New experimental results on the (spin) structure of the nucleon

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Disclaimer:

I did not try to be exhaustive in this talk. I made a (personal) selection of new/recent results, instead.

Most plots, graphs, diagrams, etc were taken from your talks (thank you)
An artist's impression of the mayhem of quarks and gluons inside the proton. Credit: D Dominguez/CERN.

Understanding the proton...

i.e. understanding the matter we are made of

...means (also) understanding the spin-momentum correlations in place

The spin crisis of the ‘80s (EMC@CERN result: $\Delta \Sigma << 1$) turned into a spin puzzle

**Proton spin:** $\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{q,g}$

- 3 decades of experimental efforts to measure each
- Key to “solving” QCD
A variety of **universal objects**, that relate to each other in a non-trivial way:

- PDFs
- Generalized PDFs
- Fragmentation Functions
- Distribution Amplitudes
- Form Factors
- TMD PDFs
- GPDs
- ...
3 collinear quark PDFs used to describe the proton and its dependences ($x$, $Q^2$):
- Unpolarized
- Helicity
- Transversity

If considering also transverse motion, 8 quark TMD PDFs are needed to describe the proton ($x$, $k_T$, $Q^2$):

Also 8 gluon TMD PDFs to be considered:

F. Celiberto talk, Wednesday, QCD & Spin
The nucleon structure functions ratio $F_2^n/F_2^p$ is important input to access at large $x$-Bjorken to $d/u$ ratio:

DIS experiment: 10 GeV electrons off $^3$He and $^3$H targets
Light sea asymmetry in the proton

SeaQuest: 120 GeV proton-induced Drell-Yan on H and D targets.

Including SeaQuest Drell-Yan and STAR data on $W^+/W^-$ production ratio to the global fits significantly constrains the sea pdfs

CJ15, arXiv:2108.05786
Strangeness content in the proton

\[ R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}} \]

ATLAS global fit results, including also HERA DIS data.

From $W^\pm$ and $Z$ boson production in association with jets

Strange-quark content similar in size to u- and d- sea quark ones at $x < 0.02$

contrary to expectations (driven by neutrino-induced DIS results)
Longitudinal double spin asymmetries

Helicity

Small-x evolution equations allow to “predict” the behaviour of the $g_1$ structure function and the helicity PDFs of the proton in the $x \to 0$ limit.

With the future EIC data, this approach will greatly constrain $g_1$ and helicity distributions.

JAMsmallx, arXiv:2102.06159
Longitudinal double spin asymmetries

Inclusive jet and dijet data: sensitivity to the gluon helicity in $0.05 < x_g < 0.5$

These results provide further evidence that $\Delta g(x,Q^2)$ is positive for $x_g > 0.05$

arXiv:2103.05571
In COMPASS the Collins angle is: \( \Phi = \phi_h + \phi_s - \pi \)

3D analysis newly available from HERMES.

Agreement between experiments, except for \( K^-(?) \)
Collins asymmetry at RHIC: $p^+ + p \rightarrow h + X$

Hard scale given by $p_{Th}$. Collinear twist-3 factorization applies. Spin effects arising from interference of multiparton states.

Only sensitive to final state effects – seen to be small
Extraction of the transversity function

In SIDIS it comes convoluted with the Collins FF.

Extraction from global analyses (SIDIS, DY, pp, e⁺e⁻)

The Collins-modulation in SIDIS cross-section for proton and deuteron targets and π⁺ and π⁻ also allows to access a simple ratio of valence quark transversity functions:

\[ R_{C,d/p} = \frac{\sigma_{C,d}^+ - \sigma_{C,d}^-}{\sigma_{C,p}^+ - \sigma_{C,p}^-} = \frac{3}{4} \frac{h_{1uv}^u + h_{1dv}^d}{h_{1uv}^u - h_{1dv}^d} \]

From the ratio of difference Collins asymmetries between π⁺ and π⁻ obtained from deuteron and proton targets one can access independently from the Collins FF.


M. Anselmino et al, PRD 102,096012 (2020)
Sivers asymmetry and $A_T$ in polarized hadronic collisions

In $\pi$-induced Drell-Yan $A_T \sin(\phi_S)$ is proportional to $f_{1\pi} \otimes f_{1\perp p}$

The small TSSA of EM-jets as compared to that of $\pi^0$ seems to indicate that the Sivers effect is not the dominant source of $\pi^0$ TSSA.
Universality of the Sivers TMD PDF
A test of the TMD approach

- Sivers function: non-vanishing orbital angular momentum
- Process dependence: $f_{1T}^{\perp} (\text{SIDIS}) = - f_{1T}^{\perp} (\text{DY})$

NEW

Oleg Eyser talk
Sunday, Spin&QCD

Extraction of the quark Sivers functions

SIDIS + Drell-Yan + $W^\pm/Z$ and inclusive jet data in pp

Impact of inclusive jet data from STAR in constraining the first $k_T$ moment of quark Sivers.

- QCD evolution modifies the shape and size of the Sivers function.
- Sivers function is 4-5 times smaller than the unpolarized TMD.
At midrapidities and low $p_T$, also $\pi^0$ production is believed to be mainly sensitive to gluon Sivers.

Sivers two-hadron asymmetry from a PGF-enriched sample

PRD 98 (2018) 1, 012006

ARXIV:2102.13585

PRD 103 (2021) 052009

PLB 772 (2017) 854

Milap Patel talk
Sunday, Spin&QCD

Hint for non-zero gluon Sivers, and thus gluon orbital angular momentum
Sensitivity to the Boer-Mulders function

In $\pi$-induced Drell-Yan (unpolarized):

At LO: $\lambda=1$ and $\mu, \nu=0$

At NLO: Lam-Tung relation $1-\lambda=2\nu$

At NNLO: Lam-Tung violated, but $1-\lambda-2\nu>0$

$\pi$-induced Drell-Yan indicates instead that $1-\lambda-2\nu<0$!

Hint for Boer-Mulders

April Townsend talk Sunday, Spin&QCD
Exclusive measurements, like Deeply virtual Compton Scattering and Hard Exclusive Meson Production give access to the GPDs that describe quark and gluon dynamics inside the nucleon:

- 4 chiral-even GPDs (conserve parton helicity): $H$, $E$, $\tilde{H}$, $\tilde{E}$
- 4 chiral-odd GPDs (parton helicity flip): $H_T$, $E_T$, $\tilde{H}_T$, $\tilde{E}_T$

Experimentally, one accesses GPDs via the Compton Form Factors:

$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\varepsilon}$$

From the azimuthal dependences/asymmetries in DVCS, having both beam charges and polarizations available, and (un)polarized targets, one can access the different GPDs.
Transverse extension of partons in the proton

PLB 793 (2019) 188

\[
\frac{d\sigma}{dx} \propto \frac{1}{y} \frac{1}{Q^2} e^{-x_B}
\]

\[
\langle r_T^2(x_BJ) \rangle \approx 2B(x_BJ)
\]

Jefferson Lab

Flavor separation of Helicity conserved CFFs


JLab Hall-A n & p DVCS

Pioneering measurements from HERMES

DOI: 10.1051/epjconf/20147302014
GPDs from TCS on the proton

Timelike Compton Scattering: the time-reversal symmetric of DVCS.

Measured now for the first time, at CLAS12 (JLab Hall-B), with quasi-real photon beam on unpolarized proton target.

Forward-backward asymmetry:

\[ A_{FB} \propto \text{Re}(\mathcal{H}) \]

This \( A_{FB} \) arises from the interference between the 2 processes, and would be =0 if there was only BH.
GPDs and HEMP

Full angular analysis of the exclusively produced $\rho$ and $\omega$

Decomposition in terms of spin density matrix elements
- 15 unpolarized SDMEs
- 8 polarized SDMEs

In COMPASS
- unpolarized HEMP, $\rho$: probing mostly GPDs $E$ and $H$;
- $\omega$: probing also GPDs $\tilde{H}$ and $\tilde{E}$

$\mu \, p \rightarrow \mu \, \pi^0 \, p$
Sensitivity to $E_T = 2\tilde{H}_T + E_T$

Po-Ju Lin talk
Sunday, Spin&QCD
Fragmentation functions

- **FFs** encode the probability that a quark or gluon converts to a hadron that carries a fraction \( z \) of the parton’s momentum \( D_q^h (z, Q^2) \)

- Single-hadron FFs and di-hadron FFs

- **TMD FFs** are the counterpart of TMD PDFs, for the final state

- At hadron colliders we also talk about jetFFs

- TMD FFs can be measured in (un)polarized SIDIS and \( e^+e^- \) collisions

- **pp collisions** data to access gluon FF
$p_T$ dependent hadron production cross-sections in $e^+e^-$

Sensitivity to (TMD) fragmentation functions

The low-$p_T$ part of cross-section is well described by Gaussian.

The Gaussian widths as function of fractional energy $z$ are important input for TMD FFs extraction.
Azimuthal asymmetries of back-to-back hadron pairs: $\pi^\pm, \pi^0, \eta$.

$\eta$: sensitivity also to the fragmentation of strange quarks.

PRD 100, 092008 (2019)

JAM20, PRD 102, 054002 (2020)

(does not include the above data)
Disagreement in polarized vs unpolarized techniques could be due to two-photon exchange contributions.

\[ \sigma_{BB}^{\text{Born}}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2} \left[ |G_M(q^2)|^2 + \frac{1}{2\pi} |G_E(q^2)|^2 \right] \]

OLYMPUS @ DESY: Elastic e^+e^- scattering

Free from TPE

PRL 124, 042001 (2020)

e^+e^- → n\bar{n}

ArXiv:2103.12486

PRL 126, 162501 (2021)

 Axel Schmidt talk
 Sunday, Spin&QCD
Past, present and future
Spin physics experiments

Alexey Guskov talk
Wednesday, Spin&QCD

arXiv:2102.00442

Bernd Surrow talk
Today, Plenary

arXiv:1212.1701

PRD 93 (2016) 114034

GPDs

Pasquale di Nezza talk
Wednesday, Spin&QCD

arXiv:1901.08002
Other experimental trends

Understanding the proton structure is closely related to understanding the mechanism by which protons (and hadrons in general) acquire mass.

Dynamic Chiral Symmetry Breaking in QCD is key to understand the phenomenom of Emergence of hadron mass.

The high precision reached in our knowledge of proton structure needs to be followed by an improved knowledge on meson structure.

π and K induced Drell-Yan

Sullivan process

π and K induced Drell-Yan

AMBER @ CERN

JLab12

EIC
Thank you!