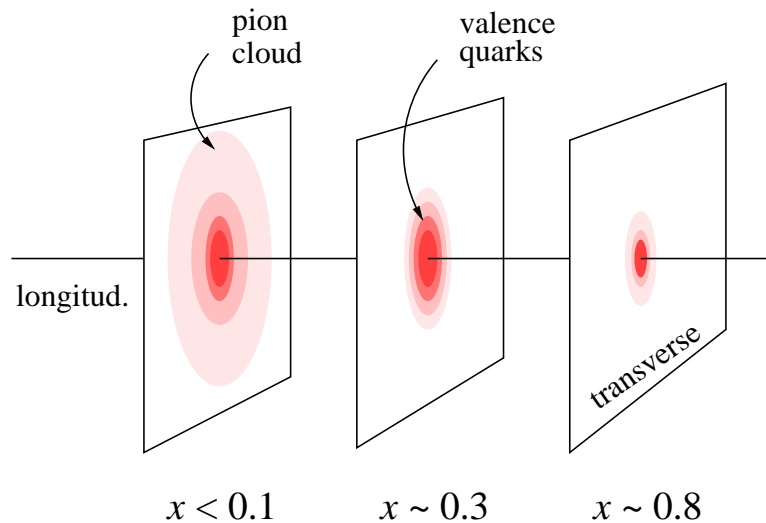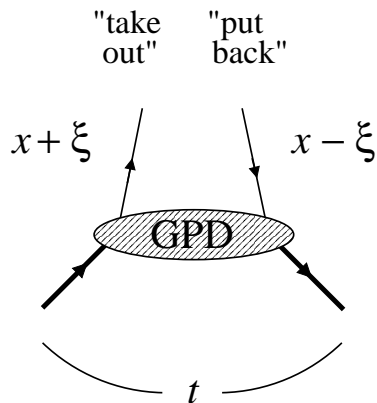# Theoretical support of the GPD program

Ch. Weiss (JLab), S & T Review, JLab, July 23–25, 2007

- GPDs: Concept, physics interest

- Theory in GPD program at JLab and beyond

  - People
  - 2006/7 results and activities
  - Future directions

- User community interaction

# GPDs and quark imaging of the nucleon

"take out"  "put back"

$x+\xi$    $x-\xi$

GPD

$t$

pion cloud    valence quarks

longitud.

transverse
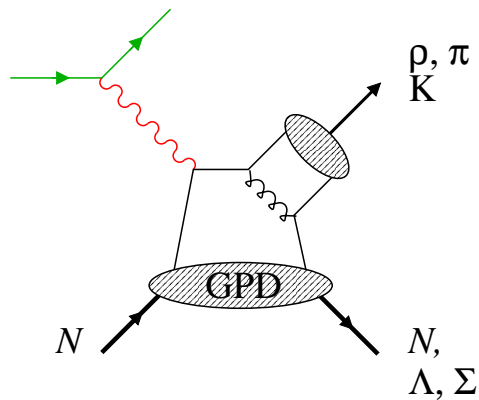
$x < 0.1$    $x \sim 0.3$    $x \sim 0.8$

- Unifies concepts of quark parton density and elastic form factor

- Describes transverse spatial distribution of quarks:

  "Quark imaging" of nucleon

- Access to static properties: $J_q$ quark angular momentum Forces inside nucleon

# Probing GPDs in $eN$ scattering



$e'$

$e$

$Q^2$

$\gamma$

$x+\xi$      $x-\xi$

GPD

$N$     $N$

$t$
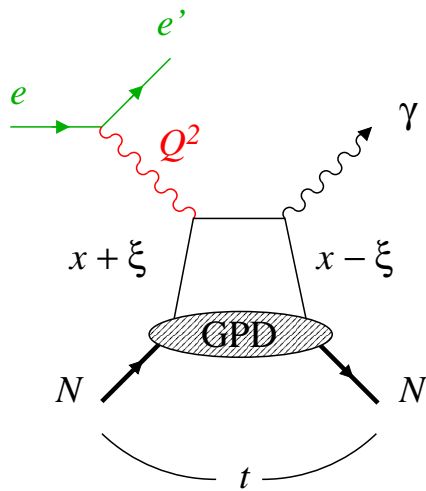
Deep−virtual
Compton
scattering



$\rho, \pi$
K

GPD

$N$      $N,$
$\Lambda, \Sigma$

Deep−virtual
meson
production

- Basic information from parton densities and elastic FFs

- Correlations $x$−$t$ from high−$Q^2$ exclusive processes

  $\rightarrow$ GPD parametrization

- QCD factorization

  $\rightarrow$ Rigorous method

  $\rightarrow$ GPDs universal, process−independent

  $\rightarrow$ Lattice QCD (moments)
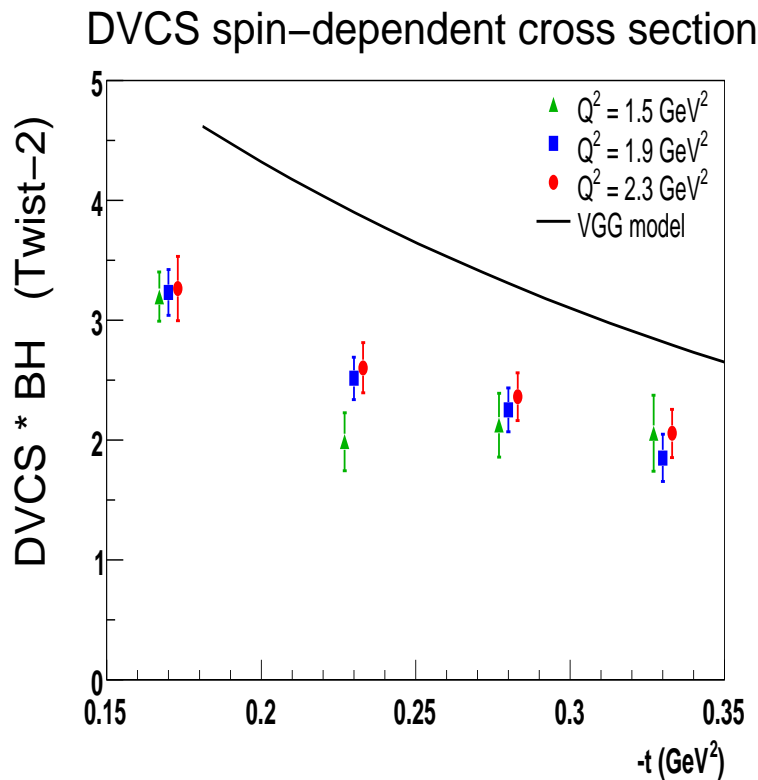
# Theory tasks in GPD analysis

- Explore relation GPDs $\longleftrightarrow$ nucleon structure

- Develop GPD parametrizations

- Calculate DVCS/DVMP observables in terms of GPDs

- Quantify/test approach to factorization regime

# GPDs in JLab Theory Center 06/07

| | | | |
|---|---|---|---|
| STAFF | A. Radyushkin | ODU/JLab | "Founding Father"<br>QCD factorization, formfactors, GPDs |
| | M. Vanderhaeghen | W&M/JLab | GPD parametrizations, reaction codes,<br>chiral EFT, phenomenology |
| | C. Weiss | JLab | GPDs $\leftrightarrow$ nucleon structure,<br>higher twist, phenomenology, small–$x$ |
| POSTDOC | V. Guzey<br>(will join 07) | JLab | GPD parametrizations, nuclear DVCS |
| STUDENT | A. Psaker | ODU | |

JLab Lattice Group: Edwards, Orginos, Richards, Lin
($\rightarrow$ presentation by R. Edwards)

# DVCS: Impact of cross section data

DVCS spin–dependent cross section



- $Q^2 = 1.5\ \text{GeV}^2$
- $Q^2 = 1.9\ \text{GeV}^2$
- $Q^2 = 2.3\ \text{GeV}^2$
- VGG model

DVCS * BH  (Twist–2)

-t (GeV$^2$)

C. Munoz Camacho et al. [JLab Hall A],
Phys. Rev. Lett. 97, 262002 (2006)

- First measurement of DVCS absolute cross sections indicate early approach to scaling

  . . . Crucial test of factorization!

- Challenge traditional VGG model which describes asymmetry data [Vanderhaeghen et al. 99]

  . . . GPD model?

  . . . Kinematic corrections?

Beginning of "real" interaction data $\longleftrightarrow$ GPD models
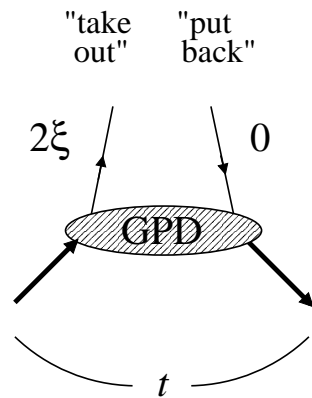
# DVCS: Projections for 12 GeV

- Dirac GPD $H(x = \xi; t)$ and "quark image" of nucleon
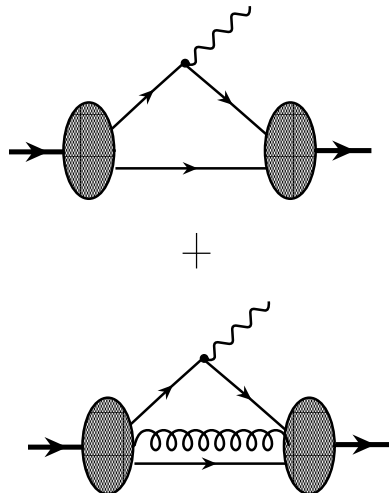  from DVCS beam spin asymmetry measurements with CLAS12
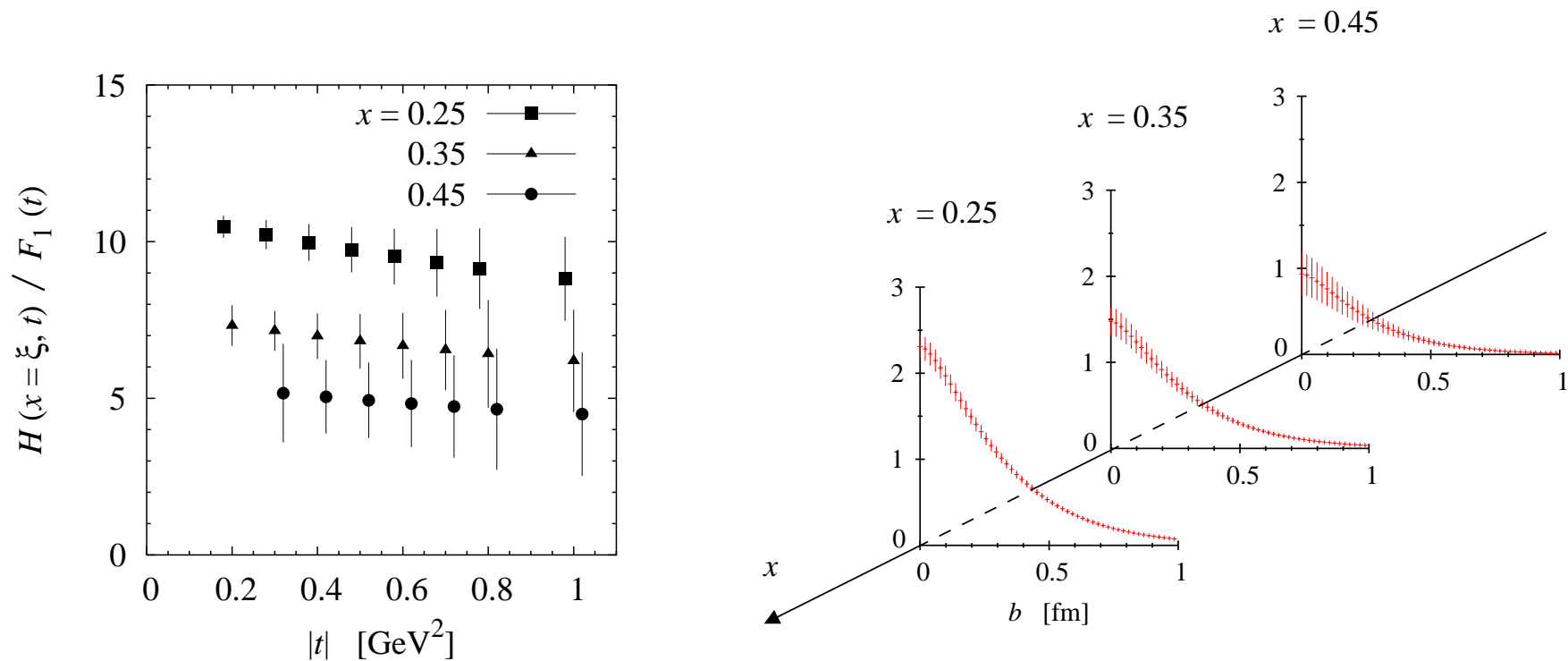


H. Avakian, C. Weiss; based on code by M. Vanderhaeghen.
To appear in GPD White Paper (H. Abramowicz et al.) 2007
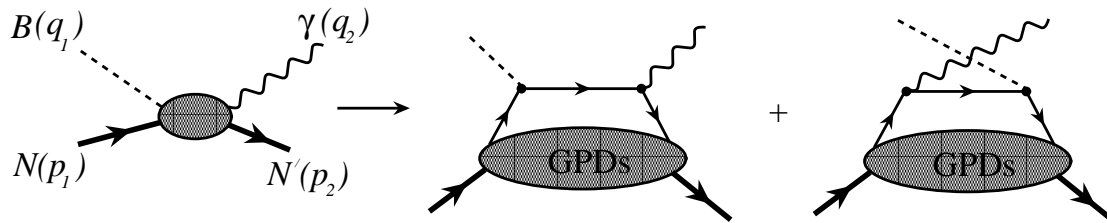
# DVCS: Physics of GPDs at $x = \xi$

"take out"   "put back"

$2\xi$   $0$

GPD

$t$

- DVCS spin asymmetries probe GPDs in "transition region" $x = \xi$

  . . . Physics content?

$+$

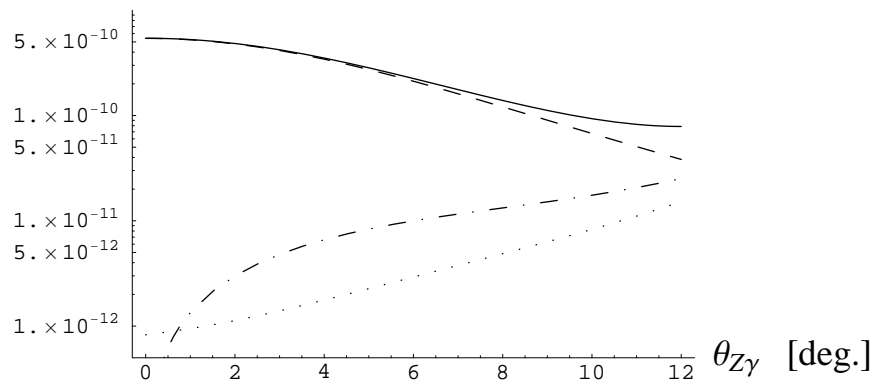- Light–front constituent quark model: Higher Fock components essential ($q\bar{q}g$ in meson)

[C.R. Ji, Mishchenko, Radyushkin, Phys. Rev. D 73, 114013 (2006)]

# DVCS: Weak currents



$B(q_1)$   $\gamma(q_2)$

$N(p_1)$   $N'(p_2)$

GPDs   +   GPDs

[Psaker, Melnitchouk, Radyushkin, Phys. Rev. D 75, 054001 (2007)]

$d^4\sigma/(dx_B dQ_1^2 dt d\varphi)$ [nb/GeV$^4$]
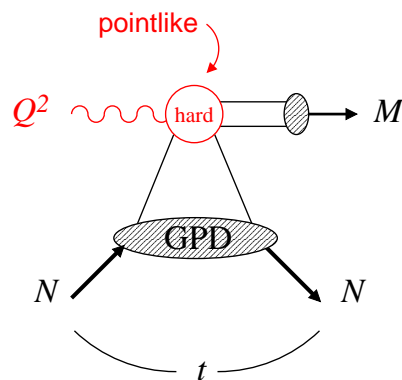


$\theta_{Z\gamma}$ [deg.]

- Probes other $C$/flavor combinations of GPDs than EM scattering

- Could be studied with high–intensity neutrino beams

  MINERVA
  CERN "Neutrino factory"

# DVMP: Approach to factorization regime



pointlike

$Q^2$ — hard — $M$

GPD

$N$ — $N$

$t$



$\pi^0$    $t$–slope    2007/07/02 14.08

$B$ [GeV$^{-2}$]

- Q2=1.3
- Q2=1.8
- Q2=2.2
- Q2=2.7
- Q2=3.2
- Q2=3.7
- Q2=4.2

CLAS 6 GeV
(very preliminary)

.1   .2   .3   .4   .5   $x_B$

- Model–independent tests of approach to factorization regime

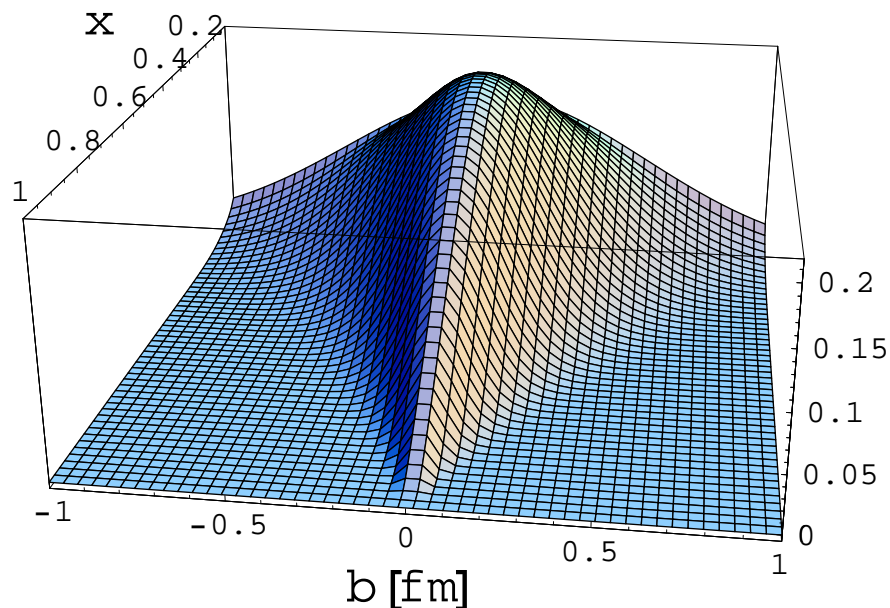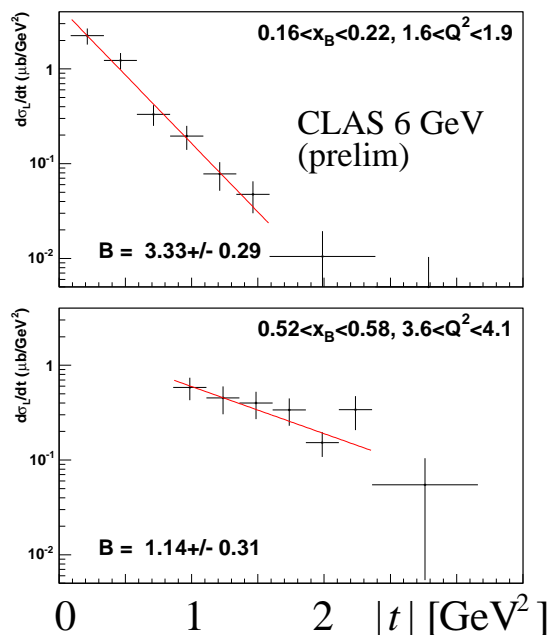- Example: $t$–slope of cross section should become independent of $Q^2$ (probe "pointlike")

  ... Can be studied already with 6 GeV data!
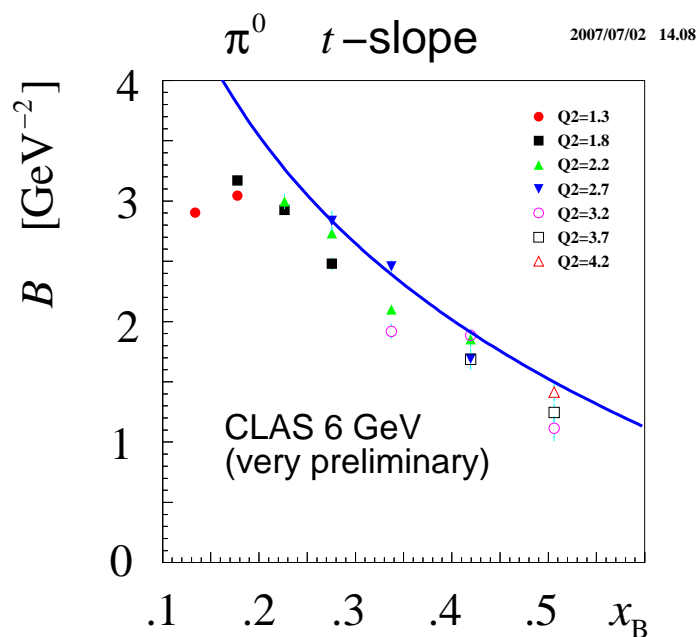
12 GeV Proposal PR12–06–108
(Theory support: Weiss)

# DVMP: Vector meson production and GPDs

$\rho^0$ cross section $d\sigma_L/dt$



- $t$–slopes agree with present GPD models

  [Guidal, Polyakov, Radyushkin, Vanderhaeghen, Phys. Rev. D 72, 054013 (2005)]

- Absolute cross sections: Need more work. . .

  [cf. Diehl, Kugler, Schäfer, Weiss, Phys. Rev. D 72, 034034 (2005)]

# GPD theory: Future efforts

- Explore physics content of GPDs in "transition region" $x = \xi$ accessed directly in Im(DVCS)

- Calculate/model corrections to partonic reaction mechanism ("higher twist") in DVCS

  Cross sections $\leftrightarrow$ asymmetries

- Study transition from hadronic to partonic regime in DVMP with increasing $Q^2$

  $\leftrightarrow$ Color transparency . . . Real surprises/discoveries possible!

- Develop quantitative dynamical models for DVMP combining partonic and hadronic degrees of freedom

# GPDs: Progress in lattice calculations
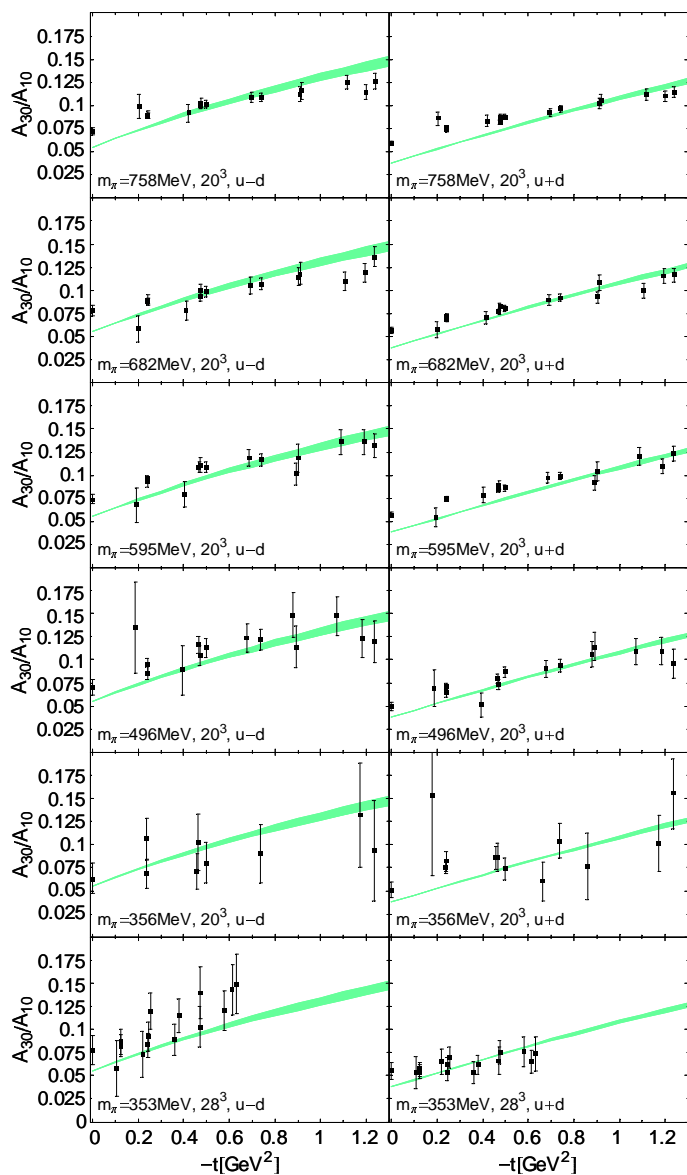


- $t$–dependence of lowest moments $(n = 1, 3)$

  - No disconnected diagrams

  - Chiral extrapolation

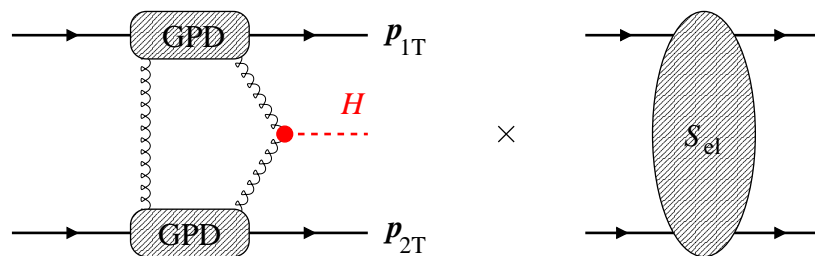  Ph. Hägler et al. [LHPC Collaborations, includes R. Edwards, K. Orginos, D. Richards] arXiv:0705.4295

  GPD parametrization: M. Diehl et al., Eur. Phys. J. C39, 1 (2005)

- Potential to constrain GPD parametrizations in the future

# GPDs in $pp$: Exclusive diffraction

$$pp \rightarrow p + \text{gap} + H + \text{gap} + p$$
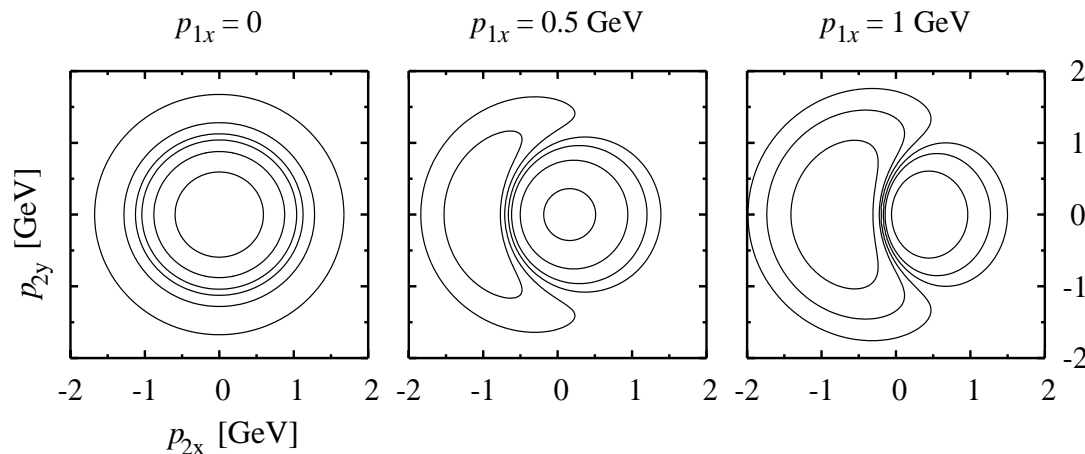
$(= \text{dijet, Higgs, } Q\bar{Q}, ...)$

- 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 @ $\sqrt{s} = 500\,\text{GeV}$ ?

Probe gluon GPD in $pp$
. . . New direction!

$p_{1x} = 0$    $p_{1x} = 0.5\,\text{GeV}$    $p_{1x} = 1\,\text{GeV}$



$p_{2y}$ [GeV]

$p_{2x}$ [GeV]

# User community interaction

- Informal working group

  Hall A — Hall B — Theory — Visitors

- Theory support for PAC 30/31 proposals

- International workshops at JLab

  Exclusive Reactions, May 21–24, 2007, $>$100 participants

- Preparations for NSAC Long–Range Plan

  - Special INT/JLab/BNL Workshop, U. Maryland, Oct. 29–30, 2006
  - "Future Opportunities in QCD," SURA Office, Dec. 15–16, 2006
  - GPD White Paper (Rutgers Town Meeting; to be published)
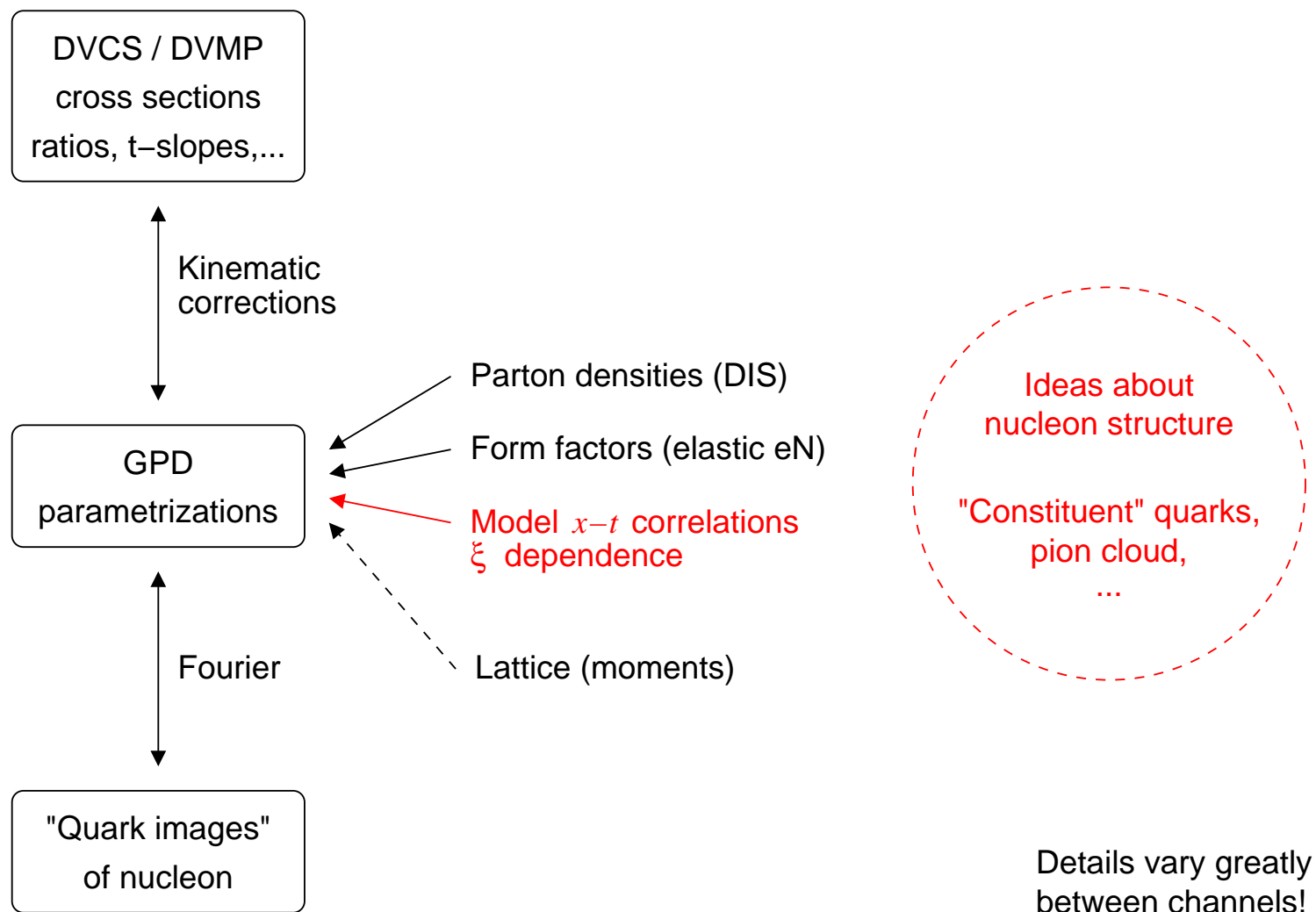  - Physics case for GPDs at EIC: "Gluon imaging"

  . . . Leading role of JLab Theory Center!

# Summary

- Exciting times. . . First real interaction experiment $\leftrightarrow$ theory   in DVCS/DVMP!

- Theory input essential for GPD program

    Reaction theory, GPD models, interpretation, . . .

- On track towards "quark imaging" of nucleon

    . . . Clearly feasible

    . . . Much work lies ahead!
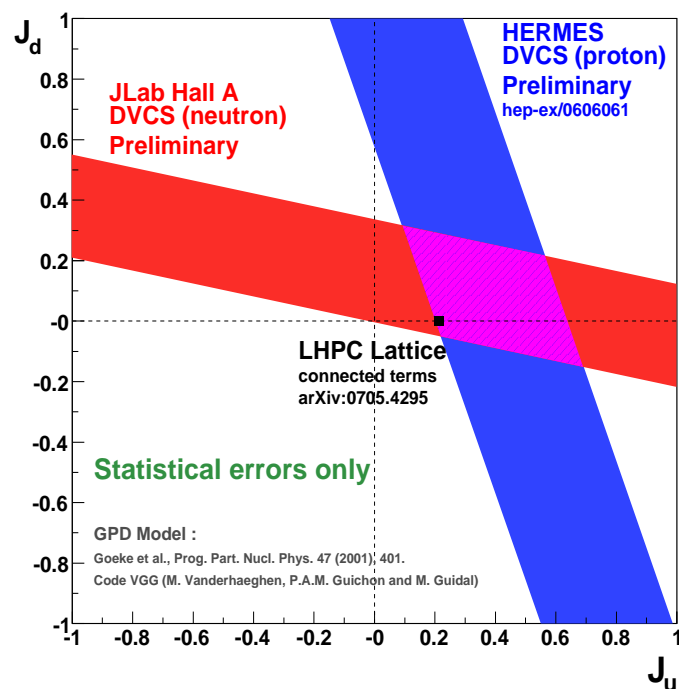
# Supplementary material

# From $eN$ data to quark images

DVCS / DVMP
cross sections
ratios, t–slopes,...

Kinematic
corrections

GPD
parametrizations

Parton densities (DIS)

Form factors (elastic eN)

Model $x-t$ correlations
$\xi$ dependence

Lattice (moments)

Fourier

"Quark images"
of nucleon

Ideas about
nucleon structure

"Constituent" quarks,
pion cloud,
...

Details vary greatly
between channels!

# DVCS: Quark angular momentum



JLab Hall A quasi–free neutron DVCS (preliminary) [M. Mazzouz et al.]

GPD model: Goeke, Polyakov, Vanderhaeghen (2001)

- First tentative extraction of quark angular momentum

  – Model–dependent!

  – Statistical errors only!

- Improved lattice results

  Ph. Hägler et al. [LHPC Collaborations, includes R. Edwards, K. Orginos, D. Richards] arXiv:0705.4295

Quark angular momentum can be estimated indirectly using GPD parametrization