New results from COMPASS

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on behalf of the COMPASS collaboration

Workshop on the Helicity Structure of the Nucleon,
BNL, June 5, 2006

- COMPASS experiment
- Inclusive asymmetries
- \( \Lambda \) and \( \rho \) production
- Gluon polarisation
- Spectrometer upgrade
- Summary and outlook
The spin of the nucleon

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

E155
\[ \Delta \Sigma = 0.23 \pm 0.07 \pm 0.19 \]

Gluons important in unpolarized case
\[ \Delta G? \]

Complete description: orbital angular momenta

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

\[ Q^2 = -q^2 \quad x = \frac{Q^2}{2M \nu} \]
\[ \nu = E - E' \quad y = \frac{\nu}{E} \]
\[ z = \frac{E_h}{\nu} \]
\[ p_T : \text{hadron transverse momentum} \]
\[ D_{q}^{h}(x) : \text{fragmentation function} \]
\[ (\text{from quark } q \text{ into hadron } h) \]

● Inclusive cross section

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

\[ F_1, F_2, g_1, g_2 \ \text{structure functions} \]
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

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

- spin structure function

\[ g_1 = \frac{1}{2} \Sigma_q e_q^2 \Delta q(x) = A_1 \cdot \frac{F_2}{2x(1 + R)} \approx \frac{A_{||}}{D} \cdot \frac{F_2}{2x(1 + R)} \]
COMPASS at CERN
Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lissabon, Mainz, Moscow, Munic, Nagoya, Prague, Protvino, Saclay, Tel Aviv, Turino, Trieste, Warsaw
(28 institutes, 240 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 scattering
- Exotic hadrons
  - Glueballs
  - Hybrids
  - Multi-quark states
- Charmed hadrons
Muon beam

Beam parameter

- energy: 160 GeV
- intensity: $2 \cdot 10^8 \mu$/spill
- polarisation: $\approx 76\%$
- emittance: $\varepsilon > 6$ mm·mrad

Energy spectrum of beam muons
**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: $T_{min} \approx 50 \text{ mK}$
- two 60 cm long target cells with opposite polarisation
- 2006 new solenoid with 180 mrad acceptance
- regular polarisation reversal by field rotation

Target Polarization 2003

E. Kabuß, Workshop, BNL, 5.6.2006
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:

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

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

• experimental asymmetry

\[ A_{\text{exp}} = p_\mu \ p_T \ f \ A_{\parallel} \quad p_\mu, \ p_T \text{ beam and target polarisation dilution factor} \]
New results on

- inclusive asymmetries
- open charm production
- high $p_T$ hadrons pairs
- $\Lambda$ polarisation
- exclusive $\rho$ production

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<thead>
<tr>
<th></th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
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<tr>
<td>Beam Time</td>
<td>106d</td>
<td>90d</td>
<td>110d</td>
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<tr>
<td>Preparation</td>
<td>30d</td>
<td>7d</td>
<td>3d</td>
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<tr>
<td>Integrated luminosity / fb$^{-1}$</td>
<td>1</td>
<td>1.2</td>
<td>$\sim$ 2.4</td>
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<td>(20% for transverse target polarisation)</td>
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Longitudinal spin structure
Inclusive measurements \((Q^2 > 1 \text{ GeV}^2)\)

- new preliminary results from 2002 – 2004
  (published 02/03: PLB 612(2005) 154, improved by a factor of > 2)
- \(88 \cdot 10^6\) events with \(x > 0.004\), \(0.1 < y < 0.9\)
- \(2/3\) inclusive triggers, \(1/3\) hadronic triggers (semi-inclusive, calorimetric)
- systematics: fake configurations, compare different microwaves settings etc
  \(\implies\) no effects seen
- bin to bin migration and bias through hadronics triggers studied with MC
  \(\implies\) negligible effects
**Inclusive asymmetries for $Q^2 > 1$ GeV$^2$**

- **systematic effects:** error on $p_\mu$ (5%), $p_T$ (5%, $f$ (2–3%), $D$ (6%)
  \[ \Rightarrow \delta A_1 \approx 0.1 A_1 \]

- **additional contributions from false asymmetries, radiative corrections**
Spin structure function $g_1(x)$

- $xg_1$ points at measured $Q^2$
- NLO QCD fit ($\overline{MS}$) to world data
- preliminary result:
  $$\Gamma_1^N = 0.0502 \pm 0.0028\text{(stat)} \pm 0.0020\text{(evol.)} \pm 0.0051\text{(syst.)}$$
- data for $0.004 < x < 0.7$, QCD fit used for extrapolation
- contribution of unmeasured region about 3%
Inclusive asymmetries for $Q^2 < 1 \text{ GeV}^2$

- 2002 – 2003 data, COMPASS error 10 times smaller than previous measurement
- $A_1^d$ is compatible with 0 at small $x$
- more data for $Q^2 < 1 \text{ GeV}^2$ and $Q^2 > 1 \text{ GeV}^2$, semi-inclusive asymmetries
Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarisation

- $\Lambda$ polarisation related to spin transfer from struck quark $\rightarrow$ sensitivity to $\Delta s$?
- 2003 data: $31000$ $\Lambda$, $18000$ $\bar{\Lambda}$ for $Q^2 > 1$ GeV$^2$
- more data from 2004
• large statistics of diffractive $\rho$, $\Phi$, $J/\Psi$
• 2.4 M events with $\rho^0$ from 2002 and 2003
• large range in $Q^2$ and $x$
• $A_1$ for $\rho^0$ compatible with zero, more data from 2004
• measurement of spin density matrix elements
Gluon polarisation
**ΔG/G measurement in DIS**

- **Photon gluon fusion**

![Diagram of photon gluon fusion](image)

\[ A_{γN}^{PGF} = \frac{\int d\hat{s} \frac{Δσ_{PGF}}{\sigma_{PGF}} \frac{ΔG}{G}(x_g, \hat{s})}{\int d\hat{s} \frac{σ_{PGF}}{G}(x_g, \hat{s})} \]

\[ \approx \langle a_{LL}^{PGF} \rangle \frac{ΔG}{G} \]

- **Methods**

  - **Open charm production**
    \[ γg \rightarrow c\bar{c} \]
    \[ \rightarrow D^0 \rightarrow πK \quad \text{BR: 4%} \]
    hard scale: \( m_c^2 \)
    clean channel, limited staticstics

  - **High \( p_T \) hadron pairs**
    \[ γg \rightarrow q\bar{q} \]
    \[ \rightarrow 2 \text{ jets or } H^+H^- \]
    hard scale: \( Q^2 \) or \( \Sigma p_T^2 \)
    oppositely charged hadrons pairs with large \( p_T \) und \( ΔΦ \approx π \)

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E. Kabuś, Workshop, BNL, 5.6.2006
Untagged: $D^0 \rightarrow K\pi$

Tagged: $D^* \rightarrow D^0\pi_{\text{slow}} \rightarrow (K\pi)\pi_{\text{slow}}$

- no decay vertex reconstruction
- Kaon identification by RICH essential
- cut on $D^0$ kinematics ($z_{D^0}$, $\cos(\theta)$)
- effective signal: $S_{\text{eff}} = \frac{S}{1+S/B}$

- cut on mass difference $M_{K\pi\pi} - M_{K\pi} - M_\pi$
- 3900 $D^0$ from $D^*$
Extraction of $\Delta G/G$

- experimental asymmetry $A_{\exp} = p_\mu p_T f a_{LL} \frac{S}{S+B} \frac{\Delta G}{G}$

- weighting method used $(p_\mu f a_{LL} \frac{S}{S+B})$

- needs $\langle a_{LL}^{P,GF} \rangle$, not exactly calculable from data

- use neural net trained on MC

- AROMA generator for MC

- good description of data distributions by MC
Result for $\Delta G/G$

COMPASS Data 2002-2004 $\Delta G/G$

- preliminary result at $\langle x_g \rangle = 0.15$ (RMS: 0.08) from 2002–2004

$$\Delta G/G = -0.57 \pm 0.41 \text{ (stat)}$$

- systematic error under study
- plans: absolute cross sections, NLO analysis, more channels
High $p_T$ hadron pairs ($Q^2 > 1 \text{ GeV}^2$)

- contributions to experimental asymmetry

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

- Monte Carlo for $R, \left\langle A_{LL} \right\rangle$

- data selection

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

- 2002/03 data (prelim.)
  
  \[
  A_{||}/D = -0.015 \pm 0.080 \text{ (stat.)} \pm 0.013 \text{ (syst.)}
  \]

- Monte Carlo sample generated with LEPTO reasonable agreement with data

- additional \( x \) cut \( \Rightarrow A_1^d \) small, LO and QCDC neglected

- preliminary result:
  
  \[
  \langle A_{LL}^{PGF} \rangle = -0.75 \pm 0.05
  \]
  
  \[
  R_{PGF} = 0.33 \pm 0.07, \langle x_g \rangle = 0.13 \text{ (RMS}=0.08)\]

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

- main contribution to systematic error: false asymmetries

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

- expectation for 2002-2004: \( \delta(\Delta G/G) = 0.22 \)

- improvement by neural net selection studied

- single hadron analysis started
High $p_T$ hadron pairs ($Q^2 < 1$ GeV$^2$)

- much more statistics (500k events from 2002–2004) but additional background from resolved photon processes
- data selection similar to large $Q^2$ but $0.35 < y < 0.9$
- preliminary result with $\langle D \rangle = 0.64$

\[ A_{||}/D = 0.004 \pm 0.013 \text{ (stat.)} \pm 0.003 \text{ (exp.syst.)} \]

- 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

**Preliminary result**

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

\[\Delta G/G(x_{g} = 0.085^{+0.07}_{-0.035}, \mu^{2} = 3 \text{ GeV}^{2}) = 0.016 \pm 0.058\text{(stat.)} \pm 0.055\text{(syst.)}\]

- systematic error includes exp. syst.(0.014) (mainly false asymmetries), MC syst.(0.052) and estimate of photon contribution (0.013)
$\Delta G/G$ measurements in DIS

\[ \int G(x)dx = 2.5 \]

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

- HERMES, all $Q^2$
- $SMC \ Q^2 > 1 \ (GeV/c)^2$
- COMPASS, $Q^2 > 1 \ (GeV/c)^2 \ (02-03, \text{prelim})$
- COMPASS, $Q^2 < 1 \ (GeV/c)^2 \ (02-04, \text{prelim})$
- COMPASS, open charm (02-04, prelim)

E. Kabuß, Workshop, BNL, 5.6.2006
Detector upgrade
Upgrades in 2006

- **Polarised target**: large acceptance magnet system
- **RICH1**: central photon detectors replaced by MAPMTs
  - new read out using APVs for outer photon detectors
- **RICH wall** (preshower for ECAL1)
- **ECAL1** Electromagnetic calorimeter in first stage
- More **large angle tracking** in first stage
- **DAQ** and **DCS** consolidation and upgrades
- Other small additions
• new target magnet: SMC (70 mrad) ➞ COMPASS (180 mrad)
• gain in statistics at least 30%
• testing of magnet completed, few problems identified
Polarised target magnet

- Field homogeneity of $3 \cdot 10^{-5}$ at Saclay
- $7 \cdot 10^{-5}$ reached in presence of SM1 dipole field
- delicate operation due to short in one correction coil
Polarised target microwave cavity

- match for larger acceptance
- new 3 cell microwave cavity (- ++ - )
- reduction of false asymmetries
New microwave cavity
Inner photon detectors

- read out changed from MWPCs to MAPMTs for the inner quarter
- telescope in front of MAPMT for cost effectiveness and to avoid dead regions
- significant increase in number of photons
- space resolution a bit worse but in total increase in precision
- excellent timing, no dead time, improved efficiency

Outer photon detectors

- new APV readout for the outer 75% of the photon detectors
- large reduction of uncorellated background
- much smaller dead time
RICH1 central photon detectors

- sketch of telescope in front of MAPMT
- Complete panel of field lenses
RICH1 outer photon detector

- new APV readout electronics for outer photon detectors
- number of photons same as before
- uncorellated background at least factor 6 smaller
RICH wall

- large area tracker (drift tubes)
- lead converter
- preshower for ECAL1
• new electromagnetic calorimeter (lead glass) in first stage
• plan to include ECAL1 into trigger
- new large area detectors in large angle spectrometer
- new straw module
- new large drift chamber DC4
Summary and outlook

Results:

- Analysis of 2002 –2004 data
- Precise results for the longitudinal spin structure function
- Inclusive asymmetries at small $Q^2$
- Gluon polarisation measured with several methods
- Results on $\rho$ meson production, $\Lambda$ polarisation

Plans:

- new target solenoid $\implies$ larger hadron acceptance
- improvement of RICH $\implies$ background, efficiency improved
- detector upgrades for enlarged acceptance
- data with $^6\text{LiD}$ for longitudinal polarisation, $\text{NH}_3$ for transverse polarisation
  $\implies$ we hope to double the statistics for most channels