Highlights of GPD 2006

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organized by

- Nicole d'Hose (CEA Saclay)
- Peter Kroll (Wuppertal)
- Ralf Kaiser (Glasgow)

Introductory Talks: (3 talks)

- A. Belitsky: Understanding Nucleon Structure with GPDs
- M. Burkardt: Hadron Tomography
- M. Diehl: An Introduction to Generalized Parton Distributions

Theoretical Developments: (7 talks)

- S. Friot: GPDs in the Photon
- D. Müller: A new representation for GPDs
- D. Robaschik: Target mass corrections to DVCS
- A. Schäfer (QCDSF): GPDs from Lattice QCD - II (Tensor GPDs)
- G. Schierholz (QCDSF): GPDs from Lattice QCD - I
- L. Szymanowski (B. Pire): Generalizing GPDs: Transition Distribution Amplitudes
- L. Szymanowski: QCD factorization in $\gamma^*\gamma^*$

Phenomenological Analyses and Models: (10 talks)

- M. Diehl: Wide-angle processes
- Th. Feldmann: Analysis of zero-skewness GPDs
- S. Goloskokov: Deeply virtual electro-production of vector mesons
- V. Guzey: Dual parametrization of GPDs and description of DVCS data
- Ph. Haegler: Generalized transversity and transverse spin densities
- S. Liuti: Space-time picture of nuclear effects in QCD
- B. Pasquini: Virtual meson cloud of the nucleon and GPD
- P. Schweitzer: GPDs in the chiral quark-soliton model . . .
- M. Siddikov: GPDs for Spin-0 Nuclei
- M. Vanderhaeghen: GPDs and Two-Photon Processes

Experimental Aspects/Results: (16 talks)

- H. Avakian (JLAB): Hard exclusive processes at CLAS
- P.-Y. Bertin (JLAB): Deep Virtual Compton Scattering in Hall A
- E. Burtin (COMPASS): Status and prospects for GPD studies at COMPASS
- F. Bradamante (Compass): Transversity Physics in DIS
- M. Düren: Physics at Panda
- F. X. Girod (JLAB): DVCS at JLAB/CLAS
- C. C. Kuo: Hadron pair production from two-photon collisions at Belle
- M. Mazouz: DVCS on neutron at JLAB Hall A
- W.D. Nowak: Hermes results and projections on exclusive photon and meson production
- A. Osborne: ρ^0 production cross section ratios at HERMES
- G. Rosner: Status of Nucleon Form Factor measurements
- A. Rostomoyan: Transverse single-spin asymmetry of exclusive ρ^0 from HERMES
- A. Sandacz: Spin dependence in exclusive ρ^0 production at COMPASS
- L. Schoeffel: Exclusive production of light states at HERA ...
- C. Van Hulse: The HERMES recoil project
- B. Wojtsekhowski (JLAB): Nucleon Compton Scattering

Outline

1. Introduction
2. Results for DVCS + Meson Production
   - JLAB – Hall A
   - JLAB – CLAS
   - DESY – HERMES
   - DESY – H1 and ZEUS
   - CERN – COMPASS
   - Theoretical GPD parametrizations for $\xi \neq 0$
   - Theoretical models for deeply virtual meson production
3. (Generalized) Form factors, Wide-angle processes etc.
   - Nucleon Form Factors
   - GPDs at zero skewness
   - Generalized form factors from lattice
   - Wide-angle processes
4. Transversity GPDs
5. More Talks
6. Conclusions

Introduction

Physical Significance:

- GPDs as hadronic input for factorization theorems (DVCS, etc.)
- Angular momentum distribution of partons ("Ji's sum rule")
- 3-dimensional structure of fast-moving nucleon from impact parameter GPDs ("nucleon tomography")

Experimental Challenge:

- Collect detailed data on (hard) exclusive processes !

Theoretical Challenge:

- Disentangle dependence on three kinematic variables (x, ξ, t) !

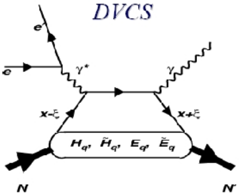
Aim of the workshop:

- Review experimental and theoretical status.
- Set the stage for the next round of GPD analyses.

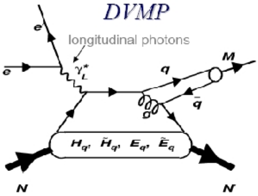
Experimental results for DVCS + Meson production:

Physics Motivation

- Describe the complex nucleon structure in terms of quark and gluon degrees of freedom.

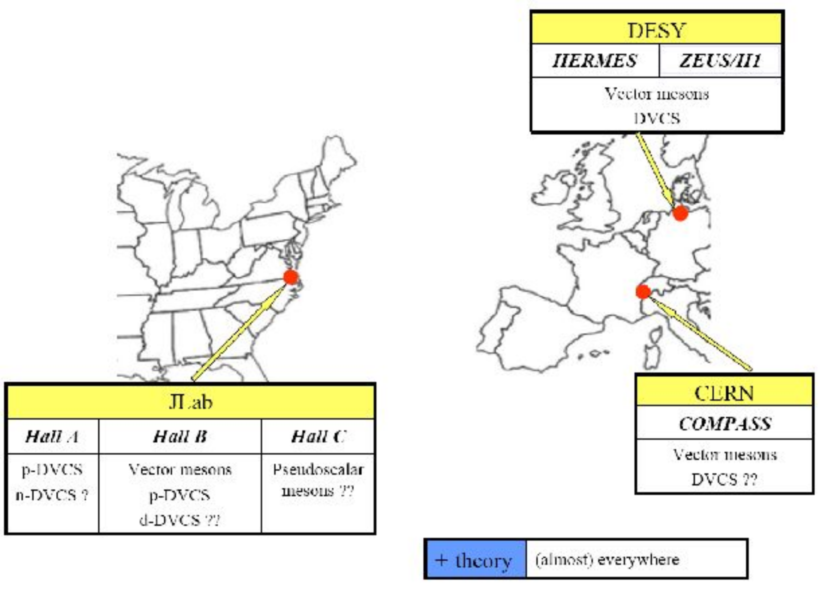


DVCS – for different polarizations of beam and target provide access to different combinations of GPDs H, $\tilde{H}$, E



DVMP for different mesons is sensitive to flavor contributions (ρ^0/ρ^+ select H, E, for u/d flavors, π, η, K select $\tilde{H}$, $\tilde{E}$)

[Avakian]


DESY
HERMES
ZEUS/H1
Vector mesons
DVCS
JLab
Hall A
Hall B
Hall C
p-DVCS
n-DVCS ?
Vector mesons
p-DVCS
d-DVCS ??
Pseudoscalar
mesons ??
CERN
COMPASS
Vector mesons
DVCS ??
+ theory
(almost) everywhere

[Schoeffel]

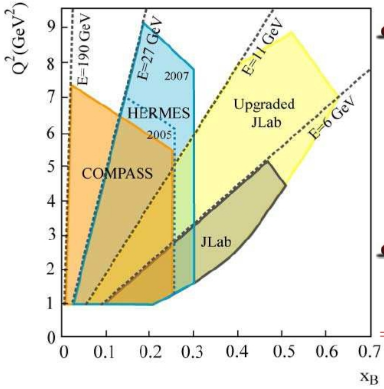
M. Dueren:

GPD studies foreseen for PANDA experiment (FAIR facility at GSI, ca. 2013)

- Input from the community for optimization of experimental program welcome!

Kinematic Coverage of DVCS Experiments

Fixed-target experiments



- Fixed-target experiments:
  $x > 0.03$, $Q^2 < 10$ GeV^2
  - COMPASS: low+medium x
  - HERMES: medium x, higher Q^2
  - JLab: medium+large x, lower Q^2
  - JLab 11 GeV: larger x, higher Q^2
- Collider experiments H1+ZEUS:
  $x < 0.01$, $Q^2 : 5 \ldots 100$ GeV^2

$\Rightarrow$ almost no overlap

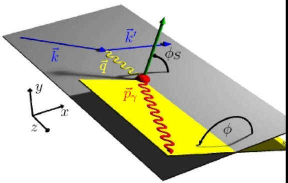
Wolf-Dieter Nowak (DESY), HERMES Collaboration Trento GPD2006 Workshop – p.

[Nowak]

Azimuthal Asymmetries in DVCS

DVCS–Bethe-Heitler Interference term $\mathcal{I}$
induces azimuthal asymmetries in cross-section:

- Beam-charge asymmetry $A_C(\phi)$ [BCA]
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$



- Beam-spin asymmetry $A_{LU}(\phi)$ [BSA]
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$

- Long. target-spin asymmetry $A_{UL}(\phi)$
  $d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$ [LTSA]

- Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli elastic nucleon form factors)

[Nowak]

P.-Y. Bertin: DVCS/Hall A

- At JLAB energies, Bethe-Heitler process dominates
- Using polarized beam on unpolarized target
  $\rightarrow$ Measure cross section sum $d\overrightarrow{\sigma} + d\overleftarrow{\sigma}$ and difference $d\overrightarrow{\sigma} - d\overleftarrow{\sigma}$
- Sum sensitive to $\mathrm{Re}\left[\mathcal{T}^{\mathrm{DVCS}}\right]$. — Difference sensitive to $\mathrm{Im}\left[\mathcal{T}^{\mathrm{DVCS}}\right]$.

- Test of handbag dominance yield positive results
  - no Q^2 dependence of extracted twist-2 coefficients
  - twist-3 contributions in $\Delta\sigma$ and σ small

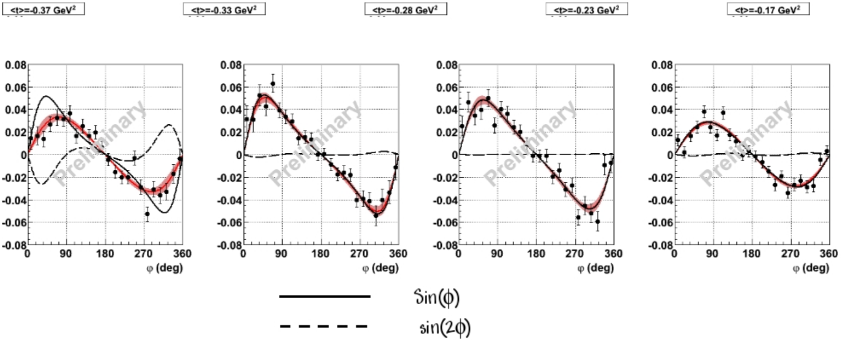
$\Rightarrow$ $d\overrightarrow{\sigma} - d\overleftarrow{\sigma}$ directly probes twist-2 GPDs

- In cross-section sum, bilinear DVCS terms cannot be neglected

$\Rightarrow$ Comparison with theory requires some model-dependence!
Also applies for asymmetry $\frac{d\overrightarrow{\sigma} - d\overleftarrow{\sigma}}{d\overrightarrow{\sigma} + d\overleftarrow{\sigma}}$

$$\frac{d^4\sigma^+}{dx_B dQ^2 d\varphi\, dt} - \frac{d^4\sigma^-}{dx_B dQ^2 d\varphi\, dt} \quad [\mathrm{nb/GeV^4}]$$

Corrected for real and virtual radiation



[Bertin]

What systematic errors?

~~At this day (June 5 2006):~~ For the future experiments

2% ~~3%~~ HRS+PbF2 acceptance +luminosity + target

1% ~~3%~~ $H(e,e'\gamma)X\gamma$ π^0 background

2% Inclusive $H(e,e'\gamma)N\pi$

2% Radiative Corrections only on the cross section difference

1% ~~2%~~ Beam polarization measurement

Total (quadratic sum)= ~~5.1% (5.6%)~~ 3.6 - 3.7 %

[Bertin]

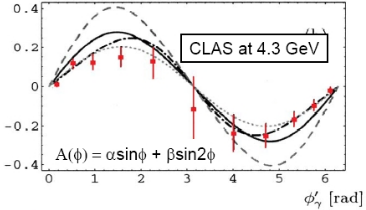
M. Mazouz: DVCS on the Neutron (Hall A)

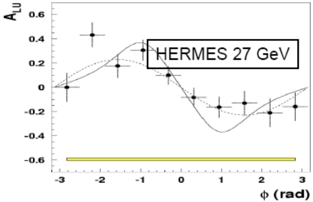
- Azimuthal asymmetry with polarized electron beam.
- Sensitivity to GPDs E^n (larger than for proton)
- π^0 contamination $\approx$ drops out from deuterium-proton
- Check of exclusivity (systematic error $< 3\%$).
- Asymmetry for DVCS on
  - deuteron (coherent)
  - neutron (incoherent)

  enter with different sign (preliminary result of simultaneous fit)

H. Avakian / F.-X. Girod: Hard exclusive processes at CLAS

- DVCS beam spin asymmetries
- DVCS target spin asymmetry
- Studies of exclusive π^0 background (beam and target SSA)
- Exclusive ρ production (Q^2 dependence, sensitivity to J_u and J_d)
- Dedicated CLAS DVCS experiment (detector upgrade)
  (43% of data taken, preliminary results on BSA)
- Prospects for CLAS12

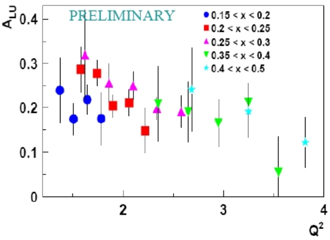


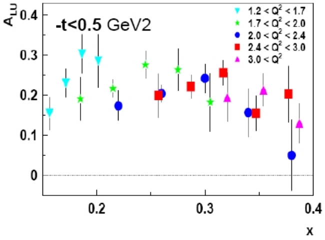


S. Stepanyan et al. Phys. Rev. Lett. **87** (2001)

A. Airapetian et al. Phys. Rev. Lett. **87** (2001)

DVCS SSA kinematic dependences at 5.7 GeV





W.-D. Nowak: HERMES results and perspectives

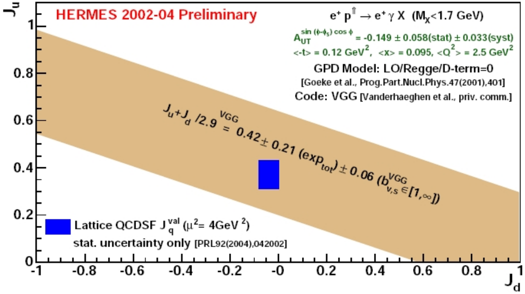
- Measurement of BSA, BCA and (long./transv.) target polarization.
- First constraints on GPD models,
  incl. (model-dependent) constraints on angular momentum J_u and J_d.
- New HERMES recoil detector (with unpolarized proton target)
  Will improve resolution and statistics for azimuthal DVCS asymmetries and exclusive π^+ production. [dedicated talk by C. Van Hulse]
- Because of two accidents: Data taking starting in July 2006.
  Only run with e^+ foreseen $\Rightarrow$ no BCA :-(

Further presentations by

- A. Rostomyan: TSSA $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive ρ^0 production at HERMES
  - Neglect (probably small) contribution from E^g
  - L/T separation not yet done
  - Not yet enough statistics to constrain J^u
- A. Osbourne: ρ^0 production at HERMES (cross section ratios)
  - Consider ratio of (longitudinal) ρ^0 production on neutron (i.e. deuterium) and on proton
  - Function of up-, down-, and gluon GPDs
  - Theoretical estimate close to 1 (gluon dominance)
  - Still large errors - should be improved with 2007 statistics and recoil detector

Model-dependent Constraint on J_u vs J_d

Unbinned maximum likelihood fit to $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ at average kinematics (fitting prel. HERMES data against VGG-model based calculations), leaving J_u and J_d as free parameters $\Rightarrow$ model-dependent 1-σ constraint on J_u vs. J_d:



- Quenched lattice calculation done with pion masses 1070, 870, and 640 MeV, and then extrapolated linearly in m_π^2 to the physical value
- Uncertainties on VGG model parameters shown as separate uncertainty (± 0.06)

Wolf-Dieter Nowak (DESY), HERMES Collaboration Trento GPD2006 Workshop – p.2

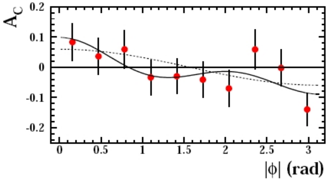
[Nowak]

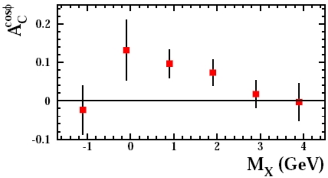
Beam-charge Asymmetry vs. ϕ and M_X^2

$$A_C(\phi) = \frac{d\sigma^+(\phi) - d\sigma^-(\phi)}{d\sigma^+(\phi) + d\sigma^-(\phi)} \propto \mathrm{Im} F_1 \mathcal{H} \cdot \cos\phi$$

$\Rightarrow$ extract 'amplitudes' by fitting in every ϕ-bin

$$A_C(\phi) = const. + A_C^{\cos\phi} \cos\phi + A_C^{\cos 2\phi} \cos 2\phi + A_C^{\cos 3\phi} \cos 3\phi$$





- published results shown for *un*polarized proton target **[hep-ex/0605108, subm. to PRL]**
- use *symmetrization* ($\phi \to |\phi|$) to get rid of sinusoidal terms
- $A_C^{\cos\phi} = 0.060 \pm 0.027$, other contributions insignificant (dashed = pure $\cos\phi$)
- asymmetry only in exclusive and 'associate' M_X^2 region ($\rightarrow$ resol. smearing)
- preliminary deuteron data (not shown) completely consistent

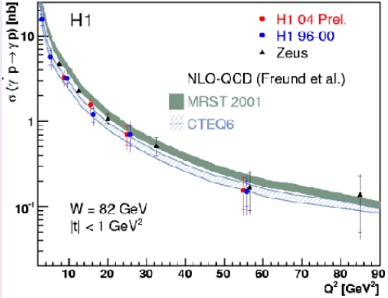
[Nowak]

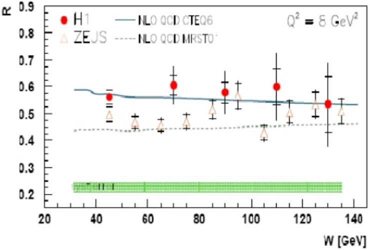
L. Schoeffel: Exclusive light states at HERA

- H1/ZEUS kinematics:
  Q^2 and W^2 span many orders of magnitude, $x \sim 0.01$
- test of QCD evolution (Q^2-dependence of cross section)
- Study t-dependence, fit exponential with slope parameter b
  ($\rightarrow$ update incl. 2004 data)
- Study W-dependence, $d\sigma \sim W^{0.8}$
- Extract the skewing factor $R = \mathrm{DIS}/\mathrm{Im}[\mathcal{A}^{\mathrm{DVCS}}]$
- Sensitivity to gluon distribution
- Comparison with dipole formulation ("geometric scaling")

Summary for the DVCS at H1/ZEUS

- Data in good agreement with NLO predictions : GPDs ≡ PDFs at low scale and skewing generated dynamically from the QCD evolution…
- 'Re' part contributes to a few %



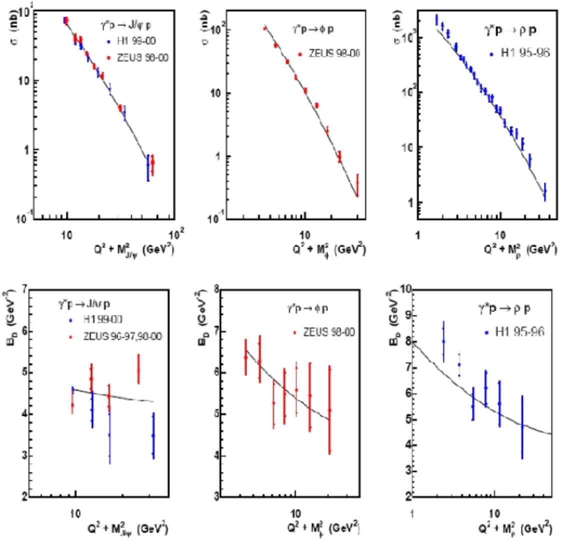


R=Im DIS / Im DVCS ~ 0.5
from a competition between Singlet and Gluons $R_{S\ and\ G}$

Perspectives : with increased stat. : more precise b(Q²) and b(W)!

[Schoeffel]

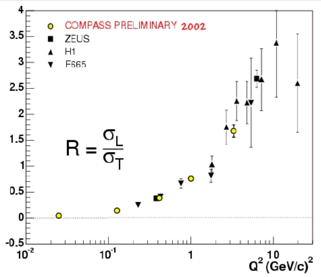
Results from all light exclusive VM production at HERA

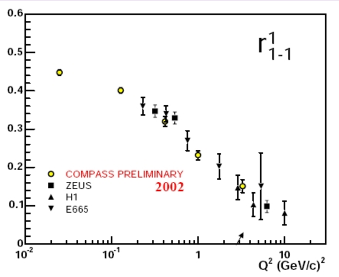


[Schoeffel]

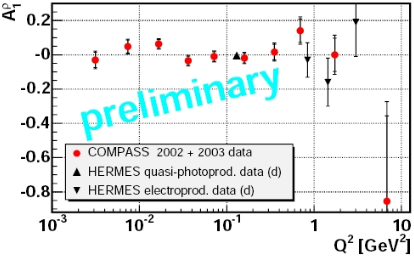
A. Sandacz: Exclusive ρ^0 at COMPASS

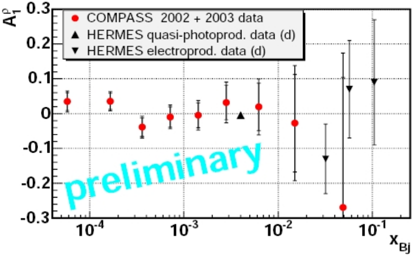
- Longitudinal double-spin asymmetry $A_1^\rho(d)$
  - first measurement at small Q^2 and small x
  - consistent with zero
- High-statistics data on ρ^0 spin-density matrix elements and $R = \sigma_L/\sigma_T$
  - σ_L dominates for $Q^2 > 2$ GeV^2
  - weak violation of s-channel helicity conservation
  - extraction of 23 SDMEs from 2003/4 data under way
- Studies of coherent ρ^0 production foreseen.
- Analysis of exclusive ϕ and J/ψ in progress.





COMPASS preliminary and HERMES results on A_1^ρ (d)





COMPASS results on A_1^ρ on polarized deuteron target consistent with 0

Extended kinematical range of COMPASS by almost 2 decades down both in Q^2 and x

COMPASS : inner bars –stat. outer – total errors
HERMES: total errors

[Sandacz]

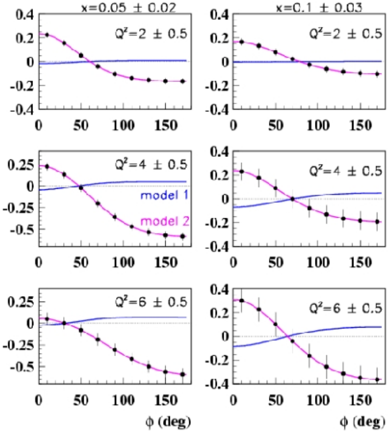
E. Burtin: GPDs at COMPASS (DVCS prospects)

- 80% polarized μ^+ and μ^- beams
- Compass could provide data on
  - Cross section (190 GeV)
  - BCA (100 GeV)
  - Wide range of Q^2 and x_{Bj} values
- possible roadmap:

2006: test of recoil detector prototype ($\surd$)
2007: proposal
2007-09: construction (rec. detector, LH_2 target, ECALO)
$\geq$ 2010: study of GPDs at COMPASS

Projected errors of a possible DVCS experiment

Beam Charge Asymmetry



$\mathcal{L} = 1.3\ 10^{32}\ cm^{-2}\ s^{-1}$

E_{beam} = 100 GeV

6 month data taking

25 % global efficiency

6/18 (x, Q^2) data samples

3 bins in x_{Bj} = 0.05, 0.1, 0.2

6 bins in Q^2 from 2 to 7 GeV^2

Model 1 : $H(x,\xi,t) \sim q(x)\ F(t)$

Model 2 : $H(x,0,t) = q(x) / x^{\alpha' t}$

Good constrains for models

[Burtin]

Theoretical GPD parametrizations for $\xi \neq 0$

- Generate non-trivial ξ-dependence.
- Satisfy polynomiality conditions.
- Satisfy positivity.
- Implement NLO evolution.

D. Müller: A new representation for GPDs

Mellin-Barnes representation of GPDs: [DM/Kirch/Manoshov/Schäfer 05]

$$q(x,\xi,t;\mu^2) = \frac{1}{2i}\int_{c-i\infty}^{c+i\infty} dn\,\frac{p_n(x,\xi)}{\sin(\pi n)}\,E_n(\mu^2,\mu_0^2)\,q_n(\xi,t;\mu_0^2)$$

- $p_n(x,\xi)$ known basis functions
- $E_n(\mu^2,\mu_0^2)$ simple evolution operator (anom. dimensions)

Constraints on $q_n(\xi,t;\mu_0^2)$:

- polynomiality in ξ
- form factors: $F(t) \equiv q_1(\xi,t;\mu_0)$
- Mellin moments of PDFs: $q_n(\mu_0) \equiv q_1(\xi=0,t=0;\mu_0)$

Summary

The *Mellin–Barnes representation* for GPDs looks complicated.

However, it has several advantages:

- crossing relation GPDs ⇔ GDAs is trivial
- partial wave decomposition ⇒ tool to study duality
- separation of variables ⇒ better GPD ansaetze/models
- convenient representation of scattering amplitudes
- simple and stable numerics that includes evolution (important for MC simulations)
- first view beyond NLO in DVCS for a special scheme

This representation is not restricted to a special scheme.

It can be implemented at NLO for hard photon and meson electroproduction in the $\overline{\mathrm{MS}}$ scheme, too.

[Müller]

V. Guzey: Dual parametrization of GPDs and DVCS

Postulate representation of proton singlet GPDs in terms of Gegenbauer polynomials and partial waves [Shuvaev/Polyakov 02]

$$H^q(x,\xi,t;\mu^2) = \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{\ell=0 \\ \text{even}}}^{n+1} B^q_{n\ell}(t,\mu^2)\, \theta(\xi - |x|)\, (1 - x^2/\xi^2)\, C_n^{3/2}(x/\xi)\, P_\ell(1/\xi)$$

- simple LO evolution and LO DVCS amplitudes
- divergent series of t-channel exchanges (→ duality)
- use Polykov/Shuvaev trick and get $B^q_{n\ell}$ from generating function
- keep minimal number of generating functions relevant for small values of ξ
- need further model assumptions on forward limit of E^q and D-term
- t-dependence: factorized vs. Regge with $\alpha' > \alpha'_P$

- economical description of DVCS observables
- Regge model for t-dependence preferred by HERMES data on A_C and A_{UT}

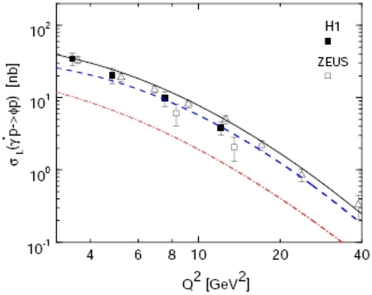
S. Goloskokov:
Deeply virtual vector meson production (theory model)

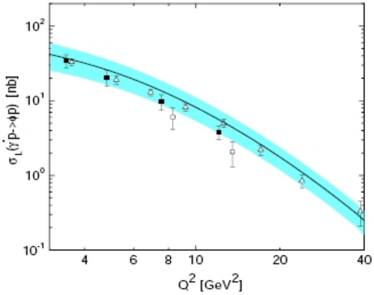
- Use DD ansatz to model GPDs.
- Use pomeron slope $\alpha' \sim 0.15$ for t-dependence of gluons/sea quarks.
- Use vector meson production to constrain gluon/sea below $x = 0.01$.

- In hard-scattering use $k_\perp$-dependent LCWF for mesons and Sudakov form factors (transverse radius = fit parameter)

- Cross sections for HERMES and HERA energies.
- Results for fitted gluon distribution.

Q^2 dependence of longitudinal cross sections of ϕ production at $W = 75\text{GeV}$.





Full line cross section, dashed blue- gluon contribution, dashed-dot- red - gluon-strange interference.

Cross sections with errors from uncertainty in parton distributions.

[Goloskokov]

Nucleon Form Factors

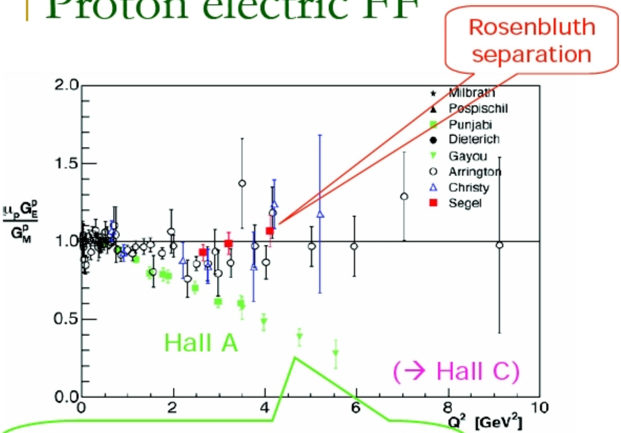
- Input for GPD and DD reduction formulas.
- Constraints on models for x-t correlation in GPDs.

G. Rosner: Nucleon form factor measurements (status)

- Vector form factors for proton and neutron (space-like)
  extended Q^2 range from JLAB upgrade
- Axial form factors (only dipole fit $\rightarrow M_A$)
  Induced PS form factor (only $G_P(\approx 0)$)
- Strangeness form factors
- Time-like form factors: factor-2 larger than space-like, neutron $>$ proton ?

  - new data from Belle/Babar . . .
  - phase between G_E and G_M from Panda [see talk by Dueren]?

Proton electric FF

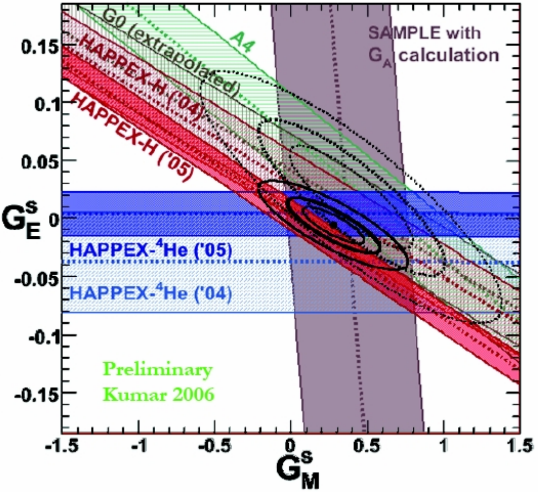


$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_e'}{2M}\tan(\frac{\theta_e}{2})$$

using **focal plane polarimeters** in A1 and Hall A

[Rosner, see below]

World data @ $Q^2 \sim 0.1\ \mathrm{GeV}^2$



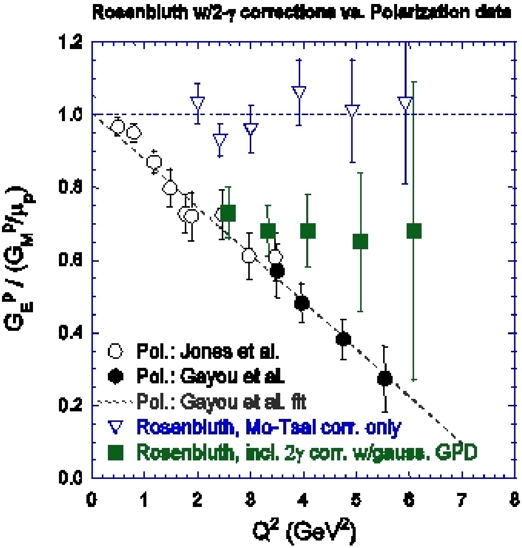
- $G_M^s = 0.28 \pm 0.20$
  $G_E^s = -0.006 \pm 0.016$
- ~ 3% ± 2.3% of magnetic moment
  ~ 0.2% ± 0.5% of charge distribution
- HAPPEX-only fit:
  - $G_M^s = 0.12 \pm 0.24$
  - $G_E^s = -0.002 \pm 0.017$

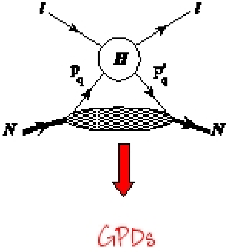
[Rosner]

M. Vanderhaeghen: GPDs and two-photon processes

- Rosenbluth separation data incompatible with recent JLAB Hall A data from polarization transfer
- May be explained by two-photon processes:
  - Big effect in Rosenbluth analysis for large Q^2
  - Small correction to polarization transfer (1-3%)
- Model-independent extraction of correction term from data.
- In line with partonic calculation (handbag + cat's ears diagrams + GPD model)

Two-photon exchange : partonic calculation





Chen, Afanasev, Brodsky, Carlson, Vdh (2004)

[Vanderhaeghen]

Th. Feldmann: (valence) GPDs at zero-skewness

- Ansatz for exponential t-dependence

$$H_v^q(x,t) := q_v(x)\,\exp\left[t\, f_q(x)\right]\,, \qquad E_v^q(x,t) := e_v^q(x)\,\exp\left[t\, g_q(x)\right]$$

- $q_v(x)$ from standard PDFs. Positivity bounds constrain $e_v^q(x)$.
- Qualitative behaviour of profile functions $f_q(x)$ and $g_q(x)$ from Regge phenomenology and physical intuition about impact-parameter GPDs.
- Fit to electromagnetic proton and neutron form factors.

- strong correlation between x and t-dependence
- transverse size for large values of x (default fit):

$$d_q(x) = \frac{b_q(x)}{1-x} \xrightarrow{x \gg 0.1} \begin{cases} 0.44 \text{ fm} & \text{(u-quarks)} \\ 0.6 \text{ fm} & \text{(d-quarks)} \end{cases}$$

- orbital momentum of valence quarks (default fit):

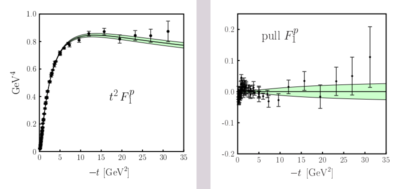
$$2(L_v^u - L_v^d) = -(0.77 \text{ to } 0.92)\,, \qquad 2(L_v^u + L_v^d) = -(0.11 \text{ to } 0.22)$$

consistent with QCDSF lattice results.

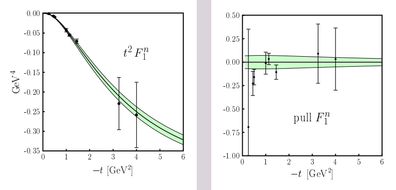
- "nucleon tomography" [also discussed by M. Burkardt]

The default fit $(\alpha' \equiv 0.9\ \mathrm{GeV}^{-2})$

proton



neutron



profile function

$$f_q(x) = -\alpha' (1-x)^3 \ln x + B_q (1-x)^3 + A_q\, x\, (1-x)^2$$

fit parameters

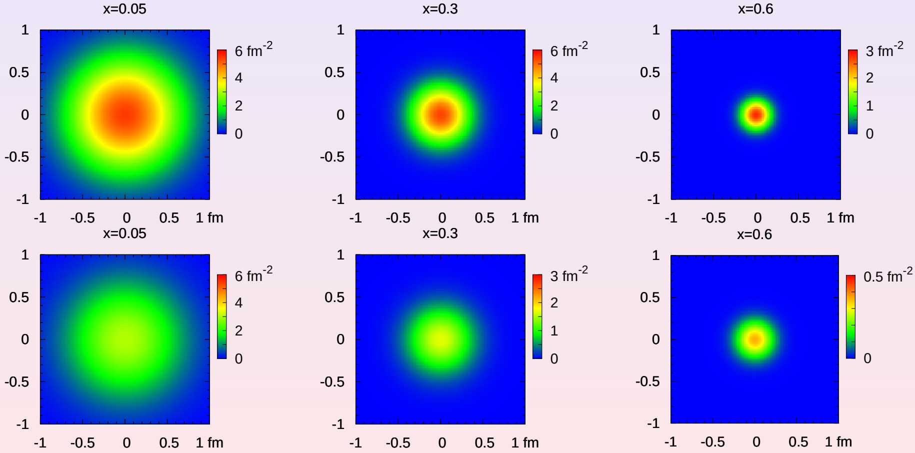
$$A_u = (1.22 \pm 0.02)\ \mathrm{GeV}^{-2}$$
$$A_d = (2.59 \pm 0.29)\ \mathrm{GeV}^{-2}$$
$$B_u \equiv B_d = (0.59 \pm 0.03)\ \mathrm{GeV}^{-2}$$

correlation

	B_q	A_u	A_d
B_q	1	-0.743	0.750
A_u	-0.743	1	-0.194
A_d	0.750	-0.194	1

Nucleon tomography from default fit to $F_{1,2}^{p,n}$

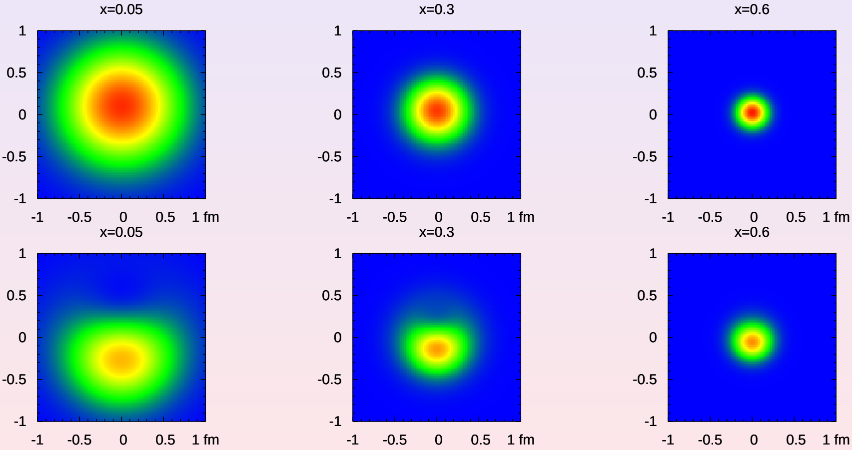
valence quarks: unpolarized (up and down)



[Diehl/TF/Jakob/Kroll 2004]

Nucleon tomography from default fit to $F_{1,2}^{p,n}$

valence quarks: polarized (sizeable systematic uncertainties due to $e_v(x)$!)



[Diehl/TF/Jakob/Kroll 2004]

G. Schierholz: QCDSF results I

- Simulations with unquenched Wilson fermions
- Generalized form factors → angular momentum:

$$J^u = 0.32(4)\,, \quad J^d = -0.21(4)\,, \quad 2L^{u+d} = 0.06(14)\,, \quad 2L^{u-d} = -0.90(12)$$

  also: $E^u + E^d \approx 0$
- Systematic uncertainties (chiral extrapolation! disconnected diagrams)
  - needs simulations with smaller pion masses
  - more studies on χPT for GPD moments
- To what extent shall we use lattice results as constraints for phenomenological parametrizations?

Wide-angle processes

M. Diehl:

- Understand dynamics in $\gamma h \to \gamma h$ and $h\bar{h} \leftrightarrow \gamma\gamma$
  at large angles and large energy ($s, t, u \gg M^2$, also VCS)
- test soft spectator mechanism
  (one fast parton in the hadron, mimics dimensional counting)
- Extract relevant (Compton) form factors (of natural size?)
- Corrections? (NLO, twist-3, target-mass)

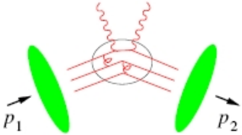
- flavour symmetry and test of handbag:

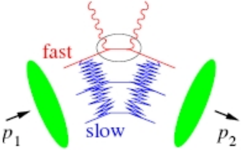
$$d\sigma[\pi^0\pi^0] \simeq d\sigma[\pi^+\pi^-] \simeq d\sigma[K^+K^-] \quad \text{and} \quad d\sigma[K_s^0 K_s^0] \simeq \frac{2}{25}\, d\sigma[K^+K^-]$$

Wide-angle Compton scattering

$\gamma p \to \gamma p$ at large $s \sim -t \sim -u$

($\theta = \angle(p, \gamma)$ away from 0° and 180°)





- hard scattering mechanism: $d\sigma/dt \sim f(\theta)\, s^{-6}$
  same problems with phenomenology as $F_1(s)$
- slow spectator mechanism: spectators soft $\sim \Lambda^2$
  fast quark semi-hard $\sim \Lambda\sqrt{-t}$ and $\gamma q \to \gamma q$ hard $\sim t$
  $\rightsquigarrow$ factorization of long- and short-distance dynamics

A. Radyushkin '98, M.D. et al. '98

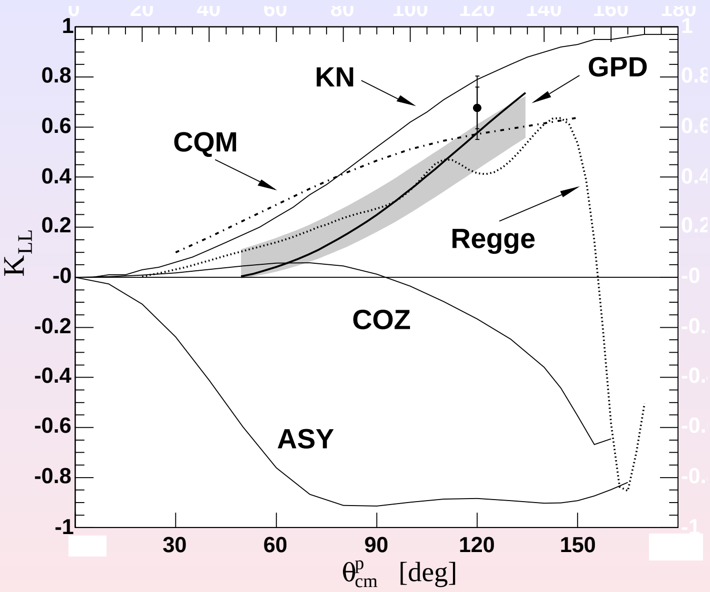
[Diehl]

B. Wojtsekhowski: Nucleon Compton Scattering (JLAB)

- Study scaling of differential cross sections with s
- Compare with handbag: fits well with predictions from Kroll et al.
- Extract Compton form factors:
  - From cross section: $R_V/F_1 > 1$ and approx. constant $\surd$
  - From polarization transfer K_{LL}: $R_A/R_V \approx 0.8$ $\surd$

    $\Rightarrow$ Only small correction of KN result:

    proton behaves almost like free fermion (fast quark takes all the photon spin)
- New measurements of K_{LL} (smaller angles) and A_{LL} planned.
- Perspectives for JLAB@12 GeV.
- Proposal for neutron CS.
- WACS prefers handbag $\rightarrow$ include results for Compton form factors into global fit?



[Wojtsekhowski]

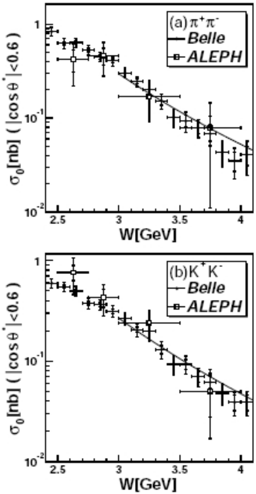
C.-C. Kuo: $\gamma\gamma \to hh$ at BELLE

- abundance of clean $\gamma\gamma$ events with $W_{\gamma\gamma} \leq 4.5$ GeV
  (pions, kaons, proton, Λ, Σ^0)
- test dynamic pictures (pQCD, diquark, handbag)

- study W-dependence: steeper than pQCD
- study θ-dependence
  - consistent with $\sin^{-4}\theta$
  - steeper for higher energies
- $\sigma(K^+K^-)/\sigma(\pi^+\pi^-)$ consistent with 1
- $\sigma(K_s^0 K_s^0)/\sigma(K^+K^-) = 0.13 \to 0.01$ (i.e. between handbag and pQCD)
- [observation of charmonium resonances]

$\gamma\gamma \to \pi^+\pi^-, K^+K^-$ at $W_{\gamma\gamma} = 2.4 - 4.1$ GeV

[Belle Collab., PL B615 (2005) 39]



$W_{\gamma\gamma}^{-n}$ dependence in $3.0 - 4.1$ GeV:

$\gamma\gamma \to \pi^+\pi^-$ $\quad n = 7.9 \pm 0.4 \pm 1.5$

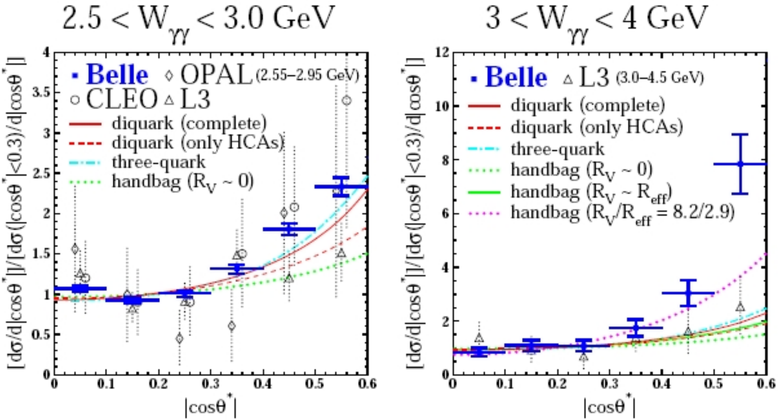
$\gamma\gamma \to K^+K^-$ $\quad n = 7.3 \pm 0.3 \pm 1.5$

---

showing a steeper dependence than $W_{\gamma\gamma}^{-6}$

[Kuo]

$\gamma\gamma \to p\bar{p}$ [Belle]



- Consistent with the ascending trend of the hard scattering amplitude $\propto \frac{1}{tu} \propto \frac{1}{1-\cos^2\theta^*}$
- Steeper at higher $|\cos\theta^*|$ than all pre: ent predictions

[Kuo]

Transversity Physics (brief)

F. Bradamante (COMPASS): Transversity Physics in DIS

- Physics issues
- Comparison of HERMES and COMPASS
- Collins and Sivers asymmetries
- Two-hadron asymmetries
- Λ polarimetry
- Perspectives (new COMPASS fixed-target proposal for transversity and GPDs)

…more during this conference …

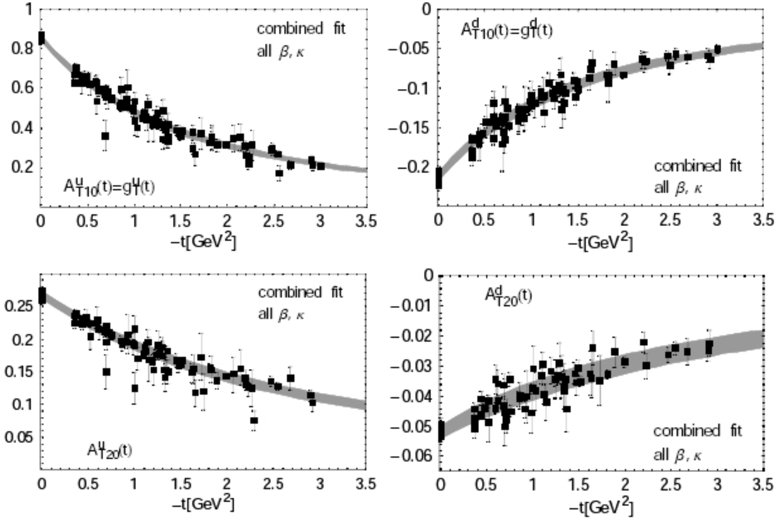
…see also introductory talk by M. Burkardt …

A. Schäfer: QCDSF results II

- Measure tensor form factors, charges: $A^u_{T10} - A^d_{T10} = 1.068 \pm 0.016$
- Tensor GPD form factors are large: $\Rightarrow$ substantial $\vec{b}_\perp \times \vec{S}$ correlations
- Also applies to Pion!

Ph. Haegler: Transversity GPDs

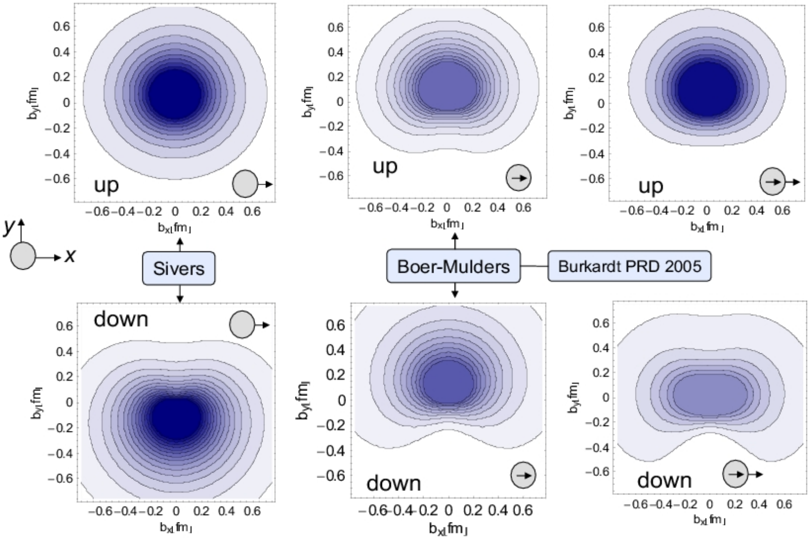
- Preliminary result for transverse spin densities
- Connection with Sivers- and Boer-Mulders effect
- Equation-of-motion constraints between twist-2 and twist-3
- Importance of tensor GPDs for positivity bounds
- Comparison with transverse-momentum-dependent PDFs (dictionary)



The generalized formfactors A_{T10} and A_{T20} together with dipole fits.

[Schäfer (QCDSF)]

preliminary results for the transverse spin densities



[Haegler (Diehl/Haegler)]

Dictionary GPDs↔TMDPDFs

	$p_\perp \leftrightarrow b_\perp$
unpolarized	$f_1 \leftrightarrow H$
polarized	$g_1 \leftrightarrow \tilde{H}$
transversity	$h_1 \leftrightarrow H_T - \Delta_b \tilde{H}_T/(4m^2)$
Sivers	$f_{1T}^{\perp} \leftrightarrow -E'$
Boer-Mulders	$h_1^{\perp} \leftrightarrow -\overline{E}'_T$
N.N.	$h_{1T}^{\perp} \leftrightarrow 2\tilde{H}''_T$
N.N.	$g_{1T} \leftrightarrow 0$
N.N.	$h_{1L}^{\perp} \leftrightarrow 0$

time reversal and Wilson lines make the difference

exact for integrated distributions

unpolarized	$\int d^2p_\perp f_1 = \int d^2b_\perp H$
polarized	$\int d^2p_\perp g_1 = \int d^2b_\perp \tilde{H}$
transversity	$\int d^2p_\perp h_1 = \int d^2b_\perp \left(H_T - \Delta_b \tilde{H}_T/(4m^2)\right)$

approximately for
non-integrated distributions
(Burkardt PRD 72 (2005))

Sivers	$f_{1T}^{\perp} \sim -\int dx E(x,0,0)$
Boer-Mulders	$h_1^{\perp} \sim -\int dx \overline{E}_T(x,0,0)$

Ph. Hägler, GPDs 06

19

[Haegler]

More Talks

- D. Robaschik: consistent implementation of target mass corrections in DVCS.
- L. Szymanowski:
  - Transition Distribution Amplitudes, e.g. $\langle\pi|q(z_1)\,q(z_1)\,q(0)|p\rangle$
  - QCD factorization in $\gamma^*\gamma^*$, perturb. analysis of kinematical limits.
- S. Friot: Photon GPDs (from perturbative calculation of box diagram)
- B. Pasquini: Virtual meson cloud of the nucleon and GPDs
  - light-cone Hamiltonian model for bare nucleon and mesons
  - calculate higher Fock states (one-meson approx.)
  - derive GPDs from overlap formula
- P. Schweitzer: Chiral quark-soliton model:
  - form factors of energy-momentum tensor
  - mechanical interpretation (pressure and shear forces)
- S. Liuti and M. Siddikov: GPDs for Nuclei
  - space-time picture of nuclear effects
    (off-forward EMC effect, nuclear shadowing, colour transparency)
  - coherent and incoherent DVCS and BH
  - modelling

GPDs: "From the Ice-Age to the Bronze-Age . . . "

[anonymous speaker]

- GPD analyses are starting to be data-driven!
  - DVCS (azimuthal asymmetries)
  - DVMP
  - Form factors and wide-angle processes
- Important to disentangle x, ξ and t dependence!
  - Experimental binning
  - Theoretical parameterizations
  - Improved lattice constraints (chiral extrapol.)
- Long-term goal: ("wish/suggestion" by W.D. Nowak)
  - Define standards $\rightarrow$ Database for GPDs
  - Perform global fits