Selected spin physics results from COMPASS, HERMES and RHIC

K. Rith, CIPANP06, 2.6.2006

\[ S_z = \frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + L_q + (\Delta G + L_g) \]
The Experiments
Inclusive Asymmetries
Quark helicity distributions
Gluon helicity distribution
(Exclusive processes $\rightarrow$ GPDs)  
M. Garcon

Transverse spin physics
- Transversity - Collins fragmentation function
- Sivers distribution function
- $A_N$ in pp collisions

Conclusions
Two stage spectrometer

Polarized beam and target

- ~80%
- ≥50%

SAT, LAT, PID

$10^{-5} < x < 0.5$, $10^{-3} < Q^2 < 100$ (GeV/c)^2
HERA $e^+/e^-$ beam of 27.6 GeV
Polarized internal gas target (H, D, $^3$He)
kinematics: $0.02 < x < 0.6$, $1.0 < Q^2 < 15$ GeV$^2$
tracking: $\delta p/p \sim 2\%$, $\delta \Theta < 0.6$ mrad, 40-220 mrad
PID: Calorimeter, Preshower, TRD, RICH

hadron separation

Aerogel $n=1.03$
$C_4F_{10}$ $n=1.0014$
2006: 1 MHz collision rate; P~0.6

Congratulations!!!
100% transverse spin!
Two spectrometer arms with good particle ID at high momenta
Four spectrometer arms with excellent trigger and DAQ capabilities.
Large acceptance TPC and EMC -1<\eta<2
Spin-dependent DIS

\[ \nu = E - E' \]

\[ Q^2 = -q^2 \]

\[ x = \frac{Q^2}{2M \nu} = \text{fraction of nucleon's momentum carried by struck quark} \]

Helicity DF: \( \Delta q(x) := q^+(x) - q^-(x) \)

Asymmetry: \( A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \leq \frac{g_1}{F_1} \)

\[ g_1(x) := \frac{1}{2} \sum q z_q^2 \Delta q(x) \]

\[ F_1(x) := \frac{1}{2} \sum q z_q^2 q(x) \]
Asymmetries in polarized pp collisions

\[ A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)} \]

\[ A_{TT} = \frac{\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow) + \sigma(\uparrow\downarrow)} \]

\[ A_L = \frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)} \]

\[ A_T = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \]
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<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
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<tbody>
<tr>
<td>$\bar{p}p \rightarrow \pi + X$</td>
<td>$q\bar{q} \rightarrow gg$</td>
<td>$\Delta g$</td>
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<td>$q\bar{q} \rightarrow gg$</td>
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<td>(as above)</td>
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<tr>
<td>$\bar{p}p \rightarrow \text{jet(s)} + X$</td>
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<td>$q\bar{q} \rightarrow \gamma q$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
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<td></td>
<td>$q\bar{q} \rightarrow \gamma\gamma$</td>
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<td>$\bar{p}p \rightarrow DX, BX$</td>
<td>$q\bar{q} \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$\Delta g$</td>
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<tr>
<td>$\bar{p}p \rightarrow \mu^+\mu^- X$ (Drell-Yan)</td>
<td>$q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$</td>
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<td>$\bar{p}p \rightarrow (Z^0, W^\pm)X$</td>
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Inclusive asymmetries in DIS
\[ A_1 \cong g_1/F_1 - \text{Proton} \]

- \( g_1^p/F_1^p \) well known for \( x \ll 10^{-3} \)
- Excellent agreement between all experiments
- \( g_1^p/F_1^p \) (within errors) 'independent' of \( Q^2 \), accuracy still insufficient to confirm \( Q^2 \) dependence predicted by QCD
- \( \langle Q^2 \rangle = f(x) \)
- Extrapolation to \( x \to 0 \) for \( Q^2 = Q_0^2 ? \)
- \( g_1^p/F_1^p \to 1 \) for \( x \to 1 \)

\( g_1^p/F_1^p \) is shown in the graph, with data points from HERMES, low-x preliminary, E-143, and SMC.
$A_1 \equiv g_1/F_1$ - Proton and Deuteron

- $A_{1d}$ vanishes below $x = 0.05$
- $A_{1d} \to \ ?$ for $x \to 1$
- High $x$: JLAB-12 GeV
$A_1^d$ and $g_1^d$ at low $x$ and $Q^2$

But:

What is the interpretation of $g_1^d$ at these low values of $Q^2$?
Quark helicity distributions
Quark helicity distributions from SIDIS

Leading hadron originates with large probability from struck quark

$D(z) := \text{Fragmentation function (FF)}$

$q(x), \Delta q(x) := \text{Distribution functions (DF)}$

Measure hadron asymmetries

$$A_1^h(x,z) = \frac{\sum_q z_q^2 \Delta q(x) \ D_q^h(z)}{\sum_d z_d^2 \ q(x) \ D_q^h(z)}$$

$$\nu = E - E'$$

$$z = \frac{E_h}{\nu}$$
The HERMES data are consistent with flavour symmetry of sea quark helicity distributions
\[ \Delta u(x) > 0, \quad \Delta d(x) < 0, \quad \Delta u(x), \Delta d(x) \cong 0 \]

Data with much higher statistical accuracy urgently needed

\[
\begin{align*}
\int \Delta u(x) \, dx &= +0.601 \pm 0.063 \\
\int \Delta d(x) \, dx &= -0.226 \pm 0.063 \\
\int \Delta u(x) \, dx &= -0.002 \pm 0.043 \\
\int \Delta d(x) \, dx &= -0.054 \pm 0.035 \\
\int \Delta s(x) \, dx &= +0.028 \pm 0.034
\end{align*}
\]

In measured range (0.023 - 0.6):

\[ x(\Delta \bar{u} - \Delta \bar{d}) \]

\[ Q^2 = 2.5 \text{ GeV}^2 \]

P.R.L.92 (2004) 012005
Inputs:

- Multiplicities for $K^+$ and $K^-$ with deuteron target
- Inclusive deuteron symmetry $A_1^d$
- Asymmetries for $K^+$ and $K^-$ from deuteron: $A_1^{K+}$, $A_1^{K-}$

\[ \int x \Delta s(x) dx = 0.006 \pm 0.029 \pm 0.007 \]
Typical example: AAC06, hep-ph/0603213

Assumptions:
- Helicity distribution of sea quarks flavour symmetric
- $\Delta u_v$ and $\Delta d_v$ constraint by F and D (SU(3) symmetry)

Results for $Q_0^2 = 1 \text{ GeV}^2$:
- $\Delta \Sigma = 0.25 \pm 0.10$
- $\Delta G = 0.47 \pm 1.08$
- $\Delta G$ undetermined by only DIS

Note: From $g_1^d$
- $\Delta \Sigma(0.01 < x < 1)_{\text{exp}} \approx 0.35 \pm 0.03$
- From NLO fits $\Delta \Sigma(0 < x < 0.01)_{\text{fit}} \approx -0.13 \pm 0.11$

Low-x data urgently needed $\rightarrow$ e-RHIC
\[ \Delta q - \Delta \bar{q} \text{ at RHIC via } W \text{ production} \]

\[ \Delta d + \bar{u} \rightarrow W^- \]
\[ \Delta \bar{u} + d \rightarrow W^- \]
\[ \Delta \bar{d} + u \rightarrow W^+ \]
\[ \Delta u + \bar{d} \rightarrow W^+ \]

\[ A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

Expected start: 2009
The Gluon helicity distribution
\[ A_{\parallel} = R_{PGF} \times a_{LL}^{PGF} \times \left( \frac{\Delta G}{G} \right) + A_{Bkg} \]
Two high $p_T$ hadrons, $p_T > 0.7$ GeV/c, $\Sigma p_T^2 > 2.5$ (Gev/c)²

- $Q^2 < 1$ (GeV/c)² analysis - large statistics  
  - perturbative QCD scale from $\Sigma p_T^2$
  - PHYTIA MC used to evaluate physical Bkg, low $p_T$, resolved $\gamma$,

- $Q^2 > 1$ (GeV/c)² analysis - lower statistics
  - perturbative QCD scale from $Q^2$,
  - LEPTO MC used to evaluate Bkg, better controlled

Different data sets and analysis. Independent results

From A. Magnon
\[ D^0 \rightarrow K + \pi \quad \text{untagged} \]

\[ D^* \rightarrow D^0 + \pi_s \rightarrow K + \pi + \pi \quad \text{tagged} \]

We have now estimate for \( \sigma \) (nb)

From A. Magnon
High $p_T$ hadron pairs, $Q^2 > 1$ GeV$^2$: $\Delta G/G = 0.06 \pm 0.31$ (stat) $\pm 0.06$ (syst) $\langle x_g \rangle \sim 0.13$

High $p_T$ hadron pairs, $Q^2 < 1$ GeV$^2$: $\Delta G/G = 0.016 \pm 0.058$ (stat) $\pm 0.055$ (syst) $\langle x_g \rangle \sim 0.085$

Open charm: $\Delta G/G = -0.57 \pm 0.41$ $\langle x_g \rangle \sim 0.15$

$\Delta G/G (x_g \approx 0.1)$ is small
How to measure $\Delta g$:

$$A_{LL}^{\pi^0} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \sim a_{gg} \ast \Delta g^2 + b_{gq} \ast \Delta g + c_{qq}$$

$\Delta G/G$ from polarized pp collisions
QCD prediction

$|\eta| < 0.35$

Mid-rapidity: PHENIX

PRL 91, 241803 (2003)

ΔG from $A_{LL}(\pi^0)$

Theory model | C.L. (%)
---|---
GRSV-std | 21.7-17.1
*GRSV-max ($\Delta g=g$) | 0.0-0.0
*GRSV $\Delta g=0$ | 16.7-18.4
*GRSV $\Delta g=-g$ | 0.7-0.0

* At input scale: $Q^2 = .4$ Gev
Theory calculation shows good agreement with the experimental cross section.

Direct Photon Cross section

Inclusive Jet Cross section

$pp \rightarrow \gamma + X$, $pp \rightarrow \text{jet} + X$
Results limited by statistical precision

Total systematic uncertainty \( \sim 0.01 \) (STAR) + beam pol. (RHIC)

GRSV-max gluon polarization scenario disfavored

\[ \hat{p} + \hat{p} \rightarrow \text{jet} + X \text{ at } \sqrt{s} = 200 \text{ GeV} \quad 0.2 < |\eta^{\text{jet}}| < 0.8 \]
Significant reduction of $\Delta G$ uncertainty
$\Delta G = 0.31 \pm 0.32$ (DIS+$p^0$)
$\Delta G = 0.47 \pm 1.08$ (DIS only)

Sign problem: gg dominates
Similar $\chi^2$ for ($\Delta G(x) > 0$) and ($\Delta G(x) < 0$)

Consistent results for partial $1^{st}$ moment ($0.1 < x < 1$)
$\Delta G(x) > 0$: $0.30 \pm 0.30$
$\Delta G(x) < 0$: $0.32 \pm 0.42$
Transverse Spin physics
Transversity DF $\delta q(x)$ and Sivers DF $f_{1T\perp q}(p_T^2)$

$\delta q(x,Q^2)$
- DF of transv. polarized quarks in a transv. polarized nucleon
- 3$^{\text{rd}}$ leading twist DF. As important as $q(x)$ and $\Delta q(x)$
- $\delta q$ is chiral-odd: not accessible in DIS
- Need 2$^{\text{nd}}$ chiral-odd object Collins FF

$f_{1T\perp q}(p_T^2)$
- DF of unpolarised quark with transv. momentum $p_T$ in a transv. polarised nucleon.
- Non-zero Sivers DF requires non-vanishing orbital angular momentum in nucleon WF
- Chiral-even & naïve T-odd
Azimuthal angular asymmetries in SIDIS

\[ A_{UT}(\phi, \phi_S) = \frac{1}{S_\perp} \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)} \]

**U:** unpol. beam  
**T:** transv. pol. Target

\[ A_{UT}(\phi, \phi_S) \sim \ldots \sin(\phi + \phi_S) \]

\[ \ldots \sin(\phi - \phi_S) \]

\[ + \ldots \]

\[ \ldots + \ldots \]

\[ \ldots \]

Collins

\[ \sum_q e_q^2 \mathcal{I} \left[ \ldots \delta q(x, \vec{p}_T^2) \cdot H_{1T}^q(z, \vec{k}_T^2) \right] \]

\[ \sum_q e_q^2 q(x) \cdot D_1^q(z) \]

Sivers

\[ \sum_q e_q^2 \mathcal{I} \left[ \ldots f_{1T}^q(x, \vec{p}_T^2) \cdot D_1^q(z, \vec{k}_T^2) \right] \]

\[ \sum_q e_q^2 q(x) \cdot D_1^q(z) \]

\[ \mathcal{I}[\ldots]: \text{convolution integral over quark transverse momenta } \vec{p}_T \text{ and } \vec{k}_T \]
Collins amplitudes for $\pi^+/-$ (proton)

$$A_{UT}^{\sin(\phi+\phi_S)} \sim \delta q(x) \cdot H_1^{(1/2)}(z)$$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002

- Non-zero Collins effect
- Both Collins FF and transversity DF sizeable
- Surprisingly large $\pi^-$ asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e.
  \[u \rightarrow \pi^-\]
  \[H_{1,\text{disf}} \approx -H_{1,\text{fav}}\]
- Substantial contribution to pion sample from exclusively produced vector mesons (PYTHIA)
Collins amplitudes for $\pi^+/-$ and $K^+/-$

$A_{UT} \sin(\phi + \phi_S) \sim \delta q(x) \cdot H_{1}^{1/2}(z)$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002
Collins Asymmetries – D target

Note: different convention: $\phi_{\text{Coll}} = \phi + \phi_S - \pi$  also: V. Yu. Alexakhin et al, PRL 94 (2005) 202002

Consistent with zero. Cancellation due to deuteron target?
LO-QCD Analysis of HERMES and BELLE Results

Combined fit to Hermes asymmetries (Transversity x Collins-FF) and Belle asymmetries (Collins-FF^2) \(\Rightarrow\) Excellent agreement!

From M. Grosse Perdekamp, DIS06
Sivers amplitudes for $\pi^+/-$ (2002-2004)

$A_{UT}^{\sin(\phi-\phi_S)} \sim f_{1T}^{1/2}(x) \cdot D_1(z)$

\[ \pi^+ \] asymmetry significantly different from zero and positive

First hint of naive T-odd DF from DIS

orbital angular momentum $L_z^q$

But: Contribution of $L_z^q$ to nucleon spin unclear

\[ \pi^- \] asymmetry consistent with zero

Substantial contribution to pion sample from exclusively produced vector mesons (PYTHIA)
Sivers amplitudes for $\pi^+/-$ and $K^+/-$

$$A^{\sin(\phi-\phi_S)}_{UT} \sim f_{1T}^{1/2}(x) \cdot D_1(z)$$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002

large!

Sea contribution non-negligible
Sivers Asymmetry – D target

also: V. Yu. Alexakhin et al, PRL 94 (2005) 202002

\[ A_{Siv} = \frac{A_{UT}^{\sin \phi_c}}{f \cdot P} \]

Consistent with zero. Cancellation due to deuteron target?
Detection of two final state pions with opposite charge:

\[ A_{UT}(\phi_{R\perp}, \phi_S) \sim \ldots \sin(\phi_{R\perp} + \phi_S) \frac{\sum_q e_q^2 \delta q(x) \cdot H_1^{\leq q}(z, M_{\pi\pi}^2)}{\sum_q e_q^2 q(x) \cdot D_1(z, M_{\pi\pi}^2)} + \ldots \]

\[ H_1^{\leq q}(z, M_{\pi\pi}^2), D_1(z, M_{\pi\pi}^2) : \text{two pion fragmentation functions} \]

- no assumptions for $\vec{p}_T$ and $\vec{k}_T$
- completely independent from single pion analysis
Two-pion Asymmetries - H target

- hadrons assumed to be pions
- fit $A_{UT}(\phi_{R\perp} + \phi_{S})/\langle \sin \theta \rangle$ with $p_1 + p_2 \sin(\phi_{R\perp} + \phi_{S})$
- significant $\sin(\phi_{R\perp} + \phi_{S})$ behaviour!
- extract $A_{UT}^{\sin(\phi_{R\perp} + \phi_{S}) \sin \theta}$ from $A_{UT}(\phi_{R\perp}, \phi_{S}, \theta)$ by three-dimensional fit

$$A_{UT}^{\sin(\phi_{R\perp} + \phi_{S}) \sin \theta} = 0.040 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}$$
Two-pion Asymmetries - H target

- positive asymmetry amplitudes in all bins
- no sign change at $m_{\rho^0}$!
- significant result for $A_{UT}^{\sin(\phi_{R\perp} + \phi_S) \sin \theta}$
  $\rightarrow$ non-zero IFF!
Asymmetries compatible with zero

Results from 2004 data analysis about to be released. Event sample has doubled
Transversity from transverse $\Lambda$ polarisation

$$P_T^\Lambda = f P_T D \frac{\sum_q e_q^2 \times \Delta T q \times \Delta D^\Lambda_q}{\sum_q e_q^2 \times q \times D^\Lambda_q}$$

All 2002+2003 transversity data

- All $Q^2$
- $0.1 < y < 0.9$

Preliminary

Statistics will double with 2004 data

Negative trend for $Q^2 > 1$ GeV$^2$, but deviation from zero not significant

But: HERMES data for quasi-real photoproduction from unpolarized and longt. polarized target: $p_T^\Lambda \sim +5\%$
Single transverse Spin Asymmetry $A_N$ in pp

- Large $A_N$ has been observed at forward rapidities in hadronic reactions: E704 and STAR.
- Possible origins:
  - Collins FF
  - Sivers DF
  - Twist-3
  - Combinations of above
- Possible connection to orbital angular momentum $L$?
- For consistent partonic description:
  Need flavor dependent $A_N(E, x_F, p_T)$,
$A_N$ for identified hadrons

- $\pi^+$ positive $\sim A_N(\pi^-)$ negative
- $A_N(K^+)$ $\sim A_N(K^-)$ positive
  (in disagreement with expectation from valence quark fragmentation)
- $A_N(p) \sim 0$, $A_N(\bar{p})$ positive
- More theoretical input needed
Conclusions

- Plenty of new data from COMPASS, HERMES, RHIC improve our understanding of nucleon spin structure

- Gluon and sea quark polarisations small. Further improvements expected soon, especially from RHIC

- First results on transverse spin physics (Transversity DF, Collins FF, Sivers DF, $A_N$) very promising

Stay tuned ...
New exiting results will come soon!

Special thanks to G. Bunce and A. Magnon