Fragmentation and Semi-Inclusive Results from HERMES

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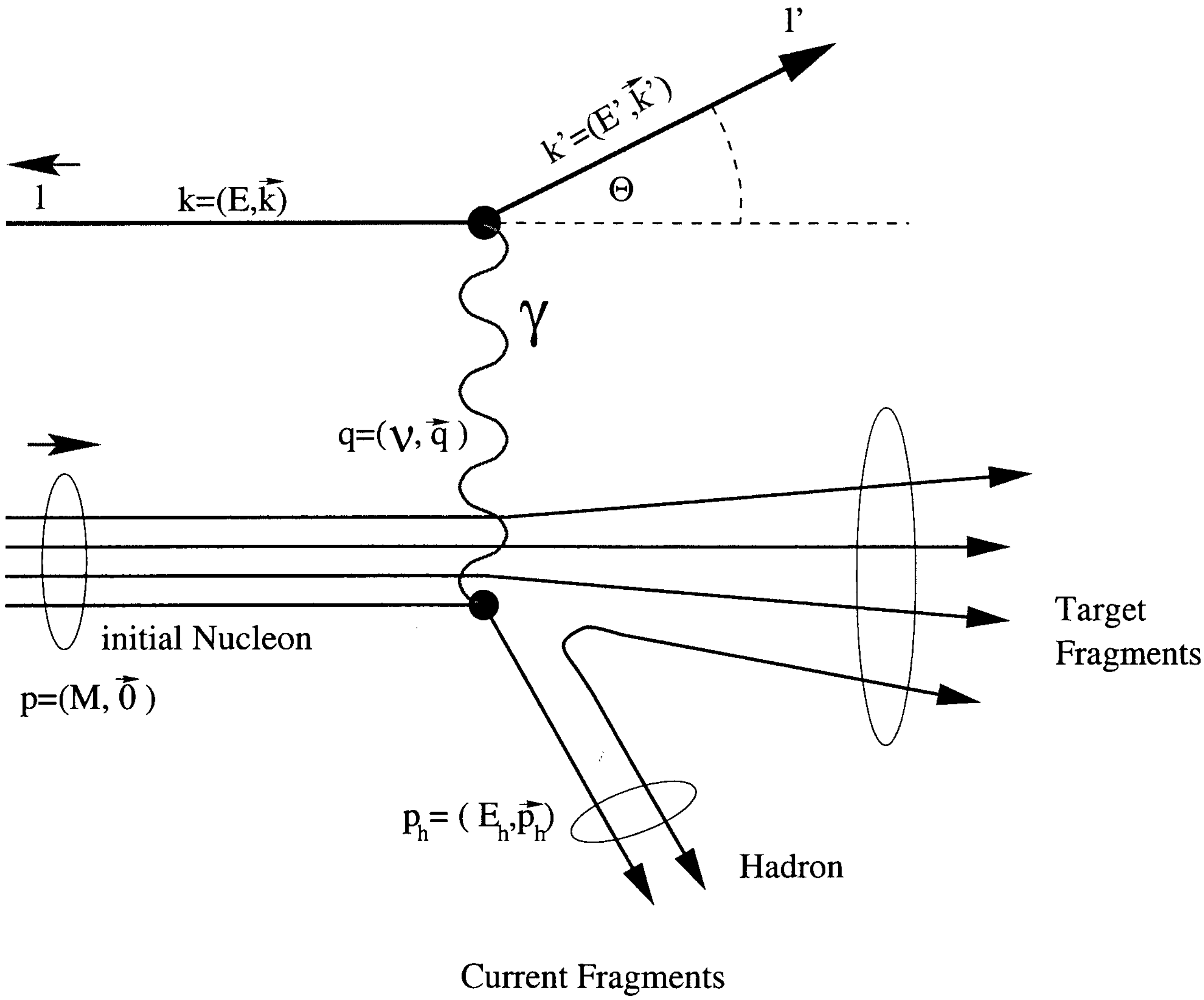
- Low x, low Q^2 inclusive data from HERMES
- Polarized Quark distributions
- Charged and Neutral Pion 'Fragmentation Functions'
- Factorization Tests/Measurements
- Single Spin Asymmetries - Transversity

Polarized Deep Inelastic Scattering



- Inclusive: detect e' only
- Semi-Inclusive: detect e' and hadrons in coincidence
- to probe spin require beam and nucleon to be polarized

HERMES Physics Program

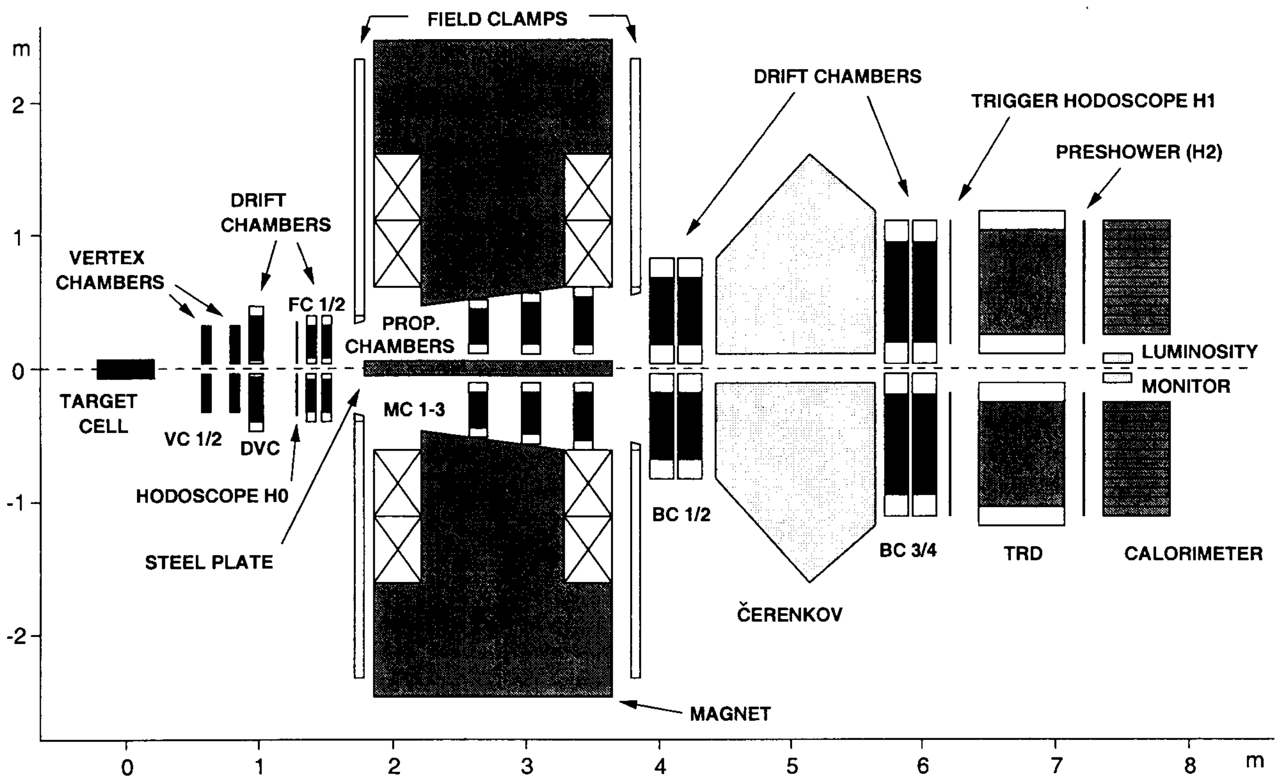
- Study of the Spin Structure of the Nucleon
  - Inclusive / Semi-Inclusive Scattering
  - Proton / Neutron Target

  $\Rightarrow g_1, g_2, \Delta u, \Delta d, \Delta s, \Delta G, h_1, \ldots$
- Unpolarized Cross Section and Structure Function Ratios

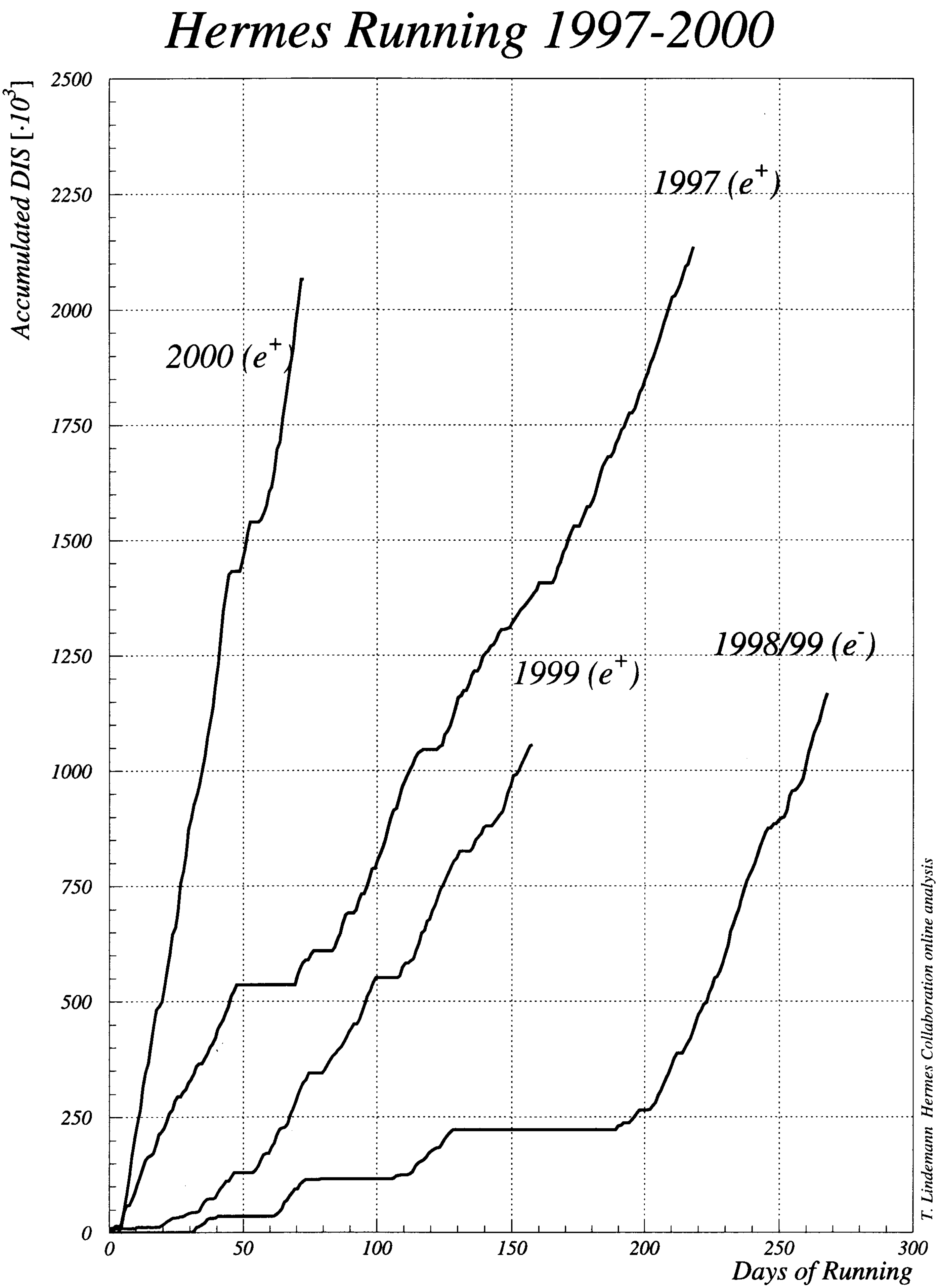
  $\Rightarrow F_2^n/F_2^p, F_2^{^3He}/F_2^D, F_2^{^{14}N}/F_2^D, F_2^{^{84}Kr}/F_2^D, R_A/R_D$
- Light Sea Flavor Asymmetry

  $\Rightarrow \frac{(\bar{d}-\bar{u})}{u-d}$
- Single-Spin Asymmetries
  - Spin-Azimuthal Asymmetries in Semi-inclusive Pion Production $\Rightarrow$ Transversity distribution in nucleon
  - Spin-Azimuthal Asymmetries for Hard Exclusive Pion P roduction $\Rightarrow$ Off-Forward Parton Distributions
- Fragmentation Functions & Hadronization in Nuclei
- Diffractive Vector Meson Production (ρ^o, ϕ, ω, J/Ψ)
  - Cross Sections
  - Decay Angular Distributions
  - Nuclear Transparency
- Polarized Λ^o Production
  - Transversity, Azimuthal Distributions
- $+$ more

The HERMES Experiment at DESY



- HERA 27.5 GeV pol. electron ring $\langle P_{\vec{e}} \rangle \approx 55\%$
  beam current: (45 - 10) mA
  2.8×10^17 – 0.5×10^16
- Internal storage cell gas target $P_{\vec{H}} \approx P_{\vec{H}} \approx 88\%$
  density: $(0.7 - 3) \times 10^{14}$ atoms/cm^2
  0.44–8.5 ×10^31
- Kinematic $0.02 < x < 0.8$ for $Q^2 > 1$ and $W^2 > 4$
- forward spectrometer 40 mrad $< \theta_{lab} <$ 220 mrad
  $\delta P/P \approx 1\%$, $\delta\theta < 0.6$ mrad
- Particle identification with four detectors:
  Calorimeter,Preshower, TRD, Čerenkov (RICH-98)
  probability of e/h misidentification $< 0.4\%$


Hermes Running 1997-2000
Accumulated DIS [$\cdot 10^3$]
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
50
100
150
200
250
300
Days of Running
2000 (e^+)
1997 (e^+)
1999 (e^+)
1998/99 (e^-)
T. Lindemann Hermes Collaboration online analysis

g_1^p at Low Bjorken-x and Low Q^2

Why low x_{bj}?

- Low x region crucial to pin down spin content of nucleon (extrapolation to unmeasured region)

Why low Q^2?

- Provide new data for studying scaling violations
- Allow further tests of pQCD concept: Down to which Q^2 is concept valid?

$$
\begin{aligned}
xg_1(x,Q^2) &= xg_1^{tw-2}(x,Q^2) \\
&+\frac{1}{Q^2}\,h^{tw-4}(x,Q^2) \\
&+\frac{1}{Q^2}\left[h_{TMC}^{tw-2}(x,Q^2)+h_{TMC}^{tw-3}(x,Q^2)\right] \\
&+\mathcal{O}\left(\frac{1}{Q^4}\right)
\end{aligned}
$$

⇒ Field in Progress

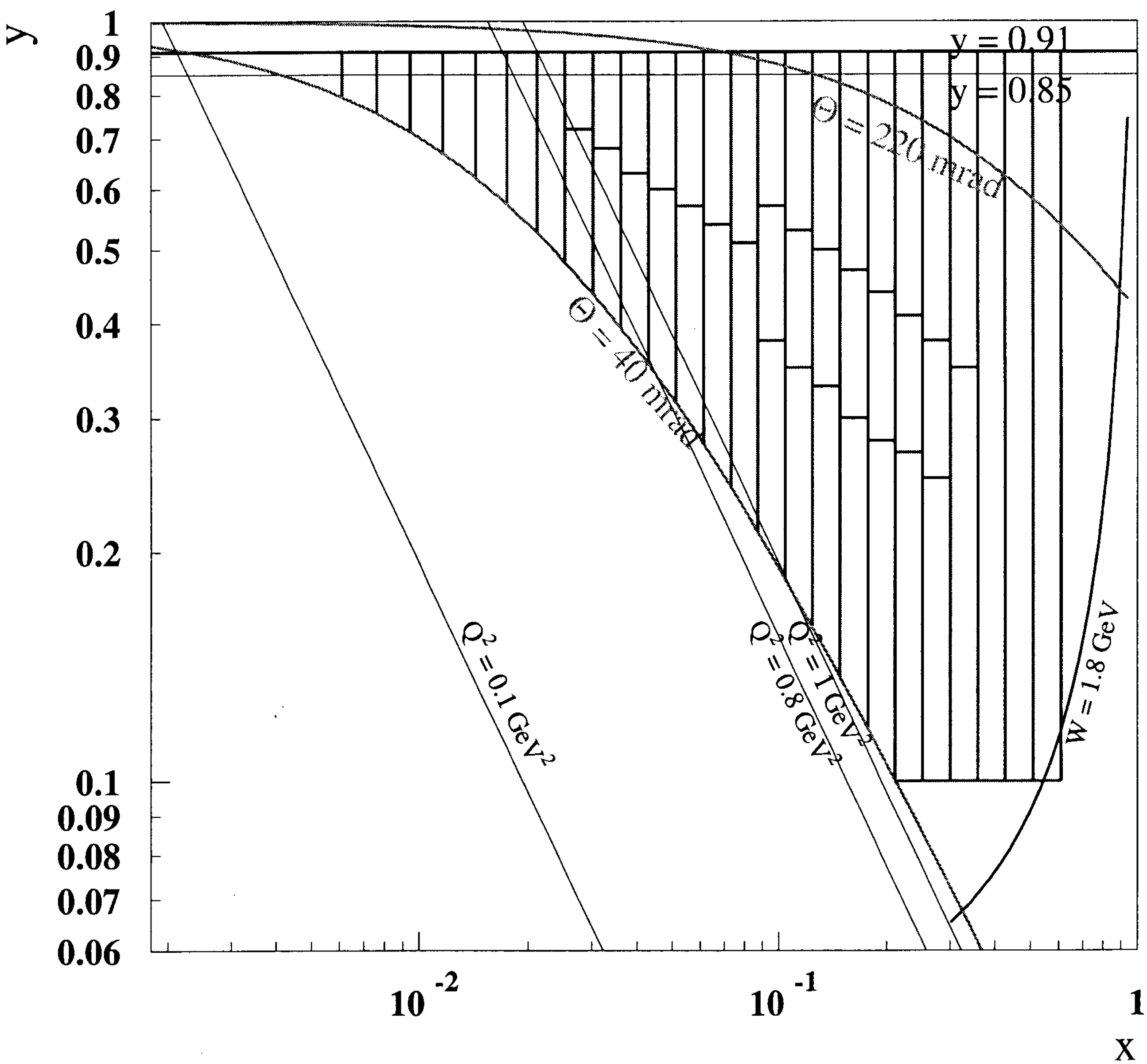
- LO tw-4 calculation for Deuteron at $Q^2 = 4$ GeV^2
  [DIS'99" E. Stein, NPB (Proc. Suppl.) 79 (1999), 567]
- LO Target Mass Contribution to $g_1^p(x,q^2)$ at tw-2 level
  [DIS'99" J. Blümlein, A. Tkabladze, NPB (Proc. Suppl.) 79 (1999), 541]

Inclusive DIS data at Low x ...

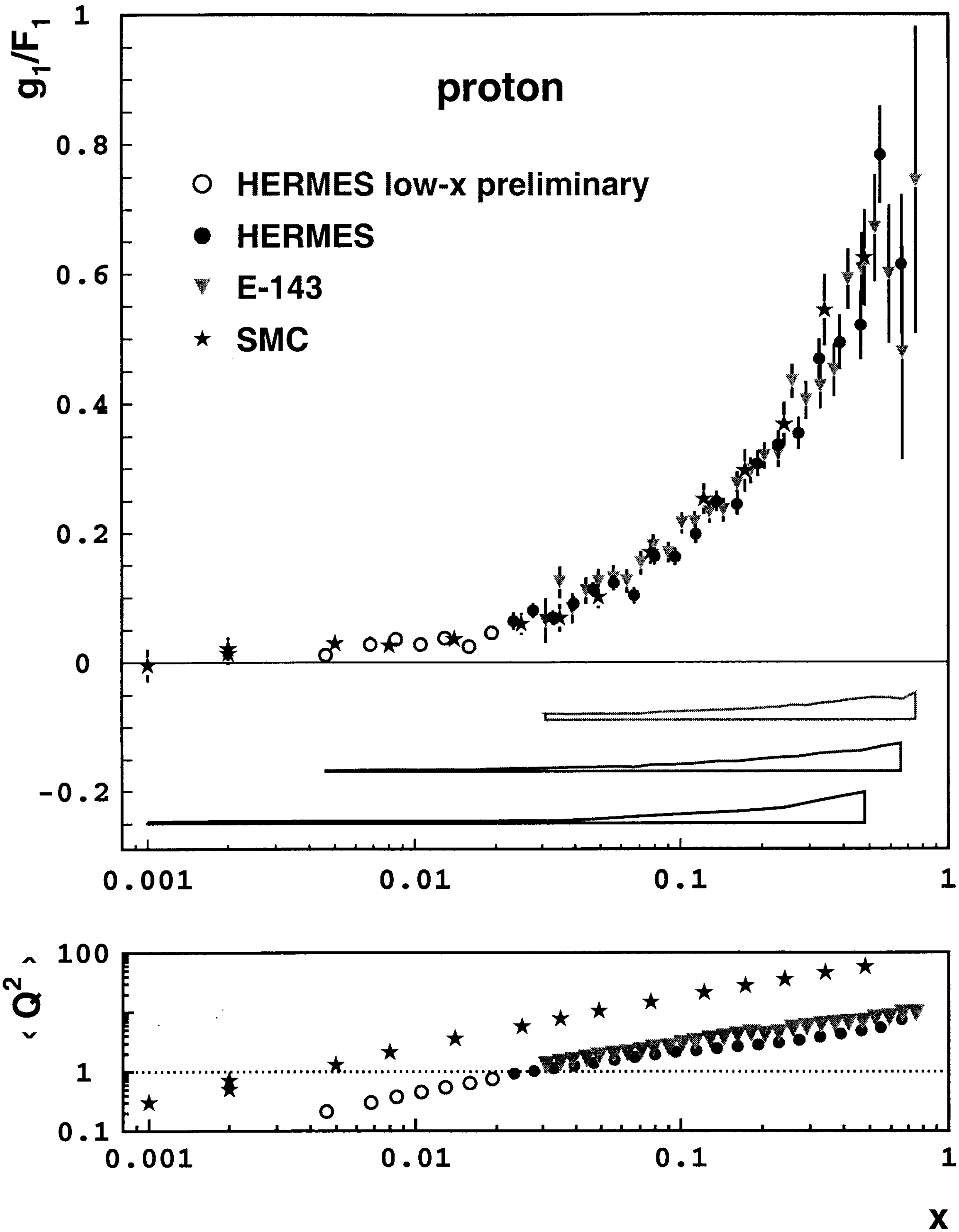
- Extension of kinematic range:

$$
\begin{array}{ccccc}
0.85 & > & x & > & 0.0021\ (0.0212) \\
0.1 & < & y & < & 0.91\ (0,85) \\
 & & Q^2 & > & 0.1\ (0.8)\text{GeV}^2
\end{array}
$$

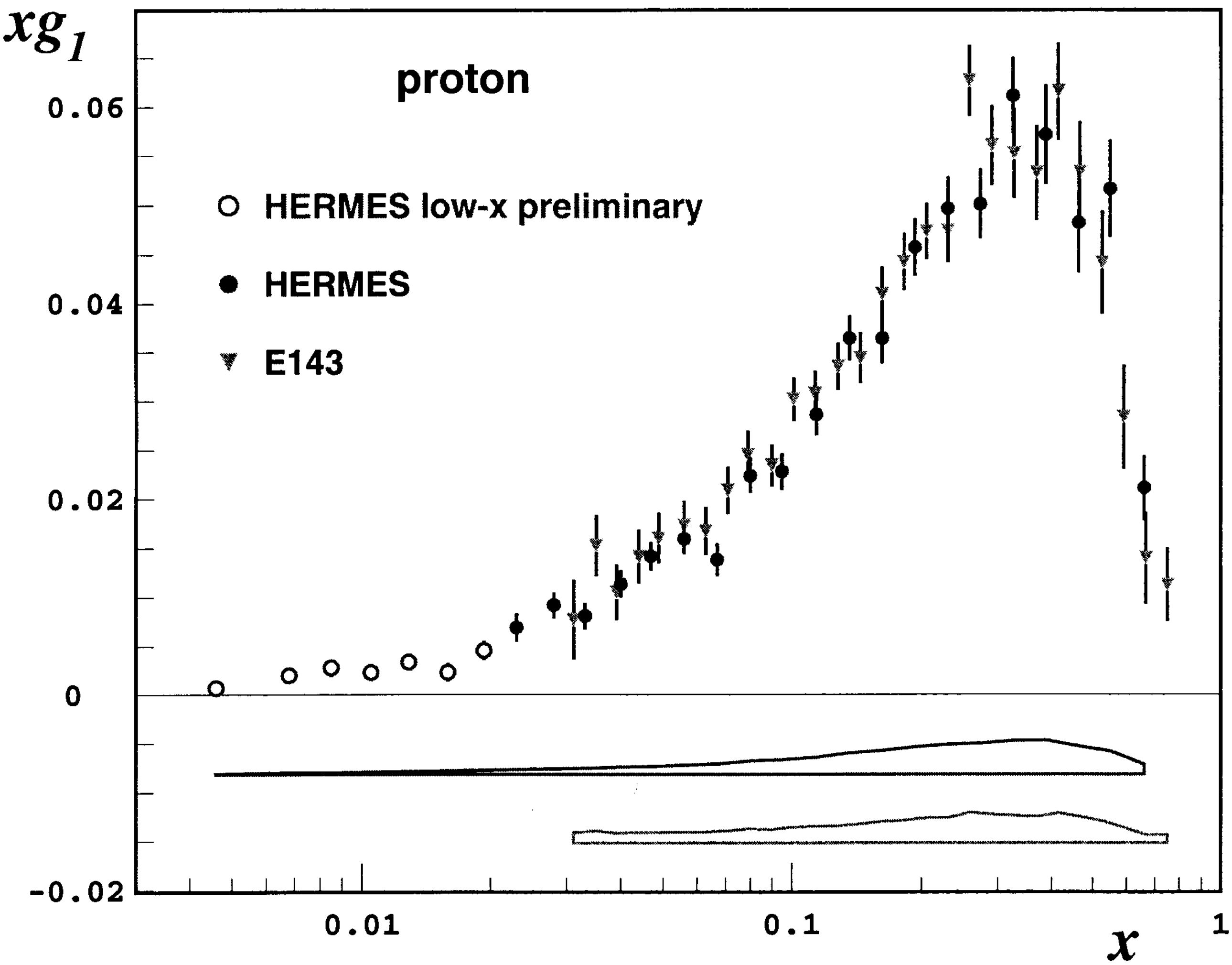
- The kinematic plane:



Resulting g_1/F_1 at Low x and Q^2



Resulting xg_1 at Low x and Q^2



Syst. Uncertainties

effects to g_1/F_1

$$\Delta_{\text{syst}} \stackrel{def}{=} \left| 1 - \frac{g_1/F_1(\text{syst})}{g_1/F_1(\text{std})} \right| \quad (\%)$$

•	beam polarisation:	$\Delta_{P_B} =$	3.4%
•	target polarisation:	$\Delta_{P_T} =$	4.4 % (new)
•	normalisation:	$\Delta_{\text{Lumi}} =$	0.2 %
		$<$	0.4 % low x
		$\Delta_{\text{dtm}} =$	0.2 % low x (new)
•	hadron cont.:	$\Delta_h <$	0.4 %

valid for alignment and beam parameter corr. data

•	alignment Θ	$\Delta_A <$	0.5 %
		$<$	2.0 % low x (new)
•	z-vertex	$\Delta_{\text{zvx}} =$	5 % low x bins
•	MC-correction	$\Delta_{C_{tot}} \approx$	1 %
	for F2ALLM+R1990	$=$	5 (11)% low x (first) bins
•	A_2-Param	$\Delta_{A_2} <$	1.5 % highest x

$\Rightarrow$ std range: 5.7% (5.9 % highest x-bin)

low-x range: 9.2 % (13.5 % lowest x-bin)

Conclusions of Low x and Low Q^2 Inclusive Data

- New HERMES data:
  match low x SMC data on g_1/F_1 to very low Q^2
  $\Rightarrow$ provide significant constraints on higher twist effects

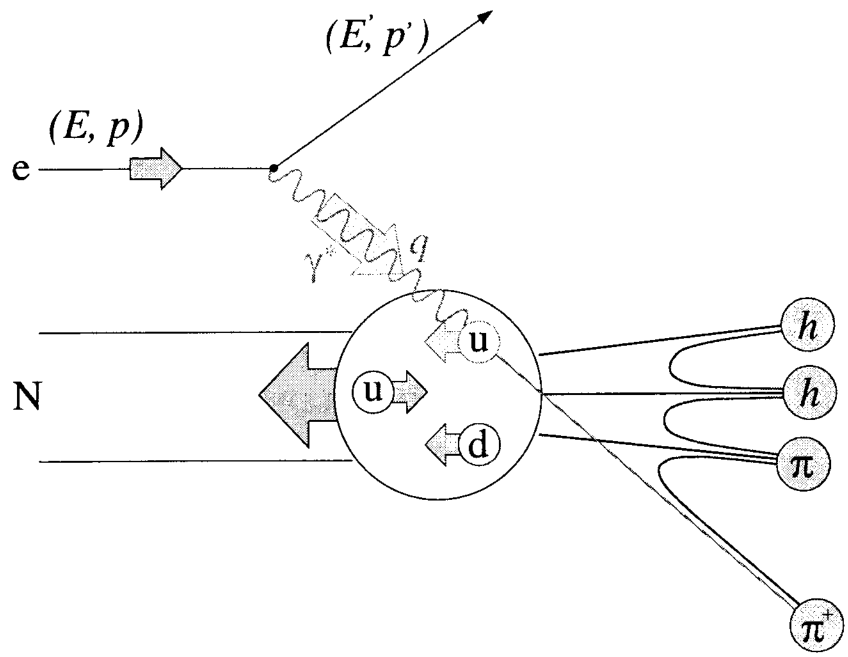
- E143:
  has performed fits including data down to $Q^2 = 0.3$
  (but higher x than HERMES)
  $\Rightarrow$ favoured small Q^2-dependence to g_1/F_1 at lowest Q^2
  $\Rightarrow$ HERMES data do not support such a Q^2-dependence

- Question to theorists?
  Why is there no Q^2-dependence at the scale of Λ_{QCD}
  $\Rightarrow$ JLAB might be right place to find the limit ...

- Higher twist effects stay small down to small Q^2
  $\Rightarrow$ help to understand Quark-Hadron Transition
  $\Rightarrow$ push QCD to still smaller Q^2 values?

Semi-Inclusive Deep Inelastic Scattering

Detect hadron h in coincidence with the scattered lepton



Flavour Tagging
Correlation between strck quark q_f and detected hadron h

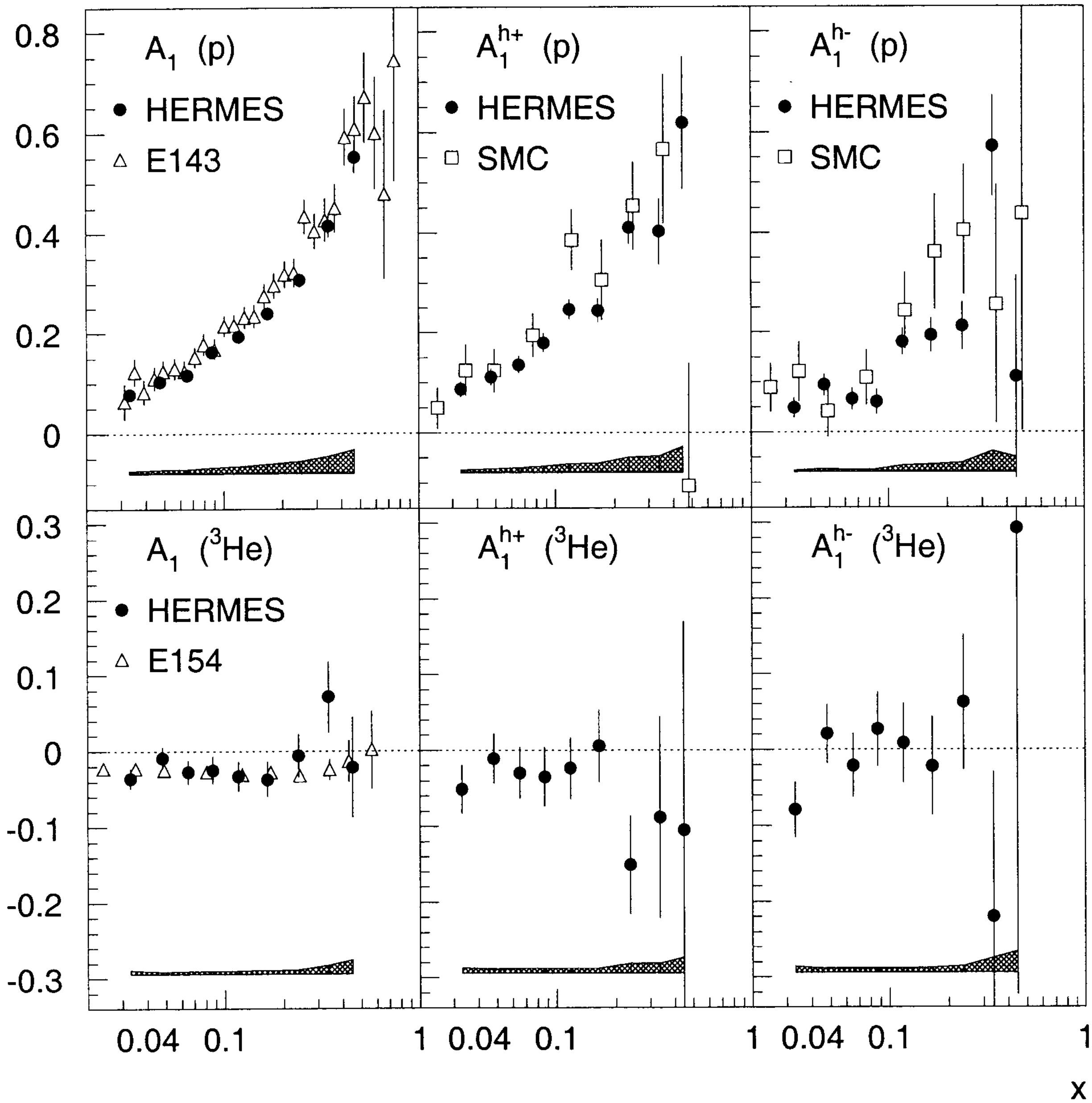
- Select hadrons from the current fragmentation region by minimum cuts on $z = E_h/\nu$ and $x_F = 2p_{||}/W$
- in LO QCD (assuming factorization and spin-independence of fragmentation)

$$A_1^h(x, Q^2) = \frac{\int_{z_{min}}^1 dz \sum e_f^2 \Delta q_f(x, Q^2) \cdot D_{q_f}^h(z, Q^2)}{\int_{z_{min}}^1 dz \sum e_f^2 q_f(x, Q^2) \cdot D_{q_f}^h(z, Q^2)}$$

$D_{q_f}^h$: Fragmentation Function

Semi-Inclusive Asymmetries

HERMES data on $^{3}\vec{He}$ (1995) and $\vec{H}$ (1996+1997)



- To distinguish between current and target fragments $z > 0.2$; $x_F > 0.1$; $W^2 > 10 \;\; GeV^2$
- Data averaged over Q^2 (and z) in each x bin:
  - agreement within 1 σ
  - no statistically significant Q^2 dependence

Δq-Extraction

- Input for extraction of polarized quark distributions:
  - measured hadron asymmetries $A_1^h(x,z)$
  - unpolarized quark distributions $q(x)$
  - fragmentation functions $D_q^h(z)$
- Global fit of inclusive and semi-inclusive p and n asymmetries
- Rewrite Photon-Nucleon Asymmetry:

$$\begin{aligned} A_1^h(x,z) &= \sum_q \frac{e_q^2 q(x) D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x) D_{q'}^h(z)} \cdot \frac{\Delta q(x)}{q(x)} \\ &= \sum_q P_q^h(x,z) \cdot \frac{\Delta q(x)}{q(x)} \end{aligned}$$

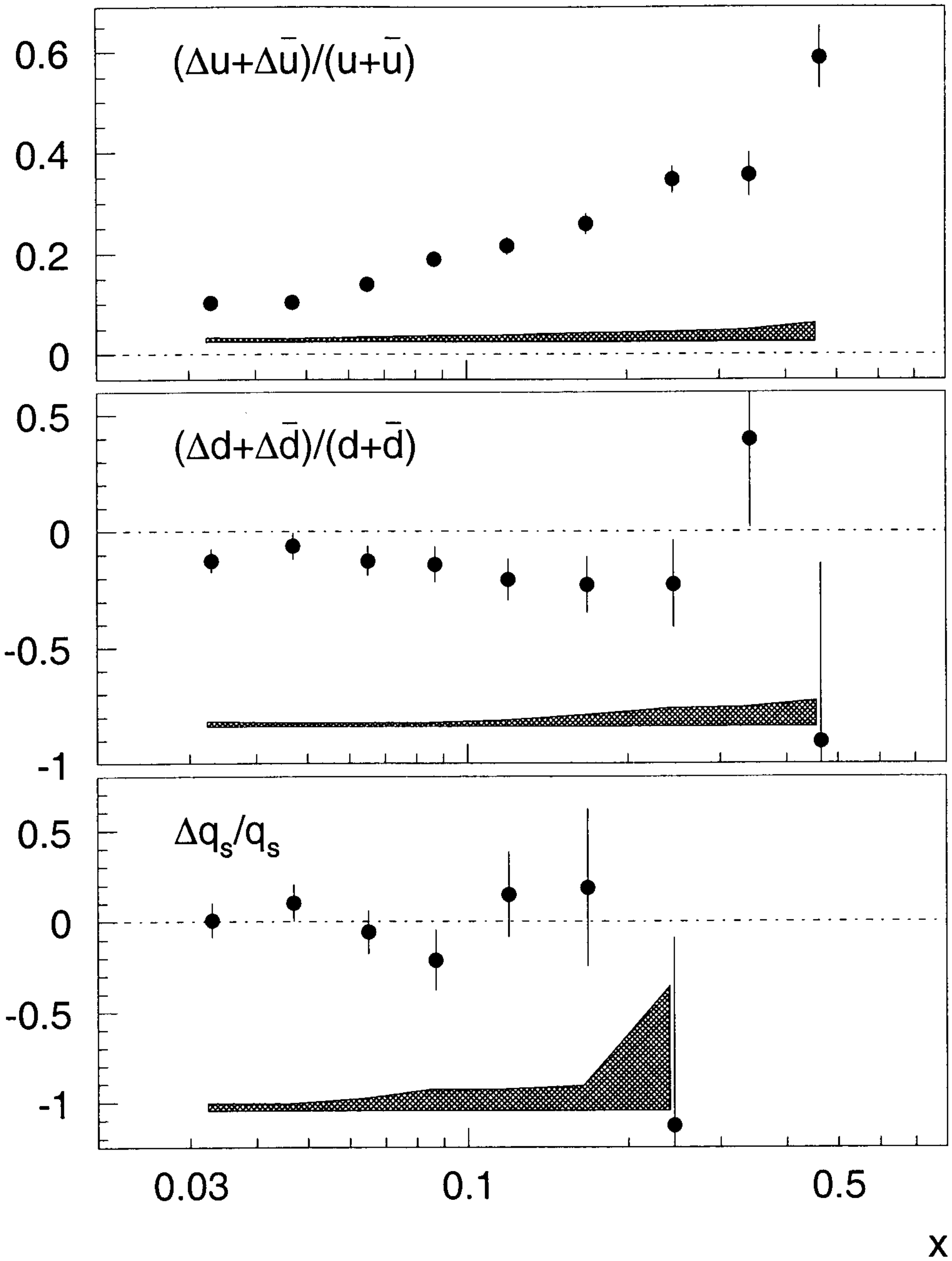
- Purity P_q^h gives probability that a quark q was struck when a hadron h is detected
- Purities are spin-independent (unpolarized) quantities !
- Define

$$\vec{A} = \begin{pmatrix} A^{h_1}(x) \\ \ldots \\ A^{h_m}(x) \end{pmatrix}, \vec{Q} = \begin{pmatrix} \Delta q_1(x)/q_1(x) \\ \ldots \\ \Delta q_n(x)/q_n(x) \end{pmatrix}, \mathcal{P} = \left[P_q^h(x)\right]$$

- To extract quark polarizations solve

$$\vec{A} = \mathcal{P}\vec{Q}$$

Flavor Decomposition

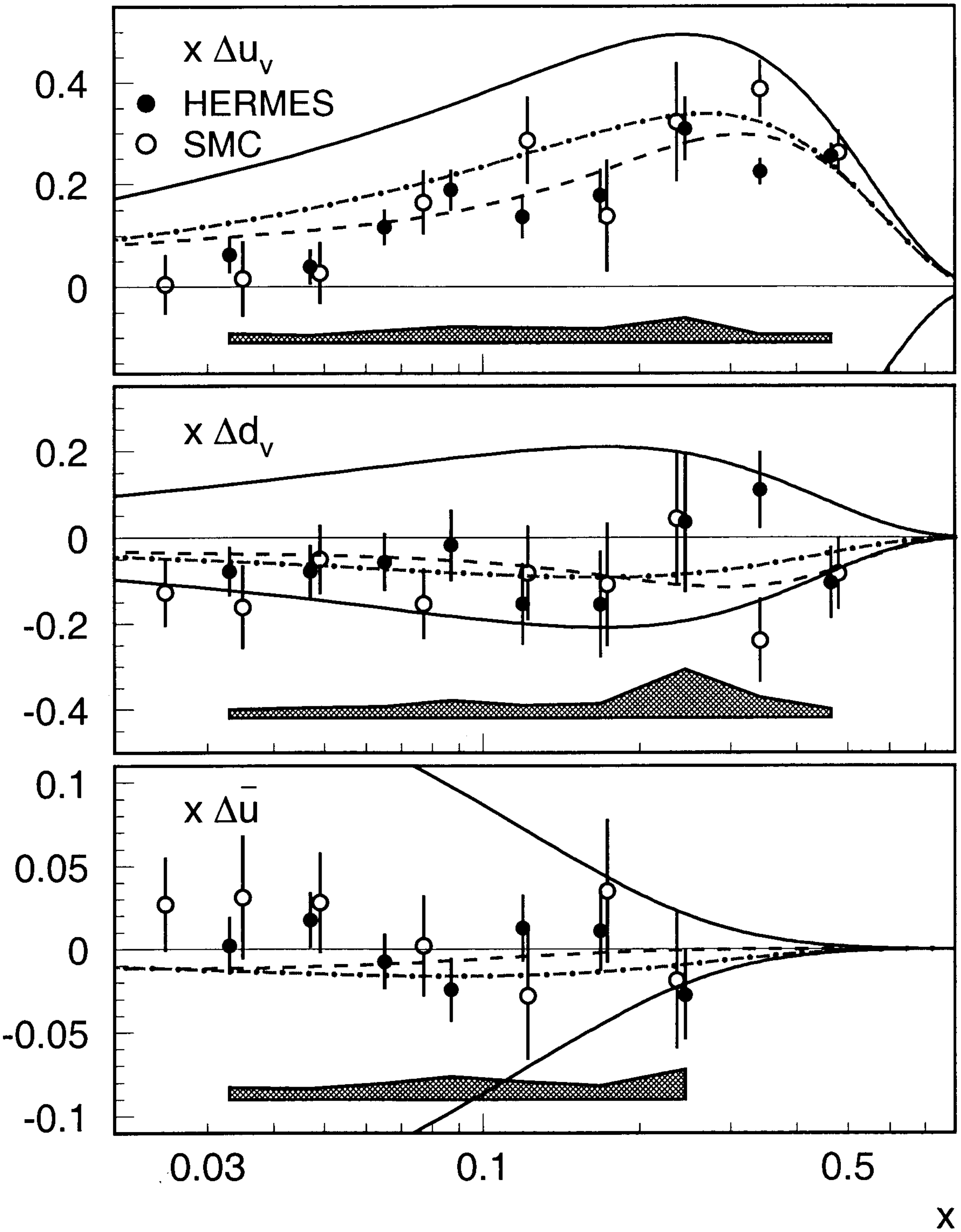


- Polarized quark distributions

  ⇒ Sea quark polarization is consistent with zero

- Need RICH to separate contributions from light sea from that of strange sea

Valence and Sea Quark Distributions



Dashed line: GS (LO); Dashed-dotted line: GRSV (LO)

Polarized valence and sea quark distributions compared to SMC (at Q^2= 2.5 GeV^2) $\Rightarrow$ good agreement

Spin Contributions and SU(3)$_f$

- Comparison of the Hermes integrals with SMC results (Q^2 = 2.5 GeV^2 and $0.023 < x < 0.6$)

	HERMES	SMC
Δu_v	$0.52 \pm 0.05 \pm 0.08$	$0.59 \pm 0.08 \pm 0.07$
Δd_v	$-0.19 \pm 0.11 \pm 0.13$	$-0.33 \pm 0.11 \pm 0.09$
$\Delta \bar{u}$	$-0.01 \pm 0.02 \pm 0.03$	$0.02 \pm 0.03 \pm 0.02$
$\Delta \bar{d}$	$-0.02 \pm 0.03 \pm 0.04$	$0.02 \pm 0.03 \pm 0.02$

→ Agreement within 1 σ

- Test of $SU(3)_f$ predictions (Q^2 = 2.5 GeV^2)

	Total Integral	SU(3)$_f$
$\Delta u + Delta(\bar{u})$	0.57 ± 0.04	0.66 ± 0.03
$\Delta d + Delta(\bar{d})$	-0.25 ± 0.07	-0.35 ± 0.03
$\Delta s + Delta(s)$	-0.01 ± 0.05	-0.08 ± 0.02

(Uncertainty for low x extrapolation not included)

→ SU(3)$_f$ violation still an open issue
→ Direct measurement of strange sea is required

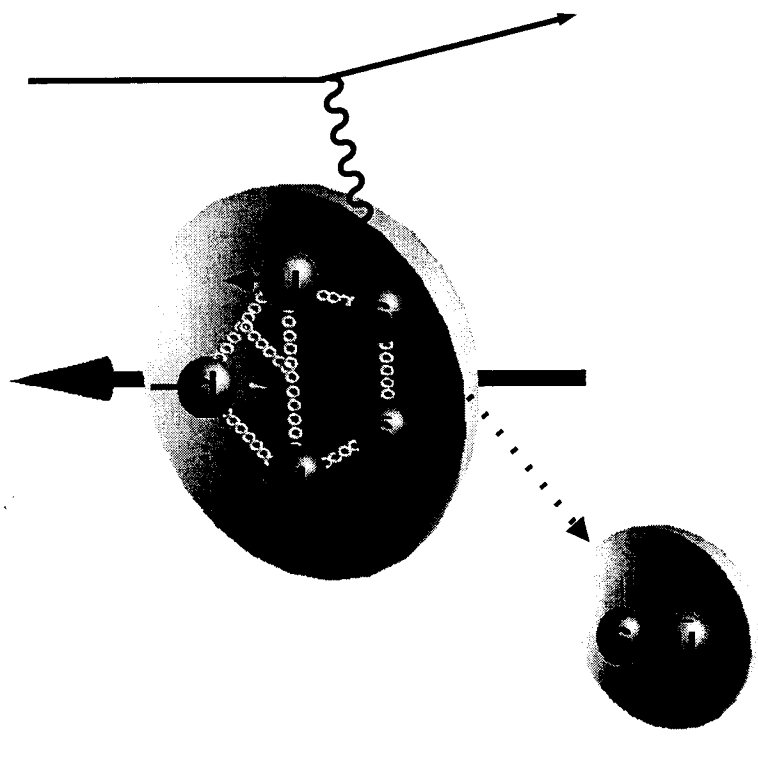
Strange Sea Polarization

- Strange quark sea is significantly negative in inclusive analysis ($\Delta s = -0.10 \pm 0.03$)

- Sea quark polarization is close to zero in semi-inclusive analysis (HERMES)

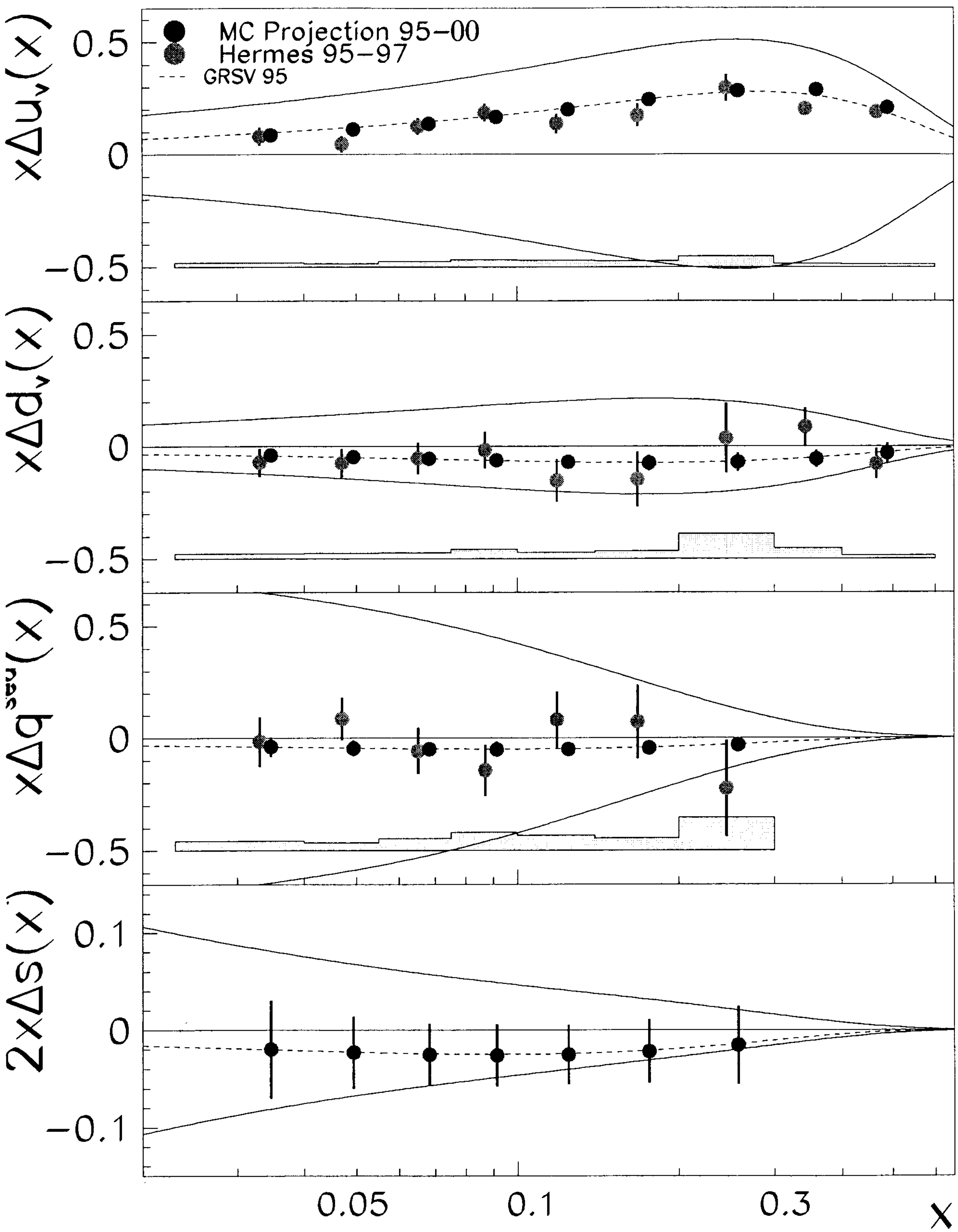
$\rightarrow$ **neither result represents direct measurement of Δs**

- RICH offers possibility of direct measurement through Kaon identification (HERMES)

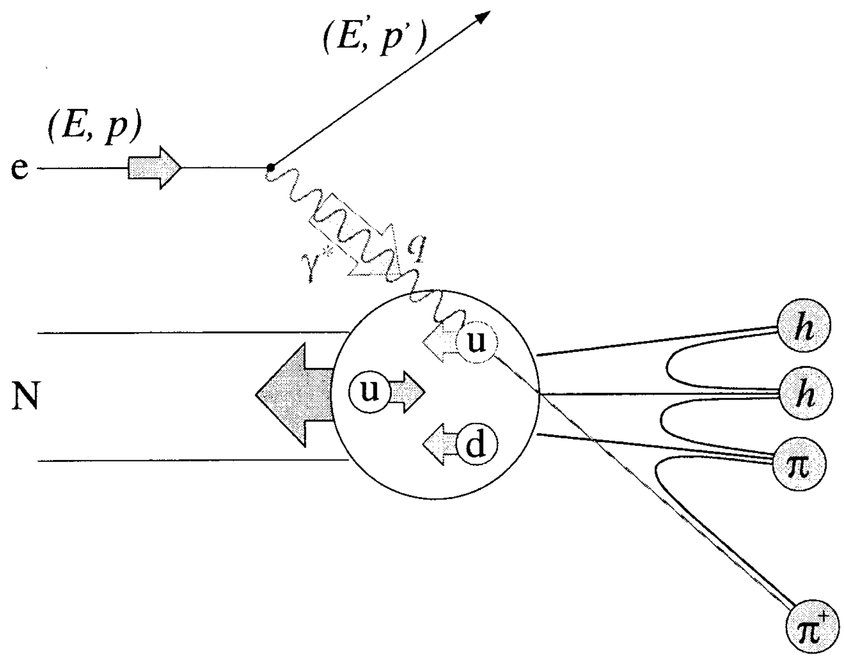


K- (KAON)

After 1998–2000 on D Target



Pion Electroproduction in DIS



In QPM:

- fragmentation function $D_f^\pi(z)$ = probability for a quark of flavor f to fragment into a pion
- leading pion determined by $z = \frac{E_\pi}{\nu}$
- assuming: factorization + scaling of D_f^h

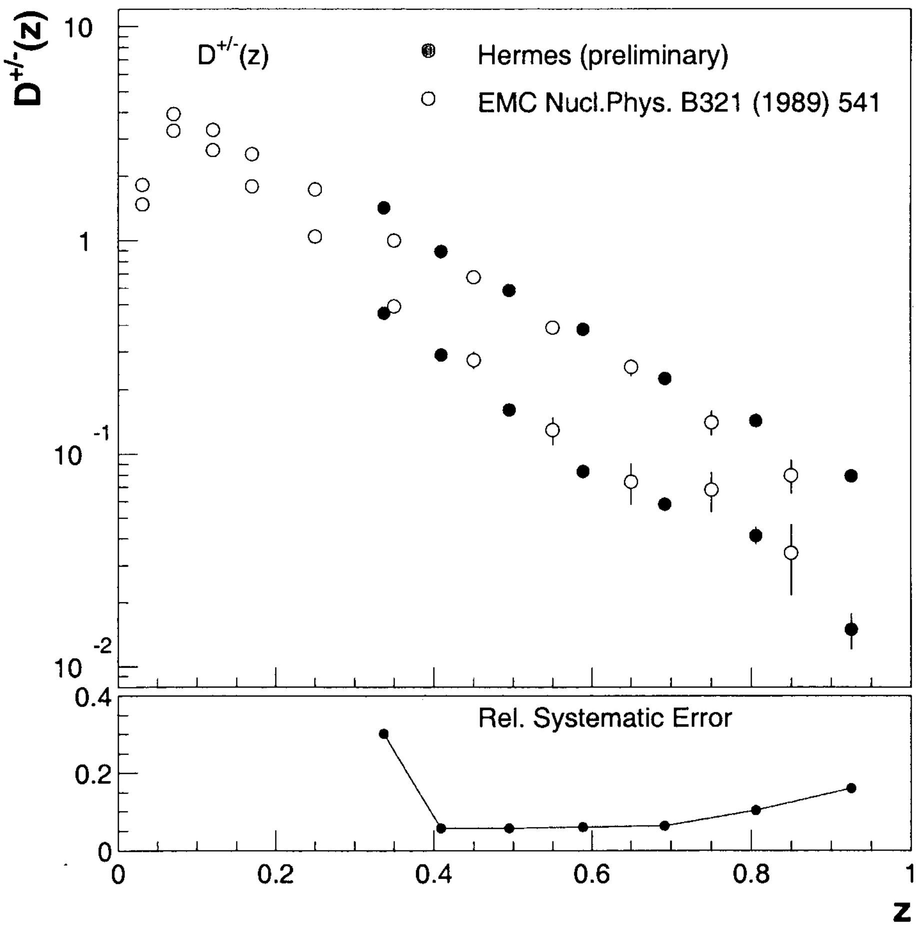
$$\frac{1}{\sigma_{DIS}} \cdot \frac{d\sigma^\pi(x,z)}{dz} = \frac{\sum e_f^2 q_f(x) D_f^\pi(z)}{\sum e_f^2 q_f(x)}$$

Assuming: strange quark contributionto is negligible
$\Rightarrow$ π multiplicity is equal to fragmentation function D^π

Note: PQCD corrections to this ansatz suggest a significant Q^2-dependence of the fragmentation process.

π Fragmentation Functions - Old Result

π fragmentation functions using EMC extraction method



- LO QCD corrections applied
- No radiative corrections applied

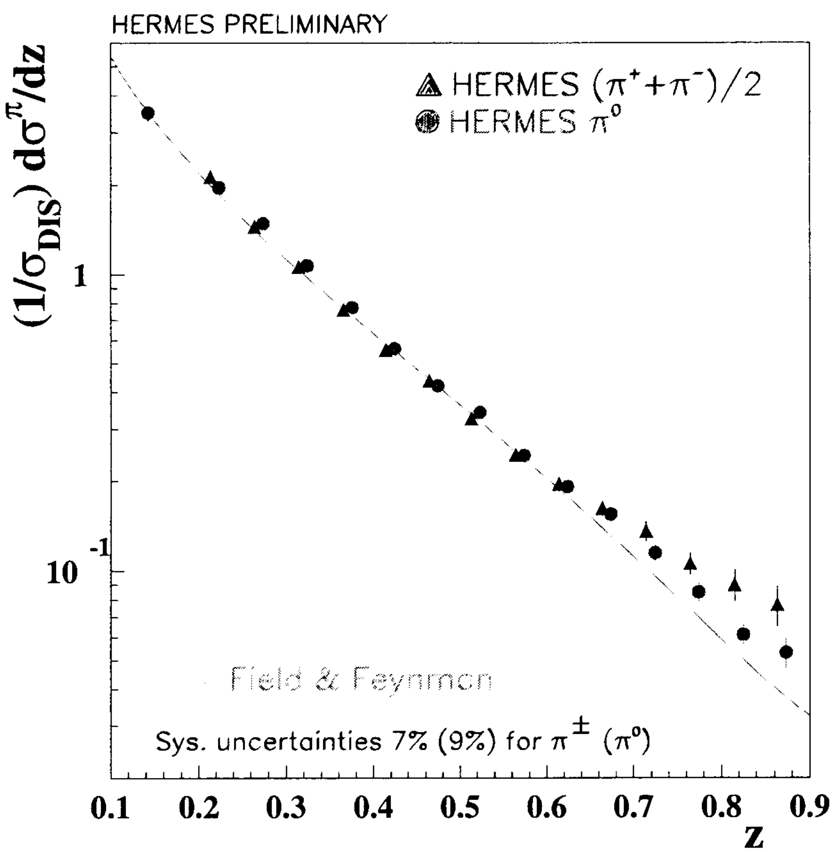
Fragmentation Functions

FAVORED D^+ leading pion contains struck quark
UNFAVORED D^- leading pion does not contain struck quark

Charged and Neutral Pion Multiplicities

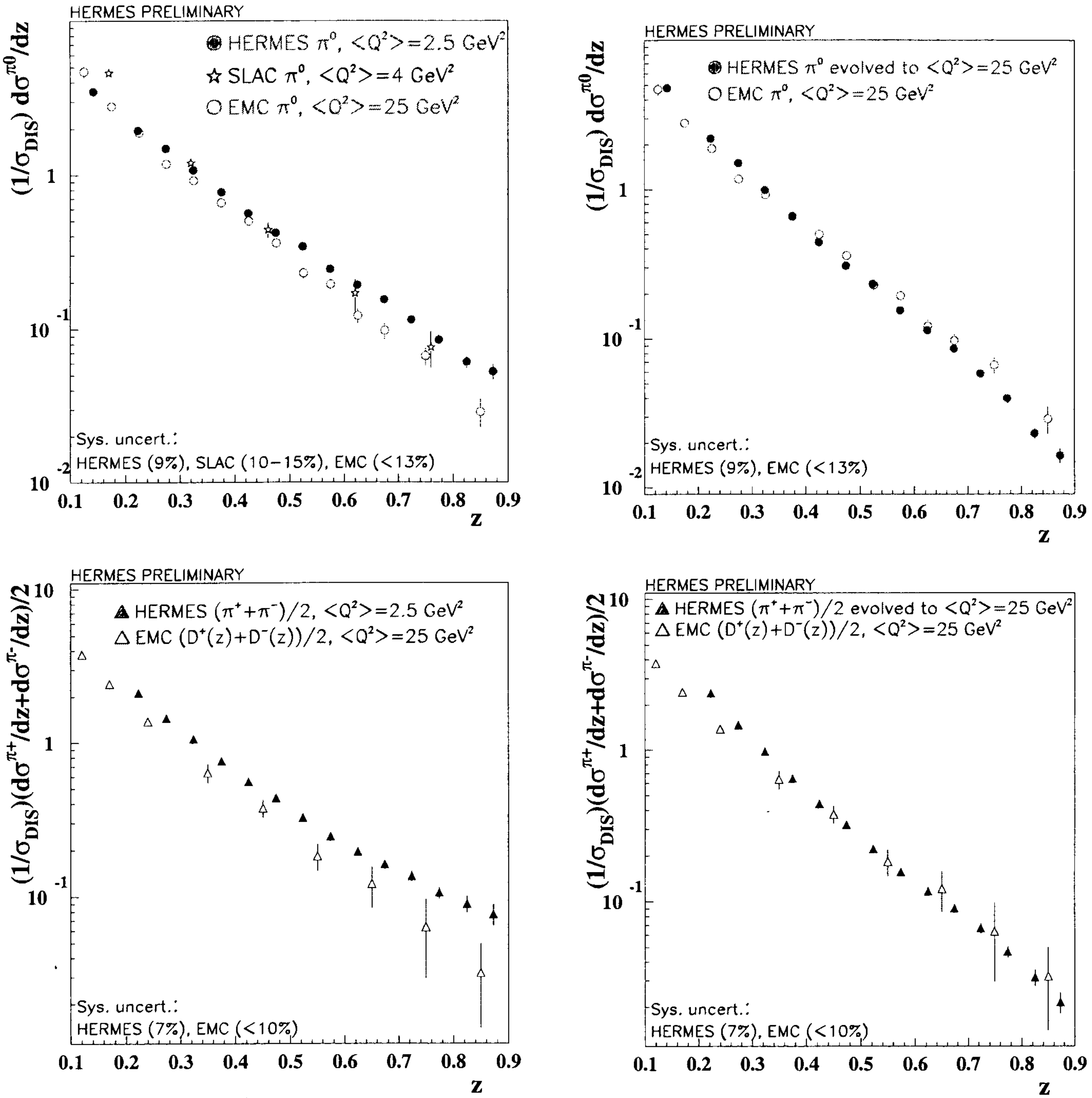
Assuming isospin asymmetry in QPM:

$$\frac{1}{\sigma_{DIS}} \frac{d\sigma^{\pi^0}}{dz} = \frac{1}{\sigma_{DIS}} \frac{1}{2} \left[\frac{d\sigma^{\pi^+}}{dz} + \frac{d\sigma^{\pi^-}}{dz} \right]$$



- Excellent agreement in most of measured z-range
- two data sets obtained with very different event reconstruction precedures
- for $z > 0.75$ multiplicity for charged pions larger than for neutral pions
  $\rightarrow$ possible contributiuons from exclusive charged diffractive channels

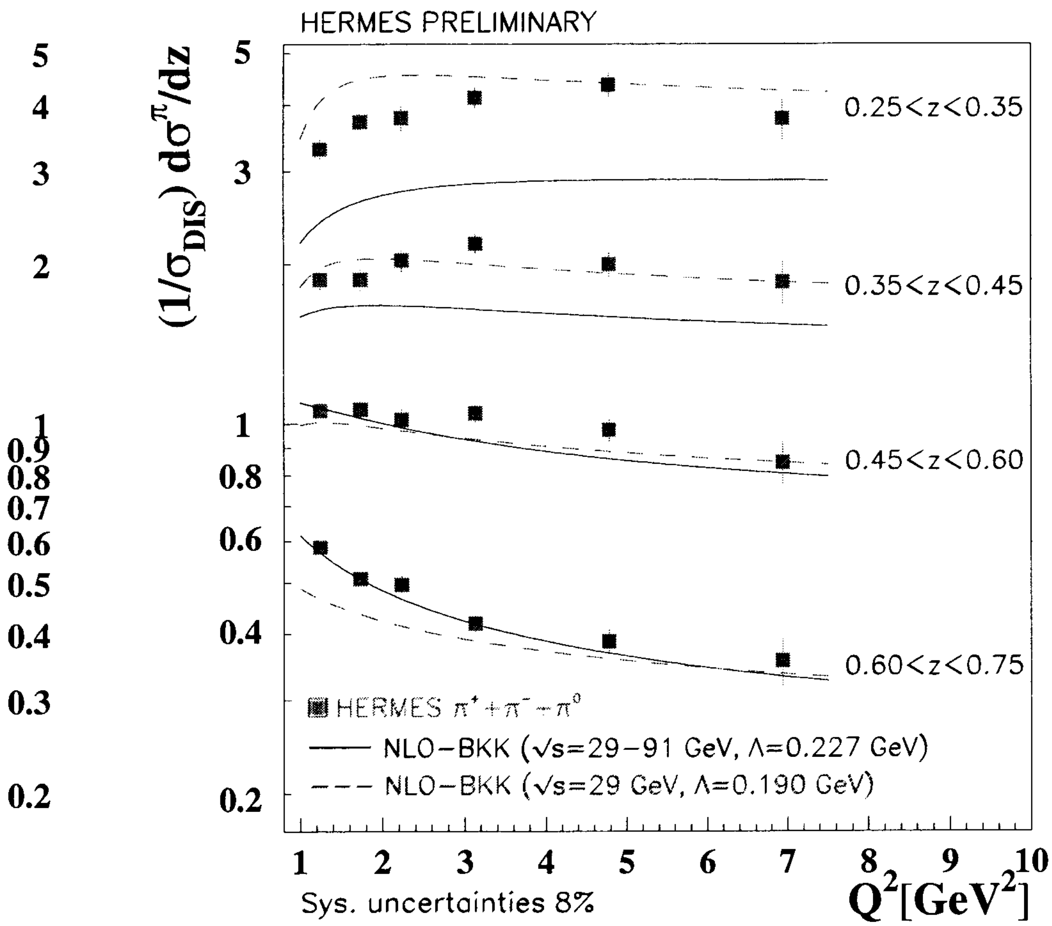
Comparison to EMC



- Excellent agreement with EMC fragmentation functions after NLO QCD evolution (to $Q^2 = 25$ GeV^2)
- Note: LO calculation suffers from significant theoretical uncertainties related to choice of renormalization scale of α_s

Total Pion Multiplicity vs Q^2

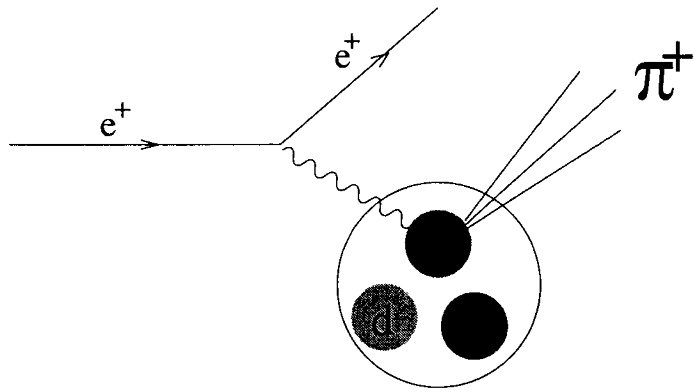
To better investigate scaling violation
$\Rightarrow$ study Q^2 dependencd at fixed z



- Clear deviation from scaling predictions of QPM, especially in high-z bin
- Absolute values of NLO QCD calculations with 10-20% uncertainties (renormalization, factorization, fragmentation scales)

Ratio of valence quark distributions

Identify leading $\pi^{\pm}$ from H and D targets.



Use charge difference and ratios to cancel effects of the sea and fragmentation functions:

$$R_\pi = \left(\frac{N_D^{\pi^+}(x) - N_D^{\pi^-}(x)}{N_p^{\pi^+}(x) - N_p^{\pi^-}(x)}\right)\frac{N_p}{N_D}\left(1 + \frac{F_2^n(x)}{F_2^p(x)}\right) - 1$$

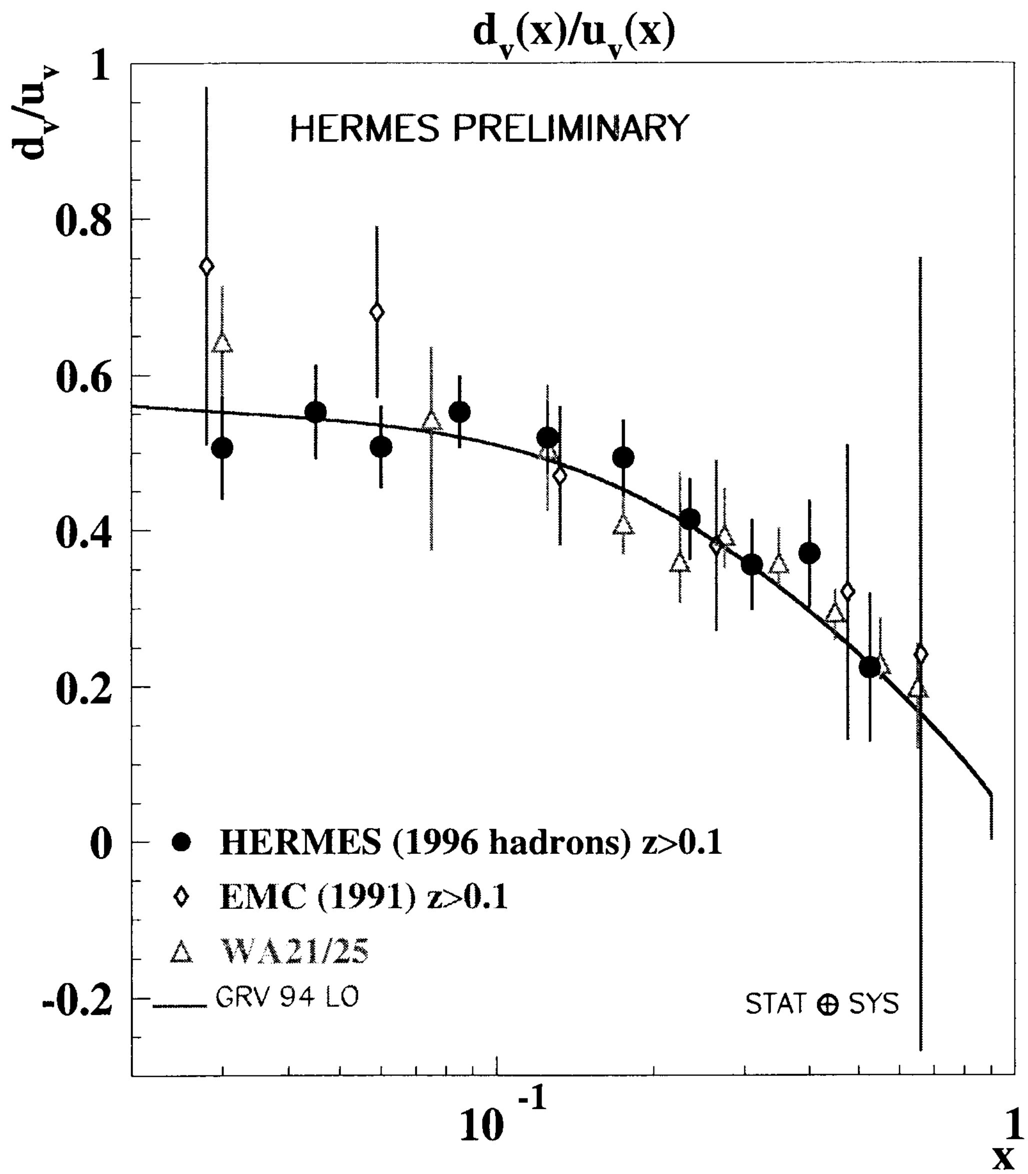
$$R_\pi = \frac{3u_v(x) + 3d_v(x)}{4u_v(x) - d_v(x)} - 1$$

The ratio of the valence distributions is

$$\frac{d_v(x)}{u_v(x)} = \frac{4R_\pi(x) + 1}{R_\pi(x) + 4}$$

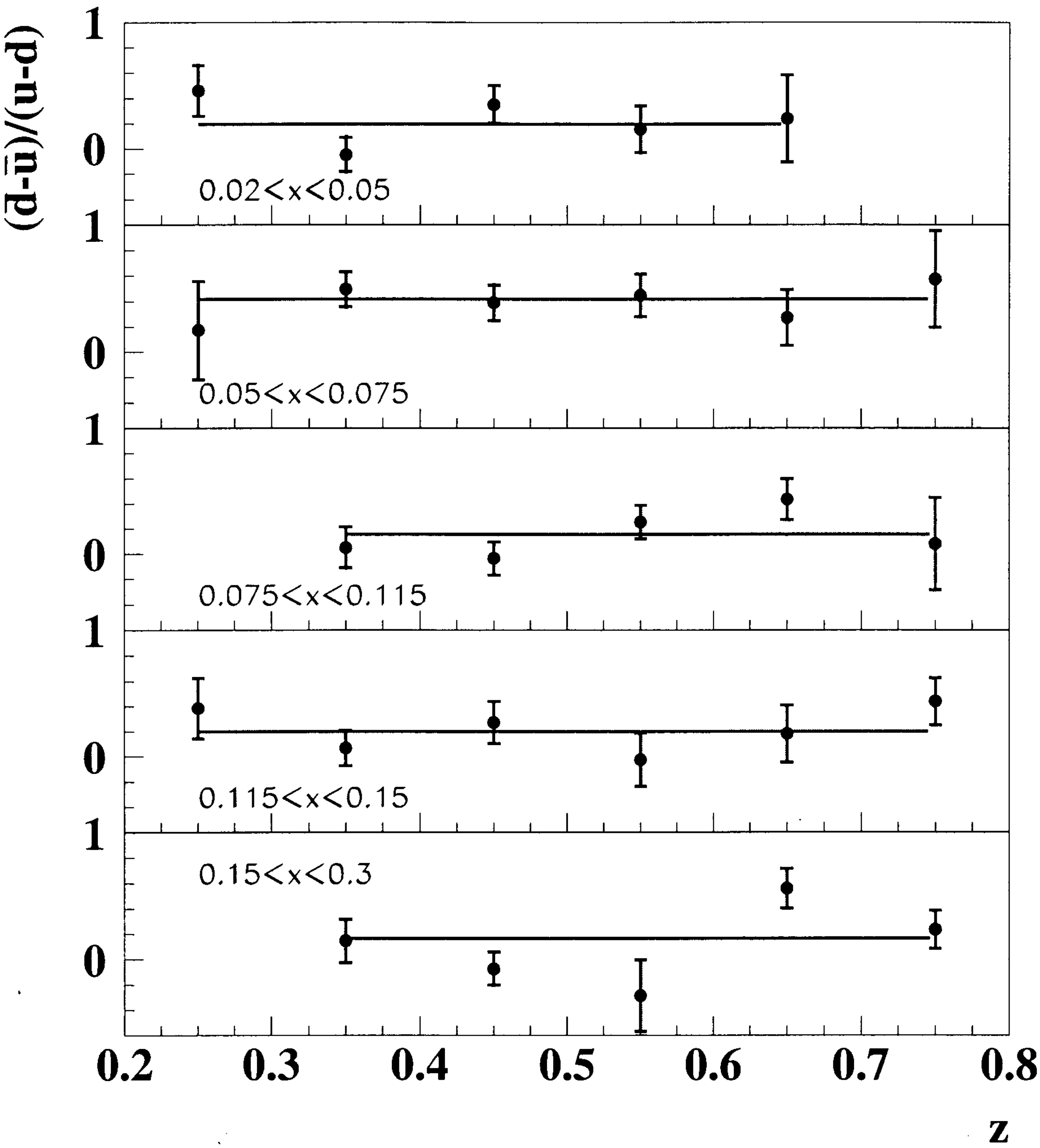
HERMES preliminary $\frac{d_v(x)}{u_v(x)}$ vs x

unpolarized H + D data



→ test of factorization

$(\bar{d} - \bar{u})/(u - d)$ vs z



→ proof of factorization

Light Sea Flavor Asymmetry

In QPM:

- assuming:
  - flavor symmetric light quark sea
  - isospin symmetry between p and n

  $\rightarrow$ results in Gottfried sum rule

$$S_G = \int_0^1 \frac{dx}{x}(F_2^p(x) - F_2^n(x)) = \frac{1}{3} - \frac{2}{3}\int_0^1 (\bar{d}(x) - \bar{u}(x))dx$$

- NMC: $S_G = 0.235 \pm 0.026$ (Phys. Rev. D50, 1 (1994))
- Hermes can measure the ratio $(\bar{d} - \bar{u})/(u - d)$ from ratio of charged pion yields in semi-inclusive DIS on ^1H and ^2D.

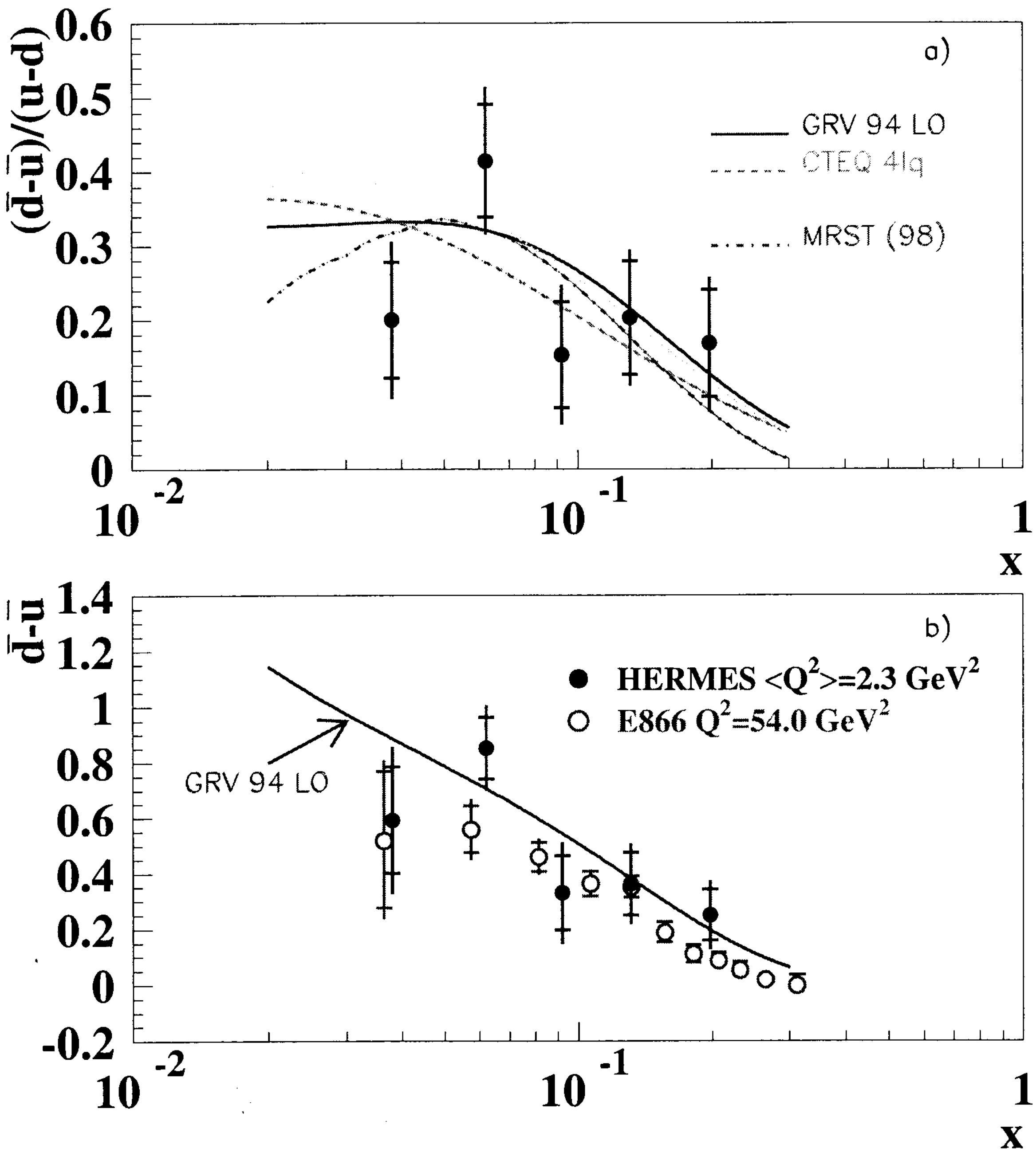
$$r(x,z) = \frac{N_p^{\pi^-}(x,z) - N_n^{\pi^-}(x,z)}{N_p^{\pi^+}(x,z) - N_n^{\pi^+}(x,z)}$$

With $J(z) = \frac{5}{3}\left(\frac{1 + D'(z)}{1 - D'(z)}\right)$ and $D'(z) = \frac{D_u^{\pi^-}(z)}{D_u^{\pi^+}(z)}$

one receives

$$\frac{\bar{d}(x) - \bar{u}(x)}{u(x) - d(x)} = \frac{J(z)\,[1 - r(x,z)] - [1 + r(x,z)]}{J(z)\,[1 - r(x,z)] + [1 + r(x,z)]}$$

Light Sea Flavor Asymmetry — Comparison to E866

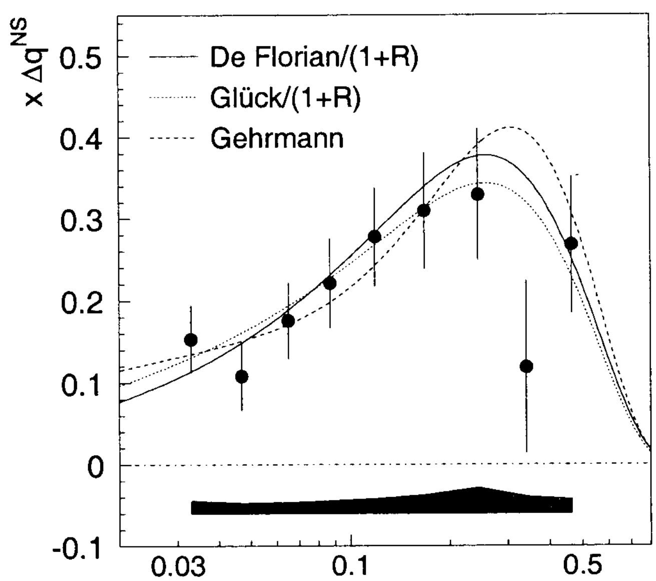


- Sea asymmetry in semi-inclusive DIS (HERMES) and Drell–Yan (E866) experiments agree
- Q^2 of two experiments differ by factor ~ 20

Summary of Factorization Test/Measurements

- Ratio of valence quark distributions: $\frac{d_v}{u_v}$
  $\rightarrow$ no further work done since 1996
- Light sea flavor asymmetry: $\frac{\bar{d}}{\bar{u}}$
  $\rightarrow$ no evidence of strange behavior
- Polarized quark distributions: Δq
  - HERMES data agree with SMC data
  - good agreement with SU(3) analyses of other inclusive data:

$$\Delta q^{NS}(x) = \Delta u(x) + \Delta \bar{u}(x) - \Delta d(x) - \Delta \bar{d}(x) = 6\,(g_1^p(x) - g_1^n(x))$$



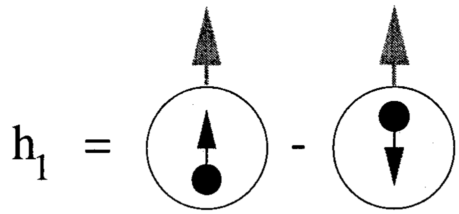
$\rightarrow$ fits are from inclusive data where factorization is not relevant

$\Rightarrow$ Factorization seems to hold at HERMES

Transversity

A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution $\delta q(x)$.

transversity:
$h_1(x) \sim \delta q(x)$



Features of $h_1(x)$:

- in the absence of relativistic and spin-orbit effects,
  $$\delta q(x) = \Delta q(x)$$
- $h_1(x)$ is a chiral-odd distribution function, related to spin flip of transversely polarized quark
- unlike for g_1, the gluon polarization does not mix with quark polarization in $h_1 \rightarrow$ different Q^2 evolution
- h_1 predominantly sensitive to valence quark polarization
- first moment of h_1 = tensor charge of the nucleon $\rightarrow$ possible comparison with lattice QCD

Measurement approach:

Transversity is inaccessible in inclusive DIS, but can be probed via azimuthal distributions in polarized semi-inclusive DIS from a transversely polarized target.

Single Spin Asymmetries

- Double Spin Asymmetries:

Polarized Beam and Target
$g_1^n \; g_1^p \; \Delta q ...$
Longitudinal quark polarization densities

- Single Spin Asymmetry (SSA):

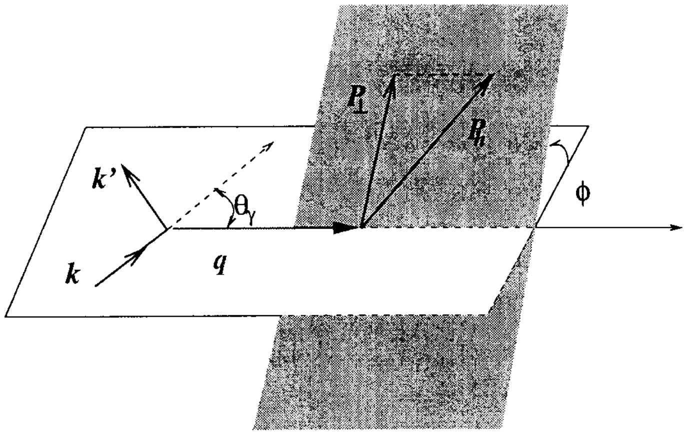
Polarized Beam or Target
Transerse quark polarization densities

Chiral odd DF (like h_1)
$\Downarrow$
Time-odd FF (like $H_1^\perp$)
$\Downarrow$
SSA

In naive parton model of colinear, non-interacting quarks
Parity, Angular Momentum, Helicity conservation
$\Rightarrow$ SSA $= 0$

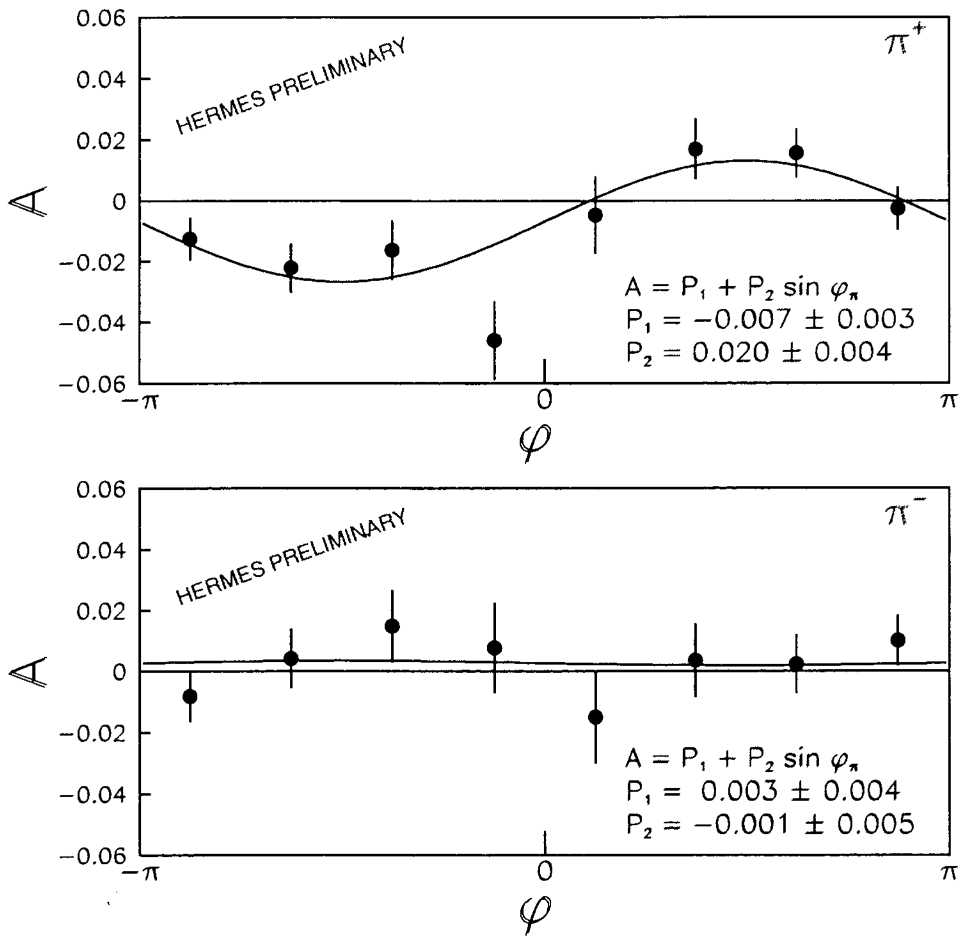
SSA originates from multi-parton correlations and vanish when PQCD becomes effective.

Spin-Azimuthal Asymmetry



Longitudinal target spin asymmetry:

$$A(\phi) = \frac{1}{P} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

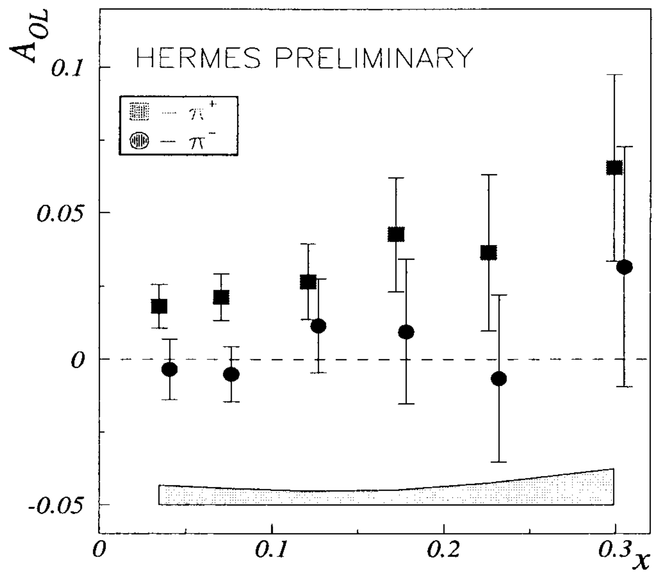


Effect observable even with longitudinally polarized target
⇒ good promise for future **transverse target program**
at HERMES

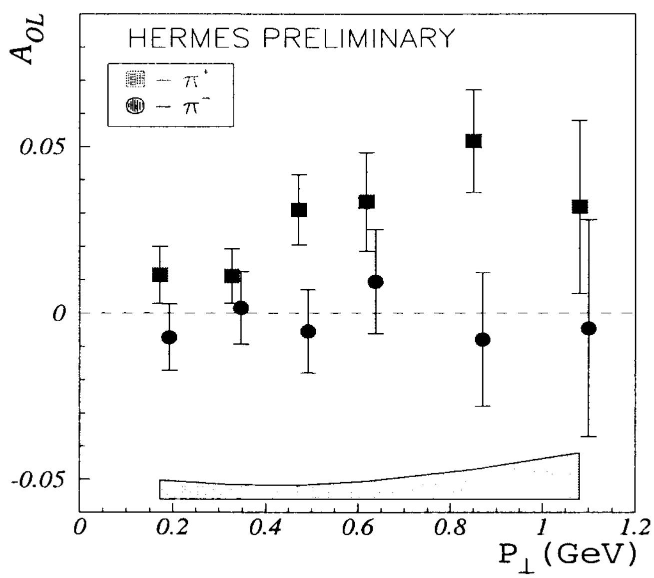
Spin-Azimuthal Asymmetries

$$A_{0L} = \frac{\int \sin\phi \, \frac{d\sigma^+}{d\phi}}{P_{T+} \int \frac{d\sigma^+}{d\phi}} - \frac{\int \sin\phi \, \frac{d\sigma^-}{d\phi}}{P_{T-} \int \frac{d\sigma^-}{d\phi}}$$

x-dependence



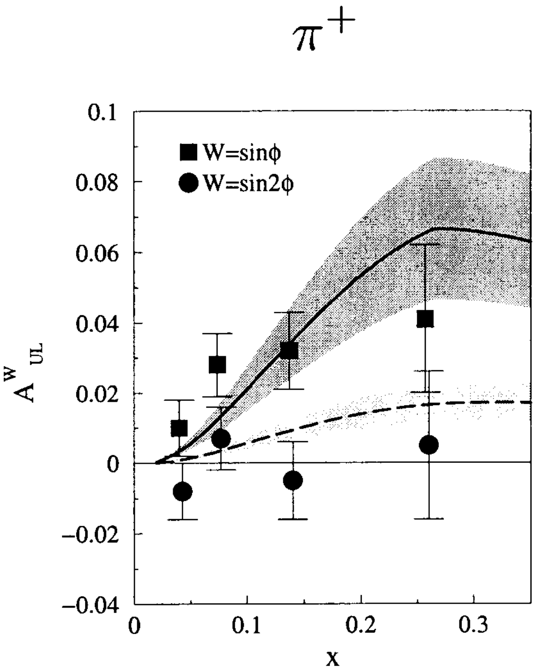
p_T-dependence

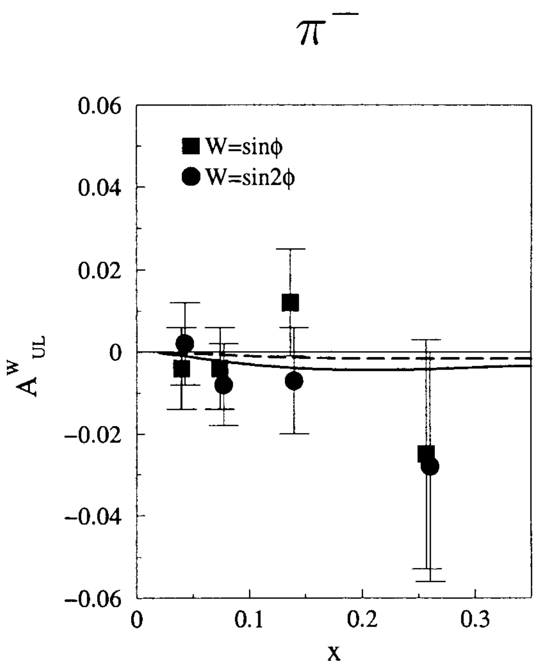


$$\langle \sin\phi \rangle \sim x h_L H_1^\perp \begin{cases} h_L = & \text{twist-3 chiral-odd distribution function, related to } h_1 \\ H_1^\perp = & \text{T-odd “Collins” fragmentation function} \end{cases}$$

Comparison to Chiral Quark Soliton Model

K. Goeke et al: hep-ph/0001119





- Chiral quark soliton model calculation at $Q^2 = 4$ GeV^2 $\rightarrow$ good agreement with HERMES SSA result

solid line: $A_{OL}^{sin\ \phi}$, dashed line: $A_{OL}^{sin\ 2\phi}$
shaded area: experimental uncertainties of $|\langle H_1^{\perp}(z)\rangle / \langle D_1(z)\rangle|$

Conclusions

- Low x, low Q^2 inclusive
  - Higher twist effects stay small down to small Q^2
  - Why is there no Q^2-dependence at the scale of Λ_{QCD}
    - ⇒ help to understand Quark-Hadron Transition
    - ⇒ push QCD to still smaller Q^2? JLAB find limit?
- Polarized Quark Distributions
  - HERMES data agree with SMC data (very different Q^2)
  - fits are from inclusive data (factorization not relevant):
    - ⇒ with completely different techniques, same result
- Charged and Neutral Pion 'Fragmentation Functions'
  - despite very different kinematics, perfectly match EMC FF after NLO QCD evolution
- Factorization Tests/Measurements
  - d_v/u_v, $\bar{d}/\bar{u}$, Δq
    - ⇒ no evidence of strange behavior
    - ⇒ Factorization seems to hold at HERMES
- Single Spin Asymmetries - Transversity
  - study transverse quark polarization densities (chiral odd DF and T-odd FF)
    - ⇒ originates from multi-parton correlations