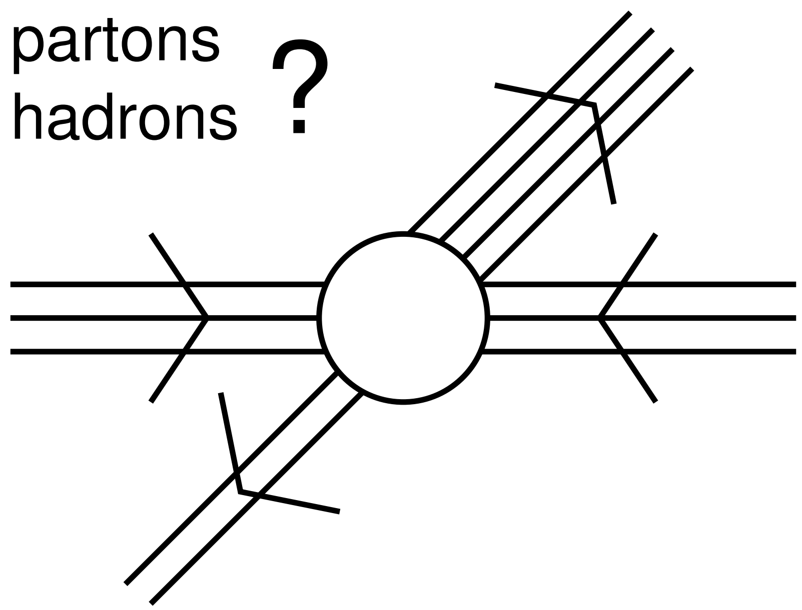
Jet physics view of hadron structure

C. Weiss (Jefferson Lab), Advancing the understanding of non-perturbative QCD using energy flows, CFNS Stony Brook, 19-22 Sep 2022 [Webpage]



This introduction

Present perspective on hadron structure in parton picture

Focus on concepts

Lecture-style, references not complete

Parton picture - soft interactions

Closed system, wave function

High-energy scattering, Regge phenomena

Parton picture - QCD

Factorization, role of scale

Single-particle densities PDFs/GPDs/TMDs

Parton correlations in target fragmentation

Factorization theorem $\gamma^* + N \to X + h(\text{target})$

Baryon number transport

Spin-flavor correlations

Future measurements ep JLab12, EIC, $\gamma p/pp$ LHC

Taken for granted, but very profound: relativity + quantum mechanics + interactions

Originated in soft interactions, pre-QCD

Two directions:
Understand high-energy scattering of hadrons
Construct particle-based description of hadron structure

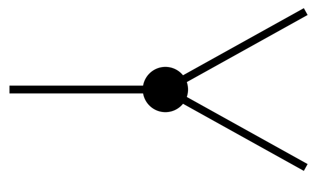
Formulations

$P \to \infty$, "infinite momentum frame" [Feynman]

$P \gg \mu_{\text{soft}}$ large but finite, quantum field theory [Gribov] ⟵

[V.N. Gribov, Space-time description of hadron interaction at high energies (1973), available as arXiv:hep-ph/0006158]

Parton picture: Soft interactions



QFT description of soft interactions

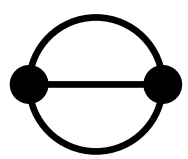
QFT with mass scale $\mu_{\rm soft}$

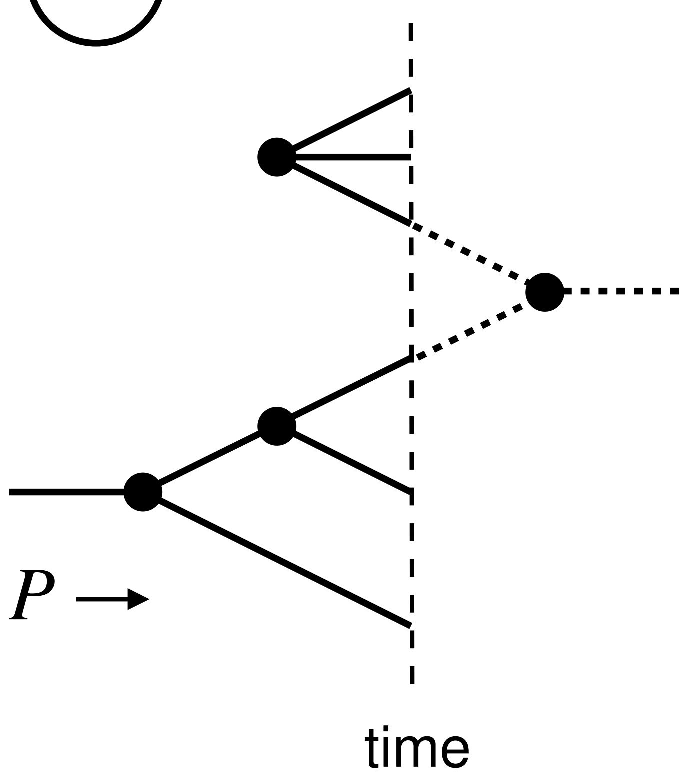
Transverse momenta $k_T \sim \mu_{\rm soft}$, integrals finite

Interactions with rapidity range $\Delta y \sim 1$

Q: What is the quantum state of a "hadron"
with momentum P in this dynamics?

Inject particle with P, follow time evolution (TOPT)



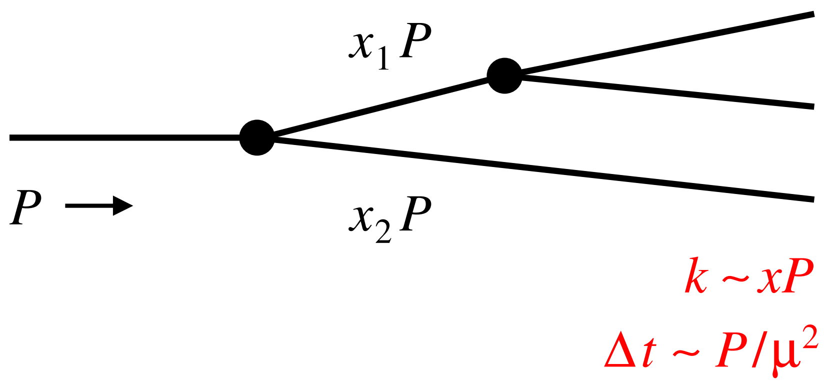


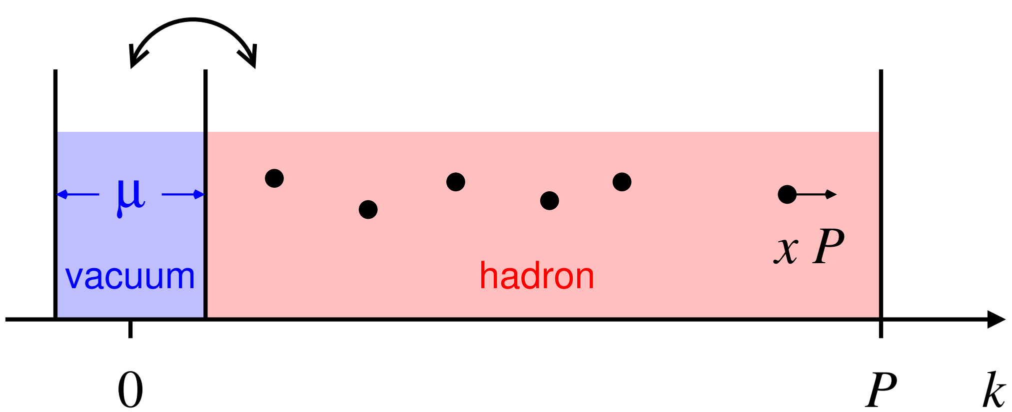
Slow hadron $P \sim \mu_{\rm soft}$

Decay processes and vacuum fluctuations

Cannot distinguish whether observed particle originates
from decay or vacuum fluctuations - no criterion!

Open system - coupled to vacuum fluctuations





Fast hadron $P \gg \mu_{\text{soft}}$

Successive decays with $x_1 \sim x_2 = O(1)$

Separate particles parametrically

momenta $k \sim xP$ lifetime $\Delta t \sim P/\mu^2$

momenta $k \sim \mu$ lifetime $\Delta t \sim \mu^{-1}$

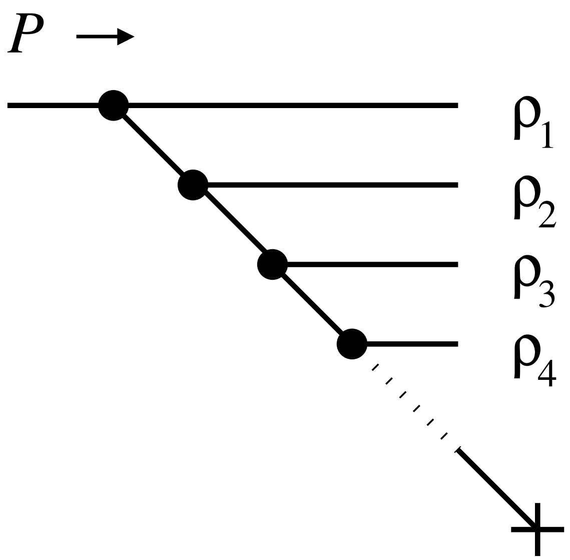
Fast particles decouple from vacuum fluctuations: closed system

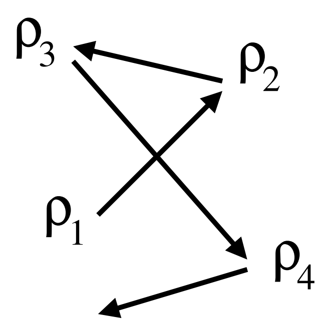
Wave function of fast hadron

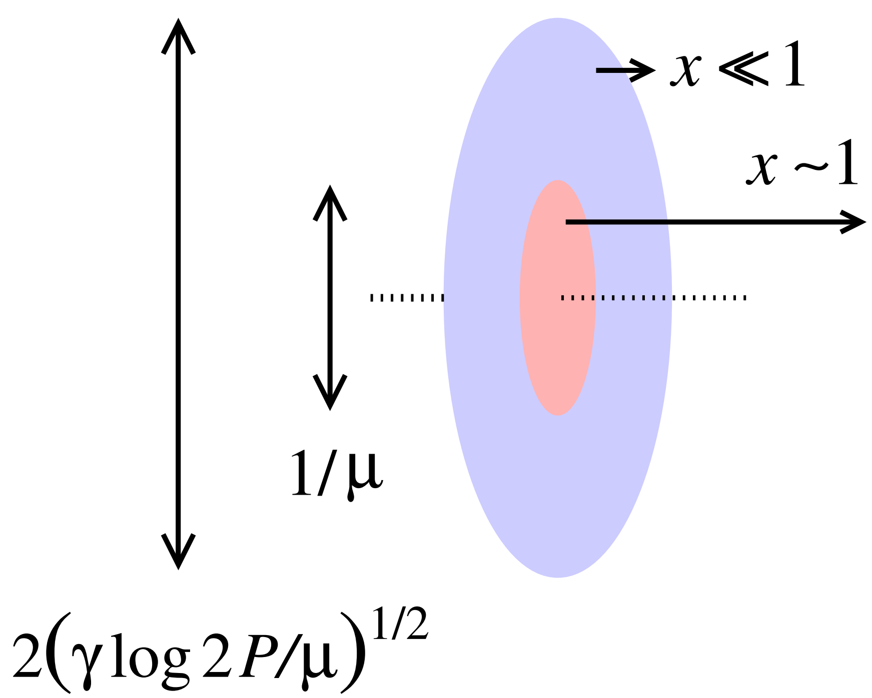
Finite number $\sim \log P/\mu_{\text{soft}}$ of particles $k \sim xP$

Can be formalized: Normalization, orthogonality, charges - sum rules

Stationary state requires equilibrium of decay and recombination. How equilibrium is attained goes beyond simple model field theory; assume that it happens [Gribov 73]. Would be interesting to simulate in realistic models!







Impact parameter representation

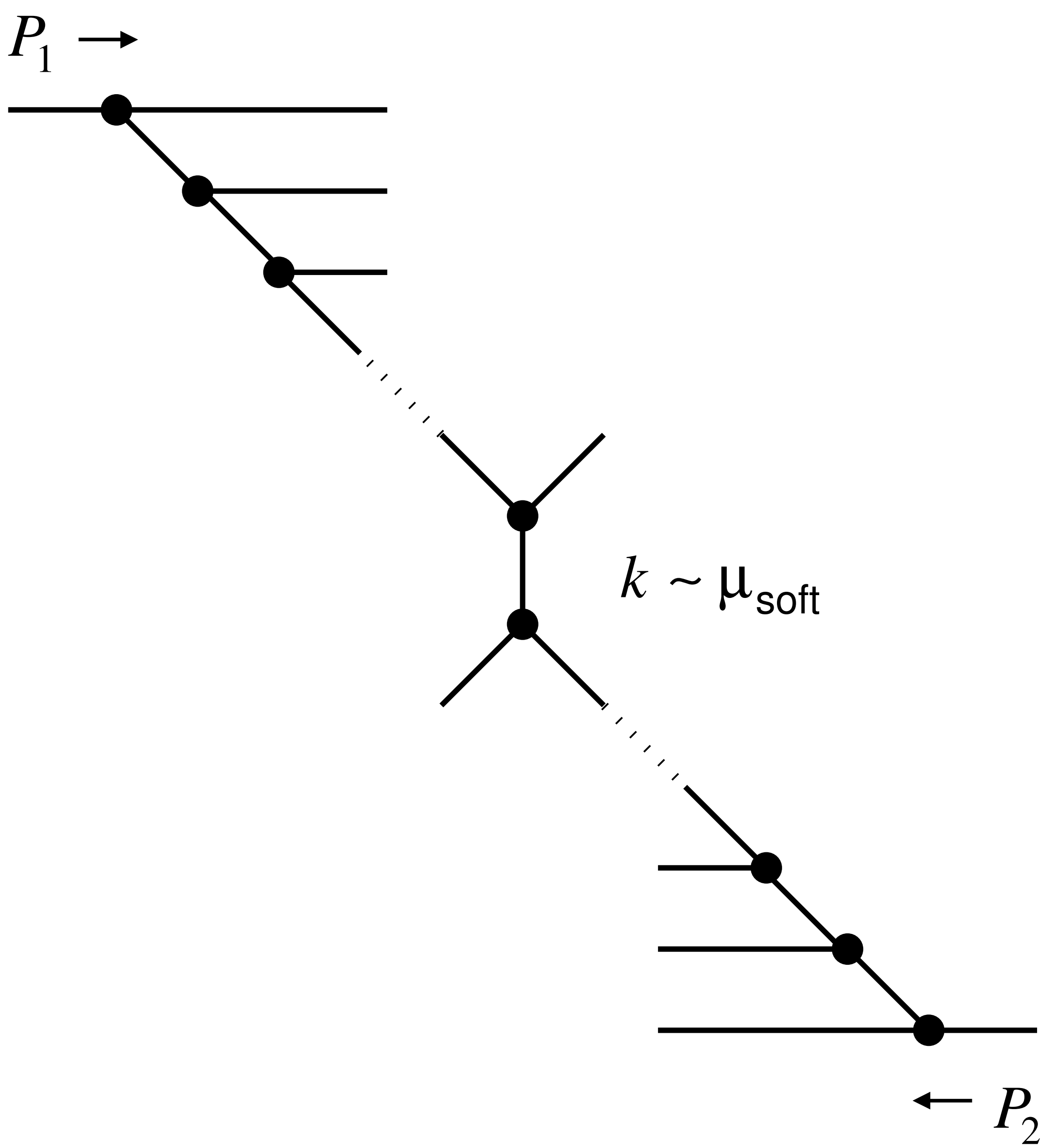
Each emission changes $\overrightarrow{\rho}$ by $1/\mu_{\text{soft}}$

Successive emissions = random walk
in transverse position

$\overline{(\Delta\rho)^2} \;=\; \gamma \times N(\text{steps})$ diffusion process

Transverse size of hadron determined by radius of partons with $x \to 0$, grows logarithmically with P

Picture explains Regge behavior in $d\sigma/dt$:
t-slope $B = B_0 + 4\alpha' \log P/P_0$



High-energy hadron-hadron scattering

Here: Generic inelastic collision

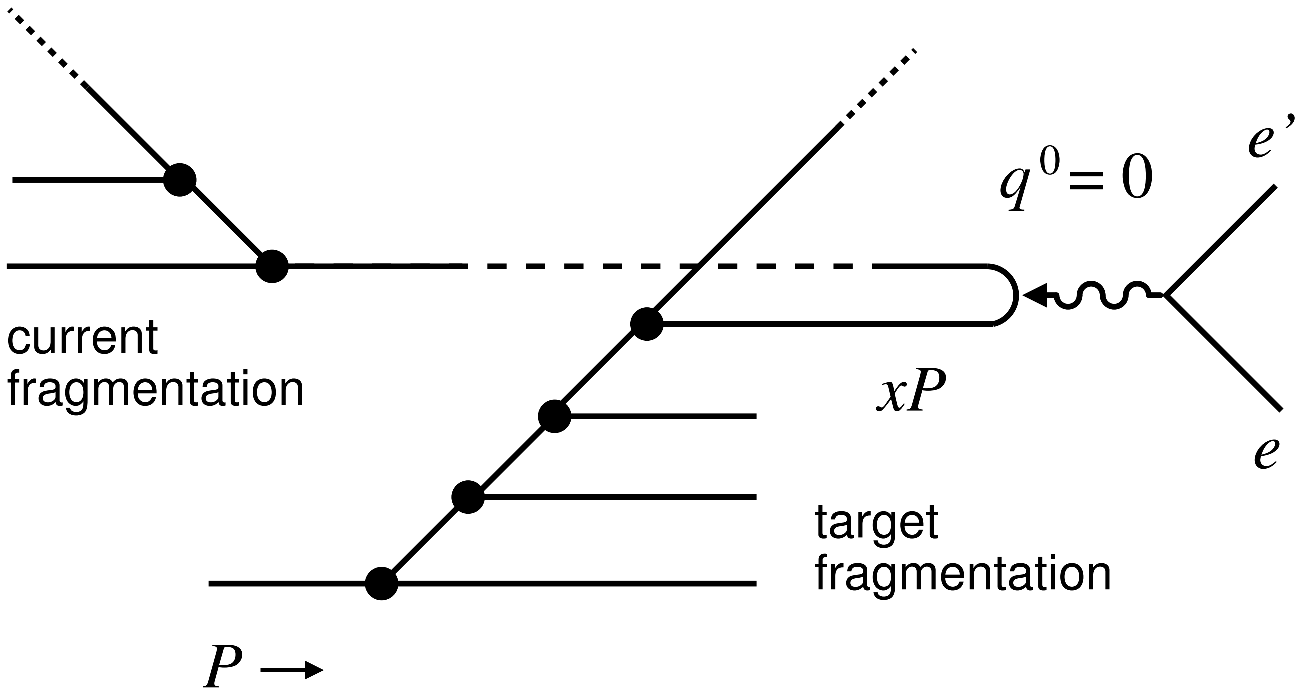
Interaction of slow partons with $k \sim \mu_{\text{soft}}$

Picture explains $dN/dy \sim$ const

Picture predicts that total hadron-hadron cross section in high-energy limit is "universal" — independent of hadron type [Gribov 70's]

"Dual parton model" combines parton picture and Regge dynamics [Capella, Sukhatme, Tan, Tran Thanh Van 1992]

Parton picture: DIS



$q^0 = 0$ frame: Photon = standing wave

Longitudinal extent of EM process
$\ll$ distance between parton interactions

Parton "free" during EM process

Energy-momentum conservation
selects parton with $k = x_B P$

Picture explains Bjorken scaling of DIS cross section

Picture also predicts hadron multiplicities and longitudinal momentum distributions in current and target fragmentation regions [Gribov 70's]

Summary: Parton picture in soft interactions

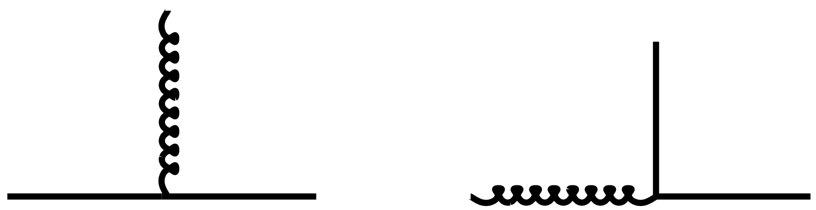
- Hadron with $P \gg \mu_{\text{soft}}$ becomes closed system, described by wave function: many-body system, single-particle densities, correlations…

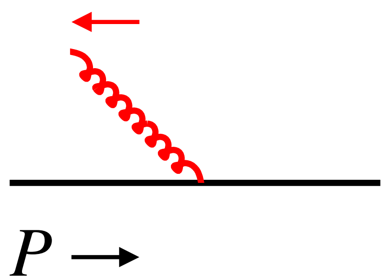
- Parton picture describes basic features of soft high-energy scattering: Regge behavior, asymptotic cross sections, multiplicity distributions…

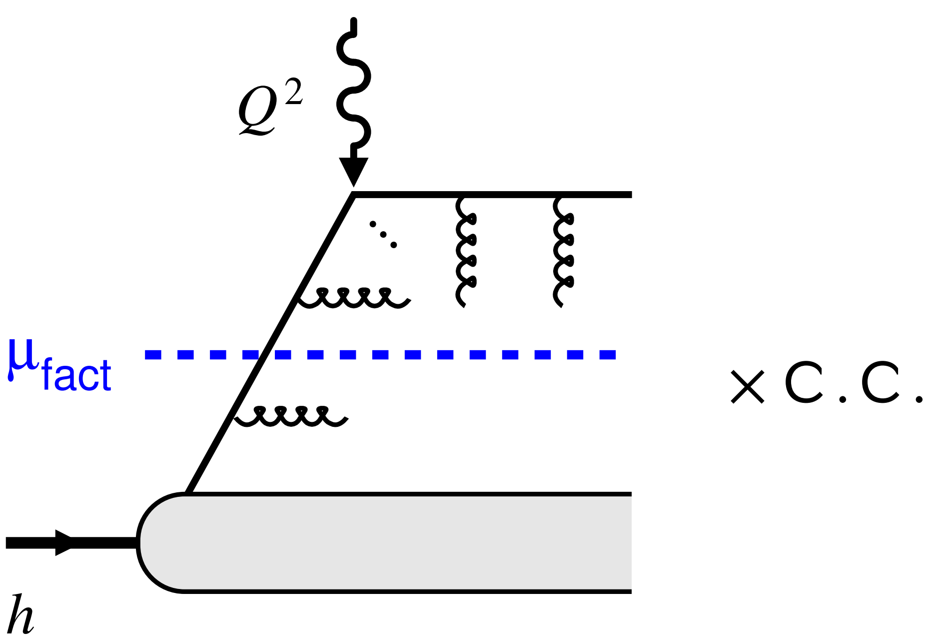
- Bjorken scaling in DIS connected with basic properties of soft interactions

Want to understand emergence of parton picture from nonperturbative QCD!

QCD: Factorization







Pointlike interactions

Interactions over rapidities $\Delta y \gg 1$

k_T not limited, UV divergences

Even if $P \gg \Lambda_{\text{QCD}}$, particles can still move in "wrong" direction

Factorization of deep-inelastic processes

Separate configurations by scale μ_{fact}

$$\langle h \,|\, \bar{\psi} \ldots \psi \,|_{\mu_{\text{fact}}} \,|\, h \rangle \quad \times \quad \sigma_{\text{hard}}$$

Composite operator normalized at μ_{fact}

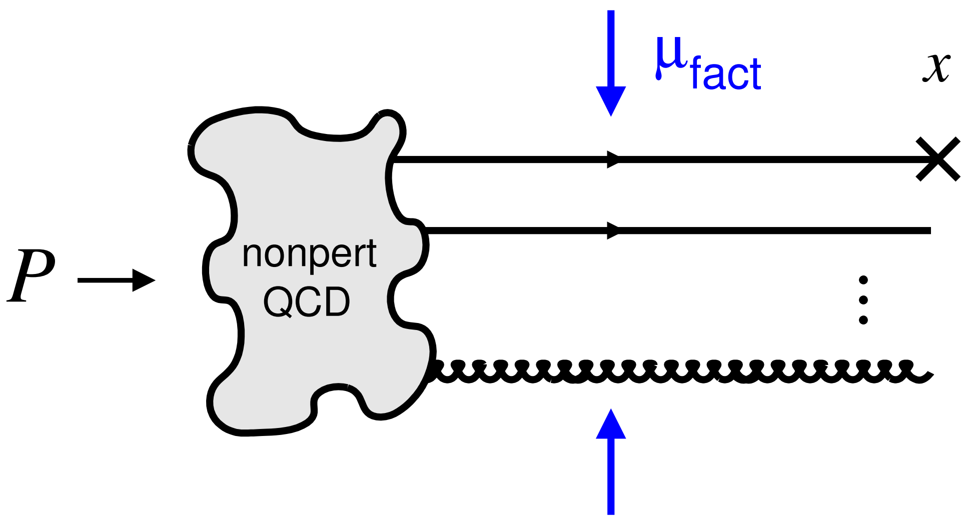
Perturbative QCD cross section

Organize QCD radiation in k_T and rapidity:

Inclusive scattering: Twist-2 light-ray operators, DGLAP evolution

Semi-inclusive $p_T \ll Q$: TMD operators, Sudakov-suppressed radiation, CSS evolution combined in scale and rapidity, soft factors

QCD: Partonic representation



Light-front quantization k^+, k_T

Expand fields in creation/annihilation operators

$$\bar{\psi}(z), \psi(z) \;\leftrightarrow\; a^\dagger(k^+, k_T), a(k^+, k_T)$$

Particle representation of renormalized QCD operators

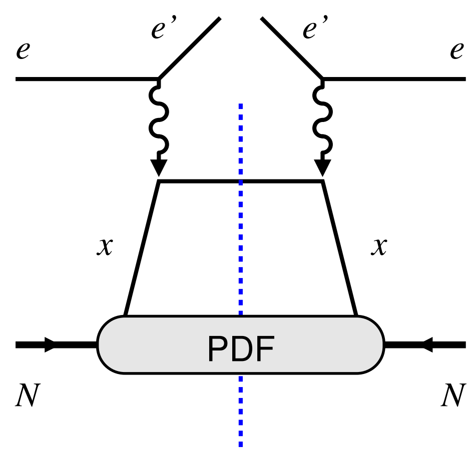
$$\bar{\psi}(0)\,\gamma^+\,\psi(z^-)\,|_{\mu_{\text{fact}}} \;=\; \int\limits_{k_T < \mu_{\text{fact}}} d^2k_T\; a^\dagger(k^+, k_T)\; a(k^+, k_T)$$

$[z^+, z_T = 0]$ $\qquad\qquad k^+ = xP^+$

TMD operators: Include interactions - gauge links, rapidity cutoff μ_{rap}

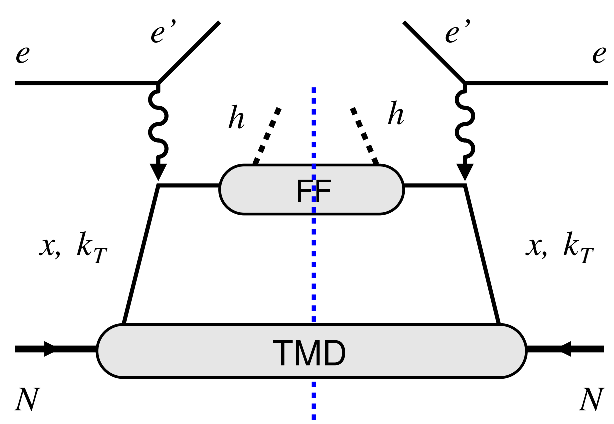
Recover parton picture of soft interactions, but with explicit scale μ_{fact}

QCD: Processes and structures



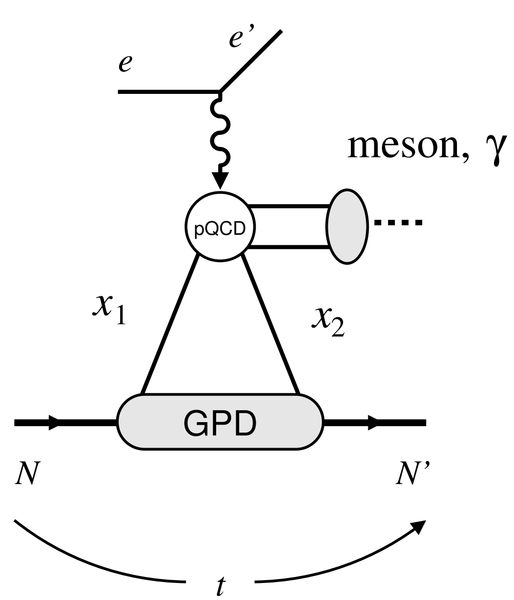
$f(x, \mu_{\text{fact}})$

Parton density
(longitudinal momentum,
spin/flavor)



$f(x, k_T; \mu_{\text{fact}}, \mu_{\text{rap}})$

Transverse momentum
dependent parton
distribution



$f(x_1, x_2, t; \mu_{\text{fact}})$

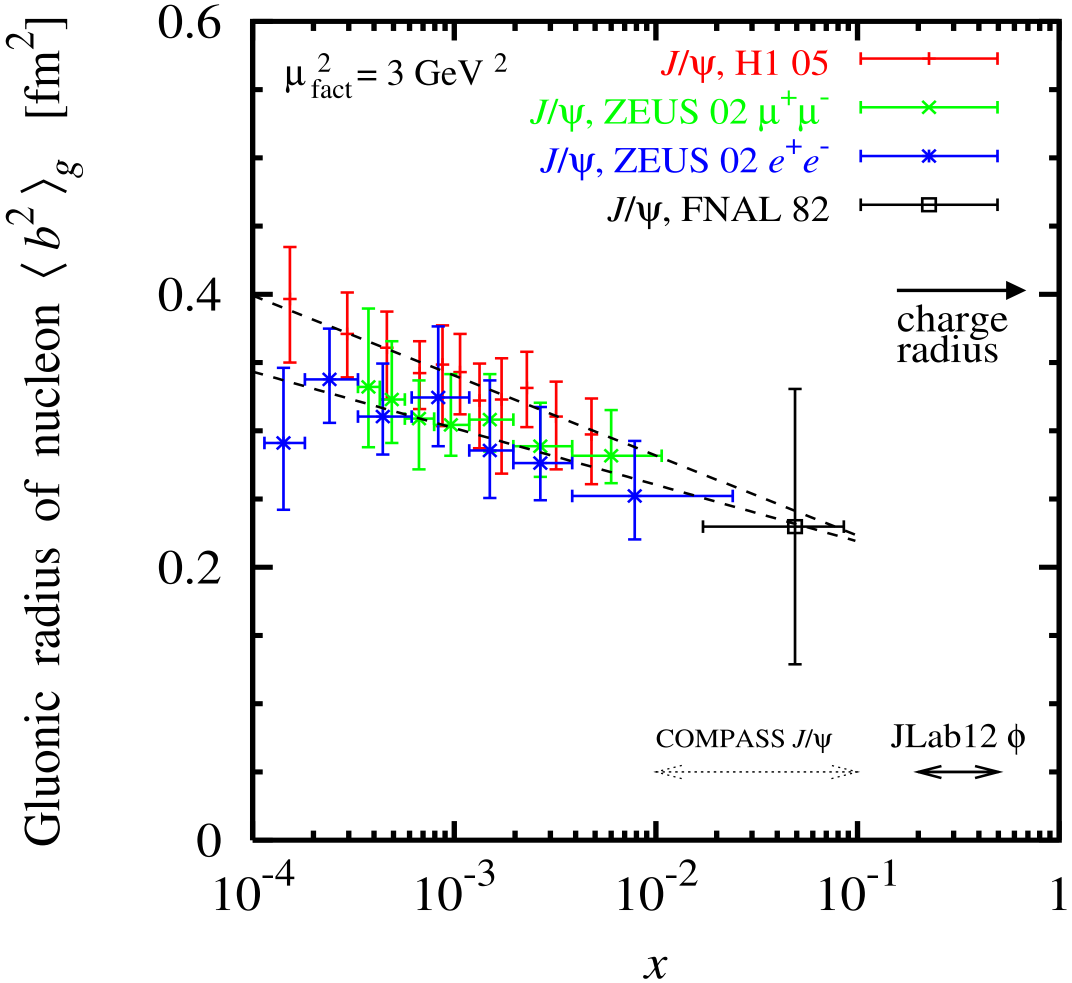
Generalized parton distribution
(= partonic form factor of hadron)

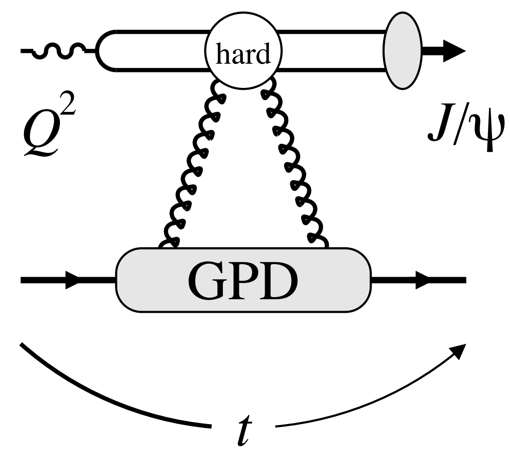
$x_1 = x_2$, Fourier $t \to b$

$\to f(x, b)$

Transverse spatial distribution
(impact parameter)

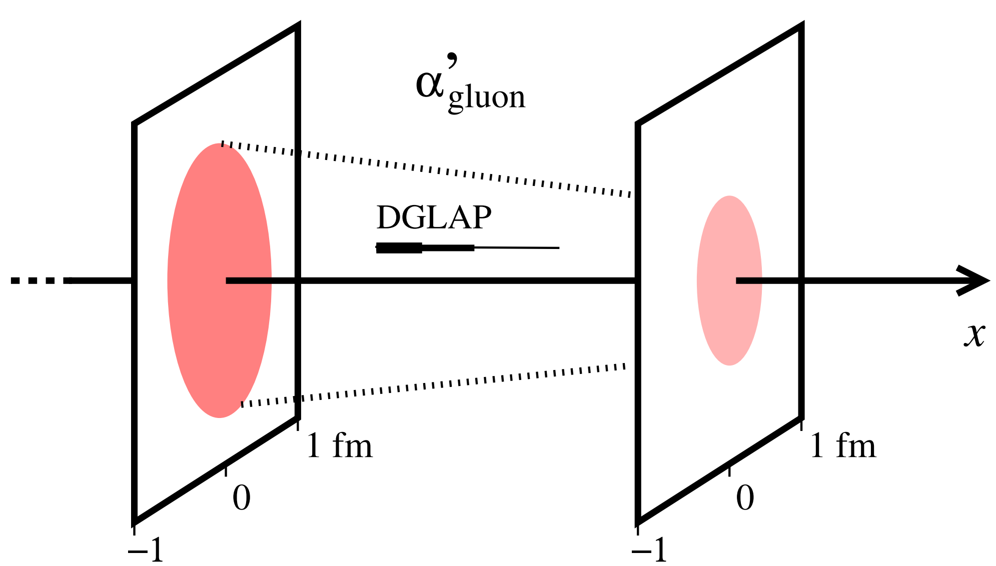
QCD: Transverse spatial distribution of gluons





Transverse spatial distribution of gluons from exclusive J/ψ electro/photoproduction [HERA, FNAL]

Gluonic radius grows with decreasing x



$\alpha'_{\text{gluon}}(\mu^2_{\text{fact}} = 3\,\text{GeV}^2) \approx 0.14\,\text{GeV}^{-2} < \alpha_{\text{soft}}$

Gribov diffusion suppressed compared to soft interactions

Gluonic radius < charge radius ($q - \bar{q}$)

Quark/gluon tomography with GPDs: Extensive program with JLab12, EIC

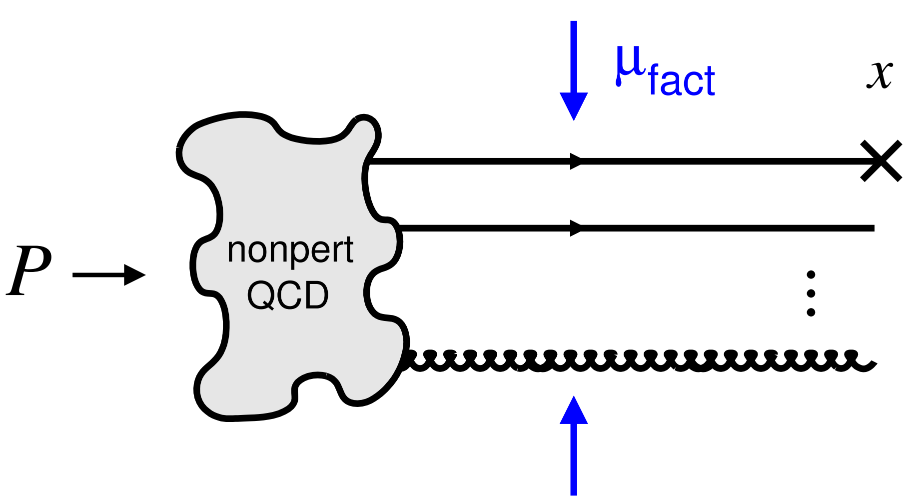
Summary: Parton picture in QCD

- Parton picture of hadron structure appears from factorization of deep-inelastic processes: Cutoff scale μ_{fact}, evolution equations

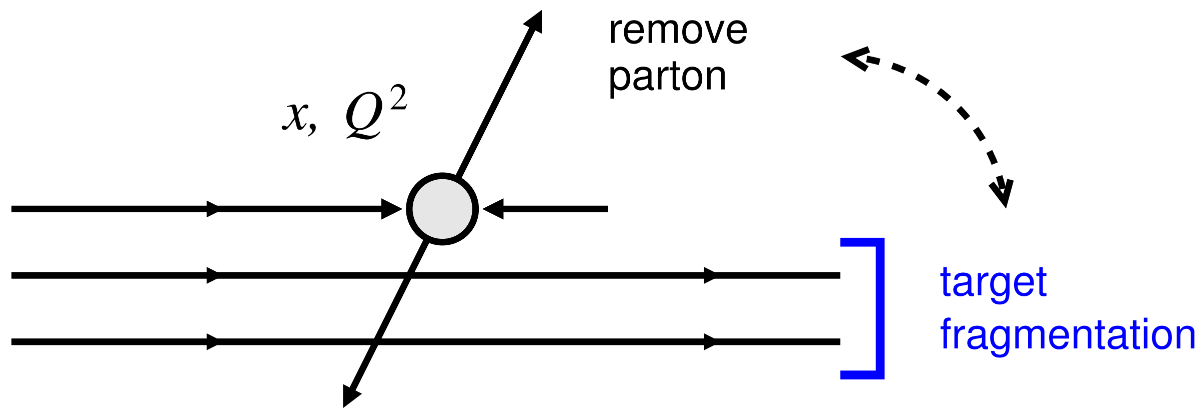
- Represent/analyze hadron as many-body system

- PDFs/TMDs/GPDs are the single-particle densities in momentum/position space: Particle content, internal motion, spatial size

Much more can be learned from multi-particle correlations: Interactions, dynamics (← Experience with nuclear structure, condensed matter)



Target fragmentation: Parton correlations



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

Experiments

Fixed-target: ep/en Cornell, μp CERN EMC, $\nu p, \bar{\nu} p$ FNAL, CERN

Collider: ep HERA

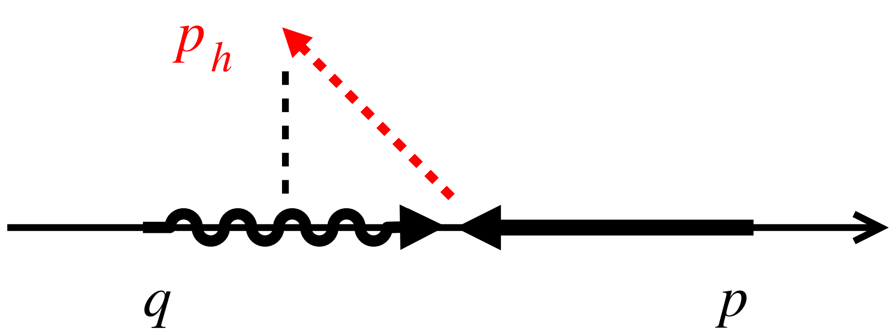
Present/future: JLab12, EIC ←

Also possible: Jets in $\gamma p, pp$ at LHC

Materials

CFNS Workshop "Target fragmentation and diffraction physics with novel processes" Feb 9-11, 2022 [Webpage]

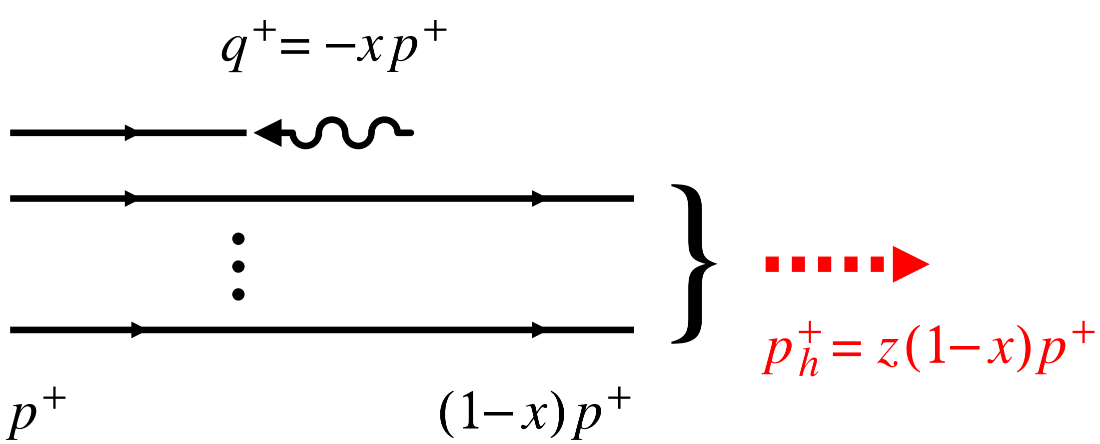
Target fragmentation: Kinematic variables



Feynman variable

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

Natural for hadron-hadron collisions

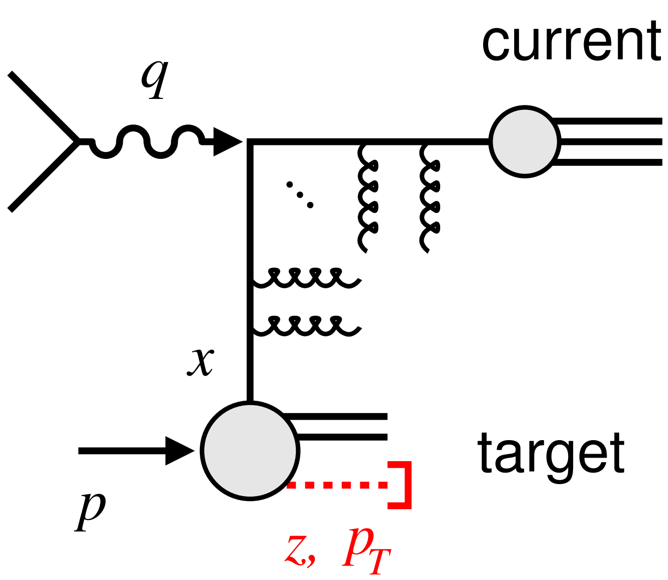


Light-cone fraction

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

Natural for parton picture, QCD factorization

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



QCD factorization $\gamma^* + N \to X + h(\text{target})$

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

QCD radiation: DGLAP, same as inclusive DIS

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

Fracture functions / Conditional PDFs

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

[Naive expression: Gauge link, renormalization]

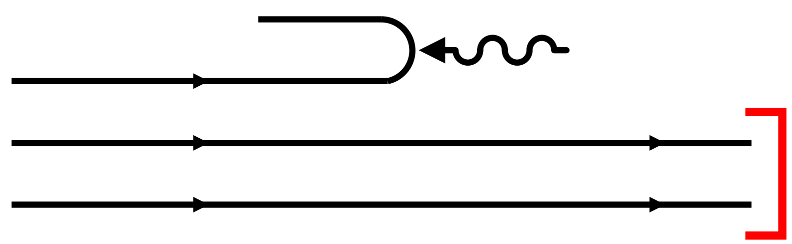
Probability to find hadron with z, p_T in target after removing parton with x

Universal, independent of hard process

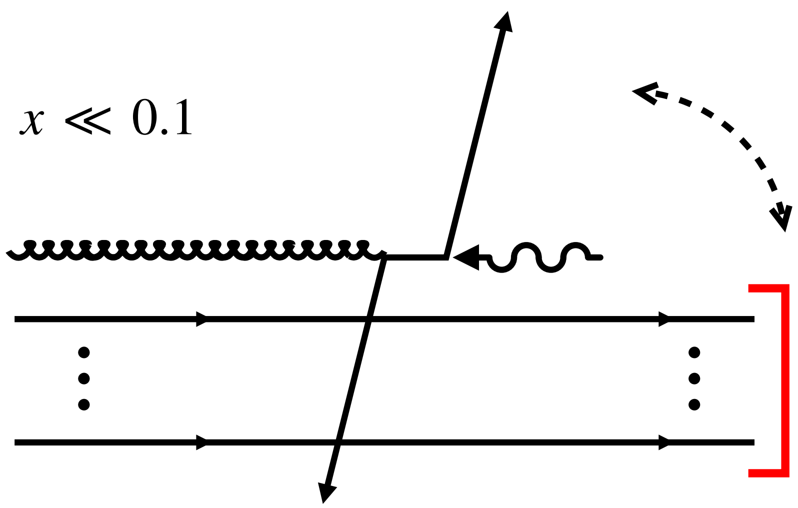
Leading-twist structures, simpler than TMDs

Target fragmentation: x, z dependence

$x > 0.3$



$x \ll 0.1$



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

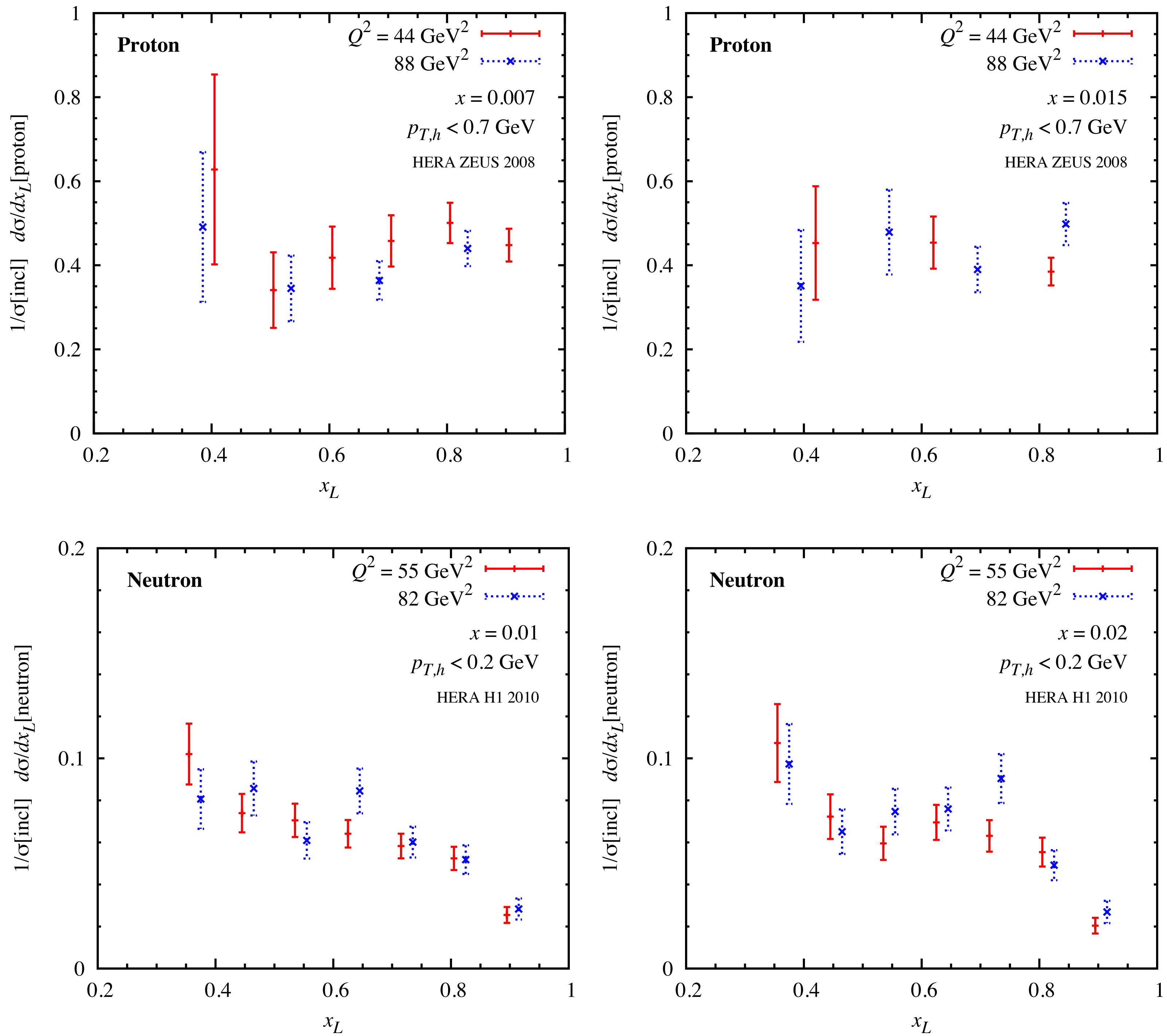
Flavor relations for proton fragmentation in p, n

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: Baryon number transport



x_L distributions of leading baryons

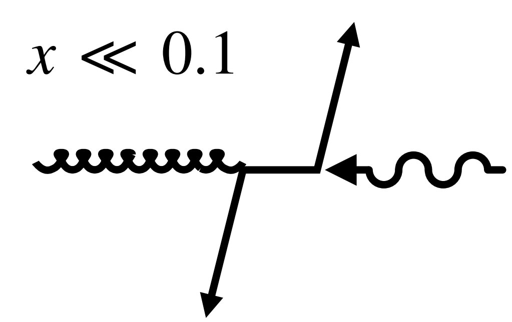
Q^2-scaling of distributions supports QCD factorization

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

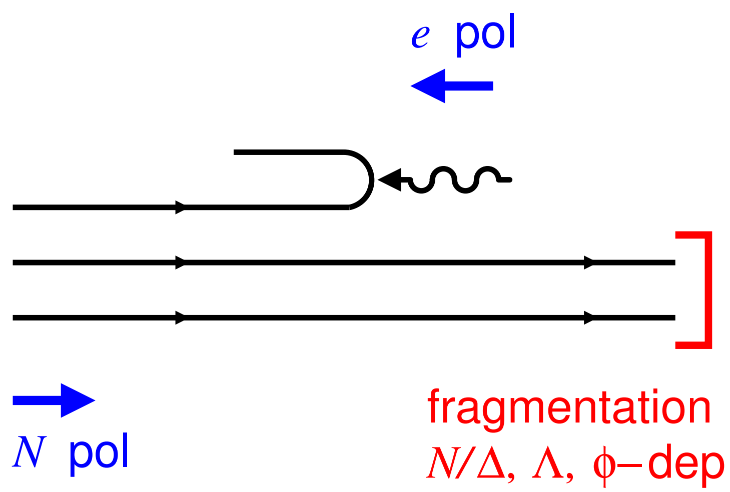
Surprising, because at $x \lesssim 0.01$ the DIS process involves mostly sea quarks/gluons, not valence quarks [M. Strikman 2021]

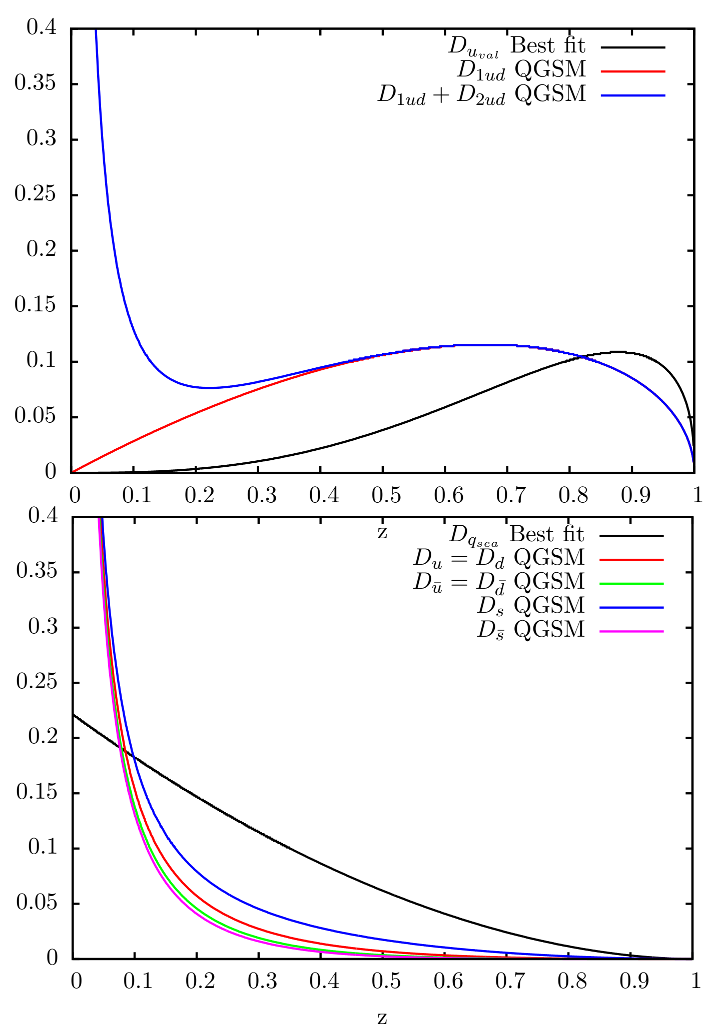


[Proton distribution does not contain diffractive peak $x_L \approx 1$]

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

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]

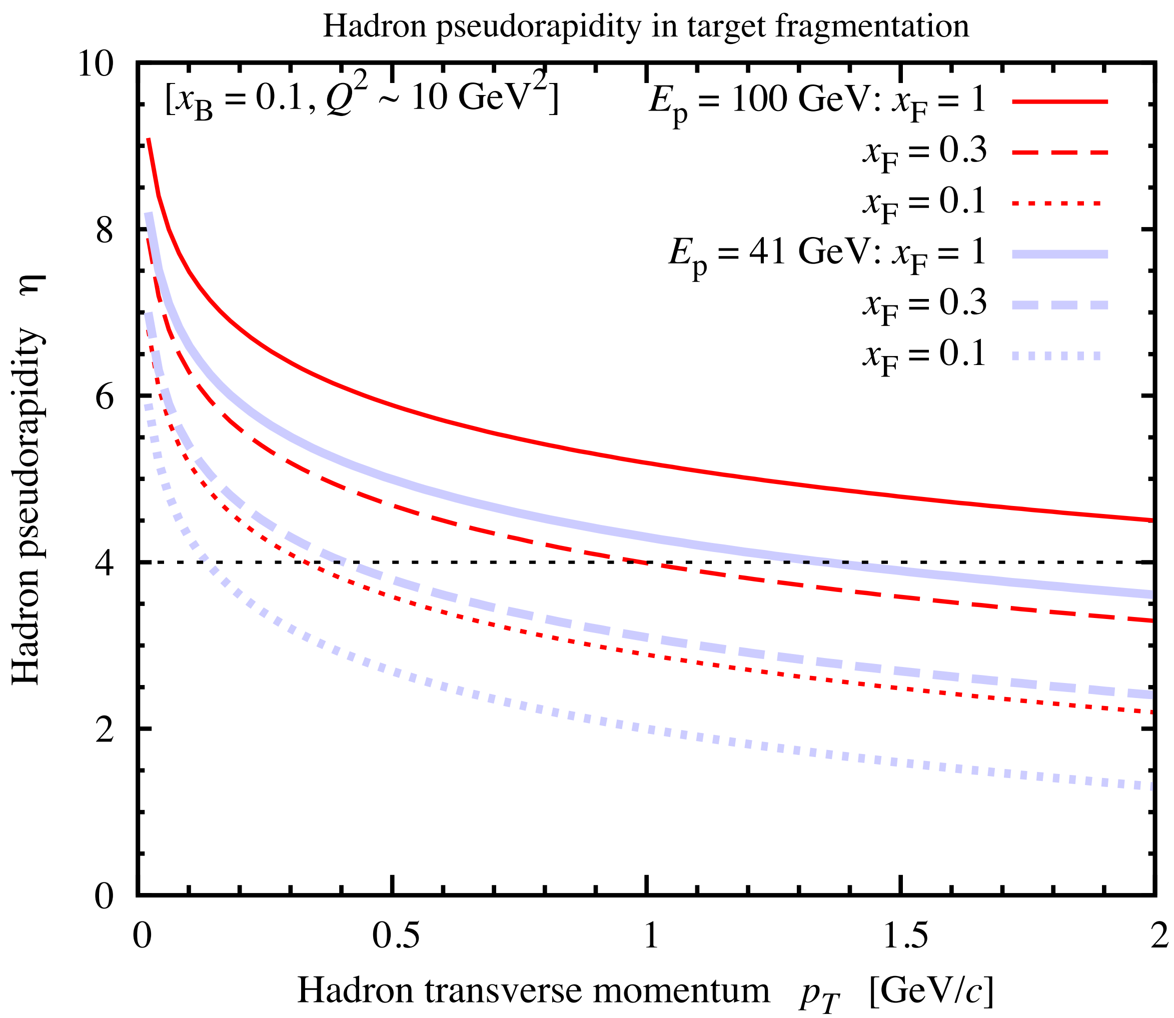
Λ production: Polarization transfer
[Ceccopieri, Mancusi 2012: Neutrino + DIS data]

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

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

Many opportunities with JLab12 and EIC

Target fragmentation: EIC detector coverage

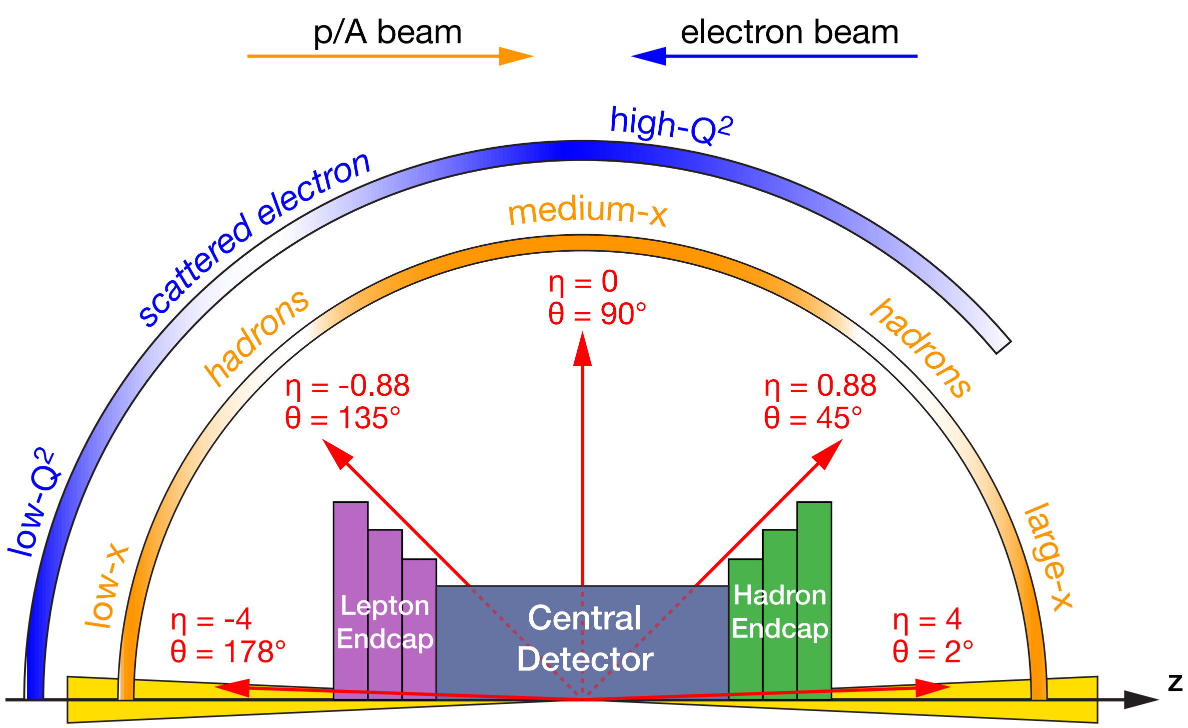


[Weiss 2021, prepared for EIC Yellow Report [INSPIRE]]

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 coverage depends on proton beam energy



Summary

- Target fragmentation gives access to parton correlations
  → configurations in wave function, non-perturbative dynamics

- QCD factorization theorem provides robust framework for target fragmentation in DIS:
  Leading-twist structures, DGLAP evolution

- Great need for modeling fracture functions, exploring connection with dynamics

- Apply jet physics methods to target fragmentation? Alternative to factorization - duality
  [Discussions with Yang-Ting Chien]

- Target fragmentation program possible with DIS at JLab12 and EIC, and jets in $\gamma p/pp$ at LHC:
  Variety of scattering energies, hard processes, detectors