Study of Short Range Correlations in A(e,e/) and A(e,e/p)A-1 Reactions

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Study of ……

- **Usually**

- **Physics Motivation (why?, for what?)**

- **How to study? (methods, approaches)**

- **Ways to study (tools, costs, etc.)**

Study of Short Range Correlations

- **In this talk**

- ~~**Physics Motivation (why?, for what?)**~~

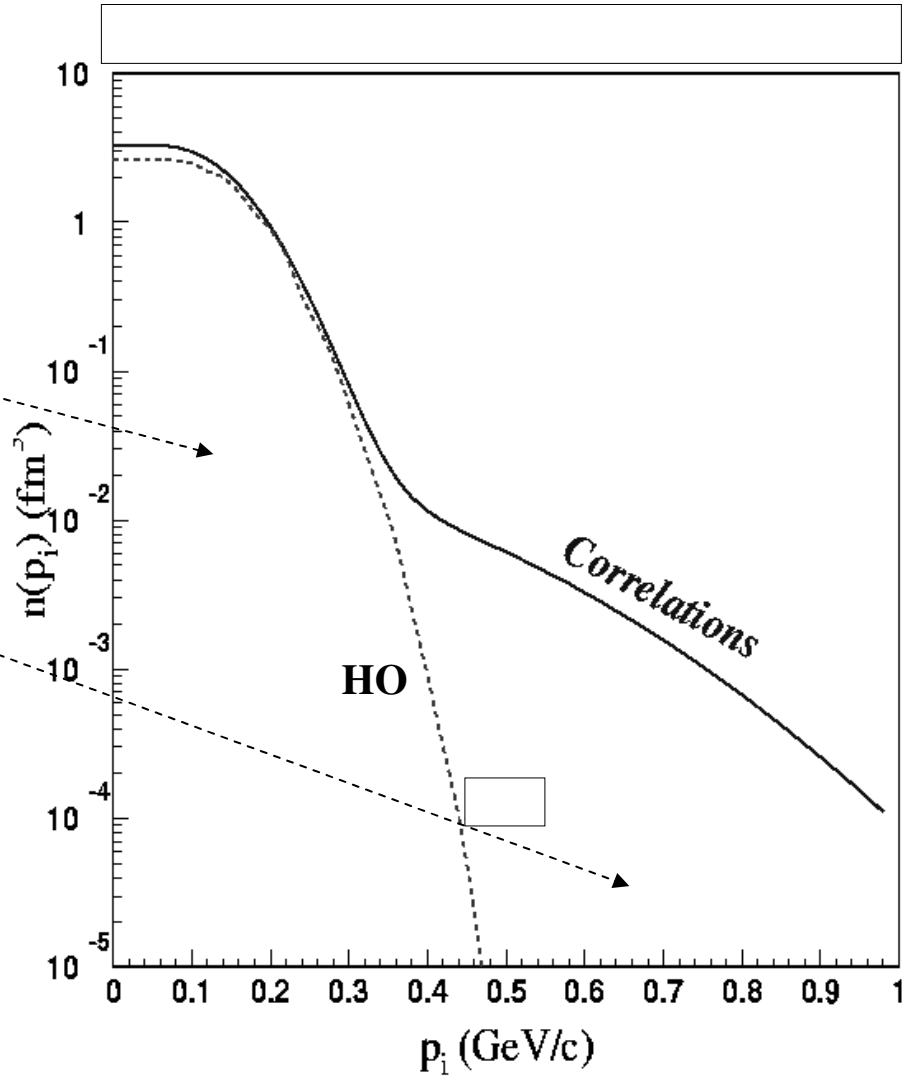
- **How to study? (methods, approaches) – with illustrations by Hall B**
  A(e,e′) and d(e,e′p)n data

- ~~**Ways (tools, costs, etc.)**~~

Short Range Correlations – How Study Them?

- **First step should be to find SRCs in nucleus**

- **Nucleus is a system of nucleons with two phases in momentum space:**
  - **First (dominant) phase is a single nucleon state, well described by shell model, and occupied by low momentum, uncorrelated nucleons**
  - **Second (NON dominant) phase consist of close-spaced, high-momentum (2-nucleon) correlations**



Short Range Correlations – How Study Them?

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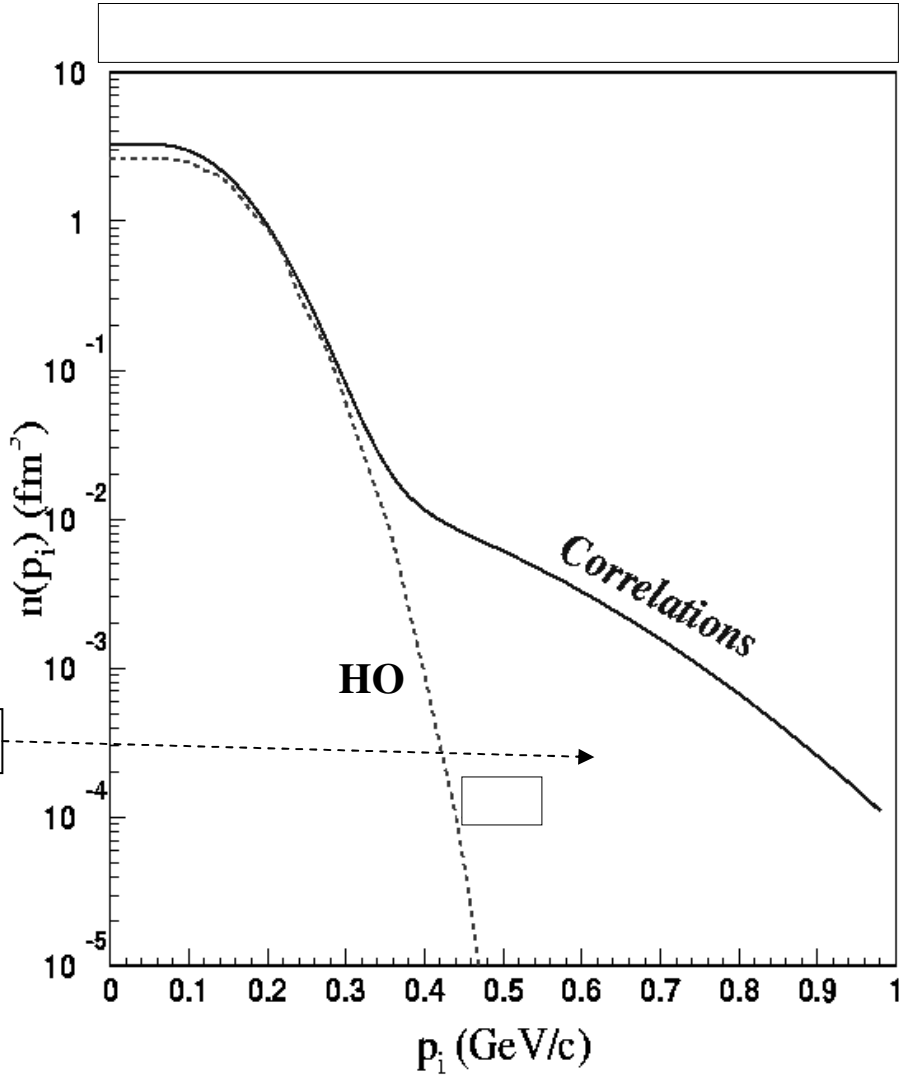
  - **Second (NON dominant) phase consist of close-spaced, high-momentum (2-nucleon) correlations**
- **Main signature for SRC is the high momentum of nucleons involved in it**
- **For SRC studies the high momentum part of nuclear wave function should be used**
- **The main problem is, how to select this high momentum part?**



Study of Short Range Correlations in A(e,e/)

Two main problems should be solved in this case:

1. **Selection of high momentum component of nuclear WF is problematic, because momentum distribution is not measurable in inclusive scattering**

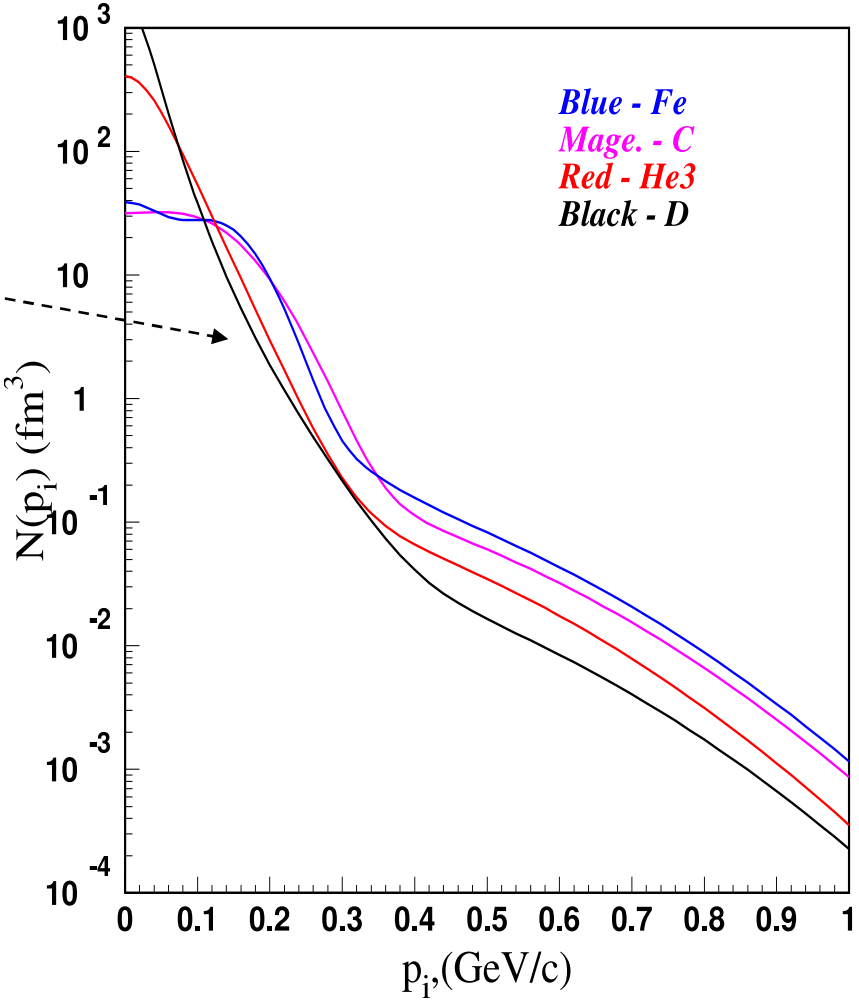
2. **Effect of Final Stat Interaction (FSI)**

How to Select the Short Range Correlations in A(e,e′)

- To suppress the contribution from the inelastic production, use cut $x_B > 1$

How to Select the Short Range Correlations in A(e,e′)

- To suppress the contribution from the inelastic production, cut $x_B > 1$
- To suppress the contribution from the low momentum part of nuclear WF
  - Use the WF-shape similarity of all nuclei in SRC dominant range of p_i
  - Since at $x_B > 1$ the A(e,e′) cross sections are primarily proportional to the WF, the ratios of of 2 nuclei (heavy to light) cross sections should SCALE with onset at some values of Q^2 and x_B, and this will be onset for SRC dominancy

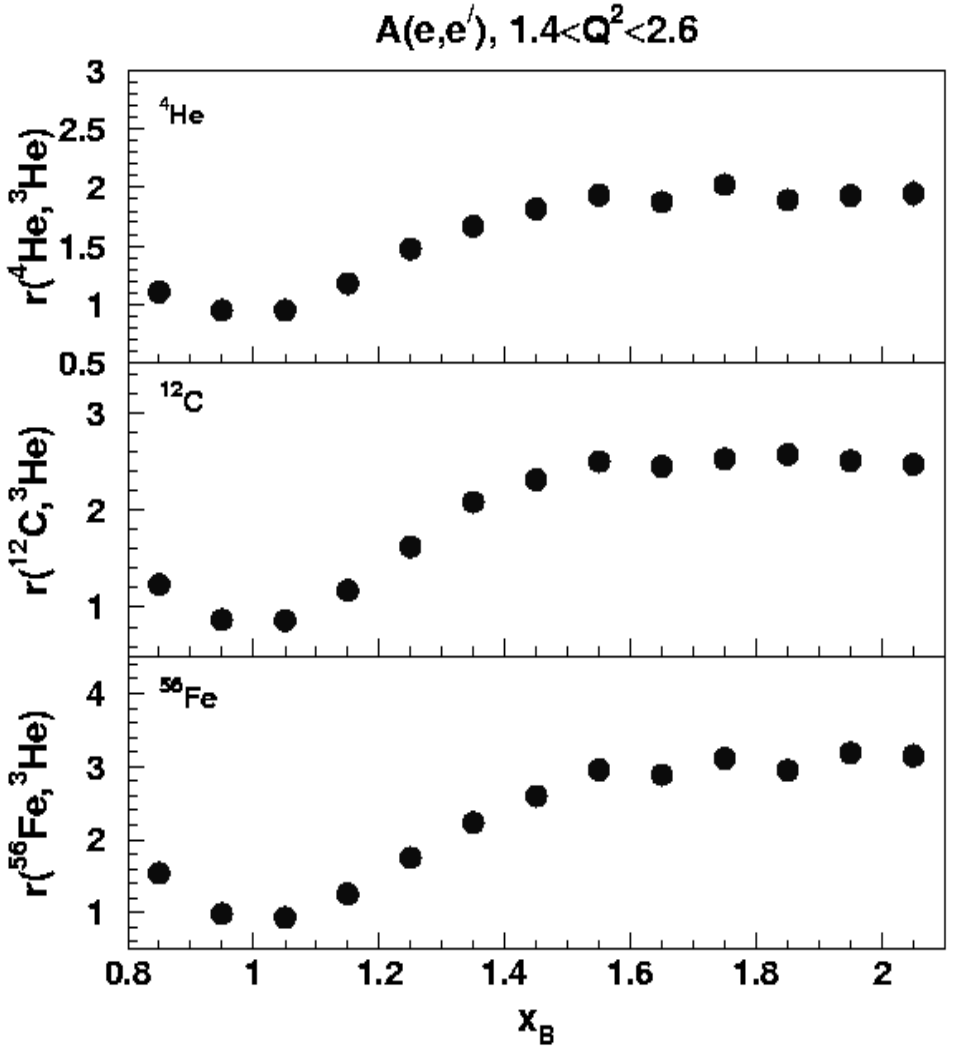


Separation of Short Range Correlations Domain in A(e,e′)

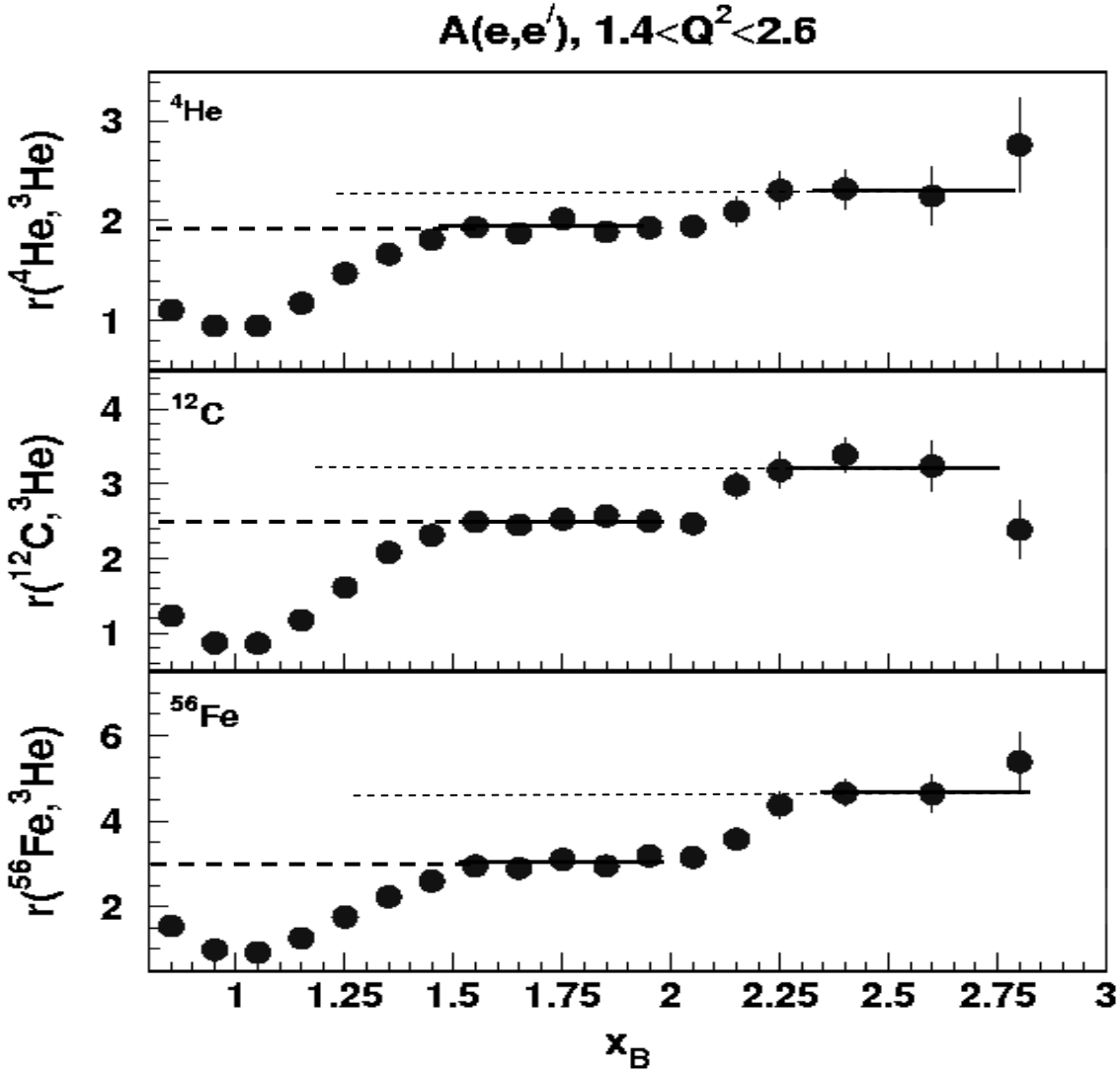
- We observed this scaling for A(e,e′)/^{3}He(e,e′) ratios
  - in $1<x_B<2$, i.e., in 2-nucleon correlation region
  - also in $2<x_B<3$, i.e., in 3-nucleon correlation region
  - We will discuss today only

    2-nucleon correlations

- Scaling region separates SRC region from others

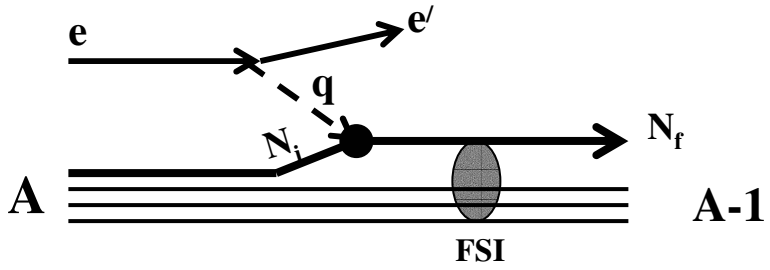


A(e,e/)/^{3}He(e,e/) Ratios at $x_B < 3$



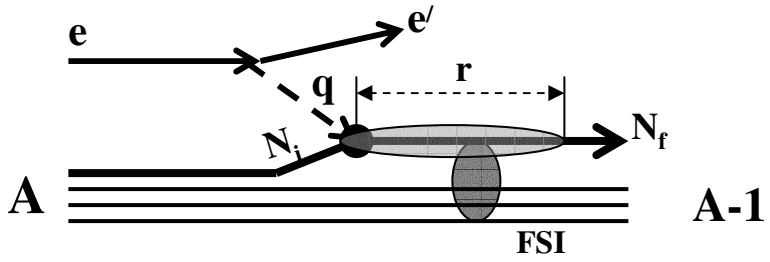
Final State Interaction in (e,SRC) Scattering

- **In Clasics the FSI of recoil nucleon can not affect on (e,N_i) scattering, occurred before!**



Final State Interaction in (e,SRC) Scattering

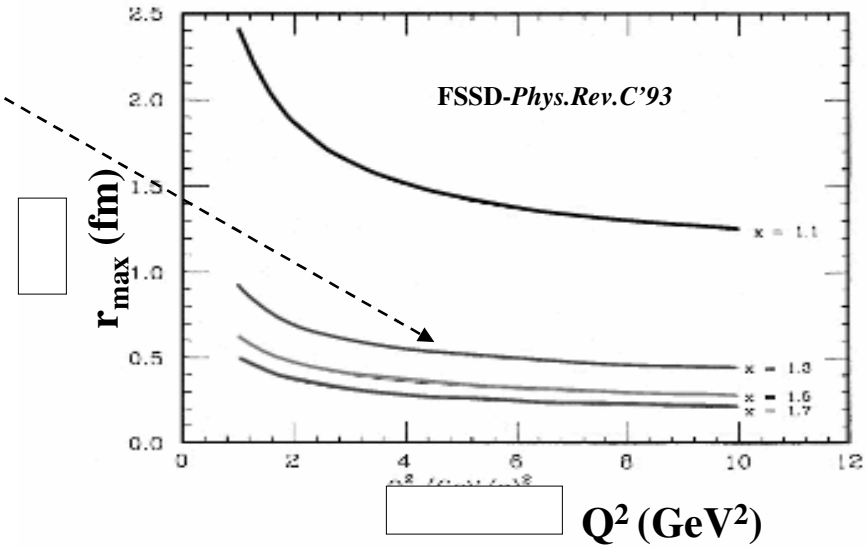
- However, in QM there is some distance (r) where FSI still can affect on (e,N_i) interaction.



- At Q2 > 1.5 GeV^2 and x_B > 1.3 the maximum value r is < 1fm.

- Since $R_{SRC} \leq r$, the FSI of nucleons from the same SRC can affect on cross section in (e,N_i) vertex!

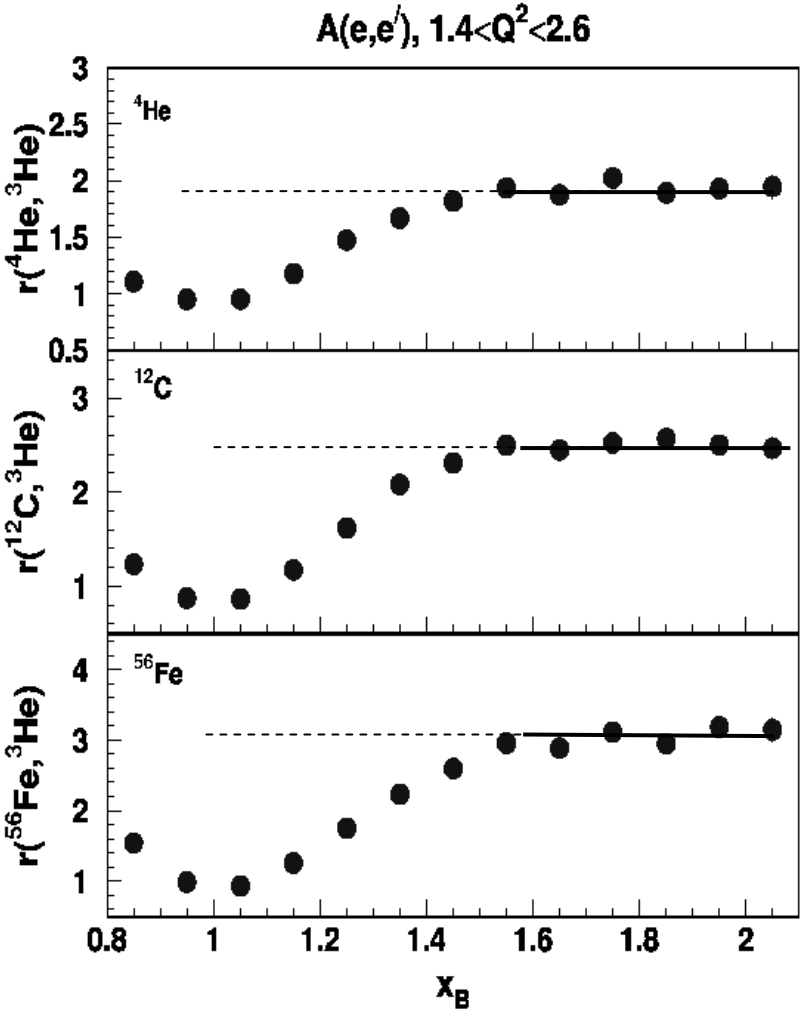
- Great advantage of ratio technique we are using is that, due to the localization of FSI in SRC, it's effect will cancel!!



Maximum distance in Fermi units from the interaction at which fsi can still contribute to the total cross section.

Three Important Results are Obtained

- **The Scaling is observed for ratios of nuclei ^{4}He, ^{12}C, ^{56}Fe and ^{3}He, indicating that WF shape-similarity hypotheses at high momenta, is correct**
- **The Scaling factors for all 3 ratios are measured**
- **The onsets of Scaling, i.e., onsets of SRC dominance, are measured**

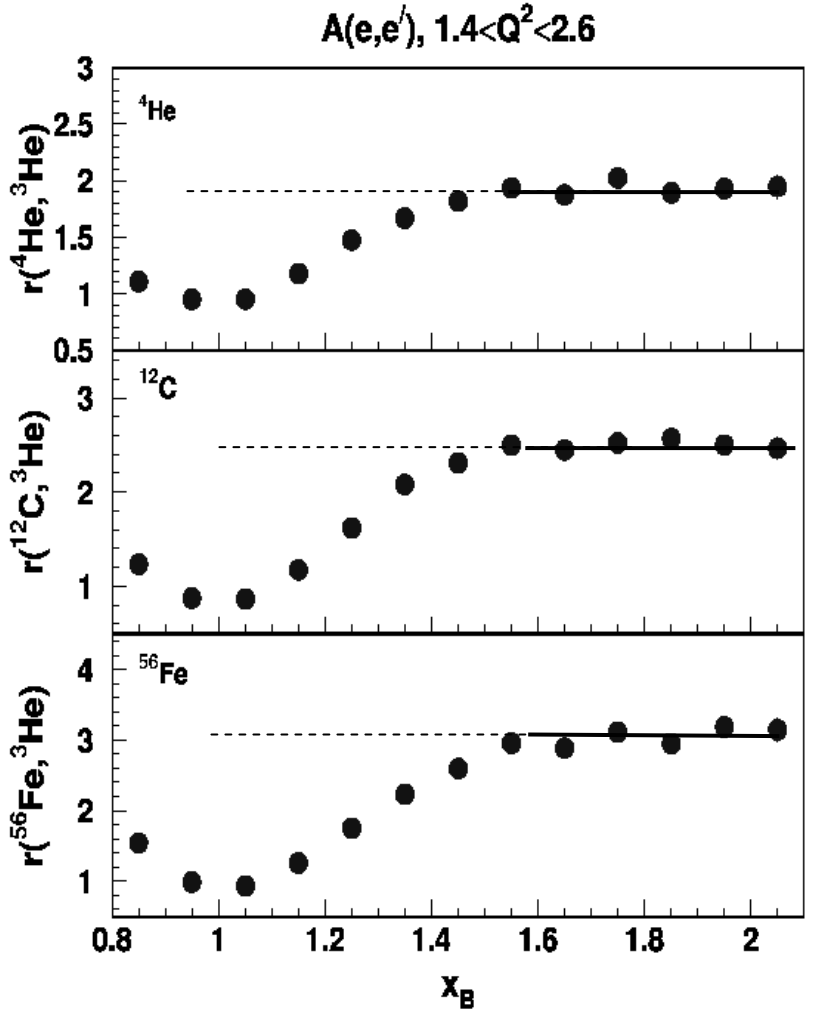


Use Measured Scaling Factors to Extract the Relative Probabilities for 2-nucleon SRCs

- Scaling factors are the ratios of probabilities of 2-nucleon SRC in nucleus A and in ^{3}He,

$$\frac{a_{2N}(A)}{a_{2N}(^3He)} = \begin{matrix} 1.96 \pm 0.02 - ^4He \\ 2.51 \pm 0.02 - ^{12}C \\ 3.00 \pm 0.03 - ^{56}Fe \end{matrix}$$

- The chance for every nucleon in nuclei ^{4}He, ^{12}C and ^{56}Fe to be involved in 2-nucleon SRC is 1.97, 2.51 and 3.0 times higher than in ^{3}He.



Use Measured Scaling Onset to Extract the Absolute Probabilities for 2-nucleon SRCs

- Absolute probabilities a_{2N} (A) can be obtained from the measured ratios

$$\frac{a_{2N}(A)}{a_{2N}(^3He)} \qquad (1)$$

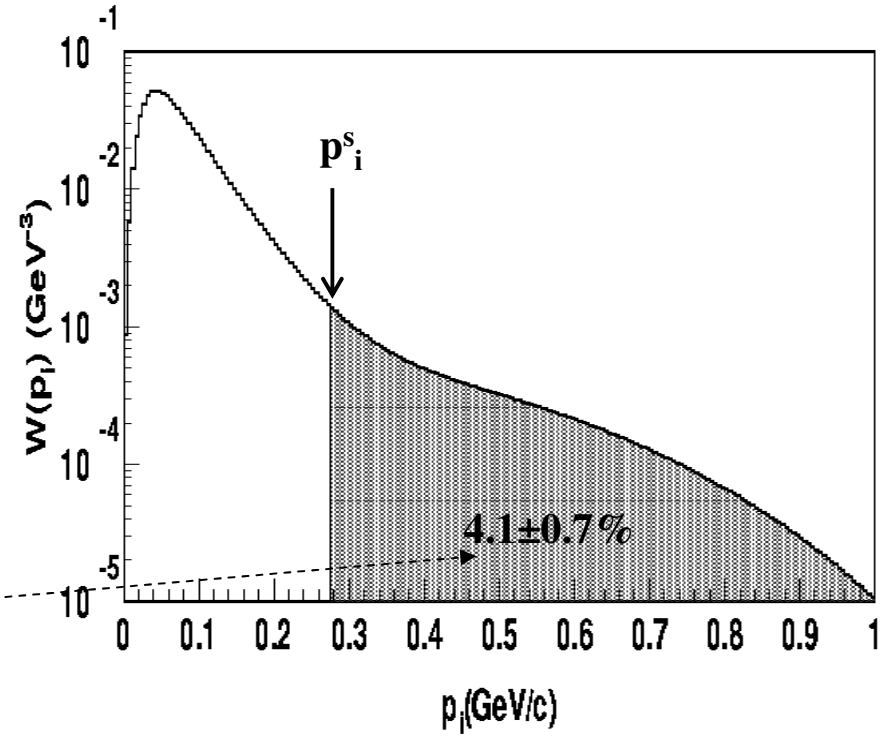
if probability $a_{2N}(^3He)$ for ^3He is known.

- 2-nucleon SRC probability in ^3He can be calculated only relative to Deuterium

$$\frac{a_{2N}(^3He)}{a_{2N}(D)} = 2\pm0.1 \qquad (2)$$

Then

$$a_{2N}(A) = (1) \times (2) \times a_{2N}(D)$$



- $a_{2N}(D)$ calculate from Deuteron WF using our measured scaling onset $p^s_i(Q^2_s, x^s_B) = 0.275\pm0.025$

The Absolute Probabilities for 2-nucleon SRCs

	$\frac{a_{2N}(A)}{a_{2N}(^3He)}$	$a_{2N}(A)$
^3He	1.00	$0.080 \pm 0.004 \pm 0.01$
^4He	$1.96 \pm 0.023 \pm 0.01$	$0.157 \pm 0.002 \pm 0.03$
^{12}C	$2.51 \pm 0.025 \pm 0.14$	$0.201 \pm 0.002 \pm 0.04$
^{56}Fe	$3.00 \pm 0.032 \pm 0.17$	$0.241 \pm 0.002 \pm 0.04$

- **In any moment in nuclei ^{56}Fe, ^{12}C, ^{4}He and ^{3}He, respectively, 6-7, 1, 1/3** and **1/8 of 2-nucleon SRC can be found**

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- **In any moment in nuclei ^{56}Fe, ^{12}C, ^{4}He and ^{3}He, respectively, 6-7, 1, 1/3** and **1/8 2-nucleon SRC can be found**
- **To obtain these results we used Deuterium and ^{3}He WF with some NN potential which is equivalent to assumption that SRCs are Nucleon-Nucleon bound state**

- **However, in our Q^2 region the quark-gluon configuration can contribute**

The Absolute Probabilities for 2-nucleon SRCs

	$\frac{a_{2N}(A)}{a_{2N}(^3He)}$	$a_{2N}(A)$	$a_{6q}(A)$
^3He	1.00	$0.080 \pm 0.004 \pm 0.01$	0.134
^4He	$1.96 \pm 0.023 \pm 0.01$	$0.157 \pm 0.002 \pm 0.03$	0.166
^{12}C	$2.51 \pm 0.025 \pm 0.14$	$0.201 \pm 0.002 \pm 0.04$	0.125
^{56}Fe	$3.00 \pm 0.032 \pm 0.17$	$0.241 \pm 0.002 \pm 0.04$	0.146

- **In any moment in nuclei ^{56}Fe, ^{12}C, ^4He and ^3He, respectively, 6-7, 1, 1/3** and **1/8 2-nucleon SRC can be found**
- **To obtain these results we used Deuterium and ^3He WF with some NN potential which is equivalent to assumption that SRCs are Nucleon-Nucleon bound state**

- **However, in our Q^2 region the quark-gluon configuration can contribute**
- **In literature there are calculations based on quark-cluster model (J. Vary -1986).**

Vary's data, surprisingly, are in qualitative agreement with experimental data

Summary on "SRCs in A(e,e/)"

- **Knematics is indicated for reaction A(e,e/) where SRC contribution is dominant**

  $Q^2 > 1.4$ GeV^2 and $x_B > 1.5$

- **Per-nucleon probabilities of 2-nucleon SRC in nuclei ^{56}Fe, ^{12}C and ^{4}He are obtained, which are**

  0.24, 0.2 and 0.16

- **Thus, studies of properties of SRCs in A(e,e/) reaction have a perspectives**

  What requires for that?

- **To solve (theoretically) the problem of FSI in SRCs**

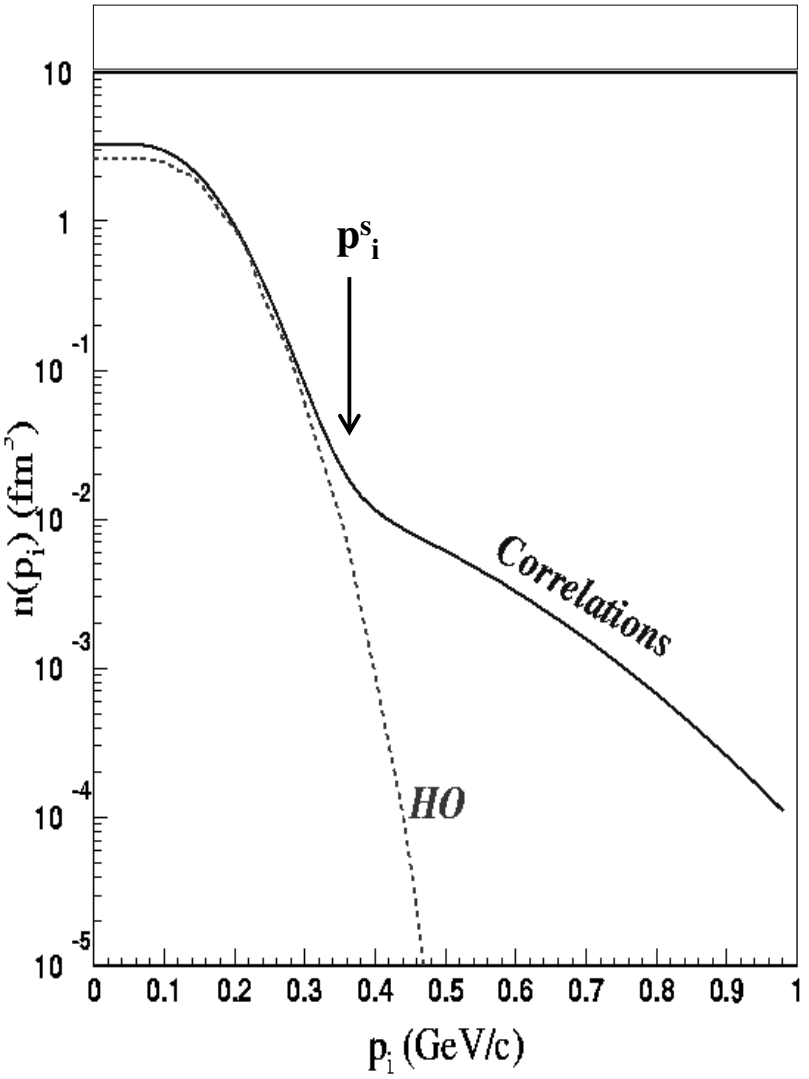
- **The CEBAF beam energy upgrade up to 11 GeV to achieve a good DIS regime for the special kinematical region $x_B > 1.5$ and $Q^2 > 1.4$ GeV^2**

Short Range Correlation Studies in Exclusive A(e,e/p)A-1reactions

- In this case situation is much cleaner, the missing momentum p_m and missing energy E_m can be obtained, then:
  - $p_m > p^s_i$ cut selects the SRC domain
  - $E_m < m_\pi$ cut suppresses the inelastic contribution

However, problem is

- Obtained p_m and E_m can differ from the initial p_i and E_i, due to the distortions at rescatterings in the final state
- Again, the FSI problem should be solved
- Start from A(e,e/p)A-1 ⟶ d(e,e/p)n



Mechanisms of exclusive d(e,e/p)n reaction

- Two diagrams of d(e,e/N)N reaction:
  - PWIA,
  - PWIA + FSI
- Interference of amplitudes is important

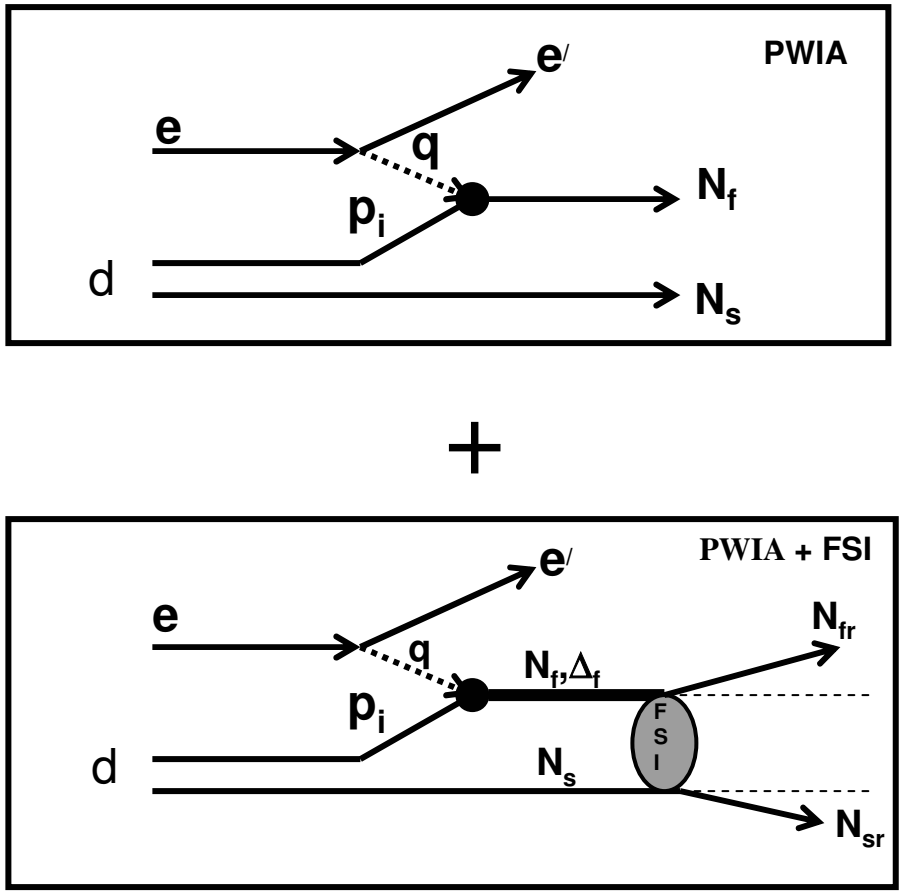
- Cross Section

$$\sigma = PW^2 + 2(PW).(FSI) + FSI^2$$

$$\sigma = PW^2 + 2(PW)_i.(FSI)_i + FSI^2$$

- First, the understanding of this reaction mechanism should be demonstrated

- Use the "Forward or Recoil Neutron Kinematics"



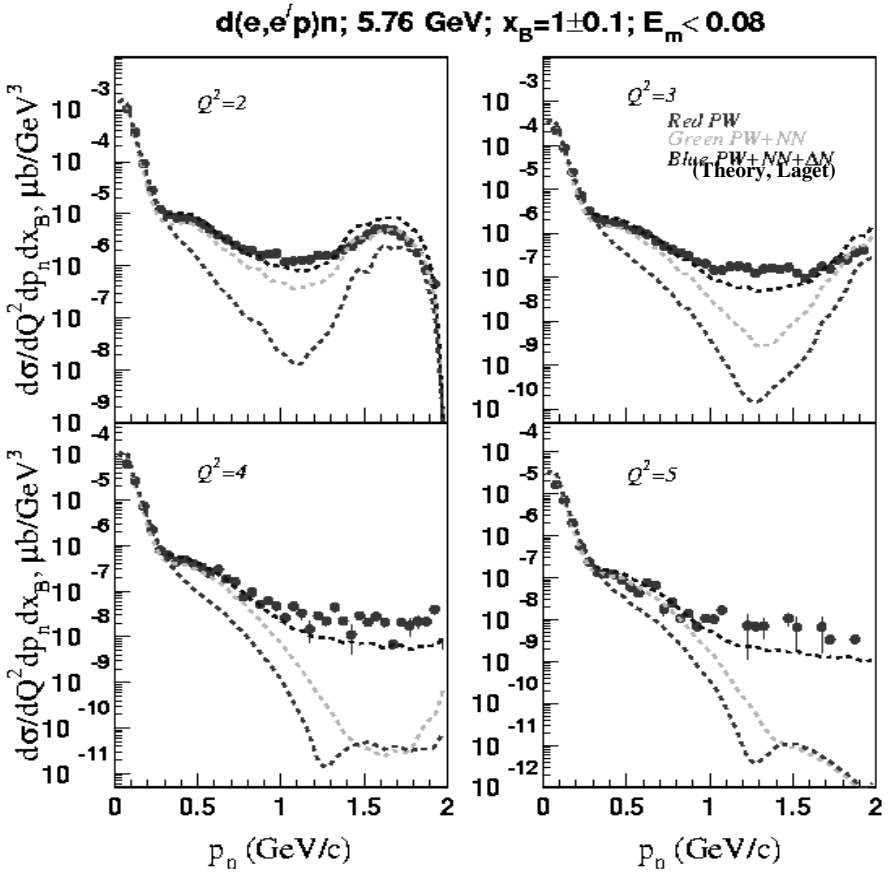
Understanding of exclusive d(e,e′p)n reaction mechanism, Momentum Distributions

- **The strategy is to measure neutron momentum and (polar) angular distributions and compare with theoretical calculations available**

  - **The recoil neutron momentum distributions**
    - **calculations are simplest at x_B=1**
    - **Experimental and theoretical (Laget) data are normalized at (Q^2=3,p_n=0.3), and normalization factor is 0.75 (exp. is smaller)**

1. **Overall well description of data is seen**

2. **FSI contribution dominates at p_n> 0.3, i.e., in the SRC expected region (x_B=1 enhances the FSI)**



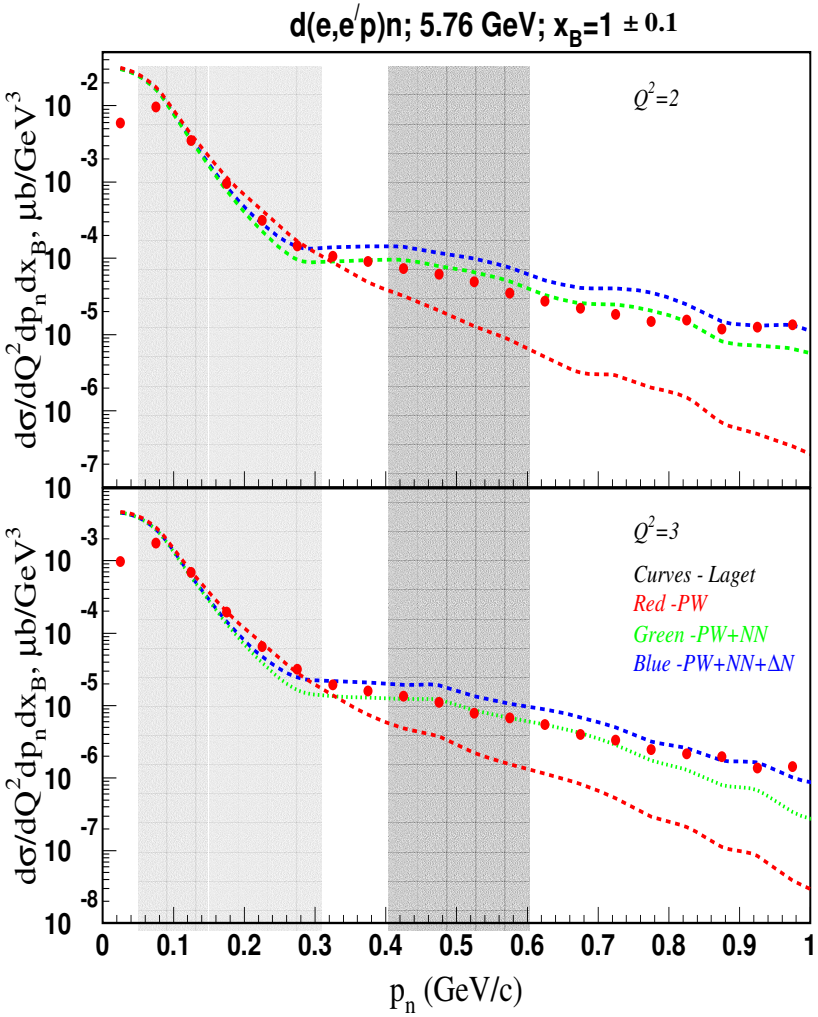
PRELIMINARY

Understanding of exclusive d(e,e′p)n reaction mechanism, Angular Distributions

- **Study of recoil neutron angular distributions using 3 p_n intervals:**

Dominates

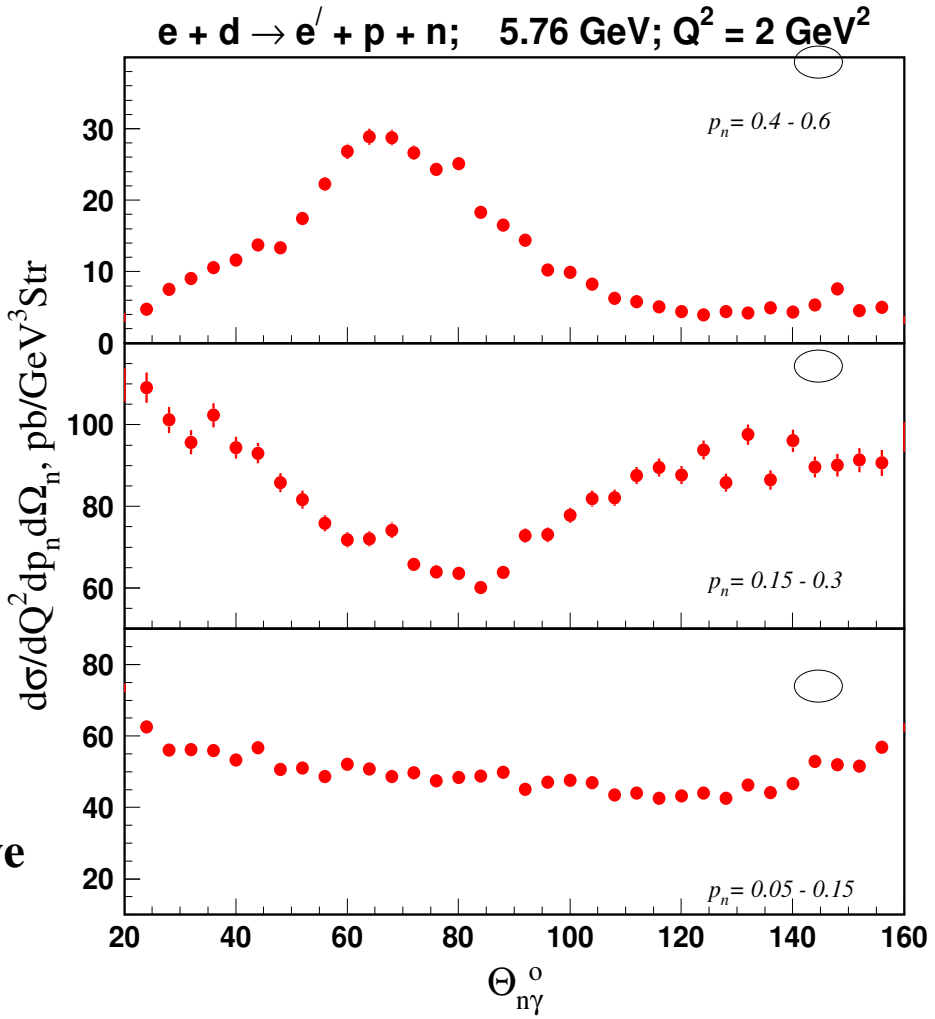
- **$0.05 < p_n < 0.15$ GeV/c (PWIA)**
- **$0.15 < p_n < 0.3$ GeV/c (PWIA+Interf)**
- **$0.4 < p_n < 0.6$ GeV/c (FSI)**



Understanding of exclusive d(e,e′p)n reaction mechanism, Angular Distributions

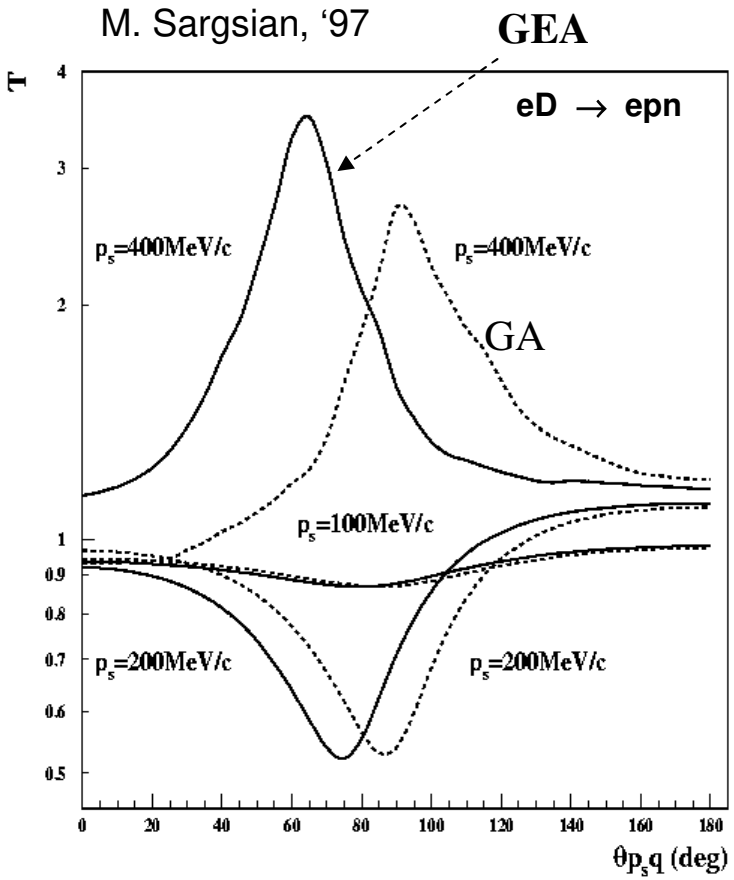
- $0.4 < p_n < 0.6$ GeV/c
  $(\sigma = PW^2 - 2(PW)_i.(FSI)_i + FSI^2)$
- $0.15 < p_n < 0.3$ GeV/c
  $(\sigma = PW^2 - 2(PW)_i.(FSI)_i + FSI^2)$
- $0.05 < p_n < 0.15$ GeV/c
  $(\sigma = PW^2 - 2(PW)_i.(FSI)_i + FSI^2)$

➢ Important observation – relative shift of peaks in FSI and Interference regions

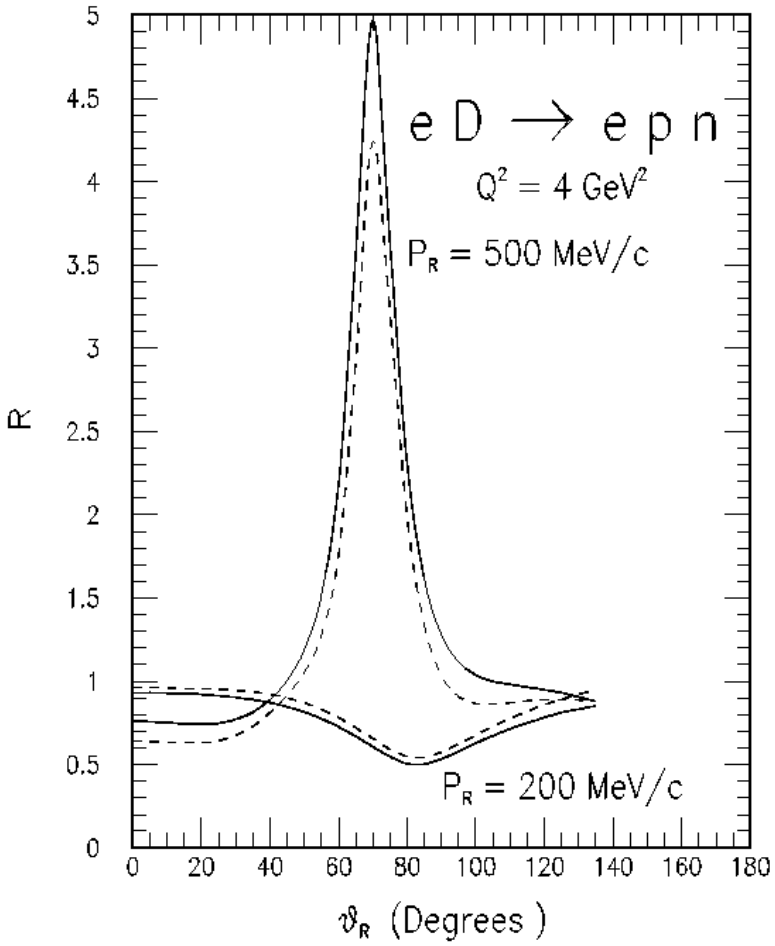


Recoil-Neutron Angular Distributions; Predictions

M. Sargsian, '97

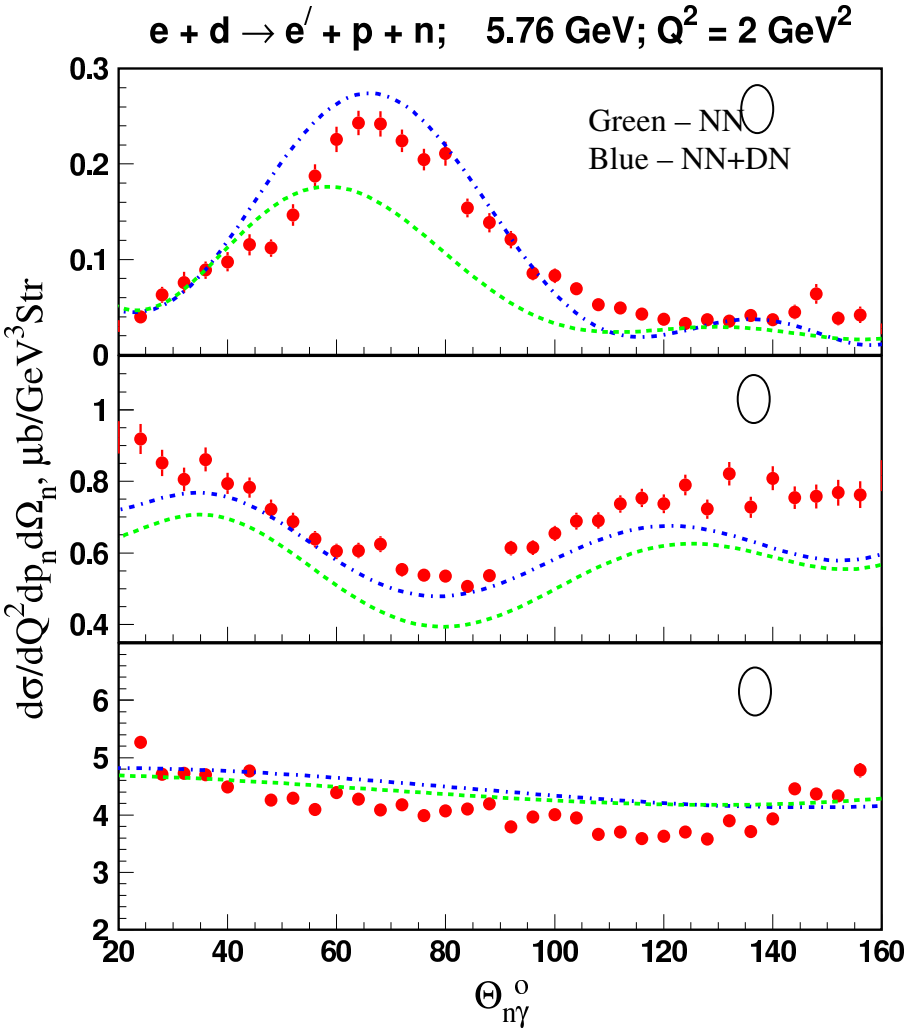


J-M. Laget, '98



Understanding of exclusive d(e,e′p)n reaction mechanism, Angular Distributions

- **Comparison with theory**
  - **Available are J-M. Laget's calculations (Diagrammatic Approach)**
  - **$0.4 < p_n < 0.6$ GeV/c (FSI)**
  - **$0.15 < p_n < 0.3$ GeV/c (Interf)**
  - **$0.05 < p_n < 0.15$ GeV/c (PWIA)**
- **Momentum and angular distribution demonstrate our well understanding of d(e,e′p)n reaction mechanism**



Short Range Correlation Studies in Exclusive d(e,e/p)n Reaction
How to Select SRC Effect from FSI "Background"?

- Conventional way is "Parallel Kinematics":

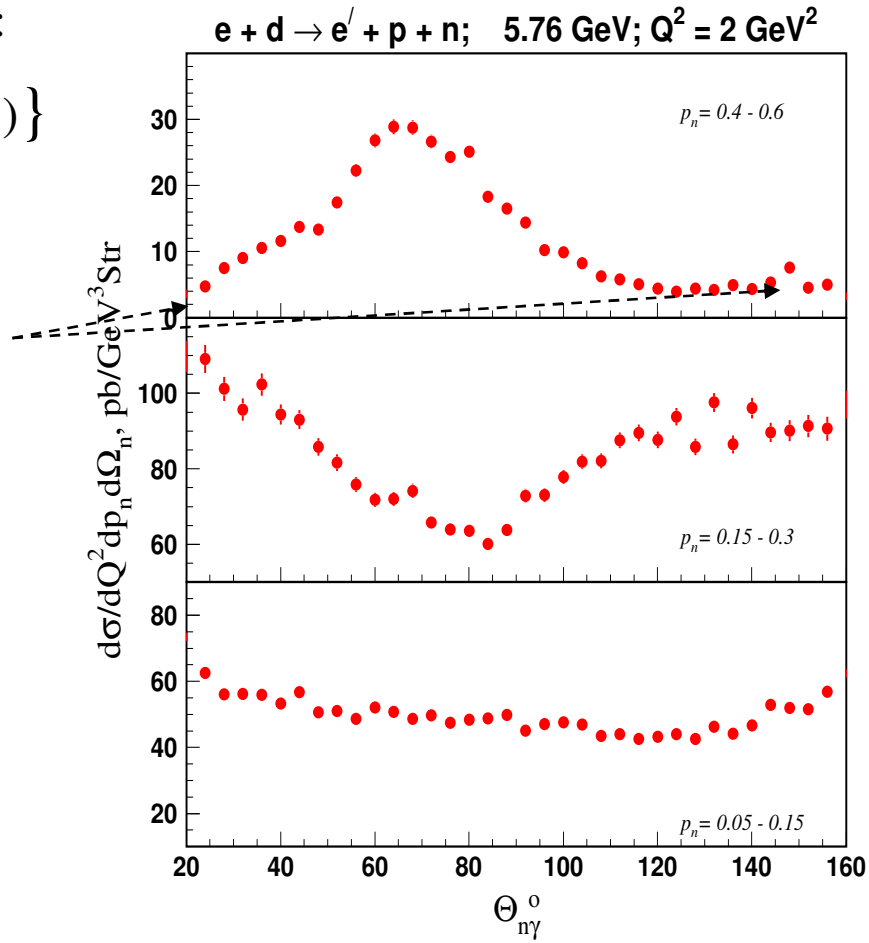
$$\{q_v \uparrow\uparrow p_p\ (q_v \uparrow\downarrow p_n)\}\ \textbf{OR}\ \{q_v \uparrow\downarrow p_p\ (q_v \uparrow\uparrow p_n)\}$$

- However, at $p_n > 0.3$ the cross sections are small in ($\theta_n < 30^o$) OR ($\theta_n > 150^o$) regions

- **Use another criteria, α- criteria, where**

$$\alpha = \frac{E - p\cos\theta}{M}$$

is the Light Cone variable



PRELIMINARY

Important characteristic of α: at high momentum it is "almost" invariant to FSI

- **The meaning? in d(e,e/p)n (e.g.)**

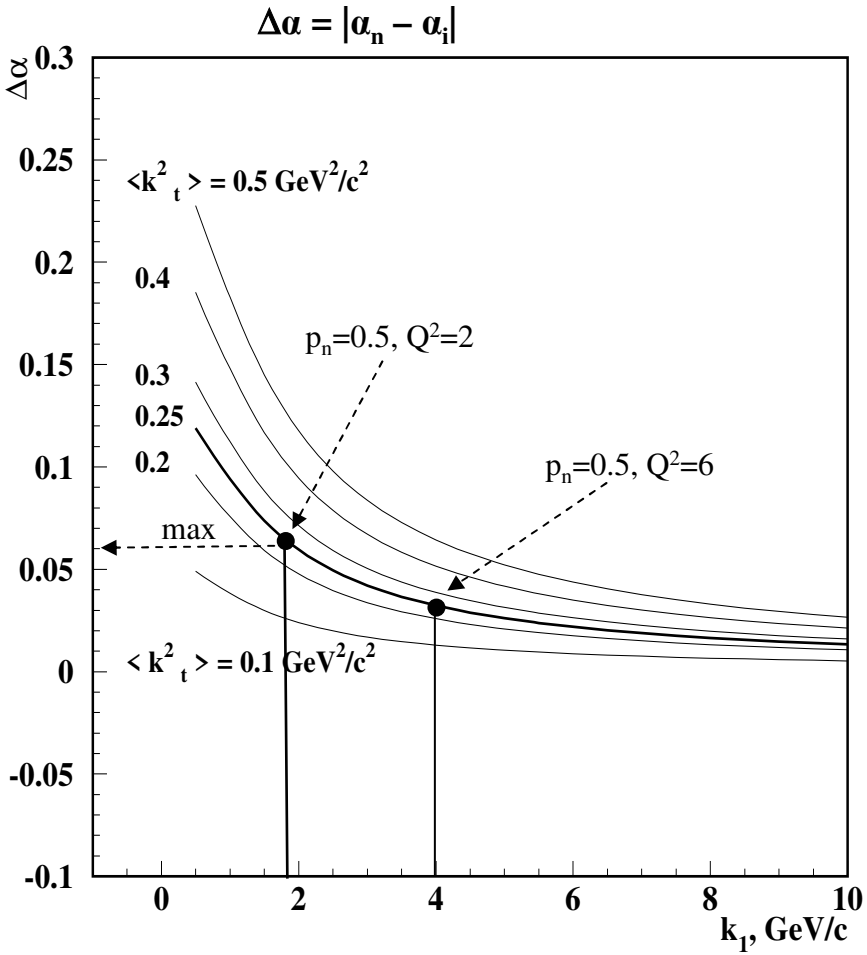
$e + d \rightarrow e' + p_f$

$p_f + n_i \rightarrow p + n$

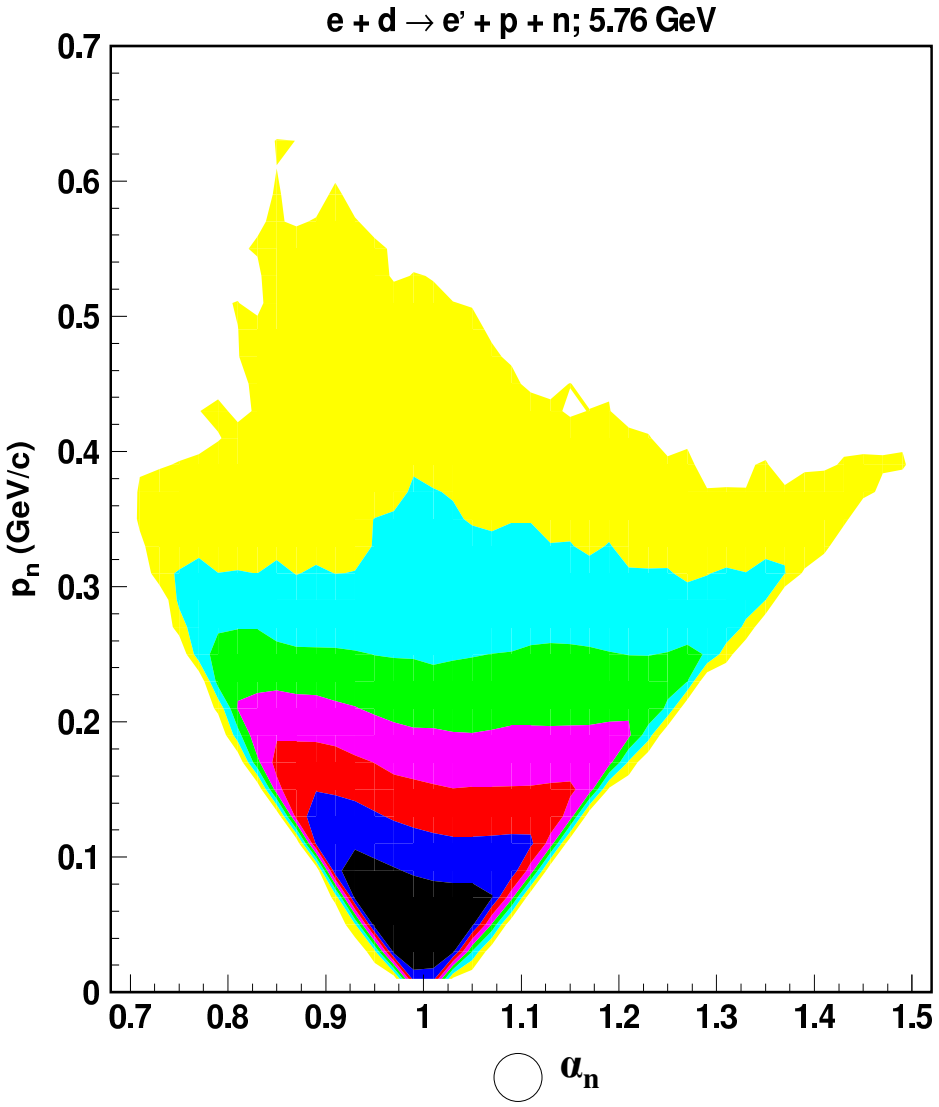
$\alpha_f \approx \alpha_p$ $\quad$ $\alpha_i \approx \alpha_n$

- **".. although both energy and momentum of the bound nucleon (n_i) are distorted due to the rescattering, the combination $E - p_z$ (α_i) is not"** *M. Sargsian, J.Mod.Phys. E,* v.**10**, *405 (2001)*

- **Measuring α_n in final state, we are measuring α_i in initial state!!**



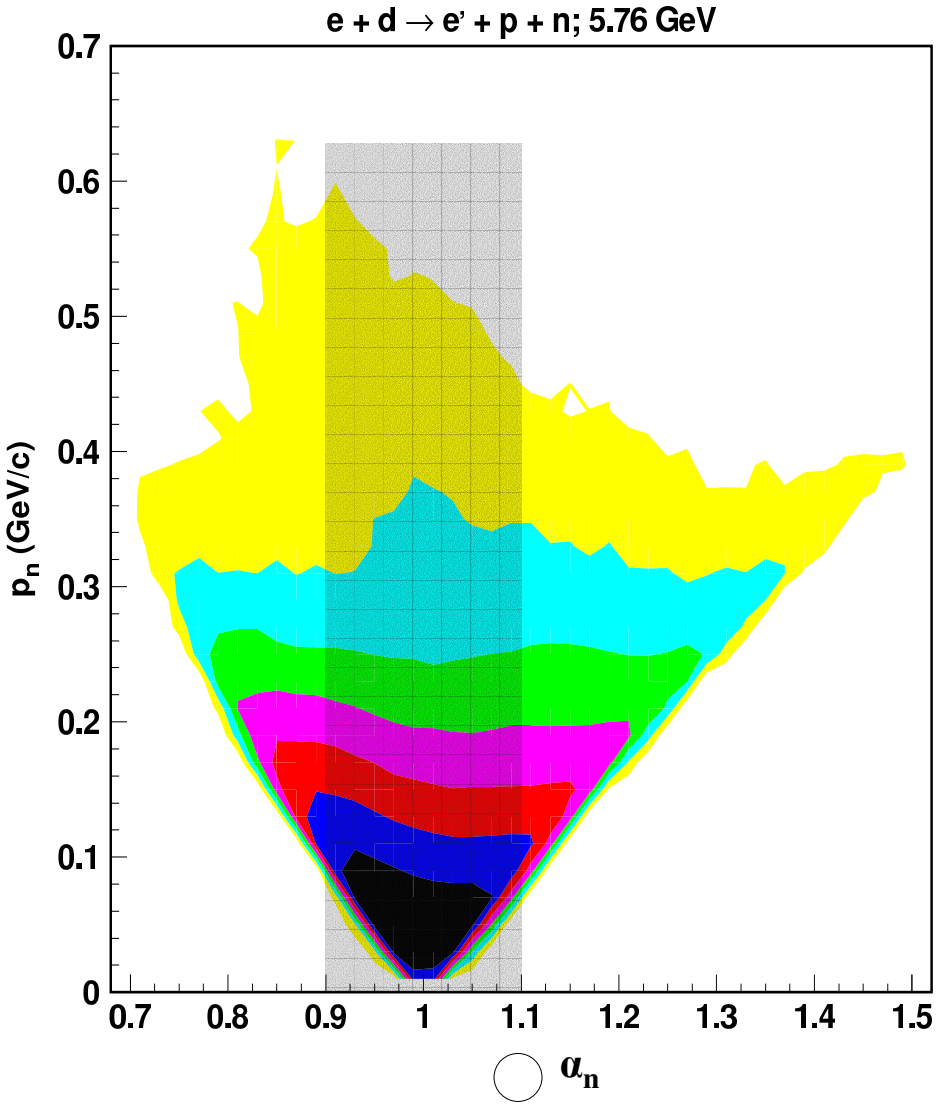
Use an α_n – cuts to suppress FSI



Use an α_n – cuts for FSI suppression

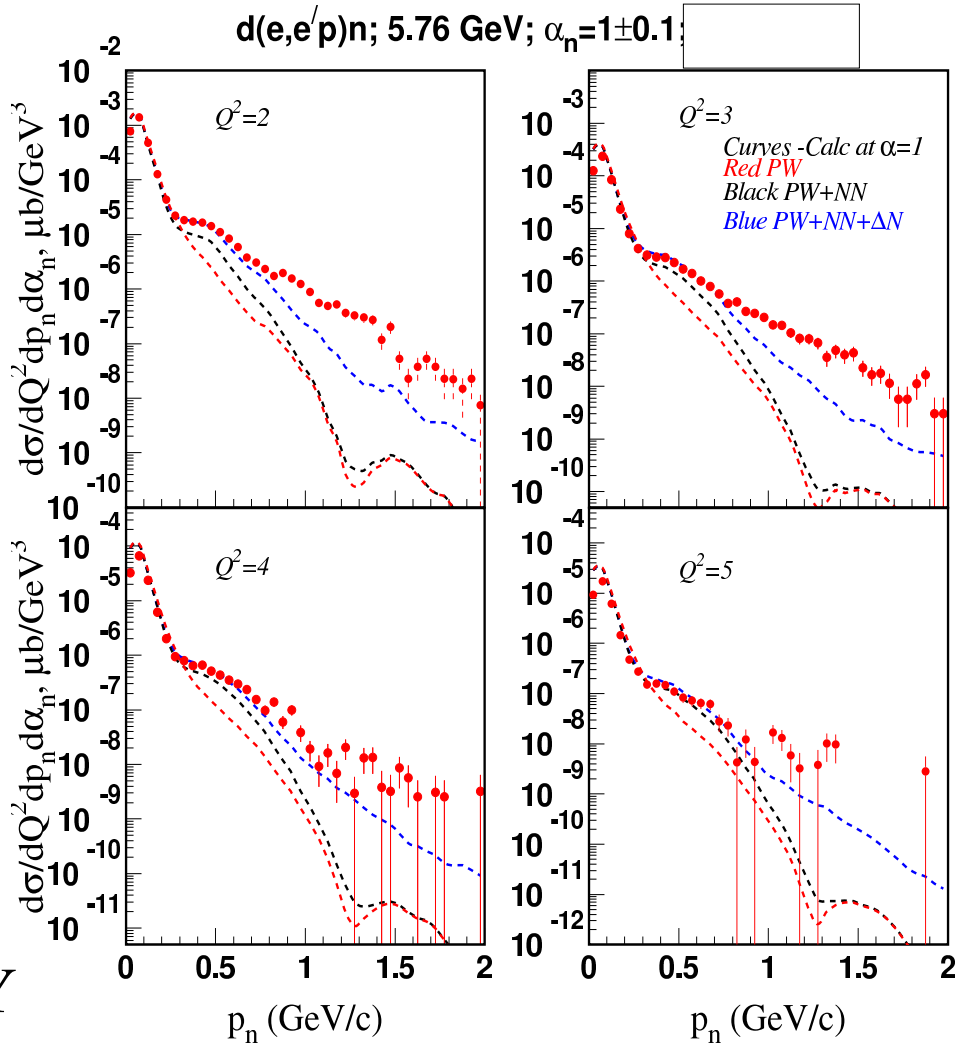
- First use an α_n =1±0.1 cut and analyze the neutron momentum distributions

- This cut selects initial neutrons with all momenta ($p_i \geq 0$) resulting in very high probability of struck protons (p_f) interaction with the low-momentum neutrons (n_i)



Recoil Neutron Momentum Spectra at α_n =1±0.1

- As in in x_B = 1 ± 0.1 case, the FSI totally dominates in p_n > 0.3 GeV/c (SRC existing) region

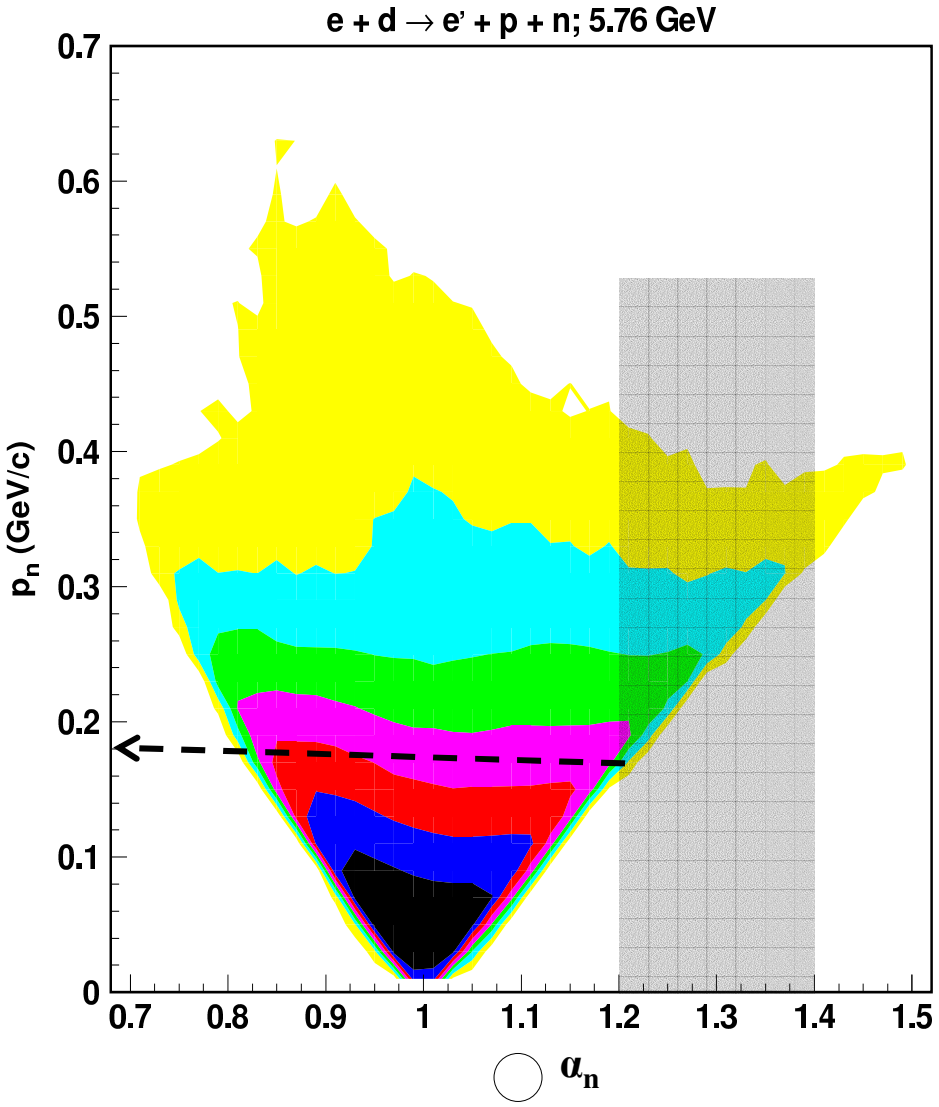


PRELIMINARY

Use an $\alpha_n = 1.3 \pm 0.1$ cut for FSI suppression

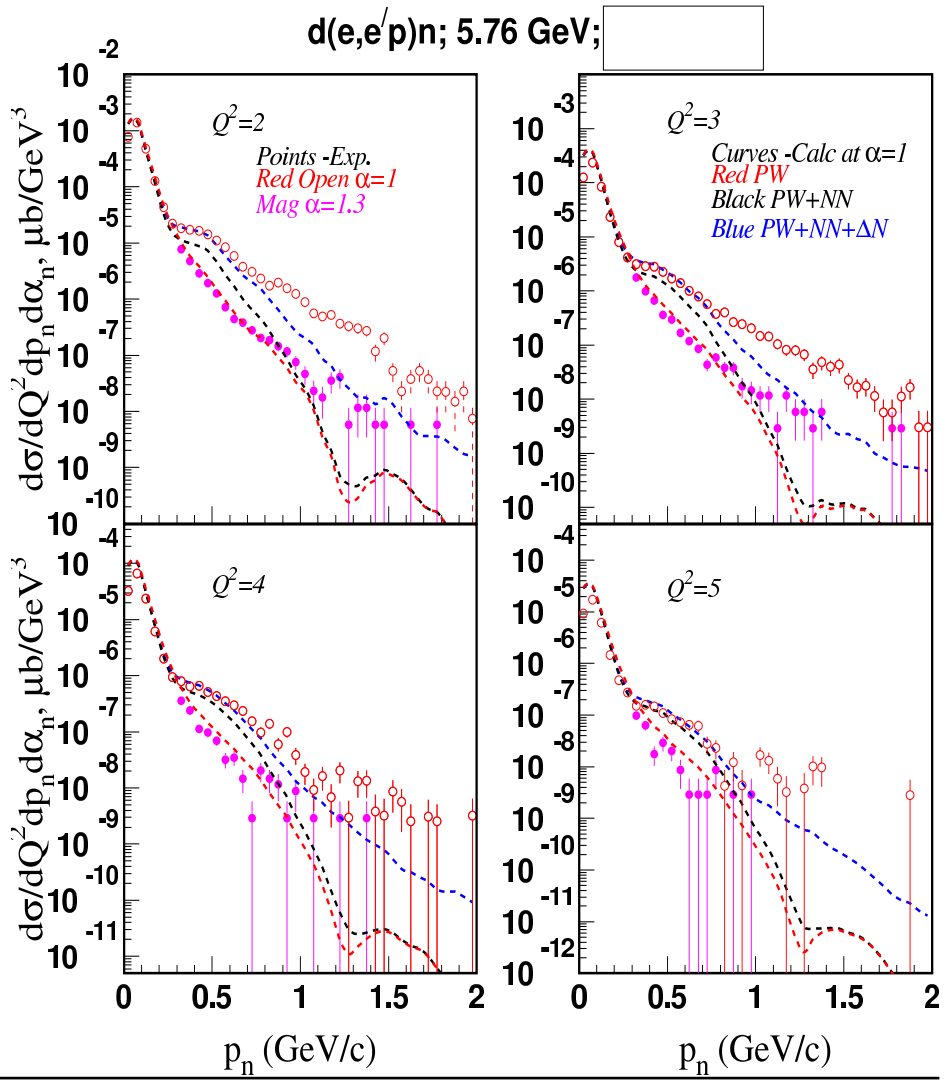
- This cut selects initial neutrons with momenta $p_n > 0.18$ Mev/c. The probability of struck protons (p_f) interaction with the initial neutrons (n_i) with such a momenta is ≈100 times less then in $\alpha_n = 1 \pm 0.1$ case (from the Deuteron WF)

- Therefore FSI should be suppressed significantly



Recoil Neutron Momentum Spectra at α_n =1±0.1 and α_n=1.3±0.1

- Experimental data for **α_n=1.3±0.1** are very close to PWIA, i.e.,
- FSI are really suppressed at least in 0.3< p_n<1.0 GeV/c interval
- Due to the low statistics, analyze the data for p_n<1.0 GeV/c only



PRELIMINARY

Nucleon (effective) Momentum Distribution in Deuterium

➢ **Combining the data**

- for $a_n = 1 \pm 0.1$ in $\mathbf{p_n < 0.3}$ **GeV/c** region (FSI contribution is still small, at $p_n < 0.15$ – very small),

and

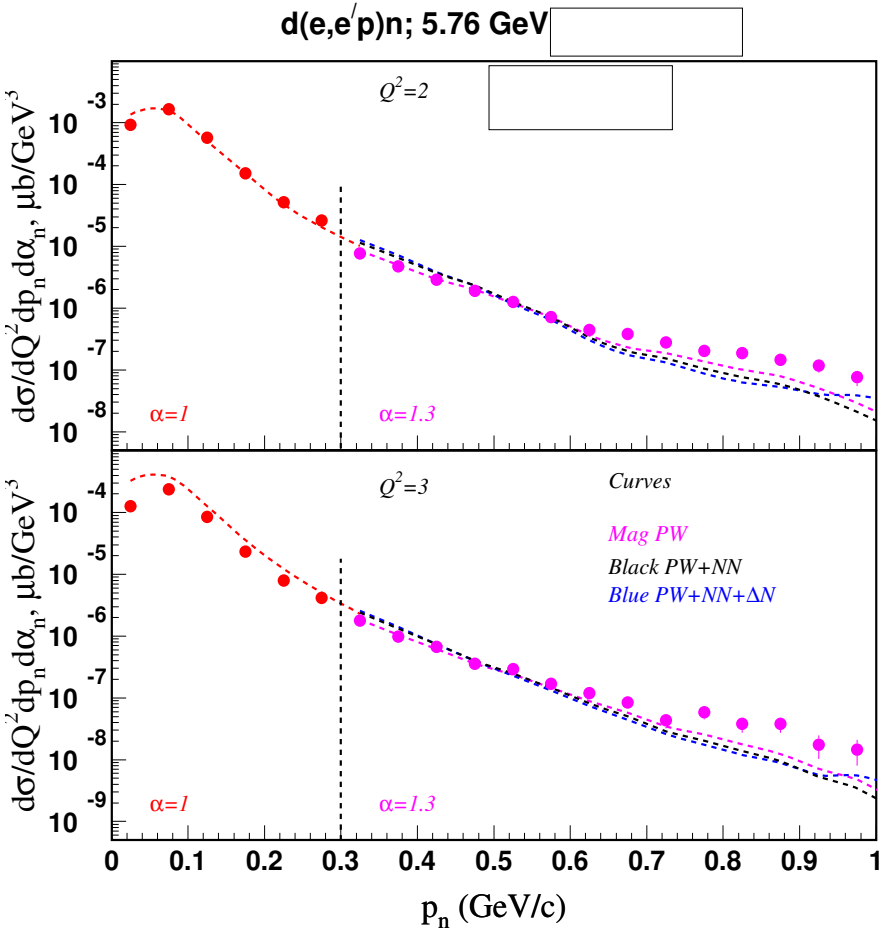
- for $a_n = 1.3 \pm 0.1$ in $\mathbf{p_n > 0.3}$ **GeV/c** region (FSI contribution is suppressed significantly),

- **the Nucleon (effective) Momentum Distribution in Deuterium is obtained**

  - **in $0 < p_i < 1.0$ GeV/c region for $2.0 \leq Q^2 < 4$ GeV^2**

  and

  - **in $0 < p_i < 0.5$ GeV/c region for $4 \leq Q^2 < 6$ GeV^2**



Extracting signal for the nucleon possible modification in SRC

- Consider the ratio

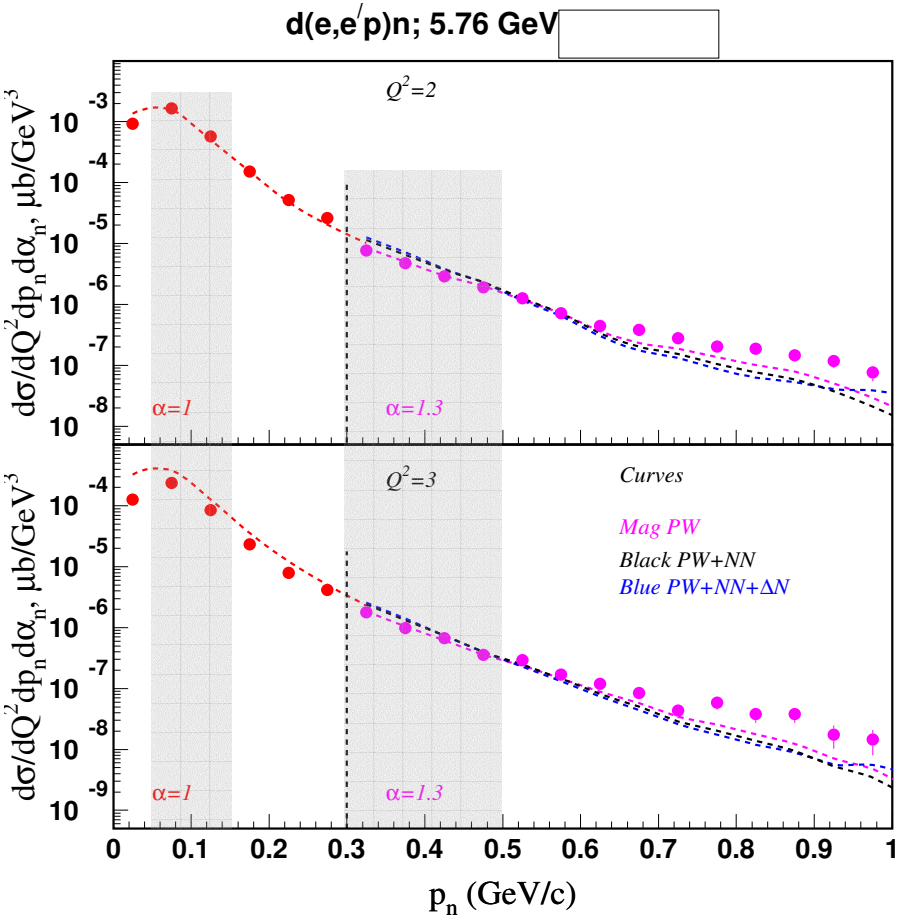
$$R_{ff} \equiv \frac{\sigma(0.3<p_n<0.5)}{\sigma(0.05<p_n<0.15)} = \frac{\sigma(SRC)}{\sigma(PWIA)} \equiv \frac{\sigma_1}{\sigma_2}$$

then

$$R_{ff} = \frac{\sigma_{1M}\, F_1(Q^2,\upsilon)\, S_1(p_m,E_m)}{\sigma_{2M}\, F_2(Q^2,\upsilon)\, S_2(p_m,E_m)} \sim \frac{F_1(Q^2,\upsilon)}{F_2(Q^2,\upsilon)}$$

- If R_{ff} is independent of Q^2 or if dose not differ from the model calculations, then there are no changes in proton configuration

- **If not …..??**



PRELIMINARY

Extracting signal for the possible nucleon modification in SRC

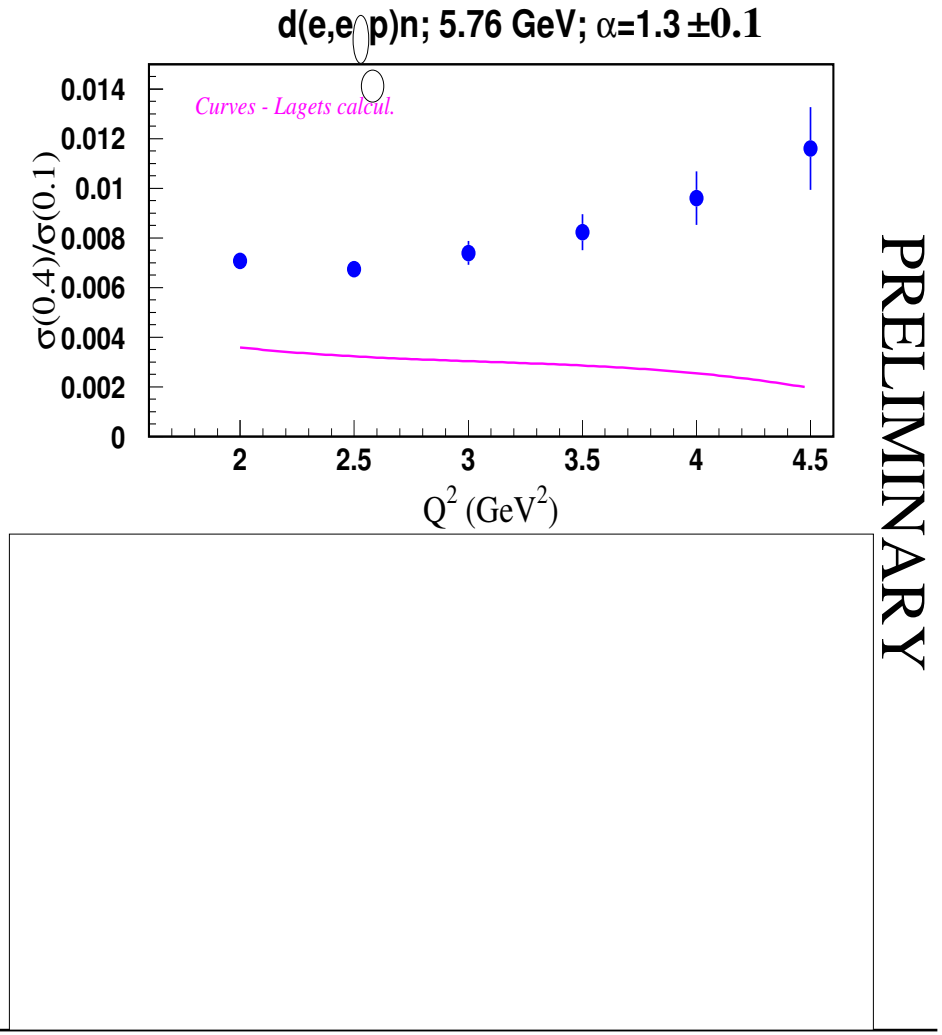
- There is clear difference between model calculations and experimental data

  (we know the origin of difference in absolute values)

- Is this a signal for proton modification in SRC?

- If it is,

- **it means that proton's effective size in SRC is smaller compared to the free (quasifree) state!!!**



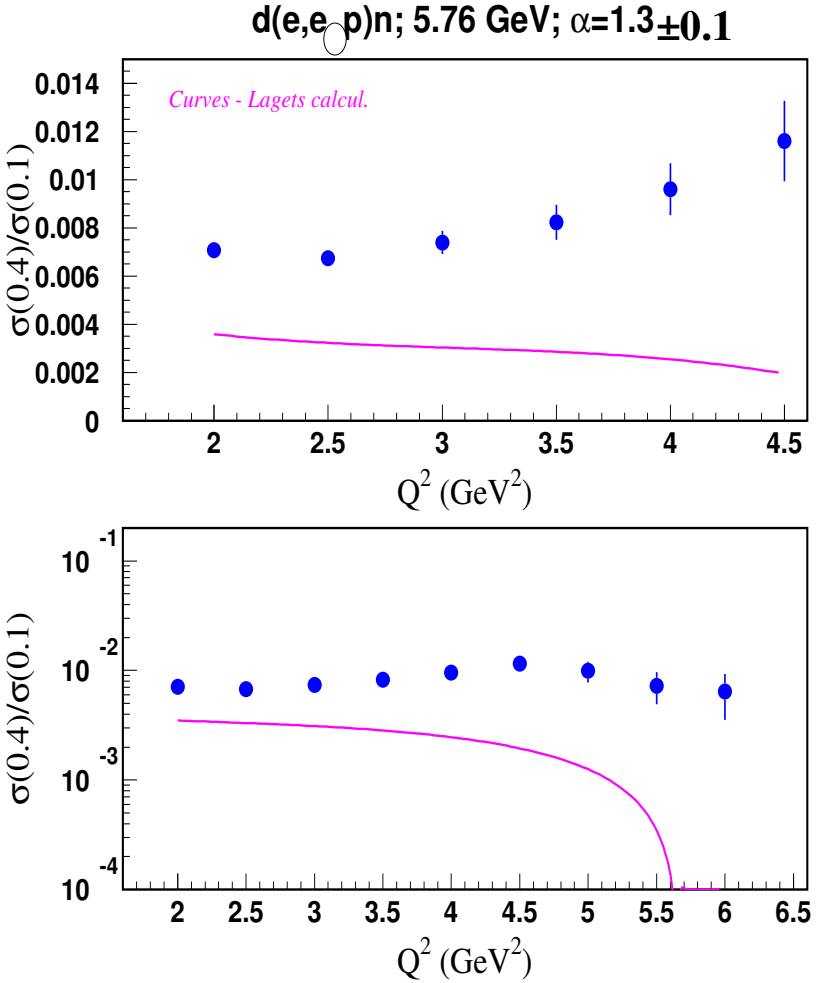
Energy upgrade is absolutely important

- To made simpler conclusions the σ_L/σ_T separation and wider Q^2 range are required

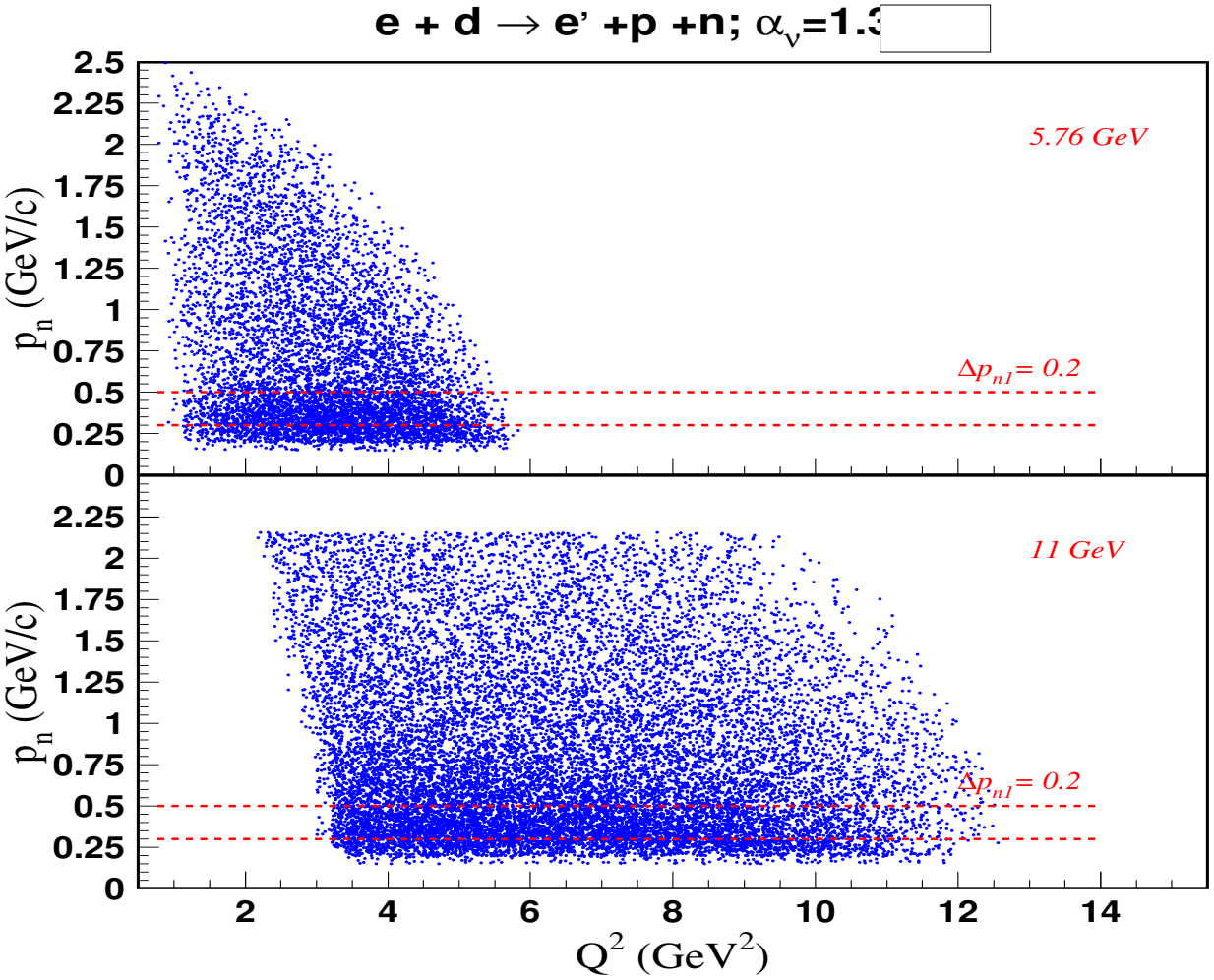
- However, at current energy the phase space limitation is limiting Q^2 range up to ≈ 4.5 GeV^2

- Only 12 GeV upgrade can provide Q^2 range up to ≈ 8-9 GeV^2

  (see next slide)



Phase spaces at 5.76 and 11 GeV beam energies for a=1.3 kinematic



Summary for SRCs in d(e,e′p)n Exclusive Reaction

- An exclusive d(e,e′p)n scattering is studied in $2 < Q^2 < 6$ GeV^2 range
- By measuring and comparing with Laget's theoretical calculations of recoil neutron momentum and angular distributions, the understanding of reaction's mechanism is achieved
- Using the α=1.3 cut, significantly suppressing the FSI, the nucleon momentum distribution in deuterium is measured in p_i<1 GeV/c range
- The ratio of SRC and PWIA cross sections as a function of Q^2 show a signal on the possible size modification of protons involved in SRC
  - Due to the energy limitation of Q^2 range, these investigations are urrently limited by 4.5 GeV^2
  - 12 GeV upgrade will allow us to extend these studies up to Q^2 = 8-9 GeV^2 and prove (or not prove) the observed effect