Longitudinal Spin Structure of the Nucleon
COMPASS Legacy

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COMPASS @ DSPIN-17

- Longitudinal spin structure
  - Artem Ivanov: Tuesday AM
    Longitudinal target spin dependent azimuthal asymmetries in SIDIS

- Fragmentation
  - Nikolai Mitrofanov: Tuesday AM
    Multiplicities of charged hadrons, pions and kaons in DIS

- TMD
  - Franco Bradamante: TSAs in SIDIS
  - Michael Pešek: TSAs in Drell-Yan
  - Jan Matoušek: $q_T$-weighted TSAs in Drell-Yan

- GPD
  - Andrzej Sandacz: DVCS and exclusive $\pi^0$
  - Bohdan Marianski TSAs in exclusive vector meson production
Partonic structure of the nucleon

- Twist-2 PDFs, integrated over $k_T$ ($k_T = \text{parton intrinsic transverse momentum}$)

  ⇒ Three parton distributions:
  - Parton momentum DF $q(x)$
  - $\Delta q(x)$ for a longitudinally polarised Nucleon via Structure Function $g_1(x, Q^2)$
  - $\Delta_T q(x)$ for a transversally polarised Nucleon

- $\Delta_T q(x)$: See talk by F. Bradamante at this conference

- Finite $A_{UL}^{\sin \phi R}$ in LSA of di-hadron production, sensitive to collinear twist-3 PDF and FF
  
  See talk by A. Ivanov at this conference
COMPASS: Spectrometer

○ **Muon Beam** (2011)
  - 160 GeV (200 GeV)
  - $2 \cdot 10^8 \mu$ per Spill of $\sim 10$ s ($1 \cdot 10^8$)
  - 76÷80% polarisation

○ **Target**
  - $LiD: f \simeq 40\%, P_T \simeq 50\%$
  - $NH_3: f \simeq 16\%, P_T \simeq 85\%$

○ **Spectrometer**
  - Two stages
    each with HCalorimeter and $\mu$-filter
  - RICH: in stage 1
  - ECalorimeters(1&2): since 2008
Double Spin Asymmetry Measurement

- **Simultaneous** recording of the two spin states in oppositely polarised target cells.

  - 2 cells: $1/2 \uparrow 1/2 \downarrow \iff 8 \text{ hours} \implies 1/2 \downarrow 1/2 \uparrow$
  - 3 cells: $1/3 \uparrow 2/3 \downarrow 1/3 \uparrow \iff 24 \text{ hours} \implies 1/3 \downarrow 2/3 \uparrow 1/3 \downarrow$

  - Reversal by **target-field** rotation to cancel acceptance diff

$$\frac{A\parallel}{D} = \frac{1}{|P_\mu P_T| f D} \frac{1}{2} \left( \frac{N^{\uparrow\downarrow}}{N^{\uparrow\downarrow}} - \frac{N^{\uparrow\uparrow}}{N^{\uparrow\uparrow}} + \frac{N^{\uparrow\downarrow}}{N^{\uparrow\downarrow}} - \frac{N^{\uparrow\uparrow}}{N^{\uparrow\uparrow}} \right)$$

  - $D = \text{Depolarisation factor}$

\[ \begin{align*}
  & LiD: \quad P_\mu \times D \times P_T \times f \approx 80\% \times 60\% \times 50\% \times 40\% \approx 10\% \\
  & NH_3: \quad \ldots \quad P_T \times f \approx \ldots \quad 85\% \times 16\% \approx 6\%
\end{align*} \]

- Reversal via re-polarisation once per year to cancel **target-field**/acceptance correlation

- $f$ corrected for spin-independent radiative processes: TERAD

- $A_1 \approx A\parallel / D$ corrected for spin-dependent radiative processes: POLRAD
Method of extraction

- \( g^{p,d}_{1}(x, Q^2) \) is extracted as:

\[
g^{p,d}_{1}(x, Q^2) = A^{p,d}_{1}(x, Q^2) \frac{F^{p,d}_{2}(x, Q^2)}{2x(1 + R(x, Q^2))}
\]

- Input \( F^{p,d}_{2}(x, Q^2) \): from NMC parametrisation at \( Q^2 > 0.2 \text{ GeV}^2 \) \( (PRD 58 (1998) 112001) \)
  at \( Q^2 < 0.2 \text{ GeV}^2 \): from the model based on the GVMD concept \( (PLB 295 (1992) 263) \)

- \( R(x, Q^2) \): R1998 from SLAC \( (PLB 452 (1999) 194) \)
  suitably extended to low \( Q^2 \), \( (PLB 647 (2007) 330) \)

- Maximum systematic uncertainties on \( A_{1} \)
  - At low \( Q^2 \): from \( D(R) \), \( \sim (0.01 - 0.39)D \) (mult.)
    and false asymm., \( 1.5\sigma_{\text{stat.}} \) (additive)
  - At high \( Q^2 \): from \( P_B, P_T \), \( \sim 0.05 P_B, P_T \) (mult.)
    and false asymm., \( < 0.8\sigma_{\text{stat.}} \) (additive)
\(g_1^d\) at low \(Q^2\)


- More than ten-fold improvement over SMC

- Consistent with 0 for \(5 \times 10^{-5} < x \lesssim 3 \times 10^{-2}\)

- Tend to indicate that \(\Delta G\) is small. Would then rule out large \(\Delta G\) solution to the spin crisis,

\[
\Sigma = \Sigma_{naiveQM} - N_f \alpha_S(Q^2)/2\pi \Delta G(Q^2)
\]

(see e.g. A. Thomas, Int. J. Mod. Phys. E 18 (2009))
$g_1^p$ at low $Q^2$

- Kinematic coverage:

\begin{align*}
(Q^2, x) & \\
(x, Q^2) & \\
(Q^2, \nu) & \\
(\nu, x) &
\end{align*}
$g_1^p$ at low $Q^2$: data sample

- **Reconstructed event**: Small scattering angle
  - ⇒ No way to be strictly inclusive and stay within polarised target cells
  - ⇒ Require one extra outgoing charged particle
  - Doesn’t bias asymmetry at low $x$ (see [SMC Coll., Phys. Rev. D 58 (1998) 112001])

- **Kinematic cuts**
  - $x > 4 \times 10^{-5}$ (at smaller $x$ uncertainties become too large)
  - $0.1 < y < 0.9$ (bad reconstruction @ low $y$, large rad. corr. at high $y$)
  - Above cuts result in: $W \gtrsim 5$ GeV

- Removed $\mu e \rightarrow \mu e$ events, around $x = m_e/M_p = 5.45 \times 10^{-4}$

- Final sample: 447 Mevnts @ 160 GeV + 229 Mevents @ 200 GeV
  - $\sim 150 \times$ SMC statistics
Low $Q^2$: results on $A_{1}^{p}(x, Q^2)$

- More than ten-fold improvement over the statistical precision of SMC.
- Clear spin effects at low $x$ and $Q^2$
Low $Q^2$: results on $A_{1}^{p}(x, Q^2)$
Importance of $g_1^p$ at low $x$, $Q^2$: results on $A_{1}^{p}(x, Q^2)$

- At low $x$: strong increase of parton density with decreasing $x$
  $\Rightarrow$ parton recombination effects

- **BUT**: in fixed-target experiments low $x$ correlated with low $Q^2$ region
  $\Rightarrow$ non-perturbative effects must be considered

- Attempts to describe that region phenomenologically:

- $g_1$ at low $Q^2$ needed for Radiative Corrections
$g_1^p$ at high $Q^2$: data samples

- Complementing earlier data at $E = 160$ GeV: (PLB 690 (2010) 466)

Reaching lower $x$ and higher $Q^2$

- Results on $A_1^p$ at both energies agree well
Results on $A_1^p$ and $g_1^p$

- $A_1^p$ and $g_1^p$ shown at the measured values of $Q^2$

- Good agreement with world data

- $g_1^p$ clearly positive at lowest measured values of $x$
$g_1^d$ at high $Q^2$: data samples

- Combined data, all @ 160 GeV: Phys. Lett. B 769 (2017) 34

- Results on $A_1^d$ agree very well
Results on $A_{1}^{d}$ and $g_{1}^{d}$

- $A_{1}^{d}$ and $g_{1}^{d}$ shown at the measured values

- Good agreement of $A_{1}^{d}$ and $g_{1}^{d}$ with world data

- $g_{1}^{d}$ compatible with zero at lowest measured values of $x$,
  contrary to hints from SMC
NLO QCD fit: conditions

- A fit of the $g_p^1$, $g_d^1$, $g_{3\text{He}}^1$ inclusive data
- $\overline{\text{MS}}$ scheme
- $W^2 < 10 \text{ GeV}^2$ excluded
- Number of data points total/COMPASS: 495/138
- Fitted: $\Delta g$, $\Delta q_0 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$, $\Delta q_3 = \Delta(u+\bar{u}) - \Delta(d+\bar{d})$, $\Delta q_8 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) - 2\Delta(s+\bar{s})$, $\Delta f_k(x) = \eta_k \frac{x^\alpha_k (1-x)^\beta_k (1+\gamma_k x)}{\int_0^1 x^\alpha_k (1-x)^\beta_k (1+\gamma_k x) \, dx}, \quad (k = 0, 3, 8, g)$
- Positivity required at every iteration: $|\Delta q + \bar{q}(x)| \leq |q + \bar{q}(x)|, |\Delta g(x)| \leq |g(x)|$ at $Q^0$
- Systematics: free/fix $\gamma_k$'s, vary $Q^0$
**NLO QCD fit: results**

- Statistical uncertainties (dark bands) $\ll$ systematic (light bands)
- Gluon polarisation poorly constraint $\Rightarrow$ Need “direct” methods
- Quark spin contribution to the nucleon spin: $0.26 < \Delta \Sigma < 0.36$ (due to poor $\Delta G$)
First moments of $g_1$ and singlet axial charge $a_0$

- First moments $\Gamma_1^p$, $\Gamma_1^d$, $\Gamma_1^N$
  
  where $\Gamma_1^i(Q^2) = \int_0^1 g_1^i(x, Q^2) \, dx$

- In particular:
  
  $$\Gamma_1^N(Q^2) = 1/36 \left[ 4a_0 \, C_S(Q^2) + a_8 \, C_{NS}(Q^2) \right]$$

  
  $$= \int_0^1 \frac{g_1^d(x, Q^2)}{1 - 1.5\omega_D} \, dx$$

- In the $\overline{\text{MS}}$: $a_0 = \Delta \Sigma = \Delta(u + \bar{u}) + \Delta(d + \bar{d}) + \Delta(s + \bar{s})$

- From COMPASS data alone:
  
  $$\Gamma_1^N(Q^2 = 3\text{GeV}^2) = 0.046 \pm 0.002_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.005_{\text{evol.}}$$

- From COMPASS data alone (and still $a_8$ from Phys. Rev. D 82 (2010)):
  
  $$a_0(Q^2 = 3\text{GeV}^2) = 0.32 \pm 0.02_{\text{stat.}} \pm 0.04_{\text{syst.}} \pm 0.05_{\text{evol.}}$$

  (consistent with value from the COMPASS NLO QCD fit of world data).
First moments of $g_{1}^{NS}$ and Bjorken sum rule

- Non-singlet structure function:
  \[ g_{1}^{NS} = g_{1}^{p}(x, Q^{2}) - g_{1}^{n}(x, Q^{2}) \]

- Bjorken sum rule:
  \[ \Gamma_{1}^{NS}(Q^{2}) = \frac{1}{6} \left| \frac{g_{A}}{g_{V}} \right| C_{1}^{NS}(Q^{2}) \]

- $g_{1}^{NS}$ calculated, NLO QCD fitted (only $\Delta q_{3}$), evolved to $Q^{2} = 3\text{GeV}^{2}$ and fit-extrapolated $x \rightarrow 0, 1$:
  \[ \Gamma_{1}^{NS}(Q^{2}) = 0.192 \pm 0.007_{\text{stat.}} \pm 0.015_{\text{syst.}} \]
  \[ \left| \frac{g_{A}}{g_{V}} \right| = 1.29 \pm 0.05_{\text{stat.}} \pm 0.10_{\text{syst.}} \]

- Neutron $\beta$ decay gives: $|g_{A}/g_{V}| = 1.2701 \pm 0.002$

  PDG, PRD86 (2012) 010001

- This validates the Bjorken sum rule with an accuracy of 9%
Δg: “direct” measurement


- Δg accessed via PGF

- Double spin asymmetries of single inclusive hadron in DIS over a wide range in $p_T$, $0.05 < p_T < 2.5$ GeV/c

- LO order interpretation:
  - Hadron level $→$ parton level via LEPTO Monte Carlo
  - 1.6 gain in statistical and systematics precision
  - $Δg/g = 0.113 \pm 0.038_{\text{stat.}} \pm 0.035_{\text{syst.}}, \langle Q^2 \rangle = 3\text{GeV}^2, \langle x_g \rangle = 0.10$
\[ \Delta g: \text{“direct” measurement (cont’d)} \]

- LO “direct” measurement, here in 3 \( x_g \) bins, compared to NLO QCD fit

(Note: 1st and 2nd bin are correlated.)

\[ \Rightarrow \text{Illustrates the potential of “direct” asymmetry data.} \]

(But cannot be included in NLO fit.)
**Δg: “direct” measurement @ low $Q^2$**

  Double Spin asymmetry of single inclusive hadron @ $Q^2 < 1$ GeV$^2$

- Extra resolved subprocesses contribute: $gg, qg$ . . .


- New calculation with resummation of large logarithms:

  ⇒ Reasonable agreement with pPDF = DSSV2014 and FF = DSS14($\pi$)+DSS17($K$)
Conclusions

- COMPASS legacy on $g_1^p(x, Q^2)$ and $g_1^d(x, Q^2)$ presented for DIS and nonperturbative regions
  - $g_1^p$ at low $x$ and low $Q^2$ is clearly positive ($g_1^d$ is consistent with zero)
    - First observation of the spin effect at such low $x$
  - $g_1^d \approx 0$ also at $Q^2 > 1 \text{ GeV}^2$

- From the COMPASS data alone:
  - First moments determined and Bjorken sum rule verified to 9 %

- NLO QCD fit of $g_1$ world data gave well constrained quark distributions.
  - Quark helicity contribution to nucleon spin: $0.26 < \Delta \Sigma < 0.36$

- “Direct” $\Delta g$ measurement
  - In DIS, LO extraction: $\Delta g/g = 0.113 \pm 0.038_{\text{stat.}} \pm 0.035_{\text{syst.}}, \langle Q^2 \rangle = 3 \text{ GeV}^2, \langle x_g \rangle = 0.10$
  - At low $Q^2$, rich asymmetry data, consistent with DSSV2014
Spares
NLO+resummation with pPDF = DSSV2014 and FF = DSS14(\(\pi\))+DSS17(\(K\))

Still tension for \(h^+\) off \(p\), despite resummation of resolved processes.

Improvement for \(h^-\) off \(p\) thanks to DSS14
NLO+resummation with FF = DSS14(\(\pi\))+DSS17(\(K\))

\(\eta \in [-0.1, 0.45]\)  \(\eta \in [0.45, 0.9]\)  \(\eta \in [0.9, 2.4]\)

\(A_{LL}^d\)}

- \(p_T\) (GeV)