Elucidating the Quark-Gluon Structure of Hadrons

[Will always talk about Electron Scattering!]

Factorization Proof →

Core Quark-Gluon Calculation + Universal Function

Examples of Universal Functions

Inclusive Scattering	Parton Distribution Functions
Semi-Inclusive Scattering	Fragmentation Functions
Exclusive Scattering	Generalized Parton Distributions

Cross sections **scale** if they follow the energy-momentum dependence of the **core quark-gluon calculation**

Question

When do cross sections scale, and how do we experimentally "prove" factorization

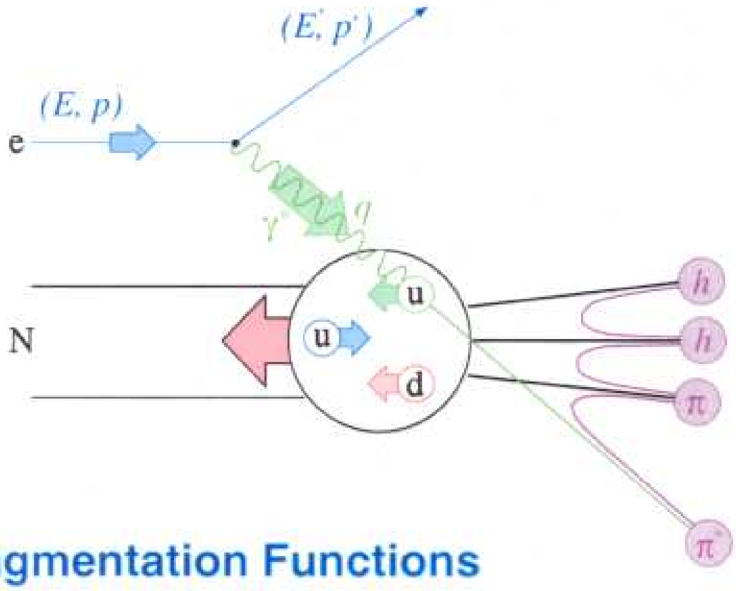
Things may not be as they seem...

Deep inelastic scattering	Scaling
	Quark-Hadron Duality
Semi-Inclusive scattering	Fragmentation
	Low-Energy Factorization?
	Meson Duality/Scaling
	P_T Dependence/Broadening
Exclusive Scattering	Meson Production
	Color Transparency
	Pion Transparency

Fragmentation Models

Hard Matrix Elem → Parton Shower → **Hadronization**

Perturbative QCD calculations — Non-perturbative models



$$z = E_h/E_q = E_h/\nu$$

Fragmentation Functions

Universal fragmentation function $D(z)$ describes the transition ($q \rightarrow hadron$) ... "distribution of hadrons within a quark". cf. other universal function = PDF $q(x)$ ... "distribution of quarks within a hadron".

$$\frac{d\sigma}{dz}(e^+e^- \rightarrow hX) = \sum_q \sigma(e^+e^- \rightarrow q\bar{q})[D_q^h(z) + D_{\bar{q}}^h(z)]$$

$$\frac{1}{\sigma}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 q(x) D_q^h(z)}{\sum_q e_q^2 q(x)}$$

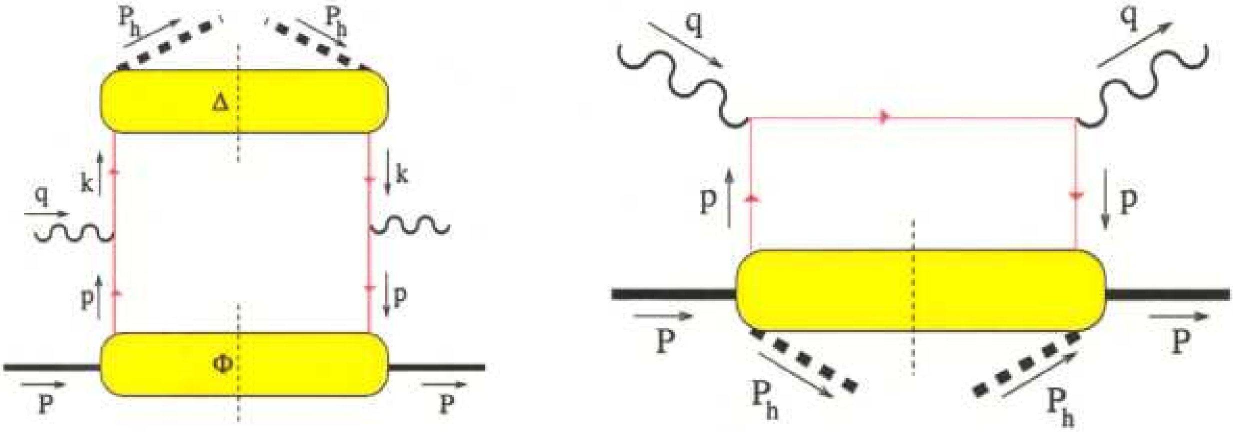
Relations

- Momentum conservation: $\sum_h \int_0^1 D_q^h(z)dz = 1$
- Probability conservation: $\sum_q \int_{z_{\min}} [D_q^h(z) + D_{\bar{q}}^h(z)]dz = n_h$
  (n_h = average multiplicity)

Factorization

Both Current and Target Fragmentation Processes Possible.

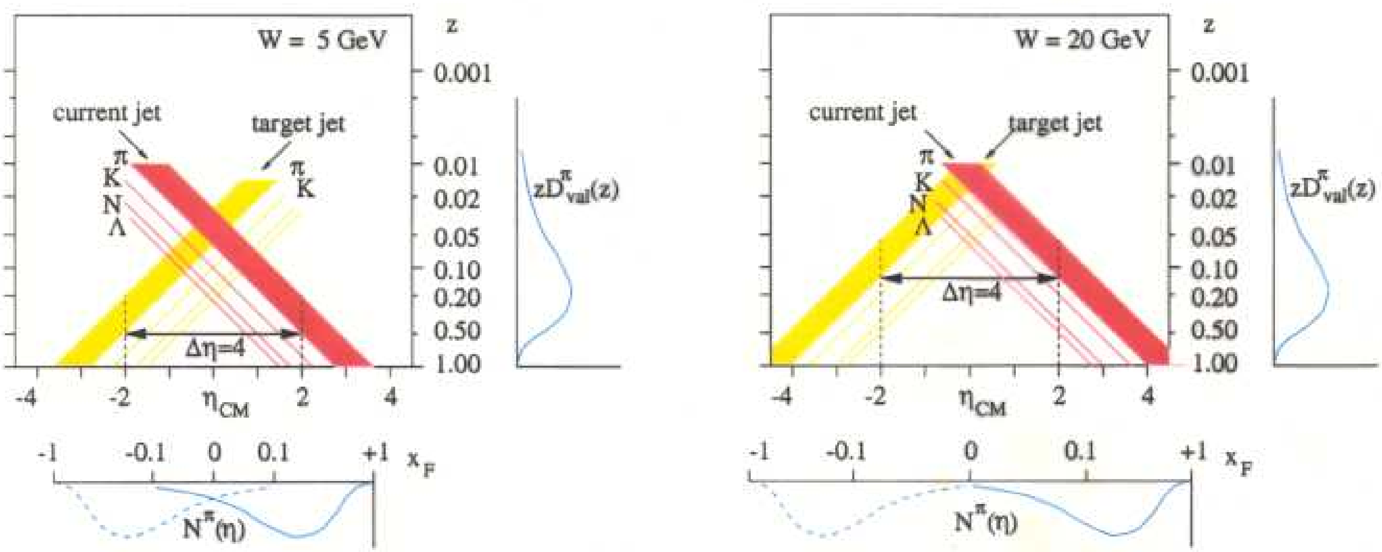
At Leading Order: .



Berger Criterion $\Delta\eta \geq 2$ Rapidity Gap for factorization

Separates Current and Target Fragmentation Region in Rapidity

P.J. Mulders, hep-ph/0010199 (EPIC Workshop, MIT, 2000)



At large z-values easier to separate current and target fragmentation region → for fast hadrons factorization "works" at lower energies

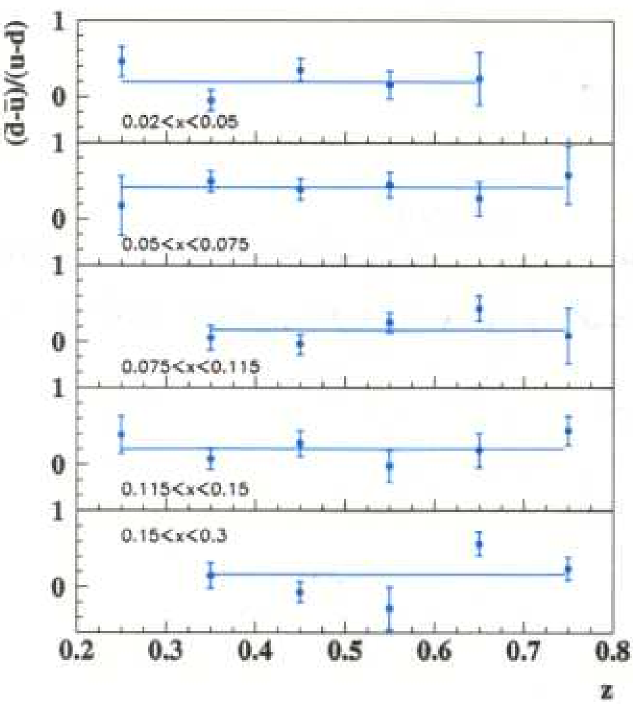
At W = 5 GeV $z > 0.3$ At W = 20 GeV $z > 0.1$

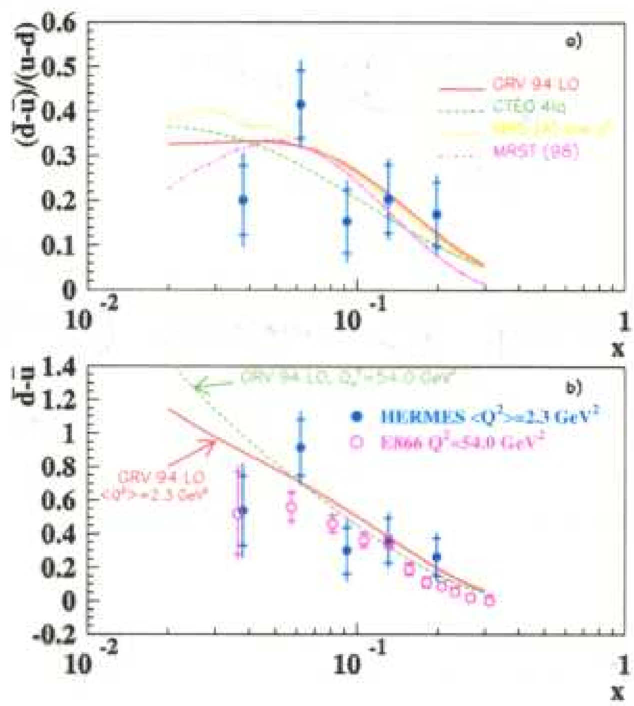
Low-Energy Factorization?

Flavor Asymmetry of the Light Quark Sea

$$\frac{\bar{d}(x) - \bar{u}(x)}{u(x) - d(x)} \sim f(D^+(z)/D^-(z)) \frac{N_p^{\pi^-}(x,z) - N_n^{\pi^-}(x,z)}{N_p^{\pi^+}(x,z) - N_n^{\pi^+}(x,z)}$$

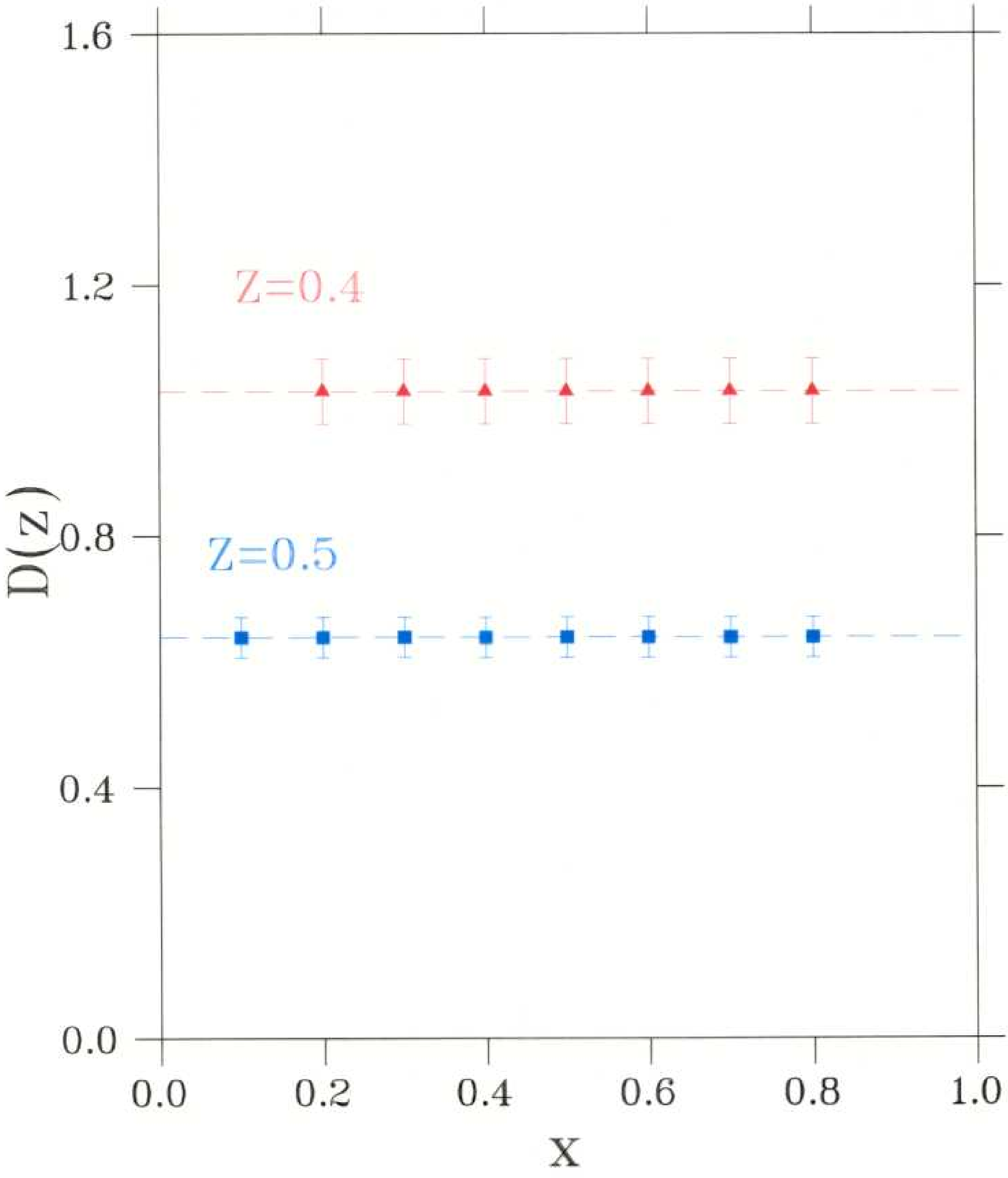
HERMES Collaboration, Phys. Rev. Lett. **81**, 5519 (1998)





- Data do, within statistics, confirm independence of x and z dependence, for $z \geq 0.25$
- HERMES data at $Q^2 \sim 2.3$ GeV^2 agree well with FNAL Drell-Yan data at Q^2 = 54 GeV^2

$x \approx$ **0.1**, $Q^2 \approx$ **2.3** $\rightarrow W^2 \approx$ **25**


1.6
1.2
0.8
0.4
0.0
Z=0.4
Z=0.5
D(z)
0.0
0.2
0.4
0.6
0.8
1.0
X

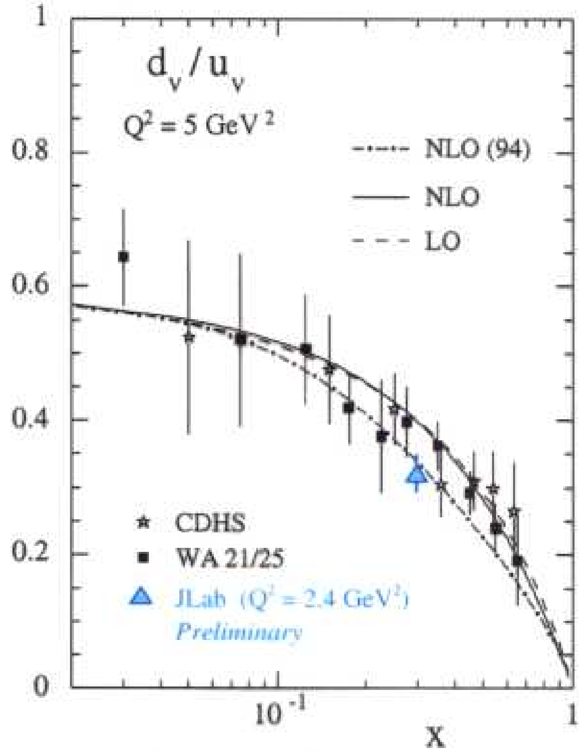
Low-Energy Factorization at JLab?

^{1}H(e,e$'\pi^{\pm}$) and ^{2}H(e,e$'\pi^{\pm}$) data

8 hours only !!!

$\nu \approx 4$ GeV, $Q^2 = 2.3$ GeV^2, $W^2 = 5$ GeV^2, $z > 0.5$

- Extracted fragmentation functions agree reasonably well with NLO fragmentation function fit to high-energy e^+e^- data



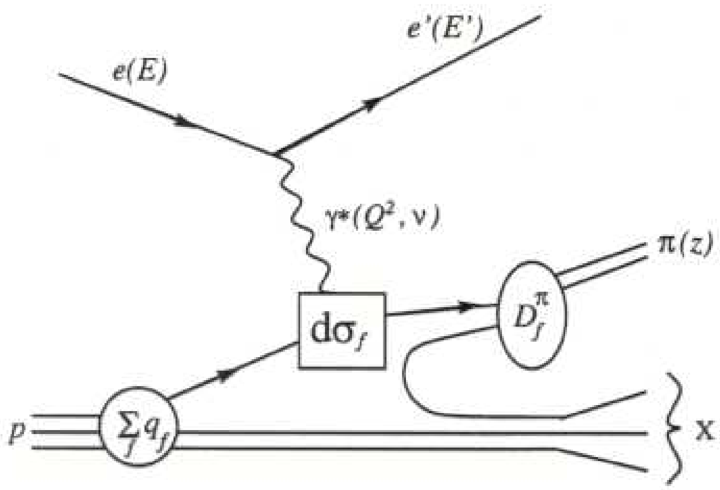
- Extraction of d_v/u_v agrees well with high energy data

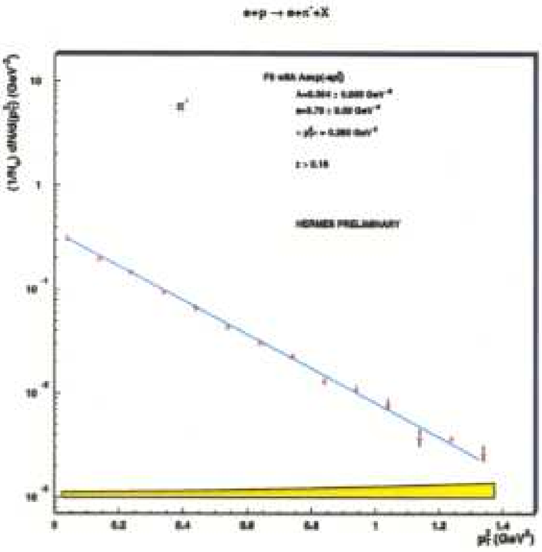
E00-108 approved for 20 days to test factorization over large x and z range

If factorization holds, large research area of quark fragmentation opens up

P_T Dependence

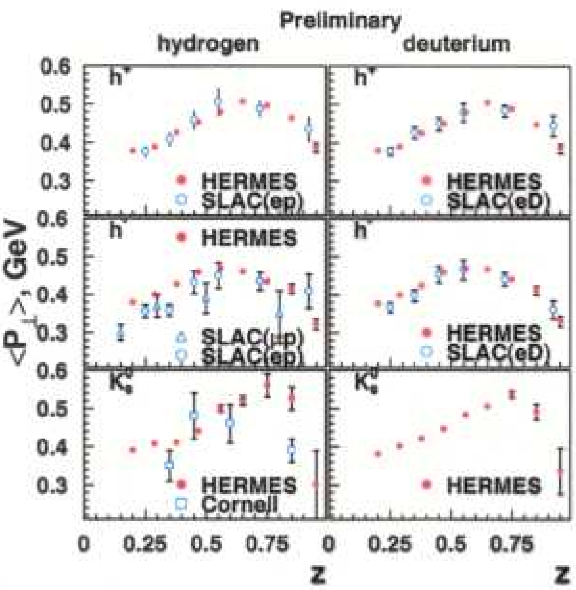
$$\frac{1}{\sigma}\frac{d\sigma}{dz\,dP_T{}^2 d\phi}(ep \rightarrow hX) \quad = \quad \frac{dN}{dz} b e^{-bP_T{}^2}(1 + A\cos(\phi) + B\cos(2\phi))$$

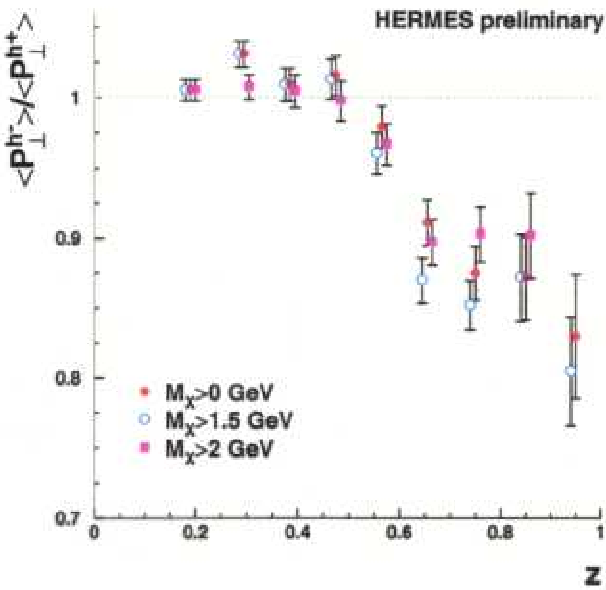




Many Open Questions

- Is P_T dependence **flavor** dependent?
- Is P_T dependence **spin** dependent?
- Is P_T dependence medium dependent? – Nuclear broadening?





P_T Broadening

Define

$$< {P_T}^2 >^{eA} = \int d{P_T}^2 {P_T}^2 \frac{d\sigma_{eA\to e\pi X}}{dx dQ^2 d{P_T}^2} / \frac{d\sigma_{eA\to eX}}{dx dQ^2}$$

and Nuclear Broadening as

$$\Delta < {P_T}^2 > \; = \; < {P_T}^2 >^{eA} - < {P_T}^2 >^{eN} \;\sim\; a + bA^{1/3}$$

Typical numbers a,b $\sim$ 0.1 GeV^2

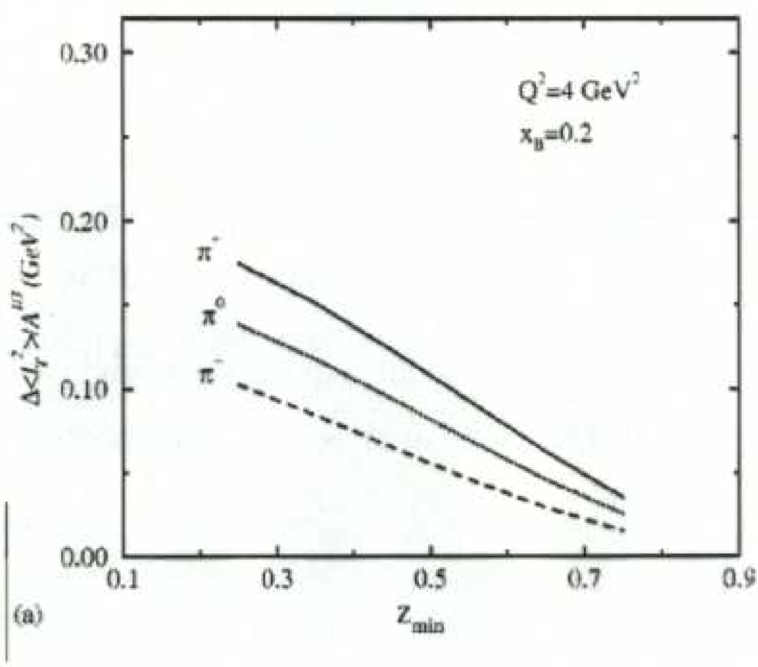
a due to localized hard scattering

b due to multiple scattering (Quark-gluon correlations)

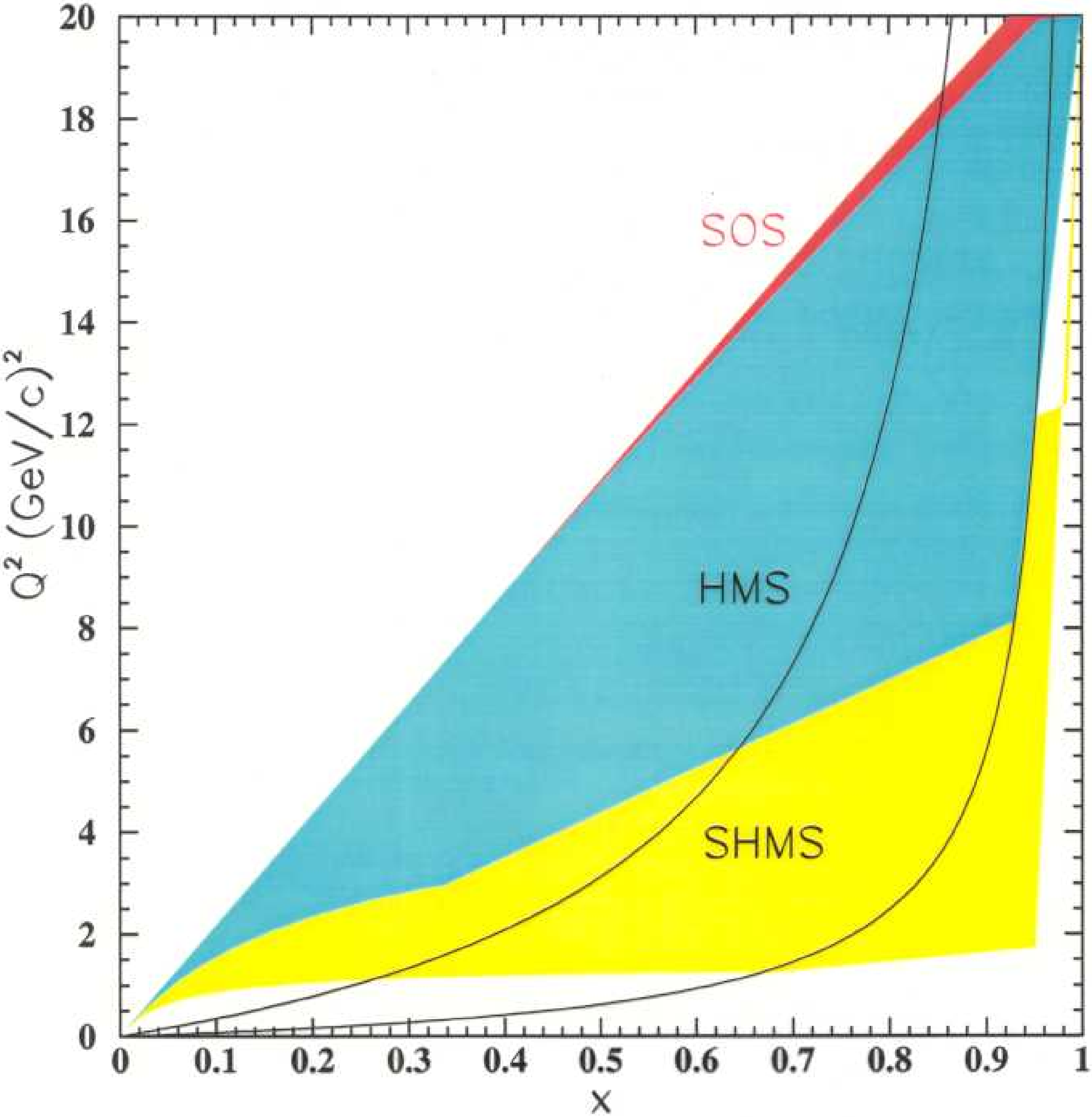
Easiest to interpret at $x \approx 0.25$ – EMC Effect small !!!

X. Guo and J. Qiu, Phys. Rev. D **61**, 096003 (2000)

$$b^{\pi^0} \approx \frac{4\pi^2 \alpha_s(Q^2)}{3} \lambda^2 \int_{z_{min}}^{1} dz z^2 D^{\pi^0}(z)$$



Hall C 12 GeV Kinematics



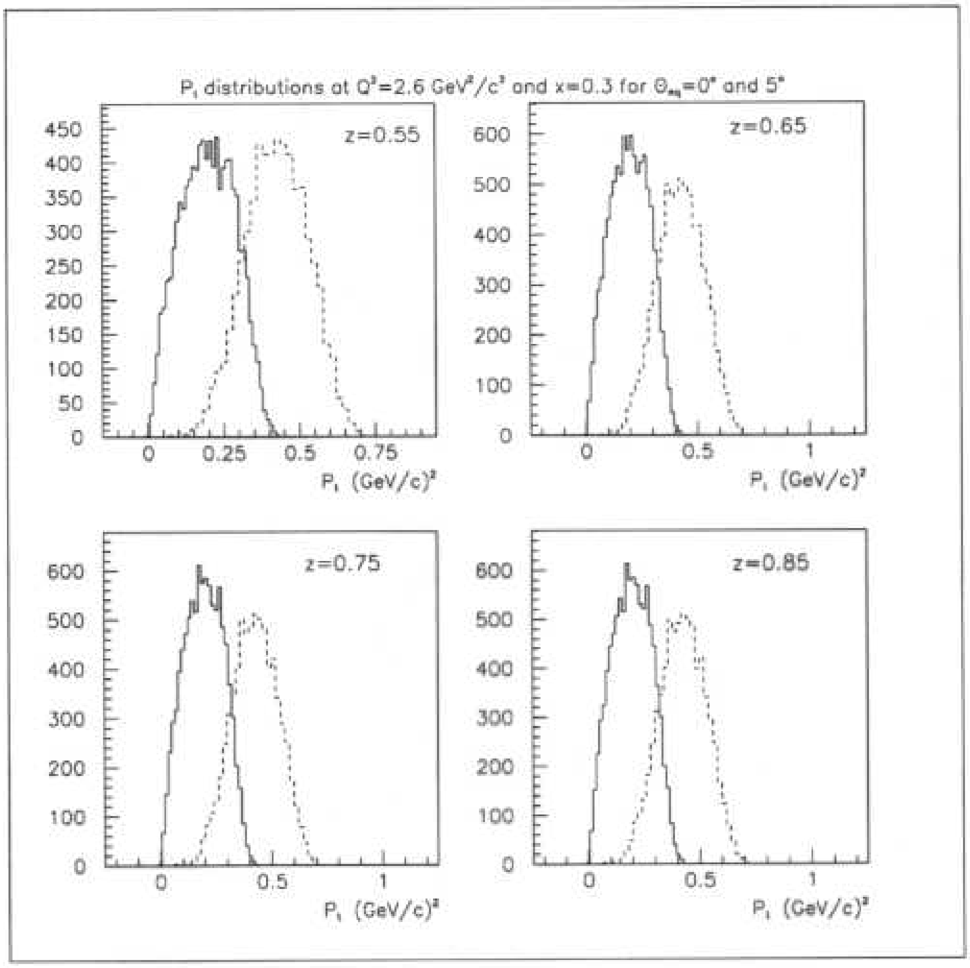
Solid lines indicate W^2 = 1.5 GeV^2 and W^2 = 4.0 GeV^2

P_T Broadening at JLab

Doable with 6-12 GeV and forward-angle spectrometer

6 GeV Example at $x = 0.3$ and $Q^2 = 2.6$

SOS + HMS



12 GeV allows larger range in P_T, and higher Q^2 and W^2

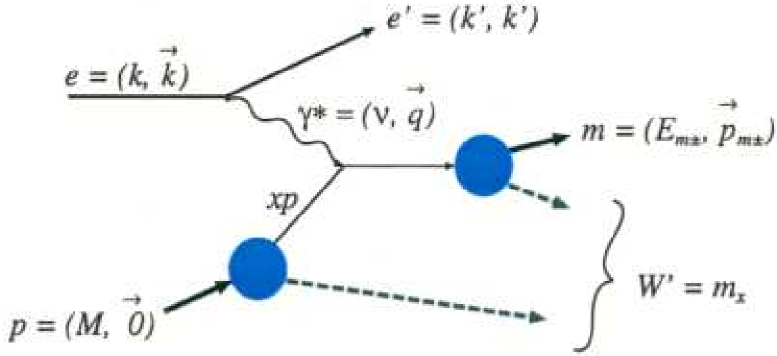
HMS + SHMS

High Luminosity and $\Theta_{SHMS} = 5.5°$ helps!

b ≈ 0.1 GeV^2 already ruled out by SLAC-Osborne experiment?

Duality in Meson Electroproduction

Afanasev, Carlson, and Wahlquist, Phys. Rev. D 62, 074011 (2000)



(e,e′) $$W^2 = M_p^2 + Q^2 \left(\frac{1}{x} - 1\right)$$

For M_m small, collinear with $\vec{\gamma}$, and $\frac{Q^2}{\nu^2} << 1$

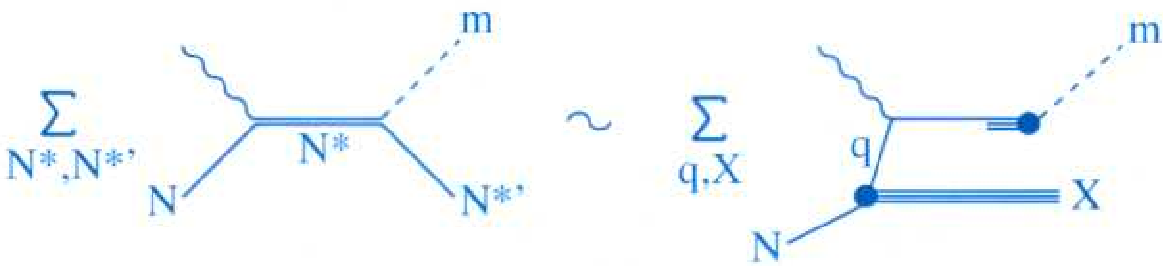
(e,e′m) $$W'^2 \approx M_p^2 + Q^2 \left(\frac{1}{x} - 1\right)(1-z)$$

$$z = E_m/\nu$$

Factorization gives (LO QCD)

$$\frac{d\sigma}{dz} \sim \sum_i e_i^2 \left[q_i(x,Q^2) D_{q_i}^m(z,Q^2) + \bar{q}_i(x,Q^2) D_{\bar{q}_i}^m(z,Q^2)\right]$$

In hadronic basis: excitation of N^* resonances and subsequent decays into mesons and lower-lying resonances $N^{*\prime}$



Requires non-trivial cancellations of Decay Angular Distributions

Scaling in Electropion Production

Calogeracos, Dombey, and West, Phys. Rev. D 51, 6075 (1995)

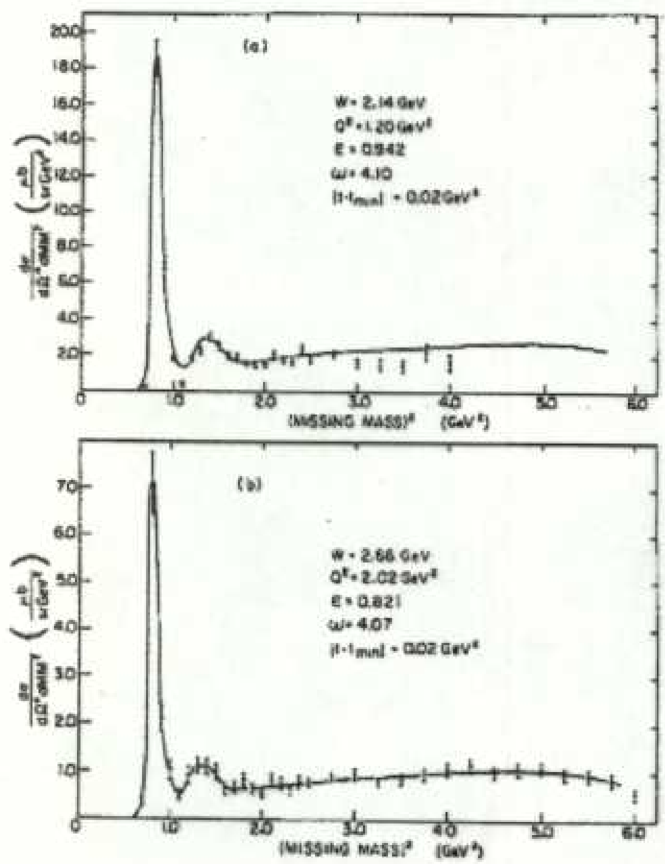
$$s^2 \frac{d^2\sigma}{dt\,dW'^2} = F(x,t,W^2)$$

Cornell : $x = 0.24$
$t = 0.02$
(end of '70's)

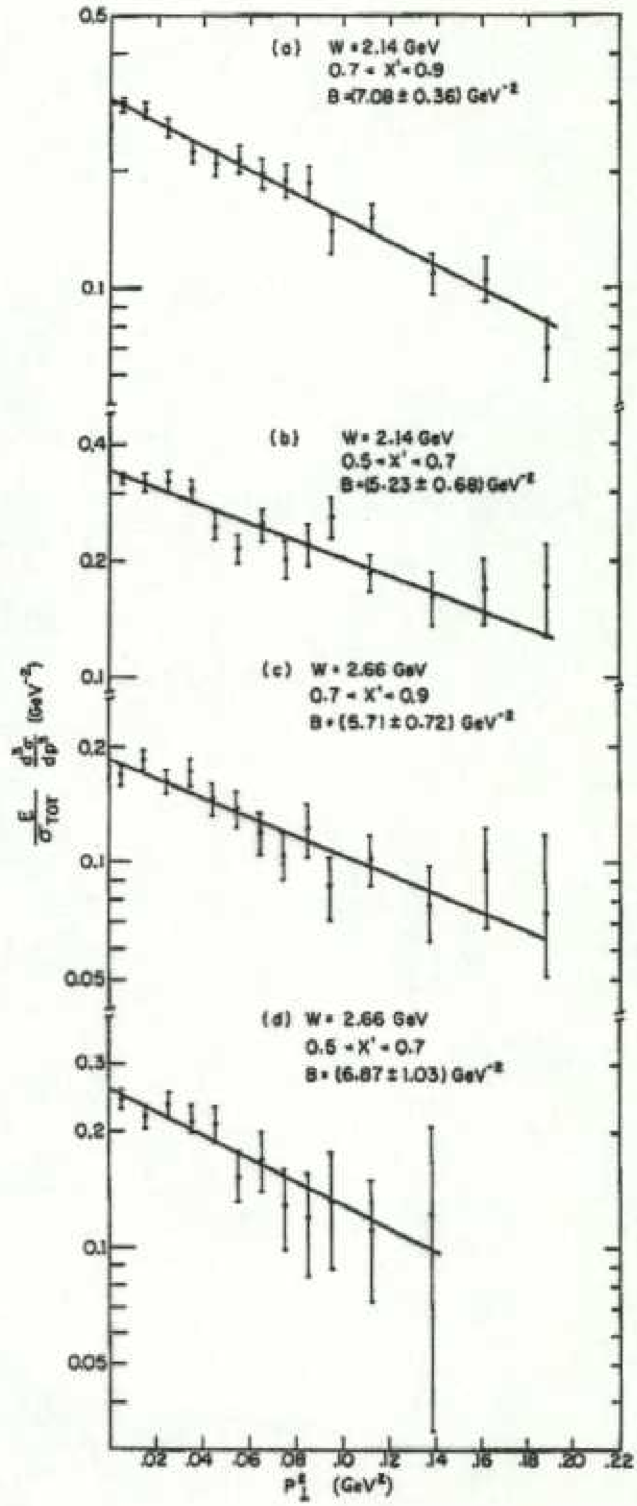
$\sqrt{s} = 2.66$ vs. 3.14

(i.e. Q^2 and W^2 different)

→ Scaling factor of 2.4



→ W'^2



Same P_T dependence

The Origins of Quark-Hadron Duality - II

How does the square of the sum become the sum of the squares?

Close and Isgur, Phys. Lett. B509, 81 (2001)

Semi-Inclusive Hadroproduction

Destructive interference leads to factorization and duality

$$F(\gamma N \to \pi X)(x,z) = \sum_{N^*,N^{*\prime}} F_{\gamma^* N \to N^*}(Q^2, W^2)\, \mathcal{D}_{N^* \to N^{*\prime}\pi}(W^2, W'^2)$$

$$\sim \quad \sum_q e_q^2\, q(x)\, D_{q\to\pi}(z)$$

with
- $F_{\gamma N \to N^*}$ — N^* contribution to structure function F
- $\mathcal{D}_{N^* \to N^{*\prime}\pi}$ — representing the decay $N^* \to N^{*\prime}\pi$
- $D_{q\to\pi}$ — $q \to \pi$ fragmentation function

$SU(6)$ and $SU(3) \times SU(2)$ Multiplet Contributions to $\pi^\pm$ Photoproduction

W'	$p(\gamma,\pi^+)W'$	$p(\gamma,\pi^-)W'$	$n(\gamma,\pi^+)W'$	$n(\gamma,\pi^-)W'$
56;8	100	0	0	25
56;10	32	24	96	8
70;^{2}8	64	0	0	16
70;^{4}8	16	0	0	4
70;^{2}10	4	3	12	1
Total	216	27	108	54

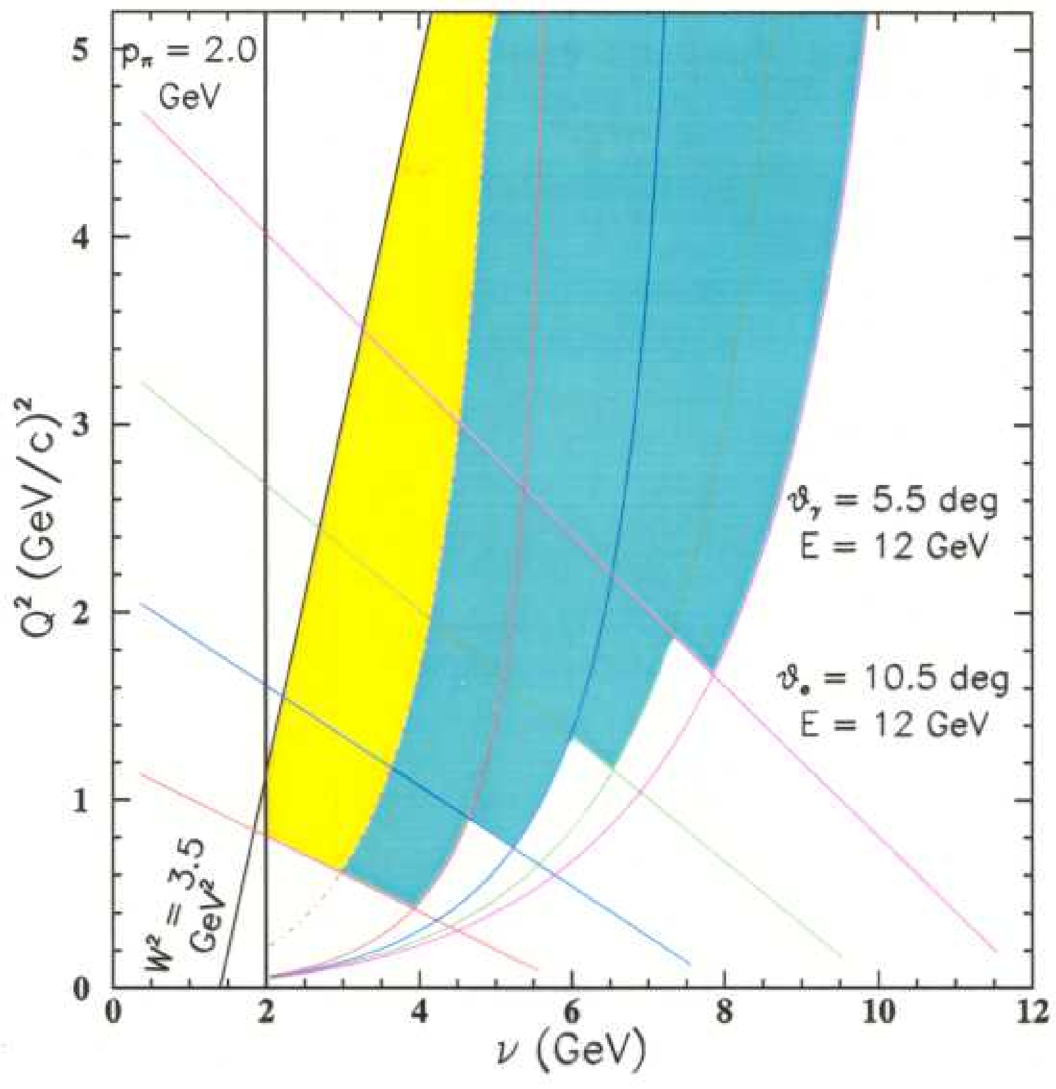
Predictions

- **Duality obtained by end of Second Resonance Region**
- **Factorization and Approximate Duality for $Q^2, W^2 \leq$ 3 GeV^2**

Hall C 12 GeV Kinematics
HMS + SHMS

Essential for two magnetic spectrometer setup to have

- One spectrometer with momentum ≈ beam energy ($z = 1$, $Q^2 \approx 18$)
- Spectrometers can reach forward angles
- Spectrometers can reach forward angles **at the same time**



Since $z = E_h/\nu$, and factorization gets better at large ν (or W^2), but not large Q^2, we want to access large ν → small angles!

z range = [0.3-0.8] , x range = [0.2-0.7], Q^2 range = [1 - 10] (GeV/c)^2

Other Cool Physics

with a little help from my friends....

Unpolarized Structure Functions at Low Q^2

- Behavior of F_2 and R at Low Q^2 (and Small x) : Niculescu/Keppel/Ent

Duality in Unpolarized Structure Functions

- Duality in $R = \sigma_L/\sigma_T$, F_1, F_L : Christy/Keppel
- F_2^n/F_2^p at Large x : Arrington/Niculescu/Keppel/Ent