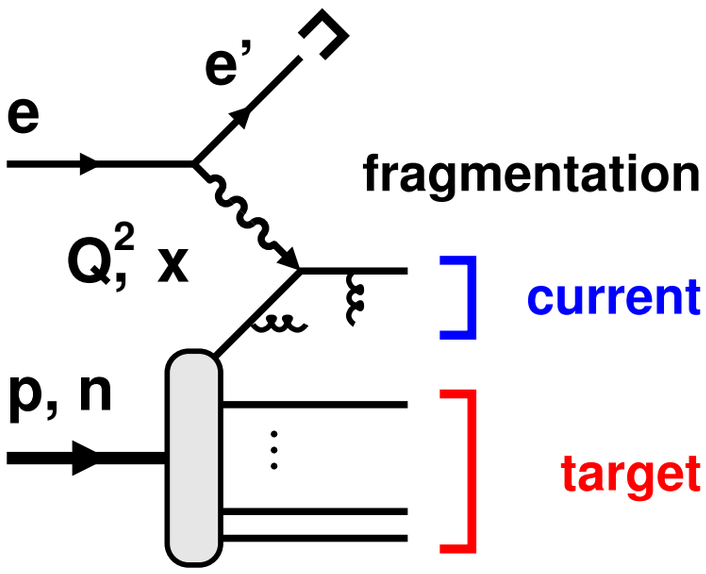
Target fragmentation in DIS on nucleon: Review of physics and measurements

C. Weiss (Jefferson Lab), Target fragmentation and diffraction physics with novel processes, CFNS Stony Brook, 9-11 Feb 2022 [Webpage]

Jefferson Lab



See also materials of 2020 CFNS Workshop "Target fragmentation physics with EIC" [Webpage]

Target fragmentation physics

Kinematic variables

QCD factorization → Rogers, Chien

Structures and dynamics

Target fragmentation measurements

ep/en: Cornell, JLab12 → Avakian

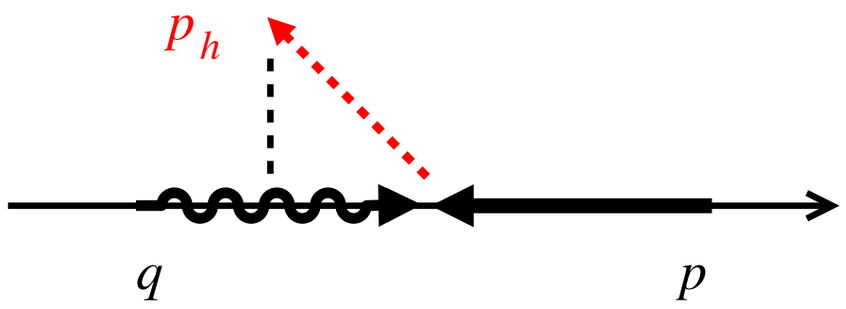
μp: CERN EMC

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

ep: HERA → Strikman

EIC detector coverage

Target fragmentation: Kinematic variables



Feynman variable

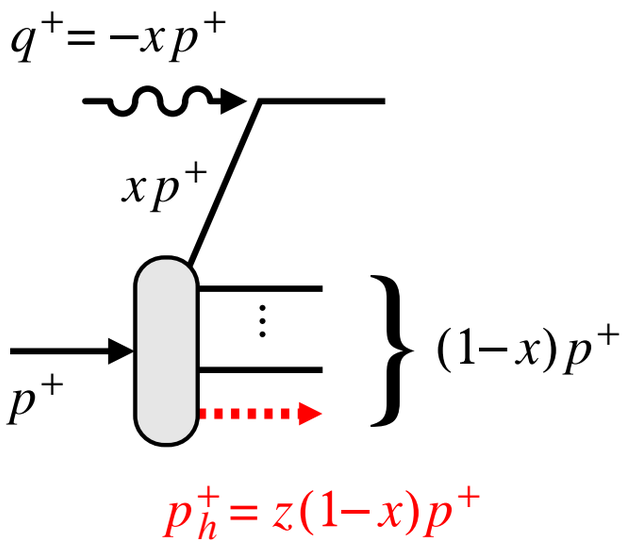
$$x_F = \frac{p_h^z}{p_h^z\,(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\,\mathbf{q}, \qquad -1 < x_F < 1$$

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



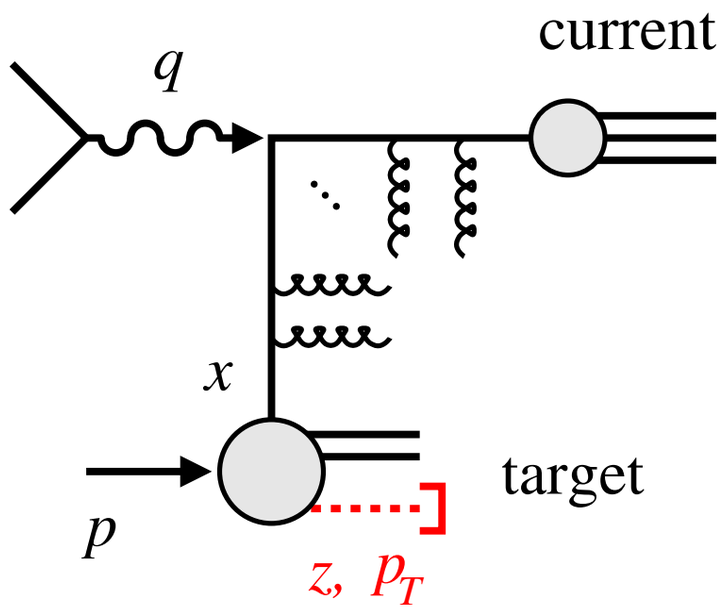
Light-cone fraction

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

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



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 $z, p_T \ll Q$

Fracture functions / Conditional PDFs

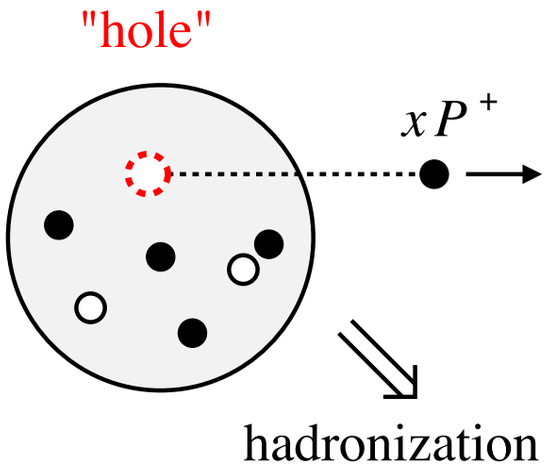
Probability to find hadron with z, p_T in target
after removing parton with x

Universal, independent of hard process

Express target structure and hadronization dynamics

Open questions in QCD factorization:
→ Rogers, Chien

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

Dependencies

x-dependence: Configurations in WF

Charge/flavor of removed quark [Ceccopieri, Mancusi 2012]

Spin dependence: Nucleon, removed quark, fragment Λ, Δ [Strikman 2013]

Azimuthal asymmetries ϕ_h [Anselmino, Barone, Kotzinian 2011]

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

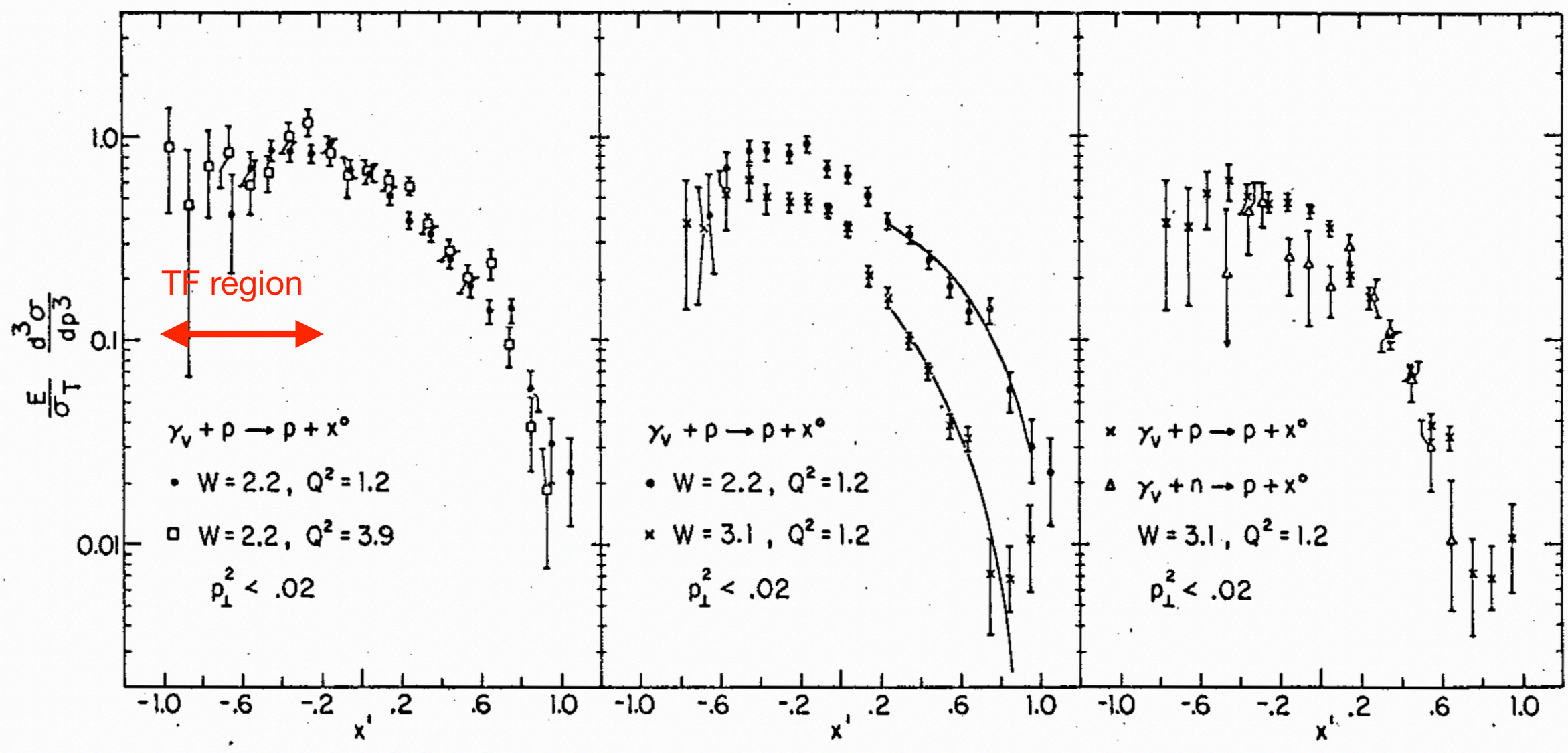
Cornell Synchrotron 1975

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

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

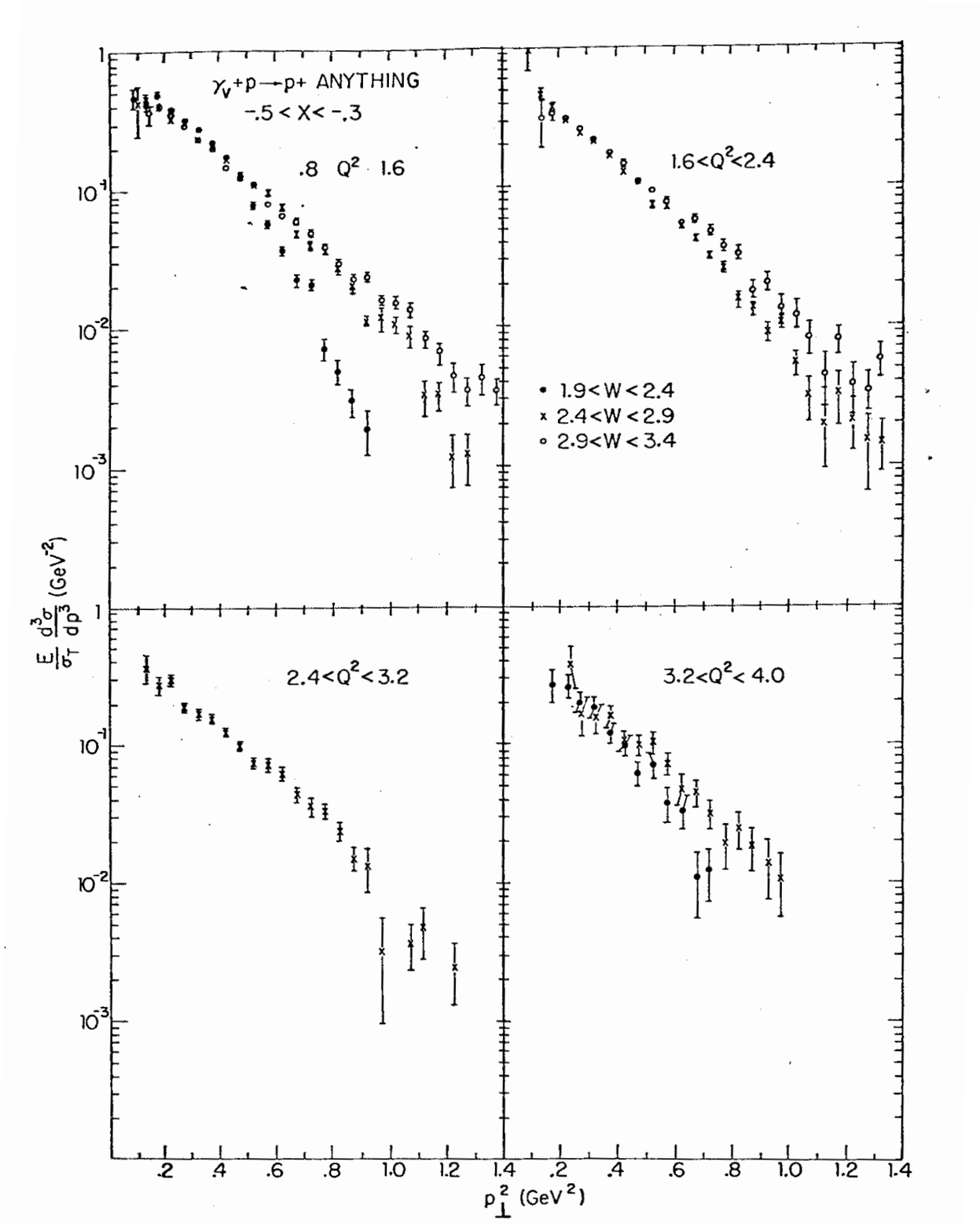
Proton x_F distribution

- 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



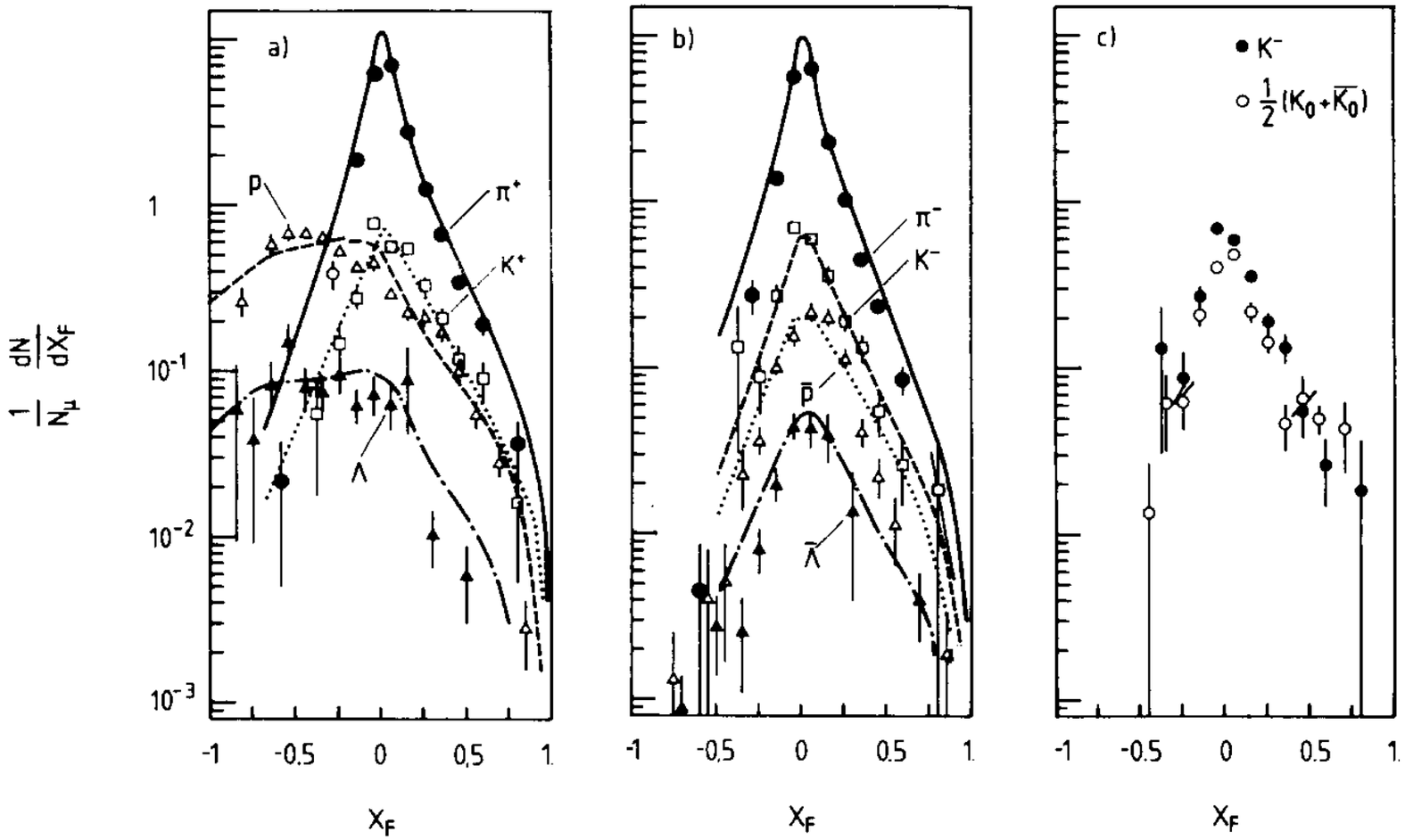
Proton p_T distribution

- 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]

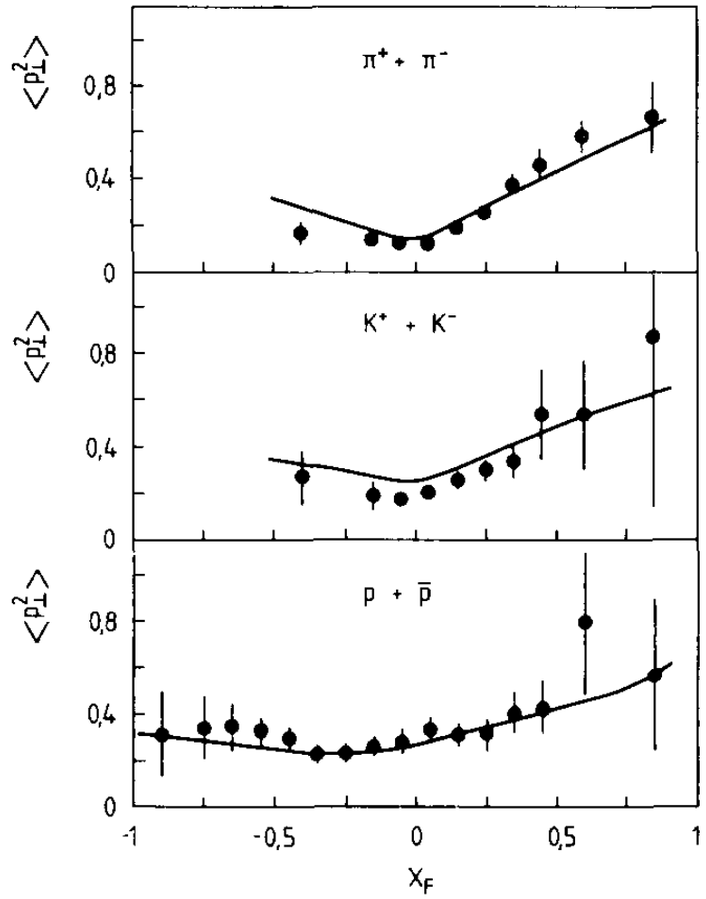
Target fragmentation: CERN EMC muon-proton



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]

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



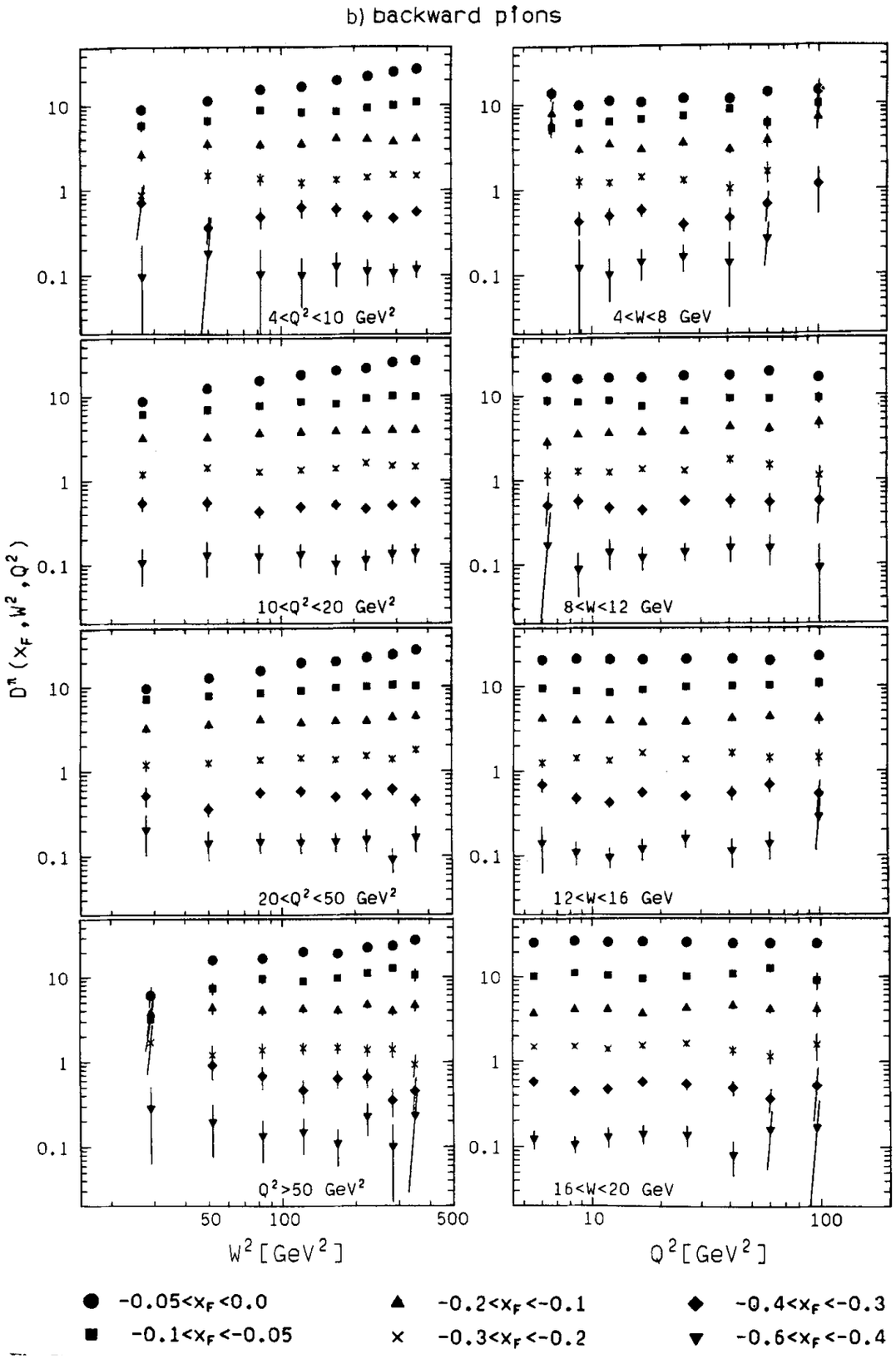
Average $\langle p_T^2 \rangle$ of π, K, p

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

CERN EMC μp 280 GeV

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

Target fragmentation: CERN EMC muon-proton



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

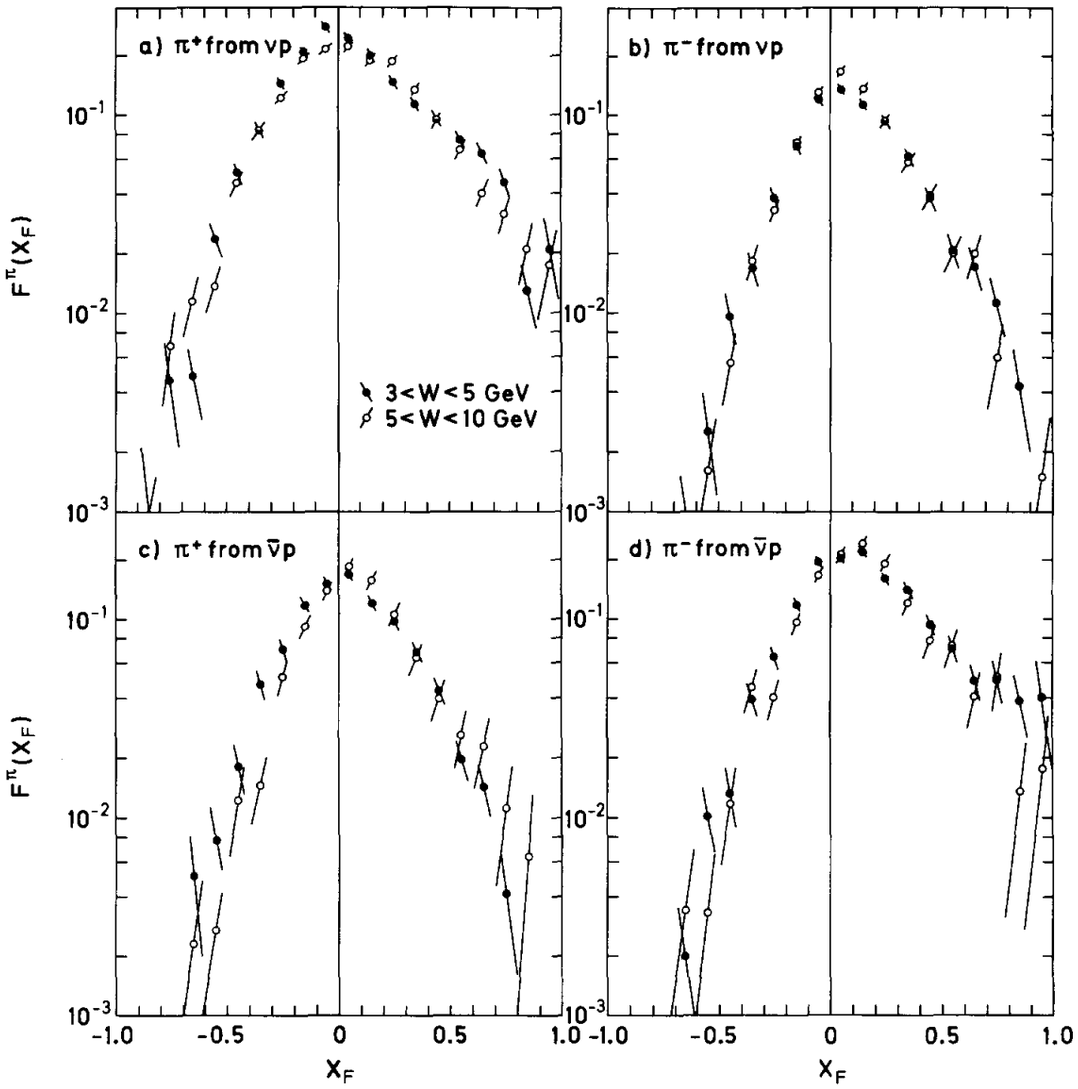
- Q^2 scaling observed at fixed W

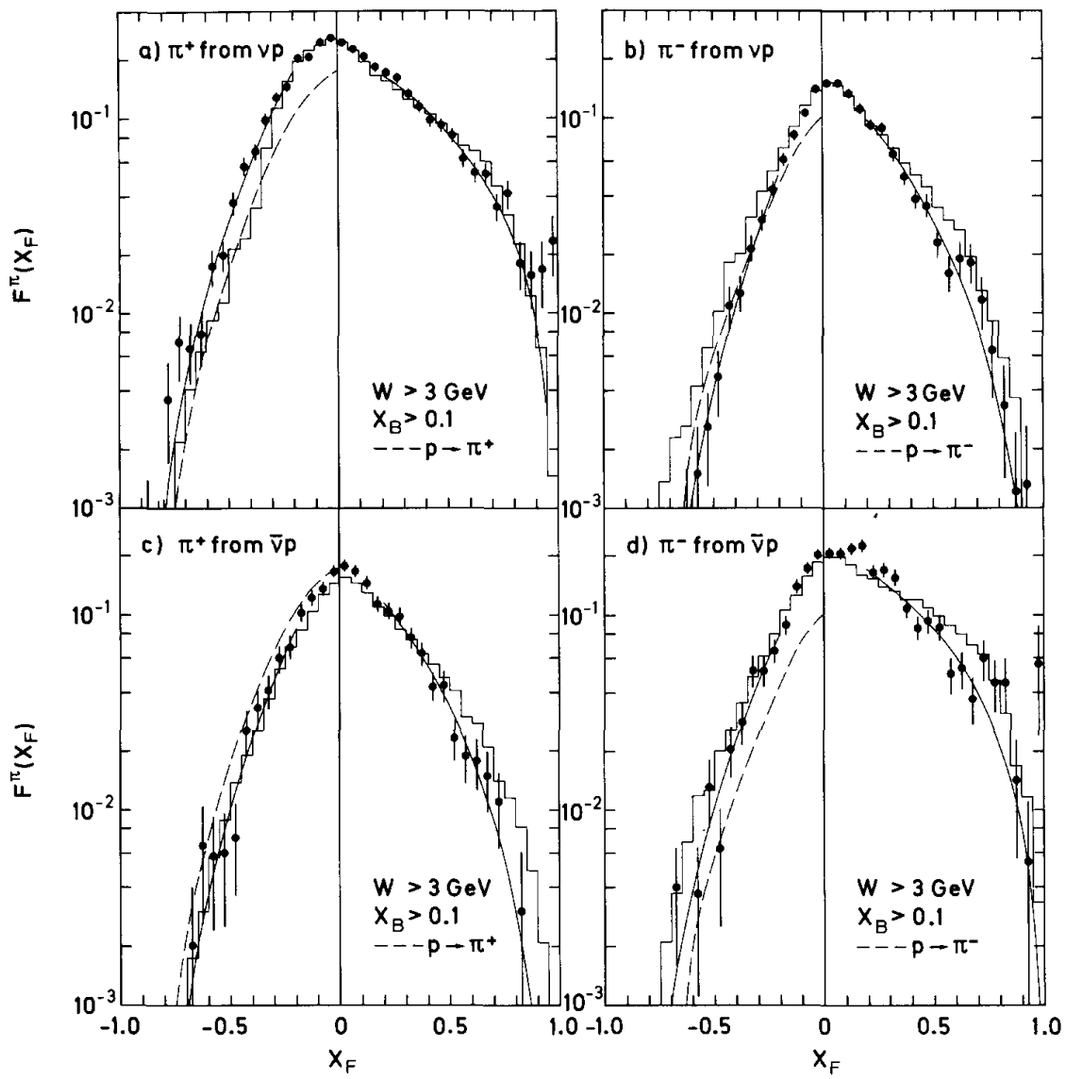
Further EMC measurements:

Correlations target-current regions, p_T balancing

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

Target fragmentation: CERN neutrino-proton





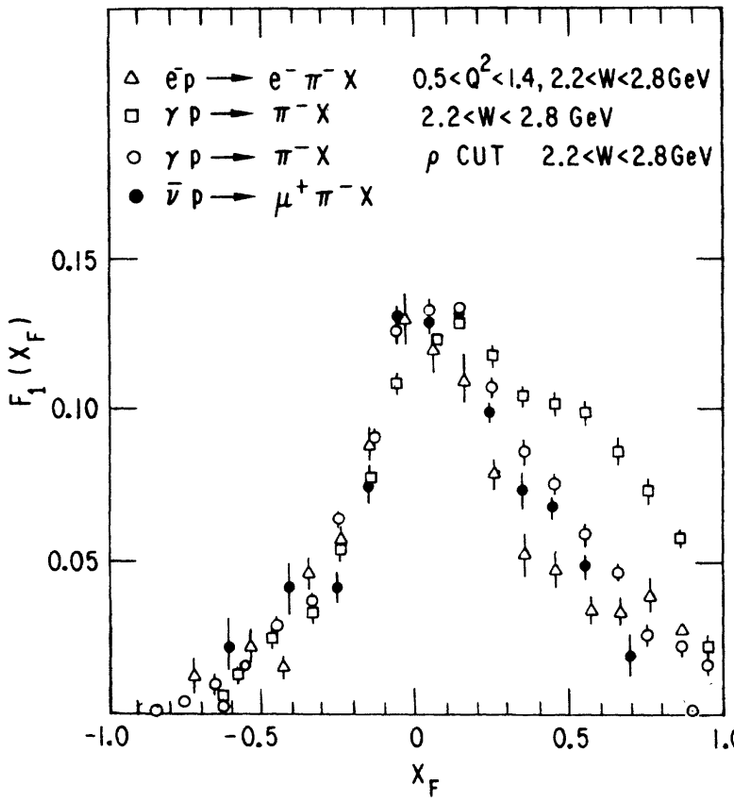
x_F distributions of $\pi^{\pm}$

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

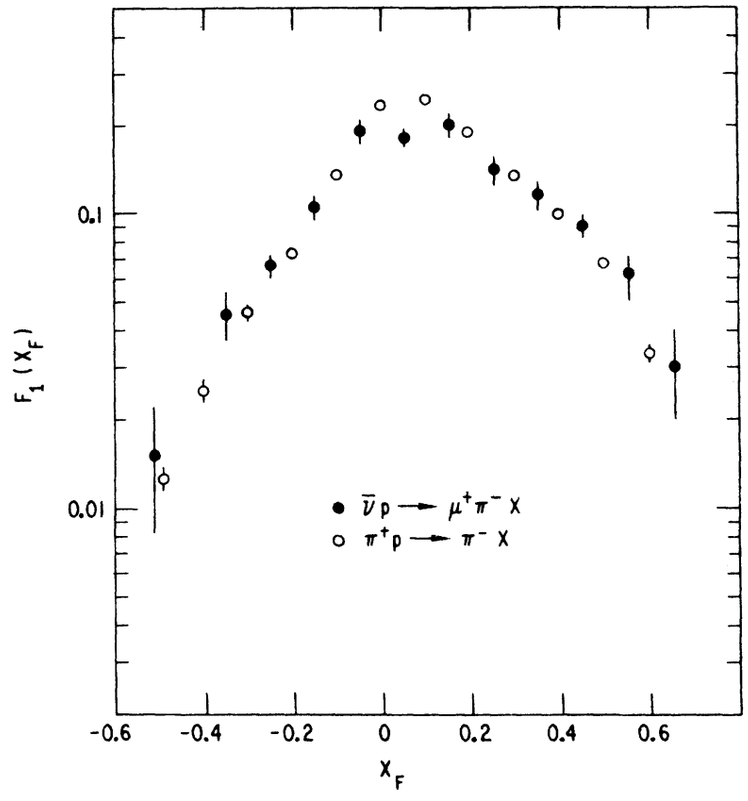
P. Allen et al. NPB 214, 369 (1983) [INSPIRE]

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

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 $x_F < 0$)

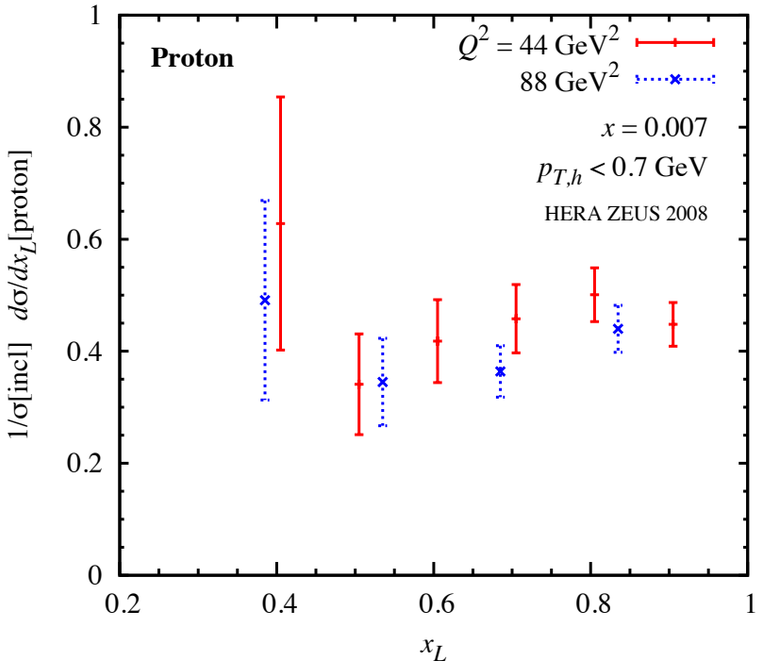


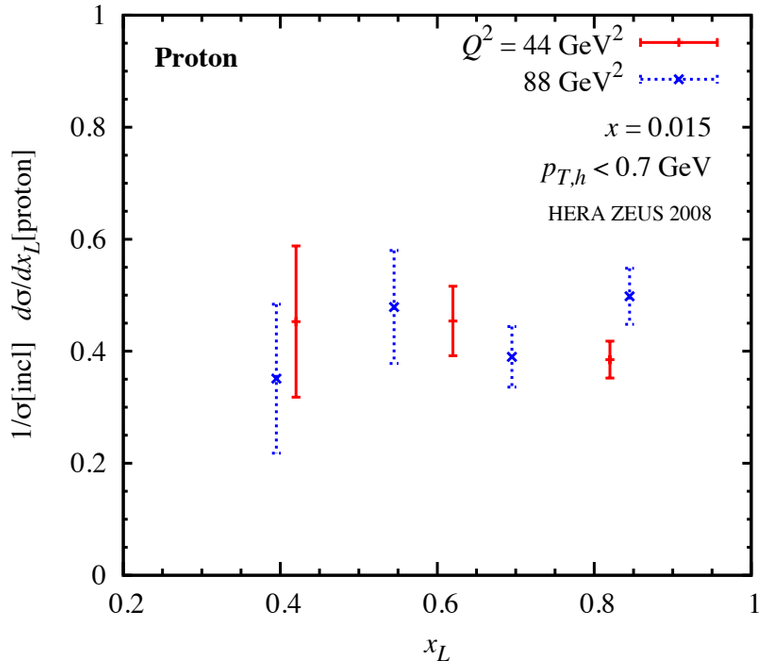
Normalized x_F distributions of $\pi^\pm$ in $\bar{\nu}p$ and πp (πp normalization adjusted)

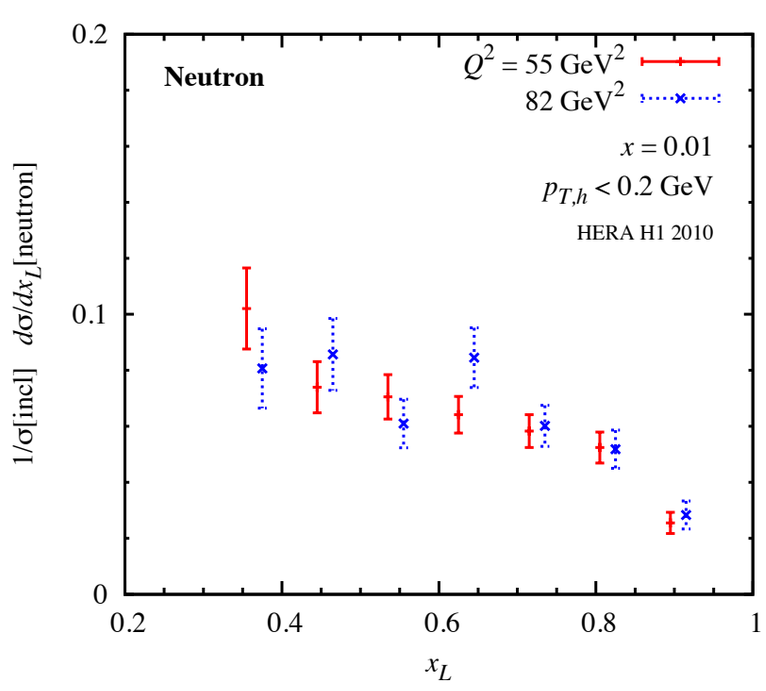
- Similar TF distributions obtained with all probes
- [Also: Rapidity, p_T distributions]

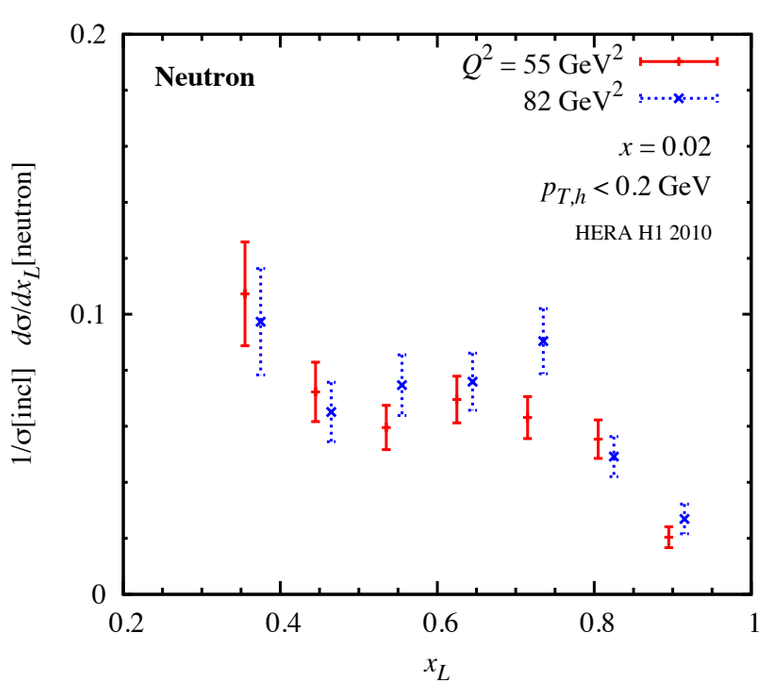
FNAL broadband neutrino beam from 300-400 GeV protons
Bubble Chamber detector for muon and charged hadrons
M. Derrick et al., PRD 17, 1 (1978) [INSPIRE]

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

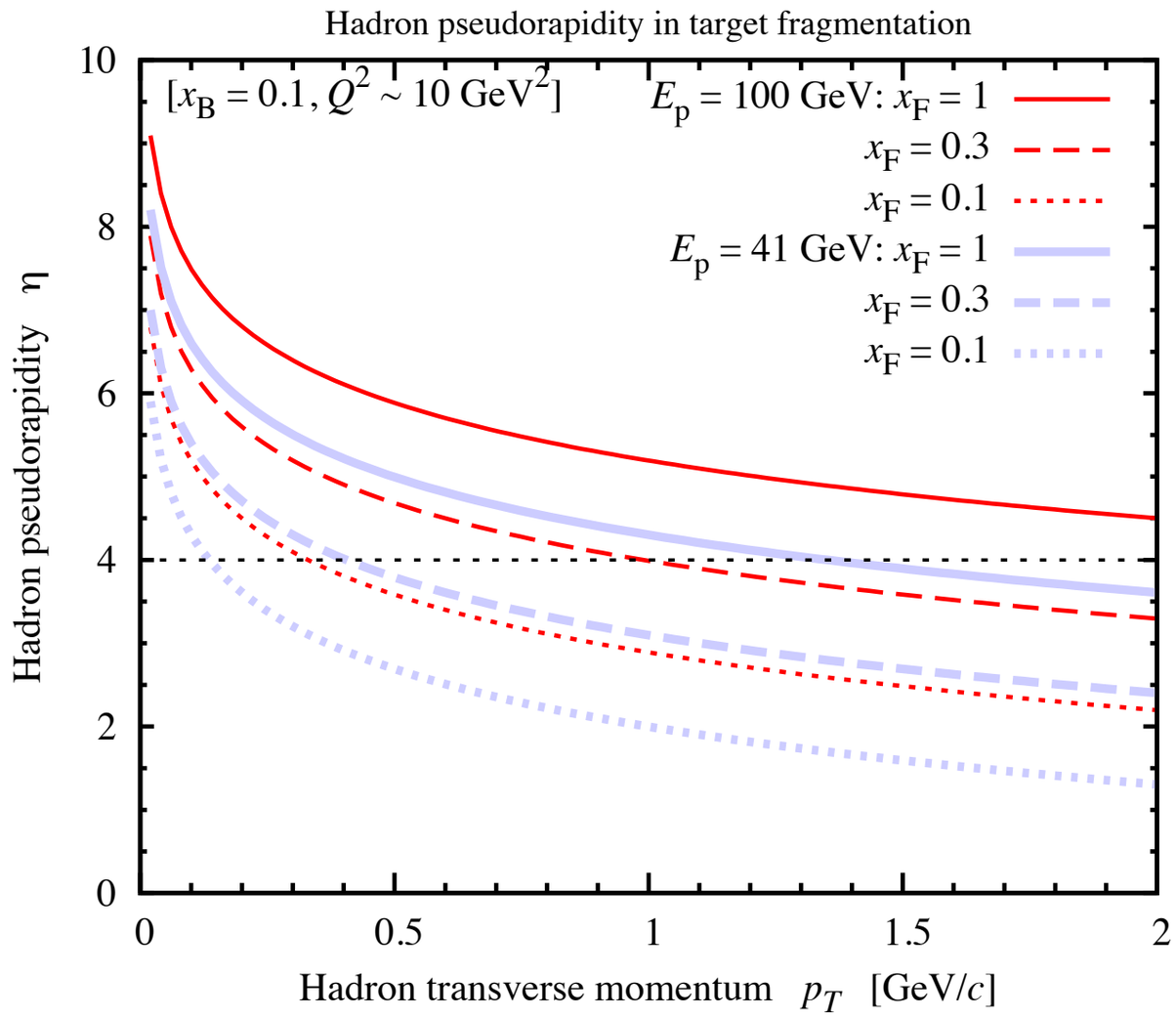
Significant baryon number transport away from TF region.

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]]

Summary and questions

- Valuable information on target fragmentation in “old” DIS data

- Observations from fixed-target experiments

  Approximate Q^2 scaling of distributions at fixed W

  Similar hadron distributions at $x_F < 0$ in DIS and in photon-hadron/hadron-hadron

- What does this imply for QCD factorization?

  Is there Q^2 scaling at fixed z? Need analysis with appropriate binning!

  Can we use Feynman scaling to construct “soft interaction” models for fracture functions?

- Observation from HERA collider experiments

  Significant baryon number transport in DIS even at $x \lesssim 0.01$.
  Difficult to reconcile with scattering from sea quarks