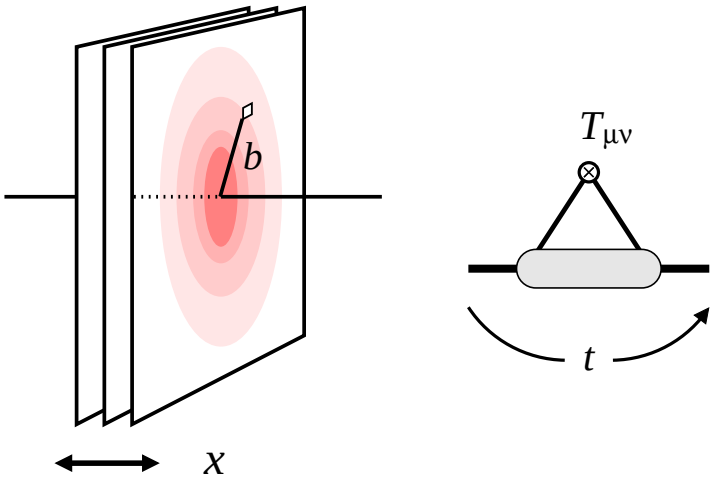
Exploring structure and dynamics with GPDs at EIC

C. Weiss (JLab), Workshop "Extraction of GPDs," NCBJ Warsaw, Poland, 22-25 Jan 2019



Focus on dynamical system

Connect structure $\leftrightarrow$ dynamics

Pose questions for discussion!

- Nucleon structure in QCD
- GPDs and hard exclusive processes

  Accessible information, dispersion relations
- Transverse structure

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

  Helicity, transversity, spin-orbit effects

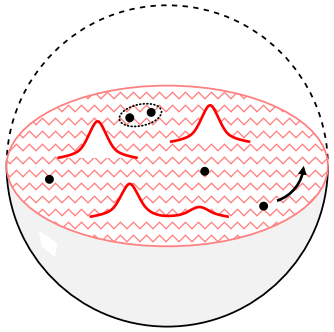
  Chiral periphery $b \sim M_\pi^{-1}$
- Energy-momentum tensor

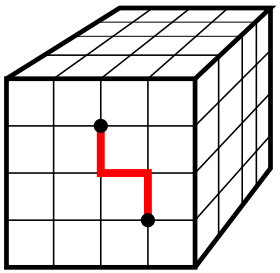
  Mass, momentum, forces $\leftrightarrow$ D-term

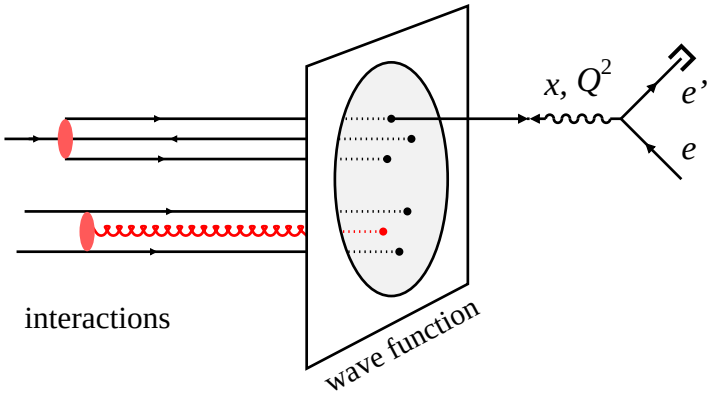
[• Connections

  GPDs in diffraction: Quantum fluctuations
  GPDs in pp: Multiparton interactions

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

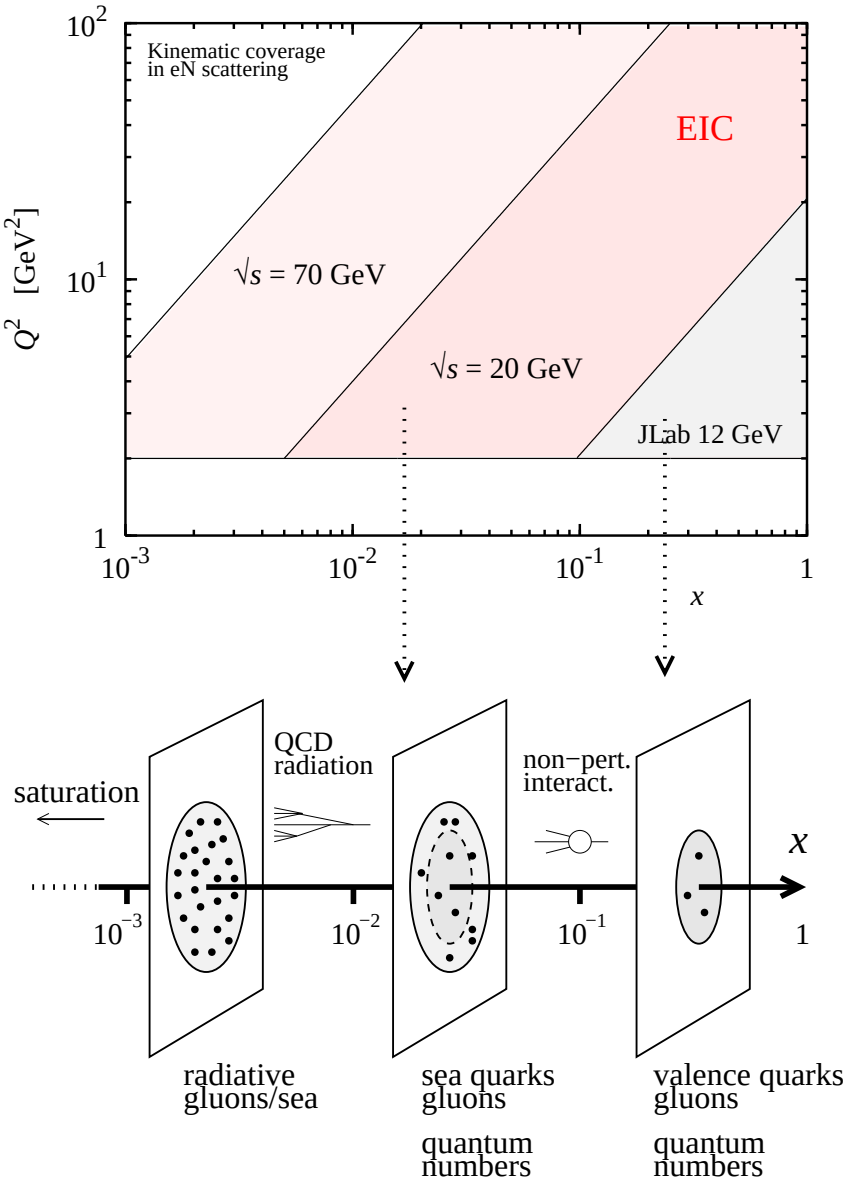
- Particle–based description

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

  Emerges from factorization of high-momentum transfer processes in QCD

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

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

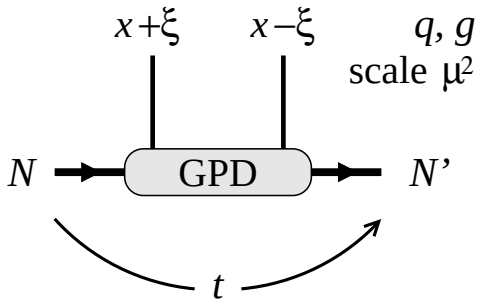
  Transverse spatial distributions GPDs

  Orbital motion, angular mom TMDs, GPDs

  Correlations, fluctuations MPDs, GPDs

  Operator definition $\langle N | \, \mathrm{QCD\text{–}Op} \, | N \rangle$
  Universal properties $\rightarrow$ renorm, LQCD

GPDs: Operators and matrix elements



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

- Transition matrix elements of twist-2 operators
  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

- Extensions

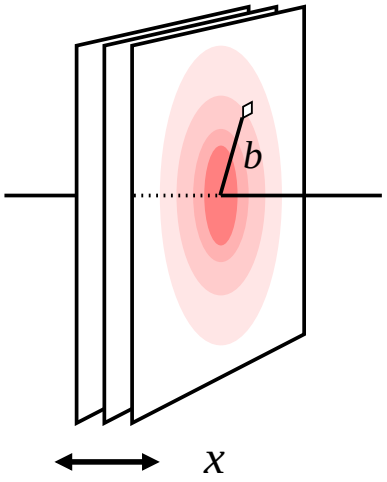
  Chiral-odd twist-2 operators → Talk Tezgin

  Twist-3 operators

  $N \to N^*, N\pi$ transition matrix elements

  Nuclear GPDs

GPDs: Nucleon structure applications

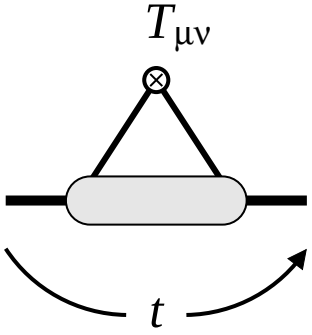


- Transverse imaging

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

Transverse spatial distribution of quarks/gluons with LC momentum x: Size and shape of nucleon in QCD
Burkardt 00+, Diehl 02

Diagonal GPD $\xi = 0$ not directly accesible



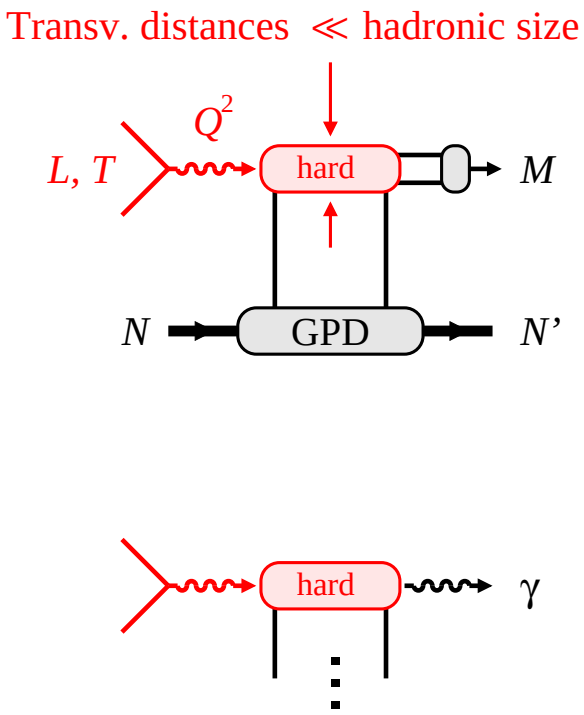
- Local spin–n operators

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

Energy-momentum tensor $n = 2$: Mass, momentum, angular momentum, forces Ji 96; Polyakov 00

Requires integration over x, not directly accessible

GPDs: Hard exclusive processes



- Exclusive production at $Q^2 \gg$ (hadronic size)$^{-2}$

  Transverse distances in interaction $\ll$ hadronic size

  Collinear factorization: GPDs $\times$ hard process $\times$ DA
  Collins, Frankfurt, Strikman 96

  $Q^2 \to \infty$: Pointlike $q\bar{q}$ pair, pQCD interactions,
  L response dominant in meson production

  $Q^2 \sim$ few GeV^2: Finite size distribution,
  non-perturbative interactions, $L + T$ responses → Talk Kroll

- Analysis in two steps

  I) Verify approach to small-distance regime through model-independent tests:
  Q^2-dependence, universality of t-slopes, ... HERA, HERMES, COMPASS, JLab → EIC

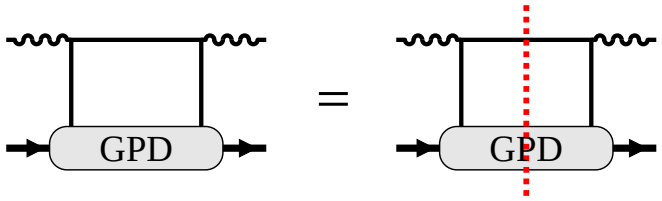
  II) Extract information on GPDs from factorized formulas

GPDs: Accessible information

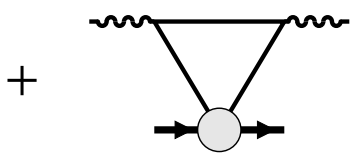
$$\text{Im}\,\mathcal{H}(\xi,t) = \text{GPD}(\xi,\xi;t)$$

$$\text{Re}\,\mathcal{H}(\xi,t) = \int d\xi' \,\frac{\text{GPD}(\xi',\xi';t)}{\xi'-\xi} + D(t)$$

$D(t)$ subtraction constant



Dispersion



Subtraction

- Dispersion relations for twist-2 amplitudes
  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

- Possible approaches

  A) Use dynamics/models to relate

  $\text{GPD}(\xi,\xi;t) \longleftrightarrow \text{GPD}(x,0;t)$

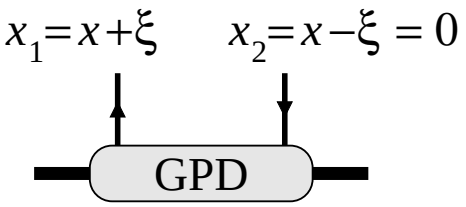
  measurable — imaging

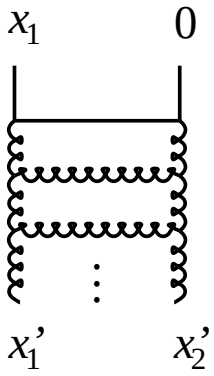
  B) Interpret directly accessible structures

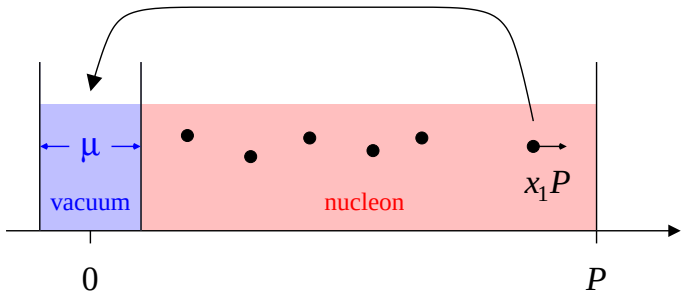
  $\text{GPD}(\xi,\xi;t)$ nucleon response to stopping of fast quark

  $D(t)$ D-term, FF of EM tensor

GPDs: $x = \xi$ interpretation and dynamics







- GPD at $x = \xi$: Amplitude for stopping of parton with LF fraction 2ξ

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

  GPD at input scale quasi-diagonal

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

- Large x, low Q^2: Configurations generated non-perturbatively, but how?

  Parton picture: $x \to 0$ vacuum fluctuations, $\leftrightarrow$ spontaneous symmetry breaking

  GPDs($x \to \xi$) sensitive to UV cutoff of effective dynamics, pert – non-pert boundary
  Boernig et al. 97

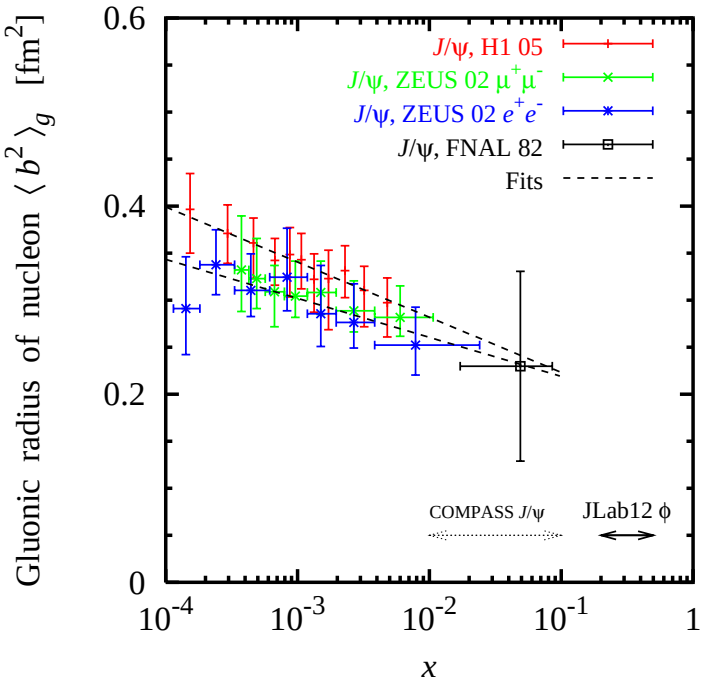
GPDs: Discussion

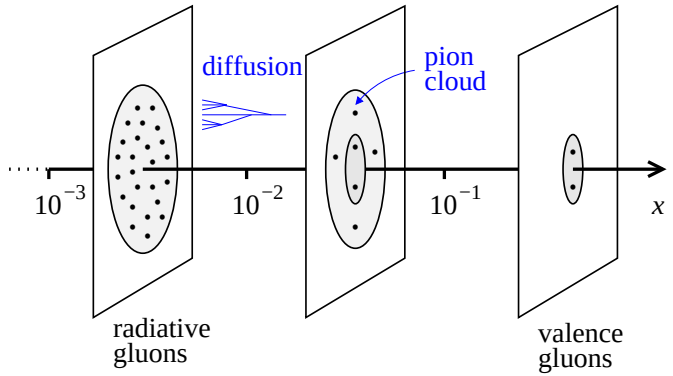
- Uses and limitations of mathematical models for "skewing"?
  Double distributions, dual parametrization

- Use of dispersion relations in analysis of hard exclusive processes?

- Physical models of $x = \xi$ GPDs?
  Dynamics? E.g. Aligned Jet Model for small x:

Transverse structure: Gluons





FSW, PRD83 (2011) 054012. $\mu 2 = 3\,\mathrm{GeV}2$

- Gluon distribution in transverse space?

  Gluonic size and shape of nucleon

  Distribution changes with x and Q^2:
  Parton diffusion $\leftrightarrow$ Regge dynamics, DGLAP

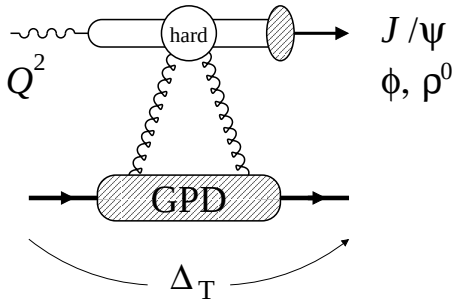
  Input for saturation models, pp@LHC

- Exclusive heavy quarkonium production

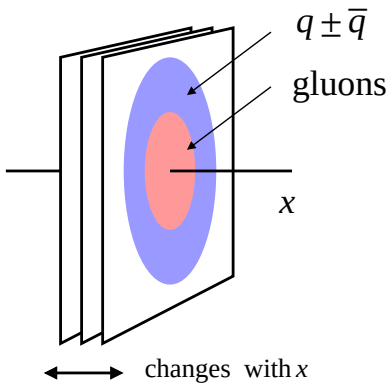
  HERA: J/ψ photo/electroproduction $x < 10^{-2}$
  Mechanism tested, slopes, universality
  Frankfurt, Strikman, Koepf 96; Goloskokov, Kroll 08+

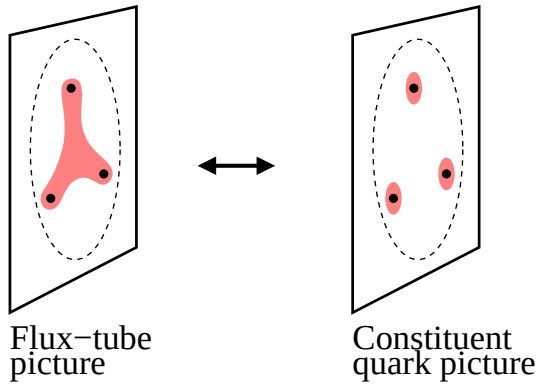
  JLab12: ϕ electroproduction $x > 0.2$ → Girod

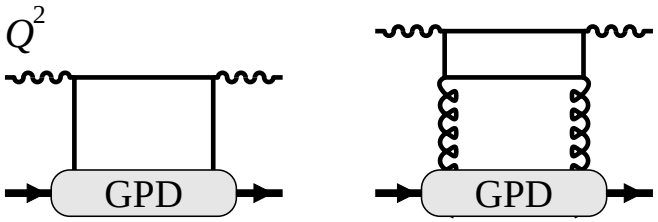
  EIC: J/ψ electroproduction → Aschenauer



Transverse structure: Gluons vs. quarks







- Gluon $\leftrightarrow$ quark distributions?

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

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

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

- Nonsinglet quark transverse distributions

  $q \leftrightarrow \bar{q}, u \leftrightarrow d$ provide information
  on nonperturbative interactions

- Exclusive processes

  DVCS NLO quarks + gluons
  EIC simulations: Aschenauer, Fazio, Kumericki, Mueller 13

  Vector mesons: ρ^0 gluon + singlet quarks
  ρ^+, K^{*+} nonsinglet quarks

Transverse structure: Discussion

- Theoretical accuracy of transverse gluon imaging with J/ψ?
  Finite-size effects, skewness

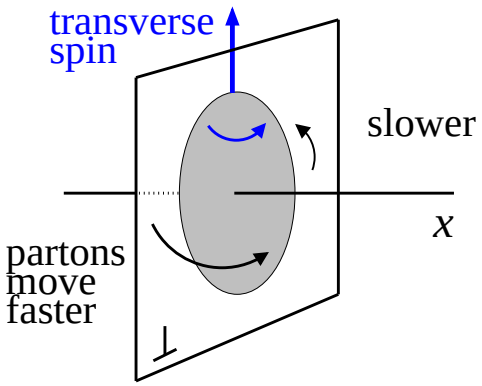
- Test universality of transverse gluon distributions with ϕ, Υ?

- Status of heavy quarkonium and light vector meson production at NLO?
  Possible joint analysis with DVCS at NLO?

- Use of non-singlet vector mesons for flavor separation at $x < 0.1$?
  Not much explored

- Theoretical models for transverse gluon distribution?

Transverse structure: Polarization



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

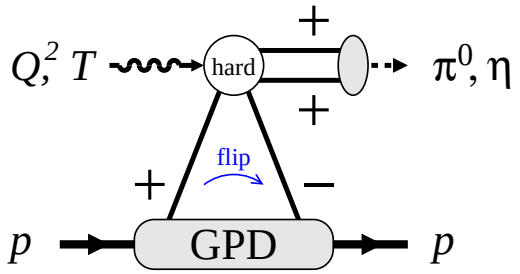
  Relativistic motion, spin-orbit effect, partonic representation of magnetic moment

  Models based on Pauli FF & PDFs for large-x
  Diehl, Kroll, Feldmann, Jakob 99; DK 13

  JLab12, EIC: GPD $E(x,\xi,t)$ in DVCS on $p\uparrow$ and n, also vector meson production

- 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+

  Describes JLab6 results; detailed studies at JLab12
  Bedlinsky et al. 12+, Kubarovsky 16

Transverse structure: Discussion II

- Status of theoretical models of $E(x,0,t)$?
  How much information needed from exclusive processes?

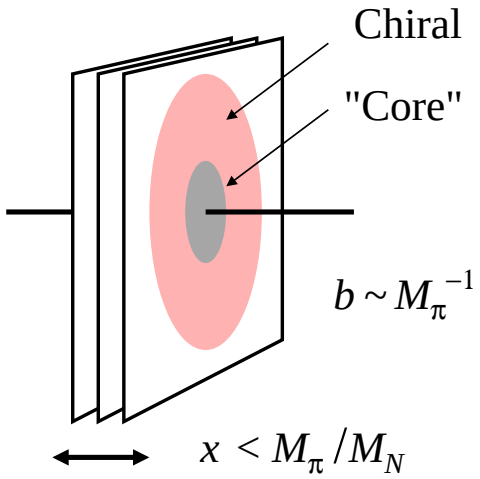
- Prospects for measurements of $E(x,\xi,t)$ in DVCS at EIC?

- Possibility of measurement of E_{gluon} in exclusive ϕ production at EIC?

- Prospects for measurements of helicity GPD $\widetilde{H}$ in DVCS?
  What about π^0/η production σ_L twist-2?

- Spatial distribution of transversity from π^0/η twist-3 at EIC?

Transverse structure: Chiral periphery



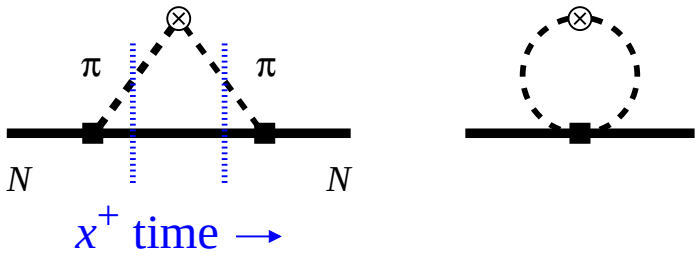
- Chiral component of partonic structure

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

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

  Parametrically distinct

  Calculable model-independently using χEFT
  Strikman, CW 03/08. See also Belitsky, Ji 02; Ando et al 06; Diehl, Manashov, Schafer 06; Kivel Polyakov 02



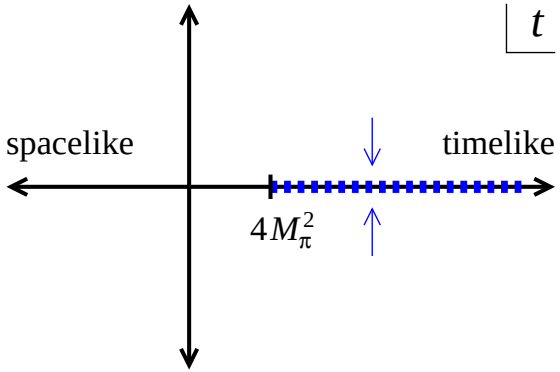
- Light-front formulation of chiral dynamics

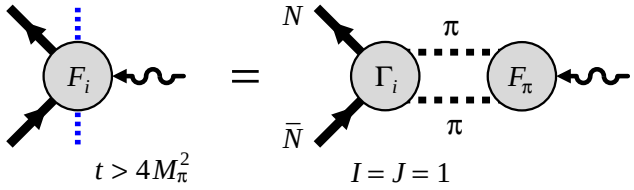
  LF wave function $N \to \pi N, \pi \Delta$
  calculable from chiral Lagrangian

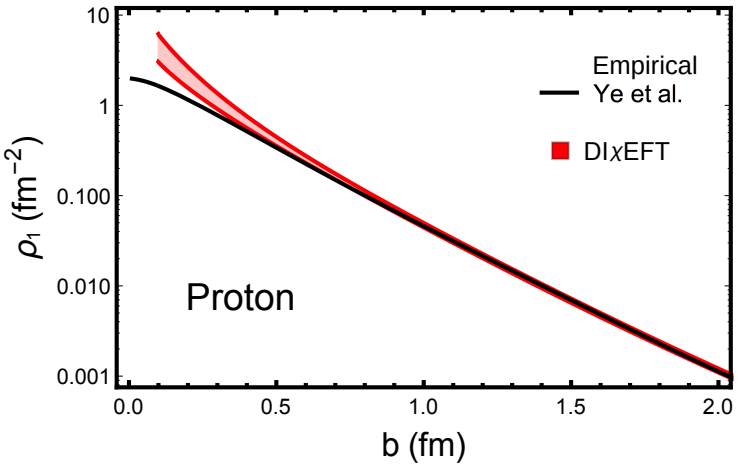
  Equivalent to invariant formulation

  Mechanical picture of peripheral densities/GPDs, orbital angular momentum, spin-orbit effects
  Granados, CW 15+

Transverse structure: Chiral periphery







- Peripheral charge/magnetization densities

  Calculated using new method combining dispersion relation for nucleon form factors, elastic unitarity in $\pi\pi$ channel, χEFT dynamics for πN amplitudes

  Includes $\pi\pi$ rescattering in t channel, effect of ρ resonance

- Extensions and applications

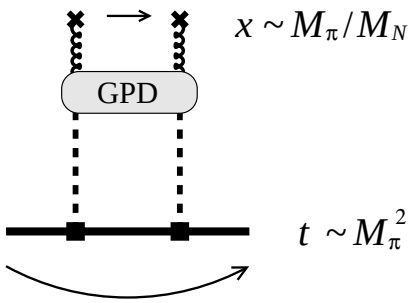
  Nucleon spacelike form factors $|t| \lesssim 1$ GeV^2

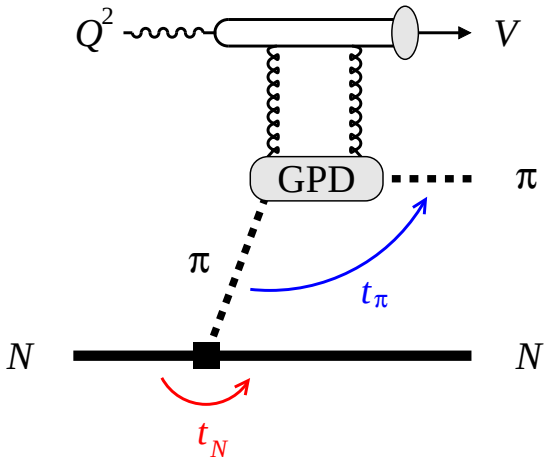
  Proton radius extraction

  Energy-momentum tensor FFs

  Resonance transition FFs $N \to \Delta, \pi N$

Transverse structure: Chiral periphery





- Chiral component of GPDs affects t-dep, difficult to observe in $\gamma^* N \to MN$

- 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 $n \to \pi^- + p$

Discussion

- Feasibility of peripheral pion knockout measurements
- Other possible tests of chiral dynamics with EIC?

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, $J^q(0) + J^g(0) = 1/2$

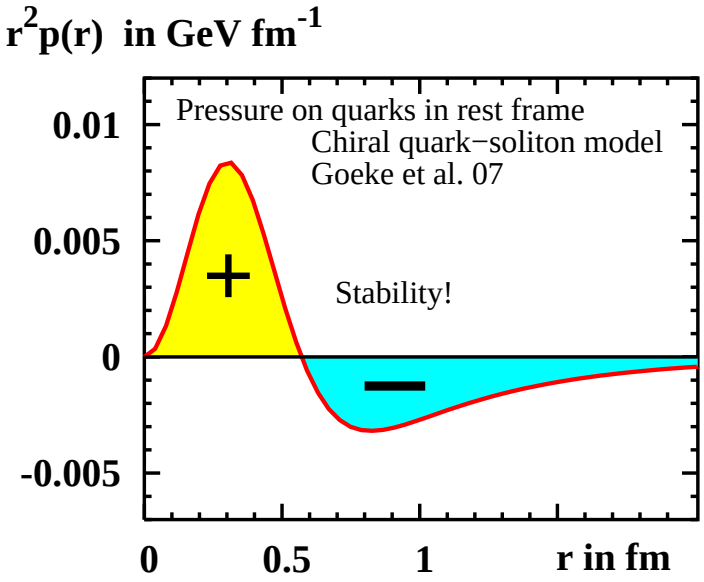
- Spatial interpretation in Breit frame — Polyakov 00

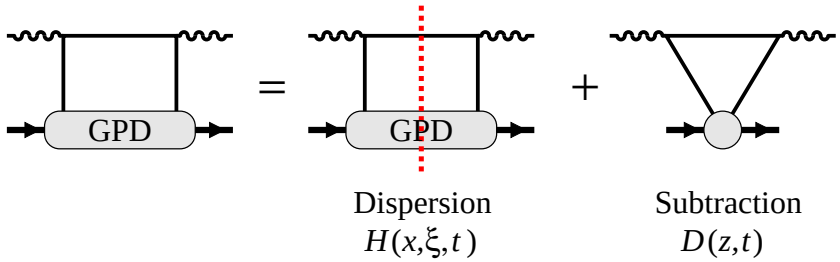
$$(1 + t\ldots) \left\{ \begin{array}{c} M_2(t) \\ J(t) \\ d(t) \end{array} \right\} = \int d^3r\; e^{-ir\Delta} \left\{ \begin{array}{ll} M_N^{-1} T^{00}(\boldsymbol{r}) & \text{energy} \\ \epsilon^{ijk} s^i r^j\, T^{0k}(\boldsymbol{r}) & \text{angular mom.} \\ -\frac{M_N}{2}(r^i r^j - \frac{1}{3} r^2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

- 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: D-term and quark pressure





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

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

  Stability requires that pressure positive inside, negative outside

  Estimated in chiral soliton model (large-N_c)
  Goeke, Schweitzer et al. 07

- $d(t)$ from DVCS

  D-term: Subtraction in dispersion relation
  Polyakov Weiss 99. Dispersive: Teryaev; Diehl, Ivanov; Vanderhaeghen, Polyakov

  Extract from measurements of DVCS ξ-dependence over broad range
  First results from JLab12 → Talk Elouadrhiri

  No GPD parametrization required!

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

EM tensor: Discussion

- Prospects for D-term extraction: JLab12, COMPASS, EIC?
  Need for high-energy data? Importance of precision vs. energy coverage?

- Dilepton pair production with EIC: Challenges, simulation tools, prospects?
  DVCS $\leftrightarrow$ TCS universality test, D-term extraction

- Possibility of extracting information on other EM tensor FFs with?
  Model dependence?

Summary

- Nonperturbative QCD dynamics expressed in partonic structure
- GPDs represent essential tool for structure and dynamics

  Transverse spatial distribution of quarks/gluons $\leftrightarrow$ diffusion, chiral dynamics, large-x gluons

  Access to QCD energy-momentum tensor $\leftrightarrow$ mass, momentum, angular mom, forces

- Analysis of hard exclusive processes remains challenging

  Large finite-size/higher-twist effects in meson production

  Possibly substantial higher-twist contributions in DVCS

  Modeling of GPDs at $x = \xi$ with soft non-perturbative interactions

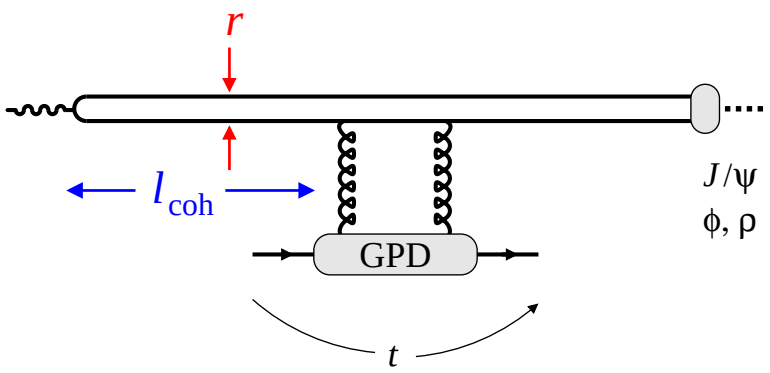
- Great prospects for exclusive processes with EIC

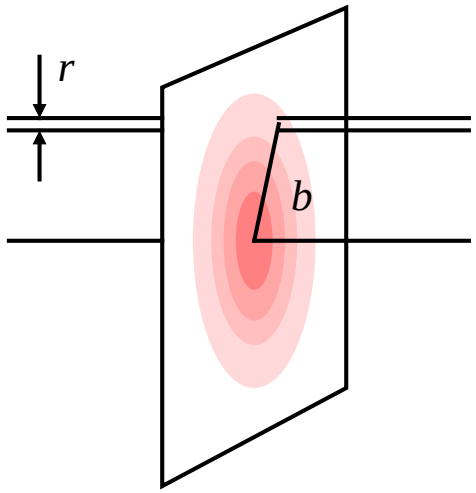
  Establish reaction mechanism: Quantify approach to small-distance regime,
  test universality of GPDs, QCD evolution effects

- Hope for specific steps from this workshop

Supplementary material

GPDs at 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 $Q^2_{\rm eff} \sim (\pi/r)^2$

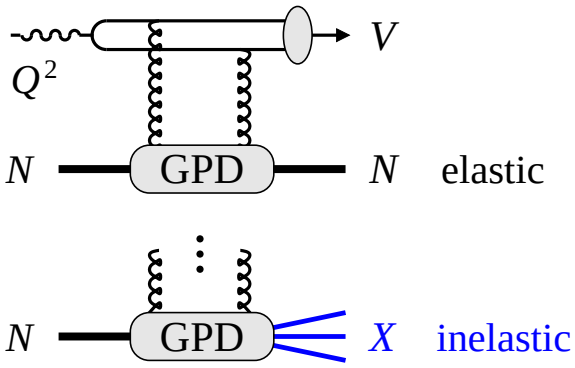
  Space–time evolution, intuition

  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

GPDs at small x: Quantum fluctuations

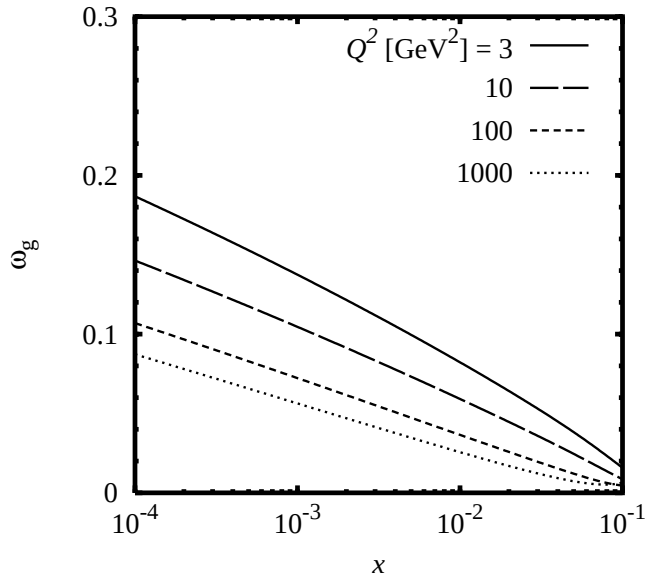


- Quantum fluctuations of gluon density?

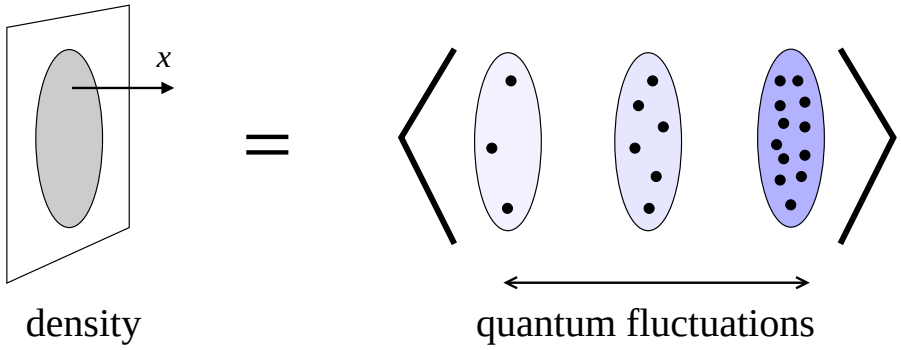
  Fluctuations cause diffractive dissociation $N \to X$ in vector meson production
  Frankfurt, Strikman, Treleani, CW 08

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

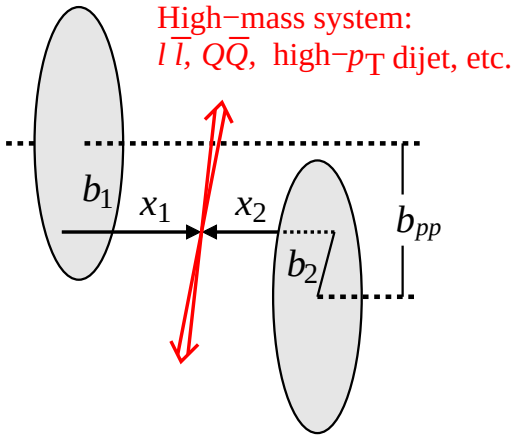
- Dynamical models of gluon fluctuations
  Scaling model: Close, Roberts, Ross 83, cf. EMC effect

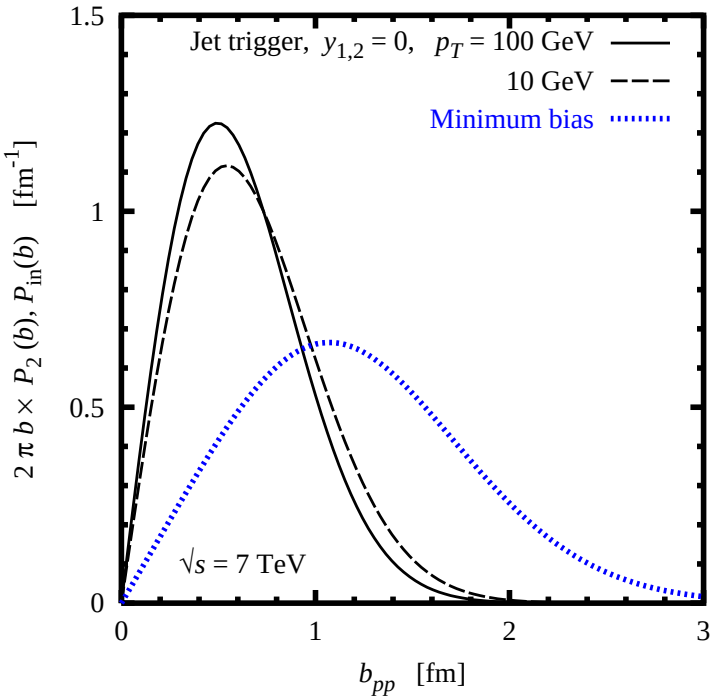


- EIC: Gluon fluctuations with inelastic diffraction



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

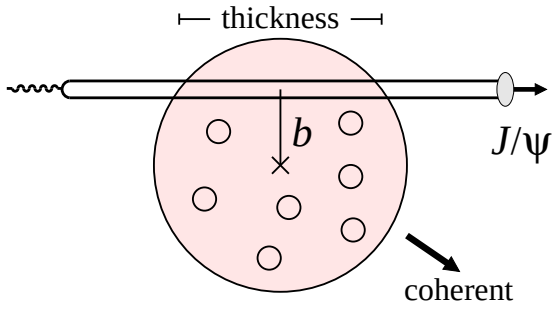
- Applications

  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

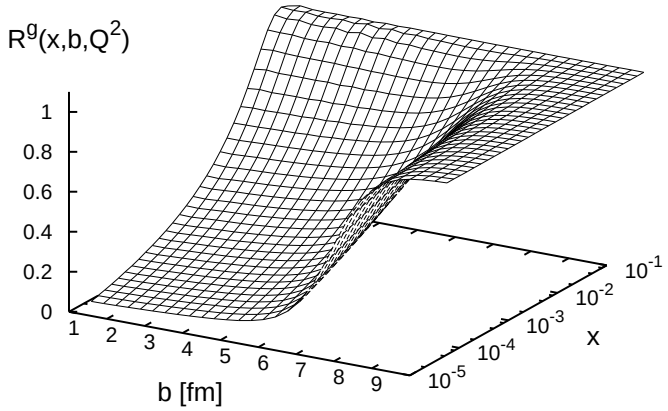


- Nuclear GPDs from coherent processes

  $\langle A|$ 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