3D nucleon structure at work

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May 30, 2014
Various processes allow study and test of evolution, universality and extractions of distribution and fragmentation functions. We need information from all of them.

1. **Semi Inclusive DIS** – convolution of distribution functions and fragmentation functions
   \[ f(x) \otimes D(z) \]
   \[ \ell + P \rightarrow \ell' + h + X \]

2. **Drell-Yan** – convolution of distribution functions
   \[ f(x_1) \otimes f(x_2) \]
   \[ P_1 + P_2 \rightarrow \bar{\ell}\ell + X \]

3. **e+ e- annihilation** – convolution of fragmentation functions
   \[ D(z_1) \otimes D(z_2) \]
   \[ \bar{\ell} + \ell \rightarrow h_1 + h_2 + X \]

Combining measurements from all above is important.
Experiment
Colored objects are surrounded by gluons, profound consequence of gauge invariance. Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)

\[ f_{1T}^{\perp \text{SIDIS}} = - f_{1T}^{\perp \text{DY}} \]

One of the main goals is to verify this relation. It goes beyond “just” check of TMD factorization. Motivates Drell-Yan experiments.

AnDY, COMPASS, JPARC, PAX, FERMILAB etc
Barone et al., Anselmino et al., Yuan, Vogelsang, Schlegel et al., Kang, Qiu, Metz, Zhou, AP etc
Drell-Yan

• COMPASS Drell-Yan run starts later this year and continues in 2015. Collaboration with experimentalists from COMPASS (Oleg Denisov (Turin), Michela Chiosso (Turin), etc)

• FERMILAB plans (stage I approval 2013) to explore Drell-Yan with polarized target (access to sea region). Collaboration with Xiaodong Jiang (LANL)

• RHIC plans to explore a possibility to study Drell-Yan at existing facilities. In particular PHENIX and STAR (~2020). Collaboration with Tom Burton, Elke Aschenauer, Alexander Bazilevsky (BNL), Xiadong Jiang (LANL)

\[ e^+ e^- \]

• BELLE (KeK) and BaBar (SLAC) collected an impressive amount of data in e+e- providing access to fragmentation functions.

• Collaboration with Francesca Giordano (CERN), Isabella Garzia (Ferrara)
Proton-Proton

Predicted to be negligible... Turned out to be very big

What generates the asymmetry?

TMD mechanism or twist-3?
TMDs and twist-3 are related

\[ T_F(x, x) = - \int d^2 \vec{k}_\perp \frac{k^2_\perp}{M} (f_{1T}(x, k_\perp))_{SIDIS} \]

Jet left-right asymmetry provides a unique access to this relation

\[ \langle y \rangle = 3.25, \quad \sqrt{s} = 500 (GeV) \]

Gamberg, Kang, AP (2013)
TMDs and twist-3 are related

\[
T_F(x, x) = - \int d^2k_\perp \frac{k_\perp^2}{M} (f_{1T}(x, k_\perp))_{SIDIS}
\]

Predictions and proposals:

\[P^+P \rightarrow \gamma X\]

\[P^+P \rightarrow \ell^+\ell^- X\]

Gamberg, Kang, AP (2013)

Time line ~ 2020
Contributor to various proposals to measure TMDs at Hall B (CLAS 12) and Hall C, Hall A (SOLID)

Collaboration with Harut Avakian, Jian-Ping Chen, Rolf Ent, Kalyan Allada, Jiaodong Jiang, Haiyan Gao, Bogdan Wojtsekhowski, etc

Proposals for new measurements and methods

Work on proposals for Electron-Ion Collider at JLab
JLab 12: examples
Inclusive pion production as a test of factorization. Proposed in 2009

Anselmino, Boglione, D’Alesio, Murgia, Melis, AP (2009)

Prediction 2009

Measurement 2014

Similar to Proton-proton

Allada et al (JLab Hall A) (2014)
$\ell P \rightarrow \ell' \pi X$

**Prediction**
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, AP, Turk
EPJA 39 (2009) 89-100

**Measurement**
X. Qian et all (JLab HALL A)
PRL 107 (2011) 072003
Hadronic tensor contains information on the structure, for SIDIS:

\[ W^{\mu\nu} \propto H^{\mu\nu}(\mu, Q) \int \frac{b_T db_T}{(2\pi)} J_0(b_T P_{h\perp}) \tilde{f}(x, z^2 b_T^2; \mu, \zeta) \tilde{D}(z, b_T^2; \mu, \zeta) + \tilde{Y}(b_T, Q) \]

Just a product in configuration space

Collins, Soper, Sterman 1985
Ji, Ma, Yuan, 2004
Collins, 2011
New methods: TMDs

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Just a product in configuration space

Can we study TMDs in configuration space directly?

Collins, Soper, Sterman 1985
Ji, Ma, Yuan, 2004
Collins, 2011
New methods: TMDs

Hadronic tensor contains information on the structure, for SIDIS:

\[ W^{\mu\nu} \propto H^{\mu\nu}(\mu, Q) \int \frac{b_T dB_T}{2\pi} J_0(b_T P_{h\perp}) \tilde{f}(x, z^2 b_T^2; \mu, \zeta) \tilde{D}(z, b_T^2; \mu, \zeta) + \tilde{Y}(b_T, Q) \]

Can we study it directly experimentally?

\[ \int P_{h\perp} dP_{h\perp} J_0(P_{h\perp} B_T) W^{\mu\nu} \rightarrow H^{\mu\nu} \tilde{f}(x, z^2 B_T^2, \mu, \zeta) \tilde{D}(z, B_T^2, \mu, \zeta) \]

Boer, Gamberg, Musch, AP (2011)

With Harut Avakyan (HALL B) method for JLab 12

“Bessel weighting”
Theory and phenomenology
Part of my collaborators is listed:

**ITALY**
- University of Torino
  - Mauro Anselmino
  - Stefano Melis
  - Elena Boglione
  - Vincenzo Barone

**BNL**
- Jianwei Qiu
- Elke Aeschenauer
- Daniel Pitonyak

**PENN STATE**
- Leonard Gamberg

**Jefferson Lab**
- Anatoly Radyushkin
- Christian Weiss
- Alberto Accardi
- Wally Melnitchouk
- Harut Avakian
- Lingyun Dai
- ... (Format not specified)

**NETHERLANDS**
- Daniel Boer

**GERMANY**
- Werner Vogelsang
- Marc Schlegel

**ITALY**
- University of Cagliari
  - Umberto D'Alesio
  - Francesco Murgia
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  - Alessandro Bacchetta

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**LANL**
- Zhongbo Kang
- Xin Qiang

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- Lingyun Dai
- ... (Format not specified)

**Stony Brook**
- Ted Rogers

**China**
- Bo-Qiang Ma
Jefferson Lab theory: QCD & structure

- Wally Melnitchouk, Alberto Accardi
  QCD, Collinear distributions: unpolarised, helicity
  TMC, hadroproduction, etc

- Anatoly Radyushkin, Christian Weiss
  QCD, Generalized parton distributions, form factors etc
  Effective theories, non-perturbative physics, etc

- Ian Balitsky
  QCD, small-x, collinear distributions

- Alexei Prokudin
  QCD, TMDs

- Jo Dudek, David Richards, Kostas Orginos, Robert Edwards, Andre Walker-Loud
  Lattice QCD
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  QCD, TMDs

- Jo Dudek, David Richards, Kostas Orginos, Robert Edwards, Andre Walker-Loud
  Lattice QCD
Global analysis of helicity PDFs

Completed project with
Christopher Lefky
(undergraduate student from Creighton University) who spent summer 2013 at JLab.
Future

- Collaboration with experimentalists on a TMD data base
- Comprehensive framework of TMD extractions

Time frame

~2015 database, ~2016 framework
Road to TMDs

- TMD formulation, 1990's
- First proofs of factorization and experiment, 2000's
- Rigorous proof of factorization and pheno, 2011-now
- Collinear factorization, 1980's
- Rigorous proof of factorization and pheno, 2011-now
Definition of TMDs

\[
\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_\perp, \mu)
\]

\[
\frac{d\tilde{K}(b_\perp, \mu)}{d \ln \mu} = -\gamma_K(g(\mu))
\]

\[
\frac{d \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{d \ln \mu} = \gamma_F(g(\mu), \zeta)
\]

Collins, Soper, Sterman 1985
John Collins, 2011

Additional parameter to cancel rapidity divergence

\[\tilde{f}(x, b_T; \mu, \zeta)\]

Renormalization Group (RG) parameter
TMD PDF and TMD FF evolve according to Collins-Soper evolution equations

Maximizing “perturbative” content, we can write

\[ \tilde{F}(x, b_T; \mu, \zeta) = (C(b_*) \otimes f(x)) \left( \mu_b e^{S(b_*)} e^{S_{NP}(b_T)} \right) \tilde{F}_{NP}(x, b_T) \]

Perturbative \hspace{2cm} Non perturbative

\[ \mu_b = C_1 / b_* \]

\[ b_* \in [0, b_{max}) \]

Non perturbative input is universal and could be accessed in various processes
TMD evolution: from low to high energy

Combination of available information from various processes
TMD extraction

- SIDIS
- Drell-Yan
- TMD
- e+ e-
TMD extraction

SIDIS + DY

Anselmino, Boglione, Melis, AP

~2015
TMD evolution: from low to high energy

SIDIS + DY
Anselmino, Boglione, Melis, AP
~2015

SIDIS + e+e-
Yuan, Sun, Kang, AP
~2014 – 2015

SIDIS
TMD
Drell-Yan
e+ e−
TMD extraction

SIDIS, DY
Anselmino, Boglione, Melis, AP
~2015

Drell-Yan

SIDIS, e+e-
Yuan, Sun, Kang, AP
~2014 – 2015

Proton-proton, twist-3

SIDIS, DY, e+e-, proton-proton
Kang, Gamberg, AP
~2015 – 2016

SIDIS

e+ e-

TMD

Proton-proton, twist-3
TMD extraction

Collaboration will be created in ~ 2015

- Drell-Yan
- SIDIS
- Proton-proton, twist-3
- e+ e-
Workshop

In order to boost the progress in the field we organized QCD Evolution Workshop in 2011, 2012, 2013, 2014

Collaboration will be created in ~ 2015
Other processes
Gamma SIDIS

$\ell P \rightarrow \ell' \gamma X$

Suggested by Bogdan Wojtsekhowski

Access to $T_F(x_1, x_2) x_1 \neq x_2$ important for evolution

Open charm SIDIS

Access to tri-gluon correlators, Evolution, Drell-Yan, Higgs production, Incusive asymmetries...

Collaboration
Radyushkin, Schlegel, AP
~2015

Collaboration
Kang, Lingyun Dai, Vitev, AP
~2014 – 2015
A. Prokudin (2012) contribution to EIC white paper
ELECTRON ION COLLIDER

A. Prokudin (2012) contribution to EIC white paper

Updates of white-paper: with Feng Yuan, Jianwei Qiu, Zhongbo Kang ~2014-2015
Experiment

- Drell-Yan
  - ~2015-2020
- Proton-proton
  - ~2015-2020
- Electron-proton
  - JLab 12
    - ~2016-2026
  - Electron-Ion Collider
    - ~2026

Phenomenology

- Jlab based analysis center
  - ~2015-2016
- Database
  - ~2016-2017
- Extraction framework in JLab
  - ~2015-2016
- “CTEQ like” TMD collaboration
  - ~2015-2016
THANK YOU!