Short Range Correlations (Hard Nuclear Processes)

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I. Short Range Correlation Studies

1. Outstanding Problems in SRC studies

2. Choosing the probe reaction

3. Probing the deuteron at small distances

4. Probing multi-nucleon SRCs in medium to heavy nuclei

II. Hard Photodisintegration of few-body systems

1. Probing the mechanism of hard QCD hadronic interaction

2. Probing Non-nucleonic degrees of freedom/hidden color

3. Extracting J/Psi-N interaction near the threshold

1. Outstanding Problems in SRC studies

- Nuclear Forces at Short Distances: **NN repulsive core**

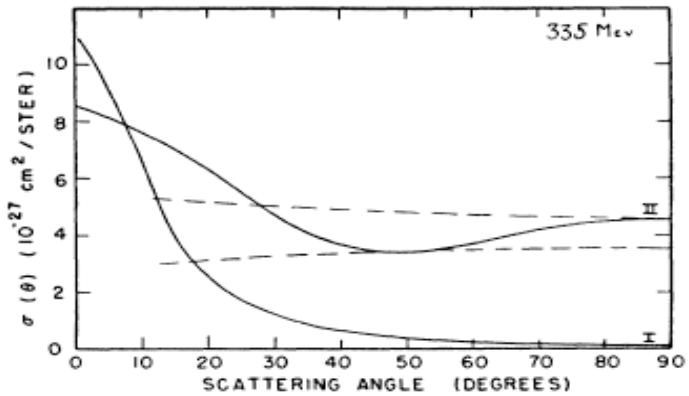
- Direct Observation of the dominance of high momentum protons in neutron rich heavy nuclei

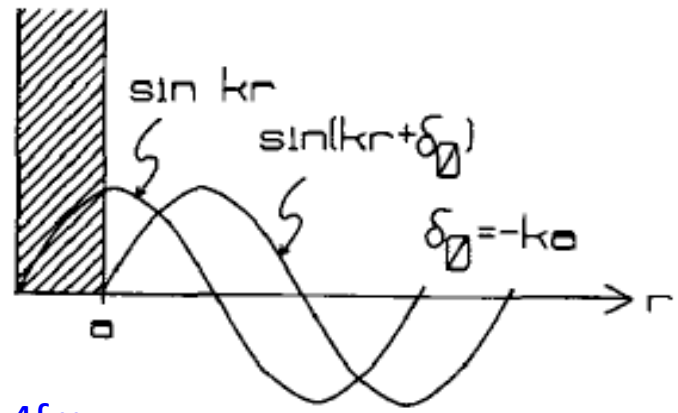
- Direct Observation of 3N SRCs

- Non-Nucleonic Content of 2N SRCs

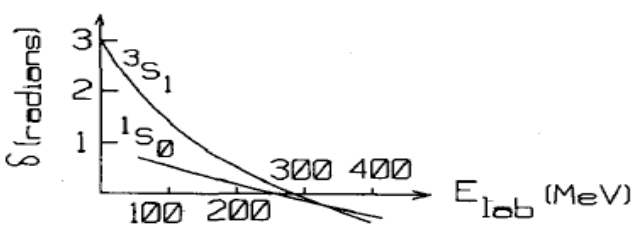
- Nuclear Forces at Short Distances: **NN repulsive core**

Jastrow 1951 assumed the existence of the hard core to explain the angular distribution of pp cross section at 340 MeV (r_0=0.6fm)





r_0 = 0.4fm



Stability Theorem: Nuclei will Collapse without Repulsive interaction 1950s Weisskopf, Blatt

Modern NN Potentials

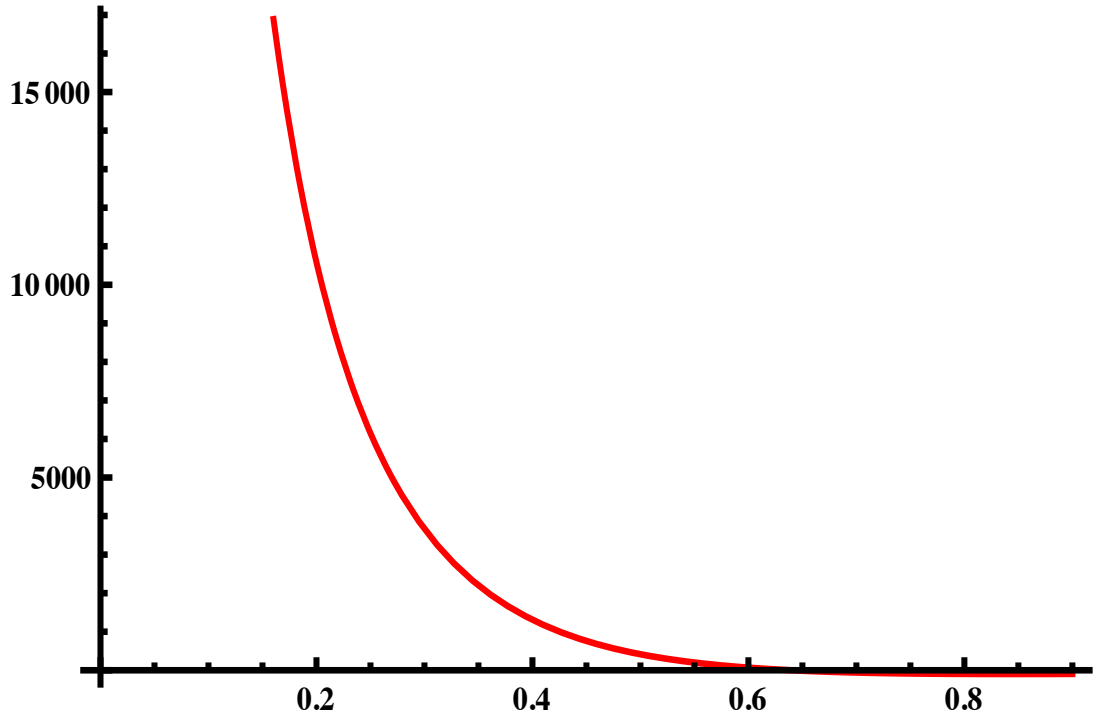
$$V^{2N} = V^{2N}_{EM} + V^{2N}_{\pi} + V^{2N}_{R}$$

$$V^{2N}_{R} = V^{c} + V^{l2}L^2 + V^{t}S_{12} + V^{ls}L\cdot S + v^{ls2}(L\cdot S)^2$$

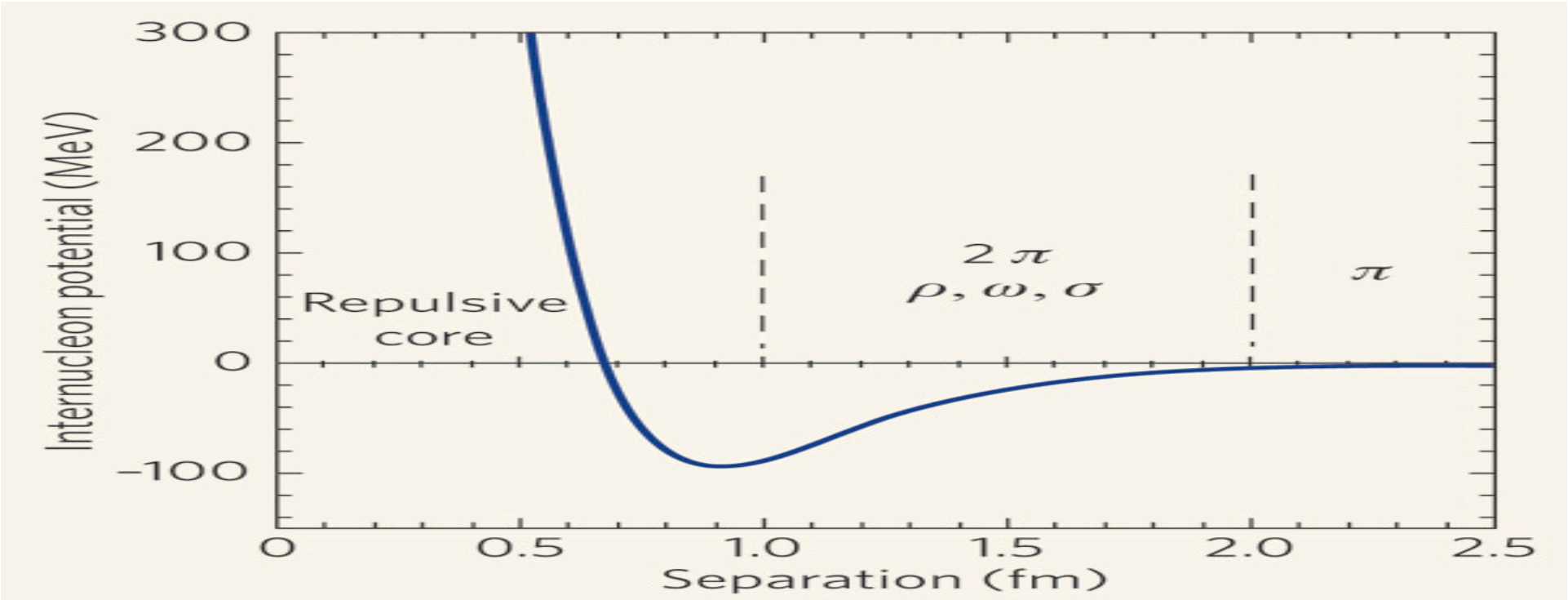
$$V^{i} = V_{int,R} + V_{core}$$

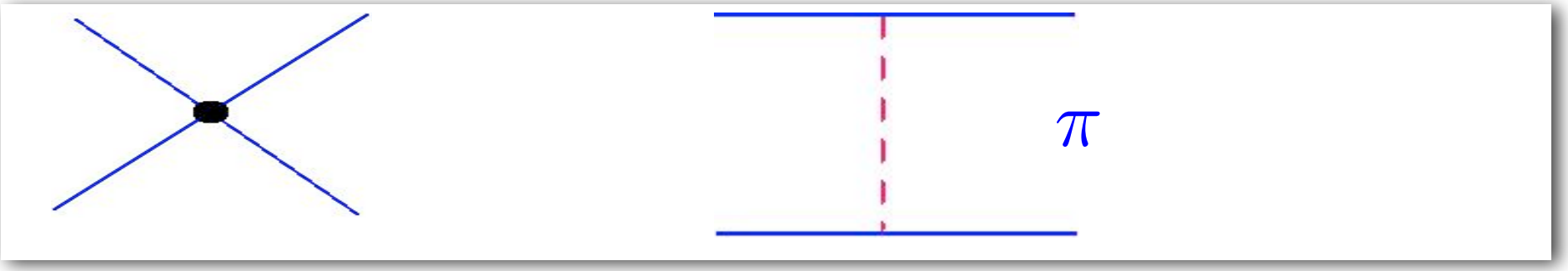
$$V_{core} = \left[1 + e^{\frac{r-r_0}{a}}\right]^{-1}$$

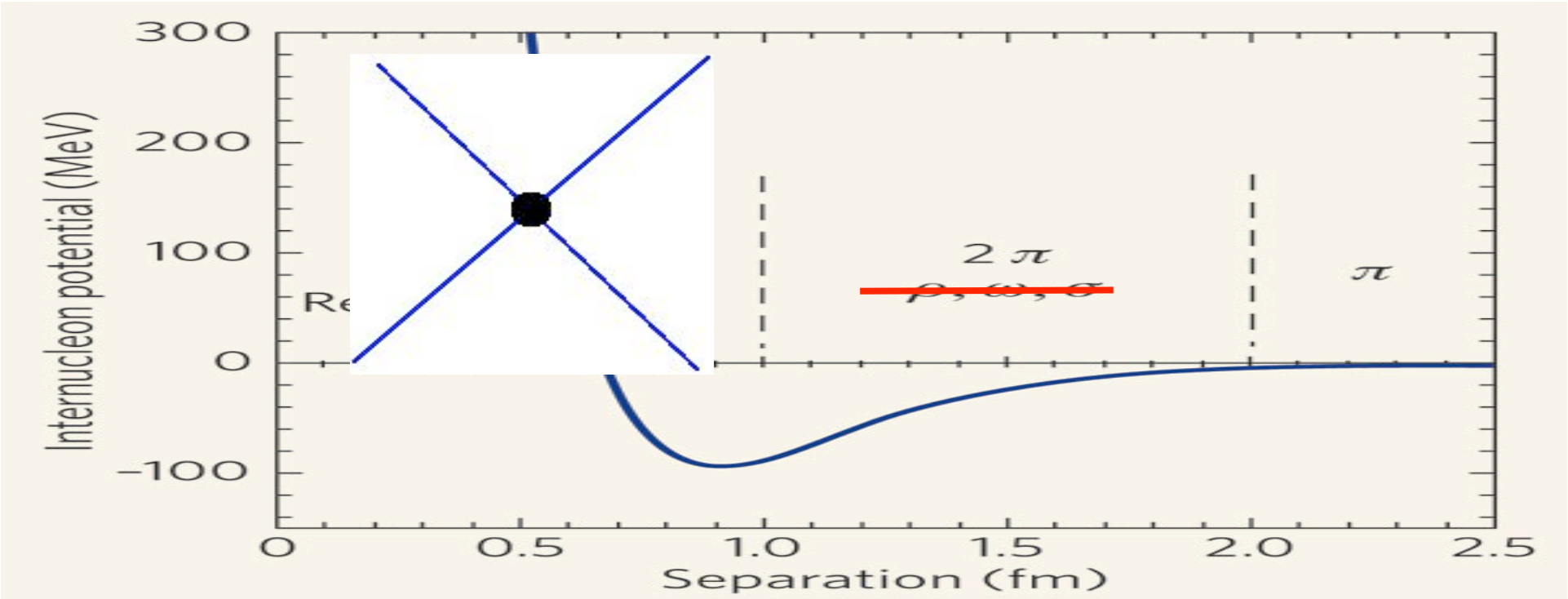
60's


15 000
10 000
5000
0.2
0.4
0.6
0.8

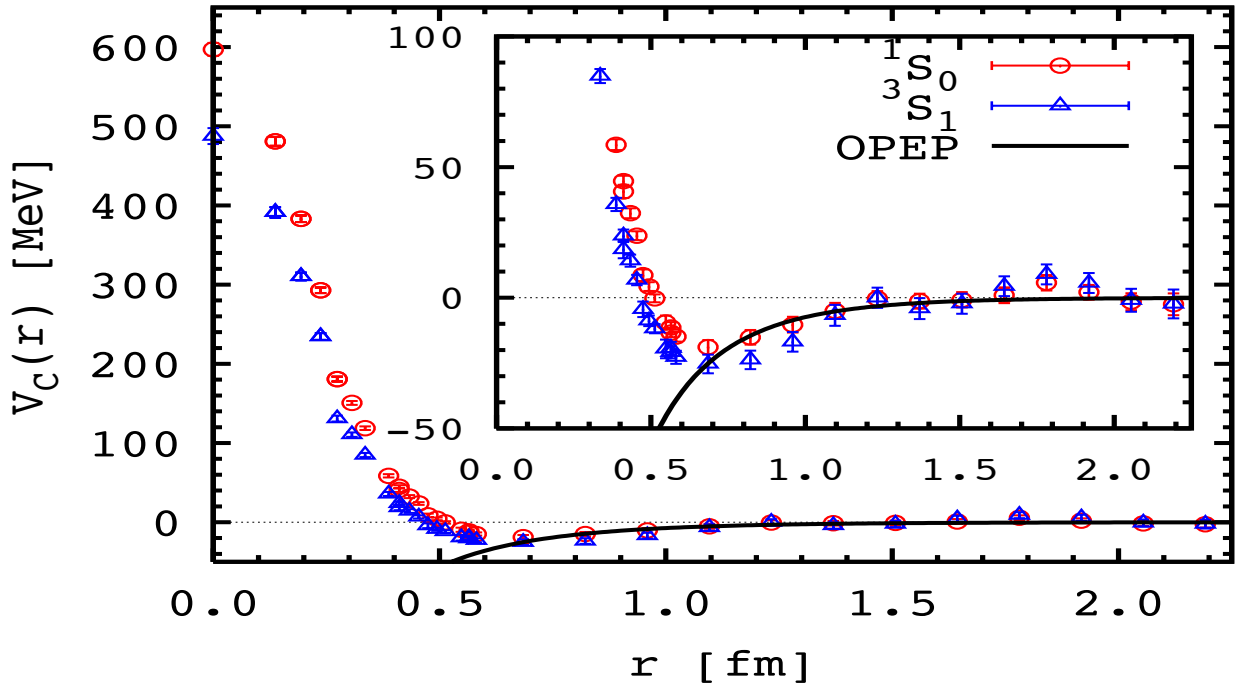
$\sigma, \quad \pi, \quad \rho, \quad \omega, \ldots$

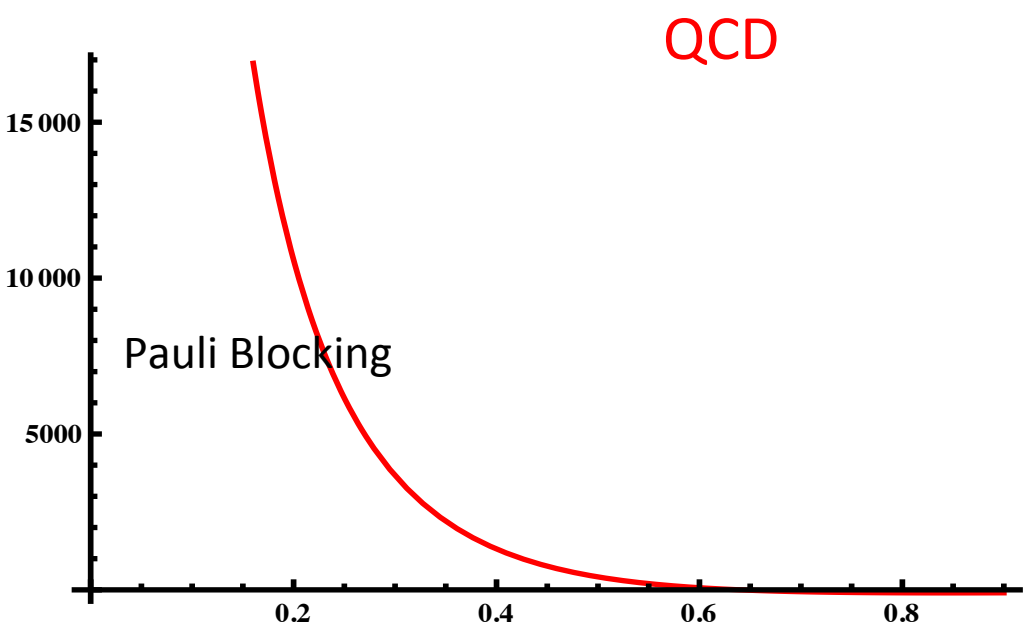



π

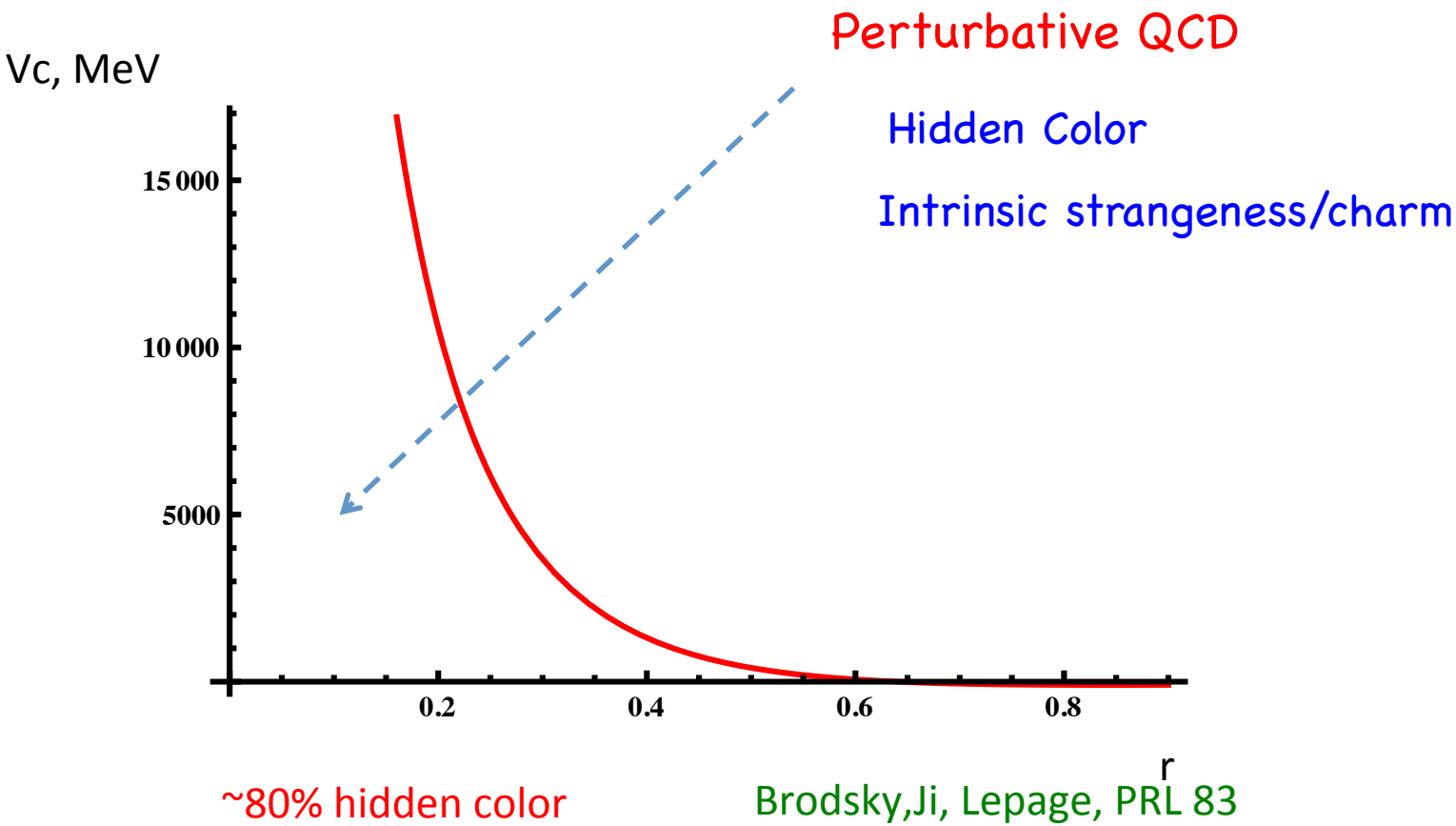

300
200
100
0
−100
Internucleon potential (MeV)
0
0.5
1.0
1.5
2.0
2.5
Separation (fm)
2 π
ρ, ω, σ
π

Lattice Calculations





Contradicts Neutron Star Observations:
will predict masses not more than 0.1 - 0.6 Solar mass



~80% hidden color

Brodsky,Ji, Lepage, PRL 83

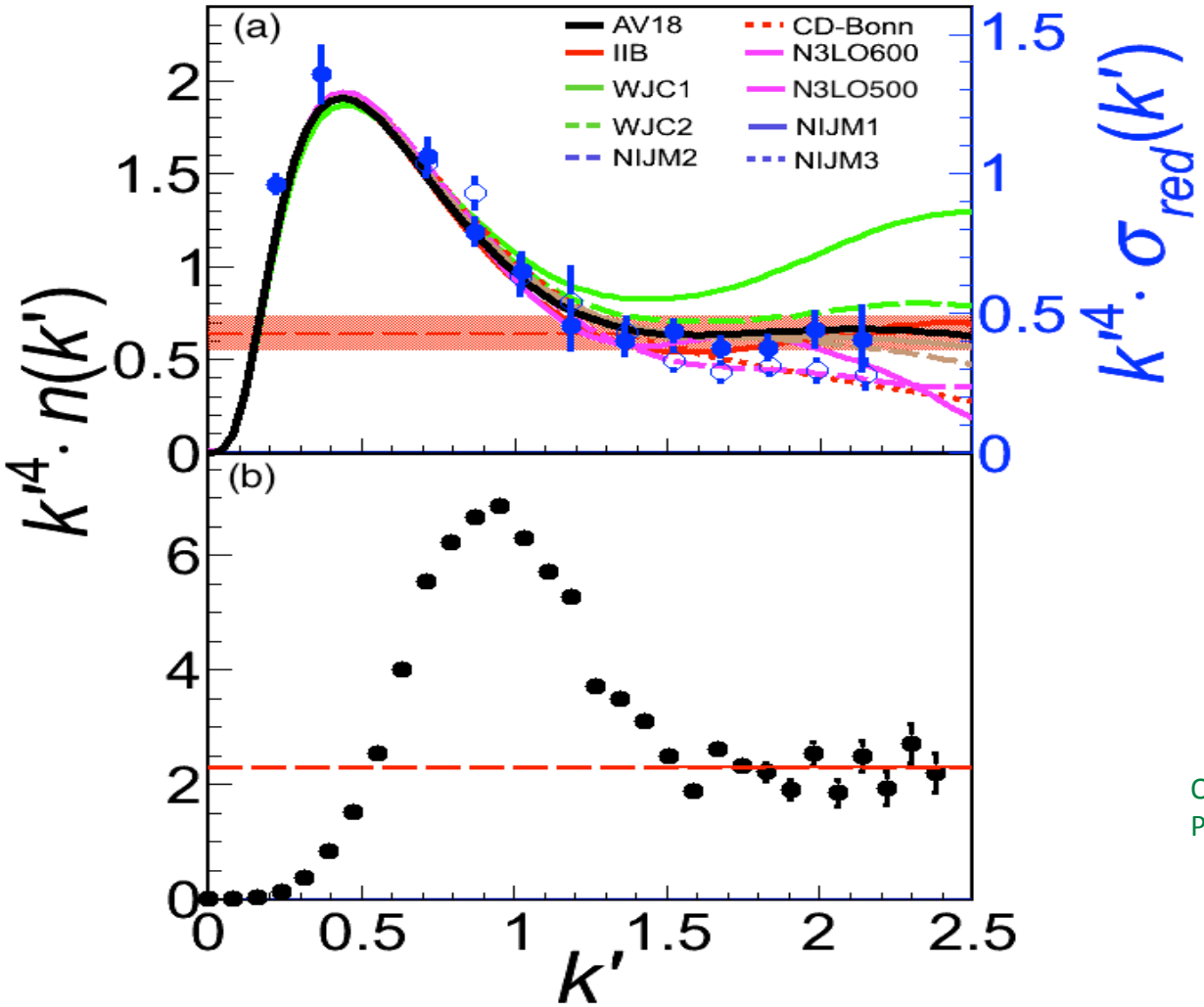
Probing the Deuteron at Short Distances

$$\Psi_d = \Psi_{pn} + \Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} \cdots$$

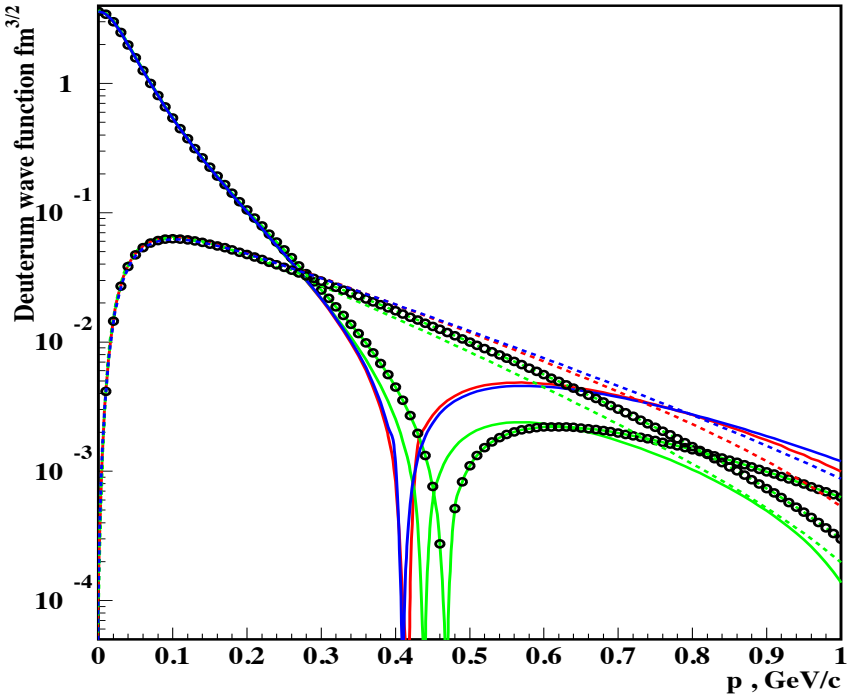
$$\Psi_{hc} = \Psi_{N_c,N_c}$$

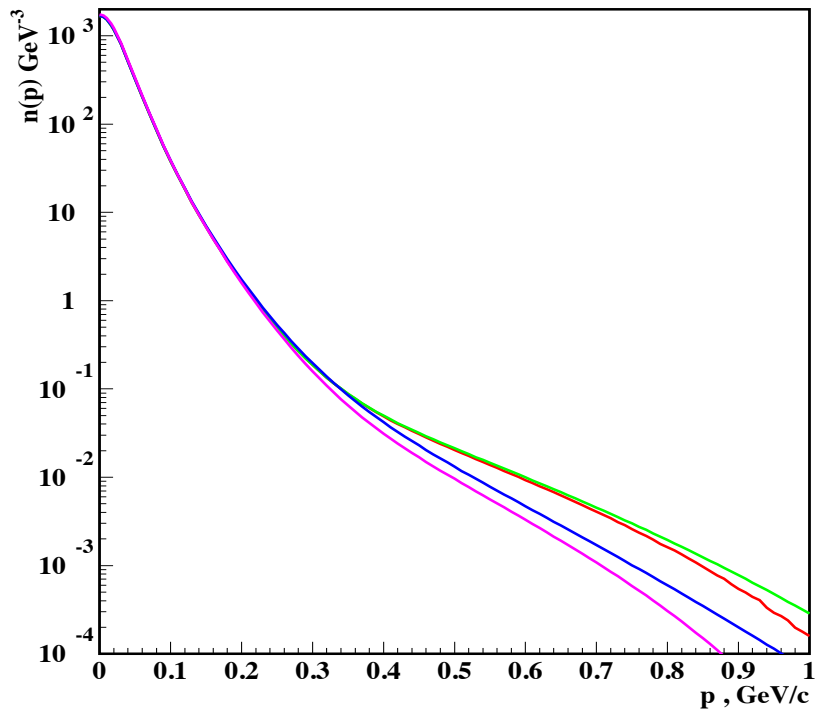
The NN core can be due to the orthogonality of

$$\langle \Psi_{N_c,N_c} \mid \Psi_{N,N} \rangle = 0$$



O.Hen et al
Phys. ReV .C 2014


Deuterum wave function fm^3/2
1
10^-1
10^-2
10^-3
10^-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
p , GeV/c


n(p) GeV^-3
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
p , GeV/c

Probing Polarized Structure of the Deuteron at x > 1

- Tensor Polarized Deuteron = Compact Deuteron

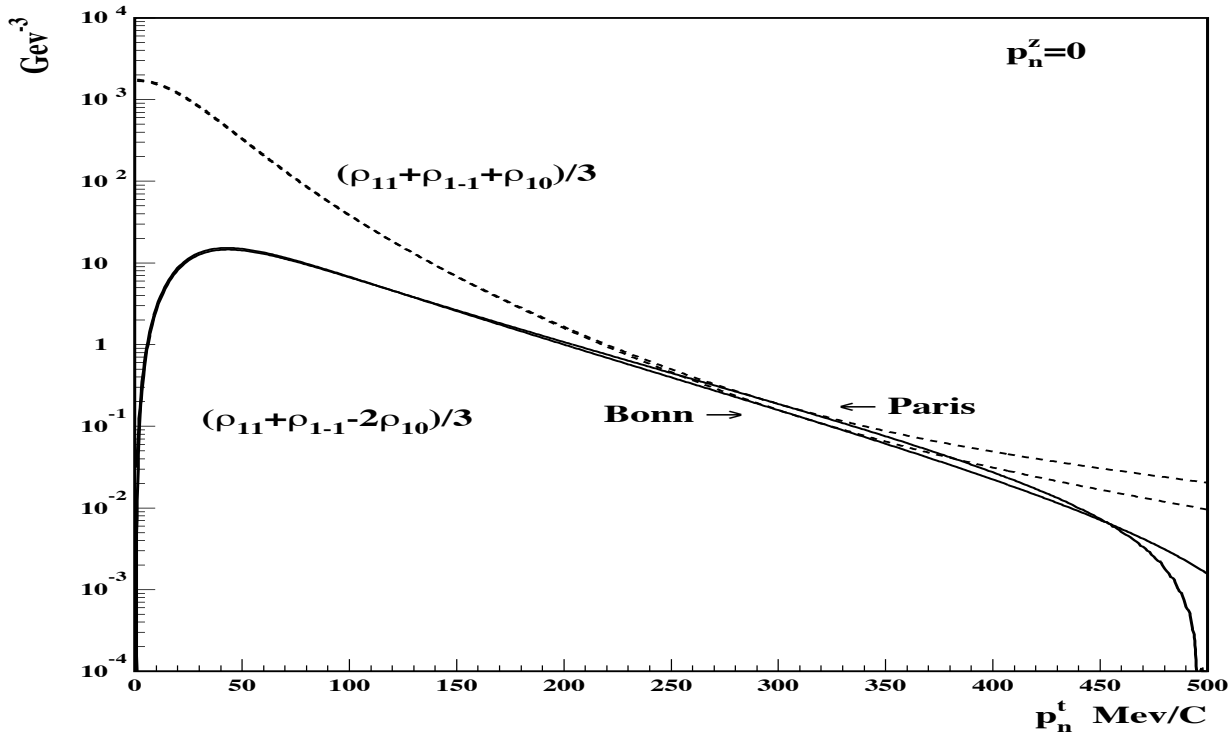


Fig.6

- Direct Observation of the dominance of high momentum protons in neutron rich heavy nuclei

for large $k > k_{Fermi}$

$$n_A(k) \approx a_{NN}(A) n_{NN}(k)$$

$$p + A \to p + p + n + X$$

$$P_{pn/px} = 0.92^{+0.08}_{-0.18}$$

$$\frac{P_{pp}}{P_{pn}} \leq \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}.$$

Theoretical analysis of BNL Data

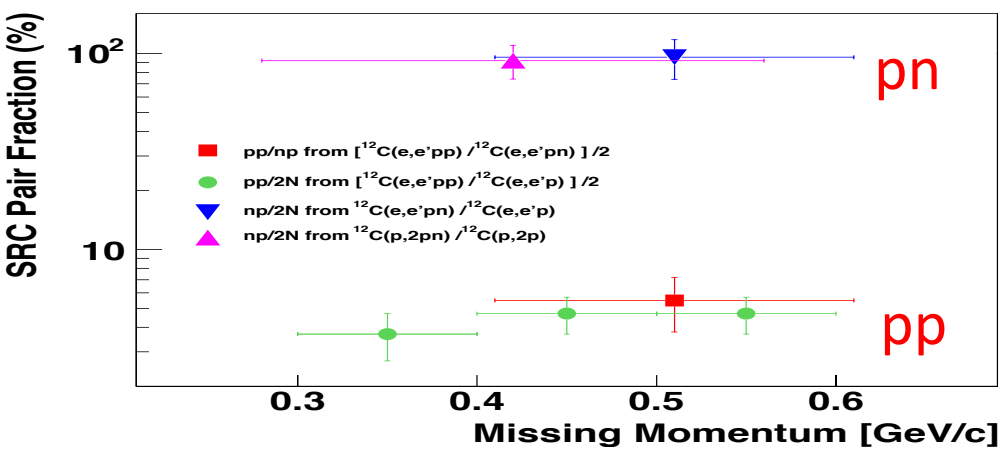
E. Piasetzky, MS, L. Frankfurt, M. Strikman,J.Watson PRL , 2006

$$e + A \to e' + p + (p/n) + X$$

$$P_{pp/pn} = 0.056 \pm 0.018$$

Direct Measurement at JLab

R.Subdei, et al Science , 2008



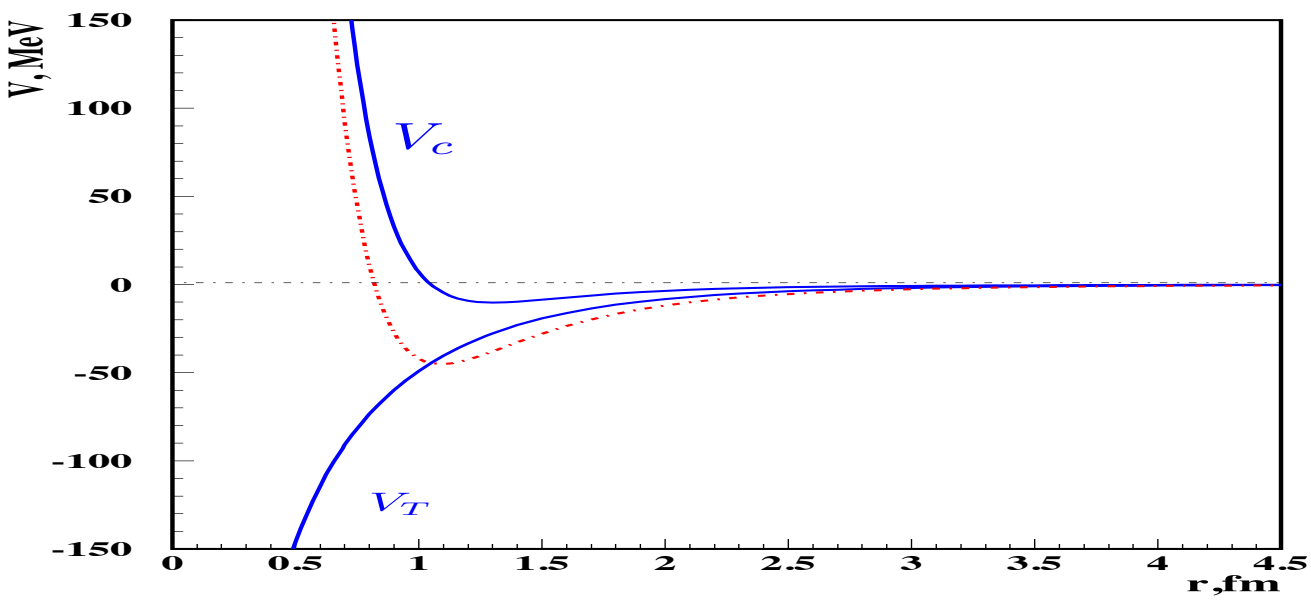
Factor of 20

Expected 4
(Wigner counting)

Theoretical Interpretation

$$\Phi^{(1)}(k_1,\cdots,k_c,\cdots,-k_c,\cdots,k_A) \approx \frac{U_{NN}(k_c)}{k_c^2} F_A(k_1,\cdots'\cdots',\cdots,k_A)$$

$$n_A(k) \approx a_{NN}(A) n_{NN}(k)$$

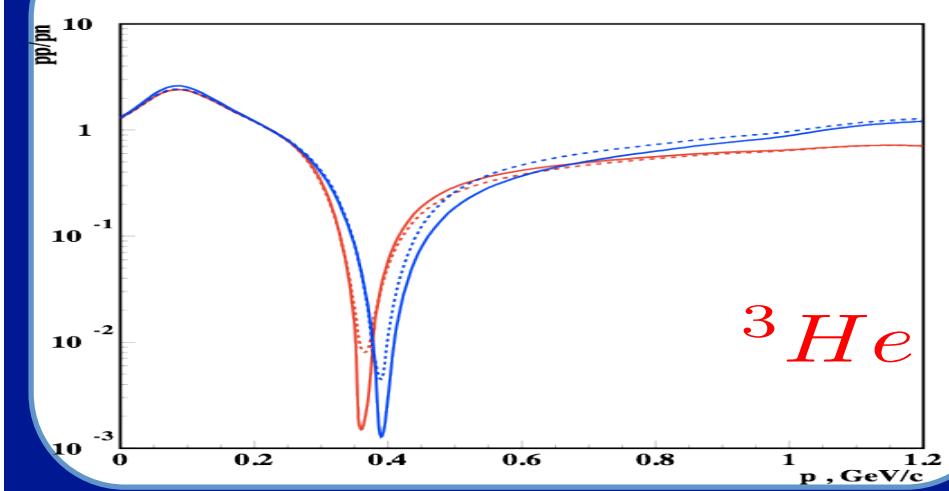


Explanation lies in the dominance of the <u>tensor</u> part in the NN interaction

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1\sigma_2$$

M.S, Abrahamyan, Frankfurt,Strikman PRC,2005



$$S_{12}|pp\rangle = 0$$

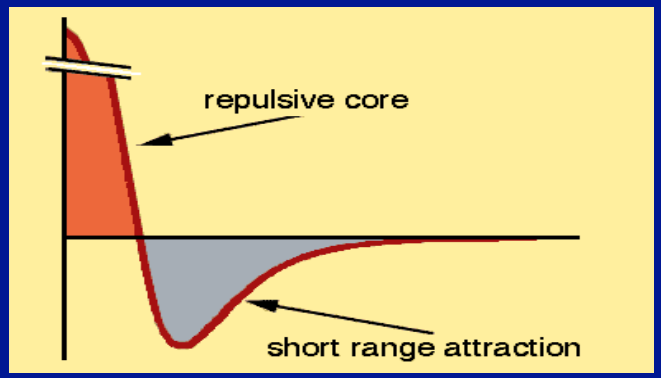
$$S_{12}|nn\rangle = 0$$

$$S_{12}|pn\rangle = 0$$

Isospin 1 states

$$S_{12}|pn\rangle \neq 0$$

Isospin 0 states



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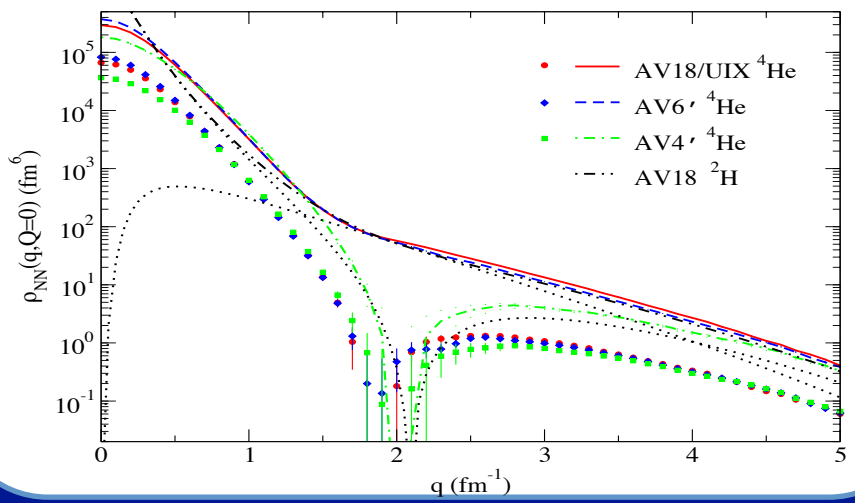
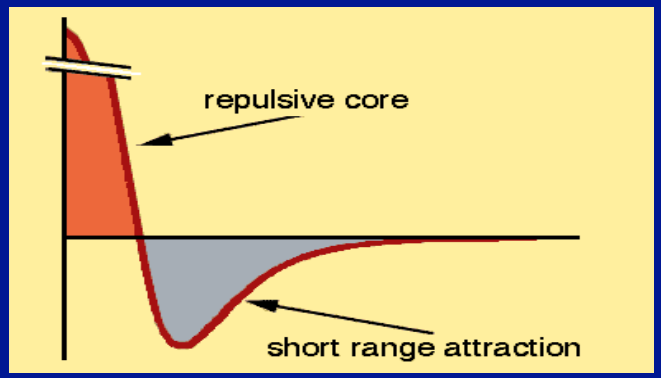
Sciavilla, Wiringa, Pieper, Carlson PRL,2007





- *Dominance of pn short range correlations as compared to pp and nn SRCS*

2006-2008s

- *Dominance of NN Tensor as compared to the NN Central Forces at <= 1fm*

- Two New Properties of High Momentum Component

- Energetic Protons in Neutron Rich Nuclei

at $p > k_F$

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p) \quad (1)$$

- Dominance of pn Correlations
  (neglecting pp and nn SRCs)

$$n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p) \quad (2)$$

$$n^A(p) \sim a_{pn}(A) \cdot n_d(p)$$

$$a_2(A) \equiv a_{NN}(A) \approx a_{pn}(A)$$

- Define momentum distribution of proton & neutron

$$n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p) \qquad (3)$$

$$\int n_{p/n}^A(p) d^3p = 1$$

- Define

$$I_p = \frac{Z}{A} \int_{k_F}^{600} n_p^A(p) d^3p \qquad I_n = \frac{A-Z}{A} \int_{k_F}^{600} n_n^A(p) d^3p$$

- and observe that in the limit of no pp and nn SRCs

$$I_p = I_n$$

- Neglecting CM motion of SRCs

$$\frac{Z}{A} n_p^A(p) \approx \frac{A-Z}{A} n_n^A(p)$$

First Property: Approximate Scaling Relation

-if contributions by pp and nn SRCs are neglected and the pn SRC is assumed at rest

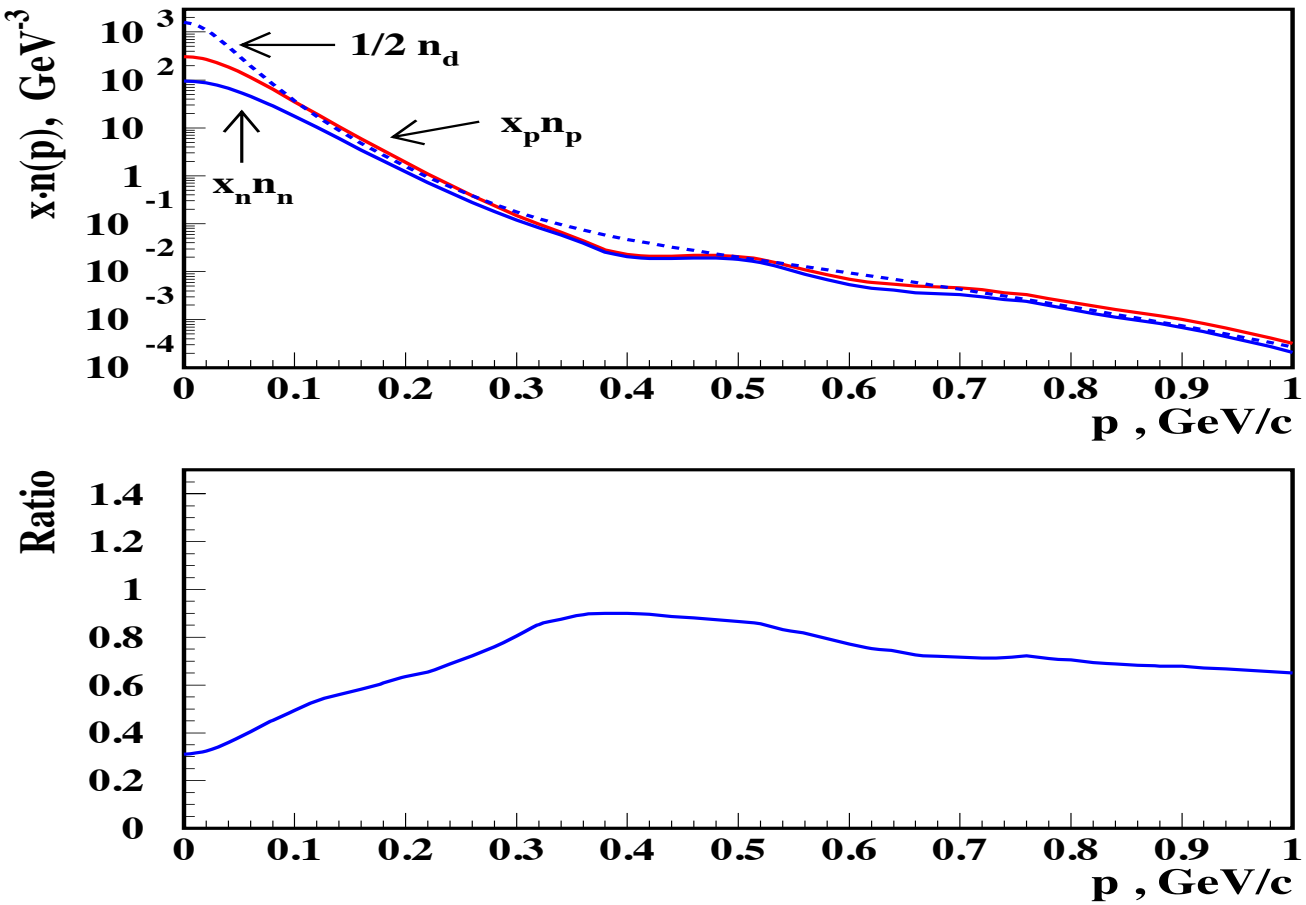
MS,arXiv:1210.3280
Phys. Rev. C 2014

- for $\sim k_F - 600$ MeV/c region:

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p)$$

where $x_p = \frac{Z}{A}$ and $x_n = \frac{A-Z}{A}$.

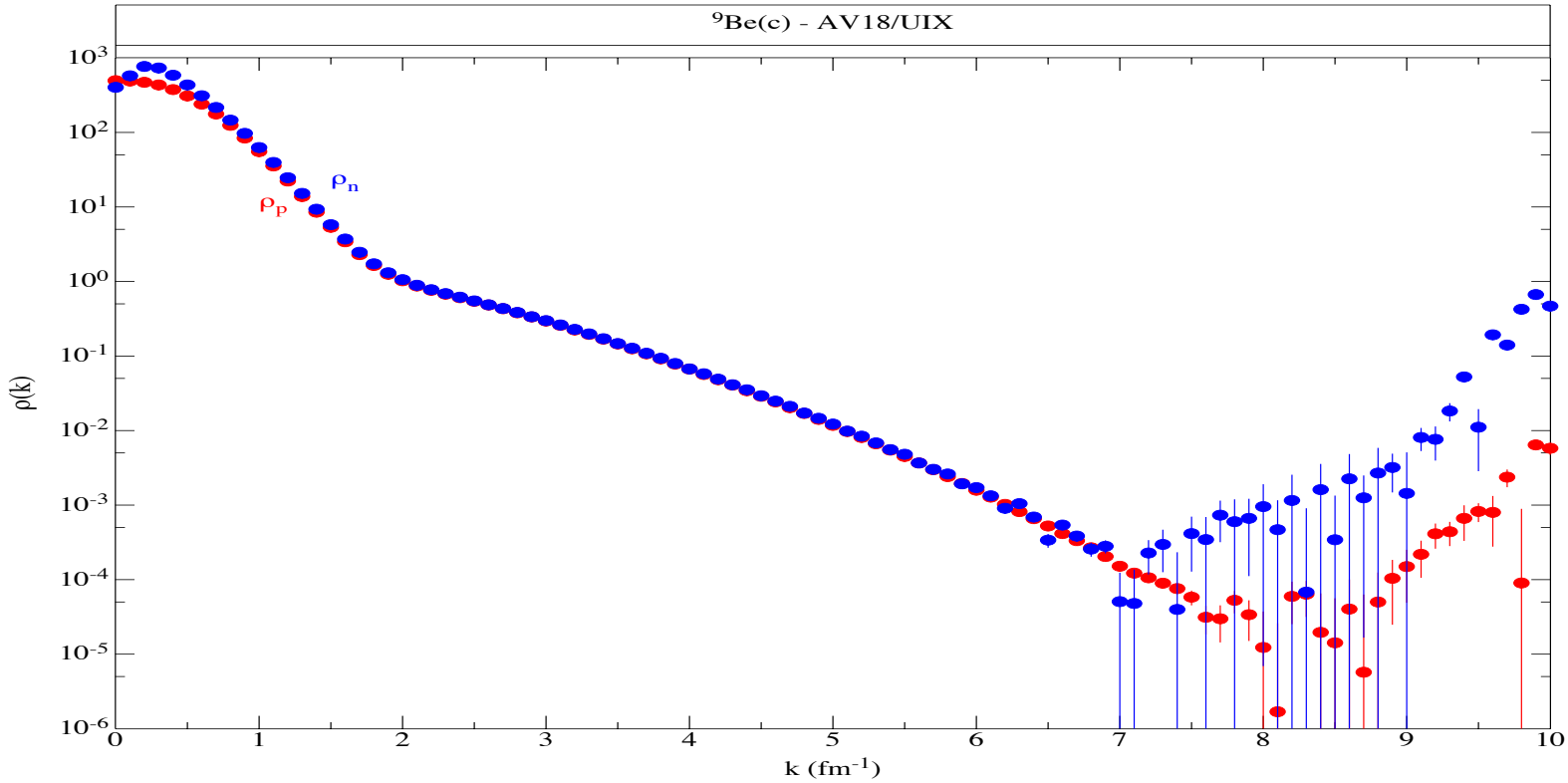
Realistic 3He Wave Function: Faddeev Equation



MS,PRC 2014

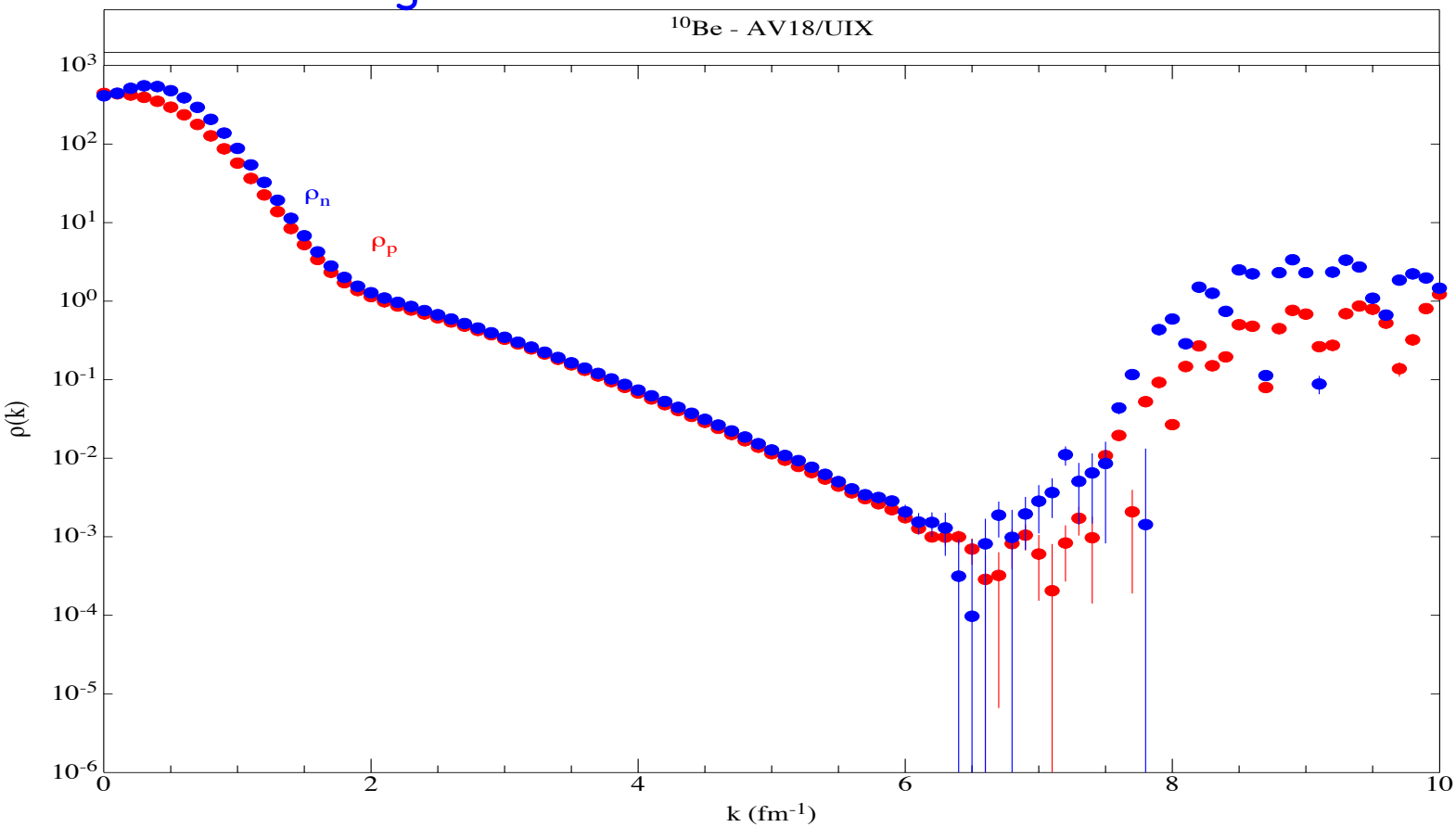
Be9 Variational Monte Carlo Calculation:

Robert Wiringa 2013 http://www.phy.anl.gov/theory/research/momenta/



B10 Variational Monte Carlo Calculation:

Robert Wiringa



Second Property:

MS,arXiv:1210.3280
Phys. Rev. C 2014

Using Definition: $n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p)$

Approximations:

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p)$$

$$n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p)$$

And: $I_p = I_n$ $\quad I_p + I_n = 2I_N = a_{pn}(A) \int_0^{600} n_d(p) d^3p$

One Obtains:

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p) \approx \frac{1}{2} a_{NN}(A, y) n_d(p)$$

where $y = |1 - 2x_p| = |x_n - x_p|$

- $a_{NN}(A, 0)$ corresponds to the probability of pn SRC in symmetric nuclei
- $a_{NN}(A, 1) = 0$ according to our approximation of neglecting pp/nn SRCs

Second Property: Fractional Dependence of High Momentum Component

$a_{NN}(A,y) \approx a_{NN}(A,0) \cdot f(y)$ with $f(0) = 1 \text{ and } f(1) = 0$

$$f(|x_p - x_n|) = 1 - \sum_{j=1}^{n} b_i |x_p - x_x|^i \text{ with } \sum_{j=1}^{n} b_i = 0$$

In the limit $\sum_{j=1}^{n} b_i |x_p - x_x|^i \ll 1$ Momentum distributions of p & n are inverse proportional to their fractions

$$\boxed{n^A_{p/n}(p) \approx \frac{1}{2x_{p/n}} a_2(A,y) \cdot n_d(p)}$$

$x_{p/n} = \frac{Z/N}{A}$

Observations: High Momentum Fractions

MS,arXiv:1210.3280
Phys. Rev. C 2014

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int_{k_F}^{\infty} n_d(p) d^3p$$

A	Pp(%)	Pn(%)
12	20	20
27	23	22
56	27	23
197	31	20

Requires dominance of pn SRCs in heavy neutron reach nuclei

O. Hen, M.S. L. Weinstein, et.al.
Science, 2014

Is the total kinetic energy inversion possible?

Checking for He3

Energetic Neutron

$E^p_{kin} = 14$ MeV (p= 157 MeV/c)

$E^n_{kin} = 19$ MeV (p= 182 MeV/c)

Energetic Neutron
(Neff & Horiuchi)

$E^p_{kin} = 13.97$ MeV

$E^n_{kin} = 18.74$ MeV

VMC Estimates: Robert Wiringa

MS,arXiv:1210.3280
Phys. Rev. C 2014

Table 1: Kinetic energies (in MeV) of proton and neutron

A	y	E^p_{kin}	E^n_{kin}	$E^p_{kin} - E^n_{kin}$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

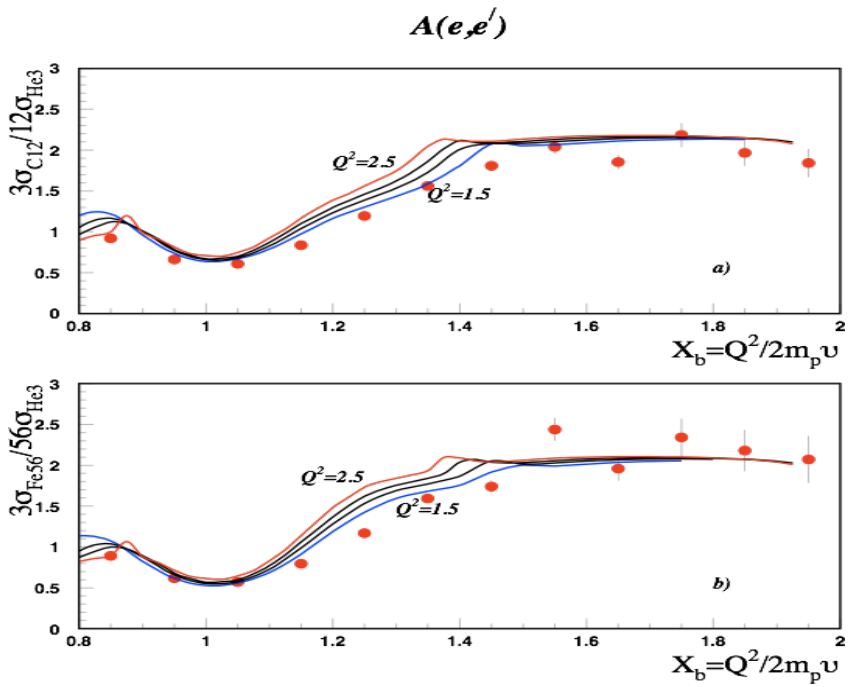
Heavy Nuclei ?

- Three Nucleon Short Range Correlations:

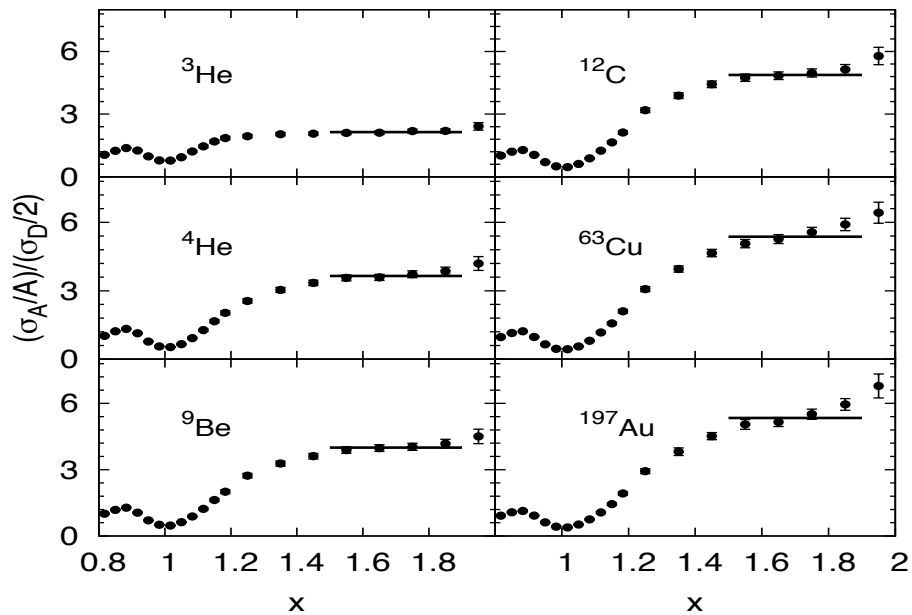
$$R = \frac{A_2\sigma[A_1(e,e')X]}{A_1\sigma[A_2(e,e')X]}$$

Factorization of 2N SRC distribution in nuclei

For $1 < x < 2$ $R \approx \frac{a_2(A_1)}{a_2(A_2)}$

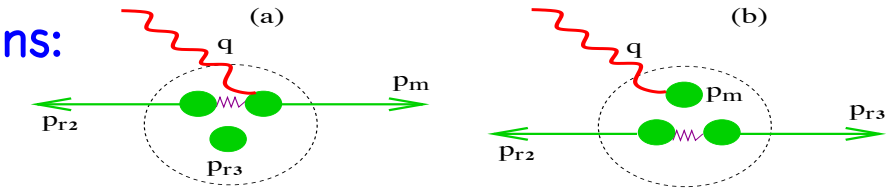


Egiyan, et al PRC 2004

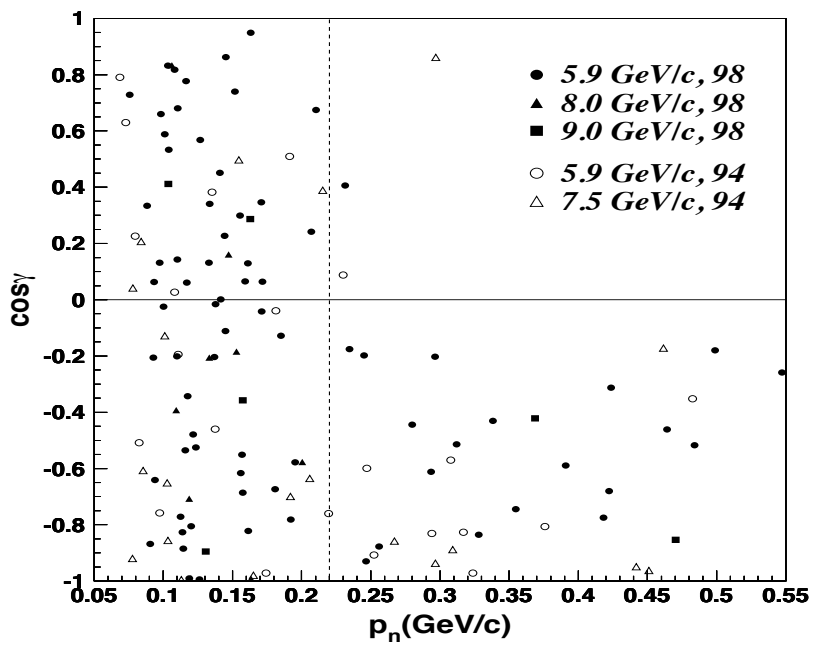


Fomin et al PRL 2011

- Three Nucleon Short Range Correlations:

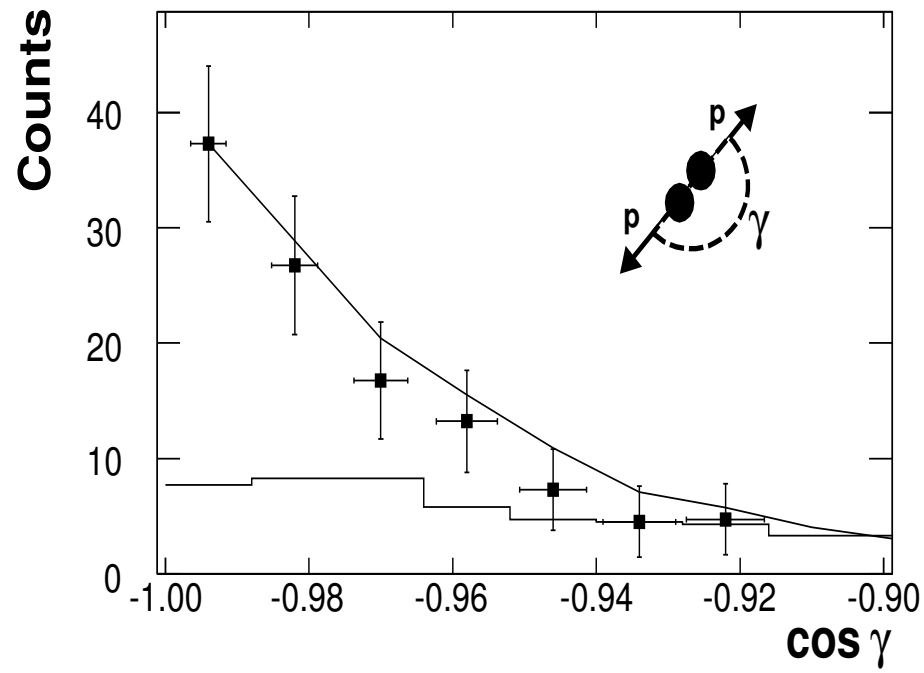


$$p + A \rightarrow p + p + n + X$$



Tang et al PRL 2002

$$e + A \rightarrow e' + p_f + p_b + X$$



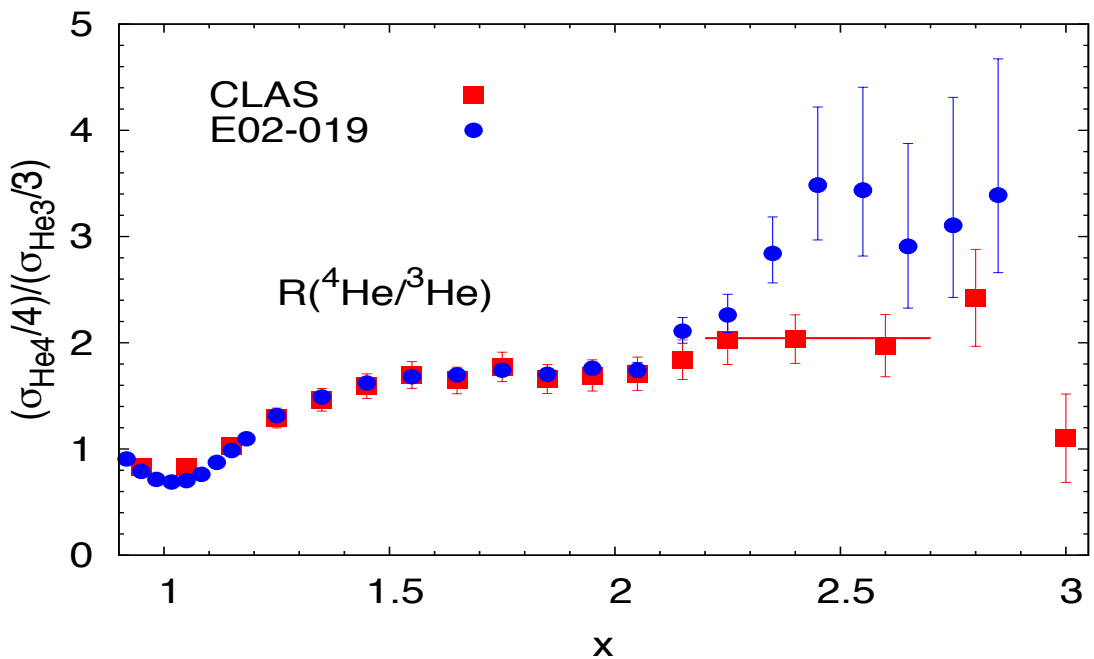
Subedi et al Science 2006

- Three Nucleon Short Range Correlations:

$$R = \frac{A_2 \sigma[A_1(e,e')X]}{A_1 \sigma[A_2(e,e')X]}$$

Factorization of 3N SRC distribution in nuclei?

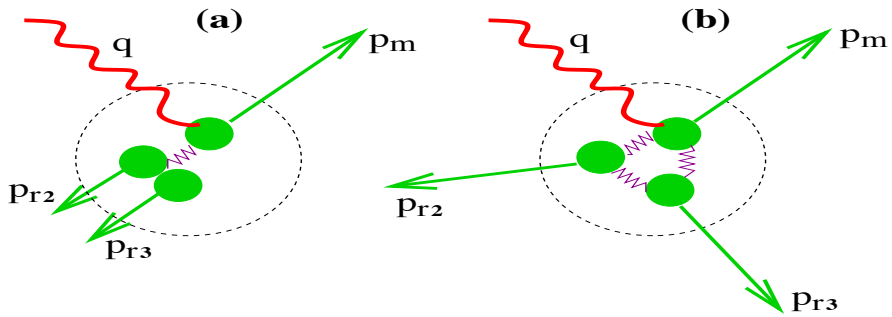
For $2 < x < 3$ $R \approx \frac{a_3(A_1)}{a_3(A_2)}$

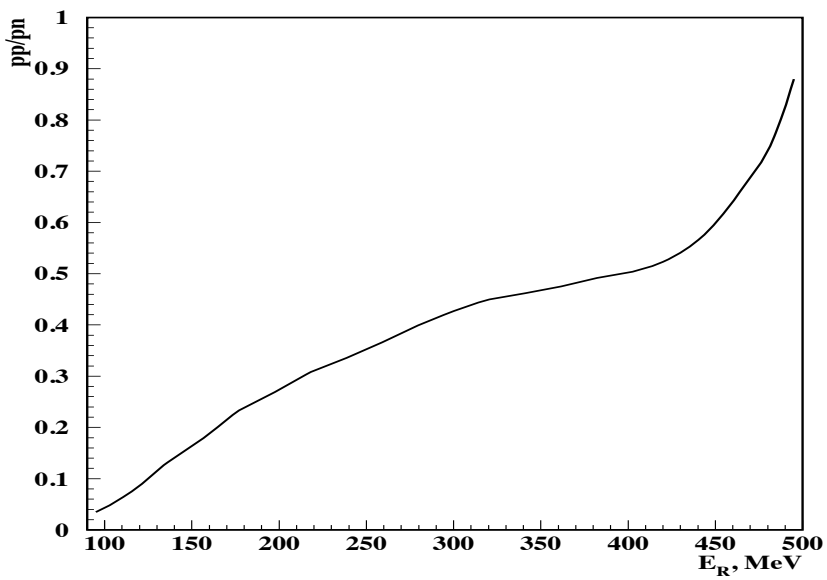


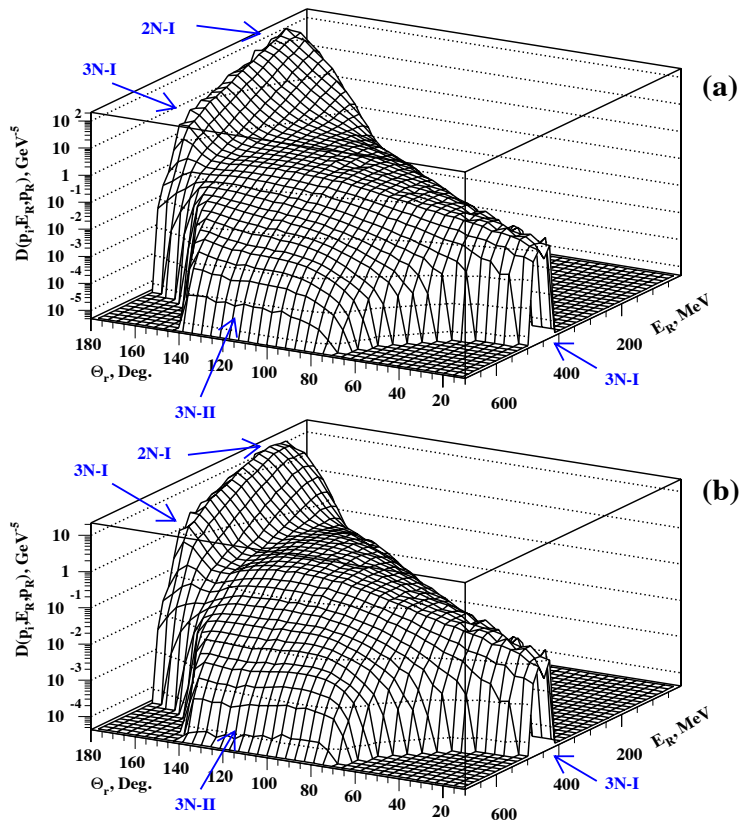
Egiyan, et al PRL 2006

Fomin et al PRL 2011

- Three Nucleon Short Range Correlations: New Signatures of 3N SRCs







- Non-Nucleonic Content of 2N SRCs

- No non-nuclonic component is observed for pn system up to 650 MeV/c

- The relative momenta in the NN system which will be sensitive to the core dynamics can be estimated based on the threshold of inelastic N-Delta transition

$$\sqrt{M_N^2 + p^2} - M_N > M_\Delta - M_N$$

$$p \geq 800 \text{ MeV/c}$$

- Outstanding Problems in SRC studies

1. Deuteron 500 - 800 MeV/c

2. Protons in neutron rich nuclei

3. Deuteron > 800 MeV/c (core physics)

4. Observation and systematic studies of 3N SRCs

2. Choosing the probe

$$\gamma + A \rightarrow N_f + \pi + N_r + X$$

$$\gamma + N_i \longrightarrow N_f + \pi \quad \text{at fixed and large } \theta_{cm} \sim 90^0$$

$$\frac{d\sigma}{dt} \sim \frac{f(\theta_{cm})}{s^7} \text{ for } E_\gamma > 1 \text{ GeV}$$

$$s_i = s_0 \cdot \alpha_i \qquad \text{Reaction chooses } \alpha_i < 1!$$

Frankfurt, Liu, Strikman, Farrar PRL 1989

$$\alpha_i = \frac{E_i - p_i^z}{M_N}$$

- External probe selects a bound nucleon moving in the probes direction

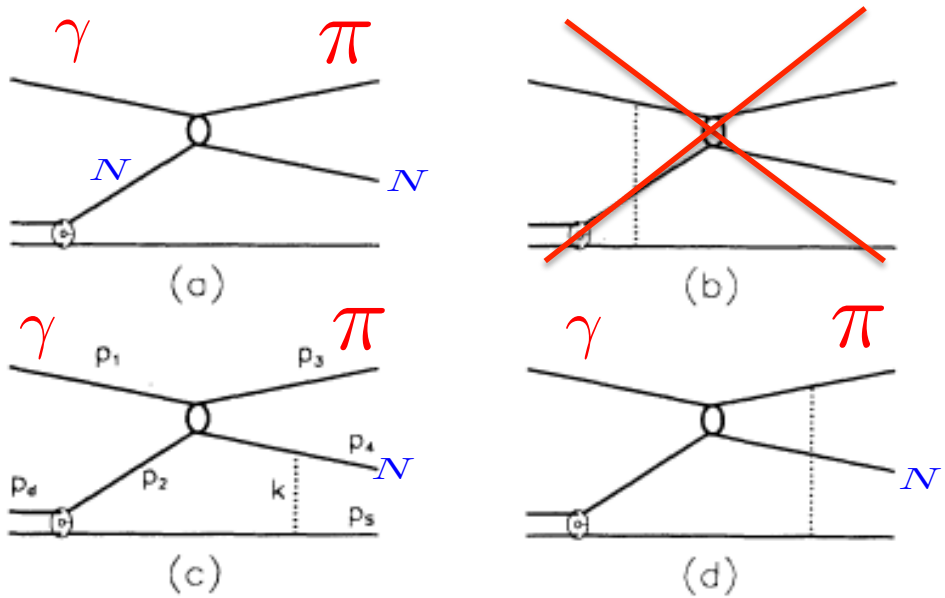
$$\gamma + A \rightarrow n + \pi^+ + N_r + X$$ Probing proton

$$\gamma + A \rightarrow p + \pi^- + N_r + X$$ Probing neutron

$$\gamma + A \rightarrow p + \pi^0 + N_r + X$$ Probing proton

Maria Patsyuk's talk

3. Probing the Deuteron at Small Distances

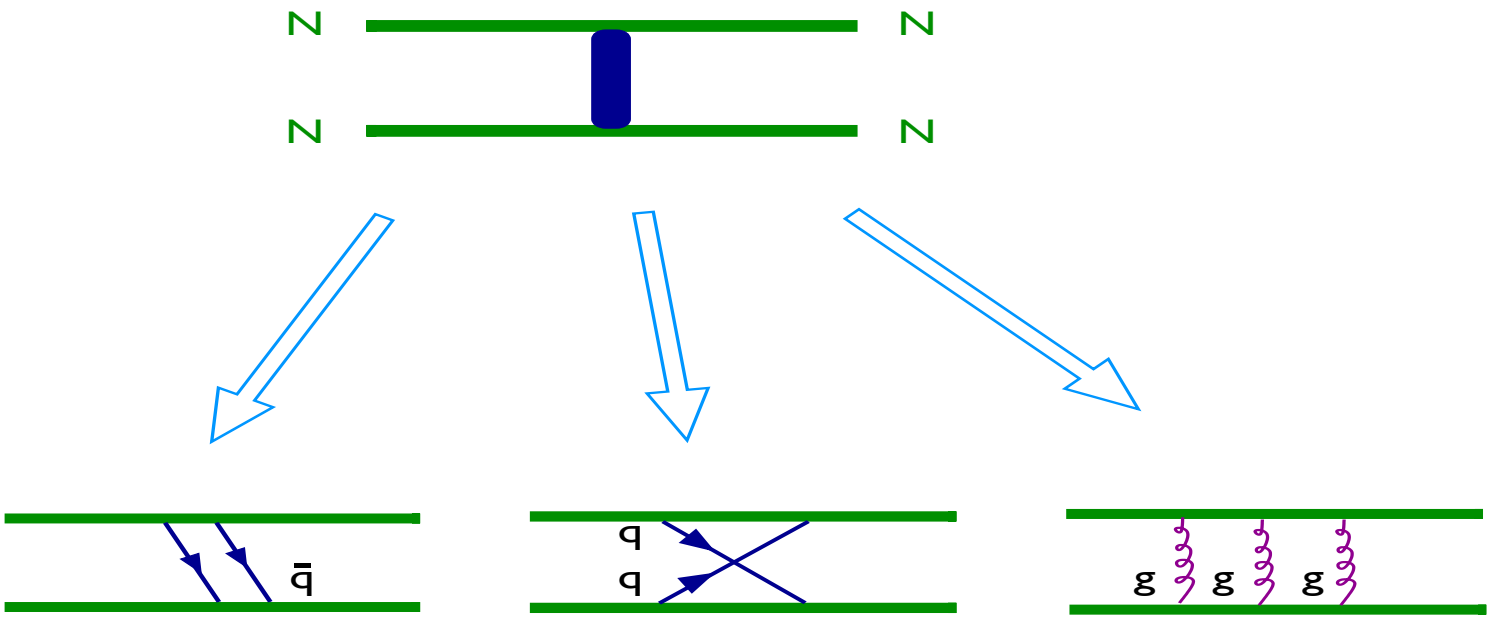


3. Probing multi-nucleon SRCs in medium to heavy nuclei

Maria Patsyuk's talk

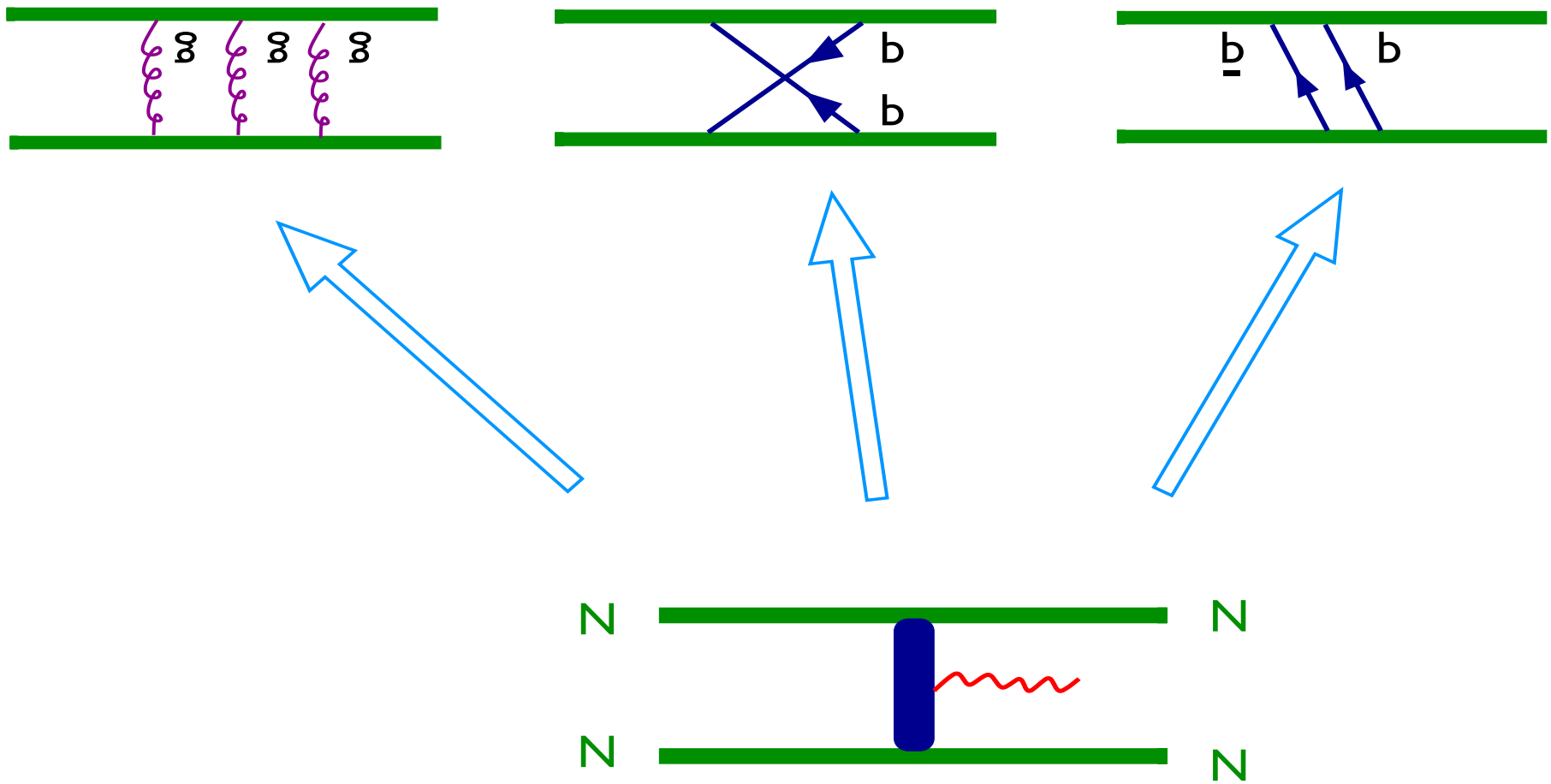
II. Hard Photodisintegration of few-body systems

1. Probing the mechanism of hard QCD hadronic interaction



-Can be Studied in Hard Exclusive NN Scattering Reactions

-Last Experiments were done at early 90's at AGS, BNL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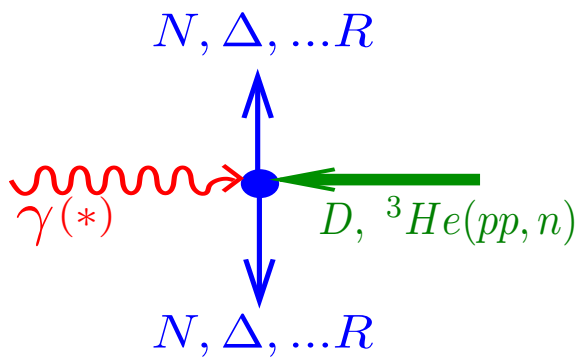
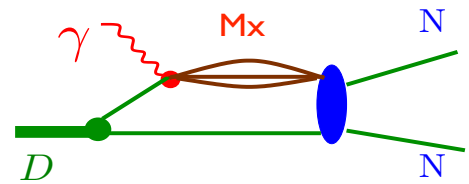




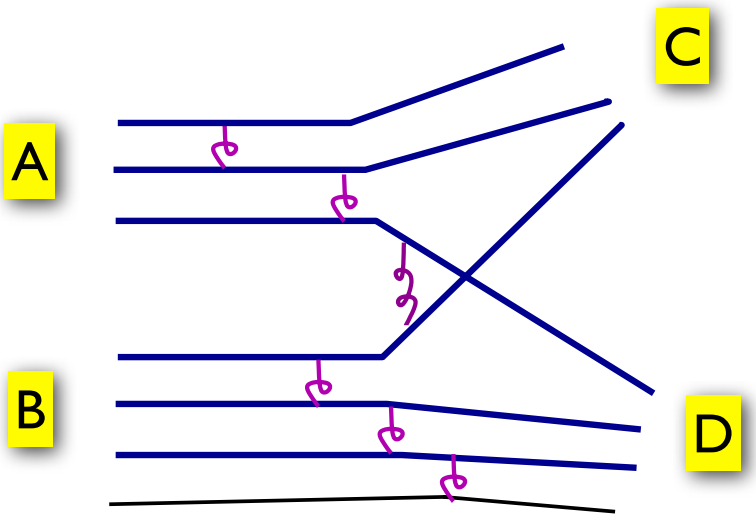
$$s = (k_\gamma + p_d)^2 = 2M_d E_\gamma + M_d^2$$

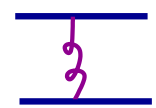
Brodsky, Chertock, 1976
Holt, 1990
Gilman, Gross, 2002

$$t = (k_\gamma - p_N)^2 = [cos\theta_{cm} - 1]\frac{s - M_d^2}{2}$$

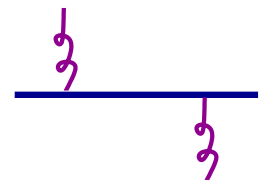
$$E_\gamma = 2\ \text{GeV},\ s = 12\ \text{GeV}^2,\ t\ |_{90^0} \approx -4\ \text{GeV}^2,\ M_x = 2\ \text{GeV}$$

$$E_\gamma = 12\ \text{GeV},\ s = 41\ \text{GeV}^2,\ t\ |_{90^0} \approx -18.7\ \text{GeV}^2,\ M_x = 4.4\ \text{GeV}$$





$$\longrightarrow \quad f\left(\frac{t}{s}\right)$$



$$\longrightarrow \quad \frac{1}{s}$$

additional $\frac{1}{s}$

$$\boxed{A \sim F\left(\frac{t}{s}\right) \frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}}$$

Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

$$\frac{d\sigma}{dt} \approx \frac{|A|^2}{s^2} = F^2\left(\frac{t}{s}\right) \frac{1}{s^{n_A+n_B+n_C+n_D-2}}$$

$\gamma d \longrightarrow pn$

Exclusive large-momentum-transfer scattering

•Dimensional counting rule:

$$\frac{d\sigma}{dt}_{AB\to CD} \propto S^{-(N=n_A+n_B+n_C+n_D-2)}\, f(\tfrac{t}{s})$$

For

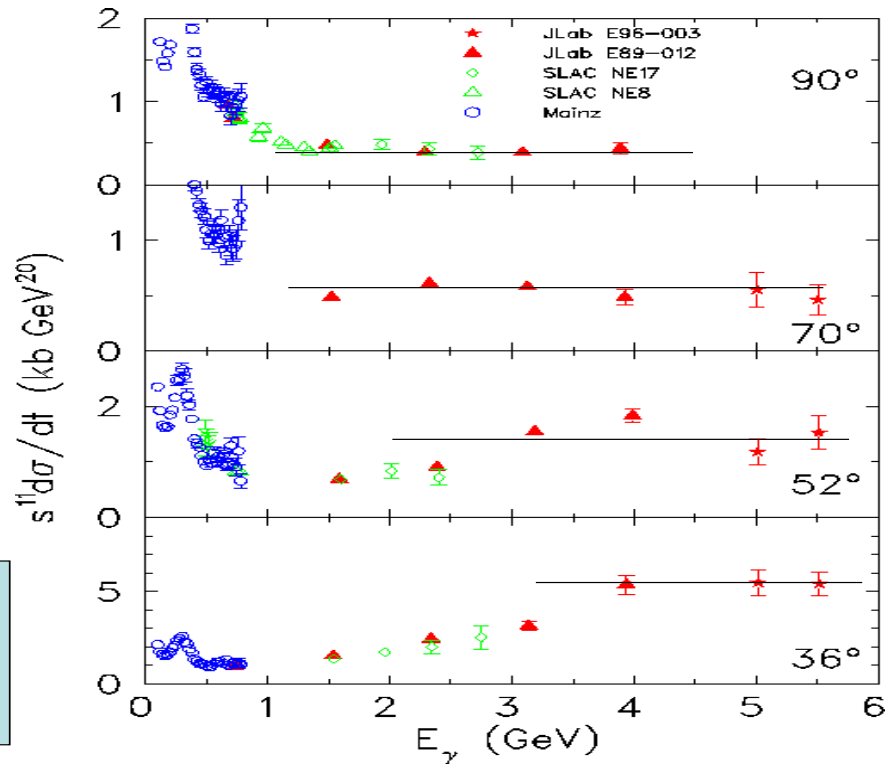
$$\gamma\, d \longrightarrow p\,(high\ p_t) + n\,(high\ p_t)$$

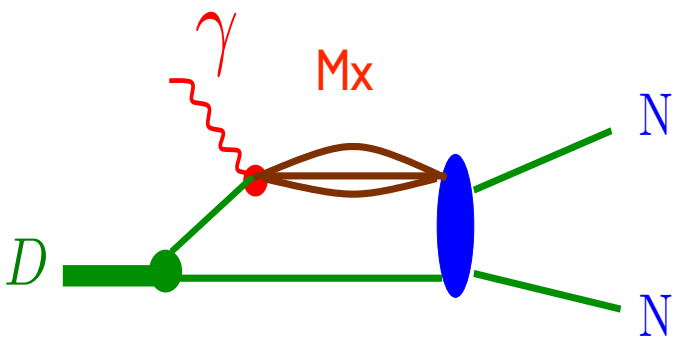
N = 1 + 6 + 3 + 3 – 2 = 11

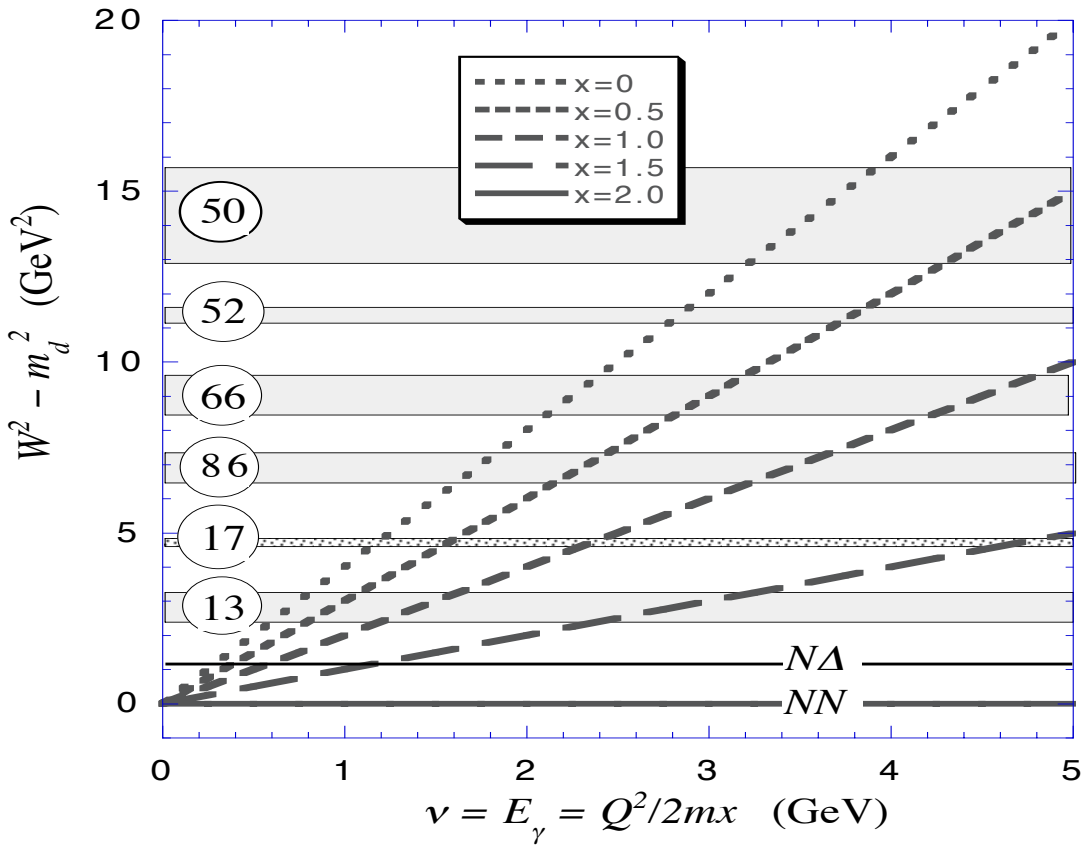
Notice:

$$\frac{d\sigma}{dt}(E_\gamma = 1\,\mathrm{GeV/c}) \,/\, \frac{d\sigma}{dt}(E_\gamma = 4\,\mathrm{GeV/c}) \approx 10^4$$

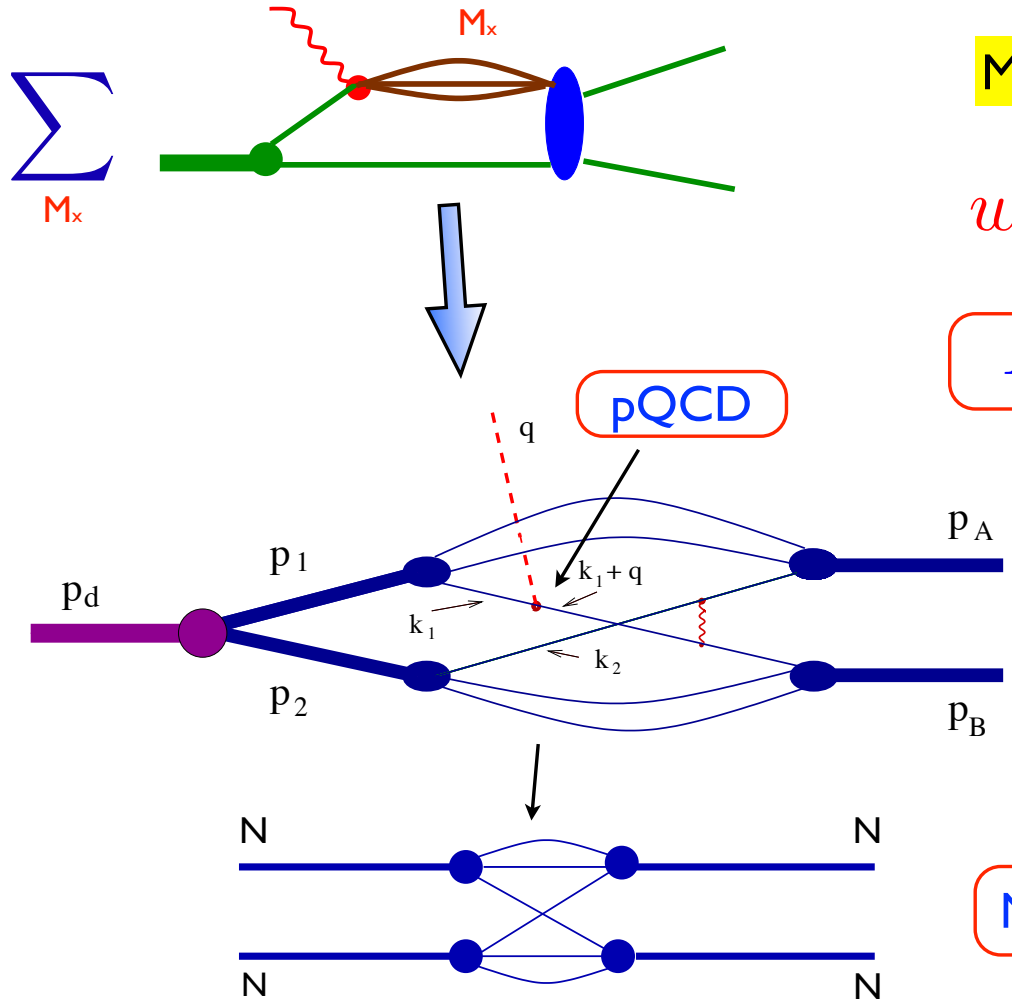
scaling







Gilman & Gross 2002



Mmax=w > 2 GeV

$$w \sim \sqrt{2E_\gamma m_N}$$

$$E_\gamma \geq 2.5 \text{ GeV}$$

Frankfurt, Miller, MS, Striman
Phys. Rev. Lett. 2000

NN -amplitude

$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$

$$\left(\langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, t_n) | p_{\lambda_\gamma}, n_{\lambda_2} \rangle - \langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, u_n) | n_{\lambda_\gamma} p_{\lambda_2} \rangle \right)$$

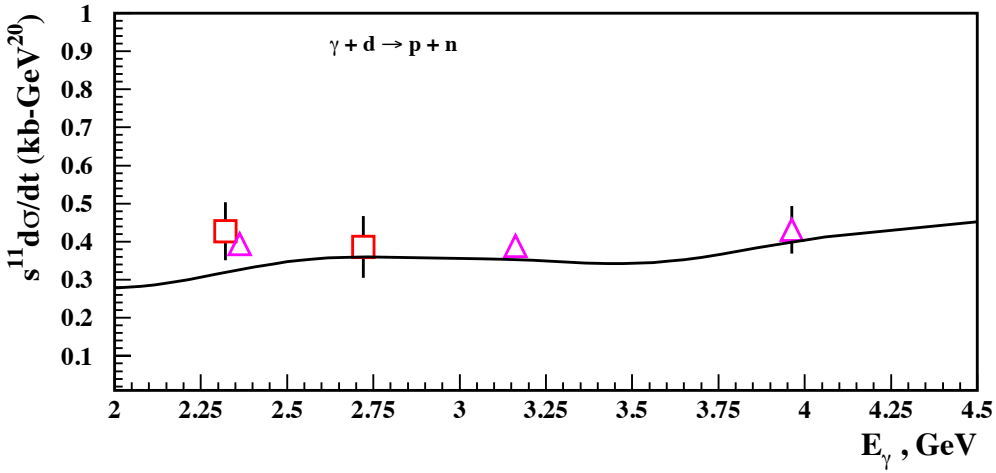
$$\int \Psi^{\lambda_D, \lambda_\gamma, \lambda_2}(\alpha_c, p_\perp) \frac{d^2 p_\perp}{(2\pi)^2} \tag{1}$$

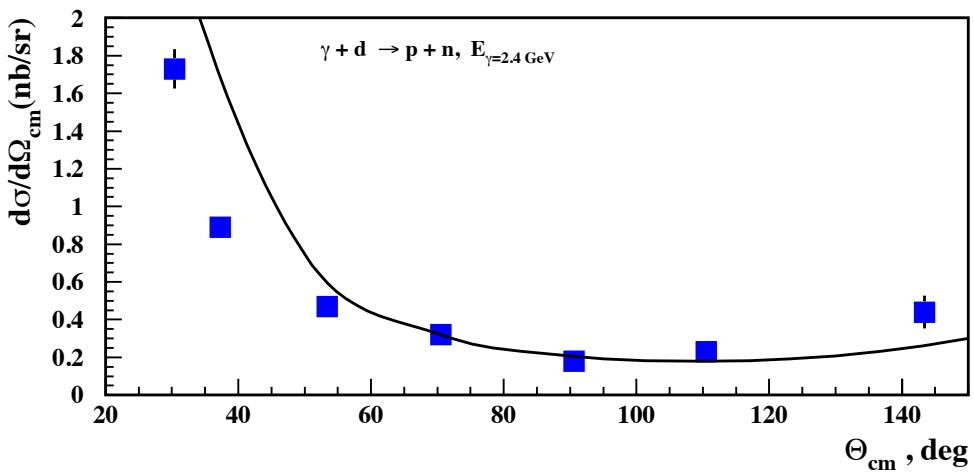
$$\Psi^{\lambda_D, \lambda_1 \lambda_2} = (2\pi)^{\frac{3}{2}} \Psi_{NR}^{J_D, \lambda_1, \lambda_2} \sqrt{m} = [u(k) + w(k)\sqrt{\tfrac{1}{8}} S_{12}] \xi_1^{\lambda_D, \lambda_1, \lambda_2}$$

$$\boxed{\frac{d\sigma^{\gamma d \to pn}}{dt} = \frac{8\alpha}{9} \pi^4 \cdot \frac{1}{s'} C(\frac{\tilde{t}}{s}) \frac{d\sigma^{pn \to pn}(s, \tilde{t})}{dt} \left| \int \Psi_d^{NR}(p_z = 0, p_\perp) \sqrt{m_N} \frac{d^2 p_\perp}{(2\pi)^2} \right|^2 ,}$$

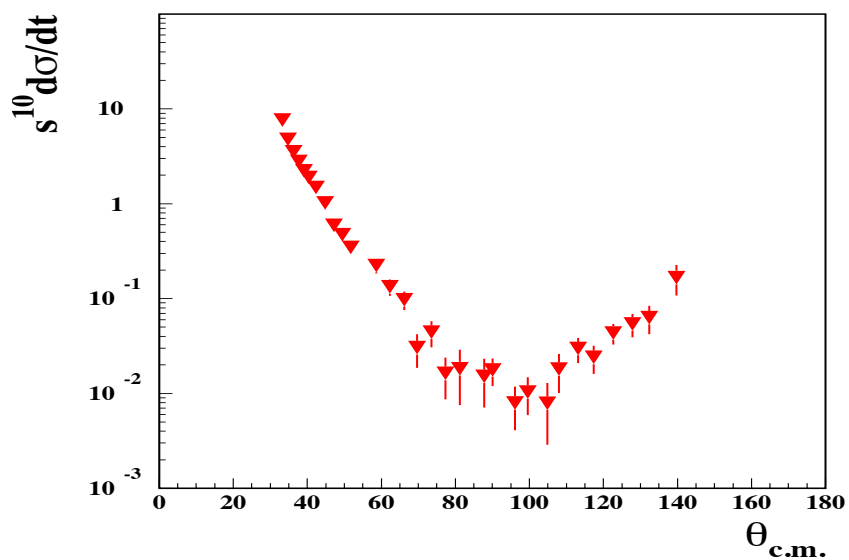
$C(\frac{\tilde{t}}{s}) \mid_{\theta_{cm}=90} = 1$

$$\gamma + d \rightarrow p + n$$

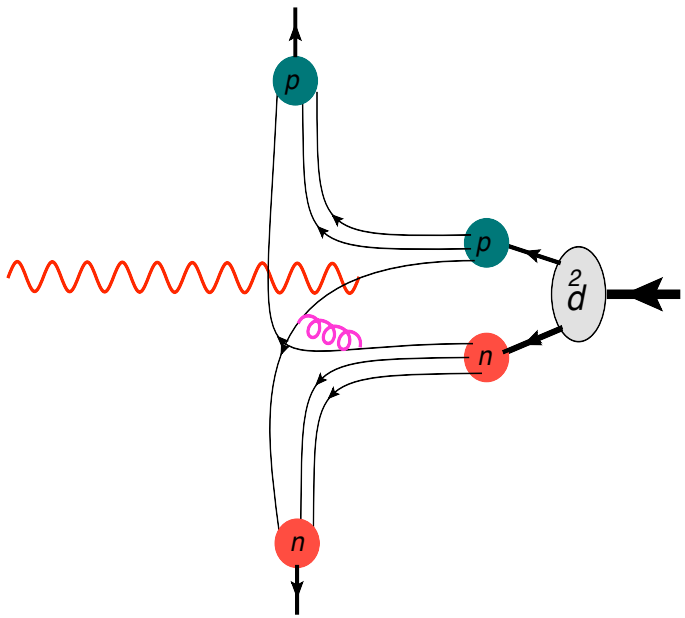




$$pn \rightarrow pn$$

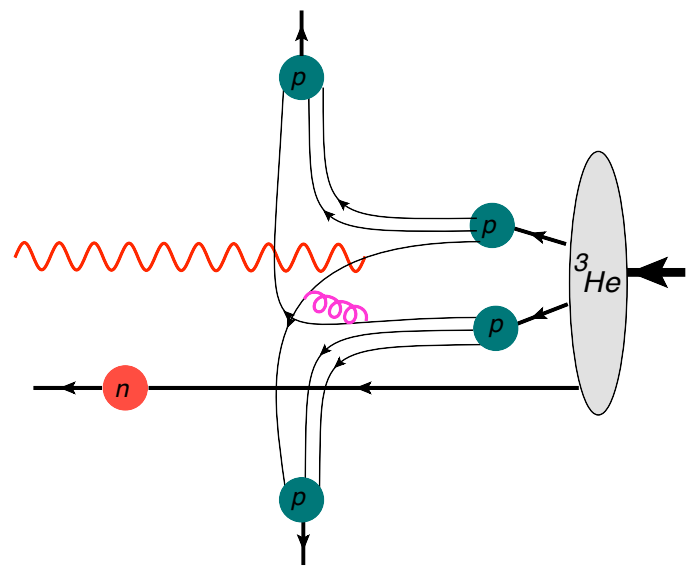


Break up of pn from the deuteron



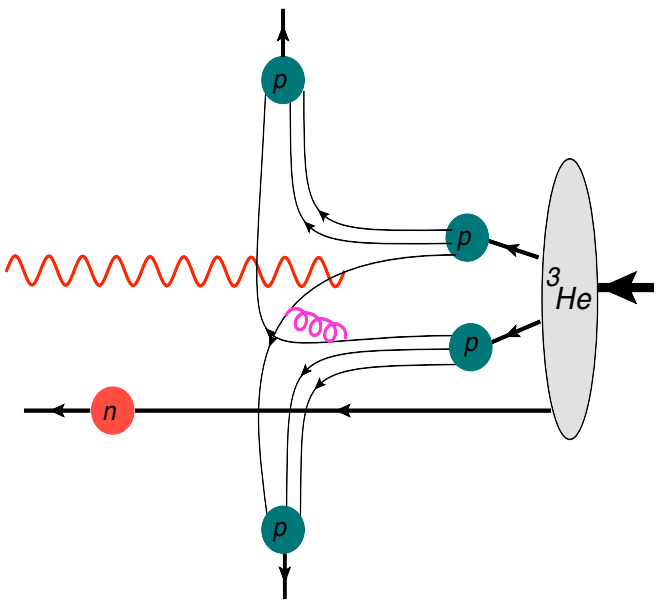
Frankfurt,Miller,M.S. Strikman Phys. Lett. Let. 2000

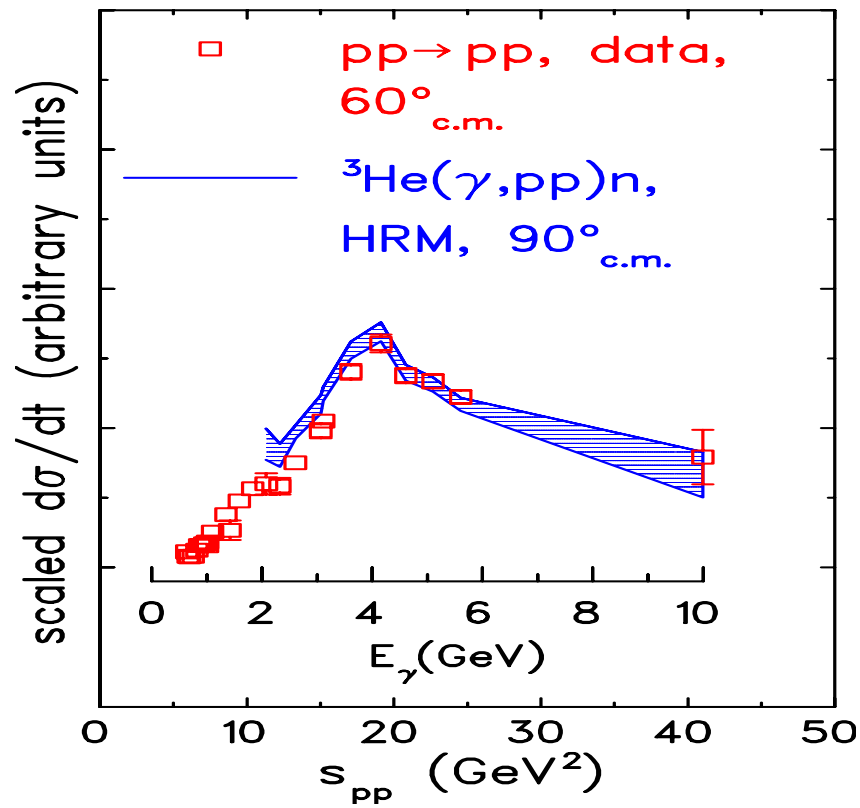
Break up of pp from Helium 3

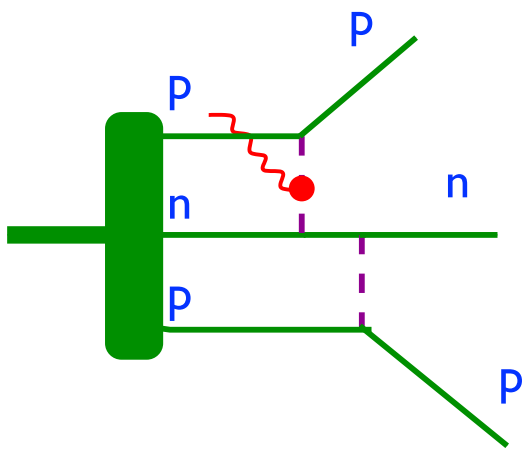


Brodsky, Frankfurt, Gilman, Hiller, Miller
Piasetzky, M.S., Strikman Phys. Lett. B 2004

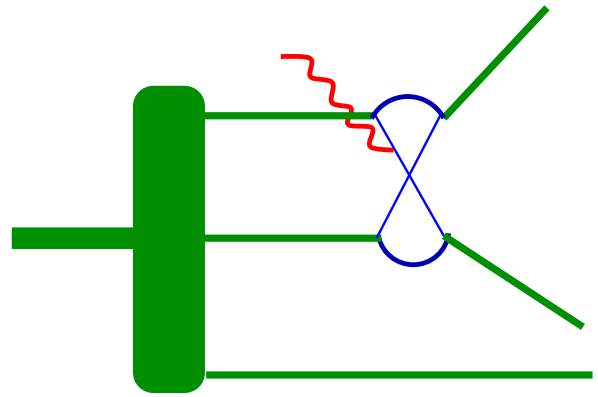
Break up of pp from Helium 3



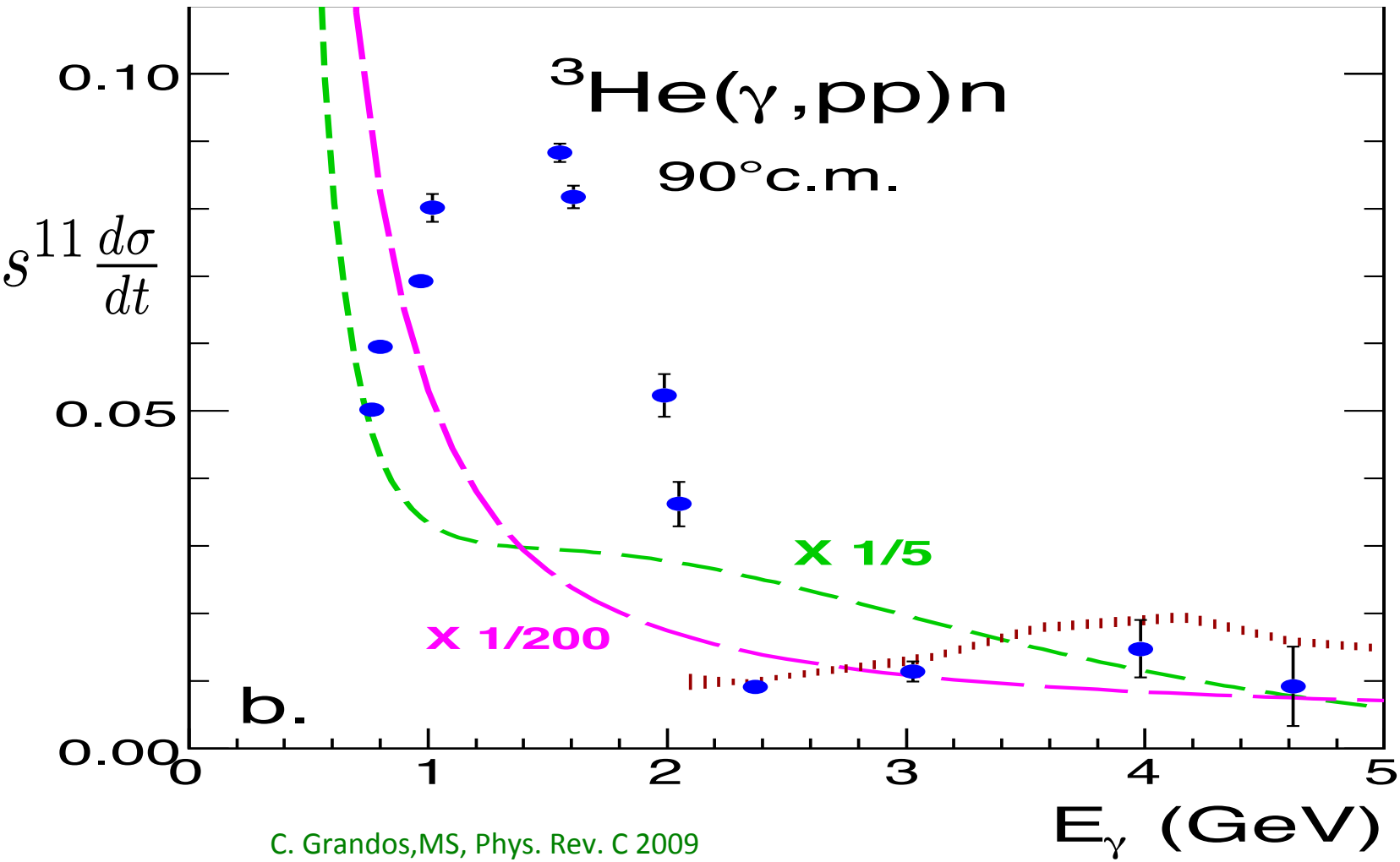




$\sim s^{-13}$



$\sim s^{-11}$

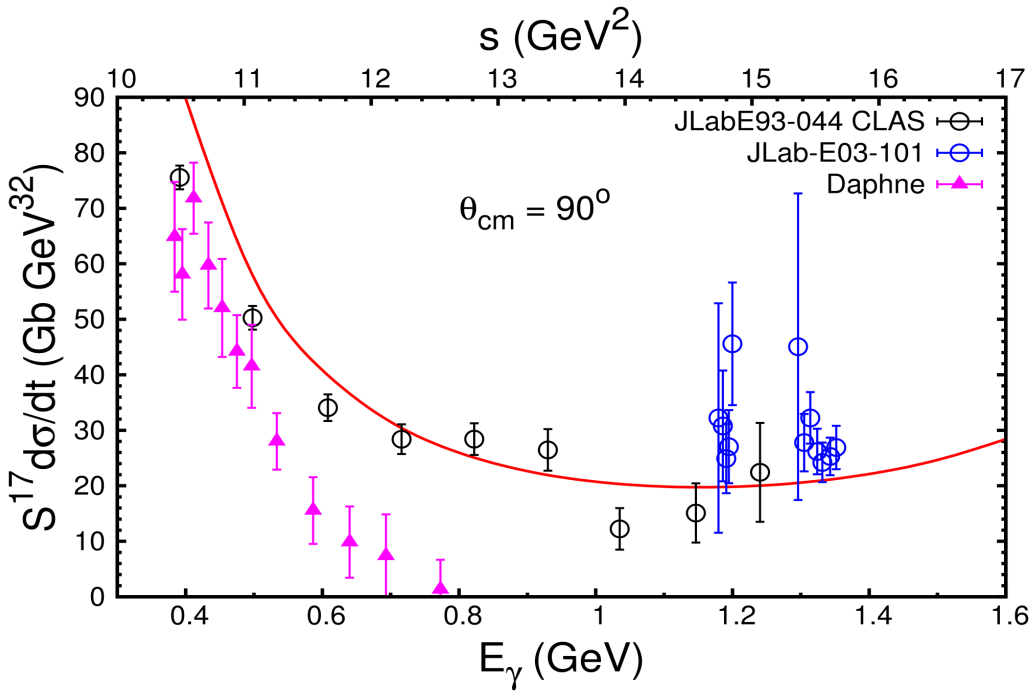


C. Grandos,MS, Phys. Rev. C 2009

Photodisintegration of ^{3}He: $\gamma +^3 He \rightarrow p + d$

$$\frac{d\sigma}{dt}(s,t) = \frac{2\pi^4\alpha}{3s'_{^3He}}\left(\frac{s'_N}{s'_{^3He}}\right)\frac{d\sigma_{pd}}{dt}(s,t_{pd}) \cdot m_N S^{NR}_{^3He/d}(p_{1z}=0)$$

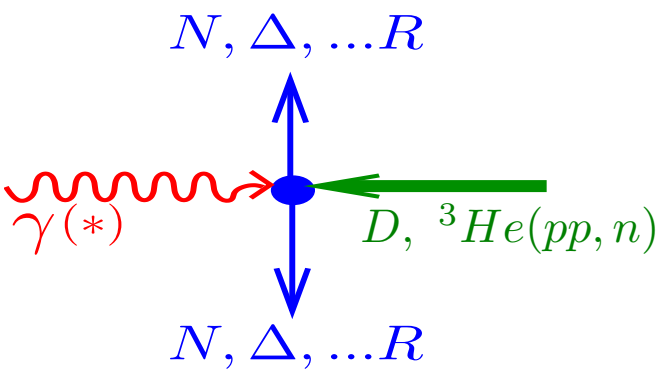
D. Maheswari,MS, 2017
Phys. Rev. C in press



I.Pomerantz , et al
Phys. Rev. Lett. 2013

What's Next:

1. Studying Hard Hadronic Processes



Break - up reactions to the deuteron break-up of other 2Baryons

$$\gamma + d \rightarrow \Delta + \Delta$$

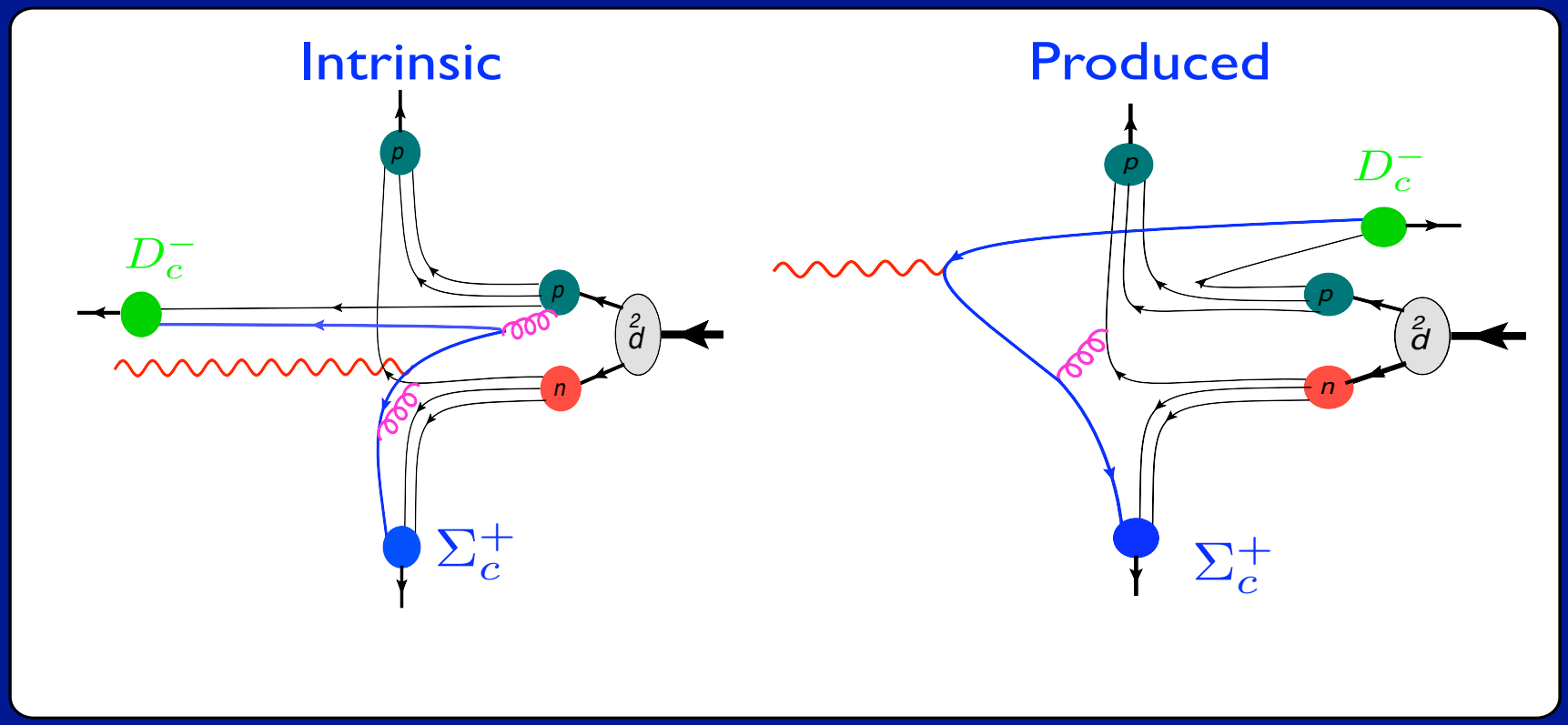
M. S., and C.Granados
Phys. Rev. C 2011

Extraction of hard Baryonic Helicity Amplitudes from Polarized measurement

2. Probing $(s\bar{s})$ or $(c\bar{c})$ component of the nucleon

Studying $c\bar{c}$ component in the deuteron

$$\gamma + d \longrightarrow p + \Sigma_c^+ + D_c^-$$



Outlook

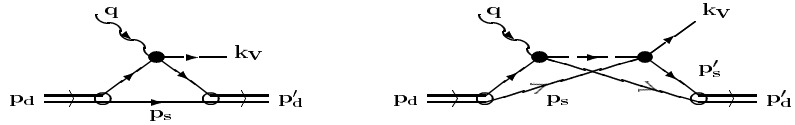
- (JLAB 4-6 GeV) : Experimentally established adequacy of QCD degrees of freedom in hard break-up of light nuclei

- (JLAB 4-6 GeV) : Hard Rescattering Mechanism consistent with major observations of the break-up reaction

- (JLAB 12 GeV) : Studying Hard Rescattering Mechanism of break up of light nuclei into baryonic resonances (including strangeness production)

III. Extracting J/Psi-N interaction near the threshold

- Vector meson photoproduction can be used to extract VN scattering cross section
- Experience from coherent vector meson photoproduction $\gamma + d \to V + d'$



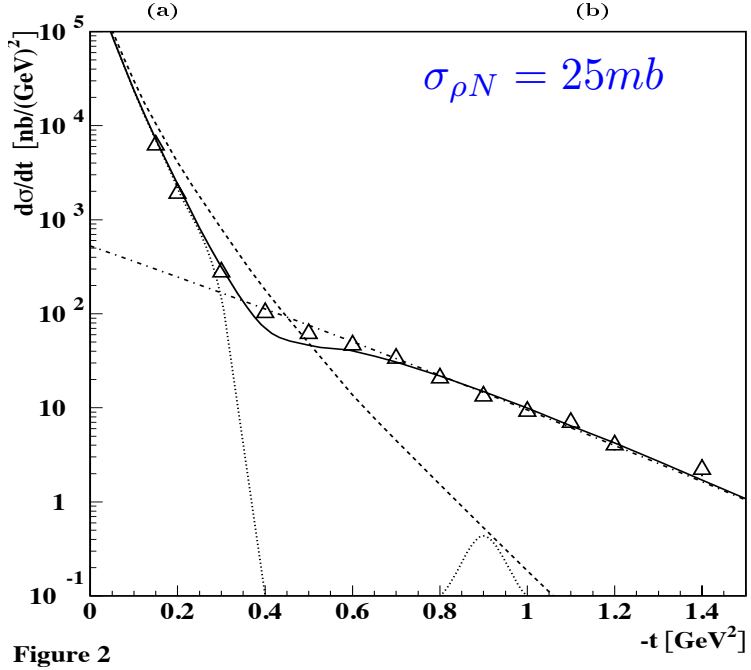
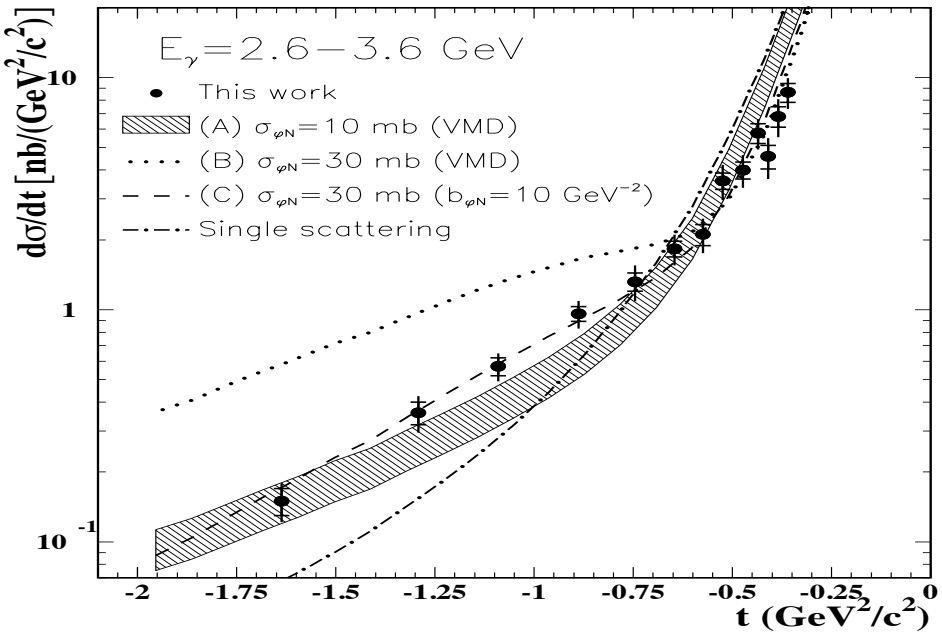


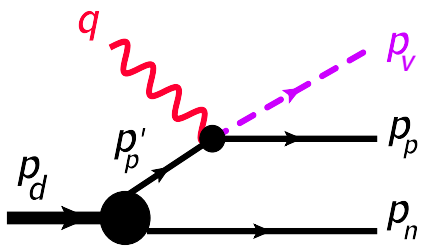
Figure 2

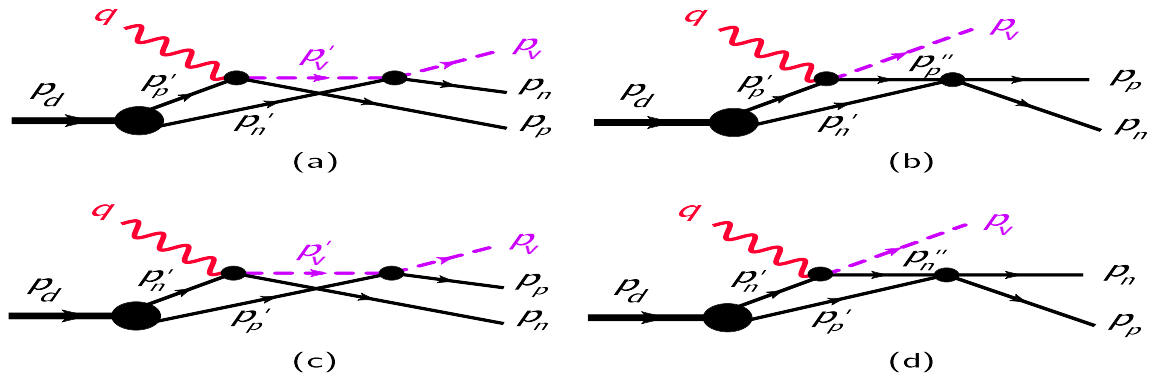


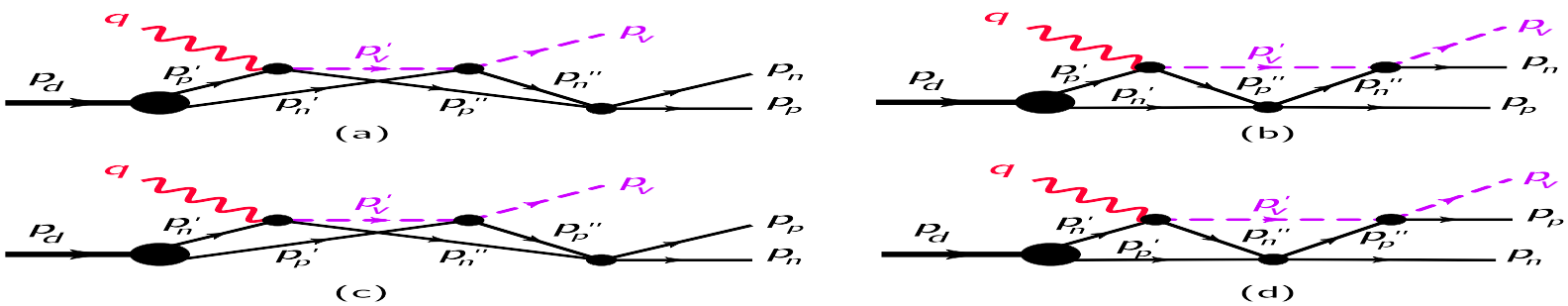
III. Extracting J/Psi-N interaction near the threshold

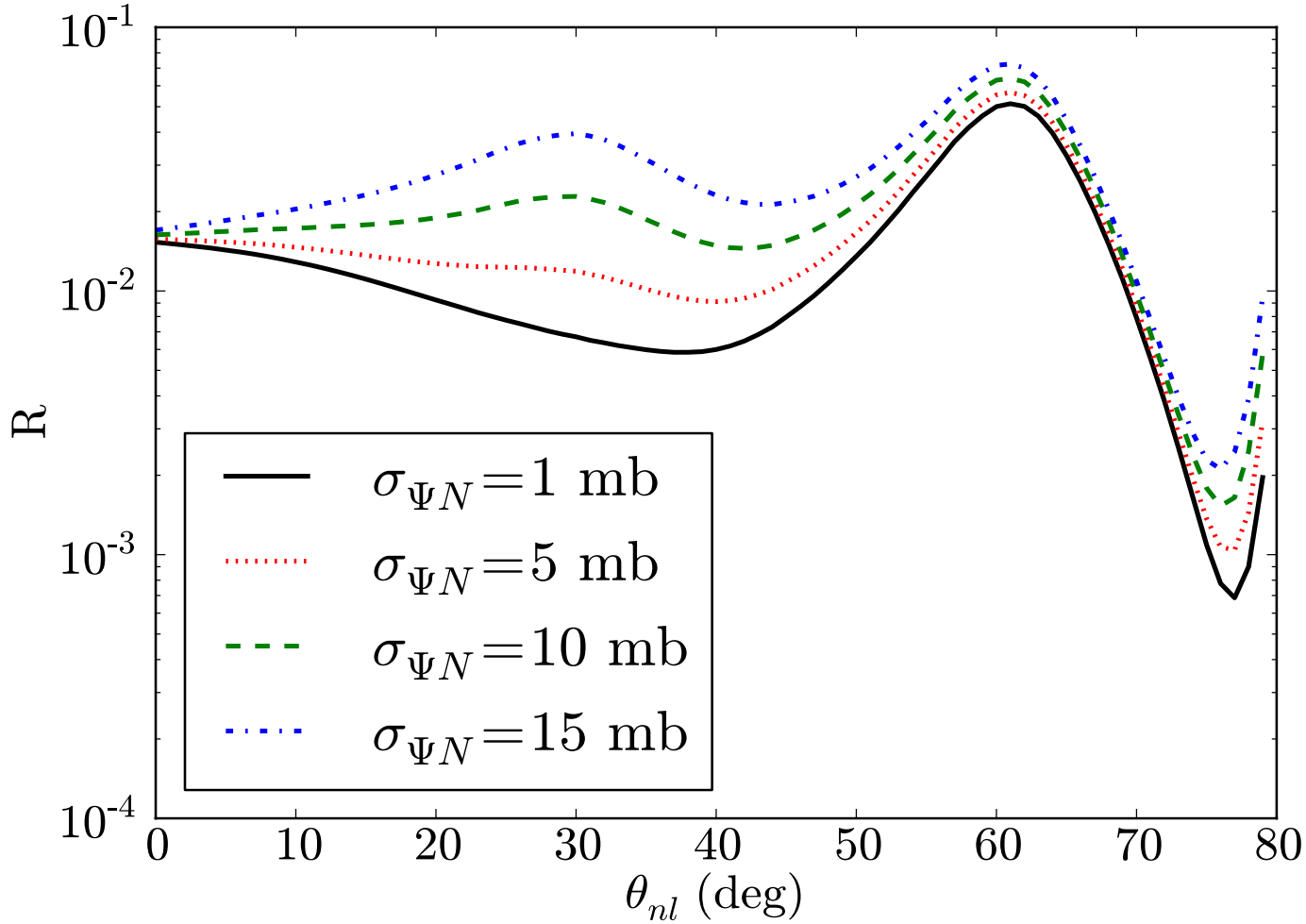
$$\gamma + d \rightarrow J/\Psi + p + n$$

Adam Freese, MS, PRC 2013








10^{-1}
10^{-2}
10^{-3}
10^{-4}
R
0
10
20
30
40
50
60
70
80
θ_{nl} (deg)
$\sigma_{\Psi N}$=1 mb
$\sigma_{\Psi N}$=5 mb
$\sigma_{\Psi N}$=10 mb
$\sigma_{\Psi N}$=15 mb

Outlook

- Vector Meson Production with deuteron break-up is an effective tools for extracting VN scattering cross section