Vijay R. Pandharipande

Correlations and inclusive scattering

Vijay studied extremely wide spectrum of physics

covered by speakers of this meeting

concentrate on aspect familiar to me:

many-body physics, electron scattering

Vijay made important contributions

both in quantitative calculations

and qualitative understanding

Emphasis in this area: correlations

introduced by tensor- and short-range NN-force

11 of Vijay's papers have "correlations" in title

among which 2 of the 3 RMP-reviews:

"Independent particle motion and correlations in fermion systems"

"Electron-scattering studies of correlations in nuclei"

curiosity: "correlation" already in his first paper

Angular correlation measurements in decay of ^{115}Cd

Mean Field MF approximation

- standard for heavier nuclei
- reproduces many properties using fit parameters
- misses *many* important aspects

Interest of Vijay: role of correlations

- primarily NM (exact calculations)
- interplay single-particle ↔ correlated aspects
- understand qualitative aspects
  - needed for A>12 where exact calculations not feasible

Close relation to work on quantum liquids (L^3He, L^4He, ..)

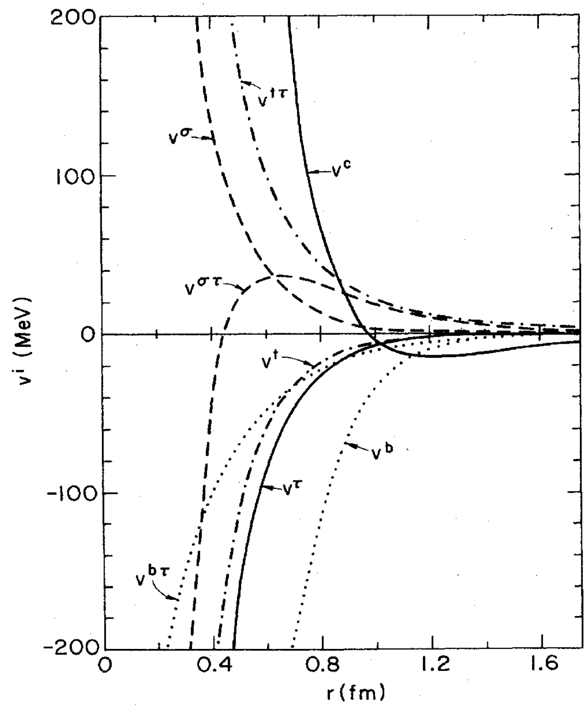
- interaction much simpler than V_{NN}
  - correlations easier to treat, although stronger
- calculations doable for finite systems (drops), not only infinite systems
- experimentally easier to isolate

My first collaboration with Vijay ($\sim$ 1986)

- role of correlations in (e,e') at large q, small ω
  - reaction with potential to elucidate correlations
- needed: quantitative description of FSI
- Vijay+collaborators developed *Correlated Glauber Theory*
  - includes correlations in final state as well

Origin of correlations: short-range structure of NN-interaction

strongly repulsive central term
short range tensor terms
various behaviors for different
spin-isospin channels



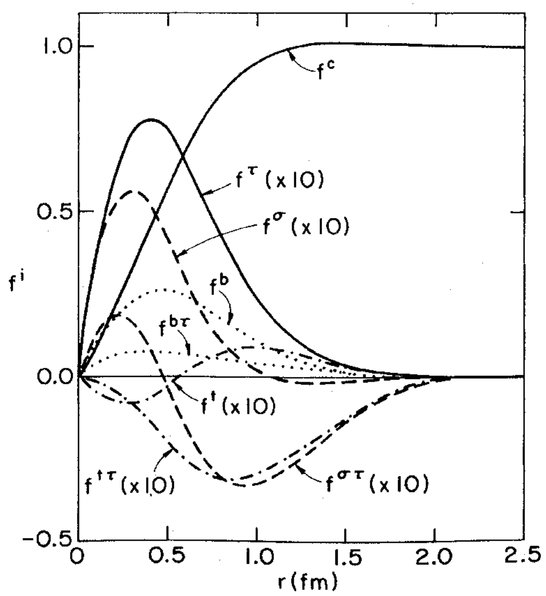
Effects of correlations

best exhibited in Correlated-Basis-Function approach
developed by Vijay and collaborators
Correlated wave function

$$|N) = \mathcal{S} \prod_{j>i} F(i,j)|N], \quad F(i,j) = \sum f^n(r_{ij})\mathcal{O}^n(i,j)$$

operator structure of F same as of V_{NN}
f's determined variationally

Result for NM



pronounced correlation hole for central component

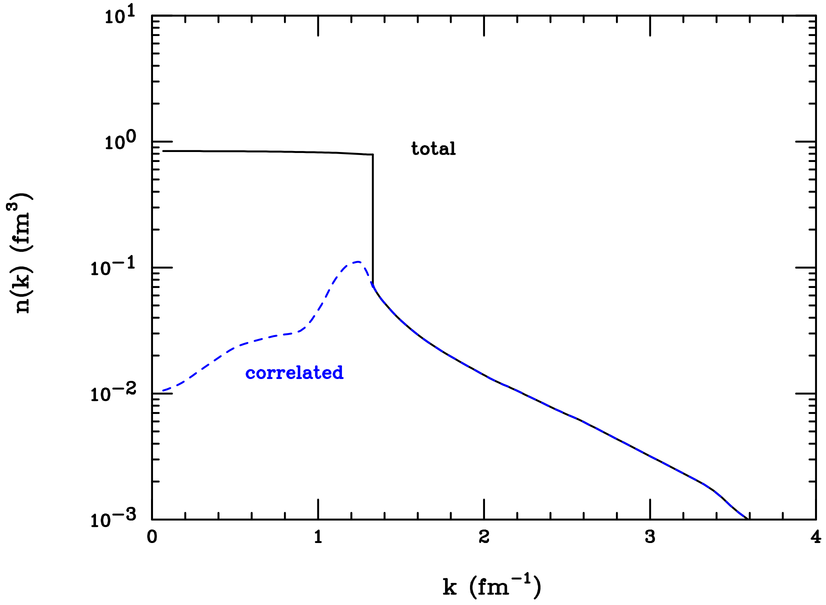
correlated nucleons provide:

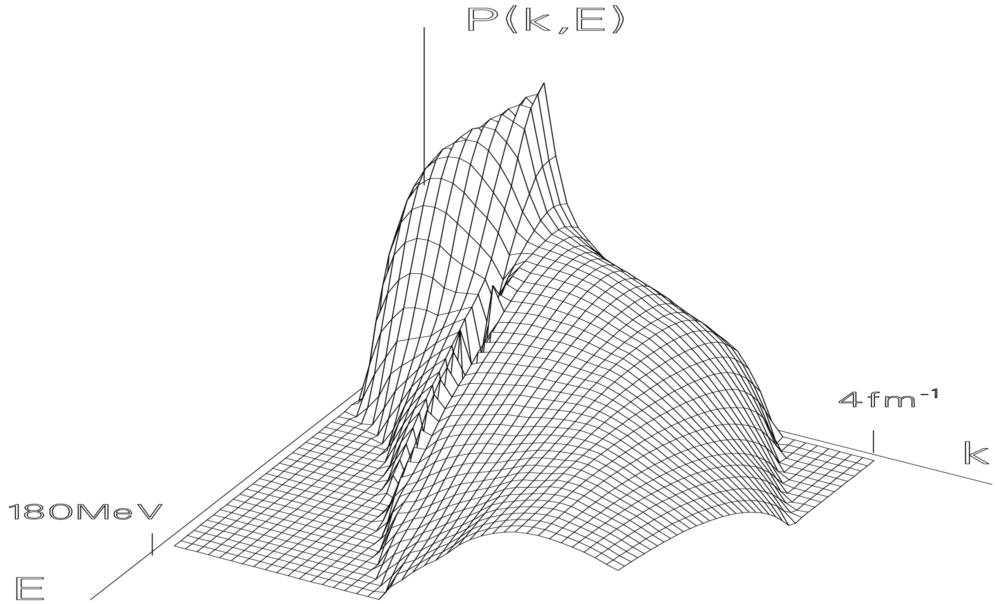
20% of strength
37% of average removal energy
47% of average kinetic energy
(CBF calculation of Benhar et al)

clearly: MF description cannot work

exception: *differences* of energies, spectroscopic factors

Consequences for nucleon momentum distribution $n(k)$ and spectral function $P(k, E)$





tail towards large momenta k and E *simultaneously*

MF ideas useful for *some* observables?

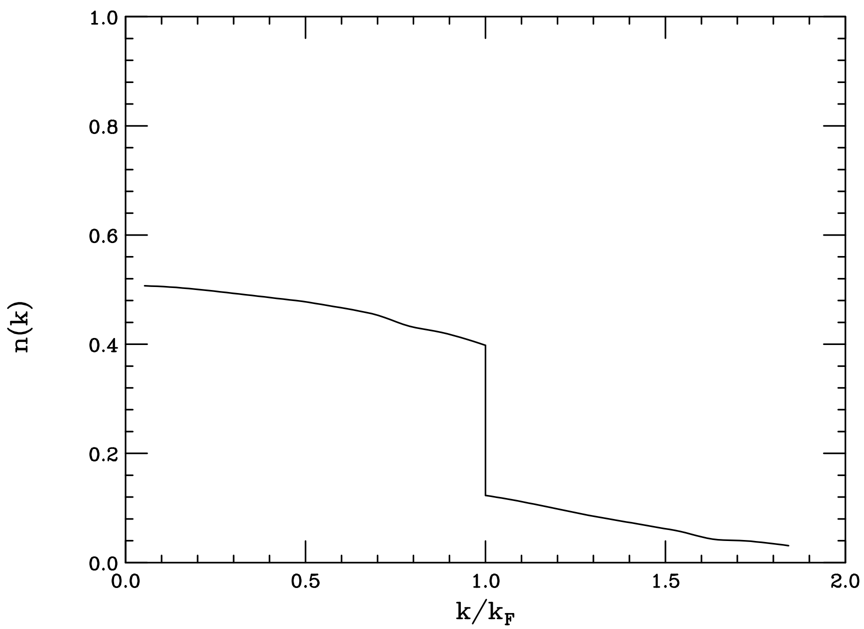
learn from studies of liquid Helium

Lennard-Jones potential $r^{-12} - r^{-6}$ even more repulsive at small r

But

find quasi-particle states for $k < k_F$
with much *reduced occupation*
occupation of MF states $\sim 30\%$
= size of discontinuity at k_F
rest moved to $k > k_F$ mainly

"depopulation" of MF states
= main consequence for MF



Shown by Moroni et al

via calculations for L^{3}He and L^{4}He

depopulation similar for bosonic/fermionic systems

mainly consequence of short-range V_{NN}, not Pauli principle

Finite systems

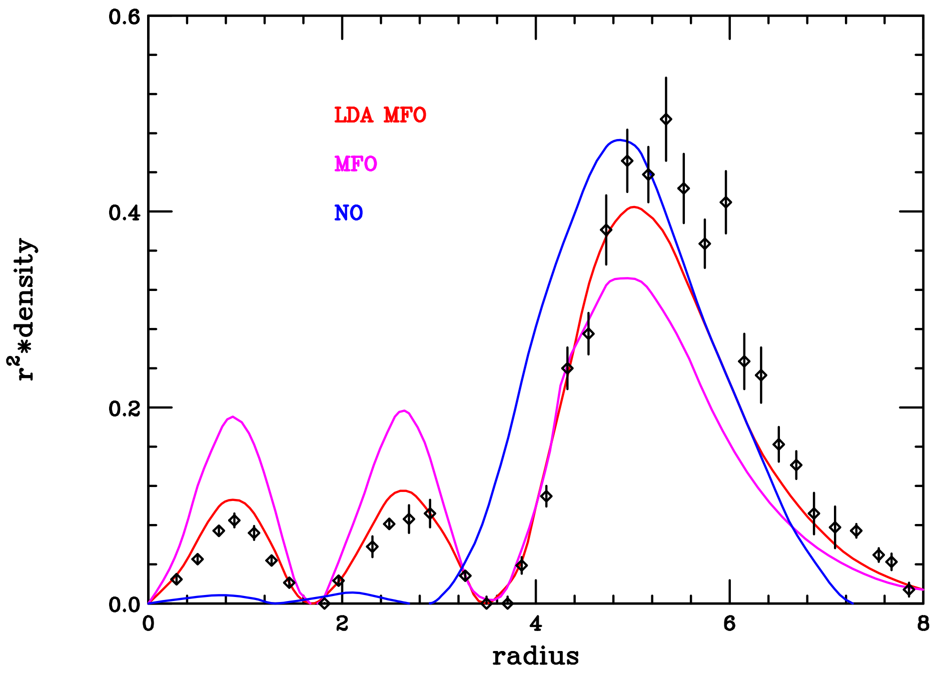
more complicated
"occupation" requires concept of "orbit"
not a priori obvious which:
mean field, overlap, natural, ..?

Studies of Vijay of L^{3}He drops

Variational Monte Carlo
drops with A, A-1 atoms
deduce difference

find

for *e.g.* 3s-state



quasi-hole orbital close to MF orbitals +LDA (———)

$\psi_{QH} = \psi_{MF}\sqrt{z(\rho(r))}$ z=renormalization

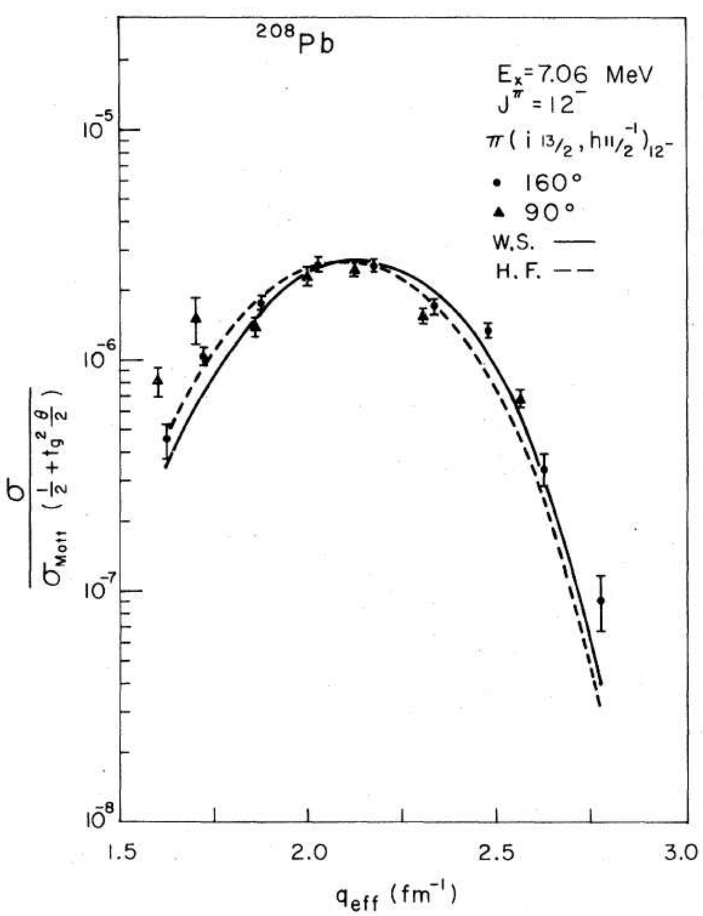
= quantities observable in transfer, (e,e), (e,e'p)

Experimental observation of depopulation

long in coming
decades of transfer reactions, no occupation numbers
only asymptotic normalization
no integral properties

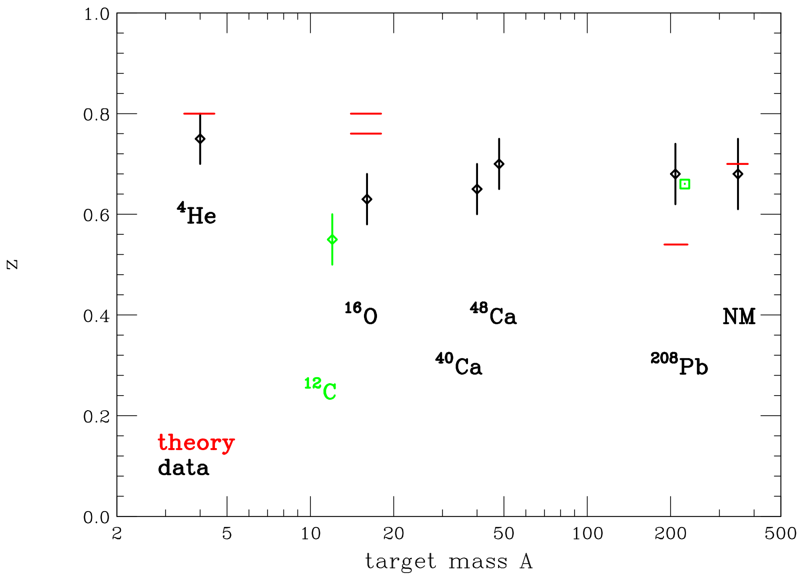
Early evidence on partial occupation

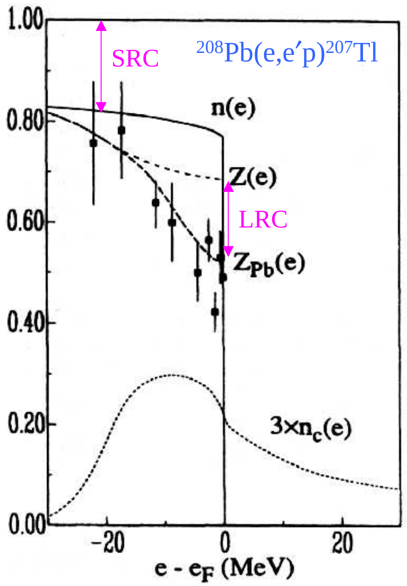
inelastic (e,e), high multipolarity
little affected by configuration mixing
sensitive to interior
analyzed by Vijay and collaborators



Systematic studies of (e,e'p)

more sensitive to nuclear interior
measure $n(k)$ *and* absolute strength



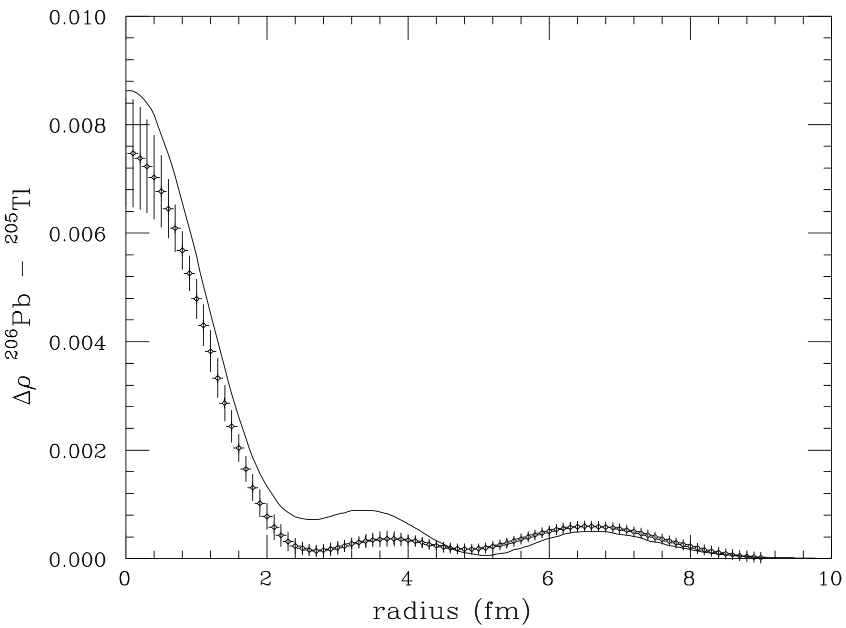


occupation $\sim$ 0.7 (outer shells)
without surface + LRC effects $\sim$ 0.8

striking erxample: 3s-state in nuclei

$^{206}Pb -^{205}Tl$

(e,e) sensitive to interior
radial distribution $\sim$ MF orbit
but: occupation = 0.7



”Missing” strength

- **up to recently only seen *lack* of strength**
  - **large $\boldsymbol{k}, \boldsymbol{E}$-strength not observed**

difficulties

- **spread over ∼200 MeV**
- **in (e,e’p) covered by multi-step reactions**
  - **of type (e,e’p) followed by (p,2p)**
- **1-2 orders of magnitude larger than correlated strength**

Recent Jlab data, hall-C: Rohe *et al.*

- **identify means to minimize background:**
  - **parallel kinematics, large q**
- **cover region of large $\boldsymbol{k}, \boldsymbol{E}$**
  - **A = 12 ... 197**

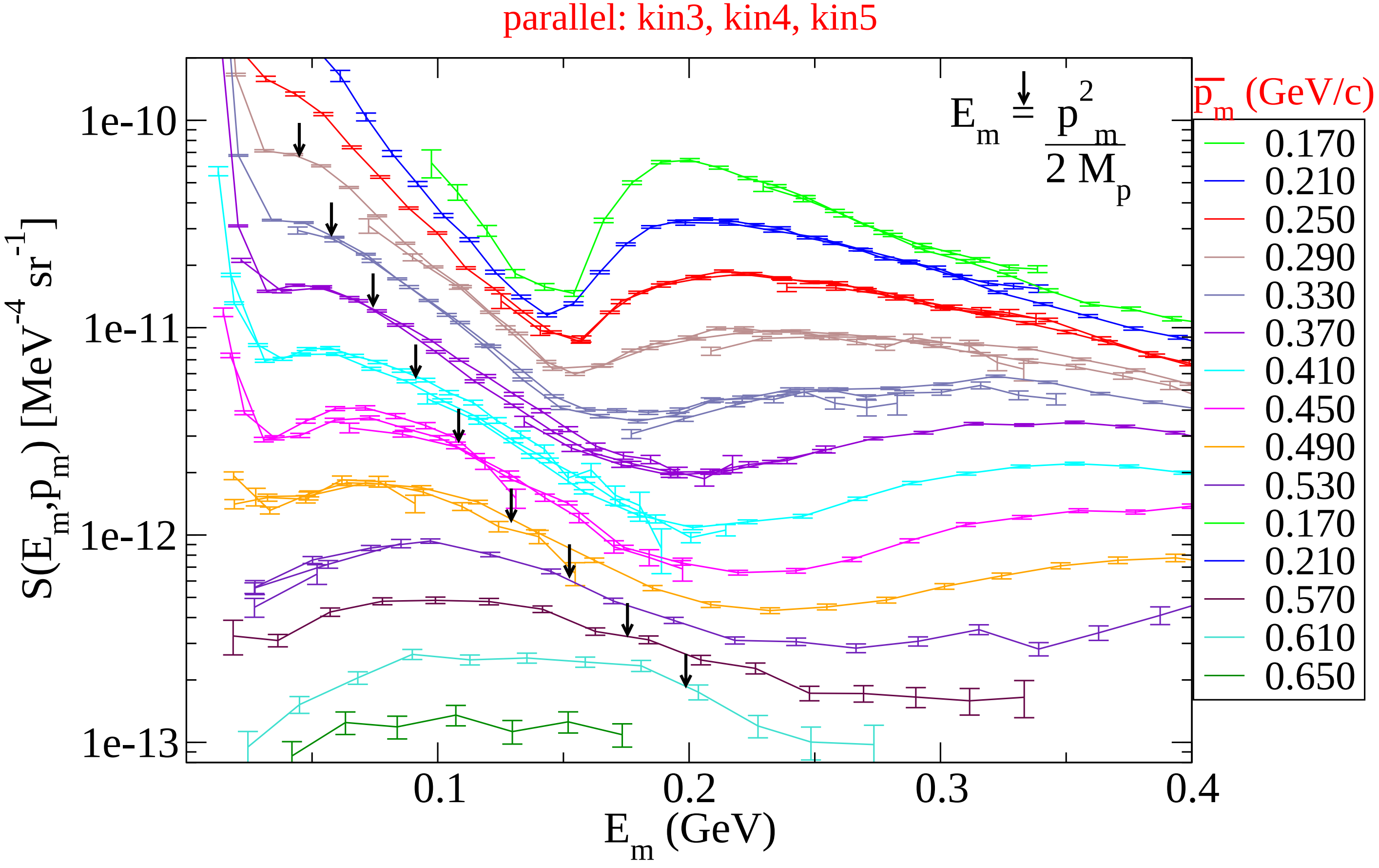
Results

test: single-particle region, kinematics with same $E_{p'}$ as production runs

use: calculated T=0.6, integrate over E <80MeV

find: occupation agrees with CBF $P(k,E)$

correlated region



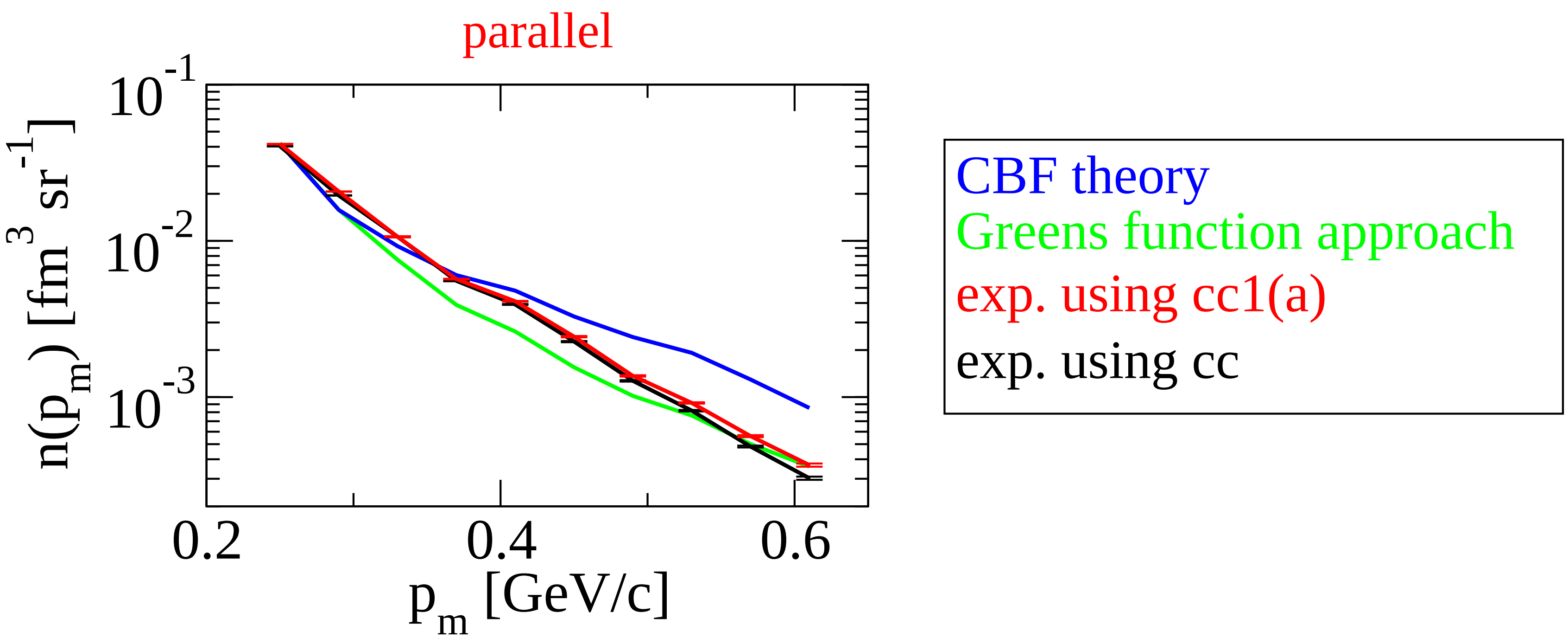
main observation on E-dependence

maximum of $P(k,E)$ of theories at too large E

understood by recent calculation of Müther+Polls?

selfconsistent GF theory, ladder approximation, finite T

momentum dependence



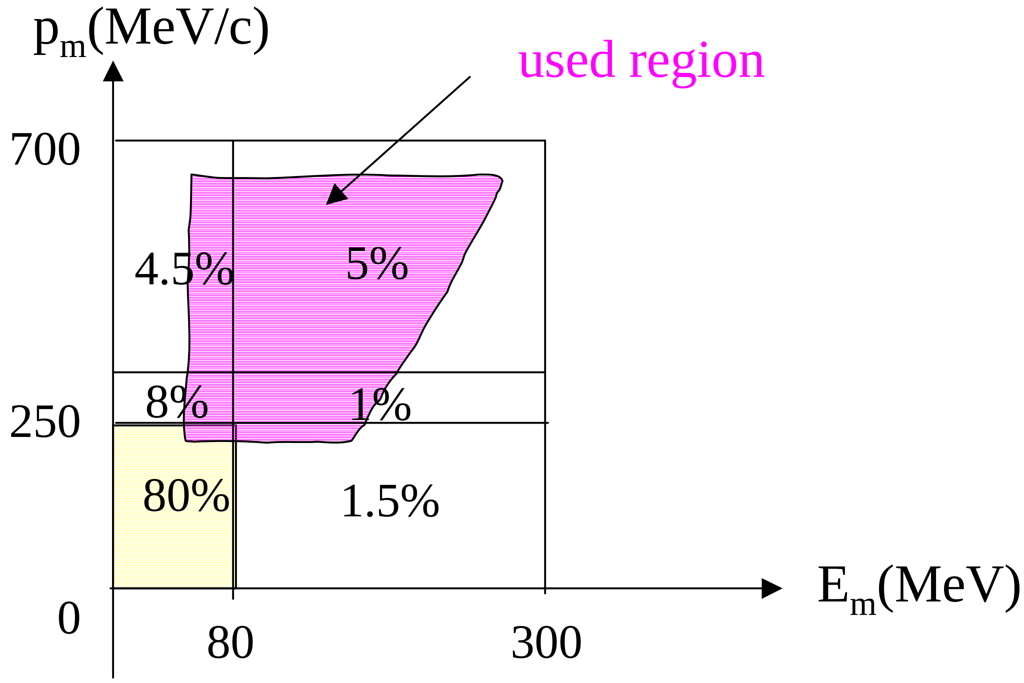
→ theory and experiment ± agree

How much correlated strength??

cannot integrate over entire correlated region

FSI and Δ-excitation and part of QP strength limit

integrate over 'clean' region, both data and theory, cover 50% of correlated strength



result

integral over P from experiment	0.55	→ good agreement
integral over P from CBF	0.59	→ can believe correlated strength from theory
integral over P from GF approach	0.53	→ 20%, integrated over $\boldsymbol{k}, \boldsymbol{E}$

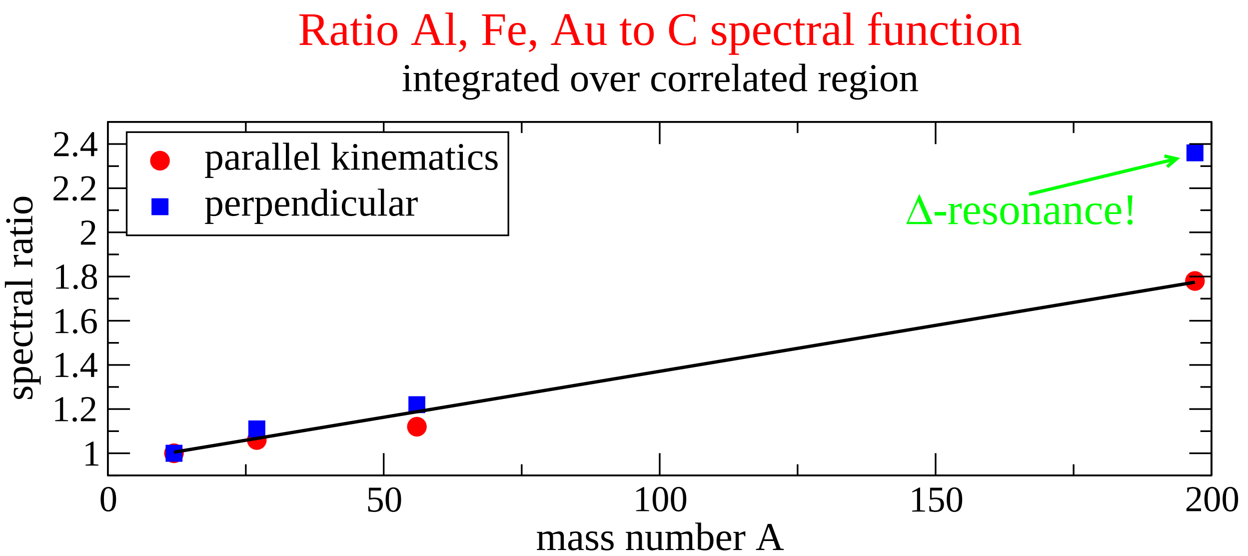
heavier nuclei

experiment performed for C, Al, Fe, Au

interest in A>>

→ nuclear matter (remember Vijays way of counting: 1, 2, 3, 4, many)

ratio to C of correlated strength



enhancement for Au

not yet understood

consequence of tensor correlations as $N > Z$?, rescattering ?

some enhancement explained by $S(k,E)$ for N≠Z

Orthogonal look

where correlated strength in r-space?

not obvious: large k $\longrightarrow$ large l $\longrightarrow$ large r?

large E $\longrightarrow$ small r?

Approach

from (e,e) get charge density of ^{12}C

unfold nucleon to get point-density $\rho_{point}(r)$

from (e,e'p) get quasi-particle $n(k)$

Fourier transform to get $\rho_{QP}(r)$

$$\rho_{point}(r) - \rho_{QP}(r) = \rho_{corr}(r)$$

find:

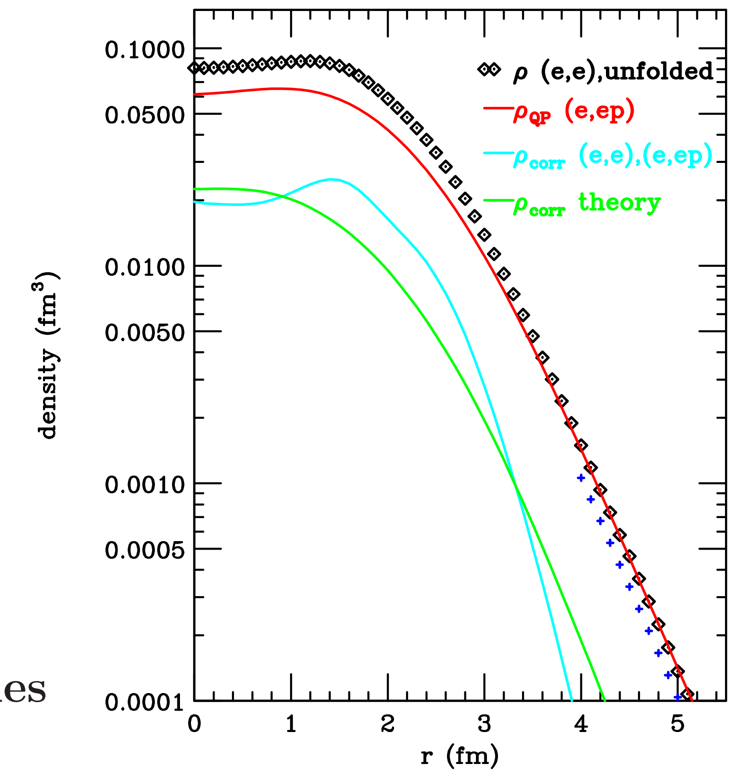
$\rho_{corr}(r)$ concentrated toward nuclear center

gives 30% contribution to $\rho(r = 0)$!

$\cong$ selfconsistent Greens function theory

explains why MF calculations work poorly

... but $\pm$ OK for surface-dominated observables



Correlations and NM equation of state

correlations decisive at higher nucleon densities
indispensable for *e.g.* neutron stars
see talk of Chris Pethick

Inclusive scattering: important area of Vijay's activities

X-ray scattering from LHe
neutron scattering from LHe (see talk Toni Legett)
electron scattering from nuclei
nucleon structure functions

goals

LHe momentum distributions
Bose condensate fraction in LHe ($k = 0$)
NN correlations in nuclei (high-k tail of $n(k)$)
role of binding of constituents
role of final-state interactions

discuss a few examles

Work on (e,e'): development of correlated Glauber theory

potential to measure effect of correlations

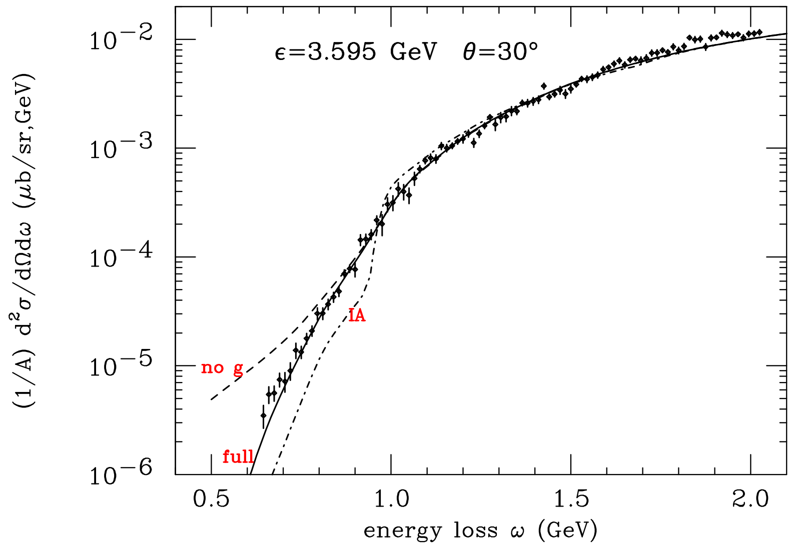
tail of response at low ω, large q

needed: good $P(k, E)$ for initial state

relativistic description of recoiling N

inclusion of correlations in final state $\longrightarrow$ CGT

Example: response of NM at 3GeV/25deg



shows importance of treating FSI correctly

good agreement in region sensitive to large k

Nucleon structure functions

consider N as many-body system in lab system

not IMF as usual

derive scaling assuming *off–shell* quarks

not on-shell as claimed when using x

find scaling variable $\tilde{y} = \nu - |\vec{q}|$

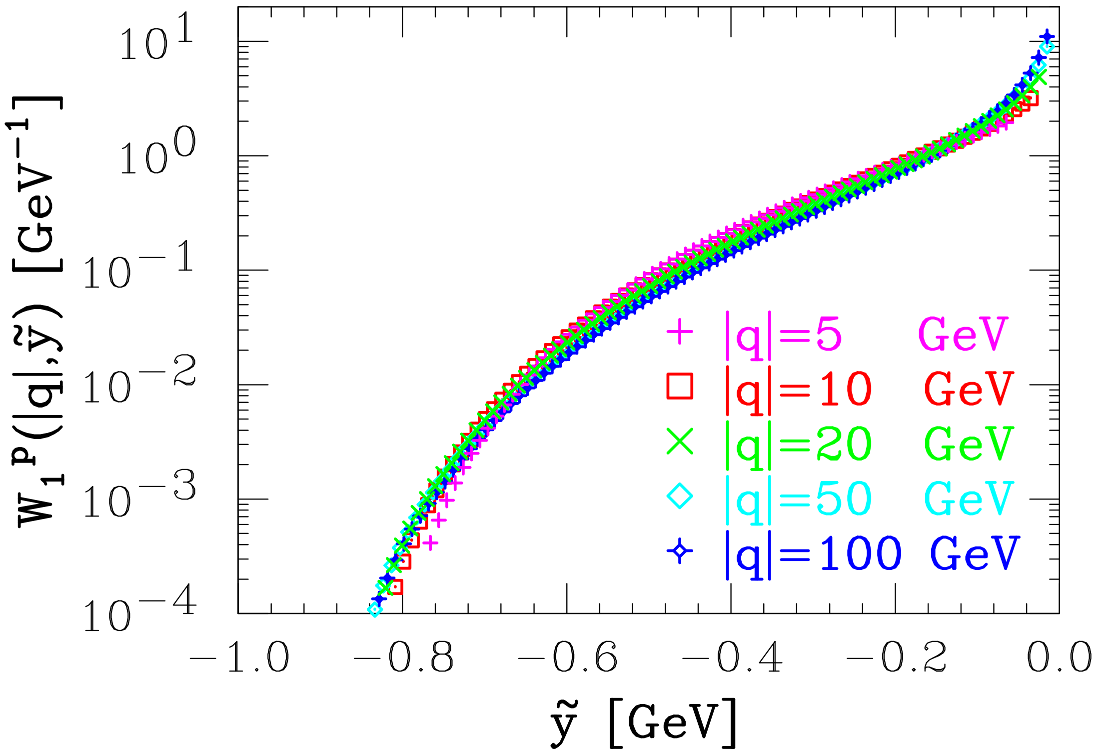
$=$ Nachtmann variable ξ/M

$=$ momentum of quark $\parallel \vec{q}$ in lab

find excellent scaling

basis for understanding

many effects



Deep Inelastic Scattering on nuclei: EMC effect

ratio DIS nucleus/deuteron $\neq 1$

vast literature

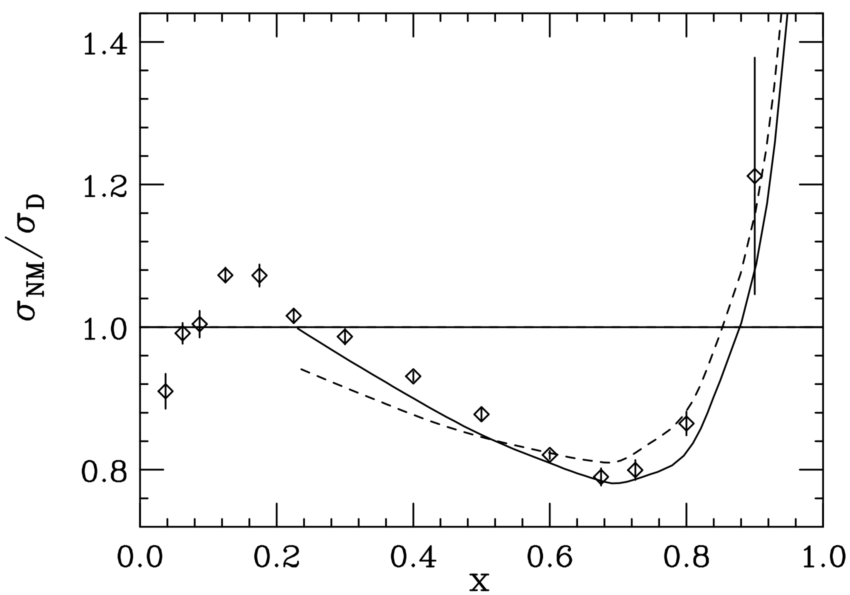
all kinds of interpretations

Most obvious effect: binding of nucleons

initially not successful

- how conceptually integrate in parton model based on *free* partons?
- provides large enough an effect?

With of–shell partons



can include nuclear binding consistently

$\bar{E}$ from (correlated) $P(k,E) = 61$MeV

not ~ 35 MeV as from MF

find

explains data quantitatively for $x > 0.3$

enhancement near $x \sim 0.1$: π-excess?

(Friman, Pandharipande, Wiringa)

DIS in recent work of Vijay

role of binding and FSI of partons

both ignored in standard approaches

Simple model

m=0 particle bound in linear potential (± realistic)

accounts for relativistic nature (Dirac eq.)

Find

binding moves strength to unphysical region $\tilde{y} > 0$

affects sum-rules

FSI affects *shape* of response (- - - = PW)

distribution function ≠ response function

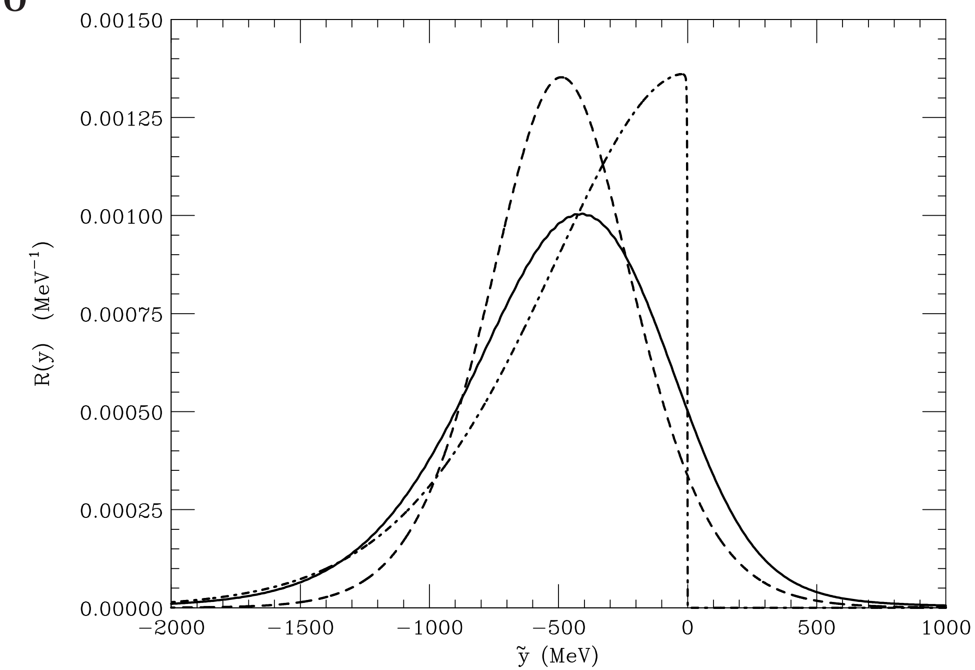
heresy for DIS community

had "proven" that FSI plays no role

but: recent work shows that proof was wrong

must correct for FSI

to get parton distribution functions



Extension to spin structure

much discussed: $g_1(x)$ accounts for fraction of N-spin only (?)

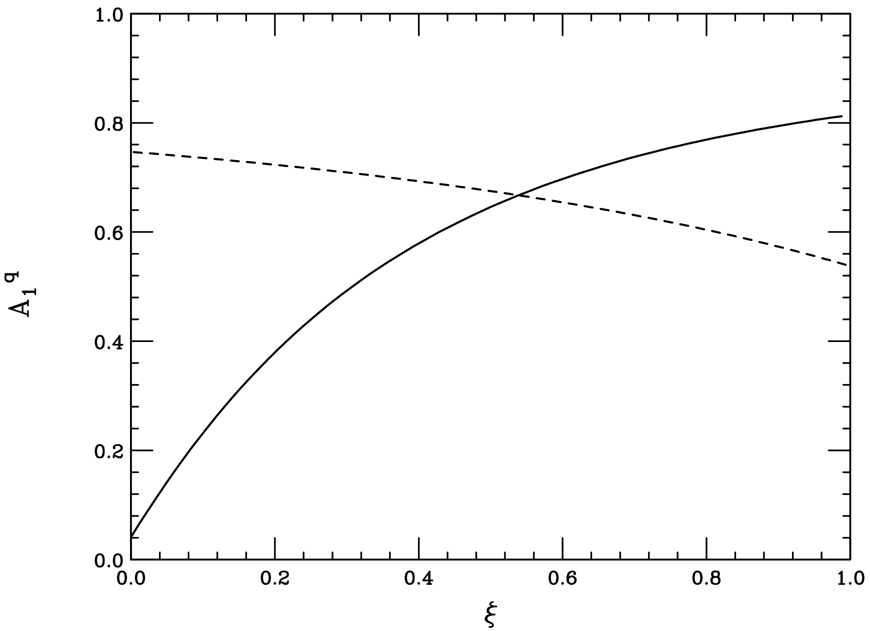
Proposed reasons

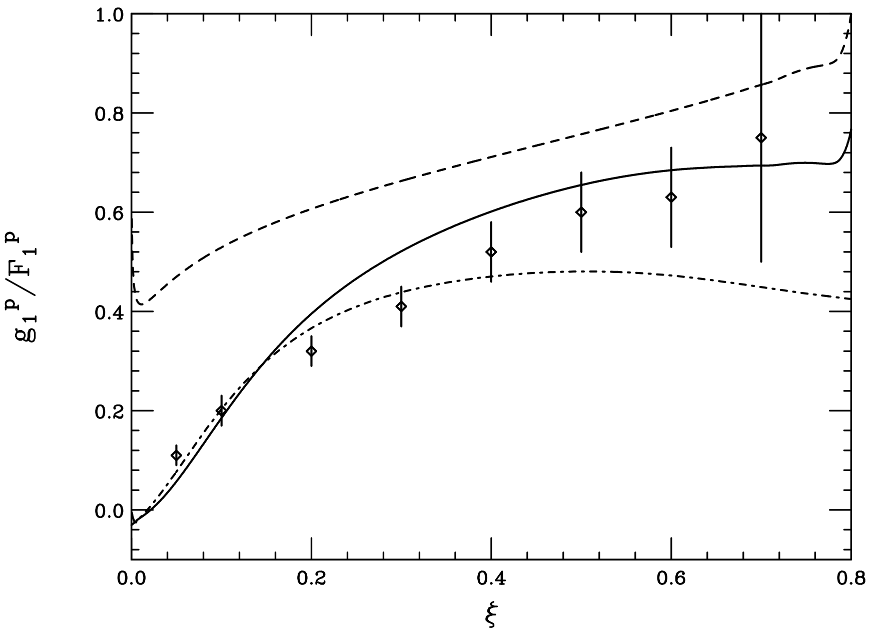
contribution of gluons ($\triangle$-diagram)

contribution of $l > 0$ -states

relativity (known from MIT bag-model)

Calculations with above model





$\longrightarrow$ reduction of g_1 in important x-region relative to bag (effect of FSI)

$\longrightarrow$ with exprimental PDF's explain $\pm$ data

Vijay's field of research

much wider than covered here

cannot do justice to in 1/2h

Vijay = prime example of a UNIVERSAL PHYSICIST

full of original ideas

ingenious to find suitable theoretical approaches

plenty of common sense to pursue *relevant* questions

deep understanding

taught me a lot of physics

Vijay was a great physicist
and a wonderful colleague

collaborators on examples shown

O. Benhar, A. Fabrocini, S. Fantoni, D.S. Lewart, J. Morales, C. Papanicolas, M. Paris, S. Pieper, D.G. Ravenhall, J. Wambach, R.B. Wiringa.