Spin Structure of Nucleons

XXVI Physics in Collisions, Búzios, Brazil, July 6-9 2006

Wolf-Dieter Nowak

DESY, D-15738 Zeuthen

Wolf-Dieter.Nowak@desy.de
Table of Contents

- Spin budget of the proton
- DIS kinematics
- Tensor structure function of the deuteron
- Spin contributions from sea quarks
- QCD Fits
- Gluon contribution to Nucleon Spin
- Transversity: Sivers & Collins moments
- DVCS: target-spin asymmetries
- Model-dependent constraint on $J_u$ vs. $J_d$
- Summary and Outlook
Spin Budget of the Proton

Naive Quark-Parton Model:

\[ \Delta q_u = \frac{4}{3}, \quad \Delta q_d = -\frac{1}{3} \]
\[ \Delta \Sigma = \Delta q_u + \Delta q_d + \Delta q_s = 1 \]

Relat. Quark-Parton Model:

\[ \text{Quark spin: } \Delta \Sigma \approx 0.6 \]

EMC [PLB206(1988)364]:
\[ \Delta \Sigma = 0.060 \pm 0.047 \pm 0.069 \]

HERA collider results:

- Gluons are important
- Measure \( \Delta G \! \)

Proton spin budget:

\[ J = \frac{1}{2} = J^Q(\mu) + J^G(\mu) \]
\[ J^G = \Delta G + L^G \]
\[ J^Q = \frac{1}{2} \Delta \Sigma + L^Q \]

Since: \( \Delta q_f = \Delta q_f^{val} + \Delta q_f^{sea} \)
\( L^Q : \) Quark orb. ang. mom.

Measure \( \Delta q_f^{sea} ! \)
Measure \( J^Q : DVCS ! \)

at: COMPASS, HERMES, RHIC

at: HERMES, polar. RHIC

at: HERMES, JLAB
DIS: Kinematics, Cross Sections, Asymmetry

Virtual-photon kinematics:

\[ Q^2 = -q^2 \quad \nu = E - E' \]

Fraction of nucleon momentum carried by struck quark:

\[ x = \frac{Q^2}{2 M \nu} \]

Fraction of virtual-photon energy carried by produced hadron \( h \):

\[ z = \frac{E_h}{\nu} \]

Hadron transverse momentum:

\[ P_{h \perp} \]

Unpolarized cross section:

\[ \sigma_{UU} \equiv \frac{1}{2} (\sigma_{\mp} + \sigma_{\mp}) \]

Cross section (helicity) difference:

\[ \sigma_{LL} \equiv \frac{1}{2} (\sigma_{\mp} - \sigma_{\mp}) \]

Double-spin asymmetry:

\[ A_{\parallel} \equiv \frac{\sigma_{LL}}{\sigma_{UU}} \sim \frac{g_1}{F_1} \] (neglecting small \( g_2 \) contribution)

Measured asymmetry:

\[ A_{\parallel} = \frac{1}{\langle P_T \rangle \langle P_B \rangle} \left( \frac{N}{L} \right)_{\mp} - \left( \frac{N}{L} \right)_{\mp} \]

\[ + \left( \frac{N}{L} \right)_{\mp} \]
**DIS Structure Functions in Quark-Parton Model**

- $h_\gamma$:
- $h_D$
- $q^\uparrow$
- $q^\downarrow$
- $q^0$

**Spin-$\frac{1}{2}$**

**Nucleon**

**Spin-1**

**Deuteron**

\[
F_1^{p,n} = \frac{1}{2} \sum_f e_f^2 \left( q_f^- + q_f^+ \right) = \frac{1}{2} \sum_f e_f^2 q_f
\]

\[
F_1^{d} = \frac{1}{3} \sum_f e_f^2 \left( q_f^- + q_f^+ + q^0 \right)
\]

\[
g_1^{p,n} = \frac{1}{2} \sum_f e_f^2 \left( q_f^- - q_f^+ \right) = \frac{1}{2} \sum_f e_f^2 \Delta q_f
\]

\[
g_1^{d} = \frac{1}{2} \sum_f e_f^2 \left( q_f^- - q_f^+ \right)
\]

\[
b_1^{d} = \frac{1}{2} \sum_f e_f^2 \left( 2q_f^0 - (q_f^- + q_f^+) \right)
\]

- $g_1$ measures a certain combination of quark + anti-quark helicity distributions $\Delta q_f = \Delta q_f^{val} + \Delta q_f^{sea}$

$\Rightarrow$ No new $g_1$ data published by HERMES or COMPASS during last 12 months

- $b_1^{d}$ measures nuclear effects that make the deuteron look different from just the most simple proton-neutron system

*Wolf-Dieter Nowak (DESY)*

*XXVI Physics in Collisions, Búzios, Brazil, July 6-9 2006*
Tensor Asymmetry in DIS on Deuteron

\[
\frac{d^2 \sigma_{\text{meas}}}{dxdQ^2} = \frac{d^2 \sigma_{\text{unpol}}}{dxdQ^2} \left[ 1 - P_z P_B D A_1 + \frac{1}{2} P_{zz} A_{zz} \right]
\]

- \( \sigma_{\text{unpol}} = \sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow} + \sigma^0 \)
- \( P_{zz} = \frac{n^+ + n^- - 2n^0}{n^+ + n^- + n^0} \)
- \( A_{zz} = \frac{(\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}) - 2\sigma^0}{3\sigma_{\text{unpol}} P_{zz}^0} \)

<table>
<thead>
<tr>
<th>vector term</th>
<th>tensor term</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma^{\uparrow\uparrow} )</td>
<td>( +</td>
</tr>
<tr>
<td>( \sigma^{\uparrow\downarrow} )</td>
<td>( -</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>( &lt; 0.01 )</td>
</tr>
</tbody>
</table>

\[ |P_z \cdot P_B| = 0.45 \pm 0.04 \]
\[ P_{zz}^0 = 0.83 \pm 0.03 \]

Tensor structure function \( b_1 \) from tensor asymmetry \( A_{zz} \):

\[
b_1^d = -\frac{3}{2} A_{zz}^d F_1^d
\]

\[
F_1^d = \frac{1 + Q^2/\nu^2}{2x(1+R)} F_2^d
\]
Tensor Structure Function $b_1^d(x)$

**HERMES result** [PRL95 (2005) 242001]

Theory work $< 1997$:
- binding & Fermi motion effects at $x \geq 0.2$

Theory $\geq 1997$: Double scattering
- diffr. nucl. shadowing + pion excess mech.
  Nikolaev et al., PLB 398, 245 (1997)
- coherent double scattering
  Edelmann et al., PRC 57, 3392 (1998)
- double scattering through VMD
  Bora & Jaffe, PRD 57, 6906 (1998)

→ observe significant enhancement of $b_1$ at small $x_B$:
- Close-Kumano sum rule $\int dx \, b_1(x, Q^2) = 0$ violated ??
- interpretable as tensor polarization of the quark sea?
Sea Quark Flavor Asymmetry

\[ A_1^h(x, z) \propto \frac{\sum_f e_f^2 \Delta q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x) D_f^h(z)} \]

with \( D_f^h(z) \): Fragmentation function

\( \text{HERMES: } 5\text{-parameter flavor separation} \)

[PRD 71(2005) 012003]: semi-inclusive pion & kaon and inclusive asymmetries:

\[ \int_{0.023}^{0.3} (\Delta q_u(x) - \Delta q_d(x)) \, dx = 0.05 \pm 0.06 \pm 0.03 \]

[PRD 71(2005) 012003]
Spin Contribution of Strange Quarks

**HERMES** ‘isoscalar’ extraction method uses only deuterium data:

- $K^+ & K^-$ multiplicities, inclusive asymmetry $A_{1}^{d}$, kaon asymmetries $A_{1}^{K^+}$, $A_{1}^{K^-}$

⇒ Fit parameters: $\Delta S(x) = q_s(x) + \bar{q}_s(x)$; $\Delta Q(x) = q_u(x) + \bar{q}_u(x) + q_d(x) + \bar{q}_d(x)$

$$\int_{0.02}^{0.6} \Delta S(x) \, dx = 0.006 \pm 0.029 \pm 0.007 \quad \text{[preliminary 2005]}$$

⇒ small $\Delta G$? (suggested: gluon splitting into strange sea through axial anomaly)

Note: uncertainties very sensitive to fragmentation function input
Next-to-leading Order QCD Fits

Typical (and most recent) results by AAC [hep-ph/0603213]: NLO in $\alpha_s$, $\overline{MS}$ scheme

Assumptions:
- Flavor-symmetric $\Delta q_{sea}$
- Integrals of $\Delta q_u^{val}$ and $\Delta q_d^{val}$ fixed by weak decay constants $F$ and $D$

Input experimental data:
- $A_1^{p,d}$ from COMPASS, JLAB, HERMES
- $A_{LL}^{\pi^0}$ from PHENIX

Results at $Q^2 = 1$ GeV$^2$: $\Delta \Sigma = 0.25 \pm 0.10$
$\Delta G = 0.47 \pm 1.08$ (DIS alone); $\Delta G = 0.31 \pm 0.32$ (DIS+PHENIX)

NOTE: From $g_1^d$: $\Delta \Sigma_{0.01<x<1}^{exp} \approx 0.35 \pm 0.03$, while $\Delta \Sigma_{0<x<0.01}^{fit} \approx -0.13 \pm 0.11$ is obtained for low-$x$ ’extrapolation’ (due to stiff shape of PDF parameterizations)

ALSO: low-$x$ data urgently needed to constrain $g_1^{p,d}$ (E-RHIC, ELIC)
Determination of Gluon Contribution to Nucleon Spin

- Process: High-$p_t$ hadron pairs in quasi-real photoprod.: $\langle Q^2 \rangle \approx 0.1$ GeV$^2$
- Sensitivity through $\gamma^* g$ ‘direct’ hard scattering or ‘resolved-photon’ process
  - left graphs: direct processes; right graphs: resolved-photon processes [COMPASS analysis]

Extraction heavily relies on PYTHIA simulation (LO only !)

Hard scale $\mu^2 \simeq 3$ GeV$^2$
  - only ‘loosely’ correlated with $x_g \langle x_g \rangle \simeq 0.1$

Other processes:

- **COMPASS**: Open-charm production ($\gamma^* g \rightarrow c\bar{c}$)
- **HERMES**: Quasi-real photoproduction of single high-$p_t$ hadrons
- **RHIC**: $A_{LL}$ in inclusive direct $\gamma$ & $\pi^0$ production, inclusive jet production
Results on Gluon Distribution $\Delta g_g(x_g)$

- Most precise result from high-$p_t$ hadron pairs $\downarrow$ COMPASS $\downarrow$

$$Q^2 < 1 \text{ GeV}^2 \ (\langle x_g \rangle \simeq 0.085):$$
$$\frac{\Delta g}{g} = 0.016 \pm 0.058_{\text{stat}} \pm 0.055_{\text{syst}}$$  
[PLB 612,154 (2005)]

$$Q^2 > 1 \text{ GeV}^2 \ (\langle x_g \rangle \simeq 0.13) \ [\text{prel.}]:$$
$$\frac{\Delta g}{g} = 0.06 \pm 0.31_{\text{stat}} \pm 0.06_{\text{syst}}$$

Open charm ($\langle x_g \rangle \simeq 0.15) \ [\text{prel.}]:$
$$\frac{\Delta g}{g} = -0.57 \pm 0.31_{\text{stat}}$$

- Results of other experiments:

- HERMES high-$p_t$ hadron pairs (all $Q^2$, $\langle x_g \rangle \simeq 0.17) \ [\text{PRL84 (2000) 2584}]$

  $$\frac{\Delta g}{g} = 0.41 \pm 0.18_{\text{stat}} \pm 0.03_{\text{exp-syst}}$$

- PHENIX: Presently only confidence limits for different $\frac{\Delta g}{g}$ assumptions  
  [PANIC05 talk]
The third twist-2 PDF: Transversity

Optical theorem:

\[ q_f(x) = q_f^>(x) + q_f^<(x) \sim Im(A_{++,++} + A_{+-,+-}) \]

\[ \Delta q_f(x) = q_f^>(x) - q_f^<(x) \sim Im(A_{++,++} - A_{+-,+-}) \]

\[ \delta q_f(x) \quad alias \quad h_1(x) \sim Im A_{+-,-+} \]

Positivity limit & Soffer bound:

\[ |\delta q_f(x)| < q_f(x) \]

\[ |\delta q_f(x)| < \frac{1}{2} (q_f(x) + \Delta q_f(x)) \]
How to Measure Transversity?

- Hard interactions conserve chirality
- In DIS: chirality-flip diagram suppressed by quark mass
- The transversity distribution function is chiral-odd
  ⇒ not accessible in DIS!

Semi-inclusive DIS:

$\sigma^{eH \rightarrow ehX} \propto \sum_q D^{H \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes F^{q \rightarrow h}$

where $D$ denotes a distribution function and $F$ a fragmentation function.

(Factorization not yet proven for transv.-mom.-dependent subleading 1/Q terms)

Need another chiral-odd object: Collins fragmentation function $H_1^\perp$

- also ‘T-odd’ (=odd under naive time reversal)
- represents interference of 2 amplitudes with different imaginary parts
  ⇒ $H_1^\perp$ can generate a single-spin asymmetry

NOTE: SIDIS alone can not independently determine $\delta q$ and $H_1^\perp$ (only shapes!)

Collins function from Belle $e^+e^-$ data: 1st result! [hep-ex/0507063, acc. by PRL]

Drell-Yan can yield transversity: upgraded RHIC, PAX? (only large $x$, 2012?)
SIDIS: Two contrasting T-odd Phenomena

A single-spin asymmetry can arise from some (naive) T-odd mechanism. With transverse target polarization two mechanisms become distinguishable:

Transversity + T-odd Collins FF

Transversity: polarizations of quark and nucleon correlated

Photoabsorption flips quark polarization component in lepton scattering plane

Quark polarization correlates with fragmentation $k_T \rightarrow P_{h\perp}$ i.e. hadron production plane

$\Rightarrow$ Single Target Spin Asymmetry $\propto \sin (\phi + \phi_S)$

T-odd Sivers distrib. function $f_{1T}^+$

$p_T$ of UNpolarized struck quark correlated with target polariz.

$p_T$ survives fragmentation, inherited by hadron $P_{h\perp}$

$\Rightarrow$ Orientation of lepton scattering plane is irrelevant

$\Rightarrow$ Single Target Spin Asymmetry $\propto \sin (\phi - \phi_S)$
Extraction of Sivers & Collins Azimuthal Moments

Study azimuthal distributions of hadrons in: $e^\pm \, p^\uparrow \longrightarrow e^\pm \, \pi^\pm + X$

unpol. beam (U), transv. pol. target (T)

$A^\ell_{UT}(\phi, \phi_S) = \frac{1}{\langle S_T \rangle} \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)}$

$\sim \sin(\phi - \phi_S) \sum_q e_q^2 \mathcal{I} \left[w_{Siv}(p_T, P_{h\perp}) f_{1T}^{q}(x, p_T^2) \, D_q^q(z, k_T^2)\right]$

$+ \sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I} \left[w_{Coll}(k_T, P_{h\perp}) h_{1T}^{q}(x, p_T^2) \, H_q^q(z, k_T^2)\right] + \ldots$

$\mathcal{I}[\ldots]$: convol. integral over initial ($p_T$) and final ($k_T$) quark transverse momenta

$\Rightarrow$ can NOT DIRECTLY extract transverse-momentum-dependent functions!

$\Rightarrow$ Determine (simultaneously) Sivers and Collins convolution integrals by a fit:

$$A^\ell_{UT}(\phi, \phi_S) = 2 \left\langle \sin(\phi - \phi_S) \right\rangle^\ell_{UT} \sin(\phi - \phi_S) + 2 \left\langle \sin(\phi + \phi_S) \right\rangle^\ell_{UT} \sin(\phi + \phi_S)$$

NOTE: asymmetry weighting by $P_{h\perp}/(zM_h)$ makes convolution integral calculable (involves acceptance dependence)
Results on Sivers Moments from 2002-2004 data

\[ 2 \left\langle \sin(\phi - \phi_S) \right\rangle^\ell_{UT} \approx 2 \left\langle \sin(\phi - \phi_S) \right\rangle^\gamma_{UT} \propto - \sum_q e_q^2 \mathcal{I} \left[ \omega_{SiV} f_{1T}^{q \perp}(x, p_T^2) D_1^q(z) \right] \]

\[ \left\langle \sin(\phi - \phi_S) \right\rangle_{UT} \]

\( \pi^+ \): positive; \( \pi^- \): consistent with zero

\( f_{1T}^{q \perp} \) negative (using Trento convention)

\( f_{1T}^{u \perp} \)

consistent with Burkhardt’s picture of ‘Chromodynamic lensing’!

\( \text{COMPASS}: \) ‘zero’ results (deuteron target!)

\[ \text{NOTE: Contamination (2-16%) by decay of exclusively produced vector mesons} \]
Results on Collins Moments from 2002-2004 data

\[ 2 \left\langle \sin(\phi + \phi_S) \right\rangle_{UT}^\ell \approx 2 \left\langle \sin(\phi + \phi_S) \right\rangle_{UT}^{\gamma^*} \propto \sum_q e_q^2 T \left[ w_{Coll} h_{1T}^q(x, p_{T}^2) H_1^\perp,q(z, k_{T}^2) \right] \]

- **pos. HERMES** $\pi^+$ results – no surprise: u-quark dom. and $\delta q > 0$ as $\Delta q > 0$
- **negative HERMES** $\pi^-$ results were a surprise – now understood to require disfavored Collins function be large and opposite in sign (Artru fragm. model)

\[ \left\langle \sin(\phi + \phi_S) \right\rangle_{UT}^{\pi^+} \]

- grey bands: predictions [hep-ph/0603054] of chiral quark soliton model:
  - **x-dependence:** mean Collins function fitted and found to be x-independent
  - **z-dependence:** Collins fct. extracted from BELLE $e^+e^-$ data [hep-ex/0507063]

**COMPASS**: ‘zero’ results (on deuteron!)

\[ \Rightarrow \text{HERMES, COMPASS and BELLE compatible} \]

**COMPASS** will take proton data in 2006
Deeply Virtual Compton Scattering

(a) \[ \begin{array}{c}
\text{e} \\
\gamma^* \\
p \\
p' \\
\end{array} \]
(b) \[ \begin{array}{c}
\text{e} \\
\gamma^* \\
p \\
p' \\
\end{array} \]

- Same final state in DVCS and Bethe-Heitler \( \Rightarrow \) Interference!

\[ d\sigma(eN \rightarrow eN\gamma) \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T_{DVCS}^* + T_{BH}^*T_{DVCS} \]

- \( T_{BH} \) is calculable in QED and parameterized in terms of Dirac and Pauli Form Factors \( F_1, F_2 \)

- \( T_{DVCS} \) is parameterized in terms of Compton form factors \( \mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}} \) (which are convolutions of resp. GPDs \( H, E, \tilde{H}, \tilde{E} \))

- (Certain Parts of) interference term \( \mathcal{I} \) can be filtered out by forming certain cross section differences (or asymmetries) \( \Rightarrow \) GPDs \( H, E, \tilde{H}, \tilde{E} \) indirectly accessible via interference term \( \mathcal{I} \)
Azimuthal Asymmetries in DVCS

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

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

- **Beam-spin asymmetry** $A_{LU}(\phi)$ [BSA]:
  \[ d\sigma(\vec{e}, \phi) - d\sigma(\vec{e}, \phi) \propto \text{Im}[F_1\mathcal{H}] \cdot \sin \phi \]

- **Long. target-spin asymmetry** $A_{UL}(\phi)$:
  \[ d\sigma(\vec{P}, \phi) - d\sigma(\vec{P}, \phi) \propto \text{Im}[F_1\mathcal{H}] \cdot \sin \phi \text{ [LTSA]} \]

- **Transverse target-spin asymmetry** $A_{UT}(\phi, \phi_S)$ [TTSA]:
  \[ d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi - \phi_S) \cos \phi \]
  \[ + \text{Im}[F_2\mathcal{H} - F_1\xi\mathcal{E}] \cdot \cos(\phi - \phi_S) \sin \phi \]

($F_1, F_2$ are the Dirac and Pauli elastic nucleon form factors)
First Data on Beam-charge Asymmetry

\[ A_C(\phi) = \frac{d\sigma^+/(\phi) - d\sigma^-/(\phi)}{d\sigma^+/(\phi) + d\sigma^-/(\phi)} \propto \text{Im} F_1 H \cdot \cos \phi + \ldots \]

⇒ extract ‘amplitudes’ by fitting in every \( \phi \)-bin

\[ A_C(\phi) = \text{const.} + A_C^{\cos \phi} \cos \phi + A_C^{\cos 2\phi} \cos 2\phi + A_C^{\cos 3\phi} \cos 3\phi \]

First measurement by HERMES (unpolar. proton target) [hep-ex/0605108, subm. to PRL]:

- use symmetrization \((\phi \rightarrow |\phi|)\) 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’ \(M_X\) region \((\rightarrow \text{resol. smearing})\)

preliminary deuteron data (not shown) completely consistent
First Conclusion on GPD Models?

BCA $t$-dependence can distinguish different GPD model versions:

- $A_C^{\cos \phi}$: elastic + associated production
- d-data: contributions per $t$-bin of associated production: 5,11,18,29%
  $\Rightarrow$ highest $t$-bin mostly affected
- GPD $H$ dominates, $\tilde{H}$ and $E$ suppressed
- Curves (code [Vanderhaeghen,Guichon,Guidal]) calculated for 4 different parameter sets
- BCA insensitive to profile fct. parameters

HERMES HERA-I data disfavor Regge-inspired $t$-dependence with D-term

5 times more precise BCA data on HERMES disk from HERA-II

(this data may benefit from recoil detector, presently being commissioned)

Further BCA data only in far future (COMPASS>2010 ?, JLAB>2015 ???)
Longitudinal Target-spin Asymmetry

\[ A_{UL}(\phi) = \frac{1}{\langle |P_L| \rangle} \cdot \frac{d\sigma \Rightarrow (\phi) - d\sigma \Rightarrow (\phi)}{d\sigma \Rightarrow (\phi) + d\sigma \Rightarrow (\phi)} \propto \text{Im}\{F_1 \tilde{H} + \xi (F_1 + F_2) \mathcal{H} + \ldots\} \sin \phi \]

\[ \Rightarrow \text{extract ‘amplitudes’ fitting per } \phi \text{-bin } A_{UL}(\phi) = c + A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi \]

- 1st published measurement: CLAS 2000-01 proton data [hep-ex/0605012]
- May 2005 prel. HERMES results (1996-2000 proton and deuteron data)
- both data sets have similar statistics and show expected \( \sin \phi \) behaviour
- HERMES can approach lower \( t \)-values
- CLAS vs GPD model [PRD60,094017(1999)]: large contribution from GPD \( \tilde{H} \)!
Transverse Target-spin Asymmetry: Sensitivity to $J_u$

First $A_{UT}$ measurement by HERMES (U: unpolar. beam, T: transv. pol. target) (twice more HERMES statistics on disk)

JLAB: transv. target ≥ 2008 ?, COMPASS: plans for 2010

GPD $E$ can be modeled in forward limit by $e(x) = Aq_{val}(x) + B\delta(x)$ acc. to $\chi$QSM model [Prog.Part.Nucl.Phys.47(2001)401]

$A_{UT}^{\sin(\phi - \phi_S)\cos\phi}$ sensitive to $J_u$, not to the other parameters [hep-ph/0506264]
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-$\sigma$ constraint on $J_u$ vs. $J_d$:

![Graph showing the model-dependent constraint between $J_u$ and $J_d$ with a shaded area indicating the 1-$\sigma$ confidence interval.]

- Quenched lattice calculation done with pion masses 1070, 870, and 640 MeV, and then extrapolated linearly in $m_{\pi}^2$ to the physical value
- Uncertainties on VGG model parameters shown as separate uncertainty ($\pm 0.06$)
Summary and Outlook

Improvement over last 4 years:

- Spin-independent & helicity PDFs:
  - **COMPASS**: $\Delta g/g$
  - **HERMES**: $\Delta q_u, \Delta q_d, \Delta q_s$
  - **JLAB**: $\Delta q_u, \Delta q_d$ at large $x$
  - **more**: COMPASS, HERMES, RHIC

- Transversity & TMD-PDFs:
  - **HERMES**: Sivers function
  - **BELLE**: Collins (fraggm.) function
  - **more**: BELLE, COMPASS, HERMES

- GPDs:
  - finishing pioneering phase ...
  - **much more to come**: HERMES, JLAB, COMPASS, JLAB-12 GeV