Spin dependent deep inelastic scattering in present and future experiments

Barbara Badelek University of Warsaw

Various Faces of QCD

NCBJ, Świerk, October 8 - 9, 2016

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Spin DIS now and in future

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• Thus the DIS experiments on which the parton distribution functions are largely based are like a keystone in the arch that supports the edifice of particle physics.



P. Mulders, DIS2015

Spin Physics and Transverse Structure

Piet Mulders (Nikhef Theory Group/VU University Amsterdam)

Spin is a welcome complication in the study of partonic structure that has led to new insights, even if experimentally not all dust has settled, in particular on quark flavor dependence and gluon spin. At the same time it opened new questions on angular momentum and effects of transverse structure, in particular the role of the transverse momenta of partons. This provides again many theoretical and experimental challenges and hurdles. But it may also provide new tools in high-energy scattering experiments linking polarization and final state angular dependence.

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Outline

Introduction

- Inclusive and semi-inclusive deep inelastic scattering
- 3 Charged hadron multiplicities
- 4 Measurements on a transversely polarised target
- 5 Drell-Yan process
- 6 Generalised Parton Distributions

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Evolution in understanding the proton structure



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Nucleon spin structure in the electroproduction





• $\frac{\mathrm{d}^2 \sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \frac{\alpha^2}{2Mq^4} \frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$

- Symmetric part of W^{μν} unpol. DIS, antisymmetric – polarised DIS
- $\hbox{\bullet Nominally $F_{{}_{1,2}}$, $q(x) \longrightarrow g_{{}_{1,2}}$, $\Delta q(x)$ but...} }$
- ...anomalous gluon contribution to $g_1(x)$
- $...g_2(x)$ has no interpretation in terms of partons.

$$\sigma = \bar{\sigma} - \frac{1}{2} h_l \left(\cos \psi \Delta \sigma_{\parallel} + \sin \psi \cos \phi \Delta \sigma_{\perp} \right)$$

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Nucleon spin structure: observables in $\vec{\mu}\vec{N}$ scattering

• Inclusive asymmetry, A_{meas} :

$$A_{meas} = \frac{1}{fP_T P_B} \left(\frac{N^{\leftrightarrows} - N^{\rightleftharpoons}}{N^{\leftrightarrows} + N^{\rightleftharpoons}} \right) \approx DA_1 = D \frac{g_1(x, Q^2)}{F_1(x, Q^2)} = D \frac{\sum_{q} e_q \Delta q(x, Q^2)}{\sum_{q} e_q^2 q(x, Q^2)}$$

$$\Delta q = q^{+} - q^{-}, \quad q = q^{+} + q^{-}, \qquad g_{1}^{d} = g_{1}^{N} (1 - \frac{3}{2}\omega_{D}) = \frac{g_{1}^{p} + g_{1}^{n}}{2} (1 - \frac{3}{2}\omega_{D});$$
$$\omega_{D} = 0.05 \pm 0.01$$

• At LO, semi–inclusive asymmetry, A_1^h :

$$A_{1}^{h}(x,z,Q^{2}) \approx \frac{\displaystyle \sum_{q} e_{q}^{2} \Delta q(x,Q^{2}) D_{q}^{h}(z,Q^{2})}{\displaystyle \sum_{q} e_{q}^{2} q(x,Q^{2}) D_{q}^{h}(z,Q^{2})}$$

 $z=\frac{E_h}{\nu} \qquad \quad D^h_q\neq D^h_{\bar{q}}$

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 $\sum a^2 \wedge a(m, O^2)$

Parton distributions in the nucleon



- parton intrinsic k_T taken into account in TMD
- TMD related to quark angular momentum, L!
- GPD and TMD are NOT connected via the Fourier transform
- TMD may be studied in 2 ways e.g. at COMPASS:
 - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
 - Drell-Yan process (π beam on unpolarised/transversely polarised target)



Partonic structure of the nucleon; distribution functions



 $h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$

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

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Acceptance of spin experiments @ $Q^2 > 1$ (GeV/c)²

Fixed target:

- JLab (Hall A, CLAS (Hall B)): polarised e of $~\lesssim~$ 12 GeV, polarised targets
- CERN (COMPASS): polarised μ^+ of 160-200 GeV, polarised protons, deuterons
- (completed) DESY (HERMES): polarised e of 27 GeV, polarised targets
- Colliders: BNL (STAR, PHENIX) polarised protons, $\sqrt{s} \lesssim~510~{
 m GeV}$



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COMPASS Spectrometer (2002-2012)

muon runs: Nucl. Instr. Meth. A577 (2007) 455

Two stages, \sim 350 planes Particle identification (RICH, calos, μ filters)



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COMPASS polarised targets



A Large Hadron Electron Collider (LHeC) at CERN

- Symposium on the European Strategy for Partice Physics, Cracow, 2012 arXiv:12111.483
- Two options: ring-ring (RR) and linac-ring (LR). Basic beam design:



electron beam 60 GeV	Ring	Linac
e^- (e ⁺) per bunch N_e [10 ⁹]	20(20)	1(0.1)
e^{-} (e^{+}) polarisation [%]	40(40)	90(0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma \epsilon_{x,y}^{e}$ [mm]	0.59, 0.29	0.05
IP β function $\beta_{x,y}^*$ [m]	0.4, 0.2	0.12
beam current [mÅ]	100	6.6
energy recovery efficiency [%]	_	94
proton beam 7 TeV		
protons per bunch N_p [10 ¹¹]	1.7	1.7
transverse emittance $\gamma \epsilon_{x,y}^p$ [µm]	3.75	3.75
collider		
Lum e^-p (e^+p) $[10^{32} \text{cm}^{-2} \text{s}^{-1}]$	9 (9)	10(1)
bunch spacing [ns]	25	25
rms beam spot size $\sigma_{x,y}$ [µm]	45, 22	7
crossing angle θ [mrad]	1	0
$L_{eN} = A L_{eA} [10^{32} \text{cm}^{-2} \text{s}^{-1}]$	0.45	1

• The "Strategy" has not recommended a continuation of R&D for LHeC!

e-p machine, EIC, planned at BNL or JLab

BNL

JLab

Electron beam facility needed (inside RHIC tunnel)

ELIC + injector needed



e-p machine, EIC, planned at BNL or JLab



EIC: main features

- Highly polarised (~ 70%) e, N beams
- ions from deuteron to uranium (lead ?)
- variable \sqrt{s} from \sim 20 GeV to \sim 100 (150) GeV
- high luminosity: $\sim 10^{33-34}$ cm⁻² s⁻¹ (cooling of hadronic beam !)
- more than one interaction rregion
- Iimits of current technology \R & D!
- staged realisation; first stage: √s = 60 100 GeV and high luminosity.

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A dedicated EIC detector



- Acceptance -5 < η < 5 (large, comparable to CMS forward)
- PID: π , K, p, leptons
- Low material density (minimal multiple scattering and bremsstrahlung)
- Hadron beams: proton to lead

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From "White paper", arXiv:1212.1701

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Inclusive and semi-inclusive deep inelastic scattering

$g_1^p(x,Q^2)$ and $g_1^d(x,Q^2)$, world data



Curves: COMPASS NLO QCD fit for $W^2 > 10 \text{ GeV}^2$ (dashed: extrapolation for $W^2 < 10 \text{ GeV}^2$)

COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

COMPASS, PLB 753 (2016) 18	COMPASS ₄	submitted,PLB, ≣ →	୬୯୯
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COMPASS NLO fit to g_1 world data; $Q^2 = 3 (\text{GeV}/c)^2$

Fitted: $\Delta q_{\rm SI}, \Delta q_3, \Delta q_8, \Delta g$ at $Q_0^2 = 1$ (GeV/c)²; 679 points, 28 params; $\overline{\rm MS}$ scheme



COMPASS NLO fit to q_1 world data... cont'd

- Little sensitive to gluon polarisation
- Quark polarisation: $\Delta \Sigma = \int \Delta q_{\rm SI}(x) dx \sim 0.3$



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JAM NLO fit to world inclusive data $(A_{\parallel}, A_{\perp})$

JAM: Jefferson Lab. Angular Momentum Collaboration

Included JLab data $W^2 > 4 \text{ GeV}^2 \Longrightarrow$ reduced errors for valence & sea at x > 0.1



JAM, PRD 93 (2016) 074005

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Inclusive $g_1(x, Q^2)$ at EIC (pseudo-data)



Errors statistical (EIC: expected, modest parameters); bands: from gluon helicity uncertainty

arXiv:1509.06489

"White paper", arXiv:1212.1701

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 $\ln^2(1/x)$ corrections to $q_1^{ns}(x,Q^2)$

- Leading low x behaviour of g_1 (g_1^s and g_1^{ns}) generated by powers of $\alpha_s \ln^2(1/x)$; a standard DGLAP for spin dependent *pdf* generate only $\ln(1/x)$ terms.
- A way of including the above to QCD evolution: through $f(x, k_t^2)$ $p(x,Q^2) = \int^{Q^2} \frac{\mathrm{d}k_t^2}{k_t^2} f(x,k_t^2)$ where conventional parton distributions: This formalism permits an easy extrapolation to $Q^2 = 0$ x'p, k² (for fixed W^2). mmimm Δp. k²
- $\ln^2(1/x)$ corrections to g_1^{ns} are generated by ladder diagrams \implies



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$\ln^2(1/x)$ corrections to $g_1^{ns}(x,Q^2)$... cont'd

• $\ln^2(1/x)$ corrections to g_1^{ns} are generated mathematically by equation:

$$f(x',k) = f^{(0)}(x',k) + \bar{\alpha}_s(k^2) \int_{x'}^1 \frac{\mathrm{d}z}{z} \int_{k_0^2}^{k^2/z} \frac{\mathrm{d}k'^2}{k'^2} f(\frac{x'}{z},k'^2)$$

and

$$g_1^{ns}(x,Q^2) = g_1^{ns(0)}(x) + \int_{k_0^2}^{W^2} \frac{\mathrm{d}k^2}{k^2} f(x' = x(1 + \frac{k^2}{Q^2}), k^2)$$
where $\bar{\alpha}_{-}(k^2) = 2\alpha_{-}(k^2)/3\pi$ and



- $\ln^2(1/x)$ terms originate from the *z*-dependent limit of the $\int dk'^2/k'^2$ and *x*-dependent limit in $W^2(x)$.
- For fixed (i.e. non-running) $\bar{\alpha}_s(k^2) \rightarrow \tilde{\alpha_s}$, small x behaviour is $g_1^{ns}(x,Q^2) \sim x^{-\lambda}$ where $\lambda = 2\sqrt{\tilde{\alpha_s}}$

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COMPASS Preliminar

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0.04

Semi-inclusive asymmetries and parton distributions

 COMPASS: measured on both proton and deuteron targets for identified, positive and negative pions and (for the first time) kaons



COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.

• NLO parameterisation of DSSV describes the data well.

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Polarisation of quark sea

• Δs puzzle. Strange quark polarisation:

 $2\Delta S = \int_0^1 (\Delta s(x) + \Delta \bar{s}(x)) dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU₃, while from semi-inclusive asymmetries it is compatible with zero

but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_{u}^{K^+}(z)dz}$







• The sea is not unsymmetric: COMPASS, Phys. Lett. B, 680 (2009) 217; \uparrow CLAS12, Update to E12-09-007 $\int_{0.004}^{0.3} \left[\Delta \bar{u}(x,Q^2) - \Delta \bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3 \text{ (GeV/}c)^2$ Thus the data disfavour models predicting $\Delta \bar{u} - \Delta \bar{d} \gg \bar{d} - \bar{u}$

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Nucleon spin structure @ high x: JLab at 12 GeV



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Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ or $q\bar{q}$ pair.



 $\Delta g/g = 0.113 \pm 0.038 (\text{stat.}) \pm 0.035 (\text{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3 \text{ GeV}^2, \quad x_G \approx 0.10$ COMPASS, K. Klimaszewski, SPIN2016

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A_L for W[±] production at \sqrt{s} =510 GeV @ STAR

- Direct coupling to $\mathrm{q}\bar{\mathrm{q}}$ of interest
- Scale set by W mass

Cartoons from D.Gunarathne, DIS2015

- Efficient spin separation
- Easy detection



WAL (ne) 2012+2011

 $u + \overline{d} \rightarrow W^+ \rightarrow e^+$







arXiv: 1304.0079

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A_{LL} for π^0 production at \sqrt{s} =200 and 510 GeV @ PHENIX





DSSV++ with 200 GeV data:

$$\int_{0.05}^{1.0} \Delta g(x) dx = 0.2^{+0.06}_{-0.07}$$

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DSSV, PRL 113 (2014) 012001

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Compilation by M.Stratmann (2015 Jlab Users Meeting)



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A. Bazilevsky, SPIN2016

EIC pseudo-data (inclusive and semi-inclusive)



From "White paper", arXiv:1212.1701

- $\succ \Delta \overline{u}, \Delta \overline{d}, \Delta s$ from SIDIS
- Flavor separation at high Q² via CC DIS:

$$g_{1}^{W^{*}} = \Delta \overline{u} + \Delta d + \Delta \overline{c} + \Delta s$$

$$g_{1}^{W^{*}} = \Delta u + \Delta \overline{d} + \Delta c + \Delta \overline{s}$$

$$g_{5}^{W^{*}} = \Delta \overline{u} - \Delta d + \Delta \overline{c} - \Delta s$$

$$g_{5}^{W^{*}} = -\Delta u + \Delta \overline{d} - \Delta c + \Delta \overline{s}$$

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E. Aschenauer, SPIN2016

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Proton Spin Puzzle will be solved @ EIC ?



Aschenauer, Stratmann, Sassot arXiv : 1509.06489

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Charged hadron multiplicities; identified kaons

- Studied to measure fragmentation functions (FF), $D_q^h(z, Q^2) \iff \text{cf. } \Delta s$). At LO: $\frac{dM^h(x, z, Q^2)}{dz} = \frac{\left(\frac{d\sigma}{dxdzdQ^2}\right)_{\text{SIDIS}}}{\left(\frac{d\sigma}{dxdQ^2}\right)_{\text{DIS}}} = \frac{\Sigma_q e_q^2 \left[q(x, Q^2)D_q^h(z, Q^2) + \bar{q}(x, Q^2)D_{\bar{\pi}}^h(z, Q^2)\right]}{\Sigma_q e_q^2 \left[q(x, Q^2) + \bar{q}(x, Q^2)\right]} \stackrel{\ell}{\longleftarrow}$
- 2006 data; ⁶LiD target; 317 kinematic bins.
- $\begin{array}{lll} \bullet \ Q^2 > 1 \ ({\rm GeV}/c)^2, & 0.1 < y < \!\!0.7, & 0.004 < x < \!\!0.4 \\ 0.2 < z < 0.85, & 12 < p_h < \!\!40 \ {\rm GeV}/c & ({\rm coverage\ in\ }W{\rm :\ 5-17\ GeV}). \end{array}$



Charged hadron multiplicities

Charged hadron multiplicities; identified kaons and pions



HERMES, PRD 89 (2014)097101



- Both π and K multiplicities on the ⁶LiD (isoscalar) target
- strong discrepancies COMPASS/HERMES in the sum of multiplicities integrated over z, p_T, Q^2 (kinematics is similar)
- Ratio π^+/π^- is OK but K^+/K^- differ by ~20% \implies under study!

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Properties of the transversity, $\Delta_T q(x)$ (or $h_1^q(x)$)

it is chiral–odd

 \implies hadron(s) in final state needed to be observed (SIDIS reaction)

- simple QCD evolution since no gluons involved
- it is related to Generalised Parton Distributions (GPD)
- there is a sum rule for transverse spin
- first moment gives a "tensor charge" (now being studied on the lattice)

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Examples (2 of 8) of measurements on a \perp polarised target

Collins asymmetry (first time by HERMES) \implies permitts to access transversity, \perp polarised $q \iff p_T^h$ of unpolarised h (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0 \left[1 \pm f P_T D_{NN} A_{Coll} \sin \phi_c \right]$$

$$\phi_C = \phi_h + \phi_S - \pi$$

which in turn gives at LO and at collinear approach:



$$A_{Coll} \sim \frac{\sum_{q} e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_{q} e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ (universal!) needed to extract $\Delta_T q(x)$ from the Collins asymmetry! Recently FF measured using data of Belle, BaBar and BES III.

Sivers asymmetry $(\phi_S = \phi_h - \phi_S)$, correlation of \perp nucleon spin with k_T of unpolarised q): if $\neq 0$ then $L_q \neq 0$ in the proton. Fundamental !

$$A_{Siv} \sim \frac{\sum_{q} e_q^2 \cdot \Delta_0^T q(x, p_T^h/z) \cdot D_q^h(z)}{\sum_{q} e_q^2 \cdot q(x, p_T^h/z) \cdot D_q^h(z)}$$

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Results for the Collins asymmetry for protons





M. Anselmino et al., Phys.Rev. D87 (2013) 094019

- Collins asymmetries for proton measured for +/- unidentified and identified hadrons...
- ...are large at $x \gtrsim 0.03$ and consistent with HERMES (in spite of different Q^2 !)
- but negligible for the deuteron
- COMPASS data on p,d + HERMES data on p (2005) + BELLE on e^+e^- : $\Longrightarrow \Delta_T u, \Delta_T d$
- Transversity also obtained from 2-hadron asymmetries (and "Interference Fragmentation Function")

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Results for the Sivers asymmetry for protons



COMPASS, Phys.Lett. B744 (2015) 250

- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+ , K⁺...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

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Multidimensional analyses: Sivers asymmetry $(x, Q^2; z, p_T)$



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Other azimuthal asymmetries



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Other azimuthal asymmetries...cont'd



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Measurements on a transversely polarised target

Example of TSA: $A_{LT}^{\cos(\phi_h-\phi_s)}$ sensitive to g_{1T}

• g_{1T} : the only T-even, chiral-even, off-diagonal, twist-2 TMD



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Quark polarimetry through $e^+e^- \rightarrow h_1h_2X$

Asymmetries in number of hadron (jet) are \sim to a convolution of two Colins FFs E.g. at lower energies (no jets): BES III results ($\sqrt{s} \sim 4.5$ GeV) PRL, 116 (2016) 042001





 $A^{UL} = R^U / R^L = A\cos(2\phi_0) + B$



And for Babar and Belle ($\sqrt{s} \sim 10.5 \text{ GeV}$):

Sivers function at EIC



From "White paper", arXiv:1212.1701



EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

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- Inclusive and semi-inclusive deep inelastic scattering
- 3 Charged hadron multiplicities
- 4 Measurements on a transversely polarised target

Drell-Yan process

6 Generalised Parton Distributions

B. Badelek (University of Warsaw)

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Drell-Yan process

Partonic structure of the nucleon; distribution functions



 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!

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Drell-Yan process

Transverse Momentum Dependent (TMD) distributions



- parton intrinsic $k_{\rm T}$ taken into account
- related to quark angular momentum, L!
- TMD at COMPASS studied in 2 ways:
 - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
 - Drell-Yan process (π beam on unpolarised/transversely polarised tgt.)



Sivers sign change?

The STAR experiment at RHIC recently reported the measurement of A_N in $p^{\dagger} + p \rightarrow W^{\pm}/Z^0$ at $\sqrt{s} = 500 GeV$. One of the beams is polarized ($\langle P \rangle = 53\%$) STAR, Phys.Rev.Lett. **116**, 132301 (2016)



 A_N compared to models where Sivers TMD is obtained from SIDIS data

SPIN 2016 C. Quintans, "Nucleon Spin Structure from Experiments using Drell-Yan Process" Pag

The COMPASS bridge



Nucleon TMD PDFs accessed via SIDIS and Drell-Yan asymmetries

SIDIS $\ell^{\rightarrow} N^{\uparrow}$	Nucelon TMD PDF	Drell-Yan πN^{\uparrow} (LO)
$A_{UU}^{\cos 2\phi_h}, \ A_{UU}^{\cos \phi_h}$	$h_1^{\perp q}$ - "Boer-Mulders"	$A_U^{\cos 2 arphi_{CS}}$
$A_{UT}^{\sin(\phi_h-\phi_s)}, A_{UT}^{\sin\phi_s}, A_{UT}^{\sin(2\phi_h-\phi_s)}$	$f_{1T}^{\perp q}$ - "Sivers"	$A_T^{\sin arphi_S}$
$A_{UT}^{\sin(\phi_h+\phi_s-\pi)}, \ A_{UT}^{\sin\phi_s}$	h_1^q - "Transversity"	$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$
$A_{UT}^{\sin(3\phi_h-\phi_s)}, A_{UT}^{\sin(2\phi_h-\phi_s)}$	$h_{1T}^{\perp q}$ - "Pretzelosity"	$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$
$A_{LT}^{\cos(\phi_h - \phi_s)}, A_{LT}^{\cos \phi_s}, A_{LT}^{\cos(2\phi_h - \phi_s)}$	g_{1T}^q - "Worm-Gear" (T)	Double-polarized DY

Color code: LO asymmetries: twist 2 TMDs \otimes FFs HT asymmetries

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Drell-Yan process

Drell-Yan @ COMPASS: experimental requirements



Drell-Yan @ COMPASS: preliminary results from 30% 2015 data



Drell-Yan process

Drell-Yan @ COMPASS: preliminary results from 30% 2015 data



Request for another Run in 2018.



Projections for the combined statistics of the 2 years.

C. Quintans, SPIN2016

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TSAs from (un)polarized DY – the future

After the check of sign of Sivers TMD in Drell-Yan wrt SIDIS, a new phase will come for studying in detail dependencies and TMD evolution. It will require input from both type of processes.

Experiment	type	$\sqrt{s}(GeV)$	when
STAR (RHIC)	collider; $p^{\uparrow}p$	510	2017
COMPASS (CERN)	fixed target; $\pi^- p^{\uparrow}, K^- p^{\uparrow}$	18.9	2018
E1039 (FNAL)	fixed target; $pp \uparrow$	15	2018-2019
J-PARC (KEK))	fixed target; $\pi^- p$	3-5.5	>2018
NICA (JINR)	collider; $p^{\uparrow}p^{\uparrow}, p^{\uparrow}d^{\uparrow}$	10-26	>2018
E1027 (FNAL)	fixed target; $p^{\uparrow}p$	15	>2020
PANDA (FAIR)	fixed target; $\bar{p}p$	5.5	>2022
J-PARC (KEK)	fixed target; $K^- p$, $\bar{p}p$	2.2 - 4.5	>2022
AFTER (CERN)	fixed target; pp^{\uparrow}	115	2025
COMPASS+ (CERN)	fixed target; $K^- p^{\uparrow}$, $\bar{p}p^{\uparrow}$	≈ 20	2025

Several (un)polarized Drell-Yan experiments are being planned:

* List possibly not complete

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3D picturing of the proton via GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, ... M. Burkardt, ... Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs Structure functions, quark longitudinal momentum & helicity distributions

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f(x)

After V.D. Volker, LANL 2007

B. Badelek (University of Warsaw)

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 $f(x,b_i)$

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Access GPD through the DVCS/DVMP mechanism



 $Q^2 \to \infty,$ fixed $x_{\rm B}, t \implies |t|/Q^2$ small

- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons plus 4 chiral odd ones $(H_T, E_T, \widetilde{H}_T, \widetilde{E}_T)$
- DVMP: factorisation proven for σ_L only
- All depend on 4 variables: x, ξ, t, Q^2 ; DIS @ $\xi = t = 0$; Later Q^2 dependence omitted. 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

•
$$H^q(x,0,0) = q(x), \ \widetilde{H}^q(x,0,0) = \Delta q(x)$$

- H, E accessed in vector meson production $via A_{UT}$ asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of H, E, H, E over x give Dirac-, Pauli-, axial vector- and pseudoscalar vector form factors respectively.

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

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Generalised Parton Distributions

DVCS/DVMP: $\mu p \rightarrow \mu p \gamma(M)$; observables



 $\mathrm{d}\sigma^{\mu p \to \mu p \gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_{\mu}\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_{\mu}(\mathrm{Re}I + P_{\mu}\mathrm{Im}I)$

Observables (Phase 1):

•
$$S_{CS,U} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2 \left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_{\mu}P_{\mu}ImI \right)$$

• $D_{CS,U} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2 \left(P_{\mu}d\sigma^{DVCS}_{pol} + e_{\mu}ReI \right)$
• $A_{CS,U} \equiv \frac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \frac{D_{CS,U}}{S_{CS,U}}$
• Each term ϕ -modulated

• Each term ϕ -modulated If ϕ -dependence integrated over \implies twist-2 DVCS contribution; if ϕ -dependence analysed: \implies Im (F_1H) and Re (F_1H) ; H dominance @ COMPASS kin.

Analogously for transversely polarised target (Phase 2): $S_{CS,T}$, $D_{CS,T}$, $A_{CS,T} \Longrightarrow E$

GPD at COMPASS: data taking in 2016-2017



- CERN high energy muon beam
 - 100 190 GeV
 - 80% polarisation
 - $-\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
 - between HERA and HERMES/JLab12
 - intermediate x (sea and valence)
- Separation
 - pure B-H @ low $x_{\rm B}$
 - predominant DVCS @ high $x_{\rm B}$
- Plans
 - DVCS
 - DVMP
- Goals
 - from unpolarised target: H (Phase 1)
 - from \perp polarised target: *E* (Phase 2)

Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated

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Acceptance of present and EIC DVCS



B. Badelek (University of Warsaw)

From "White paper", arXiv:1212.1701 Various Faces of QCD, 2016 63/64

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Instead of a summary D. Soper, DIS2015

• Thus the DIS experiments on which the parton distribution functions are largely based are like a keystone in the arch that supports the edifice of particle physics.



P. Mulders, DIS2015

Spin Physics and Transverse Structure

Piet Mulders (Nikhef Theory Group/VU University Amsterdam)

Spin is a welcome complication in the study of partonic structure that has led to new insights, even if experimentally not all dust has settled, in particular on quark flavor dependence and gluon spin. At the same time it opened new questions on angular momentum and effects of transverse structure, in particular the role of the transverse momenta of partons. This provides again many theoretical and experimental challenges and hurdles. But it may also provide new tools in high-energy scattering experiments linking polarization and final state angular dependence.

Spin DIS now and in future

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