COMPASS results on nucleon spin and structure

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- Nucleon longitudinal & transverse spin
- Quark Fragmentation functions
- Generalized parton distributions
- $\pi$ induced Drell-Yan and J/Psi production
COMPASS at CERN

160-200 GeV polarized muon beam DIS pion beam: Drell-Yan
Long solid polarized targets, LH2 target & nuclear targets for DY

DIS kinematics
Nucleon spin - longitudinal

How is the nucleon spin distributed among its constituents?

\[ \text{Nucleon Spin} \quad \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]

\( \Delta \Sigma \): sum over u, d, s, \( \bar{u}, \bar{d}, \bar{s} \)
  
  can take non half-integer value:
  
  superposition of several spin states

\[ \Delta q = \vec{q} - \vec{\bar{q}} \]

Parton spin parallel or anti parallel to nucleon spin

\( \Delta \Sigma \) Today:

Precise world data on polarized DIS: \[ g_1 + SU_f(3) \quad a_0 = \Delta \Sigma \sim 0.3 \]

Quark spin contribution \sim 30%

Confirmed by results from Lattice QCD on \( \Delta \Sigma_{u,d,s} \)

Large experimental effort on:

- **\( \Delta G \) measurement**
  
  also because \( a_0 = \Delta \Sigma - n_f (\alpha_s/2\pi) \Delta G \) (AB scheme)

- **3D mapping of nucleon and constraining L**
  
  through DVCS and Hard Exclusive Meson Production

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QCD fits- World data on $g_1^p$ and $g_1^d$

Polarized Deep Inelastic Scattering
$\Rightarrow$ Nucleon spin structure functions $g_1$

$\Rightarrow g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_i(x)$ and $\Delta g(x)$

However $x$ and $Q^2$ coverage in DIS not yet sufficient for precise $\Delta g$
Need to use constraint from pp data (as in DSSV, NNPDF… fits)
NLO pQCD fit to $g_1$ DIS world data

- Assume functional forms for $\Delta \Sigma$, $\Delta G$ and $\Delta q^{NS}$
- Use DGLAP equations, relating $\Delta \Sigma$, $\Delta G$ evolutions.
- Fit $g_1^p$, $g_1^d$, $g_1^n$ DIS world data. ($SU_3$)
- Extract $\Delta \Sigma$ Quarks $\Delta G$ Gluons

$\Delta G$ not well constrained using DIS only

Obtain solutions with $\Delta G > 0$ and $\Delta G < 0$
Solution with $\Delta G > 0$ agrees with result from DSSV++ which uses RHIC pp data

$\Delta \Sigma$ well constrained in valence region
$\Delta \Sigma = 0.31 \pm 0.05$ at $Q^2 = 3$ (GeV/c)$^2$

Still large uncertainty coming from the bad knowledge of functional forms
Global fits to polarized PDFs (I)

Fits to world data, including $\vec{p}\vec{p}$ collider data. Many fitters. Some examples:

- Blue: DSSLV from DSSV14 w. replicas and MC average
- Green: NNPDFpol1.1

More realistic evaluation of uncertainties

Still some discrepancies in $\Delta s$ sign and in $\Delta d$ position of minimum

~ unknown $\Delta G$, below $x \sim 0.05$
Gluon helicity $\Delta G/G$ direct measurement

Photon Gluon Fusion

$\mu^- p \rightarrow \mu^+ h + h + X$

Phenomenology of $\mu^- p$ collisions leading to a photon gluon fusion process. The photon is produced from the $s$-channel gluon exchange, with the quark scattering $qg$ and the gluon scattering $gg$.

$Q^2 > 1 \text{(GeV/c)}^2$

Extraction at LO:

$\Delta g/g (x=0.1) = 0.11 \pm 0.04 \pm 0.04$

Solutions from COMPASS NLO QCD fit of $g_1$ world data (see before)

Results are in agreement with fits from NNPDF and DSSV++ using RHIC $\vec{p}p$ data, which gave:

$$\int_{0.05}^{0.2} \Delta g(x) dx \approx 0.20$$
Quark helicities from semi-inclusive DIS

\[ l \rightarrow p \rightarrow l \, h^{+/-} \, x \]

Outgoing hadron tags quark flavor (via quark fragmentation functions)

Flavour separation of quark helicities:

NB: The SIDIS extraction uses input of quark Fragmentation Functions, not that well determined yet, especially for the strange quark sector.
**COMPASS \( \pi \) and K multiplicities vs \( z \) in \((x,y)\) bins**

From unpolarized SIDIS data: \( \mu^+ p \rightarrow \mu^' \pi/K\ X \)

- More than 1200 points in total, various \( Q^2 \) staggered vertically for clarity
- Strong \( z \) dependance
- \( M(\pi^+) \sim M(\pi^-) \) and \( M(K^+) > M(K^-) \)
Kaons- Quark fragmentation functions from NLO fits

Extensive sets of SIDIS kaon data change significantly flavor decomposition of FFs (& PDFs)

Ex1: DEHSS-17 fit to quark FF, includes recent kaon SIDIS data.

\[ zD^K_s \]

\[ D^K_s \] smaller than in DSS-07

\[ D^K_U \] larger than in DSS-07

Also simultaneous/ iterative fits of PDFs & FFs:

Ex: Borsa, Sasso, Stratmann, PRD96 (2017)

& JAM20-sidis, PRD104 (2021) 016015

SIA + SIDIS data : strong preference for smaller strange to nonstrange PDF ratio, and enhanced DsK'

→worth revisiting \( \Delta s(x) \) extraction from SIDIS data

Ex:2: JAM18 w/wo SIDIS data

Combined fit of PDFs and FFs (prelim)

\[ zD^K_S \]

\[ D^K_S \] w/ SIDIS agrees with DEHSS

\[ D^K_S \] w/o SIDIS

\[ Q^2 = 1.7 \text{ GeV}^2 \]

COMPASS PLB 767 (2017) 133
Motivation: High $z$ region not studied so far
Most experimental and theoretical uncertainties cancel in ratio

Simple estimation at LO, proton target
with assumptions ($D_{\text{unf}}$ neglected...):
and assuming $s = \bar{s}$,
$\Rightarrow R_K$ lower bound driven by light quarks:

$$R_K = \frac{4\bar{u}D_{\text{fav}} + sD_{\text{str}}}{4uD_{\text{fav}} + \bar{s}D_{\text{str}}}.$$

For a proton target:
$$R_K > \frac{\bar{u}}{u}$$

For a deuteron target:
$$R_K > \frac{\bar{u} + \bar{d}}{u + d}$$

In contradiction with data:

$M(K^-)/M(K^+)$ ratio well below expectations at high $z$
M(K⁻)/ M(K⁺) Results vs missing mass $M_X$

High $z$ kaon $\rightarrow$ reduced phase space for other particles
Study missing mass behaviour

$M_X = \sqrt{M_p^2 + 2M_p v(1 - z) - Q^2(1 - z)^2}$

- $M(K^-)/ M(K^+)$ shows unexpected strong rise with $M_X$
- Suggests to take into account the available phase space for hadronisation, in the formalism
$R_p = \frac{M(\bar{p})}{M(p)}$

Stronger suppression of $\bar{p}$ vs $p$, compared to $K^-$ vs $K^+$. 

**Graph:**

- $R_p$ present analysis
- $R_K$ PLB 767 (2017) 133
- $R_K$ PLB 786 (2018) 390

**Legend:**

- ISOSCALAR TARGET

**Axes:**

- $R_p$
- $R_K$
- $z_{corr}$

**Note:**

PLB 807 (2020) 135600

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Transverse Momentum Dependent distributions (TMDs)

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin of the nucleon</td>
<td>number density ( f_1^{q,g}(x, k_T^2) )</td>
<td>Helicity ( g_{1L}^{q,g}(x, k_T^2) )</td>
<td>Transversity ( h_1^{q,g}(x, k_T^2) )</td>
</tr>
<tr>
<td>spin of the parton</td>
<td>Boer-Mulders ( h_1^{q,g}(x, k_T^2) )</td>
<td>worm-gear L ( h_{1L}^{q,g}(x, k_T^2) )</td>
<td>Pretzelosity ( h_{1T}^{q,g}(x, k_T^2) )</td>
</tr>
<tr>
<td>( k_T ) of the parton</td>
<td>Sivers ( f_1^{q,g}(x, k_T^2) )</td>
<td>Kotzinian-Mulders worm-gear ( \frac{1}{2} q^g(x, k_T^2) )</td>
<td></td>
</tr>
</tbody>
</table>

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Transverse Momentum Dependent distr. : TMDs

Importance of hadron transverse momentum $p_T$:

- $P_T$ dependence results from:
  - intrinsic $k_{\perp}$ of the quarks
  - $p_{\perp}$ generated in the quark fragmentation

Global analyses of SIDIS, Drell-Yan and $Z$ production data with TMD $Q^2$ evolution

SIDIS multiplicity (example)

Drell-Yan cross section

$Z$ production

Transverse momentum distribution

A. Bacchetta et al., JHEP06 (2017) 081
TMDs- Collins and Sivers functions (SIDIS)

• Access via SIDIS, transversely polarized target
  \[ \mu p^\uparrow \rightarrow \mu h^{+/−} X \]

• Measure simultaneously several azimuthal asymmetries, out of which:
  \[ \begin{align*}
  \text{Collins:} & \quad \text{Outgoing hadron direction & quark transverse spin} \\
  \text{Sivers:} & \quad \text{Nucleon spin & quark transverse momentum } k_T
  \end{align*} \]

at LO:

Collins quark transverse spin distr.

\[
A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot x \cdot h^{q}_{1} \otimes H_{1q}^\perp}{\sum_q e_q^2 \cdot x \cdot q \otimes D_{1q}^h}
\]

Collins TMD fragmentation function, depends on spin, and hadron \( p_T \)

Sivers

\[
A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^\perp \otimes D_{q}^h}{\sum_q e_q^2 \cdot q \otimes D_{q}^h}
\]

Unpolarized quark fragmentation function
TMDs, Collins asymmetry $\rightarrow$ Transversity $h_1$

- Large signal for proton target.
  (compatible with zero for deuteron target)
- Same signal strength seen by HERMES and COMPASS, although different $Q^2$ (times 4)

Several combined analyses of polarized SIDIS data
HERMES $p$, COMPASS $p$ and $d$, and BELLE FF

$h_1^u > 0$ and $h_1^d < 0$
Smaller than helicity

NB: asymmetries also measured for $\pi$ and $K$

HERMES PLB 693(2010)
COMPASS PLB 744 (2015)

Anselmino et al., PRD87(2013) 094019
TMDs, Sivers asymmetry $\rightarrow$ Sivers function

Correlation between Nucleon spin & quark transverse momentum $k_T$

Large signal with proton target.
Was measured compatible with zero on deuteron

Compared to COMPASS, HERMES (smaller $Q^2$) has larger signal

HERMES PRL 103 (2009)
COMPASS PLB 744 (2015)

Sivers function

$A_{Siv}^P$

$\pi^+$

$K^+$

Anselmino et al., JHEP04 (2017)046
TMDs Collins & Sivers. Recent global fits

Many global analyses of SIDIS, Drell-Yan, pp and e+e-. Great progress: theoretical developments, large data sets, uncertainty studies. JAM20, Etchevaria et al., Anselmino et al., Radici, Bacchetta, Kang et al., D’Alesio et al., Boglione et., Bury et al. ...

e.g.:
TMDs, Transversity $h_1$ / tensor charge

More data on deuteron needed
COMPASS projection for 2022 data, pol. 6LiD:

<table>
<thead>
<tr>
<th></th>
<th>$xh_1^{u,v}$</th>
<th>$xh_1^{d,v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>$\delta_u = \int_{\Omega_x} dx , h_1^{u,v}(x)$</td>
<td>$\delta_d = \int_{\Omega_x} dx , h_1^{d,v}(x)$</td>
</tr>
<tr>
<td>Present</td>
<td>$0.201 \pm 0.032$</td>
<td>$-0.189 \pm 0.108$</td>
</tr>
<tr>
<td>Projected</td>
<td>$0.201 \pm 0.019$</td>
<td>$-0.189 \pm 0.040$</td>
</tr>
</tbody>
</table>

With 2022 data, expect improvement on uncertainties by factors of: $\sim 2$ (u), $\sim 3$ (d)
TMDs, new approach: weighted asymmetries

SIDIS, target transverse spin

\[ A_{Siv}^{(p_T/zM)}(x, z) = \frac{2 \sum_q e_q^2 f_{1T}^{(1)}(x) \cdot D_1^q(z)}{\sum_q e_q^2 f_1(x) \cdot D_1^q(z)}, \]

\[ f_{1T}^{(1)}(x, Q^2) = \int d^2 k_T \frac{k_T^2}{2M^2} f_{1T}(x, k_T, Q^2). \]

\( \rightarrow \) extract first moment of Sivers
without assumption on \( k_T \) dependence

Sivers asymmetry, with weight \( p_T/zM \)
No more convolution of TMDs and FFs
but a product of integrals.

Point by point extraction using \( h^+ \) and \( h^- \) asym (NH3 target)
TMDs, Target spin-depenendent azimuthal asymmetries

Results on TMDs are characterised by an unprecedented precision, covering a wider kinematic range and many observables.

<table>
<thead>
<tr>
<th>Leading twist asymmetries</th>
<th>LO LSA/TSA</th>
<th>twist-2: PDF $\otimes$ FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{UL}^{\sin(2\phi_h)}$</td>
<td>$h_{1L}^{1} \otimes H_{1q}^{h}$</td>
<td></td>
</tr>
<tr>
<td>$A_{LL}$</td>
<td>$g_{1L}^{q} \otimes D_{1q}^{h}$</td>
<td>$g_1$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(\phi_h-\phi_S)}$</td>
<td>$f_{1T}^{\perp} \otimes D_{1q}^{h}$</td>
<td></td>
</tr>
<tr>
<td>$A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$</td>
<td>$h_{1}^{q} \otimes H_{1q}^{h}$</td>
<td></td>
</tr>
<tr>
<td>$A_{UT}^{\sin(3\phi_h-\phi_S)}$</td>
<td>$h_{1T}^{\perp} \otimes H_{1q}^{h}$</td>
<td></td>
</tr>
<tr>
<td>$A_{LT}^{\cos(\phi_h-\phi_S)}$</td>
<td>$g_{1T}^{q} \otimes D_{1q}^{h}$</td>
<td></td>
</tr>
</tbody>
</table>

Example $A_{UL}(x)$

Pretzelosity: (deviation of spin density from spherical shape)

Sivers

Collins

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TMDs, Sivers gluon

Sivers asymmetry: 
correlation between nucleon transverse spin & parton transverse momentum.

Measured in SIDIS with transversely polarized target, (already done for quarks), now for **gluons** from azimuthal asymmetry for PGF process

\[
A_{PGF}^{Siv, d} = -0.14 \pm 0.15\text{(stat.)} \pm 0.10\text{(syst.)} \\
\langle x_g \rangle = 0.13
\]

\[
A_{PGF}^{Siv, p} = -0.26 \pm 0.09\text{(stat.)} \pm 0.06\text{(syst.)} \\
\langle x_g \rangle = 0.15
\]

TMDs, $\rho^0$

$\rho^0$ COMPASS first Collins and Sivers measurement

A. Moretti SPIN21

$\rho^0$ Collins
positive asymmetry
opposite to $\pi^+$, as expected from models large at small $p_T$

$\rho^0$ Sivers
positive asymmetry, similarly to $\pi^+$, as expected
GPDs - Generalized Parton Distributions

Physics goals: 160 GeV $\mu$ beam $\mu \ p \rightarrow \mu' \ p \ \gamma$
- 3D mapping of nucleon
- access to Orbital Angular Momentum

Determine 4 GPDs: $H, E, H^\ast, E^\ast$ (Re and Im parts) via ‘exclusive’ processes: DVCS ($\gamma$) and DVMP ($\rho, \omega, \phi$)

DVCS interferes with Bethe-Heitler process
$\rightarrow$ Can use interference terms or pure DVCS production with appropriate combinations of beam sign and polarization.

Way to it:
- Collect very large sample of data, for various observables and several kinematic variables
- Global analyses to extract 4x2 Compton Form Factors CFFs
- Deconvolutions to finally access GPDs.
DVCS- t-slope of Cross-section (COMPASS)

\[ \mu^+/\mu^- p \rightarrow \mu^- p \gamma \]

Measurement of proton transverse size vs \( x_B \)

\[ \sigma^{DVCS}/dt \sim \exp^{-B|t|} \]

\[ B(x_B) = \frac{1}{2} <r_{\perp}^2(x_B)> \]

Combining data from \( \mu^+ \) and \( \mu^- \) beams measure t-slope of DVCS cross section

\( \rightarrow x \) dependence of transverse size of the nucleon

New preliminary COMPASS result:

2016 data : prelim. result

3 x more stat. expected from 2017 data

See SPIN 2021, J. Giarra talk
Drell-Yan and J/ψ from π induced dimuon production

π N → μ⁺ μ⁻

190 GeV π beam

Drell-Yan: polarized NH₃ target → results on TMDs (SIDIS/DY sign change)
- W target → Lam-Tung relation study

J/ψ production: high statistics data:
- J/ψ TSA and cross-section analysis in progress
- study production mechanism, two processes:
  - q-qbar annihilation → quark TMDs
  - g g fusion → gluon TMDs
- search for J/ψ pairs
TMDs in polarized Drell-Yan

\[ \pi \text{ induced Drell-Yan on polarized NH}_3: \]

\[ \pi \text{ N} \rightarrow \mu^+ \mu^- \]

Sivers function:
- Non-vanishing orbital angular momentum
- Process dependence expected

Sign change between SIDIS and Drell-Yan
both measured in COMPASS
at similar hard scale

COMPASS, PRL 119 (2017) 112002
Preliminary results on Lam-Tung relation

$\pi$ induced Drell-Yan, W target. $\pi W \rightarrow \mu^+ \mu^-$

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[ 1 + \lambda \cos^2 \theta_{CS} + \mu \sin 2\theta_{CS} \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta_{CS} \cos 2\varphi_{CS} \right]$$ at LO

Lam-Tung violation quantity $2\nu - (1 - \lambda)$
Non zero cos $2\varphi$ dependence

Data deviate from pQCD calculation
→ Presence of non-zero TMD Boer-Mulders contribution

- Possible violation of Lam-Tung relation
- cos $2\varphi$ dependence
- Results compatible with previous data
J/ψ pair production in π –N collisions

Search for J/ψ pairs
Goals:
• investigate possible intrinsic charm
• search for T_{4c} states

2-J/ψ cross-section estimation for NH₃, Al and W targets:
(25, 4 and 21 events)

Result consistent with single parton scattering (SPS) mechanism:
q ¯q → 2 J/ψ
q g → 2 J/ψ

No sign of intrinsic charm d u c ċ c ċ ċ

See Qat 2021, A. Gridin talk
Summary –

Gluon and quark contribution to nucleon spin

Gluon $\Delta G/G=0.1$ at $x=0.1$ (photon gluon fusion process) agrees with RHIC $\int \Delta G \sim 0.2$

Unknown contribution at low $x$

Quarks: $\frac{1}{2} \Delta \Sigma \sim 0.15$ from global QCD fit of $g_1$ world data; agrees with Lattice QCD

Flavor decomposition from SIDIS, down to $x \sim 0.004$.

Quark Fragmentation functions:

High $z$ data for $K^-/K^+$ and $\bar{p}/p$ hadron multiplicity ratios

- Data disagree with current NLO QCD calculations at high $z$ and low $\nu$
- Unexpected rise of ratio $M(K^+)/M(K^-)$ with missing mass, suggesting to take into account the available phase space for hadronisation in formalism.

Transverse Momentum Dependent parton distributions

Extensive and precise results on all azimuthal asymmetries

Global analyses

GPDs via DVCS: $b$ slope prelim. result

Many data coming and promising framework for global analyses.

Polarized Drell-Yan First ever measurement → Sivers asymmetry (sign change vs SIDIS)

Angular distributions: TMDs, Lam-Tung relation…