GPDs
WHAT? WHY? WHERE?
... AND THE FUTURE !!
How do the partons form the spin of protons

Is the proton looking like this?

“Helicity sum rule” in IMF

Where do we stand solving the “spin puzzle”? 
What do we know: NLO Fit to World Data

D. De Florian et al. arXiv:0804.0422

<table>
<thead>
<tr>
<th></th>
<th>(\chi^2_{\text{DIS}})</th>
<th>(\chi^2_{\text{SIDIS}})</th>
<th>(\Delta u_v)</th>
<th>(\Delta d_v)</th>
<th>(\Delta \bar{u})</th>
<th>(\Delta \bar{d})</th>
<th>(\Delta s)</th>
<th>(\Delta g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kretzer KKP</td>
<td>206</td>
<td>225</td>
<td>0.94</td>
<td>-0.34</td>
<td>0.680</td>
<td>0.087</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KKP</td>
<td>206</td>
<td>231</td>
<td>0.70</td>
<td>-0.26</td>
<td>0.574</td>
<td>-0.049</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSSV</td>
<td>206</td>
<td>231</td>
<td>0.813</td>
<td>-0.458</td>
<td>-0.084</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\Delta \Sigma \approx 25-30\% \) in all cases.

But how do we access \(L_a\) and \(L_3\) in the IMF? ???
Beyond form factors and quark distributions

Generalized Parton Distributions


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

E.C. Aschenauer

RHIC-AGS Users Meeting, June 2010
The Hunt for $L_q$

Study of hard exclusive processes allows to access a new class of PDFs

Generalized Parton Distributions

possible way to access orbital angular momentum

Spin Sum Rule in PRF:

DIS: $\sim 0.3$

exclusive:
all reaction products are detected missing energy ($\Delta E$) and missing Mass ($M_x$) = 0

E.C. Aschenauer RHIC-AGS
GPDs Introduction

How are GPDs characterized?

- unpolarized
- polarized

conserves nucleon helicity

flip nucleon helicity
not accessible in DIS

quantum numbers of final state

select different GPD

DVCS
pseudo-scaler mesons
vector mesons

- $Q^2 = 2E_eE_e'\gamma(1-\cos\theta_e)$
- $x_B = Q^2/2Mv_v = E_e - E_e'$
- $x+\xi, x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $\xi \approx x_B/(2-x_B)$

<table>
<thead>
<tr>
<th>meson</th>
<th>composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0$</td>
<td>$2u+d, 9g/4$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$2u-d, 3g/4$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$s, g$</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>$u-d$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$g$</td>
</tr>
</tbody>
</table>
accessing GPDs: some caveats

- but only $\xi$ and $t$ accessible experimentally

- $x$ is not accessible (integrated over):
  - apart from cross-over trajectory ($x=\xi$) GPDs not directly accessible: deconvolution needed! (model dependent)
  - GPD moments cannot be directly revealed, extrapolations $t \rightarrow 0$ are model dependent

Cross sections & beam-charge asymmetry $\sim \text{Re}(T_{DVCS})$

Beam or target-spin asymmetries $\sim \text{Im}(T_{DVCS})$
inclusive vs exclusive processes

- factorization of forward Compton scattering
  - related to total cross section via optical theorem
    \[ \text{Im} A(γ^∗,\mu → γ,\nu) \times σ(γ^∗,\mu → γ,\nu) \]
  - final-state obtained by cutting the diagram
  - lower blob represents standard universal PDF
  - upper blob denotes hard interaction

- factorization of DVCS
  - exclusive cross section is square of amplitude
    \[ σ(γ^∗,\mu → γ,\nu) \times A(γ^∗,\mu → γ,\nu)^2 \]
  - final-state proton has different momentum
  - difference of long. momentum is called "skewness"
  - lower blob represents generalized PDFs
  - upper blob denotes hard interaction
physics of generalized parton densities

- distinguish two kinematical regimes:
  - probes emission of mesonic d.o.f.
  - partons emitted and reabsorbed reduce to PDFs in forward limit
  - no PDF counterpart

- $Q^2$ evolution depends on $x$ region (technically rather involved)
  - generalization of DGLAP to $\xi \neq 0$
  - evolution as for meson distribution ampl. (“ERBL regime“)

- GPDs in impact parameter space = localization of partons
  - gives distribution of quarks with
    - longitudinal momentum fraction $x$
    - transverse distance $b$ from proton center
  - find, e.g.: dyn. relation of GPD $E$ with Sivers effect & link to spin-orbit correlations

E.C. Aschenauer             RHIC-AGS Users Metting, June 2010
GPDs in impact parameter space

M. Burkardt, M. Diehl 2002

FT (GPD) : momentum space $\rightarrow$ impact parameter space:
probing partons with specified long. momentum @transverse position $b_\perp$

polarized nucleon:

$\xi = 0$

$u$-quark

$d$-quark

from lattice

E.C. Aschenauer
RHIC-AGS Users Meeting, June 2010
Extremely Model dependent statement:
M. Burkardt et al.

anomalous magnetic moment:
\[ \kappa^u = +1.67 \]
\[ \kappa^d = -2.03 \]

Lattice:
QCDSF collaboration
lowest moment of distribution of unpol. q in transverse pol. proton and
transverse pol. quarks in unpol. proton
1st moments can be computed on the lattice ...

HERMES value

[Graph showing HERMES value and disconnected diagrams not yet included]

OAM can be accessed as well

LHPC hep-lat/0705.4295

find: $\Delta u > 0$ and $L_u < 0$; $\Delta d < 0$ and $L_d > 0$, but in any quark model $L_u > 0$, $L_d < 0$

sign due to strong scale evolution of $L_q$? Myhrer, Thomas

$L_u + L_d \sim 0$ contribution from disconnected diagrams?

if $\Delta g \sim 0$, does this leave us with gluon OAM as culprit in spin audit?

note: using AdS/CFT nucleon spin comes entirely from OAM Hatta, Ueda, Xiao arXiv:0905.2493
ambiguities arise when decomposing proton spin in gauge theories

Jaffe, Manohar; Bashinsky, Jaffe

manifest gauge invariant local operators contain interactions \( /barb_2 \rightarrow /barb_2 \rightarrow /barb_2 \) interpretation?

intuitive; partonic interpretation
\( \Delta g, L^0_{q,g} \) local only in \( A^\pm = 0 \) gauge

how to determine \( L^0_{q,g} \) experimentally?

manifest gauge invariant local operators contain interactions \( \rightarrow \) interpretation?

L_q + \( \Delta q/2 \), \( J_g \) \( \leftrightarrow \) GPDs (DVCS)

- lattice results for \( L_q \) are for Ji’s sum rule and cannot be mixed with \( \Delta g \)
- num. difference between \( L_q \) and \( L^0_{q,g} \) can be sizable

3rd decomposition: like Jaffe, Manohar but w/ manifest gauge inv. operators
physical interpretation? requires new def. of PDFs – relation to experiment?
exclusive processes: from soft to hard

photoproduction of VM at HERA

soft interaction
\( W^\delta \) described by Regge “theory”

hard interaction
\( W^\delta \) governed by small \( x \) evolution of gluon distribution
VM production @ small $x$

$W$ & $t$ dependences: probe transition from soft $\rightarrow$ hard regime

$\sigma \sim W^\delta$

$\sigma \sim e^{-b|t|}$

Steep energy dependence of $\sigma$ in presence of hard scale. Universality of $b$-slope parameter.

Point-like configurations dominate.
Deeply Virtual Compton Scattering: DVCS

most clean channel for interpretation in terms of GPDs

two experimentally undistinguishable processes:

\[ e + p \rightarrow e' + p + \Delta \]

\[ e + p \rightarrow e' + p + \Delta \]

isolate BH-DVCS interference term \( \rightarrow \) non-zero azimuthal asymmetries

can measure DVCS - cross section and I

E.C. Aschenauer

RHIC-AGS Users Meeting, June 2010
\( \Delta \sigma_C \sim \cos \phi \cdot \text{Re}\{ H + \xi \tilde{H} + \ldots \} \) 

\( \Delta \sigma_{LU} \sim \sin \phi \cdot \text{Im}\{ H + \xi \tilde{H} + kE \} \)

\( \Delta \sigma_{UL} \sim \sin \phi \cdot \text{Im}\{ \tilde{H} + \xi H + \ldots \} \)

\( \Delta \sigma_{UT} \sim \sin \phi \cdot \text{Im}\{ k(H - E) + \ldots \} \)

\( \xi = x_B/(2-x_B) \quad k = t/4M^2 \)

→ different charges: \( e^+ e^- \) (only @HERA!):

→ polarization observables:

 Beam target

\( H, E \)

kinematically suppressed
Exclusivity: How is it constrained

Hermes & H1 and Zeus
for most of the data
no recoil detection

→ missing mass (energy) technique
→ background estimated by MC

E.C. Aschenauer  RHIC-AGS Users Meeting, June 2010
HERMES: combined analysis of charge & polarization dependent data
→ separation of interference term + DVCS²

Beam Charge Asymmetry

DVCS: Hydrogen Target

DVCS
higher twist
higher twist

E.C. Aschenauer
RHIC-AGS Users Meeting, June 2010
First model dependent attempt to constrain $J_q$

observables sensitive to $E$:
($J_q$ input parameter in ansatz for $E$)

- DVCS $A_{UT}$ : HERMES
- nDVCS $A_{LU}$ : Hall A

Hermes DVCS-TT:

- Neutron obtained combining deuterium and proton
- $F_1$ small $u$ & $d$ cancel in

$\phi_{UT} = 5/6, \phi_s = 0.18 \pm 0.14$

$\sin(\phi_{\phi_s})\cos\phi$

$x=0.36$ and $Q^2=1.9\text{GeV}^2$

VGG

AHLT calculation [36]
VGG calculation [37]

E.C. Aschenauer
RHIC-AGS Users Meeting, June 2010
DVCS: Deuterium Target
Latest Measurements from JLab

DVCS-BSA:

\[ Q^2 (\text{GeV}^2) \]

\[ x = 0.249, \quad Q^2 = 1.95 \]

arXiv: 0711.4805

more data on: \( A_{LU}, A_{LL} \), cross section @ 6GeV

12 GeV:
a lot to come with \( Q^2_{\text{max}} \approx 13 \text{ GeV}, \ t > 0.1 \text{ GeV} \ x > 0.2 \)
towards a global analysis of GPDs

time for crude models is over - use data to determine GPDs from global QCD fits

first attempt to extract $H(x,x)$ from DVCS data: Mueller, Kumericki, Passek-Kumericki

- so far, very good fits but only the beginning; will be an ongoing effort for years
- need to incorporate useful information from meson production (gluon GPD!)
  but theory considerably more difficult and less mature
More Results from MKK

Other Fits:
M. Guidal PLB 689 (2010) 156
M. Guidal & H. Moutarde EPJ A42 (2009) 71
H. Moutarde PRD 79 (2009) 094021
but all to limited data sets
Charge and Beam Spin Asymmetry Heavy Targets

Beam Charge Asymmetry

Why nuclear DVCS:
- How does the nuclear medium modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?
- Enhanced 'generalized EMC effect', rise of $\tau_{DVCS}$ with $A$?
- arXiv: 0911.0091
Electron accelerator

Unpolarized and polarized leptons 4-20 (30) GeV

70% $e^-$ beam polarization goal
polarized positrons?

Center mass energy range: $\sqrt{s}=28-200$ GeV; $L\sim100-1000\times$Hera
longitudinal and transverse polarisation for $p/He-3$ possible

Mission: Studying the Physics of Strong Color Fields
The latest design of eRHIC

**eRHIC staging all-in tunnel**

- Polarized e-gun
- Beam-dump

**eRHIC detector**

- 6 pass 2.5 GeV ERL

**Coherent e-cooler**

**RHIC: 325 GeV p or 130 GeV/u Au**

The most cost effective design
A detector integrated into IR ZDC provides a lot of space for polarimetry and luminosity measurements.

Dipoles needed to have good forward momentum resolution:
- Solenoid no magnetic field @ r ~ 0
- DIRC, RICH hadron identification → π, K, p
- high-threshold Cerenkov → fast trigger for scattered lepton
- radiation length very critical → low lepton energies
DIRC: not shown because of cut; modeled following BaBar
No hadronic calorimeter in barrel yet
Investigate ILC technology to combine ID with HCAL
Can we detect DVCS-protons and Au break up p

- track the protons through solenoid, quads and dipole with hector

proton track $\Delta p = 10\%$

proton track $\Delta p = 20\%$

proton track $\Delta p = 40\%$

DVCS protons are fine, need more optimization for break-up protons

Equivalent to fragmenting protons from Au in Au optics (197/79:1 ~2.5:1)

$\Rightarrow$ will need roman pots as used in pp2pp
- at low $x$ dominated by gluon contributions
- Need wide $x$ and $Q^2$ range to extract GPDs
- Need sufficient luminosity to bin in multi-dimensions
we have just explored the tip of the iceberg

**EIC**

many avenues for further important measurements and theoretical developments

**Come and join us**

The BNL EIC Taskforce
Summary

[Image with various graphs and data points]

DIS&pp

\[ f_{1T} \perp \]

\[ \Delta q \]

\[ \delta q \]

\[ L_q \]

\[ \Delta G \]

\[ x \Delta g \]

\[ x \Delta u \]

\[ p_T(Z) \]

\[ \chi^2 \]

\[ p_T(GeV/c) \]

\[ x \]

\[ \eta \]

\[ \Delta \Sigma = \Delta \Sigma = \Delta \Sigma = \Delta \Sigma = 300 \text{ pb}^{-1} \]

\[ E.C. \text{ Aschenauer} \]

\[ \text{RHIC-AGS Users Meeting, June 2010} \]

[Graphs and data points on the slide]
More insights to the proton - TMDs

Unpolarized distribution function $q(x), G(x)$

Helicity distribution function $\Delta q(x), \Delta G(x)$

Transversity distribution function $\delta q(x)$

Boer-Mulders distribution function

Sivers distribution function

peculiarities of $f_{1T}^{\perp}$

- chiral even naïve T-odd DF
- related to parton orbital angular momentum
- violates naïve universality of PDFs
- QCD-prediction: $f_{1T,DY}^{\perp} = -f_{1T,DIS}^{\perp}$
What can we learn about the nucleon spin?

Anticipated precision for one beam energy combination
Integrated Lumi: 5fb$^{-1}$ ~ 1 week data taking

interesting questions at small $x$
- charm contribution to $g_1$
- any deviations from DGLAP behavior?
- precision study of Bjorken sum rule

\[
\int_{0}^{1} dx \, x g_1(x, Q^2) \sim \frac{\alpha_s}{6} (1 - \frac{4\pi}{f} - ...) 
\] (rare example of a well understood fundamental quantity in QCD)
The Gluon Polarization (HP12)

- $\Delta g(x)$ very small at medium $x$
- best fit has a node at $x \sim 0.1$
- huge uncertainties at small $x$
- small-$x$ behavior still
completely unconstrained

$\Delta g(x)$ small !?

The small-$x$ behavior still completely unconstrained
Deeply Virtual Compton Scattering and GPDs

\[ Q^2 = - (e-e')^2 \]
\[ x_B = Q^2/2M \nu \]
\[ \nu = E_e - E_{e'} \]

- \( x+\xi, x-\xi \) longitudinal momentum fractions
- \( t = (p-p')^2 \)
- \( \xi \approx x_B/(2-x_B) \)

GPDs: Correlation between quark distributions both in momentum and coordinate space

Quark angular momentum (Ji’s sum rule)

\[ J^q = \frac{1}{2} \quad J^G = \frac{1}{2} \int x dx \left[ F^q(x, \xi, 0) + E^q(x, \xi, 0) \right] \]


"Handbag" factorization valid in the Bjorken regime: high \( Q^2, \nu \) (fixed \( x_B \))
Hard exclusive meson production and GPDs

4 Generalized Parton Distributions (GPDs)

$\gamma_{L}^{*}(Q^{2})$

$\gamma_{L}^{*}(Q^{2})$

$\pi, \rho, \omega$...

$E, E$ flip nucleon helicity

$H, H$ conserve nucleon helicity

Vector mesons ($\rho, \omega, \phi$)

Pseudoscalar mesons ($\pi, \eta$)

Factorization proven only for longitudinally polarized virtual photons and valid at high $Q^{2}$ and small $t$

Quark flavor decomposition accessible via meson production

$\sigma(\pi^{0}) \sim |\int dx \tilde{H}(x, \xi, t)|^{2}$
Questions about QCD

- Confinement of color, or why are there no free quarks and gluons at a long distance?
  - A very hard question to answer
- What is the internal landscape of the nucleons?
  - What is the nature of the spin of the nucleon?
  - What is the three-dimensional spatial landscape of nucleons?
    - Need probes to “see” and “locate” the quarks and gluons, without disturbing them or interfering with their dynamics?
- What governs the transition of quarks and gluons into pions and nucleons
- What is the role of gluons and gluon self-interactions in nucleons and nuclei?
- What is the physics behind the QCD mass scale?

The key to the solution

The Gluon

- It represents the difference between QED and QCD
- Can’t “see” it directly, but, it is behind the answers to all these questions
Transversity and Sivers, what do we know

SIDIS and $e^+e^-$

$Q^2 = 2.4 \text{ GeV}^2$

Fit to SIDIS and $e^+e^-$

E.C. Aschenauer             RHIC-AGS Users Meeting, June 2010

Anselmino et al. arXiv:0809.2677

Transversity and Sivers

$\delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \delta \d
Exclusive $\pi^+$ production

GPD model for $\sigma_L$: VGG

Regge model: JML

- LO
- LO+power corrections

- $\frac{d\sigma}{dt}$
- $\frac{d\sigma}{dt}$

- data support order of power corrections

- NLO corrections moderate $\ll$ size of power corrections [Diehl,Kugler]
The GPD Models

**VGG:** [Vanderhaegen, Guichon, Guidal 1999]
- double distributions; factorized or regge factorized or regge-inspired
- D-term to restore full polynomiality
- skeweness depending on free parameters
- includes tw-3 (WW approx)

→ describes well $A_c$ and $A_{UT}$ data
→ fails for $A_{LU}$
→ $A_c$ favor 'no D-term' ←
→ contradicts $\chi_{QSM}$ & lattice results

**dual:** [Guzey, Teckentrup 2006]
- GPDs based on infinite sum of tri-bosons
- factorized or regge-inspired
- tw-2 only

→ describes well spin-asymmetries
→ fails for unpol. cross sections (HallA)
→ call for new, more sophisticated parameterizations of GPDs

... more models on the way: e.g. generalization of Mellin transform technique
physics of generalized parton densities

GPDs depend on $x$, $\xi$, $t$, $Q^2$

- Convenient: symmetric choice of mom. fractions
  - $x$, $\xi$: mom. fractions w.r.t $p - \frac{1}{2}(p - p')$
    - where $\xi = (p - p') \cdot (p + p')$.
  - in DVCS: $x$ integrated and $\xi = x_B/(2 - x_B)$
  - $t$: trade for trans. momentum transfer

- Pioneering work by Leipzig group ('85-'94): Muller, Robaschik, Geyer, ... hep-ph/9812448 (rediscovered in '96 by Ji and Radyushkin - connection to proton spin sum rule)

- Represent interference between amplitudes for different nucleon states
  (in general not a probability)

- Transverse structure of proton accessible through $t$ dependence
  (proton "tomography": how are partons distributed in the transverse plane)

- Rich spin structure allows access to, e.g., OAM