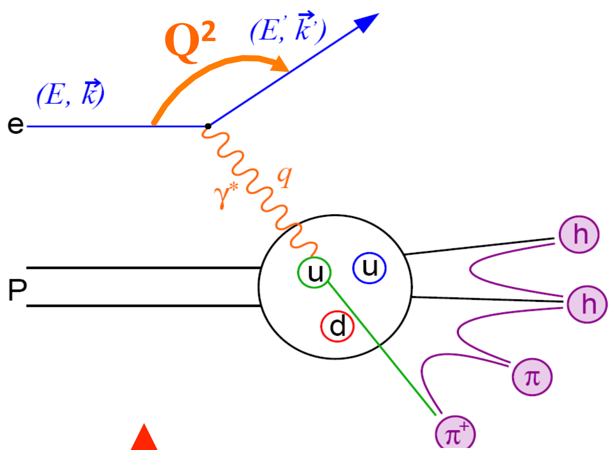


for d quarks

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

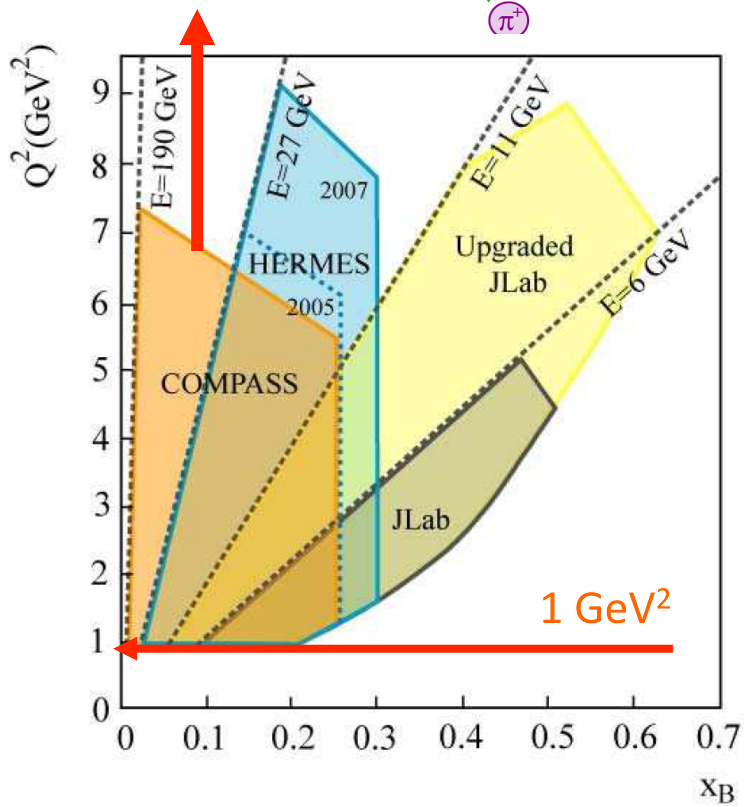
Peter Kroll

Semi-Inclusive Deep-Inelastic Scattering

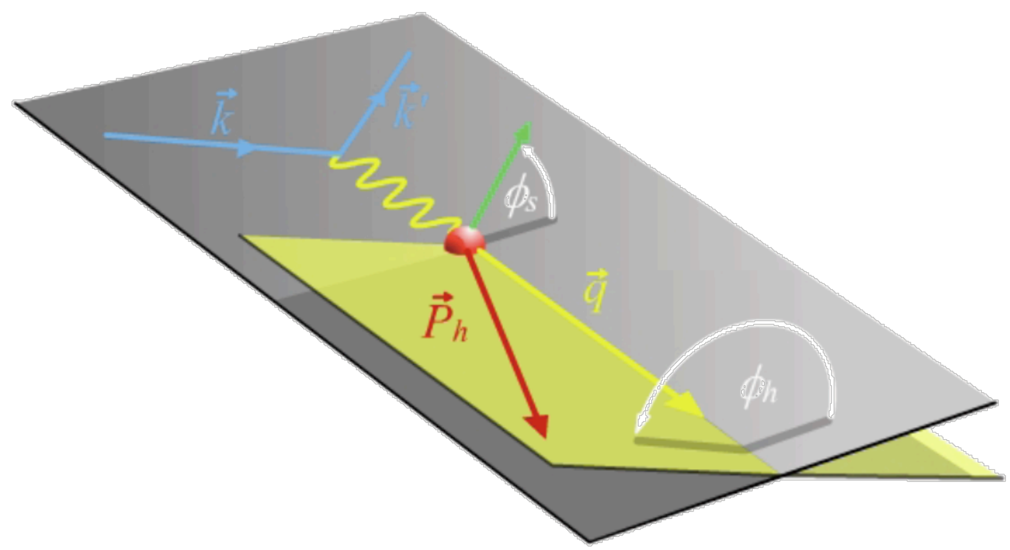


Factorization

$$\sigma^h_{l,S} \propto \sum_f \sigma^{q_f} \otimes pdf(x) \otimes frag^{q_f, g \to h}(z)$$



- Beam polarized
- Target polarized transverse (T) or longitudinal (L)



Transverse Spin Structure: Leading Twist TMDs

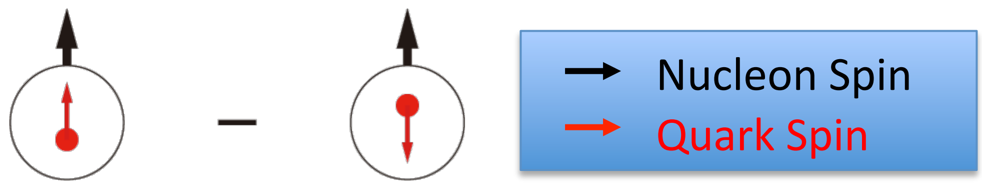
→ Nucleon Spin
→ Quark Spin

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

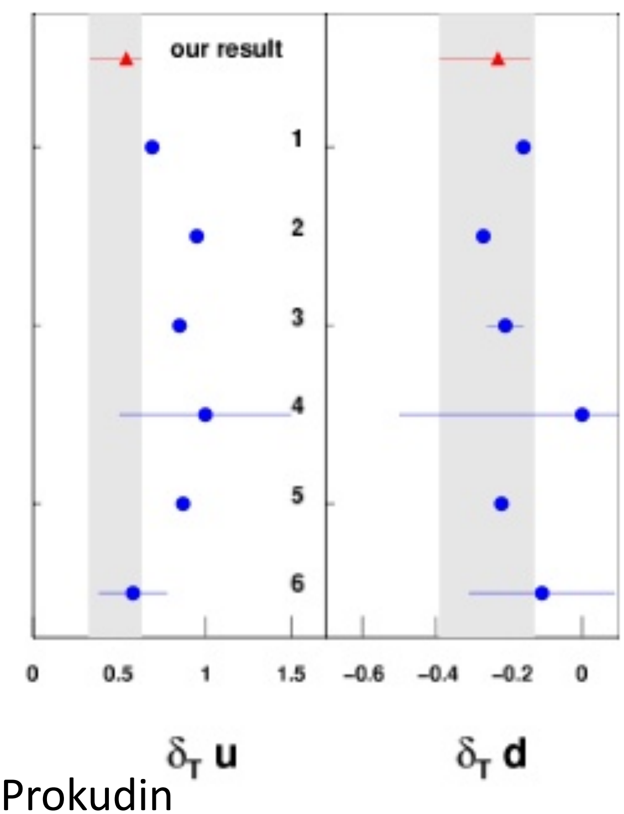
$$\int_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)] \, dx = \frac{1}{6} g_A$$

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

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

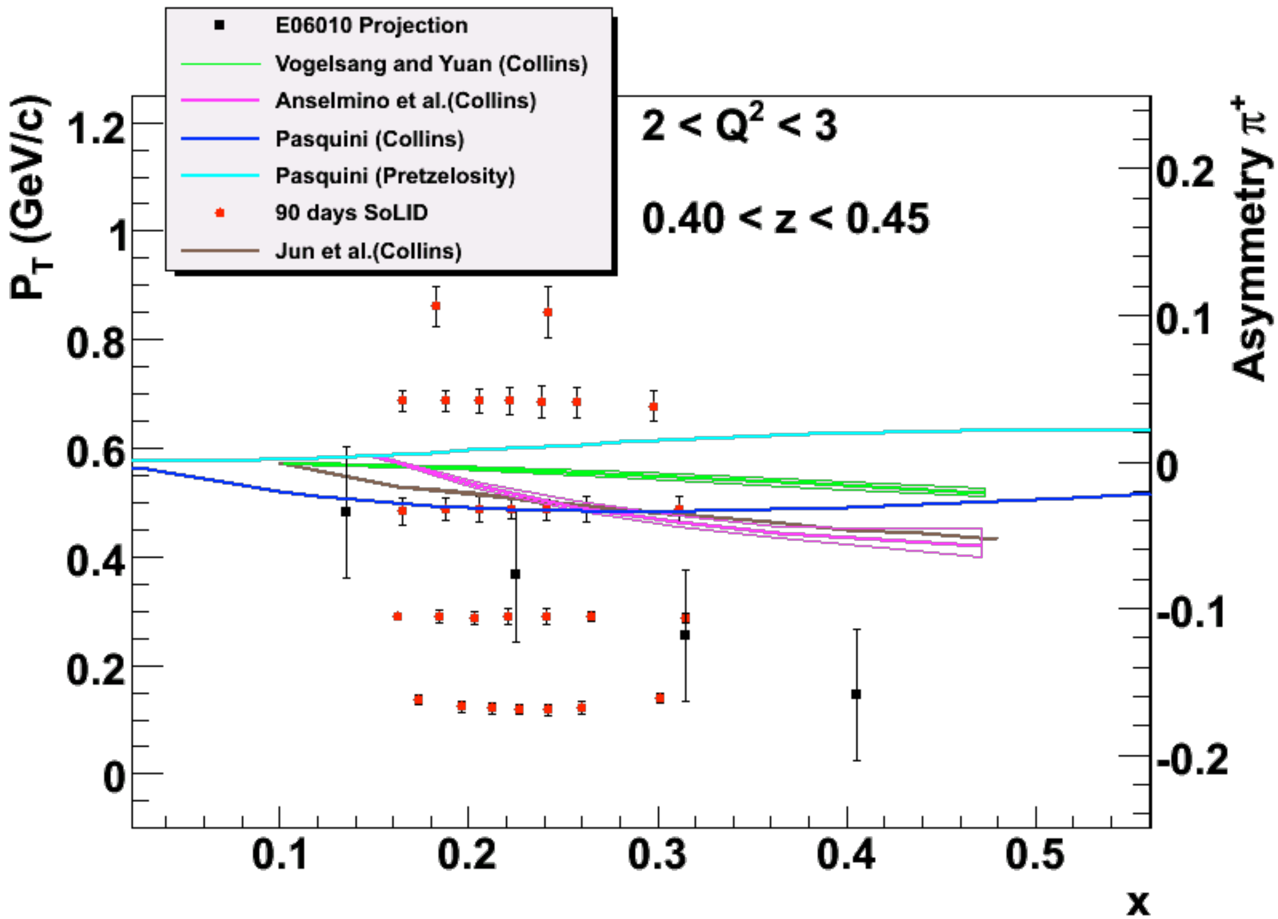
LOI12-06-108: **Pion** SIDIS
LOI12-09-004: **Kaon** SIDIS

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

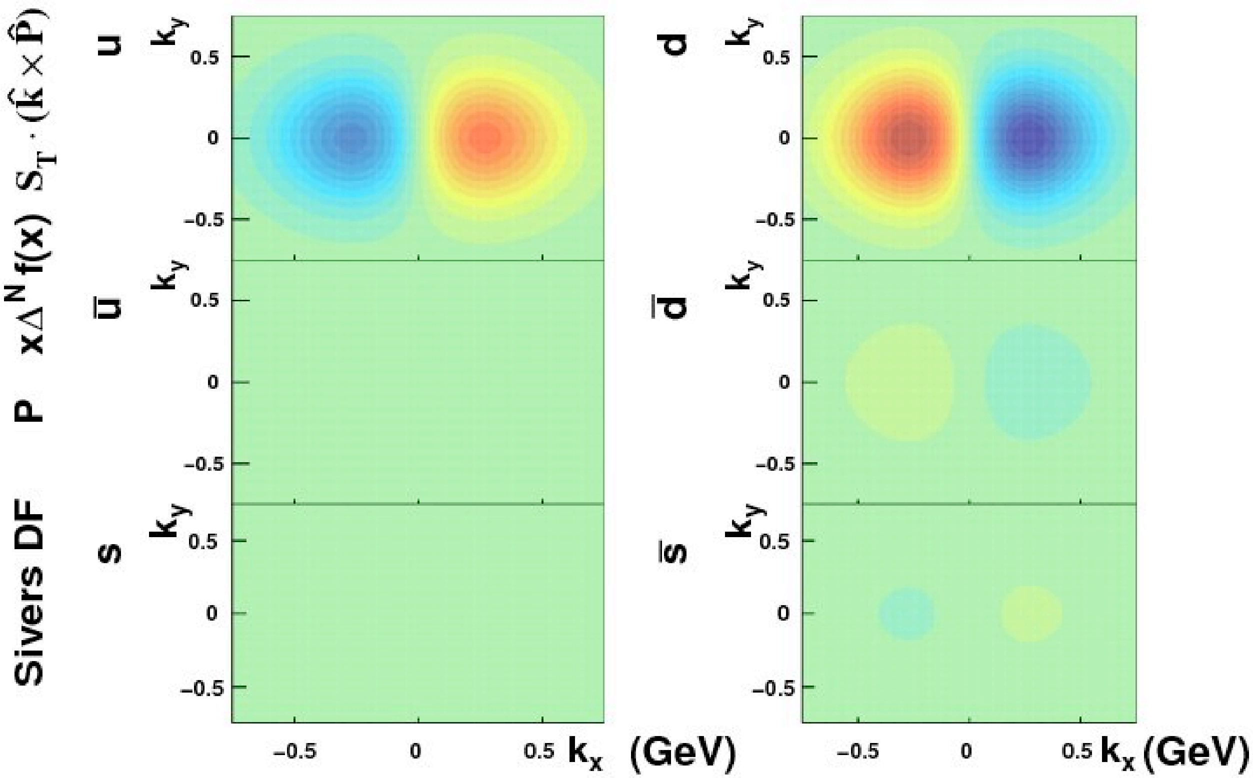
- Complete program of TMDs studies for pions and kaons
- Kaon measurements crucial for a better understanding of the TMDs "kaon puzzle"
- Kaon SIDIS program requires an upgrade of the CLAS12 detector PID RICH detector to replace LTCC
  Project under development

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)

EIC; a natural extension of studies planned for JLab but to probe the glue and the sea

Generalized Parton Distributions

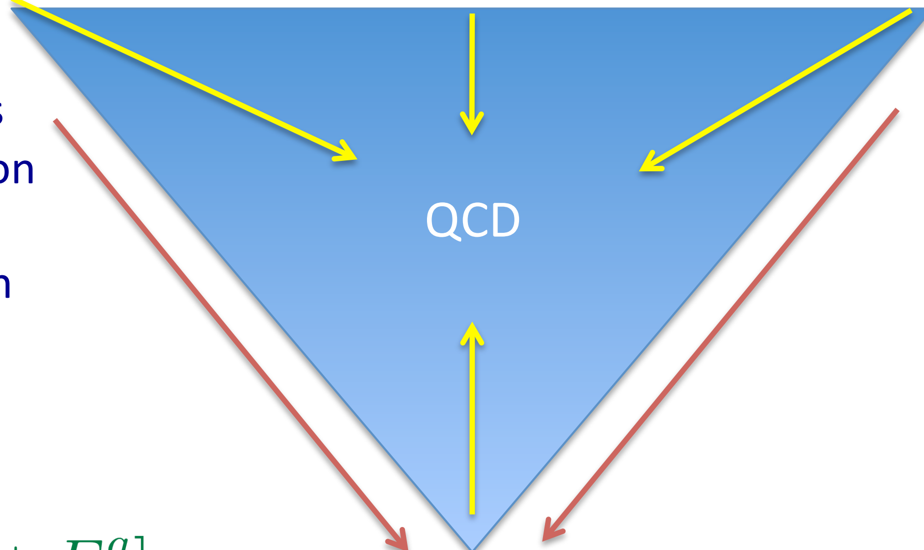
Exclusive reactions

Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production

Since 1998

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

Inclusive
Sum rules and polarizabilities



Transverse Momentum Distributions

Semi-Inclusive DIS

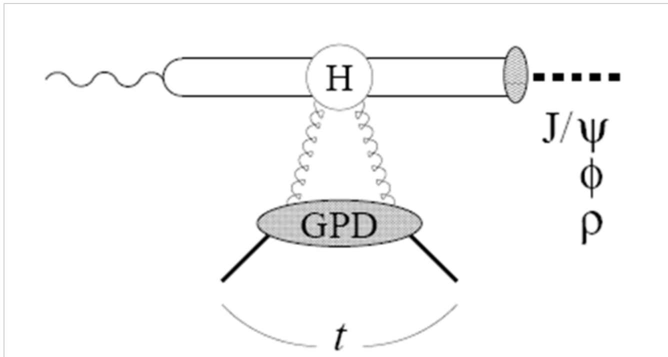
Distributions and
Fragmentation functions

Since 2000

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

Gluon Imaging with exclusive processes

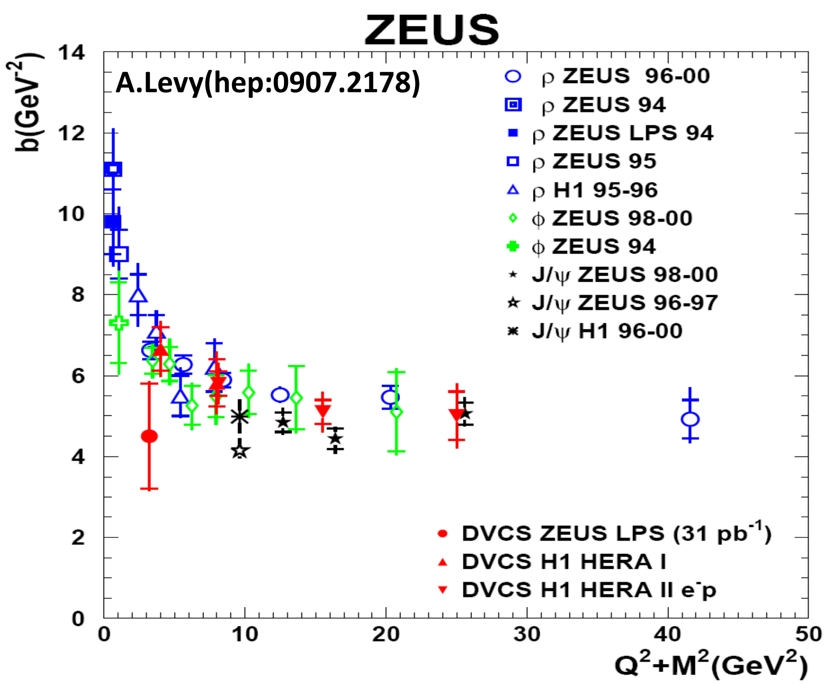
Goal: Transverse gluon imaging of nucleon over wide range of x: $0.001 < x < 0.1$



Two-gluon exchange dominant for J/ψ,φ, ρ production at large energies → sensitive to gluon distribution squared!

LO factorization ~ color dipole picture
→ access to gluon spatial distribution in nuclei

Fit with $d\sigma/dt = e^{-Bt}$



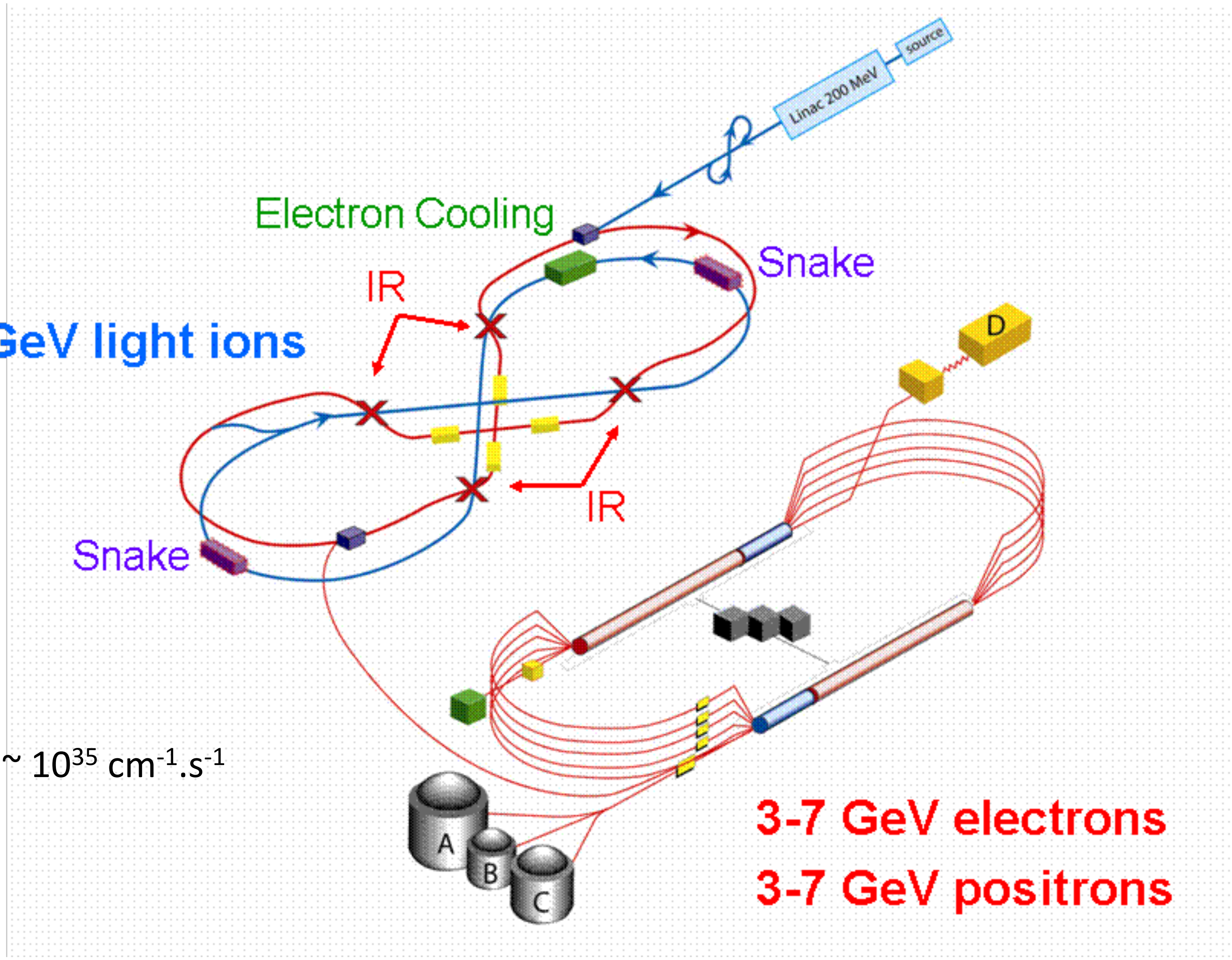
Measurements at DESY of diffractive channels (J/ψ, φ, ρ, γ) confirmed the applicability of QCD factorization:

- t-slopes universal at high Q^2
- flavor relations φ:ρ

Hard exclusive processes provide access to transverse gluon imaging at EIC!

ELIC presented at the LRP

30-150 GeV light ions



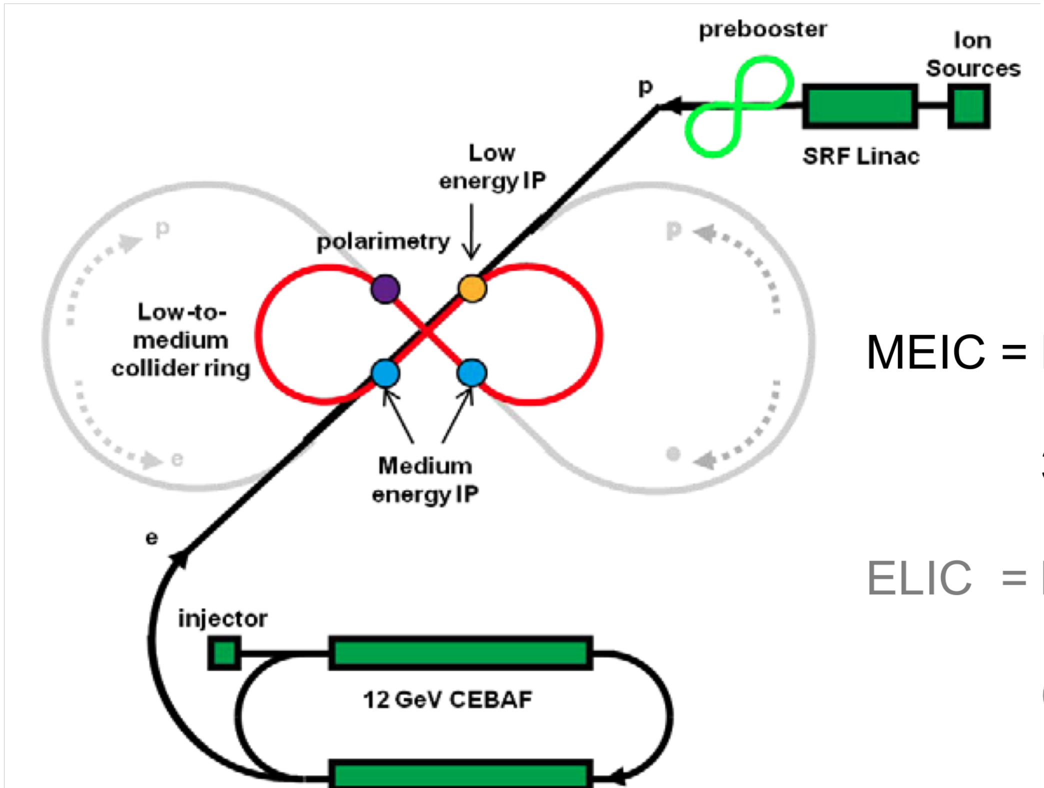
Luminosity ~ 10^{35} $cm^{-1}.s^{-1}$

Medium Energy Electron Ion Collider

Map the spin and 3D quark-gluon structure of protons

Discover the role of gluons in atomic nuclei

Understand the creation of the quark-gluon matter around us

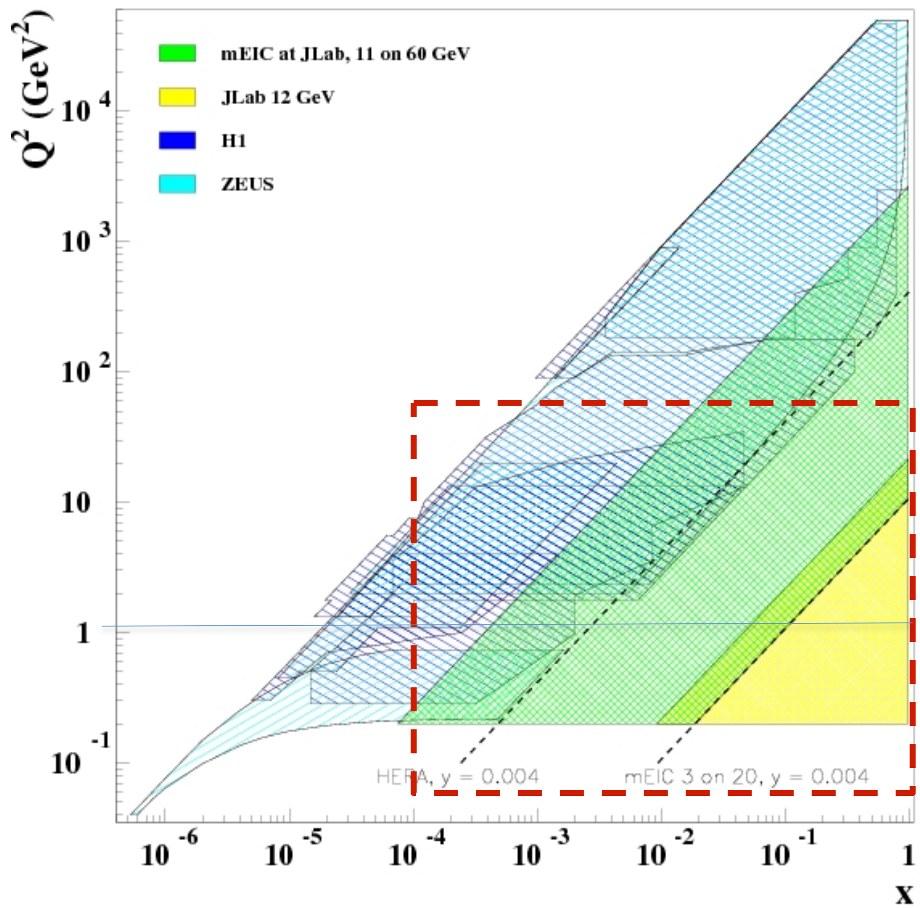


Luminosity~ few 10^{34} $cm^{-1}s^{-1}$

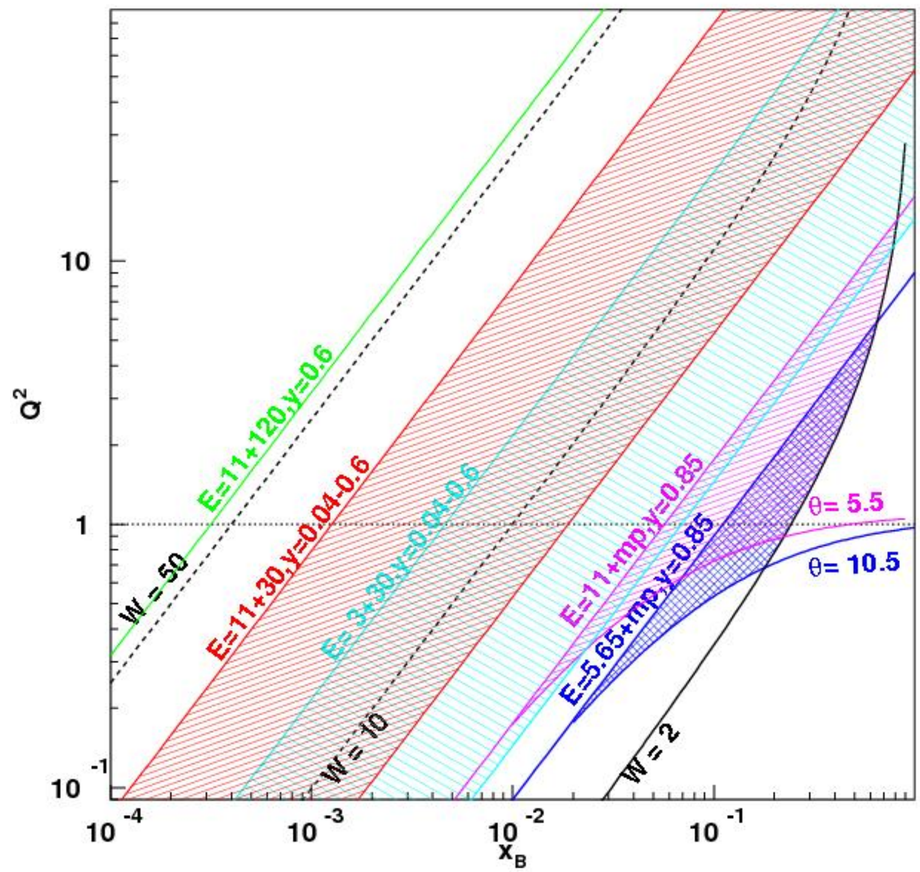
MEIC = EIC@JLab
1 low-energy IR (s ~ 200)
3 medium-energy IRs
(s < 2600)

ELIC = high-energy EIC@JLab
(s = 11000)
(limited by JLab site)

EIC Kinematic Coverage



ep mEIC: 11+60



eA mEIC: 3+30/11+30 (0.04<y<0.6)
eA eLIC: 11+120 (y=0.6)

EIC connects JLab and HERA kinematic region

Summary

- There are important observables that tell a "story" about the constituents of the nucleon but need to be measured with precision.
- Spin studies in the valence region will continue at Jefferson Lab in the 12 upgrade era
- A new program to extend the one dimensional view of the nucleon into a 2+1 dimensional will be carried in the framework of GPDs and TMDs
- Access of the orbital angular momentum carried by quarks will be will be possible using the new theoretical framework and DVCS & DVMO measurements
- EIC, a natural extension of the JLab 12 GeV physics program of hadron structure/QCD

However, the emphasis is not the valence quarks but

Gluons and Sea Quarks in the valence region and beyond

- This requires high luminosity and good center of mass energy
  - Luminosity is key for probing rare processes
  - Energy reach key for clean interpretation