# Summary of the section: Hadrons in nuclear matter

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## Outline

1. Color transparency at intermediate energies

*Objectives:*

*Study of interplay of perturbative and nonperturbative QCD in hard processes at intermediate energies*

Space-time evolution of small quark wave packages

Tools:

*Nucleon form factor*

◇ Rescattering kinematics in $e + D \to e + p + N$

◇ Transparency in $e + A \to e + p + A'$

*Two body hard processes*

◇ $\gamma^* + p \to \rho + p \Longrightarrow \gamma^* + D \to \rho + D$

◇ Large angle $\gamma + n \to \pi^- + p \Longrightarrow \gamma +^2 H \to \pi^- p + p$

## 2. Quark-gluon structure of short-range correlations in nuclei

*Objective:* "Discovery of the fundamental nature of nuclear matter"

Tools:

◇ Tagged structure functions for DIS scattering off the deuteron: $e + D \to$ *backward proton* $(\Delta - isobar) + X$ to probe the origin of the EMC effect and nonnucleonic degrees of freedom in nuclei and measure $F_{2n}(x,Q^2)/F_{2p}(x,Q^2)$ for $x \sim 1$

◇ Study of correlation of backward nucleon ($\Delta$-isobar) and forward nucleon production to study two and three nucleon short-range correlations in nuclei.

◇ Superfast quarks in nuclei via DIS at $x > 1$, and $Q^2 > 10 GeV^2$.

# Color coherent phenomena:

Color transparency, ....

* Three components:

I ◇ Small color dipoles interact with small cross section

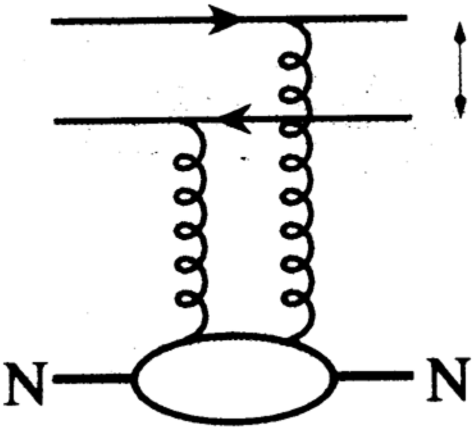
II ◇ Small size (Point-like) configurations (PLC) are produces in hard exclusive processes

III ◇ Produced PLC can survive distances comparable to internucleon distances

**High Energies: Only I & II are necessary; III is always satisfied**

[redacted]

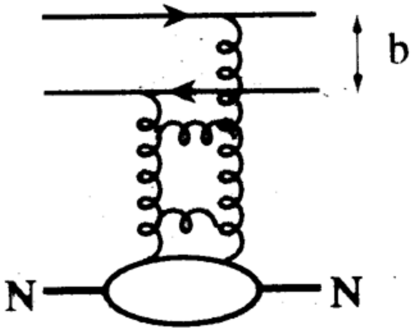
Gauge invariance for a small dipole-hadron interaction →




**Two gluon exchange model**

$\sigma = C\, b^2$ **(F.Low 75)**

**C does not depent on $E_{inc}$**




**pQCD in the leading** log b **approximation** **(Baym, Blattel,FS, 93)**

$$\sigma^{inel}(b,E_{inc}) = \frac{\pi^2}{3}\, b^2\, \alpha_s\, x\, G_N(x, \frac{\lambda}{b^2})$$

Qualitative difference from QED: cross section rapidly increases with W - **a fingerprint of small size dipole interaction in DGLAP** kinematics. ($\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$)

**Recently a [redacted] nucleus, $\gamma$... [redacted]**

**legitimately *calculated in pQCD due to color screening for interaction of small color singlets:***

◇ $\pi$ + T $\rightarrow$ 2 jets +T      Frankfurt, Miller, S. 93

◇ $\gamma_L^* N \rightarrow V(\rho, J/\Psi, \rho'..) + N$

Brodsky, Frankfurt, Gunion, Mueller, S., 94

◇ $\gamma_L^* N \rightarrow Meson(\pi, K, \eta,)\,[Few\ meson\ system] + Baryon$,

Collins, FS 96; M.Polyakov 98 $2\pi$ for finite $x$

◇ $\gamma_L^* p \rightarrow forward\ \ N + \pi, \gamma_L^* p \rightarrow forward\ \ \Lambda + K^+$

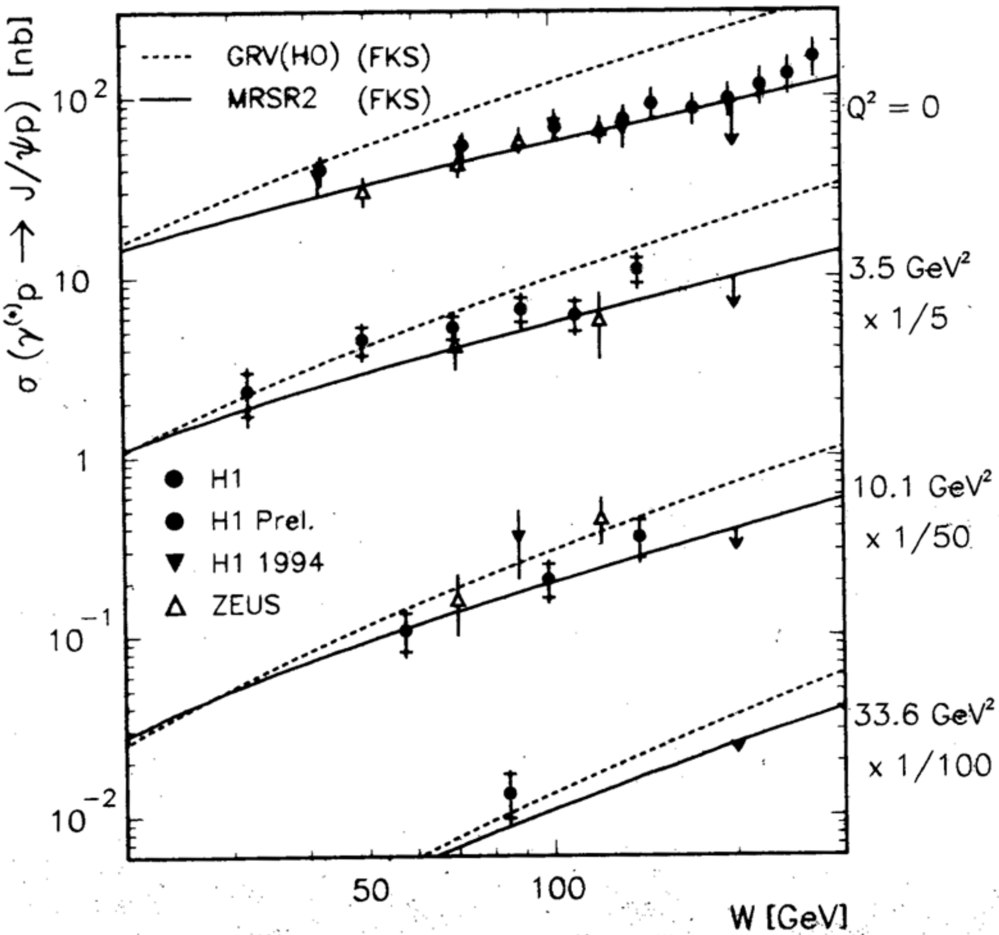
$\gamma_L^* p \rightarrow forward\ \ \bar{p} + NN$,      FS & Polyakov 98

◇ $\gamma^* + N \rightarrow \gamma + N$      Bartels &Loewe 82; Dittes, Muller, Robaschik, Geyer,Horejse 88; Ji 96-97, Radyushkin 96-98, Freund & FS 97, Freund Collins 98

◇ $\gamma^* + \gamma \rightarrow \pi\pi$ M. Diehl, T. Gousset, B. Pire 98

**Extensive data on VM production from HERA support** *dominance of the pQCD dynamics.* **Numerical calculations including finite b effects in $\psi_V(b)$ explain key elements of high $Q^2$ data. The most important ones are:**

(i) Energy dependence of $J/\psi$ production; absolute cross section of $J/\psi, \Upsilon$ production.




(ii) Absolute cross section of $\rho$ production at $Q^2 \sim 20-30\ GeV^2$ and its energy dependence at $Q^2 \sim 20\ GeV^2$. Explanation of the data at lower $Q^2$ is more sensitive to the higher twist effects, and uncertainties of the low $Q^2$ gluon densities.

(iii) **Convergence of the t slopes**

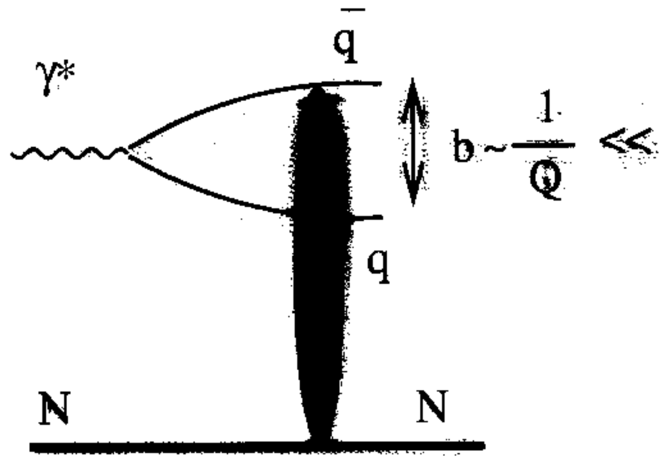
**B** ( σ= Aexp(**B**t)) of

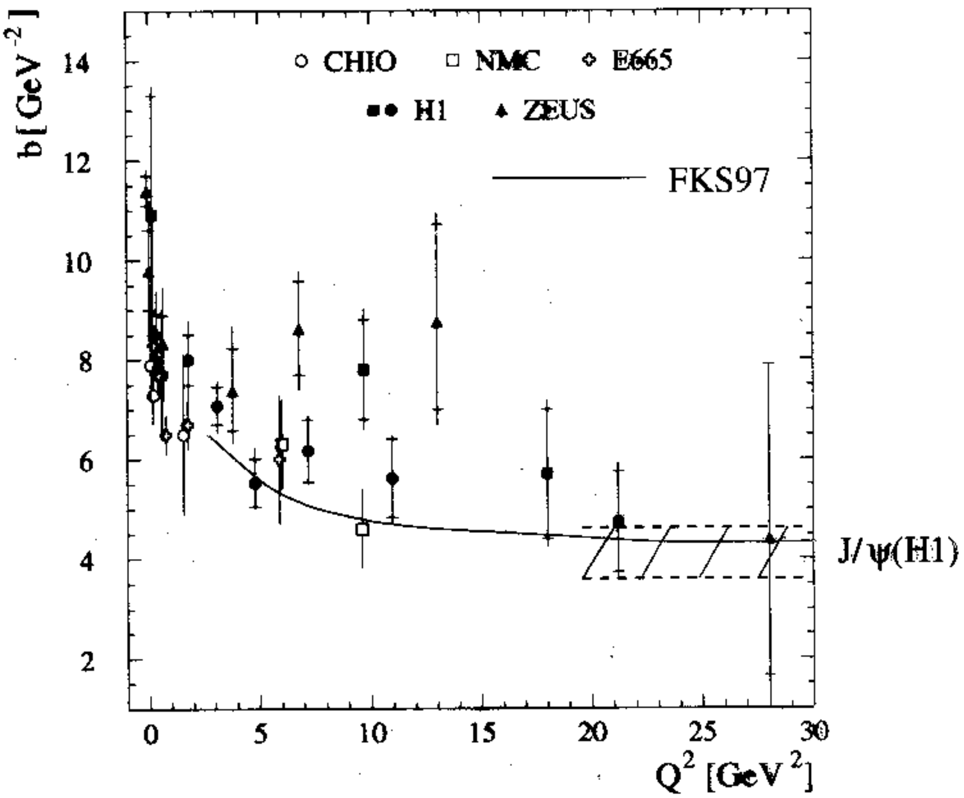
ρ− meson production

at large $Q^2$ and

J/ ψ production

(Brodsky et al 94)




$\Longrightarrow$ Small size $q\bar{q}$ Fock components are present in light mesons.

$\Longrightarrow$ At the transverse separations $b \leq 0.3fm$ pQCD reasonably describes "small $q\bar{q}$ dipole" - nucleon interactions.

Color transparency effects for scattering off nuclei are observed at FNAL

(1) $\gamma + A \to \psi + A$

(2) $\gamma^* A \to \rho + A'$      $3\sigma$ effect at $Q^2 \sim 8\,GeV^2$

(3) $\pi + A \to jet(k_t) + jet(-k_t) + A$      ($k_t > 1.5\,GeV$

suggested by Bertsch, Brodsky, Goldhaber, Gunion 81

pQCD analysis    F, Miller, S    93

<u>E 971     A-dependence</u>

| | | |
|---|---|---|
| Data | $A^{1.61 \pm 0.08}$ | |
| BB66 | $A^{1/3}$ | a factor $\sim 7$ difference. |
| FMS | $A^{1.52 + \varepsilon}$ | |
| Soft Data | $A^{2/3}$ | |

$z = \frac{E_{jet}}{E_\pi}$    dependence: $\psi_\pi^2(z) \propto (z \cdot (1-z))^2$ [BB66, FMS

consistent with data

⇒ Firm base for using CT to study QCD at intermediate energies

New features:

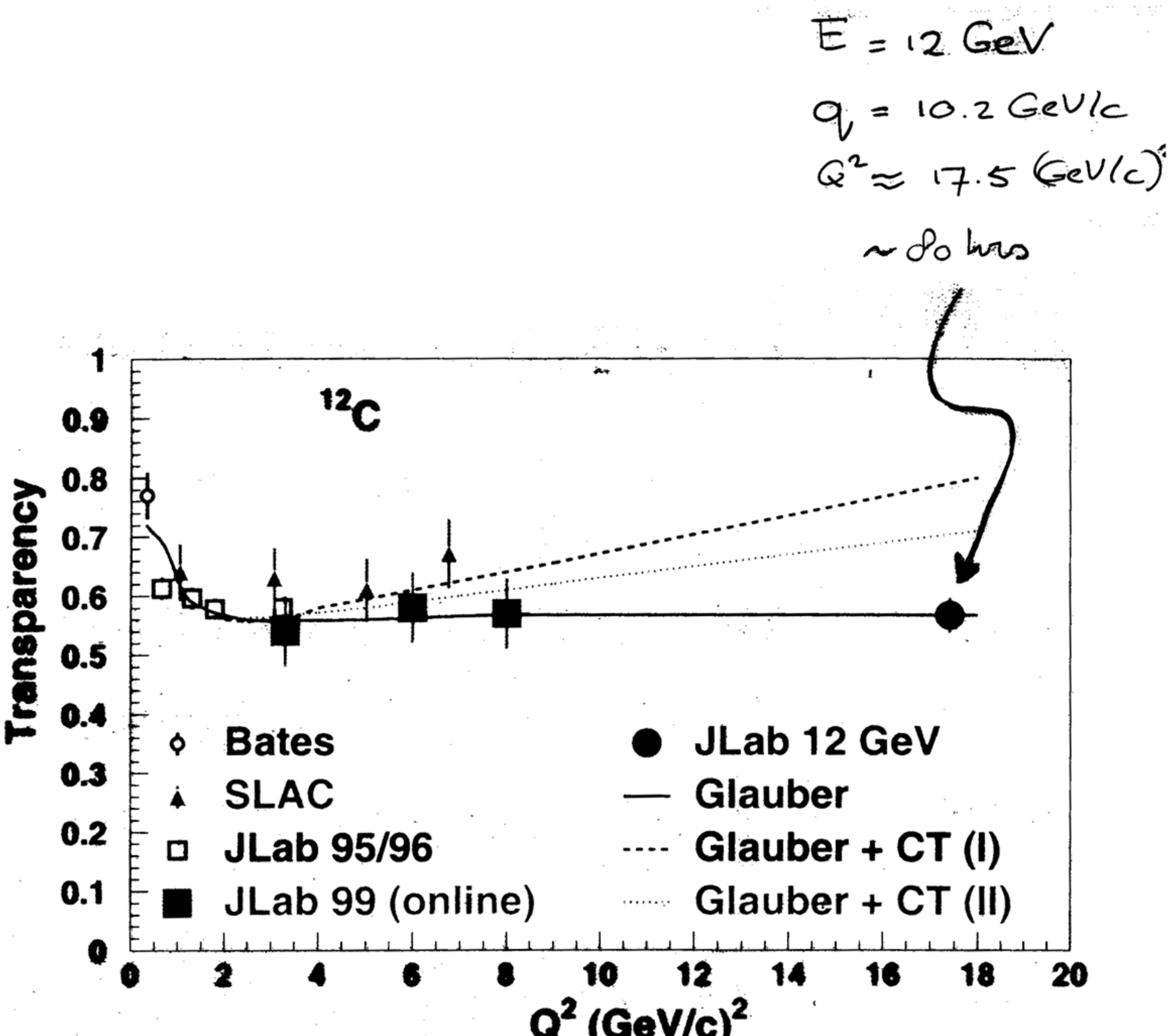
* Study of CT for "3q" no analogy naively with QED ($e^+e^-$)

** Possibility to study space-time evolution of small wave packet

At what $q\bar{q}$ ($qqq$) separations chiral symmetry breaking becomes important? Since $\sigma_{pQCD}(b)$ smaller at low energies ($\propto xG(x,b)$ at larger $b$)

– sharper transition

⟹ Need to scan interaction of ejectile as a function of distance from production point



E = 12 GeV
q = 10.2 GeV/c
$Q^2$ ≈ 17.5 (GeV/c)$^2$
~ 80 hrs
$^{12}$C
Transparency
$Q^2$ (GeV/c)$^2$
Bates
SLAC
JLab 95/96
JLab 99 (online)
JLab 12 GeV
Glauber
Glauber + CT (I)
Glauber + CT (II)

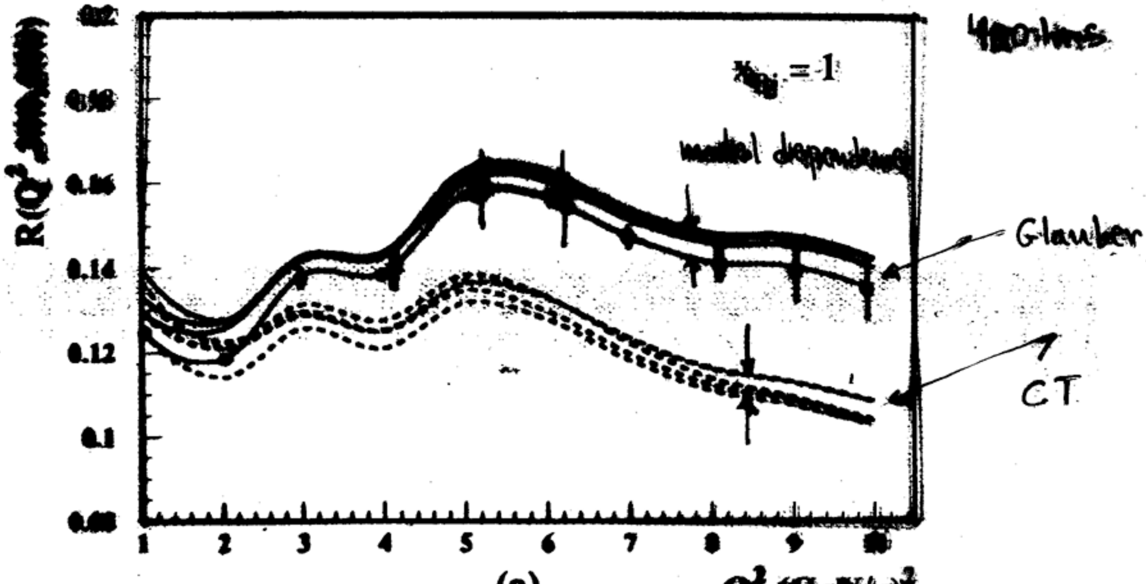
Frankfurt..., Strikman Z. Phys. A352 (1995) 97

$10^{37}$ 1/cm²/s luminosity

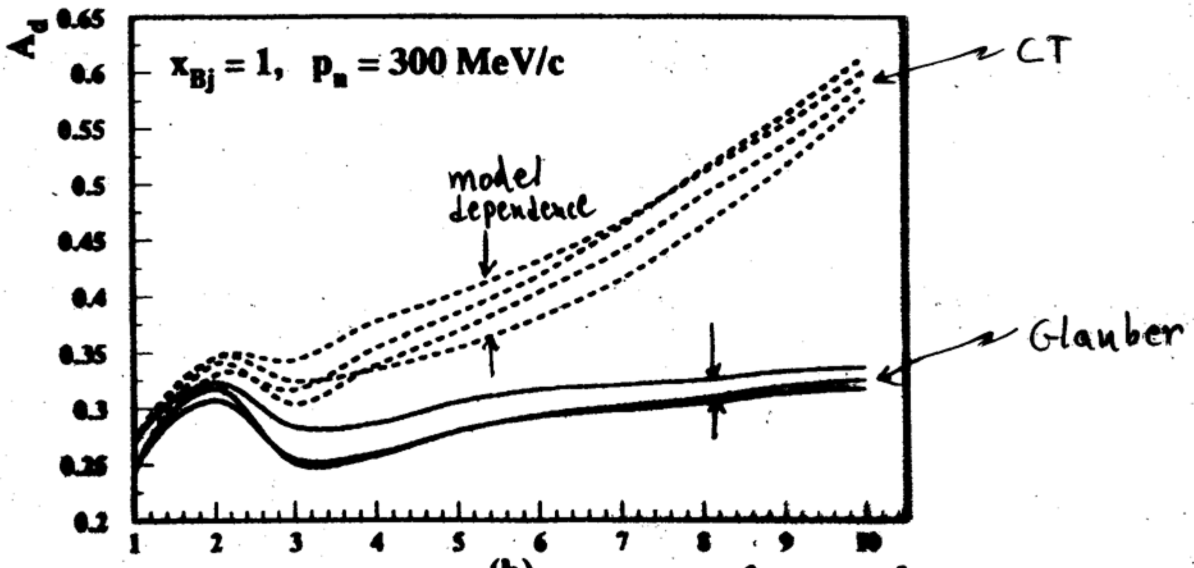
400 hrs

— 6 GeV

— 12 GeV




(a)




(b)

$$A_d = \frac{T_{20}}{\left(\frac{d\sigma^{unp}}{dE_{e'}\, d\Omega_{e'}\, d^3p_p}\right)}$$ if one has tensor polarization

$$R = \frac{\sigma(p_r \approx 300 \text{ MeV/c})}{\sigma(p_r \approx 200 \text{ MeV/c})}$$

# Two complementary methods

Survival – increases with $Q^2$ (Brodsky & Mueller 88)

$A(e,e'p)$ (distances $\ell \gtrsim 2$ fm)

Note: $Q^2 \geq 2$ GeV$^2$ necessary to avoid $Q^2$-dependence of quenching

Reinteraction – decreases with $Q^2$ (Egiyan, Miller, Sargsian, FS 95)

$eD \to epn$ (distances $\ell \sim 1$ fm)

R. Ent : $(e,e'p)$ with SHMS $Q^2 = 17.5$ GeV$^2$ feasible □

K. Griffioen $eD \to epn$ $Q^2 \simeq 10$ GeV$^2$ easy with CLAS □

Note: BNL E850 confirm transparency

$\geq 2 \cdot$ Glauber for $p_N \gtrsim 6$ GeV/c, hence for these momenta expansion does not mask effect $\Rightarrow$ if no CT in $e,e'p$ nucleon form factor for $Q^2 \sim 10$ GeV$^2$ due to average size.

# Vector meson production

$\gamma^*_L + p \rightarrow V + p$

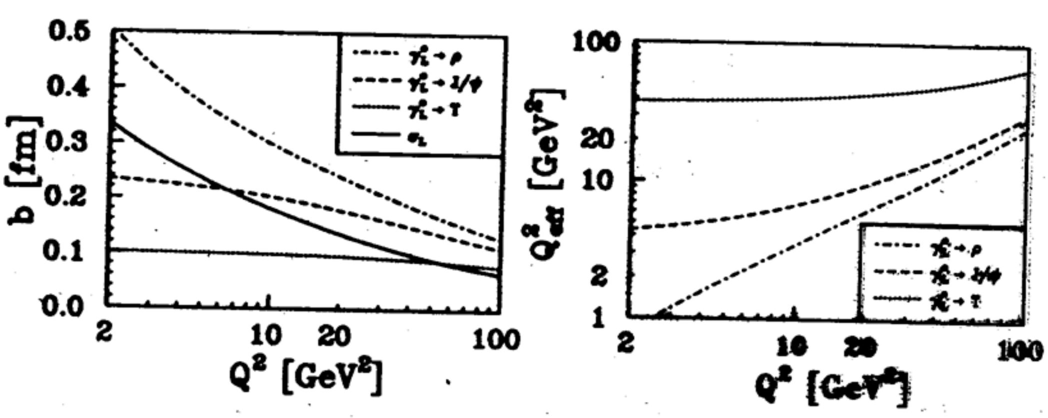



Figure 5. The dependence of average $b$ and effective $Q^2$ of $Q^2$ for production of vector mesons [Koepf, FS 96]

Transverse size maybe $\ll 2r_\rho$

even for $Q^2 = 2\,GeV^2$ due to structure

of wave function of $\gamma^*_L$.

How to check?

FRANKFURT, PILLER
SARGSIAN, STRIKMAN
EUR. PHYS. J. 1998

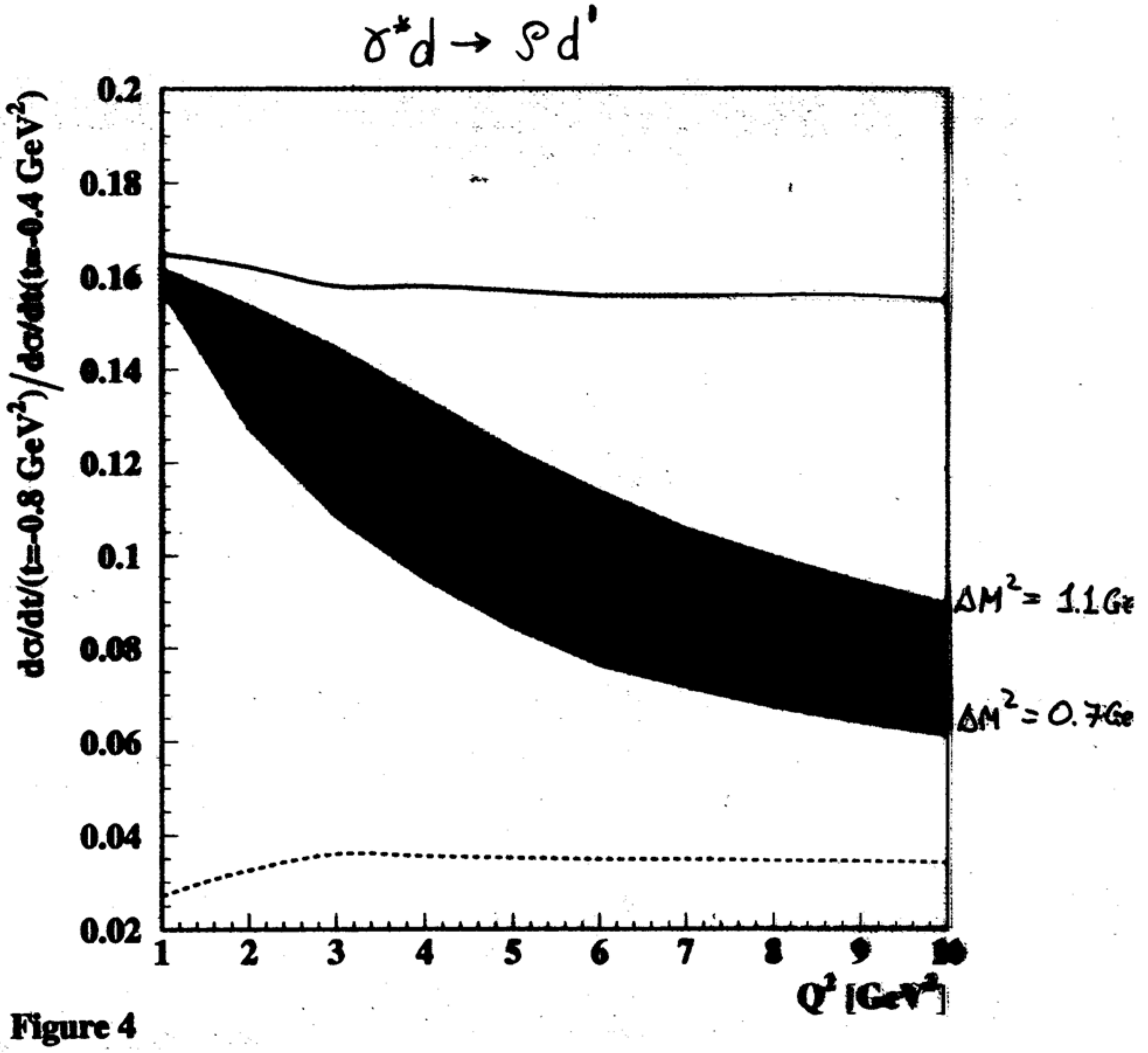
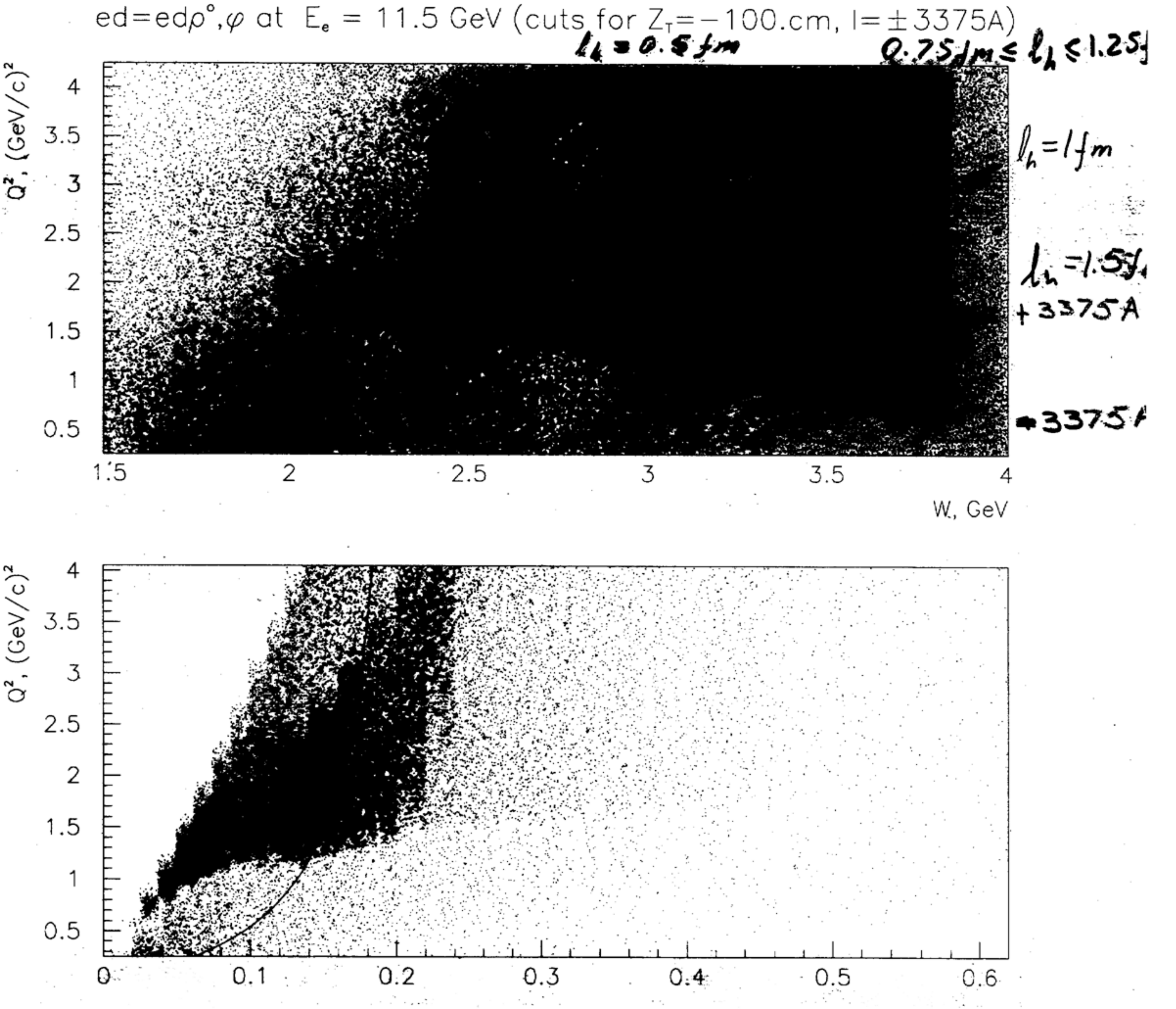



Figure 4



ed=edρ°,φ at E_e = 11.5 GeV (cuts for Z_T=−100.cm, I=±3375A)
l_h = 0.5 fm
0.75 fm ≤ l_h ≤ 1.25
l_h = 1 fm
l_h = 1.5
+3375A
−3375
Q², (GeV/c)²
W, GeV

**Problem**: Coherence length at Jlab is rather small – need to use the lightest nuclei

The simplest option - study double scattering for $\gamma^* + d \to \rho + d$

Look for disappearence of double scattering for $|t| \geq 0.4 GeV^2$

Sargsian talk: significant effect for $Q^2 \geq 3 GeV^2$

Stepanyan's talk - CLAS has good acceptance, counting rates are reasonable for $Q^2 \leq 3 GeV^2$

***Further studies are planned***

In $\gamma + n \to \pi^- + p$ at large t, the $s$ dependence consistent with quark counting rules. H.Gao suggested to study $\gamma + A \to \pi^- + p + (A-1)$, $\gamma + d \to pi^- p +\ recoil\ p$ to check CT in these processes - This interesting option needs further studies of the missing mass resolution.

# Short-range correlations in nuclei.

Expectation: Large probability

$\sim 20-25\%$ for $k > k_F$ & $A = 200$

$\sim 50\%$ kinetic energy

Dominant contribution: two-nucleon correlations.

— drops of cold superdense nuclear matter

Quark-gluon structure? Maybe rather complicated: hints from EMC effect & $\frac{\bar{q}_A}{\bar{q}_N} < 1$

Nuclear forces: phenomenological potentials work but microscopic dynamics not clear

Meson models of nuclear forces gross problem for $r_{NN} \lesssim 1.2$ fm.

Are quark & gluon degrees of freedom like quark interchange necessary?

Current best evidence

(e,e') at $x>1$, $Q^2 \geq 2\,GeV^2$ (D.Day talk)

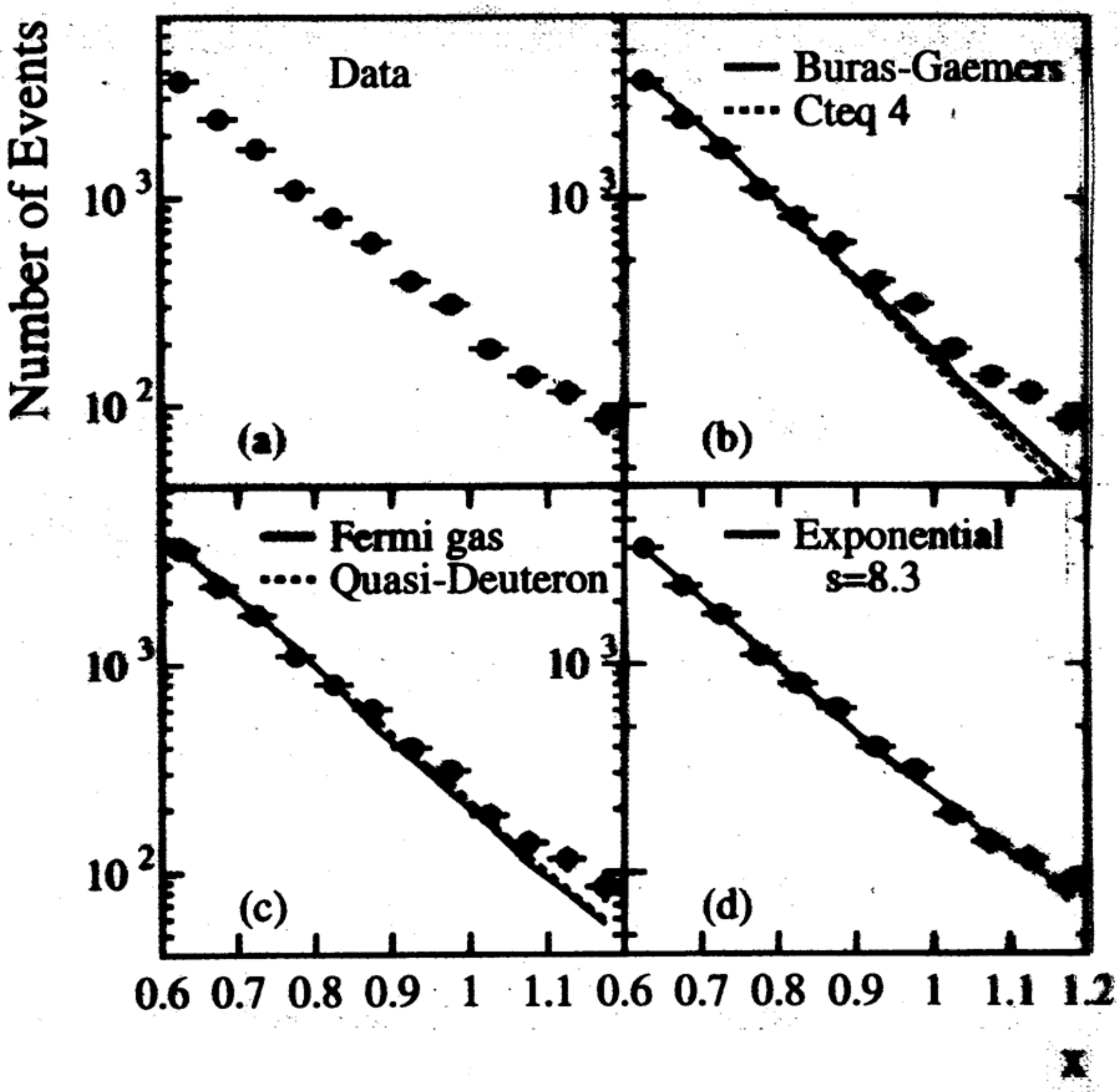
& new CCFR $\nu Fe \to \mu + X$ data

in DIS for $x>1$.

JLab with HMS at 12 GeV can reach

$x \sim 1.5$ and cover $Q^2 = 10-20\,GeV^2$

to prove scaling



Number of Events
Data
(a)
Buras-Gaemers
Cteq 4
(b)
Fermi gas
Quasi-Deuteron
(c)
Exponential
s=8.3
(d)
$10^3$
$10^2$
0.6
0.7
0.8
0.9
1
1.1
1.2
x

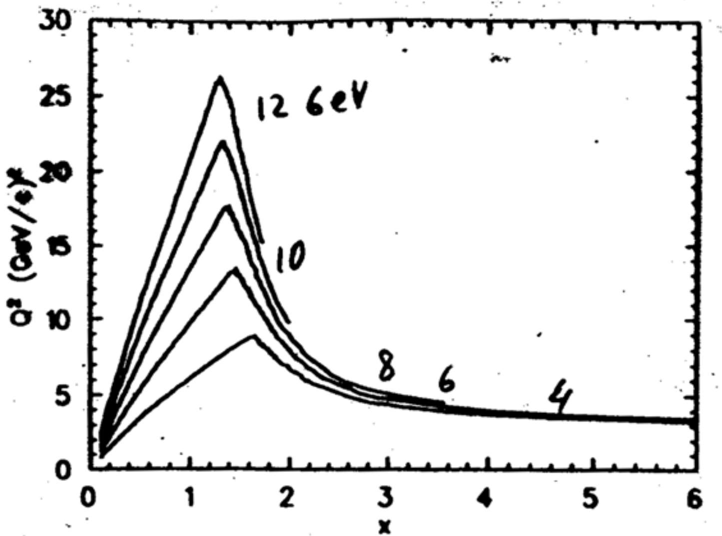



FIG. 2. Kinematic coverage $x$ vs $Q^2$ for inclusive scattering from nuclear targets. Lower curve is with a 4 GeV CEBAF beam and in increasing order 6, 8, 10, and 12 GeV beam energies.

Consistent numbers for the probability of SR 2-nucleon correlations

| | $a_2$ (e,e') | $\nu\mu + N$ | $p+A \to$ backward $p, \pi + X$ |
|---|---|---|---|
| $^3$He | $1.7 \pm 0.3$ | | |
| $^4$He | $3.3 \pm 0.5$ | | $\simeq 4$ |
| $^{12}$C | $5.0 \pm 0.5$ | | $5-6$ |
| Ne | | $6 \pm 2$ | |
| $^{27}$Al | $5.3 \pm 0.6$ | | |
| $^{56}$Fe | $5.2 \pm 0.9$ | | |
| $^{197}$Au | $4.8 \pm 0.7$ | | |

Inf. nuclear matter $\simeq 5$ (Fantoni, et al)

$a_2 \simeq 5$ corresponds to

$\simeq (25 \pm 5)\%$ nucleons above

Fermi surface.

New developments

BNL E850 observed strong correlation

in $pA \to pp + (A-1)$
$\downarrow$ backward nucleon (neutron)

between removal of fast forward proton and emission of backward neutron

(Note $pn$ correlation $\gg pp$ correlation at $k \sim 500$ MeV/c

From $\int \rho_A^N(\alpha, p_t)\, dp_t \propto \exp(-b\alpha)\big|_{\alpha > 1.}$

$$F_{2A}(x, Q^2) \propto \frac{1}{x^3} \exp(-b\alpha) \approx \exp(-$$

$B \simeq b+1$ (modulus EMC effect correction

$b \simeq 7-7.5 \longrightarrow B \sim 8-8.5$ FS 79

CCFR data $B \simeq 8.2$ → at $x = 1.2-1.$ 12 GeV scaling region

BCDMS $B \sim 16$

# Active Target

- **30 cm of 10 Atm Deuterium Gas**
  - 100 nA ⟶ $L=10^{34}$
- Sweeping Magnetic Field to Bottle Up Mollers
- **Need Good Timing to Reduce Randoms - 10 ns**
- GEM - Gas Electron Multiplier
  - Fast
  - Low Density
  - Developed at CERN
  - Good Resolution

Fundamental question: how different quark distribution in bound and free nucleon.

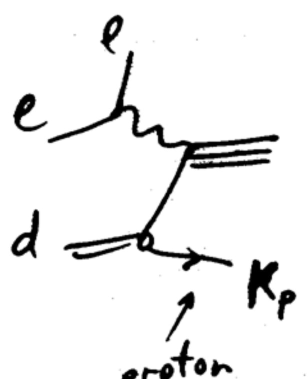
Simplest case: deuteron

Need to know the answer to measure

$F_{2n}(x,Q^2)/F_{2p}(x,Q^2)$ at $x \sim 1$

In $F_{2D}(x,Q^2)$ large corrections due to the EMC effect FS85

⇒ Two directions: ⓐ tagging for small momenta $k_p$




& do Chew & Low extrapolation to the pole

$\tilde{m}^2 - m^2 = (p_d - k_p)^2 - m^2 \simeq -(k^2 + m_D ...$

R. Ent Active target: tagging down to $p_N = 80$ MeV/c !!

① Tagging for $p_N \geq 200$ MeV

" gold plated test of the models of the EMC effect"

FS 85"

Doable with CLAS K. Griffioen talk

$$\sigma \propto \psi_D^2(\alpha) \; F_{2n}^{bound}\left(\frac{x}{2-\alpha}, k\right)$$

$$\frac{F_{2n}^{bound}\left(\frac{x}{2-\alpha}, k\right)}{F_{2n}\left(\frac{x}{2-\alpha}\right)} \neq 1$$

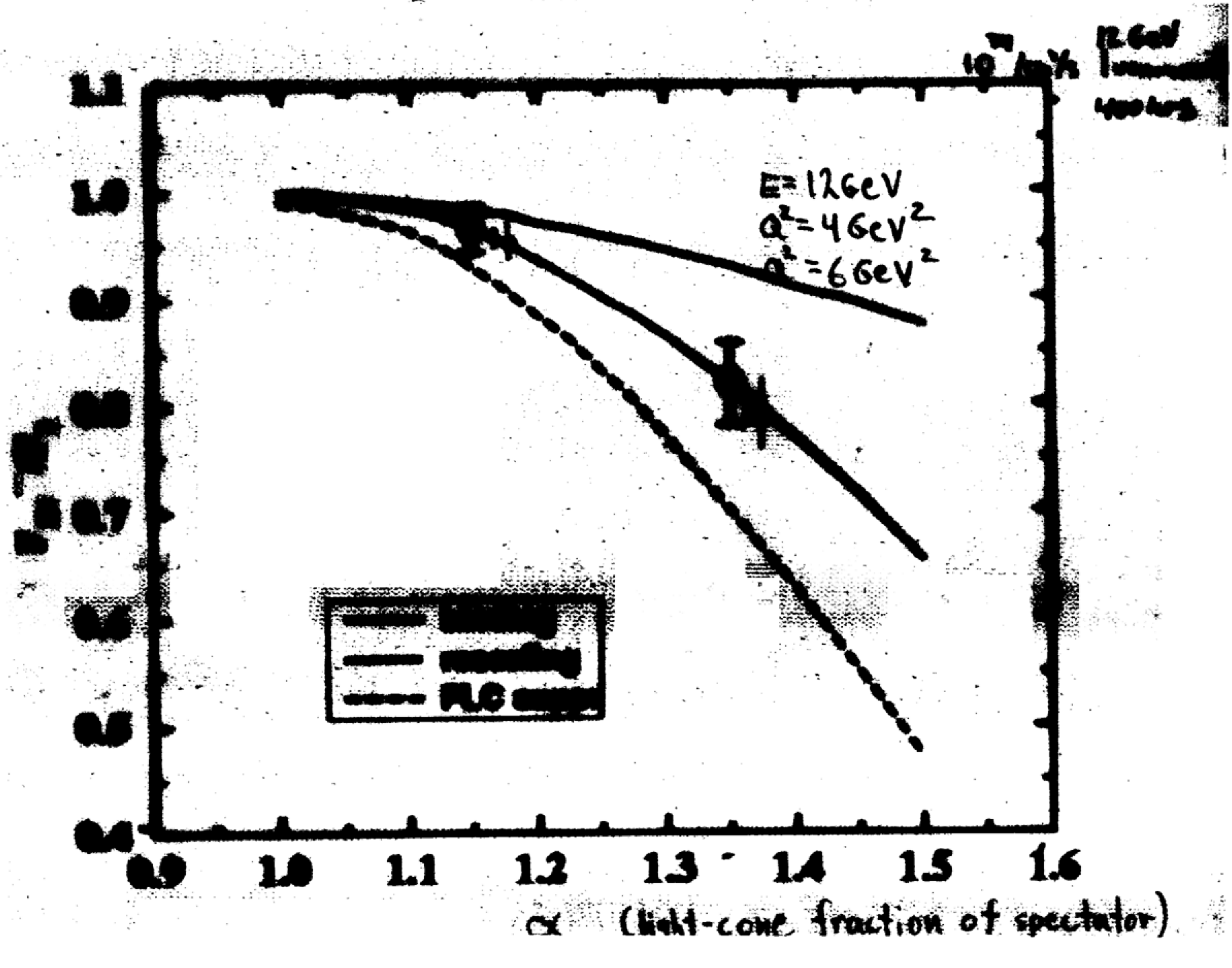
$$\boxed{\alpha = \frac{2}{m_D}\left(E_N - \frac{\vec{p}_N \cdot \vec{q}}{|\vec{q}|}\right.}$$

$\alpha > 1$

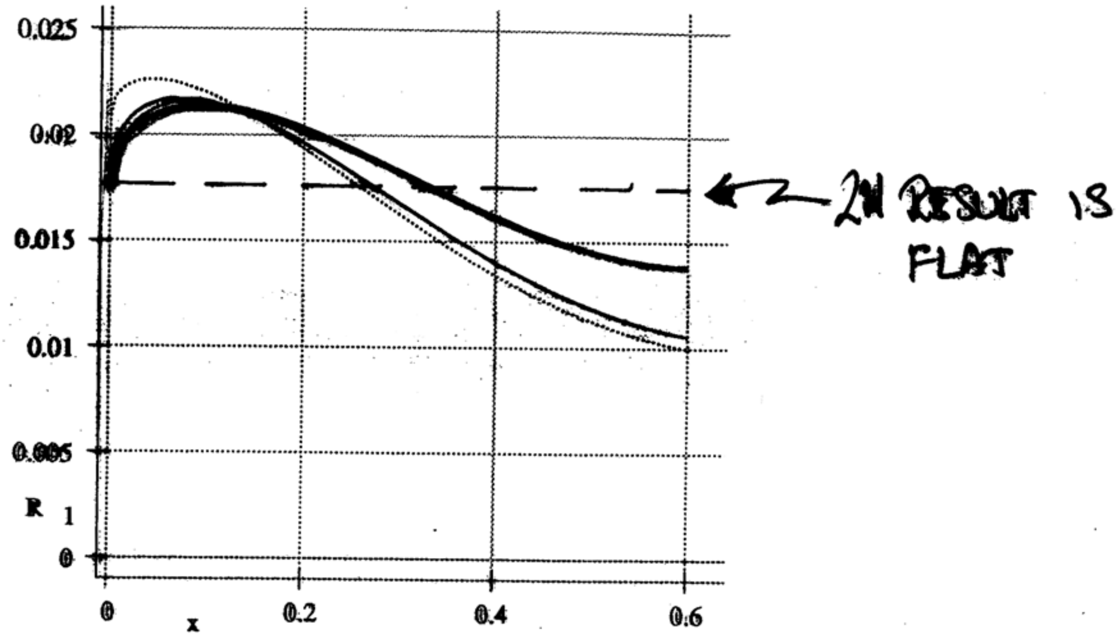
nucleon flies backwa

6GeV $Q^2 = 2\,GeV^2$, $x \sim 0.5$ } expected data for one $Q^2$

$Q^2 = 5\,GeV^2$, $x \sim 0.6$ } Calculations



Large effects in 6q model C. Carlson




# Putative $R_1$

- Simple old quark distributions for $F_{2n}$
- LS for 6q: heavy is their A, normal B, dotted C.
- $\alpha = 1.4$

## Will it work at CEBAF?

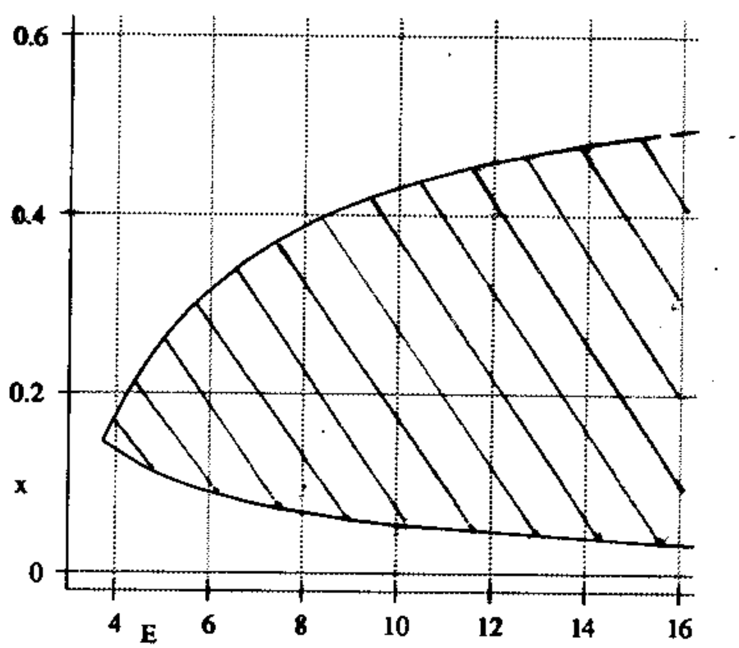
for fixed $E = E_{in}$

Yes — if we are in the scaling region. Means

- ♠ $Q^2 > 1\ \mathrm{GeV}^2$, setting lower limit to $x$ $\left[x = \frac{Q^2}{2m\nu}\right.$
- ♣ $W > 2$ GeV, setting upper limit to $x$ $\left[\frac{1}{x} = 1 + \frac{W^2 - m^2}{Q^2}\right.$

($W$ is $\gamma$–nucleon c.m. energy)

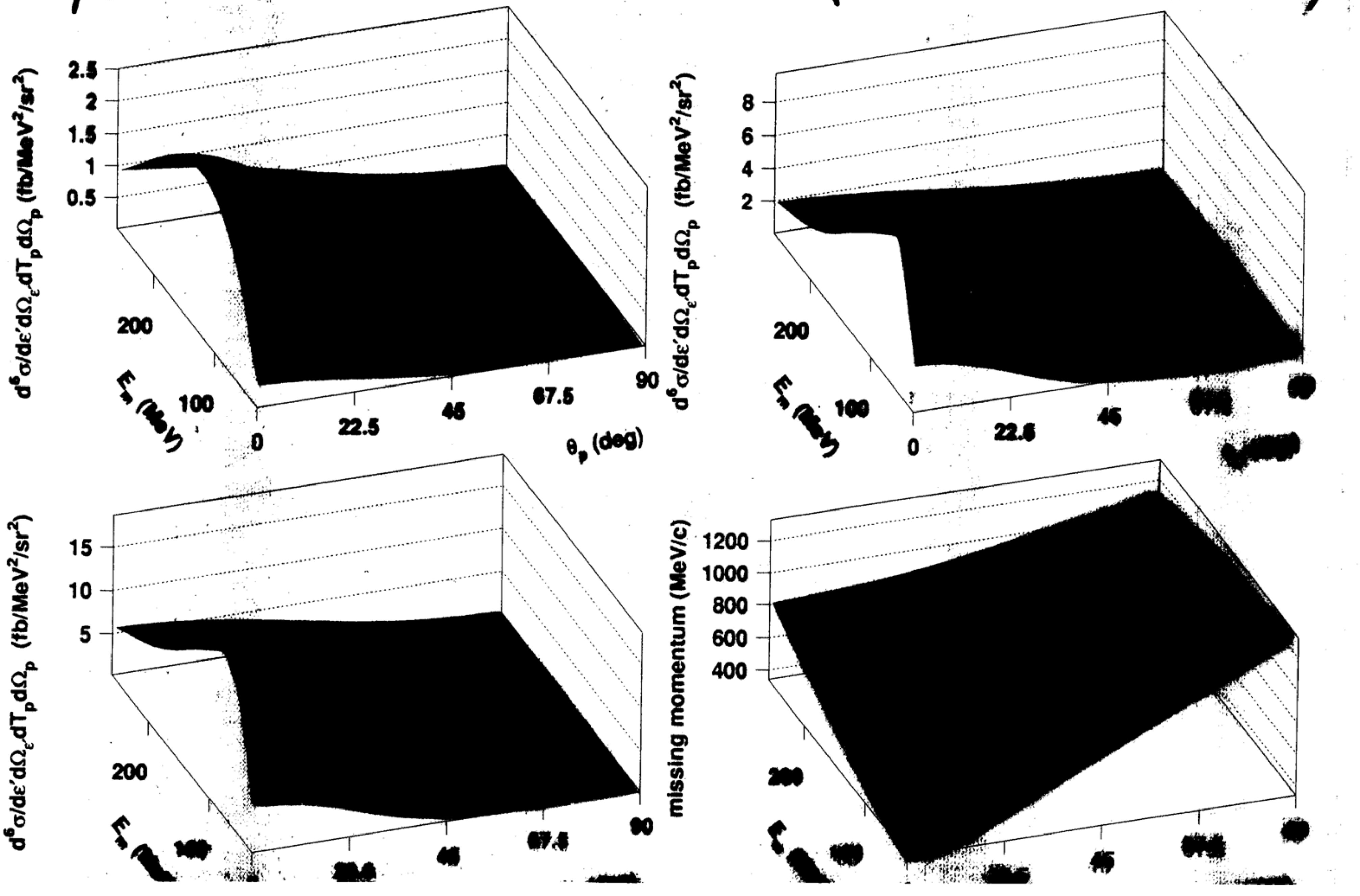
Gives "scaling window" for CEBAF, say for $\alpha = 1.4$,




$E$ = energy of incoming electron beam.

Want a bit more than 4 GeV.

$(e,e'p)$ $x \approx 2$ $Q^2 \approx 1.1\,(\mathrm{GeV})^2$ $(\varepsilon = 2.5\ \mathrm{GeV},\ \theta_e$



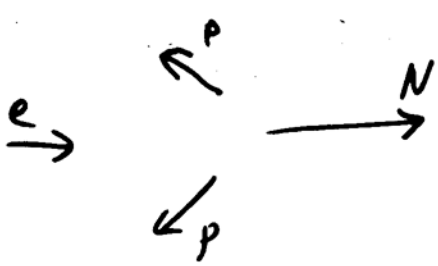
Other important directions:

- looking for backward Δ's
  - feasible in CLAS (L. Weinstein)

⇒ Sensitive to premordial Δ's, and to knedded 6q states.

- Study of pp, pn, nn short-range correlations via correlation of backward and forward production
  was pretty difficult at $E_e \leq 1\,GeV$ (Jan Ryckebuch talk)

- 3N correlations



# Conclusions

* Decisive tests of dominance of pQCD vs soft physics in nucleon form factors at $Q^2 = 10-15\,GeV^2$

** Transition from study of bulk properties of short-range correlations to the study of parton structure of correlations, determining the dynamic origin of the EMC effect.