The gluon Sivers asymmetry measurements at COMPASS

Adam Szabelski on behalf of the COMPASS collaboration

adam.szabelski@cern.ch

University of Trieste and INFN

Deep Inelastic Scattering 2016
Hamburg 12th of April 2016
Outline

Nucleon spin

COMPASS

Gluon Sivers from $J/\psi$

Gluon Sivers from high-$p_T$ hadron pairs

Summary
Nucleon spin decomposition

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- \( \Delta \Sigma \approx 0.3 \)

- \( \Delta g/g \) from COMPASS and \( \Delta G \) from global fit to RHIC data suggest small \( \Delta G \) contribution
  Marcin Stolarski on behalf of the COMPASS Collaboration, PoS (DIS2014) 211

- QCD Lattice calculations show significant but opposite contribution of \( L_u \) and \( L_d \)

- Nonzero Sivers function of gluon can be related to its orbital motion in a polarised nucleon
Gluon Sivers measurements

- Gluon Sivers from $pp^{↑}$ collisions at PHENIX@RHIC.


- $J/\Psi$ muoproduction at COMPASS.
- high-$p_T$ hadron pair production at COMPASS.
**Summary**

- Experiment polarised target
- COMPASS
- Univ. Trieste
- Gluon Sivers from $J/\Psi$
- Gluon Sivers from high-$p_T$ hadron pairs

**Unique M2 beamline**
- polarised $\mu$
- $e$
- $\pi, K, p$
  - both charges

**Flexible target area**
- $LiD, NH_3$ (polarised)
- $H_2$ and nuclear targets

**Powerful tracking system**
- ∼350 tracking detector planes (high redundancy)

**Particle identification**
- Muon Walls, H/E calorimeters, RICH

- **Two 30cm and one 60 cm long target cells** [two 60cm long cells in 2002-2004] with opposite polarization

  - material: $NH_3$ (protons) $[^5LiD$ (deuterons)]
  - polarization: $\cong90\%$ $[\cong50\%]$
  - dilution factor for exclusive $\rho^0$ production: $\cong25\%$ $[\cong44\%]$

  - Microwave reversal every week
The COMPASS target

$^3$He – $^4$He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T

acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

d (LiD) 50% p (NH$_3$) 90%
dilution factor 40% 16%
Nonzero Sivers function of gluon can be related to its orbital motion in a polarised nucleon

$$\mu^+ + N \rightarrow \mu^+ + J/\Psi + X \rightarrow 2\mu^+ + \mu^- + X$$

$$P_{J/\Psi} = p_{\mu^+} + p_{\mu^-}$$

$$\phi_{\mu^+\mu^-} = \phi_{J/\Psi} = \phi_g$$

$$\phi = \phi_{\mu^+\mu^-} - \phi_S$$

$$A_T^{\mu^+\mu^-}(\phi) = \frac{d\sigma^\uparrow(\phi) - d\sigma^\downarrow(\phi)}{d\sigma^\uparrow(\phi) + d\sigma^\downarrow(\phi)}$$

$$N(\phi) = an\Phi\sigma_0(1 + P_T f A^{\sin(\phi)}\sin(\phi))$$

**J/Ψ signal**

- COMPASS 2010: Clear $J/\Psi$ signal ($3.1 \text{ GeV}/c^2 \sigma = 55 \text{ MeV}/c^2$),
- small background, but limited statistics (2300 incl. and 4500 excl.)
Gluon Sivers from $J/\Psi$ results

The missing energy.

The Asymmetry. Black line denotes the integration region.

Results

- $A_{p}^{Siv} = -0.05 \pm 0.33$ (inclusive $J/\Psi$).
- $A_{p}^{Siv} = -0.28 \pm 0.18$ (Exclusive $J/\Psi$).
- Prospect for better statistics: max. factor of 2.
Nonzero Sivers function of gluon can be related to its orbital motion in a polarised nucleon

\[ \ell + N \rightarrow \ell' + 2h + X \]

\[ \phi = \phi_{2h} - \phi_S \]

\[ \sigma - \text{two-hadron cross-section integrated over } \phi_R; \quad A_T^{2h}(\phi) = \frac{d\sigma^\uparrow(\phi) - d\sigma^\downarrow(\phi)}{d\sigma^\uparrow(\phi) + d\sigma^\downarrow(\phi)} \]

\[ N(\phi) = an\Phi\sigma_0(1 + P_T fA^{\sin(\phi)} \sin(\phi)) \]

3 processes in the single photon exchange approximation describe well the unpolarised data.
The analysis procedure

The aim is:

- The extraction of the asymmetry of the photon gluon fusion (PGF) process (signal) and the asymmetries of the leading process (LP) (background 1) and of the QCD Compton process (background 2) from measured Sivers asymmetry

The procedure:

- Selection of events with high-$p_T$ hadron pair sample in order to:
  - enhanced the fraction of PGF events in the sample (too strong cut leads to minimal statistics)
  - have a stronger correlation between the gluon azimuthal angle and the azimuthal angle of the $p_1 + p_2$ ($\phi_{2h}$) is stronger(from MC)
- assignment of 3 weights to every event (corresponding to the 3 processes) by a neural network (NN) trained on MC data
- Solve the set of equations to obtain the asymmetries for the 3 processes
3 (single photon exchange) processes

\begin{align*}
A_{\sin \phi}^{UT} &= R_{PGF} A_{\sin \phi}^{PGF}(\langle x_g \rangle) + R_{LP} A_{\sin \phi}^{LP}(\langle x_{Bj} \rangle) \\
&\quad + R_{QDCD} A_{\sin \phi}^{QDCD}(\langle x_C \rangle).
\end{align*}

\begin{align*}
\omega_{PGF} &\equiv \omega^G = R_{PGF} f \sin \phi = \beta^G / P_T, \\
\omega_{LP} &\equiv \omega^L = R_{LP} f \sin \phi = \beta^L / P_T, \\
\omega_{QDCD} &\equiv \omega^C = R_{QDCD} f \sin \phi = \beta^C / P_T.
\end{align*}

$R_{PGF}, R_{LP}, R_{QDCD}$ - from neural network trained on MC data
Weighting method. 3 processes

\[ N_t = \alpha_t^j \left( 1 + \beta_t^G A_{PGF}^{\sin \phi}(\vec{x}) + \beta_t^L A_{LP}^{\sin \phi}(\vec{x}) + \beta_t^C A_{QCDC}^{\sin \phi}(\vec{x}) \right) \]

\[ t = ud, c, ud', c'. \]

\[ p_t^j : = \int \omega^j(\phi) N_t(\vec{x}) d\vec{x} \approx \sum_{i=1}^{N_t} \omega_i^j \]

\[ = \tilde{\alpha}_t^j \left( 1 + \left\{ \beta_t^G \right\}_i \omega^j A_{PGF}^{\sin \phi}(\langle x_g \rangle) + \left\{ \beta_t^L \right\}_i \omega^j A_{LP}^{\sin \phi}(\langle x_{Bj} \rangle) + \left\{ \beta_t^C \right\}_i \omega^j A_{QCDC}^{\sin \phi}(\langle x_c \rangle) \right). \]

\[ \left\{ \beta_t^G \right\}_i \omega^j = \frac{\int \alpha_t^j \beta_t^G \omega^j d\vec{x}}{\int \alpha_t \omega d\vec{x}} \approx \frac{\sum_{i=1}^{N_t} \beta_i^G \omega_i^j}{\sum_{i=1}^{N_t} \omega_i^j} \]

Here \( j = PGF, LP, QCDC \) and \( \tilde{\alpha}_t^{ud} \tilde{\alpha}_t^{c'} = 1 \) limits the number of unknowns to 12.

The set of equations is solved by minimising the \( \chi^2 \)
Kinematic cuts

- **DIS cuts:** $Q^2 > 1 \text{(GeV/c)}^2$; $0.003 < x_{Bj} < 0.7$; $0.1 < y < 0.9$;
- $W > 5 \text{GeV/c}^2$;
- $z_1, z_2 > 0.1$;
- $z_1 + z_2 < 0.9$;
- $p_{T1} > 0.7 \text{GeV/c}$; $p_{T2} > 0.4 \text{GeV/c}$ - optimised to enhance PGF fraction and $\phi_g, \phi_{2h}$ correlation.
Full chain MC with LEPTO generator, GEANT with COMPASS setup and reconstruction package

- MSTW08 PDFs
- Parton Shower on
- $F_L$ on
- FLUKA for secondary interactions

6 kinematic variables as an input of NN: $p_T^1, p_T^2, p_L^1, p_L^2, Q^2, x_{Bj}$

Good agreement between MC and data for distribution of these variables needed.
MC vs data. Deuteron

![Graphs showing MC vs Data comparisons for different variables](image-url)
Nucleon spin
COMPASS
Gluon Sivers from $J/\psi$
Gluon Sivers from high-$p_T$ hadron pairs
Summary

MC vs data. Proton

Events $0 \rightarrow 10000 \rightarrow 20000 \rightarrow 30000 \rightarrow 40000 \rightarrow 50000 \rightarrow 60000 \rightarrow 70000 \rightarrow 80000$

Data
MC
COMPASS preliminary

MC/Data $0.6 \rightarrow 0.8 \rightarrow 1 \rightarrow 1.2 \rightarrow 1.4$

Events $0 \rightarrow 20000 \rightarrow 40000 \rightarrow 60000 \rightarrow 80000 \rightarrow 100000 \rightarrow 120000 \rightarrow 140000 \rightarrow 160000 \rightarrow 180000$

Data
MC
COMPASS preliminary

MC/Data $0.6 \rightarrow 0.8 \rightarrow 1 \rightarrow 1.2 \rightarrow 1.4$

Events $0 \rightarrow 10000 \rightarrow 20000 \rightarrow 30000 \rightarrow 40000 \rightarrow 50000 \rightarrow 60000 \rightarrow 70000 \rightarrow 80000 \rightarrow 90000 \rightarrow 100000 \rightarrow 110000 \rightarrow 120000 \rightarrow 130000 \rightarrow 140000 \rightarrow 150000 \rightarrow 160000 \rightarrow 170000 \rightarrow 180000$

Data
MC
COMPASS preliminary

MC/Data $0.6 \rightarrow 0.8 \rightarrow 1 \rightarrow 1.2 \rightarrow 1.4$
Results

- Gluon Sivers asymmetry for proton: $A_{PGF,p}^{s\sin(2h_2\phi_1 - \phi_s)} = -0.26 \pm 0.09\,(\text{stat.}) \pm 0.06\,(\text{syst.})$ at $\langle x_G \rangle = 0.15$.

- Gluon Sivers asymmetry for deuteron: $A_{PGF,d}^{s\sin(2h_2\phi_1 - \phi_s)} = -0.14 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.})$ at $\langle x_G \rangle = 0.13$.

- Limited precision on deuteron. More data needed.

- The results for the LP compatible with single hadron measurements.

Summary

1. Two methods of gluon Sivers measurements have been performed at COMPASS.

2. The $J/\Psi$ selection method gives negative values but suffers from low statistics.

3. The high-$p_T$ hadron pair method:
   - The result on deuteron is compatible with zero but the central value is negative with large error.
   - 2010 proton data show a value which is negative ($3\sigma$ from 0).
Backup slides
Method Validation

\[
\sin(\phi_{2h} - \phi_s) = A_{\text{PGF}}
\]

\[
\sin(\phi_{2h} - \phi_s) = A_{\text{QCDC}}
\]

\[
\sin(\phi_{2h} - \phi_s) = A_{\text{LP}}
\]
## Systematics summary.

<table>
<thead>
<tr>
<th>Source</th>
<th>Deuteron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>value</td>
<td>assigned error</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>False asymmetries</td>
<td>0.016</td>
<td>0</td>
</tr>
<tr>
<td>selection of charges $q_1 \cdot q_2 = -1$</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>0.018</td>
<td>0.018</td>
</tr>
<tr>
<td>large $Q^2$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$x_{\text{Bj}}$ binning</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>all asyms vs only Sivers</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>ML vs Weighted</td>
<td>0.008</td>
<td>0</td>
</tr>
<tr>
<td>target polarisation</td>
<td>0.0075</td>
<td>0.0075</td>
</tr>
<tr>
<td>dilution factor</td>
<td>0.0075</td>
<td>0.0075</td>
</tr>
<tr>
<td>total $\sqrt{\sum \sigma_i^2}$</td>
<td>-</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Table**: Systematics summary.
RMS : 0.040; min : -0.300; max : -0.193; (max-min)/2 = 0.054
NN training validation

- LP
- QCDC
- PGF

COMPASS preliminary

Gluon Sivers at COMPASS
Nucleon “tomography“

TMD: longitudinal momentum $x$ and transverse momentum $\vec{k}_T(3D)$

alternatively: GPDs gives simultaneous distribution of quarks w.r.t.: longitudinal momentum $xP$ and transverse position $\vec{b}_\perp$ - impact parameter (3D)

\begin{itemize}
\item (a) longitu.
\item (b) $x \sim 0.003$ $x \sim 0.03$ $x \sim 0.3$
\end{itemize}
Chromodynamic lensing

Burkardt model:

\[
q_{\hat{\gamma}}(x, \vec{b}_\perp) = \mathcal{H}(x, \vec{b}_\perp) - \frac{1}{2M} \frac{\partial}{\partial b_y} \mathcal{E}(x, \vec{b}_\perp)
\]

\(\mathcal{H}\) - unpolarised GPD function (symmetric)
\(\mathcal{E}\) - spin-flip function, when nonzero \(\Rightarrow\) nonzero OAM