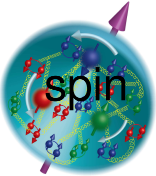
Introduction to spin physics



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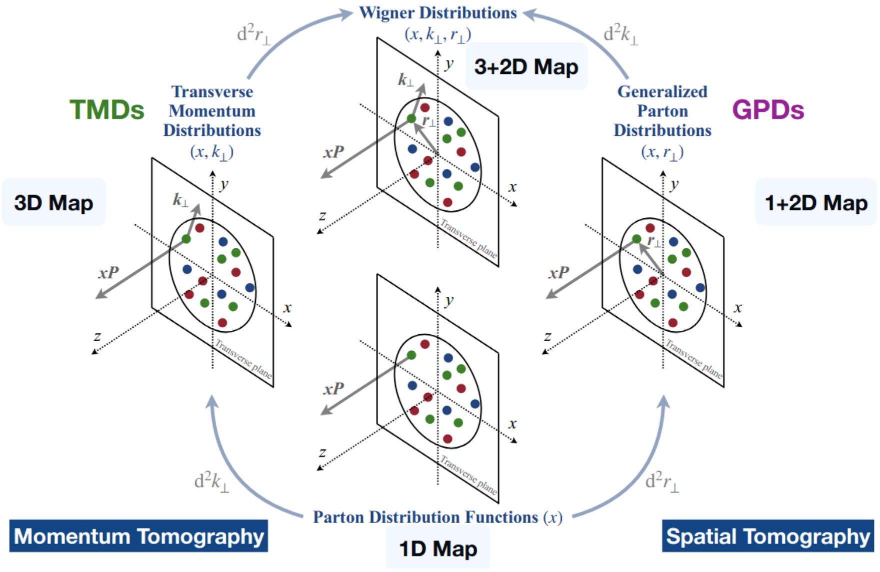
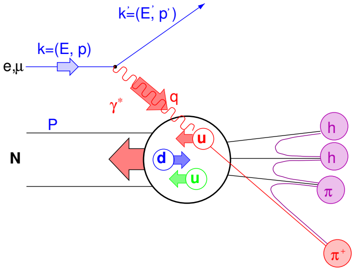
Diffraction and Low-x

Corigliano Calabro, 24 – 30, 2022

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



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

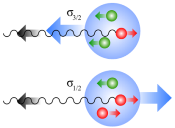


- $\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2},\ \ q(x,Q^2) \longrightarrow g_{1,2},\ \ \Delta q(x,Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, 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):



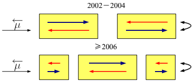
$$A_1(x,Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Observables

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

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

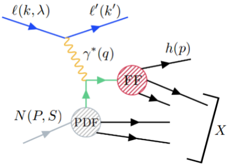
f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations;
$N^{\leftrightarrows,\leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell:
(upstream, downstream) or (outer, central)



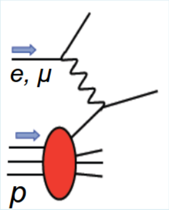
- Semi–inclusive asymmetry, $A_1^h(x, z, Q^2)$, at LO:

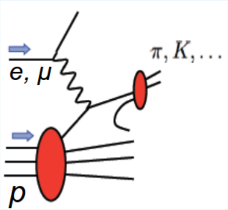
$$A_1^h(x, z, Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}, \qquad z = \frac{E_h}{\nu}$$

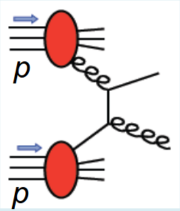
$$D_q^h \neq D_{\bar{q}}^h$$

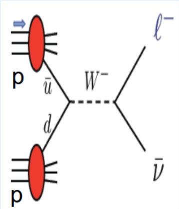


Processes available for parton (helicity) distributions









DIS:

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

Δg (From Q^2 evolution of g_1)

SIDIS:

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

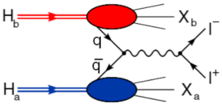
Δg

pp:

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

Δg

A. Bazilevsky, SPIN2016



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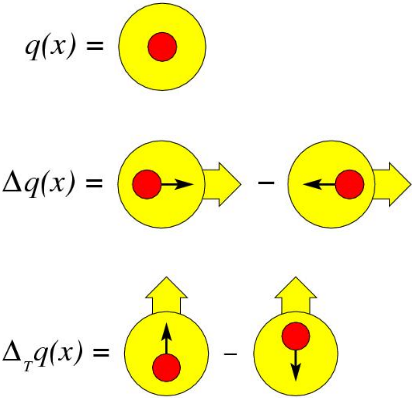
Drell-Yan process, complementary to SIDIS; COMPASS, FNAL, STAR, PHENIX

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 $\rightarrow \mathbf{g_1(x, Q^2)}$).

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

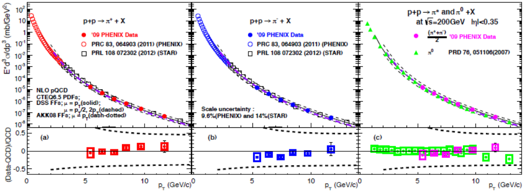
Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd

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)

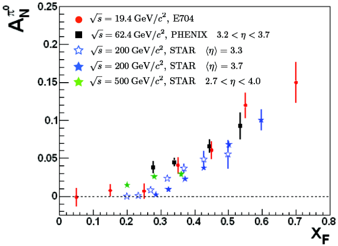
large P_T single pion production $p\,p \to \pi\, X$



good agreement between RHIC data
and collinear pQCD calculations

BUT for $\perp$ polarised p

A_N large and persistent at high energies ....



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

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

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta \mathrm{G} + \mathrm{L_q} + \mathrm{L_g}$$ **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 $\int_0^1 \mathrm{d}x \left[\Delta s + \Delta\bar{s}\right] < 0$)

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

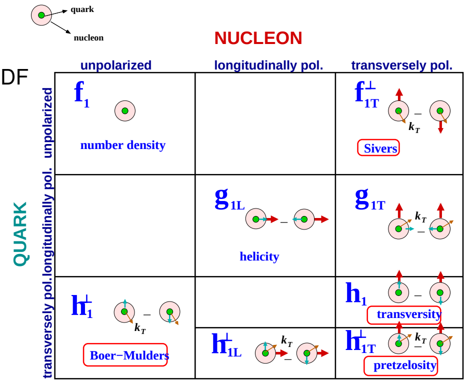
papers cited **4089** times

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$^\mathrm{target}$

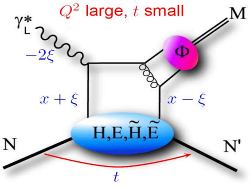


- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
- TMD parton distributions need TMD Fragmentation Functions!

Generalised Parton Distributions



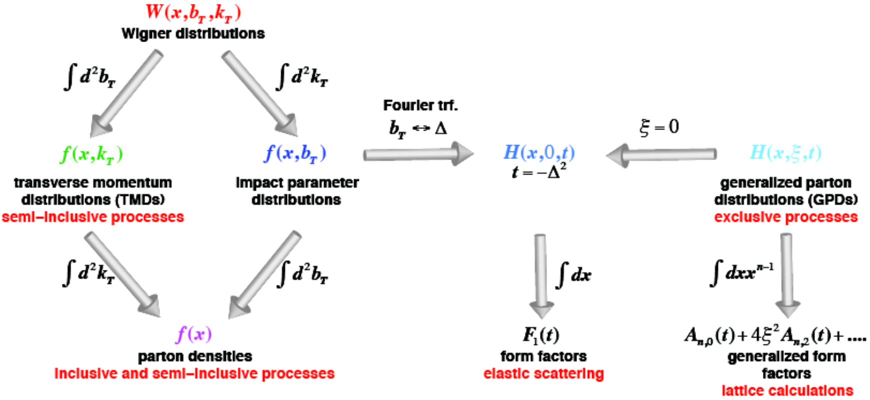
- Accessible via DVCS/DVMP: $\mu p \to \mu p \gamma(M)$
- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons

  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:

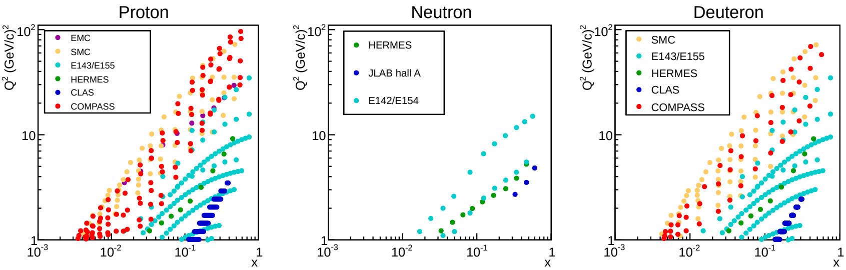
$$J_z^q = \frac{1}{2}\int dx\, x\, [H^q(x, \xi, t=0) + E^q(x, \xi, t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q \quad \text{(X. Ji)}$$

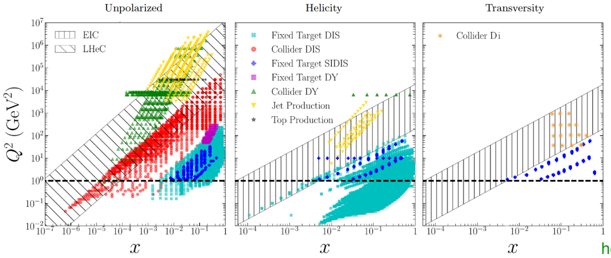
Descriptions of *pdf* ^{s} in the nucleon



From “White paper”, arXiv:1212.1701

Map of experimental results





hep-ph 2006.08636v2

OPEN QUESTIONS

(to be addressed at the end of the session)

- Spin as a goal (nucleon spin structure) and as a tool (fundamental properties of QCD);
- Three fundamental elmgt 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;