Introduction to spin physics

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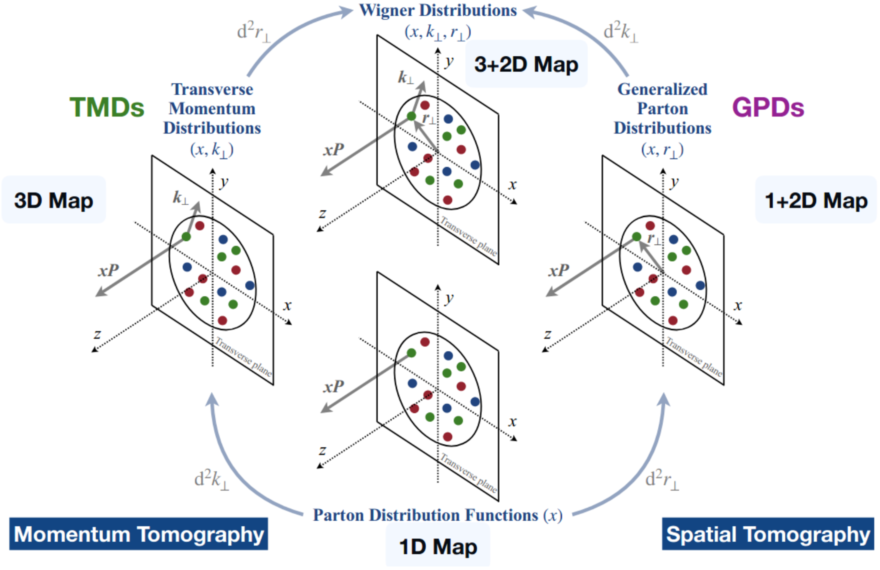
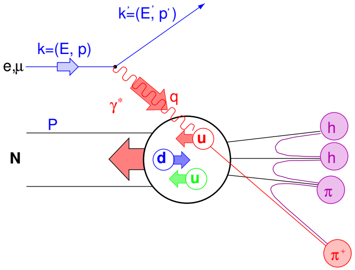
Epiphany2023

Cracow, 16 – 19 January, 2023

Nucleon partonic structure (courtesy of Yu-Hsiang Lien, COMPASS)



Nucleon spin structure in DIS: $\mu + \mathrm{N} \rightarrow \mu' + \mathrm{X}$

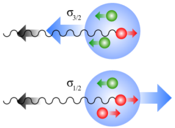


- $\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \dfrac{\alpha^2}{2Mq^4}\dfrac{E'}{E} L_{\mu\nu}W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}, \;\; q(x,Q^2) \longrightarrow g_{1,2}, \;\; \Delta q(x,Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, but...
- ...anomalous gluon contribution to $g_1(x,Q^2)$
- ...$g_2(x,Q^2)$ has no interpretation in terms of partons.

Definitions of DIS variables...

$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

...and of the γ^*-N asymmetry (e.g. for γ^*-p):



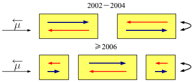
$$A_1(x,Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Observables

- Inclusive asymmetry, $A_{meas}(x,Q^2)$, γ^*-N asymmetry, $A_1(x,Q^2)$, and $g_1(x,Q^2)$:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} \overset{\mathrm{LO}}{=} D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

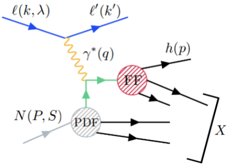
f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations;
$N^{\leftrightarrows,\leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell:
(upstream, downstream) or (outer, central)



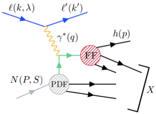
- Semi–inclusive asymmetry, $A_1^h(x,z,Q^2)$, at LO:

$$A_1^h(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}, \qquad z = \frac{E_h}{\nu}$$

$$D_q^h \neq D_{\bar{q}}^h$$



THE 18 SIDIS STRUCTURE FUNCTIONS



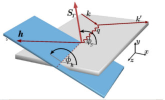
Unpolarized structure function

$f_1 \otimes D_1$

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} &= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

Sivers structure function

$f_{1T}^{\perp} \otimes D_1$

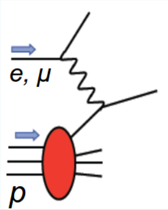


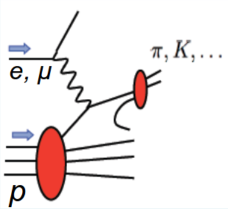
Collins structure function

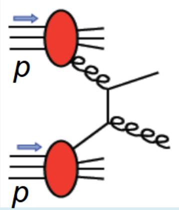
$h_1 \otimes H_1^{\perp}$

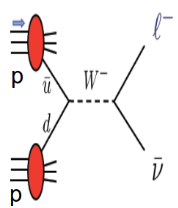
Slide courtesy A. Bacchetta, IWHSS2022 (with changes)

Processes available for parton (helicity) distributions









DIS:

$\Delta q + \Delta\bar{q}$

Δg (From Q^2 evolution of g_1)

SIDIS:

$\Delta q, \Delta\bar{q}$

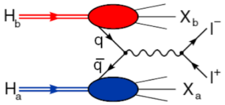
Δg

pp:

$\Delta q, \Delta\bar{q}$

Δg

A. Bazilevsky, SPIN2016



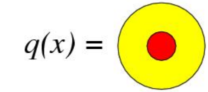
JLab
(HERMES@HERA)
COMPASS@CERN

STAR@RHIC
PHENIX@RHIC
LHC/Spin
$\Longrightarrow$ talk by P.Di Nezza

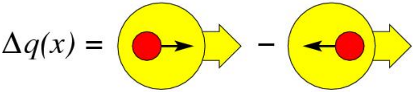
Drell-Yan process, complementary to SIDIS; COMPASS, FNAL, STAR, PHENIX

Partonic structure of the nucleon; distribution functions

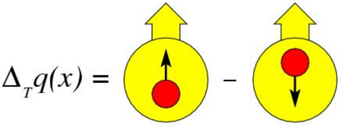
Three twist-two quark distributions in QCD and after integrating over the quark intrinsic k_t



Quark momentum DF;
well known (unpolarised DIS $\rightarrow \mathbf{F_{1,2}(x, Q^2)}$).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow \mathbf{g_1(x, Q^2)}$).
$\Longrightarrow$ talk by M. Żurek



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

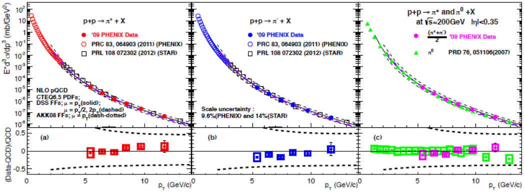
Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd

If the k_t taken into account $\Longrightarrow$ 8 TMD distr.; e.g. $f_{1T}^{\perp}$ (accessible through "Sivers asymmetry").

Transverse Single Spin asymmetry (SSA) in pp$\to \pi$ X

mid-rapidity RHIC data, unpolarised cross sections
(arXiv:1409.1907 [hep-ex], Phys. Rev. D91 (2015) 3, 032001)

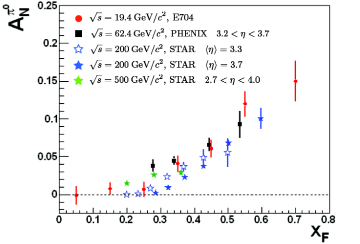
large P_T single pion production $p\,p \to \pi\,X$



good agreement between RHIC data
and collinear pQCD calculations

BUT for ⊥ polarised p

A_N large and persistent at high energies ....



...but QCD at quark level: $A_N \sim \dfrac{m_q}{E_q}\,\alpha_s$

Many other spin effects @ high energies
cannot be understood in the collinear QCD...

From M. Anselmino, Bad Honnef School, 2017

1987: European Muon Collaboration at CERN:

J. Ashman et al., Phys. Lett. B **206** (1988) 364

J. Ashman et al., Nucl. Phys. B **328** (1989) 1

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta \mathrm{G}(\mu) + \mathrm{L_q}(\mu) + \mathrm{L_g}(\mu)$$ **Jaffe–Manohar**

$$\Delta\Sigma(Q^2) = \int_0^1 \mathrm{d}x \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x, Q^2), \qquad \Delta G(Q^2) = \int_0^1 \mathrm{d}x \Delta g(x, Q^2)$$

(with $\int_0^1 \mathrm{d}x\,[\Delta s + \Delta\bar{s}] < 0$)

EMC measured: $\Delta\Sigma \sim 0.1!$ and broken Ellis-Jaffe sum rule

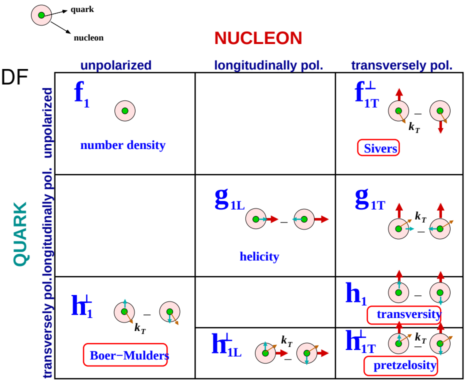
papers cited **4099** times (2 XII 2022)

Nucleon in 3-D

(two approaches)

Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T},
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  with different angular modulations
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$



- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.

talks by V.Bertone, A.Bressan

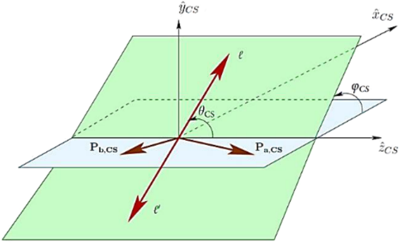
- TMD parton distributions need TMD Fragmentation Functions!

SIDIS and Drell-Yan compatibility

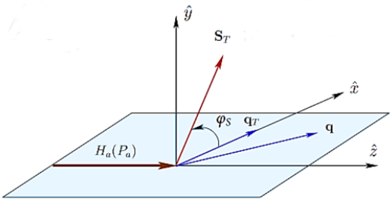
$$A_{SIDIS} \propto \color{red}{PDF_p} \color{black}{\otimes FF} \qquad \Big| \qquad A_{DY} \propto PDF_\pi \otimes \color{red}{PDF_p}$$

SIDIS		DY
$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	**Boer-Mulders** ⟷	$A_{U}^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$	**Sivers** ⟷	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$	**Pretzelosity** ⟷	$A_{T}^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$	**Transversity** ⟷	$A_{T}^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

(courtesy of R. Longo, COMPASS)

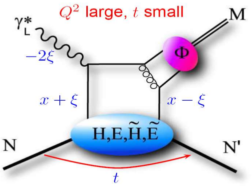


Collins-Soper ref. frame (CS)



Target rest frame (S)

Generalised Parton Distributions



- Accessible via DVCS/DVMP: $\mu p \rightarrow \mu p \gamma(M)$
- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons

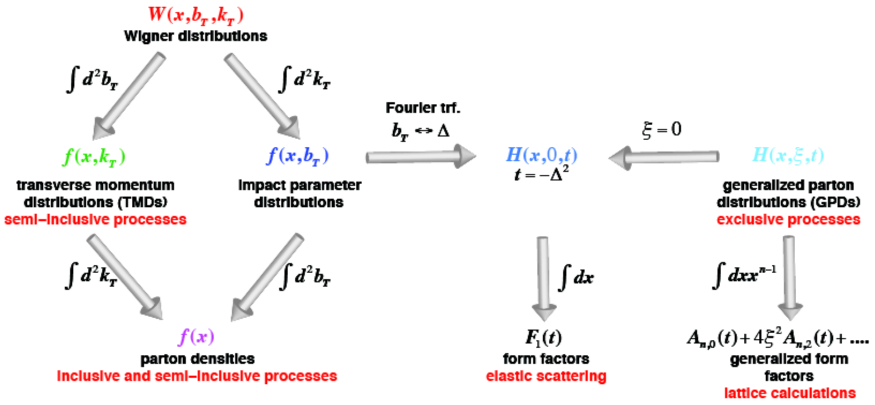
  plus 4 chiral odd ones $(H_T, E_T, \widetilde{H}_T, \widetilde{E}_T)$
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$;
  Careful ! Here $x \neq x_B$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x, 0, 0) = q(x), \quad \widetilde{H}^q(x, 0, 0) = \Delta q(x)$

Important:

$$J_z^q = \frac{1}{2} \int dx\, x \left[H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)\right] = \frac{1}{2}\Delta\Sigma + L_z^q \quad \text{(X. Ji)}$$

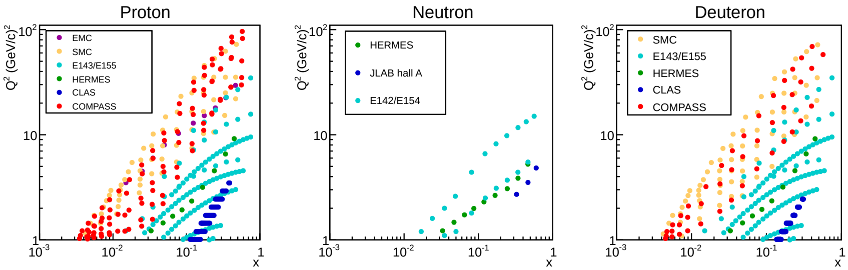
$\Longrightarrow$talks by J.Wagner, F.Kunne, K.Cichy (lattice)

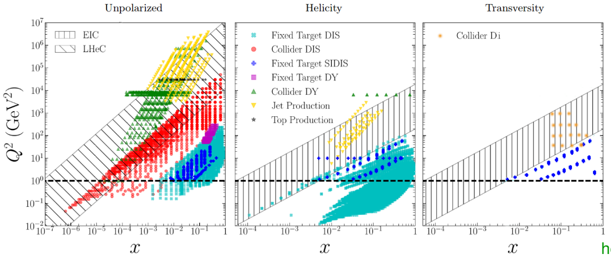
Descriptions of *pdf* ^{s} in the nucleon



From "White paper", arXiv:1212.1701

Map of present experimental results





hep-ph 2006.08636v2

The EIC perspective

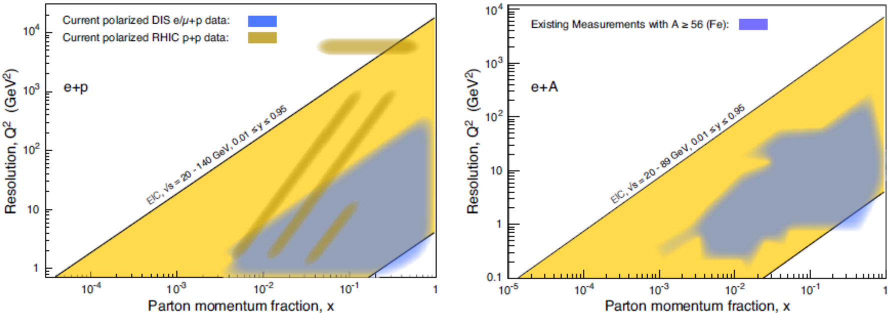


Figure 2.1: Left: The x-Q^2 range covered by the EIC (yellow) in comparison with past and existing polarized $e/\mu+p$ experiments at CERN, DESY, JLab and SLAC, and $p+p$ experiments at RHIC. Right: The x-Q^2 range for e+A collisions for ions larger than iron (yellow) compared to existing world data.

Nucl. Phys. A 1026 (2022) 122447

OPEN QUESTIONS

to be addressed in the near/LHC-Spin/EIC❥ future

(originally formulated with Umberto D'Alesio
at the "2022 Diffraction and Low x" workshop)

- ❥Spin as a goal (nucleon spin structure) and as a tool (fundamental properties of QCD);
- ❥Three fundamental electromagnetic interactions: SIDIS, DY, $e^+e^- \to h_1\ h_2\ X$:
  TMD factorization proven; azimuthal modulations to access separately all TMDs;
  test of factorisation, evolution and (modified) universality properties;
  - ❥SIDIS: (un)polarised TMDs; Sivers, Collins, Boer-Mulders;
  - DY: clear channels for TMD-PDFs; bridge DY $\Longleftrightarrow$ SIDIS;
    recent extractions unpolarised TMDs from a global fit on SIDIS and DY;
  - e^+e^-: clear channel for TMD Fragmentation Functions;
    universality of TMDs; spontaneous Λ polarisations;
    single and double hadron production; new advancements in TMD factorization;
- pp $\to$ h(jet) X; ep -> h(jet) X: complementary processes to learn on TMD-FFs
  and check their universality;
- pp $\to$ h X, pp $\to$ jet X, pp$\to \gamma$ X: twist-3 parton-hadron correlators
  and their relation with TMDs;
- ❥TMD factorisation: interplay of perturbative (calculable) and nonperturbative effects;
  matching low and high scales, improvements in Collins-Soper-Sterman formalism;