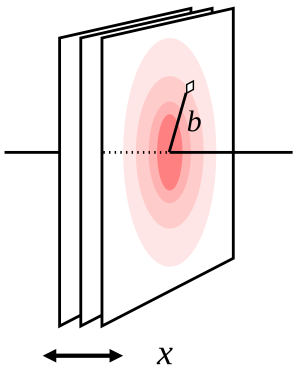
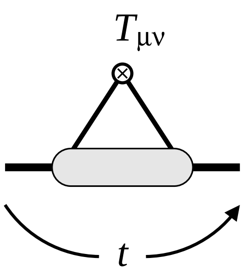
Generalized parton distributions: Overview

C. Weiss (JLab), A.I. for Nuclear Physics Workshop, JLab, 4-6 Mar 2020





- Definition and properties

- Interpretation and interest

  Nucleon spatial structure, quark/gluon imaging

  QCD energy-momentum tensor: Angular momentum, forces

- Information and construction

  Limiting cases: Parton densities, form factors

  Hard exclusive processes: Analysis methods

- Physical regimes

  Small x: Gluons, singlet quarks, radiation

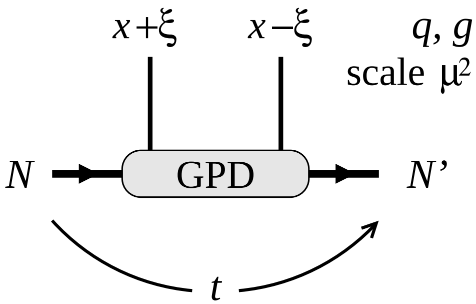
  Large x: Nonsinglet quarks, spin/flavor, transversity

[• AI example: DVCS analysis using Neural Networks]

This overview:
Focus on formal properties, information content

Respect physical complexity and limitations

GPDs: Definition and properties



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

$$\rightarrow \quad \text{GPDs}(x, \xi, t)$$

- Transition matrix elements of twist-2 operators
  Müller et al 94+, Ji 96, Radyushkin 96

  Unify concepts of parton density and form factor

  Quark/gluon and nucleon helicity components

  Renormalization and scale evolution DGLAP–ERBL

  "Simple operator, complex matrix element"

- Partonic interpretation

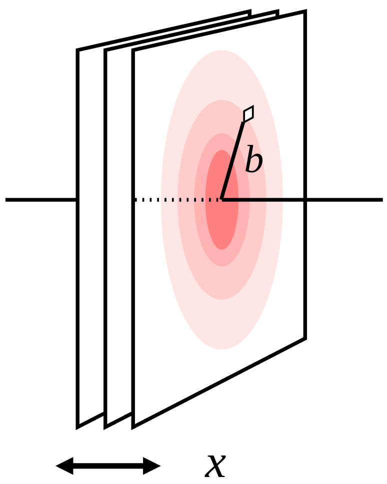
  $|x| > \xi$: Amplitude for nucleon to emit/absorb quark — cf. parton density

  $|x| < \xi$: Amplitude to emit quark-antiquark pair — cf. distribution amplitude

- Moments = form factors of local twist-2 spin-n operators

  $\int_{-1}^{1} dx\, x^{n-1}$ GPD(x, ξ, t) = Polynomial of deg n in ξ — "2D array of moments"

GPDs: Interpretation and interest



- Spatial distribution of quarks/gluons in nucleon
  Burkardt 00+, Diehl 02

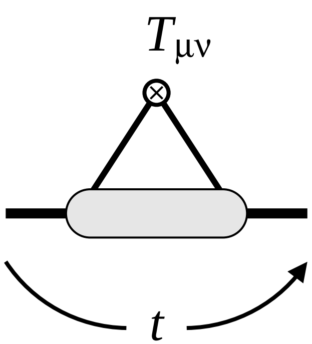
$$f(x, b) \quad = \quad \underset{\boldsymbol{\Delta}_T \rightarrow \boldsymbol{b}}{\text{Fourier}} \quad \text{GPD}(x, \xi = 0, t = -\boldsymbol{\Delta}_T^2)$$

Transverse spatial distribution of partons with x

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

Distributions change with x, dynamics, quarks vs. gluons

GPD($\xi = 0, t$) not exp accesible, model dependence



- QCD energy-momentum tensor
  Ji 96; Polyakov 00; Lorce et al.

$$\langle T^{\mu\nu} \rangle (t) \quad \leftrightarrow \quad \int_{-1}^{1} dx \; x \; \text{GPD}(x, \xi, t) \qquad \text{GPD} = H, E$$

Total and orbital angular momentum of quarks/gluons,
nucleon spin decomposition

QCD forces acting inside nucleon,
e.g. D-term $\leftrightarrow$ pressure distribution

GPD integral over x not directly accessible

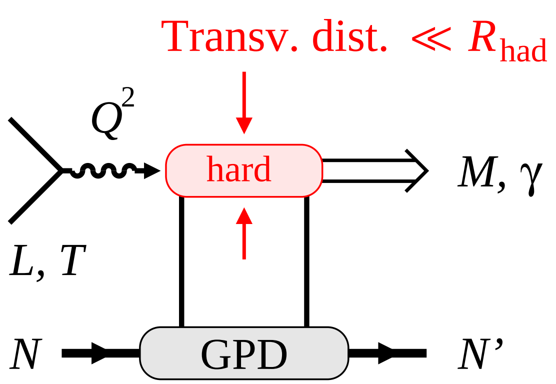
GPDs: Information and construction

- "Basic" information from limiting cases

  GPDs$(x, \xi = 0, t = 0)$ = PDFs(x),

  $\int_{-1}^{1} dx$ GPDs(x, ξ, t) = Vector/Axial FFs(t)

- "New" information from hard exclusive processes



Photon production: Hard $= O(1)$
Meson production: Hard $= O(\alpha_s)$

Basic idea: At large Q^2 and W^2, transverse distances in interaction become $\ll$ hadron size

Collinear factorization in asymptotic regime:
Amplitude = GPDs $*$ [hard] $*$ DAs
Radyushkin 96; Ji 96; Collins, Frankfurt, Strikman 96

$\xi \sim x_{\mathrm{B}}/2$ fixed kinematically, x integrated over

Validity of asymptotic approximation must/can be tested experimentally and theoretically

Subasymptotic corrections (higher-twist, finite-size) large in meson production, included semi-empirically
Frankfurt, Strikman, Koepf 96; Goloskokov, Kroll 08+

GPDs: Information and construction II

- Amplitudes as convolution integrals (amplitudes = observables)

$$\mathrm{Amp}(\xi, t) = \int dx \frac{\mathrm{GPD}(x, \xi, t)}{x \pm \xi - i0} = i\pi\, \mathrm{GPD}(x = \xi, \xi, t) + \mathrm{PV} \int dx \frac{\mathrm{GPD}(x, \xi, t)}{x \pm \xi}$$

$\mathrm{GPD}(x = \xi, \xi, t)$ directly accessible from Im(Amp) e.g. DVCS beam spin asymmetry

$\mathrm{GPD}(x \neq \xi, \xi, t)$ only accessible "under integral"

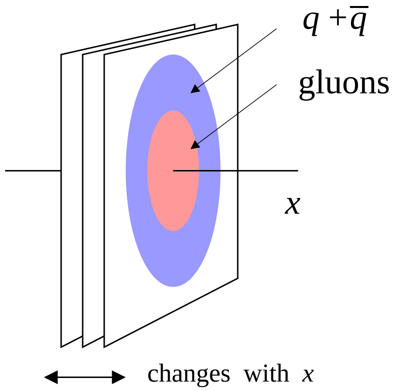
- Possible analysis strategies

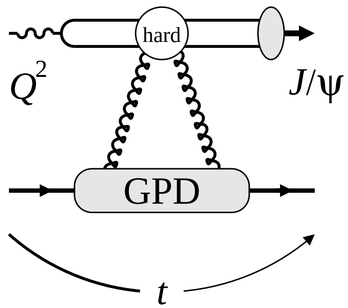
A) Use GPD models to generate x, ξ dependence
Input PDFs, FFs, polynomiality condition.
Several implementations: Double distributions, dual parametrization
Substantial model dependence at large $x, \xi \gtrsim 0.1$
Radyushkin 97; Polyakov, Shuvaev 00. See also Talk Liuti

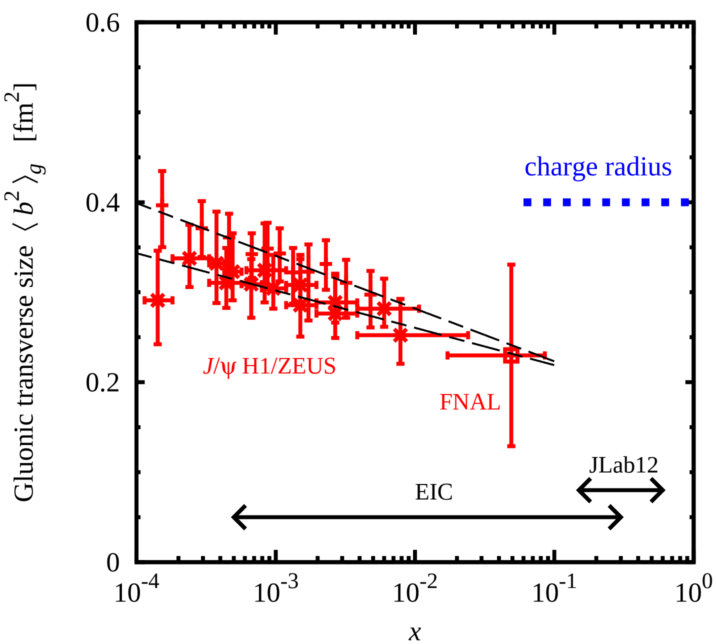
B) Work directly with amplitudes w/o representation in terms of GPDs [→ Neural Network Exmpl]
Use dispersion relations Im(Amp) → Re(Amp) + subtraction
Successful method for DVCS, but no direct information on GPDs
Teryaev; Diehl; Ivanov; Polyakov, Vanderhaeghen; Belitsky, Müller

C) Small x: Generate GPD at $\xi \neq 0$ from PDF through evolution
Reasonable approximation, successful phenomenology
Frankfurt, Strikman; Golec-Biernat, Martin, Shuvaev

GPDs: Small x regime, gluon imaging







Frankfurt, Strikman, CW 10

- Simplifications at small x [$\ll 0.1$]

  Gluon and singlet quark GPDs dominate

  Selective probes: Gluons with J/ψ, ϕ, gluons + singlet quarks with γ, ρ^0

  $\xi \neq 0$ GPDs from $\xi = 0$ + evolution

  Collinear factorization $\leftrightarrow$ dipole model

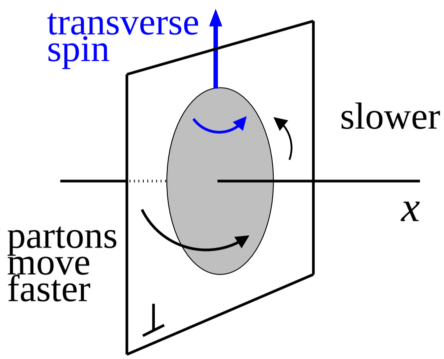
- Gluon distribution in transverse space

  $J/\psi, \phi$ HERA, COMPASS
  Ultraperipheral pA at LHC down to $x \sim 10^{-6}$
  "Gluon imaging" with future EIC

  Gluonic radius $<$ quark radius, grows with $x \to 0$

- Extensive work on theory and analysis
  Vector mesons: Frankfurt, Strikman, Koepf 96; Ivanov, Schäfer, Szymanowski, Krasnikov 04; Anikin, Invanov, Pire, Szym. 10+; Kroll, Goloskokov 08+
  DVCS: Müller, Kumericki

GPDs: Large x regime, quarks, spin



- Quark GPDs at large x [$\gtrsim 0.1$]

  Quark helicity unpol/pol
  Nucleon spin transverse/longitudinal
  Flavor/isospin dependence

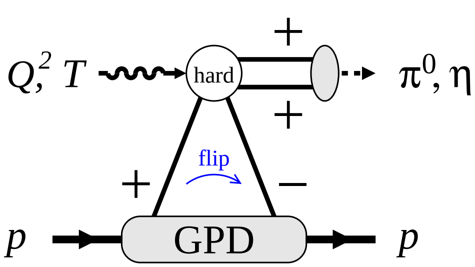
  GPD $E(x, \xi, t)$: Effect of T nucleon spin
  on x-distribution of quarks $\leftrightarrow$ orbital AM

- DVCS program JLab12, COMPASS, EIC

  Polarization observables + cross sections

  Leading-twist observables
  Belitsky, Müller, Kirchner 98; others

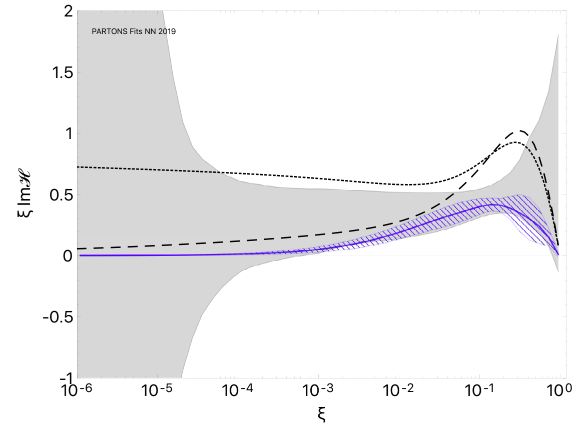
  GPD extraction essentially model-dependent

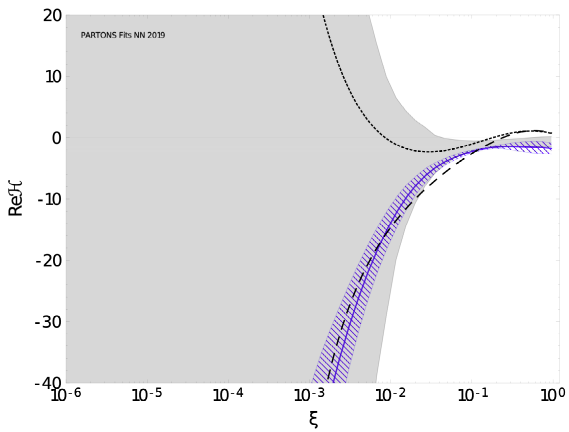


- Quark transversity GPDs with meson production

  π^0, η: Helcity-flip nucleon GPDs & meson DAs
  Describes JLab6 results; detailed studies with JLab12
  Goldstein, Liuti et al 08+, Goloskokov, Kroll 09+;
  CLAS Bedlinsky et al. 12+, Kubarovsky 16

GPDs: DVCS amplitude analysis using NNs





- Amplitude extraction from DVCS observables
  Here: Moutarde, Sznajder, Wagner 2019; see also Kumericki, Müller, Schäfer 2011

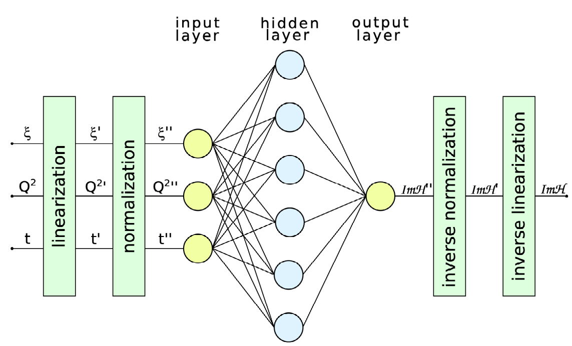
  Artificial Neural Network Parameterization of amps

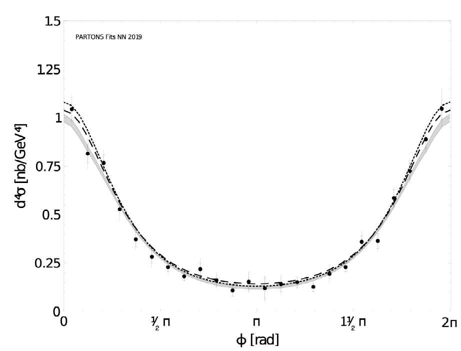
  Feasibility of extraction studied using GPD models

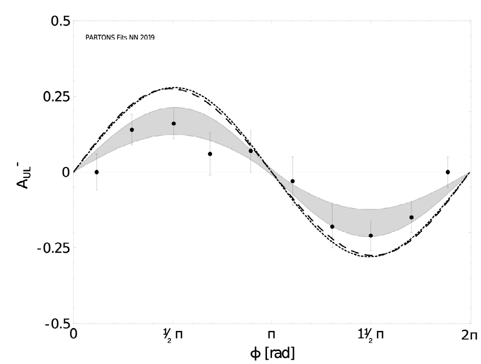
  Regularization to avoid overfitting

  Uncertainty quantification using replica method

  Model-independent method; does not directly access GPDs but extracts "observable" information







GPDs: Summary

- GPDs should be regarded as “concept” more than “function”

  Synthesize information, relate various structures/measurements

  Not necessarily to be measured “point by point”

- Main limitations of GPD studies on physics side

  Relevance of asymptotic expressions for observables, power/higher-twist corrections?

  Complex structure of GPDs; connection between regions depends on dynamics

  Relation to observables through singular integrals

- Small x: Reduced complexity, successful phenomenology

- Large x: GPD extraction essentially model-dependent

  Alternative: Amplitude extraction, model-independent, reduced information

- Potential role of AI: Amplitude extraction from DVCS

  Other applications?