Spin Physics -
Summary (Theory)

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Sketch of main results, Apologies to those missed

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Content of WG Spin Physics Session

• Longitudinal Spin Physics - 14 talks
  ➤ Long. DSA ($A_{LL}$), Helicity Parton Distributions, $\Delta G$, ...
  ➤ Partonic Orbital Angular Momentum

• Transverse Spin Physics - 15 talks
  ➤ Transverse SSA, collinear formalism, ...
  ➤ TMD - factorization, Sivers/Collins effect, transversity ...

• Exclusive Processes - 9 talks
  ➤ GPDs, DVCS, TCS ...
  ➤ Lattice calculations of spin observables ➤ 1 overview talk

Friday, March 30, 2012
Orbital Angular Momentum
(Overview talk by F. Yuan)

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + (\Delta G + L_g) \]

- (Long.) Spin Sum rule: many versions: Jaffe, Manohar; Ji; Leader; Chen et al.; Hatta
- Dedicated Workshop: INT-Workshop “Orbital Angular Momentum in QCD”

**Quark spin:**

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

**Gluon spin:**

\[ \Delta G(Q^2) = \int_0^1 dx \Delta g(x, Q^2) \]

\[ \rightarrow \text{polarized ep, pp - collisions} \]

**Quark Orbital Angular Moment:**

\[ J_q = \frac{1}{2} \sum_i \int dx x \left[ q_i(x) + E_i(x, 0, 0) \right] \]

\[ \rightarrow \text{exclusive processes} \]

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Longitudinal Spin Physics

Talks by Vogelsang, Stratmann, Collins, Nocera, Kataev, Pfeuffer, ...

Collinear Factorization in pQCD:

• Cross Section at high energies \( \rightarrow (\text{hard part}) \times (\text{soft part}) \)

• Hard Part \( \rightarrow \) pQCD ; Soft Part \( \rightarrow \) Universal

• Soft Part \( \rightarrow \) collinear Parton Distributions (1-dimensional)

quarks:

\[ q(x, \mu), \Delta q(x, \mu), \delta q(x, \mu) \]

|gluons:|\[ G(x, \mu), \Delta G(x, \mu) \]| Helicity distributions: Information on the longitudinal spin structure of hadrons |
**Long. Spin: Observables**

Inclusive DIS: Structure function $g_1 \rightarrow$ HERMES, COMPASS, JLab, ...
Semi-Inclusive DIS (SIDIS) at large $P_T$ or $P_T$-integrated \(\rightarrow\) investigation of flavor

polarized pp - collisions ($A_{LL}$) \(\rightarrow\) RHIC
Pion - production, Drell-Yan leptoproduction, *new RHIC W-program*
Helicity Distributions

(W. Vogelsang, M. Stratmann)

Report on DSSV “global QCD analysis” on polarized DIS, SIDIS and RHIC data

- new COMPASS data: minor modification of analysis
- DSSV analysis for an EIC: mock data + error projection
(M. Stratmann): error band for \( \Delta g \) dramatically reduced
NNPDF fits of helicity PDFs

(E. Nocera)

- Conventional fits from global analyses (DSSV and others) ➔ assume functional form, bias
- unbiased fits ➔ neural networks

- larger error bands, in particular on $\Delta g$
- Only DIS data included, no SIDIS or RHIC data
- certain inconsistencies with BB10 fits, in agreement with DSSV

\[ \langle S_z \rangle = \frac{1}{2} \langle \Delta \Sigma \rangle + \langle \Delta g \rangle + L_q + L_g \]
\[ \frac{1}{2} = (-0.1 \pm 1.1) + L_q + L_g \]
Lattice Calculation for Helicities & OAM

(S. Collins, QCDSF)

Calculations of moments on the lattice

Focus on polarized strange quark distribution Δs: include “disconnected contributions”

Lattice specifications:
improved Clover fermions, lattice spacing a=0.072 fm, pion mass m_π=285 MeV
need to match continuum renormalization:

\[ \frac{\Delta q}{2} s_\mu = \frac{1}{m_N} \langle N, s | \bar{q} \gamma_\mu \gamma_5 \frac{1}{2} q | N, s \rangle \]

Main result:

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s = 0.45(4)(9) \]
\[ \Delta s = -0.020(10)(4) \]

negative strange quark polarization ➔ disagreement with DSSV analysis

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Transverse Spin Physics - Transversity via IFF

(A. Courtoy)

Motivation: Study of the transversity distribution $\delta q(x) \rightarrow$ absent in inclusive DIS $\rightarrow$ SIDIS

1-hadron fragmentation $\rightarrow$ Collins effect (TMD fact.)

$\begin{align*}
h_1 \otimes H_1^\perp \\
h_1 \otimes H_1^\perp
\end{align*}$

2-hadron fragmentation $\rightarrow$ Interference FF (coll. fact.)

Transverse SSA in 2-hadron DIS at LO:

Consistent with extraction from Collins effect

- Fit: work in progress
Transverse SSA - twist-3 coll. Approach

(J.-W. Qiu)

Long history of large transverse spin asymmetries in pp - collisions:

Simple parton model explanation fails:

\[ \sigma_{AB}(pT, \vec{s}) - \sigma_{AB}(pT, -\vec{s}) = \propto \alpha_s \frac{m_q}{p_T} \]

\[ \text{Too small to explain available data!} \]

\[ \Rightarrow \text{need multi-parton correlations (twist-3)} \]
Twist-3 approach for 1-scale processes

Transverse SSA $\Rightarrow$ Quark-Gluon-Quark correlation

Evolution of $T_F(x,x)$ studied by different groups $\Rightarrow$ inconsistencies resolved

- like DGLAP at large $x$
- differences at smaller $x$
**TMD factorization**

Talks by Mulders, Bacchetta, Yuan, Boglione, Mukherjee, Zhou, den Dunnen, ...

**Idea of TMDs:**

Implement "intrinsic" transverse parton momentum $k_T$ ➔ different kind of factorization ➔ opportunity to study different aspects of hadron spin structure (e.g. spin-orbit correlations, overlap rep. etc.)

"intrinsic" transverse parton momentum through small final state transverse momenta

$q_T \ll Q$

$P_{hT} \ll Q$
(Naive) definition of the quark TMD correlator

\[
\Phi_{ij}(x, k_T; S) = \int \frac{dz_+ d^2z_T}{(2\pi)^3} e^{ik_T \cdot z} \langle P, S| \bar{\psi}_j(0) W_{SIDIS/DY}[0, z] \psi_i(z) | P, S \rangle \bigg|_{z^+ = 0}
\]

(talk by P. Mulders)

\[
\Phi(x, p_T) \quad p_T^2 > \mu^2 \quad \frac{1}{\pi p_T^2} \frac{\alpha_s(p_T^2)}{2\pi} \int \frac{dy}{y} P\left(\frac{x}{y}\right) \Phi(y; p_T^2)
\]

- Consistent matching to collinear situation: CSS formalism
  JC Collins, DE Soper and GF Sterman, NP B 250 (1985) 199

- Gauge links for TMD correlators process-dependent with simplest cases

Color entanglement \(\rightarrow\) TMD factorization broken for more complicated processes
Eight leading twist TMDs

- Unpolarized quark distribution with $p_T$
  - $f_1^q(x) = q(x)$
  - $g_1^q(x) = \Delta q(x)$
  - $h_1^q(x) = \delta q(x)$
- Helicity or chirality distribution with $p_T$
- Transverse spin distribution or transversity with $p_T$
Evolution of TMDs
(talks by M. Boglione, F. Yuan)

all-order TMD factorization theorems include soft factor, non-lightlike Wilson lines

\[
\Phi_{ij}(x, \vec{k}_T; S; \xi, \mu)
\]

Collins-Soper evolution equations for $\xi, \mu$

\[
\tilde{F}(x, b_T; Q) = \tilde{F}(x, b_T; Q_0) \tilde{R}(Q, Q_0, b_T) \exp \left\{ -g_K(b_T) \ln \frac{Q}{Q_0} \right\}
\]

Input function

Unknown, but universal and scale independent, input function

Aybat, Collins, Qiu, Rogers

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Sivers effect with evolution

Sivers effect: Transverse SSA in SIDIS, Drell-Yan,...

\[ A_{UT} \propto \sin(\phi - \phi_s) \frac{f_{1T}^{\perp q} \otimes D_1^q}{f_1^{\perp q} \otimes D_1^q} \]

Evolved Sivers functions
- DGLAP-evolution slow
- TMD evolution: big effects

Data fits with evolution
- improved fits
- \( \chi^2 \) reduced by factor \( \sim 3 \)
OAM and the Sivers effect

(A. Bacchetta)

Idea: use SIDIS data to constrain OAM
(model-inspired) fit ansatz for the Sivers function (lensing picture)

\[
f_{1T}^{(0)}(x; Q_L^2) = -L(x) E^a(x, 0, 0; Q_L^2)
\]

- Lensing function constraint by anomalous magnetic moments

\[
L(x) = \frac{K}{(1-x)^\eta}
\]

\[
k^p = \int_0^1 \frac{dx}{x} \left[ 2E^{u\nu}(x, 0, 0) - E^{d\nu}(x, 0, 0) - E^{s\nu}(x, 0, 0) \right]
\]

\[
k^n = \int_0^1 \frac{dx}{x} \left[ 2E^{d\nu}(x, 0, 0) - E^{u\nu}(x, 0, 0) - E^{s\nu}(x, 0, 0) \right]
\]

- Sivers function: fit from HERMES, COMPASS, JLab data

\[
f_{1T}^{q\nu}(x, p_T^2) \propto C^{q\nu} (1 - x/\alpha^{q\nu}) (1 - x) f_1^{q\nu}(x) e^{-p_T^2/M_1^2} e^{-p_T^2/(p_T^2)}
\]
Linearly polarized Gluons

(J. Zhou, W. den Dunnen)

Define gluon TMDs through gluonic field-strength tensor

\[
\frac{1}{2} \delta_{ij} x_1 G(x_1, k_{1\perp} = 0) + \frac{1}{2} \delta_{ij} x_1 H_{1g}^1(x_1, k_{1\perp}), \quad \delta_{ij} = \langle [p^i, p^j]\rangle/p \cdot n
\]

Connection: gluon TMDs - small x physics in large nuclei

Calculation of Distribution of lin. pol. gluons in Color Dipole Model, Weizsäcker-William Model, ...

\(\rightarrow\) (partial) saturation of positivity bound

Connection: gluon TMDs - Higgs physics

linearly polarized gluons sensitive to Higgs parity \(\rightarrow\) measure q_T distribution at small q_T
Parton Structure in Hard Exclusive Processes

(Theory overview by M. Diehl)

Generalized Parton Distribution from DVCS, Meson Production, ...

\[ \Delta = p' - p \quad \Delta^+ = -2\xi P^+ \quad t = \Delta^2 \rightarrow \text{GPD} (x, \xi, t, \mu) \]

DVCS amplitude

\[ T_{\text{DVCS}} \sim \int_{-1}^{1} dx \frac{\text{GPD}(x, \xi, t)}{x - \xi + i\epsilon} \rightarrow \Re T \sim \mathcal{P} \int_{-1}^{1} dx \frac{\text{GPD}(x, \xi, t)}{x - \xi}, \quad \Im T \sim \text{GPD}(\xi, \xi, t) \]

Impact parameter Parton Distributions \( \rightarrow \) “Hadron Tomography”

\[ \mathcal{F}_{ij}(x, \vec{b}_T) = \int \frac{d^2\Delta_T}{(2\pi)^2} e^{-i\vec{\Delta}_T \cdot \vec{b}_T} \mathcal{F}_{ij}(x, 0, \vec{\Delta}_T) \]
DVCS and GPD fits

(D. Müller)

Overview on extraction of GPDs from DVCS and Meson Production using global fits and neural networks

Asymmetry / Compton Form Factor fits of HERMES, JLab data
Time-like Compton Scattering

(H. Moutarde, J. Wagner)

Complementary process to DVCS: “crossed process” TCS $\gamma p \rightarrow l^- l^+ p'$

- Measurable at JLab 6, 12
- can test universality of GPDs
- NLO-corrections studied: large effects from gluons

feasible also in ultraperipheral hadron/nuclei collisions at RHIC

RHIC estimates for Bethe-Heitler, Compton, Interference
Compton Form Factors in GK-Model

(H. Moutarde)

Goloskokov-Kroll model designed to describe meson production data ➔ application to DVCS and TCS also describes data reasonably well ➔ supports universality of GPDs
Summary

- Nice data on polarized processes from COMPASS, HERMES, RHIC, JLab, ...
- Future EIC can reduce error bands on data fits for all branches of spin physics.
- Progress in Theory: Global fits, evolution of twist-3 objects, TMDs
- Thanks to all the speakers!