Summary of WG5: Spin and 3D Structure

Conveners: Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu
Pasquale Di Nezza

DIS2022 Santiago de Compostela – 6/5/22
List of Speakers

Jan Matousek
Matteo Cerutti
Patrick Barry
Andrea Simonelli
Miguel Arratia
Bakur Parsamyan
Abhiram Kaushik
Dillon Scott Fitzgerald
Navagyan Ghimire
Maxime Defurne
Johannes Vincenzo Giarra
Jakob Schöngleber
Oskar Grocholski
Paweł Sznajder
Andreas Metz
Scott Wissink
Yiyu Zhou
Daniel Adamiak

Michael Murray
Sergio Leal Gómez
Alexey Vladimirov
Francesco Giovanni Celiberto
Zhongling Ji
Shohini Bhattacharya
Miguel Echevarria
David Frenklakh
Aurore Courtoy
Charles Hyde
Daria Sokhan
Olga Bessidskaia Bylund
Zhite Yu
Qintao Song
Ted Rogers
Fanyi Zhao
Fatma Pinar Aslan
Kemal Tezgin
Poona Choudhary
Stefan Diehl

Kei Nagai
Shunzo Kumano
Yajin Zhou
Wai Kin Lai
Amol Pawar
Ting Lin
Xilin Liang
Yi Yu
Taoya Gao
Yukun Song
Ralf Seidl
Kim Minho

Disclaimer

Many interesting subjects and lots of interesting results
Apologies if we have missed some topic or if I am not accurate in reporting your results
Longitudinal Spin

Courtesy of F. Cuicchio INFN
Jet spin asymmetries: probing gluon helicity distribution

Does the gluon spin contribute significantly to that of the proton?

\[ A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \]

Results from 510 GeV push down to lower \( x_T \)

- Overall consistency seen among STAR data sets, a slight preference for DSSV14

Midrapidity dijets at 510 GeV and 200 GeV

Midrapidity results indicate ~40% of the proton’s spin may be due to contributions from the spins of gluons that each carry at least 5% of the proton’s momentum. Consistency old and new data will allow combined analysis.
Measurement of Direct Photon Cross Section and Double Helicity Asymmetry at 510 GeV in pp Collisions

- Gluon spin is important for proton spin decomposition.
- Direct photons have little fragmentation contributions.
- First direct photon xsec and $A_{LL}$ at 510 GeV.
- Independent constraint on the gluon spin contribution.

First published direct photon $A_{LL}$

Isolated direct photon cross section

- $p + p \rightarrow \gamma + X$, $\sqrt{s} = 610$ GeV, $h_T < 0.25$

Data vs. Theory

- NLO pQCD
  - (by W. Vogelsang)
  - NNPDF3.0 PDF
  - GRV FF

- PHENIX Data
Transversity and Transverse Spin Asymmetries
Probing transversity with **Interference Fragmentation Function** and **Collins asymmetry** in pp collisions

Navagyan Ghimire

**Preliminary results of IFF asymmetry for charged pion pair in pp 200 GeV**

\[ \pi^{\pm} \text{ Azimuthal Distribution in Jets: most precise results of Collins asymmetry in pp at 200 GeV from STAR 2012+2015 data} \]

![STAR Preliminary 2015](image)

- Strong rise of \( A_{UT} \) signal towards higher \( \eta_{pair} \)
- Significant reduction of the PID uncertainty is expected by including TOF

![Graphs showing results](image)

- Collins TMD FF is sensitive to the \((j_T, z)\) dependence;
- Our results slightly favor the KPRY model than DMP+2013;
- Sizable differences between data and both theoretical calculations.
Transverse spin asymmetries in SIDIS and Drell-Yan

New preliminary results on Sivers asymmetry in pion induced Drell-Yan with 2015+2018 COMPASS data

1st results of …

COLLINS ASYMMETRY FOR $\rho_0$
• indication for a positive asymmetry
• opposite to $\pi^+$ and $\pi^0$ as predicted by the models
• Large effect at small $P_T$

SIVERS ASYMMETRY FOR $\rho_0$
• indication for a positive asymmetry
• similar to $\pi^0$ as expected from the models

Sivers DY TSA
$$A_T^{sivers} \propto f_{1_{\pi}}^{q} \otimes f_{1T}^{q}$$

Transversity DY TSA
$$A_T^{2\phi_{cs}^{\pi}} \propto h_{1,\pi}^{q} \otimes h_{1T}^{q}$$

Pretzelosity DY TSA
$$A_T^{2\phi_{cs}^{\pi}} \propto h_{1,\pi}^{q} \otimes h_{1T}^{q}$$

2015 + 2018 data NEW!

Sign-change preferred
TSSA for forward inclusive and diffractive electromagnetic (EM) jets in pp collisions

The EM-jet $A_N$ decreases with photon multiplicity

New preliminary results on the diffractive EM-jet $A_N$
Non-zero diffractive EM-jet $A_N$ Negative sign? $\rightarrow$ theory inputs needed

EM-jet or isolated $\pi^0$ have larger $A_N$

Any contribution from diffractive process?

Note1: All red points are shifted by -0.005 along x-axis

① Only 1 proton track on FMS side and no proton track on the away side.
② Only 1 proton track on FMS side and only 1 proton track on away side.
New results of longitudinal spin transfer $D_{LL}$ versus $z$

Results of transverse spin transfer $D_{TT}$ vs. $z$ for $\Lambda(\bar{\Lambda})$ in pp collisions

$\rightarrow$ connected to transversity & FF
$D_{TT}$ is consistent both with the model predictions and with zero

Ongoing analysis of $\Lambda$ polarizing fragmentation function in unpolarized pp collisions at STAR

Sensitive to polarized FF and strange quark helicity
Transverse spin asymmetries for very forward neutron in pp/pA

$A_N$ of forward neutron in pp at 510 GeV at RHICf:

At high $x_F \rightarrow A_N$ increases

It seems there is an $x_F$ dependence at high $p_T$

$A_N$ increases with $p_T$ consistently, with a weak $x_F$ dependence, in particular at lower $p_T$
Transverse spin asymmetries for heavy flavor electron/positron

$A_N$ of Open Heavy Flavor Electron and Positron provides access to nonperturbative spin-momentum correlations for gluons (contributions from twist-3 $ggg$ correlators and antisymmetric and symmetric $ggg$ correlators).

Data is consistent with theoretical predictions for best-fit parameters and with zero across the measured $p_T$ range.
Spin Independent
Angular correlations are present in data. \( <\cos(2\phi)> \) in data is below back-to-back expectation and RAPGAP prediction. \( <\cos(2\phi)> \) constant for \( Q_T > 2 \) GeV as in the Hatta calculations which includes soft gluon radiation (standard TMD framework) and no effect from elliptic gluons.
Unpolarized SIDIS

New preliminary results (August 2020) on liquid H$_2$ target (11% of stat.)

Azimuthal asymmetries – 1h

Strong kinematic dependences, differences between h$^+$, qualitative agreement with published deuteron results

$P_T$ distributions

Sensitive to \( k_T \) and $P_\perp$ dependence of f1 and D1
Angular distribution of Drell–Yan cross section

\[
\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi
\]

- Naively, \( \lambda = 1, \mu = \nu = 0 \) (\( d\sigma \propto 1 + \cos^2 \theta \)) at leading order

Bakur Parsamyan

DY-2018: tungsten data, NH\textsubscript{3} analysis in progress

Kei Nagai
Lepton-Jet correlation in DIS

lepton jet momentum and azimuthal imbalance in DIS → provides a new way to constrain TMD PDFs and their evolution

“matching” between collinear and TMD frameworks

First time seen in DIS!
GPDs
DVCS Beam Spin Asymmetries with CLAS12

The data shown represents approximately 25% of the beam time allocated to DVCS study with an unpolarized target.

In many bins, data agrees with KM15 predictions except in some bins at large $x_B$ where data agrees better with GK/VGG models.
DVCS cross section t-slope

Full statistics of 2016 and 2017 (about 3 times more than 2016)

... some “tension” between old and new data
Hard exclusive $\pi^- \Delta^{++}$ electroproduction off the proton (CLAS12)

Beam Spin Asymmetries ($Q^2$ and $x_B$ integrated)

BSA clearly negative and $\sim 2$ times larger than for the hard exclusive $\pi^+$ production

$\rightarrow$ potential first “clean” observable sensitive to $p-\Delta$ transition GPDs
Time-like Compton scattering at the Electron-Ion Collider

Expected precision on Beam Spin Asymmetries at EIC

Very good agreement between generated and reconstructed asymmetries

Measurement of BH-TCS interference is possible at EIC with good acceptance and efficiency
Theory
High precision TMD global analysis

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: 2031 data points
- Perturbative accuracy: $N^{3LL}$
- **Normalization** of SIDIS multiplicities beyond NLL
- Number of fitted parameters: 21
- Extremely good description: $\chi^2/N_{\text{data}} \approx 1.00$

Pion PDF & TMD global analysis from pion-induced Drell-Yan with threshold resummation

$q_{\nu}(x) \propto (1 - x)^{\beta}$

Inclusion of $q'$-dependent DY data slightly constrains the sea quark distribution

Then, extend framework to LHC data and nucleon PDFs
The assumption of positive $\Delta g$ puts a significant bias. The positivity is not a general property of MS-bar renormalized PDFs.

First extraction of twist-3, scalar $\bar{g}(x)$ from CLAS beam-spin asymmetry data.

First global analysis of polarized world SIDIS data with small-$x$ evolution.
Power corrections in TMD factorization

\[ d\sigma = H \otimes F \otimes F + \mathcal{O}(q_T/Q) + \mathcal{O}(q_T^2/Q^2) \]

Leading: standard TMD factorization

Next-to-Leading Power (NLP)

NNLP

Soft Collinear Eff. Th. (SCET) approach, focus on
DY analytic calculation of power corrections
at fixed order

OPE approach, all processes

NLP corrections factorizable in terms of
twist-3 TMD

\[ \int dze^{-i\mathbf{p}+\sum_i x_i z_i (p, s|\bar{q}[z_1 n + b, z_2 n + b|F_{\mu+}[\ldots, \infty] \gamma^+ [\infty, z_3 n]q |p,) \]

NLO evolution & coefficient functions derived

Electroweak corrections are subleading
compared to power corrections

General analysis of twist-3,4 TMD and FF for spin-1 particles
New (G)TMD observables

Factorization for thrust distribution in e⁺e⁻ in Region 2 → Access to TMD fragmentation functions

\[ d\sigma_{R_2} \sim H \cdot J \cdot \frac{S}{\gamma_L} \cdot \tilde{D}_{j \to h} \]

Andrea Simonelli

Probing T-odd TMDs (Sivers, Boer-Mulders) using T-odd jet function in SIDIS

Wai Kin Lai

Francesco Celiberto

Amol Pawar

Yajin Zhou

Linearly polarized photon TMD in UPC

Azimuthal asymmetries in \[ \gamma \to \rho^0 \to \pi^+ \pi^- \]

\[
\cos 2\phi \quad \text{Well explained by QED effects}
\]

\[
\cos 4\phi \quad \text{Need QCD (Wigner) contributions?}
\]

γ = 275 GeV, E_p = 10 GeV

Q^2 > 100 GeV^2, 0.15 < η < 0.3

η_b,c production at LHC from gluon TMD at NNLL

Probing T-odd TMDs (Sivers, Boer-Mulders) using T-odd jet function in SIDIS

\[
F_{UU}^{\cos(2\phi J)} \sim h_T^1 \otimes J_T
\]
Nucleon spin & mass sum rule

Double spin asymmetry in dijet production at the EIC

→ Novel observable for gluon orbital angular momentum

Extend the nucleon spin sum rule to QCD x QED

Miguel Echevarria

Calculated all the new 1-loop DGLAP splitting functions

Shohini Bhattacharya

Andreas Metz

David Frenklakh

Different proton mass sum rules: 2-term, 3-term, 4-term decompositions

Helicity distribution in 2D QCD (‘t Hooft model), exact

Enhanced by topological effect at small x
Single spin asymmetry

Old, naive estimate of partonic SSA

\[ A_N \sim \alpha_s \frac{m_q}{P_{hT}} \]

New, complete 2-loop calculation in SIDIS

\[ A_N \sim \alpha_s \frac{xM_N}{P_{hT}} g_T(x) \]

Up to 2\% asymmetry for

\[ \sin(\phi_h - \phi_S) \] (Sivers)
\[ \sin(\phi_S) \]
\[ \sin(2\phi_h - \phi_S) \]

in SIDIS at the EIC

\[ \Lambda \text{ polarization w.r.t. the production plane} \]

Possible origin: spin-dep. TMD FF? Respect isospin symmetry!

\[ e^+ e^- \rightarrow \Lambda hX \]
High precision DVCS

DVCS Compton form factor, 2 loops, 70 diagrams

\[ \mathcal{H} = \sum_{q=u,d,s} \frac{1}{\xi^2} \int_{-1}^{1} dx \ C_q(x/\xi, Q, \mu) H_q(x, \xi, t, \mu) \]

\[ + \frac{1}{\xi^2} \int_{-1}^{1} dx \ C_g(x/\xi, Q, \mu) H_g(x, \xi, t, \mu) \]

\[ \tau(C_F)(z) = \frac{1}{z^{3/2}} \left\{ z^2 \left( -H_{2,1}(z) + 2H_{2,2}(z) - \frac{23}{2} H_{3,0}(z) - \frac{17}{2} H_{2,0,0}(z) - 11H_{2,1,0}(z) - \frac{23}{2} H_{0,0,0,0}(z) \right) 
+ \frac{1}{2} \left( -9H_{1,0,0,0}(z) - 9H_{1,1,0,0}(z) \right) 
+ \frac{1}{2} \left( -9H_{1,2,0,0}(z) - 9H_{2,0,0,0}(z) \right) 
+ \frac{1}{4} \left( 6 + 7z^2 \right) z H_{0,0,0}(z) + \frac{5}{2} \left( 4z^2 + 1 \right) z H_{0,0,0,0}(z) \right\} \]

Including three loop evolution is needed to complete NNLO program → three loop single evolution is not known yet, but will be available soon.
MC and neural network for DVCS

EpIC: a new MC event generator for exclusive reactions

Bridge between models of GPDs and experimental data

problem of the model dependency of GPDs is still poorly addressed

Generate replicas of GPD using NN satisfying all theory constraints
New GPD observables

Exclusive 2-photon production in $\pi N$

QCD factorization proven

$$M(t, \xi, q_T) = \int_{-1}^{1} dx \, F(x, \xi, t; \mu) \cdot C(x, \xi; q_T/\mu)$$

GPD $x, q_T$ dependences do not factorize, unlike in DVCS!

$\rightarrow$ stronger constraint on GPD

NLO calculation of diphoton photoproduction

Sensitive only to charge-odd GPDs

Access to Generalized Distribution Amplitude of pion (timelike analog of GPD)

Access to (spacelike) GPD via dispersion relation

$\rightarrow$ mass radius, mass distribution, pressure distribution and shear force distribution
An exiting session!
Once more we understood how “Spin and 3D structure physics” is interesting and intriguing

Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu
Pasquale Di Nezza
An exiting session!

Once more we understood how “Spin and 3D structure physics” is interesting and intriguing.

Yoshitaka Hatta, Yoshiyuki Miyachi, Qinghua Xu
Pasquale Di Nezza

A big thank to Super-Nestor and the LOC for a fantastic conference!