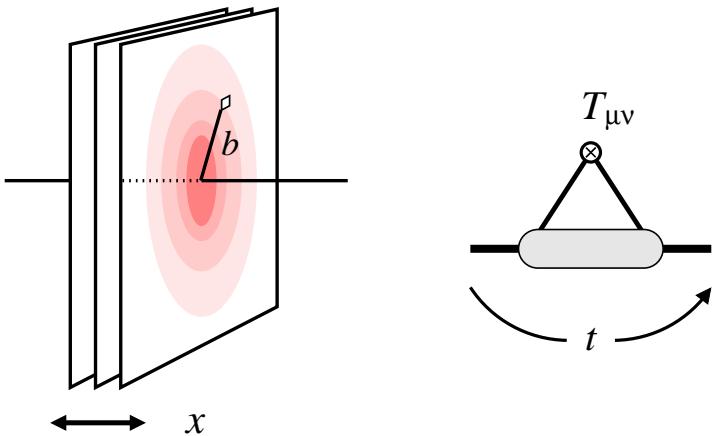


Exploring hadron structure with generalized parton distributions

C. Weiss (JLab), IWHSS2020 Hadron Structure and Spectroscopy, Trieste, 16-18 Nov 2020



- Hadron structure in QCD

Emergent phenomena and dynamics

Parton picture and GPDs

- Parton imaging of nucleon

Transverse distribution gluons \leftrightarrow quarks

Helicity and spin-orbit effects

Transversity and chiral-odd structures

- Energy-momentum tensor

Mass, momentum, forces, D-term

- Extensions

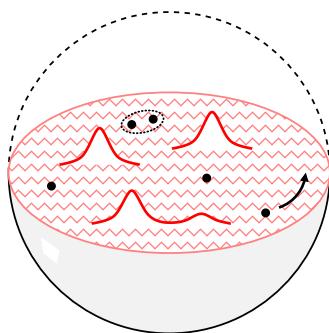
Dilepton production, other processes

Connect partonic structure with dynamics:
Chiral symmetry breaking, emergence of mass

Pose specific questions to be answered by
measurements: JLab12, COMPASS, EIC

Nucleon in QCD: Dynamical system

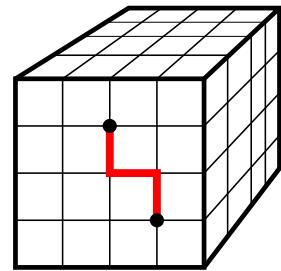
2



- Emergent phenomena

Unique dynamical system: Relativistic, quantum-mechanical, strongly coupled

Chiral symmetry breaking: Strong fields, $q\bar{q}$ pairs, dynamical mass generation, effective DoF



- Field-theoretical description

Imaginary time $t \rightarrow i\tau$: Statistical mechanics, lattice and continuum methods

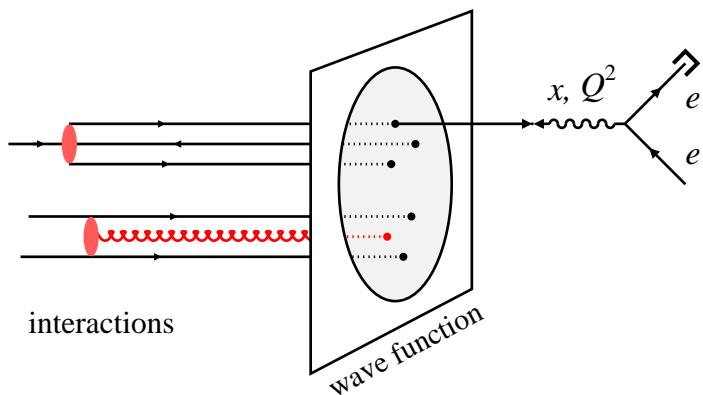
- Particle-based description

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

Emerges from factorization of high-momentum transfer processes in QCD: Scale, collinear sector

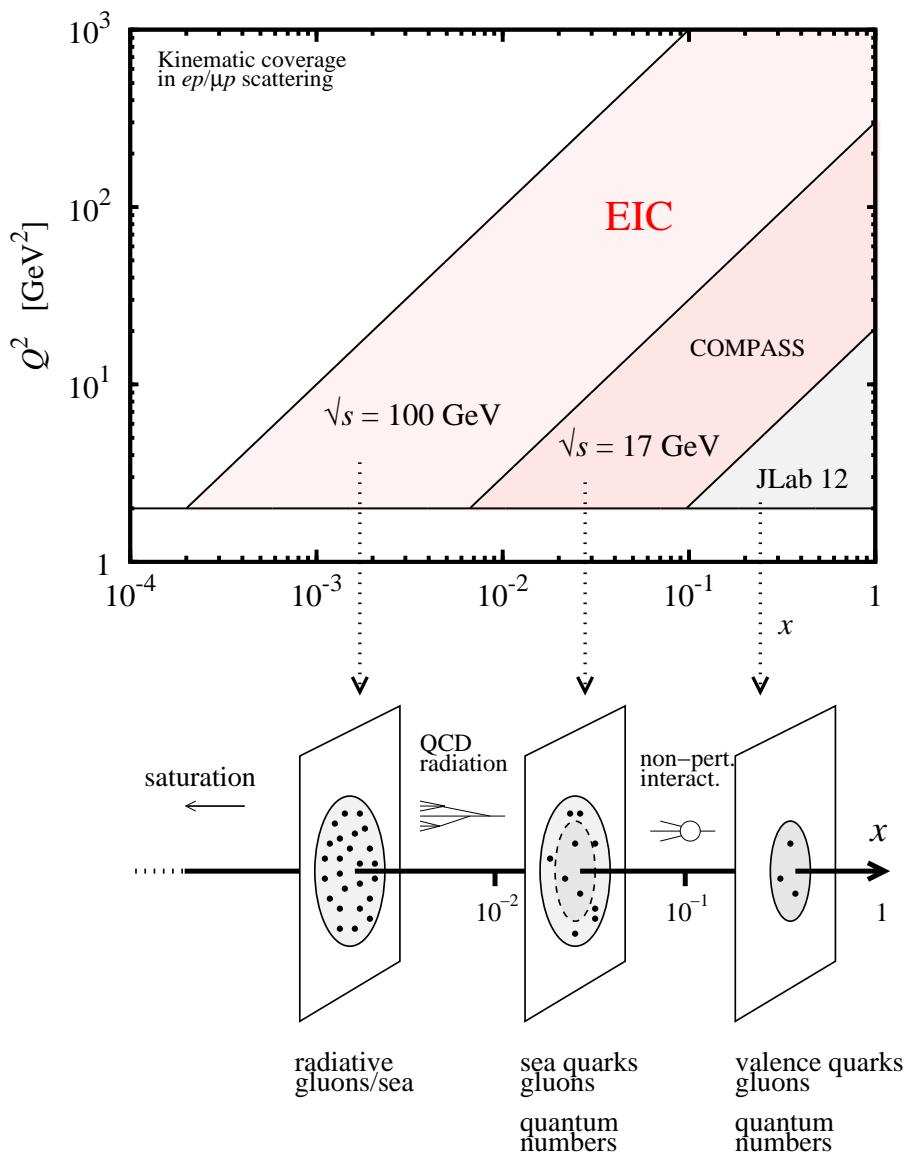
Many-body system: Constituents, spatial structure, orbital motion, . . .

Dynamics expressed in particle distributions



Nucleon in QCD: Landscape

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- Components and dynamics

$x > 0.2$ "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

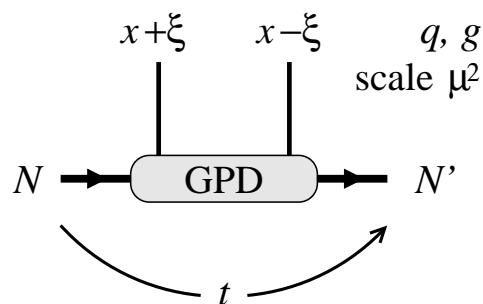
Orbital motion, angular mom TMDs, GPDs

Correlations, fluctuations MPDs, GPDs

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

GPDs: Operators and processes

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

- Transition matrix elements of twist-2 operators

Unify concepts of PDF and elastic FF

Müller et al 1994+, Ji 1996, Radyushkin 1996

Quark/gluon and nucleon helicity components

Renormalization and scale evolution DGLAP–ERBL

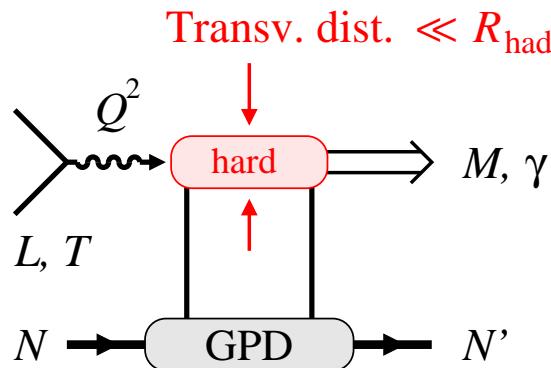
Extends to $N \rightarrow N^*, Nh$, nuclei

- Hard exclusive processes

Collinear factorization

Collins, Frankfurt, Strikman 1996; Collins Freund 1999

Transverse distances in interaction \ll hadron size



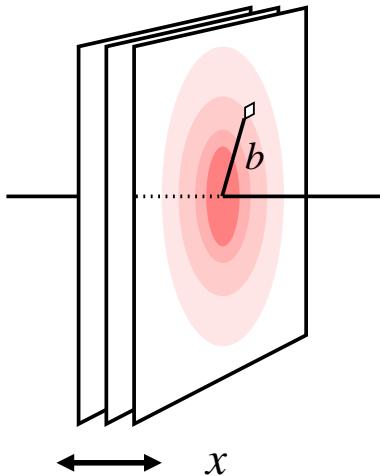
Approach to short-distance regime must/can be tested experimentally and theoretically, depends on channel and kinematics

GPDs: Nucleon structure applications

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- Transverse imaging

$$f(x, b) = \underset{\Delta_T \rightarrow b}{\text{Fourier}} \quad \text{GPD}(x, \xi = 0, t = -\Delta_T^2)$$

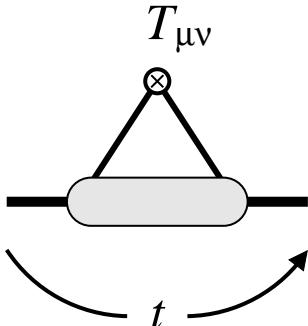


Transverse spatial distribution of quarks/gluons with
LC momentum x : Size and shape of nucleon in QCD
Burkardt 2000+, Diehl 2002

Diagonal GPD $\xi = 0$ not directly accessible

- Local spin- n operators

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

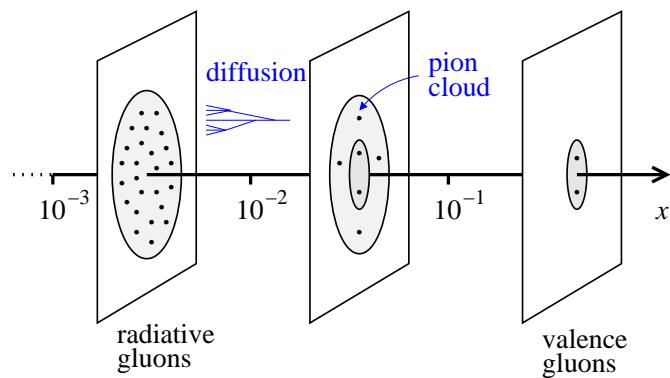
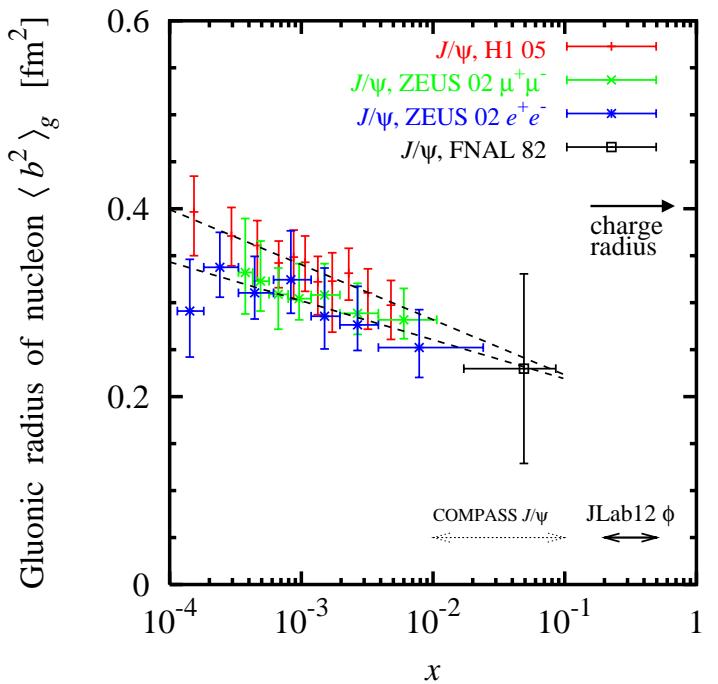


Energy-momentum tensor $n = 2$: Mass, momentum,
angular momentum, forces
Ji 1996; Polyakov 2000

Requires integration over x , not directly accessible

Parton imaging: Gluons

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- Gluon distribution in transverse space?

Gluonic radius and shape of nucleon
Input for $pp@\text{LHC}$ MC, small- x physics

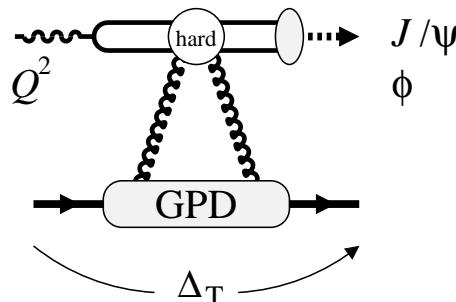
Spatial distribution changes with x :
 $x < 10^{-2}$ Diffusion in QCD radiation
 $x \sim 10^{-1}$ Non-perturbative interactions $\leftrightarrow \chi\text{SB}?$

- Exclusive heavy quarkonium production

HERA: J/ψ photo/electroproduction $x < 10^{-2}$
Mechanism tested, slopes extracted, universality
Frankfurt, Strikman, Koepf 1996; Goloskokov, Kroll 2008+

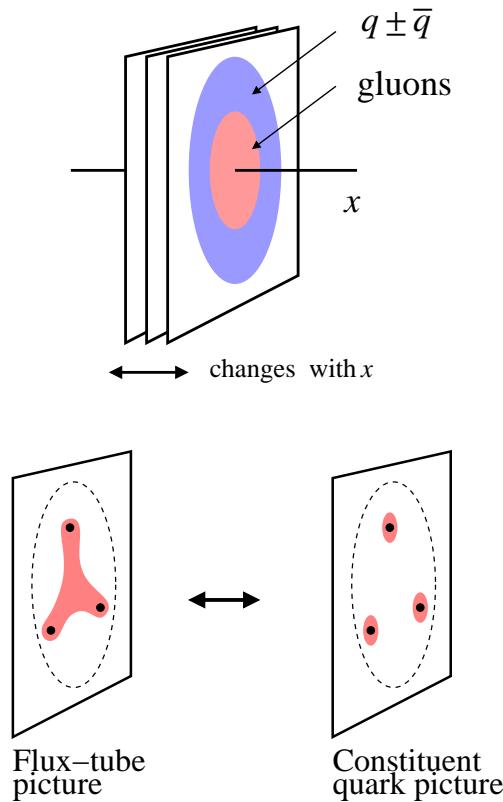
COMPASS: J/ψ electroproduction
JLab12: ϕ electroproduction $x > 0.2$
EIC: Gluon imaging program

→ d'Hose



Parton imaging: Gluons vs. quarks

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- Gluon vs. quark transverse distributions?

$$\langle b^2 \rangle(\text{gluon}) < \langle b^2 \rangle(q + \bar{q}) \text{ at } x < 0.1$$

HERA J/ψ + DVCS, COMPASS DVCS

$$\langle b^2 \rangle(\text{gluon}) < \langle b^2 \rangle(\text{charge})$$

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

- Nonsinglet quark transverse distributions

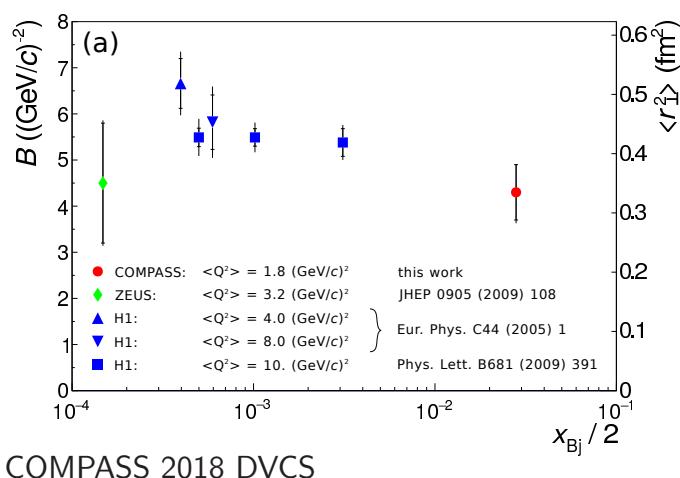
$q \leftrightarrow \bar{q}$, $u \leftrightarrow d$ provide information
on nonperturbative interactions

- Exclusive processes

DVCS NLO quarks + gluons

Belitsky, Müller, Kirchner 2001; Freund, McDermott 2001;
Kumericki, Mueller, Paszek-Kumericki 2008

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

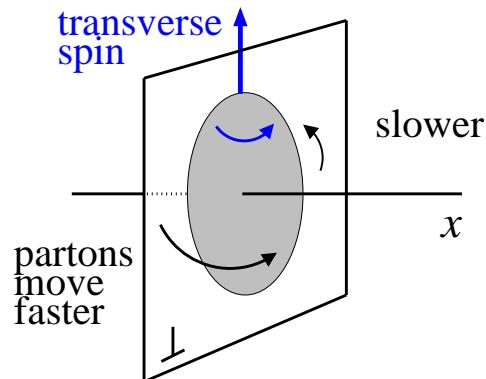


COMPASS 2018 DVCS

Parton imaging: Nucleon and quark polarization

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



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

Partonic composition of anomalous magnetic moment

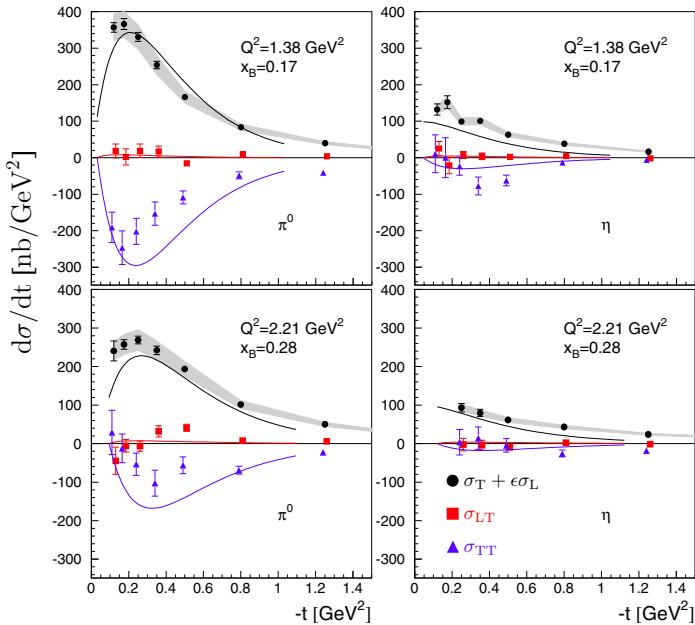
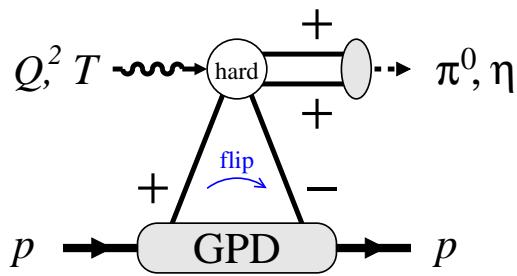
Orbital angular momentum, relativistic motion

GPD E_g from exclusive ϕ

- Spatial distribution of quark helicity?

Parton imaging: Transversity

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CLAS6 2017 Bedlinskiy et al.

Also flavor separation with π^0/η Kubarovsky 2014

- Chiral-odd structures from χ_{SB}

Pion chiral-odd DA: Twist-3, quark helicity-flip, angular momentum $L = 1$ in pion

Nucleon chiral-odd GPDs: Transversity

Large helicity-flip amplitudes, formally subleading
Goldstein Liuti et al. 2008+, Goloskokov, Kroll 2011+

Direct evidence of χ_{SB} in hard processes

- Pseudoscalar meson production

JLab6/12 $x > 0.1$: Support helicity-flip mechanism, L/T, absolute cross secns

COMPASS 2019: First measurement of π^0 at $x \lesssim 0.1$

- Other transversity probes

Exclusive production of high-mass pairs $\rho\rho, \rho\gamma$
Ivanov, Pire, Szymanowski, Teryaev 2000; Szymanowski, Pire et al

EM Tensor: Form factors and interpretation

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- Form factors of quark/gluon EM tensor (traceless)

Ji 1996; Polyakov 2000; Lorce et al

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

$$M_2(0) \quad \text{quark/gluon light-cone momentum}, \quad M_2^q(0) + M_2^g(0) = 1$$

$$J(0) \quad \text{quark/gluon angular momentum}, \quad J^q(0) + J^g(0) = 1/2$$

- Spatial interpretation in Breit frame

Polyakov 2000

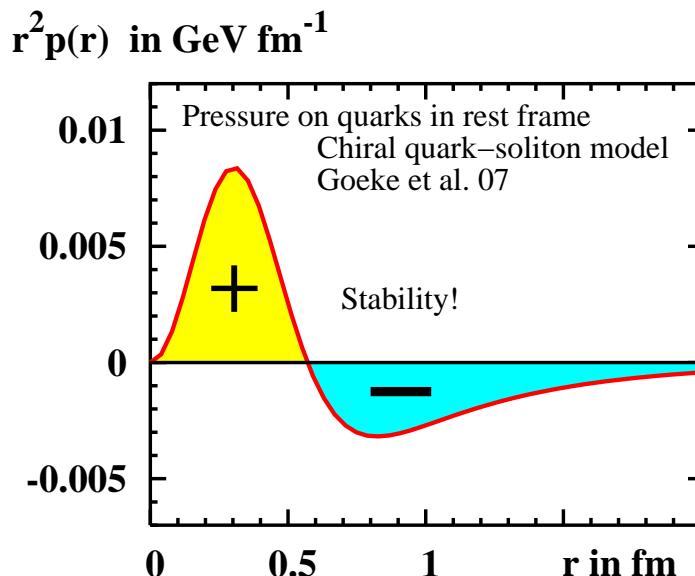
$$(1 + t \dots) \begin{Bmatrix} M_2(t) \\ J(t) \\ d(t) \end{Bmatrix} = \int d^3r e^{-ir\Delta} \begin{Bmatrix} M_N^{-1} \mathbf{T}^{00}(\mathbf{r}) \\ \epsilon^{ijk} s^i r^j \mathbf{T}^{0k}(\mathbf{r}) \\ -\frac{M_N}{2} (r^i r^j - \frac{1}{3} r^2 \delta^{ij}) \mathbf{T}^{ij}(\mathbf{r}) \end{Bmatrix} \quad \begin{array}{l} \text{energy} \\ \text{angular mom.} \\ \text{shear forces} \\ \leftrightarrow \text{pressure} \end{array}$$

- Accessible through GPD moments

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

EM Tensor: Quark pressure from D-term

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

Stability requires that pressure positive inside, negative outside

Model estimates: Large- N_c limit
Goeke, Schweitzer et al. 2007

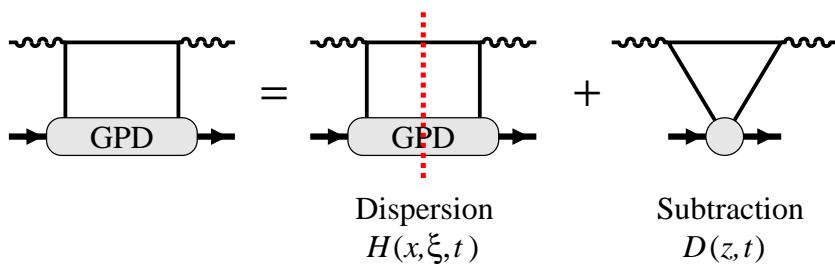
- EIC: $d(t)$ from DVCS

D-term: Subtraction in dispersive representation of DVCS amplitude

Polyakov, Weiss 1999. Dispersive: Teryaev; Diehl, Ivanov; Vanderhaeghen, Polyakov

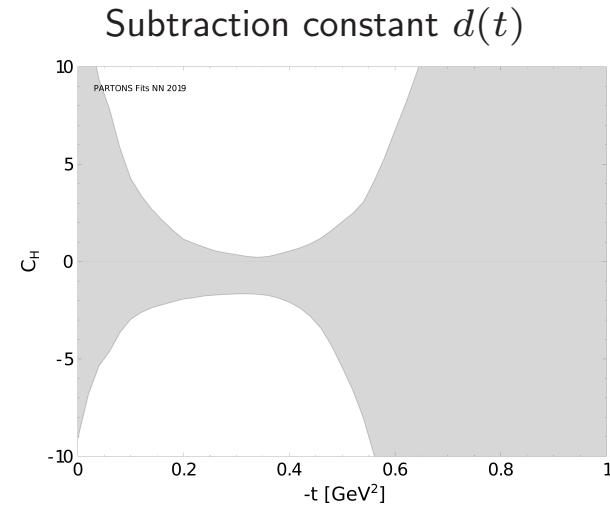
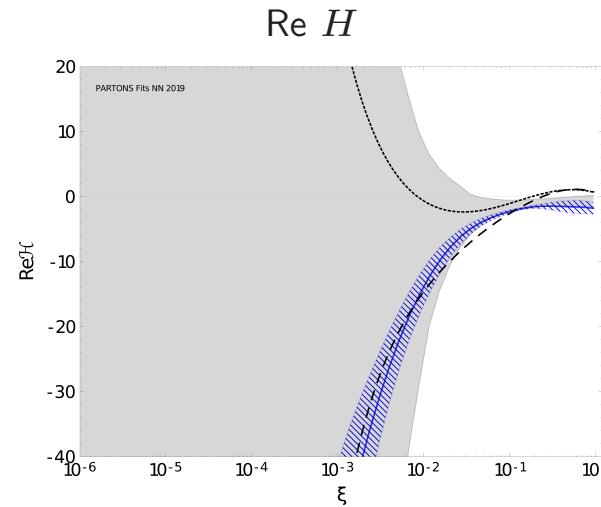
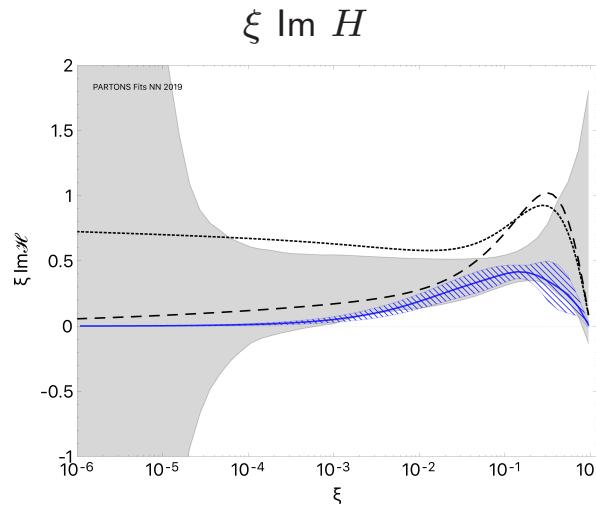
Extract from measurements of ξ -dependence over broad range

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



EM Tensor: Dispersive analysis of DVCS

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- Dispersive analysis of DVCS amplitudes

Moutarde, Sznajder, Wagner 2019

$\text{Im } H(\xi, t)$ from beam-spin asymmetry; $\text{Re } H(\xi, t)$ from cross section

Model-independent, does not use/require GPD parametrization

Subtraction constant $d(t)$ determined, consistent with $d < 0$

Uncertainties quantified using Neural Network, could be reduced further by theory input

- Impact of future data

$\text{Im } H$ at all ξ – improves calculation of dispersion integral

JLab12, COMPASS, EIC

$\text{Re } H$ at $\xi < 0.1$ – improves determination of subtraction constant

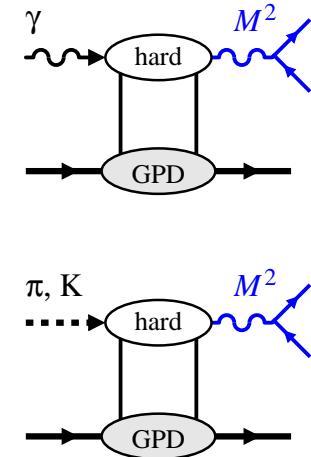
COMPASS, EIC

GPD-based analysis: Kumericki, Müller; PARTONS Moutarde, Sznajder, Wagner et al; Liuti et al

Exclusive dilepton production

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- Exclusive photoproduction of high-mass dilepton
Cross-channel process to DVCS, factorizable, sensitive to $\text{Re } H$
JLab12, EIC, ultraperipheral AA at RHIC
Pire, Szymanowski, Wagner; Boer, Guidal, Vanderhaeghen
- Exclusive hadroproduction of high-mass dilepton
Cross-channel process to meson electroproduction, cf. Drell-Yan
Option for COMPASS, J-PARC
Kroll, Teryaev 20



High- t and backward meson production

- Near-threshold heavy quarkonium production $\gamma^{(*)} + N \rightarrow Q\bar{Q} + N$
Large $|t_{\min}|$, probes high- t gluon GPD
JLab12 J/ψ , EIC
- Backward-angle (u-channel) meson electroproduction $\gamma^* + N \rightarrow N + M$
3-quark exchange in t-channel, factorizable, probes $N \rightarrow M$ transition DAs
JLab12, EIC
Frankfurt, Polyakov, Pobylitsa, Strikman 1999; Pire, Semenov-Tian-Shansky, Szymanowski 2010

Nuclear coherent processes

- Exclusive processes $\gamma^* + A \rightarrow M + A$
Nuclear GPDs, quark/gluon image of nucleus, novel studies of nuclear shadowing
JLab12, EIC
Scopetta, Strikman et al, Guzey et al, Liuti et al

Summary

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- Hadrons in QCD – emergent phenomena
 - Chiral symmetry breaking expressed in partonic structure, many manifestations
- Parton imaging connected with specific questions of dynamics
 - Non-perturbative sea quarks $\leftrightarrow \chi$ SB
 - Origin of large- x gluons?
 - Chiral-odd structures
- Form factors of energy-momentum tensor as fundamental characteristics
 - Mechanical interpretation, intuition developing
 - D-term accessible in dispersive analysis – subtraction constant
- Looking forward to forthcoming data
 - $eN/\mu N$: JLab12, COMPASS, EIC
 - γN : JLab12, EIC, LHC ultraperipheral pA/AA
 - Meson- N : COMPASS, J-PARC