Quasi-elastic scattering and Spectral Function

Ingo Sick

remembering a fruitful collaboration with Adelchi

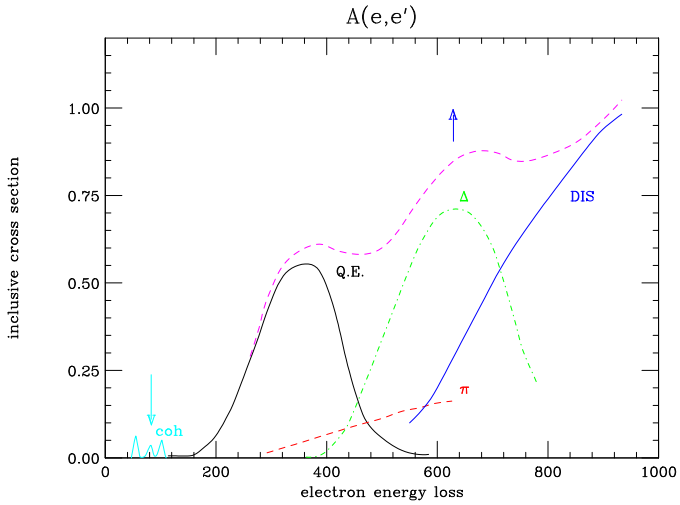
Contents:

what I learned on q.e scattering over the years
strongly influenced by collaboration with Adelchi

Two parallel lines of research

my experimental interest in q.e. (e,e')
theory of nuclear matter (NM)
Adelchi, Omar, Stefano, Vijay, ...

came together in 1989 with work on
'Scattering of GeV electrons by NM'



Discuss first my interest in (e,e)

My first contact with QE scattering: at HEPL

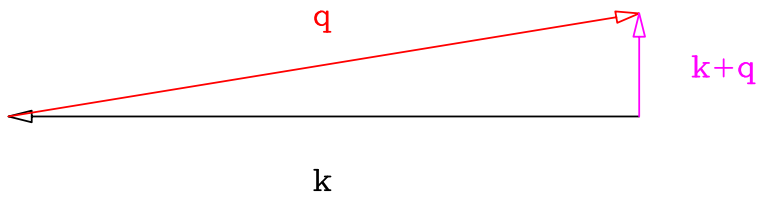
dynamical determination of Fermi momentum
curiously never redone
became *the* reference for Fermi-gas model

My longstanding interest: high-k components in nuclei from SRC

available at the time: many naive ideas:
(X,p) with backward going p
(π,p), (K,p) in kinematics not accessible with low-k nucleons
mainly sub-threshold production on nucleons

Main difficulty: FSI of strongly interacting projectile/reaction product

Follow-up work on (e,e'): study of region of low ω, large q



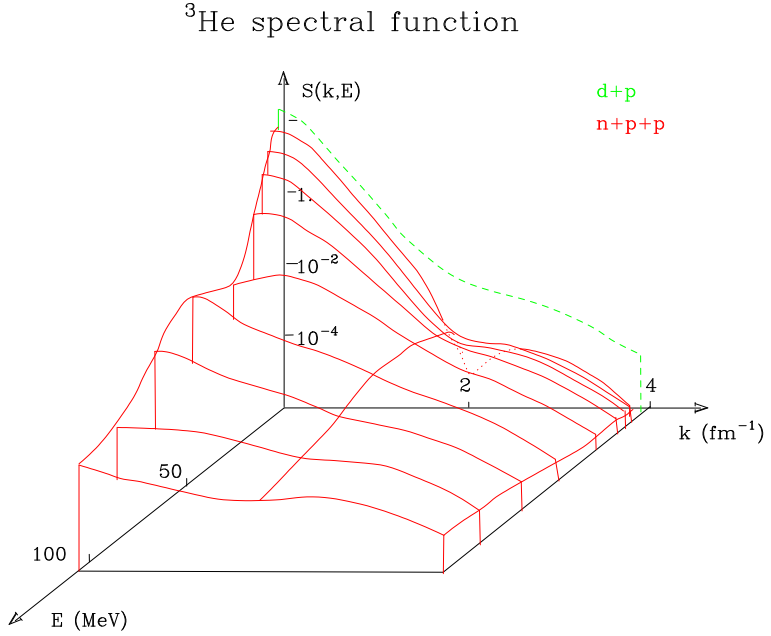
small $\omega \sim$ small $k + q \rightarrow k \sim -q$, large
observe only e $\rightarrow$ no FSI (... wrong, in retrospect)

^3He form factor experiment at SLAC in 1977

provided chance to do threshold-(e,e') experiment
parasitic beam time for 6 weeks
greatly increased interest in (e,e') as tool
discovered y-scaling

Important theoretical progress

first calculation of spectral function $S(k, E)$ by Dieperink, for ^3He
could be done as $\pm$ exact wave function (Faddeev) available



showed strong correlation large $k \Longleftrightarrow$ large E
was easily understandable
knockout of high-k nucleon leaves correlated partner with $-k$
which leaves nucleus, costs energy $\sim (-k)^2/2M$

Main progress: $S(k, E)$ allowed to calculate $\sigma(q, \omega)$ at large q in PWIA
but curiously did *not* explain scaling property
calculation of Sauer *et al.* showed importance of FSI

Suboptimal: limitation to ^3He

not exactly 'typical ' nucleus

although high-k probably not nucleus-specific

Idea: other case of $\pm$ exact calculation: nuclear matter

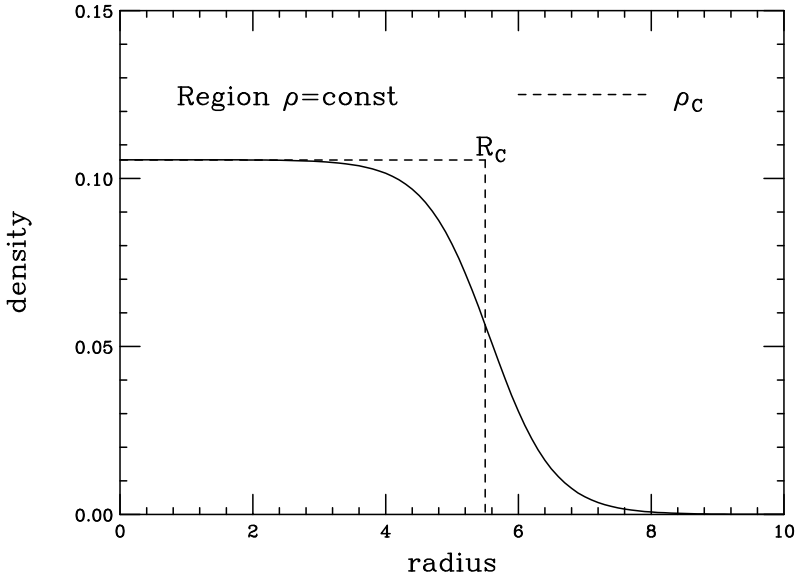
main problem: data for $A = \infty$

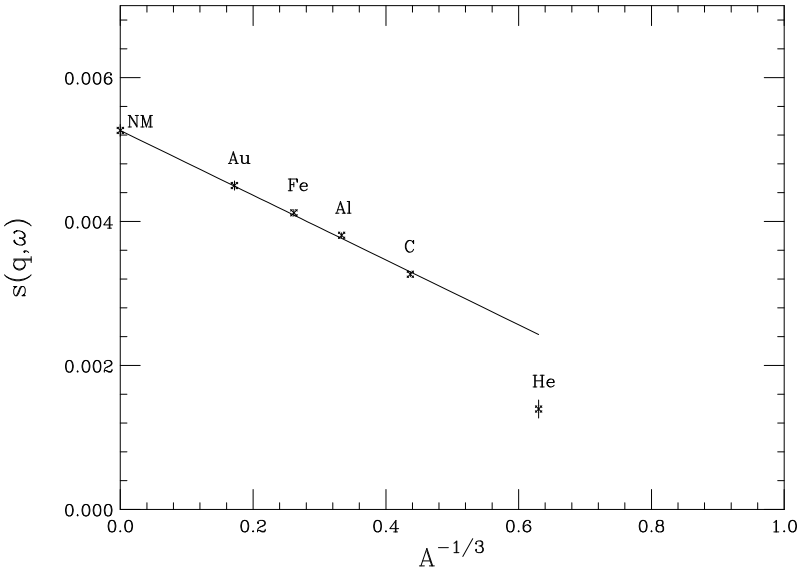
Idea: extrapolate from nuclei using LDA, as $q >>\sim$ short range

split conceptually density in two pieces $\rho(r) = \rho_C(r) + \rho_S(r)$

ρ_C independent of A, corresponds to NM

$\rho_S(r - r_C)$ universal, with r_C proportional to $A^{1/3}$





perfect extrapolation in $A^{-1/3}$, 1/3 verified, not possible in terms of A

Quasi-elastic scattering: theory side

Longstanding interest in LHe

deep inelastic neutron scattering from quantum liquids
strong short-range interaction similar to nuclei
presence of Bose condensate (δ-function peak) *vs* FSI
discussed in terms of $n(k)$

Work on $n(k)$ of NM

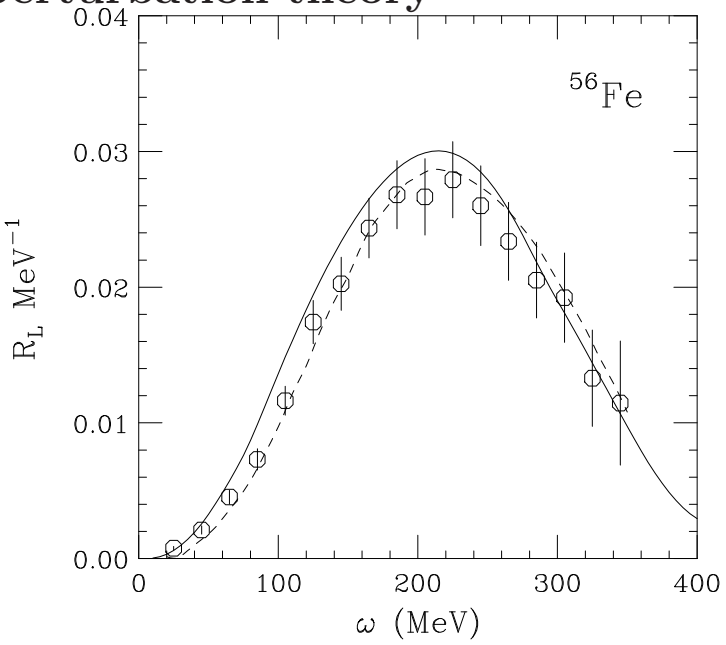
Stefano, Vijay
variational + 2. order correlated basis perturbation theory
v_{14}+TNI, ∼84
many insights, but still ...$n(k)$

Low-q longitudinal response of NM

Adelchi, Rocco, Stefano, Vijay
OCBF, 1p-1h + 2p+2h states
Urbana v_{14}+TNI, ∼88
importance of tails

Spectral function S(k,E) of NM

Adelchi, Omar, Stefano, 89
useful for high-q observables, PWIA



$S(k, E)$ for NM

Nuclear Physics **A505** (1989) 267–299
North-Holland, Amsterdam

THE NUCLEON SPECTRAL FUNCTION IN NUCLEAR MATTER

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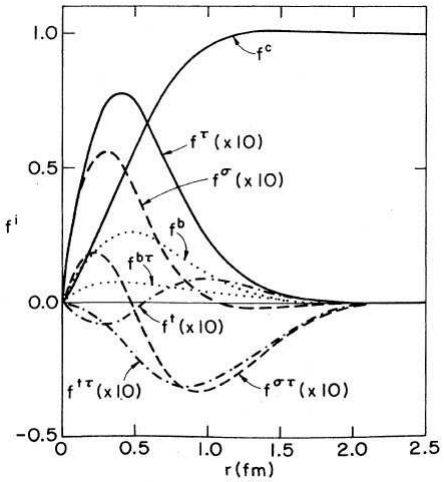
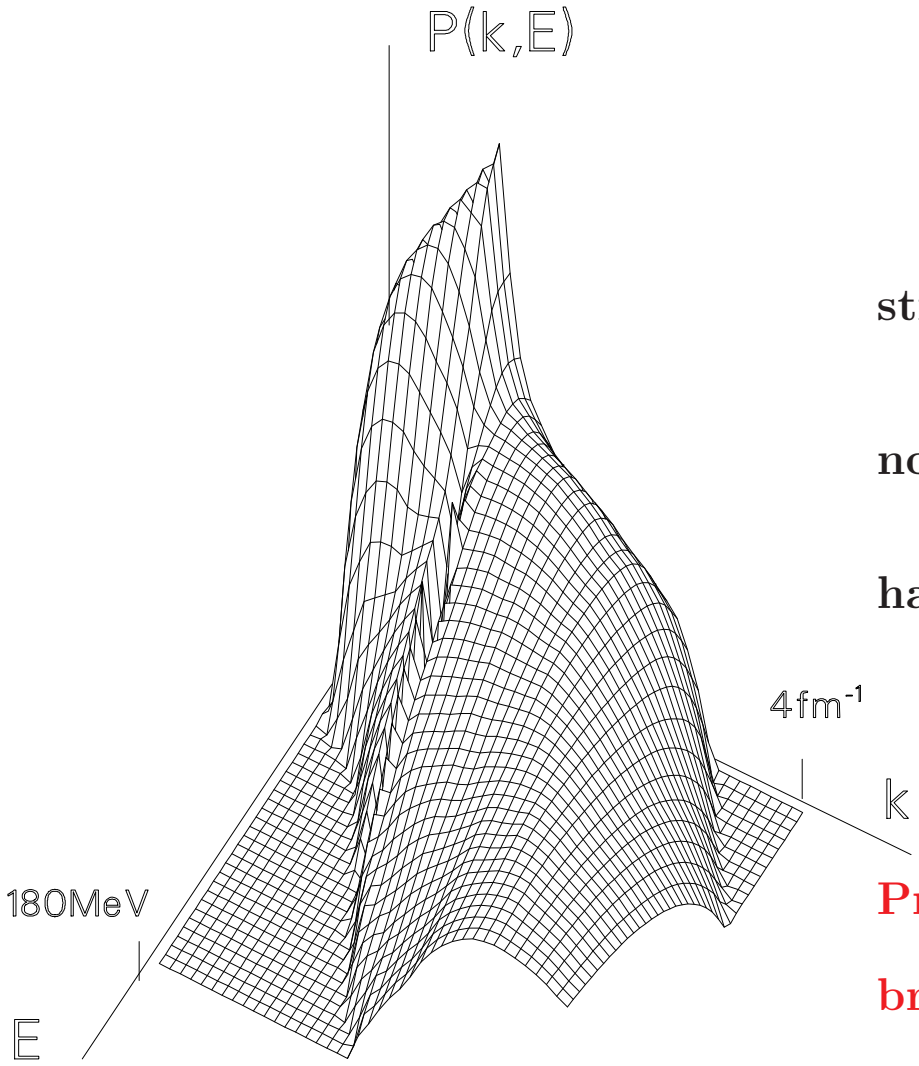


Use Correlated Basis Function theory

start from NN interaction fit to NN scattering
includes all NN short-range correlations
no shortcuts such as effective interactions, BHF, ...
bit the bullet, do the hard calculation
state-dependence of correlation functions

$S(k, E)$ shows the (by now) familiar features



strong correlation large $k \Longleftrightarrow$ large E
large $k \pm$ exclusively at large E

no point in looking for large k at low E

half of $\langle k^2 \rangle, \langle E \rangle$ from high-k tail
although tail has only 20% probability

Project to calculate (e,e') using $S(k, E)$

brought me into collaboration with
Adelchi, Omar, Stefano, Vijay

a collaboration going on since, ... with sadly red

collaborators

Project: calculate NM response at high q and $x > 1$

Main challenge: go beyond PWIA

- FSI known to be important from response of ^4He
- FSI corresponds to folding of IA response
  - with width proportional to ImV

Difference to scattering from ^4He

- for relativistic kinematics width of q.e peak $\pm$ constant
  - does *not* grow with q
  - folding does not get unimportant wit $q \to \infty$

Approach chosen: Glauber for recoil-N

- suitable for high q
- nucleon moves on straight line trajectory
- based directly on NN interaction
  - plus in-medium modifications

Main innovation: *Correlated* Glauber

- hit N surrounded by correlation hole
- leads to important reduction of FSI
- calculated using pair distribution function of initial state

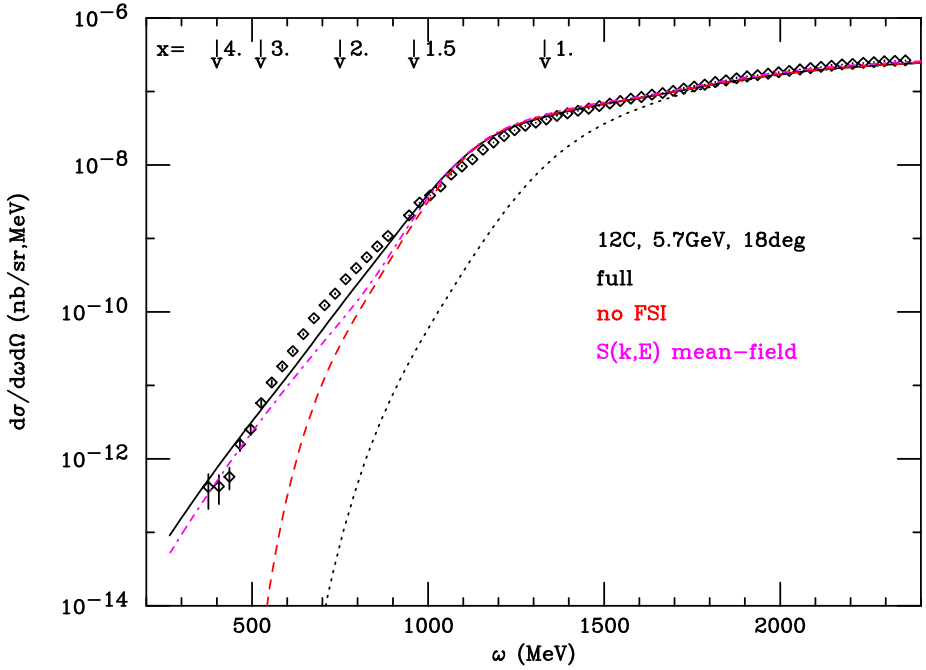
PS: during elaboration of approach at Pisa/Trieste originated idea of Elba meetings

Results of calculation (1991):

cross section in PWIA from $S(k, E)$
huge difference to calculation with $n(k)$

FSI using correlated Glauber theory
explains strong enhancement of σ in tail

FSI *not* small
FSI covers totally large-k!
FSI depends on $g(r - r')$
FSI proportional to density
FSI *additive*, peak $\rightarrow$ tail



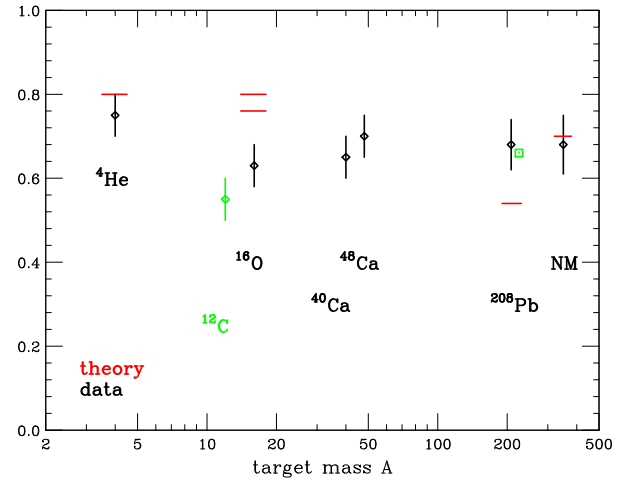
FSI explains convergence of $F(q, y)$ from *above*

followed by several papers on (e,e') at low ω

Thinking in terms of $S(k, E)$ has far-reaching consequences
location of strength in E

Occupation probabilities and hole strengths

quenching of SM occupation probabilities
= clear signature of correlations
experimentally seen in (e,e'p) and $\Delta\rho$ (Pb-Tl)$_N$



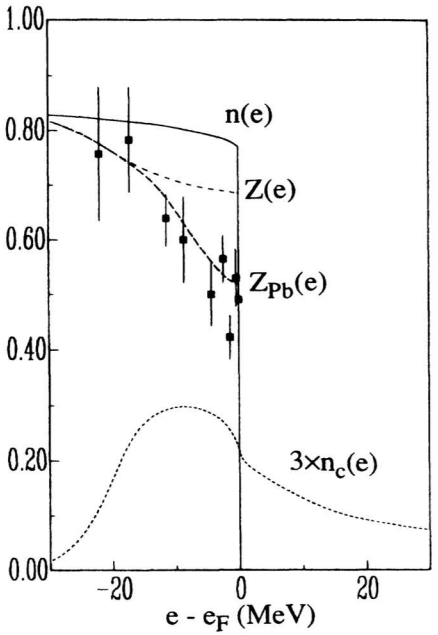
For NM: n(E) $\sim$ 0.8 for $E < E_F$

Quasi-hole strength Z

spread in E due to 2p-1h from correlations
quenches SP peaks
– – – Z(E)

Surface effect in finite systems

further reduction
- - - - - Z_{Pb}



Inclusive transverse response: added complication due to MEC

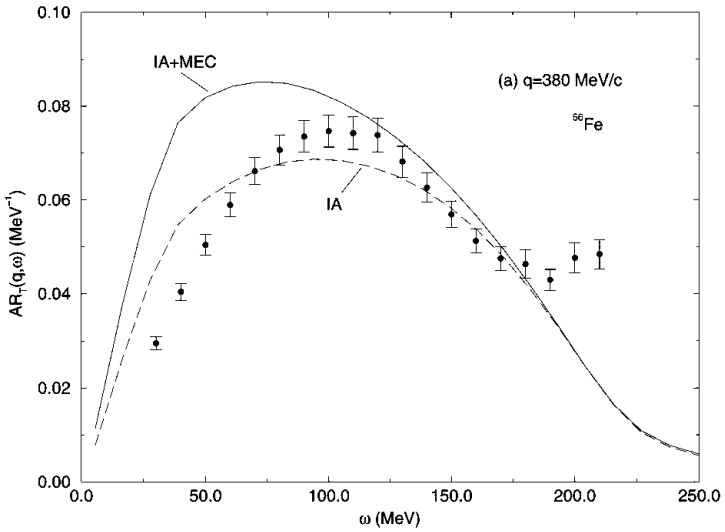
longstanding problem: enhancement beyond PWIA response
studied previously for A=3,4 via Euclidian response

Adelchi's calculation 1997

for nuclear matter, v_{14}+TNI
correlated basis function perturbation theory
300-550MeV/c (data for ^{40}Ca,^{56}Fe)
includes MEC, consistent with V_{NN}

Findings

MEC enhance transverse response
due tensor-isospin-dependent correlations
in contrast to Jastrow correlations
which *reduce* transverse response
effect small *without* correlations



for finite nuclei: see Alessandro's talk

One more theme in NM: EMC effect in DIS

describe DIS same way as q.e. scattering on N in nuclei;
take $k + E$ conservation seriously

DIS in terms of $\tilde{y}$

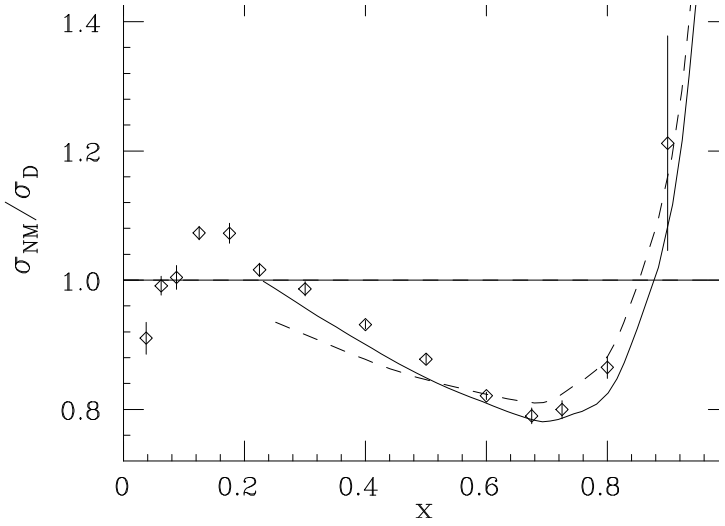
assume constituents = u, d-quarks, m$\sim$0
assume quarks to be off-shell
derive scaling variable in N restframe
$\tilde{y}$ = momentum component parallel to q

Can include N binding without conceptual difficulties

can use $S(k, E)$
get *large* E due to correlations

Compare to EMC effect in NM

extrapolated in $A^{-1/3}$ to A=∞
get 'too good' results



Largely ignored by DIS community, could not overcome habit to use x

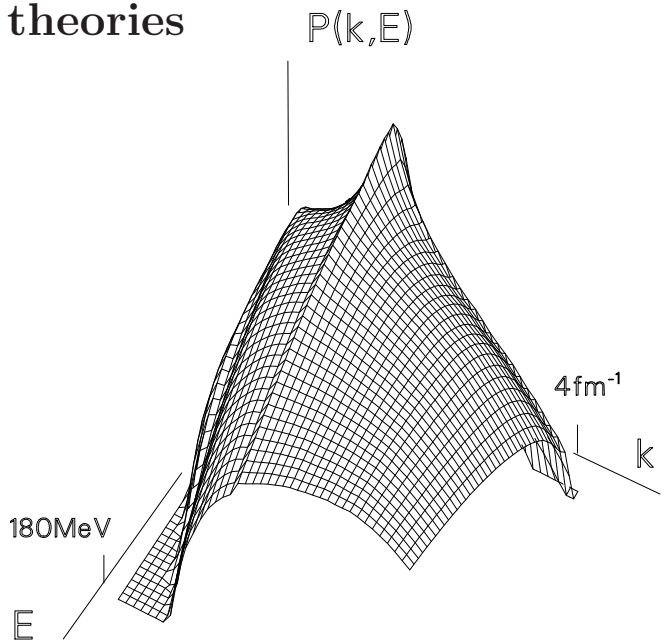
Extension to finite nuclei (1995)

availability of NM data limited
need $\sigma(q, \omega)$ for specific nucleus, L/T-separated data

Idea: split $S(k, E)$ into mean-field + correlated part

correlated part: short range
- can treat in LDA
- need S_{corr} for different NM densities

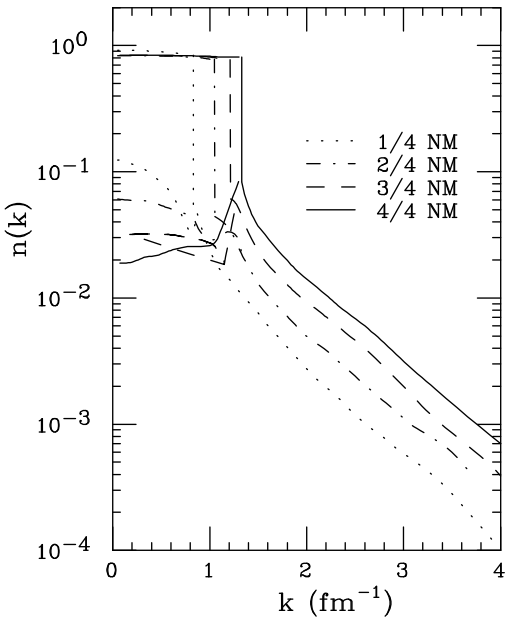
mean field part
- can calculate from standard mean-field theories
- or $n(k)_i$ from WS potential
  - with WS fit to (e,e)

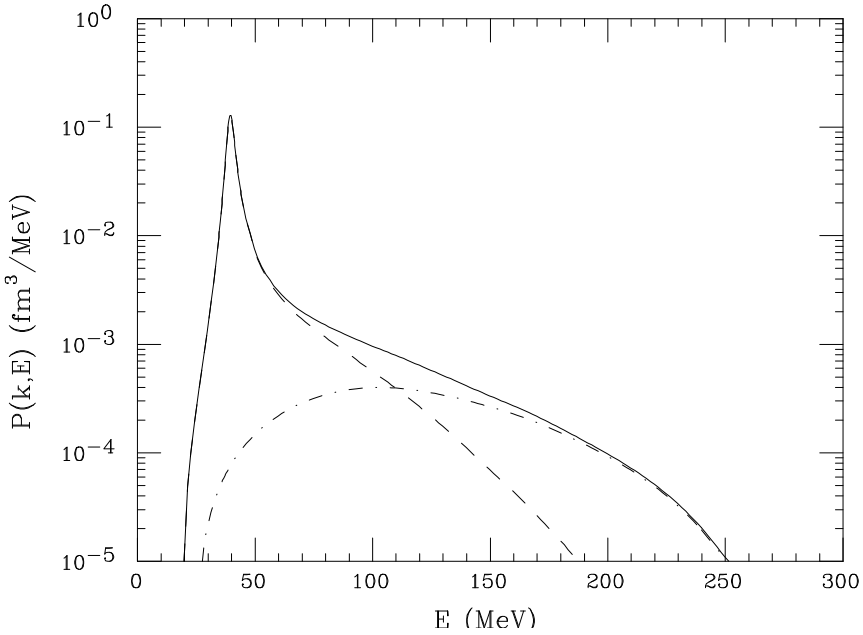


Adelchi's calculation for S_{corr}:

S_{mf} corresponds to 1p-1h excitations
S_{corr} accounts for np-nh excitations
OCBF theory
Urbana v_{14}+TNI interaction

Properties better seen in 1D-plots





correlated strength extends to below k_F
quasi-hole pole pretty independent of ρ

large-k tail quite universal

height QP peak increases with decreasing density
width decreases

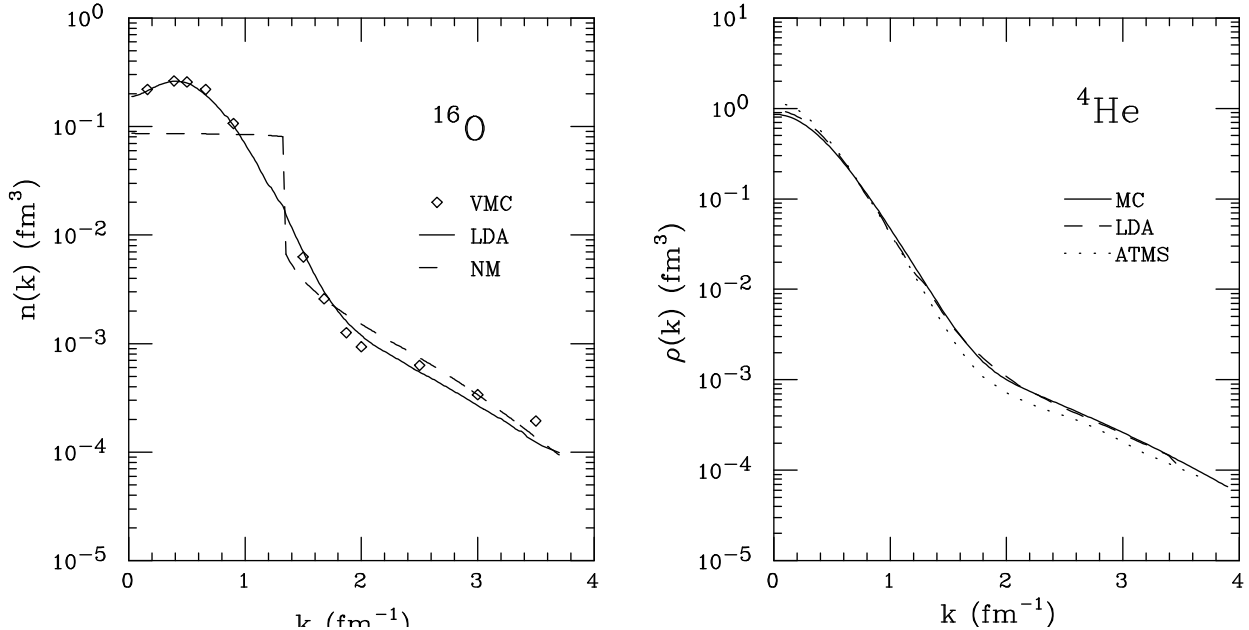
How good is LDA?

can test using $n(k)$

for cases where finite-nucleus calculation available

Oxygen

compare to VMC (Pieper *et al.*)



Can even try for ^4He where LDA very questionable

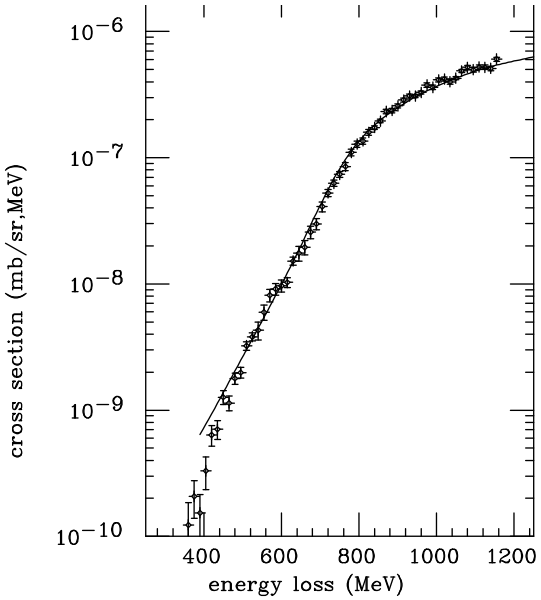
MC (Schiavilla *et al.*) and ATMS (Morita *et al.*)

find amazingly good agreement

Overall

can now calculate response for $\pm$ any nucleus
treat folding function (accounting for FSI) in LDA too
using correlated Glauber theory
find results very similar to NM

Example" Iron, 3.6GeV, 25°

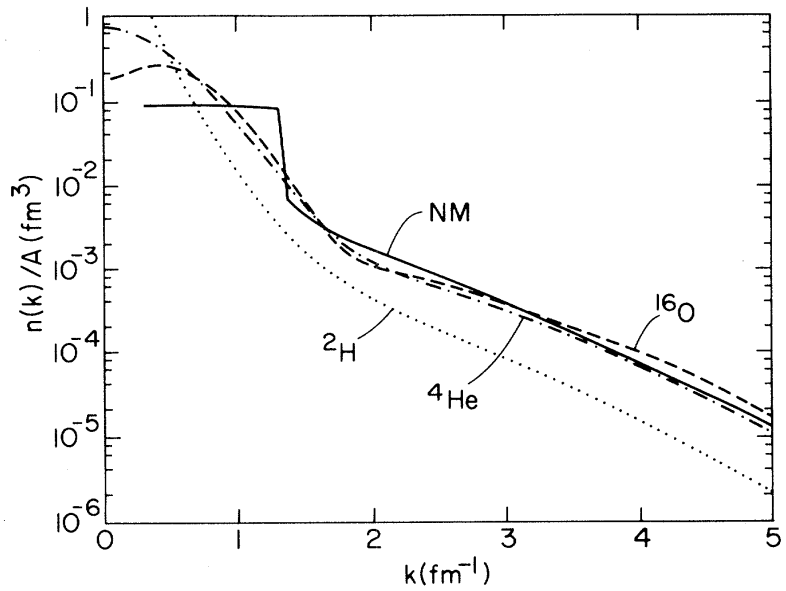


good agreement
LDA treats correctly evolution of $S(k, E)$ and FSI as function of A

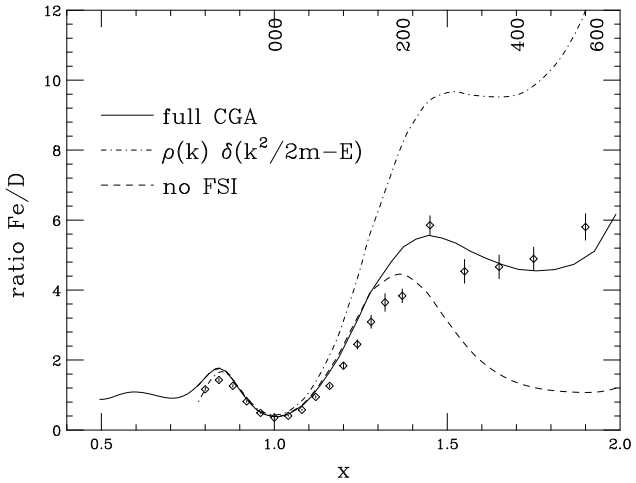
Still the only microscopic $S(k, E)$ for finite nuclei available

But use of $S(k, E)$ in (e,e') has not become 'mainstream'

simpleminded physicists still use $n(k)$
endemic at Jlab
$n(k)$ plot nice, but useless



Example: cross section ratios $^{56}Fe/^2H$



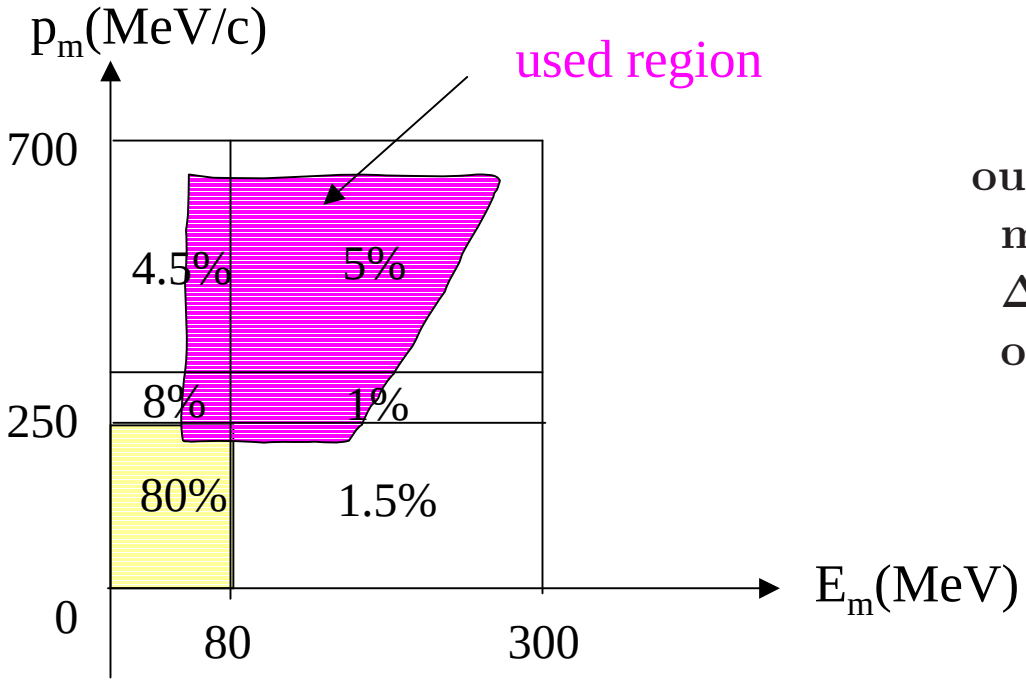
$n(k)$ gives totally wrong ratio
PWIA also totally wrong

Need $S(k, E)$ *and* FSI to get close to data

Since: measurement of $S(k, E)$ at large k, E by Rohe *et al.*

only experiment in as close as practical *parallel* kinematics

discuss only integrated strength



outside used region:

mean-field dominates

Δ too important

or no data

# of correlated protons in ^{12}C	used	total
integral over S from experiment	0.59	
integral over S from CBF	0.64	1.32
integral over S from SGGF	0.61	1.27

$\rightarrow$ good agreement

$\rightarrow$ can believe total from theor

$\rightarrow$ 20%, integrated over k, E

but both data and theory could stand some improvement

perhaps Omar's $Ar(e, e'p)$ experiment will move things along

Not so theory-oriented activity of Adelchi

Organization of Elba meetings

initially together with Omar, Stefano
starting in $\sim$ 1988

photo from $\sim$1989
practical organization done by Adelchi
with Laura again strong Pisa involvement

Meetings at Marciana

great service to community
interesting physics program
relaxed atmosphere
flexible organization

I enjoyed (all of) them very much