Exploring parton correlations with target fragmentation

C. Weiss (Jefferson Lab), Correlations in partonic and hadronic interactions,
Duke University, 7-12 Mar 2022 [Webpage]

Parton picture

Soft interactions vs QCD
Particle densities and correlations

Target fragmentation in DIS

Kinematic variables
QCD factorization and fracture functions
Dynamics

Exploring parton correlations

$x, z$, charge/flavor, spin: Collinear factorization

$p_T$: TMD factorization

Dedicated physics/detector workshops

Target fragmentation physics with EIC
CFNS Stony Brook 28-30 Sep 2020 [Webpage]

Target fragmentation and diffraction physics with novel processes, CFNS, 9-11 Feb 2022 [Webpage]
**Parton picture: Many-body system**

**Parton picture**

Hadron in high-energy processes as “beam” of particles

Closed system: Wave function, many-body system

Soft interactions: Limited range in rapidity, multi-step interactions [Feynman, Gribov 70s]

**QCD**

Quarks/gluons not normally collinear: Interactions at large rapidities, UV divergences, renormalization

Collinear sectors in high-energy processes

Factorization: Radiation separated in collinear - hard - soft

Partonic wave function emerges in context of factorization, scale-dependent
**Parton picture: Correlations**

**Many-body system**

One-body density describe particle content, momentum distribution

Correlations reveal interactions, configurations in system

Example: NN correlations in nuclei

**Target fragmentation in high-energy scattering**

High-energy process removes parton

Observe fragmentation of target remnant

Correlations: Longitudinal momentum, spin/flavor, transverse momentum

DIS $ep$: QCD factorization for target fragmentation

Other processes: $\gamma p, pp$
Target fragmentation: Kinematic variables

Feynman variable

\[ x_F = \frac{p_h^z}{p_h^z (\text{max})} \] in CM frame \( p = -q \), \(-1 < x_F < 1\)

Natural for hadron-hadron collisions

Scaling hypothesis in soft int: \( E_h (dN_h/d^3p_h) = F(x_F, p_T) \)

Rapidity

\[ y = \frac{1}{2} \log \frac{p_h^+}{p_h^-} = \frac{1}{2} \log \frac{E_h + p_h^z}{E_h - p_h^z} \]

Collinear boost simple \( y \to y + \Delta y \)

Natural for soft interactions, e.g. string fragmentation

Light-cone fraction

\[ z = \frac{p_h^+}{(1-x)p^+} = \frac{\text{hadron}}{\text{remnant}} \]
\( 0 < z < 1 \)

Natural for parton picture, QCD factorization

\( z \approx -x_F \) in target fragmentation region \( z = O(1) \)

Definition of “target fragmentation region” is a matter of criteria/judgment → Discussion
Target fragmentation: QCD factorization

Semi-inclusive hadron production in target region
\( \gamma^* + N \rightarrow X + h(\text{target}) \)

Trentadue, Veneziano 1994: \( p_T \)-integrated
Collins 1998: Fixed \( p_T \)

QCD radiation: DGLAP, same as inclusive DIS

Predicts \( Q^2 \)-scaling for fixed \( z, p_T \ll Q \)

Fracture functions / Conditional PDFs

Probability to find hadron with \( z, p_T \) in target after removing parton with \( x \)

Universal, independent of hard process

Leading-twist structures, simpler than TMDs

QCD factorization

\[
\begin{align*}
f_h(x, z, p_T) &= \sum_{X'} \int d^2k_T \\
& \langle p \mid a^\dagger(k) \mid hX' \rangle \langle hX' \mid a(k) \mid p \rangle_{k^+=xp^+}
\end{align*}
\]

[Naive expression: Gauge link, renormalization]
Target fragmentation: Dynamics

Information in fracture functions

Hadronization of nucleon with “hole” in partonic wave function

→ Parton correlations in initial state
→ Interactions in final state

Dynamics

Color forces — string fragmentation?

Chiral symmetry breaking interactions, $q\bar{q}$ pairs?

Challenge in model building:
Interactions in both initial and final state

Example: $\Lambda$ fracture function extracted from analysis of neutrino and DIS data

[Ceccopieri, Mancusi 2012]

Strong discrepancy with string model

[Kaidalov, Piskounova]
Correlations: Longitudinal momentum, parton type

$x$-dependence of target fragmentation

Remove parton from different configurations in wave fn

$x > 0.3$: mostly valence quarks, few-body dynamics

$x \ll 0.1$: mostly singlet quarks and gluons, many-body dynamics, radiation

Dependence on charge/flavor of removed parton

Hadronization of system after removal of valence or sea quark

Flavor relations for proton fragmentation in p, n

Hadronization after gluon removal? Largely unknown

$z$-dependence of target fragmentation

Counting rules $(1 - z)^n$ for leading hadron fragmentation [Frankfurt, Strikman 81]
Target fragmentation in polarized DIS

Polarized DIS leaves remnant system with definite spin

Study spin dependence of fragmentation

Fragmentation observables sensitive to spin

\[ N - \Delta \text{ production ratio [Strikman 2013]} \]

\[ \Lambda \text{ production: Polarization transfer} \]

Azimuthal asymmetries with beam and target spin:
T-even and odd structures, as in current fragmentation SIDIS [Anselmino, Barone, Kotzinian 2011]

\[
\frac{d\sigma}{dx dQ^2 dz dp_T d\phi_h} = \ldots + \sum_n \ldots \cos n\phi_h + \sum_n \ldots \sin n\phi_h
\]

[→ Talk T. Hayworth]
Correlations: Transverse momentum

**$P_T$ of current fragmentation hadrons**

Compounded from several mechanisms:
- Intrinsic $k_T$ of partons in target
- QCD radiation, Sudakov-suppressed
- Fragmentation process

Separate different mechanisms?

**$P_T$ correlation measurements**

$P_T$ correlations as function of rapidity distance

“Balancing” of current fragmentation $P_T$

Soft interactions: Simple interpretation

QCD: Radiation. Description to be developed.

SCET methods?

Current-current or current-target correlations
Summary

• Target fragmentation in DIS presents simple process for exploring parton correlations
  
  Collinear factorization, leading-twist structures, simpler than TMD factorization

• Dynamical modeling of fracture functions remains major challenge
  
  Combine initial-state structure and final-state interactions

• Parton correlations can be explored through fracture function dependencies
  
  Longitudinal momentum $x, z$; parton flavor/charge, spin, transverse momentum $p_T$

• Target fragmentation experiments
  
  Existing data: $ep/\mu p$ Cornell, EMC, HERA; $\nu p$ FNAL, CERN

  JLab12: Explore applicability of fracture function description, many opportunities

  EIC: Target fragmentation studied in 2021 Yellow Report, topical workshops

• Other processes complementary to DIS: $\gamma p$ ultraperipheral, $pp$ at LHC, RHIC → program
Target fragmentation: DIS measurements

Fixed-target experiments

\textit{ep/en}: Cornell, JLab12

\textit{\mu p}: CERN EMC

\textit{\nu p, \bar{\nu} p}: FNAL, CERN

These experiments had detector coverage at $x_F < 0$ and reported target fragmentation measurements.


Collider experiments

\textit{ep}: HERA

EIC detector coverage
Target fragmentation: Cornell electron-proton

Cornell Synchrotron 1975
\[ \gamma^* + p(n) \rightarrow p + X, \text{ also } \pi^\pm + X \]
Proton acceptance \( x_F \approx x' = [-1, 1] \)

Proton \( x_F \) distribution
- Protons mostly produced in TF region
- Comparison of \( Q^2 \) and \( W \) bins
- Fewer \( p \) produced with \( n \) target

K.M. Hanson, CLNS-317 (1975) [INSPIRE]
Target fragmentation: Cornell electron-proton

Proton $p_T$ distribution

- Approximate Gaussian dependence
  $$\propto \exp(-bp_T^2)$$
- Slope $b \approx 4 \text{ GeV}^{-2}$
- Practically no $W$ dependence

Many more results: $\pi^\pm, K^\pm$
Could be compared with JLab 6/12 GeV

K.M. Hanson, CLNS-317 (1975) [INSPIRE]
$x_F$ distributions of $p, \pi^\pm, K^\pm, \Lambda, K^0$

- Comparison $p \leftrightarrow \pi$ in TF region
- Comparison $\pi^\pm \leftrightarrow K^\pm$
- Comparison with Lund model
- [Also: Rapidity distributions]

M. Arneodo et al., PLB 150, 458 (1985) [INSPIRE]

Average $\langle p_T^2 \rangle$ of $\pi, K, p$

- Comparison $\pi \leftrightarrow K \leftrightarrow p$
- Comparison with Lund model

CERN EMC $\mu p$ 280 GeV

$Q^2 > 4 \text{ GeV}^2, x > 0.02, 16 < W^2 < 400 \text{ GeV}^2$
$Q^2$-dependence of pion distributions at $x_F < 0$

- $Q^2$ scaling observed at fixed $W$

Further EMC measurements:

Correlations target-current regions, $p_T$ balancing
$x_F$ distributions of $\pi^\pm$

- Independent of $W$ — Feynman scaling
- Deviations from Lund model at $x_F < 0$

CERN broadband neutrino beam from 350-400 GeV protons
$\nu p/\bar{\nu}p$ CC events, $E_{\text{vis}} > 5$ GeV, $p_\mu > 3$ GeV

P. Allen et al. NPB 214, 369 (1983) [INSPIRE]

Aachen-Bonn-CERN-Munich-Oxford Collaboration
Target fragmentation: FNAL antineutrino-proton

Normalized $x_F$ distributions of $\pi^\pm$ produced in $\bar{\nu}p, \gamma p, ep$ ($\bar{\nu}p$ normalization adjusted at $x_F < 0$)

- Similar TF distributions obtained with all probes
- [Also: Rapidity, $p_T$ distributions]

Normalized $x_F$ distributions of $\pi^\pm$ in $\bar{\nu}p$ and $\pi p$ ($\pi p$ normalization adjusted)

FNAL broadband neutrino beam from 300-400 GeV protons
Bubble Chamber detector for muon and charged hadrons
M. Derrick et al., PRD 17, 1 (1978) [INSPIRE]
**Target fragmentation: HERA electron-proton**

Proton distributions of leading baryons:
Protons $p_T < 0.7$ GeV,
Neutrons $p_T < 0.2$ GeV

[Proton distribution does not contain diffractive peak at $x_L \approx 1$]

- $Q^2$-scaling of leading baryon distributions

- Integrated baryon number at $x_L > 0.1$ is only ~0.6-0.7

Significant baryon number transport away from TF region.

Surprising result, because in the kinematics $x \lesssim 0.01$ the DIS process involves mostly sea quarks, not valence quarks

**ZEUS:** S. Chekanov et al., JHEP 06, 074 (2009) [INSPIRE]
**H1:** F. Aaron et al., Eur.Phys.J.C 68, 381 (2010) [INSPIRE]
Target fragmentation: EIC detector coverage

Pseudorapidity $\eta$ covered in proton target fragmentation measurements at various $x_F$ and $p_T$

- Significant part of target fragmentation hadrons between central detector $\eta \gtrsim 3.5$ and forward detectors $\eta \gtrsim 4.5$
- Target fragmentation coverage depends on proton beam energy

[Weiss 2021, prepared for EIC Yellow Report [INSPIRE]]