# The Early Days of the EMC (Fe/D)Effect
# (a personal perspective)

Hugh Montgomery
Jefferson Lab
(EMC Spokesman 1981-83
E665 Spokesman 1987-89)

# Outline

**Expectations**

**The NA2 Experiment**

**EMC data**

**Bodek Thesis reanalysis**

**E665 Data**

**Theory Reactions**

**Comments**

**Conclusion**

# Shadowing - Daresbury Pion ElectroProduction (PEP) Experiment

**Real photons had been seen to behave like hadrons (ρ, ω, ϕ)**

**Shadowing: Aeff/A is less than unity for $Q^2=0$**

**What happens for $Q^2>0$ ?**

**PEP saw shadowing!**

**(Radiative corrections were an issue)**

382 *J. Bailey et al. / Shadowing in low $|Q^2|$ electroproduction*

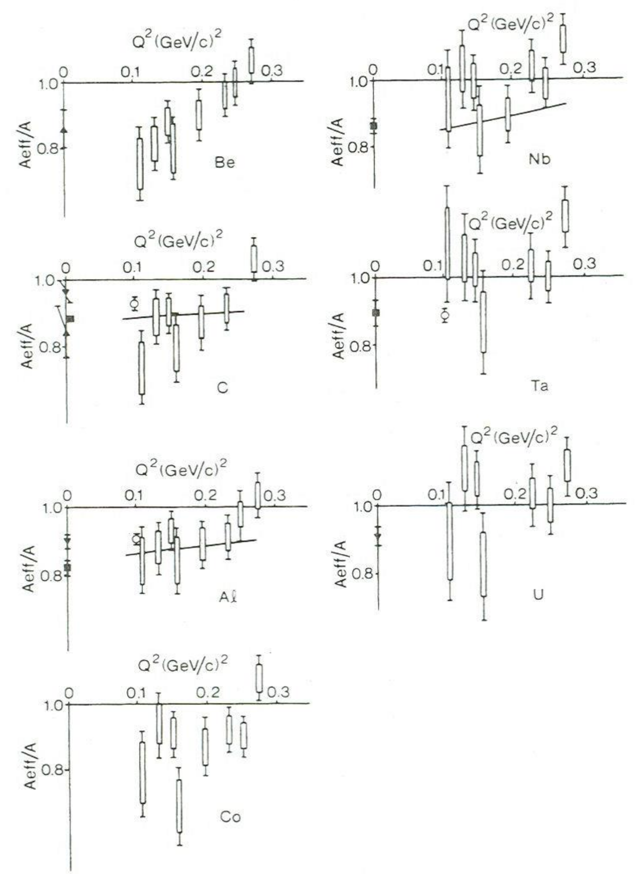
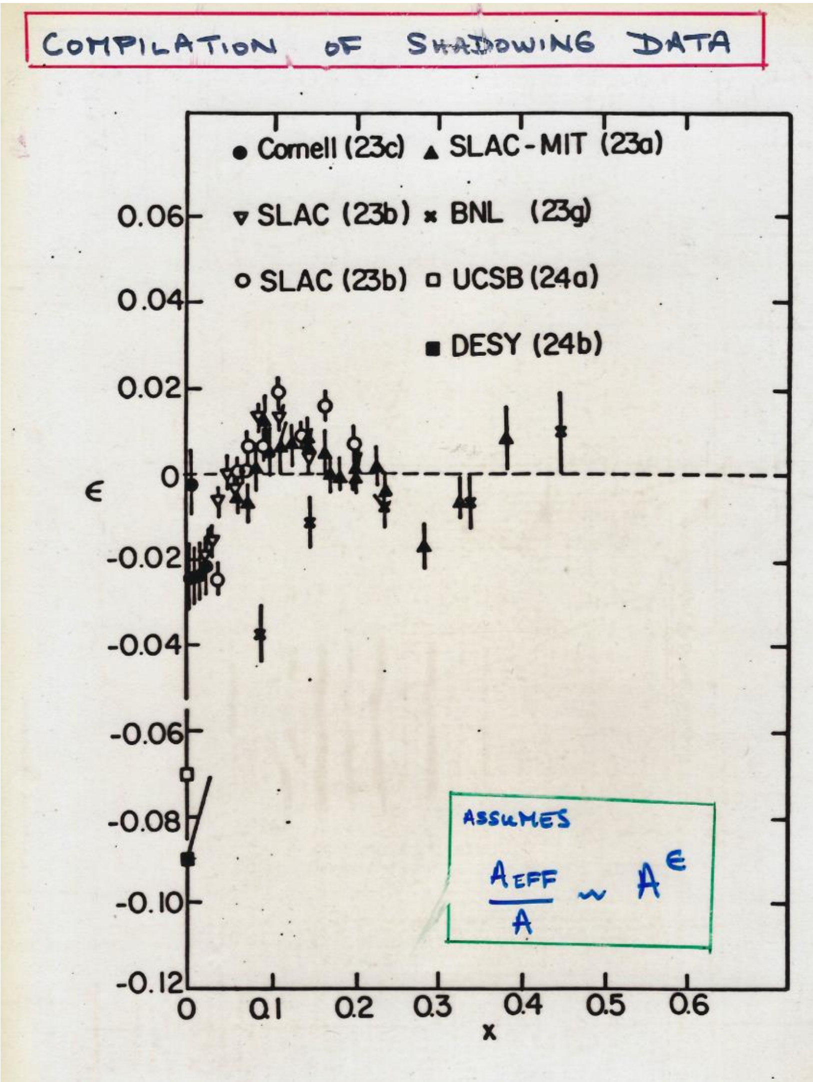



Fig. 5. Experimental values of $A_{eff}/A$ as a function of $Q^2$. ○ ref. [9], ▲ ref. [1], ■ ref. [3], ▼ ref. [4], —— ref. [21], □ this experiment: the systematic error is indicated by the rectangle and the statistical error by the lines.

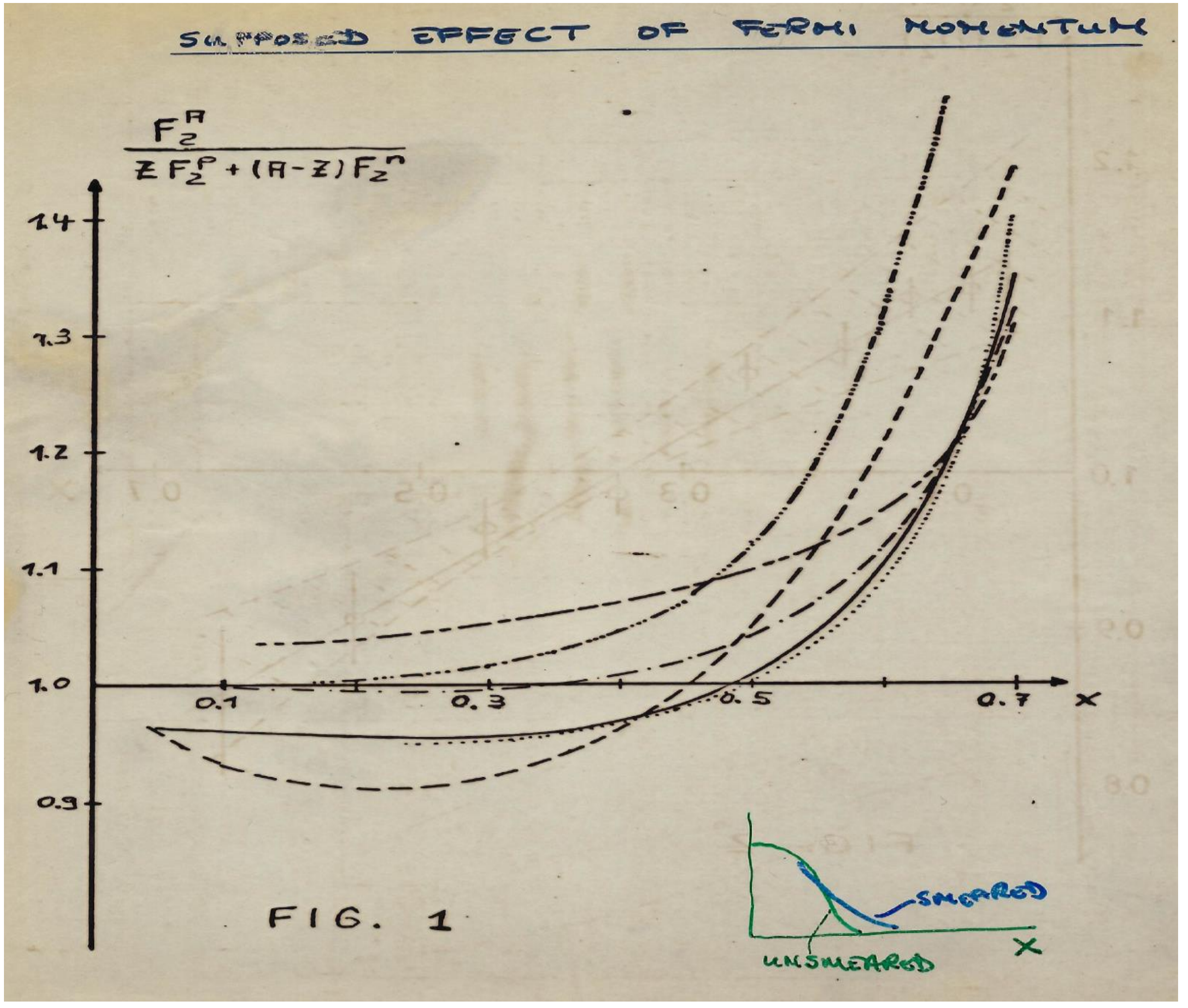
# Compilation of Shadowing Data

For $Q^2$ away from zero, the data were confusing



# Fermi Motion Calculations

- **Fermi Motion expected to affect kinematics at high $x_{Bj}$**



# Expect Iron is just Dense

**So will enhance the luminosity compared to $H^2$ or $D^2$**

**Note that for muons, radiative effects are much reduced compared to electrons**

**Text from EMC LOI CERN/I 73-15**

<u>2.3 μ + A → μ + anything</u>

(muon completely measured)

Present electron nucleus scattering experiments(9) show that there is no shadowing of the total virtual photon cross section contrary to photoproduction experiments. This situation may change at higher energies as predicted for example by the generalized vector dominance model(10). Thick targets can be used with muons to enhance the counting rate at very large $q^2$ enabling a comparison to be made with neutrino reactions.

**Neutrino Experiments typically used Iron (CDHS) or Marble (CHARM)**

# European Muon Collatoration (NA2) Authors

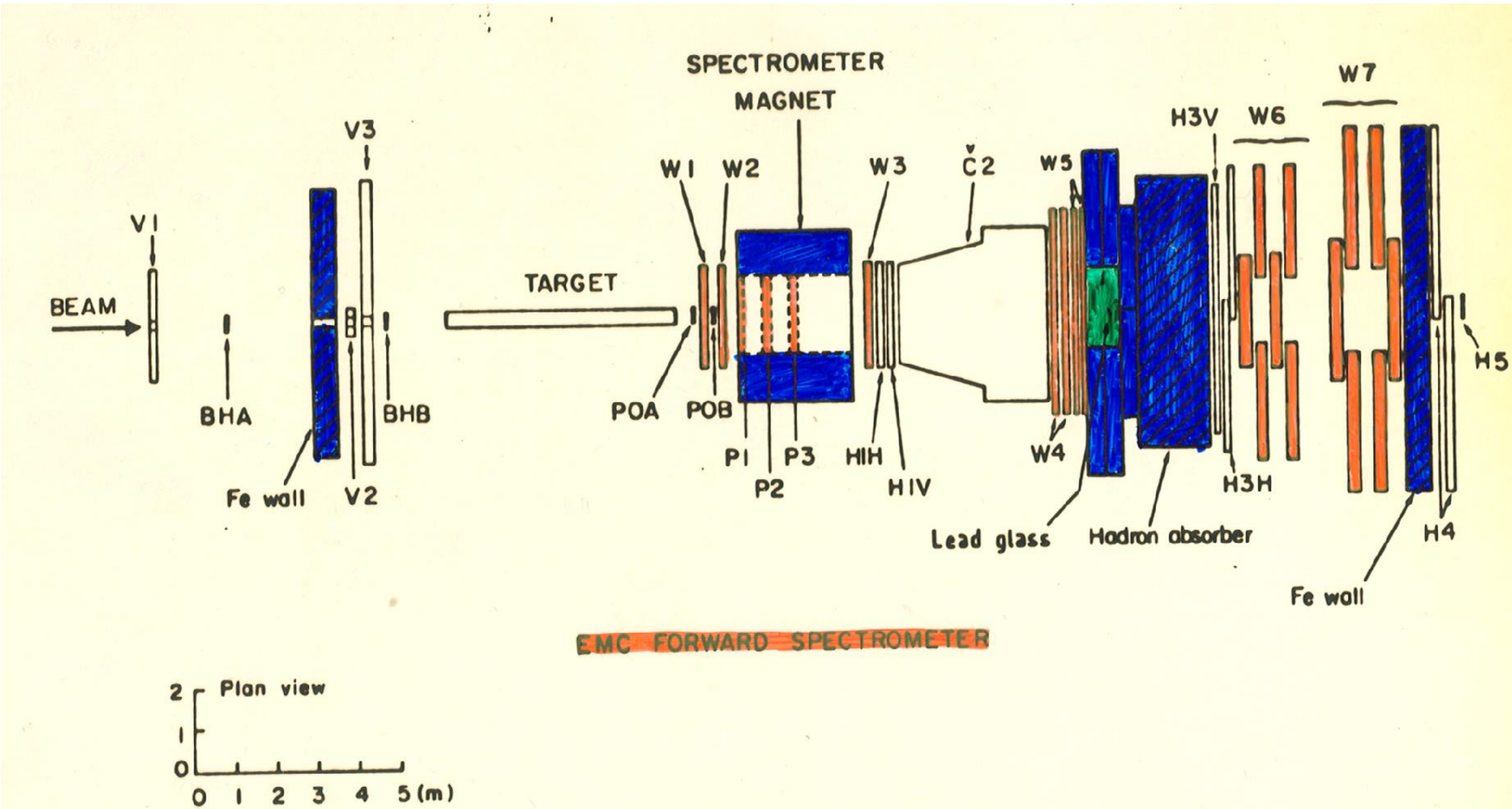
E. M. C.

The European Muon Collaboration

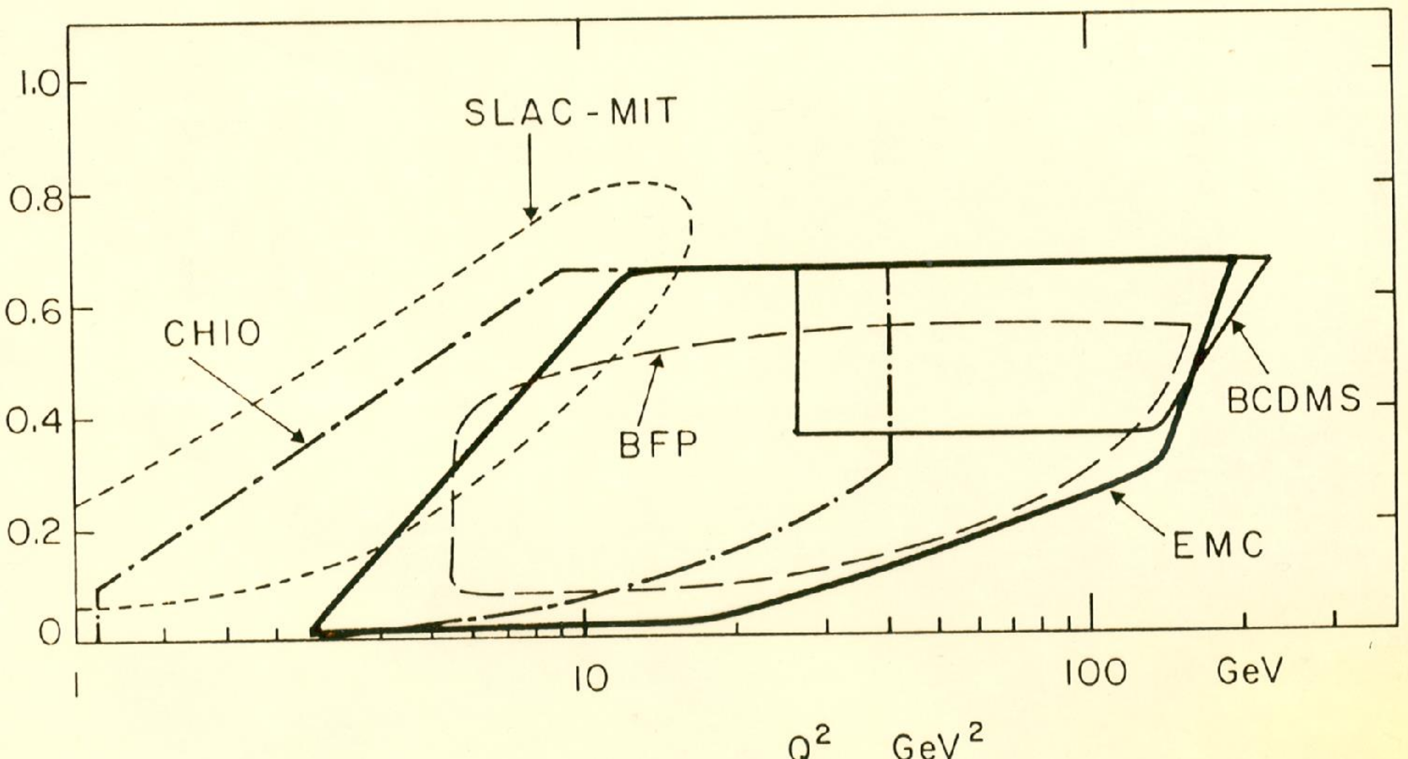

CERN[1]-DESY(Hamburg)[2]-Freiburg[3]-Kiel[4]-Lancaster[5]-LAPP(Annecy)[6]-Liverpool[7]-Oxford[8]-Rutherford[9]-Sheffield[10]-Turin[11] and Wuppertal[12]

J.J. Aubert[6]*, G. Bassompierre[6], K.H. Becks[12], C. Best[9], E. Böhm[4], X. de Bouard[6], F.W. Brasse[2], C. Broll[6], S. Brown[7], J. Carr[9], R.W. Clifft[9], J.H. Cobb[12], G. Coignet[6], F. Combley[10], G.R. Court[7], J.M. Crespo[6]**, P.F. Dalpiaz[11], P. Dalpiaz[11], W.D. Dau[4], J.K. Davies[8], Y. Déclais[6], R.W. Dobinson[1], U. Dosselli[1], J. Drees[12], A. Edwards[1], M. Edwards[9], J. Favier[6], M.I. Ferrero[11], W. Flauger[2], E. Gabathuler[1], R. Gamet[7], J. Gayler[2], V. Gerhardt[2], P. Ghez[6], C. Gössling[2], P. Gregory[1], J. Haas[1], U. Hahn[3]***, K. Hamacher[12], P. Hayman[7], M. Henckes[12], H. Jokisch[4], V. Korbel[2], U. Landgraf[3], M. Leenen[1], M. Maire[6], L. Massonnet[6], W. Mohr[3], H.E. Montgomery[1], K. Moser[3], R.P. Mount[8], E. Nagy[6], P.R. Norton[9], J. McNicholas[8], A.M. Osborne[1], P. Payre[6], C. Peroni[11], H. Pessard[6], U. Pietrzyk[12], K. Rith[3], E. Schlösser[3], M. Schneegans[6], T. Sloan[5], H.E. Stier[3], W. Stockhausen[12], J.M. Thénard[6], J.C. Thompson[9], L. Urban[6]+, H. Wahlen[12], M. Whalley[10], D. Williams[7], W.S.C. Williams[8], S.J. Wimpenny[7].

# EMC (NA2) Muon Scattering Experiment



# Experimental Playing Field




**With Muons Rad. Corr are less, can use Heavy Target**

**BFP(FNAL E203 – Iron, CERN (NA4) Carbon → high luminosity**

**EMC STAC: Sampling Total Absorption Calorimeter**

G. SMADJA
BONN

# The STAC Target

## STAC: Sampling Total Absorption Calorimeter

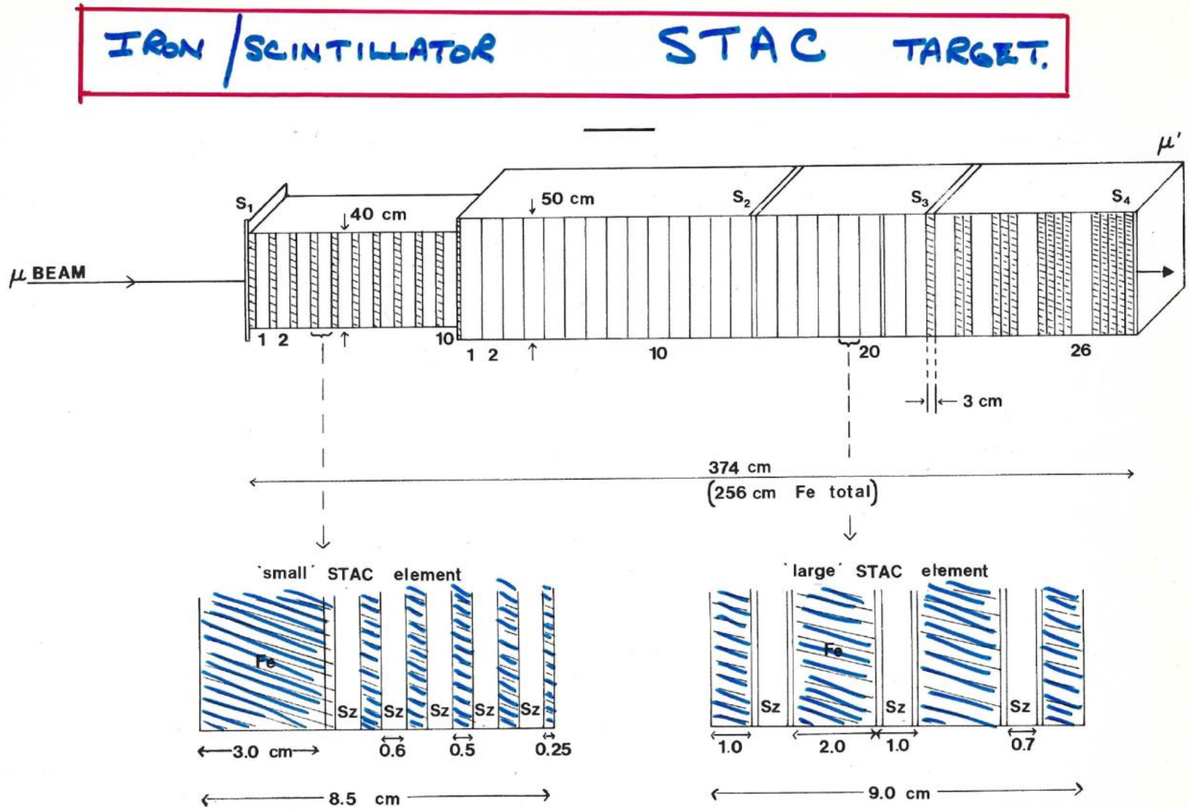



FIG. 6

$$\frac{\sigma(E)}{E} = \frac{0.56}{E^{0.4}}$$

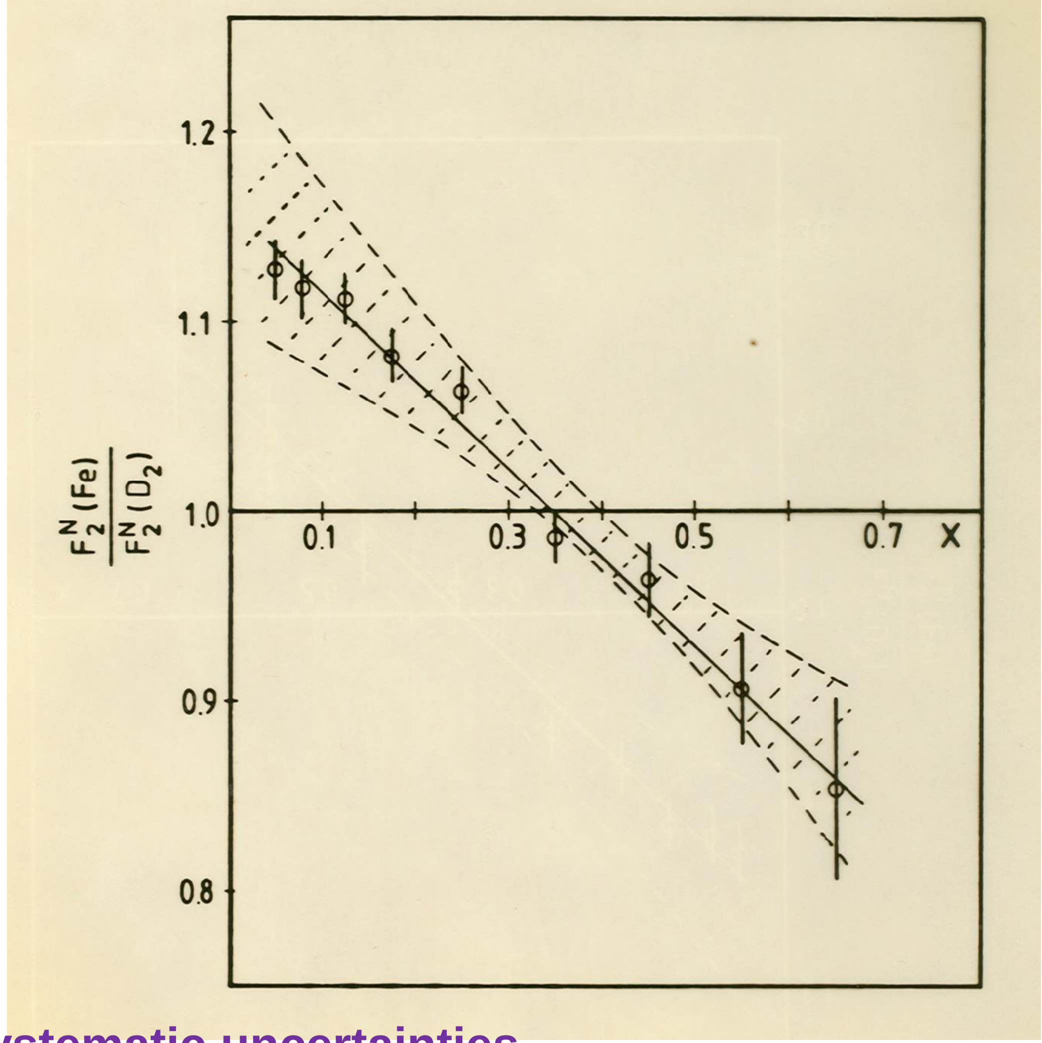
# A Surprise: The EMC Effect

**Unexpected**

**Despite the high momentum transfers involved**

**the measured $F_2^N$ depends on the nucleus!!!!!**

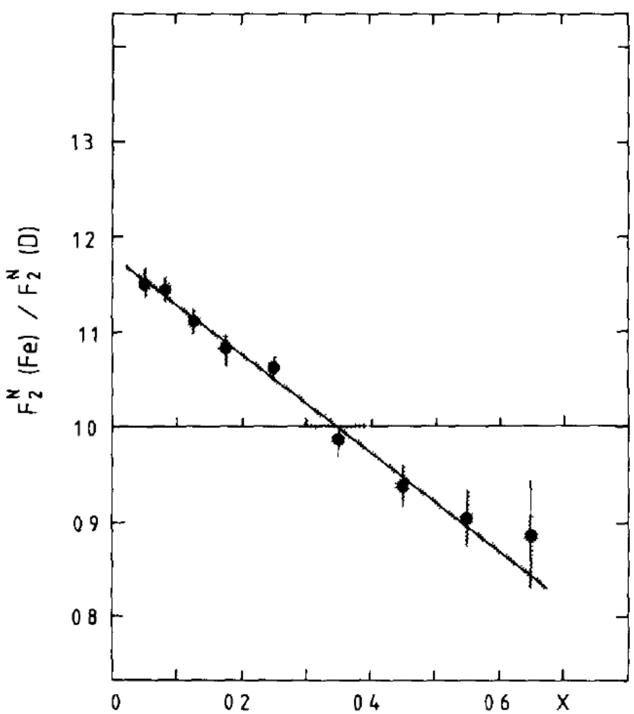
**Lots of post-data wisdom from theorists!!**




**Shaded Band represented systematic uncertainties**

# The EMC Publication

The Ratio of the Nucleon Structure Functions $F_2^N$ for Iron and Deuterium
J. J. Aubert et al, PL **123B**, 275 (1983)




> We are not aware of any published detailed prediction presently available which can explain the behaviour of these data. However there are several effects known and discussed which can change the quark distributions in a high $A$ nucleus compared to the free nucleon case and can contribute to the observed effect. Amongst them one can list: the change of mass or radius of nucleons embedded in nuclei [11], the existence of excited baryon states like Δ's [12] or of six-(nine, ...)-quark states inside the nucleus [13], the presence of an additional nuclear sea component due to the mutual interactions between the nucleons [14] and possibly several other effects.

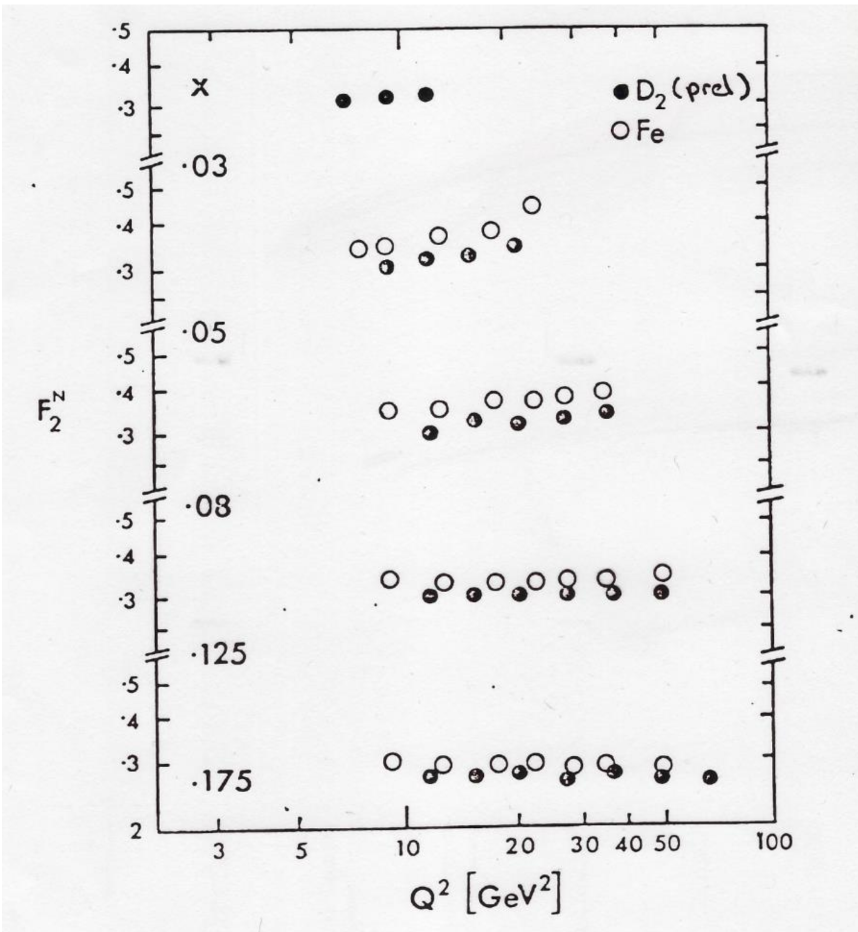
Slope -0.52 +/- 0.04 (stat) +/- 0.21 (syst)

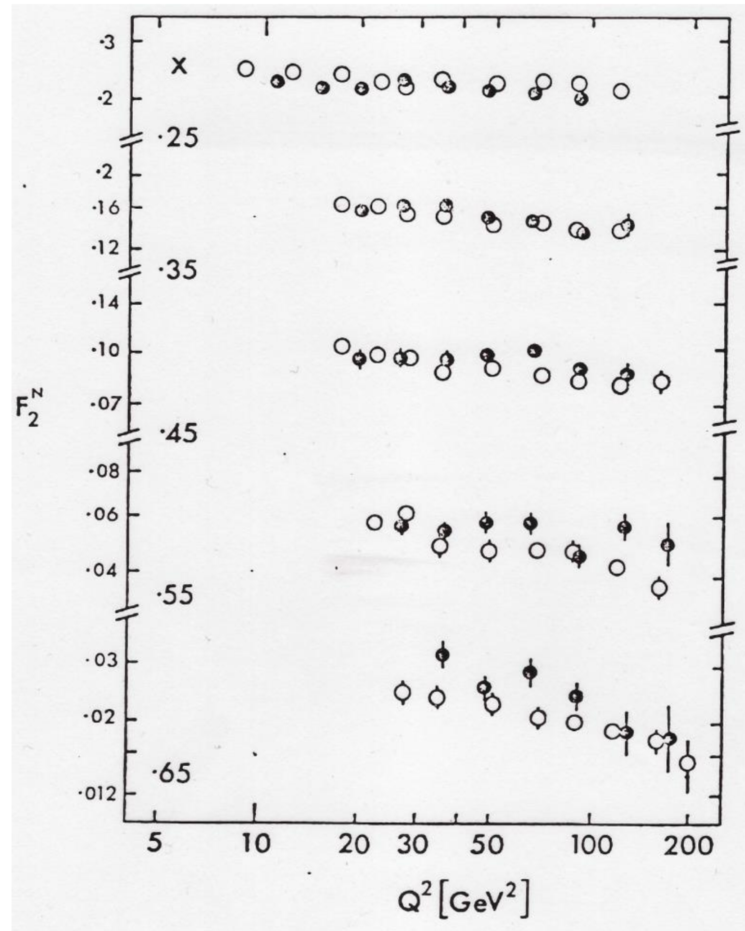
**No PREdictions,**
**So no theory explanations included**
**(see later)**

# Fe/D x, Q2 Dependence

EMC Data

Fe: 120, 250, 280 GeV
D : 280 GeV



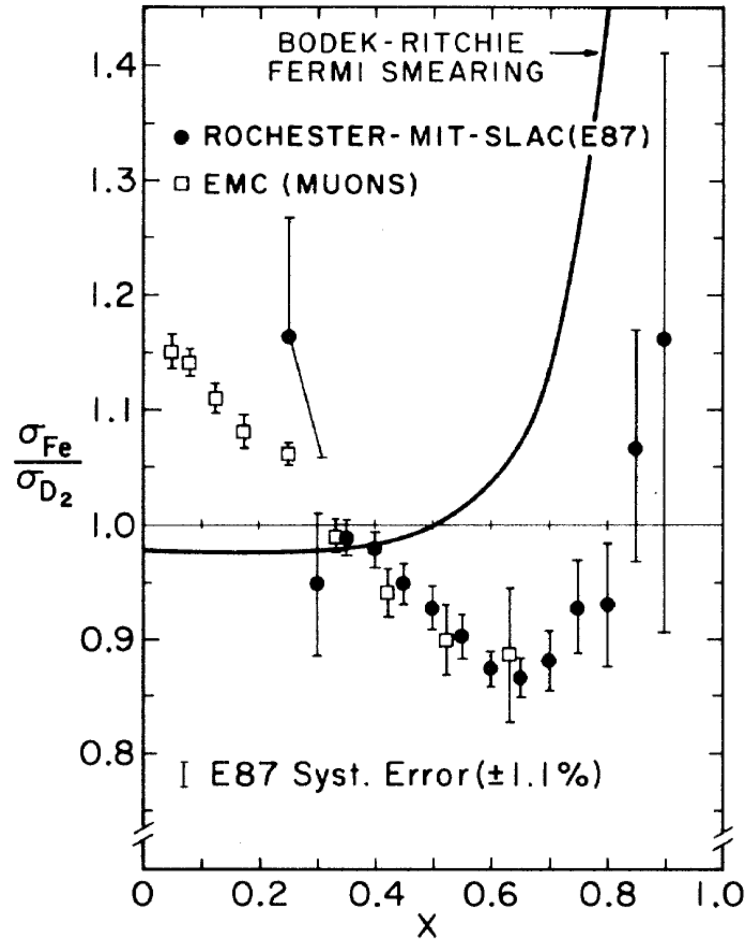
# Arie Bodek Thesis Reanalysis

## SLAC E87

The SLAC experiment[9,10] was designed to measure deep-inelastic electron scattering from hydrogen and deuterium at large values of $x$ and $Q^2$ in order to extract the proton and neutron structure functions. The structure functions were extracted with use of hydrogen and deuterium targets and a steel empty-target replica. Results on the ratio of neutron and proton structure functions were reported[9] in 1974. A later comprehen-

A. Bodek et al, PRL **50**,1431 (1983)

We wish to express our gratitude and appreciation to all members of the Stanford Linear Accelerator Center. We thank Ron Sax and Mark Barnett from SLAC, Jim Schlereth from Argonne, and Harald Johnstad from Fermilab for their help in recovering the E87 data from old IBM tapes. This work was supported in part by the

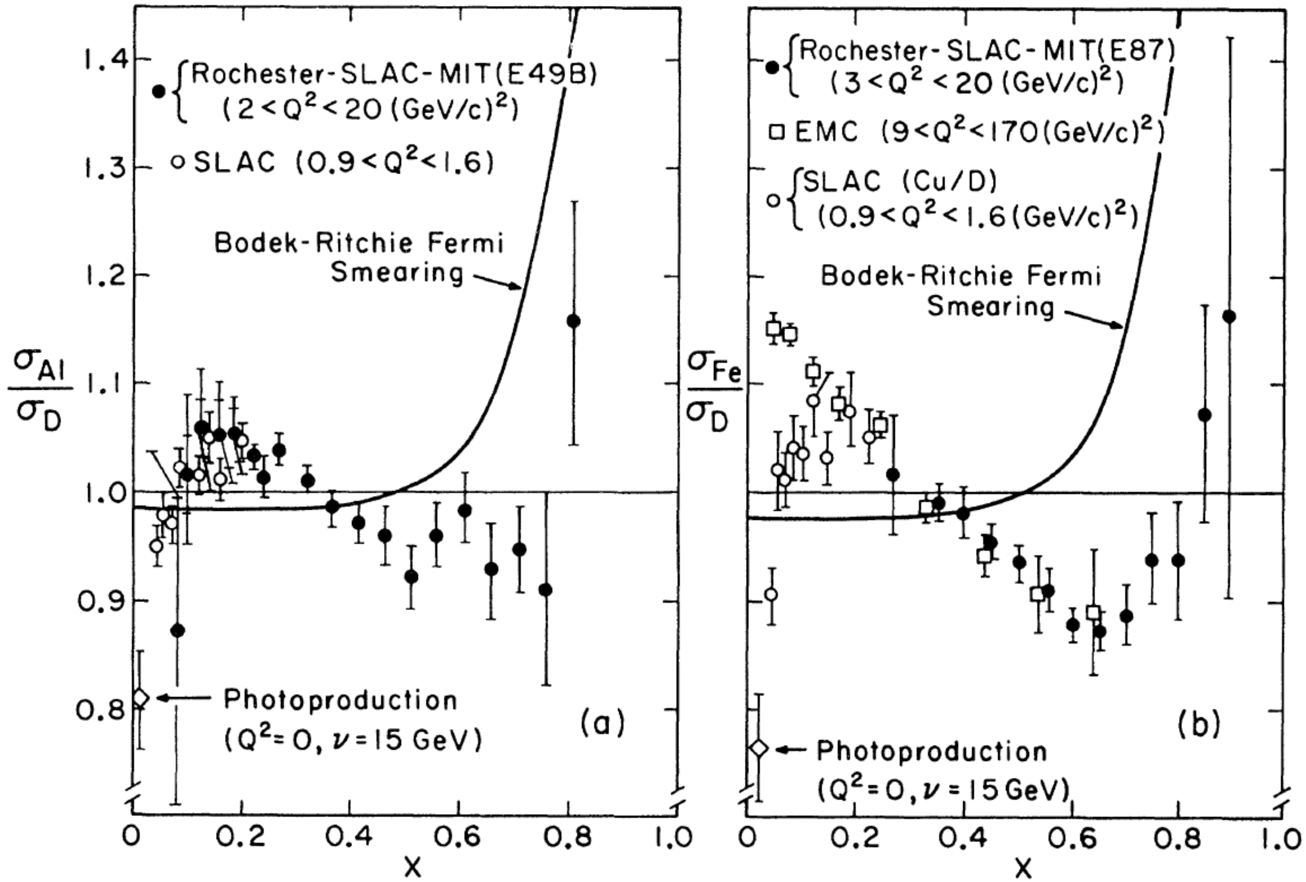



**Strong argument for data retention!**

# Bodek finds more

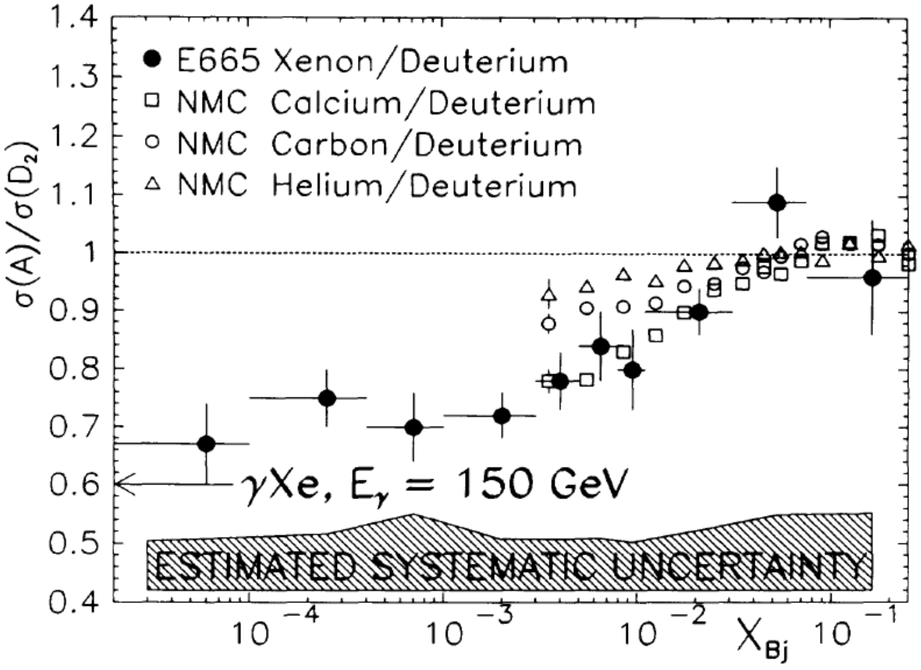
A. Bodek et al, PRL **51**, 534 (1983)

**SLAC E49B, E87**

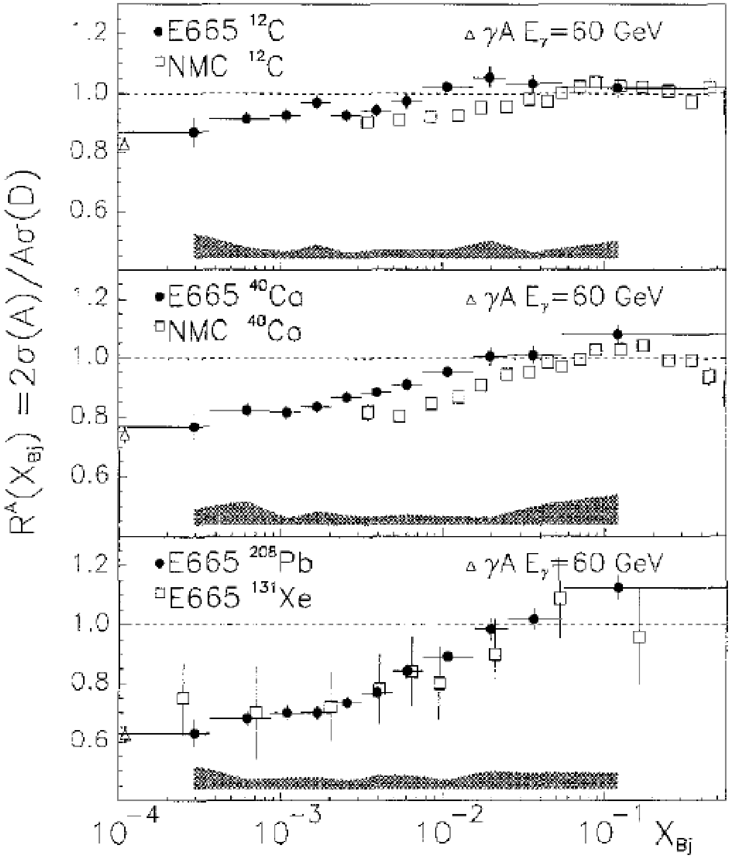


# Fermilab E665 Results

E665
M.R. Adams et al, PRL **68** 3266 (1992)




E665
M.R. Adams et al, Z. Phys. **C67** 403 (1995)




**Shadowing at low $x_{Bj}$ now clearly established.**

# Theorists were quick off the mark

The preliminary result was made public at the 1982 (Paris) Rochester Conference:

Among the theoretical ideas, one that this was all due to pions in the nucleus was discussed by telephone in office in

| | |
|---|---|
| Theory Division at CERN | and in office at MIT? |
| Chris Llewellyn-Smith | Bob Jaffe |
| Kolya Nikolaev ($N^3$) | |
| Tony Thomas | |
| + me | |

I stayed quiet!

# Pions at low x plus 6-quark bag
# Bob Jaffe

Quark Distributions in Nuclei
R. L. Jaffe, PRL **50**,228 (1983)

[1]A. Edwards, in Proceedings of the Twenty-First International Conference on High Energy Physics, Paris, July 1982 (to be published).

I wish to thank Erwin Gabathuler for drawing my attention to and providing me with the data of Ref. 1. I am grateful to my colleagues in the Center for Theoretical Physics for discussions and suggestions and to C. H. Llewellyn Smith and N. N. Nikolaev for pointing out an error in an early version of the manuscript.

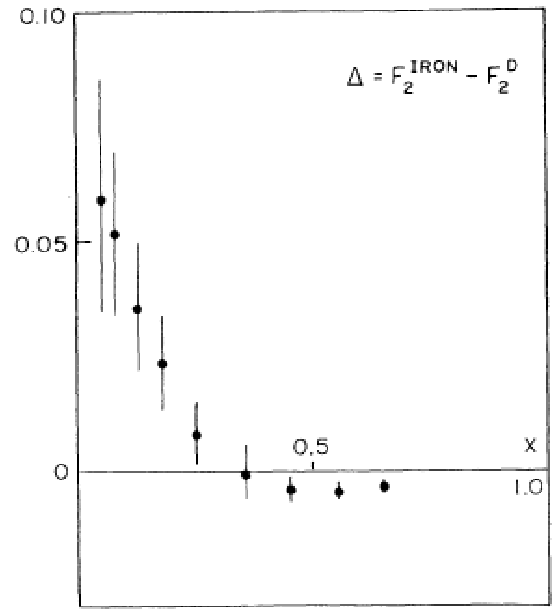



FIG. 1. EMC data on $\Delta(x) = F_2^{\rm iron}(x) - F_2^{\rm D}(x)$.

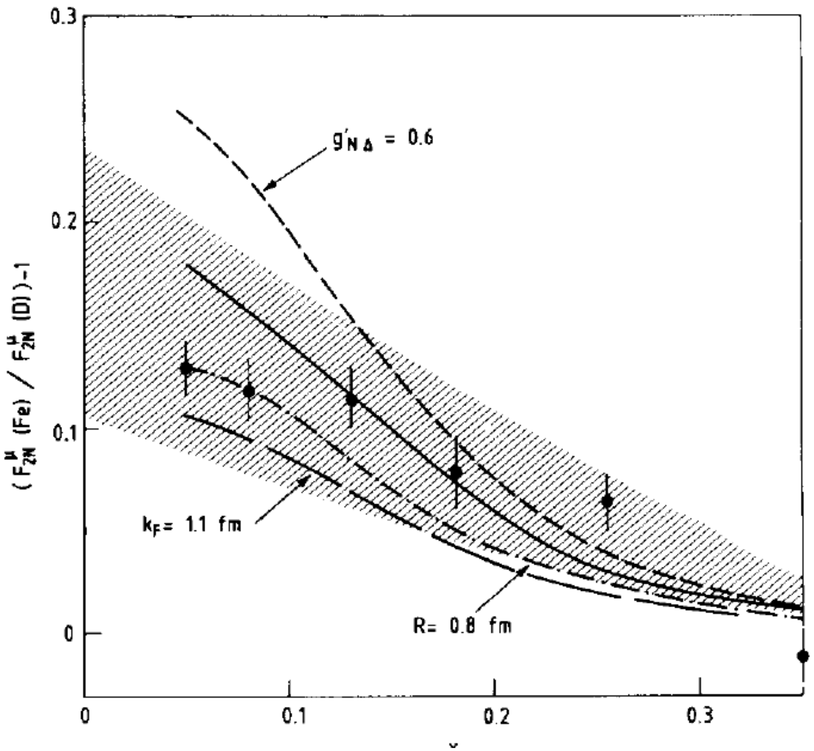
C.H. L.S debates impact on QCD fits

[8]The large magnitude of $\delta o$ casts doubt on previous QCD parton-model fits to inelastic leptoproduction in which data from proton, deuteron, and iron targets were fitted with a single $o(x)$. Extractions of the QCD scale parameter $\Lambda$ may be affected by this complication. I thank H. Montgomery for a discussion on this subject.

# Pions in the Nucleus
# Tony Thomas

Pionic Corrections and the Enhancement of the Sea in Iron
M.A. Ericson & A. W. Thomas, Phys. Lett. **128B** 112 (1983)

It is a pleasure to acknowledge many extremely valuable discussions with C.H. Llewellyn Smith on the subject of deep inelastic scattering with and without pions. We are also indebted to E. Gabathuler for drawing our attention to the EMC data, and for lively discussions of it. We thank G. Coignet for suggestions on possible signatures of the effect in the hadron states. One of us (M.E.) would like to thank G. Chanfray, J. Delorme, M. Giffon and J. Uschersohn for informative discussions. Finally we thank W. Alberico and N.N. Nikolaev for useful discussions.



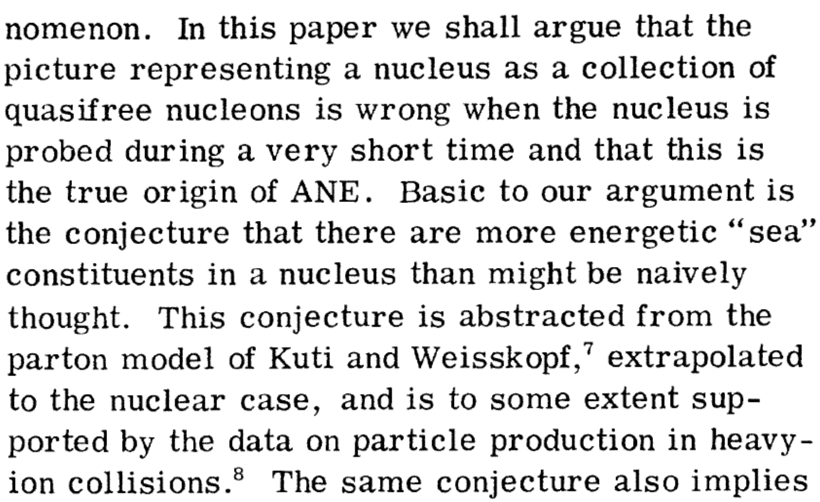
# A Smorgasbord of Post-dictions

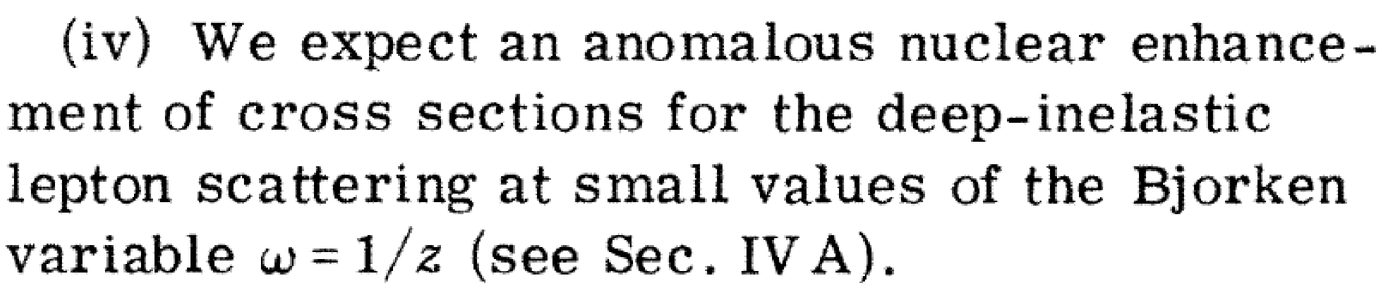
Nuclear Effects in Deep Inelastic Scattering
C. H. Llewellyn Smith, Oxford 37/83

- 6 Quark bags: Jaffe
- Pions in Nucleus: Llewellyn Smith, Ericson & Thomas
- Change of Confinement Scale: Close, Roberts & Ross
- Nucleus as single bag: Nachtman & Pirner
- Nucleus as a single bag: Furmanski & Krzywicki
- $\alpha$ clusters: Faissner & Kim
- More $\Delta$ in Iron: Szwed

# One belatedly recognized PREdiction

Anomalous nuclear enhancement of inclusive spectra at large transverse momentum
Andre Krzywicki, Phys. Rev D **14**, 152 (1976)


nomenon. In this paper we shall argue that the picture representing a nucleus as a collection of quasifree nucleons is wrong when the nucleus is probed during a very short time and that this is the true origin of ANE. Basic to our argument is the conjecture that there are more energetic "sea" constituents in a nucleus than might be naively thought. This conjecture is abstracted from the parton model of Kuti and Weisskopf,[7] extrapolated to the nuclear case, and is to some extent supported by the data on particle production in heavy-ion collisions.[8] The same conjecture also implies


(iv) We expect an anomalous nuclear enhancement of cross sections for the deep-inelastic lepton scattering at small values of the Bjorken variable $\omega = 1/z$ (see Sec. IV A).

# Conversation in Leningrad with Frankfurt & Strikman

Notes from Russia.

1) Recoil protons.

Their ideas of nuclear $F_2$ interactions etc lead them to large $x_F < -1$ yields of nucleons from nuclear targets. For them the two Eqs we linked and (see next section) they expect that observation of the recoil protons may be the only way to get at a "real" neutron F…

Mon 6.

23/9/83.

**Frankfurt & Strikman seem to connect EMC effect to backward nucleons -- connection to this workshop??? (also to BONUS experiment!)**

# Reactions to the Result

Franz Eisele (CDHS) gave the summary talk at the Paris Conference. He suggested that the systematic uncertainties needed to be scrutinized.

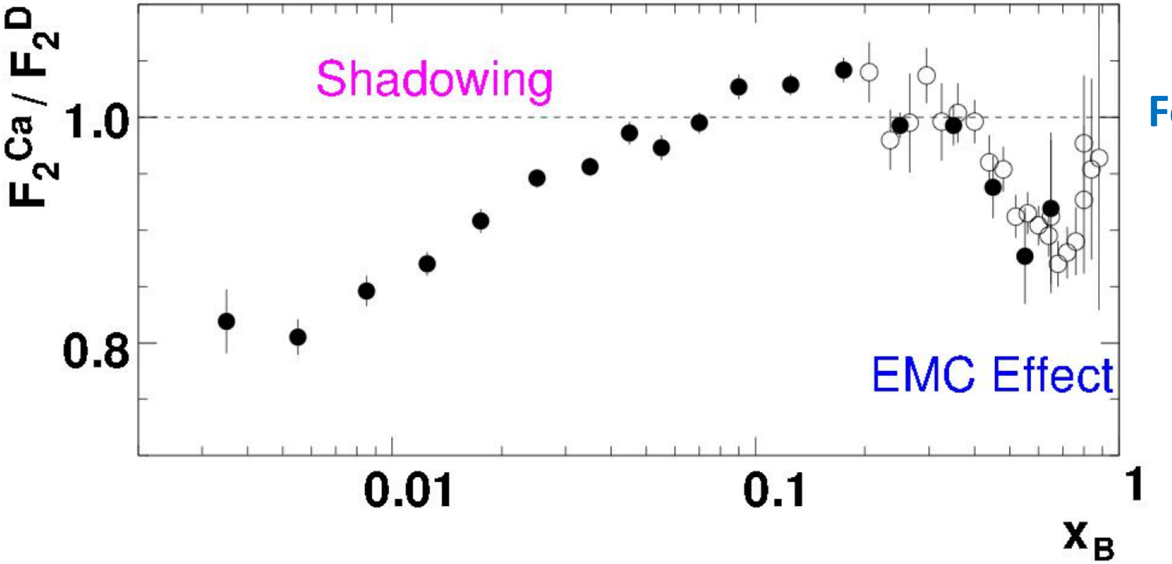
**The result in its gross characteristics was confirmed**

When I talked with Roy Holt after I had moved to Jefferson Lab, he said that his initial reaction was that EMC members were all particle physicists and that real (read nuclear) physicists would sort it out in a few months.

**~ 40 years and still standing**

# The Story Cleaned up

**From Higinbotham, Hen, Miller & Rith**
**CERN Courier *30th Anniversary of the EMC Effect***




**Fermi Motion**

Fig. 2: The image shows the ratio of deep inelastic cross sections of Ca to D from NMC (solid circles) and SLAC (open circles). The downward slope from 0.3 < x < 0.7 and subsequent rise from $x_B$ > 0.7 is a universal characteristic of EMC data and has became known as the EMC effect. The reduction of the ratio at lower values of $x_B$, where valence quarks should no longer be playing a significant role, is known as the shadowing region.

**Klaus Rith led the analysis of the seminal 250 GeV Iron Data**

# Summary

**When we proposed and planned the EMC experiment, we were looking to extend the experimental studies characterized by the Quark Parton Model, the scaling observed at SLAC, and to test the (literally) evolving QCD understanding of Deep Inelastic Scattering.**

**The observation of a difference between $F_2^N$ for $0.1 < x_{Bj} < 0.7$ as measured in Iron and in Deuterium was a complete surprise.**

**The best kind of experimental result!**

# Acknowledgements

**Thank you to all my experimental colleagues from many years ago, and the theorists with whom we enjoyed lively interactions.**

**Thanks to the organisers for giving me the opportunity to revisit those exciting days. It was a real pleasure.**

# Pion ElectroProduction Experiment (PEP)

## Daresbury Nuclear Physics Laboratory

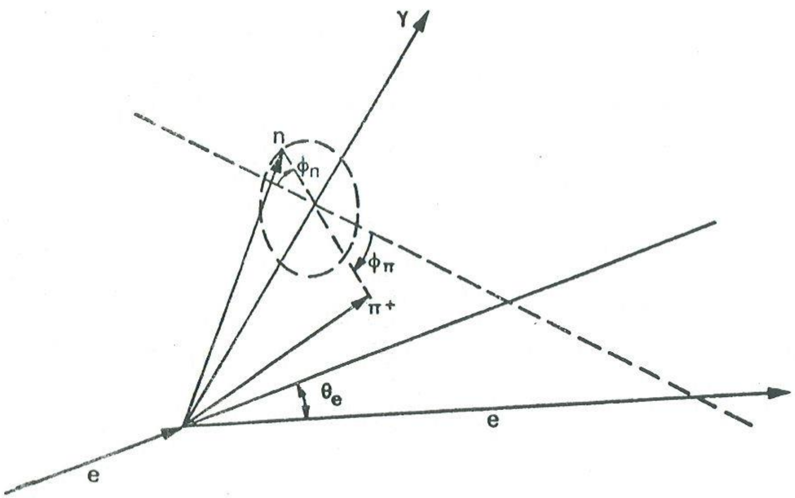



Fig.1

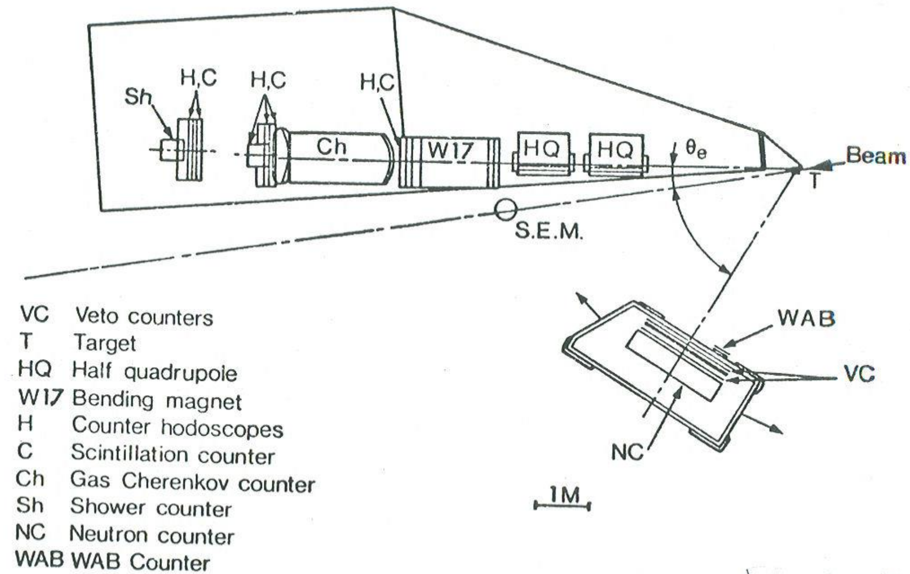



Fig. 2

# Nature of the Photon

**Situation was very confusing**

- **Real photons behave like hadrons:**
  - **Shadowing: Aeff/A is less than unity for $Q^2=0$**
- **At relatively low Q2 we see point-like behavior, eg in Deep Inelastic Scattering**

**We found ( ~ 1 day before Christmas 1973?) that the experiment is very difficult; radiative effects are ~ $Z^2$**

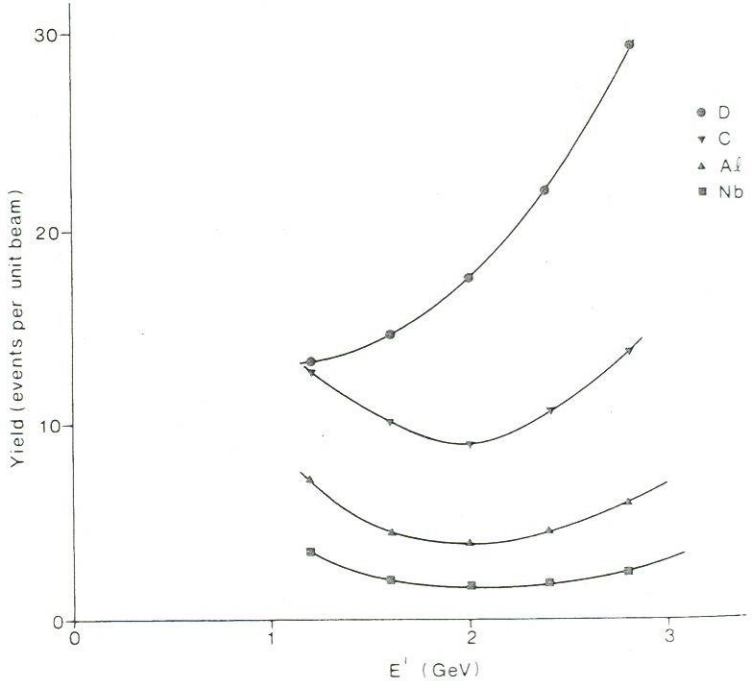


Fig. 1. Electroproduction yields as a function of $E'$ for various elements for $E$ = 5 GeV and $\theta_e = 6°$.

# FNAL Muon Experiments: Phase I

**E26 (Chen-Hand) -- Fe Target apparatus scaled with Eμ**

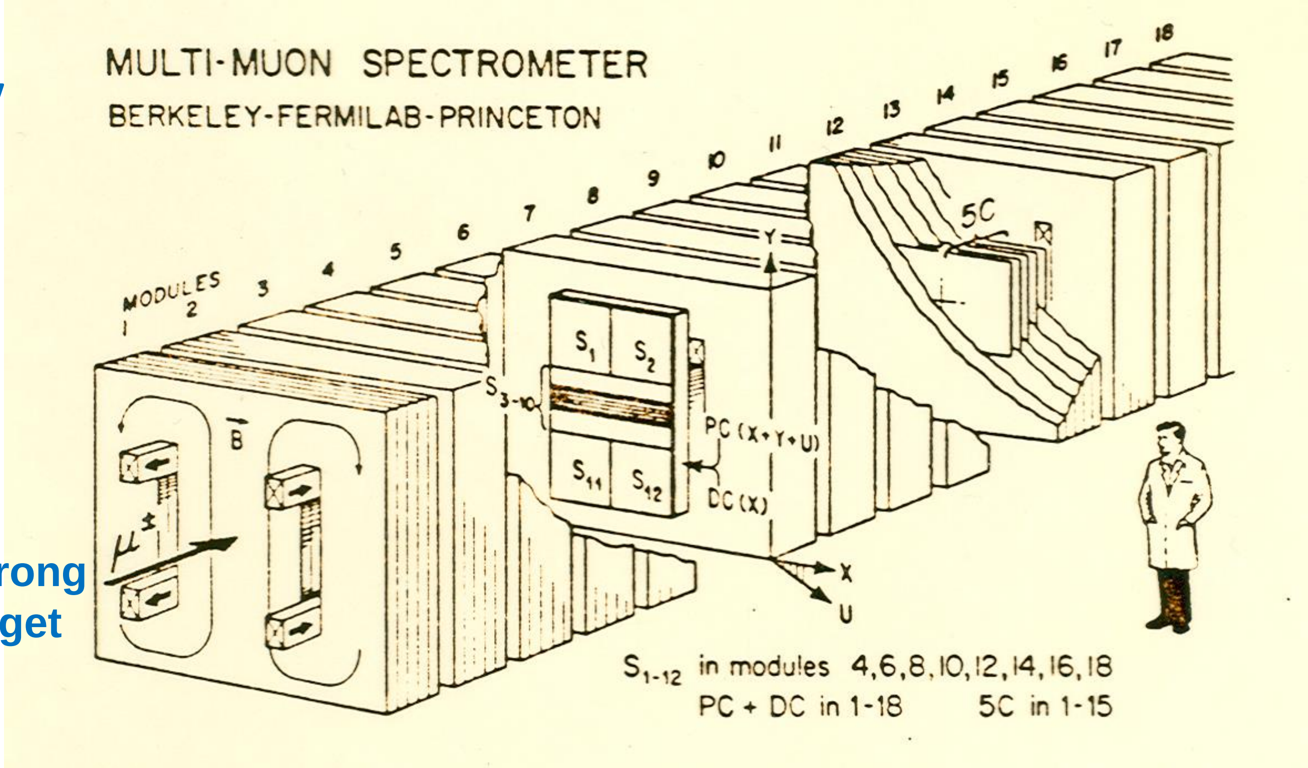
**E98, E398 (CHIO) – Chicago Cyclotron Magnet H2, D2 target**

**E319 (Chen)**

**Step at $W^2$=80 GeV**

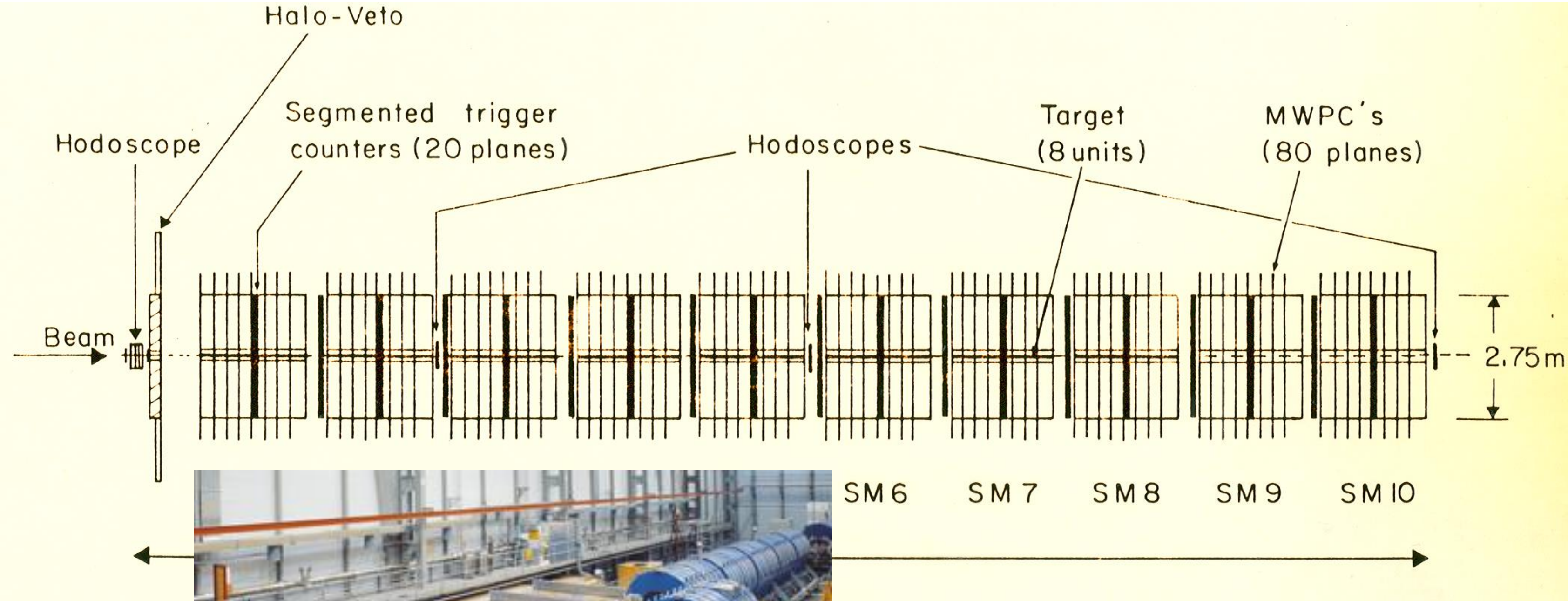
**E203 (BFP)**

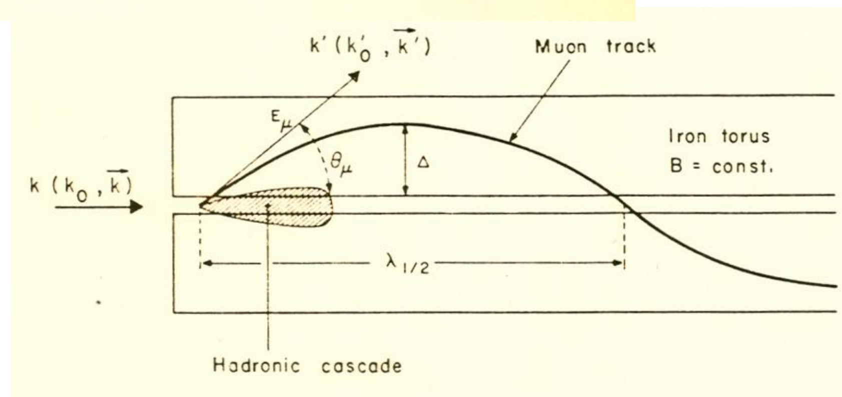
**Multi-μ, high L**




**BFP potential scoop was strong motivation for EMC Iron Target**

# BCDMS Muon Scattering Experiment



# CERN Courier takes ownership

**From Higinbotham, Hen, Miller & Rith**
**CERN Courier *30th Anniversary of the EMC Effect***

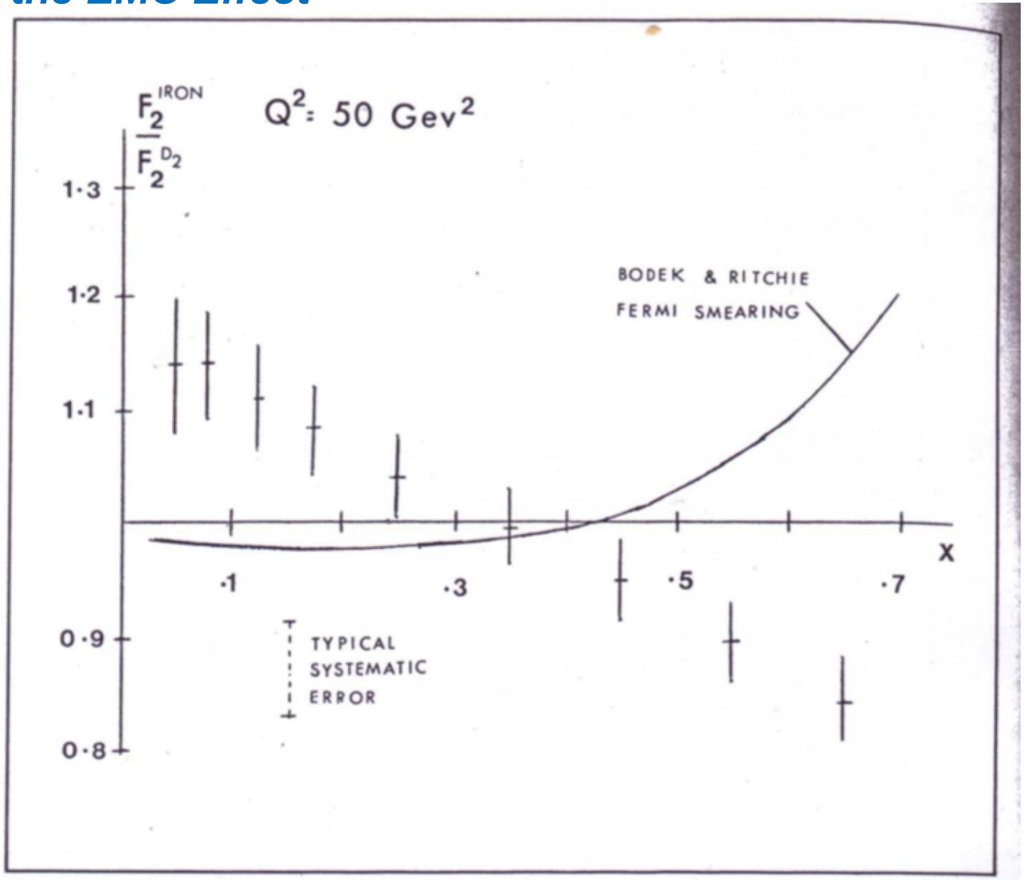
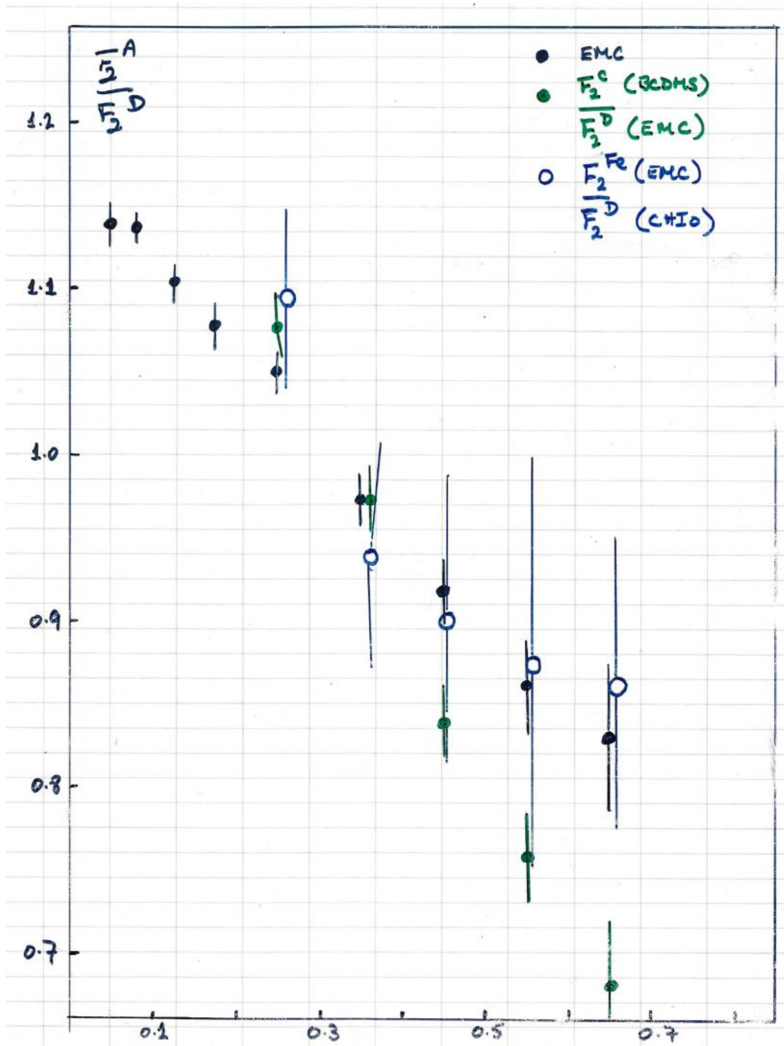



Fig. 1: Image of the EMC data as it appeared in the November 1982 issue of the CERN Courier. This image nearly derailed the highly cited refereed publication (Aubert et al., 1983), as the editor argued that the data had already been published.

# Some Mongrel Plots



# Conversation in Leningrad with Frankfurt & Strikman

Notes from Russia.

On my visit to Russia there was significant interest in many aspects of our data from several groups of theoreticians.

The attached notes contain a summary of the points they made to me some of which should be interesting for our future work.

Mark.

23/9/83.

# Conversation in Leningrad with Frankfurt & Strikman

Notes from Russia.

1. Conversation with Frankfurt + Strikman

Leningrad.

a) EMC effect

Their explanation of EMC effect involves antishadowing of the valence part and is inextricably linked to the $x_{Bj} > 1$ behaviour of $F_2(x)$ from nucleon targets. We have seen (see K. Rith Brighton) a preliminary version of their paper. They emphasise that the neutrino measurements of the sea leave their ideas intact.