The Jefferson Lab 12 GeV Upgrade

Ch. Weiss (JLab), NNPSS Summer School, FSU, July 13, 2007

- Electron scattering

  Basics, history, facilities, . . .

- Jefferson Lab and 12 GeV Upgrade

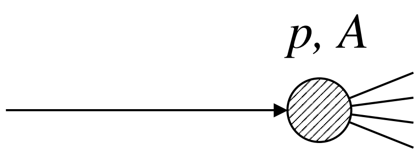
- Physics program
  - Nucleon structure in QCD: Quark distributions, spin, spatial (GPDs), . . .
  - Nuclei: Short–range correlations, color transparency, . . .
  - Search for gluonic excitations → Lecture J. Dudek
  - Tests of fundamental symmetries

- Future opportunities

  Postdocs, students

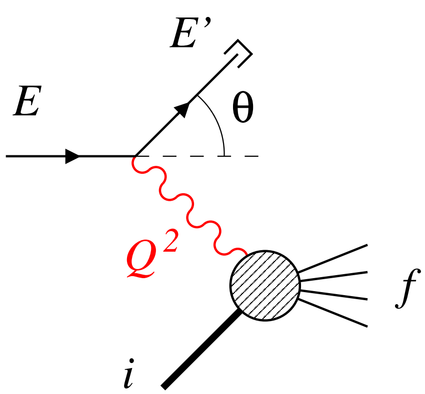
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Scattering experiments in nuclear physics



$p, \pi, \ldots$	hadron
$e, \mu, \nu, \ldots$	lepton
γ	photon

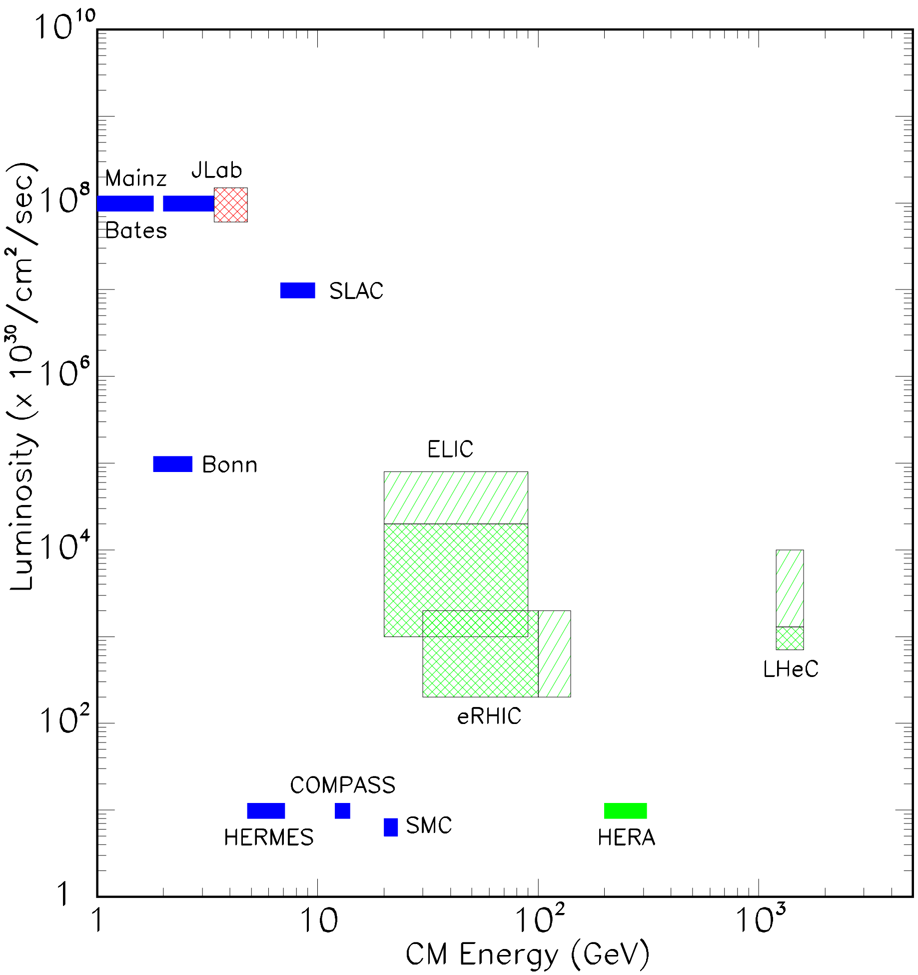
- Uses of scattering experiments
  - Structure of target
  - Produced system (mesons, resonances)
  - Properties of interaction (high energy, p_T)



$$\langle f |\, J_\mu(x)\, | i \rangle$$

- Advantages of electron scattering
  - Structureless probe, "clean"
  - Controlled energy/momentum transfer, "microscope" with resolution Q^2
  - Interaction through well–known EM current operator

Characteristics of eN facilities



JLab: High–luminosity frontier

- CM energy of eN system

  fixed target $\quad E^2_{\text{CM}} \sim 2E_e M_N$
  colliding beams $\quad 4E_e E_N$

  $\rightarrow$ max. Q^2, final state mass M_f

- Luminosity L: Number of possible eN collisions per time [cm^{-2} s^{-1}]

  $$dN_{\text{event}} = L\,\sigma\,dt$$

  $\rightarrow$ "Rarity" of observable process (cross section), statistics

- Polarization (beam, target)

Typical cross sections and rates in eN/eA

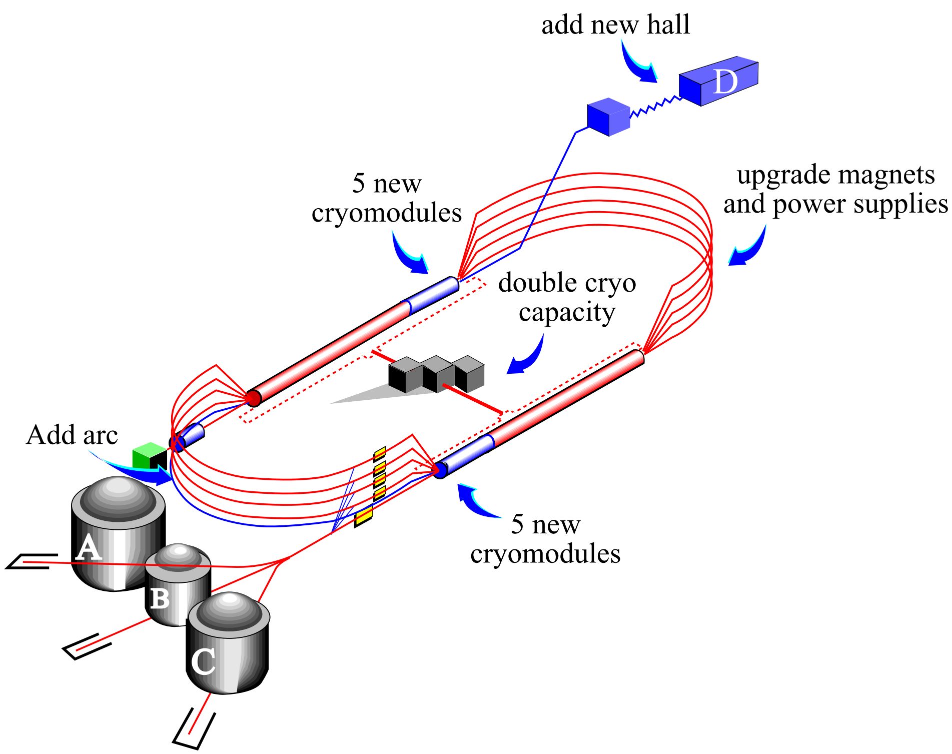
Process		Cross section	Rate*,** (s^{-1})
$ep \to e'X$	inclusive DIS	$\sim$ few 10 nb	10^5
$ep \to e'\gamma p$	exclusive DVCS	$\sim$ 1 nb	10^4
$eA \to e'X$	nuclear DIS at $x > 1$	$\sim$ 1 pb	10
$eA \to e'A$	nuclear elastic FF at high t	$\sim$ 1 pb	10

$*$ Luminosity $L = 10^{37}\text{cm}^{-2}\text{s}^{-1}$ [$1\,\text{nb} = 10^{-33}\,\text{cm}^2$]

$**$ Does not include detector acceptance, kinematic cuts etc.

- "Reasons" for small cross sections
  - Small coupling constant (e.g. higher–order EM processes)
  - Rare configurations in target wave function (e.g. form factors at high t)

JLab and 12 GeV Upgrade



CW beam $\sim 100\,\mu A$
Present beam energy 6 GeV
Operating since 1994

- "Race track–like" accelerator (linacs + arcs), extensible to 24 GeV
- Uses unique superconducting RF technology + energy recovery
- Experimental halls

A, C	Magnetic spectrometers
B	Large acceptance CLAS

- 12 GeV Upgrade
  - Double beam energy 6 $\rightarrow$ 12 GeV
  - Add Hall D (γ beam, GlueX detector)
  - Upgrade existing halls

DOE project (CD0 2004, CD1 2006)
Construction 2009, beam exp. 2013
Total cost $\sim$ 300M$

JLab 12 GeV physics program

I) Search for gluonic excitations

Exotic/hybrid mesons, dynamics of confinement, . . .

II) Nucleon structure in QCD

Parton densities, spin, spatial structure (form factors, GPDs), quark–hadron duality, . . .

III) Physics of nuclei

Short–range correlations, quark propagation in medium, nuclear modifications of parton structure, . . .

IV) Fundamental symmetries

Parity–violating electron scattering, $U(1)$ anomaly (Primakoff effect), . . .

Nucleon structure in QCD

- Probe nucleon in "extreme" configurations where only the three valence quarks are present

  Large–x parton densities (d/u etc.)

- Explore how spin and orbital motion of quarks are correlated with the nucleon spin

  Polarized parton densities, "higher twist," spin–orbit correlations

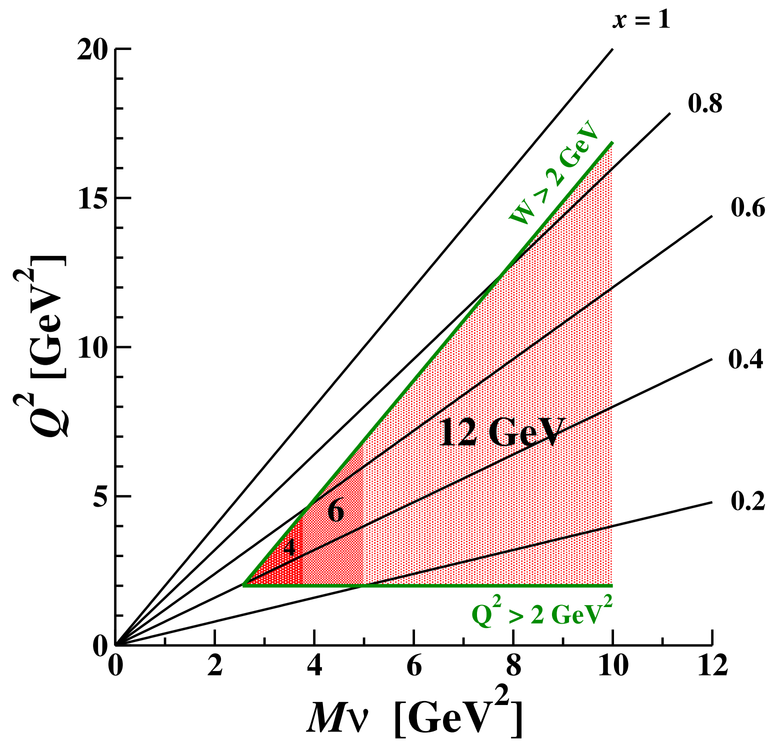
- Map the spatial distribution of quarks in the nucleon ("quark imaging")

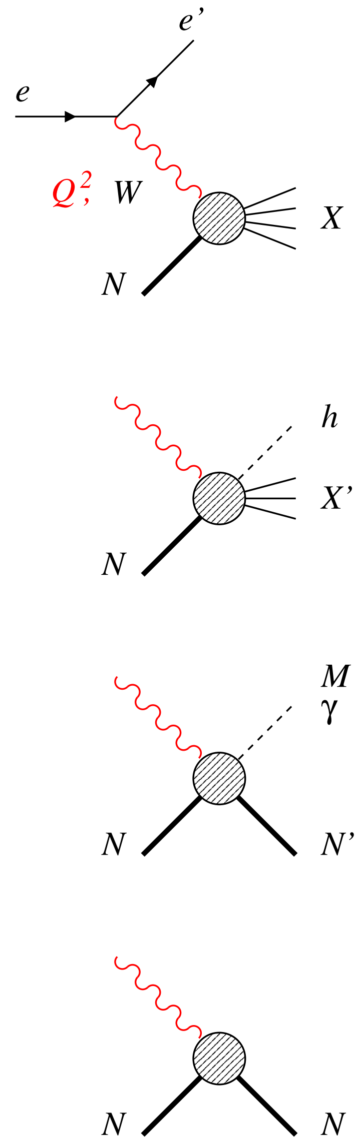
  Form factors, generalized parton distributions (GPDs)

- Explore the transition from quark/gluon to hadronic degrees of freedom

  Parton–hadron duality, low $\leftrightarrow$ high Q^2 sum rules

DIS kinematics and measurements





inclusive

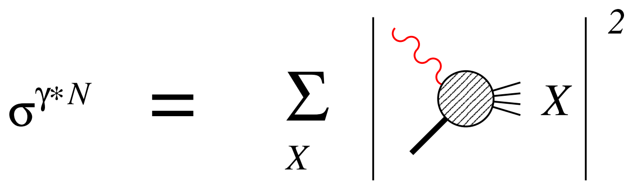
semi–inclusive
(h identified)

exclusive

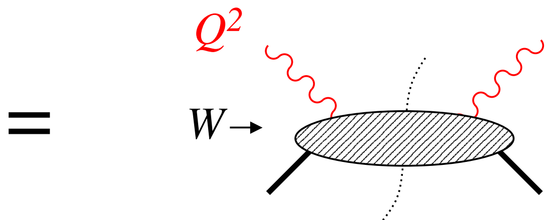
elastic

Q^2, ν	γ^* virtuality/energy
W	$\gamma^* N$ CM energy
$x = Q^2/2M\nu$	Bjorken variable

QCD factorization in DIS

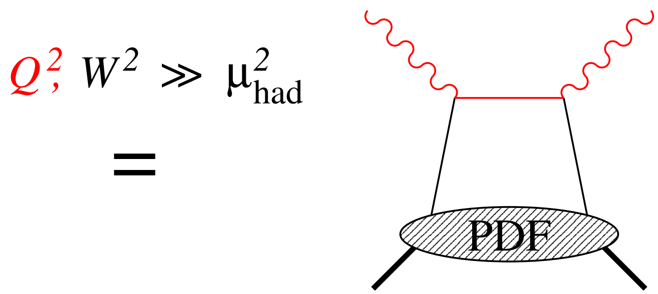


- eN ($\gamma^* N$) total cross section



- Virtual Compton amplitude

  $\langle p | \mathrm{T}\, J_\mu(0)\, J_\nu(z)\, | p \rangle$ current–current correlation function

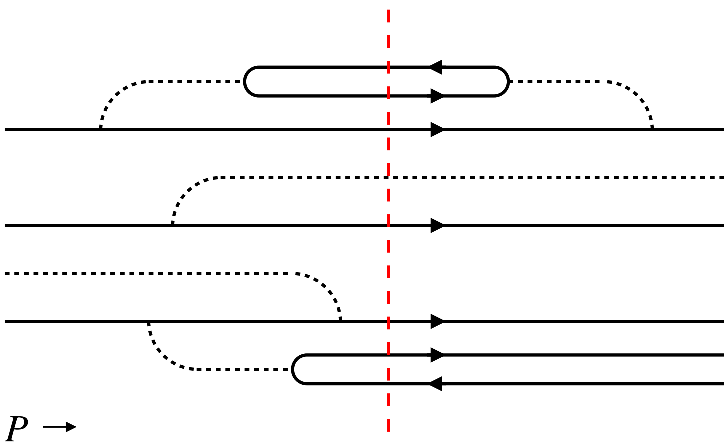


- Factorization in

Quark subprocess	short distance $\sim 1/Q$
Quark distribution in nucleon (PDF)	long distance $\sim 1/\mu_{\text{had}}$

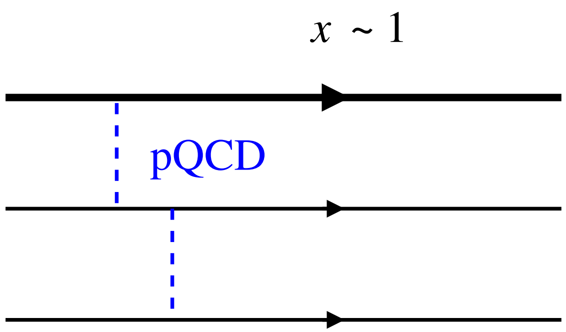
Properties of quark distributions

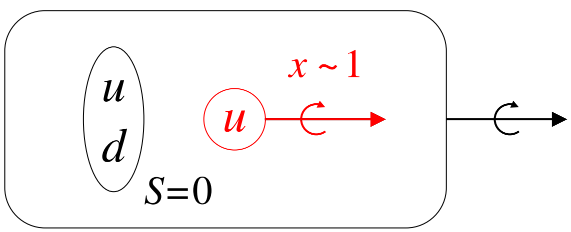
$$\langle p|\, \bar\psi(0)\,\gamma_\mu\,\psi(z)\,|p\rangle_{z^2=0}$$
$$= \bar u \gamma_\mu u \int_0^1 dx \left[e^{-ix(pz)}\, q(x) - e^{ix(pz)}\, \bar q(x) \right]$$



- Formal: Nucleon matrix element of bilinear quark operator ("density")
  - Sum rules $\int dx\, [u - \bar u] = 2$ etc.
  - Moments $\int dx\, x^{n-1}$ related to local twist–2 operators $\rightarrow$ lattice
- Space–time interpretation: Density of quarks with longitudinal momentum fraction x in wave function of fast–moving nucleon ($P \gg \mu_{\mathrm{had}}$)

$x \to 1$: Theoretical ideas





- PDF at $x \to 1$ dominated by qqq component of nucleon wave function

- Spectator quarks far off–shell $k^2 \gg \mu^2_{\text{had}}$
  $\to$ perturbative QCD interaction
  [Brodsky, Farrar 75]

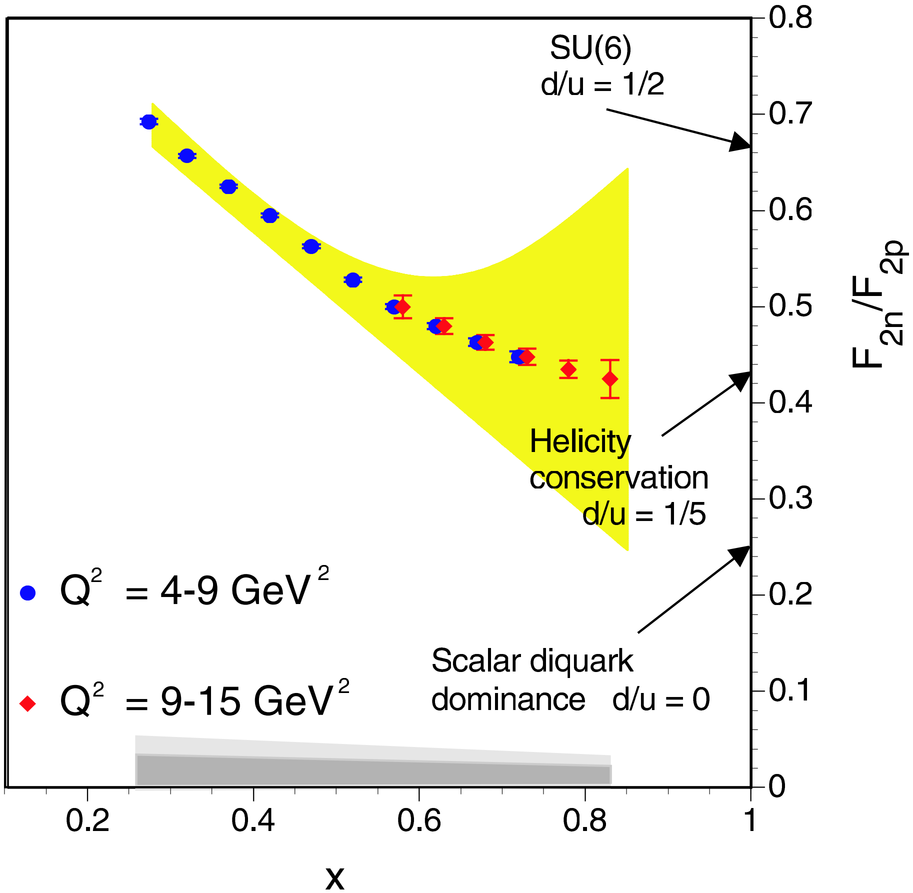
- Nucleon helicity carried by $x \sim 1$ quark

  $\to$ d/u ratio

  $\to$ spin asymmetry

> $x \to 1$ probes properties of "extreme" qqq configurations in nucleon

$x \to 1$: d/u ratio in proton

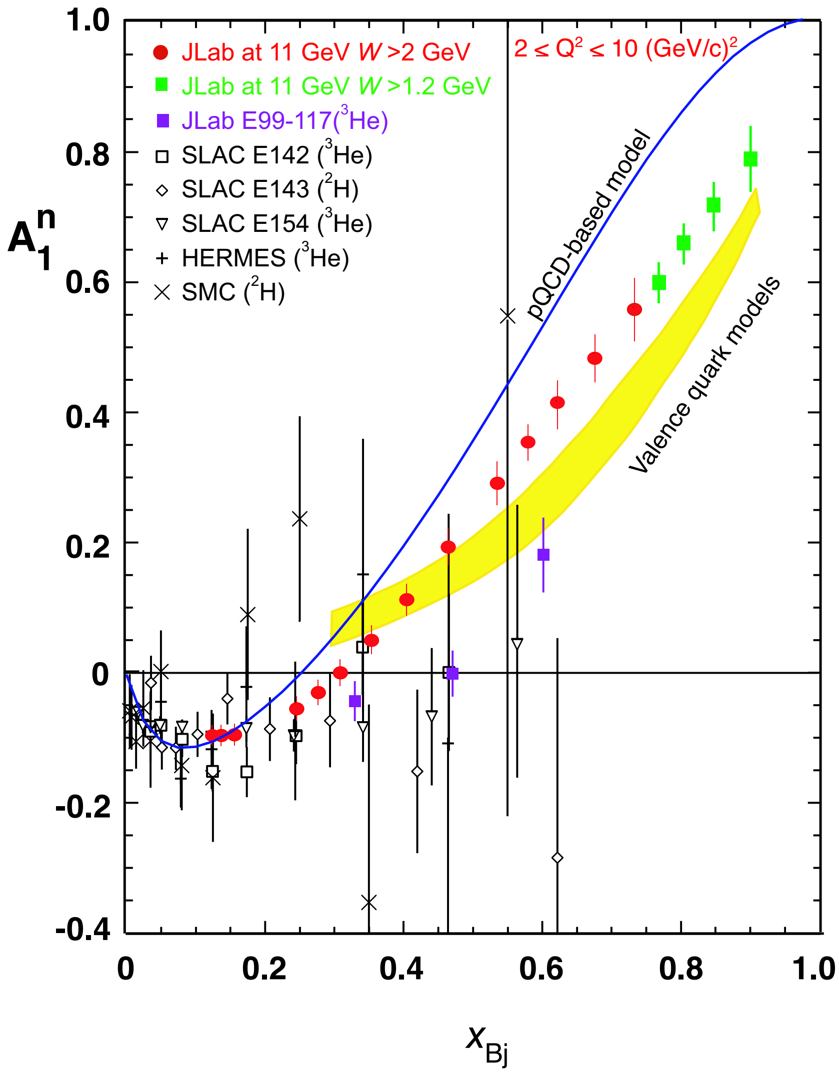


Neutron accessed through
^{2}H target + spectator tagging
(alt: ^{3}H/^{3}He ratio)

- pQCD + SU(6) spin/flavor
  $d(x)/u(x) \to 1/5$ for $x \to 1$
- Observable $F_{2p}(x)/F_{2n}(x)$
  $\to$ need to measure neutron
- Important for QCD processes
  at pp colliders (W^+/W^- at LHC)

$x \to 1$ region can be probed for the first time with JLab 12 GeV

$x \to 1$: Polarization



JLab 12 GeV projected data

- pQCD predicts nucleon helicity carried by $x \to 1$ quark

$$A_1 = \frac{\sum_a e_a^2 \, \Delta q_a(x)}{\sum_a e_a^2 \, q_a(x)} \to 1$$

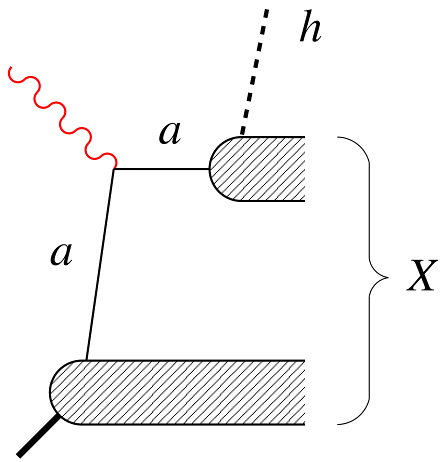
Other ideas: Non–perturbative dynamics

- Observed for proton . . . neutron?

- Deviations related to orbital angular momentum ($\leftrightarrow$ high–t formfactors)

> $x \to 1$ probes “extreme” qqq configurations in nucleon

Spin: Semi–inclusive DIS



Fragmentation function $D_a^h(z)$

- Probability for quark a to decay into hadron h (mom. fraction z) $+$ unspecified rest

- Measured independently in $e^+e^- \to h + X$

- Inclusive DIS alone cannot separate $u, \bar{u}, d, \bar{d}, s, \bar{s}$

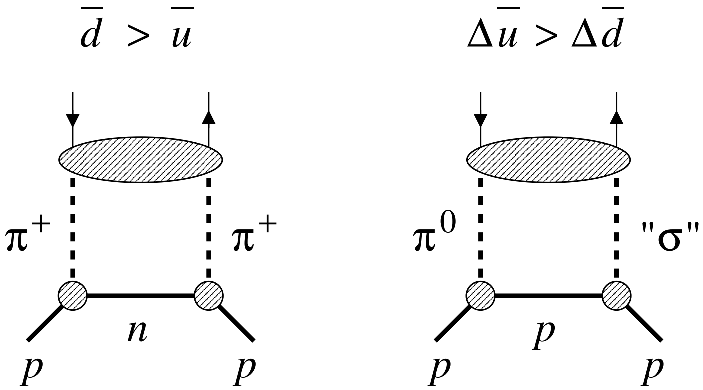
- Semi–inclusive DIS can tag charge/flavor of "active" quark

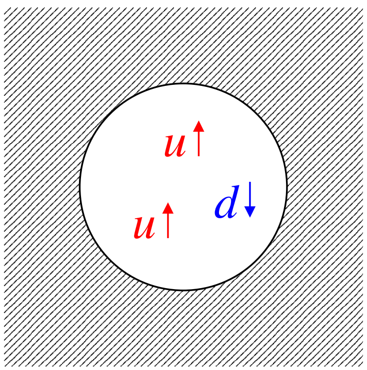
$$A_1^h = \frac{\sum_a e_a^2 \, \Delta q_a(x) \, D_a^h(z)}{\sum_a e_a^2 \, q_a(x) \, D_a^h(z)}$$

$$D_u^{\pi+} \neq D_{\bar{u}}^{\pi+}, \;\; D_s^{K+} \neq D_d^{K+} \quad \text{etc.}$$

Possible to measure antiquark polarization $\Delta\bar{u}, \; \Delta\bar{d}, \Delta\bar{s}$

Spin: Theoretical ideas about $\Delta\bar{u} - \Delta\bar{d}$





Strong evidence for large $\Delta\bar{u} - \Delta\bar{d} > 0$

- Antiquarks not flavor symmetric $\bar{d} > \bar{u}$ [NMC, Fermilab E866]
  - Non-perturbative origin
  - Polarization?
- Pion cloud model

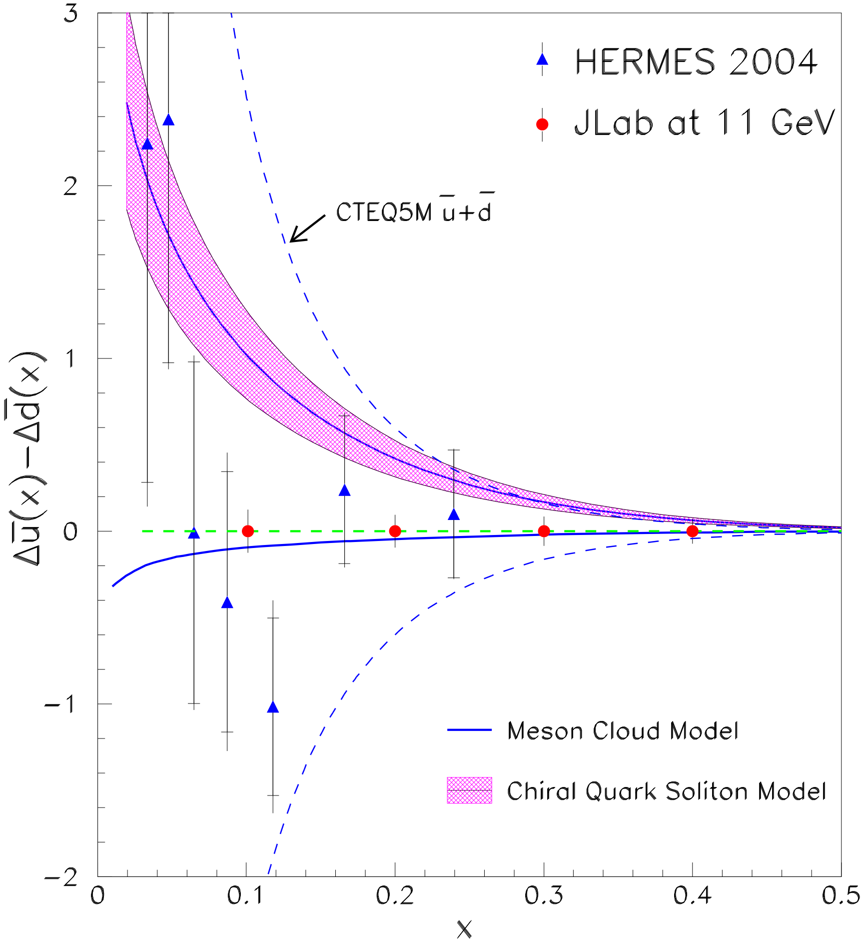
  $\bar{d} > \bar{u}$ from virtual π^+

  $\Delta\bar{u} > \Delta\bar{d}$ from π–σ interference
- Quark–based models: "Pauli blocking"

  $u\uparrow, d\downarrow$ reduce $\bar{u}\downarrow, \bar{d}\uparrow$ in sea
- Consistent description: Chiral quark–soliton model (based on large–N_c limit of QCD)

  [Thomas 83, Diakonov et al. 96]

Spin: $\Delta\bar{u} - \Delta\bar{d}$ from semi–inclusive DIS



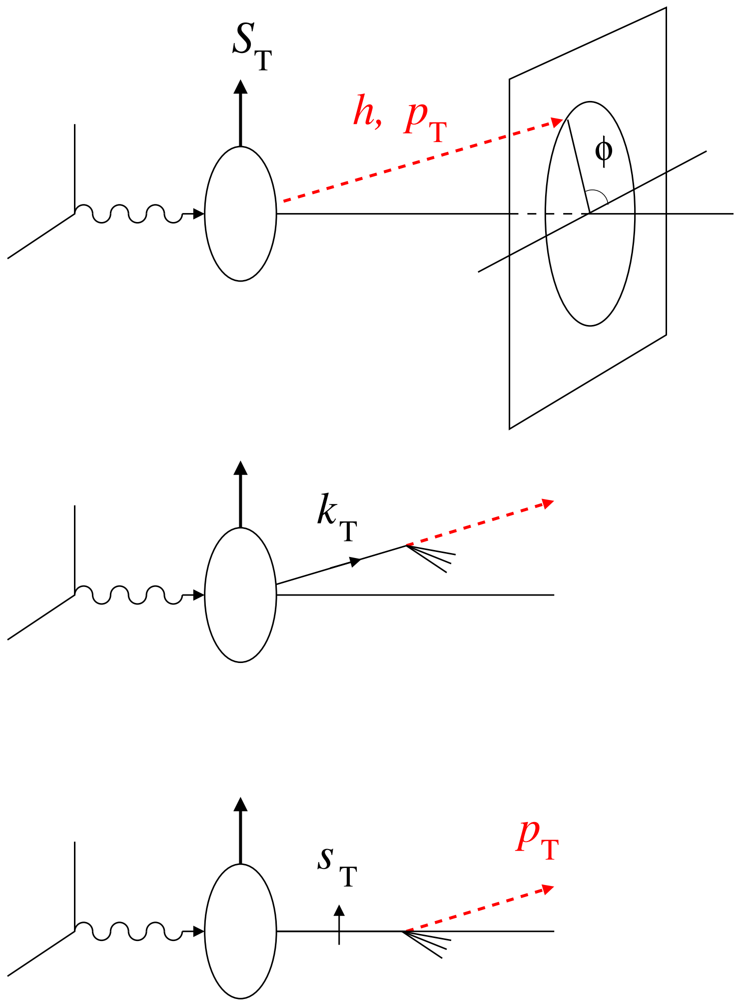
JLab 12 GeV projected data

- Semi–inclusive DIS with JLab 12 GeV will test model predictions for $\Delta\bar{u} - \Delta\bar{d}$

- Can also be measured in $\vec{p}p \to W^{\pm} + X$ at RHIC

Probe non-perturbative dynamics governing sea quark spin and flavor structure

Spin: Quark spin–orbit correlations



- Spin–orbit interactions produce azimuthal asymmetry in semi-inclusive DIS $\gamma^* N(\uparrow) \ \rightarrow \ h + X$

- Dynamical mechanisms in QCD
  - Sivers: Distortion of quark transverse momentum distribution in target

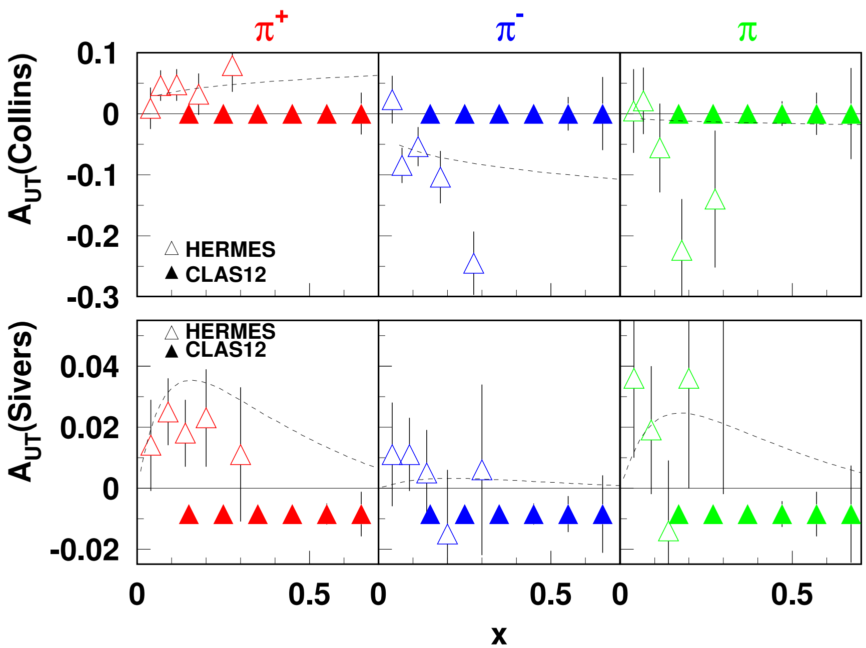
    Asym $\sim \ h_a(x, \boldsymbol{k}_T) \ D_a^h(z)$

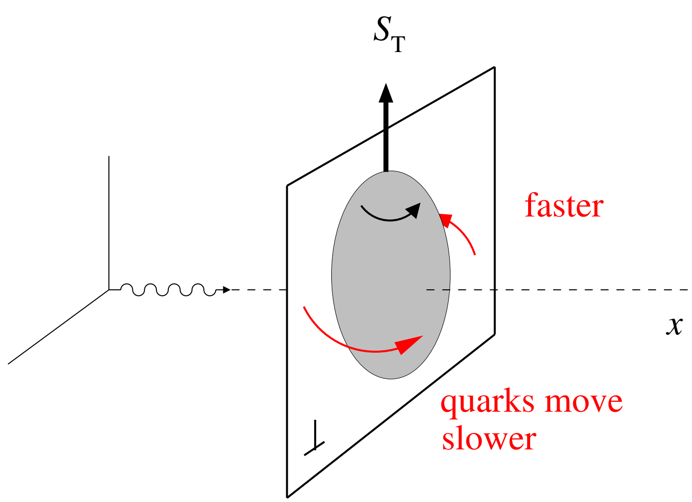
  - Collins: Effect of quark transverse spin on fragmentation process

    Asym $\sim \ h_{T,a}(x) \ H_a(z, \boldsymbol{p}_T)$

- Theory more challenging than inclusive DIS (QCD factorization, modeling)

Spin: Quark spin–orbit correlations





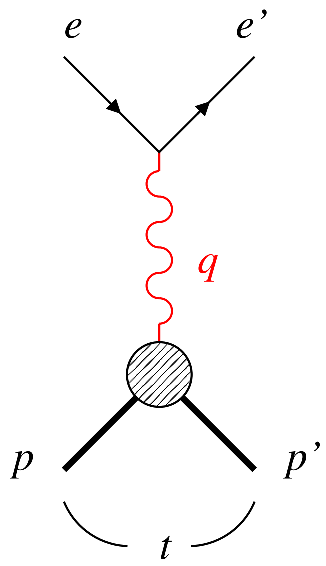
- Sivers/Collins mechanism can be separated experimentally

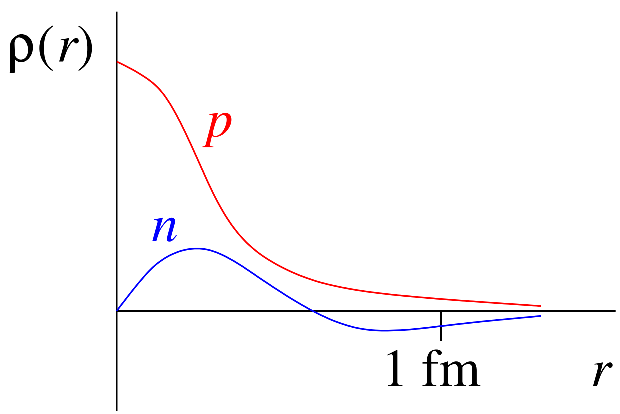
- Physics of Sivers effect
  - Dragging effect on quarks? [Burkardt 03]
  - Final–state interaction with spectator system? [Brodsky et al. 02]

- Analogous effects in $pp(\uparrow) \to h + X$ [RHIC Spin]

Probe spin–orbit interactions in QCD

Spatial: Form factors





- Elastic form factors

$$\langle p'|J_\mu|p\rangle \;=\; \bar{u}\gamma_\mu u\, F_1(t) \;+\; \bar{u}\sigma_{\mu\nu}q^\nu u\, \frac{F_2(t)}{M}$$

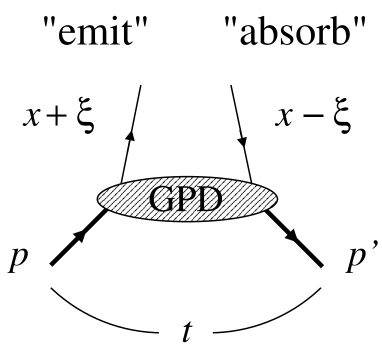
$t \equiv q^2 < 0$ invariant momentum transfer

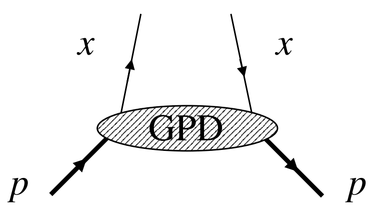
- Spatial interpretation: Charge/current distribution in Breit frame $q^\mu = (0, \boldsymbol{q})$

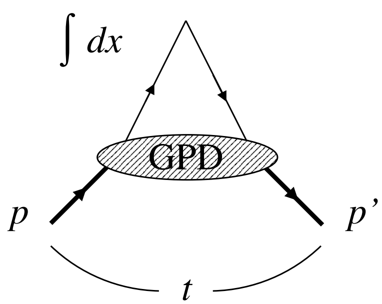
$$F_1(-\boldsymbol{q}^2) \;=\; \int d^3r\, e^{-i(\boldsymbol{q}\boldsymbol{r})}\, \rho(r)$$

Can we extend this to quark parton densities?

Spatial: Generalized parton distributions







- GPD = Amplitude for nucleon to emit/absorb quark with different longitudinal/transverse momentum

$$H(x, \xi; t) \quad \longleftrightarrow \quad \langle p' | \, \bar{\psi}(0) \, \gamma_\mu \, \psi(z) \, | p \rangle_{z^2 = 0}$$

- Unifies elastic formfactor and quark parton density

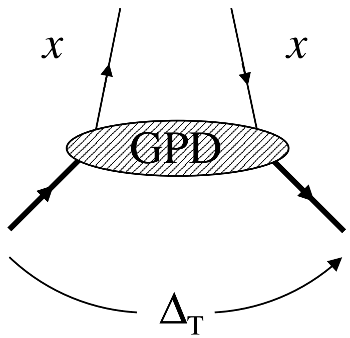
$$H(x, \, \xi = 0; \, t = 0) \quad = \quad q(x)$$

$$\int dx \; H(x, \, \xi; \, t) \quad = \quad F_1(t)$$

- Describes correlation of x and t dependence

[D. Müller et al. 94, Ji 96, Radyushkin 96]

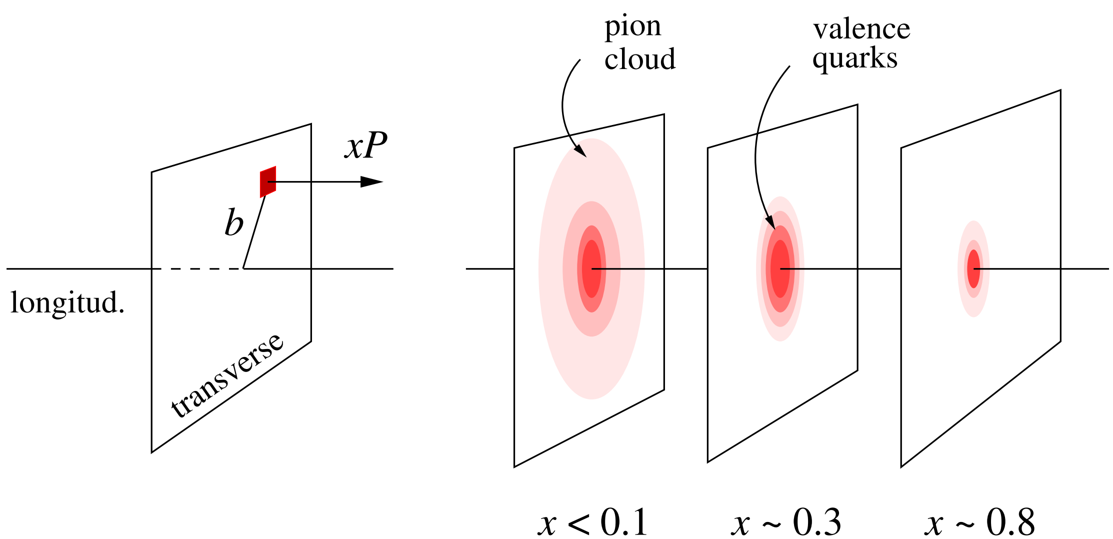
Spatial: Coordinate representation of GPD



- Transverse coordinate representation ($\xi = 0$)

$$H(x, t = -\boldsymbol{\Delta}_T^2) \;=\; \int d^2b\, e^{-i(\boldsymbol{\Delta}_T \boldsymbol{b})}\, q(x, b)$$

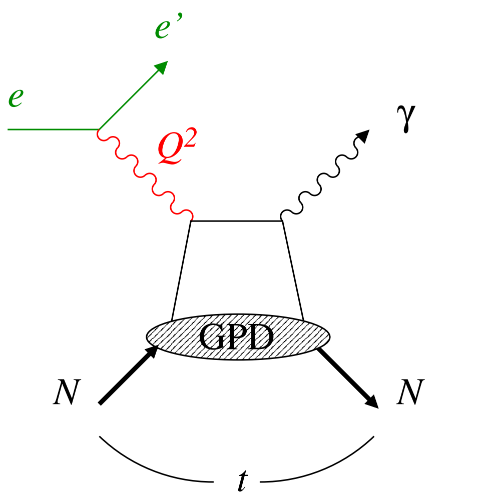
- $q(x, b)$ transverse spatial distribution of quarks with longitudinal momentum fraction x



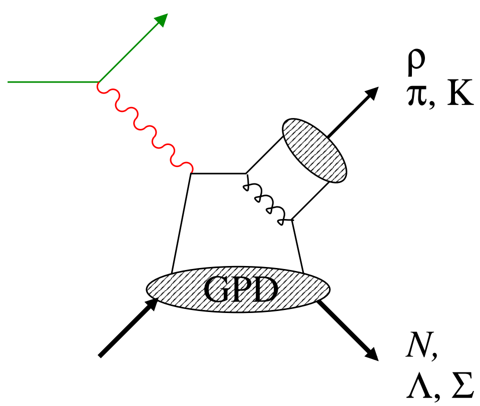
- Tomographic quark images of nucleon at fixed x
  [Burkardt 02, Diehl 03]

Quark imaging of nucleon through GPDs

Spatial: Probing GPDs in exclusive processes



Deep–virtual Compton scattering



Deep–virtual meson production

- "Bulk" information on GPDs from parton density/form factor data

- Space–momentum correlations from high–Q^2 exclusive processes

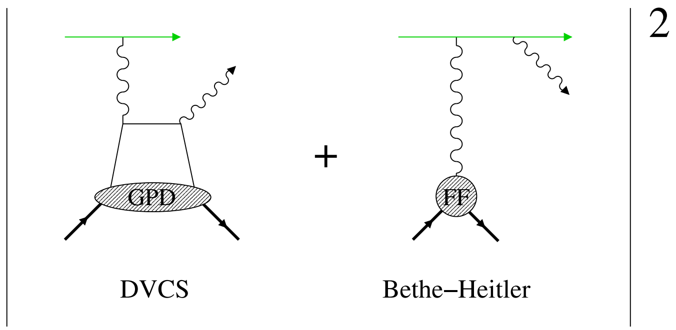
  $Q^2 > 1\text{–}2\,\text{GeV}^2$ DVCS

  $Q^2 > 10\,\text{GeV}^2$ DVMP

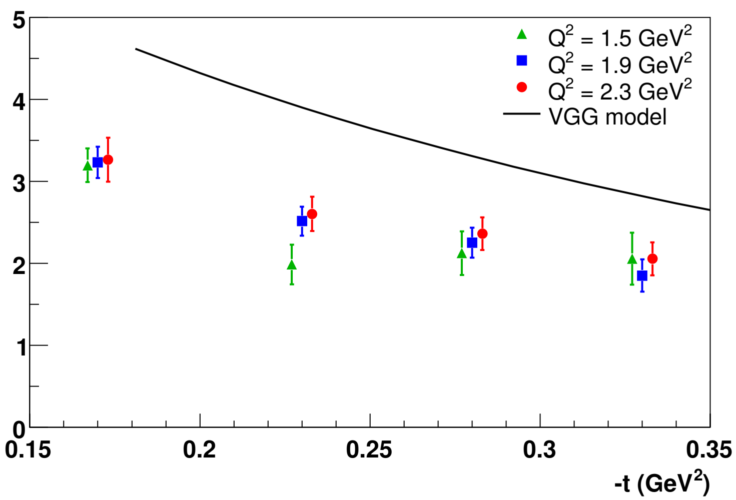
- QCD factorization (cf. inclusive DIS) GPDs universal, process–independent

  [Ji 96; Radyushkin 96; Collins, Frankfurt, Strikman 96; . . .]

Spatial: Deeply–virtual Compton scattering



DVCS–BH interference cross section



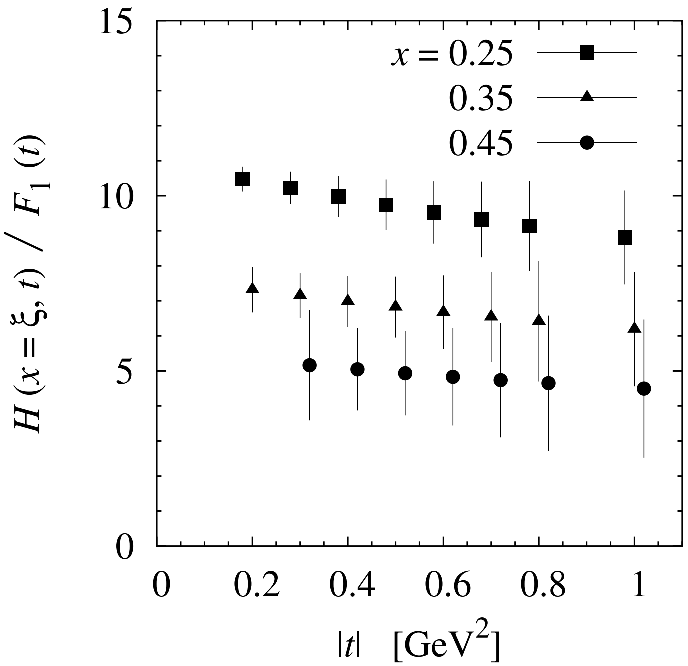
[JLab Hall A 06]

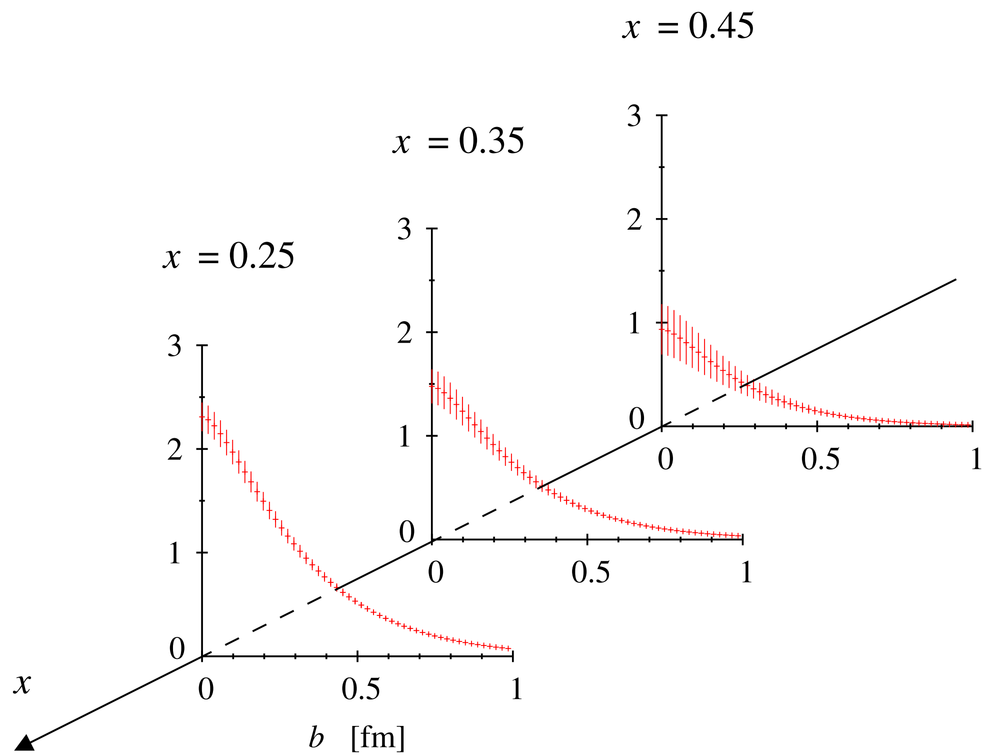
- DVCS interferes with known Bethe–Heitler process
  - "Amplifier"
  - GPDs probed at amplitude level, many external handles

- First measurement of DVCS–BH interference cross sections indicate early approach to scaling/factorization

Spatial: DVCS at 12 GeV

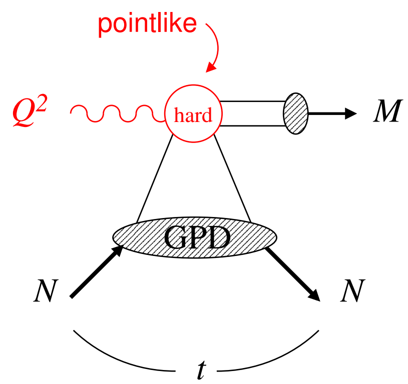
- Dirac GPD $H(x = \xi; t)$ and "quark image" of nucleon from DVCS beam spin asymmetry measurements with CLAS12



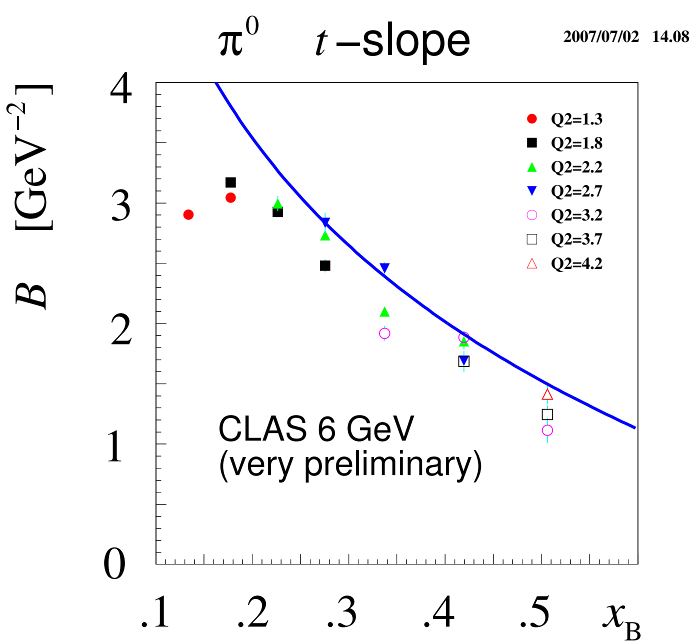


To appear in GPD White Paper (H. Abramowicz et al.) 07

Spatial: Deeply virtual meson production



- Model–independent tests of approach to factorization regime



- Example: t–slope of cross section becomes independent of Q^2 (probe "pointlike")

  . . . Can be studied already with 6 GeV data!

12 GeV Proposal PR12–06–108

Summary: Nucleon structure in QCD

- Importance of QCD factorization
  - Rigorous conceptual/calculational framework
  - PDFs, GPDs universal process–independent characteristics
  - Connection with lattice QCD/other non–pert. methods
  - Need high Q^2 and W available with 12 GeV

- Same concepts apply to
  - ep colliders: "Small x physics," QCD at high energies, . . .
    HERA, EIC
  - $pp/\bar{p}p$ with hard processes: High–p_T, $W^{\pm}$ production, Higgs, . . .
    RHIC, Tevatron, LHC

QCD in nuclear physics

- Short–range correlations

  Probe local high–density configurations
  in nuclei and their quark structure

  "Superfast" quarks $x > 1$, . . .

- Color transparency

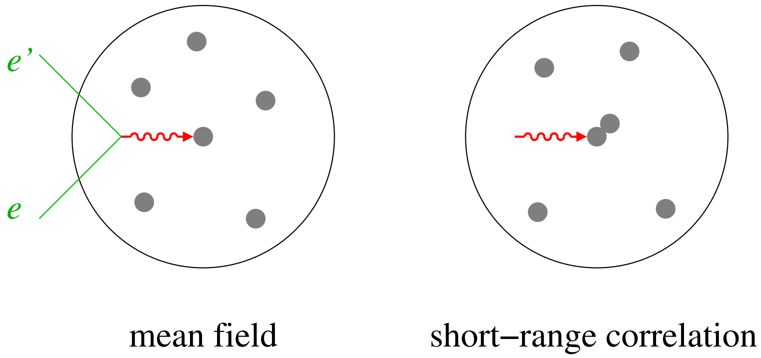
  Study interaction of small–size color singlet
  configurations with nuclear matter

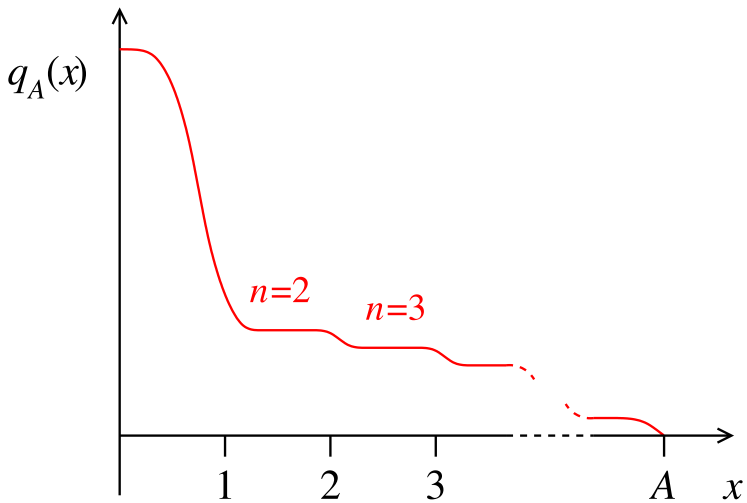
  High–Q^2 knockout $(e, e'p)$, meson production, . . .

- Open color

  Study quark propagation and hadronization
  in the nuclear environment

Short–range correlations: $x > 1$





- Average configurations:
  Mean field $\lambda_{\text{free}} \gg R_{NN}$

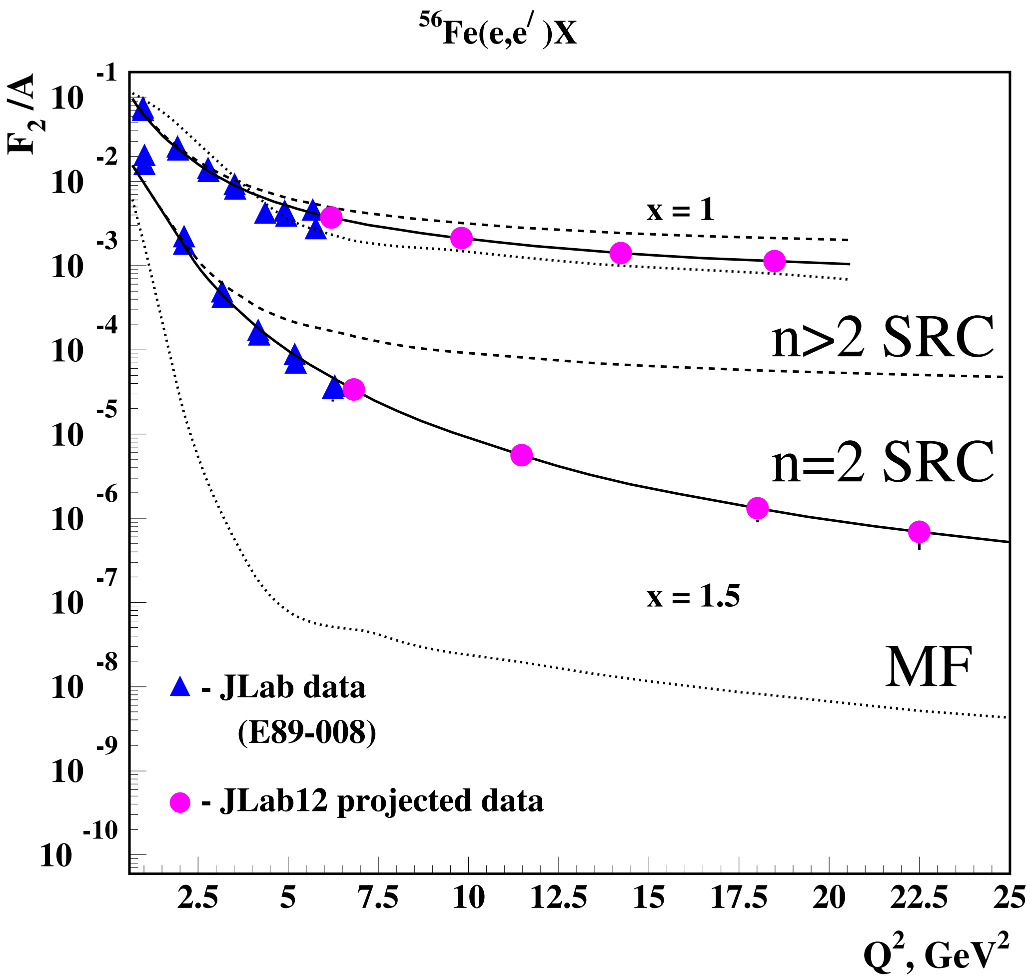
- Rare high–density configurations:
  Short–range correlations

- Can be probed in nuclear DIS
  at $x > 1$ ("superfast quarks")

  $\rightarrow$ Properties of superdense matter (neutron stars)

  $\rightarrow$ Quark structure of short–range NN interaction

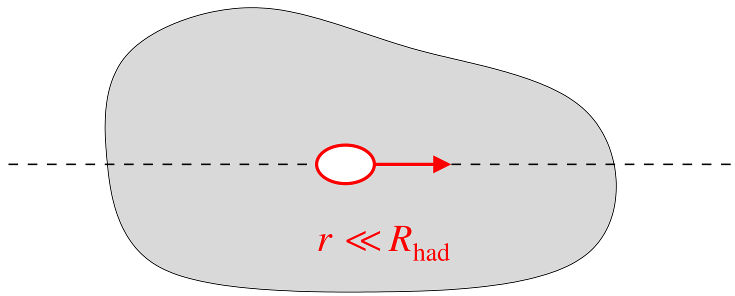
Short–range correlations: Experiments



- Can be studied with Q^2, W available at 12 GeV
- Requires high luminosity $L \sim 10^{37}\text{cm}^{-2}\text{s}^{-1}$

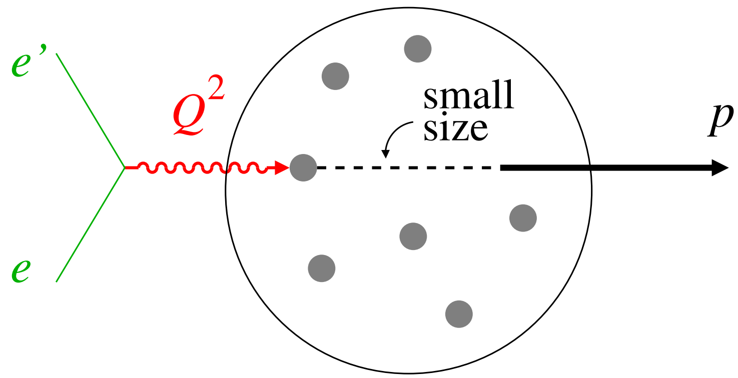
Direct probe of SRCs
& their quark/gluon structure

Color transparency: Idea



- Color singlet configurations $(\bar{q}q, qqq)$ of small size $r \ll R_{\mathrm{had}}$ interact weakly with hadronic matter

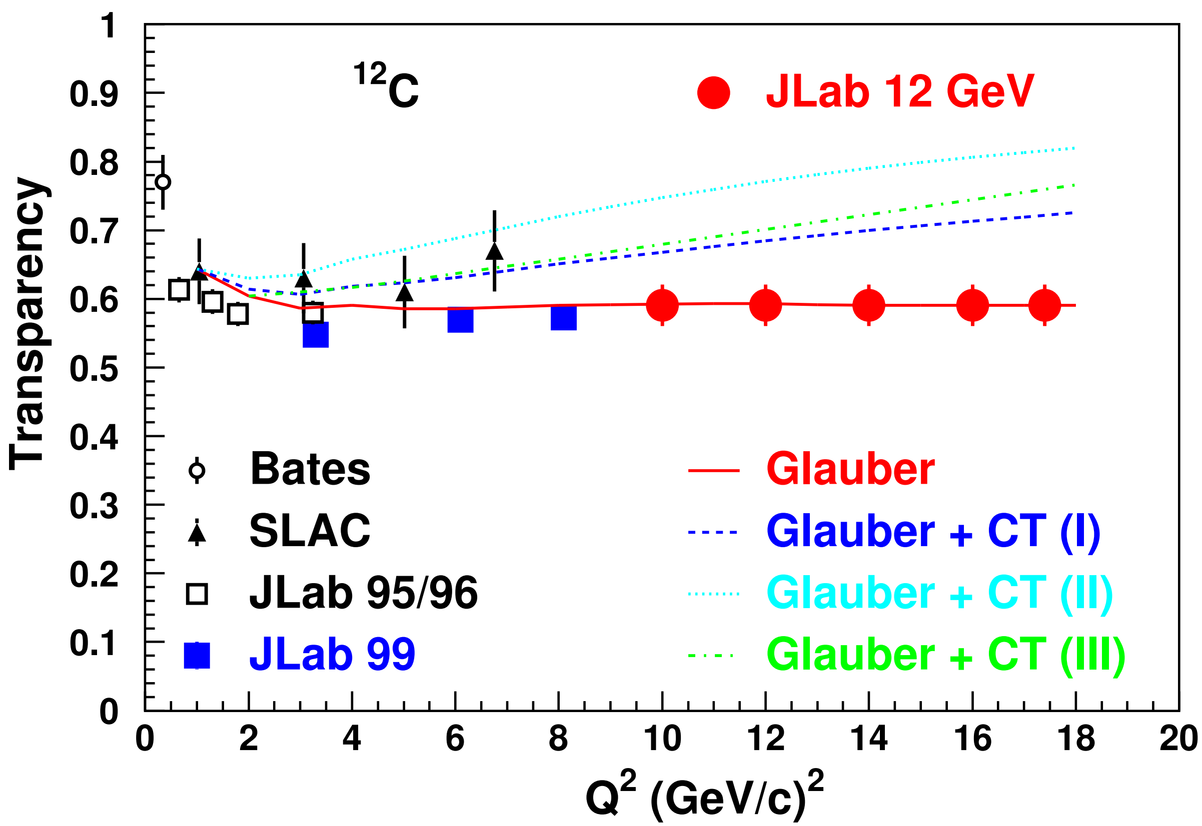
  . . . Fundamental property of QCD
  as gauge theory!



- High–Q^2 elastic scattering produces proton in small–size configuration

- Probe color transparency in high–Q^2 knockout $(e, e'p)$

Color transparency: $(e, e'p)$ data



Color transparency:
Manifestation of
QCD dynamics
in nuclear physics

- Can be studied with Q^2 available at 12 GeV
- Other CT experiments: π, ρ production

Future opportunities at JLab

- Postdocs/Students at JLab

  ~ 1200 active users (national/international)

  > 100 students presently working on thesis,
  $\sim 1/3$ of U.S. PhDs in nuclear physics JLab–related

  ~ 80 postdocs (university/joint/lab positions)

- Opportunities for young researchers
  - 12 GeV construction to start 2009
  - Special Program Advisory Committee (PAC) accepting 12 GeV experimental proposals
  - Theory (QCD, nucleon/nuclear structure, phenomenology, lattice)

For more information visit `www.jlab.org`
Contact user groups at universities or JLab Hall leaders/Theory

Summary

- Jefferson Lab essential facility for both
  - QCD/hadron structure
  - Nuclear physics

- 12 GeV Upgrade will enable unique physics program

  Combination energy — luminosity — detectors

- Great opportunities for young researchers!

References

- General summary of JLab 12 GeV science program:

  "Conceptual Design Report for the Science and Experimental Equipment for the 12 GeV Upgrade," presented to the DOE 12 GeV Science Review, April 6–8, 2005.

  http://www.jlab.org/div_dept/physics_division/GeV/doe_review/CDR_for_Science_Review.pdf

- GPDs and quark imaging:

  H. Abramowicz et al., "Exploring the 3D quark and gluon structure of the proton: Electron scattering with present and future facilities," White Paper prepared for the National Science Advisory Committee Long–Range Plan (2007).

  http://www.jlab.org/~weiss/gpd_white_paper/gpdwp.pdf

- Nuclear physics program:

  M. Sargsian et al., "Hadrons in the nuclear medium," J. Phys. G **29**, R1 (2003) [arXiv:nucl-th/0210025].

  http://www.slac.stanford.edu/spires/find/hep/www?eprint=nucl-th/0210025

References to original research publications can be found in these articles