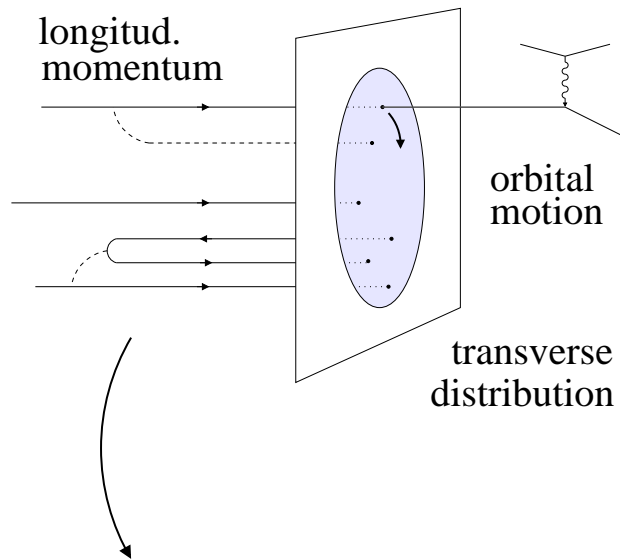


Partonic structure and exclusive processes

C. Weiss (JLab), TMD2010, ECT* Trento, 21-Jun-10



- Nucleon structure in parton picture

Rest frame vs. partonic description

Nucleon as many-body system

Physical properties

- Nucleon structure from exclusive processes

Reaction mechanism and GPDs

Transverse spatial distributions:
Diffusion, chiral dynamics

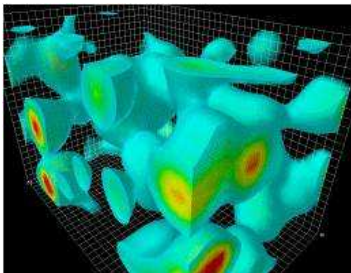
Longitudinal structure: Stopping of fast quark

$q\bar{q}$ pairs in nucleon: QCD vacuum

- Beyond distributions: Correlations

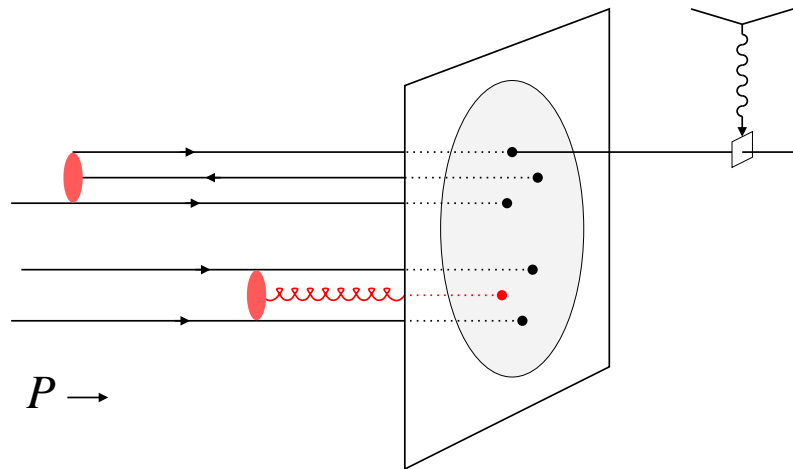
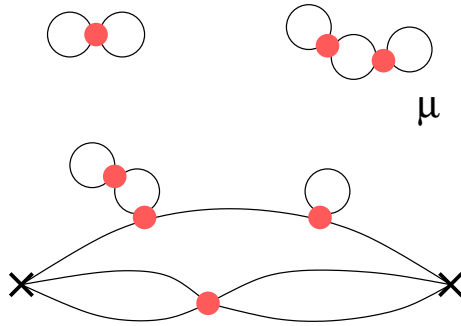
Multiparton correlations

Exclusive diffraction $pp \rightarrow p + H + p$



Dynamics!

Nucleon structure: Parton picture



- QCD vacuum not empty

Strong non-perturbative gluon fields,
scale $\mu \gg 1 \text{ fm}^{-1}$

$\bar{q}q$ pair condensate, π as collective excitation

- Slow-moving nucleon $P \sim \mu$

$\langle N|O|N \rangle$ from Euclidean correlation functions
→ lattice, analytic methods

No concept of “particle content!”

- Fast-moving nucleon $P \gg \mu$

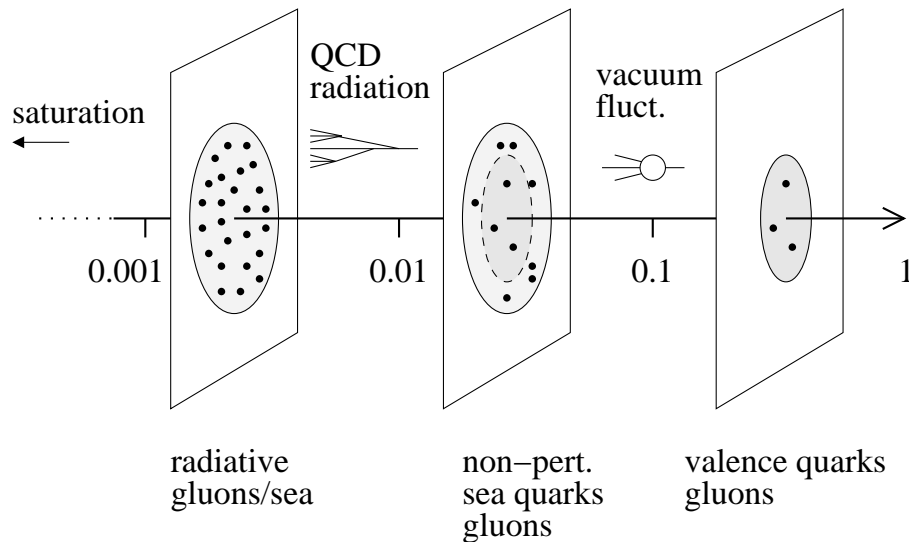
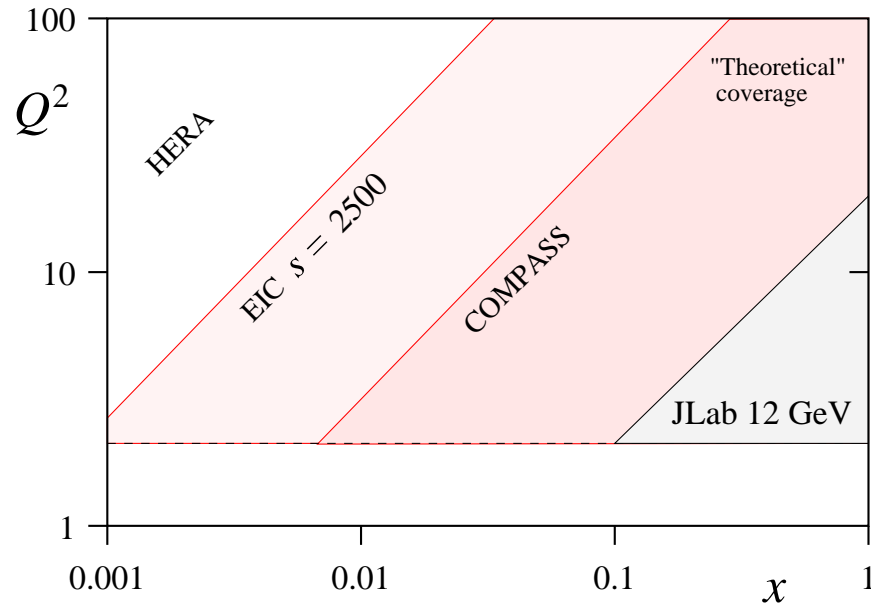
Closed system: Wave function description
Gribov, Feynman

Components with different numbers of particles

Deep-inelastic process:
“Snapshot” with resolution $1/Q$

pQCD radiation: Scale 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

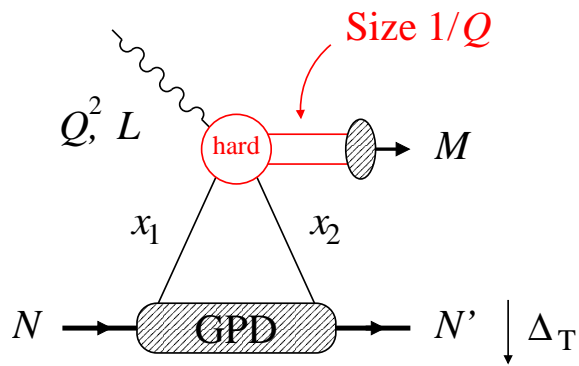
Transverse spatial distributions

Orbital motion: k_T dependence, angular momentum

Correlations: Transverse, longitudinal

+ Q^2 dependence

Exclusive processes: Factorization, GPDs



- Mechanism for $Q^2 \gg$ hadronic scale

Reaction takes place over transverse distances $\sim 1/Q$
 Experimentally testable, finite-size corrections

$Q^2 \rightarrow \infty$: QCD factorization theorem

Collins, Frankfurt, Strikman 96; Ji 96, Radyushkin 96; Collins, Freund 98

Target structure in GPDs: Universal, process-independent

- Properties of GPDs

$\langle N' | \text{twist-2} | N \rangle$ operator definition, renormalization

Unify concepts of PDF and elastic form factors

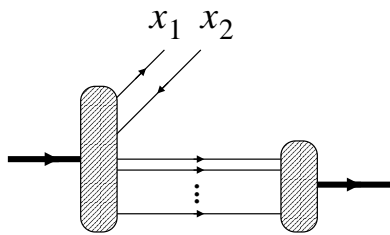
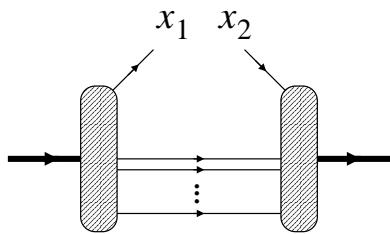
Moments form factors of twist-2 spin- n operators

$n = 2$ QCD energy momentum tensor $\rightarrow J_{q,g}$

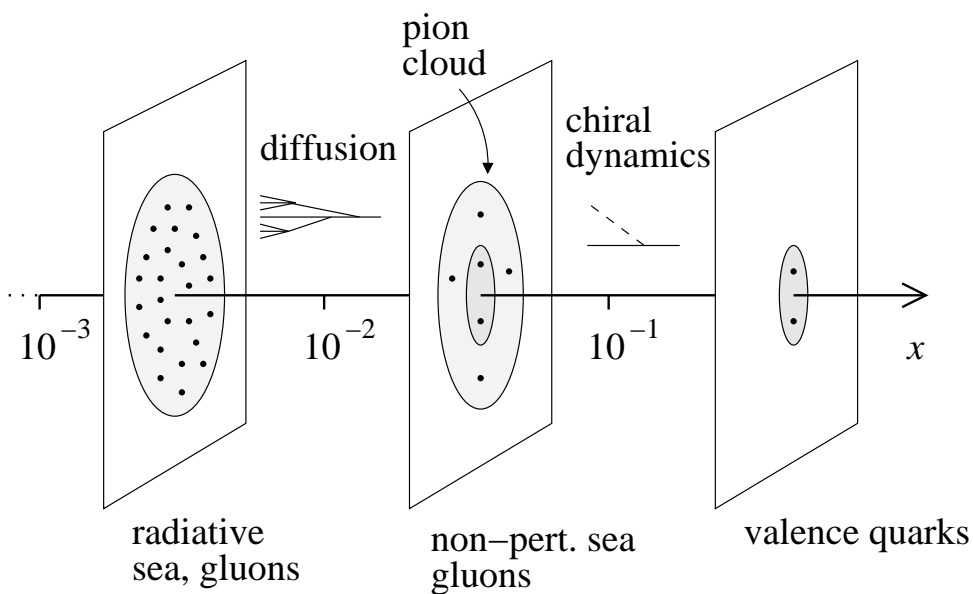
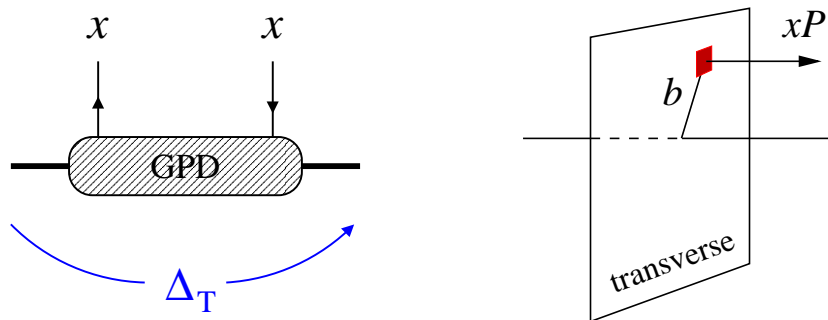
- Partonic interpretation

x_1, x_2 same sign transition parton density

different sign distribution amplitude of $q\bar{q}$ pair



GPDs: Transverse distributions



- Transverse spatial distribution

Fundamental twist-2 characteristics, cf. elastic FFs

- Transverse size changes with x

$x > 0.1$ Valence quark binding

$x < 0.1$ Chiral dynamics:
Yukawa tail $b \sim 1/M_\pi$
from soft pions in WF

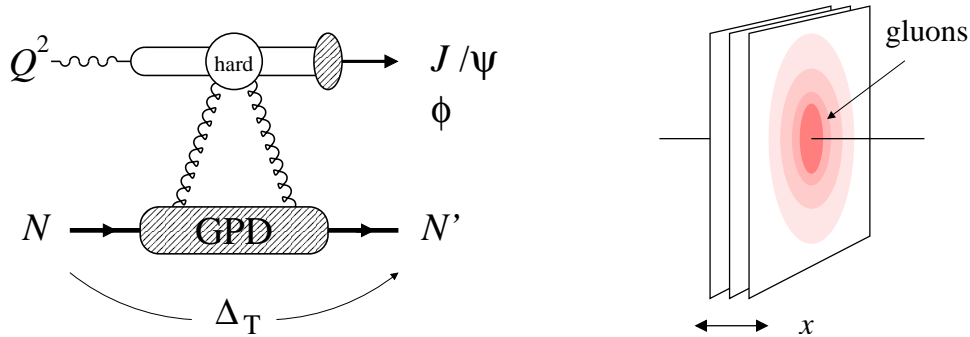
$x \ll 0.01$ Diffusion in parton decay,
suppressed at high Q^2

- Nucleon polarization

Longitudinal Different size q_+, q_-

Transverse Rotation distorts
spatial distributions

GPDs: Transverse distribution of gluons



- Transverse distribution of gluons from exclusive J/ψ and ϕ

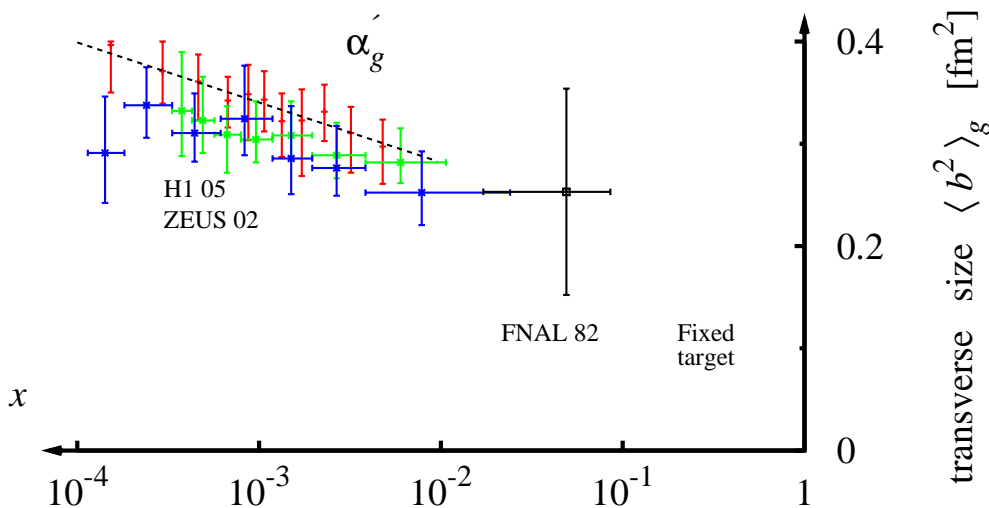
Reaction mechanism tested at HERA

- Nucleon's gluonic size

HERA: Size small $\langle b^2 \rangle_g < \langle b^2 \rangle_{\text{charge}}$, increases with slope $\alpha'_g \ll \alpha'_{\text{soft}}$

COMPASS: New data at $x > 10^{-2}$

Lower-energy data: Poor quality, suggest small gluonic size



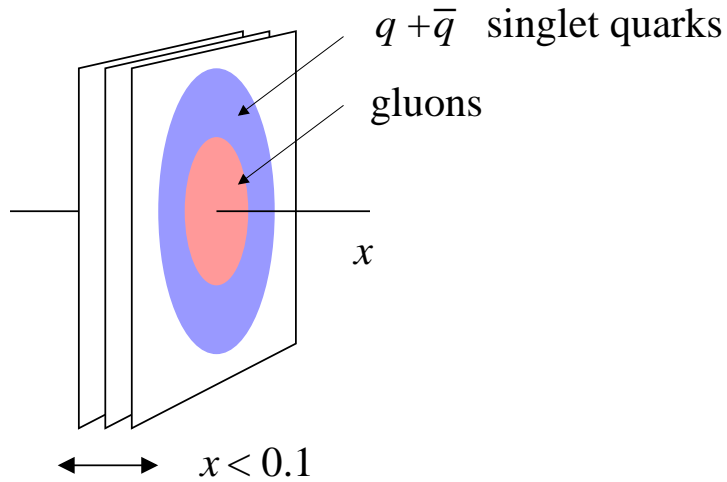
SW, arXiv:0812.1053, $Q^2 \approx 3 \text{ GeV}^2$

- Interest beyond nucleon structure

Initial conditions for small- x evolution equations, $Q_{\text{sat}}(x)$

MC generators for pp@LHC:
Transverse geometry

GPDs: Gluon imaging with EIC

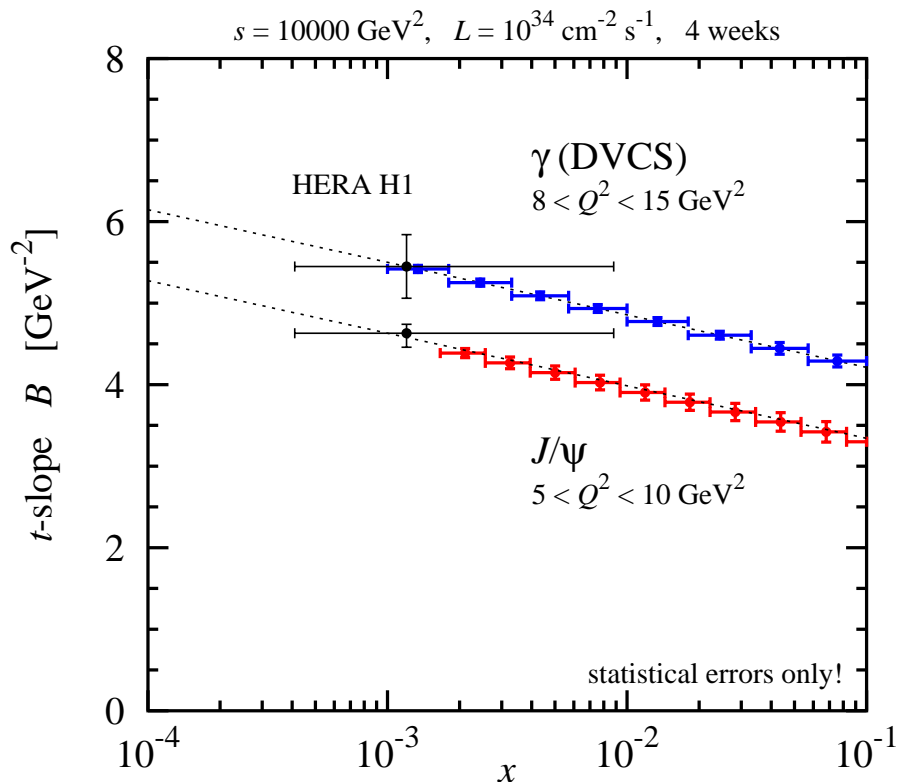


- Gluon imaging with J/ψ
Large- x region with lower CM energy

- Singlet quark imaging with DVCS

Hints from HERA:
 $\text{Area}(q + \bar{q}) > \text{Area}(g)$

Dynamics: Pion cloud, constituent quarks,
quark vs. gluon diffusion



- Experimental requirements

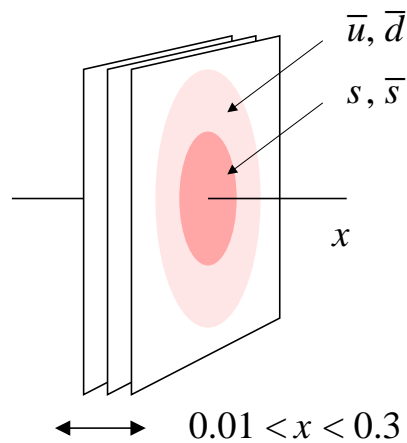
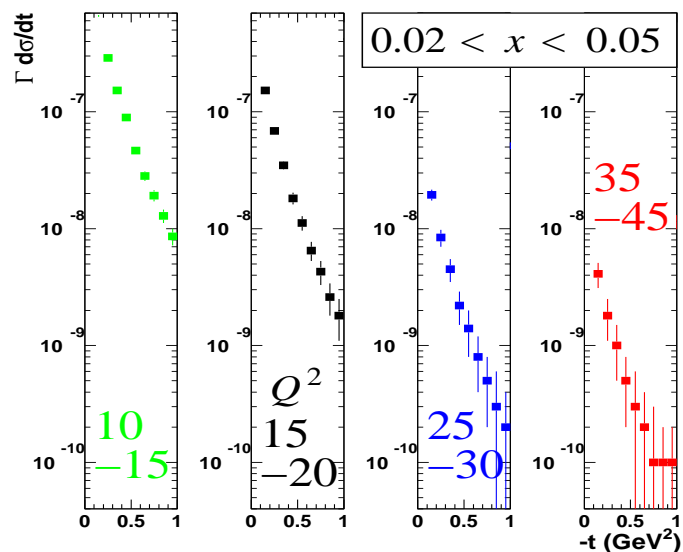
Fully differential measurements in x, Q^2, t
to control reaction mechanism

Wide coverage in t for Fourier

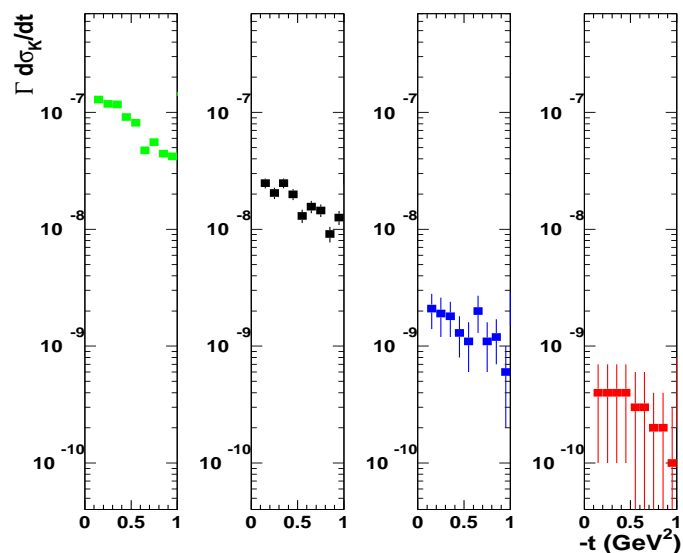
Recoil detection for exclusivity, resolution

GPDs: Sea quark imaging with EIC

$$ep \rightarrow e' \pi^+ n$$



$$ep \rightarrow e' K^+ \Lambda$$



- Non-singlet sea with exclusive $\pi, K/\rho^+, K^*$

QCD vacuum fluctuations,
 πN or $K \Lambda$ components in WF?

Spin/flavor separation of non-perturbative sea

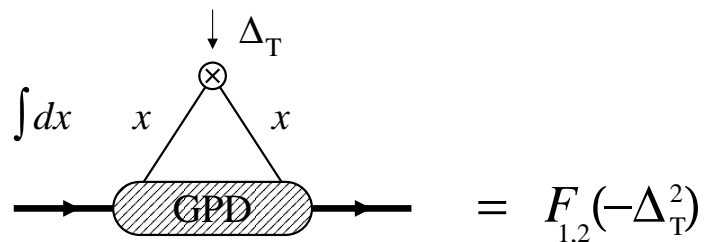
- More demanding than singlets

High luminosity for low rates

Horn et al. 09.

4 on 60 GeV, $L = 10^{34} \text{ cm}^{-2} \text{ cm}^{-1}$

GPDs: Transverse charge densities



- Transverse charge/current densities Miller 07

Measurable in elastic eN scattering

Constrain valence quark GPDs $q - \bar{q}$

- Chiral dynamics at $b \sim 1/M_\pi$ Strikman, CW 10

Equivalence between invariant ChPT and partonic picture of “pion cloud”

Non-chiral core of charge density dominant up to distances $b \sim 1.5$ fm

- Many interesting results

Empirical charge densities:

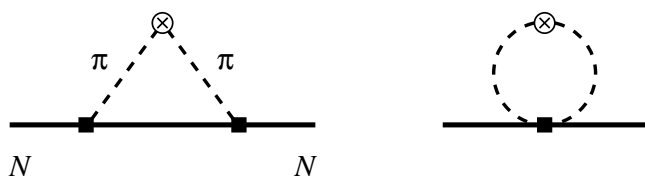
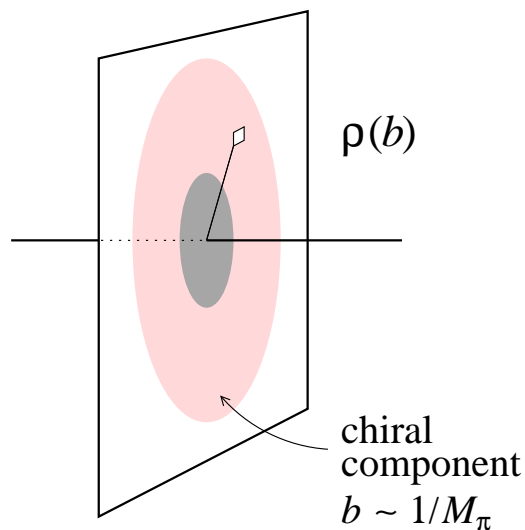
Neutron positive at $b \sim 1$ fm Miller 07

$N \rightarrow \Delta$ from empirical FF, lattice

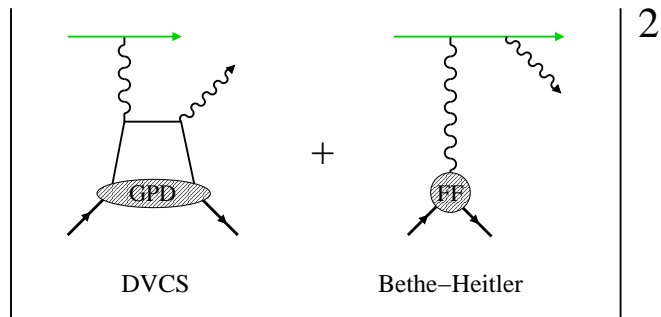
Carlson, VdH 08; Alexandrou et al. 09

Matter density from AdS/QCD

Abidin, Carlson, 08



GPDs: Valence quarks with DVCS



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

$$\text{Im DVCS} \quad e\uparrow - e\downarrow$$

$$\text{Re DVCS} \quad \text{unpolarized, } e^+ - e^-$$

- Reaction mechanism

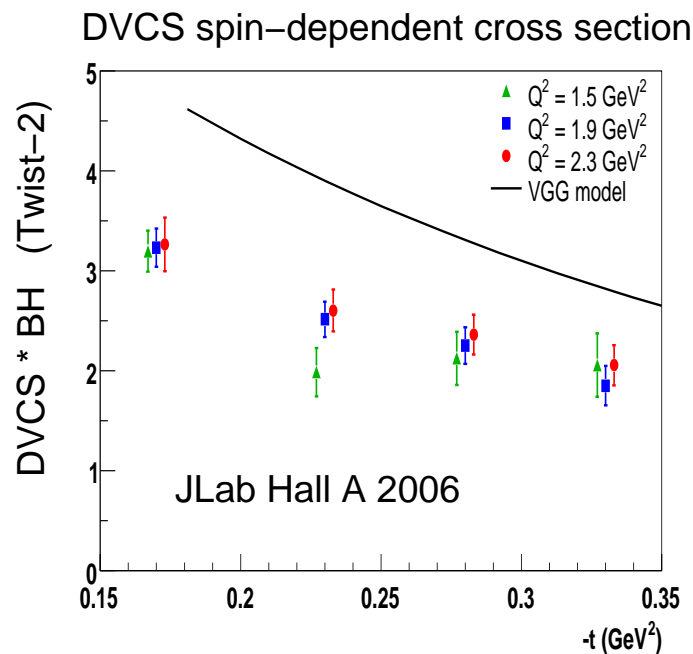
JLab Hall A 6 GeV cross section data indicate “normal” approach to scaling

More tests needed!

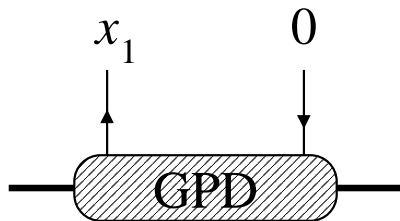
- Extensive program with JLab 12 GeV

Separate GPDs $H \leftrightarrow E$ etc. through polarization observables, neutron target

Large skewness $x_1 - x_2$ and t_{\min} , transverse images model–dependent

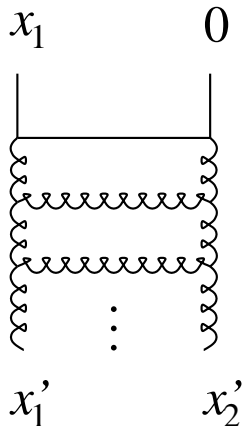


GPDs: Longitudinal structure



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

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



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

Successful phenomenology at HERA

$$R = A(\text{DVCS})/F_1$$

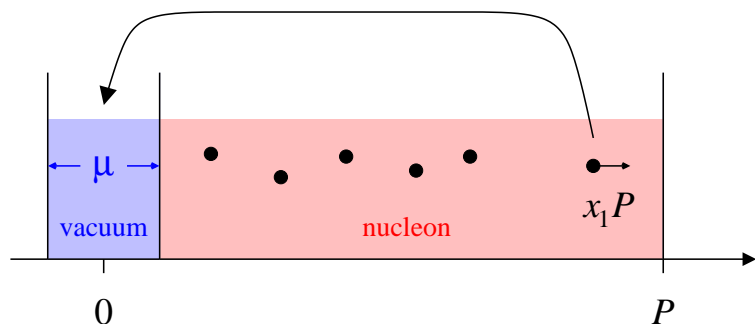
- Valence region: Configurations generated non-perturbatively, but how?

Difficult to realize with soft interactions

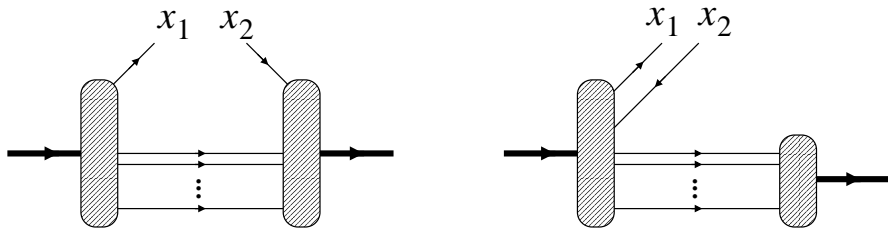
Very sensitive to boundary
perturbative – non-perturbative

Cf. discussion $\gamma^* \gamma \rightarrow \pi^0$

Radyushkin 09; Polyakov 09; Dorokhov 10

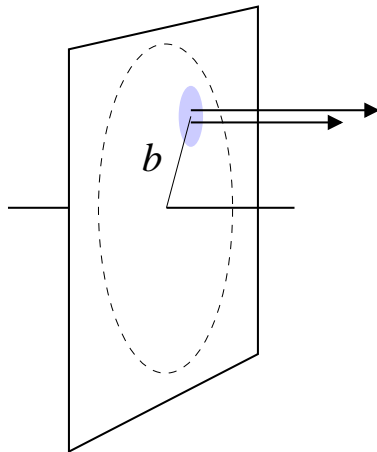


GPDs: Quark–antiquark pairs



$$\text{Re } A(t) = \int dx_1 \frac{\text{GPD}(x_1, 0; t)}{x_1} + D(t)$$

$$\text{Im } A(t) = \text{GPD}(x_1, 0; t) \quad \text{measurable!}$$



- Partonic regions of GPD

Transition PDF

Distribution amplitude of $q\bar{q}$ pair

Related by Lorentz invariance:

Polynomiality of moments

- Dispersion relations for LT hard exclusive amplitudes

Frankfurt, Strikman, Freund 97; Teryaev 05; Anikin, T. 07; Müller et al. 07; Diehl, Ivanov 07 → Goldstein, Liuti

Subtraction term: D -term PW 99

Emission/absorption of $q\bar{q}$ pair:

QCD vacuum structure

Form factor of EM momentum tensor:

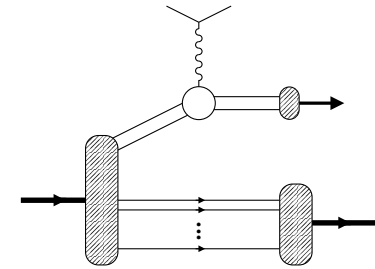
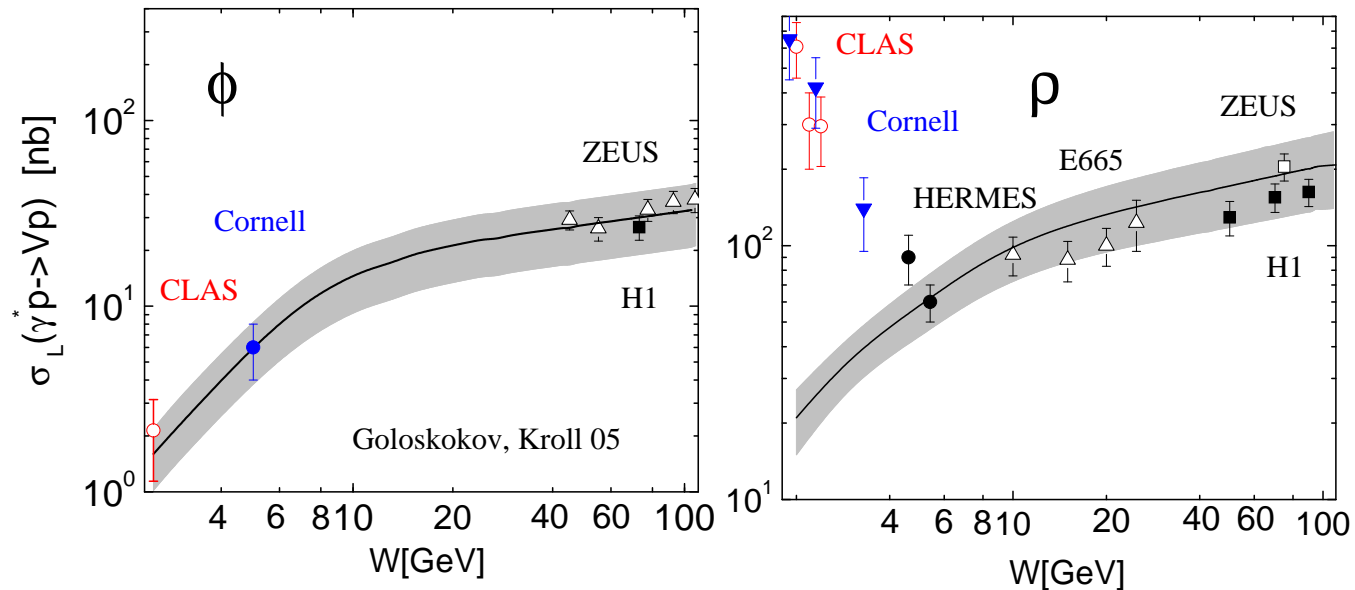
Lattice, semiclassical models

Polyakov 02; Schweitzer et al. 08 → Hägler

Dispersion analysis of JLab DVCS data

Polyakov, Vanderhaeghen 08

GPDs: Quark–antiquark pairs



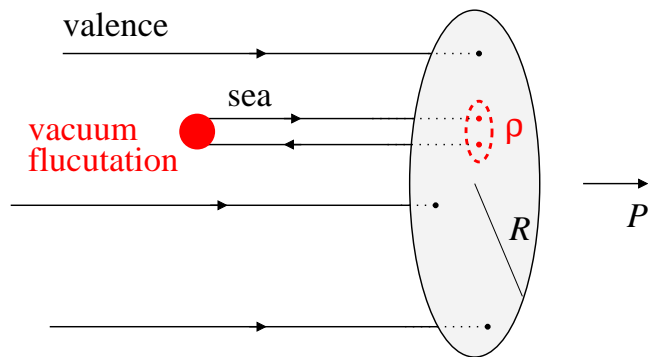
- Important in meson production at lower energies?

Missing strength in ρ^0 amplitude [Goloskokov, Kroll 08](#); [Guidal, Morrow 08](#)

Comparison $\phi \leftrightarrow \rho^0 \leftrightarrow \rho^+$ data from JLab CLAS [Fradi et al. 09](#)

Substantial finite-size effects: On-going discussion

Correlations: Multiple hard processes



- Transverse correlations in partonic wave function

Cf. short-range NN correlations in nuclei
JLab Hall A, CLAS

Vacuum fluctuations $\rho \ll R_{\text{had}}$

- Observable through enhancement of multiple hard processes in pp

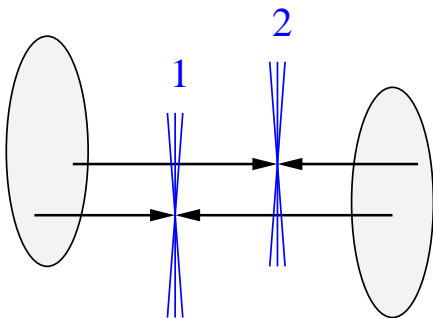
CDF 3 jet + gamma data
consistent with $\rho \sim 0.3 \text{ fm}$

High rates for multijets at LHC:
New field of study!

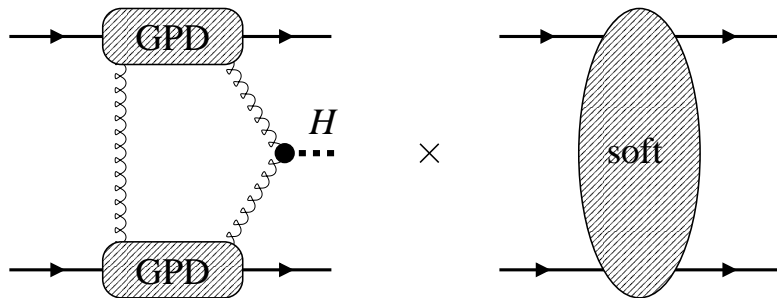
- Implications for TMDs and SIDIS

Sea quark intrinsic $k_T \sim \rho^{-1} \gg$ valence quarks?
Schweitzer, Strikman, CW; in progress

Higher-twist effects governed by scale ρ^{-2}
Balla, Polyakov, CW 97; Sidorov, CW 05



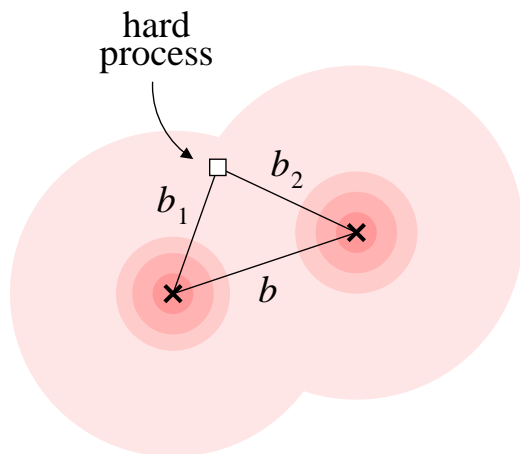
Correlations: Exclusive diffraction



- Correlation of hard process and soft spectator interactions

Heavy system H produced in hard two-gluon exchange

Concurrent soft spectator interactions must not produce particles



- Survival probability S^2

Calculable from gluon GPD and pp elastic amplitude

Diffraction pattern in p_{T1}, p_{T2}

Dynamical suppression in saturation regime, important for Higgs at LHC

$$S^2 = \int d^2b P_{\text{hard}}(b) P_{\text{no inelastic}}(b)$$

- Probe GPDs in pp scattering?

CMS/TOTEM or LHC420
STAR pp2pp @ $\sqrt{s} = 500$ GeV

Summary

- Attempt to discuss non-perturbative dynamics directly in partonic picture
- GPDs quantify essential elements of the nucleon's partonic structure
 - Transverse spatial distributions
 - Longitudinal structure
 - Quark–antiquark pairs
- Much insight already from present exclusive data, looking forward to future measurements
 - COMPASS: DVCS, J/ψ
 - JLab 12 GeV: Valence quark region
 - EIC: Gluon and sea quark imaging
 - LHC: Diffraction, multiparton correlations
 - RHIC, J-PARC, GSI FAIR: Partonic structure in $pp/\bar{p}p/\gamma p$
- Correlations as next step after one–body densities
 - “Expanding view” of nucleon structure in QCD