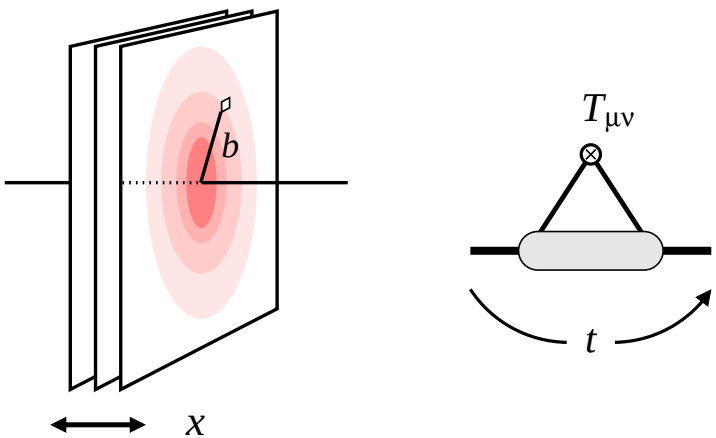
Exploring hadron structure with generalized parton distributions

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

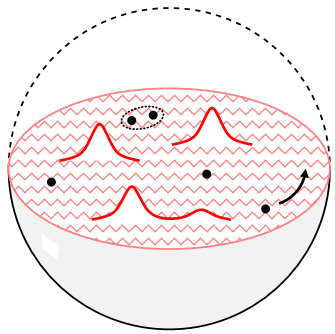
- Extensions

  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

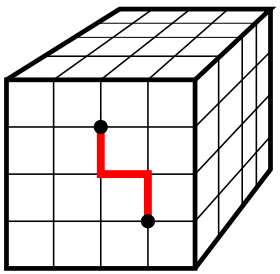
Nucleon in QCD: Dynamical system



- Emergent phenomena

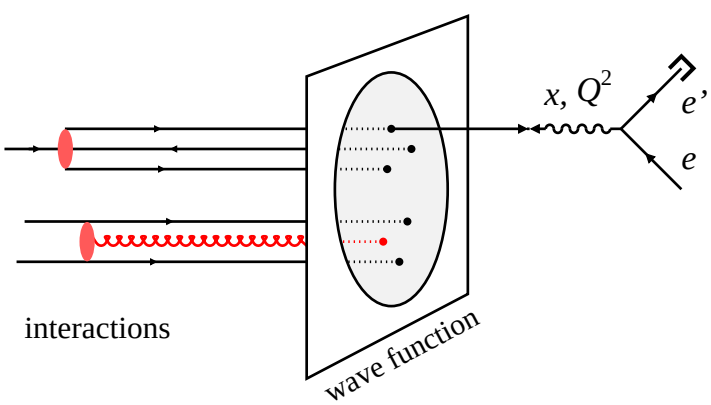
  Unique dynamical system: Relativistic, quantum-mechanical, strongly coupled

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



- Field–theoretical description

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



- Particle–based description

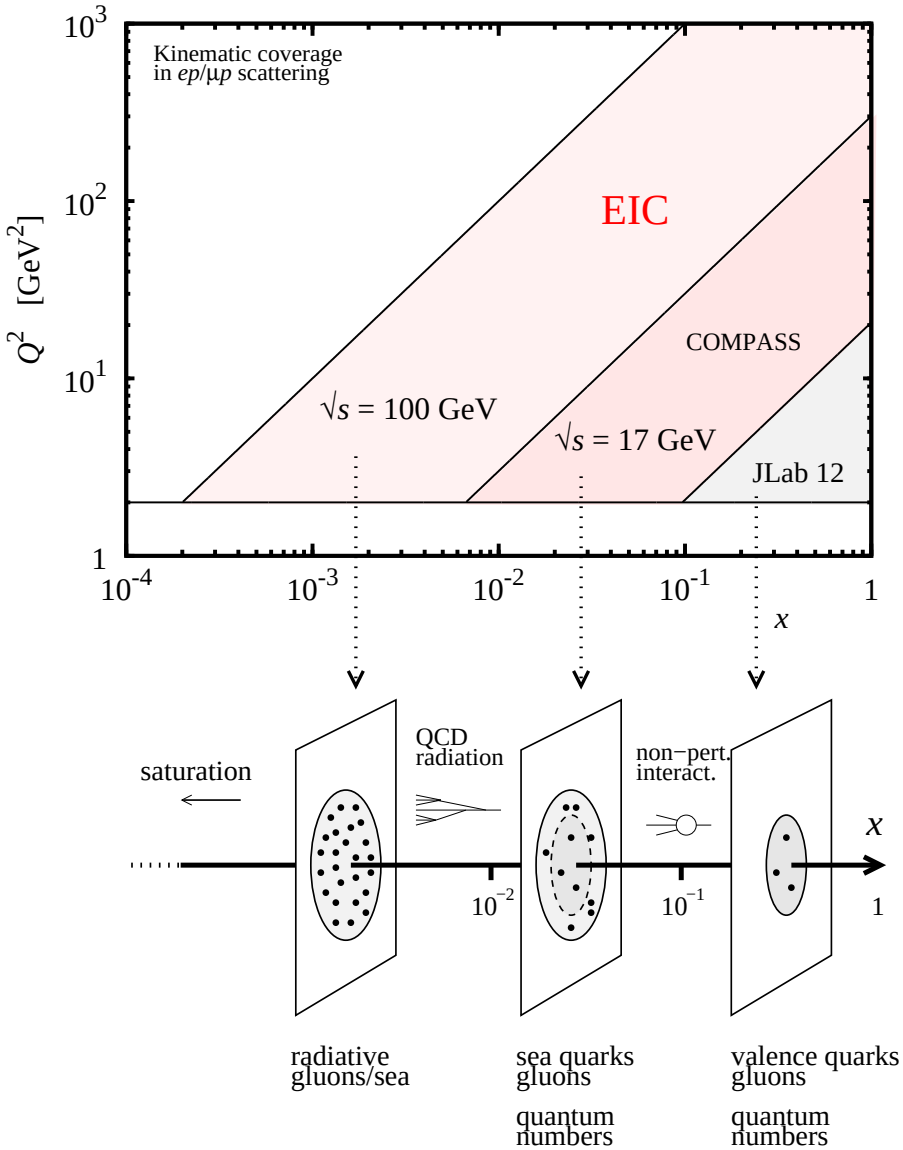
  Parton picture $P \to \infty$: Closed system
  Feynman, Gribov. Alt. viewpoint: Light–front quantization

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

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

  Dynamics expressed in particle distributions

Nucleon in QCD: Landscape



- 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

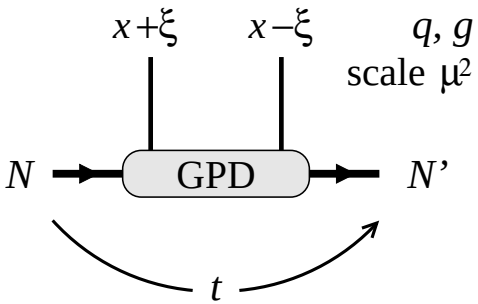
  Transverse spatial distributions GPDs

  Orbital motion, angular mom TMDs, GPDs

  Correlations, fluctuations MPDs, GPDs

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

GPDs: Operators and processes



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

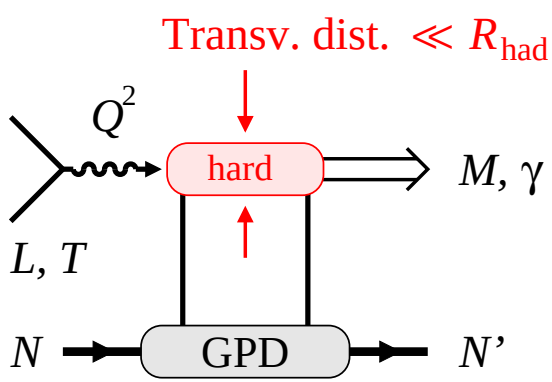
- Transition matrix elements of twist-2 operators

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



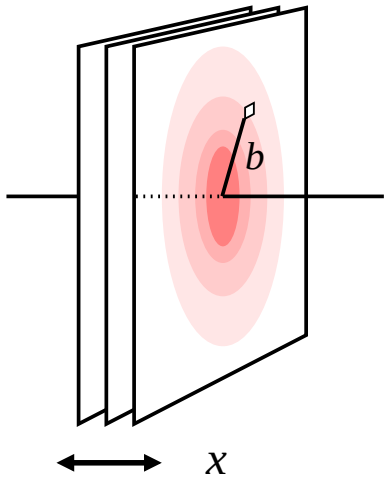
- Hard exclusive processes

  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

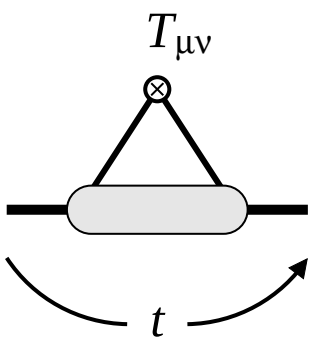


- Transverse imaging

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

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

Diagonal GPD $\xi = 0$ not directly accesible



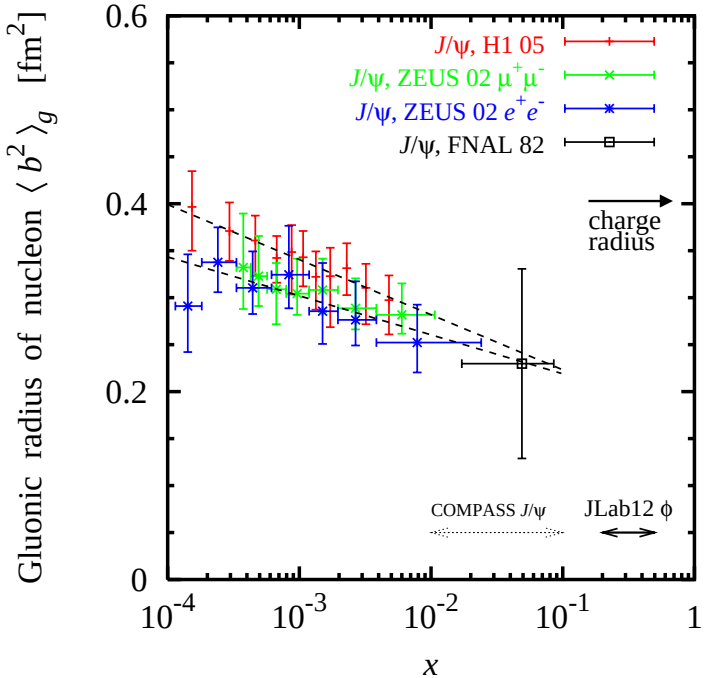
- Local spin–n operators

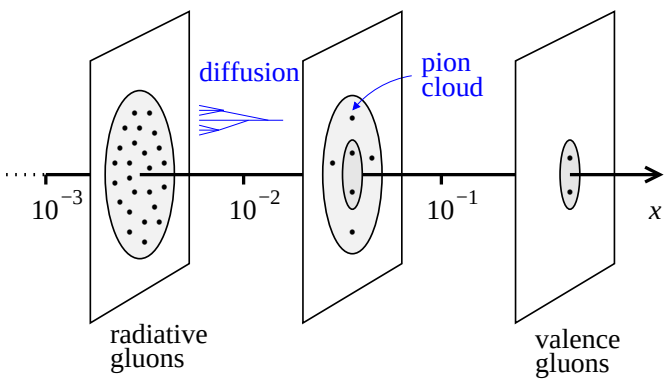
$$\text{FF[spin-}n](t) \quad = \quad \int dx\; x^{n-1}\; \text{GPD}(x,\xi,t=-\boldsymbol{\Delta}_T^2)$$

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

Requires integration over x, not directly accessible

Parton imaging: Gluons





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

- Gluon distribution in transverse space?

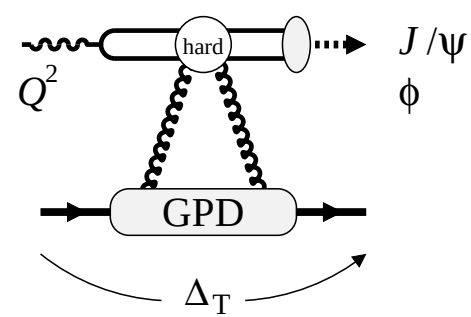
  Gluonic radius and shape of nucleon
  Input for pp@LHC MC, small-x physics

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

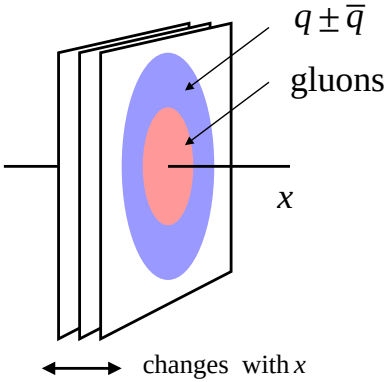
- Exclusive heavy quarkonium production

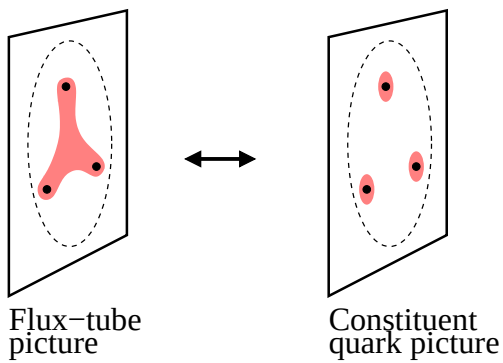
  HERA: J/ψ photo/electroproduction $x < 10^{-2}$
  Mechanism tested, slopes extracted, universality
  Frankfurt, Strikman, Koepf 1996; Goloskokov, Kroll 2008+

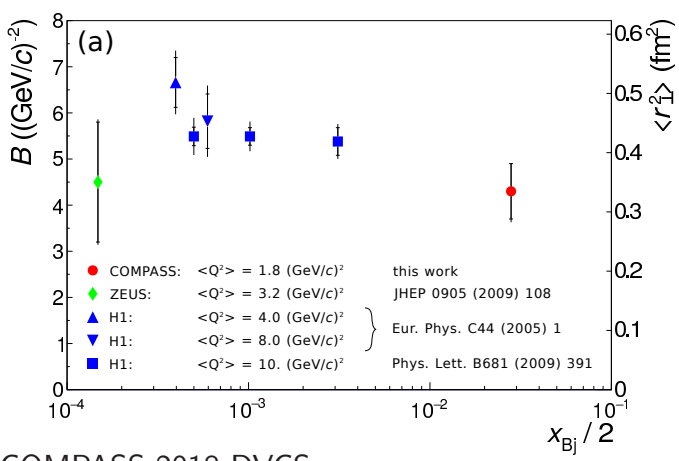
  COMPASS: J/ψ electroproduction $\rightarrow$ d'Hose
  JLab12: ϕ electroproduction $x > 0.2$
  EIC: Gluon imaging program



Parton imaging: Gluons vs. quarks







COMPASS 2018 DVCS

- Gluon vs. quark transverse distributions?

  $\langle b^2 \rangle$(gluon) $< \langle b^2 \rangle (q + \bar{q})$ at $x <$0.1
  HERA J/ψ + DVCS, COMPASS DVCS

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

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

- Nonsinglet quark transverse distributions

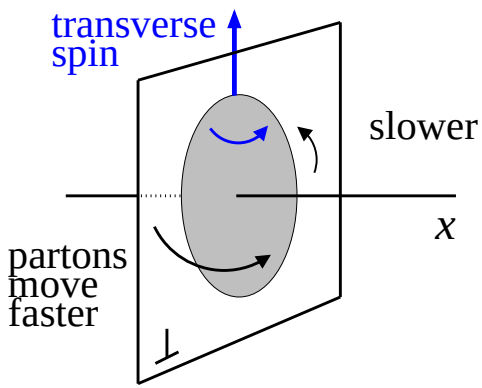
  $q \leftrightarrow \bar{q}, u \leftrightarrow d$ provide information
  on nonperturbative interactions

- Exclusive processes

  DVCS NLO quarks + gluons
  Belitsky, Müller, Kirchner 2001; Freund, McDermott 2001;
  Kumericki, Mueller, Passek-Kumericki 2008

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

Parton imaging: Nucleon and quark polarization



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

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

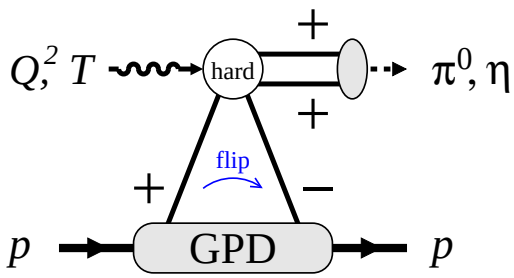
  Partonic composition of anomalous magnetic moment

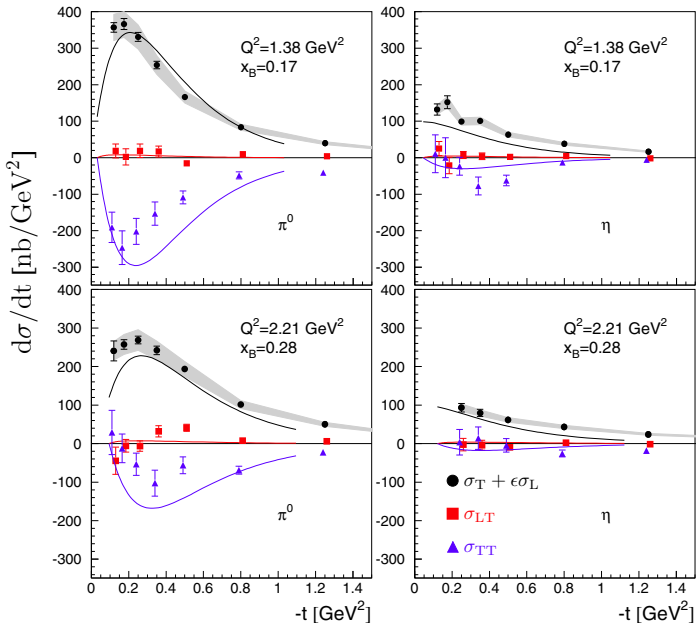
  Orbital angular momentum, relativistic motion

  GPD E_g from exclusive ϕ

- Spatial distribution of quark helicity?

Parton imaging: Transversity





CLAS6 2017 Bedlinskiy et al.

Also flavor separation with $\pi 0/\eta$ Kubarovsky 2014

- Chiral-odd structures from χSB

  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 χSB in hard processes

- Pseudoscalar meson production

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

- Form factors of quark/gluon EM tensor (traceless) Ji 1996; Polyakov 2000; Lorce et al

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

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

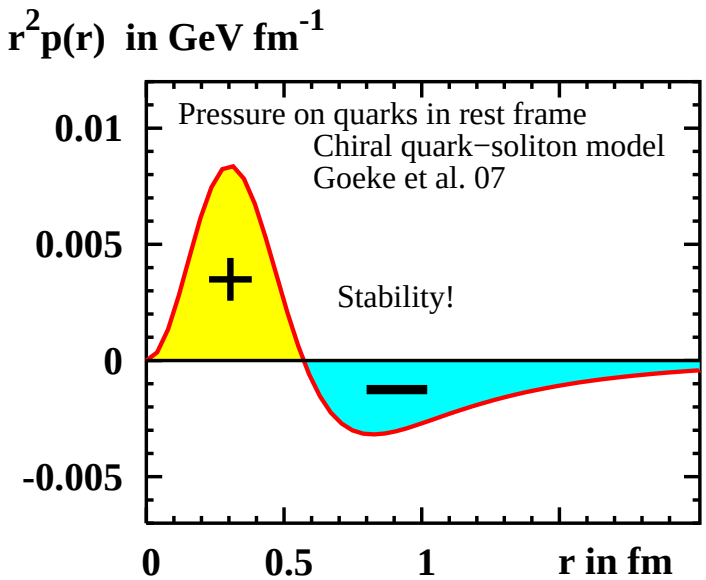
- Spatial interpretation in Breit frame Polyakov 2000

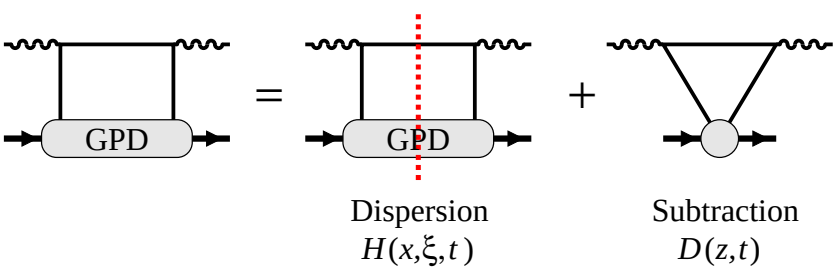
$$(1 + t \ldots) \left\{ \begin{array}{c} M_2(t) \\ J(t) \\ d(t) \end{array} \right\} = \int d^3r \; e^{-i\boldsymbol{r}\boldsymbol{\Delta}} \left\{ \begin{array}{ll} M_N^{-1} T^{00}(\boldsymbol{r}) & \text{energy} \\ \epsilon^{ijk} s^i r^j \, T^{0k}(\boldsymbol{r}) & \text{angular mom.} \\ -\frac{M_N}{2}(r^i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

- Accessible through GPD moments

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

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

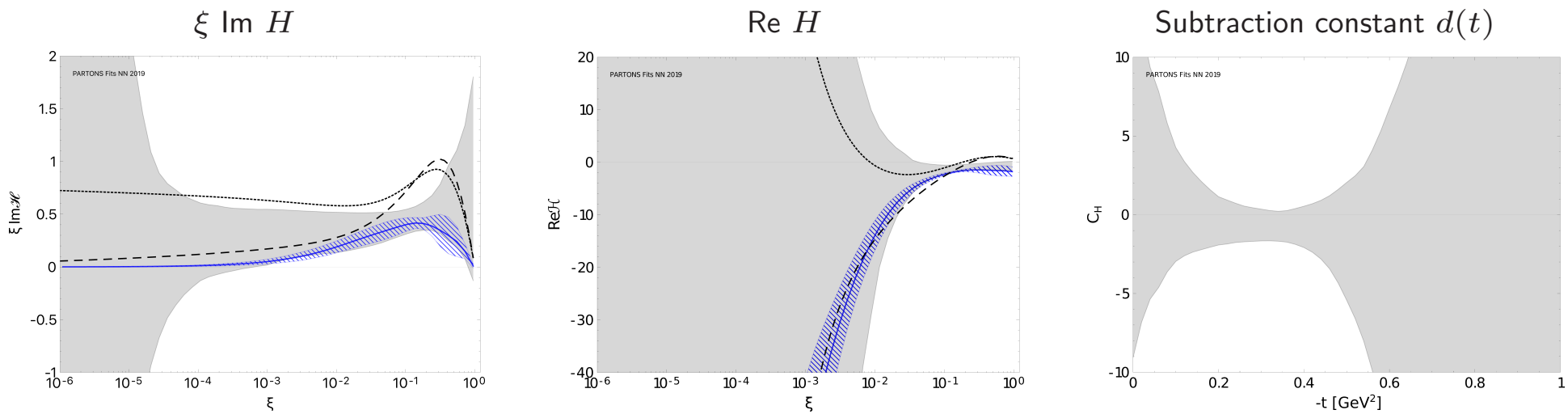
  Model estimates: Large-N_c limit
  Goeke, Schweitzer et al. 2007

- 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

EM Tensor: Dispersive analysis of DVCS



- Dispersive analysis of DVCS amplitudes — Moutarde, Sznajder, Wagner 2019

  Im$H(\xi, t)$ from beam-spin asymmetry; 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

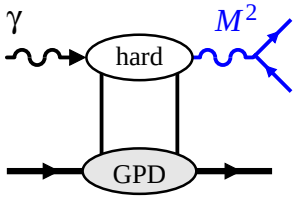
  ImH at all ξ – improves calculation of dispersion integral — JLab12, COMPASS, EIC

  ReH at $\xi < 0.1$ – improves determination of subtraction constant — COMPASS, EIC

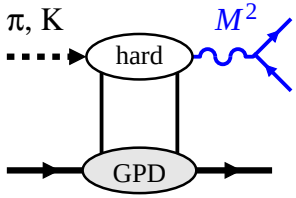
GPD-based analysis: Kumericki, Müller; PARTONS Moutarde, Sznajder, Wagner et al; Liuti et al

Exclusive dilepton production

- Exclusive photoproduction of high-mass dilepton
  Cross-channel process to DVCS, factorizable, sensitive to 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 $\gamma^{(*)} + N \to Q\bar{Q} + N$
  Large $|t_{\min}|$, probes high-t gluon GPD
  JLab12 J/ψ, EIC

- Backward-angle (u-channel) meson electroproduction $\gamma^* + N \to N + M$
  3-quark exchange in t-channel, factorizable, probes $N \to M$ transition DAs
  JLab12, EIC
  Frankfurt, Polyakov, Pobylitsa, Strikman 1999; Pire, Semenov-Tian-Shansky, Szymanowski 2010

Nuclear coherent processes

- Exclusive processes $\gamma^* + A \to M + A$
  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

- 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 $\leftrightarrow$ χSB

  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