Large Q^2 (e,e' N) processes.

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Based on the theoretical analyses performed together with

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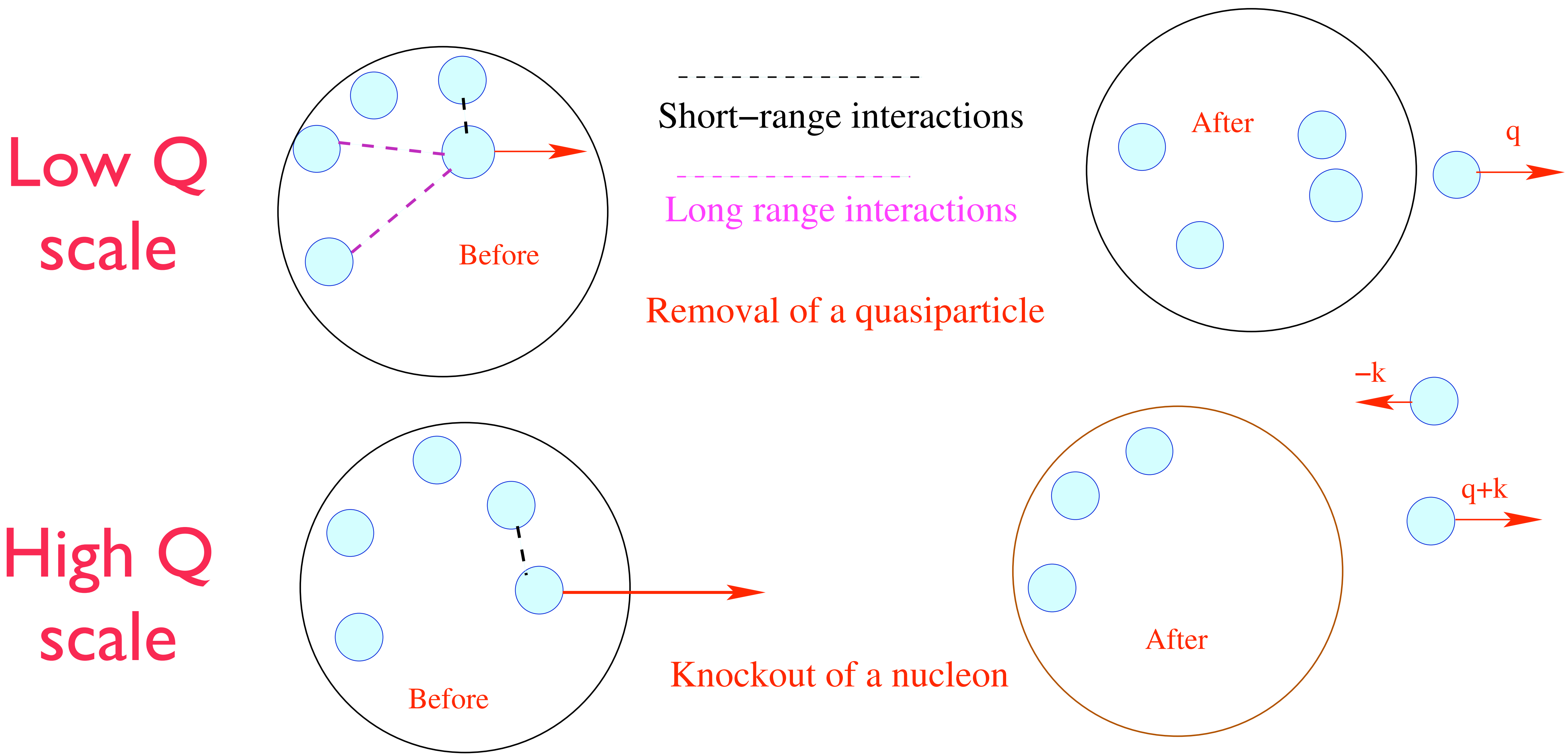
Experience of quantum field theory - interactions at different resolutions (momentum transfer) resolve different degrees of freedom - renormalization,.... No simple relation between relevant degrees of freedom at different scales.



Outline

- Why high-energy people are interested - a bit of history.
- Absorption dynamics for $Q^2 \geq 2$ GeV^2 - why eikonal should be a good approximation.
- Comparison with the JLab data - evidence for small quenching at large Q.
- Possible interpretation of the observed dependence of the dynamics on Q^2 - from quasiparticles to resolved nucleons.
- Expectations of new dynamics for $Q^2 \geq 5$-8 GeV^2.

Interest of high energy community - prediction of color transparency - onset of the impulse approximation regime at large Q (Brodsky and Mueller 82).

(p,2p) experiment at BNL at E=6-14 GeV reported evidence for the energy dependence of absorption in 88, confirmed in new experiment in 98.

SLAC and JLAB - (e,e'p) experiments - no strong dependence of transparency on Q^2 for $Q^2 \geq 2$ GeV^2 - first comparison with predictions based on eikonal - pretty good agreement with the data.

G. van der Steenhoven questioned this interpretation - he used the spectral function with quenching as measure at $Q^2 \leq 0.2\ GeV^2$ to conclude that transparency observed at SLAC is close to one for carbon. Color transparency?

Need to check critically:

- ☛ *Accuracy of the absorption model.*
- ☛ *Definitions of transparency used in the data analysis.*
- ☛ *Model for the nuclear spectral function.*

Our tentative conclusion is that effect is due to the complicated nature of low energy interaction which effectively changes quenching.

Meanwhile:

☀ Color transparency is observed in a number of high energy processes including confirmation of the prediction of Frankfurt et al of CT in pion coherent diffraction into two jets.

☂ Radiation corrections may require further analysis - already a problem in ep elastic scattering at similar Q^2

☝ New preliminary data from hall B suggest onset of the new regime (which is similar to predictions of color transparency) in a special rescattering kinematics in eD $\rightarrow$ epn reaction at Q^2 in the range of (e,e'p) experiments.

E-791 (FNAL) experiment (PRL2001) at $E^{\pi}_{inc} = 500$ GeV : π + A → 2 jets + A

♡ Coherent peak is well resolved.

♡♡ Observed A-dependence $A^{1.61 \pm 0.08}$ $[C \to Pt]$

FMS prediction $A^{1.54}$ $[C \to Pt]$ for large k_t & extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

♡♡♡ The z dependence is consistent with dominance of the asymptotic pion wave function $\propto z(1-z)$.

♡♡♡♡ k_t^{-n} dependence of the cross section is close to the QCD prediction - $n \sim 8.0 \pm 0.2$ for the kinematics of E971

$\Longrightarrow$
- High-energy color transparency is **directly** observed.
- The pion $q\bar{q}$ wave function is **directly** measured.

Calculating high-energy absorption

Large momentum transfer processes automatically correspond to production of high-energy protons with energies > 0.8 GeV where NN interaction become relativistic and highly inelastic. One cannot use anymore a notion of the NN potential. One has to derive the amplitudes from the basic features of the theory of strong interaction.

For the case of the incoming hadrons this was done by V.Gribov who used the Feynman diagram technique to demonstrate that corrections to the Glauber approximation for the cross section of the elastic (total) hA scattering can be expressed through the cross sections of the inelastic diffractive processes. So as soon as $\sigma_{diff} << \sigma_{el}|_{t=0}$ (T_p < few GeV) the Glauber approximation should work with accuracy of few %.

No free parameters in the interaction model – *total cross section and Re/Im for the elastic pp and pn amplitude measured with accuracy of few % in independent experiments.*

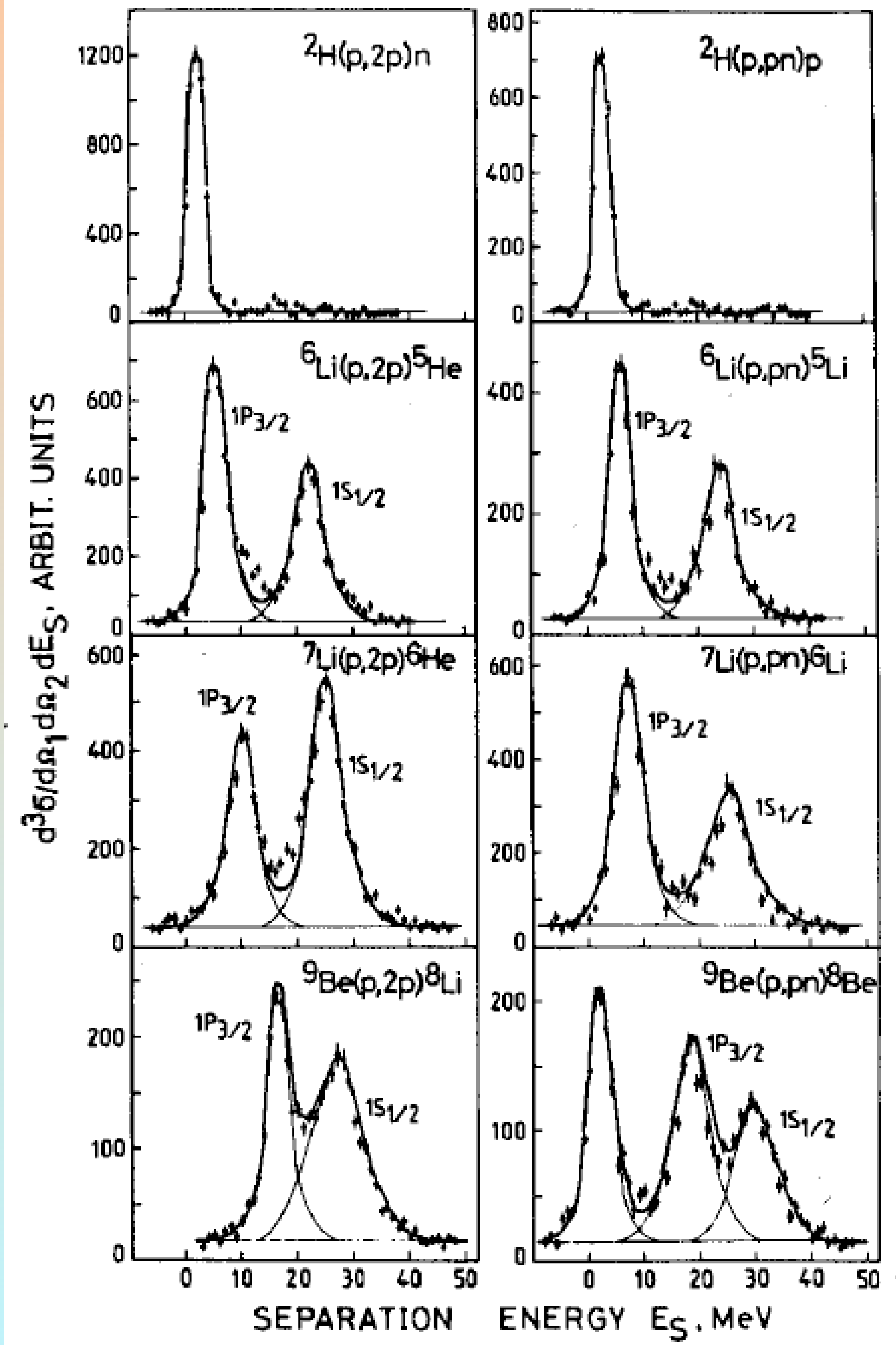
Indeed, the studies at $T_p = 1$ GeV have shown excellent agreement with the theory – with 40 Ca shape coinciding with the e.m. data. Glauber approximation becomes progressively worse below 0.8 GeV (remember Q=1 GeV <-> $T_p = 0.4$ GeV)

Even more relevant for (e,e'p) studies is investigation of the (p,2p), (p,pn) at $T_p = 1$ GeV. It was performed at Gatchina for a wide range of the targets both in pp and pn channels.

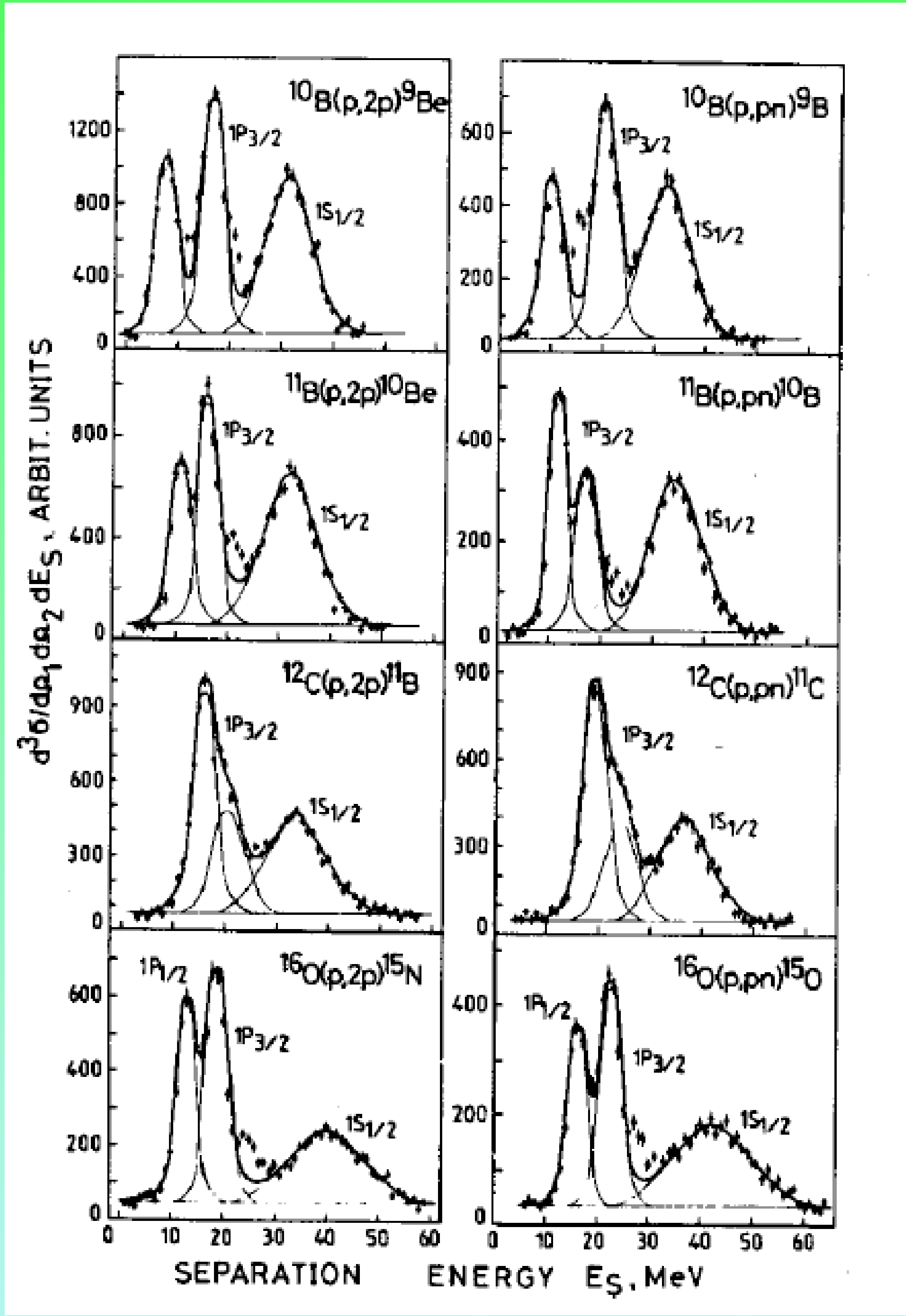
The eikonal approximation combined with Hartree-Fock Skyrme model was used to generate the wave functions, and P-shell splitting were used to fit the deformation parameter which was the only parameter which was not fixed from the calculation of the nuclear energy levels. HFS also described well the elastic pA scattering and nuclear charge distribution. The overall normalization uncertainty was less than 20%. In all comparisons shown in the next slides the data were normalized in one point for the scattering off oxygen.

The discussed model neglects transitions between the shells. This effect somewhat changes relative occupation numbers for s and p shells but it is very small in the sum of s and p shell contributions which is the main focus of our (e,e'p) analysis.

HFS wave/spectral functions do contain a significant high momentum component. So they mimic significant part of the high momentum component of the more realistic wave function. On the scale of 10% of p> 300 MeV/c is missing. Should have very little effect on p< 150 MeV/c region.



$^2H(p,2p)n$
$^2H(p,pn)p$
$^6Li(p,2p)^5He$
$^6Li(p,pn)^5Li$
$^7Li(p,2p)^6He$
$^7Li(p,pn)^6Li$
$^9Be(p,2p)^8Li$
$^9Be(p,pn)^8Be$
$1P_{3/2}$
$1S_{1/2}$
$d^3\sigma/d\Omega_1 d\Omega_2 dE_S$, ARBIT. UNITS
SEPARATION ENERGY E_S, MeV



$^{10}B(p,2p)^{9}Be$
$^{10}B(p,pn)^{9}B$
$^{11}B(p,2p)^{10}Be$
$^{11}B(p,pn)^{10}B$
$^{12}C(p,2p)^{11}B$
$^{12}C(p,pn)^{11}C$
$^{16}O(p,2p)^{15}N$
$^{16}O(p,pn)^{15}O$
$1P_{1/2}$
$1P_{3/2}$
$1S_{1/2}$
$d^3\sigma/d\Omega_1 d\Omega_2 dE_S$, ARBIT. UNITS
SEPARATION ENERGY E_S, MeV

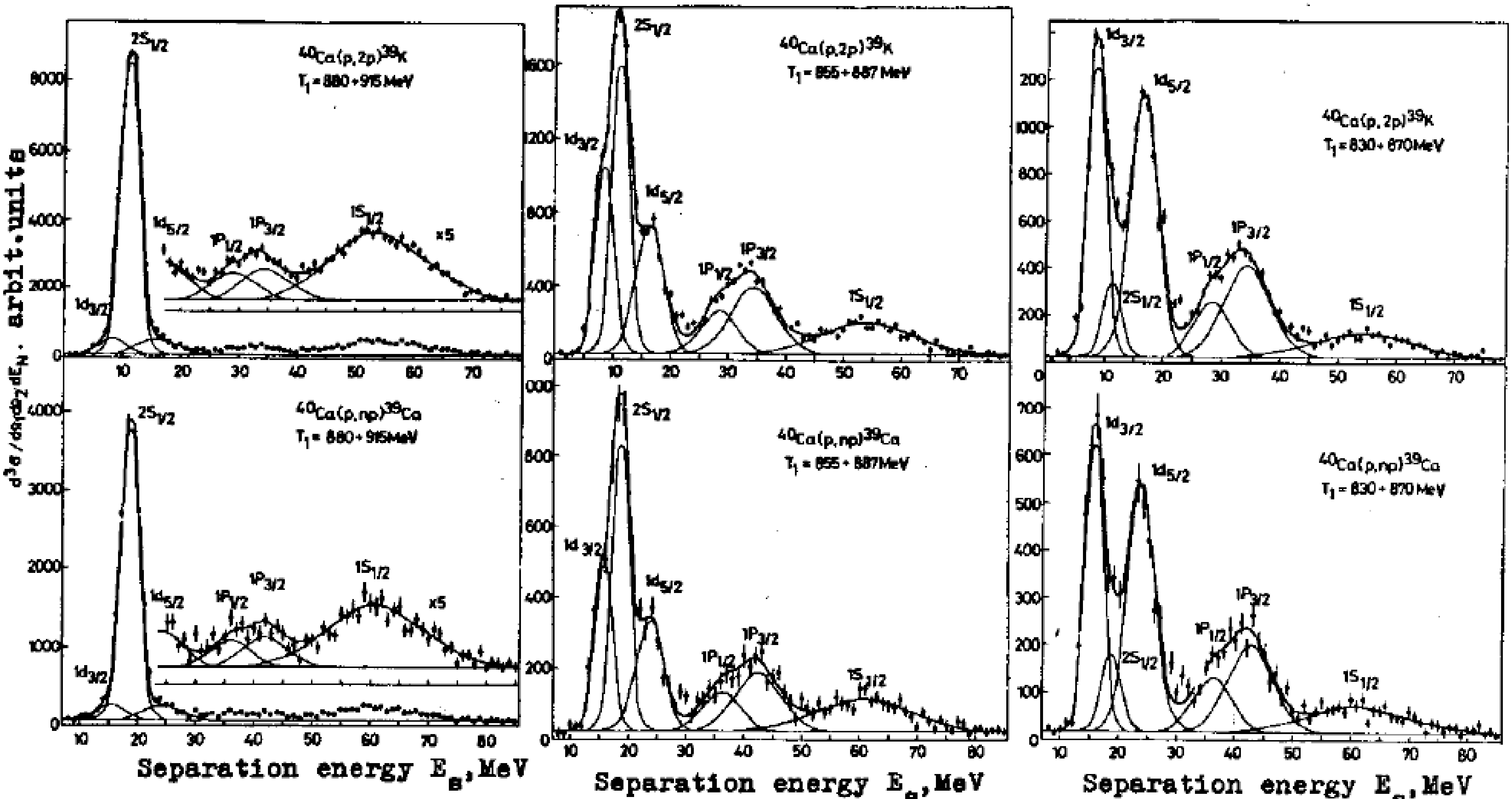


Fig.4. Proton and neutron separation energy spectra for ^{40}Ca corresponding to different T_1 ranges.

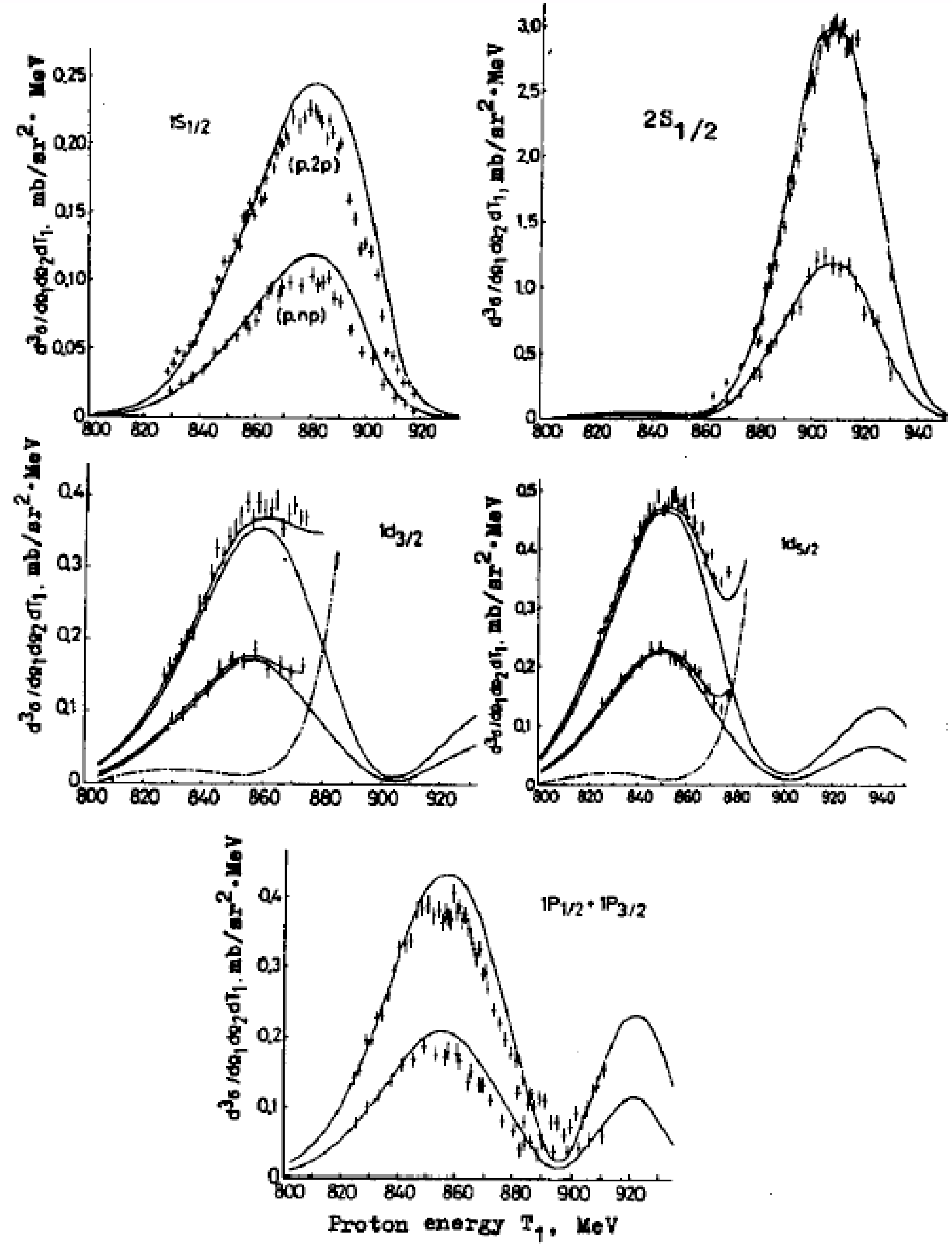
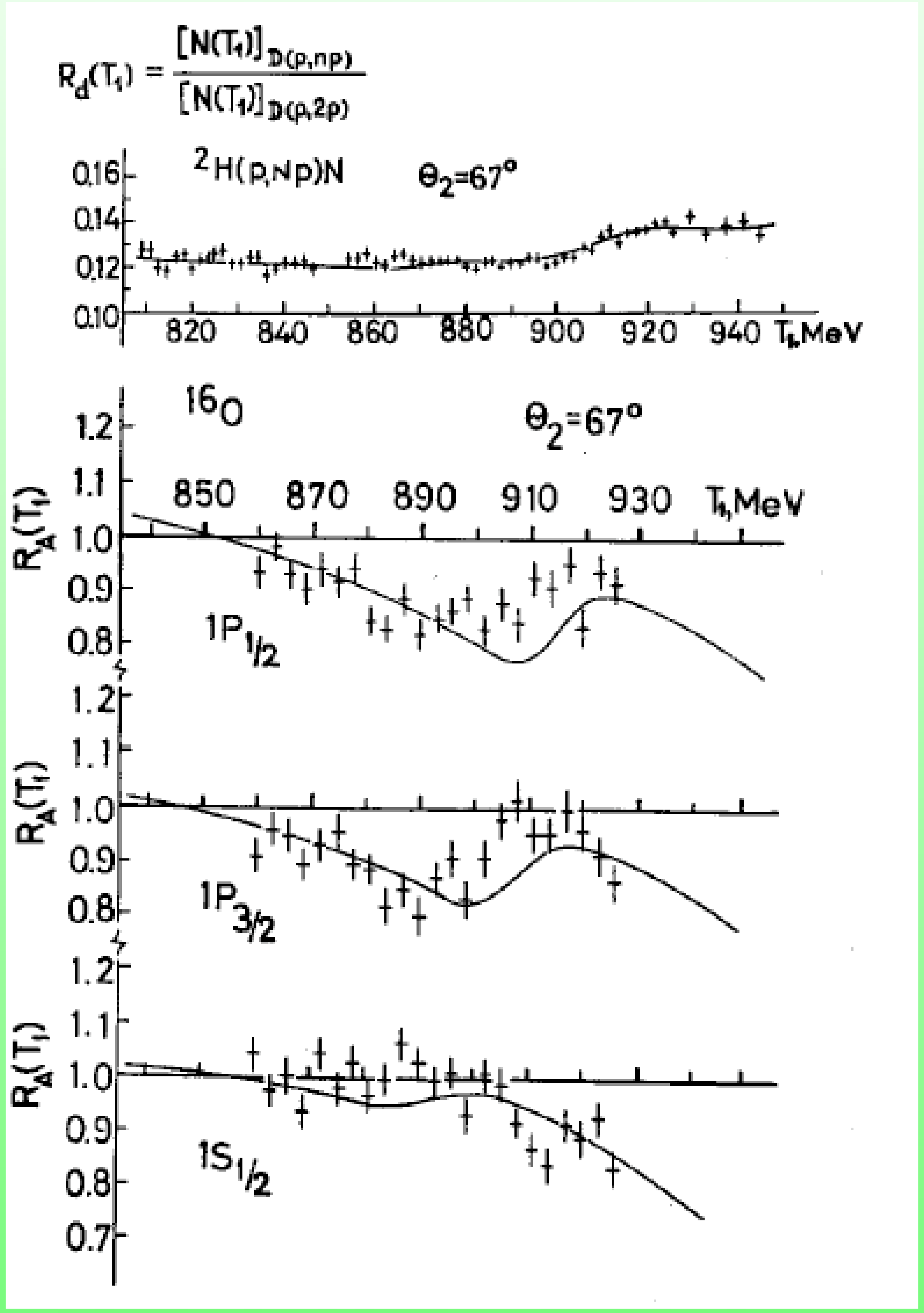
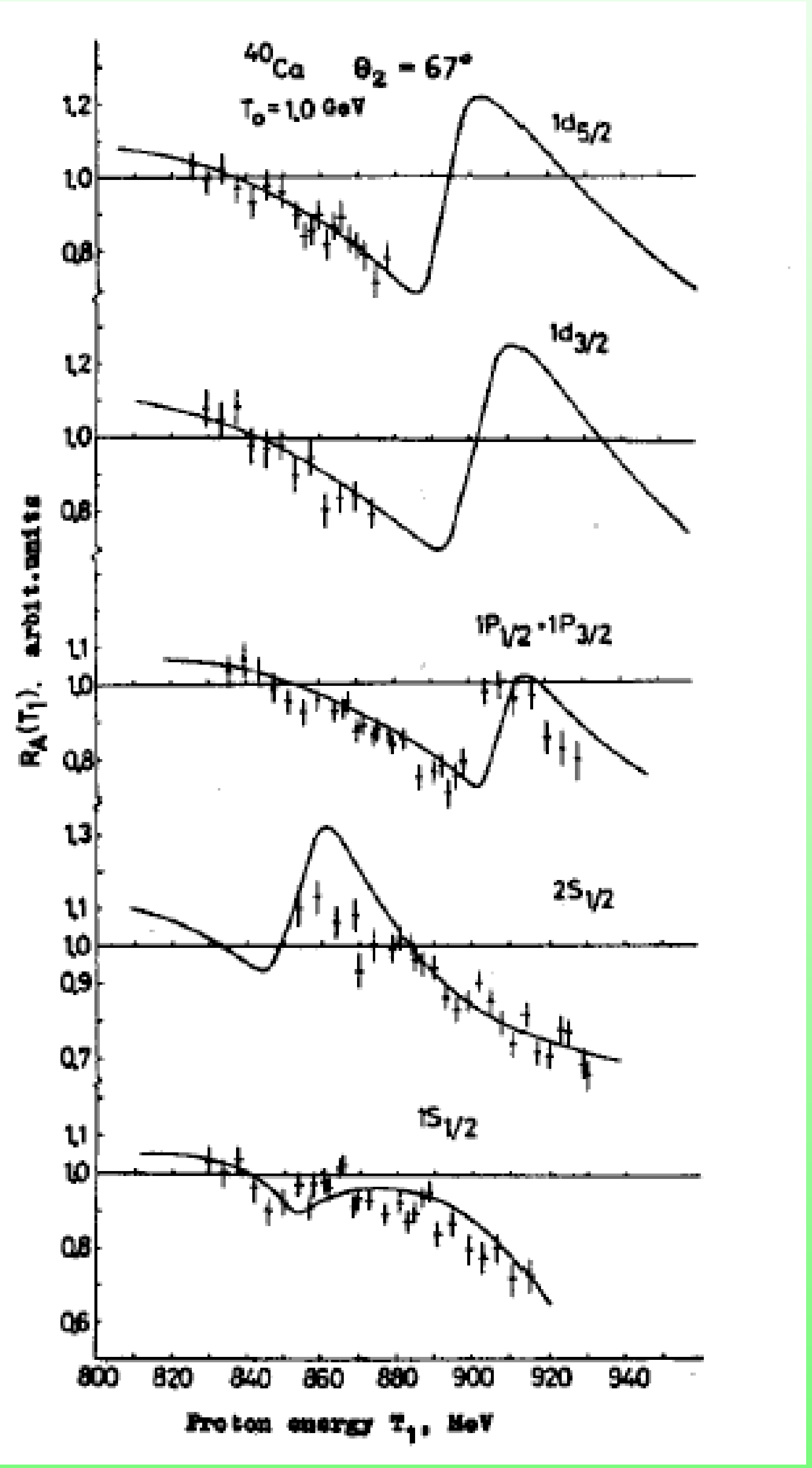


Fig.8. Differential cross-sections of the quasi-elastic nucleon knock-out reaction for ^{40}Ca.

Experimental and theoretical relative structure functions of 16O, 40Ca.



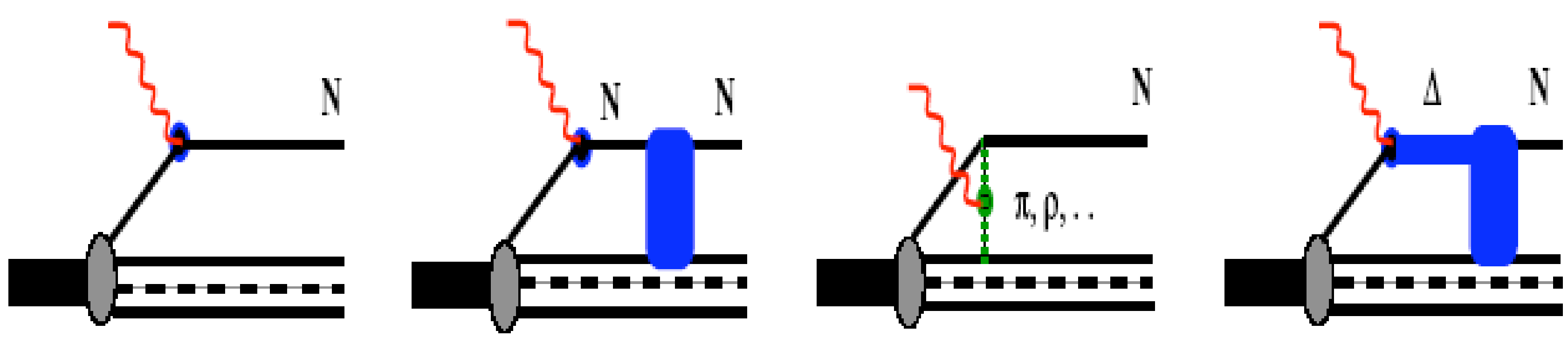


Overall, the data are described with accuracy better than 20 % so the main uncertainty in the interpretation is the overall 20% uncertainty in the absolute normalization which is the same for light and heavy nuclei. Since the quenching is not a strong function of A for discussed A-range we conclude that eikonal works to better than about 20% in predicting absolute absorption in (p,pN) processes at T=1 GeV.

The 20% accuracy in (p,2p) corresponds to 7-10 % accuracy of eikonal in (e,e'p) since in (p,2p) initial and two final nucleons propagate

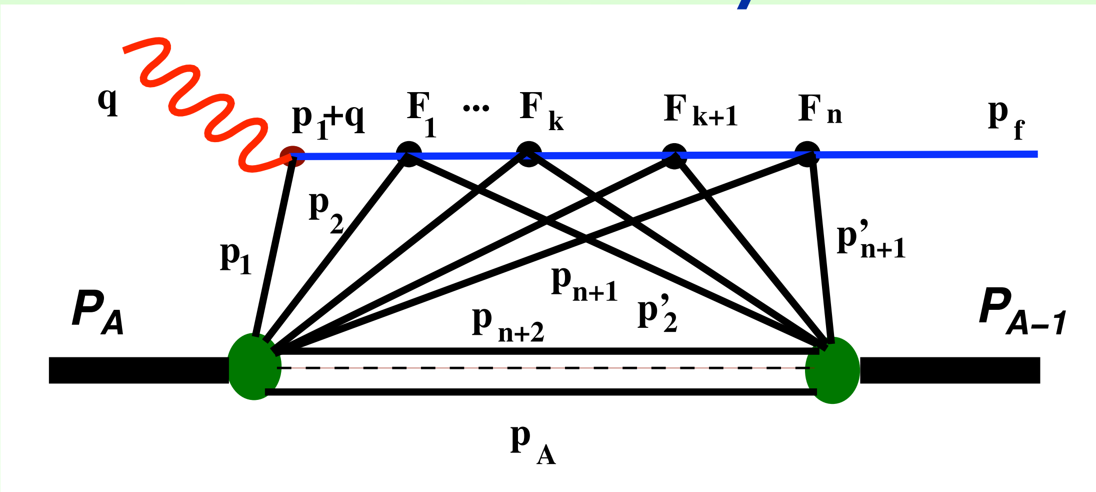
To derive analog of the eikonal approximation for high Q (e,e'N) processes one needs to account for two effects - different velocity of the initial virtual photon and the final nucleon and fixed momentum of the final nucleon as in the conventional Glauber approximation one integrates over all momenta of nucleons in the target.

Derivation is based on the analysis of the relevant Feynman diagrams. Great simplification for x~1 where only diagrams "b" are important for Q > 1 GeV.



(a) (b) (c) (d)

Relevant formulae derived from analysis of the Feynman diagrams



in series of papers of Frankfurt, Sargsian, MS 95-97 and reviewed in Sargsian 2001 - GEA - generalized eikonal approximation. Key difference/complication is the need to take into account longitudinal momentum transfer in the propagators (no time to describe the final answer in this talk). However for the small nuclear excitation energies (x~ 1) the answer is reduced to the conventional Glauber eikonal approximation. Hence we expect that approximations which worked for (p,pN) at 1 GeV should work also for Q^2 ~ 2- 4 GeV^2

The high energy (e,e'p) data are taken in the x=1 transverse kinematics at small average nucleon momenta ~ 100 MeV/c - so effects are nucleon correlations in the wave function are small - Frankfurt, Moniz, Sargsian, MS 95

Analysis of the transparency for $Q^2 \geq 2$ GeV^2

Interest of high energy community - prediction of color transparency - onset of the impulse approximation regime at large Q.

Experimental definition:

T= "experimental cross section"/σ_{pwia}

Delicate question - subject of our workshop what is σ_{pwia}?

$$\sigma_{pwia} = F_{kin}\sigma^{ep}_{cc1} \int S(\mathbf{k}, E)\, d^3k\, d\, E$$

where F_{kin} is a kinematic factor and σ^{ep}_{cc1} is off-shell extrapolation of σ^{ep}. This extrapolation is a small effect for large Q.

Our procedure:

(a) Calculate absolute differential cross sections and compare directly with the data.

$$S_{HF}(\mathbf{k},E)=\sum_{\alpha} n_{\alpha}\delta(E-E_{\alpha})|\varphi_{\alpha}(\mathbf{k})|^2.$$

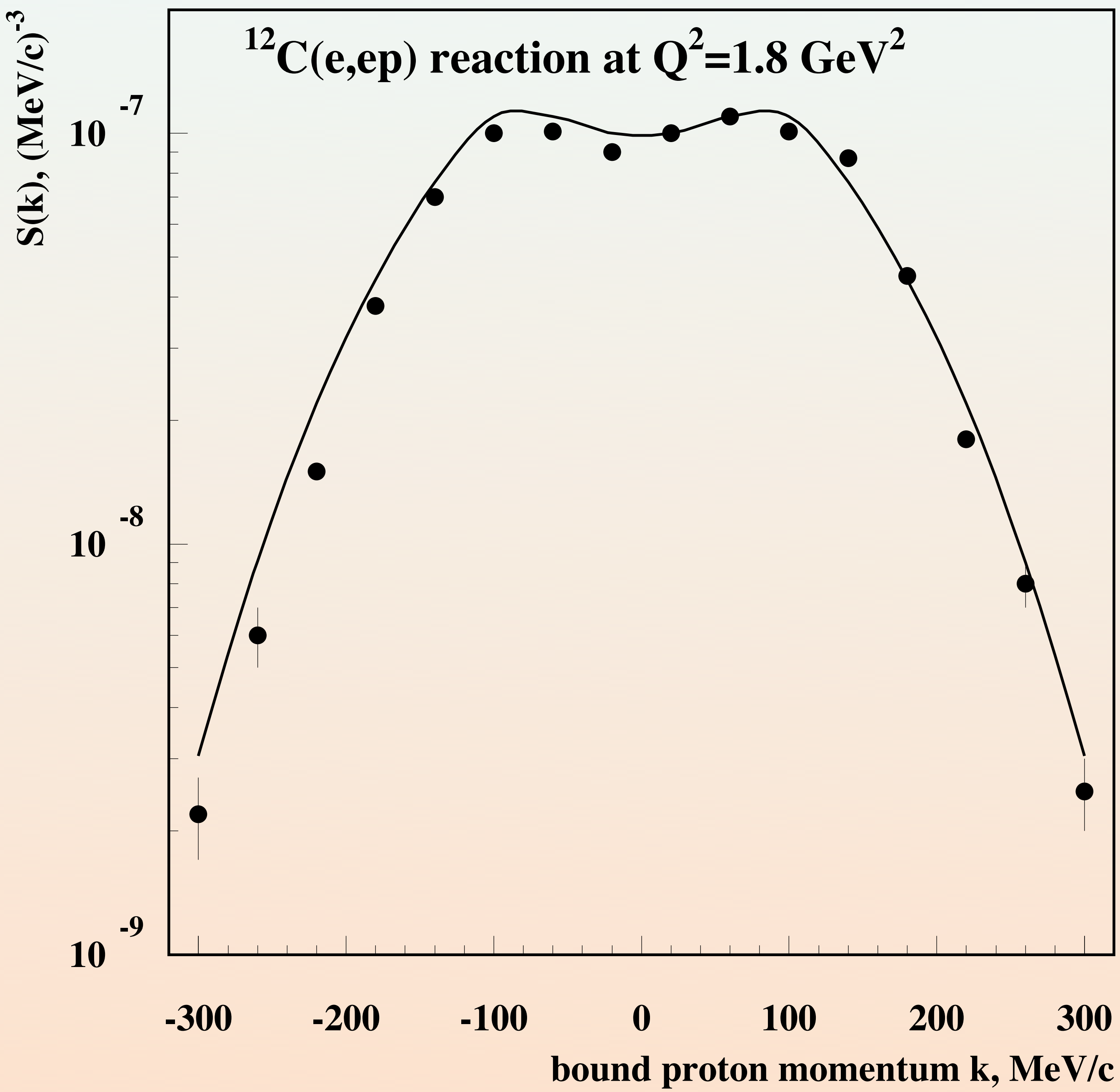
with $n_{\alpha}=1.$

$$S_{HF}^{fsi}(\mathbf{k})=$$

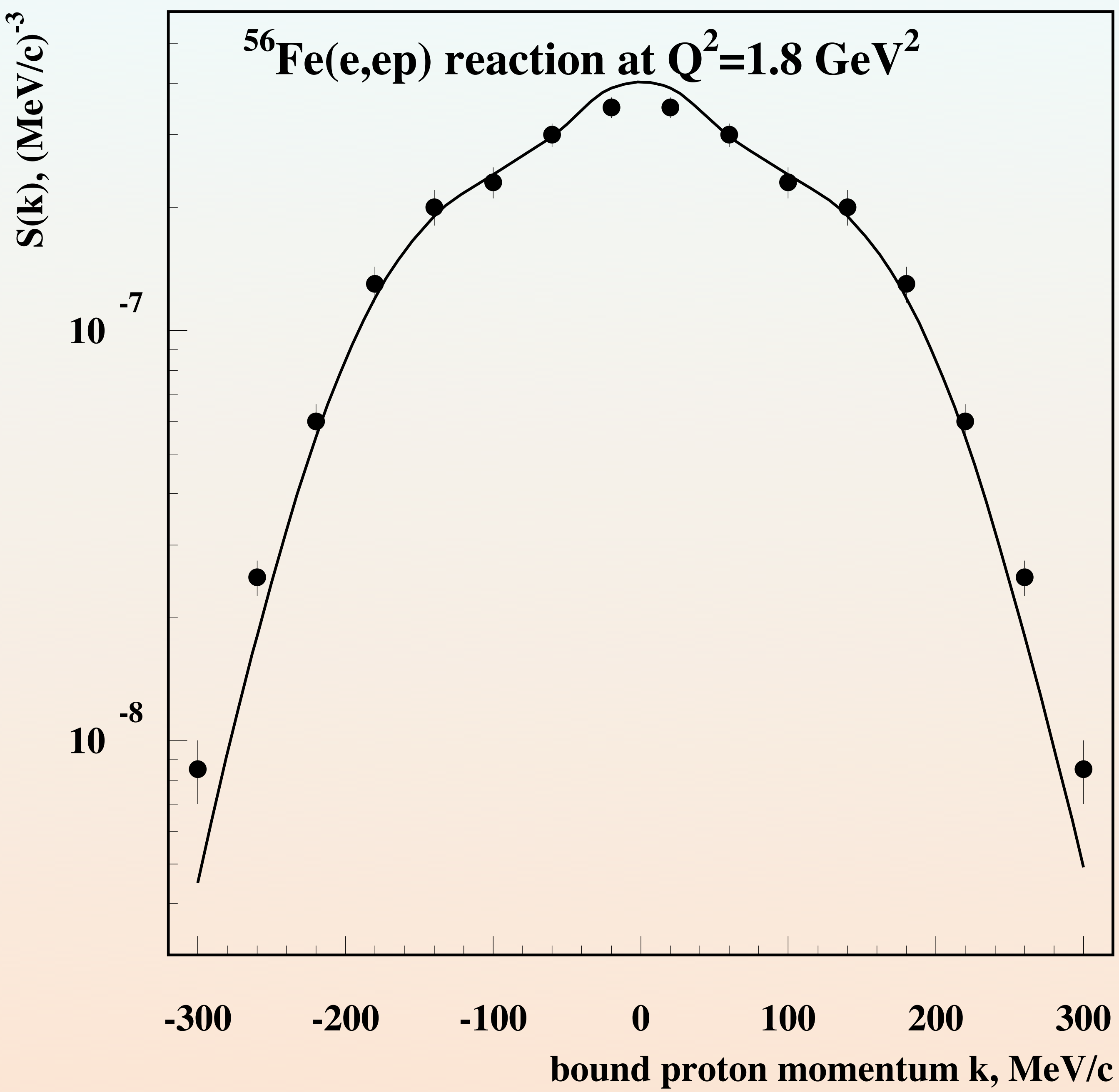
$$\sum_{\alpha} n_{\alpha}\left|\int d\,\mathbf{r}\,e^{[i\mathbf{k}\cdot\mathbf{r}]}\,\phi_{\alpha}(\mathbf{r})\left\langle(A-1)\right|\prod_{j=1}^{A-1}[1-\Gamma(\mathbf{b}-\mathbf{b_j})\theta(z-z_j)]\left|(A-1)\right\rangle\right|^2.$$

$$\Gamma(\mathbf{b}-\mathbf{b_j})=(2\pi ip)^{-1}\int d^2q_t\,exp[-\mathbf{q_t}\cdot(\mathbf{b}-\mathbf{b_j})]\cdot f_{NN}(\mathbf{q_t}),$$

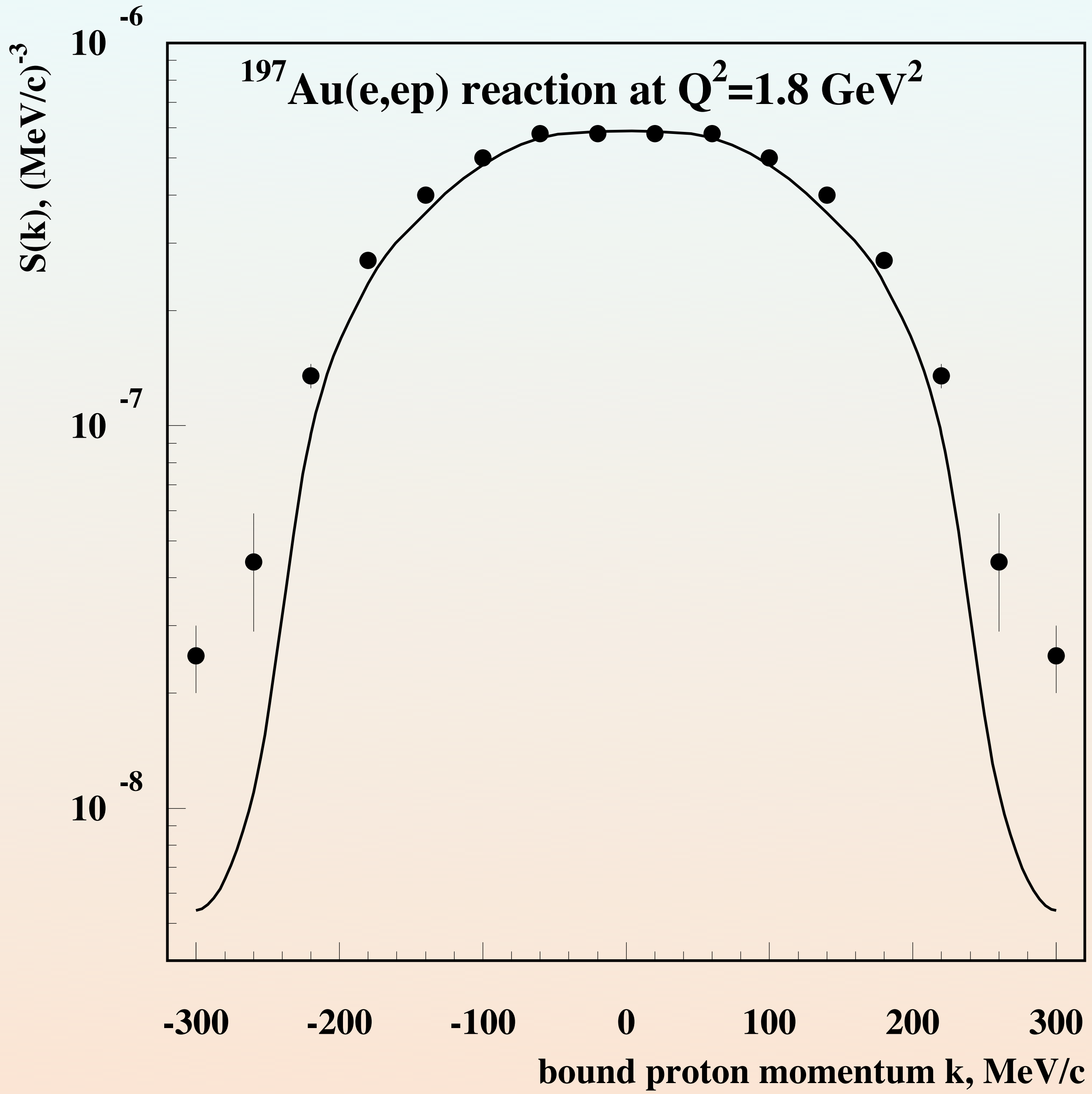
$$f_{NN}(\mathbf{q_t})=\frac{p\sigma_{pN}^{tot}(1-i\kappa_{NN})}{4\pi}e^{-\frac{B^2q_t^2}{2}}.$$



$^{12}C(e,ep)$ reaction at Q^2=1.8 GeV^2
S(k), $(MeV/c)^{-3}$
10^{-7}
10^{-8}
10^{-9}
-300
-200
-100
0
100
200
300
bound proton momentum k, MeV/c

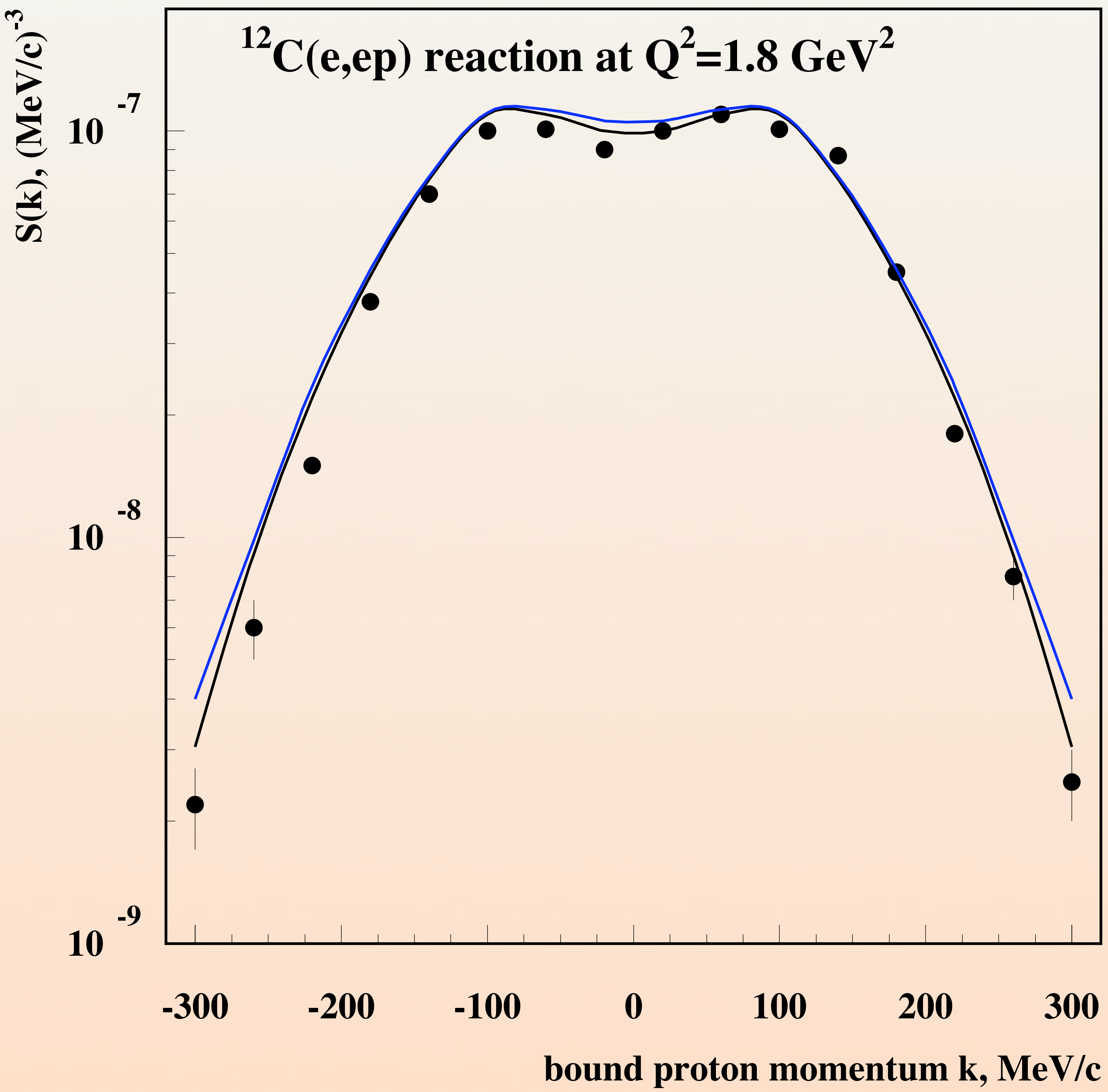


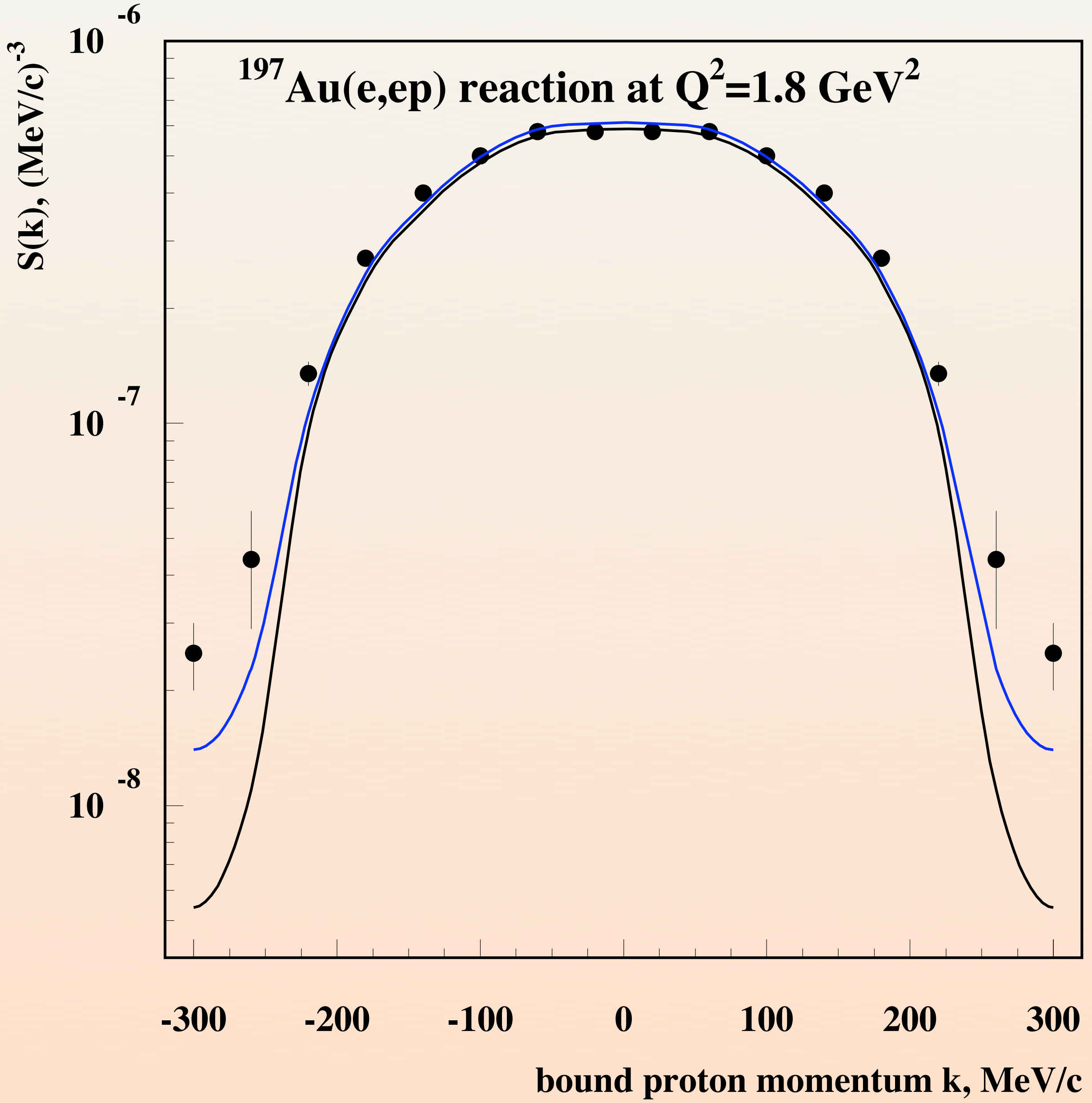
$^{56}Fe(e,ep)$ reaction at Q^2=1.8 GeV^2
S(k), $(MeV/c)^{-3}$
10^{-7}
10^{-8}
-300
-200
-100
0
100
200
300
bound proton momentum k, MeV/c



^{197}Au(e,ep) reaction at Q^2=1.8 GeV^2
S(k), (MeV/c)$^{-3}$
10^{-6}
10^{-7}
10^{-8}
-300
-200
-100
0
100
200
300
bound proton momentum k, MeV/c

Eikonal approximation usually neglects change of the transverse nucleon momentum in the final state rescatterings. We checked that account of this effect leads to a small correction for k<200 MeV/c





(b) Study the transparency which is defined as

$$\mathbf{T} = \frac{1}{\sigma_{pwia}} \int_{\Delta^3 k} d^3\, k \int_{\Delta E} d\, E\; d\, \sigma_{exp}(\mathbf{k}, E) \equiv$$

$$\equiv \frac{\int_{\Delta^3 k} d^3\, k \int_{\Delta E} d\, E\; S^{exp}(\mathbf{k}, E)}{\int_{\Delta^3 k} d^3 k \int_{\Delta E} d\, E\; S(\mathbf{k}, E)}$$

To determine reliably T it is crucial to test how realistic is the model of S(k,E). We used (e,e') data at x=1 and Q^2=1 - 2 GeV^2 where inelastic contribution is still very small (and we corrected for it).

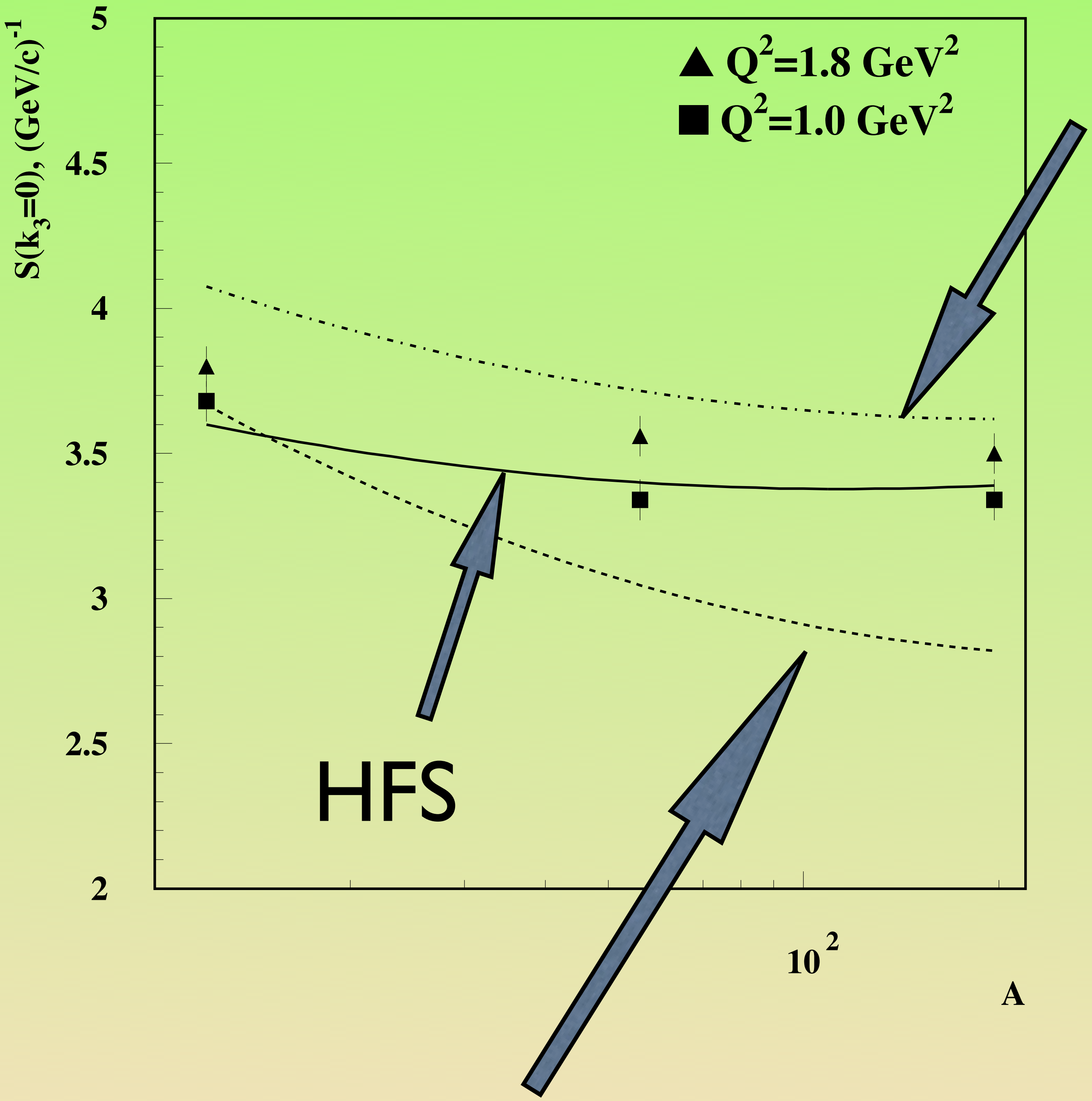
Key point: in transverse kinematics at x=1 and in inclusive case - (e,e') at x=1, the same integral

$$S(k_3=0)=\frac{1}{2}\int S(\mathbf{k},E)\frac{d^3k}{k}dE$$

High-momentum component of S gives much smaller contribution to this integral than to the d^3k integral

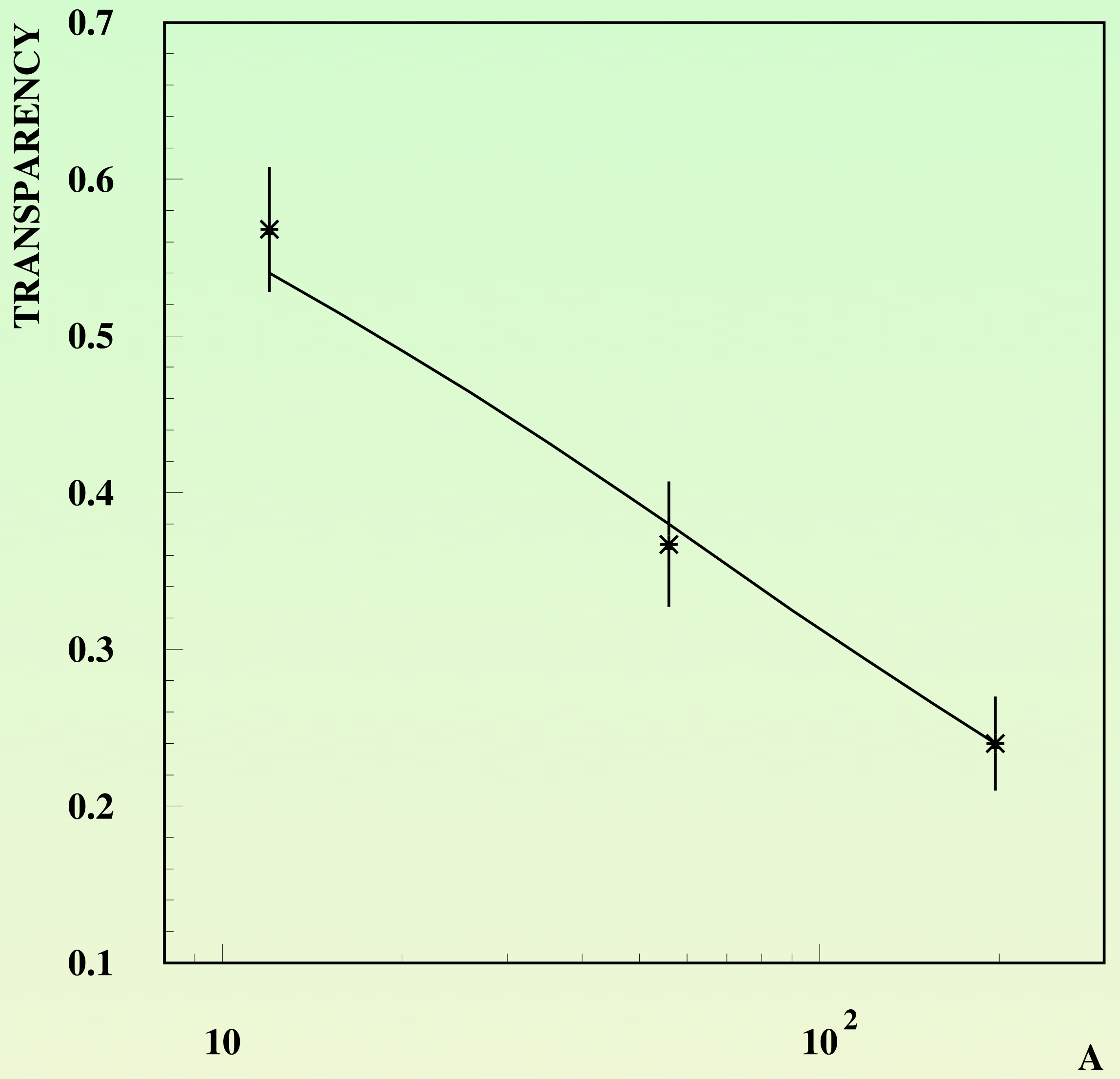
In the data analysis by high energy groups the data for transparency were corrected for the region not measured in the experiment based on the information provided by V.Pandharipande who gave numbers for the d^3k integral . Renormalization was quite large 0.9, 0.82, 0.78 for A=12,56,197.

Miscommunication between theory & experiment.



Shell model used in exper.papers

Result of renormalization applied in exper. papers.



Comparison of transparency calculated using HFS spectral function with the data. No room for large quenching, though 10-15% effect does not contradict to the data.

Small quenching in NE-18 is consistent with a small strength at large excitation energies for the momentum range of the experiment (R. Milner - private communication)

Substantially smaller value of quenching for large momentum transfer/high resolution is likely to be due to different effective degrees of freedom at low energies (absorbed in the renormalized effective interactions/ optical potential?)

Analogy with quantum field theory where effective Hamiltonian always changes with resolution.

It is well known that quasiparticles of Fermi liquid /Migdal theory have effective masses quite different from the free nucleon mass. Magnetic moments are renormalized. Could radii be renormalized as well? For example

$$r^2_{eff}/r^2 \sim m_N/m_{Neff}$$

Photon absorption by a quasiparticle:

$\gamma^* + q.p. \rightarrow N?$

$\gamma^* + q.p. \rightarrow N \mp$ excitation energy ?

In view of inherent uncertainties of interaction models which are at least 5%, it is hardly possible to measure directly quenching at large in Q^2 in a reliable way if it is $\leq 15\%$.

A much better way would be to perform measurements at

$Q^2 = 2\ \mathrm{GeV}^2$

for small nucleon momenta at high excitation energies. No reasons to expect similar high/low energy ratio as at low Q if the change of the quenching is due to renormalization of interaction.

To test calculations of nuclear transparency it would be advantageous to perform (p,2p) experiments with high missing energy/momentum resolution in the symmetric kinematics:

$$\theta_{c.m.}=90^o,\ T_p^{inc}=2\text{GeV}.$$

In this case $T^f_1=T^f_2=1\text{GeV}$, the same as the proton in (e,e'p) at $Q^2=2\ \text{GeV}^2$.

The ratio of transparencies in electron and proton case would be practically a pure test of the accuracy of the eikonal approximation, and hence ultimately would allow more precise measurement of quenching at high energies.

(e,e'p) at $Q^2 \geq 4 - 6\ GeV^2$

Two competing phenomena:

- Graduate onset of color transparency - first due to suppression of the pion field, next due to squeezing of 3 quarks in the nucleon.

- Suppression of point-like configuration in bound nucleons - analog of the EMC effect, leading to suppression of the high-momentum component of the spectrum: $\propto 1/(1+k^2/\Delta)^2$ FS85

These studies would be impossible without detailed investigation of (e,e'p) reactions at lower Q.

Conclusions.

- Quenching at high resolution is modest.
- It is natural to expect a decrease of quenching with resolution.
- Further systematic studies of (e,e'p) with high resolution and wide angular, recoil energy coverage are necessary for $Q^2 \sim 2\ GeV^2$. They should be complemented by (p, pN) studies in symmetric configuration at energies 2-4 GeV.
- These studies will be important also for the future investigations of color transparency.