Exploring nucleon structure with GPDs

C. Weiss (JLab), Hall A Collaboration Meeting, 14–Dec–11

Goals

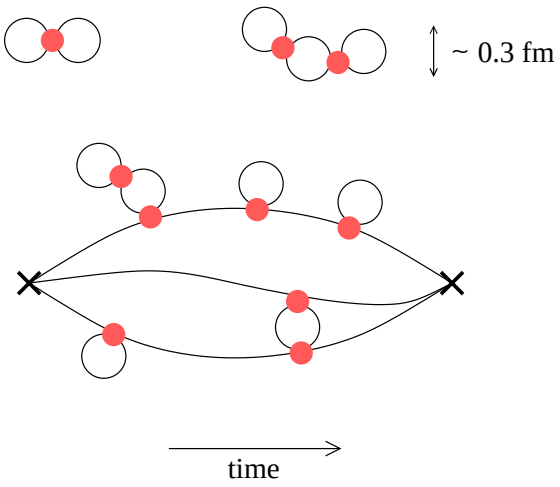
Focus on dynamical system, not formal descriptors

Develop specific examples data → GPDs → structure

Cover JLab12 and "beyond" from unifying perspective

- Nucleon structure in QCD
  - Why parton picture
  - Many–body system cf. Condensed matter
  - Exclusive processes and GPDs
- 3D quark/gluon imaging
  - Gluon imaging with $J/\psi, \phi$
    HERA, COMPASS, JLab12, EIC
  - Valence quark transverse densities → Talk K. DeJager
  - Longitudinal response, $q\bar{q}$ correlations in DVCS
    JLab12, COMPASS, EIC
- Static nucleon properties Brief!
  - EM tensor: Forces, quark/gluon angular momentum
    Lattice QCD, models → INT Workshop 6-17 Feb 12
- GPDs in pp and multiparton processes New field!

Nucleon structure: Parton picture



- QCD vacuum not empty

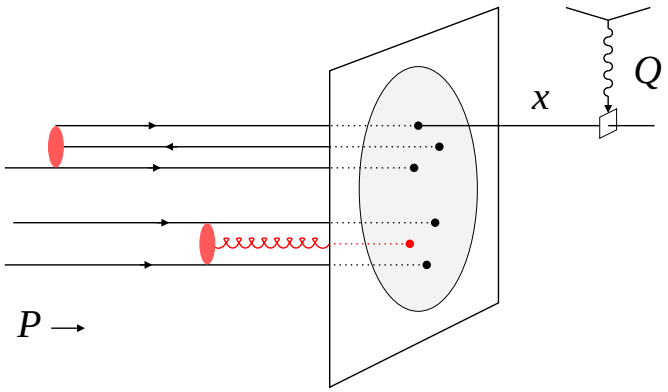
  Strong non-perturbative gluon fields
  of size $\ll 1\,\mathrm{fm}$ Lattice QCD, analytic models

  Chiral symmetry breaking: $\bar{q}q$ pair condensate,
  π as collective excitation

- Nucleon at rest

  $\langle N|O|N\rangle$ from Euclidean correlation functns

  No concept of particle content!
  Cannot separate "constituents" from vacuum fluctuations



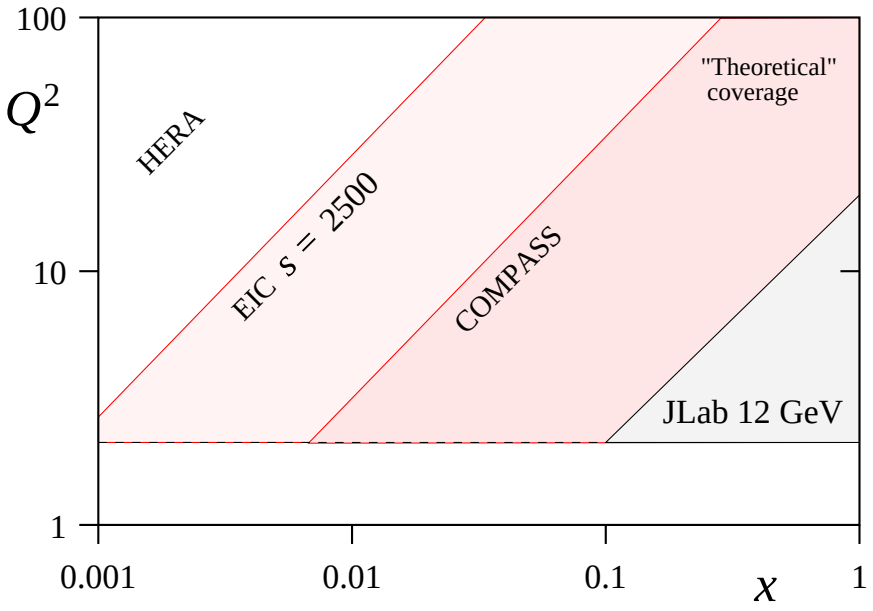
- Fast–moving nucleon $P \gg \mu_{\mathrm{vac}}$

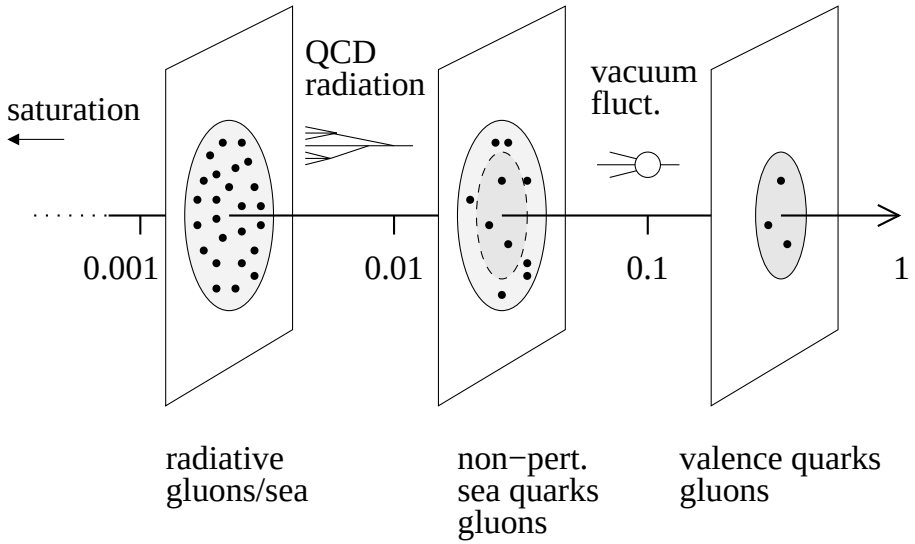
  Closed system: Wave function description
  Gribov, Feynman

  Components with different particle number,
  characterized by x_i, $\boldsymbol{k}_{Ti}$

  Deep–inelastic process:
  "Snapshot" with resolution $1/Q$
  pQCD radiation: Q^2 dependence

Nucleon structure: Landscape





- Nucleon many–body system

  Different components of wave function, effective dynamics

  "Face" changes with excitation energy and resolution scale!

- Physical properties

  Parton densities: Spin, flavor — PDFs

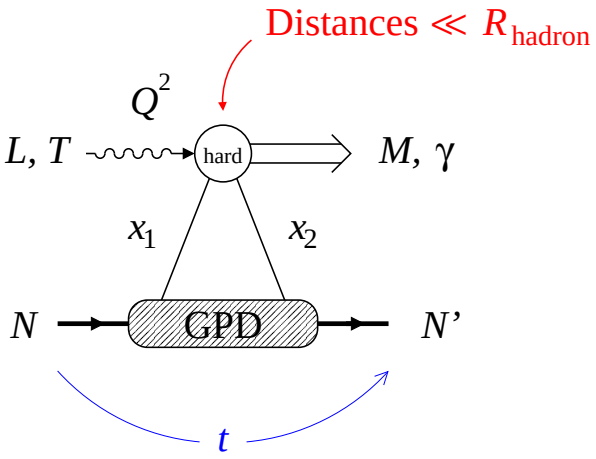
  Transverse spatial distributions — GPDs, FFs

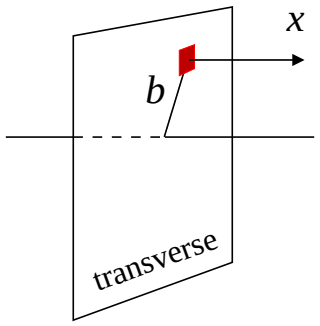
  Orbital motion: k_T dependence, angular momentum — TMDs, GPDs → Talk A. Prokudin

  Correlations: Transverse, longitudinal — GPDs, multiparton dist. higher twist

  $+ Q^2$ dependence

Nucleon structure: Exclusive processes and GPDs





- Exclusive processes at $Q^2 \gg$ hadronic scale

  Reaction takes place over distances $\ll R_{\rm hadron}$:
  Experimentally testable, quantifiable

  $Q^2 \to \infty$: QCD factorization theorem
  Collins, Frankfurt, Strikman 96; Ji 96, Radyushkin 96; Collins, Freund 98
  Finite–size corrections: Sudakov

  Target structure in GPDs: Universal, process–indep.

- Properties of GPDs

  $\langle N' | \bar{\psi} \ldots \psi | N \rangle$ QCD operator definition, twist–2
  Renormalization, non–perturbative methods

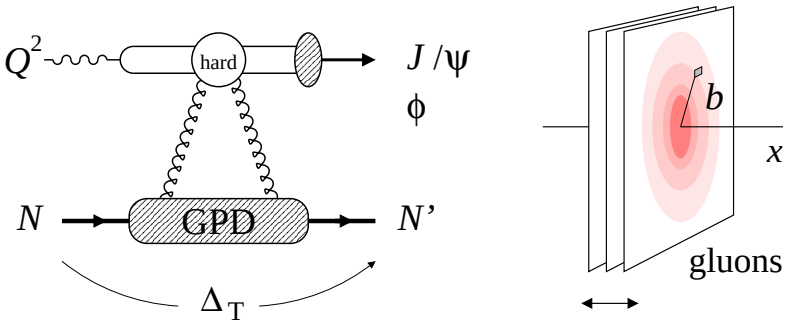
  Unify concepts of PDF and elastic form factors:
  Spatial quark/gluon imaging of nucleon

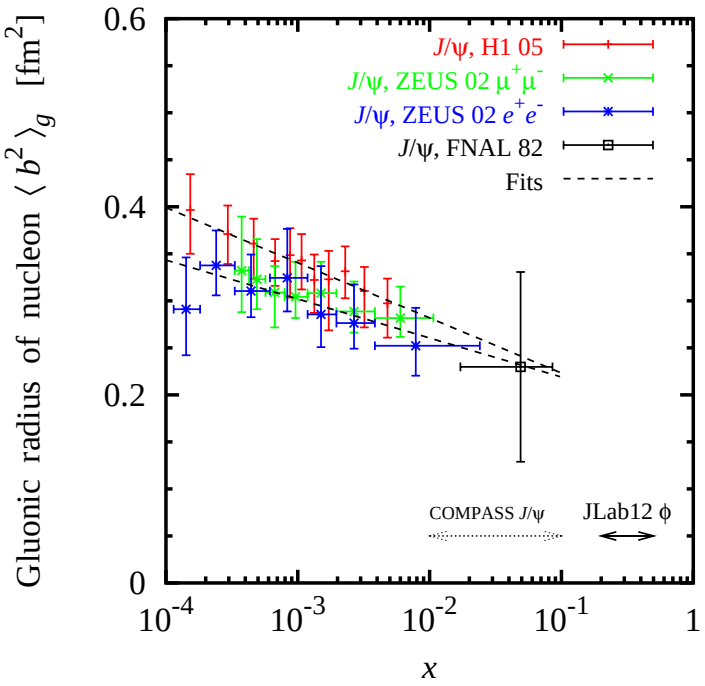
  $x_1 = x_2$: Transverse spatial distribution

  $x_1 \neq x_2$: Dynamical response, quark correlations
  Longit. momentum transfer $x_1 - x_2 = 2\xi \sim x_B$

  Moments are form factors of spin–n operators.
  $n = 2$ QCD EM tensor: Forces, $J_{q,g}$

Gluon imaging: Structure and probes





- What is the spatial distribution of gluons in the nucleon?

  Fundamental "gluonic size"

  Dynamical origin of non–perturb. glue?

  Input for small–x evolution, MC for pp@LHC
  Multiparton processes: Needed for Higgs/BSM signals

- Exclusive J/ψ and ϕ as clean probes

  Small–size regime established at HERA
  Universaily of t–slope above $Q^2 \sim 10\,\text{GeV}^2$

  Spatial distribution from relative t dep.

  GPD calc's describe absolute cross sections
  Frankfurt et al. 95; Goloskokov, Kroll 08+; Müller et al. 11

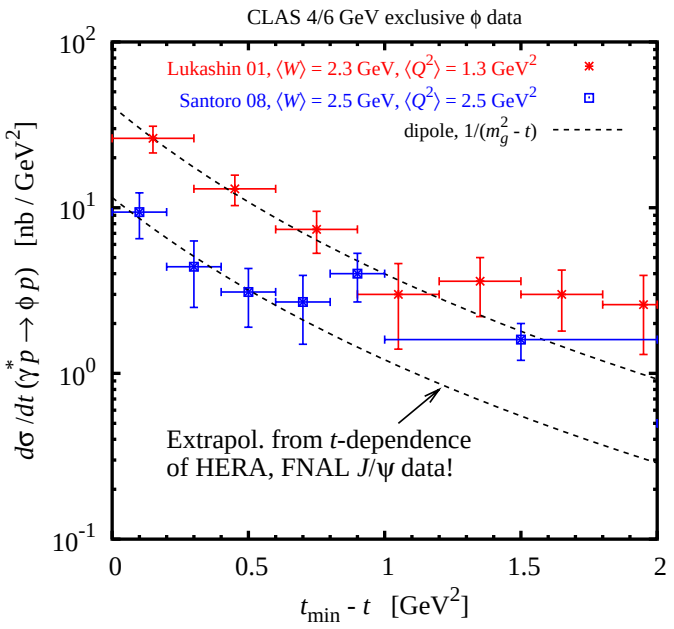
- Nucleon's gluonic size

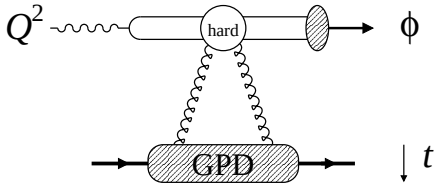
  $x < 0.01$ Average size $\langle b^2 \rangle_g$ from HERA

  $x \sim 0.01$ Data expected from COMPASS

  $x > 0.1$ Practically unknown: JLab12, EIC
  DIS: Lots of gluons above $x > 0.1$,
  carry $\sim 30\%$ of nucleon's momentum

Gluon imaging: ϕ at JLab12





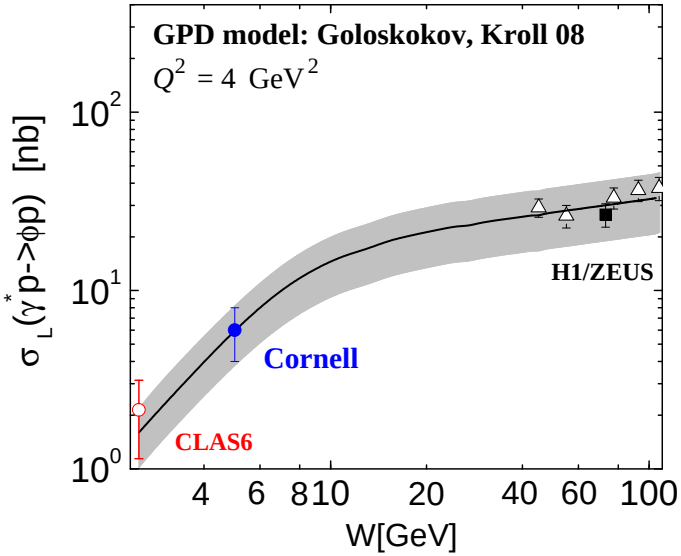
- Exclusive ϕ clean probe of gluon GPD even at JLab energies

  Relative t–dependence not sensitive to finite–size corrections

- Encouraging signs in 6 GeV data

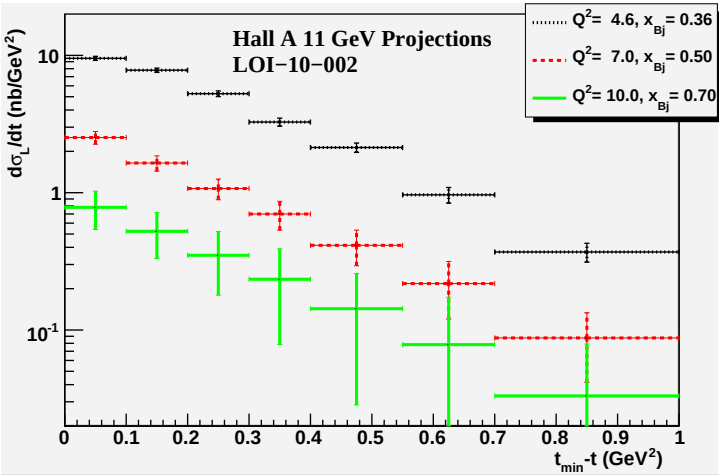
  t–dependence of 6 GeV ϕ data consistent with extrapolation of HERA, FNAL J/ψ results
  Universal "gluonic size" as function of x

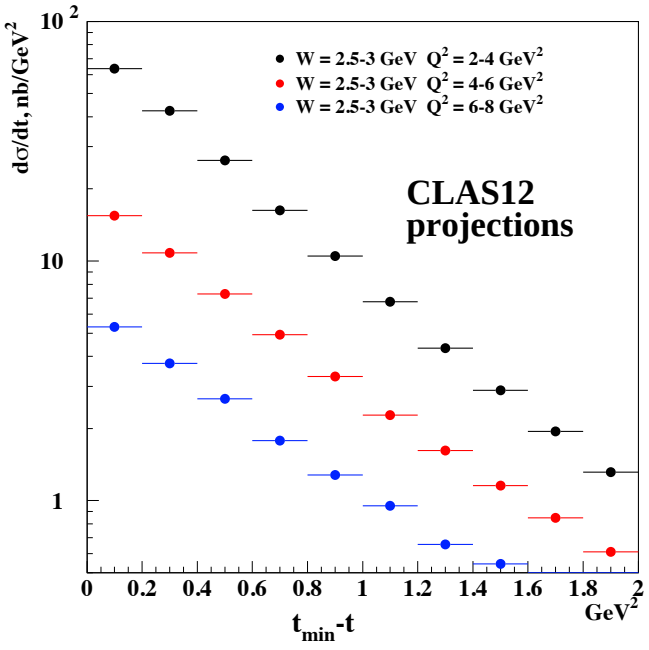
  GPD calculation with finite–size corrections describes absolute cross section
  Goloskokov, Kroll 08



- Prospect of gluon imaging with 12 GeV
  Hall A LOI-10-002 Fuchey et al., CLAS12 PR12-11-103 Stoler et al.

Gluon imaging: ϕ at JLab12





- Test reaction mechanism Use 12 GeV kinematic range!

  When does t–slope become independent of Q^2?

  How does W–dependence change with Q^2?

  L/T from s–channel helicity conservation

- Extract t–dependence of gluon GPD

  $x \sim 0.2 - 0.5$

- Needs more work

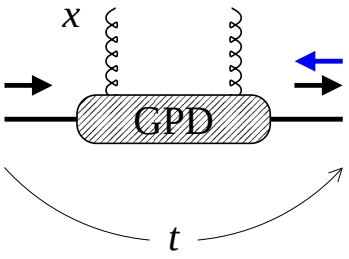
  Harden GPD description: $x_1 \neq x_2$, model dependence, Re/Im of amplitude, large $|t|$

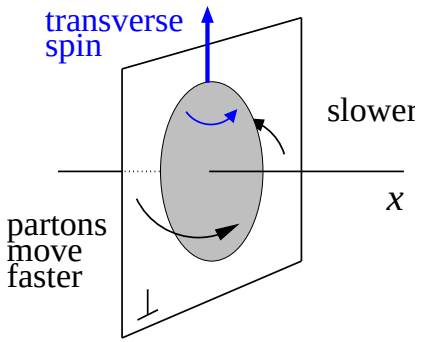
  Construct spatial images with controlled accuracy
  Technology exists, preliminary studies done. Miller INT report 11

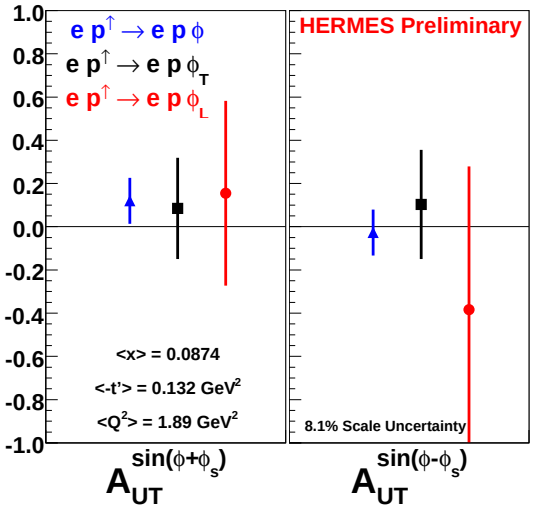
  Develop dynamical models of gluonic structure
  Constituent quarks? Correlations? "Next level" of understanding nucleon structure in QCD!

First gluonic images of nucleon at large x!

Gluon imaging: Transverse polarization







- Helicity–flip gluon GPD: Gluonic Pauli FF

  Distortion of gluons' spatial distribution by transverse spin of nucleon Burkardt 03

  Reveal coupling of non-perturbative gluon fields to valence quarks

- Exclusive ϕ transverse target asymmetry A_{UT}

  Constrains ratio E_g/H_g = Pauli/Dirac GPD

  HERMES 08 data, large errors see e.g. Gliske, Lorenzon 08

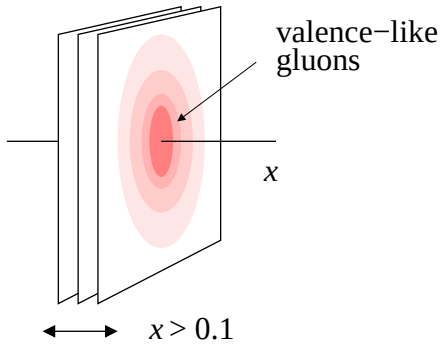
  Accurate measurement with JLab 12 Hall A?

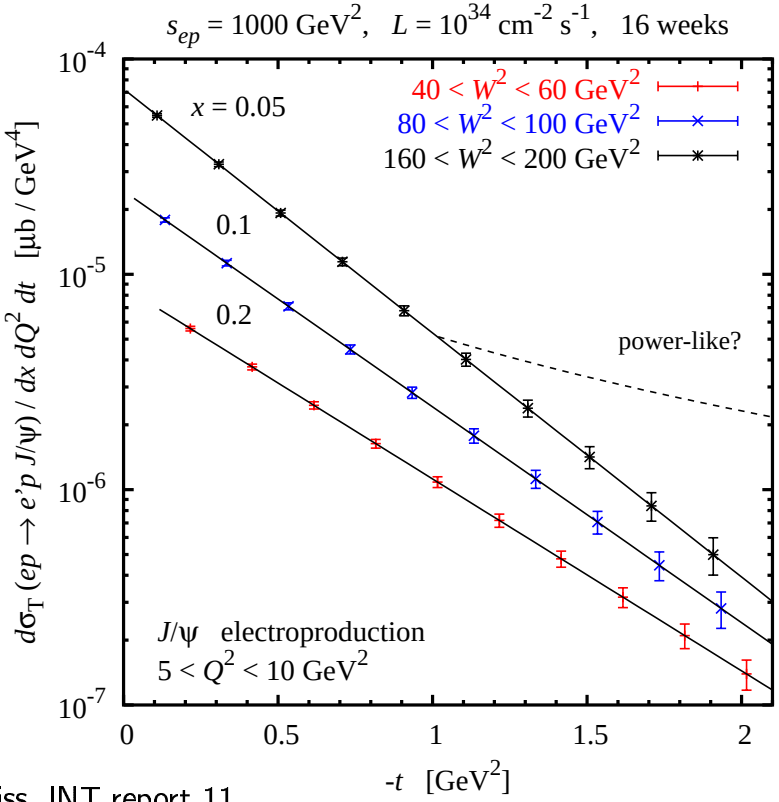
- Gluon spin through Ji sum rule Ji 96

  E_g contribution expected to be small, but should be measured!
  Positivity bounds: Diehl et al. 04; Goloskokov, Kroll 08

"Next step" after establishing GPD description

Gluon imaging: Large–x gluons with EIC





Weiss, INT report 11

- EIC: Precise gluon imaging through exclusive J/ψ and ϕ

  $x > 0.01$: Map unkown region of non-perturbative gluons!

  Full t–distribution $\rightarrow$ Fourier
  Non-exponential? Power–like at $|t| > 1\,\mathrm{GeV}^2$?

  Electroproduction with $Q^2 > 10\,\mathrm{GeV}^2$:
  Test of reaction mechanism, different channels

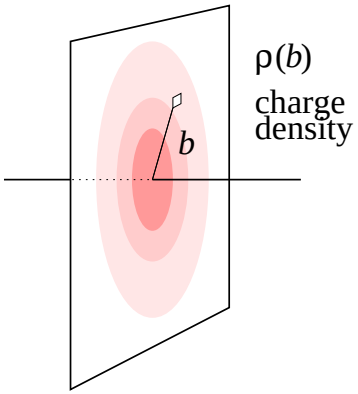
- Machine requirements

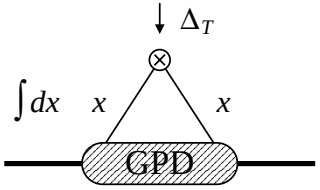
  Recoil detection for exclusivity, t–measurements

  Luminosity $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $x > 0.1$, electroproduction, high–t

Detailed gluonic image of nucleon at large x!

Quark imaging: Transverse charge densities





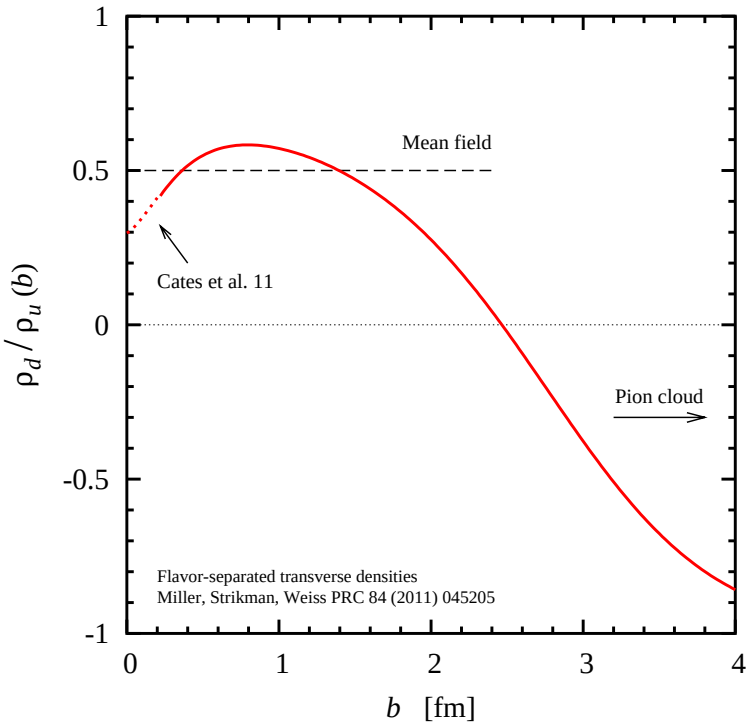
- What is the spatial distribution of valence quarks in the nucleon?

  Bound–state dynamics: Mean–field, pion cloud

  "Source" of other components

- Transverse charge/current densities
  Constrain x–integral of valence density

  $$\rho(b) = \sum_q e_q \int dx \; [q(x,b) - \bar{q}(x,b)]$$



- Flavor–separated densities Cates et al. 11

  Mean–field picture at $b \sim 0.3 - 2\,\mathrm{fm}$
  Pion cloud at $b > 2\,\mathrm{fm}$ Miller, Strikman, CW 11

- Connect GPDs and hadronic structure

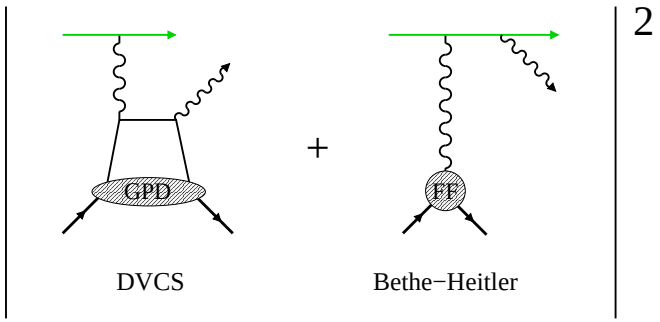
  Dispersion representation relates partonic structure to meson spectrum

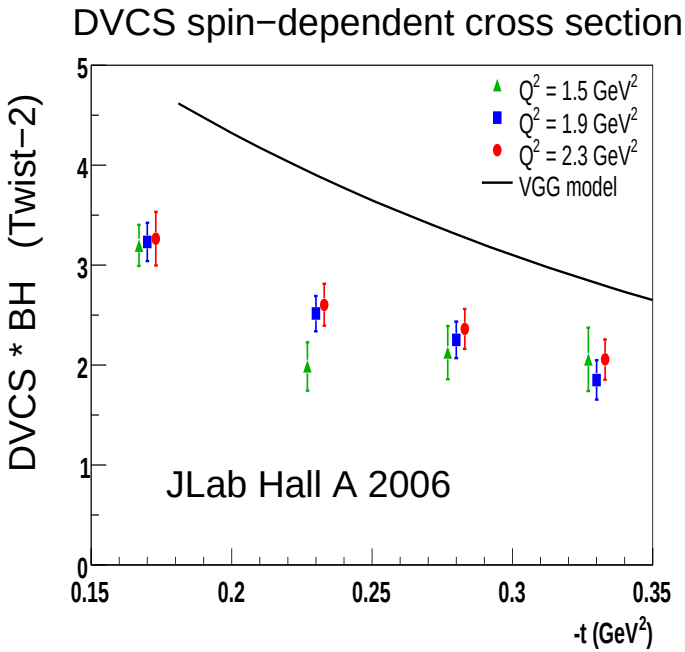
  χPT at $b \to \infty$ Strikman, CW 11

  $N \to N^*$ resonance transition densities
  Carlson, Vanderhaeghen 08; Lorce 09. N^* White Paper Mokeev et al.

  Large–N_c QCD, AdS/CFT Abidin, Carlson 08

Quark imaging: DVCS





- Interference BH–DVCS in $N(e, e'\gamma)N'$ gives access to DVCS at amplitude level

  Im DVCS $\vec{e} - \overleftarrow{e}$

  Re DVCS unpolarized, $e^+ - e^-$ Alt: timelike VCS

- Reaction mechanism

  Hard scattering process simple, $O(\alpha_S^0)$
  "Handbag" diagram"

  JLab Hall A 6 GeV cross section data show first hint of approach to Q^2 scaling

  More tests available with 12 GeV kinematics

- Extensive program with JLab 12 GeV

  Aim to separate Dirac/Pauli GPDs $H \leftrightarrow E$, etc. through polarization observables, neutron target

  Formalism for leading–twist analysis LO, NLO
  Belitsky, Müller, Kirchner 02; Müller et al. 04+

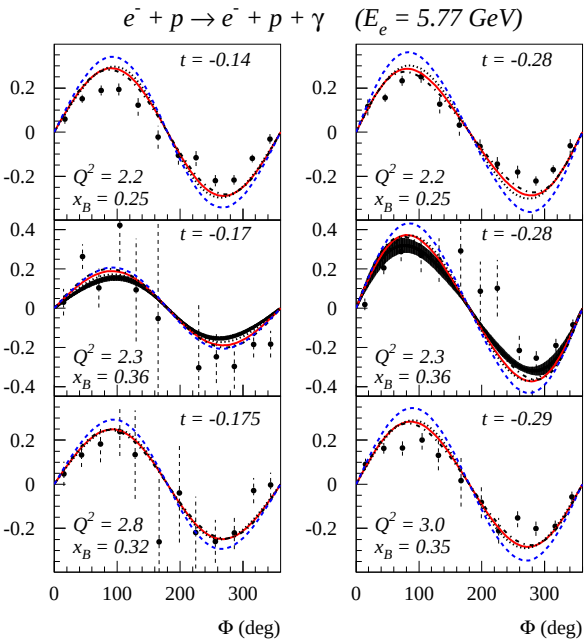
  Experimental focus on extraction of amplitudes: Raw material for GPD analysis
  Guidal 08+; Moutarde, Guidal 09+ → Talk Ch. Hyde

Quark imaging: DVCS analysis

$$\text{Im}\,\mathcal{H}(t) = \text{GPD}(x_1, 0; t) \qquad x_1 \sim x_B$$

$$\text{Re}\,\mathcal{H}(t) = \int dx_1 \frac{\text{GPD}(x_1, 0; t)}{x_1}$$

$$+ \quad D(t) \qquad \text{subtraction constant}$$



CLAS6 BSA explained by dispersion analysis
with Hall A cross secn. Vanderhaeghen, Polyakov 08

- Dispersion relations for DVCS amplitude
  Frankfurt, Strikman, Freund 97; Teryaev 05; Anikin, T. 07;
  Müller etal. 07; Diehl, Ivanov 07

  Follow from Lorentz invariance: "Polynomiality"

  Powerful constraint, limits accessible information

- Two possible approaches

  A) Use GPD models to relate

  $$\underset{\text{measurable}}{\text{GPD}(x, 0; t)} \longleftrightarrow \underset{\text{imaging}}{\text{GPD}(x, x; t)}$$

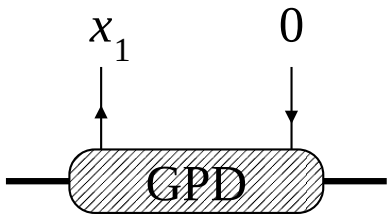
  B) Interpret accessible information directly in terms of partonic structure

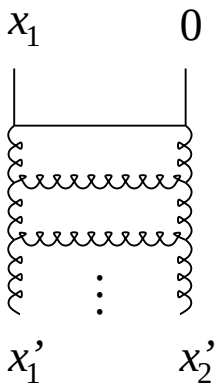
  $\text{GPD}(x_1, 0; t)$ nucleon response to stopping of fast quark

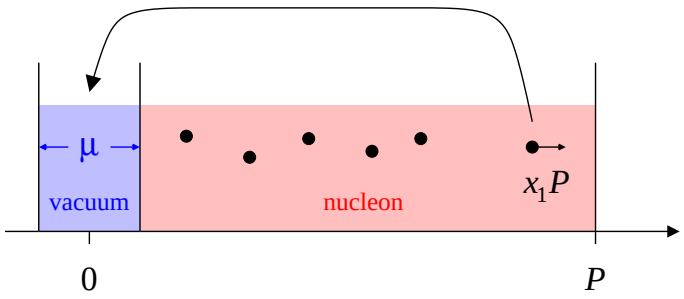
  $D(t)$ $q\bar{q}$ correlations in nucleon

Greatly reduced complexity!

Quark imaging: Longitudinal response







- GPD at $x_2 = 0$: Amplitude for stopping of parton with momentum fraction x_1

  Accessible experimentally in $\mathrm{Im}\, A(\mathrm{excl})$

- Small x, high Q^2: Configurations generated by QCD evolution

  Successful phenomenology at HERA
  $R = A(\mathrm{DVCS})/F_1$ Review Schoeffel 09

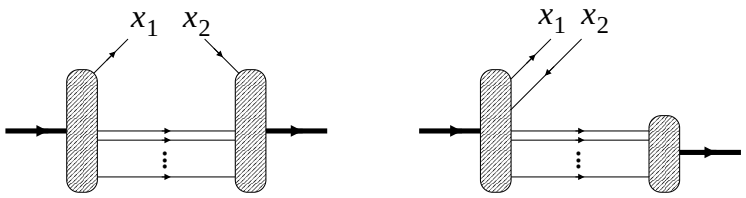
- Valence region: Configurations generated non-perturbatively, but how?

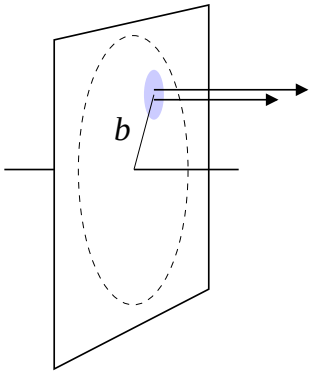
  QCD vacuum structure important

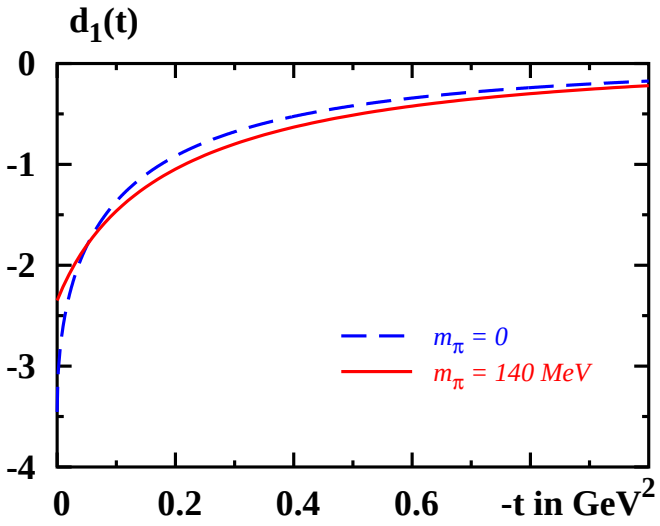
  Sensitive to boundary pert. – non-pert.
  Cf. $\gamma^*\gamma \to \pi^0$ Radyushkin 09; Polyakov 09; others

Stopping still poorly understood!

Quark imaging: Pair correlations







D-term in large–N_c nucleon model: Schweitzer et al. 07

- GPDs contain components describing emission of $q\bar{q}$ pair by nucleon
  Amplitude, not density

  Many–body system!

  QCD vacuum: Chiral symmetry breaking

  Predictions from dynamical models, lattice QCD
  Polyakov 02; Schweitzer et al. 08, LHPC Hägler et al. 07

- Accessible in DVCS

  Subtraction constant in DVCS amplitude: D–term Polyakov, Weiss 99

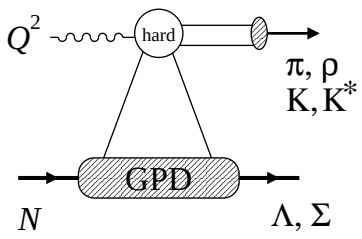
  Seen in dispersion analysis of DVCS data
  JLab 6 GeV Hall A, CLAS: Polyakov, Vanderhaeghen 08.
  Would benefit from higher-energy data: COMPASS, EIC

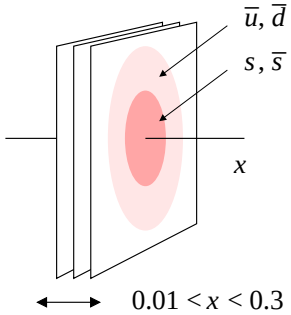
- More information from meson production

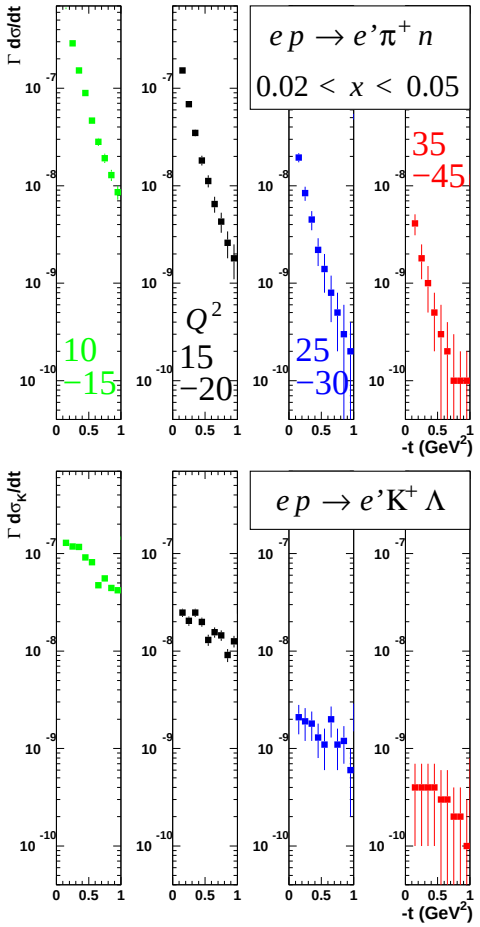
  Pion pole in exclusive π^+ Frankfurt et al. 99

  Likely important in exclusive ρ^0, ρ^+ at JLab
  Guidal, Morrow 08. Exploratory stage... needs more work!

Quark imaging: Sea quarks with EIC







- What is the spatial, flavor and spin structure of the non–perturbative sea in nucleon?

  Carries quantum numbers: $\bar{d} - \bar{u} > 0$

  Dynamical origin: QCD vacuum, mesonic components in wave function?

- Meson production with EIC

  Focus on $0.01 \lesssim x \lesssim 0.3$:
  Ideal with medium energy $\sqrt{s} = 20 - 70$ GeV

  Non–singlet channels, $Q^2 > 10\,\text{GeV}^2$:
  Low rates require $L \sim 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$

  Example: Exclusive π/K production maps transverse distribution of non–strange and strange sea T. Horn et al. 08

Explore dynamical origin of nucleon sea

Quark/gluon imaging: More structures

- Valence quark spin structure in exclusive π^0, η E12-06-108

  Dominant role of quark helicity–flip GPD? Goloskokov, Kroll 10; Ahmad, Goldstein, Liuti 08

  Reassessment of L/T, reaction mechanism

- J/ψ production near threshold with JLab12 → Workshop Temple U. 2012

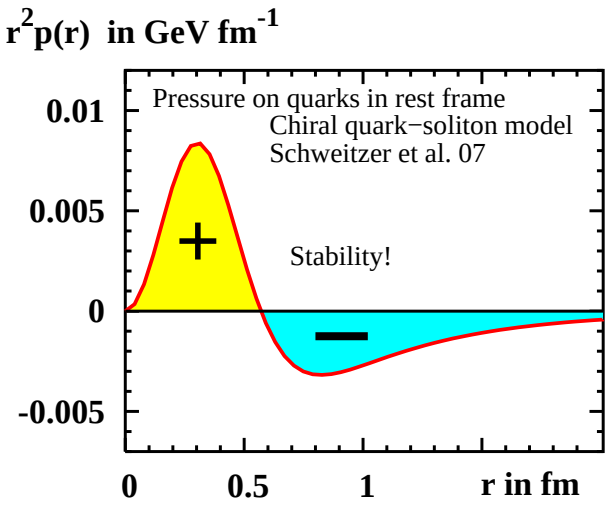
  Probes gluon GPD at large skewness $x_2 - x_1$, $|t_{\rm min}| \sim 2\,{\rm GeV}^2$

- Quark/gluon imaging of nuclei

  Small x: Nuclear shadowing as function of impact parameter Guzey et al.; Caldwell, Kowalski 08

  Valence region: ^{4}He as spin–0 target

Static properties: EM tensor

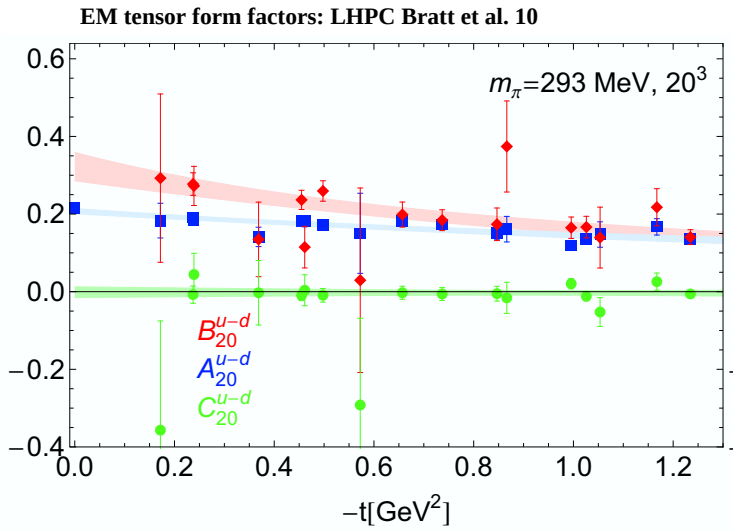


- What are the distribution of energy, momentum and angular momentum in the nucleon?

  QCD energy–momentum tensor
  $\langle N|T_{\mu\nu}|N\rangle \sim A, B, C(t)$ form factors

  Rest frame interpretation: Energy/momentum density, forces on quarks Polyakov 02

  Fundamental interest: Lattice QCD, large–N_c semiclassical models



- Accessible through 2nd moment of GPDs

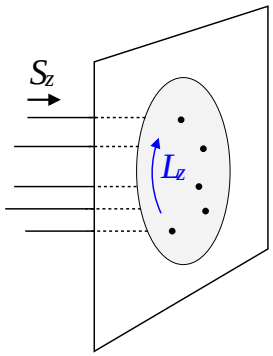
  Local spin–2, twist–2 operator
  Electroweak currents only give spin–1

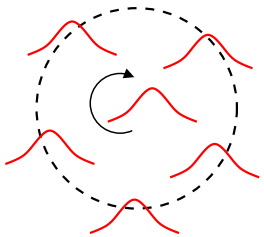
  Ji sum rule $x_{1,2} = x \mp \xi$

$$\int dx\, x\, [H_q + E_q](x_1, x_2; t) \;=\; J_q$$

Access fundamental static properties through GPDs

Static properties: Orbital angular momentum





- Formulations of angular momentum

  EM tensor $\langle N| \int d^3r\, \boldsymbol{r} \times \boldsymbol{T} |N\rangle$ "fields"

  partonic $|N\rangle = \sum |q \ldots \bar{q} \ldots g; J_z\rangle$ "particles"

- Questions and challenges Recent summary: Leader 2011

  Separate quark $\leftrightarrow$ gluon angular momentum in interacting theory? Yes, but conventional

  Separate gluon spin and orbital momentum? No

  Complications: Gauge invariance, renormalization

- Different definitions Jaffe, Manohar 90; Ji 97; Chen et al. 08; Wakamatsu 10

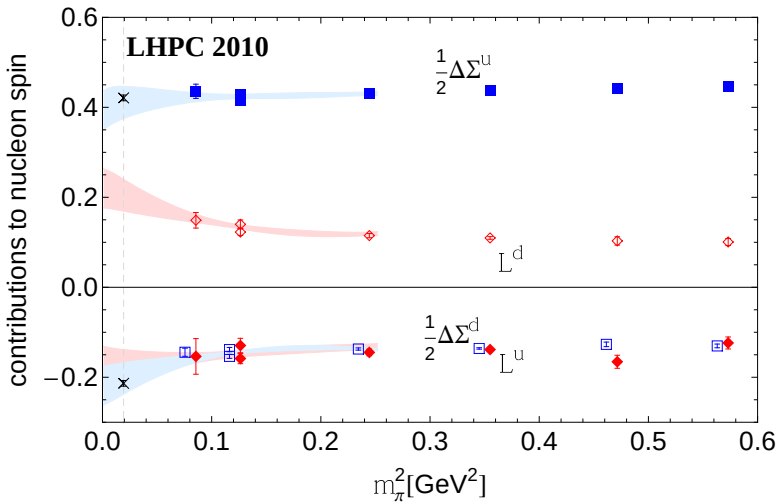
  Ji: Belinfante version of EM tensor; connection with GPDs

  $$J_{q,g} = \int_0^1 dx\, x\, [H_{q,g} + E_{q,g}](x_1, x_2, t \to 0)$$

  Integrand not "partonic" density of angular momentum Burkardt, BC 09
  No correspondence: $J_{g,\mathrm{Ji}} \neq \Delta G + L_{g,\mathrm{Jaffe\text{-}Manohar}}$

  No simple answers. Much more work needed!

Static properties: Orbital angular momentum



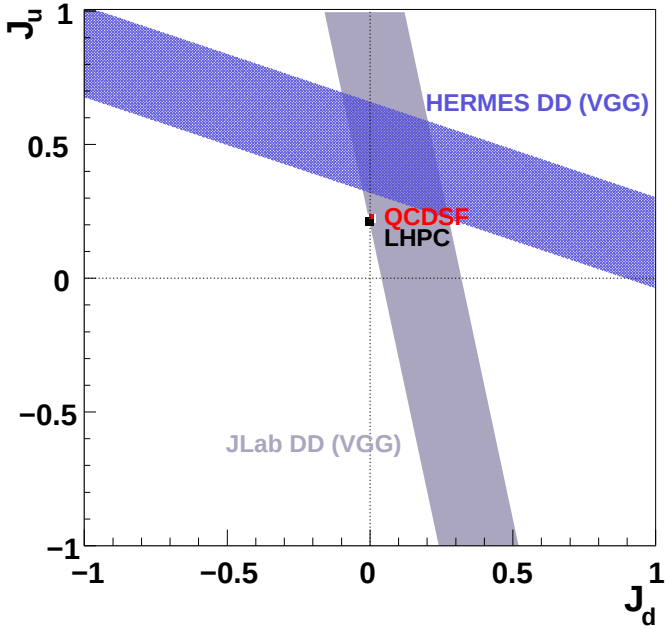
- Large isovector component of OAM

  Lattice results for J_q, Σ_q
  QCDSF, LHPC. Here $L_q \equiv J_q - \Sigma/2$

  Hints at chiral dynamics: πN configs
  in nucleon light–cone WF have $L = 1$
  $\leftrightarrow$ large sea quark Sivers function at HERMES, COMPASS?

  Models: Chiral quark–soliton model;
  quark model + pion cloud
  Wakamatsu 05+; Goeke et al. 07. Thomas, Myhrer 08

  Model–independent understanding?

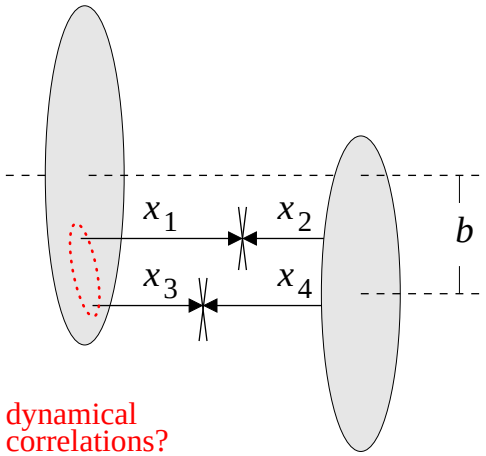


- Future directions

  Ji SR with GPDs constrained by exclusive data?
  DVCS: E_q from neutron and transverse target,
  charge asymmetry JLab 6/12 GeV, HERMES
  DVMP: E_q from ρ with transverse target,
  E_g from ϕ? Challenging! Difficult to quantify errors.
  Need 12 GeV data to test reaction models.

  Comprehensive approach using exclusive,
  semi–inclusive and inclusive observables
  Light–front phenomenology; needs better conceptual understanding!
  Dedicated INT Workshop 6-17 Feb 2012

GPDs in pp: Multiparton processes, diffraction



- Transverse distribution of partons essential input to pp@LHC

  Spectator interactions in hard procs depend on pp impact parameter "Underlying event"

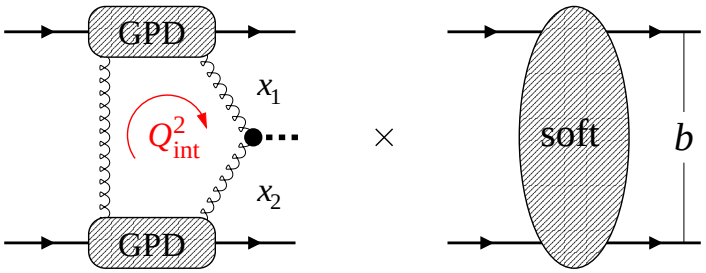
  Use ep results to predict/quantify impact parameter distribution
  Frankfurt, Strikman CW 03, 10

- Multiple hard processes

  Geometric probability calculable from transverse parton distributions

  Dynamical correlations?
  Tevatron CDF/D0 3 jet + γ show enhancement

  High rates expected at LHC:
  Background to new particle production
  New field of study! MPI@LHC 2010
  Dokshitser et al. 10, Diehl et al. 11



favors central favors peripheral

- Exclusive diffraction $pp \to p + H + p$
  Frankfurt, Hyde, Strikman, CW 08

  Gap survival probability
  Hard process $\leftrightarrow$ soft spectator interactions

Summary

- GPDs enable new level of insight in nucleon structure in QCD

  Transverse imaging

  Longitudinal response, $q\bar{q}$ correlations

  EM tensor, angular momentum

- Great potential in Hall A at 12 GeV

  Gluon imaging with ϕ — transverse pol. target?

  DVCS cross sections for dispersion analysis

  High–t form factors for transverse densities at $b \lesssim 0.2$ fm

- JLab12 part of larger program to explore nucleon structure with GPDs

COMPASS, EIC, 24 GeV+	gluon/sea quark imaging
RHIC, LHC	GPDs in diffraction, multiparton processes