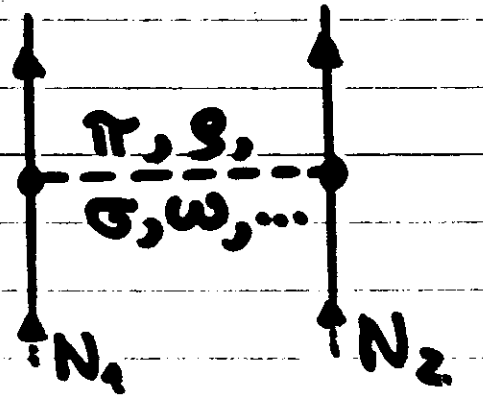
Amand Faessler
Triest; Sept. 1990

The QUARK MODEL, the NUCLEON-NUCLEON INTERACTIO and the DEUTERON FORMFACTOR

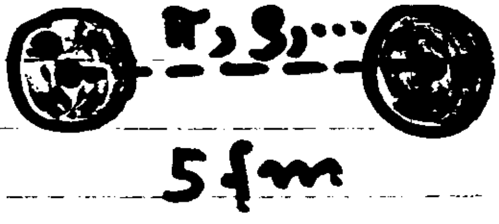
U. Straub, K. Bräuer, [redacted]
[redacted]; [redacted]; Shimizu;
Lübeck; Zang Zong-ye



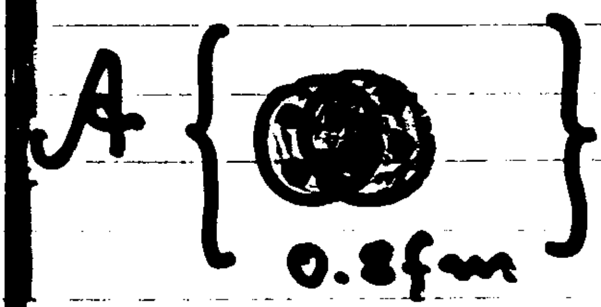
Meson Exchange:

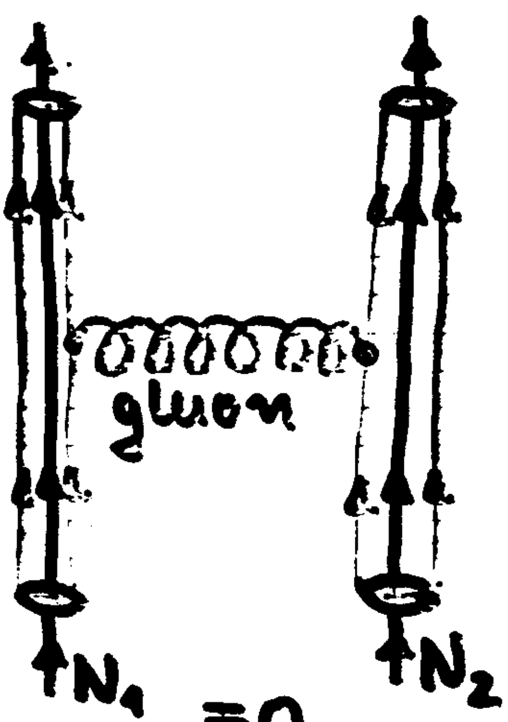
[redacted]

G. Breit ω 1958

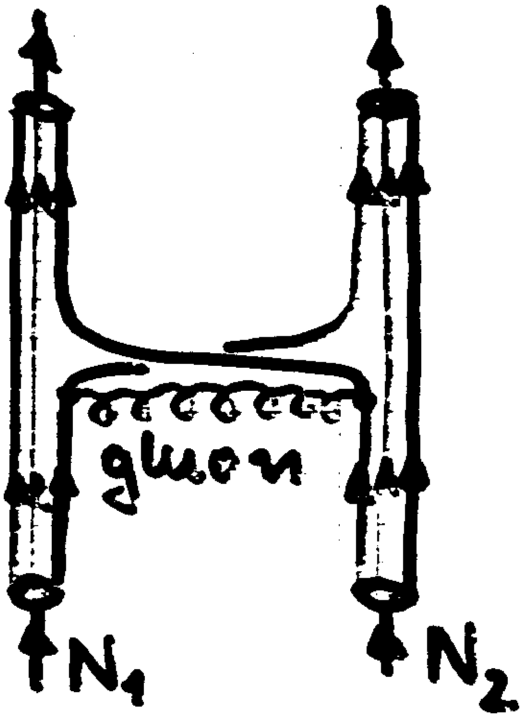


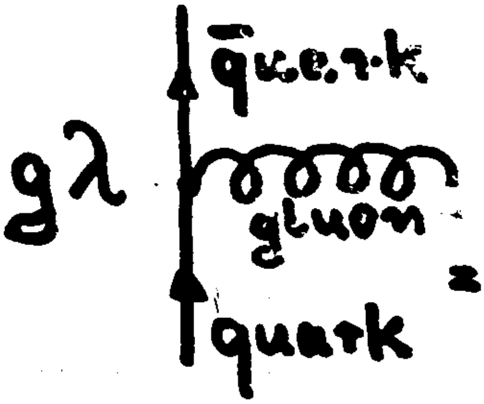
QUARK MODE and NNINTERAC





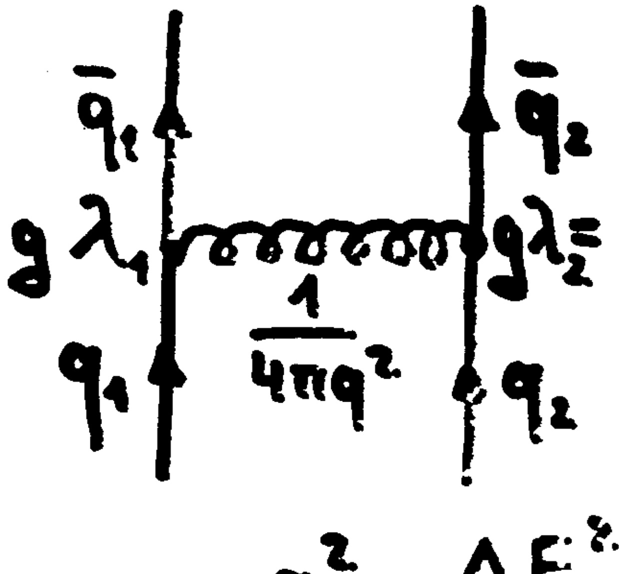
$\equiv 0$





$$= g\, j^{a}_{\mu} \cdot A^{a\,\mu}$$

$$= g\{\bar{q}\, \gamma_\mu\, \tfrac{1}{2}\, \lambda^{a}_{qq}\, q\}\, A^{a\,\mu}_{(x)}$$

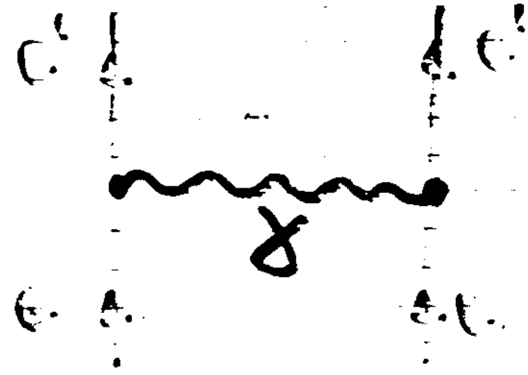


$$= \frac{g^2}{4\pi} \{\bar{q}\, \gamma^\mu\, \tfrac{1}{2}\, \lambda^a_1\, q\}_1\, \frac{1}{q^2}$$

$$\cdot \{\bar{q}\, \gamma_\mu\, \tfrac{1}{2}\, \lambda^a_2\, q\}_2$$

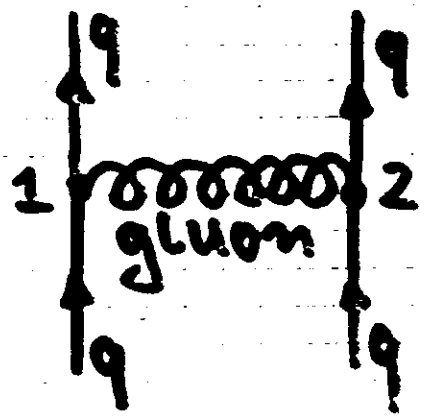
$$q^2 = \Delta E^2 - \vec{q}^{\,2}$$

QED: NON-RELATIVISTIC REDUCTION (Fermi-Breit)



$$\approx \frac{e^2}{4\pi}\left[\frac{1}{r_{12}} + \dots\right]$$

QCD:



$$\approx \frac{g^2}{4\pi}\,\frac{1}{4}\,\tilde{\lambda}_1\cdot\tilde{\lambda}_2\Big[\frac{1}{r_{12}}$$

$$+ \frac{\pi}{m_q^2}\left(1+\frac{2}{3}\vec{\sigma}_1\cdot\vec{\sigma}_2\right)\delta(r_{12}$$

$+$ tensor

$+$ two-body $\vec{L}\cdot(\vec{S}_1+\vec{S}_2)\Big]$

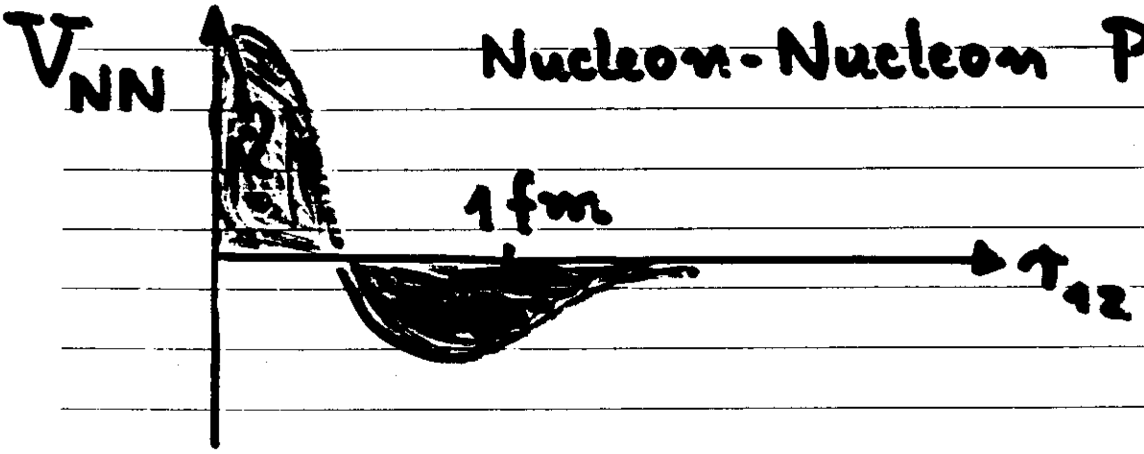
$$\hat{H}_{\text{Quark}} = \sum_{i=1}^{6}\left[m_i + \frac{p_i^2}{2m}\right]$$

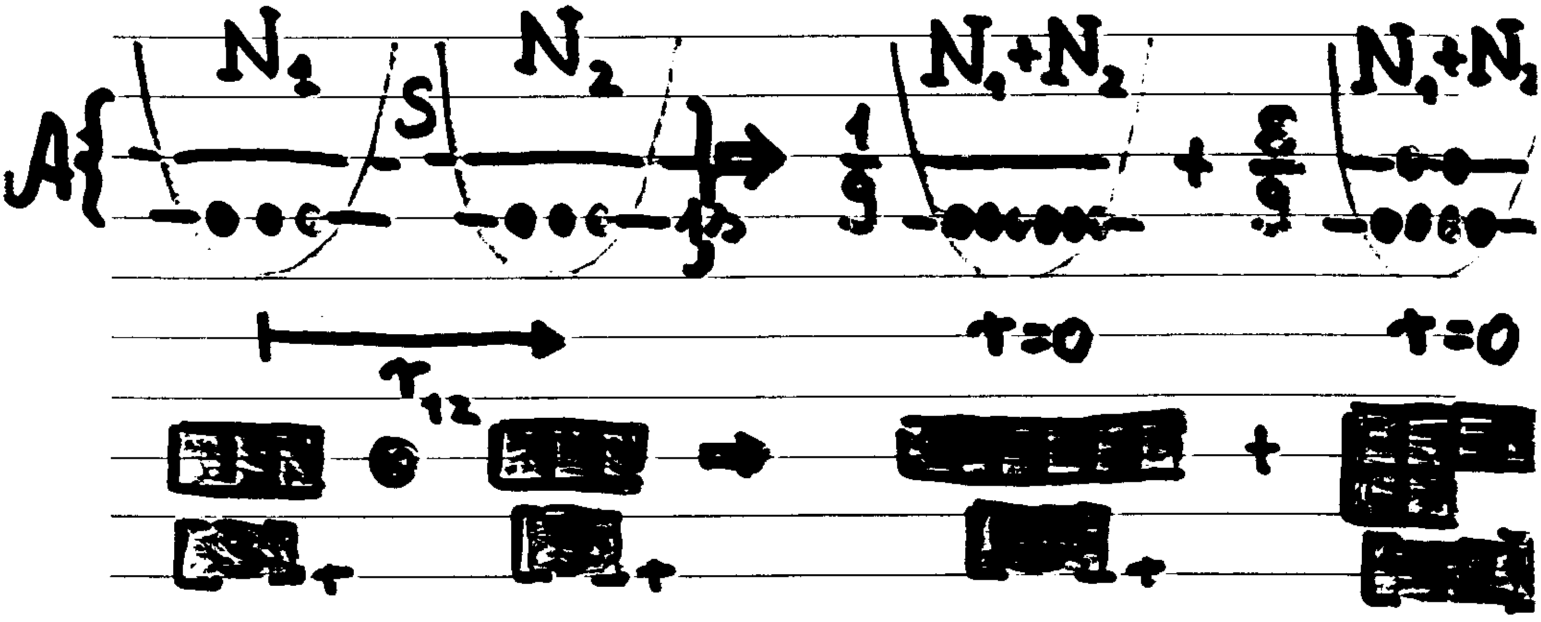
$$+\sum_{i<j=1}^{6}\left[V_{qq}(i,j) - a\,\lambda_i\cdot\lambda_j\, r_{ij}^2\right]$$

N-N-Interaction:

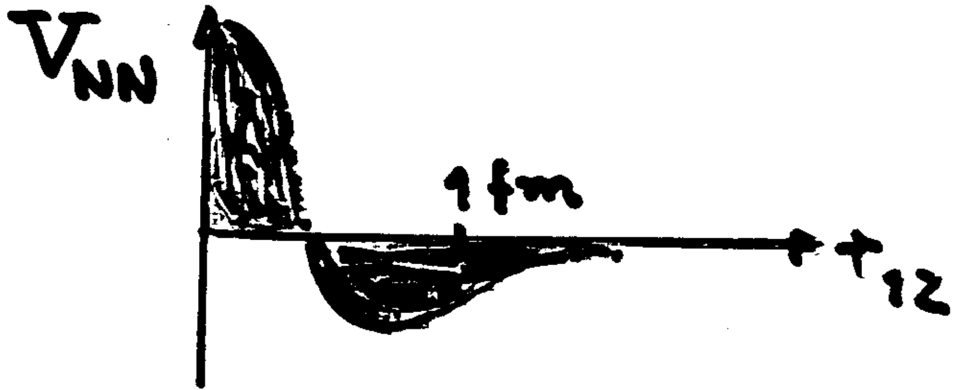
The Nature of the Short Range Repulsion?

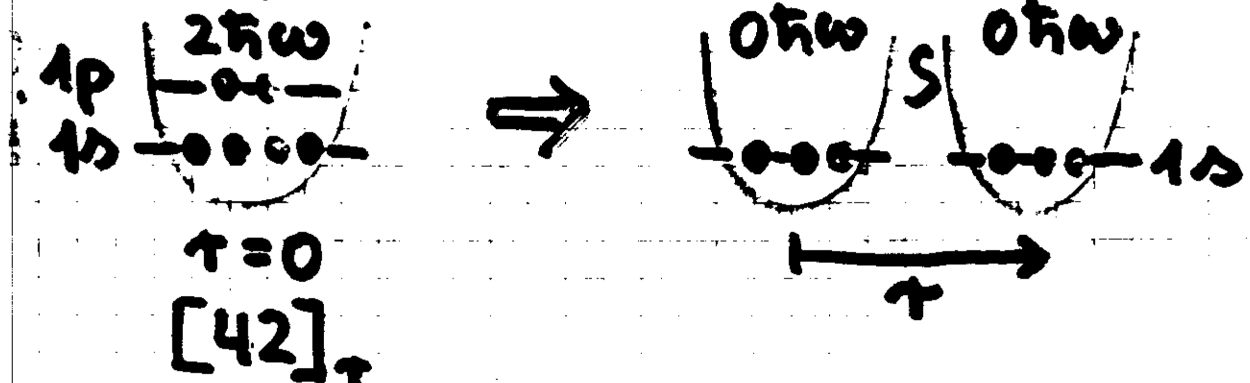
Nucleon-Nucleon Potential

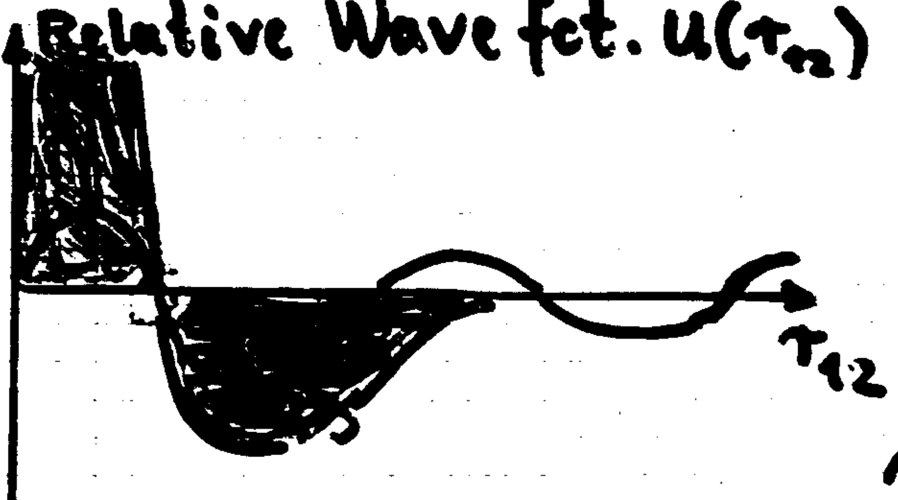


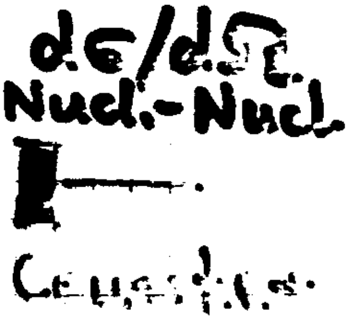


Nature of Short Range Repulsion!









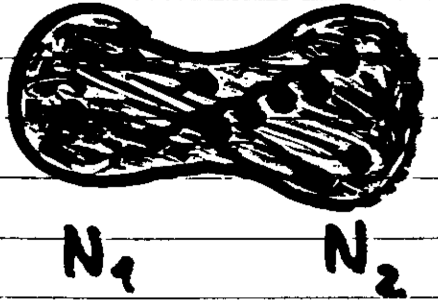
Phase shift

$$u(r_{12}) = \cancel{\alpha_1 |1s\rangle} + \alpha_2 |2s\rangle + \alpha_3 |3s\rangle + \dots$$

forbidden

Short range Part: Nucleon-Nuck

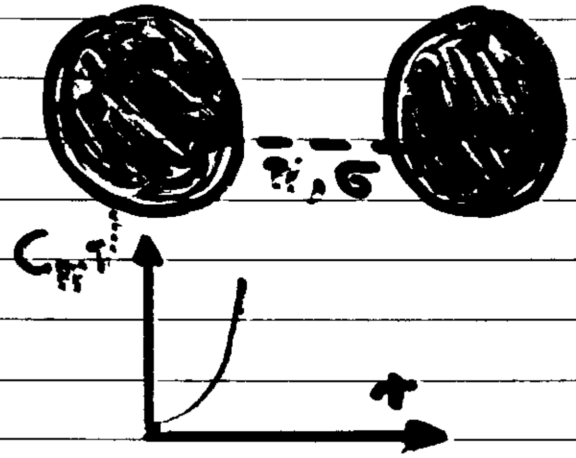
[illegible]

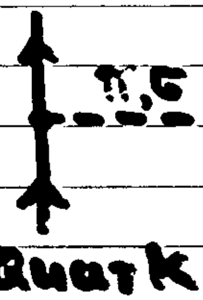


Quark and
Gluon-exchange

- ■ form facto
- ■ o----o
- ■ $\mathcal{A}\{\quad\}$
- ■ finite size

Long range Part:





$= g_{\pi qq}(\;) = C_{\pi}$

$$\frac{g^2_{\pi NN}}{4\pi} = 14.5$$

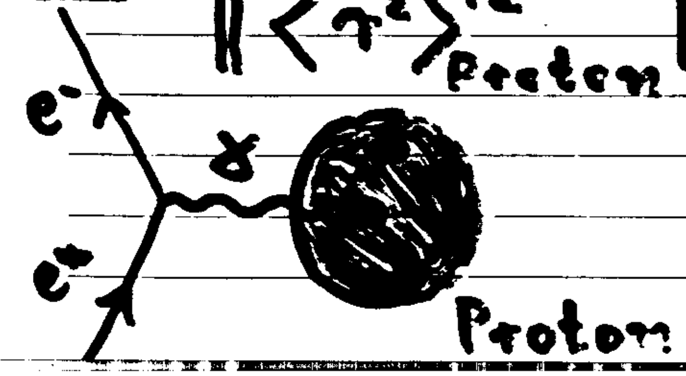
---

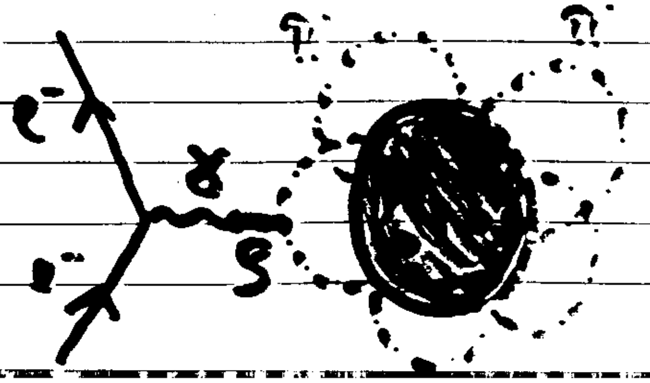
6 Adjusted Parameters by:

m_q
α_s
b, a
$C_{\pi,\sigma}$

$$\boxed{\begin{array}{ll} m_N = 938\,\text{MeV} & m_\Delta = 1232\,\text{MeV} \\ g^2_{\pi NN}/4\pi = 14.5 & g^2_{\sigma NN}/4\pi = 3.4 \end{array}}$$

$$\| \langle r^2 \rangle^{1/2}_{\text{Proton}} \|$$





Resonating Group Method:

$$\Psi_{6q} = \mathcal{A}\Big\{ |NN,\tau\rangle\, \underline{u}_{N}\underline{(\tau)} + |\Delta\Delta,\tau\rangle\, \underline{u}_{\Delta}\underline{(\tau)} + |CC,\tau\rangle\, \underline{u}_{C}\underline{(\tau)} \Big\}$$

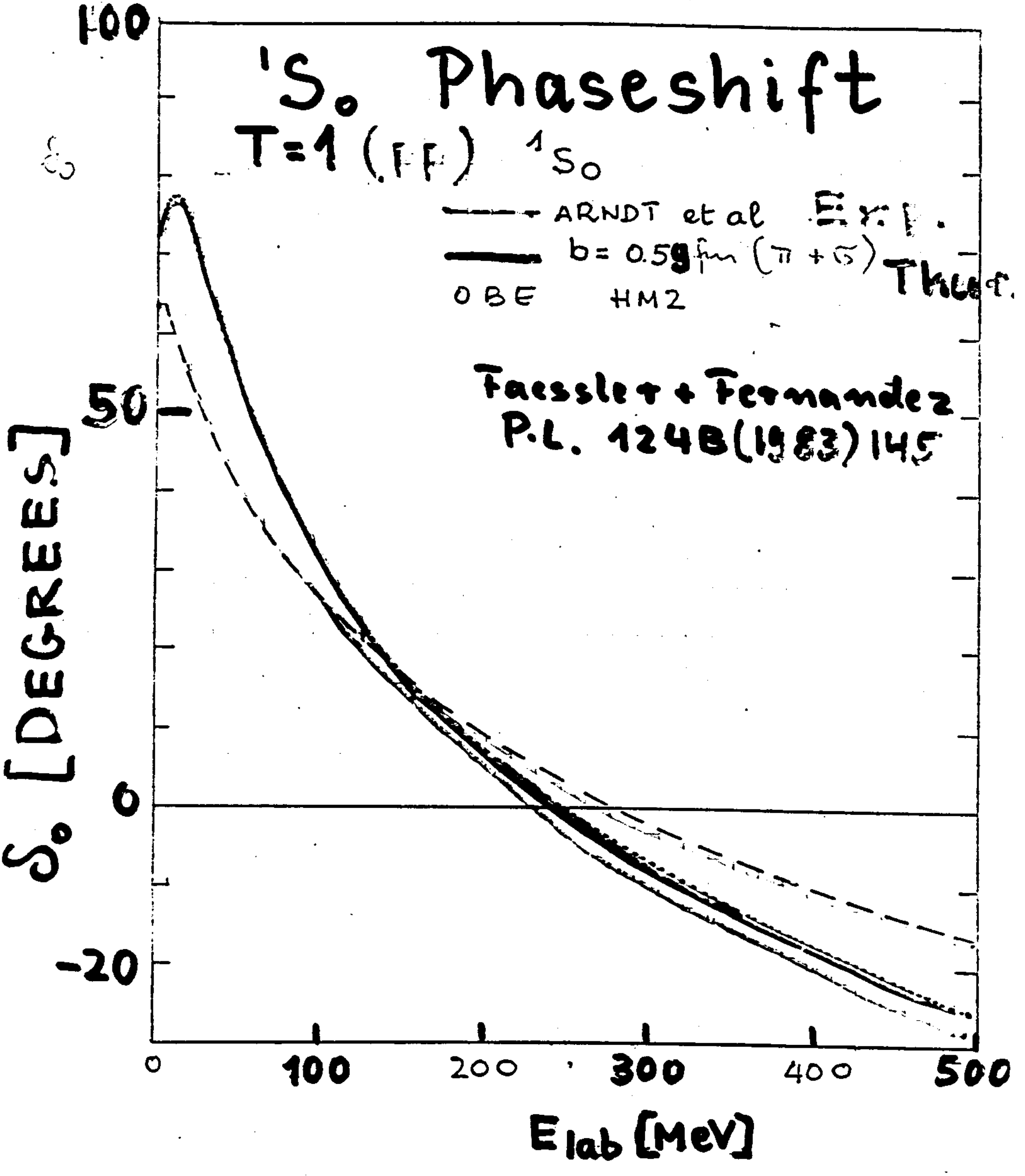
^1S T=1
^3S T=0

$$\langle \delta\Psi_{6q} | \hat{H}_6 + \hat{V} + \hat{V}_6 - E | \Psi_{6q} \rangle =$$

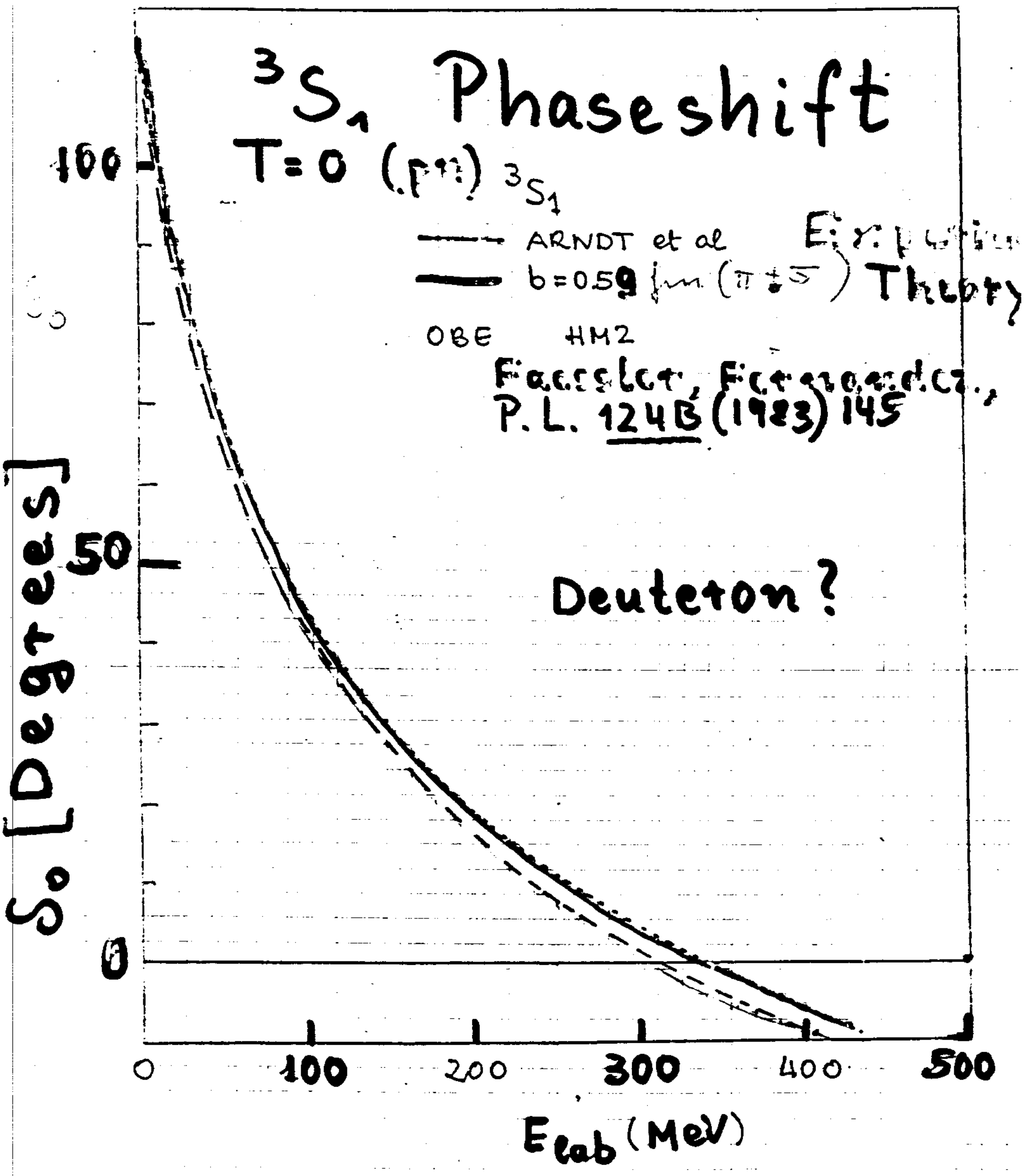
$\rightsquigarrow$ System of integral equations for:

$\underline{u}_{N}\underline{(\tau)}$, $\underline{u}_{\Delta}\underline{(\tau)}$, $\underline{u}_{C}\underline{(\tau)}$

$\lim\limits_{\tau\to\infty} \underline{u}_{N}\underline{(\tau)}$ $\rightsquigarrow$ Phase shift



Faessler + Fernandez
P.L. 124B(1983)145


³S₁ Phaseshift
T=0 (pn) ³S₁
ARNDT et al Experiment
b=0.59 fm (π+σ) Theory
OBE HM2
Faessler, Fernandez et al.,
P.L. 124B (1983) 145
Deuteron?
δ₀ [Degrees]
100
50
0
0
100
200
300
400
500
E_lab (MeV)

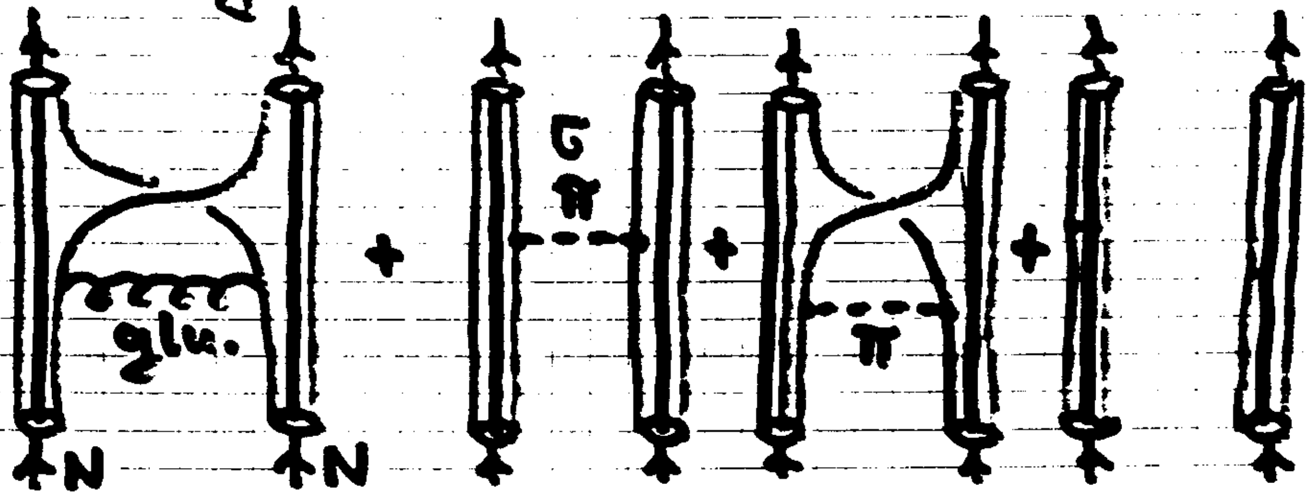
NN scattering:

$g_\sigma^2/4\pi \approx 3.4$

B(Deuteron) = 3.3 MeV

Adjusted: B (Deuteron) = 2.2 MeV

$g_\sigma^2/4\pi \approx 2.68$ (instead 3.4)



Resonating Group Method

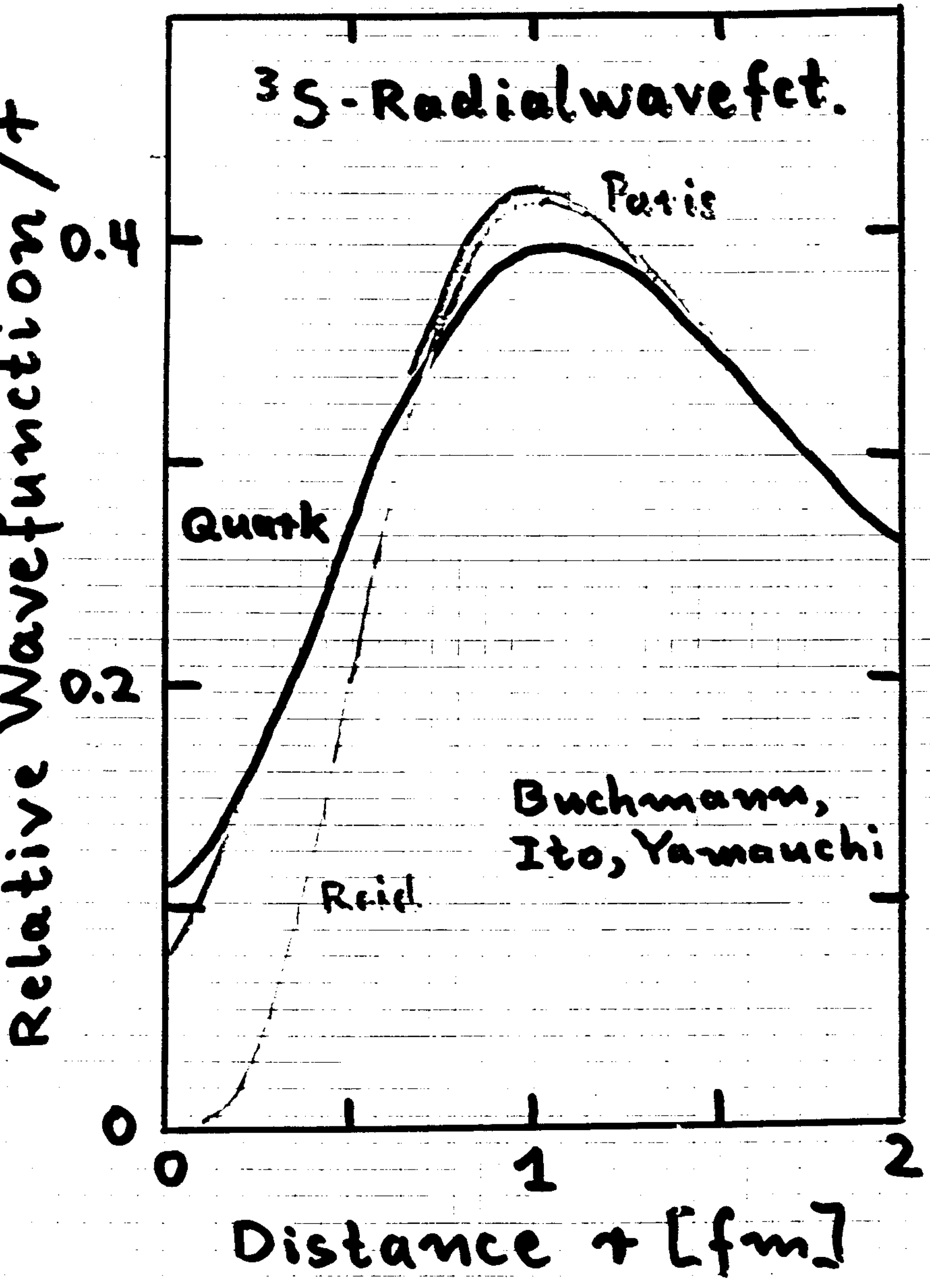
	$P_D[\%]$	$\mu_D[\mu_N]$	Q_D[f
Quark M.	5.23	0.850	0.26
Exp.	—	0.857	0.28

Buchmann, Ito, Yamauchi, Fae

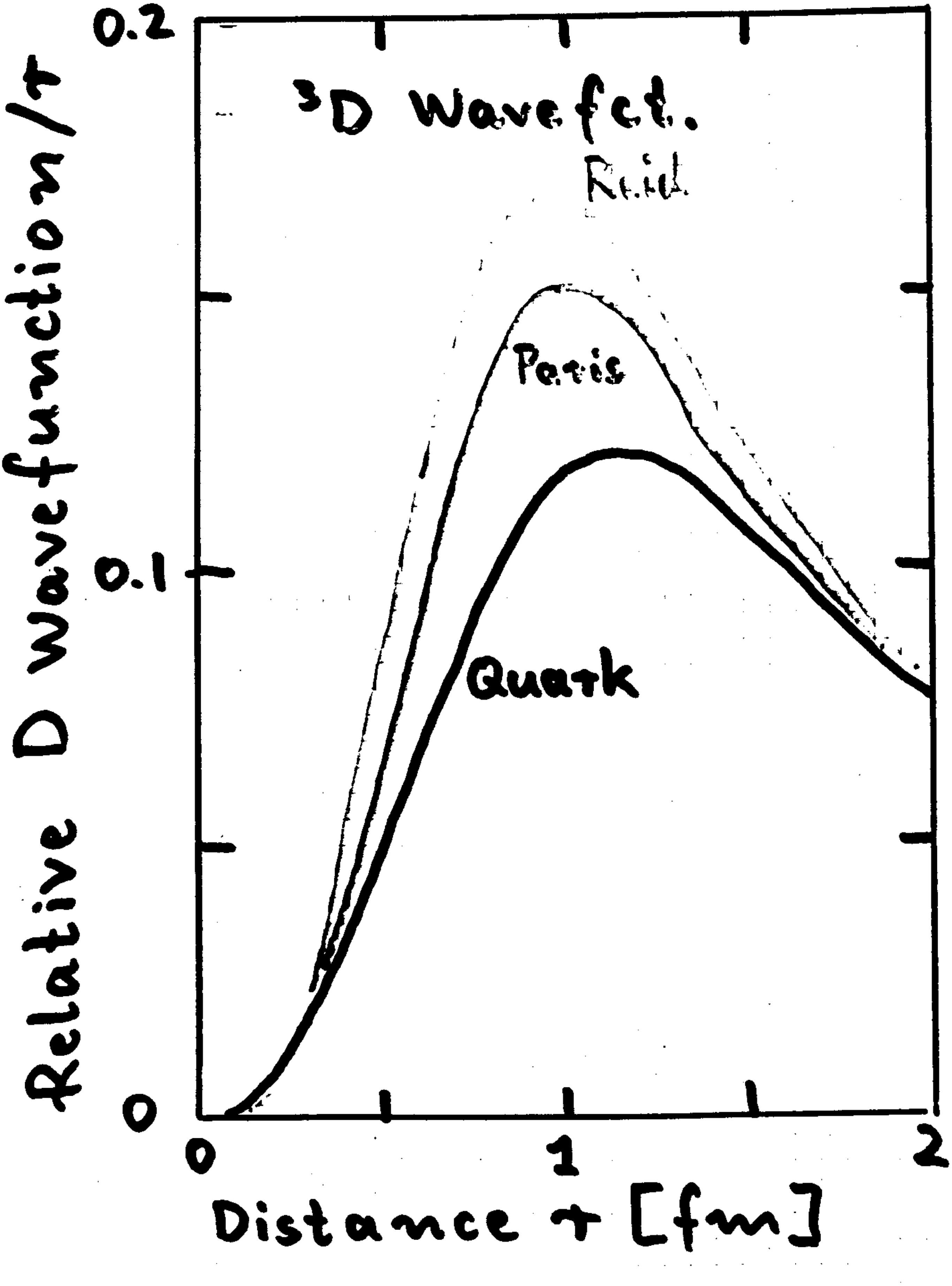
Nucl. Phys. A496 (1989) 621

J. Phys. G. 14 (1988) 1072

Deuteron


^3S-Radialwavefct.
Paris
Quark
Reid
Buchmann, Ito, Yamauchi
Relative Wavefunction / r
0.4
0.2
0
0
1
2
Distance r [fm]

Deuteron

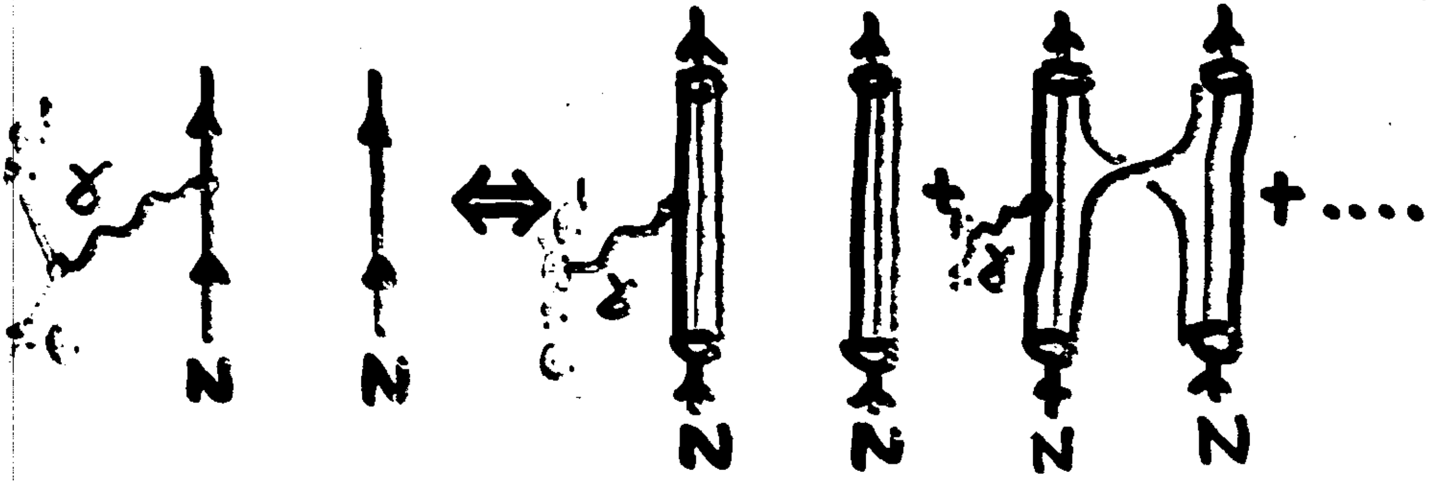


Relative D wavefunction/r
0.2
0.1
0
0
1
2
Distance r [fm]
³D Wavefct.
Reid
Paris
Quark

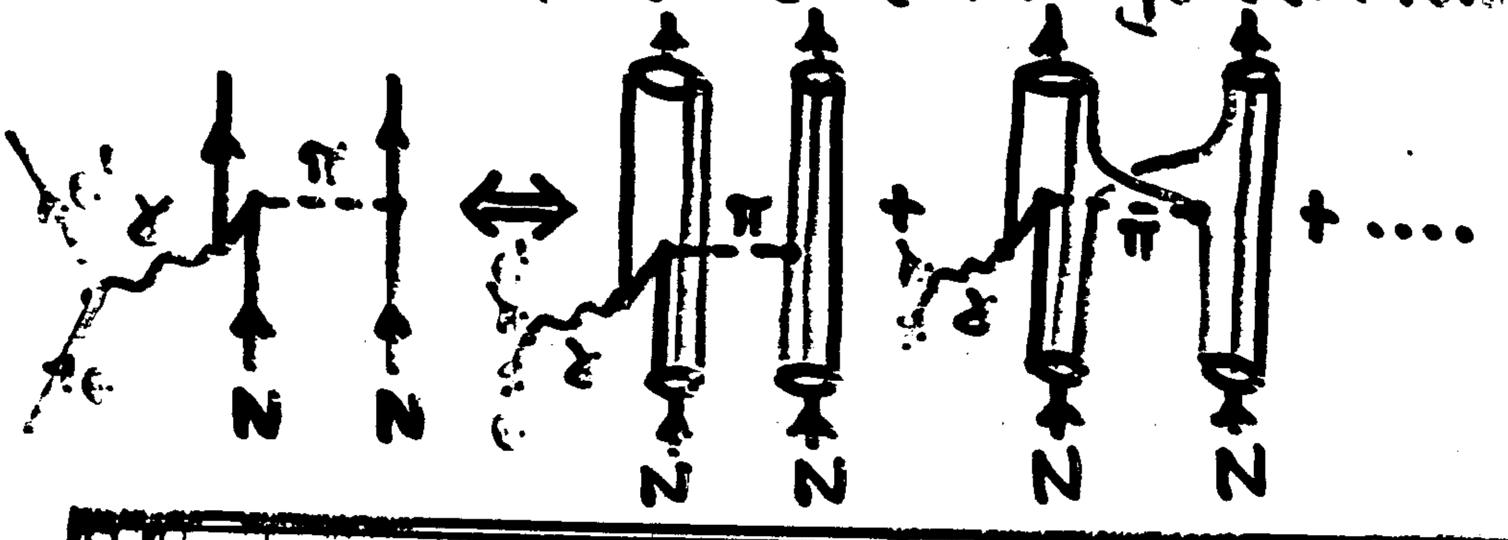
Form Factors:

Electron-Deuteron Scattering

- Impulse Approximation



- Plus Meson Exchange Current

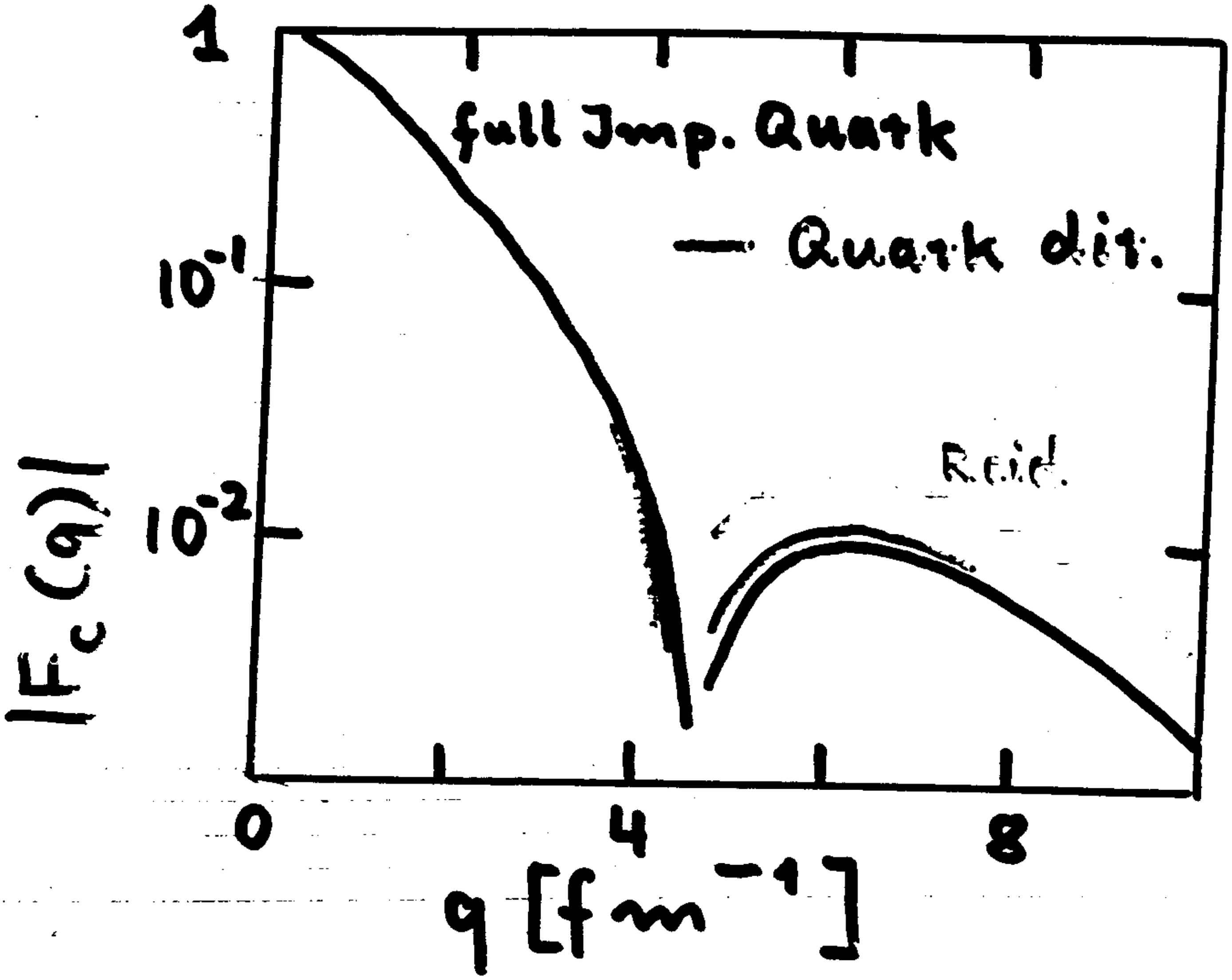


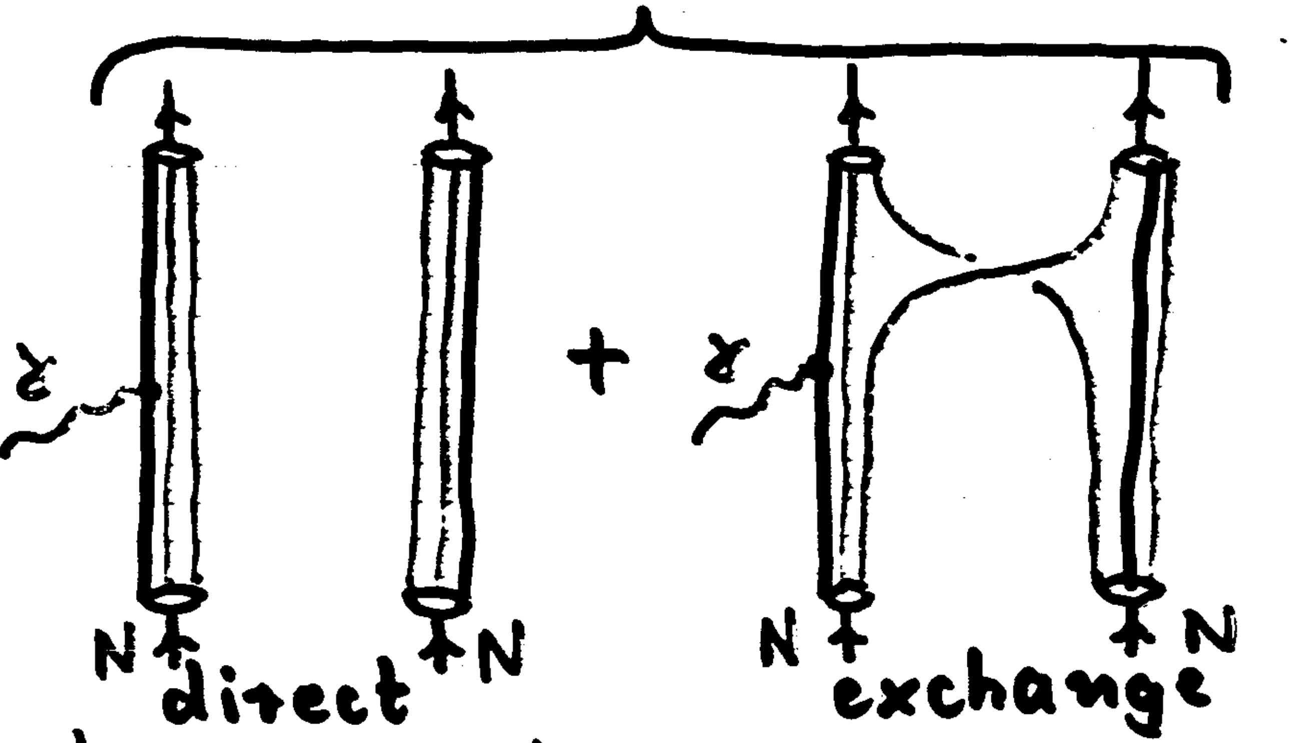
$$\boxed{\frac{d\sigma}{d\Omega_{e.D}} = \frac{d\sigma}{d\Omega_{Mott}}\left[A(q) + B(q)\, tg^2\frac{\vartheta}{2}\right]}$$

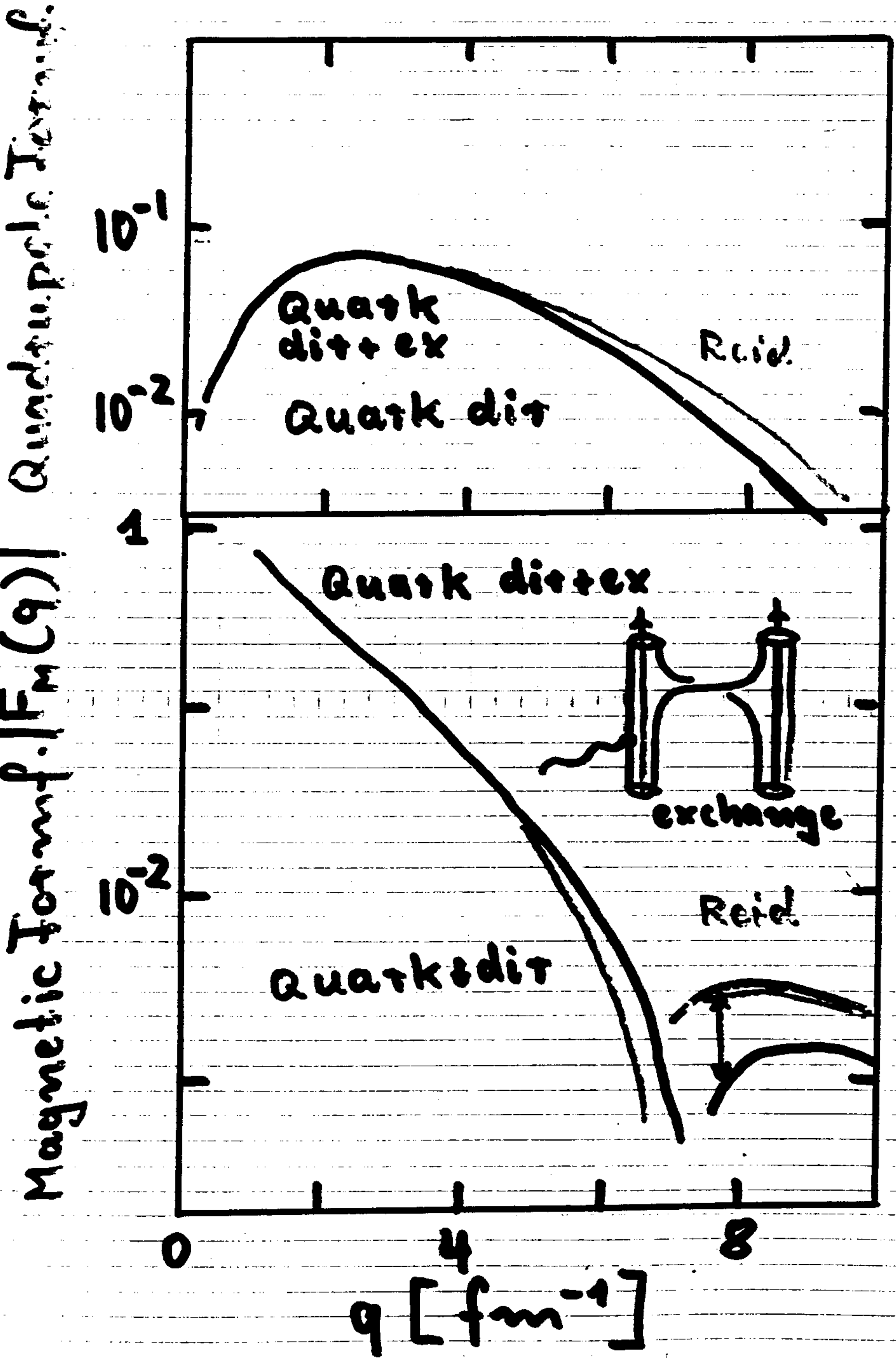
$$A(q) = F_C^2(q) + \alpha_1 q^2 F_Q^2(q) + \alpha_2 q^2 F_M^2(q$$

$$B(q) = B q^2 (1+q^2)\, F^2(q^2)$$

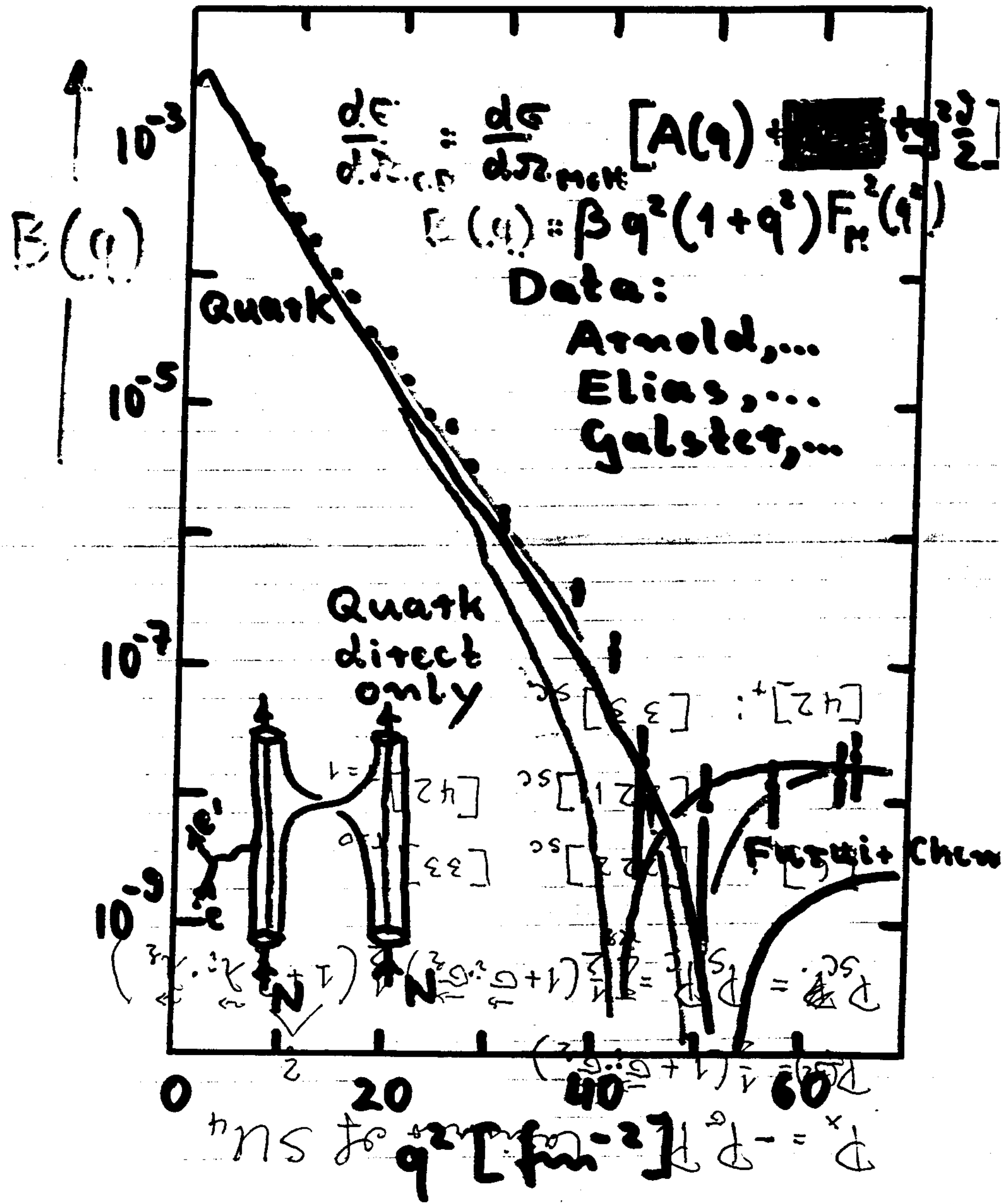
CHARGE MONOPOLE FORMFAC



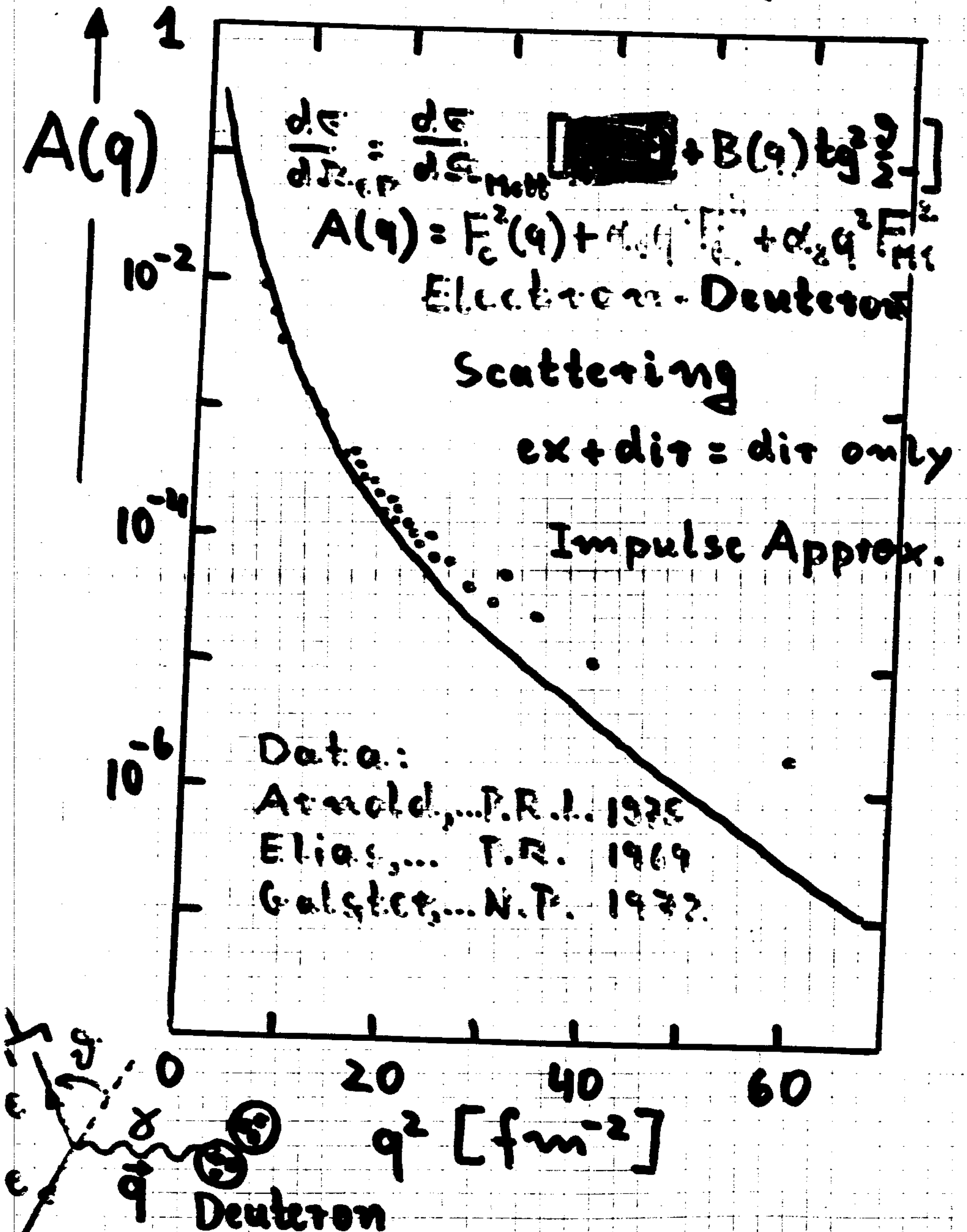



Quadrupole Formf.
10^-1
Quark dir+ex
Reid
10^-2
Quark dir
Magnetic Formf. |F_M(q)|
1
Quark dir+ex
exchange
10^-2
Reid
Quark+dir
0
4
8
q [fm^-1]

Electron-Deuteron Scatterin



Longitudinal Formfactor



Tensor-Polarisation: e D

$$T_{2.0}(q^2) = f\left(\frac{F_Q(q^2)}{F_C(q^2)}, \frac{F_M^2(q^2)}{F_C^2(q^2)} ; tg^2 \frac{\vartheta}{2} \right)$$

Problem: Single Nucleon Formf

Quarkmodel: $e^{-b^2 q^2/6}$

Experiment: $\left[1 + \frac{q^2}{0.71\,\mathrm{GeV}^2} \right]^{-2}$

Divide out and multiply

$$T_{20}(\vartheta) = \frac{\left[d\vec{\sigma}/d\Omega \right]_2 - \frac{d\sigma_0}{d\Omega}}{\frac{d\sigma_0}{d\Omega}} \sqrt{2}$$

Impulse Approximation

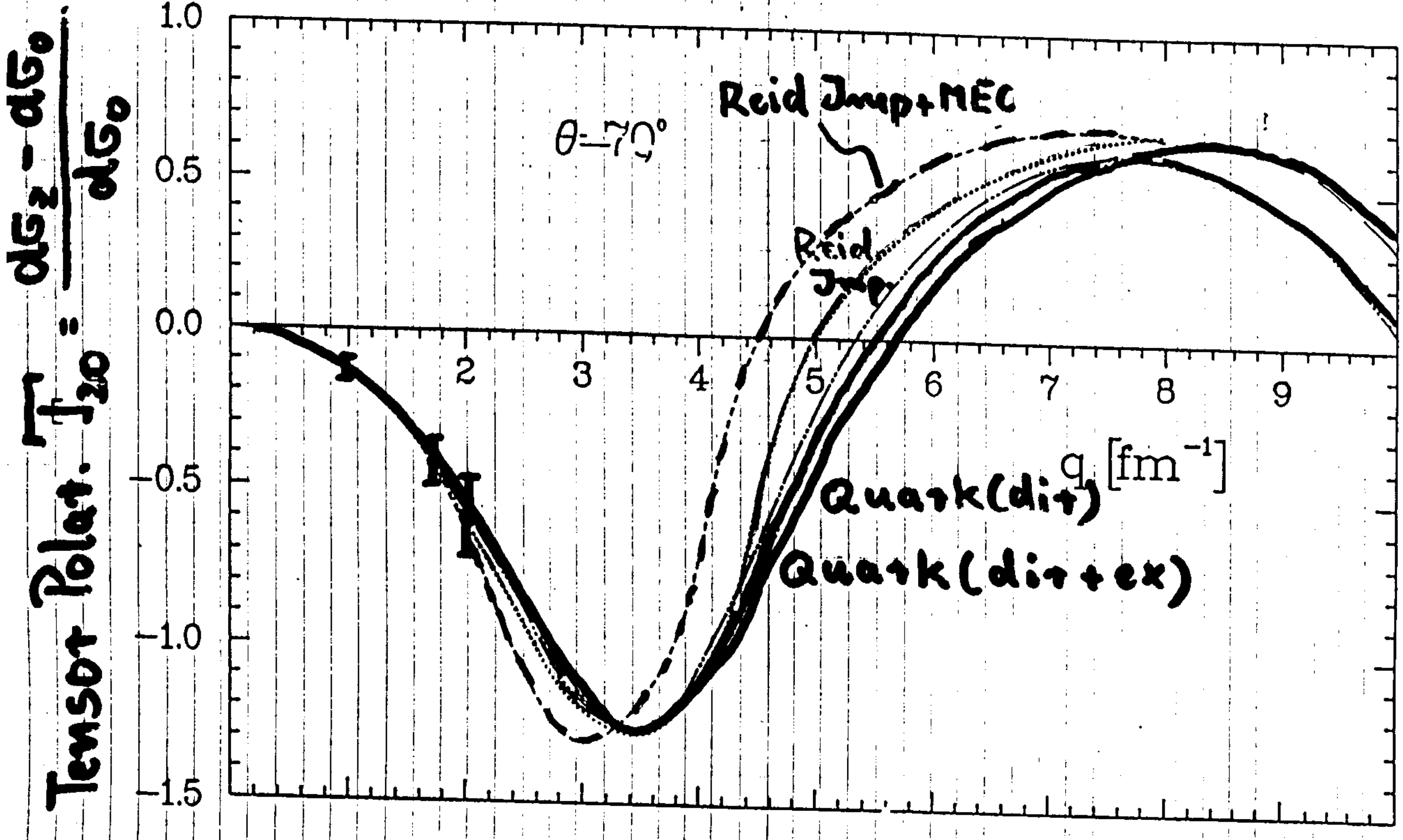


Fig.15

$$\boxed{\frac{d\sigma}{d\Omega_{c.m.}} = \frac{d\sigma}{d\Omega_{Mott}}\left[A(q) + B(q)\,tg^2\frac{\theta}{2}\right]}$$

$$\begin{cases} A(q) = F_c^2(q) + \alpha_1 q^2 F_Q^2(q) + \alpha_2 q^2 F_M^2(\\ B(q) = \beta q^2(q^2+1)\, F_M^2(q^2) \end{cases}$$

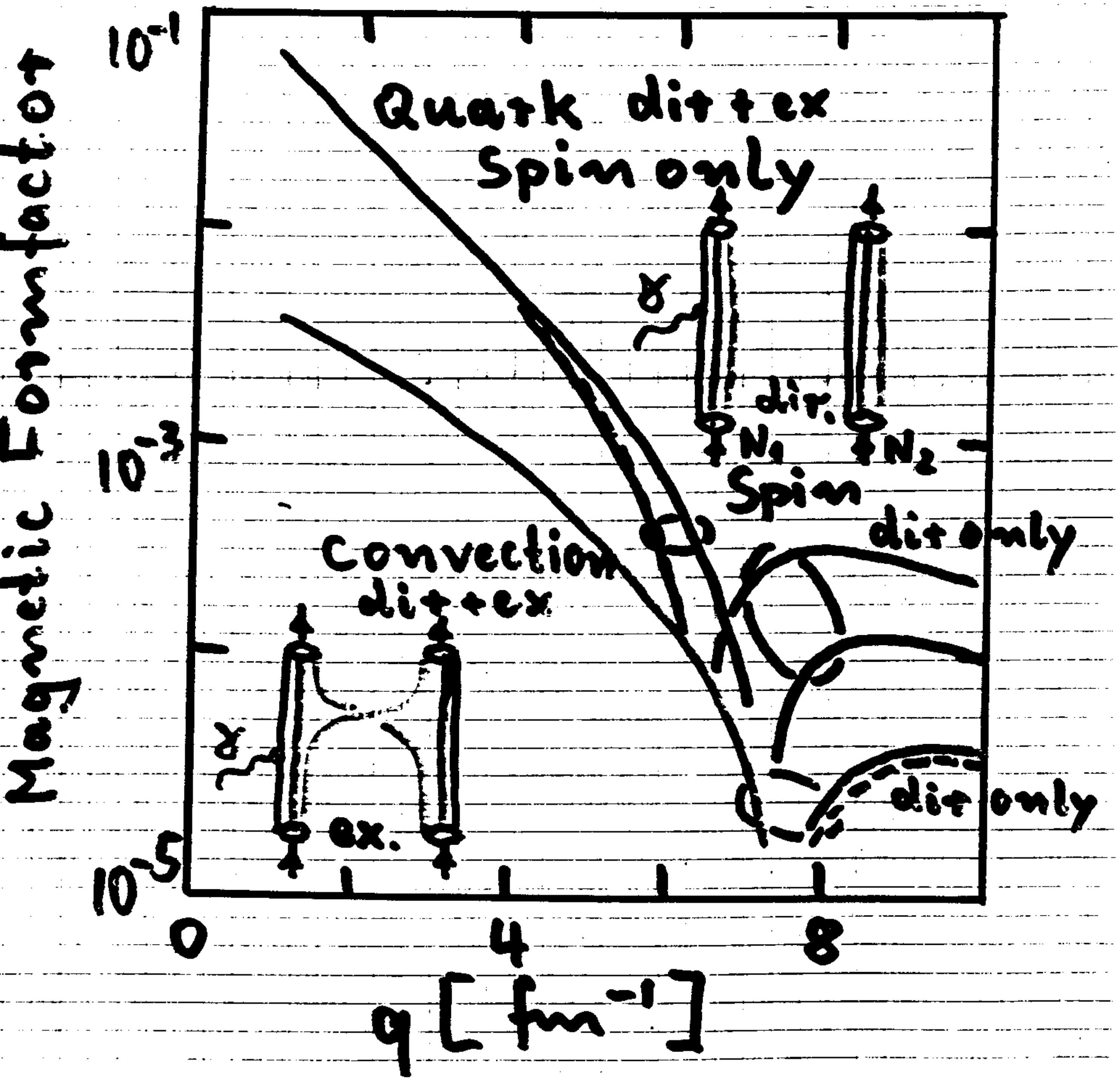
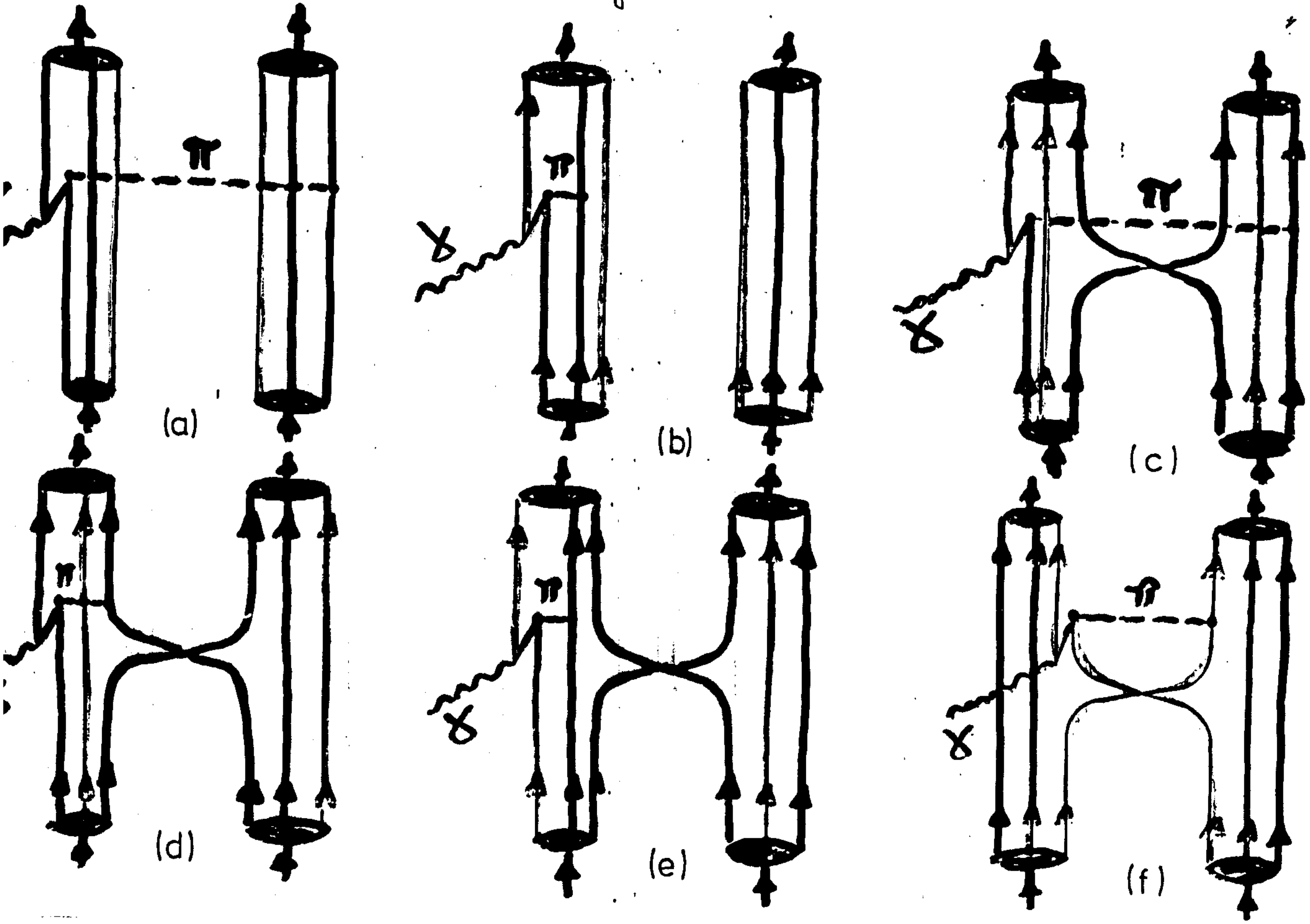


Fig. 1



GLUON Exchange:

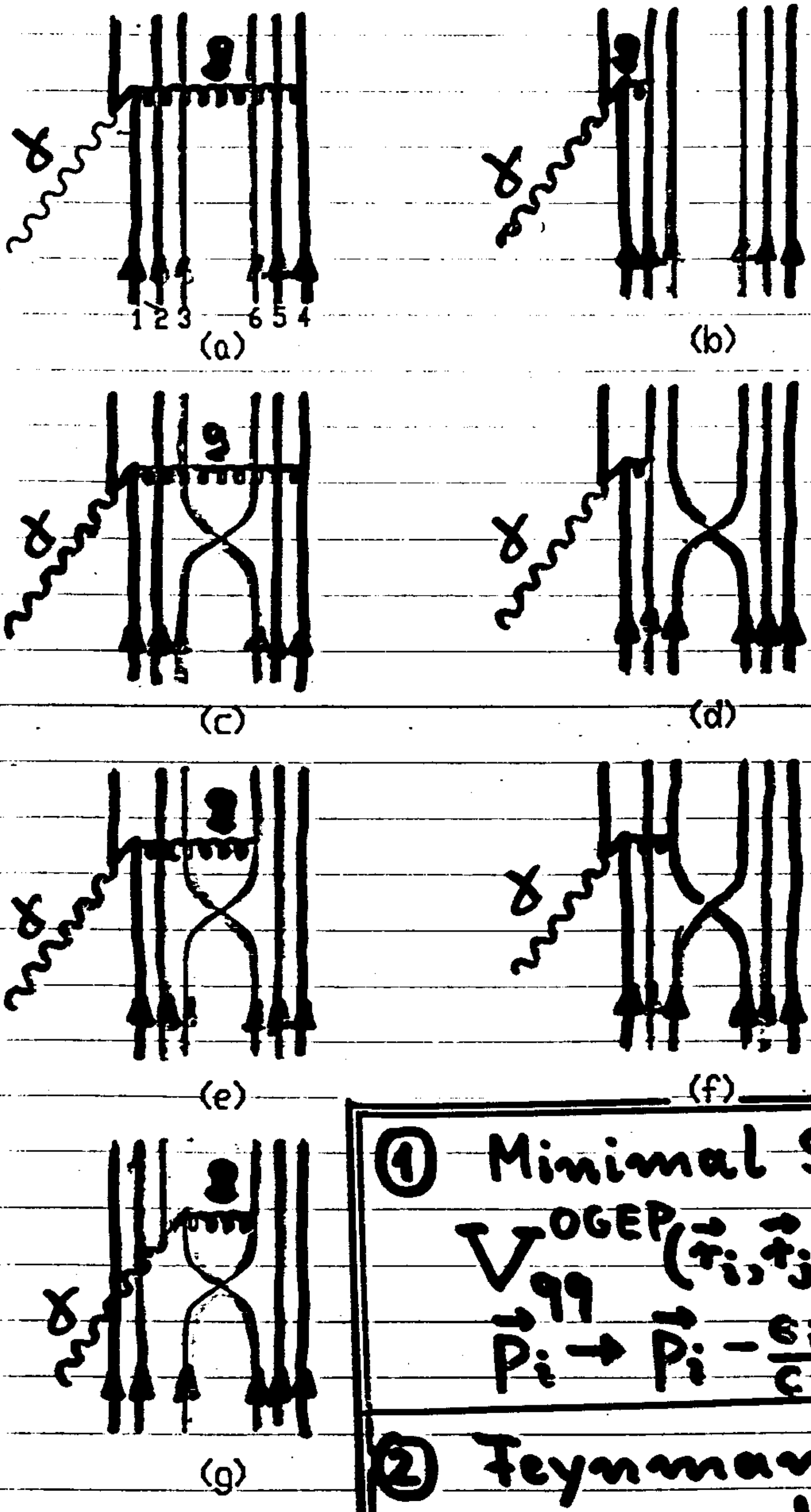


Fig. 1

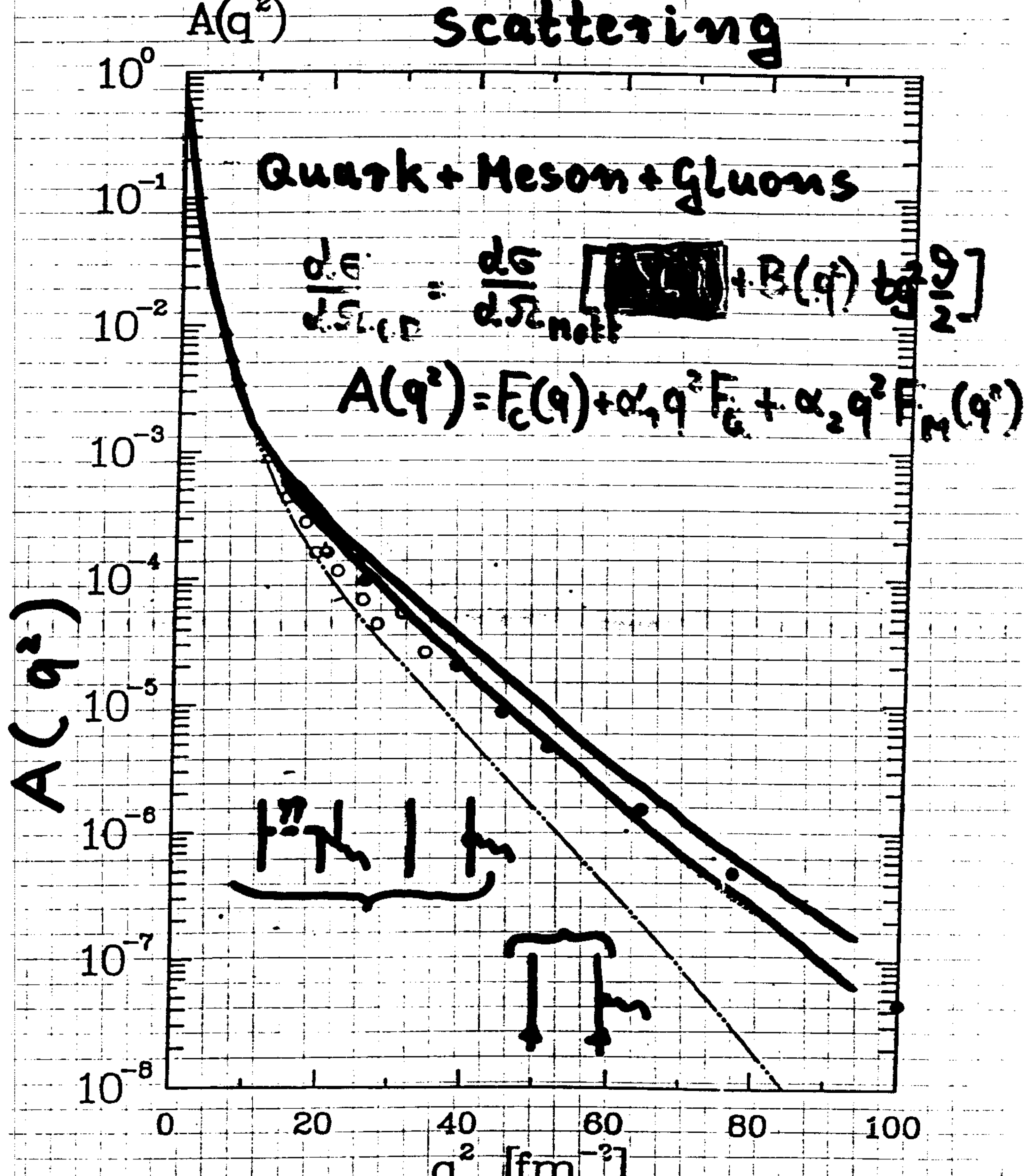
① Minimal Substitut.

$$V^{OGEP}_{qq}(\vec{r}_i, \vec{r}_j; \vec{p}_i, \vec{p}_j)$$

$$\vec{p}_i \rightarrow \vec{p}_i - \frac{e_i}{c}\vec{A}$$

② Feynman rules + non-relativ.

Elastic e-Deuteron Scattering



Quark + Meson + Gluons

$$\frac{d\sigma}{d\Omega_{e.D}} = \frac{d\sigma}{d\Omega_{Mott}}\left[\text{[redacted]} + B(q^2)\, tg^2\frac{\theta}{2}\right]$$

$$A(q^2) = F_C(q) + \alpha_1 q^2 F_G + \alpha_2 q^2 F_M(q^2)$$

Fig. 13

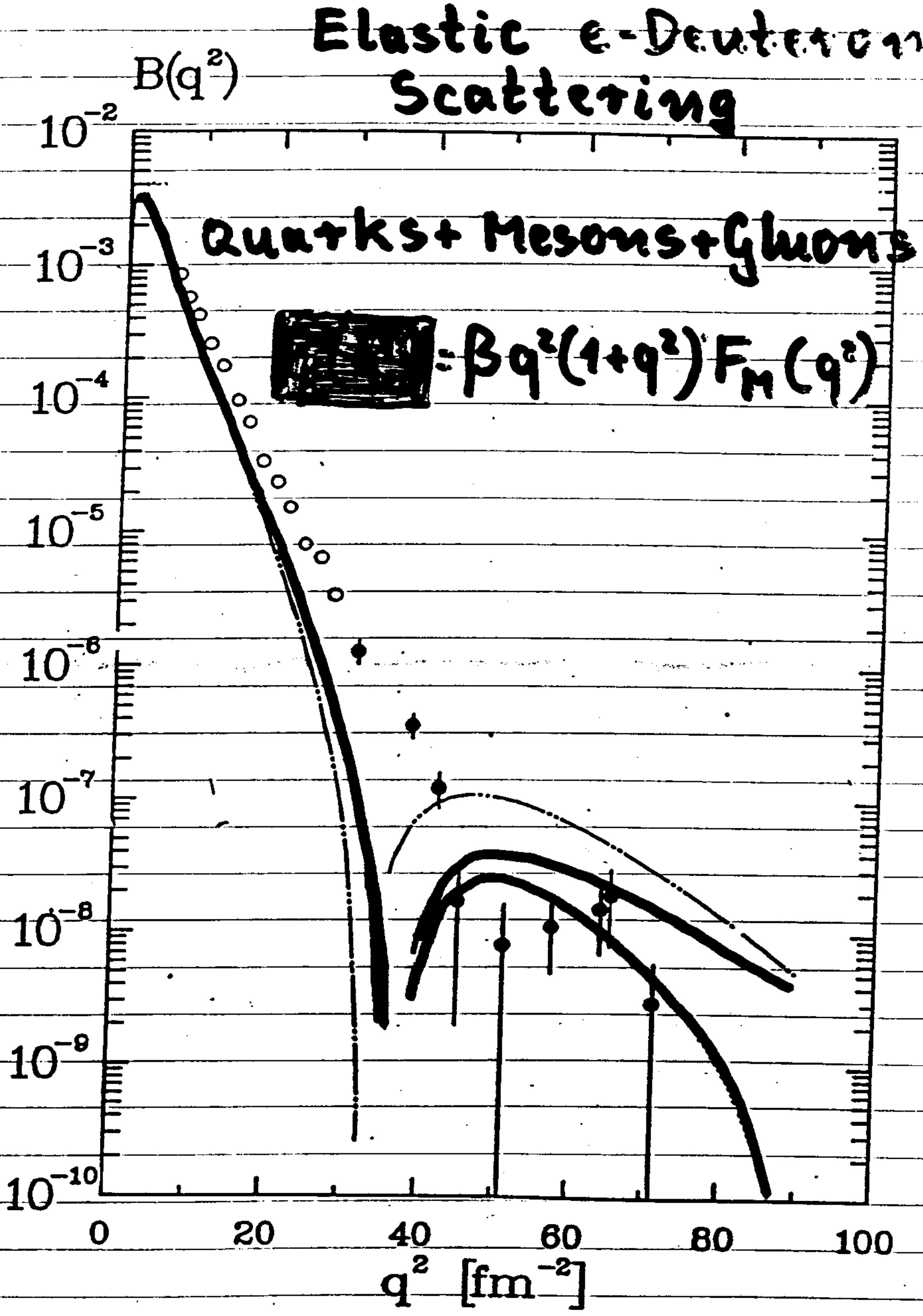
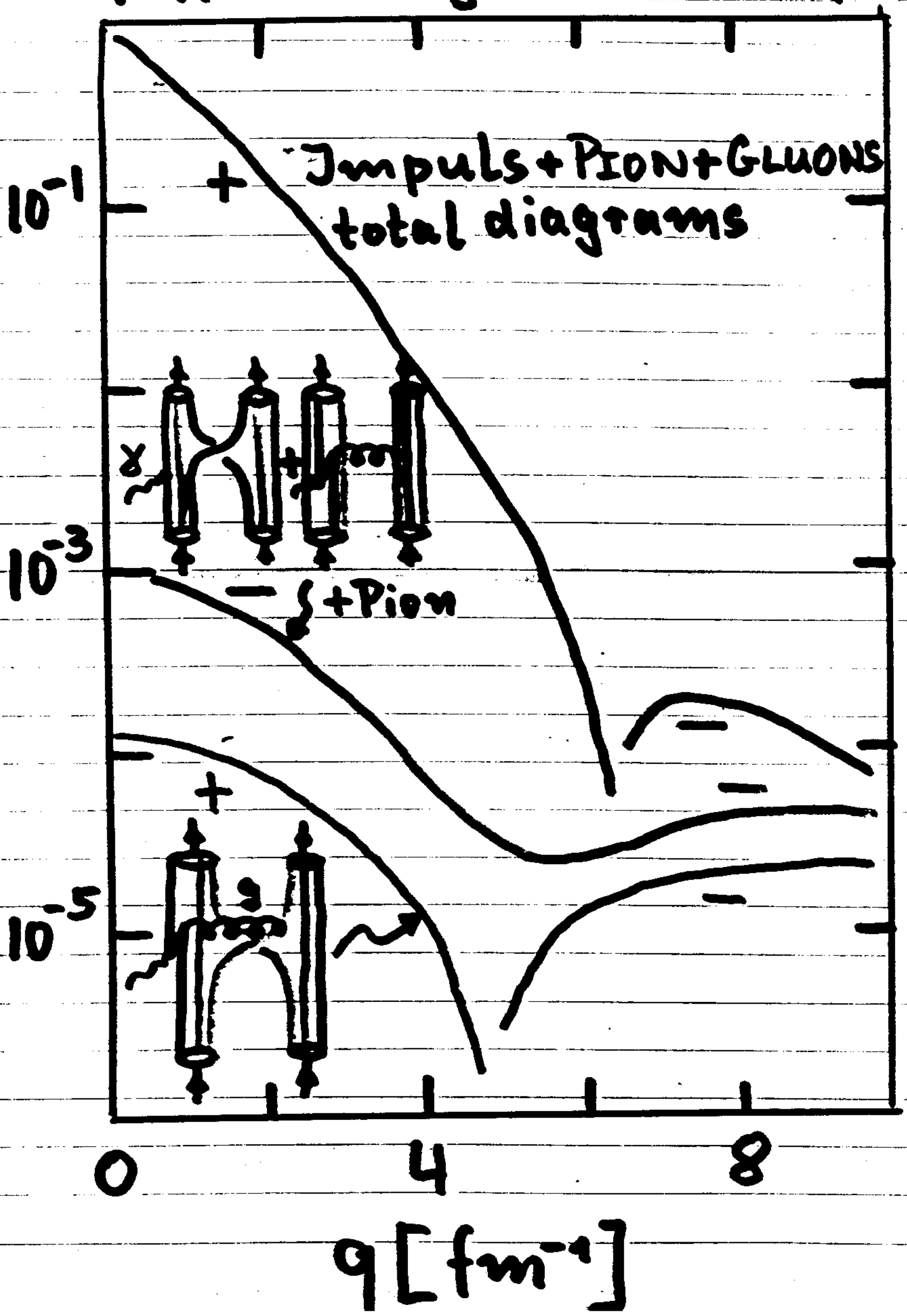

Elastic e-Deuteron Scattering
B(q^2)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Quarks+Mesons+Gluons
[redacted] $=\beta q^2(1+q^2)F_M(q^2)$
0
20
40
60
80
100
q^2 [fm^{-2}]

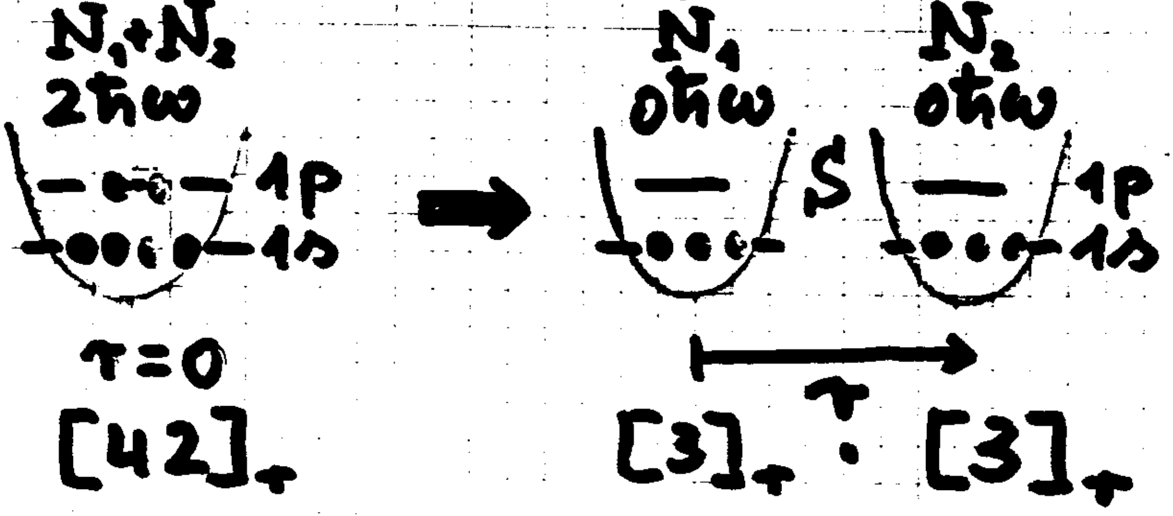
Fig. 14

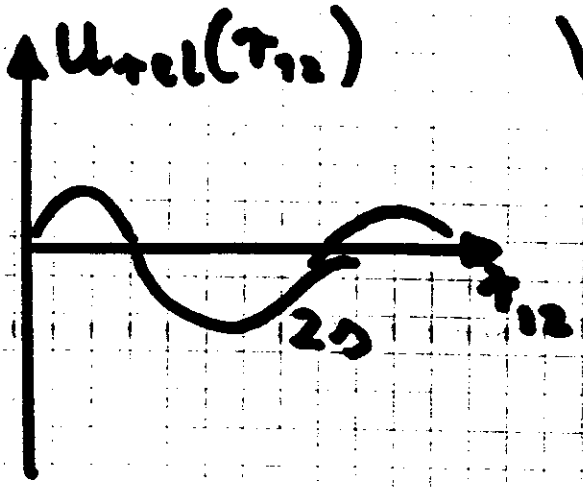
$|F_M(q)|$ Magnetic Formfactor

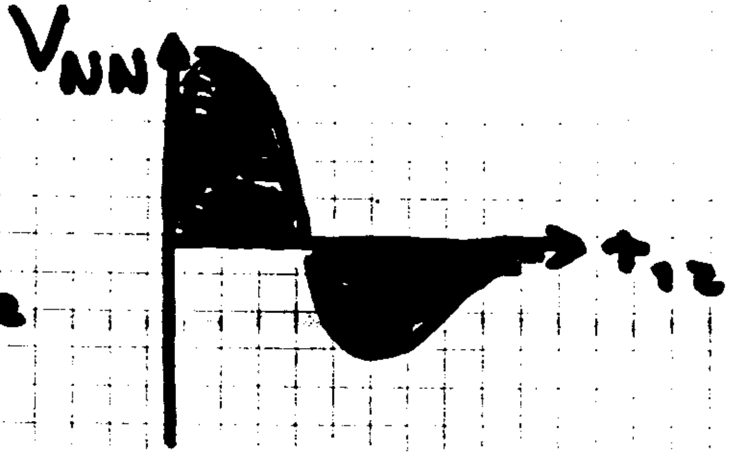


SUMMARY:

$\omega | \sigma$







$m_N; m_\Delta; \langle r^2\rangle^{1/2}_{r.ch.}\ \frac{g^2_{\pi NN}}{4\pi}; \frac{g^2_\sigma}{4\pi}$

- Nucleon-Nucleon
- Nucleon-Hyperon
- → Hyperon-Hyperon

WHAT IS THE NATURE OF SHORT-RANGE REPULSION?

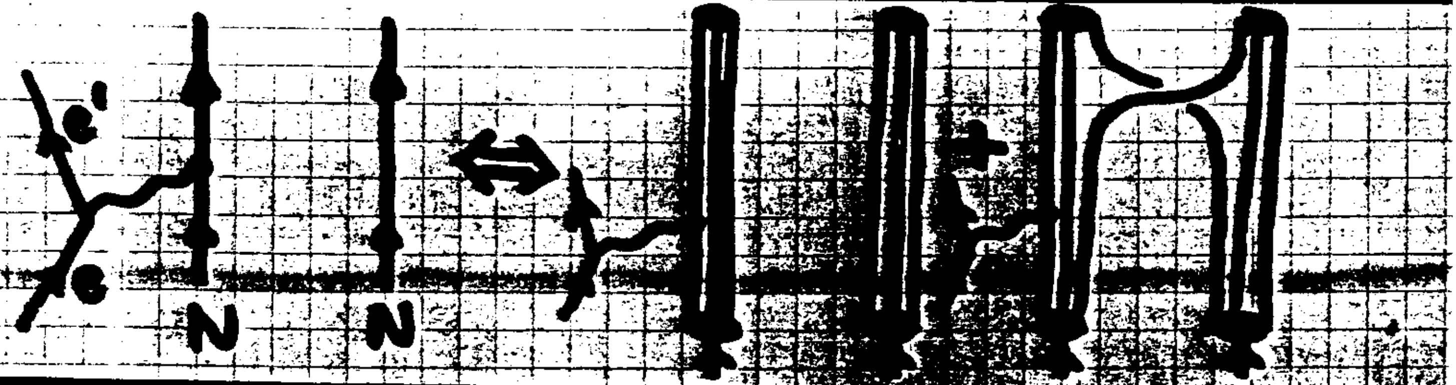
Conclusion: of ②

Deuteron Properties

Elastic e^- D Scattering:

NN ⇔

IMPULSE APPROX:



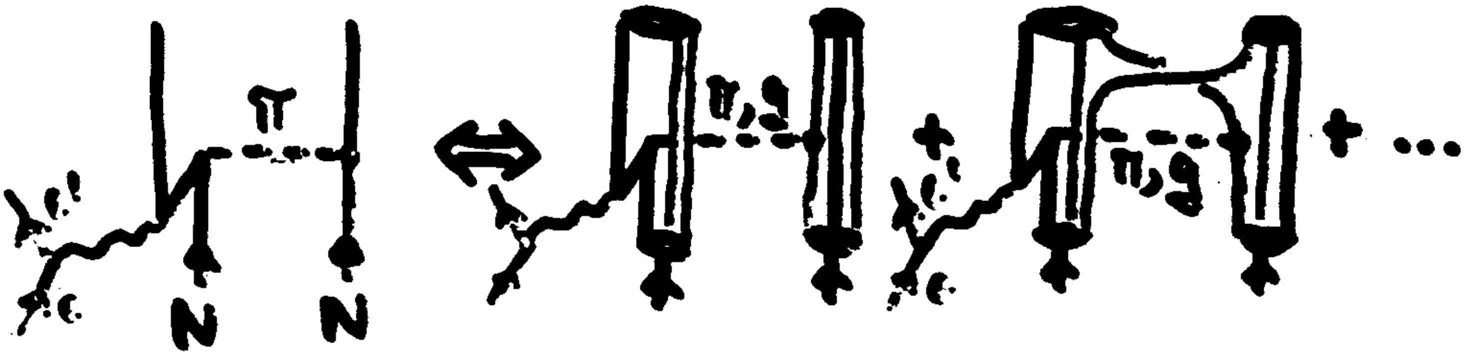
Nucleons ⇔ Quarks

$F_C(q^2) \approx F_C(q^2)$

$F_Q(q^2) \approx F_Q(q^2)$

$F_M(q^2) \neq F_M(q^2)$ in Spin

Meson Exchange Current:



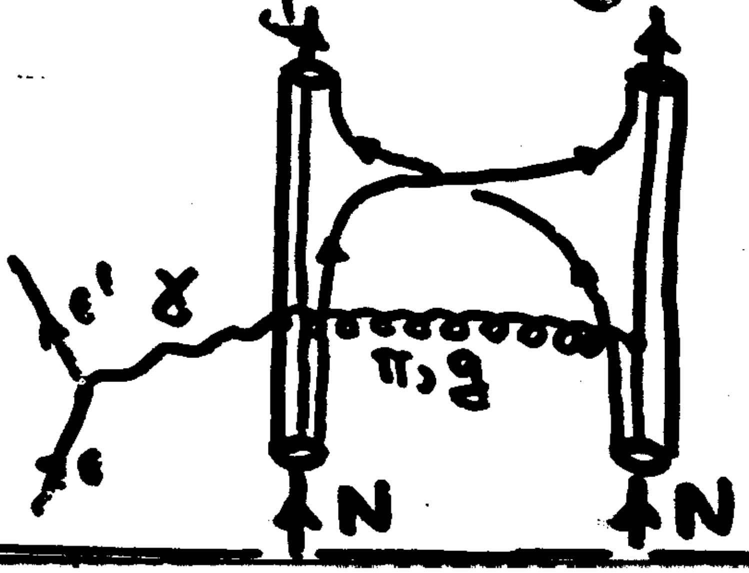
Nucleons ⇔ Quarks

$$\downarrow \quad E_{p+q} = \sqrt{m_q^2 + (\vec{p} + \vec{q})^2} \to m_q$$

$$E_{p+q} \approx \sqrt{m_q^2 + \vec{q}^2}$$

No large Difference:
ex MEC small.

Magnetic (Transverse) Formfact



Spin part
at high $|\vec{q}|$
large.
+ Pion + Gluon
Exchange