New results from COMPASS

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Gordon conference on nuclear physics, Bates 2005

– COMPASS experiment
– Longitudinal spin structure
– Gluon polarisation
– Transversity
– Summary and outlook
The spin of the nucleon

Naive parton model:
\[ \Delta \Sigma = \Delta u_v + \Delta d_v = 1 \]

EMC (1988)
\[ \Delta \Sigma = 0.12 \pm 0.09 \pm 0.14 \]

gluons important in unpolarized case

complete description: orbital angular momenta

\[
S_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g
\]
Deep inelastic scattering

$(E, p)$

$Q^2 = -q^2 \quad x = Q^2 / 2M \nu$

$\nu = E - E' \quad y = \nu / E$

$z = E_h / \nu$

$p_T$ : hadron transverse momentum

$D_h^q(x)$ : fragmentation function

(from quark q into hadron h)

- Inclusive cross section

\[
\frac{d^2\sigma}{d\Omega dE'} \sim \left[ c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2) \right] + \left[ c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2) \right]
\]

spin independent

spin dependent

$F_1, F_2, g_1, g_2$ structure functions
COMPASS at CERN
Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Heidelberg, Lissabon, Mainz, Moscow, München, Nagoya, Prague, Protvino, Saclay, Tel Aviv, Turino, Trieste, Warsaw
(29 institutes, >200 physicists)

COMMON MUON AND PROTON APPARATUS
FOR STRUCTURE AND SPECTROSCOPY

Muon beam
Gluon polarisation
Polarised quark distributions
Polarised fragmentation functions
Transversity
Lambda polarisation
Vector meson production
DVCS

Hadron beam
Primakoff effect
Glue balls
Charmed baryons
Exotic charm states
Muon beam

160 GeV/c
2 \cdot 10^8 \mu /16.8 \text{ s}
78\% polarisation

Spectrometer

Two stages:
SM1 1Tm, SM2 4.5Tm

Tracking:
SciFi, Silicon, MicroMegas, GEM, MWPC, Drift, Straws, Driftubes

PID: RICH, ECAL, HCAL, muon filter
The polarised target

- target material: $^6$LiD
- polarisation: $> 50\%$
- dilution factor: $\sim 0.4$
- Dynamic Nuclear Polarization
- solenoid field: 2.5 T
- $^3$He/$^4$He: $T_{min} \approx 50$ mK
- two 60 cm long target cells with opposite polarisation
- 2006 new solenoid with 180 mrad acceptance

Reconstructed interaction vertices

<table>
<thead>
<tr>
<th>Vertex Position $z$ / mm</th>
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<tbody>
<tr>
<td>-1500</td>
</tr>
<tr>
<td>-1000</td>
</tr>
<tr>
<td>-500</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>1000</td>
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<tr>
<td>1500</td>
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<tr>
<td>2000</td>
</tr>
<tr>
<td>2500</td>
</tr>
<tr>
<td>3000</td>
</tr>
<tr>
<td>3500</td>
</tr>
</tbody>
</table>

$N_{trk} > 2$ vertex distribution along Z.
Method

• to be measured:

\[ A_\parallel = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \]

• flux normalization:

\[ A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d} \]

• acceptance difference:

Polarisation rotation

• take average asymmetry:

\[ \Rightarrow A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N_d' - N_u'}{N_u' + N_d'} \right) \]

\[ \Rightarrow \text{minimization of bias} \]

• experimental asymmetry

\[ A_{\text{exp}} = p_\mu \ p_T \ \oint \ A_\parallel \]

\[ p_\mu, \ p_T \]

beam and target polarisation dilution factor
**πK separation with RICH**

- π/K separation **up to 50 GeV/c**
- 80 m³ C₄F₁₀, n=1.00153
- 116 VUV spherical mirrors (21 m³)
- MWPCs with CsI kathodes, 8×8 mm²
- \(<n>\geq 15\) photons
Data taking 2002 – 2004

Kinematic ranges for IT, LT, MT, OT

- OT, MT inclusive triggers
- IT, LT semi-inclusive triggers

<table>
<thead>
<tr>
<th></th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Time</td>
<td>106d</td>
<td>90d</td>
<td>109d</td>
</tr>
<tr>
<td>Preparation</td>
<td>30d</td>
<td>7d</td>
<td>3d</td>
</tr>
<tr>
<td>Integrated luminosity / fb⁻¹</td>
<td>1</td>
<td>1.2</td>
<td>∼ 2.4</td>
</tr>
</tbody>
</table>
Longitudinal spin structure
Polarised deep inelastic scattering

- absorption of polarised photons (QPM)

\[ q(x) = q(x)^+ + q(x)^- \]
\[ \Delta q(x) = q(x)^+ - q(x)^- \]

+ quark ↑↑ nucleon
- quark ↓↑ nucleon

- photon nucleon asymmetry

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\sum_q e_q^2 (q(x)^+ - q(x)^-)}{\sum_q e_q^2 (q(x)^+ + q(x)^-)} = \frac{g_1(x)}{F_1(x)} \]

- spin structure function

\[ g_1 = \frac{1}{2} \sum_q e_q^2 \Delta q(x) = A_1 \cdot \frac{F_2}{2x(1 + R)} \approx \frac{A_\parallel}{D} \cdot \frac{F_2}{2x(1 + R)} \]
Inclusive asymmetries for $Q^2 > 1$ GeV$^2$

- high statistics $A_1$ at low $x$, factor 2–3 improvement
- good agreement at high $x$, systematically above SMC data at low $x$
- asymmetries for $Q^2 < 1$ GeV$^2$ soon
\[ g_1 \text{ at low } x \]

- \( xg_1 \) points at measured \( Q^2 \)
- NLO QCD fit (M\( \bar{S} \)) to world data:

\[
\Delta \Sigma = 0.202^{+0.042}_{-0.077} \quad \Rightarrow \quad 0.237^{+0.024}_{-0.029} \quad \text{at } Q^2 = 4 \text{ GeV}^2
\]
Recent AAC03 analysis using most of the published data
Valence quark distributions well determined, antiquark distribution larger errors
Polarised gluon distribution not determined
Gluon polarisation
$\Delta G/G$ measurement in DIS

- **Photon gluon fusion**
  
  $$A_{\gamma N}^{\text{PGF}} = \frac{\int d\hat{s} \Delta \sigma_{\text{PGF}} \Delta G(x_g, \hat{s})}{\int d\hat{s} \sigma_{\text{PGF}} G(x_g, \hat{s})} \approx \langle a_{\text{LL}}^{\text{PGF}} \rangle \frac{\Delta G}{G}$$

  analysing power

- **Methods**
  
  - **Open charm production**
    
    $$\gamma g \rightarrow c\bar{c} \rightarrow D^0 \rightarrow \pi K \quad \text{BR: 4%}$$
    
    scale: $m_c^2$
    
    clean channel, limited staticstics

  - **High $p_T$ hadron pairs**
    
    $$\gamma g \rightarrow q\bar{q} \rightarrow 2 \text{ jets or } H^+H^-$$
    
    scale: $Q^2$ or $\Sigma p_T^2$
    
    oppositely charged hadrons pairs with large $p_T$ und $\Delta \Phi \approx \pi$
\[ \Delta G \text{ from open charm} \]

\[ D^* \text{ tagging: } D^* \rightarrow D^0\pi_{\text{slow}} \rightarrow (K\pi)\pi_{\text{slow}} \]

- No decay vertex reconstruction
- Kaon identification by RICH essential
- Cut on mass difference \( M_{K\pi\pi} - M_{K\pi} - M_\pi \)
Mass spectra

- **D* candidates 2003**
  - $S_{\text{eff}} = 523.0 \pm 25.86$
  - $N(D^0) = 1076.8 \pm 55.0$
  - Mass: $6.14 \pm 1.38$ MeV/c$^2$
  - Sigma: $26.82 \pm 1.58$ MeV/c$^2$

- **D^0 candidates 2003**
  - $S_{\text{eff}} = 297.0 \pm 9.34$
  - $N(D^0) = 4198.2 \pm 345.2$
  - Mass: $3.14 \pm 2.11$ MeV/c$^2$
  - Sigma: $27.77 \pm 2.63$ MeV/c$^2$

- **1500 D^0 from D***
- **Effective signal**
  $$S_{\text{eff}} = \frac{S}{1 + S/B}$$
- **Experimental asymmetry**
  $$A_{\text{exp}} = p_{\mu} p_T f a_{\text{LL}} \frac{S}{S + B} \frac{\Delta G}{G}$$
- **No physics background**

E. Kabuß, GNC, Bates, 11.7.2005
Extraction of $\Delta G/G$

- needs $\langle a_{LL}^{PGF} \rangle$
calculated from MC

- AROMA generator

- good description of
data distributions by MC

- preliminary result
  at $\langle x_g \rangle = 0.15$ (RMS: 0.08)
  from 2002+2003

$\Delta G/G = -1.08 \pm 0.73 \text{ (stat)}$

- improvements with 2004 data
  and additional channels
High $p_T$ hadron pairs ($Q^2 > 1$ GeV$^2$)

- contributions to experimental asymmetry

\[
\frac{A_{\parallel}}{D} = R_{\text{PGF}} \left( \frac{A_{L L}^{\text{PGF}}}{D} \right) \frac{\Delta G}{G} + \left( R_{\text{QCDC}} \left( A_{L L}^{\text{QCDC}} \right) + R_{\text{LO}} \left( A_{L L}^{\text{LO}} \right) \right) A_1^d
\]

- Monte Carlo for $R, \left( A_{L L} \right)$
- data selection

Current fragmentation: $x_F > 0.1$ and $z > 0.1$
Radiative corrections/ photon polarisation: $0.1 < y < 0.9$
High $p_T$: $p_{T,1}, p_{T,2} > 0.7$ GeV and $p_{T,1}^2 + p_{T,2}^2 > 2.5$ GeV$^2$
\( \Delta G/G \) for \( Q^2 > 1 \) GeV\(^2\)

- 2002/03 data

\[
A_{||}/D = -0.015 \pm 0.080(\text{stat.}) \pm 0.013(\text{syst.})
\]

- Monte Carlo sample generated with LEPTO reasonable agreement with data

- additional \( x \) cut \( \Rightarrow A_d^1 \) small, LO and QCDC neglected

- \( \langle A_{LL}^{PGF} \rangle = -0.75 \pm 0.05 \)
  \( R_{PGF} = 0.33 \pm 0.07 \)
  \( \langle x_g \rangle = 0.13 \) (RMS=0.08)

\[
\Delta G/G = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.})
\]

- only 10% of statistics at \( Q^2 > 1 \) GeV\(^2\)

- single hadron analysis started

- expectation for 2002-2004: \( \delta(\Delta G/G) = 0.22 \)
\[ \Delta G/G \text{ for } Q^2 < 1 \text{ GeV}^2 \]

- Much more statistics
  but additional background from resolved photon processes

- Data selection same as for large \( Q^2 \)

\[ A_{||}/D = 0.002 \pm 0.019(\text{stat.}) \pm 0.003(\text{syst.}) \]

- MC simulation with PYTHIA compared to data (blue points)
Contributions to asymmetry

- LO, low $p_T$ neglected
Extraction of $\Delta G/G$

Estimate of resolved photon contribution

- polarised PDFs in deuteron and photon needed
- polarised photon PDFs are sum of non perturbative and perturbative part
- estimate non perturbative contribution from unpolarised photon PDFs:
  
  $-q_{\text{VMD}}^\gamma < \Delta q_{\text{VMD}}^\gamma < q_{\text{VMD}}^\gamma$

- use as contribution to systematic error

2002/2003 data

- determination of $R_{\text{PGF}}$ and $a_{\text{LL}}$ from Monte Carlo
- most sensitive parameters in PYTHIA: $k_T^N$ and $k_{\gamma}^N$

$$\Delta G/G(x_g = 0.095^{+0.08}_{-0.04}, \mu^2 = 3 \text{ GeV}^2) = 0.024 \pm 0.089(\text{stat.}) \pm 0.057(\text{syst.})$$

- systematic error includes exp. syst. (0.014), MC syst. (0.052) and estimate of photon contribution (0.018)
- expectation for 2002-2004: $\delta(\Delta G/G) = 0.05$
$\Delta G/G$ measurements in DIS

$\Delta G/G$ is small or has a node around $x_g \approx 0.1$
Transversity
Transversity

• transversity not measurable in inclusive DIS as quark helicity must flip
  ⇒ SIDIS

• two methods:

  1) polarisation of struck quark measured by azimuthal asymmetry of produced hadrons
  ⇒ Collins–Effect

  second contribution: azimuthal asymmetries due to quark transverse momenta
  ⇒ Sivers–Effect

  2) azimuthal dependence of hadron pair production
  ⇒ interference fragmentation function \( H_1^{qT} \)

• \( \Delta_T D \) and \( H_1^{qT} \) measurable in \( e^+e^- \) collisions  ⇒ BELLE
Collins and Sivers effect

Using a transversely polarized target allows to disentangle Collins and Sivers–Effect.

\[
A_T^h = \frac{1}{|S_T|} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}
\]

\[
\sim \sin(\phi + \phi_s - \pi) \frac{\sum_i e_i^2 \Delta T q_i(x) \Delta T D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Collins–Effect}
\]

\[
+ \sin(\phi - \phi_s) \frac{\sum_i e_i^2 f_{1T}^i(x) D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Sivers–Effect}
\]

- \(\Delta_T q(x)\) transversity DF
- \(f_{1T}^i(x)\) Sivers DF
- \(q(x)\) unpolarized DF
- \(\Delta_T D_{q}^h(z)\) Collins FF
- \(D_{q}^h(z)\) unpolarized FF
Results for asymmetries

Collins and Sivers asymmetries for positive hadrons (closed symbols) and negative hadrons (open symbols)

asymmetries small: cancellation in deuteron?

more statistics from 2003 and 2004, proton target (NH$_3$) in 2006
Two hadron asymmetries

2002-2003 data

preliminary

(March 23, 2005)

- results from 2002/2003
- \( A_{\Phi_{RS}} \sim \sum_i e_i^2 \Delta T q_i(x) H_{1q_i}^h(z) \)
- asymmetry vs. \( M_{\text{inv}}, x, z \) on deuterons consistent with 0
Summary

• Many new results from COMPASS from 2002 and 2003 data
• Gluon polarisation measured with several methods
  ⇒ more statistics needed
• New precise data for the longitudinal spin structure function at small $x$
  ⇒ improvement of polarised PDFs
• Two methods to determine transversity
• More results on semi-inclusive DIS, $\rho$ meson production, $\Lambda$ polarisation
• Exploratory run in 2004 for Primakoff reactions ⇒ analysis going on

• Plans:
  – more data (> factor 2) from 2004
  – data taking continues in 2006, $^6$LiD for longitudinal polarisation, NH$_3$ for transverse polarisation
  – new target solenoid ⇒ larger hadron acceptance
  – improvement of RICH (electronics, photon detection)
  – next hadron run probably 2007