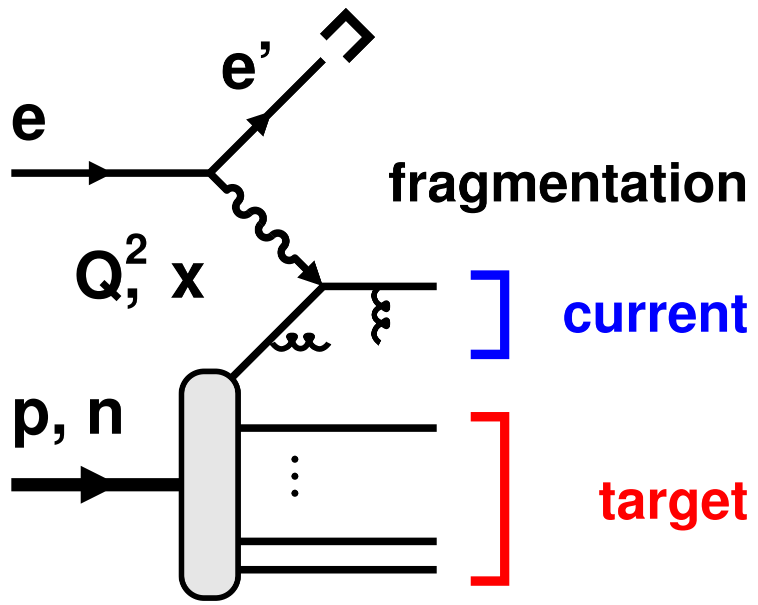
Exploring parton correlations with target fragmentation

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

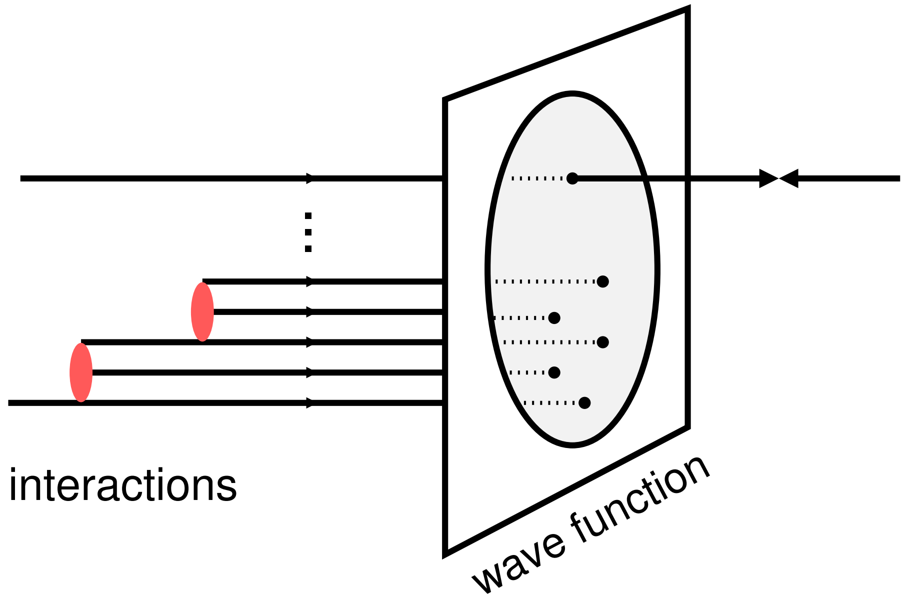
p_T: TMD factorization

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

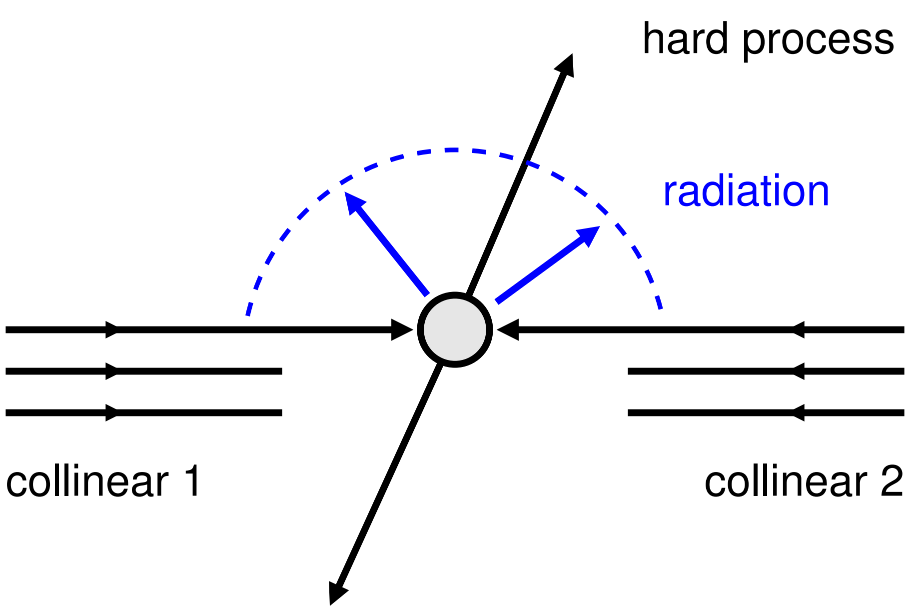


Parton picture

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

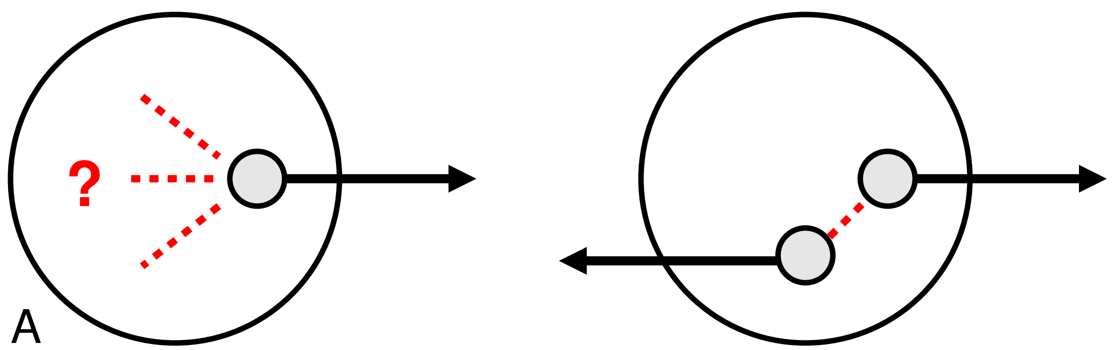
Quarks/gluons not normally collinear: Interactions at large rapidities, UV divergences, renormalization

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

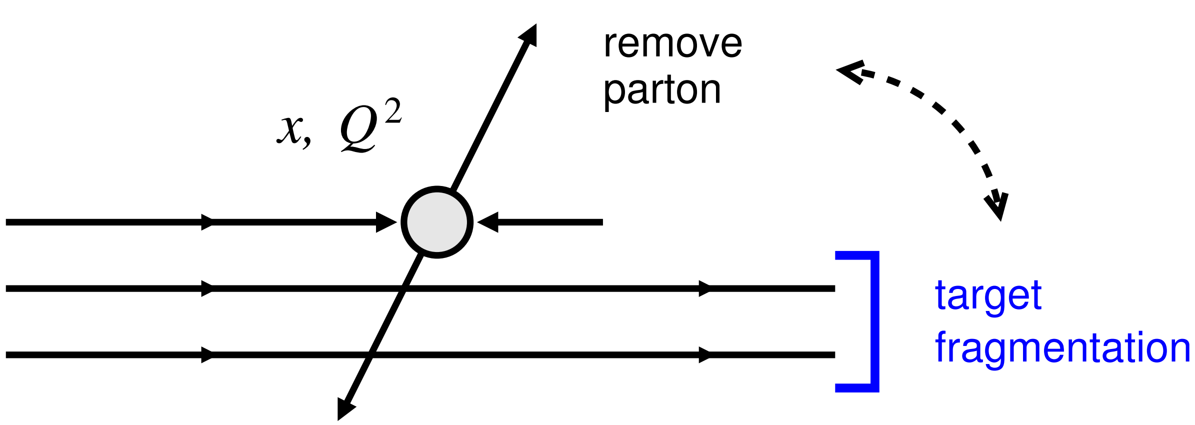


Many-body system

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

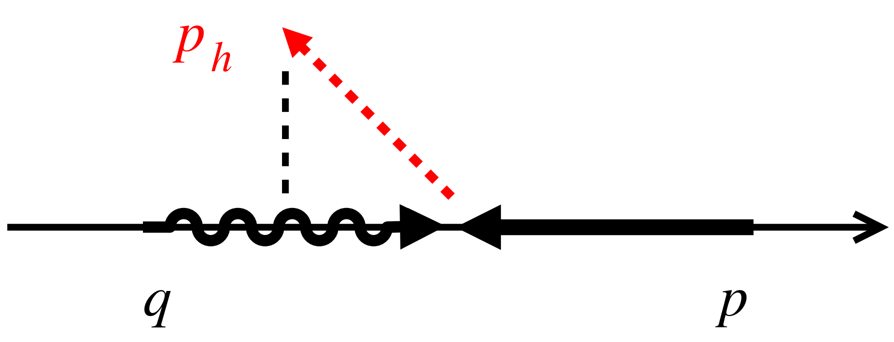
Observe fragmentation of target remnant

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

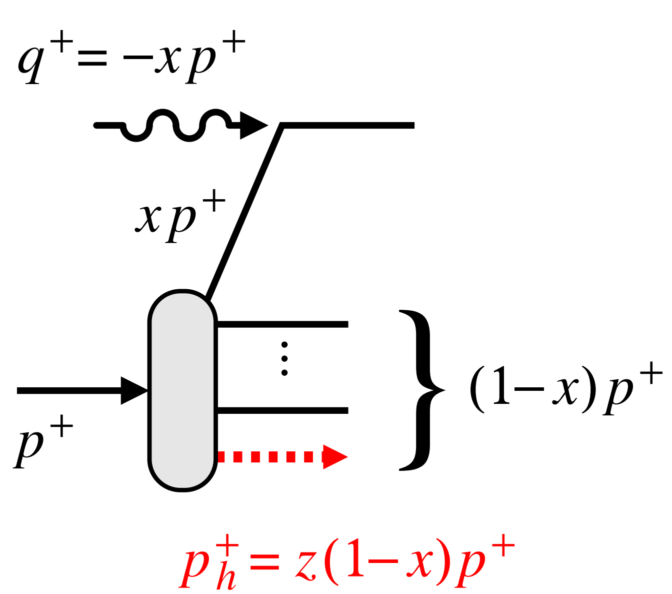
$$x_F = \frac{p_h^z}{p_h^z\,(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

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



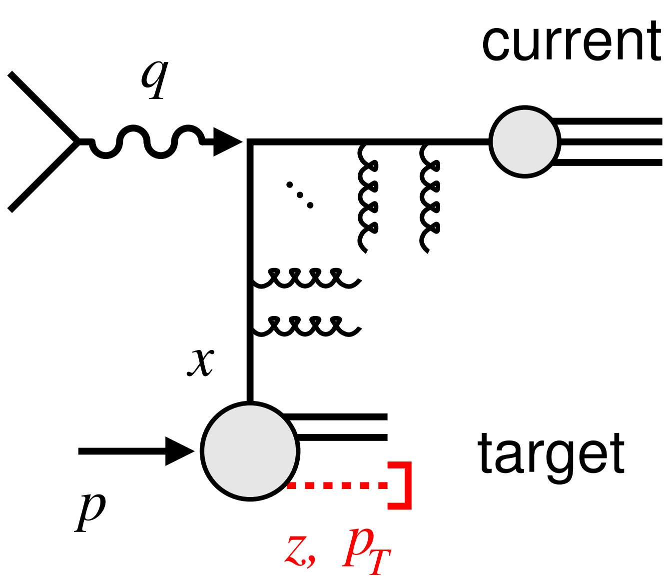
Light-cone fraction

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

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



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

[Naive expression: Gauge link, renormalization]

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

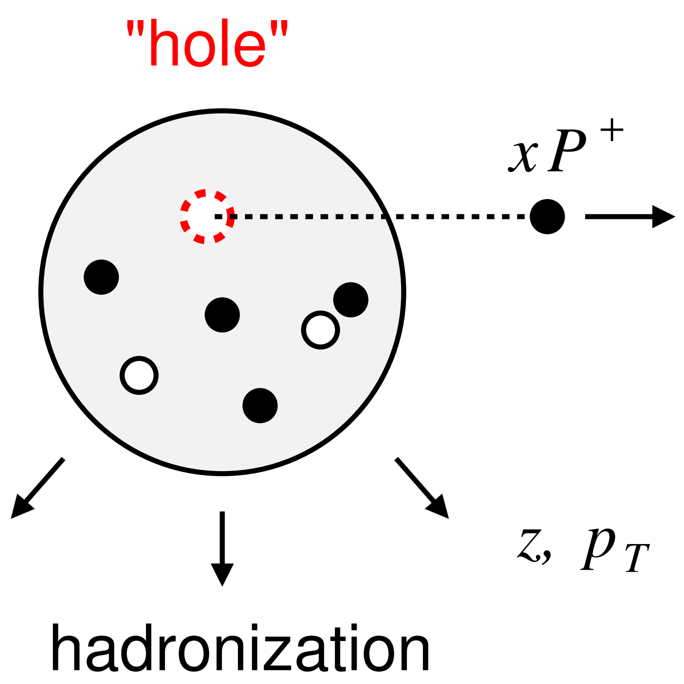
Predicts Q^2-scaling for fixed $z, p_T \ll Q$

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



[Rest frame view: Light-front wave function]

Information in fracture functions

Hadronization of nucleon with “hole” in partonic wave function

→ Parton correlations in initial state

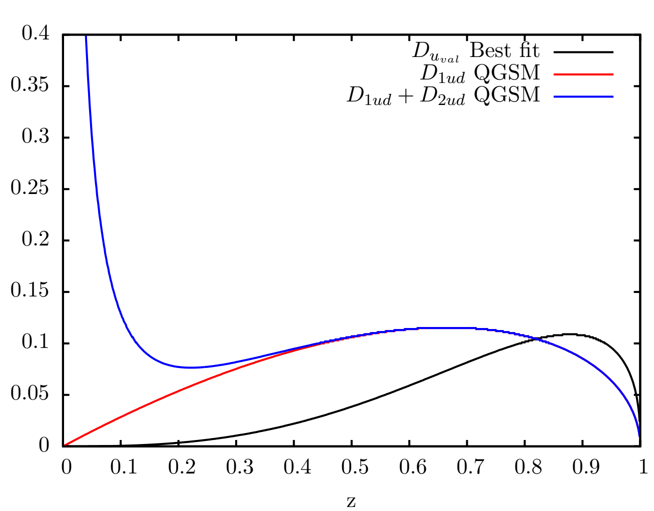
→ Interactions in final state

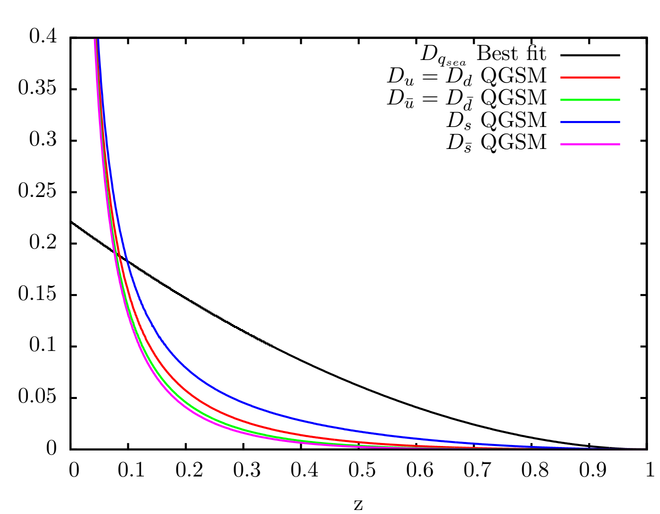
Dynamics

Color forces — string fragmentation?

Chiral symmetry breaking interactions, $q\bar{q}$ pairs? [Schweitzer, Strikman, Weiss 2011]

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

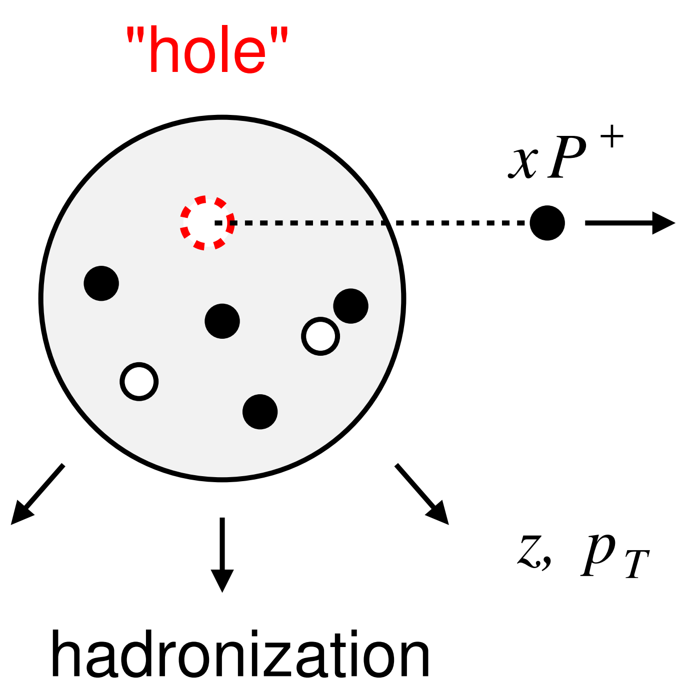




Example: Λ fracture function extracted from analysis of neutrino and DIS data [Ceccopieri, Mancusi 2012]

Strong discrepancy with string model [Kaidalov, Piskounova]

Correlations: Longitudinal momentum, parton type



Parton correlations explored in collinear factorization!

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

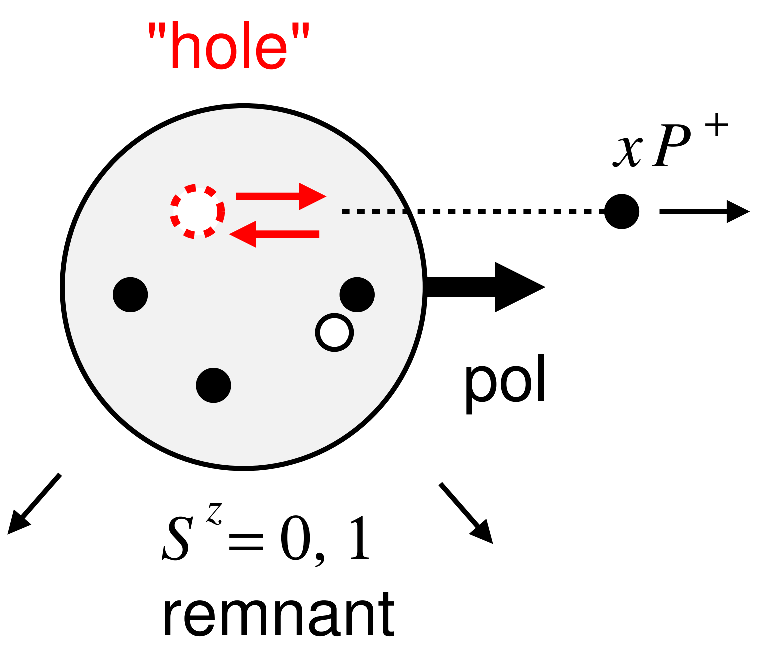
Flavor relations for proton fragmentation in p, n

Hadronization after gluon removal? Largely unknown

z-dependence of target fragmentation

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

Correlations: Spin



Target fragmentation in polarized DIS

Polarized DIS leaves remnant system with definite spin

Study spin dependence of fragmentation

Fragmentation observables sensitive to spin

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

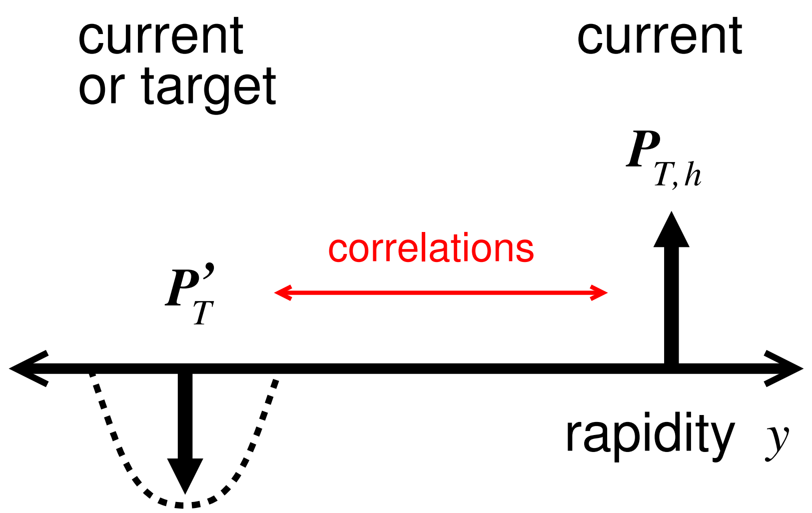
Λ production: Polarization transfer

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; νp FNAL, CERN [→ materials]

  JLab12: Explore applicability of fracture function description, many opportunities

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

- Other processes complementary to DIS: γp ultraperipheral, pp at LHC, RHIC → program

Target fragmentation: DIS measurements

Fixed-target experiments

ep/en: Cornell, JLab12

μp: CERN EMC

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

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

Review of old fixed-target data: P. Renton, W. Williams, Annu.Rev.Nucl.Part.Sci. 31, 193 (1981) [INSPIRE]

Collider experiments

ep: HERA

EIC detector coverage

Target fragmentation: Cornell electron-proton

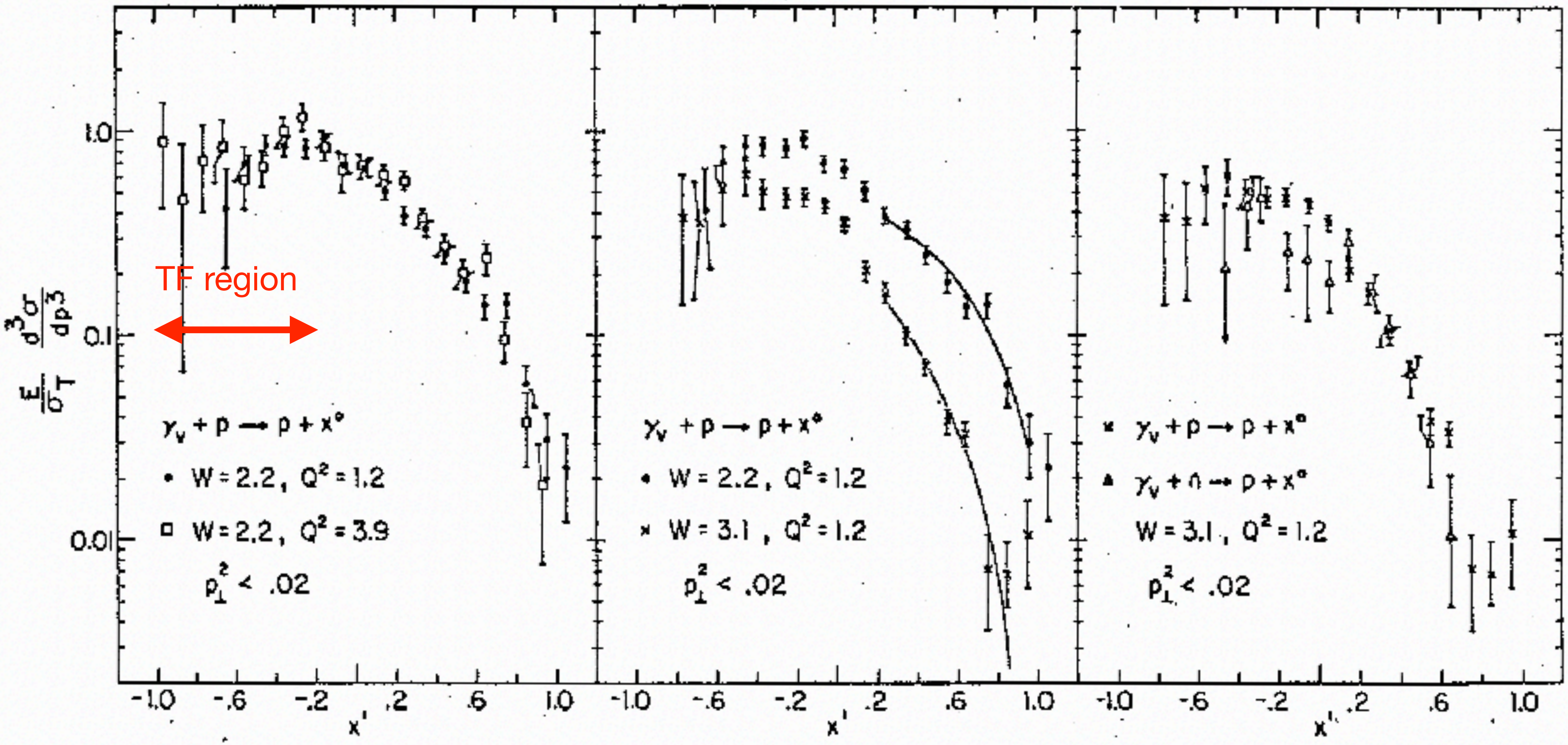
Cornell Synchrotron 1975

$\gamma^* + p(n) \to p + X$, also $\pi^\pm + X$

Proton acceptance $x_F \approx x' = [-1,1]$

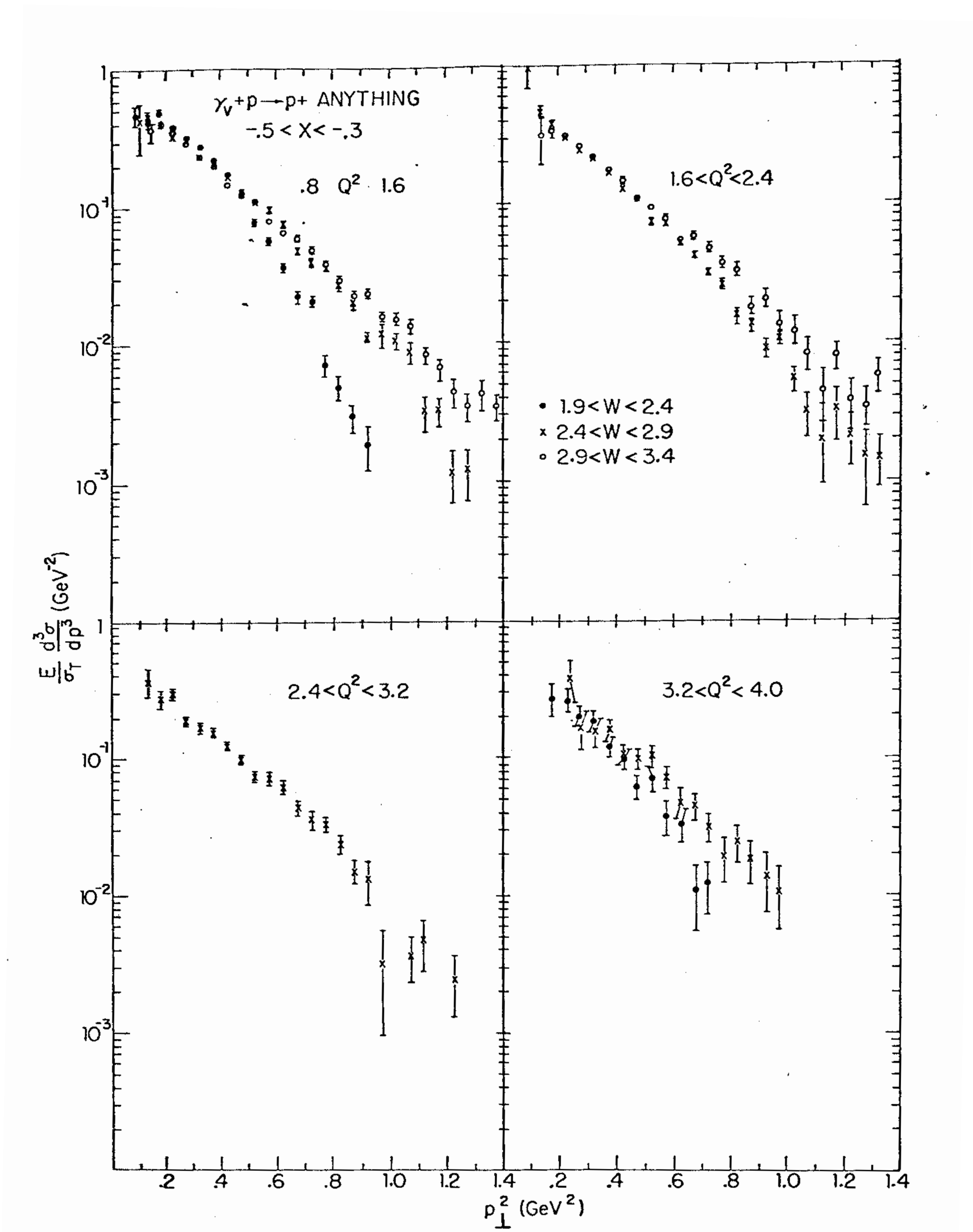
Proton x_F distribution

- 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



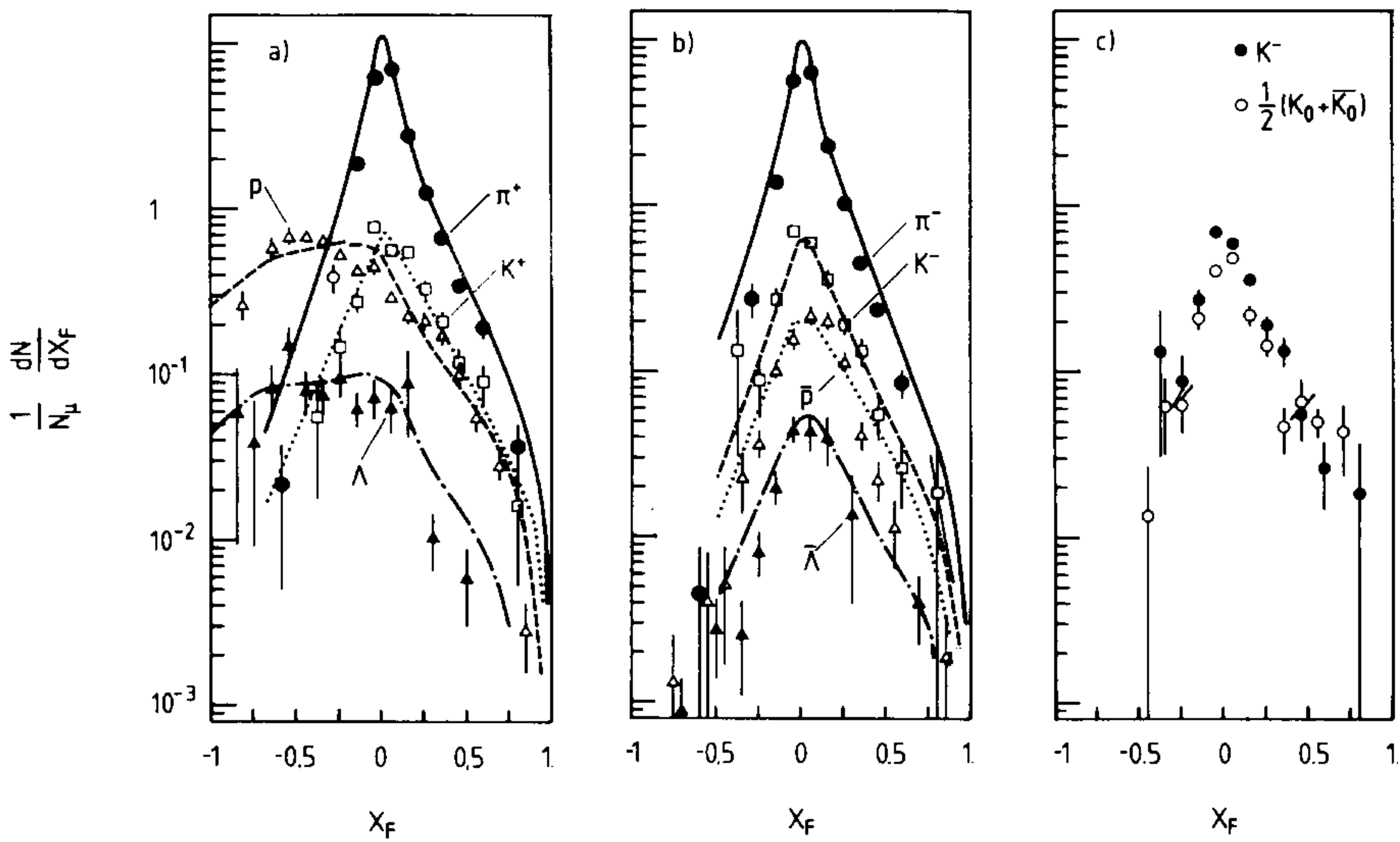
Proton p_T distribution

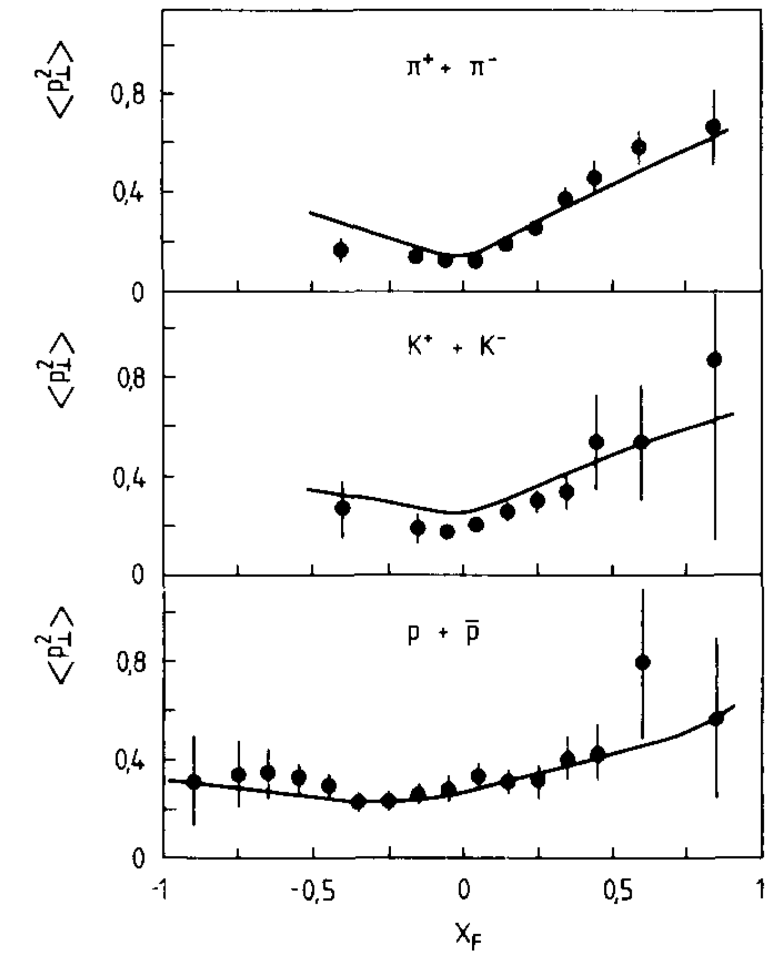
- Approximate Gaussian dependence $\propto \exp(-bp_T^2)$
- Slope $b \approx 4$ GeV^{-2}
- Practically no W dependence

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

K.M. Hanson, CLNS-317 (1975) [INSPIRE]

Target fragmentation: CERN EMC muon-proton





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]

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

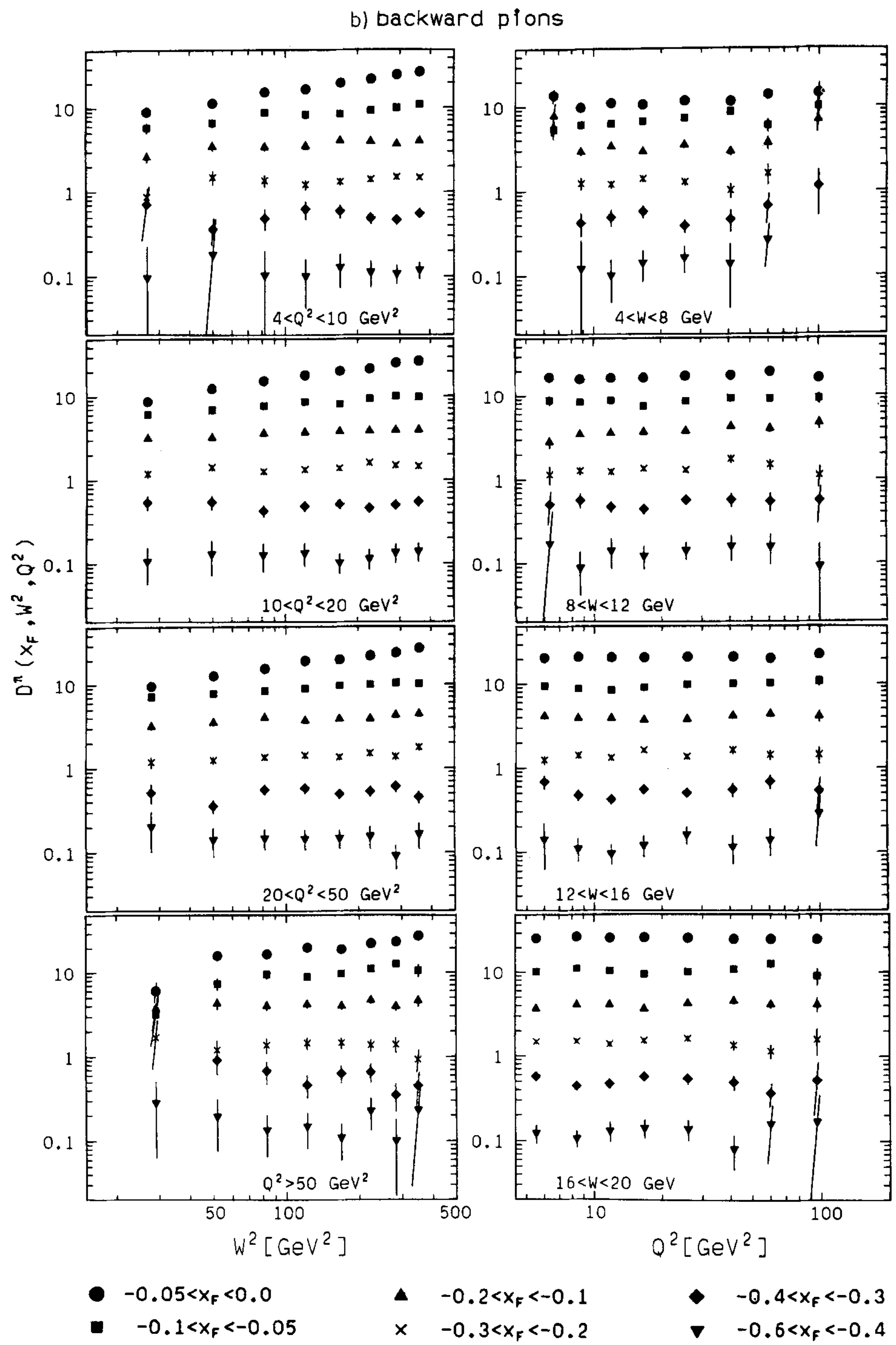
- Comparison $\pi \leftrightarrow K \leftrightarrow p$
- Comparison with Lund model

CERN EMC μp 280 GeV

$Q^2 > 4\,\text{GeV}^2,\ x > 0.02,\ 16 < W^2 < 400\,\text{GeV}^2$

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

Target fragmentation: CERN EMC muon-proton



Q^2-dependence of pion distributions at $x_F < 0$

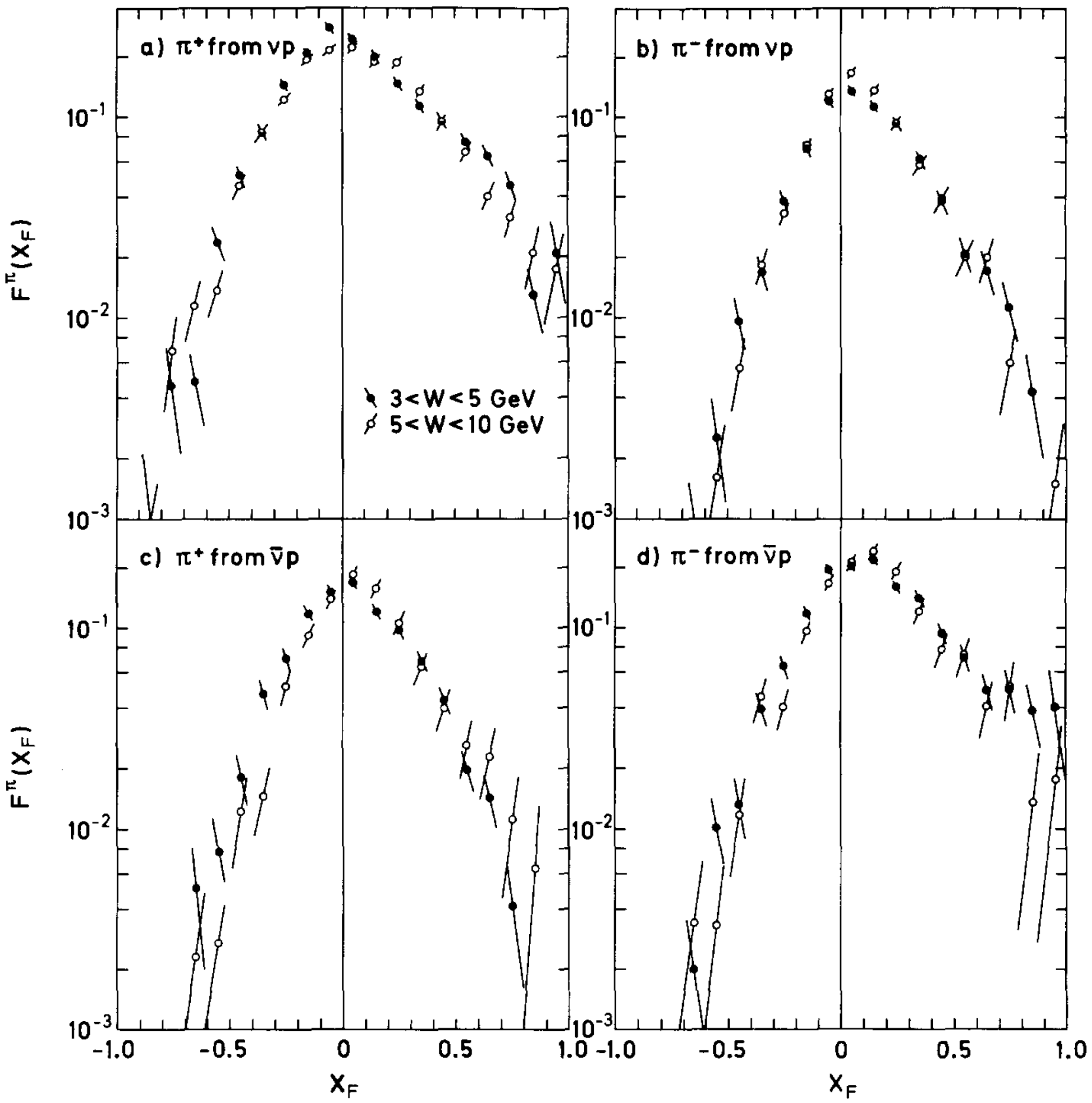
- Q^2 scaling observed at fixed W

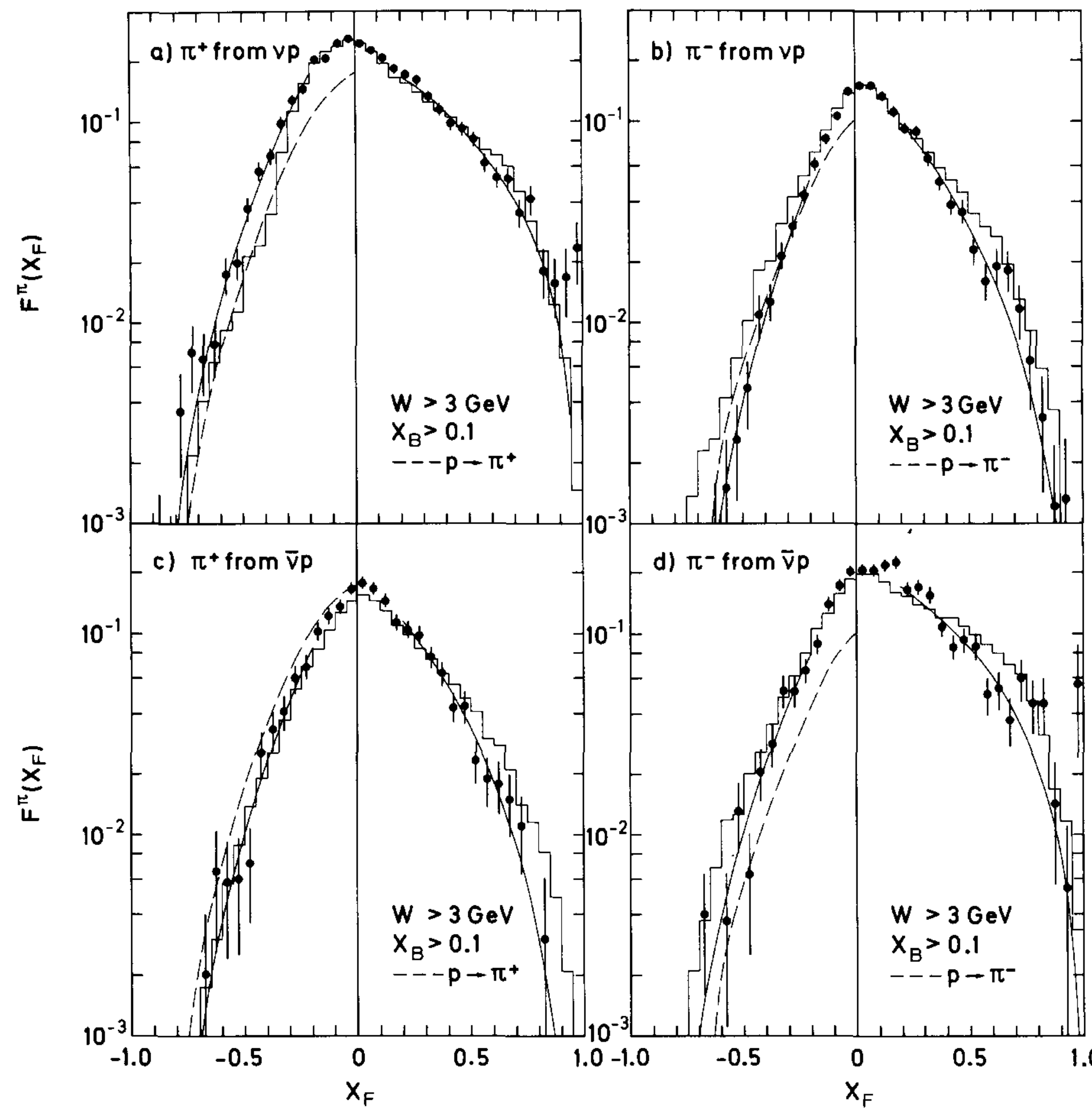
Further EMC measurements:

Correlations target-current regions, p_T balancing

M. Arneodo et al., Z.Phys.C 31, 1 (1986) [INSPIRE]

Target fragmentation: CERN neutrino-proton





x_F distributions of $\pi^\pm$

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

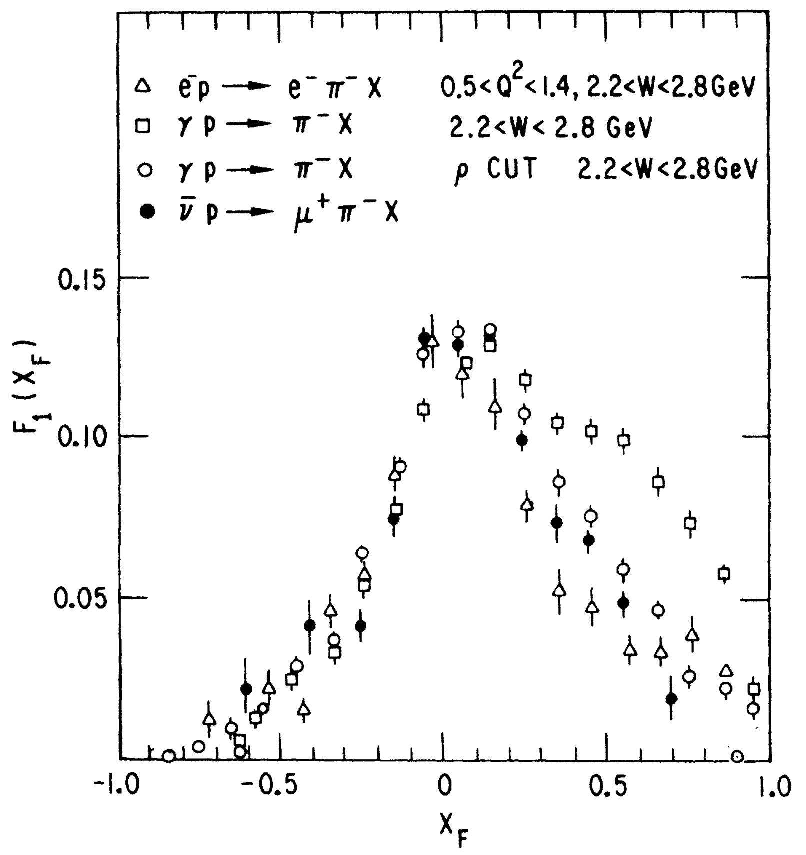
CERN broadband neutrino beam from 350-400 GeV protons

$\nu p / \bar{\nu} p$ CC events, E_{vis} > 5 GeV, p_μ > 3 GeV

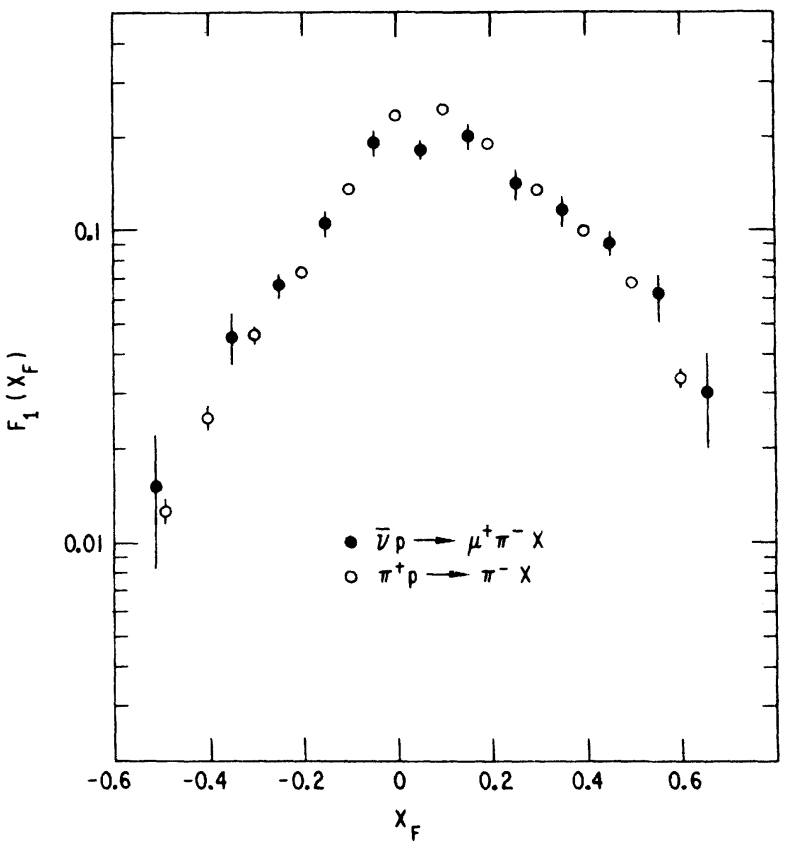
Aachen-Bonn-CERN-Munich-Oxford Collaboration

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

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 $x_F < 0$)



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

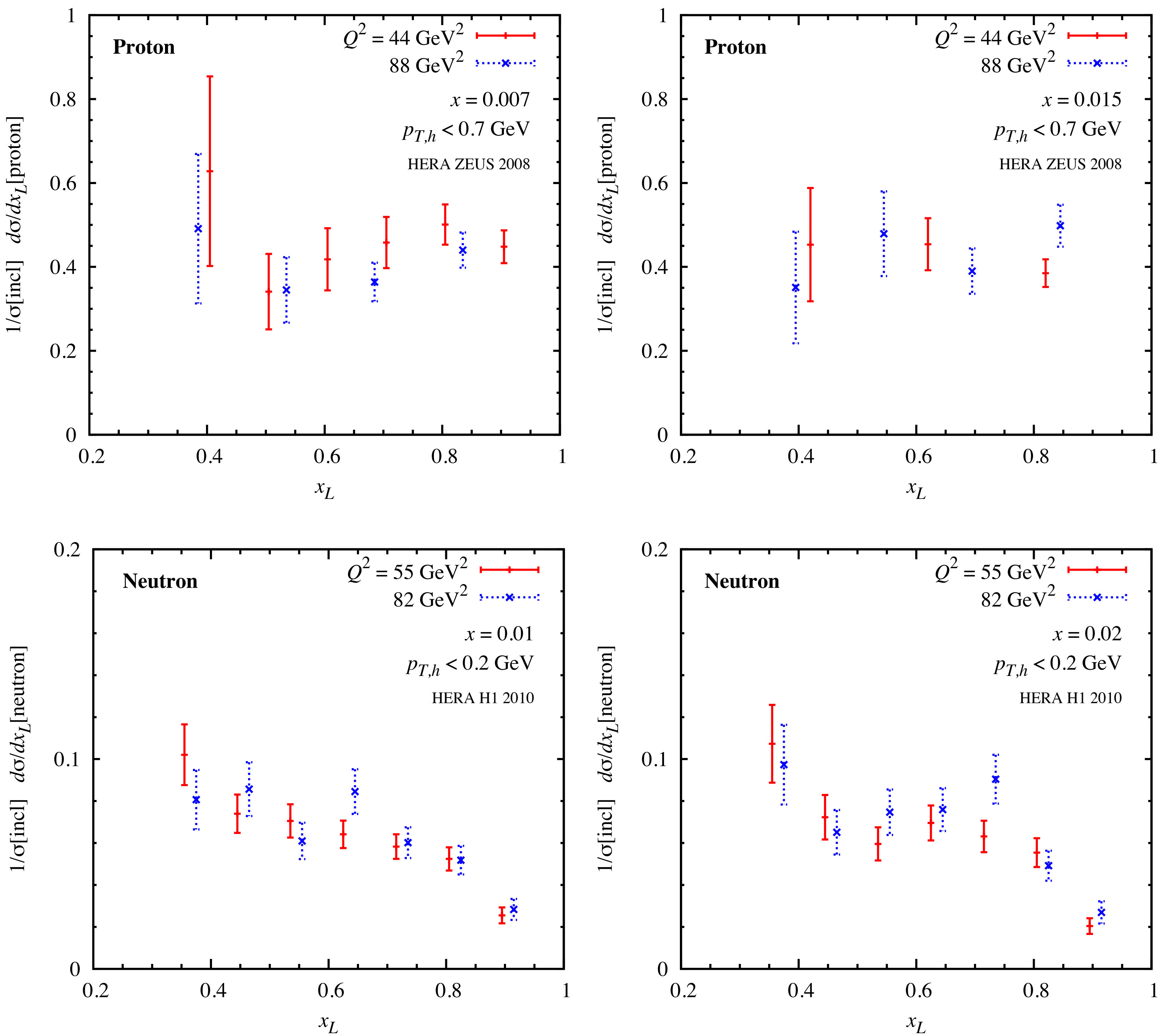
- Similar TF distributions obtained with all probes
- [Also: Rapidity, p_T distributions]

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



x_L 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

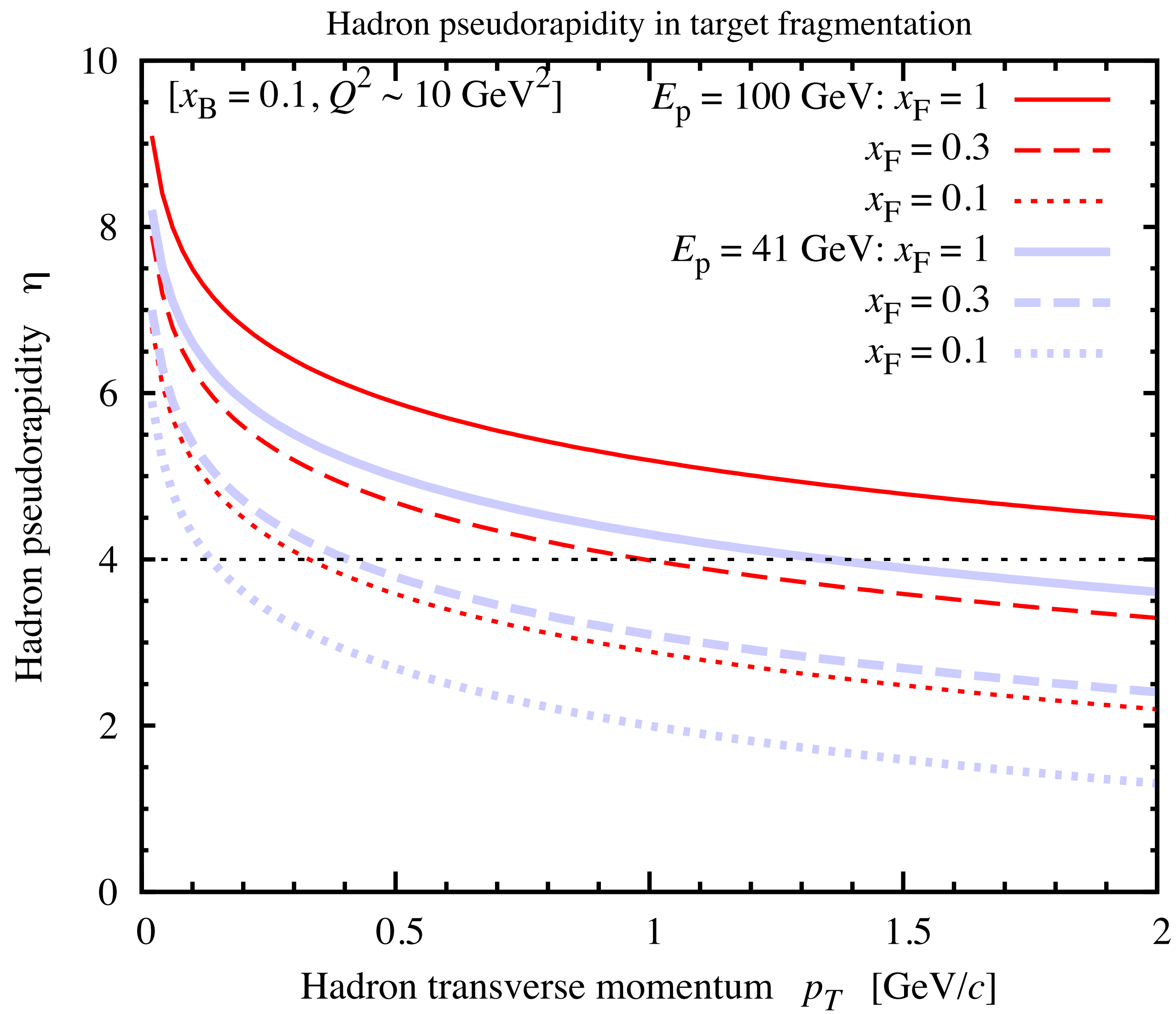
  Significant baryon number transport away from TF region.

  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 η 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]]