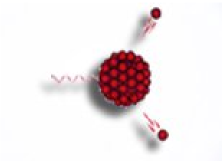
The short-range structure of Nuclei



1. Beyond the nuclear mean-field – the role of Nucleon-Nucleon correlations
2. Review of recent 2-N knockout experiments

   a) (γ,NN) and (e,e'NN) experiments at Mainz and NIKHEF

   b) Recent experiments at JLab
3. Inclusive reactions
4. The role of 3-body interactions

Effects of Short-Range Correlations in Nuclei

- A (e,e'p) experiments in quasi-elastic kinematics

  => measure of the momentum distribution of the initial proton

  => agree with mean-field theoretical predications up to ~250 MeV/c

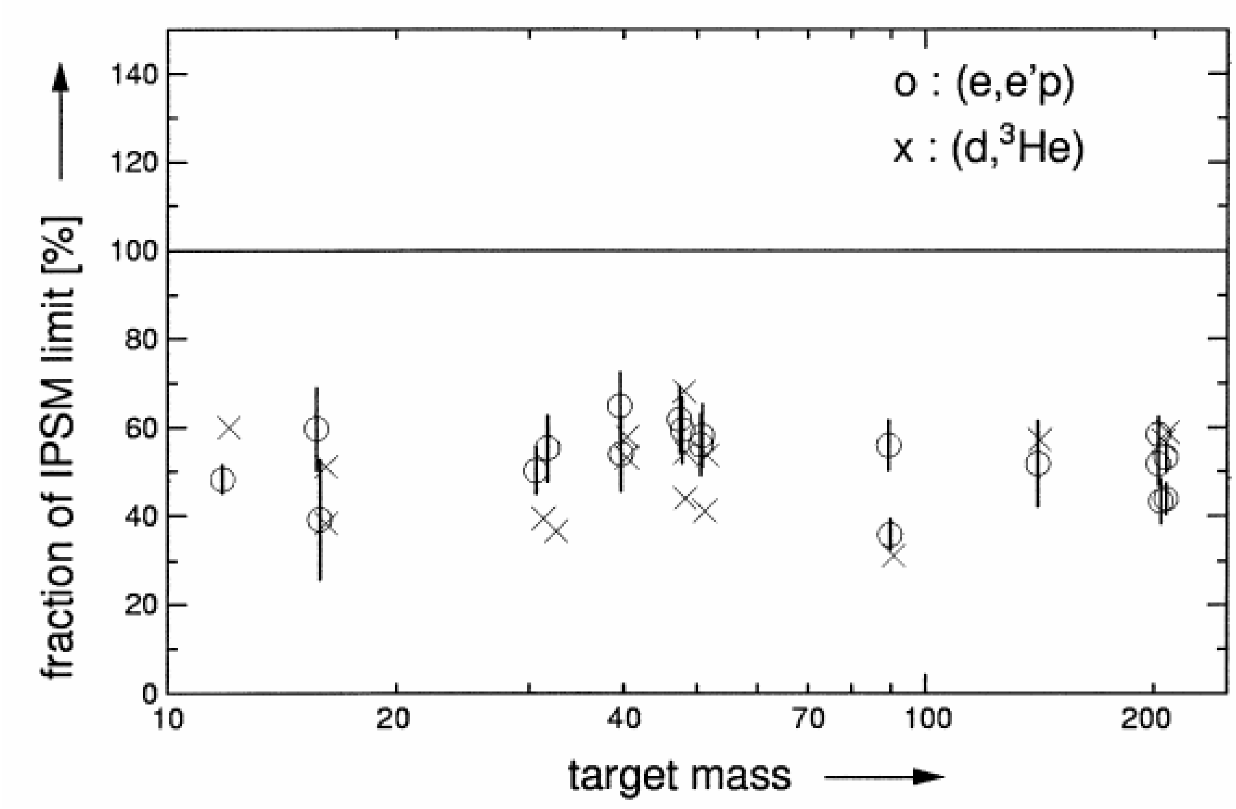
  => absolute magnitude only ~60-70% of expected on basis of full orbitals.

  => missing strength attributed to NN correlations beyond mean field description, which remove strength to high E_m and P_m.

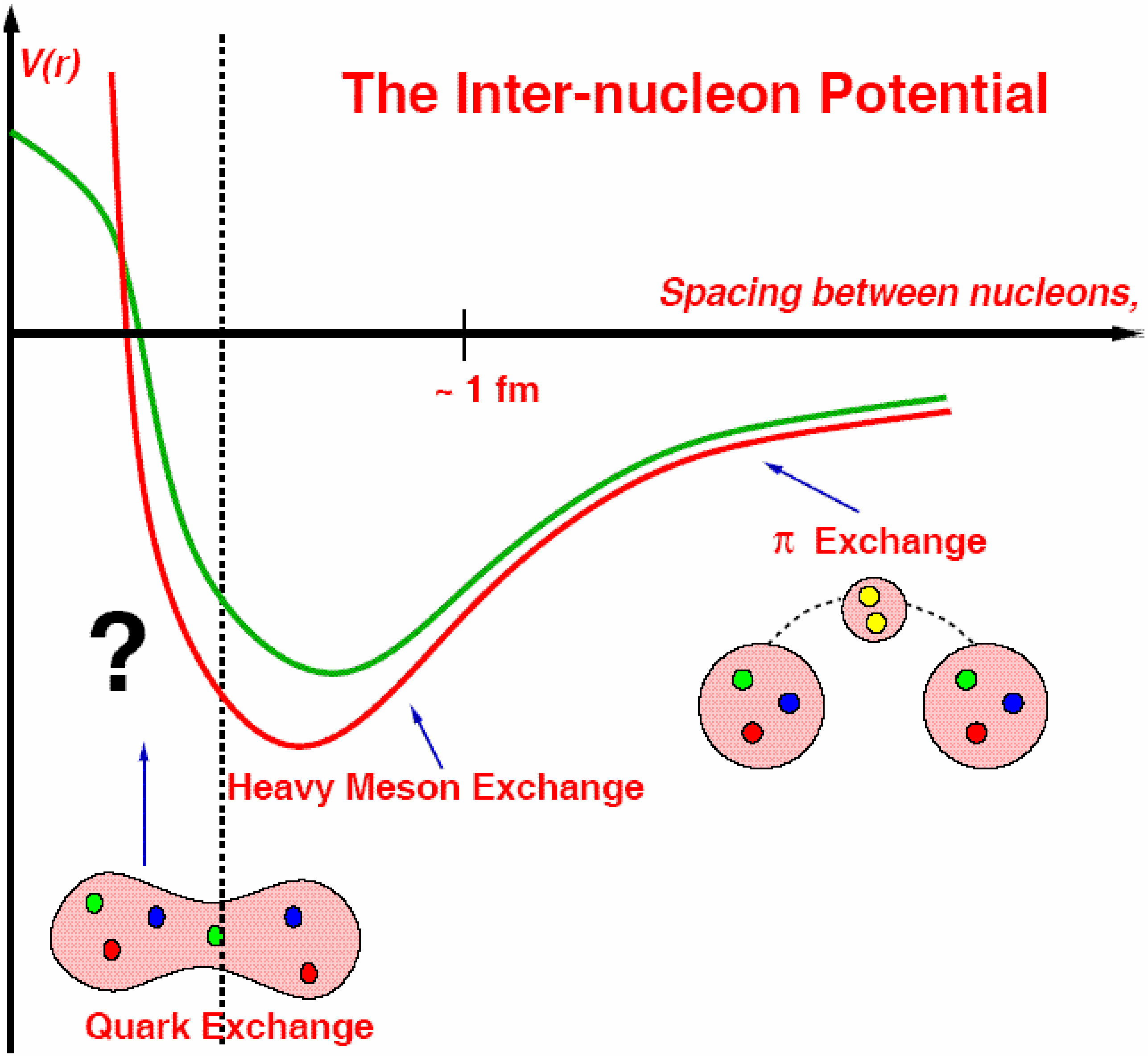
- Theoretical Calculations for finite nuclei and nuclear matter

  => influence spectral distribution of nucleons and binding energies of nuclear systems

Spectroscopic factors as a function of mass

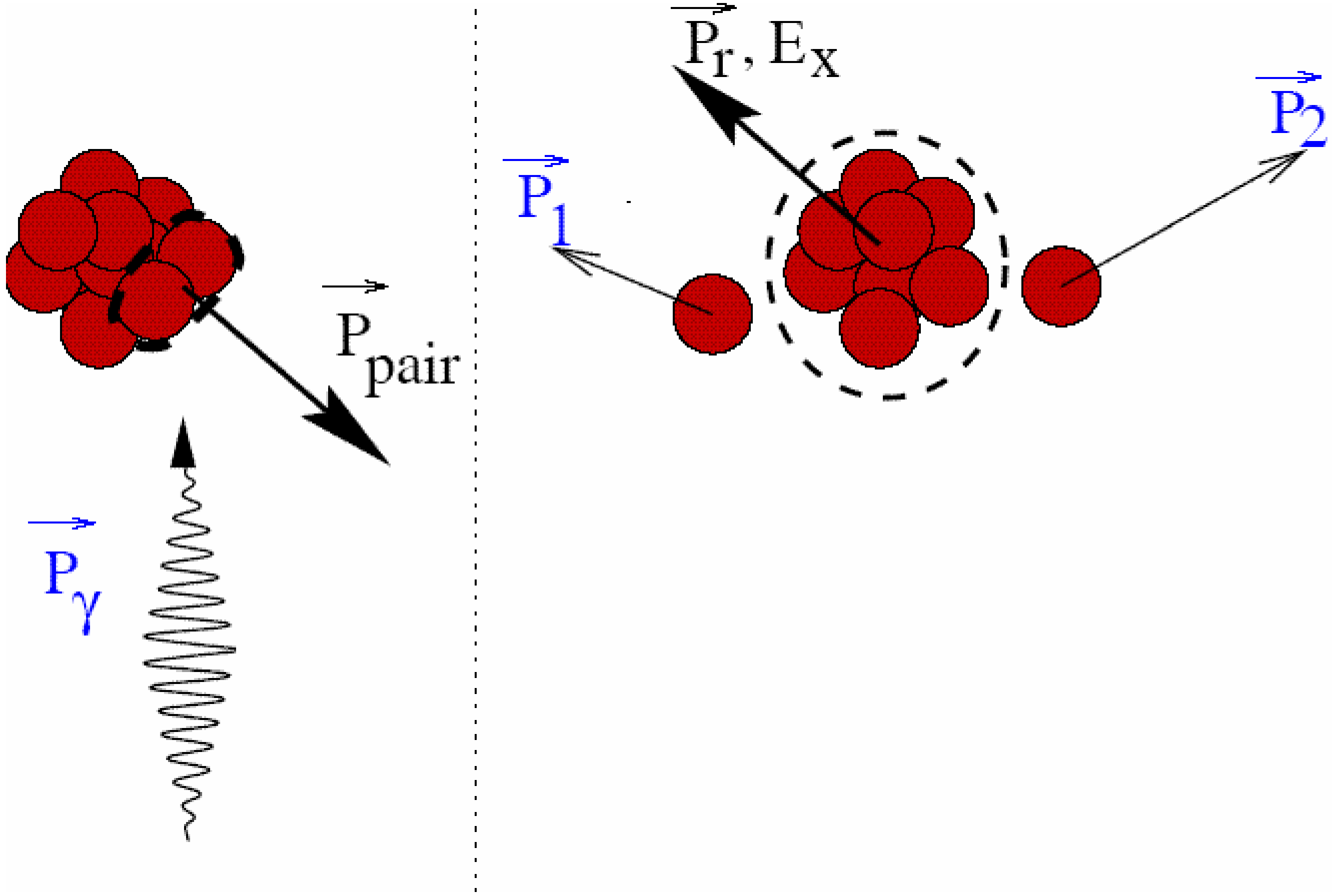


G J Kramer *et al.*, NPA 679 (2001) 267



V(r)
The Inter-nucleon Potential
Spacing between nucleons, r
~ 1 fm
π Exchange
?
Heavy Meson Exchange
Quark Exchange

2-Nucleon Knockout reactions



Electromagnetically induced 2-Nucleon knockout reactions

- Electromagnetically induced 2-Nucleon knockout reactions are a natural way to study interactions between nucleon pairs

- No complications from ISI, the probe sees the nucleons as they are in the nucleus.

- Provides access to 1-body nucleon currents at low E_m and moderate values of P_m, but high values of P_{rel}

- Competition from 2-body currents: MEC (seagull, π-in-flight) and Δ-currents

- FSI effects have to be taken into account

• There are four accessible 2-N emission reaction channels: (e,e'pp), (e,e'pn), (γ,pp) and (γ,pn)

• These show different sensitivity to different aspects of the 1- and 2-body currents.

• Real photon induced reactions are transverse in nature and have greater sensitivity to MEC.

• Virtual photons have longitudinal as well as transverse character. Longitudinal interactions have stronger 1-body (SRC) component.

• In reactions emitting pp pairs, MEC are suppressed.

• pn pairs are sensitive to tensor correlations in addition to central SRC, whereas pp pairs are only sensitive to central SRC

• FSI between outgoing nucleons and residual nucleus and between two emitted nucleons have to be taken into account.

• Different kinematics conditions have strong effects on contributions from Δ-currents and FSI.

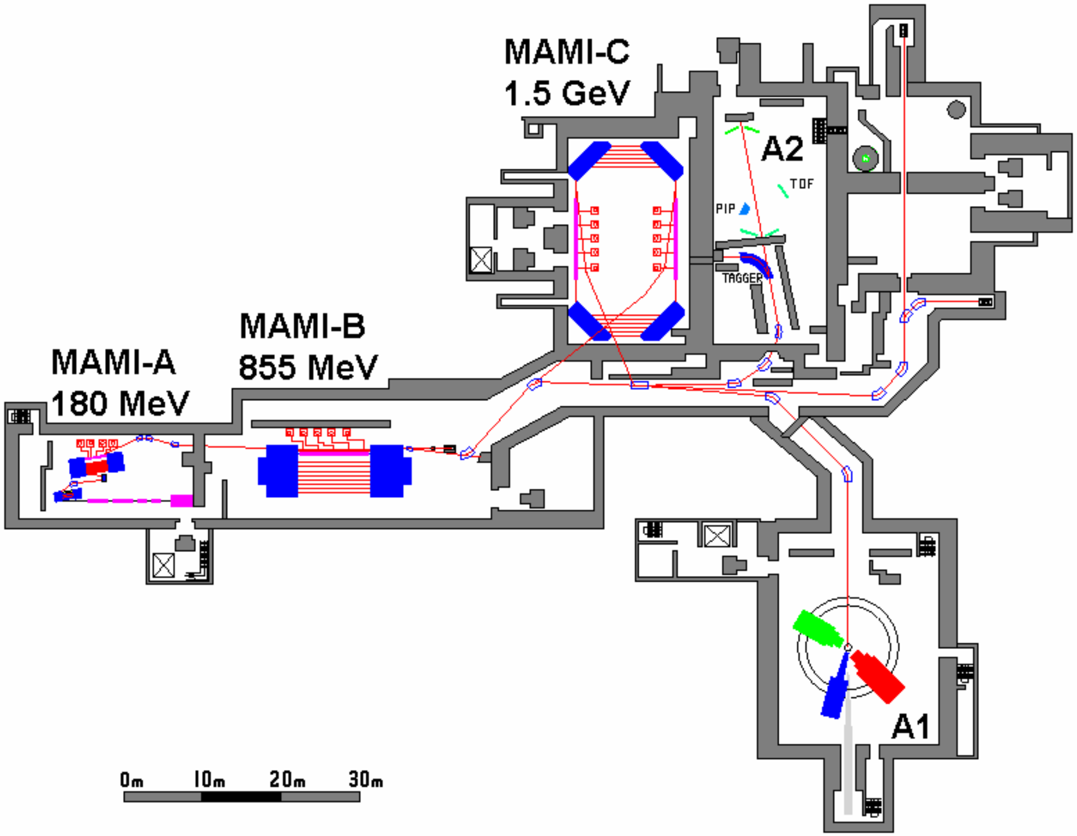
• SRC have a strong dependence on the angular momentum of the pair in the nucleus and on the relative angular momentum of the pair and hence depend strongly on the state of the residual nucleus.

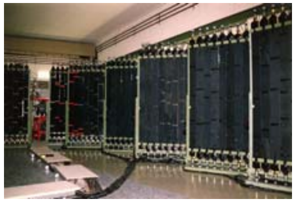
• Polarisation variables also show a strong sensitivity to SRC.

• A complete study requires measurements of all four reaction channels, preferably with enough resolution to distinguish individual states in the residual nucleus.

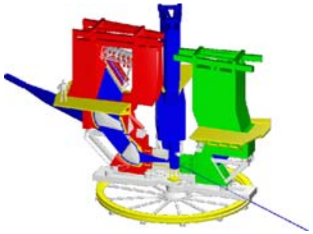
The main part of this talk will review recent work in this area which is beginning to open up our understanding of short-range processes in nuclei.

Experiments at the Mainz Electron Microtron MAMI





Real Photons

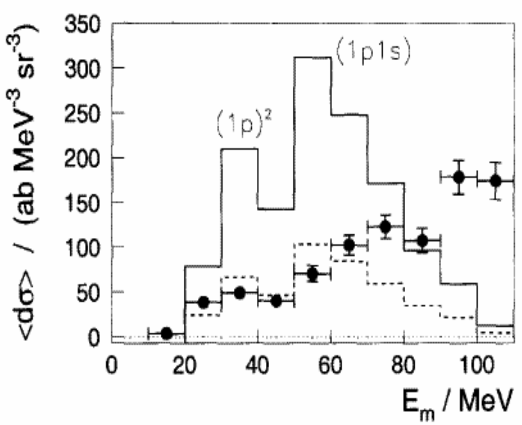


Virtual Photons

$^{12}C(e,e'pp)$ Mainz A1 collaboration

Rosner, Prog. Part. Nucl. Phys. 44 (2000) 99

Missing Energy Spectrum



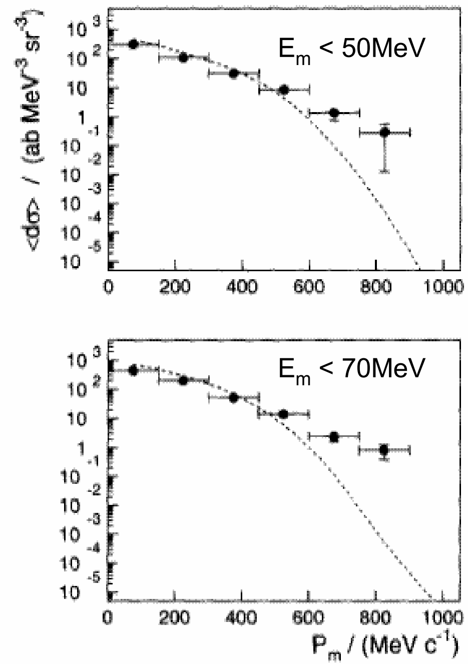
——— Hard Core

- - - - - - - - Soft Core (VMC)

- E_e=705 MeV
- ω = 225 MeV
- q = 412 MeV/c
- BGO crystal ball

=> Large Phase Space

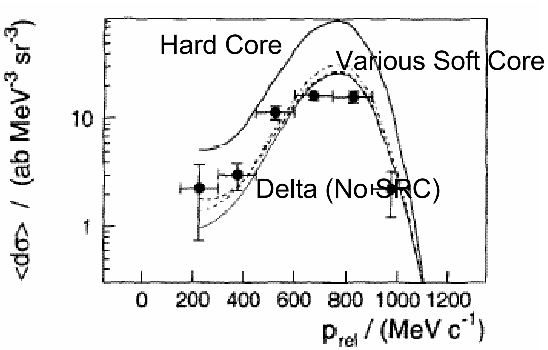
Missing Momentum Spectra



- - - - - - - - Soft Core (VMC)

Deviation at large Pm attributed to multi-nucleon correlations

pp Relative Momentum



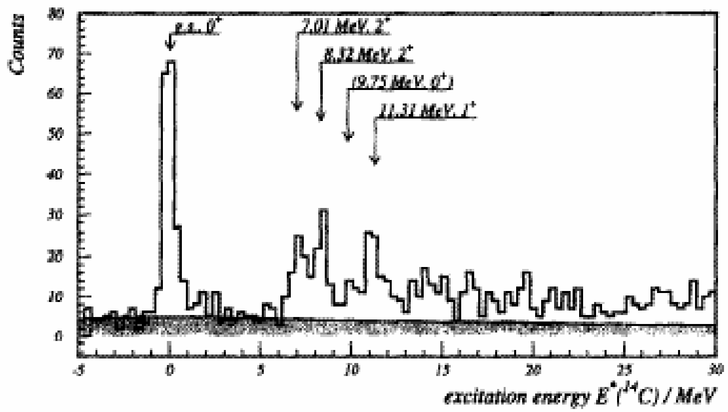
- E_m & P_{rel} spectra rule out Hard Core correlations
- Do not distinguish various Soft Core correlations
- Large Δ contribution even at high P_{rel}

$^{16}O(e,e'pp)$ Mainz A1 collaboration

Rosner, Prog. Part. Nucl. Phys. 44 (2000) 99

- High Resolution
- E_e= 855 MeV
- ω = 215 MeV
- q = 316 MeV/c
- 3 – Spectrometer facility
  => Super-parallel kinematic

Missing Energy Spectrum



Main states observed:		For P_m~0
O^+ gs	$(1p_{1/2})^{-2}$	$^1S_0$, L=0,2
2^+ (7.0 MeV)	$(1p_{1/2}, 1p_{3/2})^{-1}$	$^1S_0$, L=0,2
2^+ (8.3 MeV)	$(1p_{1/2}, 1p_{3/2})^{-1}$	$^1S_0$, L=0,2
1^+(11.3 MeV)	$(1p_{1/2}, 1p_{3/2})^{-1}$	^3P , L=1

SRC predicted to be strongest for $^1S_0$

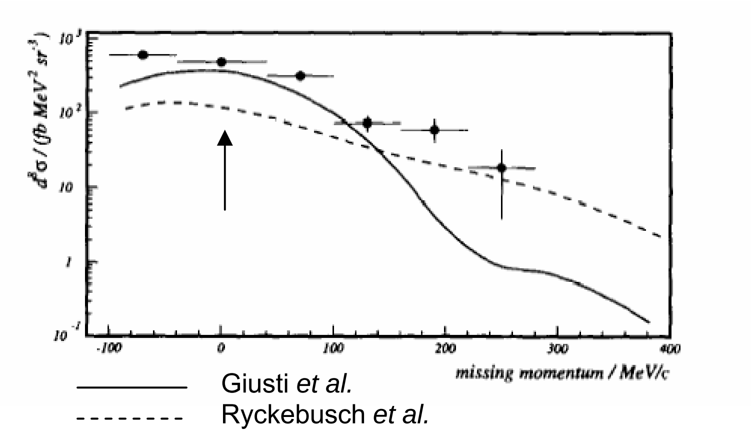
Expect large contribution at P_m~0,

for 0^+ gs and 2^+ states

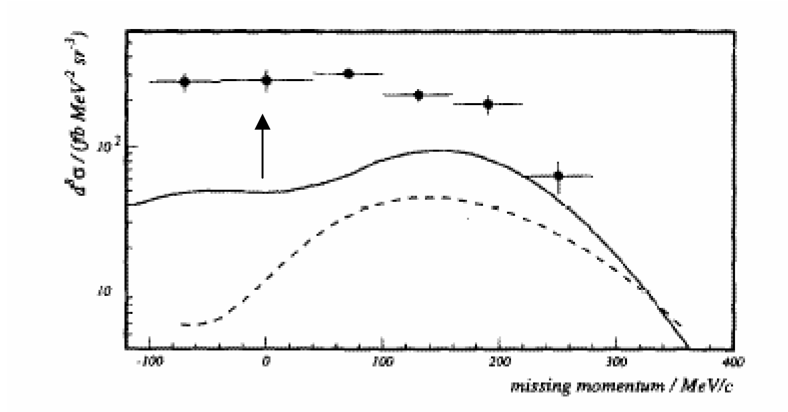
$\Rightarrow$ Expect 1+ state dominated by two-body currents

Missing Momentum Distributions

0^+ Ground State



Sum of 2^+ States

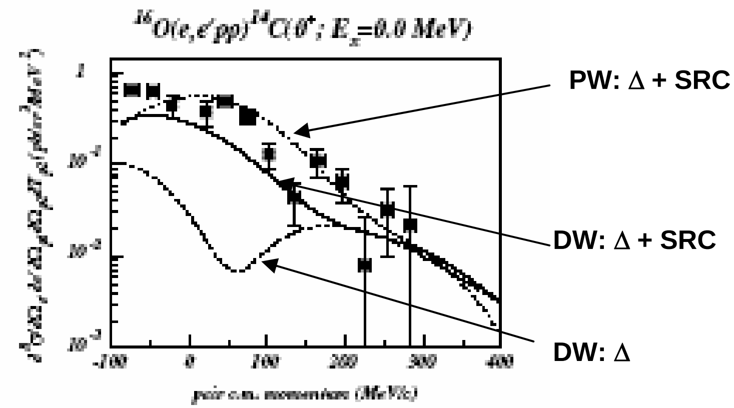


Differences in predictions from calculations available in 2000 which include SRC. Around P_m~0 calculation of Giusti *et al*. is closest to describing gs data, but underpredicts 2^+ states.

$^{16}O(e,e'pp)$ Calculations

J Ryckebusch & W Van Nespen EPJA 20 (2004) 435

Results for 0^+ gs.



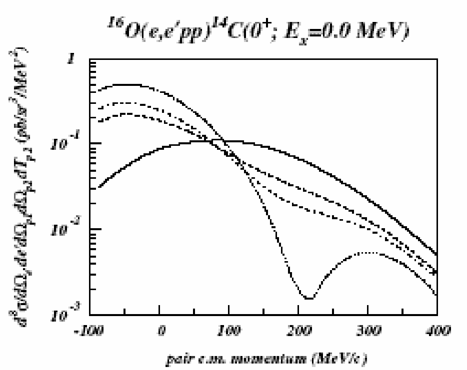
Calculations:

- Non-relativitistic, DW
- 2N correlations input through Two-nucleon-overlap (TOF) functions
- Overlap amplitudes treated as Input parameters

Sensitivity to overlap amplitudes:

$$|0^+; E_x = 0\,\text{MeV}\rangle = m\left|(1p_{1/2})^{-2}; 0^+\right\rangle + n\left|(1p_{3/2})^{-2}; 0^+\right\rangle .$$

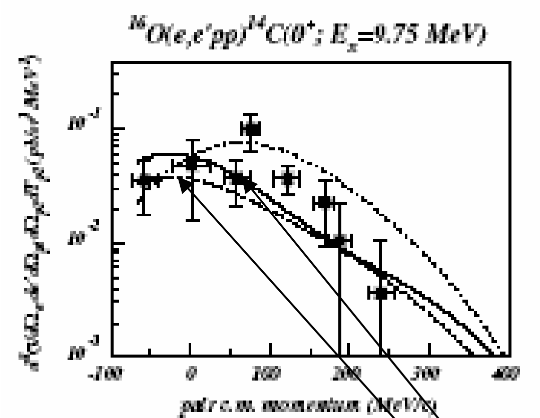
	Ref. [23]	Ref. [24]	Ref. [25]	Ref. [26]
m	0.97	0.91	0.76	0.576
n	0.24	0.41	−0.65	0.818



- Use overlaps from [24]
- Protons in relative $^1S_0$ state with L=0 or $^1P_3$ state with L=1
- Dominated by $(1p_{1/2})^{-2}$ at P_m~0
- Large sensitivity to SRC at P_m < 200 MeV/c
- Full curve underestimates data by factor of ~2

Other States

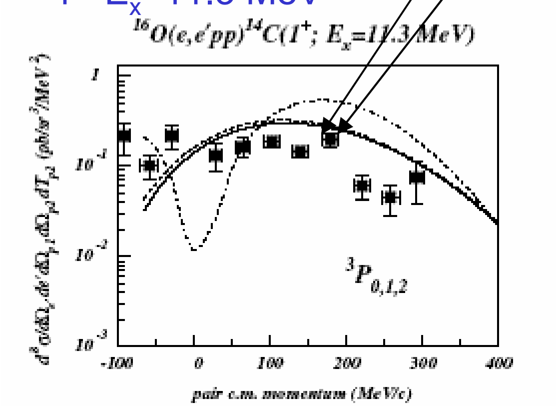
$0^{+,}$ E_x=9.75 MeV



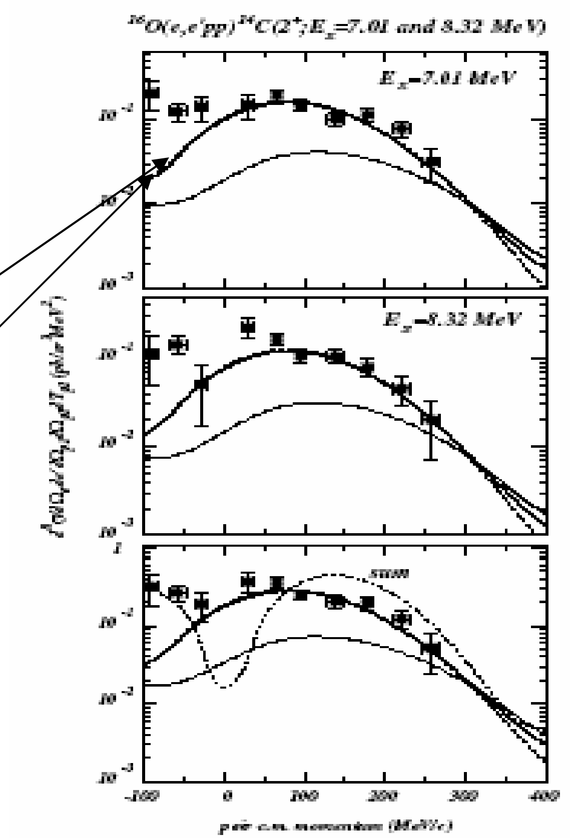
DW: Δ + SRC

DW: Δ

$1^{+,}$ E_x=11.3 MeV



$2^{+,}$ E_x=7.01 and 8.32 MeV



$0^{+,}$ E_x=9.75 MeV shows only a little sensitivity to SRC

Other states calculated show almost no sensitivity to SRC.

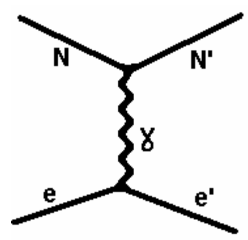
SRC strongly dependent on the detailed configurations of individual states

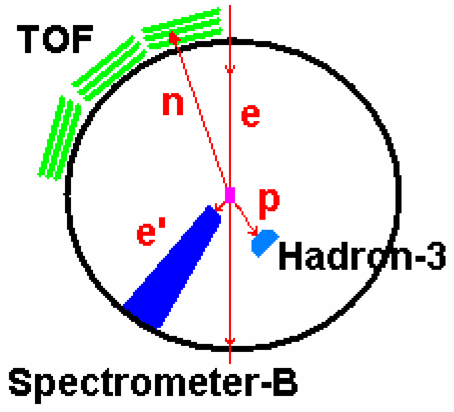
(e,e'pn) Experiments at Mainz

A1 Collaboration: Glasgow, Amsterdam, Tübingen, Mainz

In electron scattering the electron exchanges a Virtual Photon with the target.

This allows independent variation of the energy and momentum transfer to the target.





- (γ,pn) channel emphasises tensor components of SRC
- A wide range of momentum transfers to separate contributions from SRC, MEC, Δ-currents and FSI
- Use Time-of-Flight (TOF) detectors to detect neutrons
- First operation of TOF with virtual photons

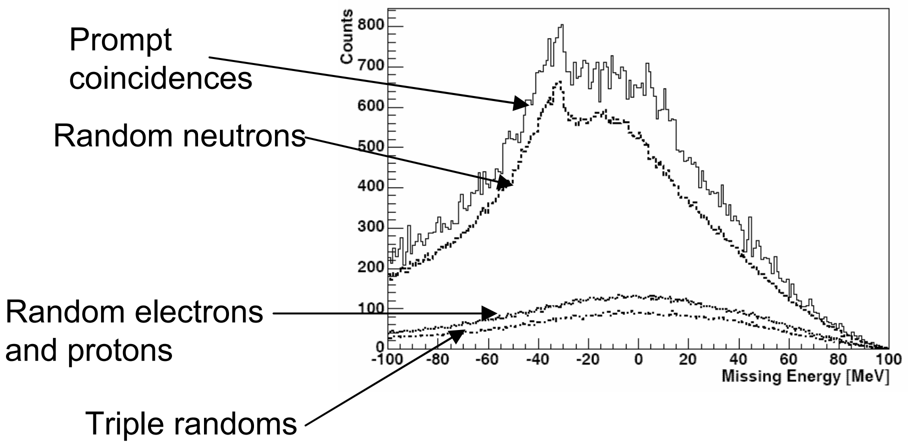
^{16}O(e,e'pn) Glasgow-Tübingen-Mainz

Middleton *et al*. to be published

Preliminary

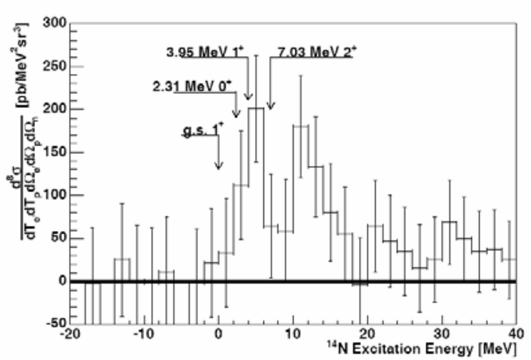
Pilot experiment to test feasibility of using Time-of-flight neutron detectors in an electron scattering environment.

Random Subtractions



Large background of Random Neutrons

Missing Energy Spectrum



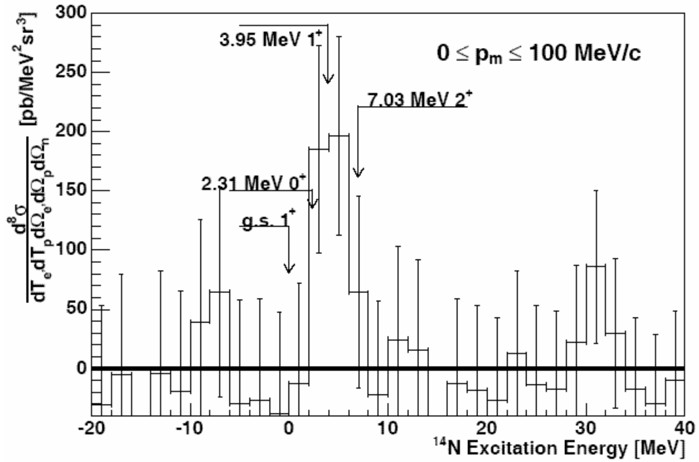
Resolution: ~ 3MeV (FWMH)

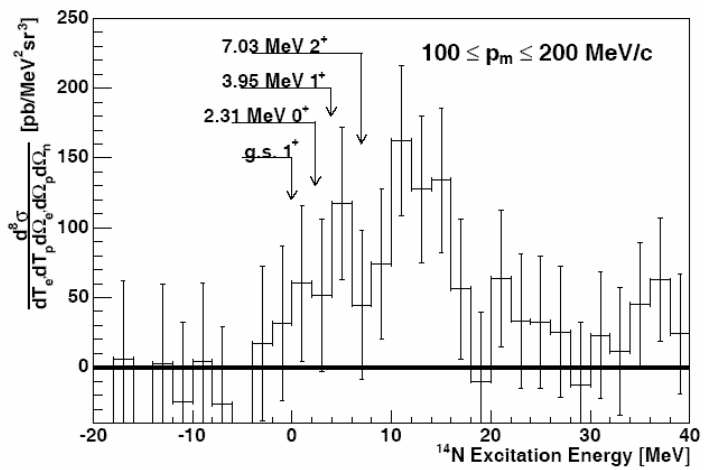
Sufficient to distinguish groups of states, but not individual states.

Preliminary Results

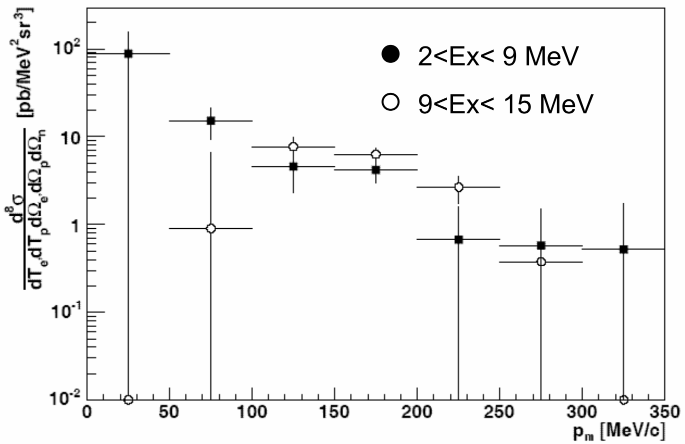
Preliminary

Missing Energy for two P_m regions



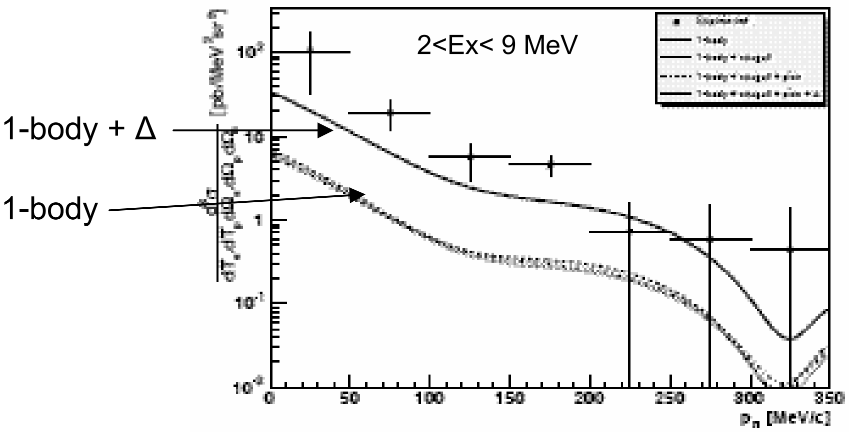


Missing Momentum for two E_x regions



Comparison with theory

(Barbarieri, Giusti *et al.*)

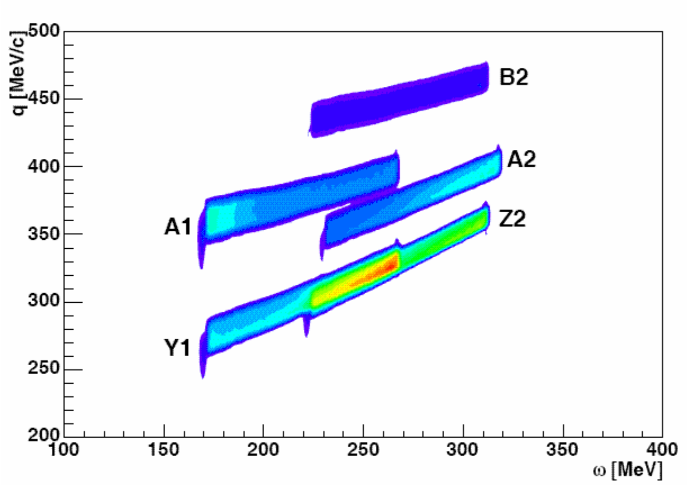


^{3}He(e,e'pn) Glasgow-NIKHEF-Mainz

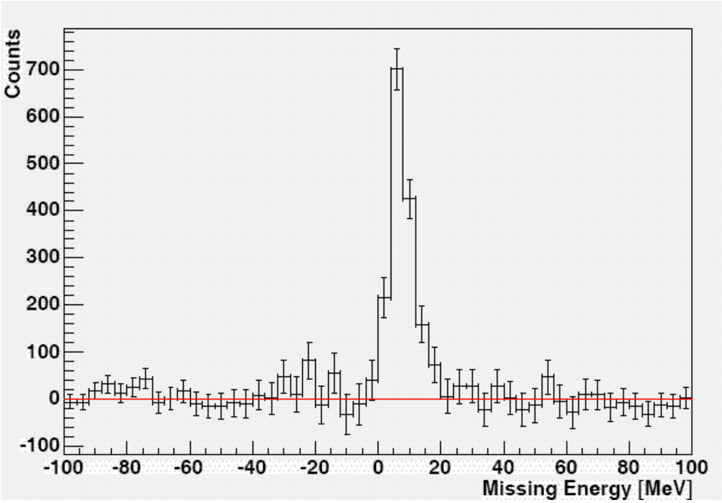
Preliminary

A more detailed series of experiments were carried out on ^{3}He to map out the ω and q dependence of the ^{3}He(e,e'pn) reaction.

Kinematic coverage

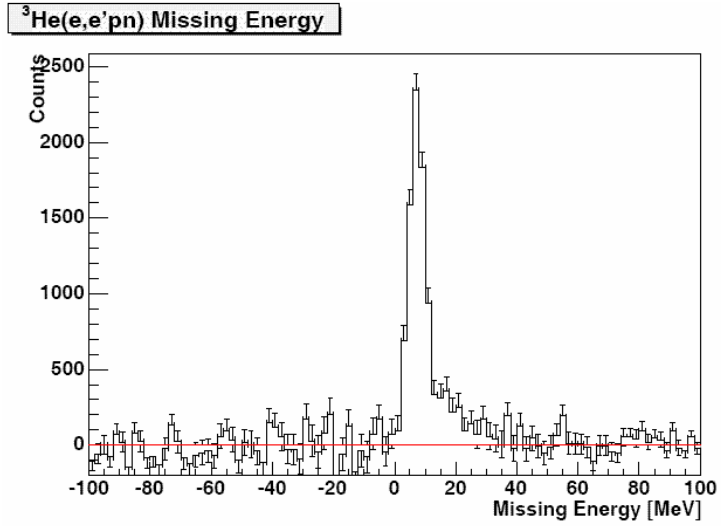


Missing Energy

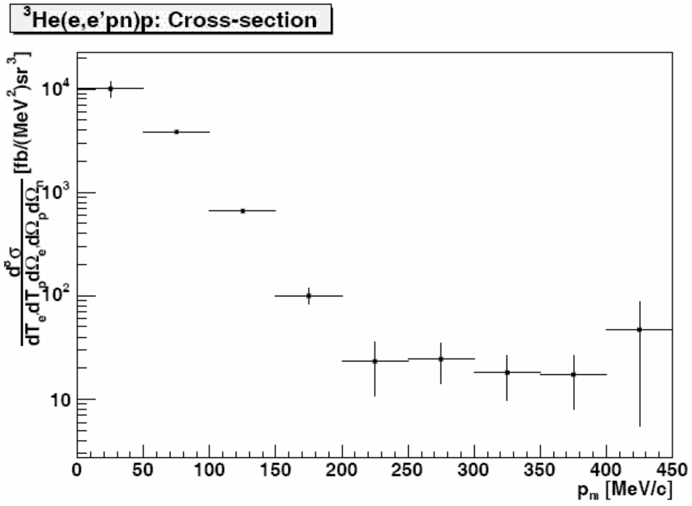


Preliminary results from A1 Kinematics

Preliminary

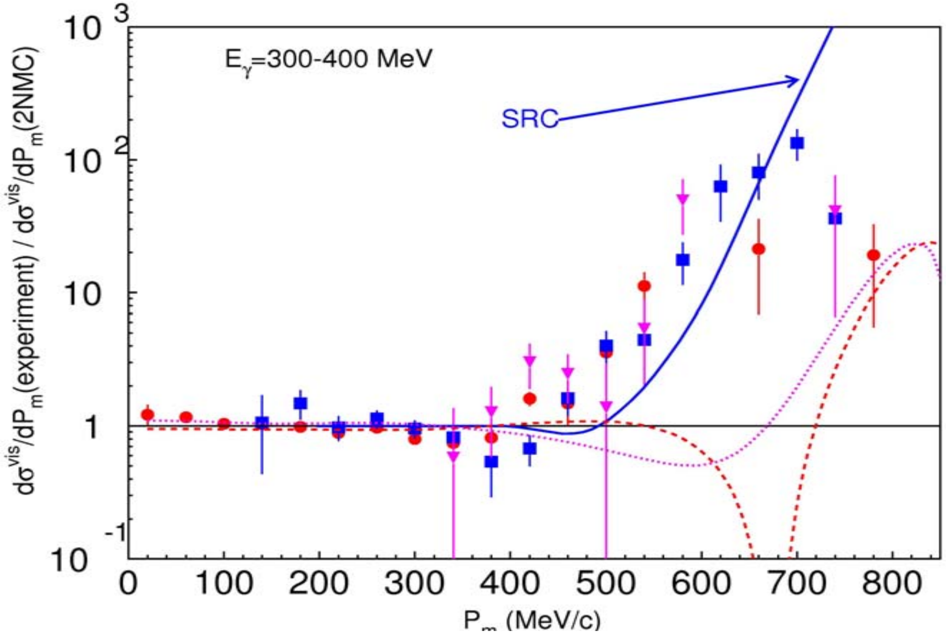


- Observed reaction cross section holds up at large P_m
- Fadeev Calculations (Bochum code) currently being carried out



$^{12}C(\gamma,pn)$ Recoil momentum distribution

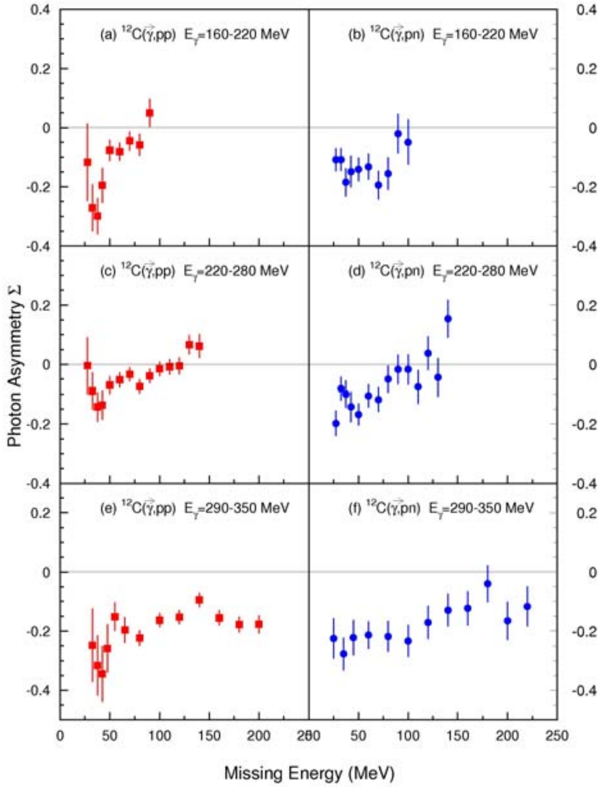
DP Watts et al



- Long range $P^2F(P)$ factor divided out
- Excess strength at high P_m cf mean field predictions
- Data agree with a simple model of SRC for ^{16}O (Orlandini and Sarra)

(γ,pN) Asymmetry

IJD MacGregor et al.



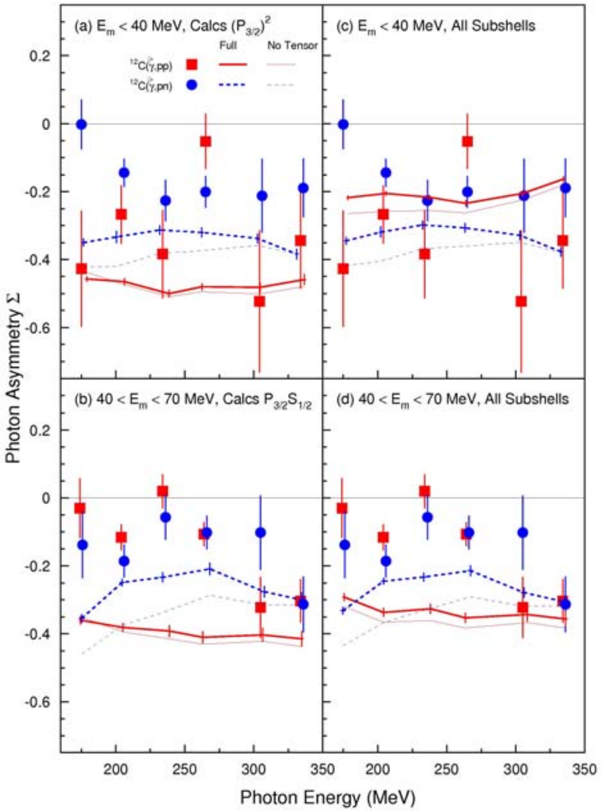
- Photon Asymmetry $\Sigma = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$

  sensitive to SRC

- Pronounced structure in Σ at low E_m in (γ,pp) channel
- Distinct differences observed between (γ,pp) and (γ,pn)

Comparison with theory

• Comparison with unfactorized calculations (Ryckebusch et al.) including central and tensor SRC, averaged over detector acceptance



• However, in Δ–resonance interference from 2-body currents dominates

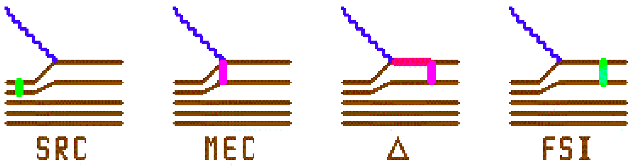
• Theory fails to properly account for Δ-current parallel and perpendicular contributions

• Need for improved theoretical treatment of Δ-resonance

• And better measurements over a wider range of kinematics

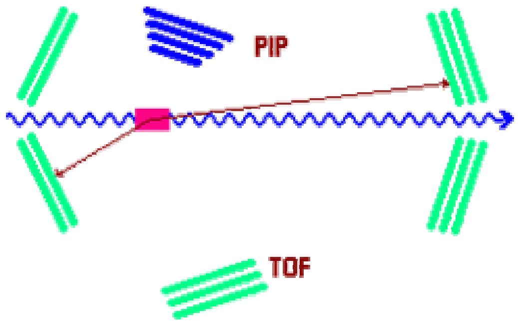
(γ,NN) Experiments in near Super-Parallel kinematics
Mainz A2 Collaboration
(Glasgow, Edinburgh, Tübingen, Mainz)

Short Range Correlations (SRC) can be studied using (γ,NN) 2-nucleon emission reactions.



The key is to separate contributions from competing processes such as:

- Meson Exchange Currents (MEC),
- Δ-currents, and
- Final State Interactions (FSI).



<u>2001/2002 Mainz Experiments use:</u>

- Super-parallel kinematics to emphasise contribution from SRC
- (γ,pp) channel to suppress MEC
- $E\gamma$>400 MeV, above Δ-resonance
- Energy and angle information to reject FSI

No results available yet from this experiment

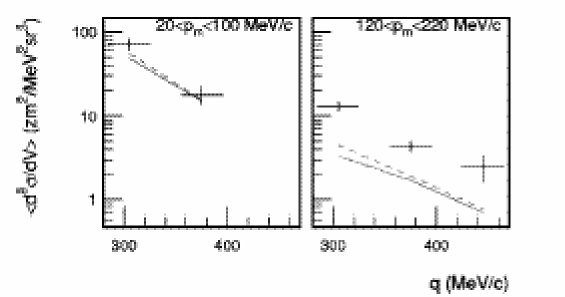
Measurements of the $^3He(e,e'pp)n$ Reaction at Nikhef

D L Groep et al, PRC 63 (2000) 014005

- $^3He(e,e'pp)n$ allows comparison with exact Fadeev calculations (Bochum-Cracow)
- Measure wide range of kinematics to investigate relative importance of 1- and 2-body currents
- Measure in "Dip" region to emphasise two-nucleon knockout
- q= 305-445 MeV/c, ω=220 MeV

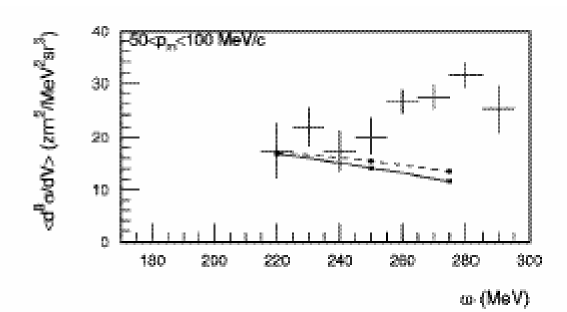
and q=375 MeV/c, ω=170-290 MeV

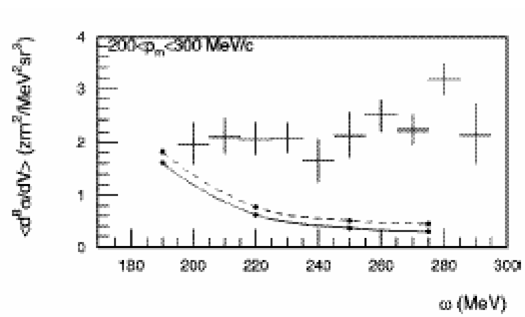
Results



1-body

1-body + MEC





- Differential Cross sections compared to Fadeev calculations (Bochum-Cracow) based on Bonn-B NN potential
- 1-body terms dominate for P_m<100 MeV/c
- At higher P_m MEC are larger, but not enough to explain difference with data => difference due to isobar currents not included in the calculations
- 1-body terms also appear largest at low values of ω

Recent Experimental Work at JLab

1. Exclusive reactions:

   a) ^{3}He(e,e'pp)

   b) ^{3}He(e,e'pN) proposal (Hall-A)

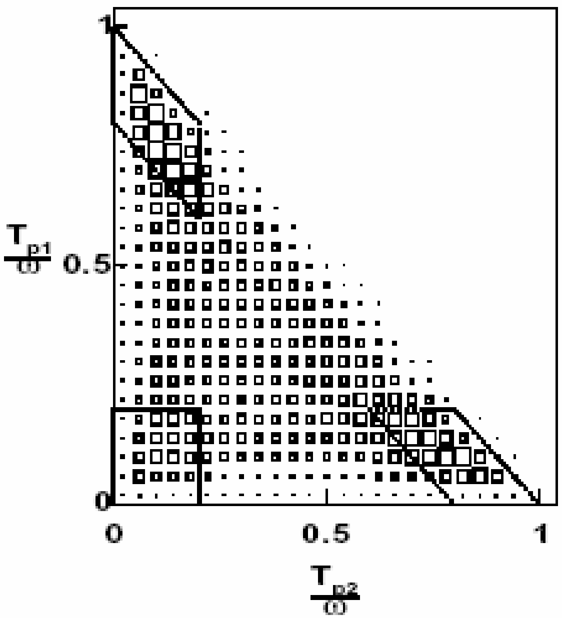
2. Inclusive reactions: A(e,e') – Scaling of inclusive cross-section at high (Q^2,x_B)

3. 3-particle emission reactions: ^{3}He(e,e'ppn)

^{3}He(e,e'pp)n 2N momentum distributions

Niyazov *et al.*, CLAS Collaboration, nucl-ex:/0308013v1

SRC => NN pairs with large relative momentum and low total momentum



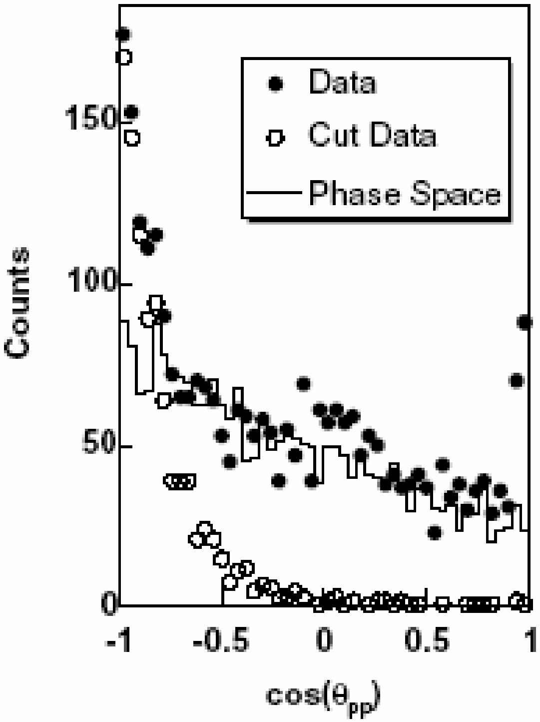
Select data with

⇒ Nucleon momenta >250 MeV/c

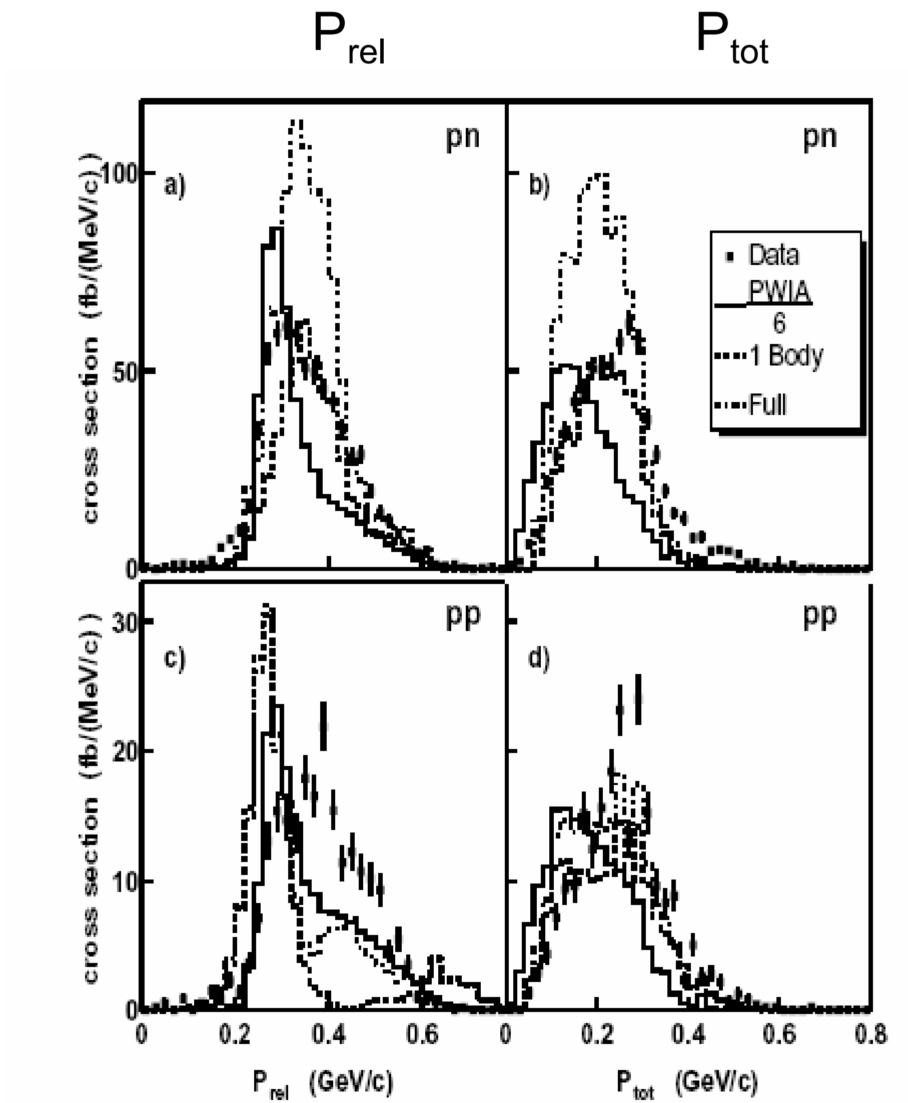
⇒ Regions where two nucleons have <20% of ω

⇒ P_L>300 MeV/c (leading neutron) to reduce FSI

Opening Angle Distribution



Relative momentum distributions



⇒ Pair of nucleons selected are spectators.

⇒ Information on initial momentum distributions

⇒ plot P_{rel} and P_{tot} (Note: upper limit determined by cuts on data)

⇒ Various calcs (Sargsian, Glöckle *et al.*, Cioffi degli Atti and Kaptari, Laget) used to interpret data

⇒ PWIA calcs predict correct σ_{pp}/σ_{pn} ratio, but overestimate strength of both channels

⇒ 2-body currents and leading nucleon FSI are negligible

⇒ Reduction in strength (cf PWIA) due to continuum state interactions of emitted pair which also suppress s-wave contributions and shift peaks to higher momentum

⇒ Considerable strength due to 3-body currents (20% for pp and 50% for pn pairs)

Inclusive A(e,e') electron scattering

Egiyan *et al.*, CLAS Collaboration, nucl-ex:/0301008v1

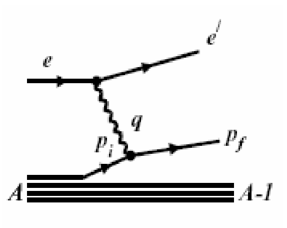
SRC => high momentum components in nuclear wavefunction

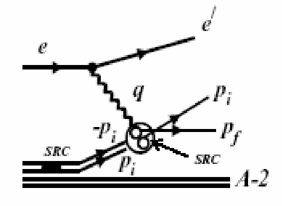
=> expect similar nucleon momentum distributions at high momentum from all nuclei

=> Strength of cross section at high momentum reflects the probability of SRC.

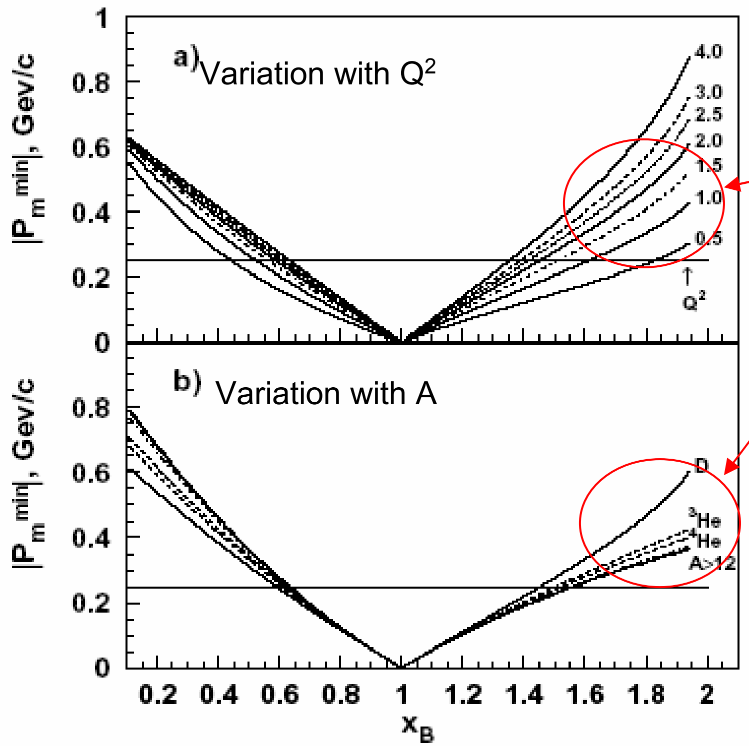
$\Rightarrow$ Measure at high Q^2 and $x_B=(Q^2/2M\nu) > 1$ to suppress quasi-elastic (e,e'p) and MEC

$\Rightarrow$ Competing single nucleon absorption + FSI contributions, calculated (Benhar *et al*.) using Glauber approximation (& colour transparency at high Q^2) predict dependence on A and Q^2 but no scaling behaviour





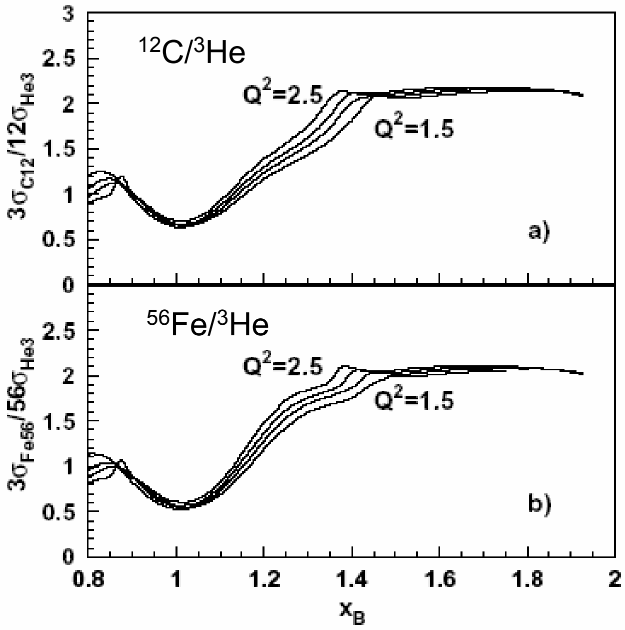
Kinematic region where Q^2 exceeds quasi-elastic fermi values (P_m>0.25 GeV/c)



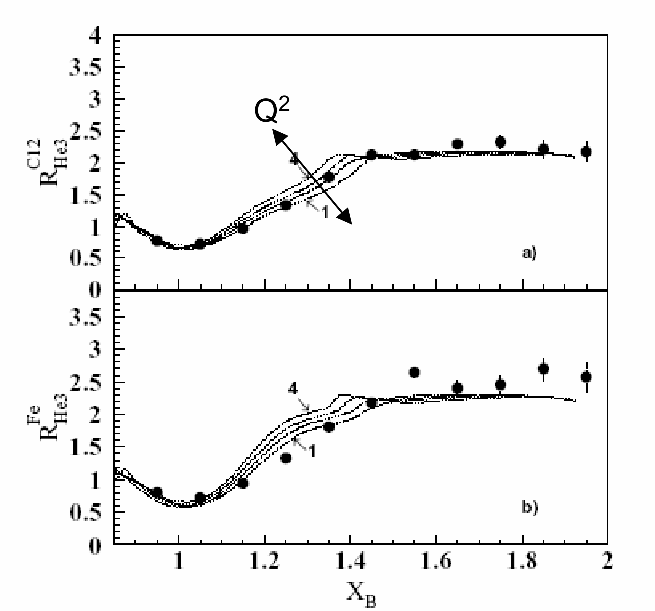
Ratio of Cross section per nucleon

$$R^{A1}_{A2}(Q^2, x_B) = \frac{\sigma_{A1}(Q^2, x_B)/A_1}{\sigma_{A2}(Q^2, x_B)/A_2}$$

Predicted scaling of ^{12}C and ^{56}Fe cross sections to ^3He values at x_B>1.4 (model of Frankfurt and Strikman)



Observed scaling of ^{12}C and ^{56}Fe cross sections to ^{3}He values



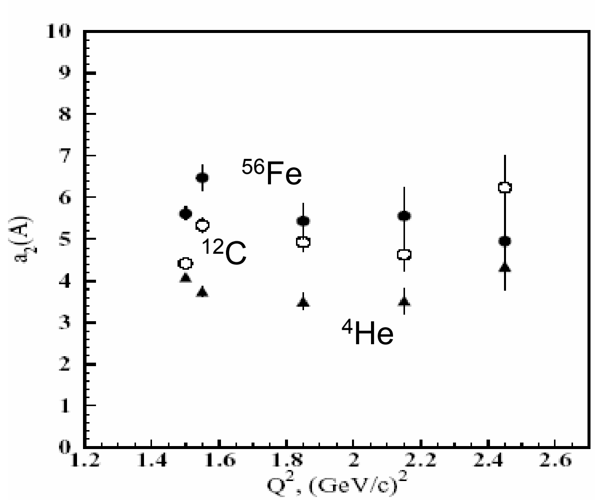
Relative probabilities of SRC compared to ^{3}He

$$r^{A}_{^3He} = R^{A}_{^3He}(Q^2, x_B) \times \frac{A(2\sigma_p + \sigma_n)}{3(Z\sigma_p + N\sigma_n)}$$

Per nucleon probability compared to deuterium

$$a_2(A) = r^{A}_{^3He} \cdot a_2(3)$$

Per-nucleon SRC probability relative to deuterium



Hall-A Proposal

Studying the internal small-distance structure of nuclei via (e,e'p+N)

Proposal 97-106, S A Wood *et al.*

- Experiment will measure both $^{12}C(e,e'pp)$ and $^{12}C(e,e'pn)$
- Use Hall-A spectrometers HRS_h and HRS_e to measure the scattered electron and one emitted (high momentum) proton
- BigBite is currently being upgraded to handle the expected luminosities and with the addition of a plastic scintillator array to detect neutrons, will be used to measure the second emitted nucleon
- The focus of these experiments will be at high Q^2 and $x>1$, in contrast to previous (e,e'pN) experiments which were performed at low Q^2

Kinematics

Theoretical calcs predict several advantages of carrying out experiments at $x>1$ and high Q^2, although cross sections are expected to be small

$\Rightarrow$ e.g. MEC have additional $1/Q^2$ dependence (cf. electron scattering off a nucleon) and are suppressed

$\Rightarrow$ 2-body currents and isobar currents are also suppressed at $x>1$

$\Rightarrow$ FSI, calculated in Glauber approx., become less important at high Q^2

$\Rightarrow$ Large (e,e'p) missing momenta accessible for either

a) $x<1$, "parallel kinematics" or

b) $x>1$, "anti-parallel kinematics"

$\Rightarrow$ Final proposal is to measure the proportion of ^{12}C(e,e'p) events associated with NN SRC in "anti-parallel" kinematics, at $Q^2 \sim 2$ (GeV/c)^2, $x\sim1.5$, for p_p up to 600 MeV/c

3-Nucleon Interactions

1. $^{12}C(\gamma,ppn)$ experiments at Mainz
2. $^{3}He(\gamma,ppn)$ Photodisintegration

   A) Work by Niccolai et al

   B) Analysis by D Watts

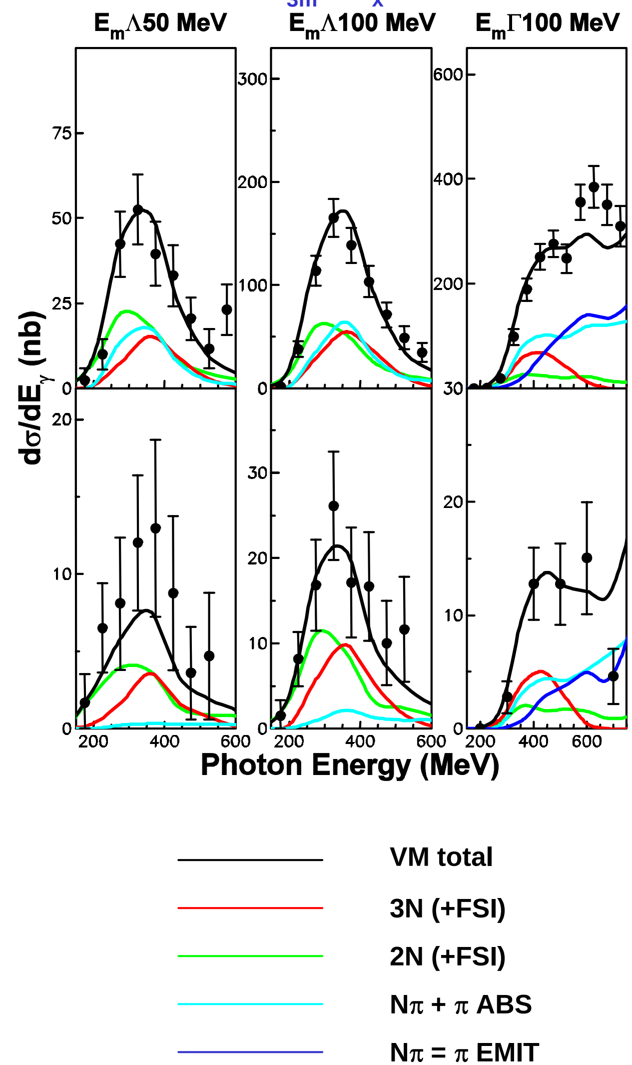
$^{12}C(\gamma,ppn)$ experiments at Mainz

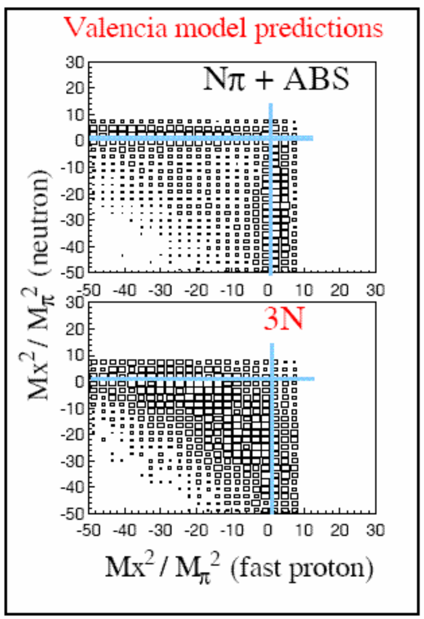
DP Watts *et al.* PLB 553 (2003) 25

- **3-nucleon emission from a complex nucleus**
- **In addition to absorption on 3N, significant background from 2N+ FSI, Nπ + πABS,**
- **Use Valencia Model as guide to distribution of these processes**

Top: E_{3m} cut

Bottom: E_{3m} +M_x cuts





- **Cut E_{3m} < 100 MeV**
- **For γ+N -> N+X , cut on invariant mass M_x to suppress Nπ + πABS**

Three body photodisintegration of ^{3}He

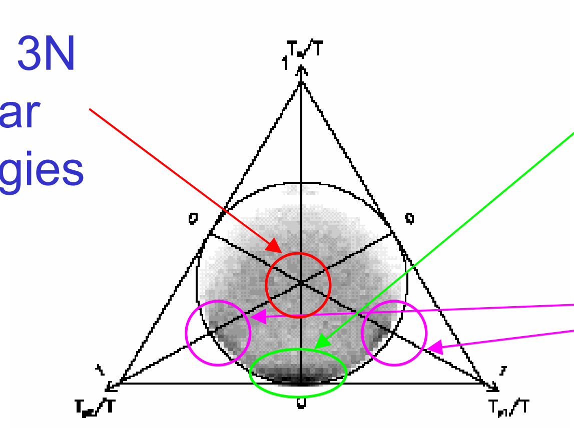
S Niccolai *et al*., CLAS Collaboration nucl-ex/0409013

- ^{3}He(γ,ppn) measured using CLAS tagged photon beam
- E_γ= 0.35- 1.55 GeV
- Large kinematic coverage and good statistical accuracy

Kinematic Regions

Star: 3N similar energies

Neutron spectator



Quasi 2-body Breakup

Dalitz Plot: accepted ppn data

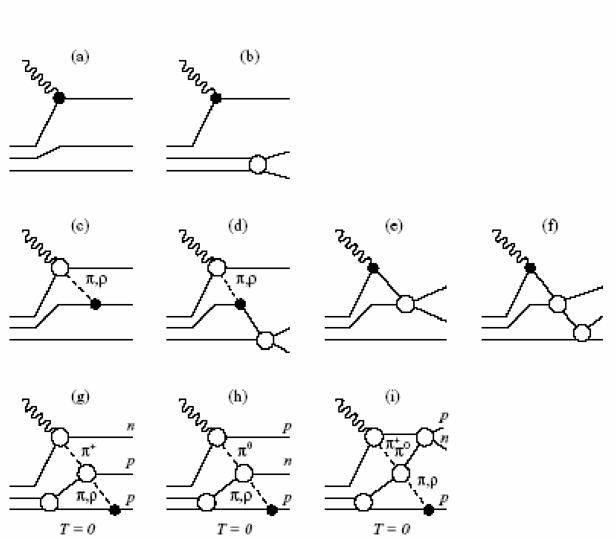
Cross section comparison with Theory

Diagrams included in Theory (Laget)

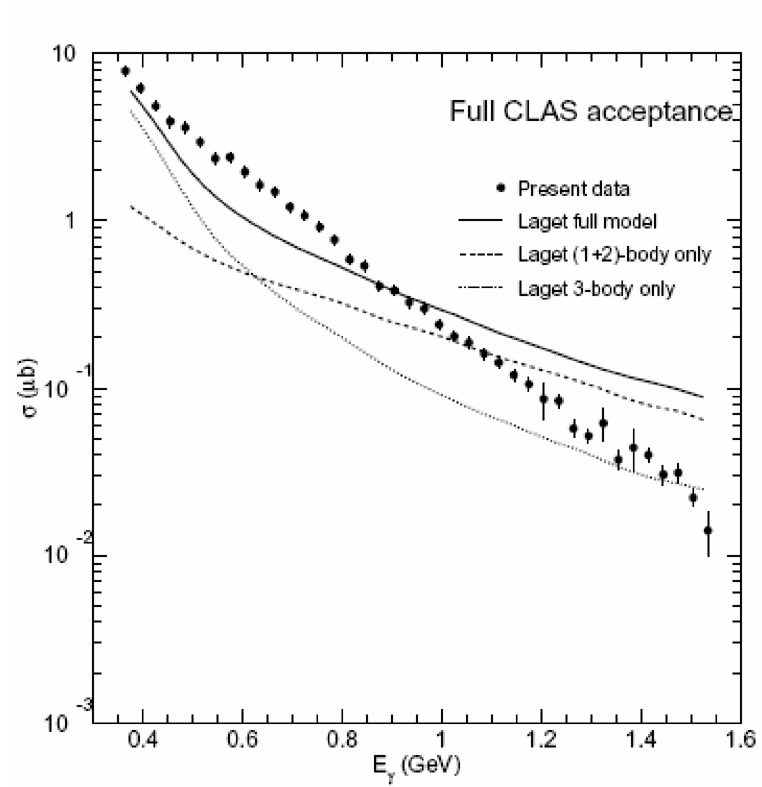
1N + FSI

2N + FSI

3N + FSI

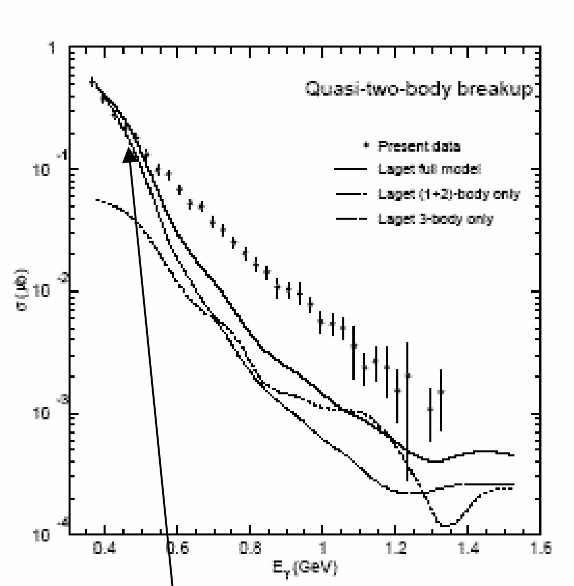


Full CLAS Acceptance



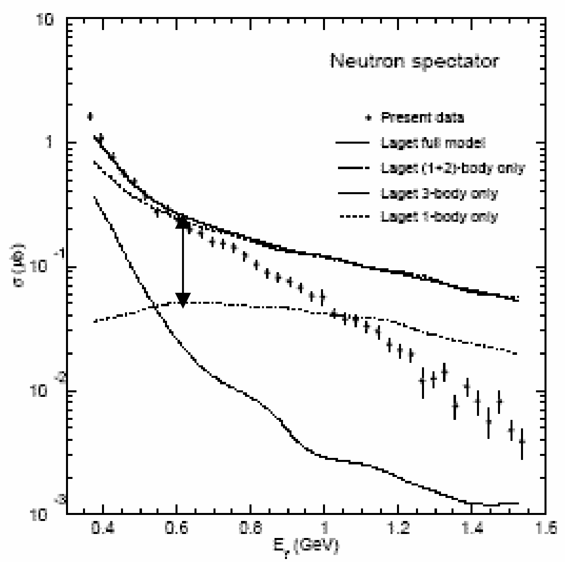
Specific Kinematics

Quasi 2-body breakup



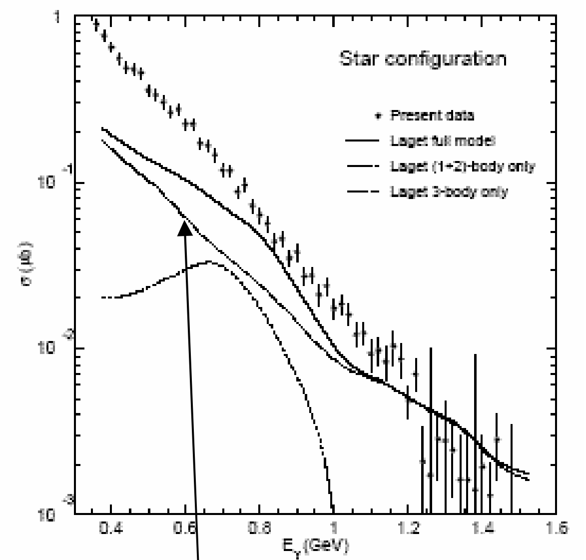
Large 3-body contribution at low E_γ

Neutron Spectator



Mostly 2-body contribution

Star configuration



Large 3-body contribution

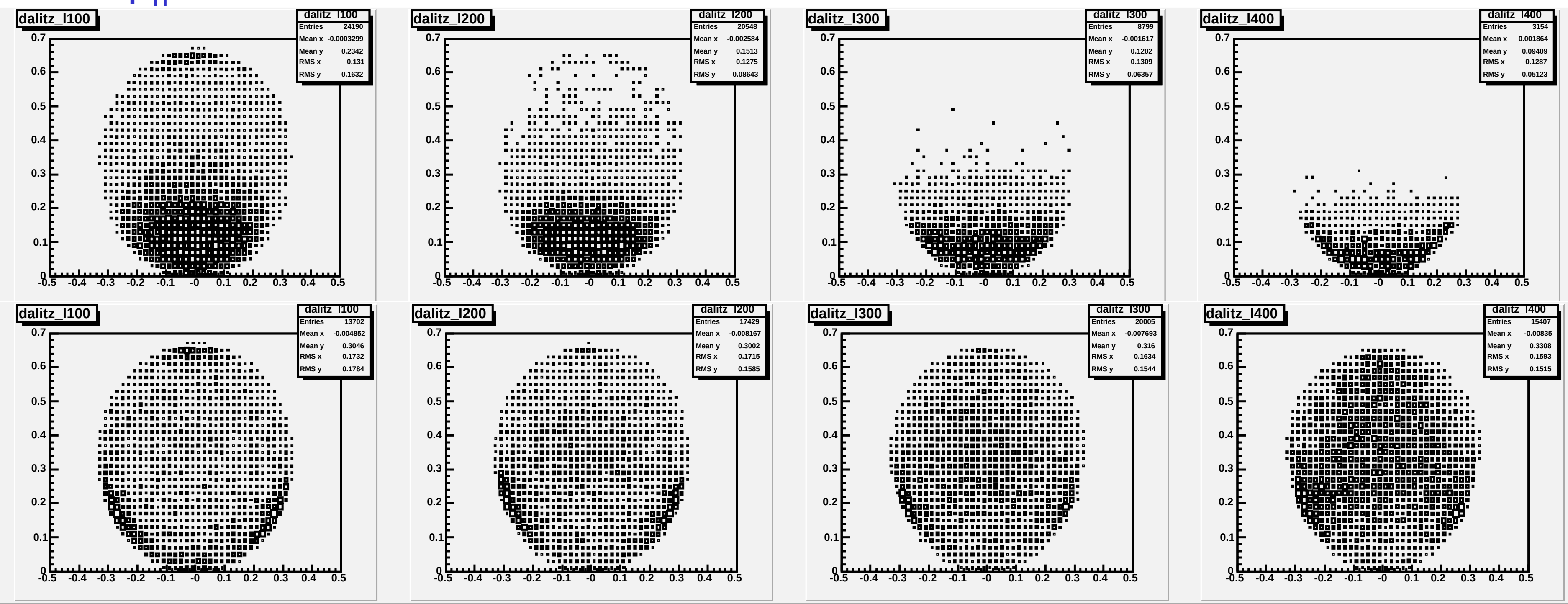
Further analysis of CLAS data

D Watts, Edinburgh

To investigate further whether specific kinematic regions can be identified which emphasise contributions from 3-body forces, specific cuts on ω and p_n are made.

Top: "Spectator" neutron (P_n < 200 MeV/c)

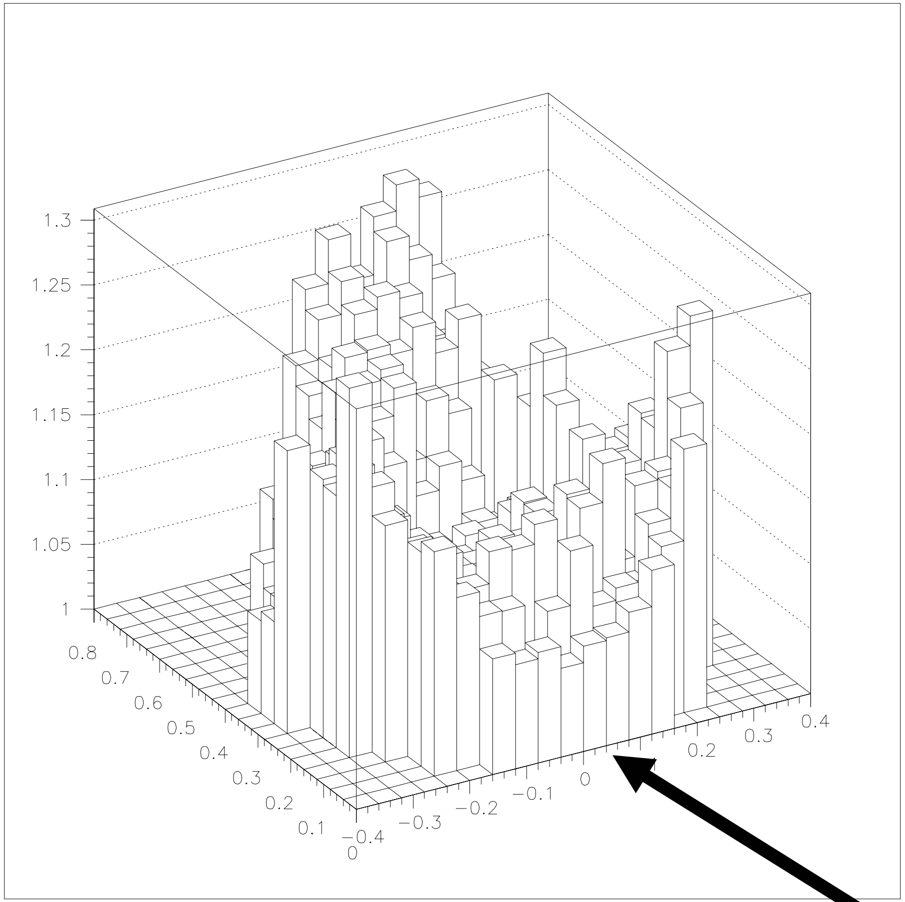
Bottom: "Active neutron (Pn > 200 MeV/c)



ω_c<100 MeV **ω_c=100 - 200 MeV** **ω_c=200-300 MeV** **ω_c=300-400 MeV**

Monte Carlo Modeling

Work in Progress



Monte Carlo modeling, using Fadeev calculations

⇒ Identify kinematic regions where 3BF provide enhanced contribution

⇒ Dalitz plot gives information on only 2 of the 5 variables needed to define the final state. By looking in more detail the sensitivity to 3BF can be increased significantly and regions of phase space where the 3BF increases the cross section by 85% are predicted.

Faddeev ω=120 MeV

Z axis = $\sigma_{3BF+2BF}/\sigma_{2BF}$

Summary

• Short-range Nucleon-Nucleon Interactions are spin and isospin dependent and have central and tensor contributions.

• Information on the short-range interactions between nuclei is obscured by other contributions: MEC, Isobar-currents and FSI.

• (e,e'), (e,e'p), (e,e'pp), (e,e'pn), (γ,pp) and (γ,pn) are all sensitive to different contributions and measurements on all reactions are required to disentangle competing mechanisms and study the various components of SRC.

• Experimentally we have only scratched the surface of this topic.

• Recent experiments have sought various ways to enhance the signal from SRC and to minimise other contributions to the cross section, e.g.:

High resolution => individual states => spin filter.

Choice of energy transfer to minimise isobar currents.

Choice of kinematics: parallel, anti-parallel, super-parallel to suppress FSI

Increasing the virtuality Q^2 to suppress FSI, MEC and Isobar-currents.

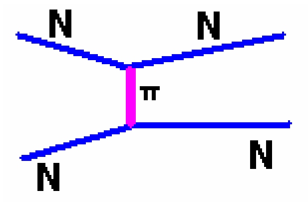
Choice of large x values

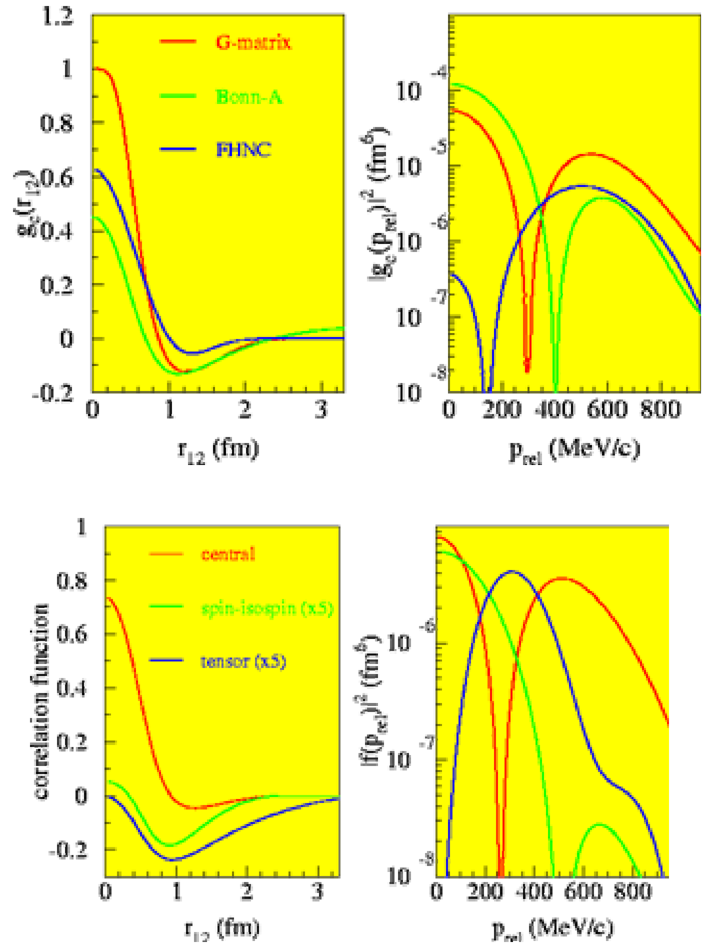
Summary Continued

- We have hardly looked at the role of polarisation variables which offer further discrimination between the contributory processes.
- Need improved theoretical treatments for light nuclei before meaningful information can be deduced about the properties of SRC.
- High resolution studies to resolve individual states seem best suited to low energy machines.
- The future for high-energy machines appears to be in the direction of higher Q^2 and large x-values, or the study of inclusive reaction studies.
- There is a need to investigate further 3-body (and multi-body) correlations which require large acceptance detector systems.

Short Range Nucleon-Nucleon Correlations

At distances of 1-2 fm nucleon-nucleon forces are attractive and well described by single π exchange.





At shorter distances the forces are repulsive and their exact nature is not well understood.

Possible mechanisms are:
- heavy meson exchange
- multiple meson exchange
- direct quark exchange

NN correlations are theoretically expected to have radial, spin, isospin and tensor dependences.