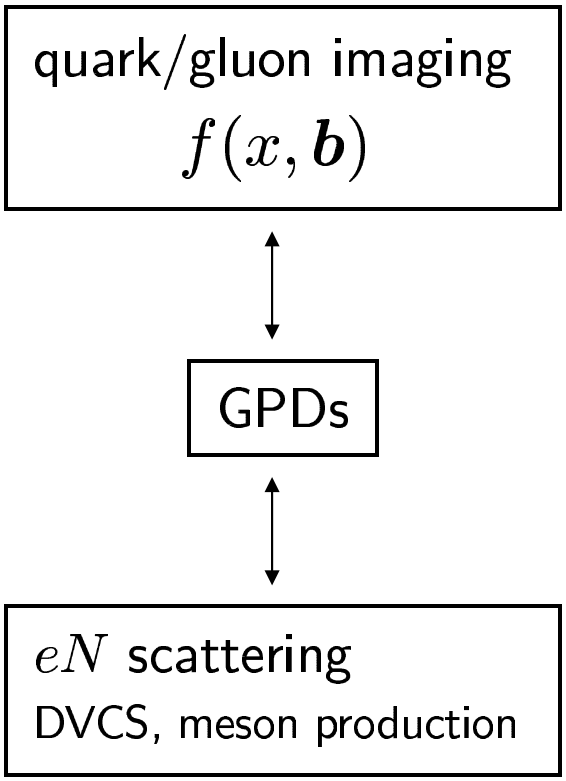
Generalized parton distributions: Status and perspectives

C. Weiss (Jefferson Lab), SPIN2008, 10–Oct–08

Jefferson Lab



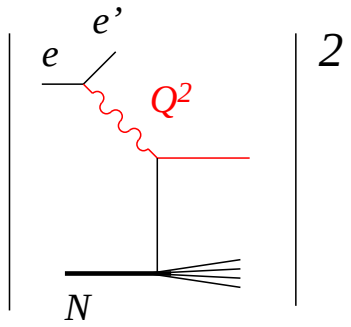
- Concepts
  - QCD factorization
  - GPDs and nucleon structure
- GPDs in eN scattering
  - Test reaction mechanism
  - Extract information on GPDs

  JLAB 6/12
  HERMES
  COMPASS
  EIC
- GPDs in small x and pp
  - Gluon imaging, diffraction

  HERA, EIC
  LHC, RHIC

Factorization: Inclusive eN scattering

σ_{incl} =



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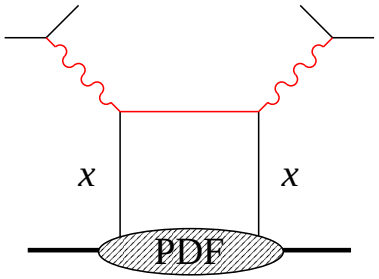


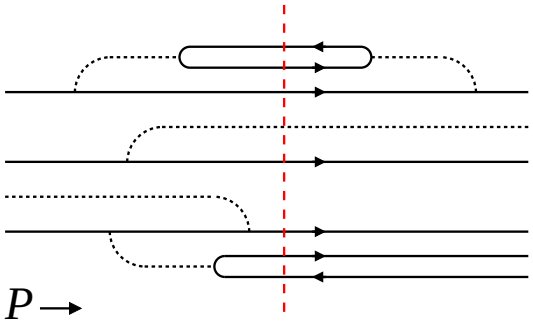
- Factorization of cross section

  Quark subprocess — short distance $\sim 1/Q$

  Parton distribution — long distance $\sim R_{\text{hadron}}$

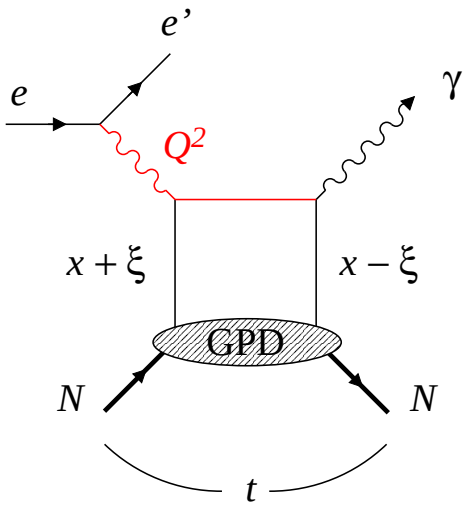
- PDF as matrix element

  $\langle N|\, \bar{\psi}(0) \ldots \psi(z)\, |N\rangle_{z^2=0}$ QCD operator



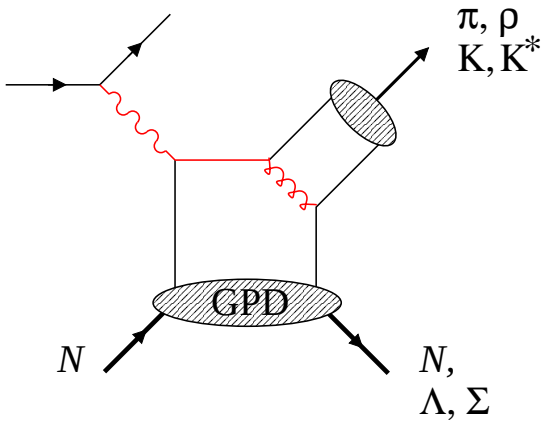
- Space–time interpretation:
  Density of quarks with longitudinal momentum xP in fast–moving nucleon
  [Feynman, Gribov 70's]

Factorization: Exclusive processes in eN



- Photon/meson produced in reaction with single parton in target

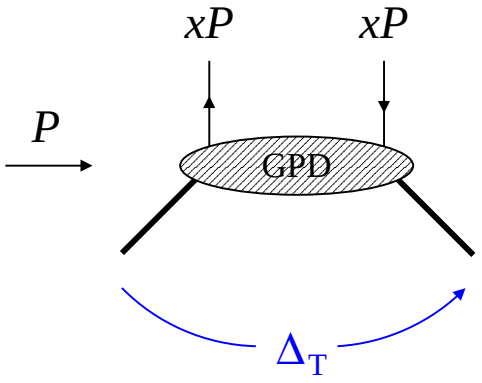
- Generalized parton distribution $H(x, \xi; t)$
  - combines aspects of PDF and elastic FF
  - universal, process–independent!



- Factorization = short–distance dominance
  Finite–size corrections?

[D. Müller et al. 94; Brodsky et al. 94;
Collins et al. 96; Radyushkin 96, Ji 96]

GPDs: Transverse spatial distribution

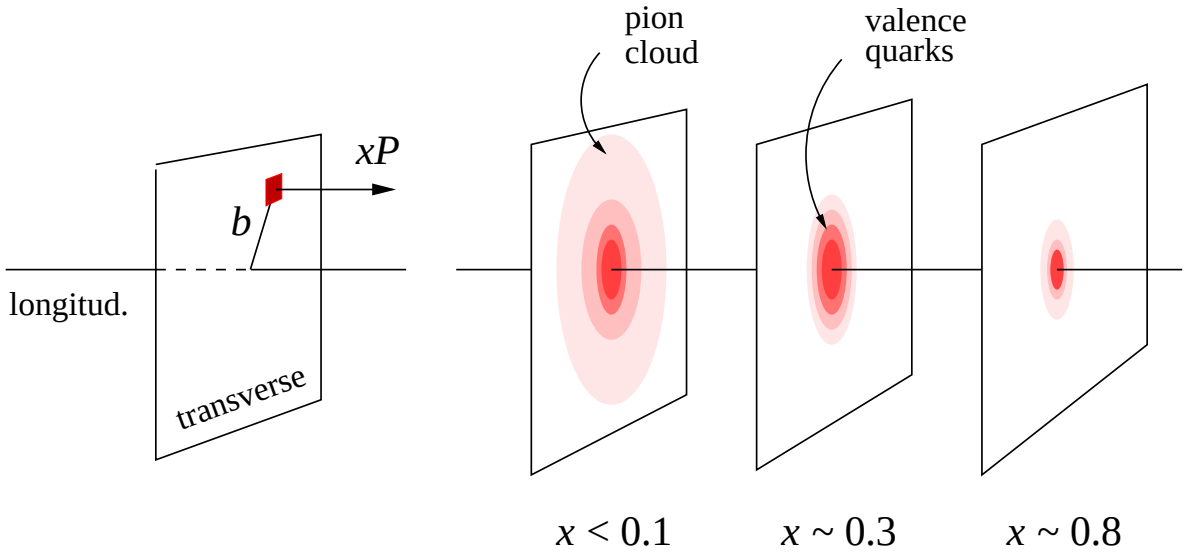


- Transverse coordinate representation ($\xi = 0$)

$$H(x, -\Delta_T^2) \;=\; \int d^2b \; e^{-i\boldsymbol{\Delta}_T \boldsymbol{b}} \; f(x, \boldsymbol{b})$$

FF of partons with mom. xP

transverse spatial distribution



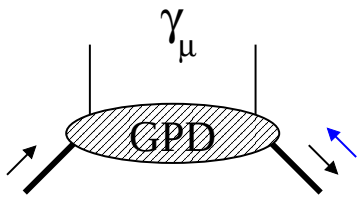
- "Tomographic" image of nucleon at fixed x

- Nucleon structure! Valence quarks "pion cloud" gluons . . .

[Burkardt 02; Diehl 02]

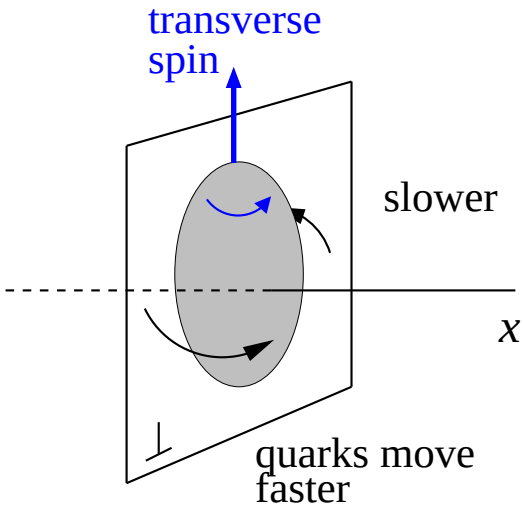
GPDs: Polarization

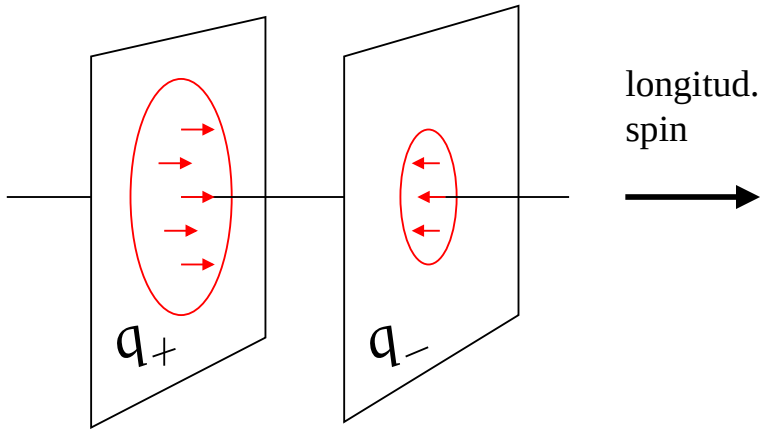
Quarks unpolarized:



$=$ H, Dirac E Pauli (+ Transversity)

polarized: $\gamma_\mu\gamma_5$ $\tilde{H}$, axial $\tilde{E}$ pseudoscalar





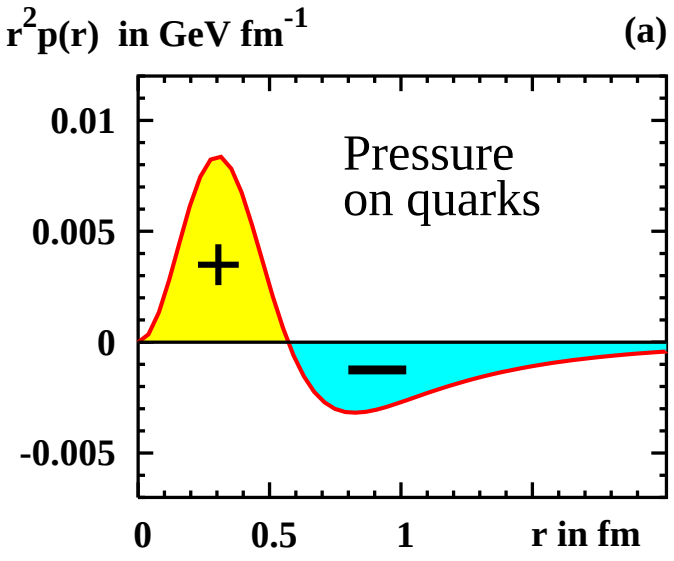
E : Distortion of quark longitudinal motion by transverse spin [Burkardt 03]

$H \pm \tilde{H}$: Spatial distribution of quark helicity

GPDs: Sum rules

$$\int dx\, x\, [H^q + E^q](x, \xi; t) \;=\; J^q$$

Quark angular momentum [Ji 97]



Stability: Positive $\leftrightarrow$ negative
[Goeke, Schweitzer et al. 07]

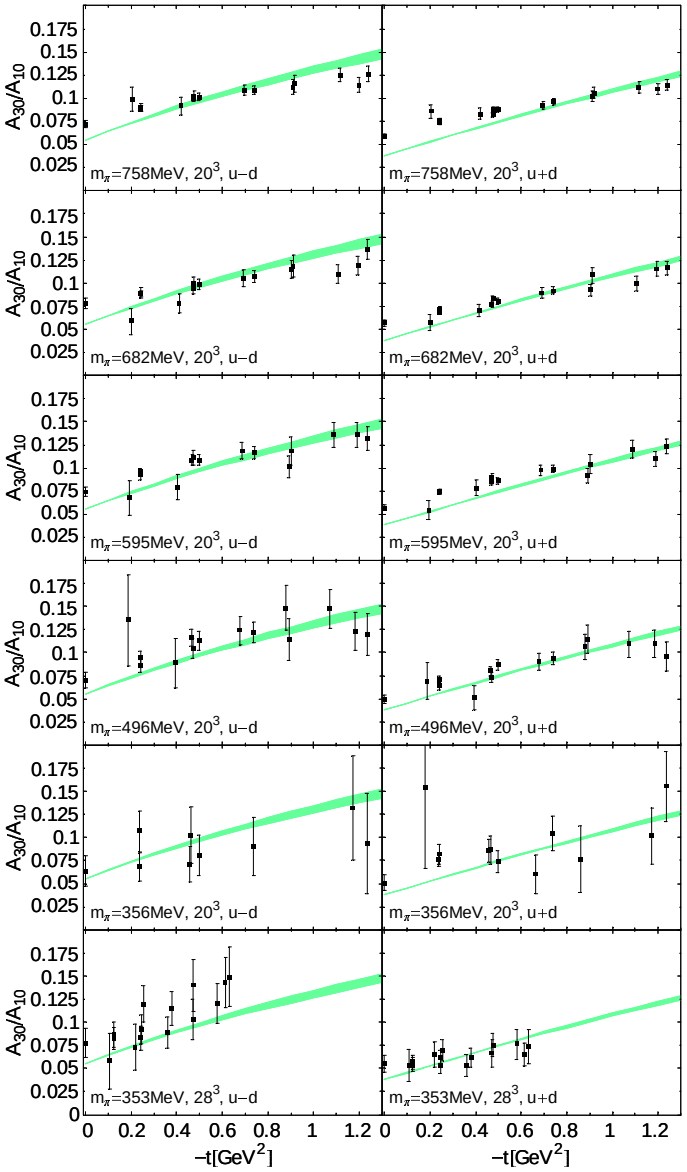
- Moments $\int dx\, x^{n-1} \leftrightarrow$ local operators

  $n = 2$: QCD energy–momentum tensor

- Access to J^q
  - E^q: neutron DVCS, transv. target
    $\rightarrow$ Talk by E. Voutier
  - Model dependence: x integration, extrapolation $t \to 0$

- Other formfactors of EM tensor: Distribution of forces on quarks (pressure, shear forces) [Polyakov 03]

GPDs: Lattice calculations



- GPDs universal, Twist–2 operator } can be calculated on lattice

  $\leftrightarrow$ TMDs ?

- Lowest moments $n \leq 4$, t–dependence

- Presently non-singlet $q - \bar{q}, u - d$
  Singlet: Disconnected diagrams
  Hägler et al. [LHPC Collab. 07]
  $\rightarrow$ Talk by H.–W. Lin

- Potential to constrain GPD parametrizations in the future
  [see e.g. Liuti et al. 06]

GPDs in eN scattering

- Basic information from

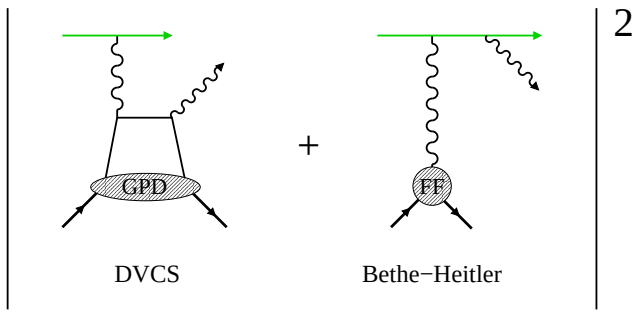
$$\left.\begin{array}{lrcl} \text{parton densities} & q(x) & = & H(x,\xi=0,t=0) \\ \text{elastic form factors} & F(t) & = & \displaystyle\int dx\, H(x,\xi,t) \end{array}\right\} \text{GPD models, parametrizations}$$

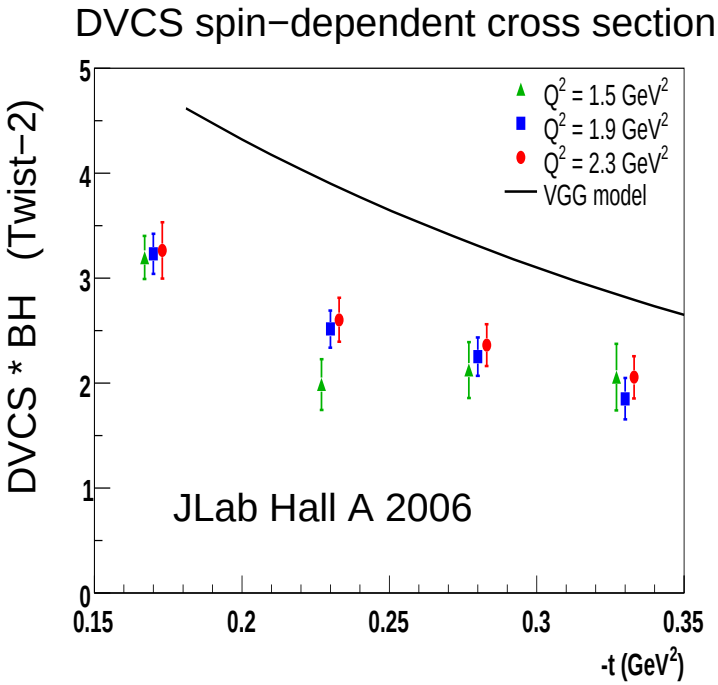
- "New" information about $x, \xi \leftrightarrow t$ correlation from hard exclusive processes

  - Test reaction mechanism!
    Short–distance dominance? Corrections? Factorization?

  - Extract information about GPDs!

DVCS: Reaction mechanism





- Interference Bethe–Heitler DVCS allows access at amplitude level

$$\text{Im(DVCS)} \sim H(x=\xi,\xi;t)$$

$$\text{Re(DVCS)} \sim \int dx \frac{H(x,\xi;t)}{x-\xi}$$

$$\xi \leftrightarrow x_B$$

- Recent cross section measurements indicate early approach to scaling

  "Test" of factorization

- Need to separate H, E

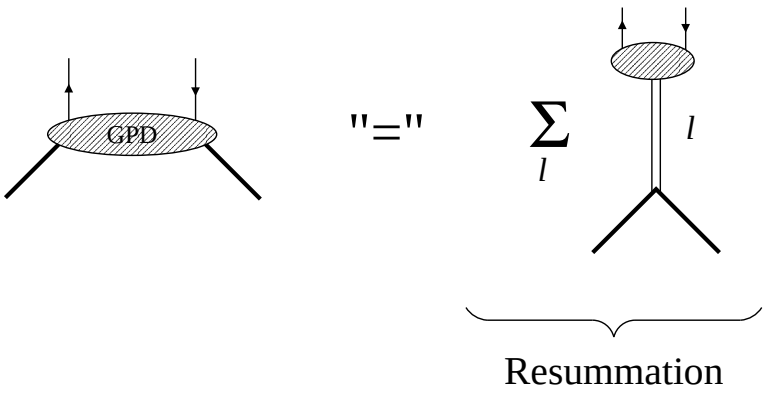
  → Talk by E. Voutier

DVCS: New analysis tools

$$\mathrm{Re}A \;=\; \underbrace{\int_{\mathrm{Disp}} \mathrm{Im}A}_{H(\xi,\xi;t)} \;+\; D(t)$$

- Dispersion relation for hard exclusive amplitude
  - Model–independent
  - Accessible information $H(\xi,\xi;t)$ + "D–term" [Polyakov, CW 99]

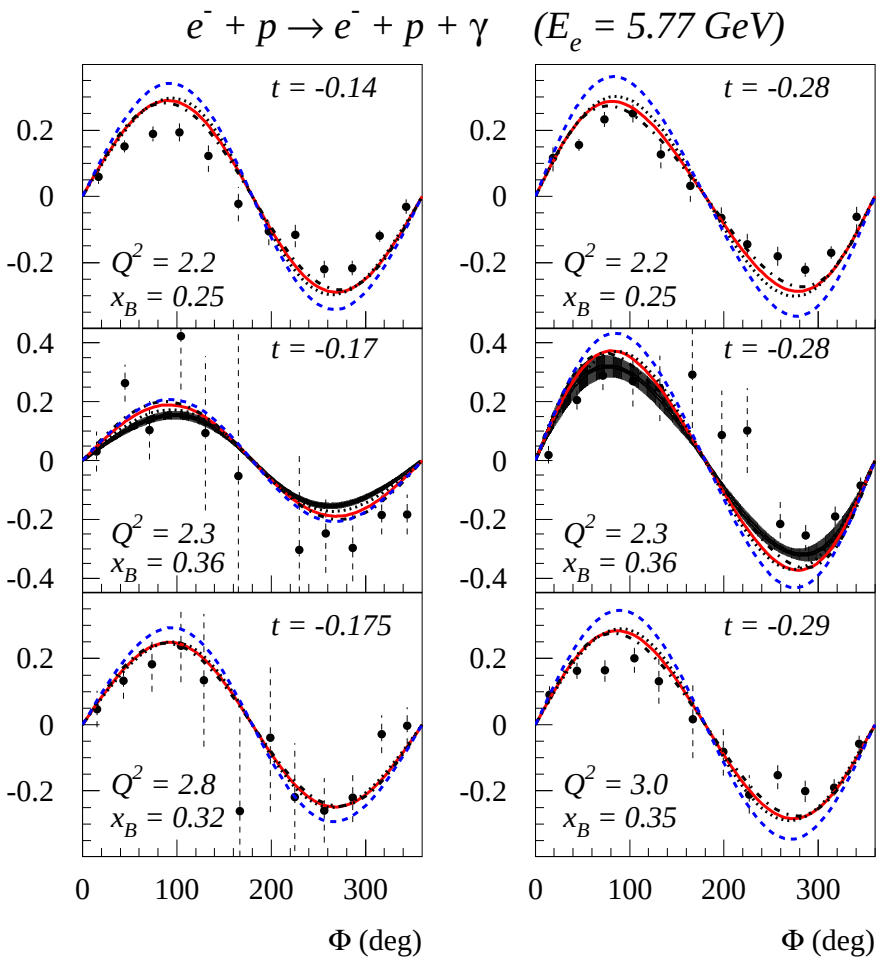
[Teryaev 05; Anikin, T. 07; Müller et al. 07; Diehl, Ivanov 07]



- Parametrizations based on t–channel exchanges (cf. dual amplitudes)
  - Regge–like behavior at small x
  - QCD evolution "automatic"

[Polyakov, Shuvaev 02; Kumericki et al. 06: NLO]

DVCS: New analysis tools II

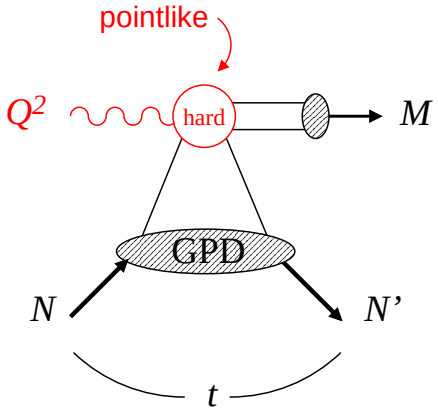


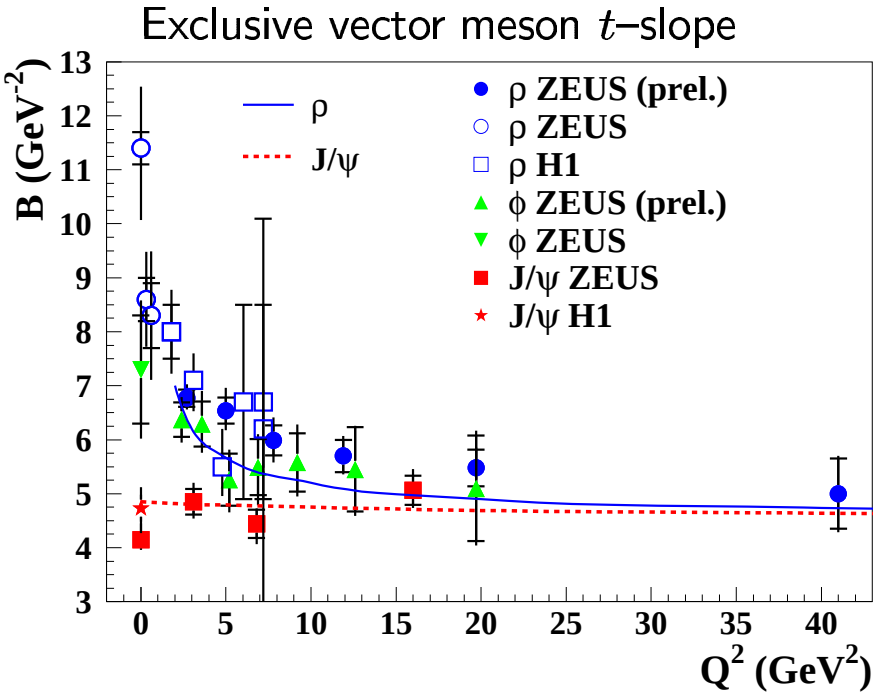
JLab CLAS DVCS beam spin asymmetry

- Combined analyisis of JLab DVCS data
  - Im A from absolute cross section data (Hall A)
  - Re A from "minimal model" + dispersion relation
  - Reproduces well beam spin asymmetry data (CLAS, Hall A)

[Vanderhaeghen, Polyakov 08]

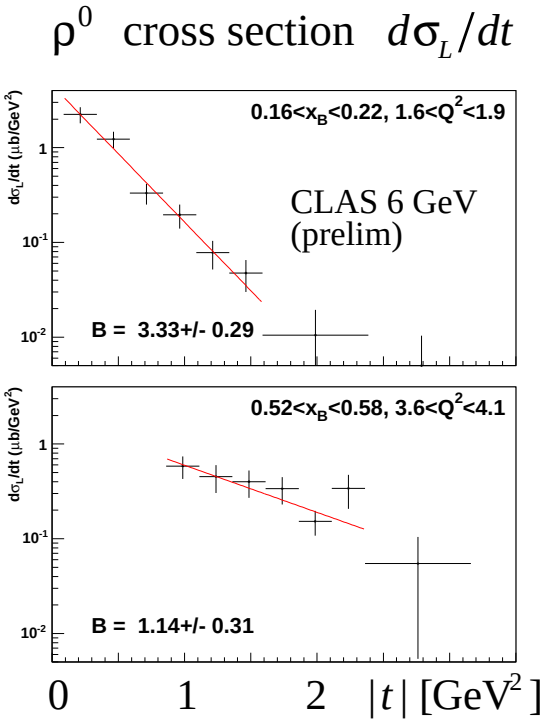
Meson production: Reaction mechanism

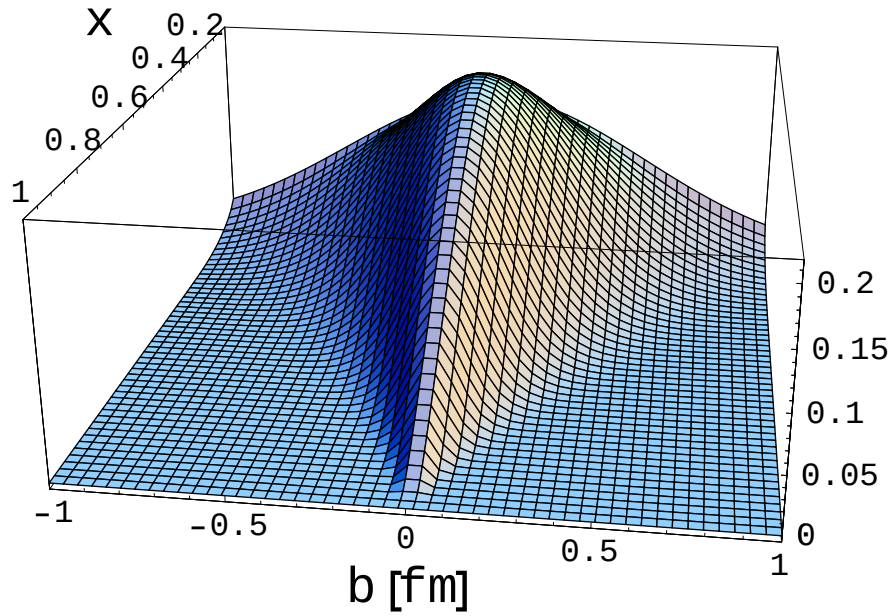




- J^{PC} + flavor select GPD
- $Q^2 \to \infty$: Meson produced in pointlike configuration
  - t–slope independent of Q^2
  - Seen in HERA vector meson data!
- $Q^2 \sim$ few GeV^2: Substantial finite–size corrections (higher twist)
  - Dynamical models w. intrinsic k_T [Frankfurt et al. 96; Vanderhaeghen et al. 98; Kroll, Goloskokov 05]

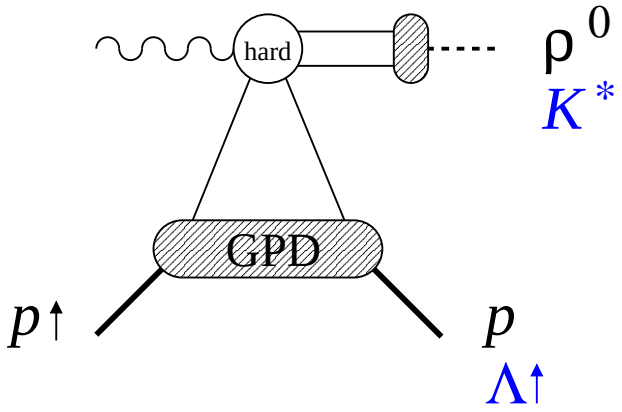
Meson production: Reaction mechanism II





- CLAS ρ^0 t–slope agrees with present GPD models [Guidal et al. 05]
- Absolute cross sections: Need more theoretical work. . .

Meson production: Cross section ratios



$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\mathrm{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \text{corr.}}$$

Model–dependent analysis!

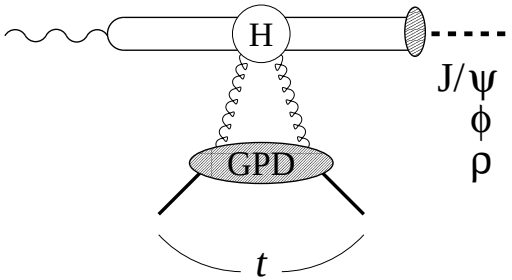
- Transverse target spin asymmetry in $\gamma_L^* p \to \rho^0 p$ sensitive to helicity–flip GPD E
- Alt: Transverse recoil polarization in $\gamma_L^* p \to K^* \Lambda$

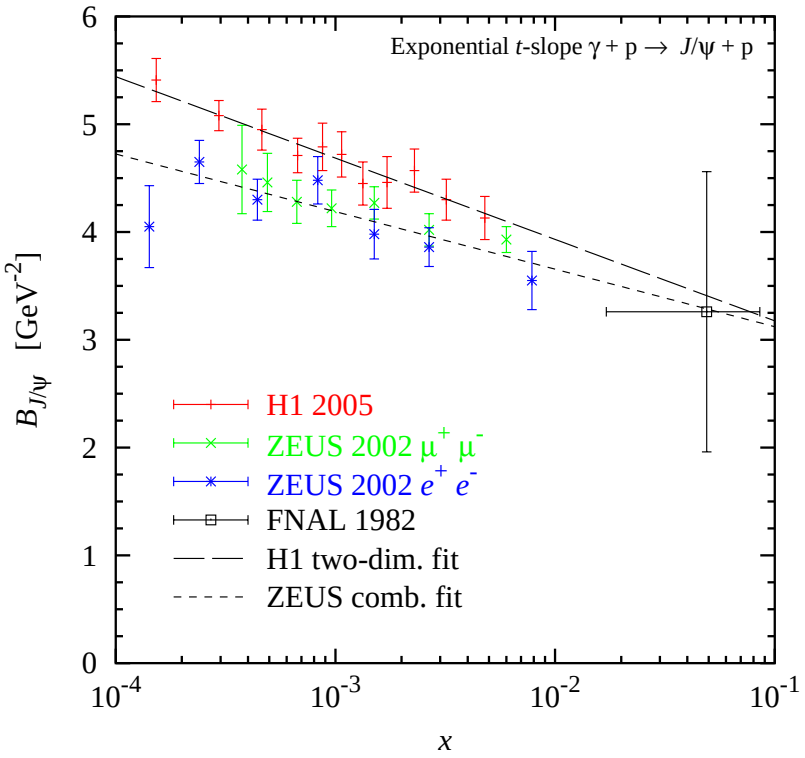
  $SU(3)$ symmetry: $\langle \Lambda | \ldots | p \rangle \to \langle p | \ldots | p \rangle$
- Pseudoscalars π, K probe polarized GPDs

  $\tilde{H}$: Flavor structure $\Delta q, \Delta \bar{q}$

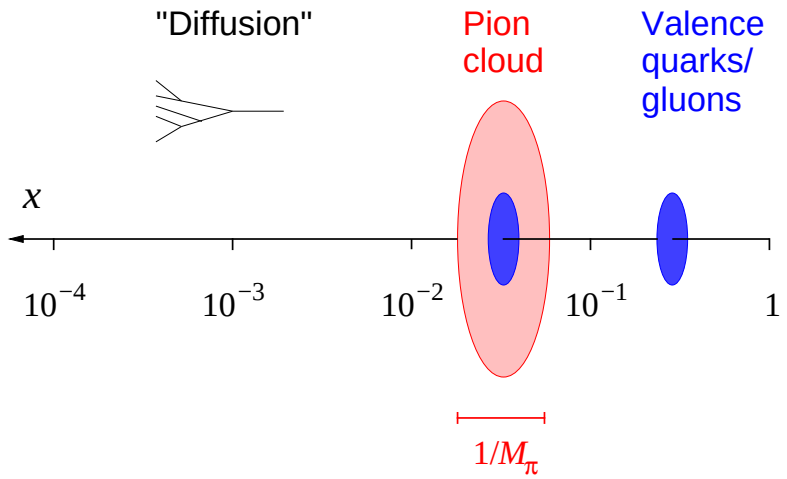
  $\tilde{E}$: "Pole term" in π^+, K^+

GPDs at small x: Gluon imaging

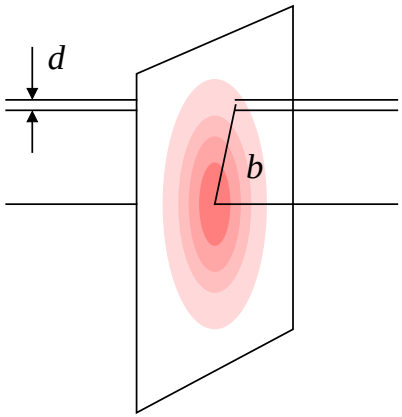


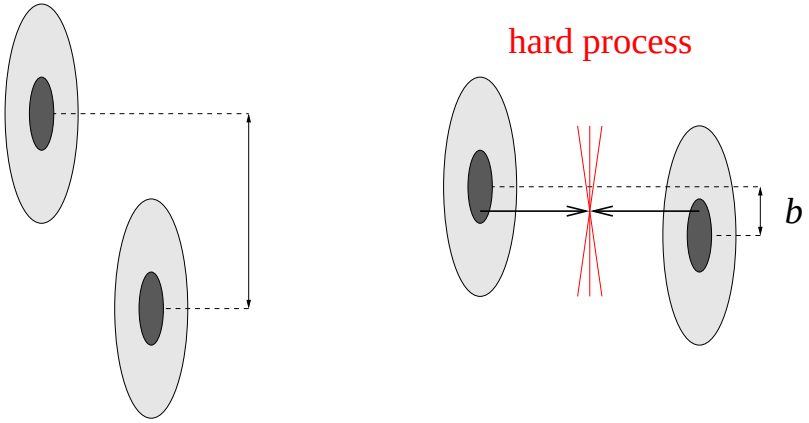


- HERA measurements of t–slope in exclusive $\gamma p \to J/\psi + p$
  - t–dependence of gluon GPD
  - transverse distribution of gluons
- Precise "gluon imaging" with EIC
  [→ Talk by R. Milner]



GPDs at small x: Gluon imaging II





- Transverse gluon distribution essential ingredient in studies of unitarity limit/saturation at small x
  - QCD dipole model

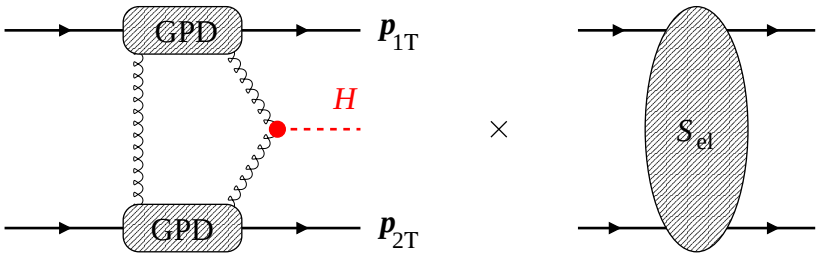
- pp collisions with hard processes
  - centrality dependence
  - spectator interactions, underlying event structure

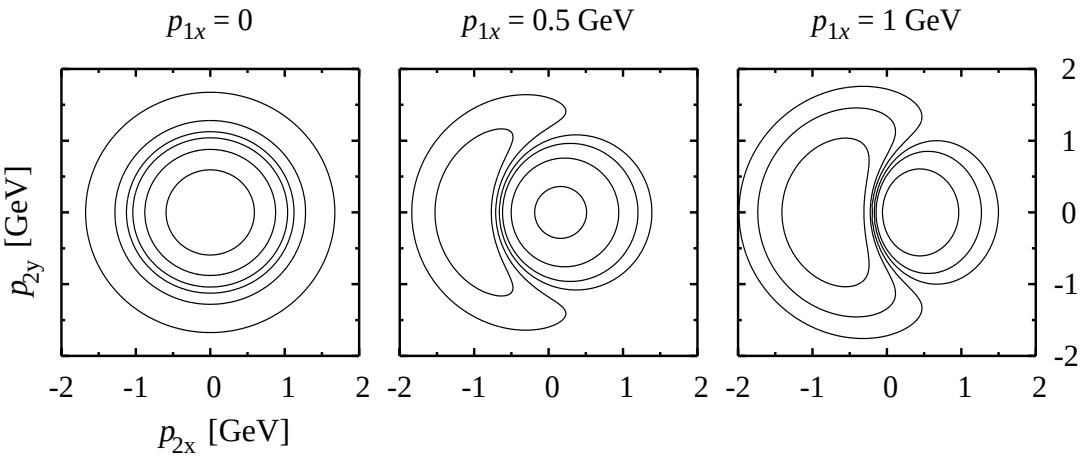
[Frankfurt, Strikman, CW 04/05]

GPDs in pp: Exclusive diffraction

$$pp \to p + \text{gap} + H + \text{gap} + p$$

(= dijet, Higgs, $Q\bar{Q}$, ...)





- Diffraction pattern in $\boldsymbol{p}_{1T}, \boldsymbol{p}_{2T}$ sensitive to gluon GPD
- Could be observed in pp with forward detectors

  CMS/TOTEM at LHC
  STAR pp2pp @ $\sqrt{s} = 500$ GeV ?

[Frankfurt, Hyde, Strikman, CW 07]

Probe gluon GPD in pp
. . . New direction!

Summary

- GPDs unifying framework for discussing single–particle quark/gluon structure of hadrons in QCD

  "Quark/gluon imaging"

- DVCS: Leading–twist analysis well developed; work on kinematic and higher–twist corrections

- Meson production: Many interesting possibilities! Need quantitative theory of finite–size effects to fully utilize data at $Q^2 \sim$ few GeV^2

- Interesting new connections $ep \leftrightarrow pp$!