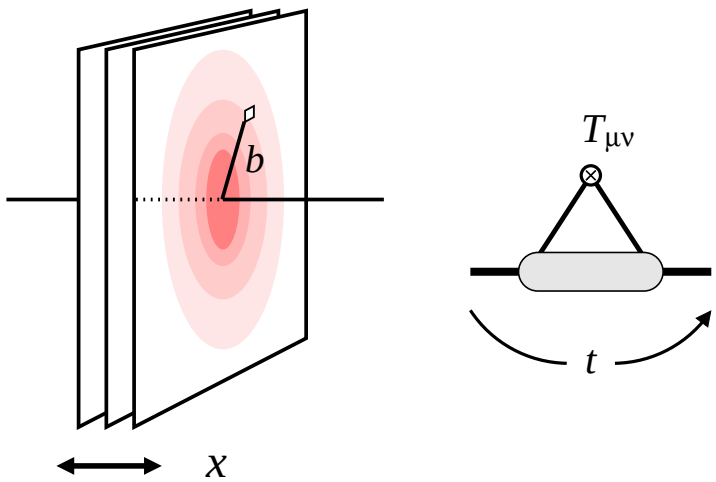
GPDs at an EIC

C. Weiss (JLab), POETIC VII Workshop, Temple U, 14-16 Nov 2016



Focus on dynamical system!

Use "imaging" for dynamics!

- Nucleon structure in QCD
- Transverse imaging

  Gluons $\leftrightarrow$ singlet quarks $\leftrightarrow$ nonsinglets

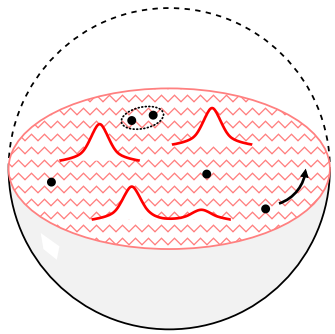
  Helicity, transversity, spin-orbit effects
- Energy-momentum tensor

  Mass, momentum, forces $\rightarrow$ D-term
- GPDs at small x

  Dipole picture, quantum fluctuations
- GPDs in pp@LHC

  Geometric correlations, multiparton interactions, gap survival in diffraction

Nucleon in QCD: Dynamical system

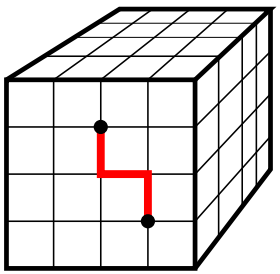


- Unique dynamical system

  Relativistic: Creates/annihilates particles, momenta $\gg$ masses, picture frame-dependent

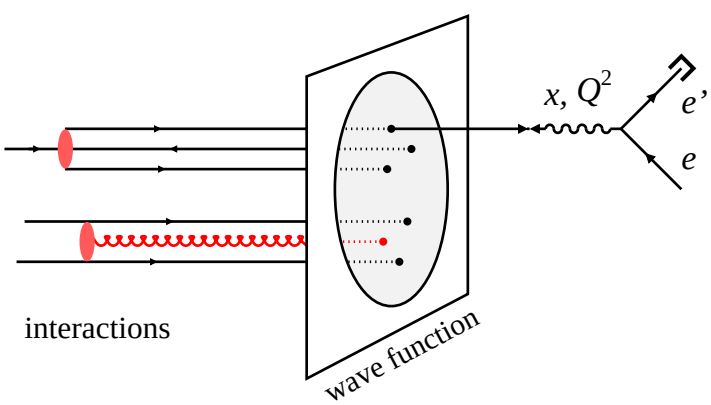
  Quantum-mechanical: Superposition of configurations, fluctuations

  Strongly coupled: Chiral symmetry breaking, dynamical mass generation, effective DoF



- Field–theoretical description

  Imaginary time $t \to i\tau$: Statistical mechanics, lattice methods



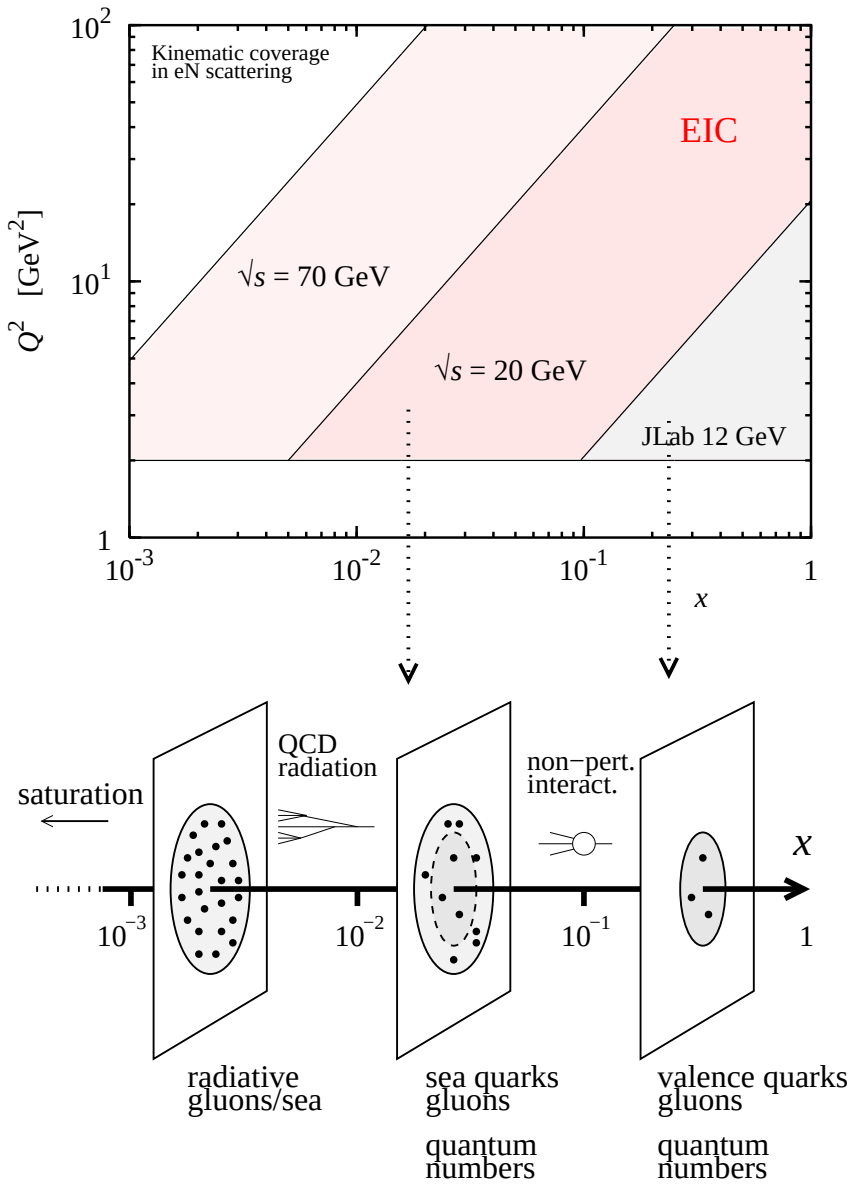
- Particle–based description

  Parton picture $P \to \infty$: Closed system
  Feynman, Gribov. Alt. viewpoint: Light–front quantization

  Many–body system: Constituents, interactions, orbital motion, spatial structure, . . .

  High–momentum transfer processes: Snapshot

Nucleon in QCD: Landscape



- Dynamical regimes

  $x > 0.2$ "Few-body"
  Valence quarks, gluons, quantum nrs
  non-pert interactions

  $x \sim 10^{-1}$–10^{-2} "Many-body"
  Sea quarks, gluons, quantum nrs
  non-pert interactions

  $x \ll 10^{-2}$ "Radiative"
  Gluons, singlet sea
  Radiation processes, saturation

- Physical characteristics

  Particle number densities,
  incl. spin/flavor dependence PDFs

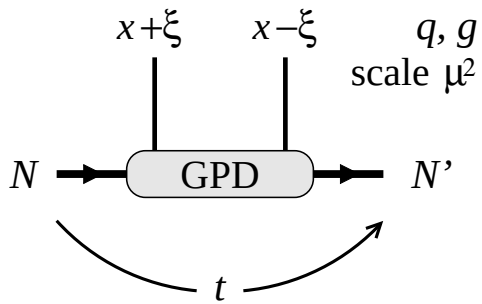
  Transverse spatial distributions GPDs

  Orbital motion, angular mom TMDs, GPDs

  Correlations, fluctuations MPDs, GPDs

  Operator definition $\langle N | \, \mathrm{QCD{-}Op} \, | N \rangle$
  Universal properties $\longrightarrow$ renorm, LQCD

GPDs: Operators and processes



$$\langle N'|\,\bar{\psi}(-z)\,\Gamma\,\psi(z)\,|N\rangle_{z^2=0}$$

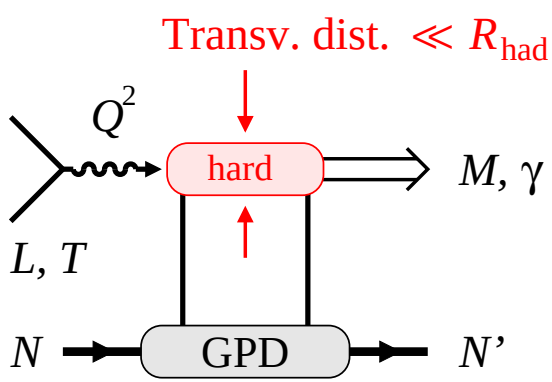
- Transition matrix element of Twist–2 operator
  Müller et al 94+, Ji 96, Radyushkin 96

  Unify concepts of PDF and elastic FF

  Quark/gluon and nucleon helicity components

  Renormalization and scale evolution DGLAP–ERBL

  Extends to $N \to N^*$, Nh, nuclei



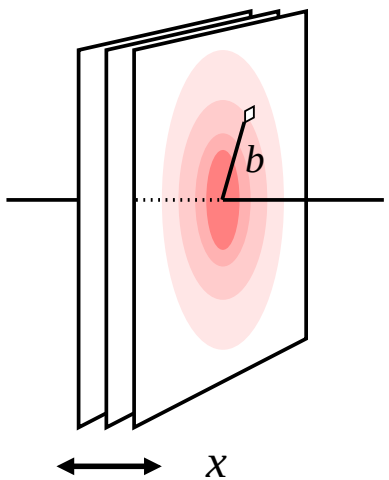
- Hard exclusive processes

  Collinear factorization
  Collins, Frankfurt, Strikman 96; Collins Freund 99

  Transverse distances in interaction $\ll$ hadron size

  Approach to short-distance regime must/can be tested experimentally and theoretically, depends on channel and kinematics

GPDs: Nucleon structure



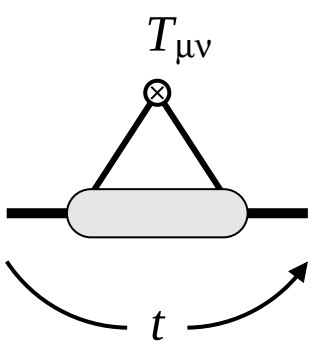
- Transverse imaging

$$f(x,b) \quad = \quad \underset{\boldsymbol{\Delta}_T \to \boldsymbol{b}}{\text{Fourier}} \quad \text{GPD}(x, \xi = 0, t = -\boldsymbol{\Delta}_T^2)$$

Transverse spatial distribution of quarks/gluons with LC momentum x
Burkardt 00+, Diehl 02

Defines "size" and "shape" of nucleon in QCD

Diagonal GPD $\xi = 0$ not directly accesible, theory/model dependence, under control at $x \ll 0.1$



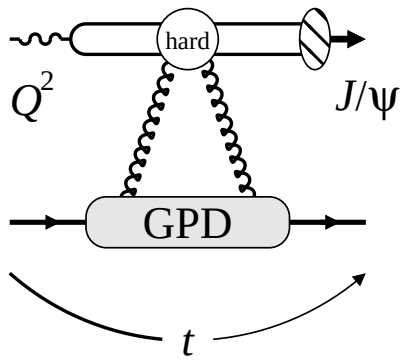
- Local spin–n operators

$$\text{FF[spin-}n](t) \quad = \quad \int dx \; x^{n-1} \; \text{GPD}(x, \xi, t = -\boldsymbol{\Delta}_T^2)$$

EM tensor $n = 2$: Mass, momentum, forces
Ji 96; Polyakov 00

Requires integration over x, not directly accessible

Imaging: Gluons

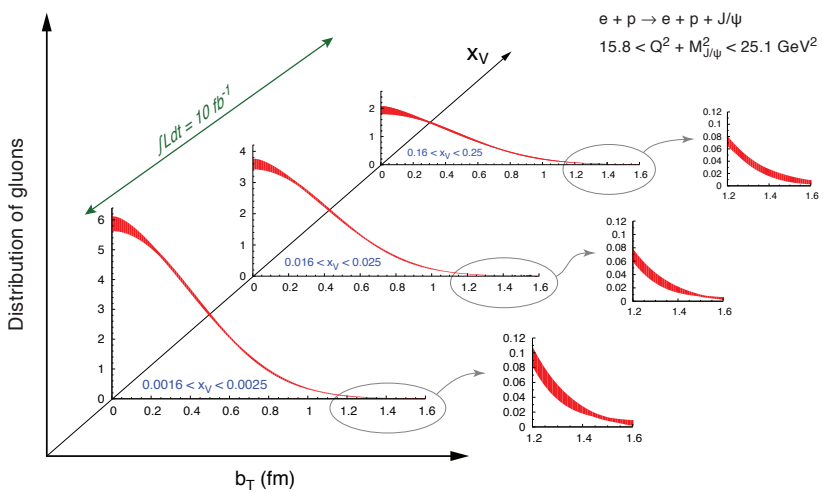


- Gluon distribution in transverse space?

  Gluonic size and shape of nucleon

  Distribution changes with x:
  Parton diffusion $\leftrightarrow$ Regge dynamics,
  chiral dynamics, DGLAP

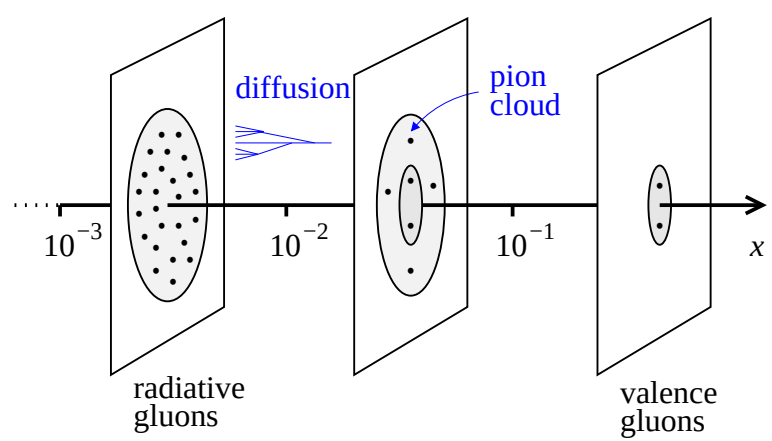
  Input for saturation models,
  multiparton interactions in pp@LHC



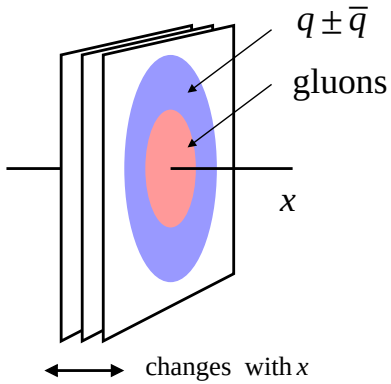
EIC White Paper 2012

- EIC: Gluon imaging with exclusive J/ψ electro- and photoproduction

  Test mechanism through Q^2 dependence,
  comparison with ϕ, DVCS NLO



Imaging: Gluon vs. quark sizes

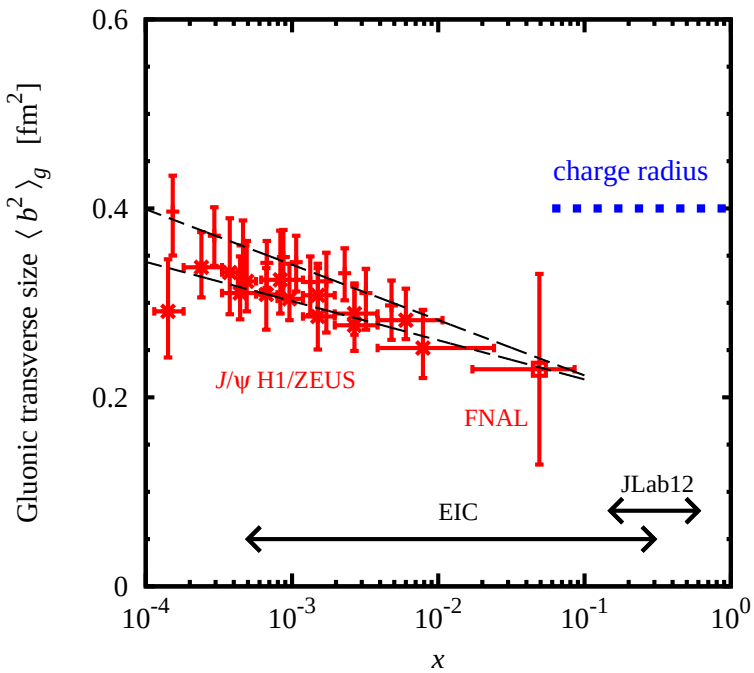


- Nucleon's gluon $\leftrightarrow$ quark sizes?

  $\langle b^2 \rangle(\text{gluon}) < \langle b^2 \rangle(q + \bar{q})$ at x <0.01
  suggested by HERA J/ψ and DVCS

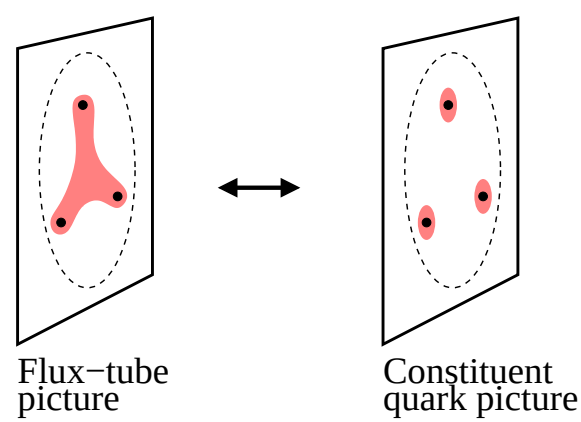
  $\langle b^2 \rangle(\text{gluon}) < \langle b^2 \rangle(\text{charge})$ at x >0.01

  Dynamical origin of valence gluons:
  Chiral symmetry breaking, confinement?

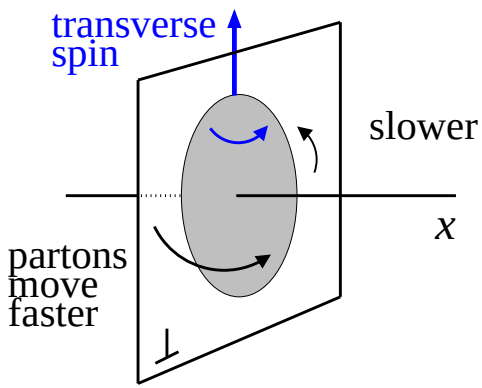


- EIC: Quark-gluon imaging with DVCS

  Detailed simulations: Aschenauer, Fazio, Kumericki, Mueller 13;
  PARTONS framework Moutarde et al.



Imaging: Nucleon and quark polarization



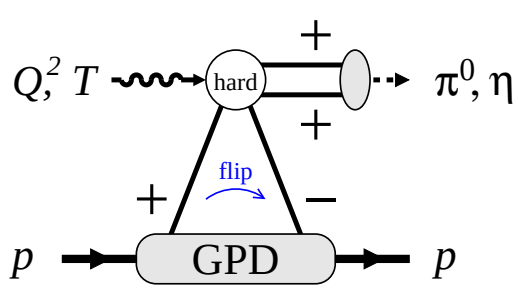
- Effect of transverse nucleon polarization on quark/gluon distributions? Burkardt 00+

  EIC: GPD $E(x, \xi, t)$ from DVCS on $p\uparrow$ and n

  Orbital angular momentum, relativistic motion

- Spatial distribution of quark helicity?

  $q_+(x, b) \leftrightarrow q_-(x, b)$? Spin-orbit effects?

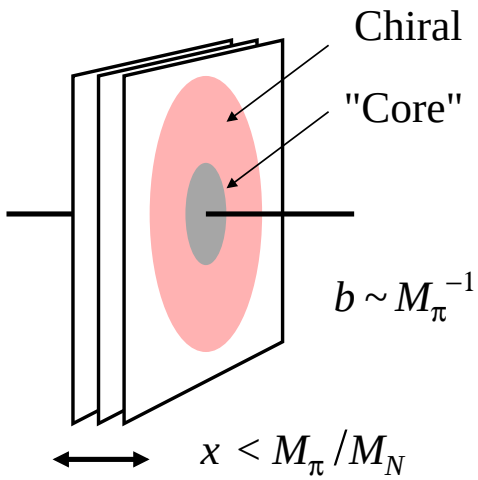


- Spatial distribution of transversity?

  π^0, η production: Twist-3 mechanism with helcity-flip nucleon GPDs & meson DAs
  Goldstein, Liuti et al 08+, Goloskokov, Kroll 09+

  Pattern agrees with JLab6 results; further studies at JLab12
  Bedlinsky et al. 12+, Kubarovsky 16

Imaging: Chiral periphery



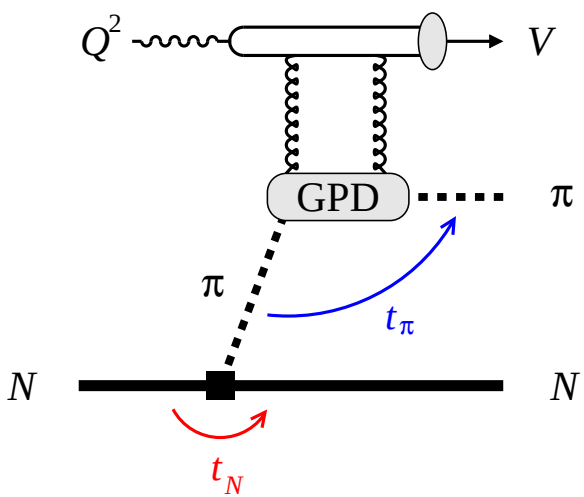
- Chiral component of partonic structure

  Transverse distances $b \sim M_\pi^{-1}$

  Longitudinal momenta $x < M_\pi / M_N \sim 0.1$

  Calculable model-independently using χEFT
  See also: Belitsky, Ji 02; Ando et al 06; Diehl, Manashov, Schafer 06; Kivel Polyakov 02

  Quantum-mechanical interpretation $|N\rangle \to |N\pi\rangle$ with orbital motion, spin-orbit effects
  Granados, CW 15+



- EIC: Peripheral pion knockout
  Strikman, CW 04

  Kinematics $t_N = O(M_\pi^2)$ and $|t_\pi| \gg |t_N|$ selects production on peripheral pion

  Measure pion GPDs, quark/gluon size: Fundamental interest, LQCD

  Use $p \to \pi^0 + p$ or $n \to \pi^- + p$

EM Tensor: Form factors and interpretation

- Form factors of quark/gluon EM tensor (traceless) Ji 96, Polyakov 00

$$\langle p' | \, T^{\mu\nu} \, | p \rangle \;\leftrightarrow\; M_2(t),\; J(t),\; d(t) \qquad [\leftrightarrow A, B, C]$$

$M_2(0)$	quark/gluon light-cone momentum,	$M_2^q(0) + M_2^g(0) = 1$
$J(0)$	quark/gluon angular momentum,	$J^q(0) + J^g(0) \quad = 1/2$

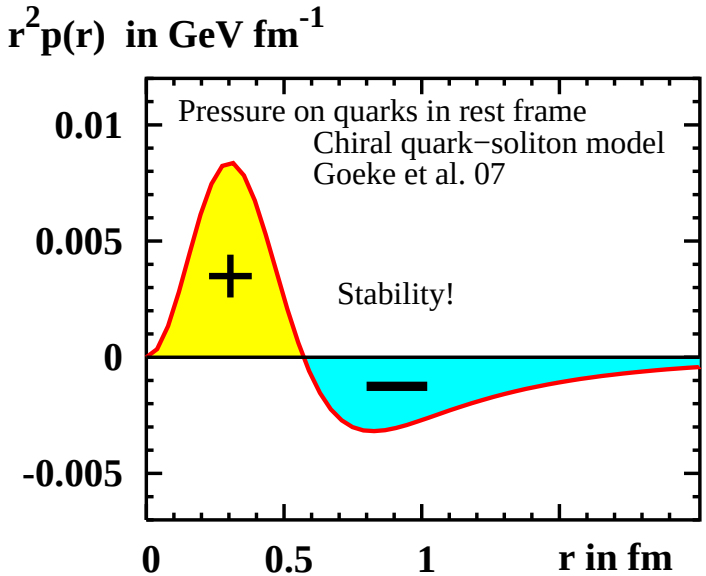
- Spatial interpretation in Breit frame Polyakov 00

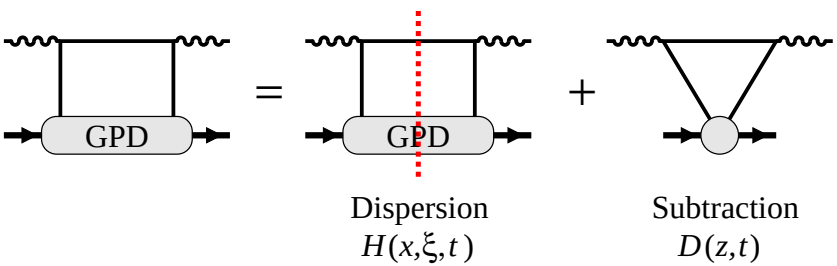
$$(1 + t \ldots) \left\{ \begin{array}{c} M_2(t) \\ J(t) \\ d(t) \end{array} \right\} = \int d^3r \; e^{-i\boldsymbol{r}\boldsymbol{\Delta}} \left\{ \begin{array}{ll} M_N^{-1} T^{00}(\boldsymbol{r}) & \text{energy} \\ \epsilon^{ijk} s^i r^j \, T^{0k}(\boldsymbol{r}) & \text{angular mom.} \\ -\frac{M_N}{2}(r^i r^j - \frac{1}{3} r^2 \delta^{ij}) \, T^{ij}(\boldsymbol{r}) & \text{shear forces} \\ & \leftrightarrow \text{pressure} \end{array} \right\}$$

- Accessible through GPD moments

$$\int_{-1}^{1} dx \; x \left\{ \begin{array}{c} H(x,\xi,t) \\ E(x,\xi,t) \end{array} \right\} = \left\{ \begin{array}{ccc} M_2(t) & & + \frac{4}{5}\,\xi^2\, d(t) \\ -\, M_2(t) & +2J(t) & -\frac{4}{5}\,\xi^2\, d(t) \end{array} \right\}$$

EM Tensor: Quark pressure from D-term





$$d(t) = \int_{-1}^{1} dz\, z\, D(z,t)$$

- FF $d(t)$ describes shear forces and pressure on quarks

  Stability requires that pressure positive inside, negative outside

  Quantative estimates from chiral soliton model (large–N_c limit)
  Goeke, Schweitzer et al. 07

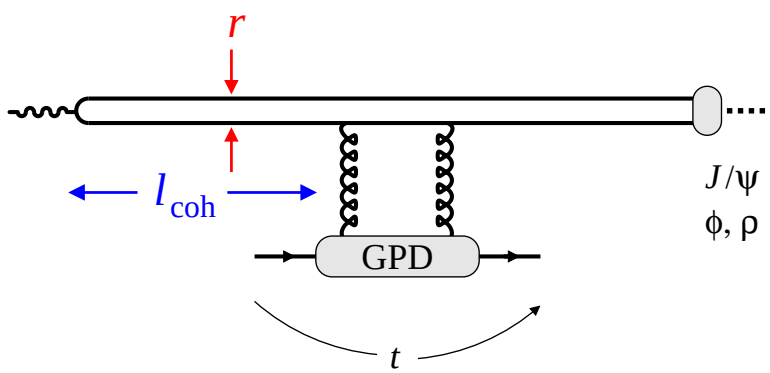
- EIC: $d(t)$ from DVCS

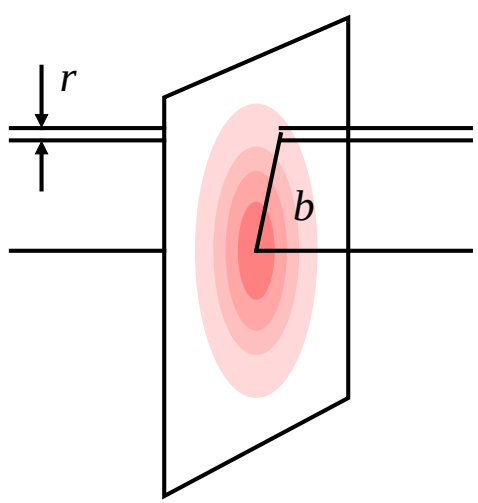
  D-term: Subtraction in dispersive representation of DVCS amplitude
  Polyakov CW 99. Dispersive: Teryaev; Diehl, Ivanov; Vanderhaeghen, Polyakov

  Extract from measurements of ξ–dependence over broad range

  Alt: Dilepton pair photoproduction $\gamma + N \to (l^+ l^-) + N$
  Pire, Szymanowski, Wagner; Boer, Guidal, Vanderhaeghen

Small–x: Dipole picture





- LO collinear factorization for exclusive VM production at small x is equivalent to dipole picture in rest frame
  Brodsky, Frankfurt, Gunion, Müller, Strikman 94
  Frankfurt, Radyushkin, Strikman 98

  Gluon GPD as color dipole moment of nucleon

  Effective LO scale $Q^2_{\rm eff} \sim (\pi/r)^2$

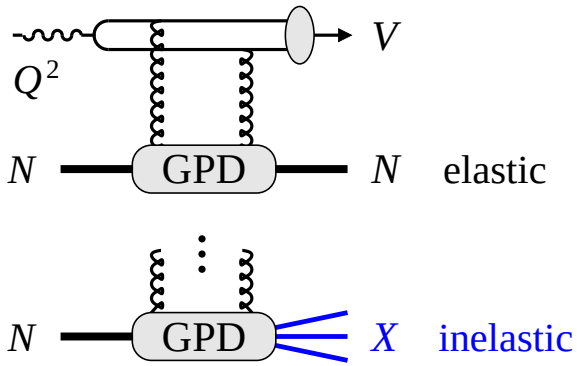
  Space–time evolution, intuition

  Modeling of higher-twist effects:
  VM size, T polarization

- Transverse gluon distribution is essential ingredient in small-x phenomenology
  Frankfurt, Strikman, Rogers, Guzey; Kowalski, Teaney

  Approach to unitarity limit in $eN/\gamma N$:
  Black-disk regime, saturation

Small–x: Quantum fluctuations

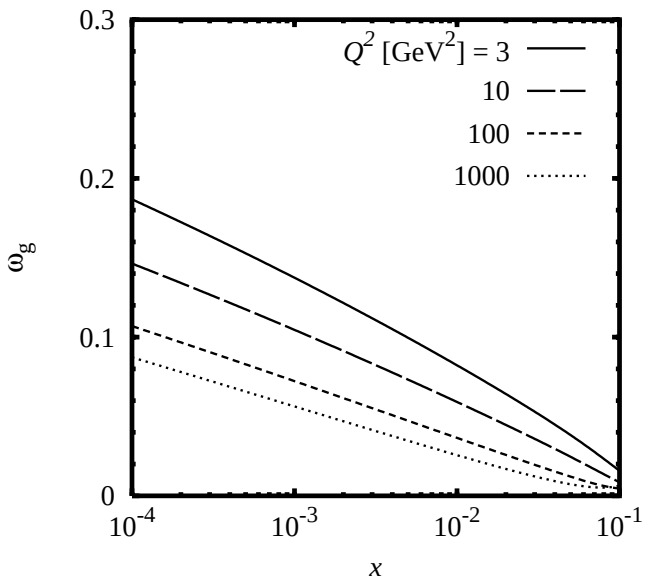


- Quantum fluctuations of gluon density?

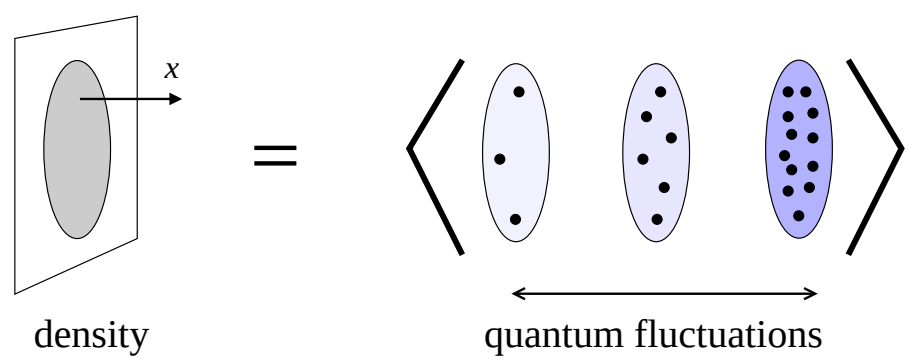
  Fluctuations cause diffractive dissociation $N \to X$ in vector meson production
  Frankfurt, Strikman, Treleani, CW 08

$$\omega_g \equiv \frac{\langle G^2 \rangle - \langle G \rangle^2}{\langle G \rangle^2} = \frac{d\sigma/dt\,(\gamma^* N \to V X)}{d\sigma/dt\,(\gamma^* N \to V N)}\bigg|_{t=0}$$

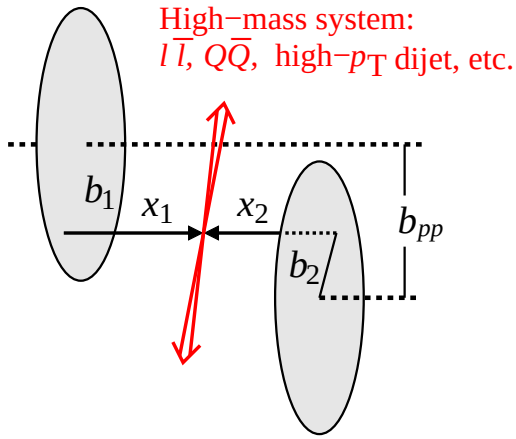
- Dynamical models of gluon fluctuations
  Scaling model: Close, Roberts, Ross 83, cf. EMC effect

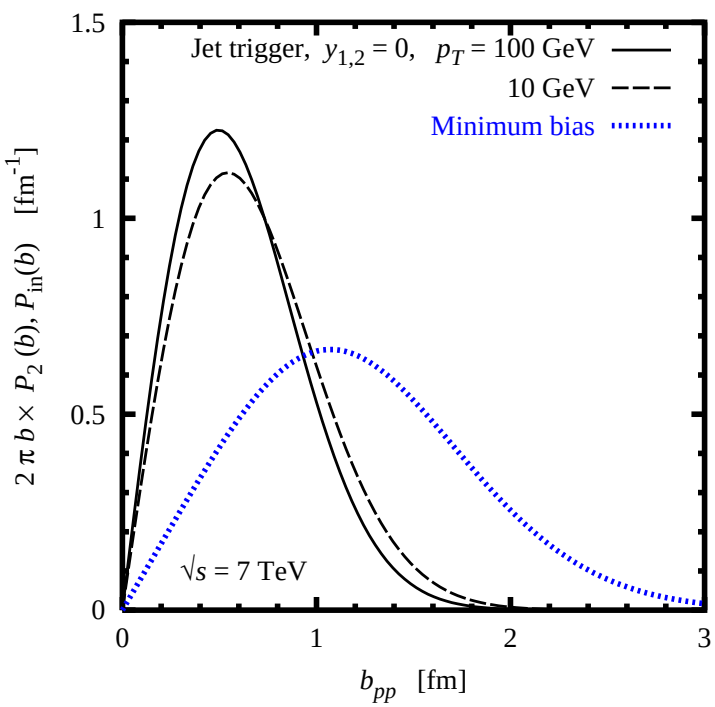


- EIC: Gluon fluctuations with inelastic diffraction



GPDs in pp: Transverse geometry





- Transverse geometry in pp collisions

  Probability for hard process depends on pp impact parameter b_{pp}

  Calculate probability using GPDs from ep
  Frankfurt, Strikman, CW 04

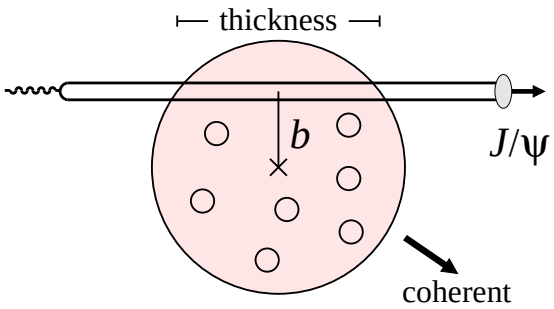
- Applications

  Underlying event $\overset{b_{pp}}{\longleftrightarrow}$ hard process: Geometric correlations
  Frankfurt, Strikman, CW 11

  Multiparton interaction rate $1/\sigma_{\rm eff}$
  Blok, Dokshitzer, Frankfurt, Strikman 11+

  Rapidity gap survival probability in central exclusive diffraction
  Frankfurt, Hyde, Strikman CW 06

GPDs of nuclei: Coherent processes

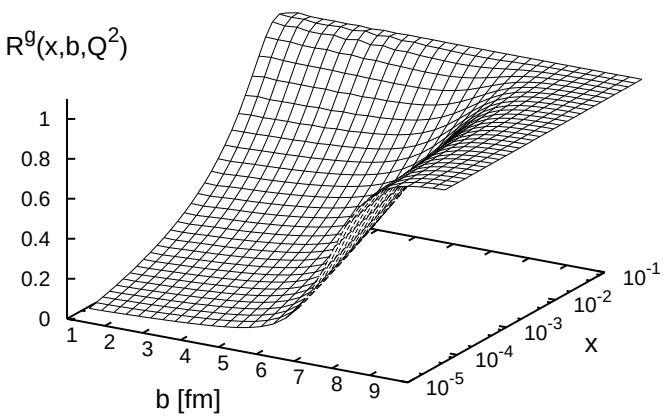


- Nuclear GPDs from coherent processes

  $\langle A|$ Twist-2 $|A\rangle$ $\rightarrow$ nuclear structure, LQCD

  Quark-gluon imaging of nuclei

  Nuclear modifications
  $\leftrightarrow$ NN interactions in QCD



- EIC: Nuclear gluon profile with J/ψ (coh)

  New approach to nuclear shadowing:
  Thickness $\leftrightarrow$ impact parameter b

  Theoretical predictions
  Goeke, Guzey, Siddikov 09

  Forward ion detection
  Light ions $A \lesssim 12$: Positive detection
  Heavy ions: Veto nuclear breakup
  Caldwell, Kowalski 09

Summary

- GPDs as unifying concept in nucleon structure

- Transverse imaging connected with specific dynamical questions

  Origin of large-x gluons, diffusion & Regge dynamics, chiral dynamics

- Form factors of energy–momentum tensor as fundamental characteristics

  Broader context for angular momentum sum rule
  Access to forces and pressure in nucleon

- Quantum fluctuations of gluons from inelastic diffraction

- GPDs provide crucial insight into pp@LHC