Landscape of nucleon structure in QCD

C. Weiss (JLab), EINN 2009, Milos, 27–Sep 2009

Jefferson Lab

- **Parton picture as a many–body system**   cf. condensed matter, nuclei

    Wave function description, different components

    Unified perspective   large $x \leftrightarrow$ small x, $ep \leftrightarrow pp$

    Role of QCD vacuum structure

- **Physical properties**

Momentum distributions	PDFs
Transverse spatial structure	GPDs, form factors
Orbital motion of partons	TMDs, angular momentum
Correlations	"Higher twist," multiparton distributions

    $\downarrow$ "expanding interest"

Nucleon structure in QCD

- QCD vacuum not empty

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

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

- Slow–moving nucleon $P \sim \mu$

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

  No concept of "particle content"

- Fast–moving nucleon $P \gg \mu$
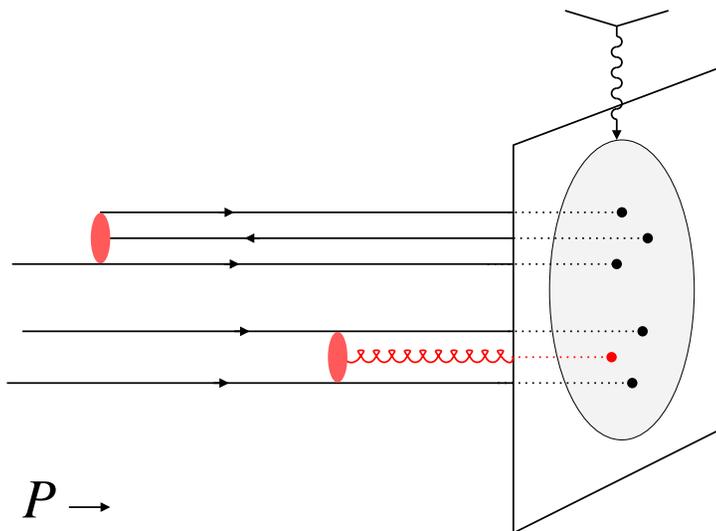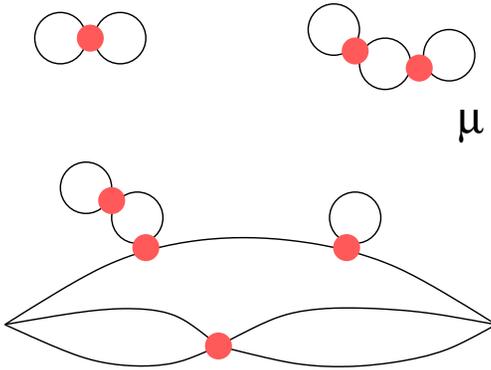
  Closed system: Wave function description
  Gribov, Feynman

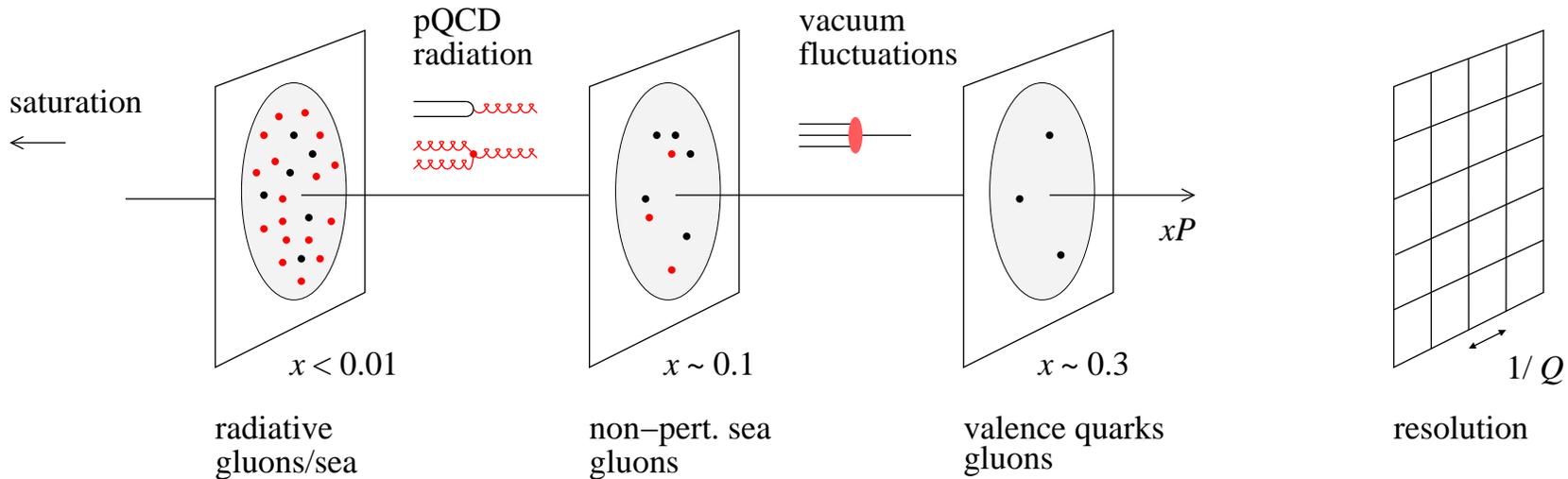 Components with different numbers of particles

  Deep–inelastic processes in $ep, pp, \gamma p$:
  "Snapshot" with resolution $1/Q$

  Perturbative fluctuations $\rightarrow$ scale dependence

μ

$P \rightarrow$

Nucleon structure: Landscape

- **Many–body system with different components**

  Energy of configurations $\sim 1/x$ momentum fraction

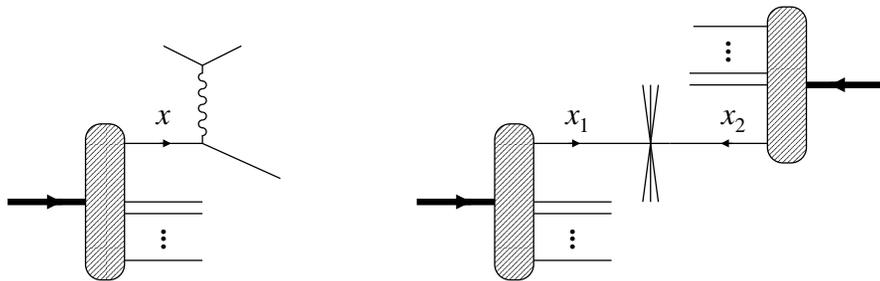- **Measurable properties**

  Longitudinal momentum densities

  Transverse spatial distributions

  Orbital motion: k_T dependence, angular momentum

  Correlations between partons

  incl. x, Q^2 dependence, spin/flavor

Parton densities: Unpolarized quarks and gluons

Inclusive DIS

Drell–Yan, jets

CTEQ6.1
$Q^2 = 10$ GeV²
$xg(x)$
$xu(x)$
$xd(x)$

relative err.

0.01   0.1   1
X

- Global QCD fits to ep/pp data with controlled uncertainties
  CTEQ, MSTW, GJR, Alekhin

  "Infrastructure" for LHC

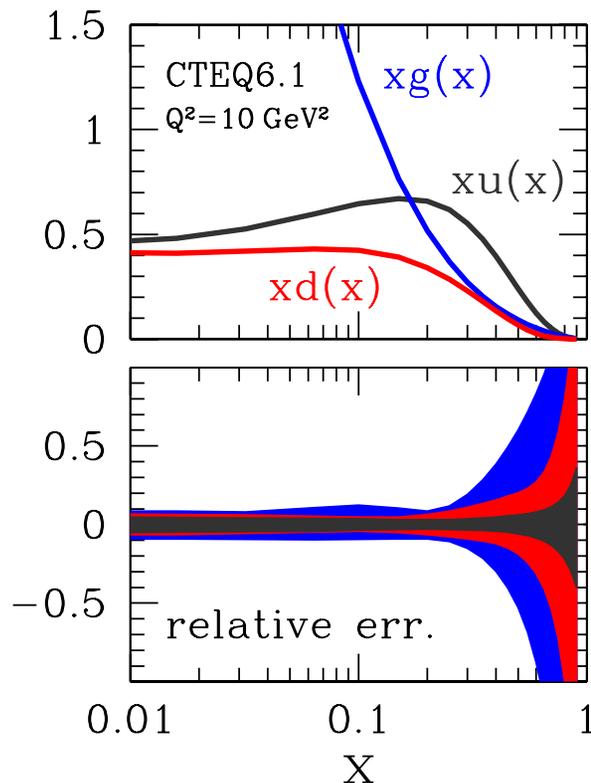- Quark densities at large x still poorly known

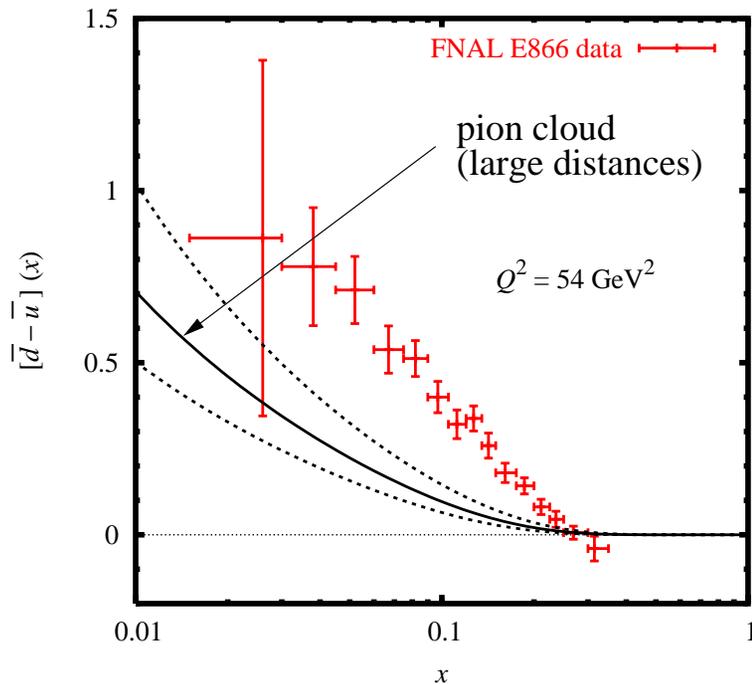 Reveal basic qqq configuration of N

  JLab 12 GeV → L. Cardman

- Gluon density at $x > 0.3$: Direct probes?

  High–mass jets at LHC $+\ d/u$ from JLab 12 GeV

  Open charm at EIC?
  → H. Avakian, EIC Workshop

Parton densities: Non-singlet sea quarks

- Non-singlets $\bar{d} - \bar{u}$, $s - \bar{s}$ etc. are of non-perturbative origin

  Weak scale/scheme dependence

- $\bar{d} - \bar{u}$ from FNAL E866 Drell–Yan and HERMES SIDIS
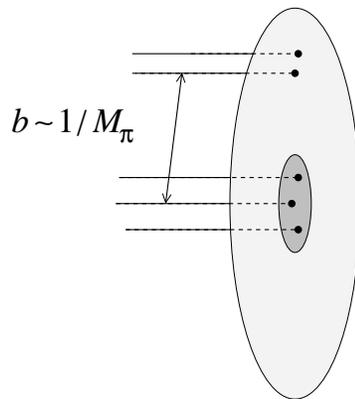
  Pion cloud at distances $\sim 1/M_\pi$ carries only $\sim 30\%$ of asymmetry
  Strikman, CW

- $s \neq \bar{s}$ from NuTeV CC neutrino DIS with $W^+ + s \to c$ tagging
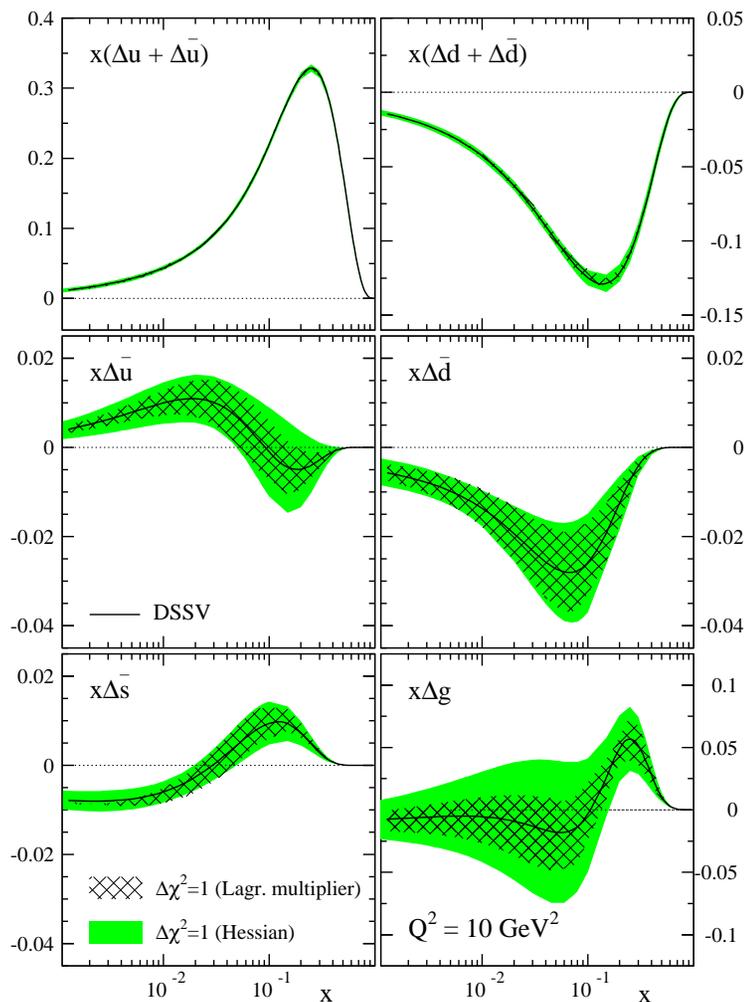
  $K\Lambda$ fluctuations? Brodsky, Ma

  Semi-inclusive DIS with EIC!

Much room for improvement!
Direct impact on vacuum/nucleon structure

Parton densities: Polarization

$x(\Delta u + \Delta\bar{u})$

$x(\Delta d + \Delta\bar{d})$

$x\Delta\bar{u}$

$x\Delta\bar{d}$

—— DSSV

$x\Delta\bar{s}$

$x\Delta g$

$\Delta\chi^2 = 1$ (Lagr. multiplier)

$\Delta\chi^2 = 1$ (Hessian)

$Q^2 = 10\,\text{GeV}^2$

De Florian, Sassot, Stratmann, Vogelsang 09

$Q^2 = 10\,\text{GeV}^2$

- NLO QCD fits to polarized inclusive and semi-inclusive ep and pp data

  → D. De Florian

  New fragmentation functions DSS 07

- Gluon polarization $\Delta G(x)$ small

  Dynamical explanation?

  Nucleon spin requires quark/gluon orbital angular momenta!

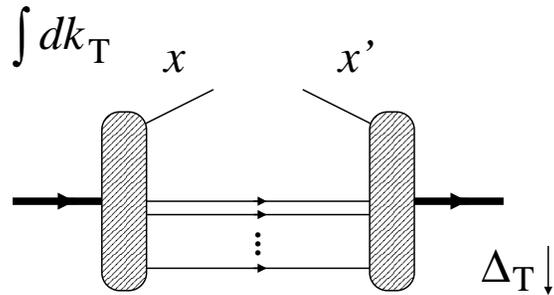 Improvement from COMPASS + JLab 12 GeV inclusive data

  Future EIC   → D. De Florian, H. Avakian, EIC Workshop

- Polarized sea quark flavor asymmetries: First hint that $\Delta\bar{u} - \Delta\bar{d} > 0$, large

  Non-perturbative vacuum fluctuations, chiral symmetry breaking

  Dorokhov, Kochelev; Diakonov et al.
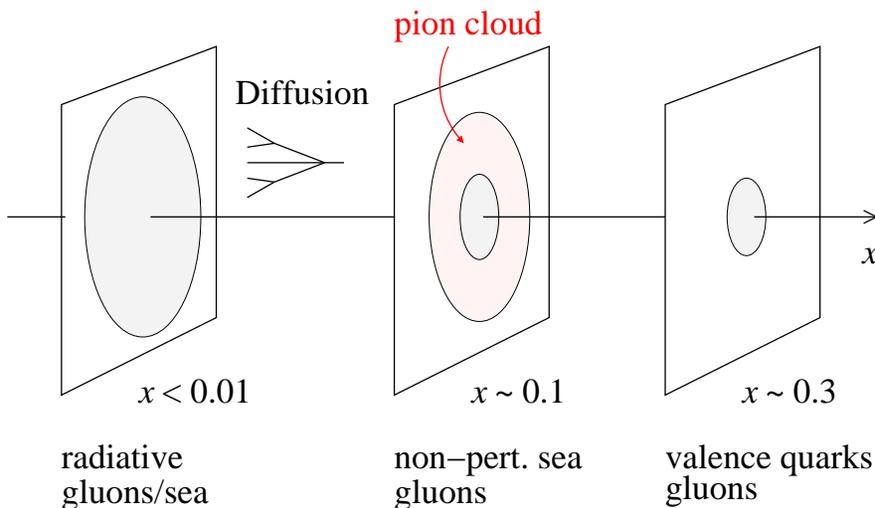
Transverse spatial distributions: GPDs

$\int dk_{\rm T}$ x x'

$\Delta_{\rm T}\downarrow$

pion cloud

Diffusion

$x < 0.01$ $x \sim 0.1$ $x \sim 0.3$

x

radiative gluons/sea

non–pert. sea gluons

valence quarks gluons

- GPD at $x' = x$: Transverse form factor of quarks with longitud. momentum x

$$\mathrm{GPD}(x, \boldsymbol{\Delta}_{\rm T}) \xrightarrow{\text{Fourier}} f(x, \boldsymbol{b}) \quad \text{Burkardt}$$

- Nucleon's transverse size grows with decreasing x

    Different mechanisms

- Hard exclusive processes $eN \to e' + M + N$: QCD factorization theorem
    Müller et al.; Ji; Radyushkin; Collins, Frankfurt, Strikman
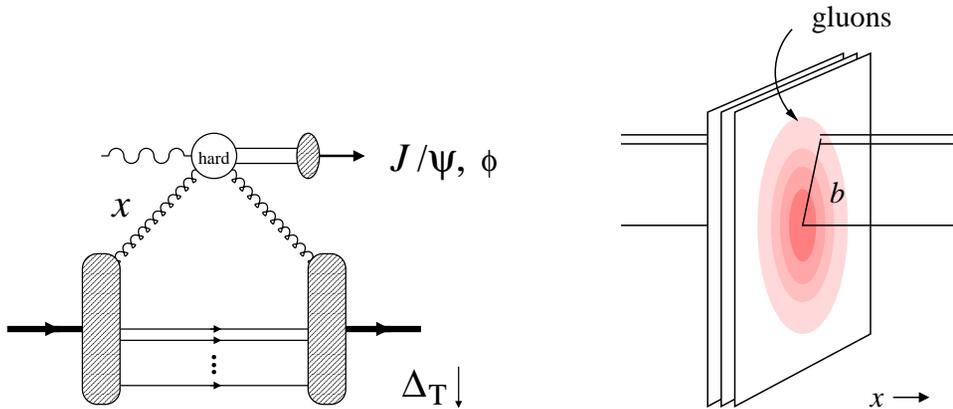
    Pointlike in transverse space: $\int d^2 k_T$
    Recent results $\gamma^*\gamma \to \pi^0$? Radyushkin, Polyakov

- Practical challenges

    Higher twist effects in hard process: intrinsic k_T, finite size of produced meson

    $x \neq x'$, non-diagonal pieces
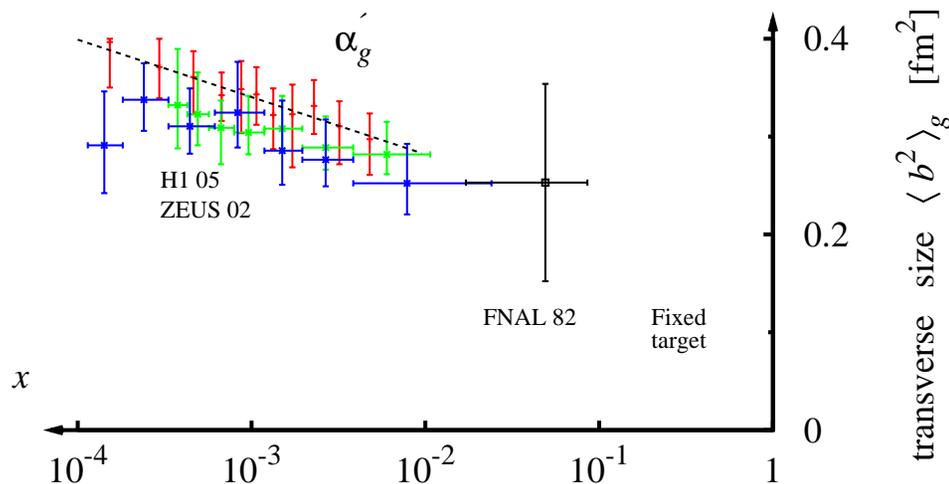
Transverse spatial distributions: Gluons

gluons

b

$x \rightarrow$

$J/\psi, \phi$

x

hard

$\Delta_{\mathrm{T}} \downarrow$

α'_g

H1 05
ZEUS 02

FNAL 82

Fixed
target

x

10^{-4} 10^{-3} 10^{-2} 10^{-1} 1

0.4

0.2

0

transverse size $\langle b^2 \rangle_g$ [fm^2]

- Transverse distribution of gluons
  from exclusive J/ψ photoproduction

  HERA: Small x, overall area only

  $x > 10^{-2}$ poor ... COMPASS?

  Valence gluons: ϕ electroproduction
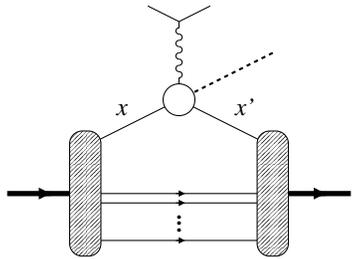 with JLab 12 GeV

  "Gluon imaging" with EIC

- Essential ingredient in
  small–x phenomenology
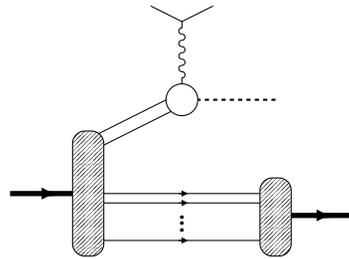
  QCD dipole model in impact parameter
  representation Frankfurt et al.; Kowalski et al.
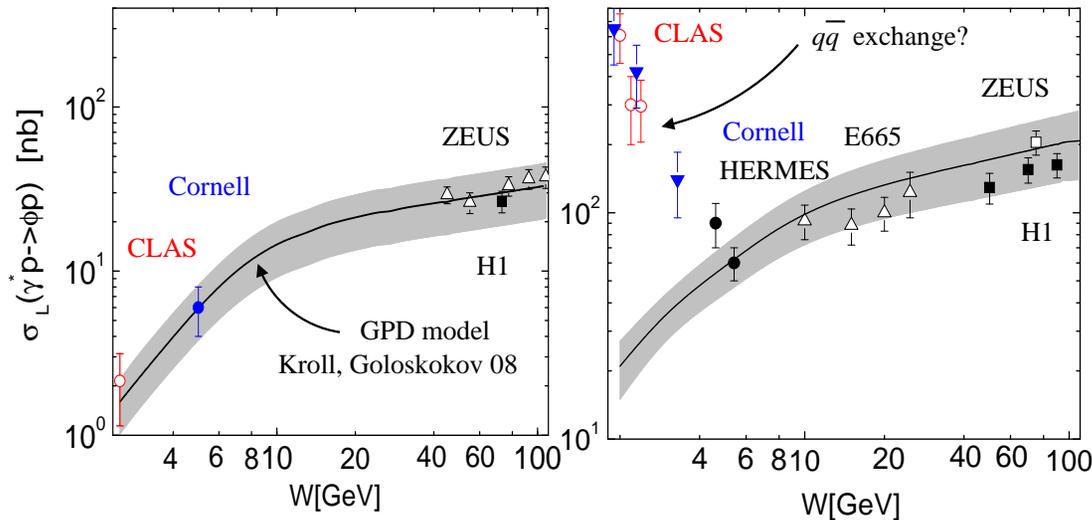
  Saturation in ep, nuclear enhancement
  $\rightarrow$ F. Gelis

Transverse spatial distributions: Quarks

Scattering from q or $\bar{q}$

Knockout of $q\bar{q}$ pair

$\sigma_L(\gamma^* p \to \phi p)$ [nb]

Cornell

CLAS

ZEUS

H1

GPD model
Kroll, Goloskokov 08

W[GeV]

CLAS

$q\bar{q}$ exchange?

ZEUS

Cornell

E665

HERMES

H1

W[GeV]

→ A. Fradi: CLAS ρ^+

- **Exclusive amplitude: Two parts**

  GPD contains both, related by
  Lorentz invariance, "polynomiality"

  Included in GPD parametrizations
  → M. Polyakov, D. Müller

- **Dynamics of $q\bar{q}$ knockout?**
  Cf. absolute cross sections

  QCD vacuum structure!

  π^+ production: Pion pole term

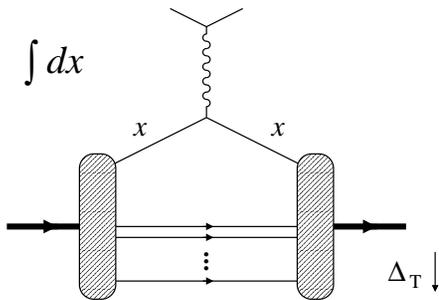- **DVCS $eN \to e'N\gamma$: Both needed**

  Im/Re from spin/charge asymmetries
  → F.X. Girod, A. Mussgiller

  Dispersion approach: Im → Re,
  subtraction constant

Transverse spatial distributions: Charge, current

$\int dx$

x $\qquad$ x

$\Delta_\mathrm{T}\downarrow$

- Partonic interpretation of elastic FF:
  Transverse charge/current density
  Burkardt; Miller

$$F_\mathrm{el}(\mathbf{\Delta}_\mathrm{T}) \xrightarrow{\text{2D Fourier}} \rho_\mathrm{T}(\boldsymbol{b})$$

- Transverse charge densities
  from empirical FFs

  Neutron negative at center,
  counter to $\pi^- p$ picture Miller

  Deformation through transverse polarization,
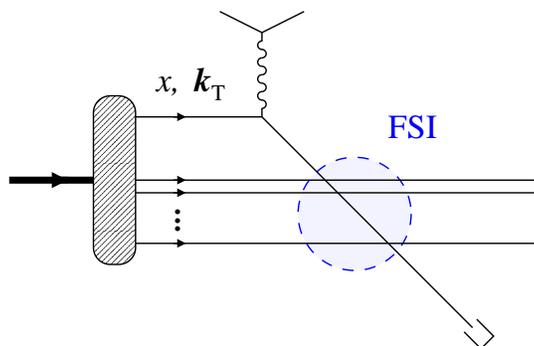 extension to $N \to \Delta$ Carlson, Vanderhaeghen

Transversely polarized p, n. Carlson, Vanderhaeghen 07

- Calculable in lattice QCD:
  Local operators in $N, \Delta \to$ C. Lorce

New insights from "old" observables

Orbital motion: Transverse momentum

$x, \boldsymbol{k}_{\mathrm{T}}$

FSI

$Q^2 = 2.4 \text{ GeV}^2$

$x\Delta^N f_u^{(1)}(x)$

$x\Delta^N f_d^{(1)}(x)$

$x\Delta^N f_u(x, k_\perp)$

$x\Delta^N f_d(x, k_\perp)$

$x = 0.1$

$k_\perp$ (GeV)

Phenomenological extraction of Sivers distribution from
HERMES and COMPASS SIDIS data. Anselmino et al. 08
$\rightarrow$ Workshop summary by A. Bacchetta

- Transverse motion, $\boldsymbol{k}_T$ dependence observable in semi-inclusive DIS

- QCD factorization with $\gamma^* N$ collinear: TMDs, soft factor

  Matching of non-pert. and pert. mechanisms Ji et al., Bacchetta et al.
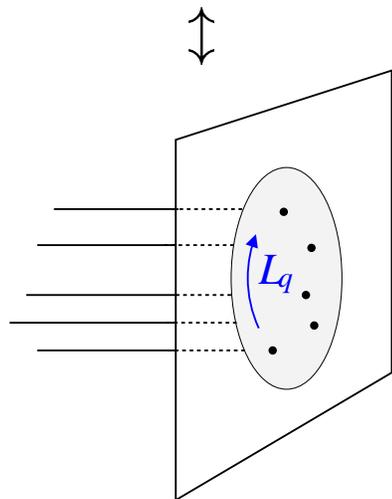
- Measures of parton orbital motion

  Sivers: Deformation of k_T distribution by transverse nucleon spin; interference of $\Delta L = 1$ wave function components + FSI

  Pretzelosity: Deviation from spherical shape through $\Delta L = 2$ in wave function Miller

- EIC: Fully differential measurements, low $\leftrightarrow$ high p_T

Orbital motion: Angular momentum

$$J_q \sim \langle N|\, \boldsymbol{x} \times \boldsymbol{T}\, |N\rangle$$

$\updownarrow$

L_q

contributions to nucleon spin

$\Delta\Sigma^u/2$

L^d

$\Delta\Sigma^d/2$ L^u

0.4

0.2

0

−0.2

0.2   0.4   0.6   0.8

m_π^2 [GeV^2]

Lattice shows large isovector $Lu - L_d$.
Hägler et al. 08

- Two basic definitions of quark/gluon angular momentum

  Matrix element of EM tensor in rest frame → Ji sum rule, GPDs

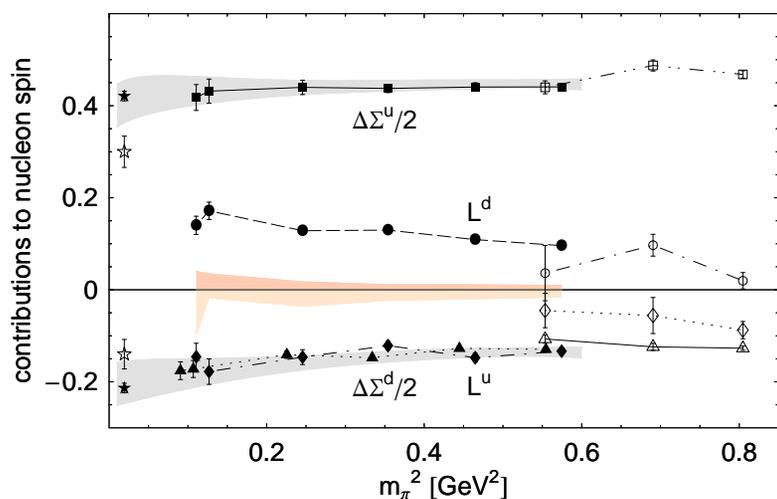 L in partonic wave function

- Need to understand connection!

  Many interesting issues: Gauge dependence
  → M. Burkardt, A. Bacchetta

- Rest frame calculations of J_q

  Lattice: Dynamical fermions,
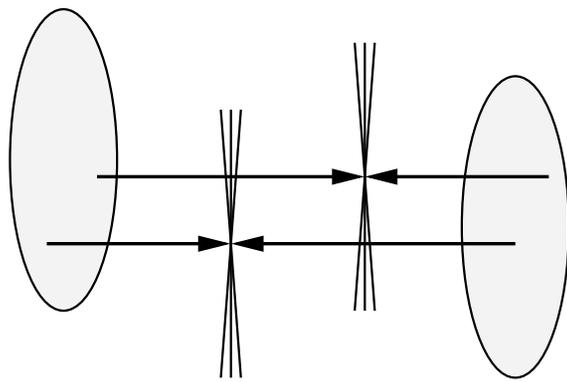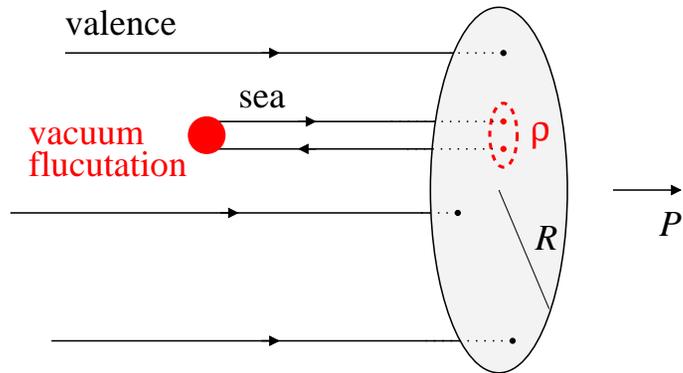 no disconnected diagrams → Ph. Hägler

  Quark model at low scale Myhrer, Thomas
  Chiral quark–soliton model Wakamatsu

- Requires comprehensive approach:
  SIDIS + GPDs (Ji sum rule)

Correlations

- Transverse correlations in partonic wave function

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

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

- Sea quarks have intrinsic $k_T \sim \rho^{-1}$ $\gg$ valence quarks

  $\rightarrow$ Semi-inclusive DIS

  $\rightarrow$ Higher twist in inclusive DIS $\sim \langle k_T^2 \rangle$ Sidorov, CW

- Observable in pp through enhancement of multiple hard processes

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

  High rates for multijets at LHC!

Small x and new correspondences $ep \leftrightarrow pp$

- **Unitarity limit and saturation** $\rightarrow$ F. Gelis

  Appearance of new dynamical scale $Q_s(x) \gg \mu_{\mathrm{vac}}$, systematic approximations!

  Nucleon/nuclear wave function develops component with $k_T \sim Q_s$ observable in particle production at RHIC, LHC, eA at EIC

- **Hard diffractive scattering** $pp \rightarrow p + H + p$

  Interplay between hard process and soft spectator interactions: Rapidity gap survival

  Sensitive to transverse distribution of partons . . . probe GPDs in pp scattering! LHC, Tevatron, RHIC?

- **Ultraperipheral** pA/AA **collisions** $\rightarrow$ D. D'Enterria

  $\gamma A/\gamma\gamma$ scattering with Weizsäcker–Williams photons from field of heavy nucleus $Z \gg 1$ RHIC, LHC

  $\rightarrow$ Small–x physics, e.g. high–p_T jets $W(\gamma p) = 10\,\mathrm{TeV}$ at LHC $= 30\times$ HERA!

  $\rightarrow$ Heavy quarkonium spectroscopy

  $\rightarrow$ Higher–order QED processes

Summary

- The nucleon as a many–body system – a unifying perspective

  different probes, excitation energies, resolution scales . . .
  physical properties

- New synergies/correspondences between $ep \leftrightarrow pp \leftrightarrow \gamma p$

- Great prospects with present and future facilities

COMPASS	RHIC	Ultraperipheral RHIC, LHC
JLab 12 GeV	LHC	J-Parc
EIC/ENC/LHeC	GSI FAIR	GlueX at JLab