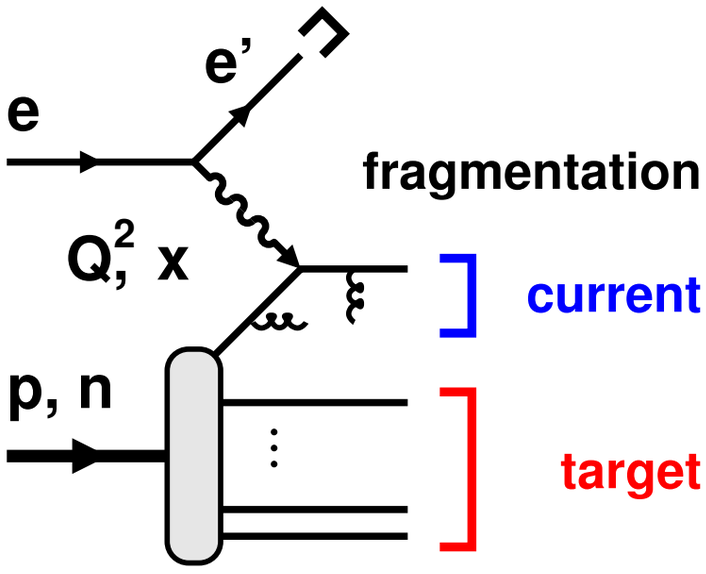
Exploring parton correlations with target fragmentation

C. Weiss (Jefferson Lab), EIC 2nd Detector Workshop, CFNS Stony Brook, 6-8 Dec 2022 [Webpage]

Jefferson Lab



Many-body systems

1p densities → 2p correlations

Hadrons: Parton picture, QCD collinear sectors

Target fragmentation in DIS

Kinematic variables

QCD factorization and fracture functions

Exploring parton correlations

x, z, charge/flavor, spin dependence

p_T dependence in current-target correlations
↔ chiral symmetry breaking in QCD vacuum

EIC measurements

Detector coverage for proton fragments

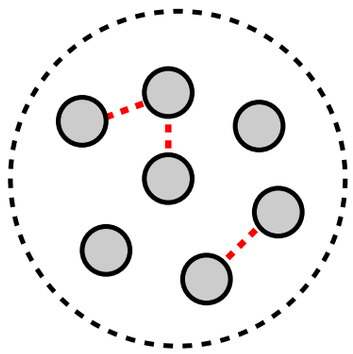
Dedicated physics/detector workshops

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]

Topic in 2021 EIC Yellow Report [INSPIRE]]

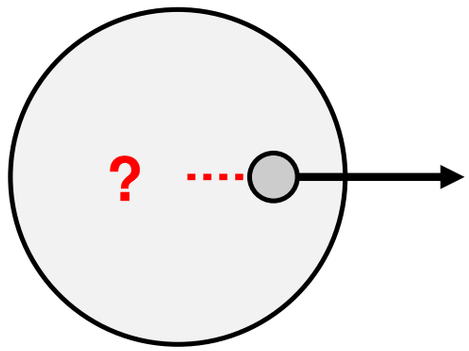
Many-body systems: Densities and correlations



Interacting many-body system

Here: Fixed particle number

$\Psi(\mathbf{r}_1, \ldots \mathbf{r}_N)$ $\Phi(\mathbf{p}_1, \ldots \mathbf{p}_N)$ N-particle wave function

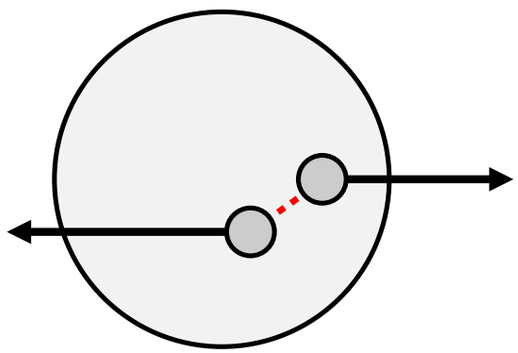


1p density

$$\rho^{(1)}(\mathbf{r}) = \int d^3r_1 \ldots d^3r_n \sum_i \delta(\mathbf{r} - \mathbf{r}_i) \, |\Psi(\mathbf{r}_1, \ldots \mathbf{r}_N)|^2$$

Average particle density in position/momentum

No information on configurations or interactions



2p density

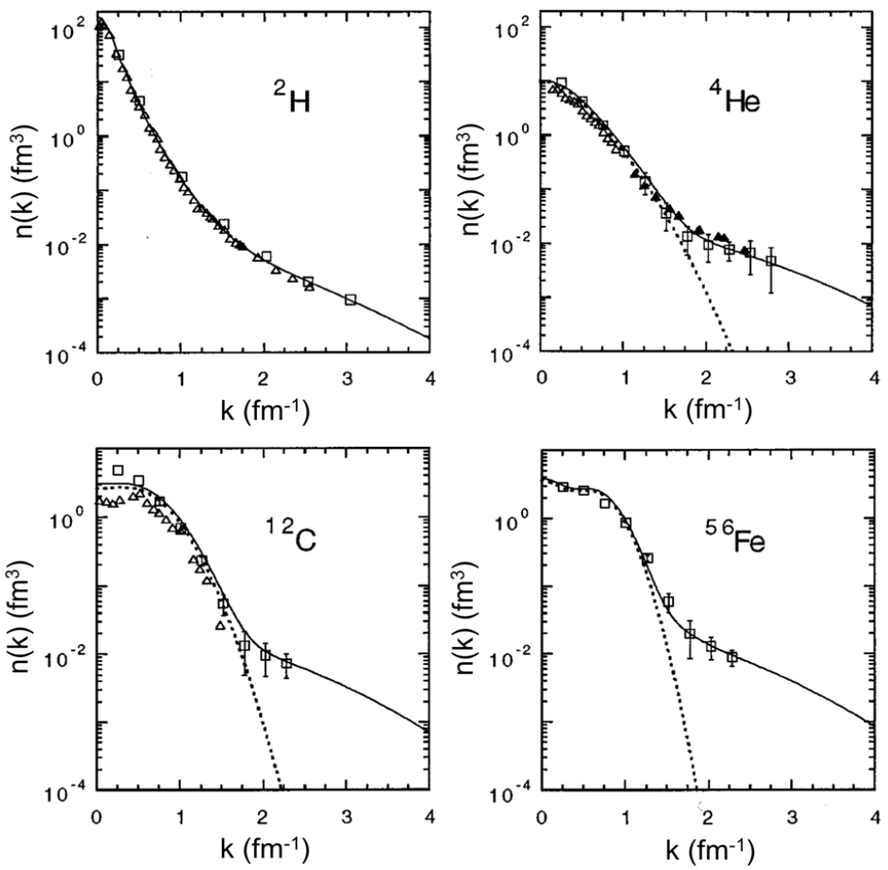
$$\rho^{(2)}(\mathbf{r}, \mathbf{r}') = \int d^3r_1 \ldots d^3r_n \sum_{i,j} \delta(\mathbf{r} - \mathbf{r}_i) \, \delta(\mathbf{r}' - \mathbf{r}_j) \, |\Psi(\mathbf{r}_1, \ldots \mathbf{r}_N)|^2$$

Interactions in system

Character of motion: independent, correlated $\rho^{(2)} \leftrightarrow \rho^{(1)}\rho^{(1)}$

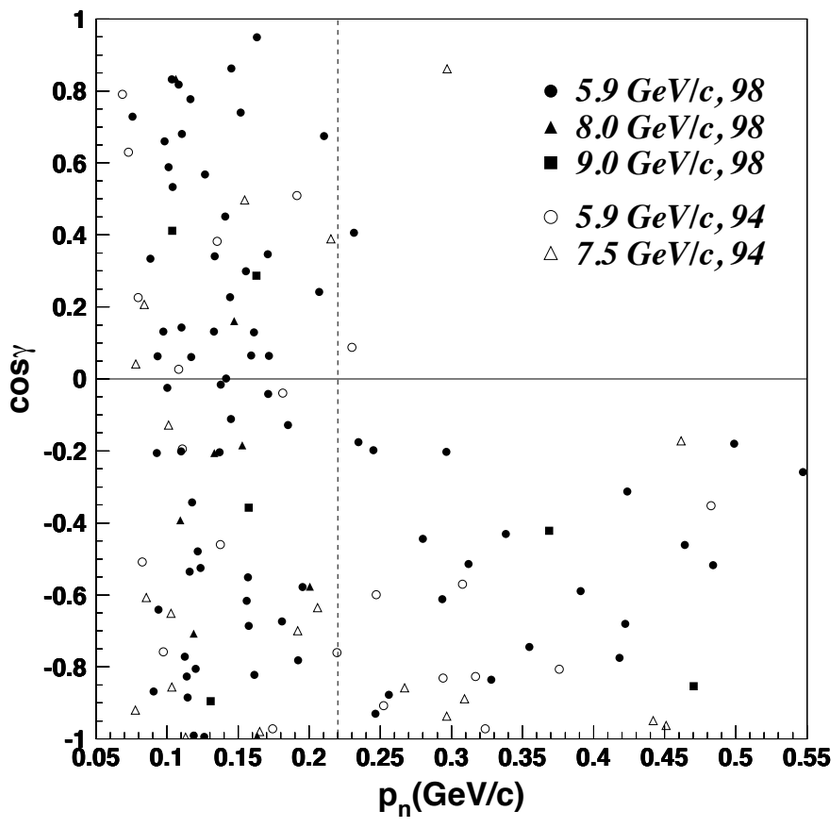
Many-body systems: NN correlations in nuclei

Ciofi degli Atti, Simula 1996

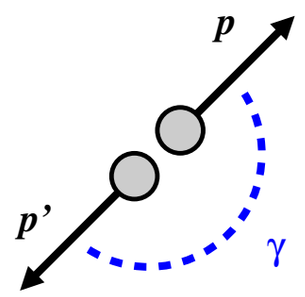


from $e + A \to e' + N + X$ and similar

Piasetzky et al 2006



from $p + A \to NN + X,\ 3N + X$
or $e + A \to e' + NN + X$

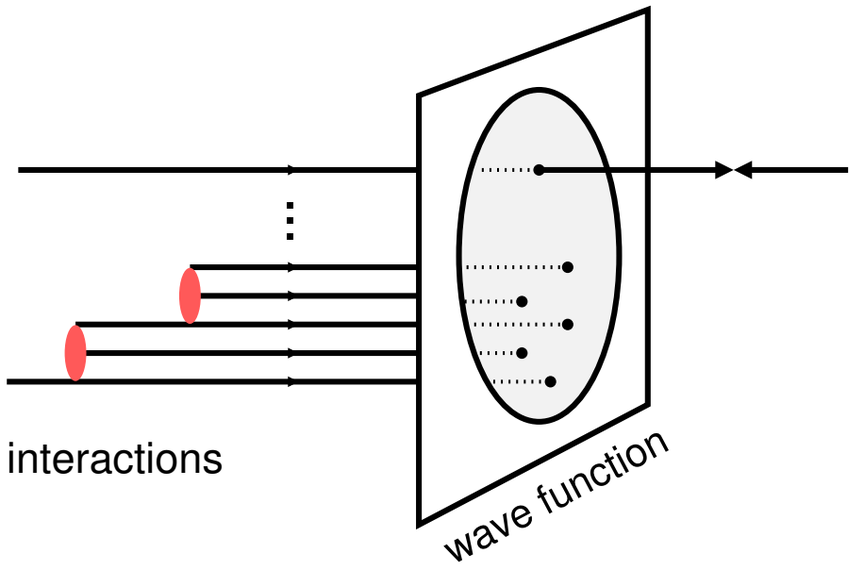


1p nucleon density shows high-momentum tail

2p nucleon density reveals that tail results from correlated NN pairs

Many interesting results: Isospin structure pn, universality, 3N correlations…

Many-body systems: Hadrons

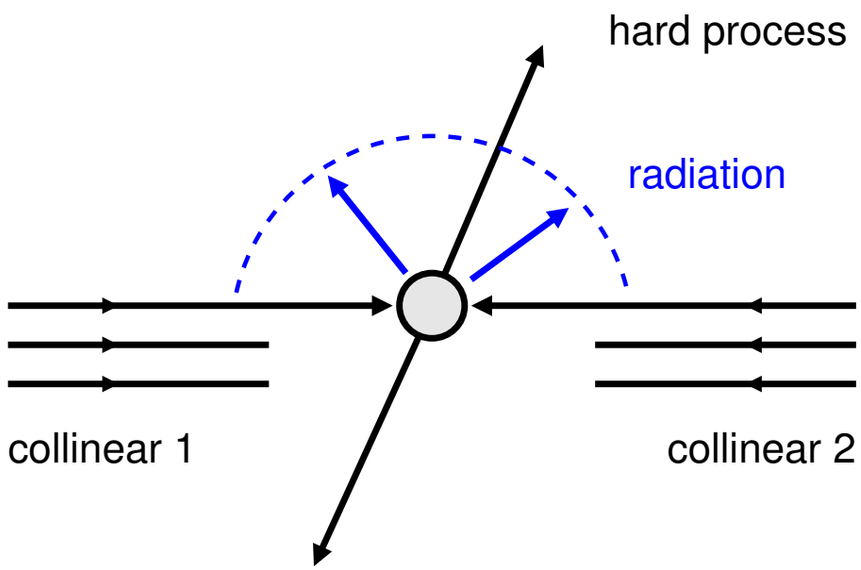


Parton picture

Hadron in high-energy processes as composite system of point particles

Closed system: Wave function

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



QCD

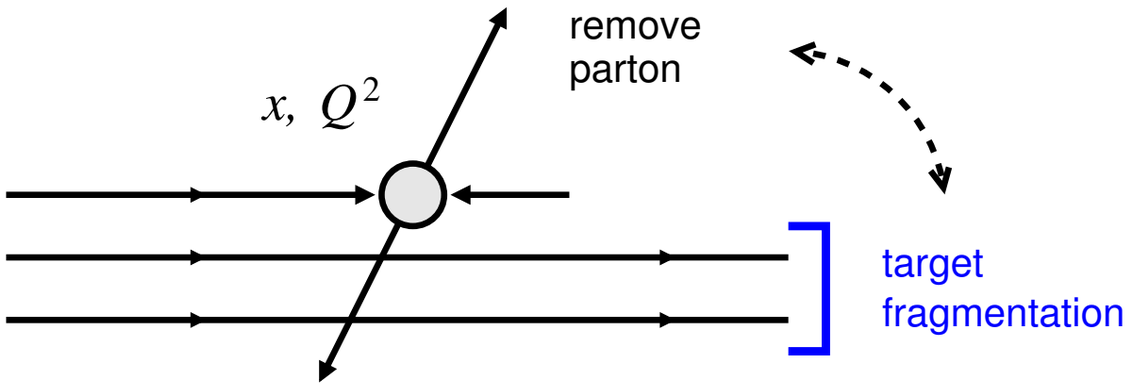
Quarks/gluons not normally collinear: Interactions at large rapidities, UV divergences, renormalization

Collinear sectors in high-energy processes

Factorization: Radiation separated in collinear - hard - soft

Partonic wave function emerges in context of factorization, scale-dependent

Many-body systems: Target fragmentation



High-energy process removes parton

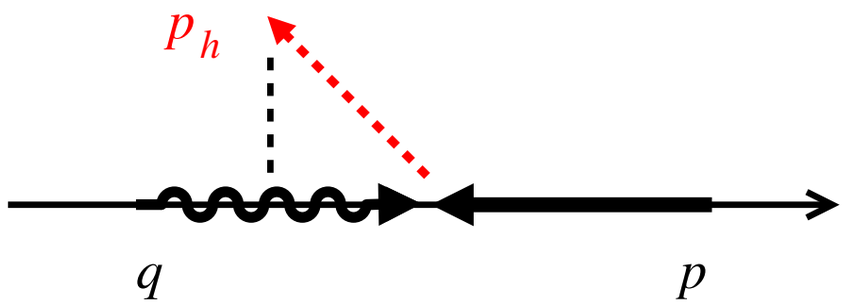
Observe fragmentation of target remnant

Correlations: Longitudinal momentum, spin/flavor, transverse momentum

DIS in ep: QCD factorization theorem for target fragmentation

Learn about interactions!

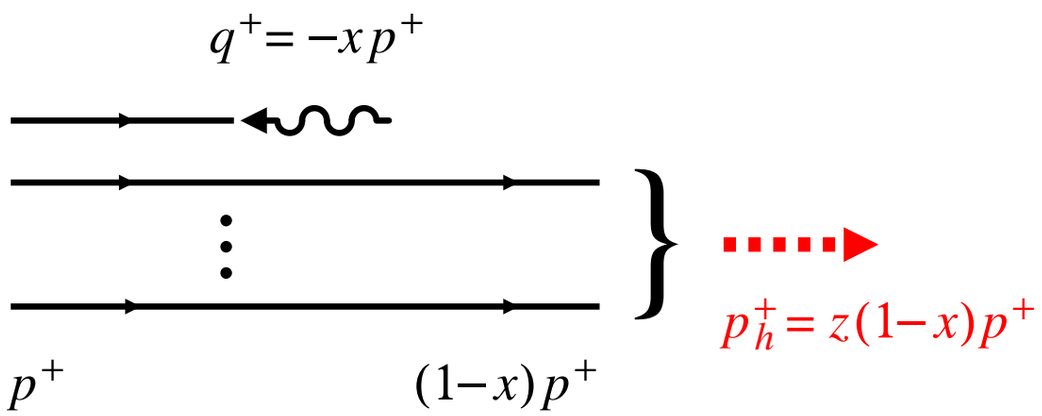
Target fragmentation: Kinematic variables



Feynman variable

$$x_F = \frac{p_h^z}{p_h^z\,(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

Natural for hadron-hadron collisions



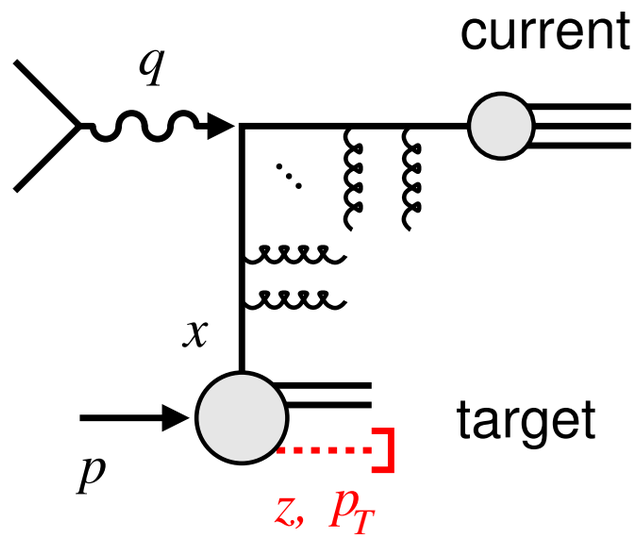
Light-cone fraction

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

Natural for parton picture, QCD factorization

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

Target fragmentation: QCD factorization



QCD factorization

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

Trentadue, Veneziano 1994: p_T-integrated
Collins 1998: Fixed p_T

QCD radiation: DGLAP, same as inclusive DIS

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

$$f_h(x,z,p_T) = \sum_{X'} \int d^2k_T$$
$$\langle p \,|\, a^\dagger(k) \,|\, hX' \rangle \langle hX' \,|\, a(k) \,|\, p \rangle_{k^+ = xp^+}$$

[Naive expression: Gauge link, renormalization]

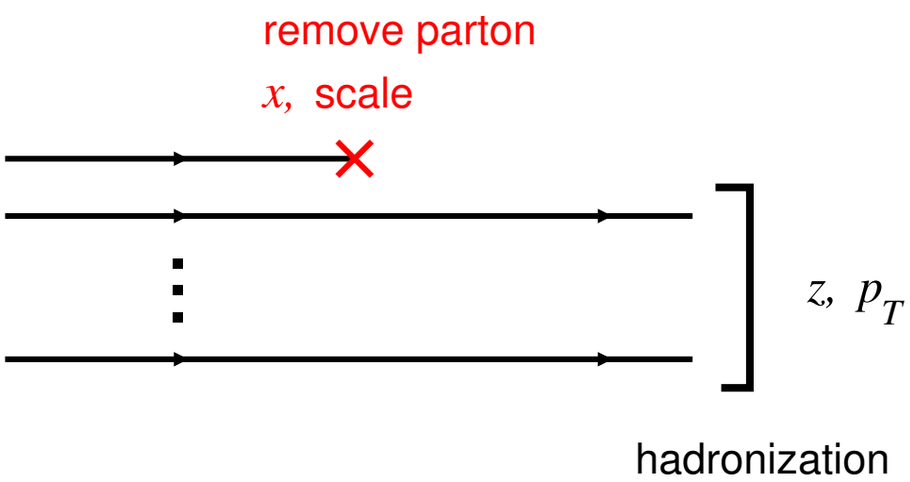
Fracture functions / Conditional PDFs

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

Target fragmentation: Dynamics

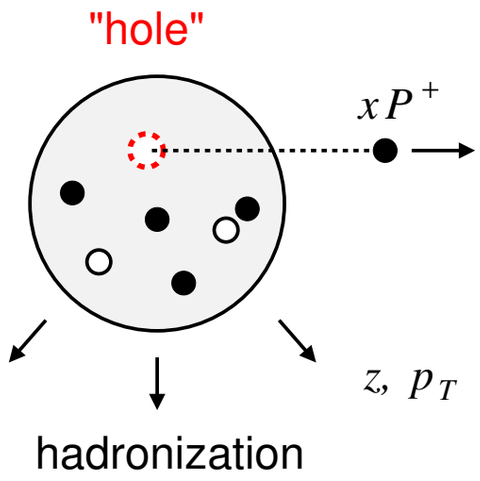


Information in fracture functions

Hadronization of nucleon with “hole” in partonic wave function

→ Parton correlations in initial state

→ Interactions in final state



[Rest frame view: Light-front wave function]

Nonperturbative dynamics

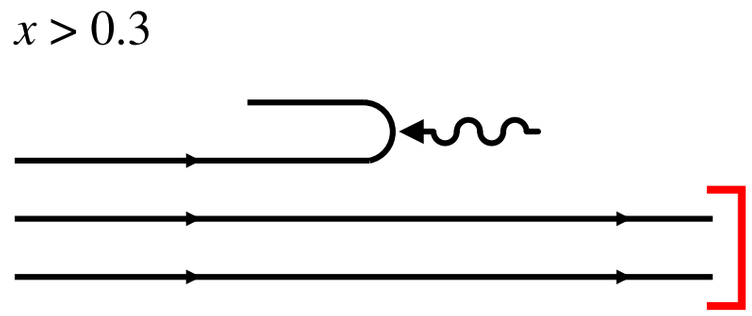
Color forces — string fragmentation?

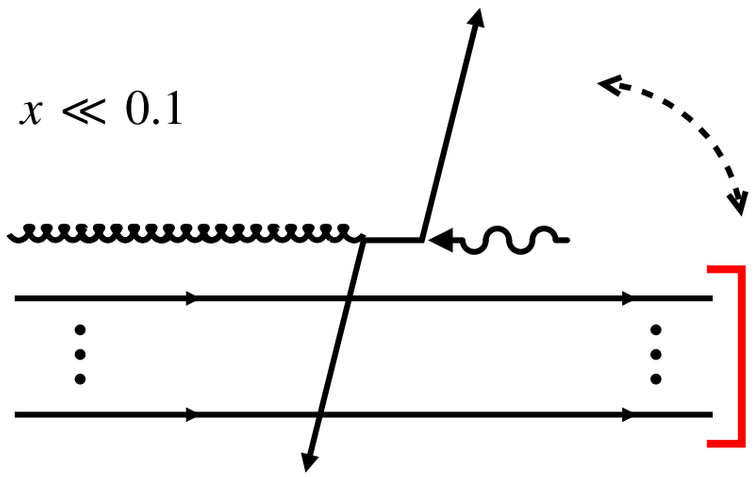
Diquark correlations between valence quarks?

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

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

Target fragmentation: x, z dependence





x-dependence of target fragmentation

Remove parton from different configurations in wave fn

$x > 0.3$: remove valence quarks - “source” of wave fn

$x \ll 0.1$: remove singlet quarks or gluons in multiparticle configurations

Dependence on charge/flavor of removed parton

Hadronization of system after removal of valence or sea quark

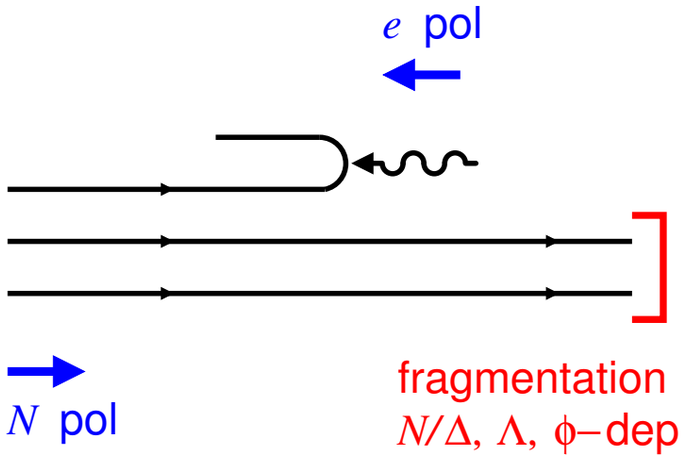
Flavor relations for proton fragmentation in p, n

Hadronization after gluon removal? Largely unknown

z-dependence of target fragmentation

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

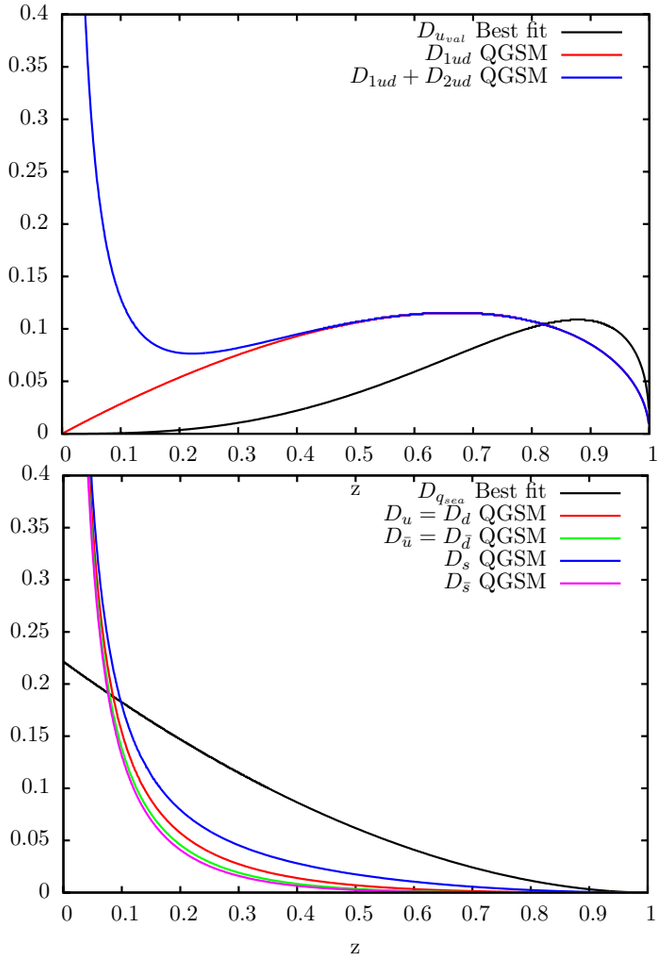
Target fragmentation: Spin correlations



Target fragmentation in polarized DIS

Polarized DIS leaves remnant system with definite spin

Study spin dependence of target fragmentation



Fragmentation observables sensitive to spin

$N - \Delta$ production ratio [Strikman 2013]

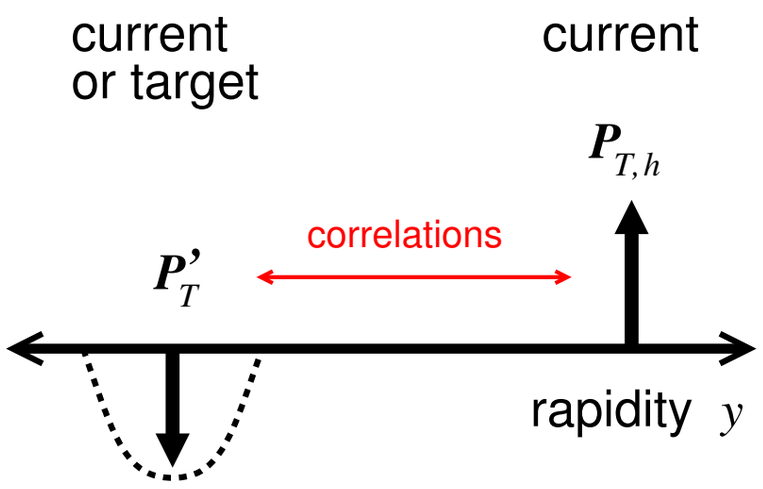
Λ production: Polarization transfer
[Ceccopieri, Mancusi 2012: Neutrino + DIS data]

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

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

Many opportunities with JLab12 and EIC

Target fragmentation: P_T correlations



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

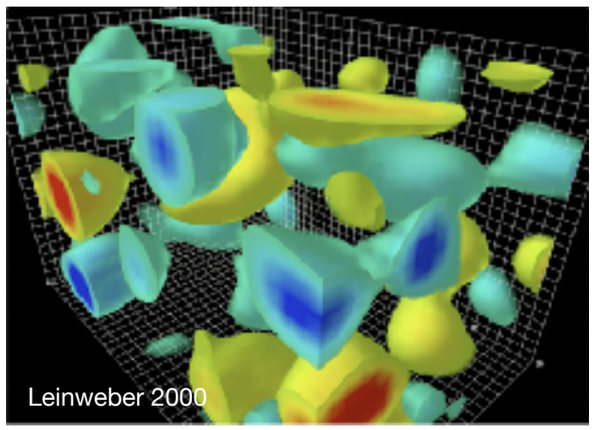
“Balancing” of current fragmentation P_T

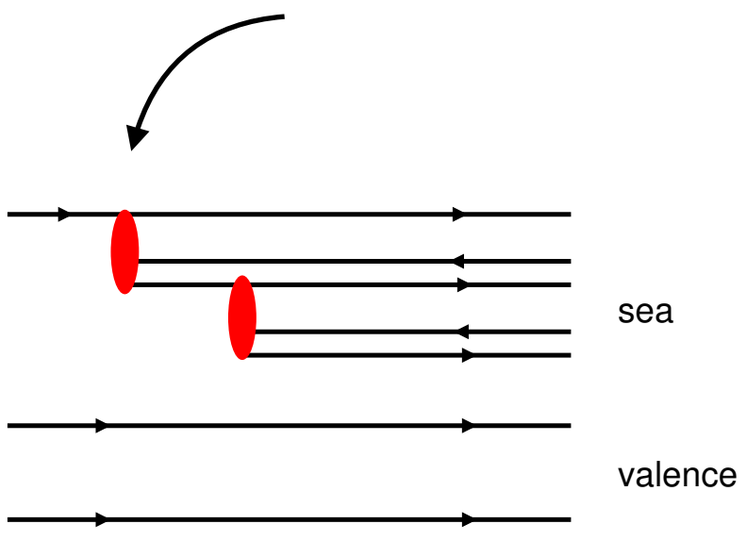
Soft interactions: Simple interpretation

QCD: Radiation. Description to be developed.
SCET methods?

Current-current or current-target correlations

Target fragmentation: P_T correlations from ChSB





Nonperturbative gluon fields in QCD:
Strong, localized ~0.3 fm, topologically charged ± 1

Vacuum state: Chiral condensate $\langle \bar{q} q \rangle \neq 0$

Nucleon state: $\bar{q} q$ pairs in partonic wave function

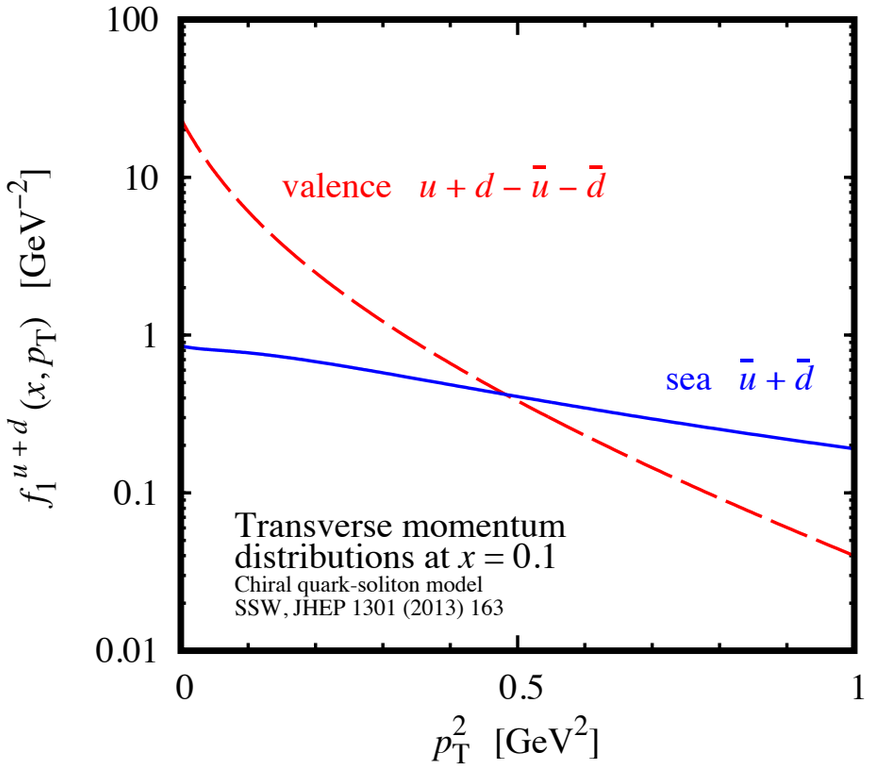
$\rightarrow \; p_T(\text{sea}) \sim \rho^{-1} \; \gg \; p_T(\text{valence})$

$\rightarrow \; \bar{q} q$ correlations in sea

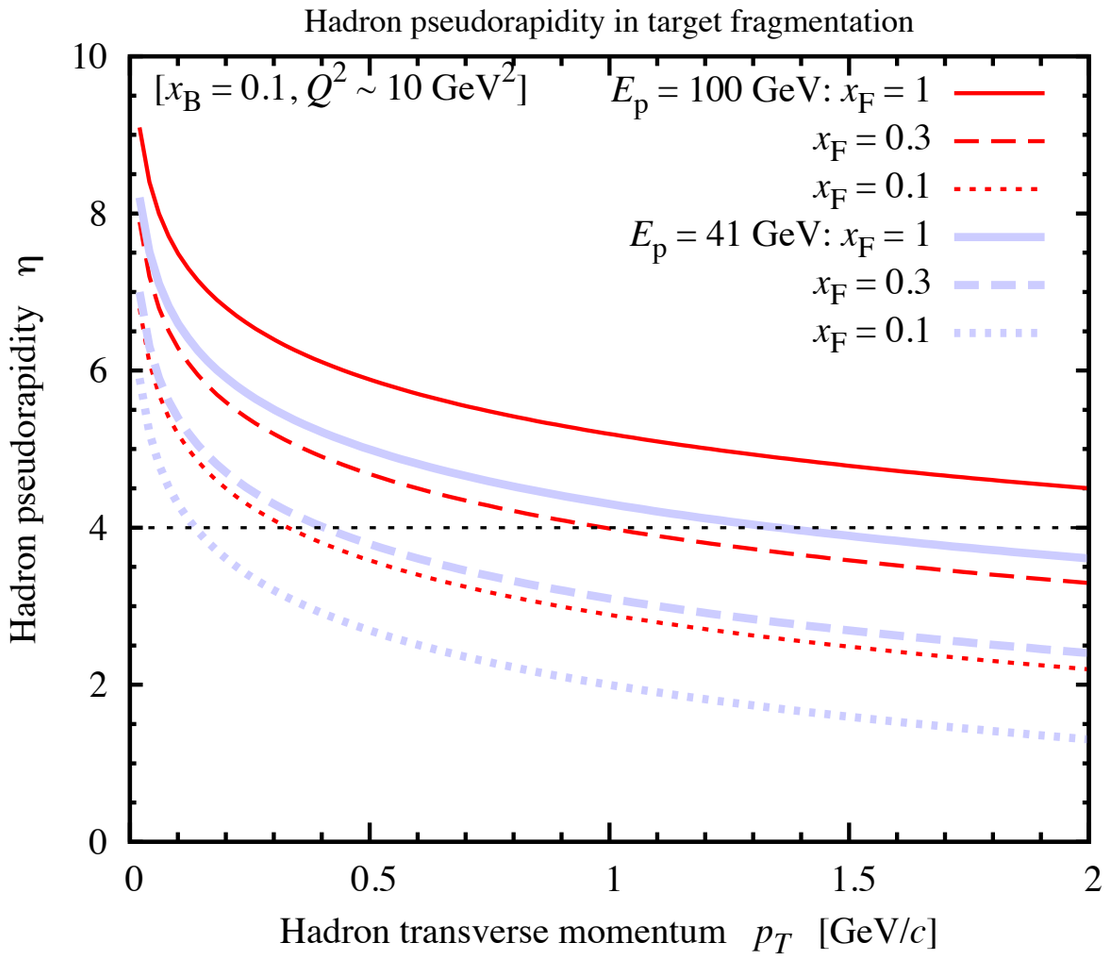
Can be probed in current-target correlations
Kinematics $\Delta y \approx 4$, $Q^2 \sim$ few GeV^2 limits pert radiation

Direct manifestation of chiral symmetry breaking in QCD!

Further modeling/simulations needed
Schweitzer, Strikman, Weiss 2013



EIC measurements: Detector coverage



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

Pseudorapidity η covered in proton target fragmentation measurements at various x_F and p_T

Some target fragmentation hadrons between central detector $\eta \gtrsim 3.5$ and forward detectors $\eta \gtrsim 4.5$

Target fragmentation = inclusive measurements, desire full coverage

Target fragmentation coverage depends on proton beam energy

Summary

- Study of hadron structure in QCD will move from 1p densities to 2p correlations:
  → configurations, interactions?

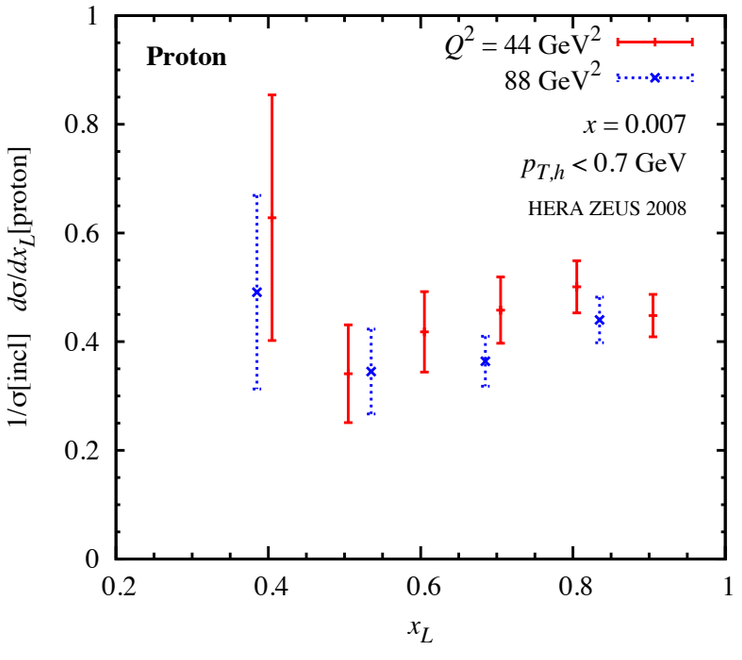
- Target fragmentation and current-target correlations can provide unique access to parton correlations: Theory/modeling/simulations needed

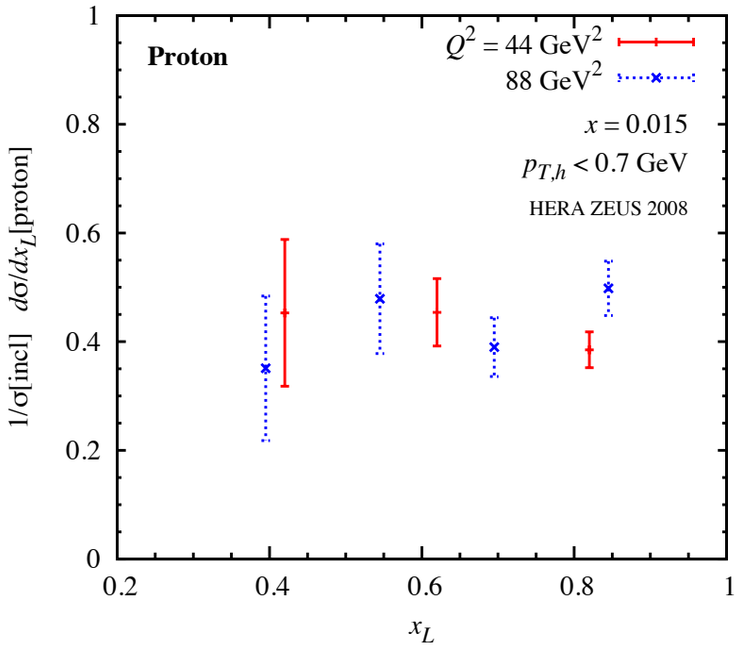
- Nonperturbative $q\bar{q}$ correlations in nucleon sea from chiral symmetry breaking in QCD
  ↔ “origin of mass”

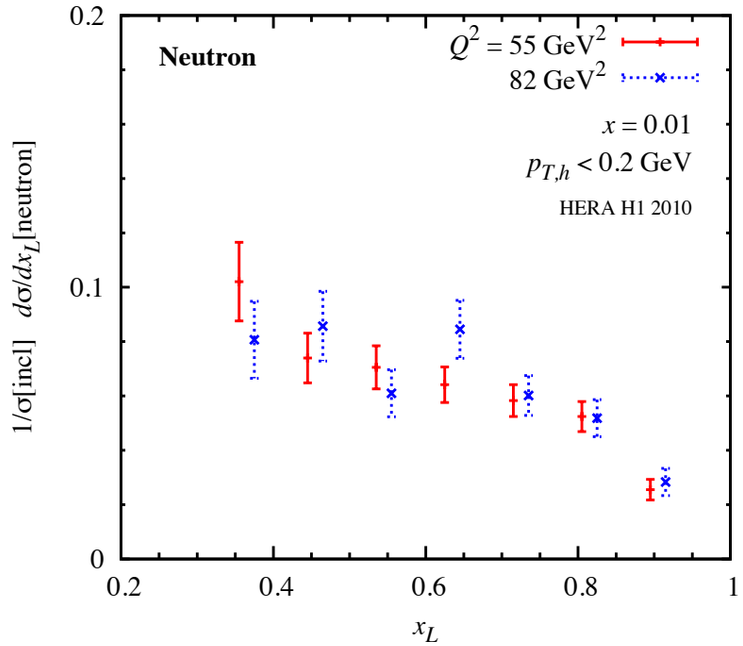
- Target fragmentation measurements with EIC require detector coverage “between” central $\eta < 3.5$ and far-forward $\eta > 4.5$ systems

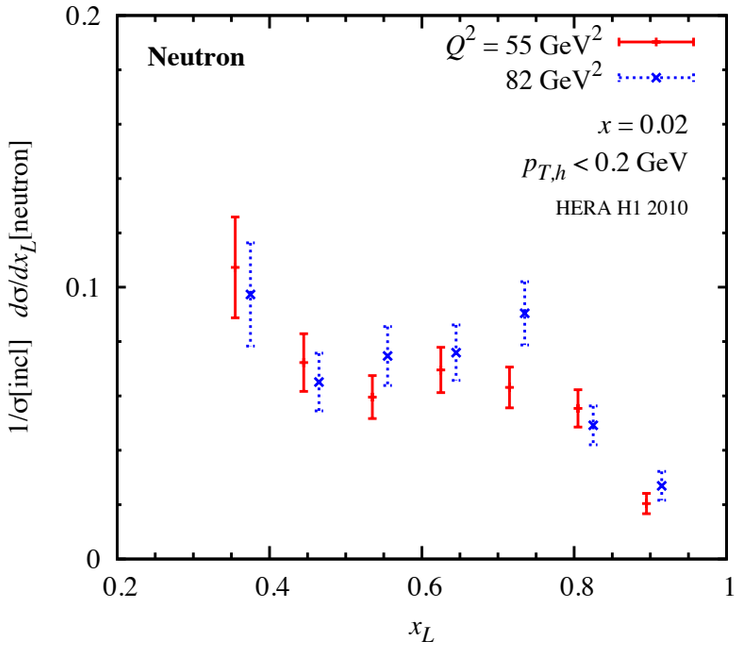
- Connections with multiparton interactions in high-energy pp collisions at LHC:
  Very active field of study!

Target fragmentation: Baryon number transport









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

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

x_L distributions of leading baryons

Q^2-scaling of distributions supports QCD factorization

Baryon number transport

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

Significant baryon number transported away from TF region

Surprising, because at $x \lesssim 0.01$ the DIS process involves mostly sea quarks/gluons, not valence quarks [M. Strikman 2021]