Theoretical overview - looking forward

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Outline

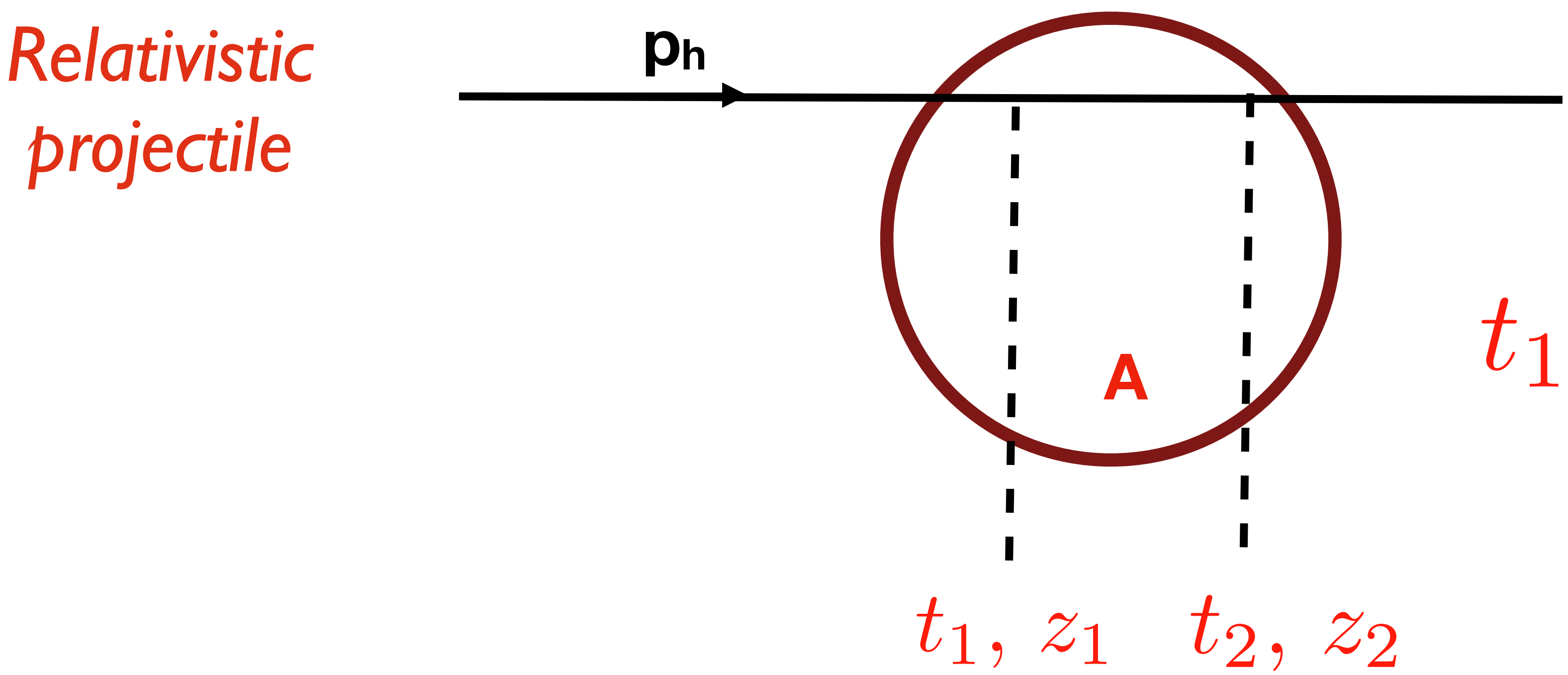
- Emergence of light cone (LC) dominance at high energies
- Deuteron - LC - nonrelativistic correspondence
- Construction of LC density matrix, spectral and decay function
- Quest for 3N SRCs
- Quest for nonnucleonic degrees of freedom - have no time

To resolve short-range structure of nuclei *on the level of nucleon/hadronic constituents* one needs processes which transfer to the nucleon constituents both energy and momentum larger than the scale of the NN short range correlations $q_0 \geq 1GeV, \vec{q} \geq 1\,GeV$

much larger for SRC with momenta up to 1 GeV/c

$\Rightarrow$ Need to treat the processes in the relativistic domain. The price to pay is a need to treat the nucleus wave function using light-cone quantization - - One cannot use (at least in a simple way) nonrelativistic description of nuclei.

$\Rightarrow$ High energy process develops along the light cone.



$$t_1 - z_1 = t_2 - z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. In the nucleus rest frame

$$\alpha_N = (E_N - p_{N\,z})/(m_A/A)$$

In the reference frame of collider (LHC,RHIC) $\alpha_N = AE_N/E_A$

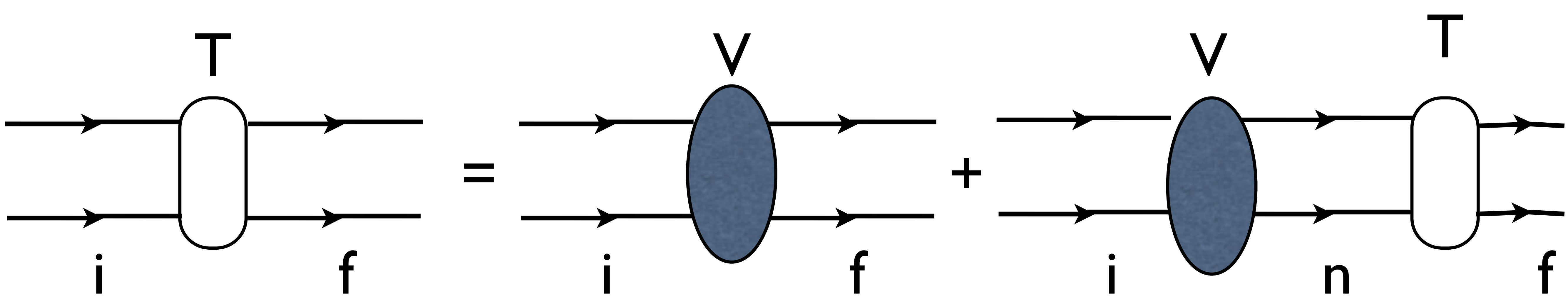
Note: in general no benefit for using LC for low energy processes.

Light-cone Quantum mechanics of two nucleon system

Due to the presence of a small parameter (inelasticity of NN interactions) it makes sense to consider two nucleon approximation for the LC wave function of the deuteron.

Key point is presence of the unique matching between nonrelativistic and LC wave functions in this approximation. Proof is rather involved.

First step: include interactions which do not have two nucleon intermediate states into kernel V (like in nonrel. QM) to build a Lippman-Schwinger type (Weinberg type) equation [LF & MS 81]



Second step: Impose condition that master equation should lead to the Lorentz invariance of the on-energy-shell amplitude of NN scattering

Introduce three- vector $\vec{k} = (k_3, k_t)$ with

$$\alpha = 1 - \frac{k_3}{\sqrt{k^2 + m^2}}$$

Invariant mass of two nucleon system is $M_{NN}^2 = 4\frac{m^2 + k_t^2}{\alpha(2-\alpha)} = 4m^2 + 4k^2$

$$T(k,k_{\mathrm{f}}) = V(k,k_{\mathrm{f}}) + \int V(k,k') \frac{\mathrm{d}^3 k'}{4\sqrt{{k'}^2+m^2}} \; \frac{1}{{k'}^2 - k_{\mathrm{f}}^2} \; \frac{1}{(2\pi)^3} \; T(k',k_{\mathrm{f}})$$

$$\Big\downarrow$$

Very similar structure for the equation for the scattering amplitude in NR QM and for LC. If a NR potential leads to a good description of phase shifts the same is true for its LC analog. Hence simple approximate relation for LC and NR two nucleon wave function

$$\alpha = (\sqrt{p^2 + m^2} - p_3)/(m_D/2)$$

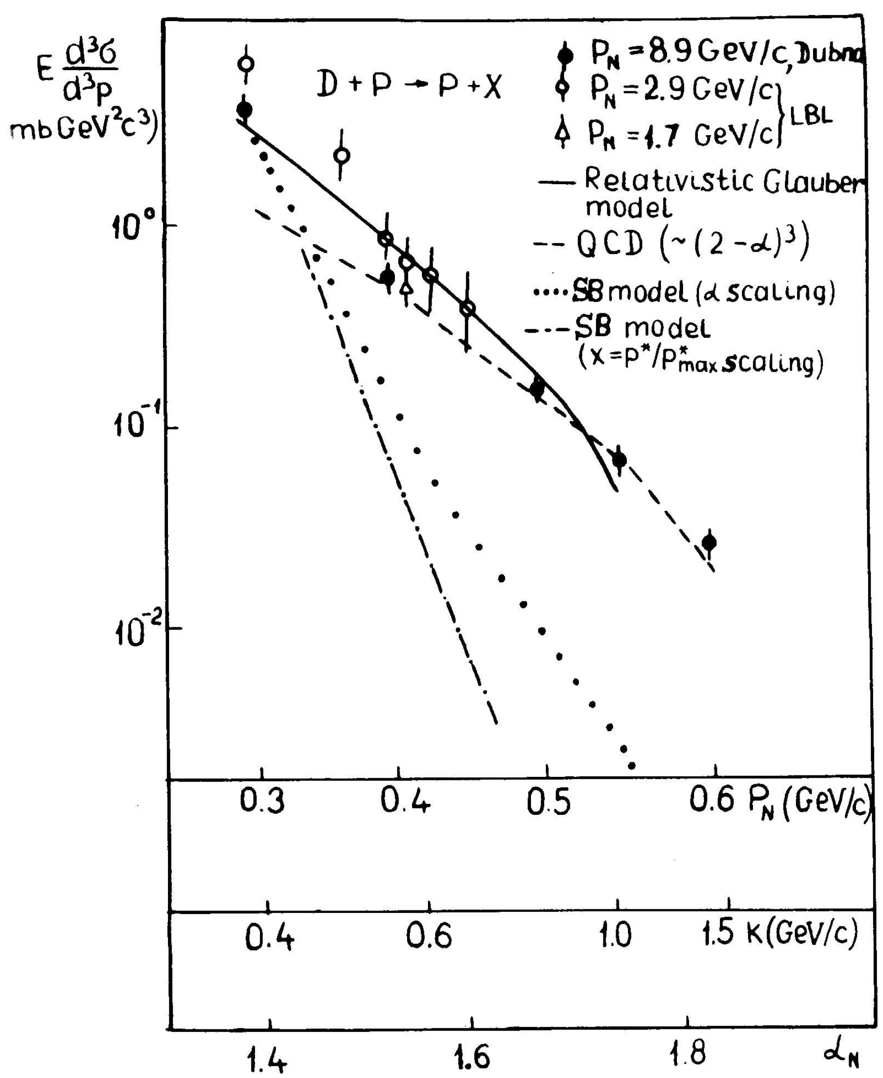
where p is rest frame momentum of nucleon spectator in reaction h+ D—> p +X

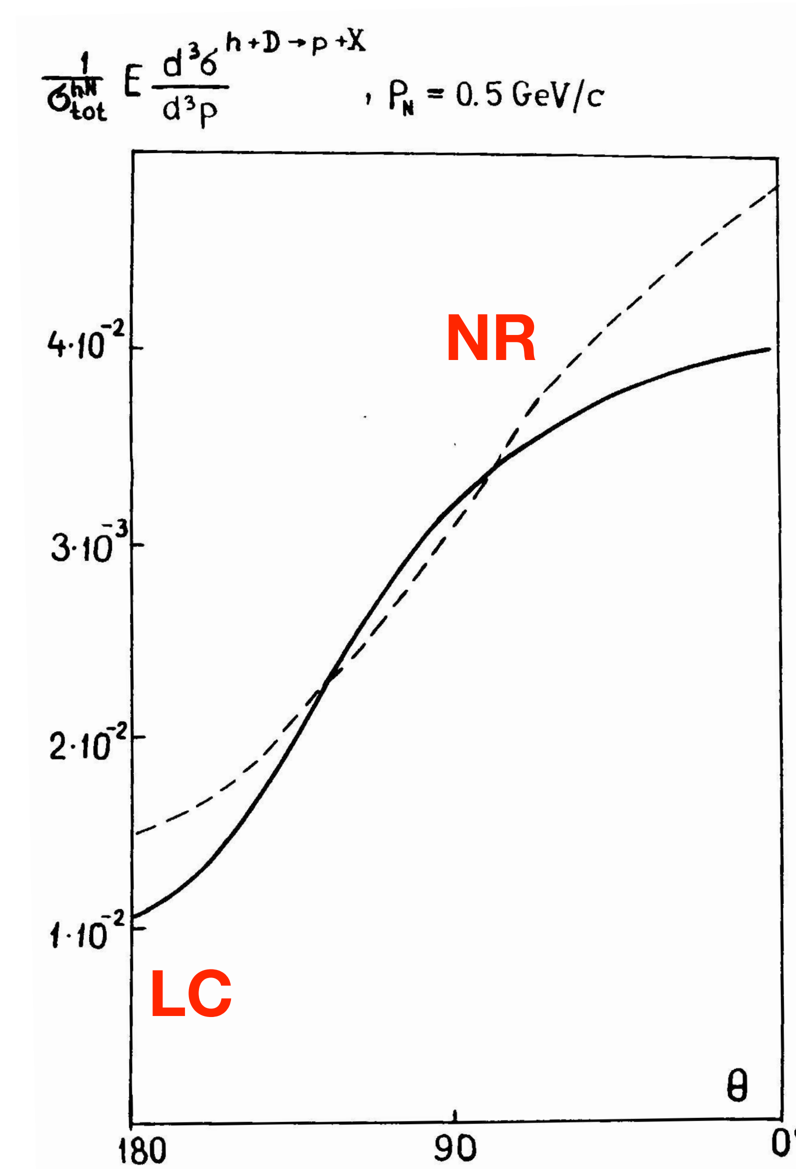
Highly nonlinear relation between momentum k and momentum p: backward p=3m/4 $\Longleftrightarrow k \to \infty$

backward p=0.5 GeV—> k=0.8 GeV

$$\frac{d\sigma(p + D \to p + X)}{d^2k_t d\alpha/\alpha} = \sigma_{NN}^{inel}\psi_D^2(\alpha, k_t)$$

large momentum transfer in NN scattering, spectator mechanism -decay function



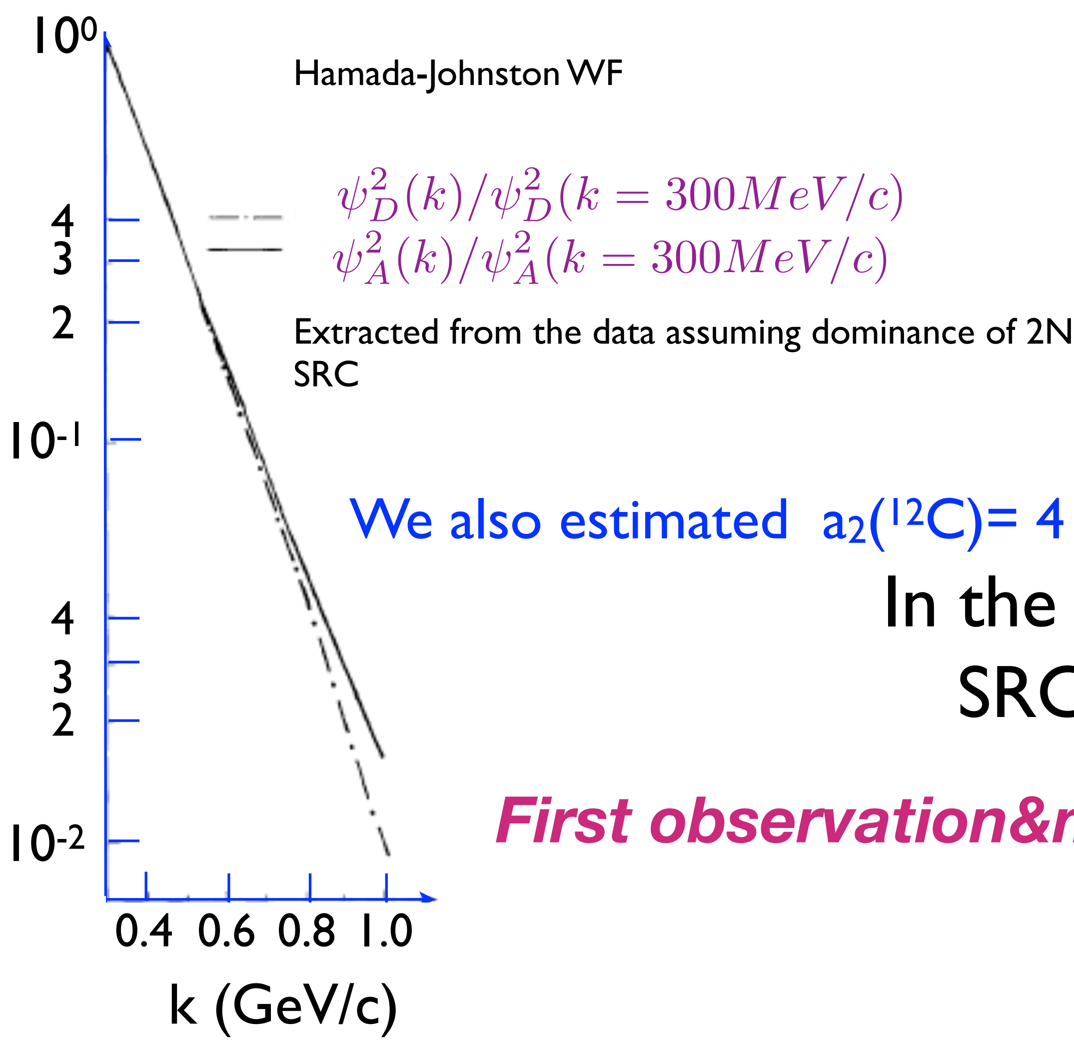


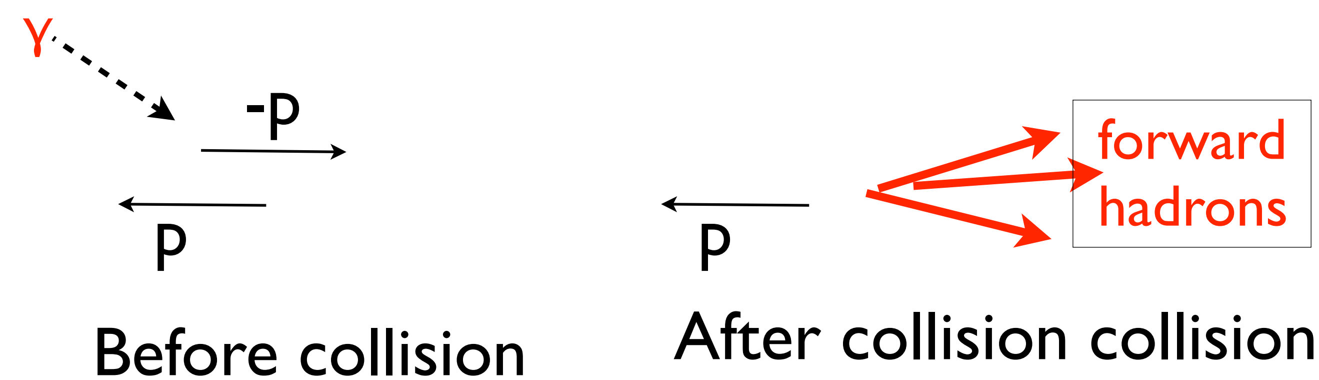
would be desirable to have data from Jlab (real photon, moderate x ~.1- .2)

First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion , photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys.Lett 1977) two nucleon correlation function from analysis of

$\gamma(p)\ ^{12}C \to$ backward p+X processes [no backward nucleons are produced in the scattering off free protons!!!]

Spectator production of the backward proton from 2N SRC





We also estimated $a_2(^{12}C) = 4 \div 5$

In the collider frame where nucleus has momentum Ap: SRC is two nucleons with momenta αp and $(2-\alpha)p$

First observation&measurement of 2N SRC in high energy processes

Momentum distributions normalized to its value at 300 MeV/c.

Backward direction is very good for looking for decay of SRCs

Dynamical quantity (ones which can be directly observe)

Nonrelativistic

momentum distribution **n(k)**

not observable directly

Light cone

LC density matrix $\rho_A(\alpha, k_t)$

calculated for A=3
and nuclear matter

Spectral function

modeled in 2N moving in mean field model

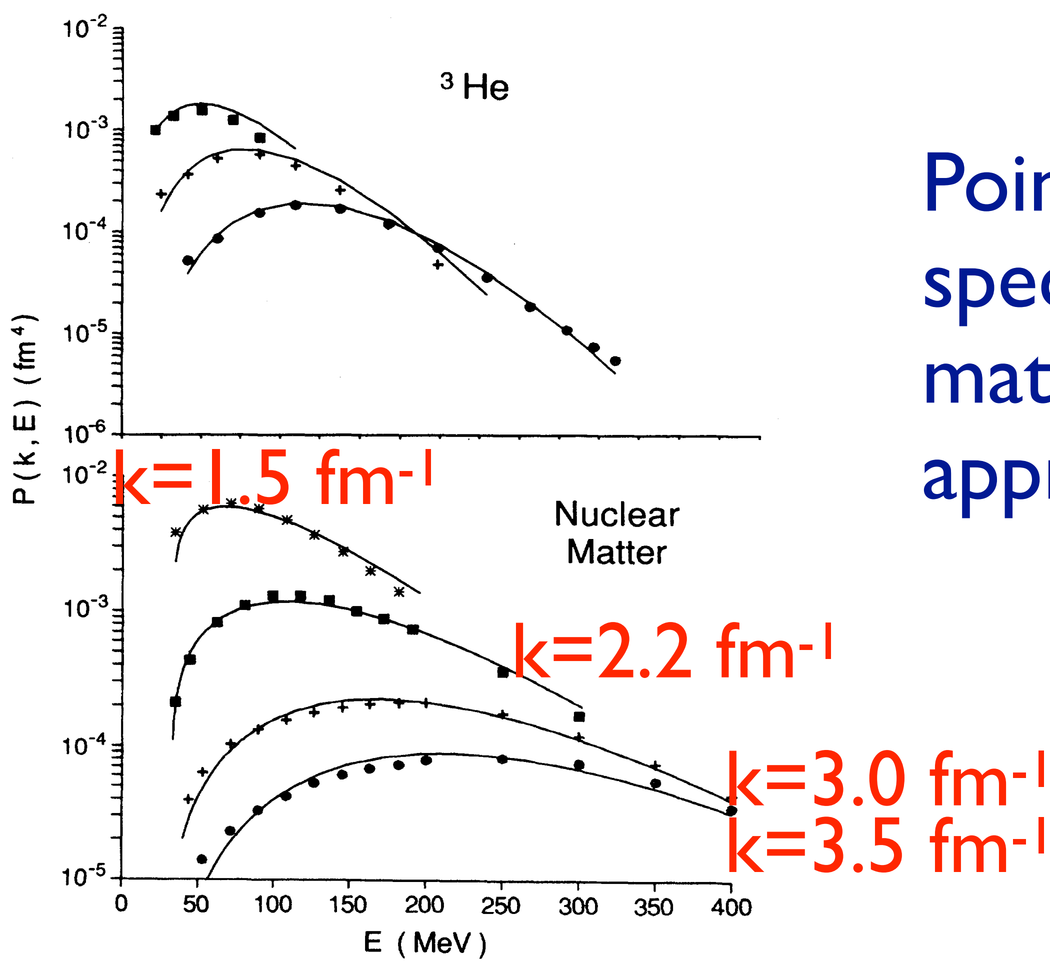
Decay function

$$D_A(k_2, k_1, E_r) = \left|\langle \phi_{A-1}(k_2, \ldots) \left| \delta(H_{A-1} - E_r) a(k_1) \right| \psi_A \rangle\right|^2$$

FS81 -88

Ab-initio NR calculation of double momentum distribution +
ansatz 2N moving in mean field are used for modeling spectral and decay functions

Numerical calculations in NR quantum mechanics confirm dominance of two nucleon correlations in the spectral functions of nuclei at k> 300 MeV/c - could be fitted by a motion of a pair in a mean field (Ciofi, Simula,Frankfurt, MS - 89-91). However numerical calculations for nuclear matter ignored three nucleon correlations - 3p3h excitations. Relativistic effects maybe important rather early as the recoil modeling does involve k^2/m_N^2 effects.



Points are numerical calculation of the spectral functions of ^{3}He and nuclear matter - curves two nucleon approximation from CSFS 91 question/concern : removing one nucleon of SRC does not destroy interactions of second nucleon of SRC with mean field - *should suppress emission from pairs with high momenta of the pair.*

Additional Ansatz - LC implementation of motion of the pair in the mean field

symmetry in LC NN fraction around $\alpha_{NN}=2$

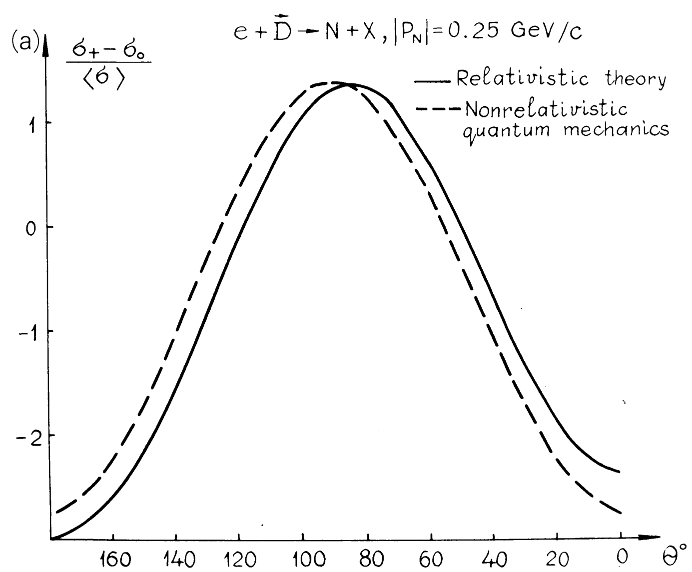
Phenomenologically such model works well for A(e, e'p), A(e,e'pp),… - several talks

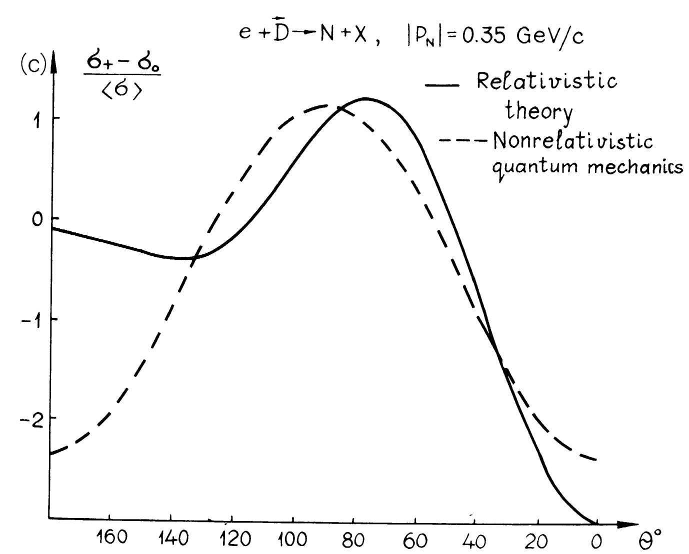
further open questions:

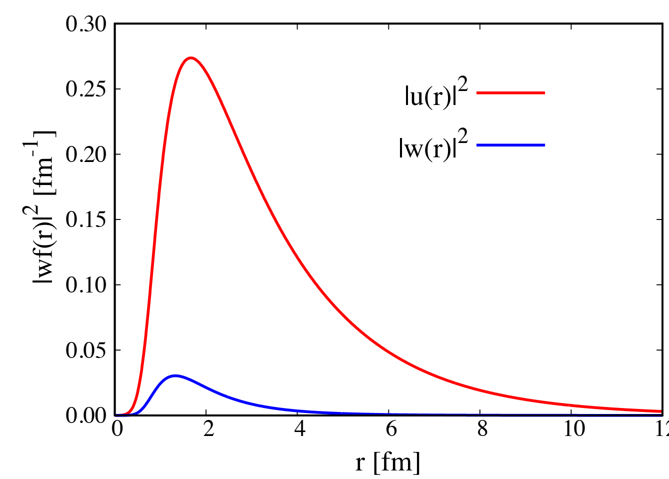
- ✷ **with what is accuracy WF of pn pair $\propto$ $\psi^2_D(\kappa)$?; FSIs** Boeglin talk

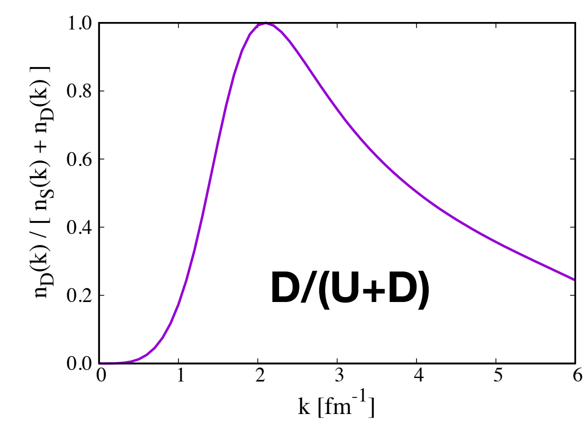
- ✷ **Need observables sensitive to LC dynamics**

study scattering off polarized deuteron (S/D ratio) or studying variation of scalar/tensor ratio for different angles and same momentum









small component in coordinate space generates dominant contribution in momentum space

- ✷ **off shell eN cross section**

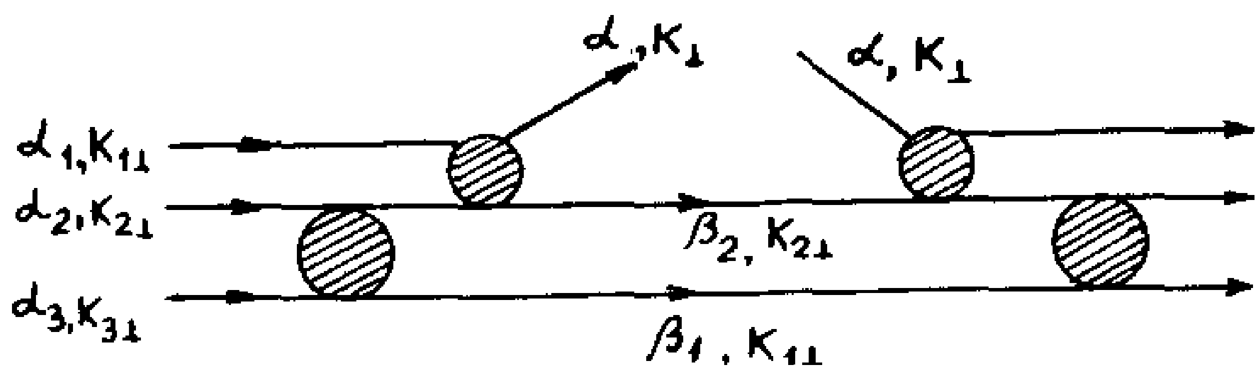
Three nucleon SRCs = three nearby nucleons with large relative momenta

Since NN interaction is sufficiently singular for large momenta

$\rho_A^N(\alpha, p_t)$ can be expanded over contributions of j-nucleon correlations $\rho_j(\alpha, p_t)$

$$\rho_A^N(\alpha > 1.3, p_t) = \sum_{j=2}^{A} a_j(A)\rho_j(\alpha, p_t)$$ FS 79

iterations of NN interactions (Plus 3N from 3N forces possible)



$$\rho_j(\alpha, p_t)(j-\alpha)^{n(j-1)+j-2}, \; where \; \rho_j(\alpha, 0) \propto (2-\alpha)^n$$

α up to 2 (3) are allowed for 2N (3N) SRC (plus small mean field corrections)

NR case large k = 2N SRC, qualitative difference relativistic and nonrelativistic dynamics

Evidence from NR calculations? *3N SRC can be seen in the structure of decay of ³He* (Sarsgian et al).

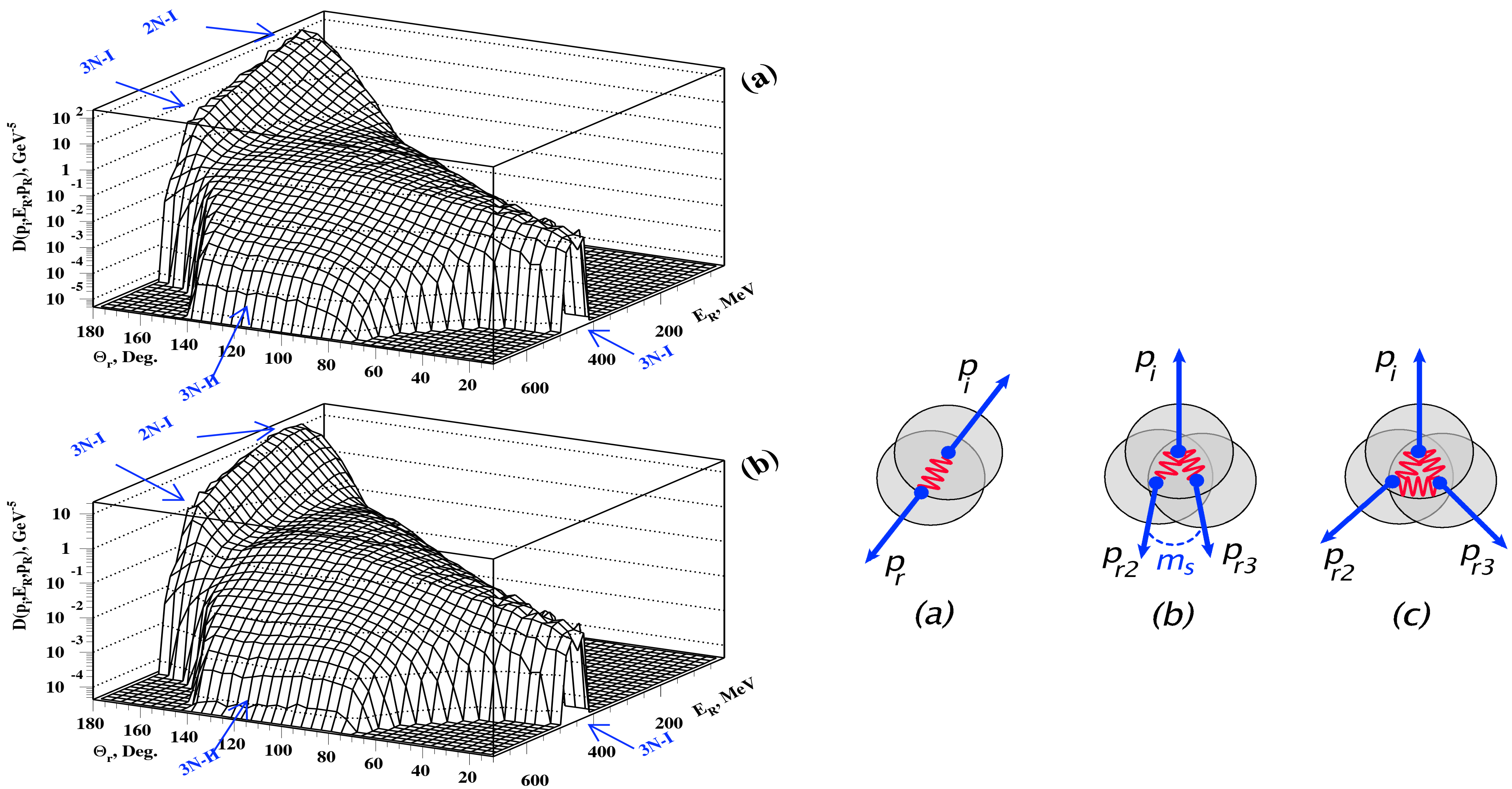
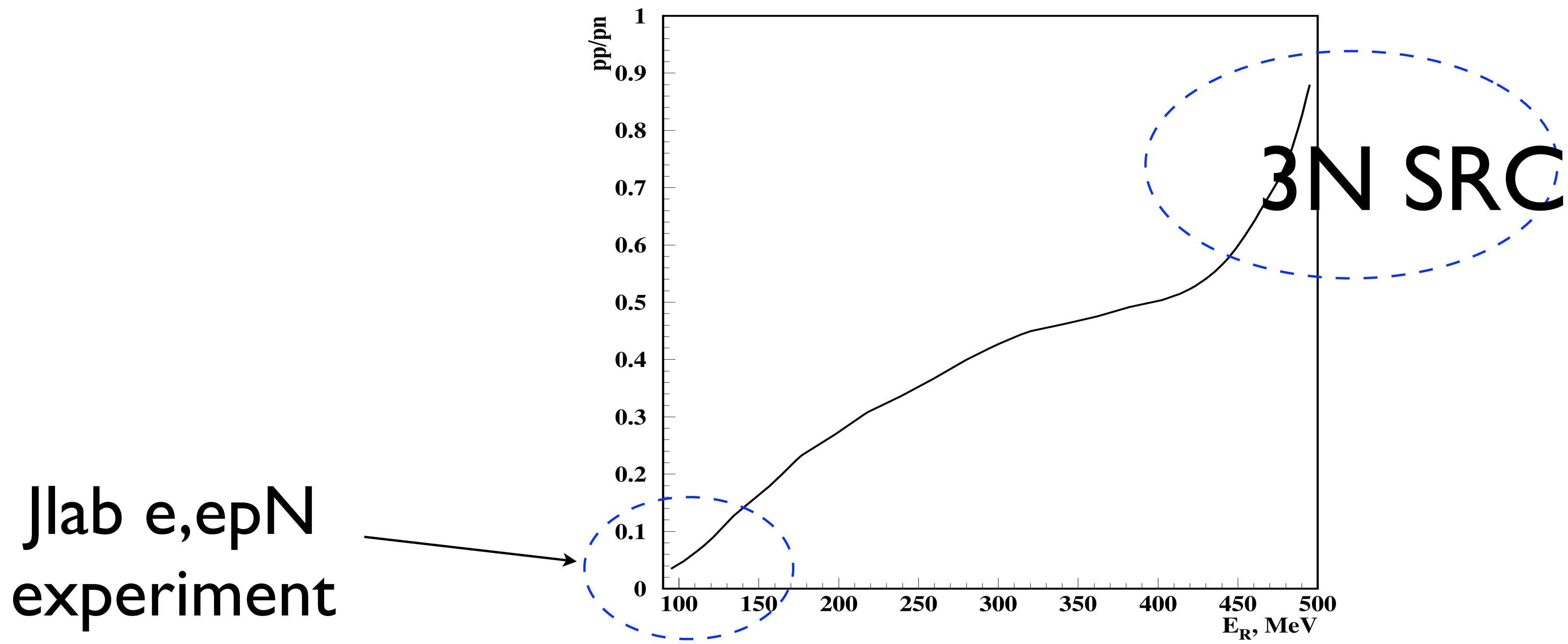


Figure 8: Dependence of the decay function on the residual nuclei energy and relative angle of struck proton and recoil nucleon. Figure (a) neutron is recoiling against proton, (b) proton is recoiling against proton. Inital momentum of the struck nucleon as well as recoil nucleom momenta is restricted to $p_{in}, p_r \geq 400$ MeV/c.

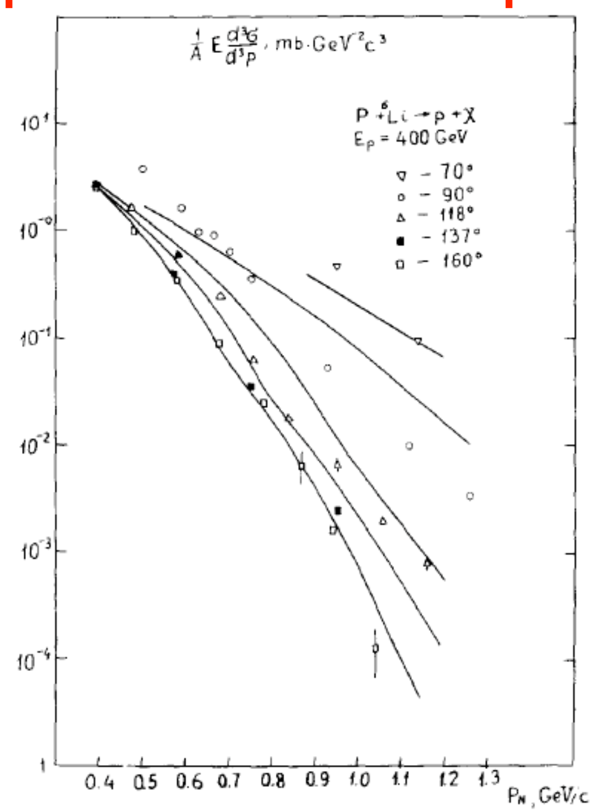


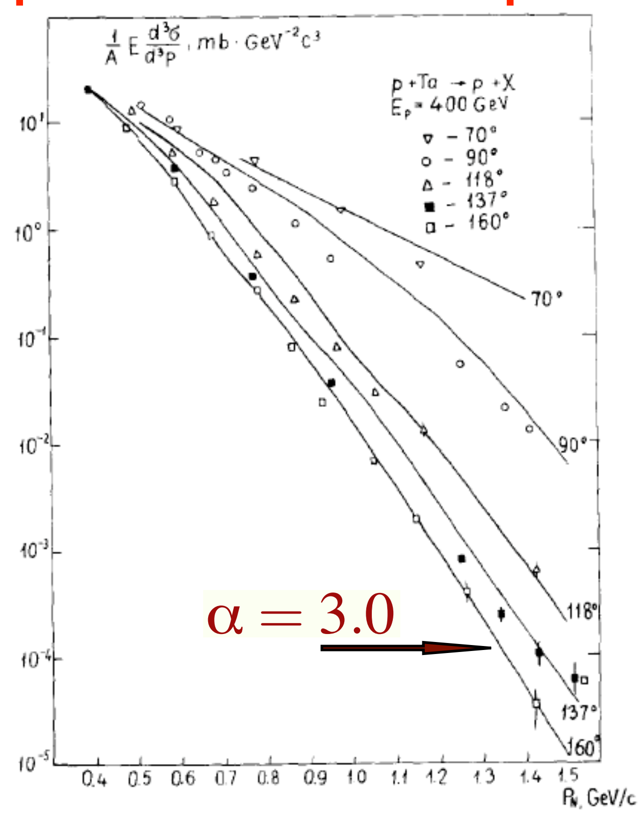
Recoil energy dependence of the ratio of decay function calculated for the case of struck and recoil nucleons - p_s & p_r for struck proton and recoil proton and neutron for p_s & $p_r >$ 400MeV/c & $180^\circ > \theta(p_s\ \ p_r) > 170^\circ$

Some of experimental evidence in historic order

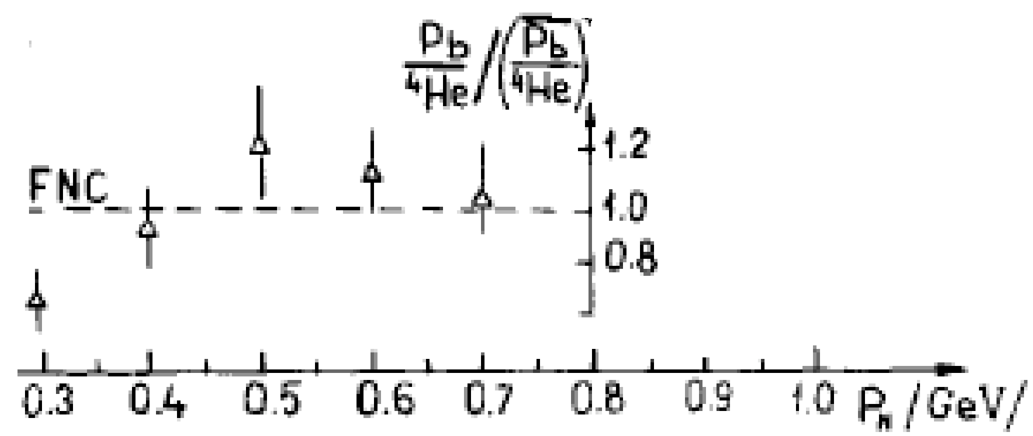
Plenty of data were described using few nucleon SRC approximation with 3N, 4N correlations dominating in certain kinematic ranges. Strength of 2N correlations is similar to the one found in (e,e'),(p,2p)

$p^6Li \to$ backward $p+X$ $pTa \to$ backward $p+X$





Comparison of few nucleon SRC approximation with pA data at E_p^{inc}=400 GeV

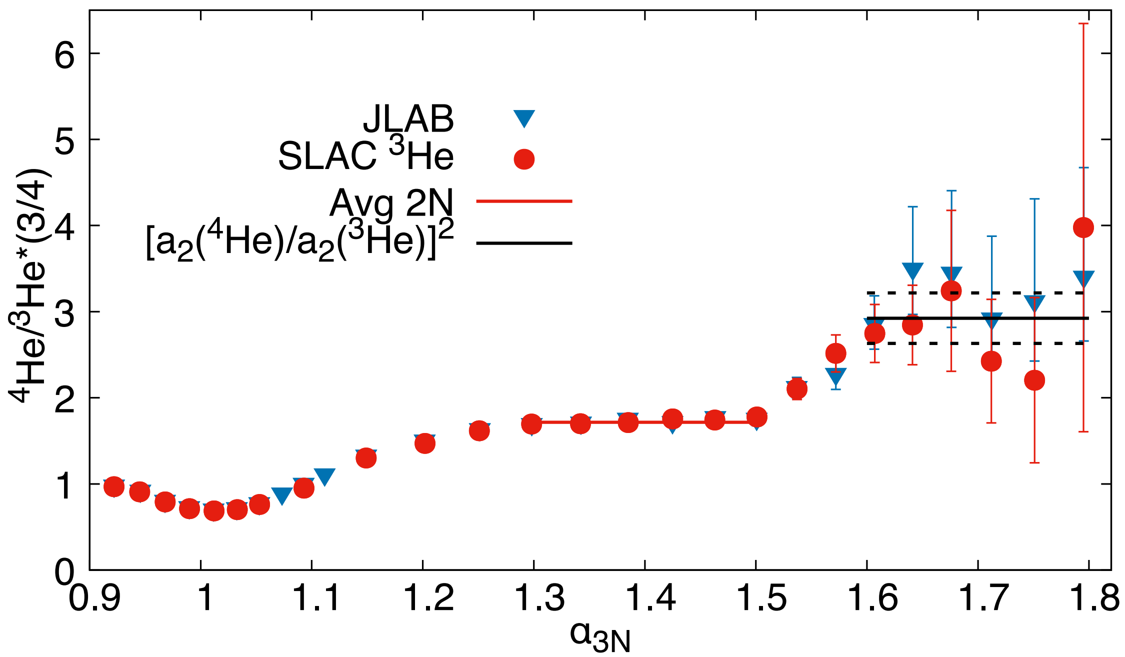


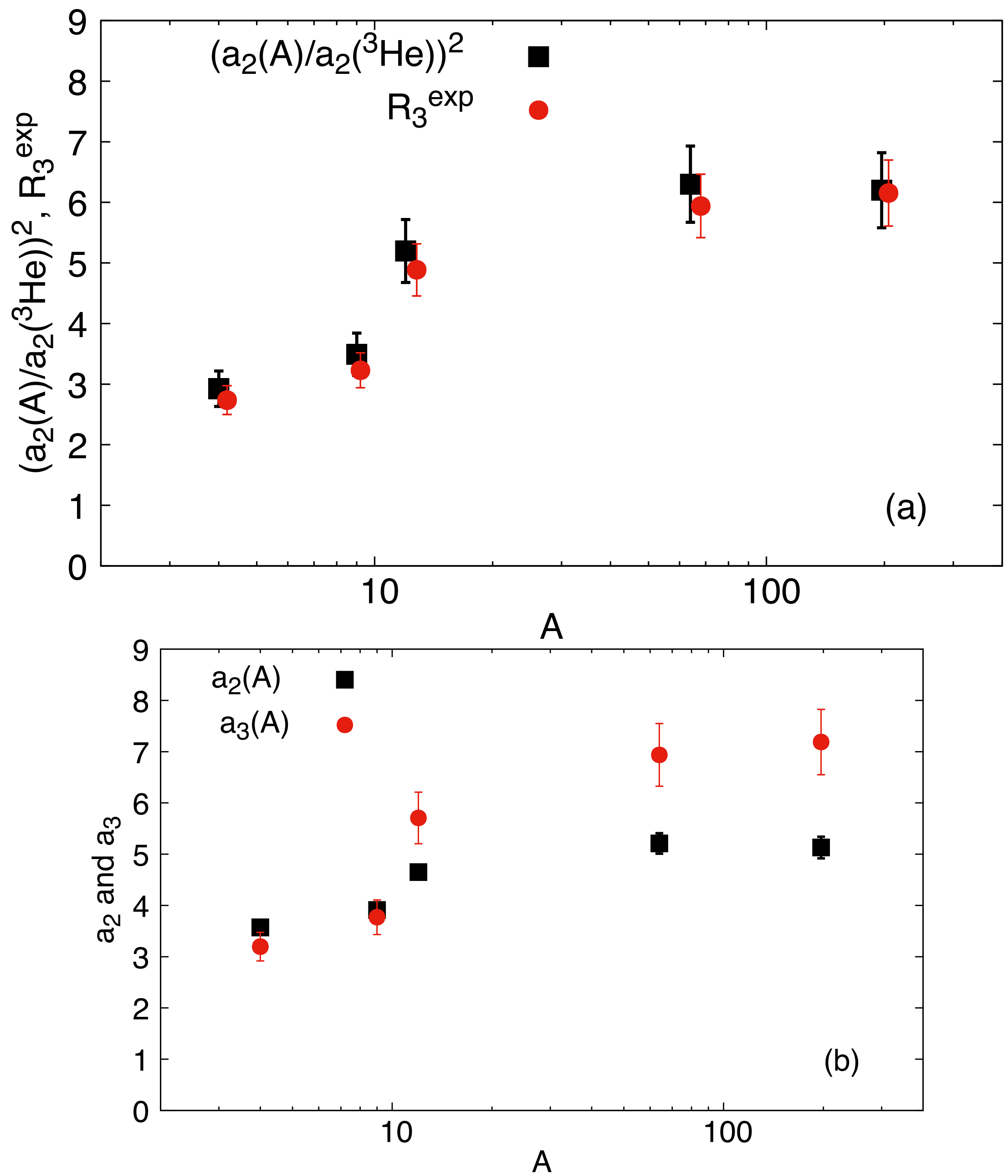
Test of universality for pA→p+X spectra for backward emission at Ep= 9 GeV

Observations of (p,2pn) &(e,e') at x>1 confirm the origin of SRC as the dominant source of the fast backward nucleons

recent analysis of (e,e’) x> 2 (Day, Sargsian, LF , MS)

need larger Q^2





Onset of 3N dominance at α~ 1.6

Further studies are necessary of LC scaling of the ratios, etc. Recoil structure more complicated than in 2N case

Correlations in p A→ p (backward) + p (backward) +X

measurements of Bayukov et al 86

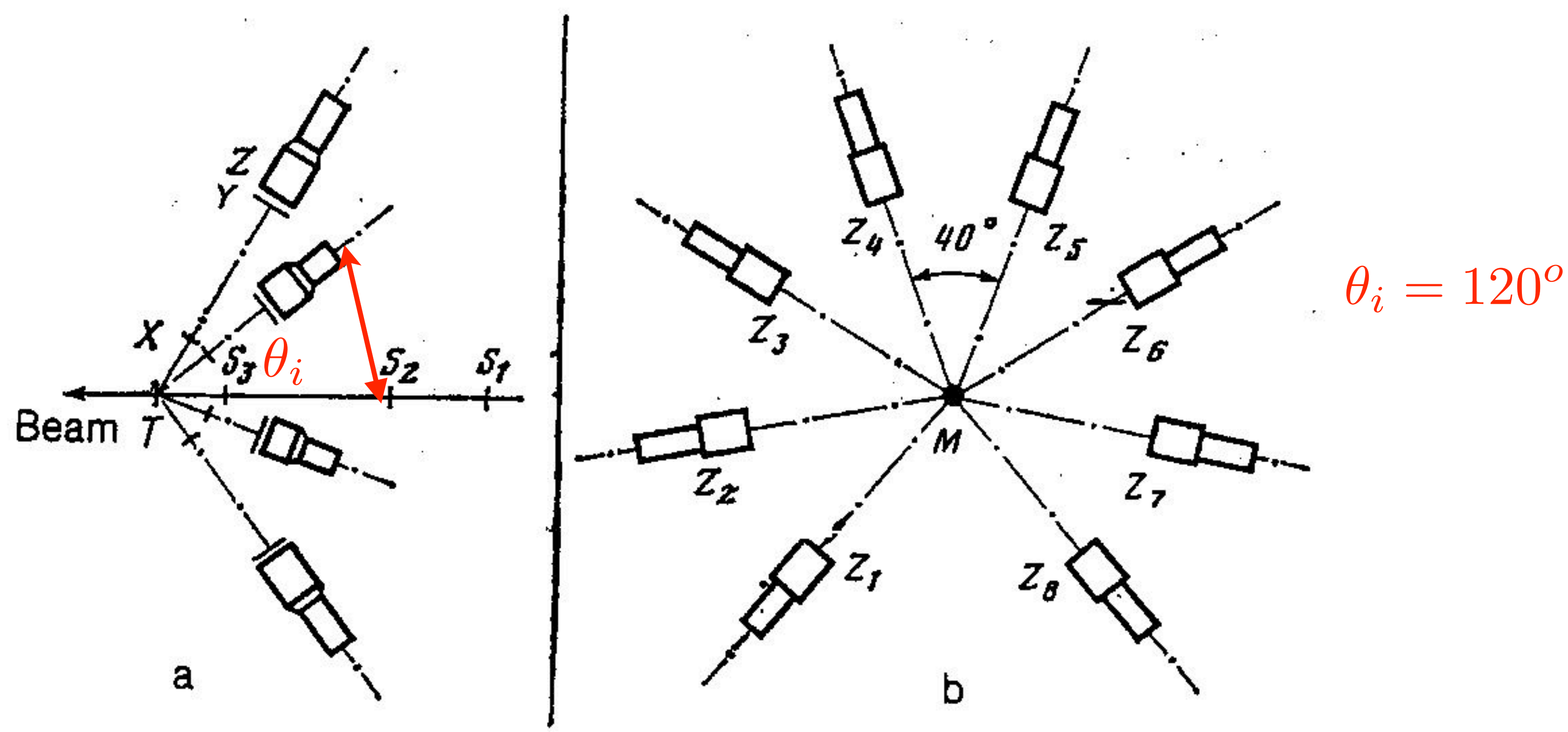
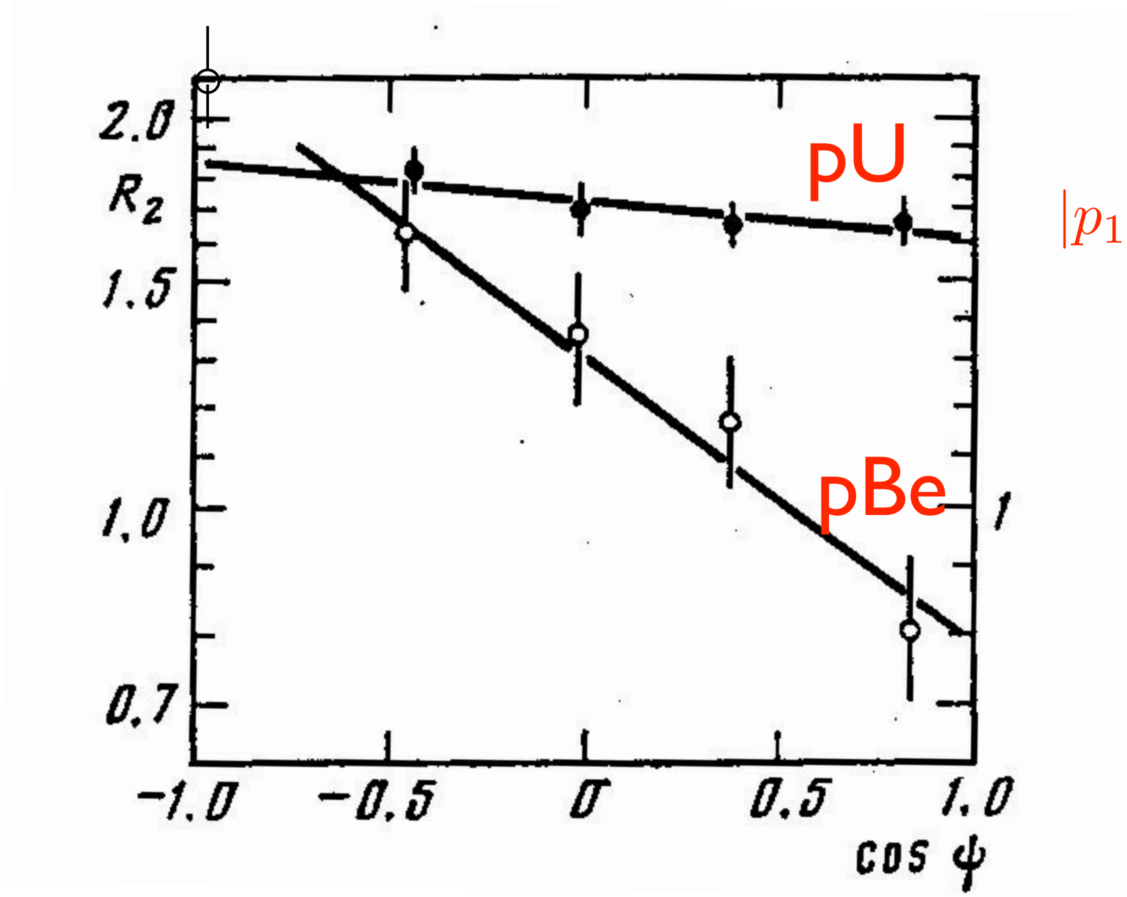


FIG. 1. Diagram of apparatus. (a)—Side view, (b)—view along the beam direction. Only the Z counters are shown.

$$p_i \approx 0.5\,GeV, \alpha \approx 1.4, p_t \approx .25\,GeV$$

$$R_2 = \frac{1}{\sigma_{pA}^{in}} \frac{d\sigma(p+A \to pp+X)/d^3p_1 d^3p_2}{d\sigma(p+A \to p+X)/d^3p_1 d\sigma(p+A \to p+X)/d^3p_2}$$

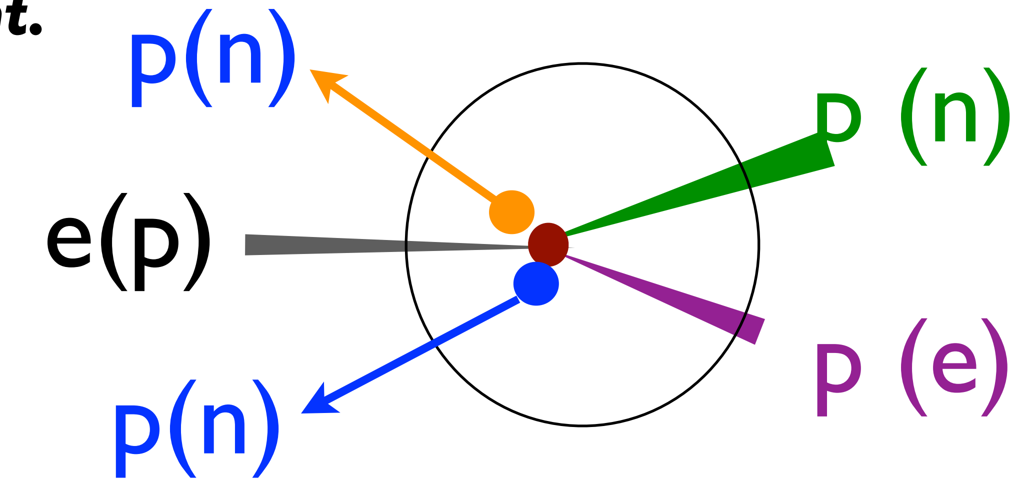


$|p_1| = |p_2| \approx 500 MeV/c$

Curves is experimental fit.

the pattern of ψ dependence of R_2 can be reproduced

Study 3N correlations in A(e,e' p +2 backward nucleons) &A(p,p' p +2 backward nucleons). Reminder: for the neutron star dynamics mostly isotriplet nn, nnn,.. SRC are relevant.



Start with ^{3}He, followed by ^{4}He, C. Expectations:

(a) $\alpha_{1\,Back.Nucl} + \alpha_{2\,Back.Nucl} + \alpha_{3\,Forw.Nucl} \approx 3$

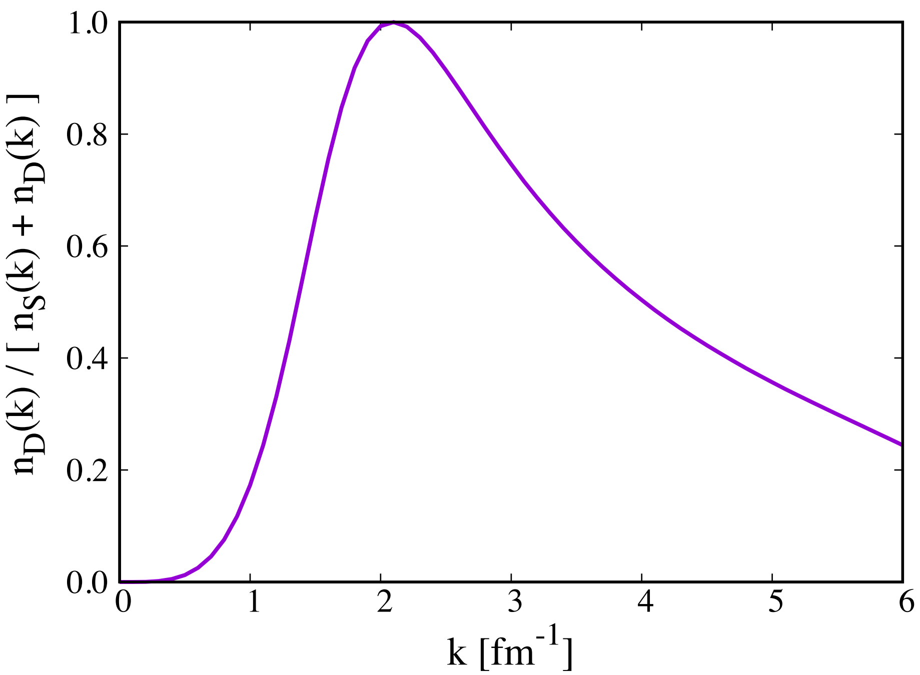
(b) ppn ~ nnp >> nnn, ppp

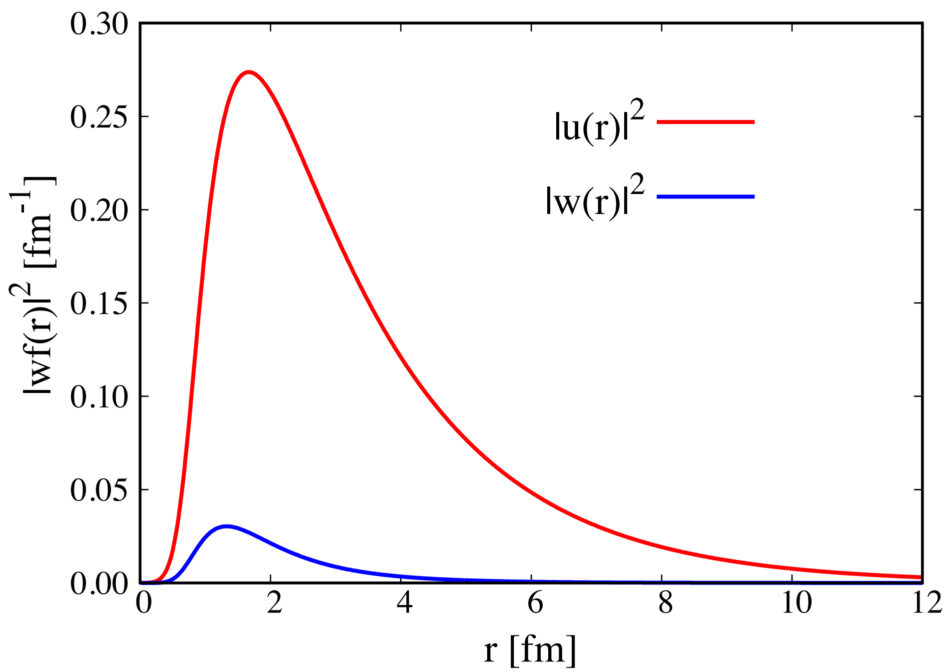
(c) e+A → e+ 2N +X stronger angular dependence and larger $R_2(\psi=-180^\circ)$ than in pA.

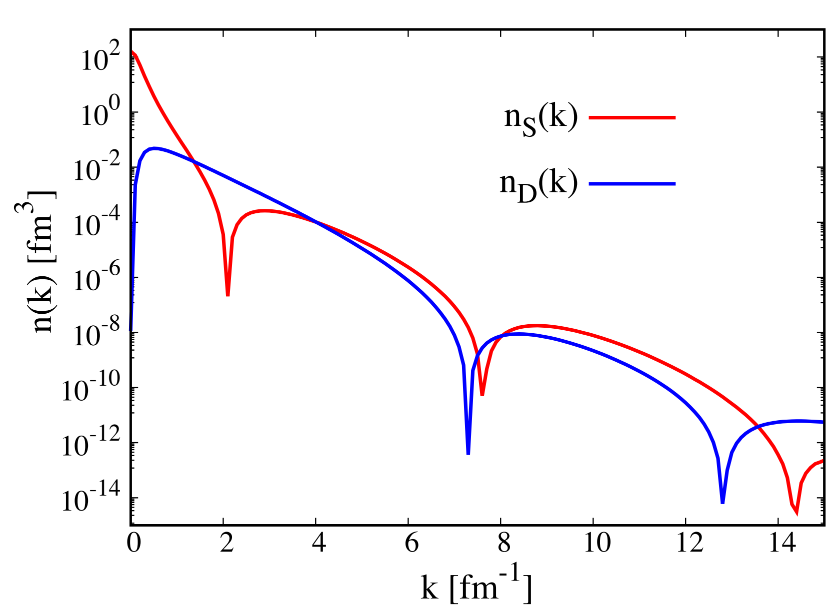
Can inverse kinematics help? Lumi

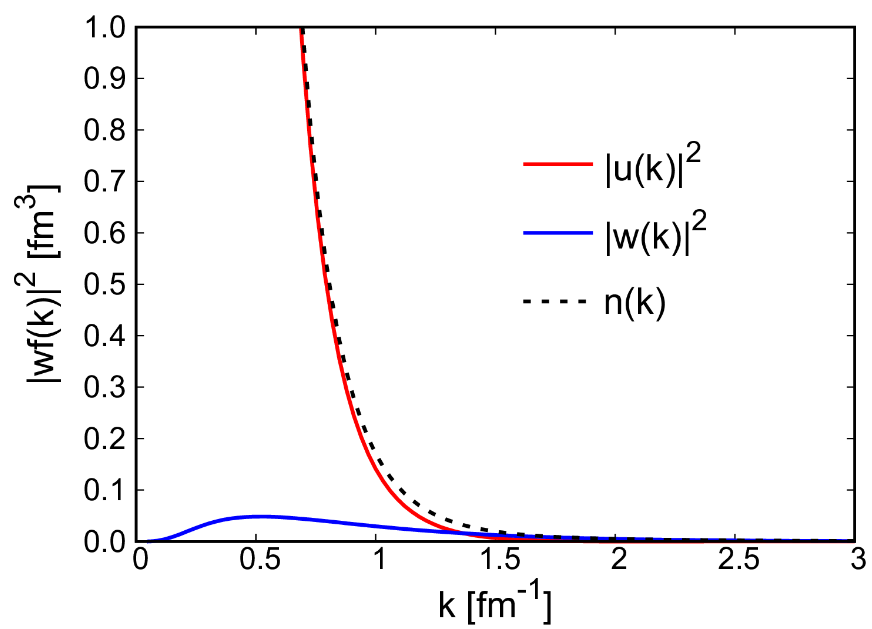
Summary - discoveries through precision and through new processes

- ☛ Precision theoretical and experimental studies of the lightest nuclei, including relativistic dynamics
- ☛ Tests of realistic modeling of FSI
- ☛ Tests of factorization (comparing electron, photon, nucleon- nucleus SRC sensitive processes.
- ☛ Tests of dynamic assumptions of LC many nucleon approximation.
- ☛ Separation of S and D waves in SRCs
- ☛ Calculating and looking for 3N SRC
- ☛ Looking for Δ-isobars and other non-nucleonic degrees of freedom in nuclei









a question - is w(k) /u(k) universal for k> 300 MeV/c?