Nuclear Forces at Short Distances and Stability of the Neutron Stars

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Flordia International University, Miami

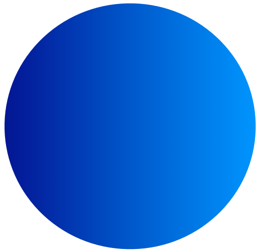
The Modern Physics of Compact Stars
Yerevan, September 17-21, 2008

- High Density Fluctuations in Nuclei

- What they can tell us about structure of Neutron Stars

High Energy Nuclear Physics

Structure of the Nucleon

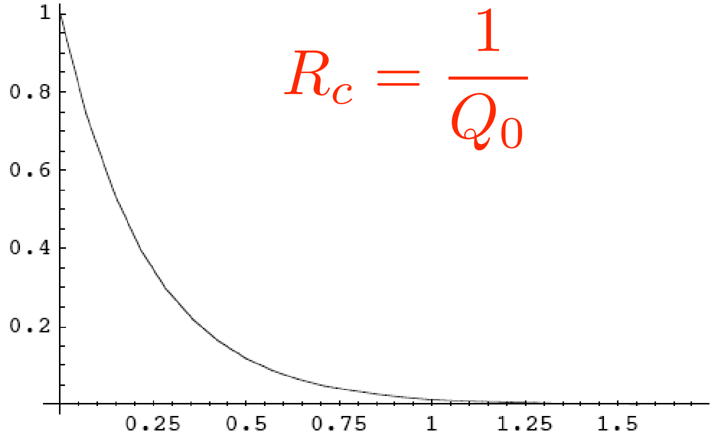


$$r_N \approx 0.86 fm$$

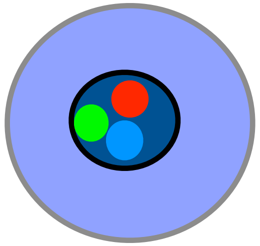
$$G_E = \frac{1}{(1+\frac{q^2}{Q_0^2})^2}$$

$$\rho(r) = \frac{Q_0^3}{8\pi} e^{-Q_0 r}$$

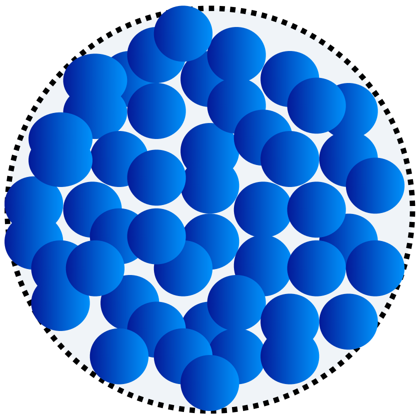
$$Q_0 \approx 4.27 fm^{-1}$$



$$R_c = \frac{1}{Q_0}$$

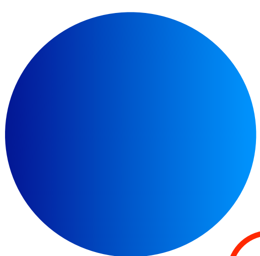


Nuclear Matter



$$\rho_0 = 0.17 fm^{-3}$$

Electromagnetic Interaction



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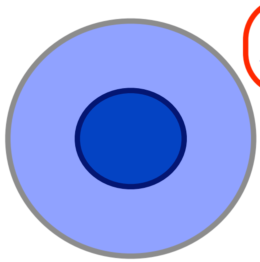
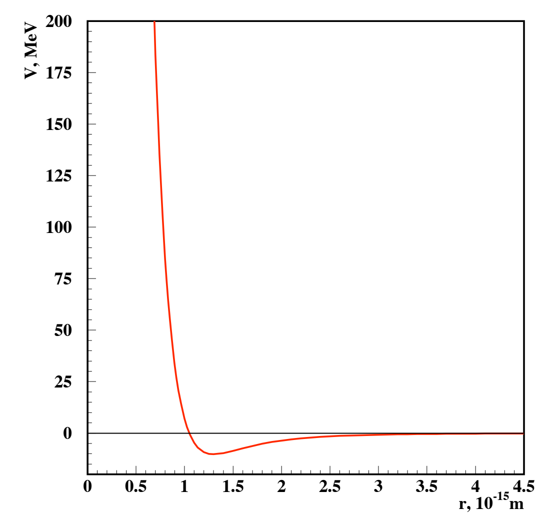
Strong Interaction



$R_c \sim 0.3 - 0.5 Fm$

$$R_c \approx \frac{1}{Q_0}$$



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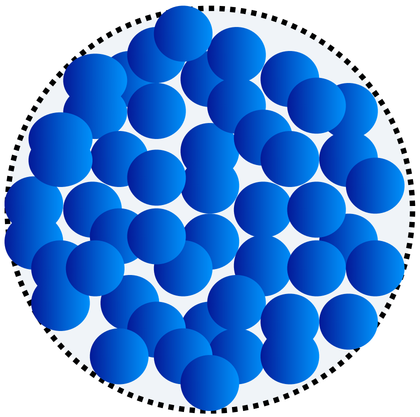

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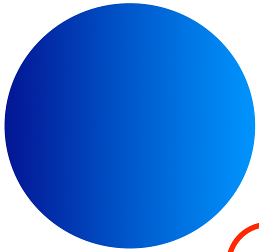

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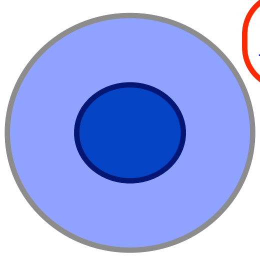

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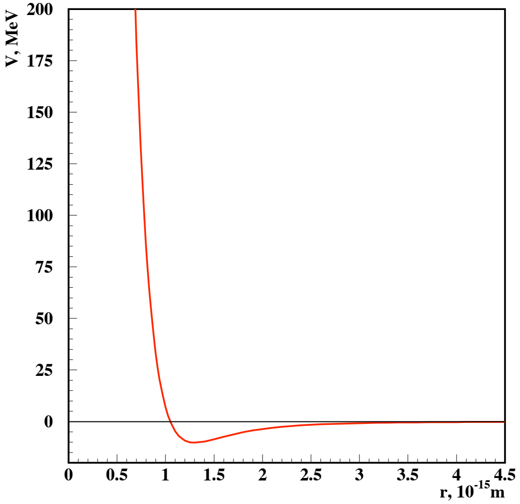

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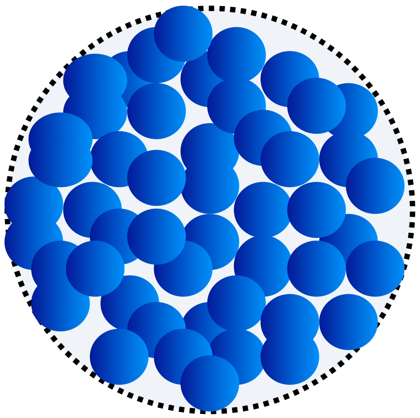

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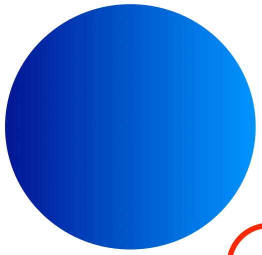

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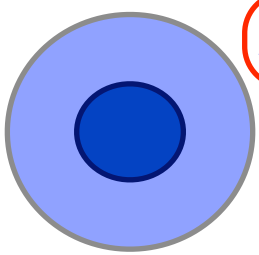

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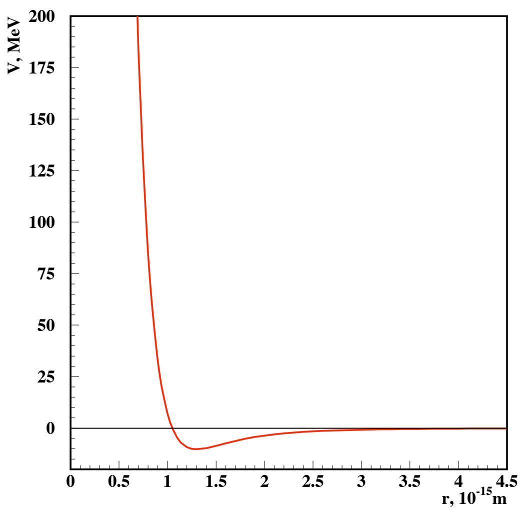


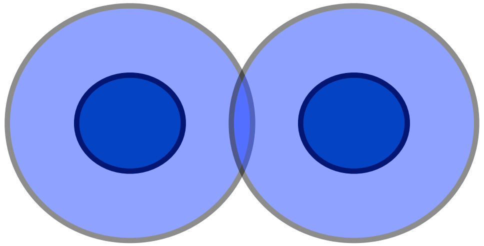
$$\rho(r) = \frac{Q_0^3}{8\pi} e^{-Q_0 r}$$

$$Q_0 \approx 4.27 fm^{-1}$$

$$\frac{\rho(r{=}0.3fm)}{\rho_0} = 5.1$$

$$\frac{\rho(r{=}0.68fm)}{\rho_0} = 1$$

$$\frac{\rho(r{=}0.84fm)}{\rho_0} = 0.5$$



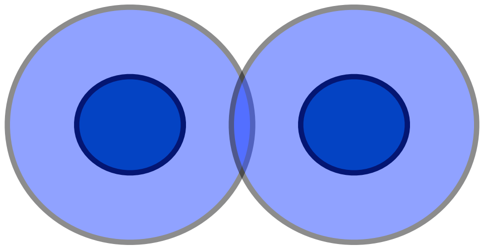
Quark Degrees of Freedom

$$r \sim 0.5 \div 03 fm$$

$$\frac{\rho}{\rho_0} = 4 - 10$$

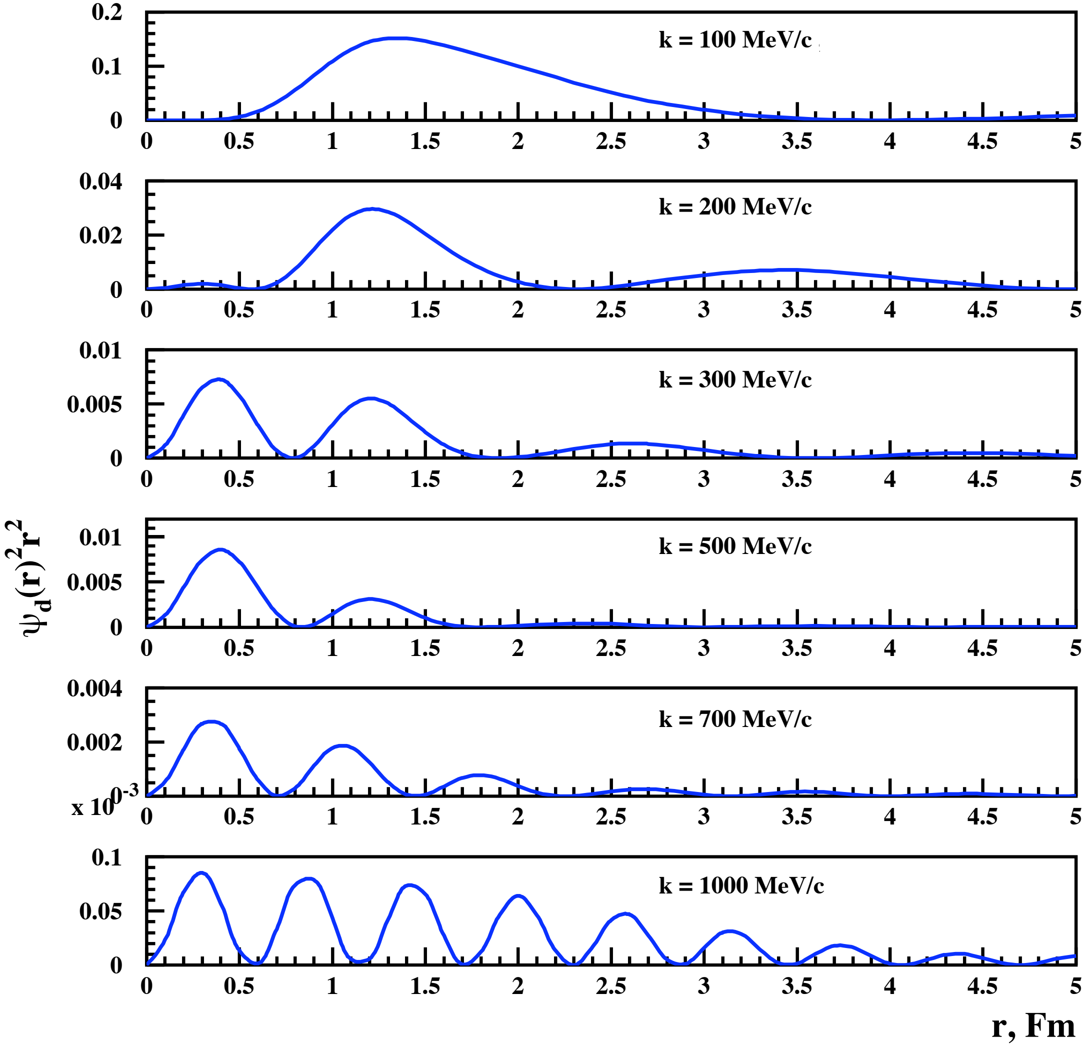
Neutron Stars

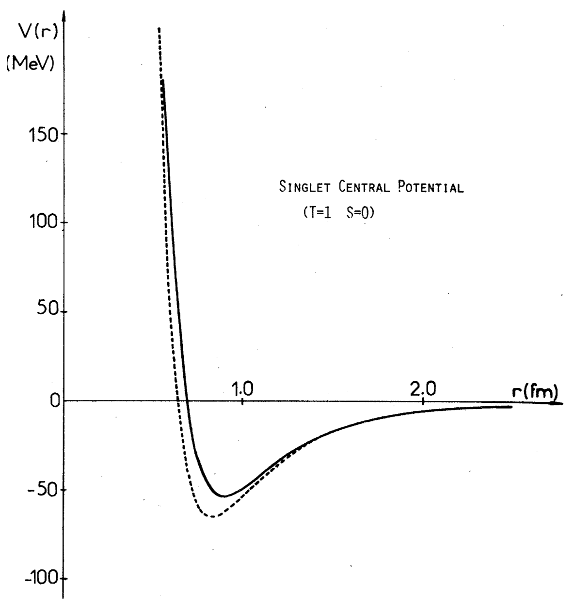
How to get nucleons close together



Probing at large relative momenta

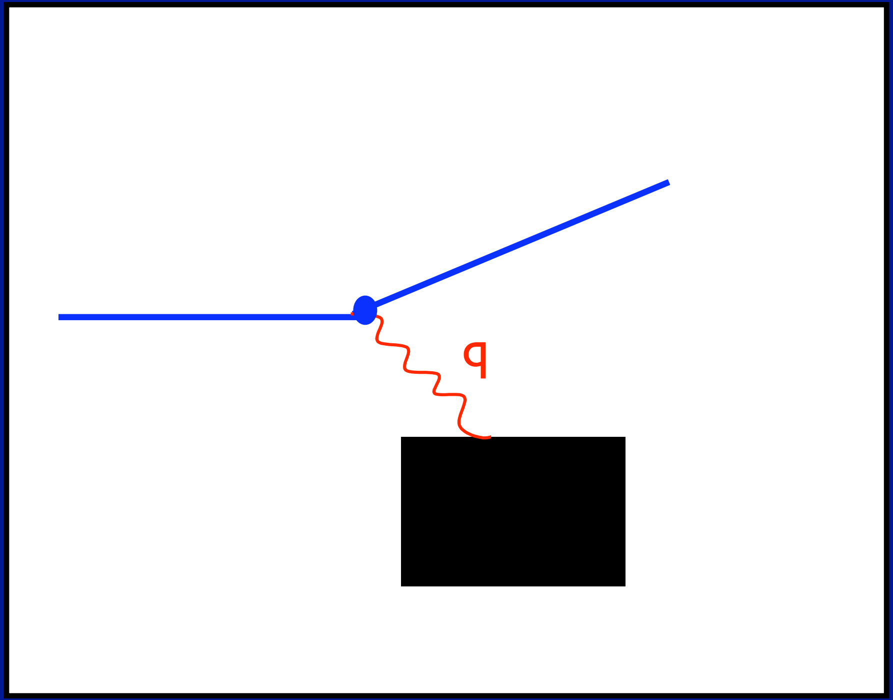
$$r \sim \frac{1}{k}$$





Inclusive Scattering

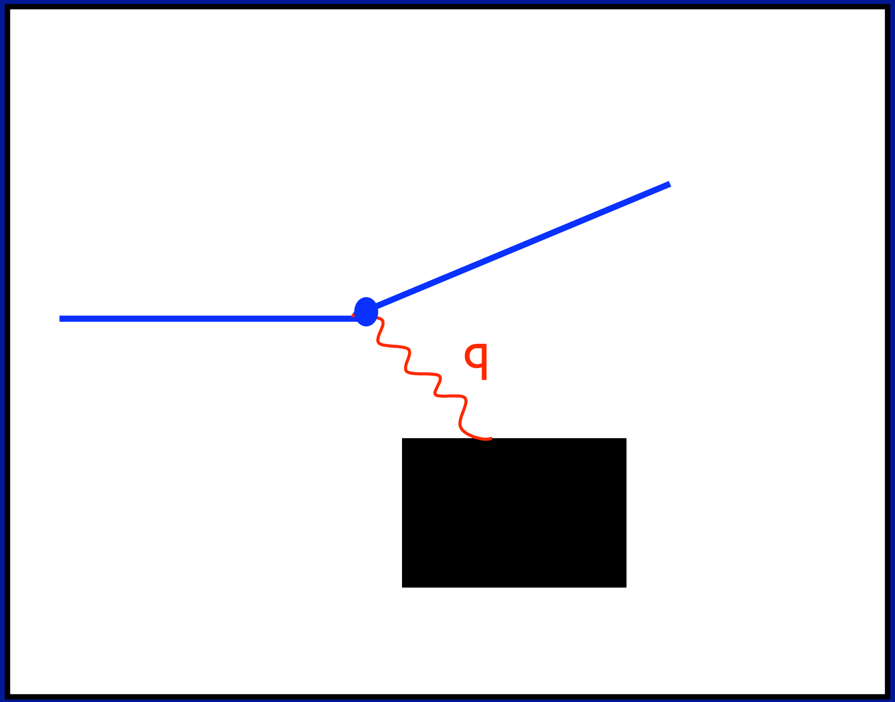
Inclusive Scattering From the Black Box



What we can learn
about BB without detecting it ?

Inclusive Scattering

Inclusive Scattering From the Black Box



What we can learn about BB without detecting it ?

- Black Box has constituents

Inclusive Scattering

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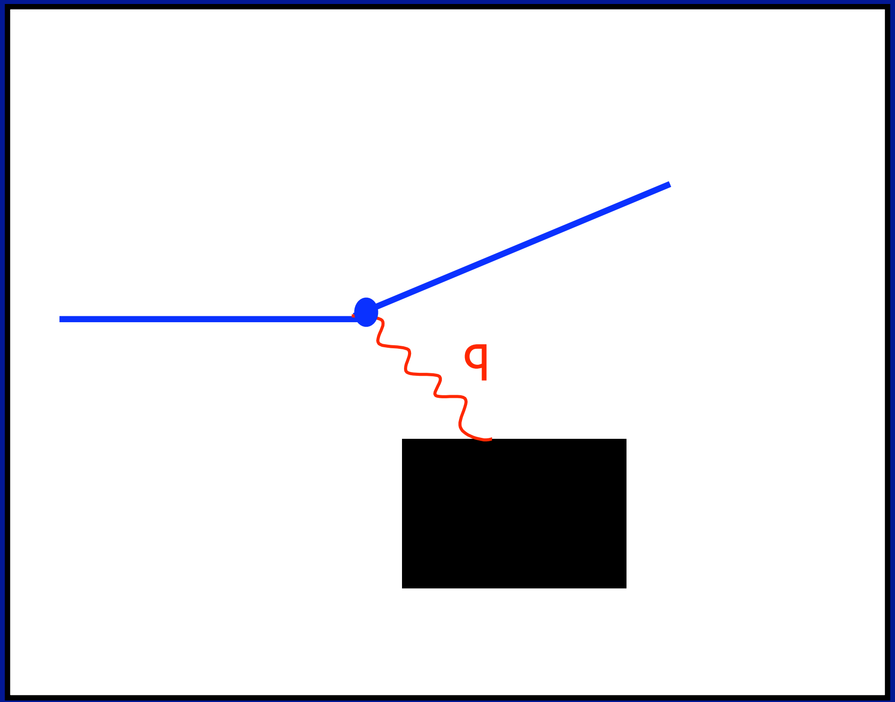

What we can learn about BB without detecting it ?

- Black Box has constituents
- Probe knocks-out one of such constituents without breaking it

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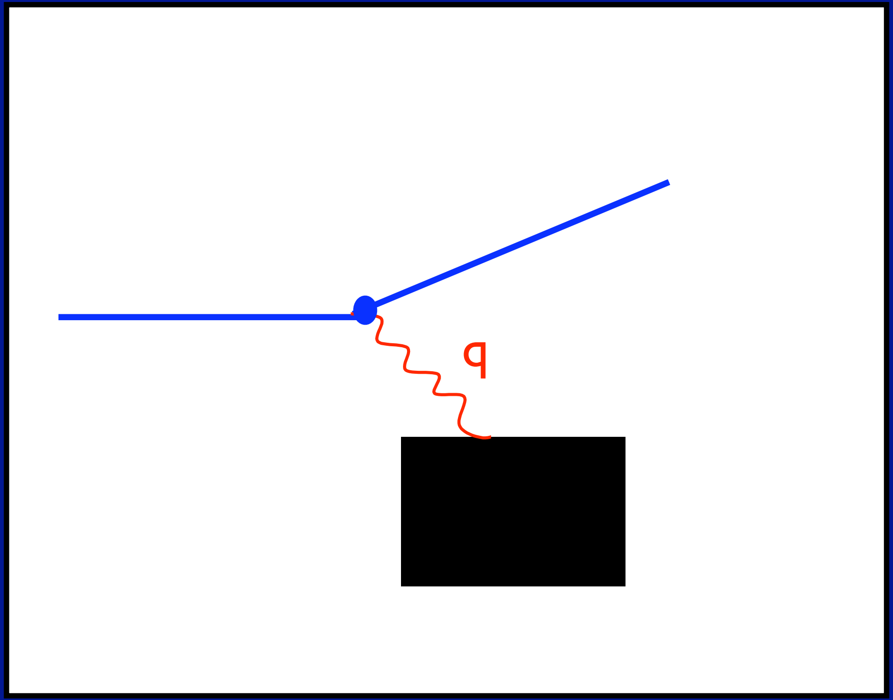

What we can learn about BB without detecting it ?

- Black Box has constituents
- Probe knocks-out one of such constituents without breaking it
- Remnant of the BB was a spectator to this action

$$p_i = P_{BB} - P_R$$

$$(q + p_i)^2 = m_c^2$$

$$-Q^2 + 2qp_i + m_i^2 = m_c^2$$

$$-Q^2 + q_+ p_{i-} + q_- p_{i+} + m_i^2 = m_c^2$$

$$p_{i-} = \frac{Q^2}{q_+} - \frac{q_-}{q_+} p_{i+} + \frac{m_c^2 - m_i^2}{q_+}$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$z || q$$

$$p_{i\pm} = E_i \pm p_{iz}$$

$$q_\pm = q_0 \pm q$$

$$\frac{Q^2}{q_+} = fixed$$

$$q_0 \longrightarrow \infty$$

$$q_+ \longrightarrow 2q_0$$

$$\frac{q_-}{q_+} = -\frac{fixed}{q_+} \longrightarrow 0$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$p_{i-} = ?$$

$$\frac{p_{i-}}{P_{BB-}}$$

$$\frac{p_{i-}}{P_{BB-}} \Big|_{LAB} = \frac{Q^2}{2q_0 M_{BB}}$$

$$\frac{p_{i-}}{P_{BB-}} \Big|_{IMF} = \left(\frac{E_i + p_i^z}{E_{BB} + P_{BB}^z} \right)_{IMF} \approx \left(\frac{p_i^z}{P_{BB}^z} \right)_{IMF}$$

$$p_{i\perp} \ll p_{iz}^{IMF}$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$p_{i-} = ? \longrightarrow \frac{p_{i-}}{P_{BB-}}$$

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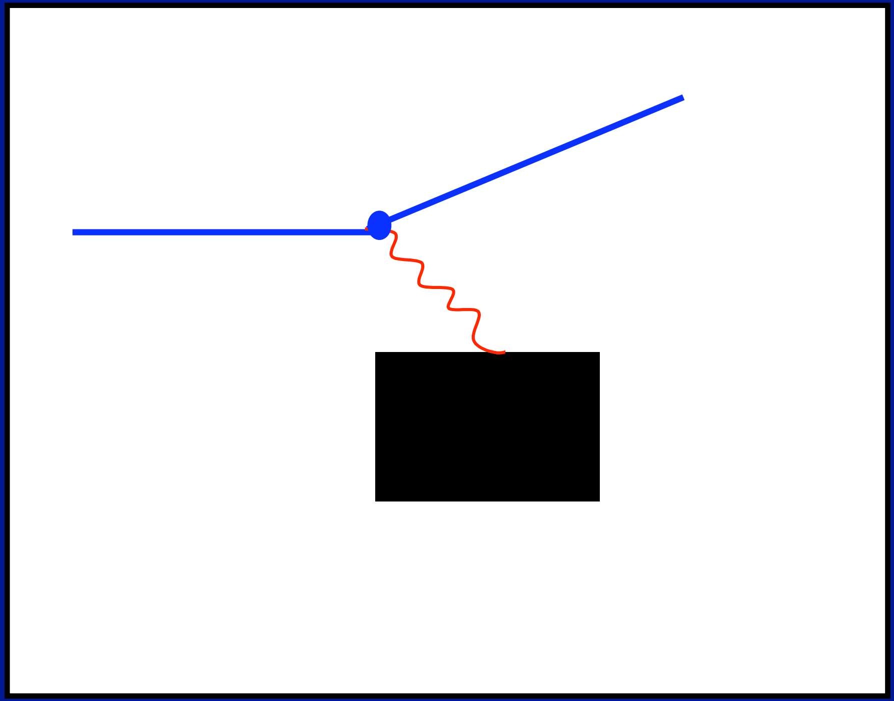
Invariant with respect to Lorentz transformation in z

$$\frac{p_{i-}}{P_{BB-}} |_{LAB} = \frac{Q^2}{2q_0 M_{BB}}$$

$$\frac{p_{i-}}{P_{BB-}} |_{IMF} = \left(\frac{E_i + p_i^z}{E_{BB} + P_{BB}^z} \right)_{IMF} \approx \left(\frac{p_i^z}{P_{BB}^z} \right)_{IMF}$$

$$p_{i\perp} \ll p_{iz}^{IMF}$$

$$Y = \left(\frac{Q^2}{2q_0 M_{BB}} \right)_{LAB} = \left(\frac{p_{iz}}{P_{BBz}} \right)_{IMF}$$



$$\frac{\sigma_{e,BB}}{\sigma_{e,c}} \sim F(Y)$$

If BB = nucleon $Y \equiv x_{Bj} = \frac{Q^2}{2mq_0}$

knocked out constituent is quark

$$F(Y) = f(x_{Bj})$$

Quasi-Elastic Scattering

If BB = nucleus

knocked out constituent is quark

$$\alpha = A \cdot Y \approx \frac{Q^2}{2mq_0} \equiv x_{BJ}$$

IMF momentum fraction of nucleus carried by nucleon

Each nucleon in average carries $Y = \frac{1}{A}$ or $x_{Bj} = 1$

$$\frac{\sigma_{e,A}}{\sigma_{e,N}} \sim F(\alpha) \equiv \rho_A(\alpha)$$

Quasi-Elastic Scattering

If BB = nucleus

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$$\frac{\sigma_{e,A}}{\sigma_{e,N}} \sim F(\alpha) \equiv \rho_A(\alpha)$$

Correlation Parameter

$$\alpha_i = A\frac{E_i - p_i^z}{E_A - p_A^z}$$

Momentum Fraction of Nucleus carried by the constituent nucleon

$\alpha_i > j$ corresponds to j-nucleons involved in the scattering

For finite Q2

$$x = \frac{\alpha - \frac{m_N^2 - m_i^2}{2mq_0}}{\left(1 + \frac{p_{i+}}{q_+}\right)\frac{2q_0}{q_+}}$$

signatures for short range correlations

$x > 1$ at least 2 nucleons are needed

$x > 2$ at least 3 nucleons are needed

$x > j$ at least j+1 nucleons are neede

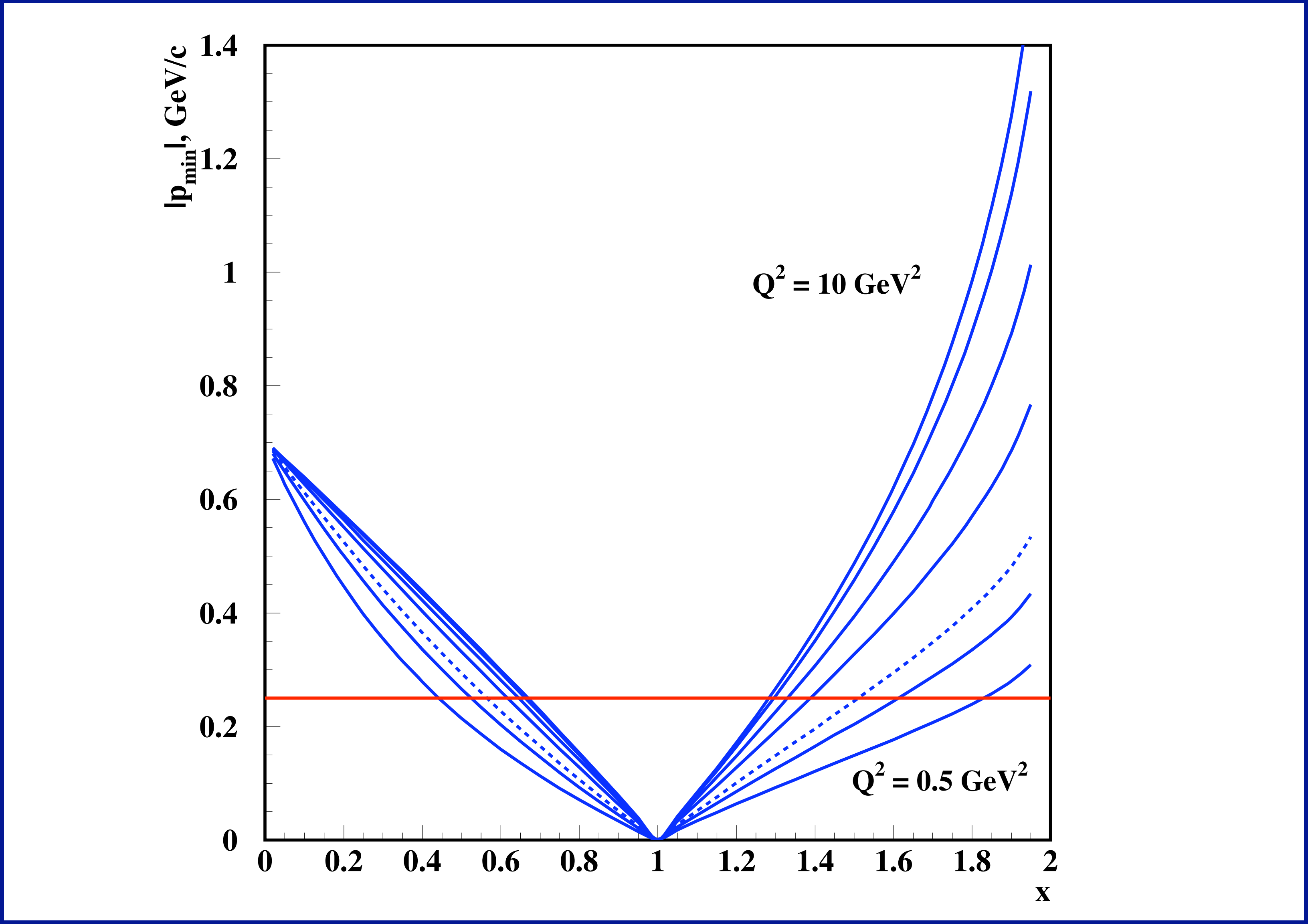
Transverse size of the probe $\sim 1/\sqrt{Q^2}$. $Q^2 \uparrow$

$x > 1$ if only 2 nucleons then $\frac{\sigma_A}{\sigma_D}$ scales

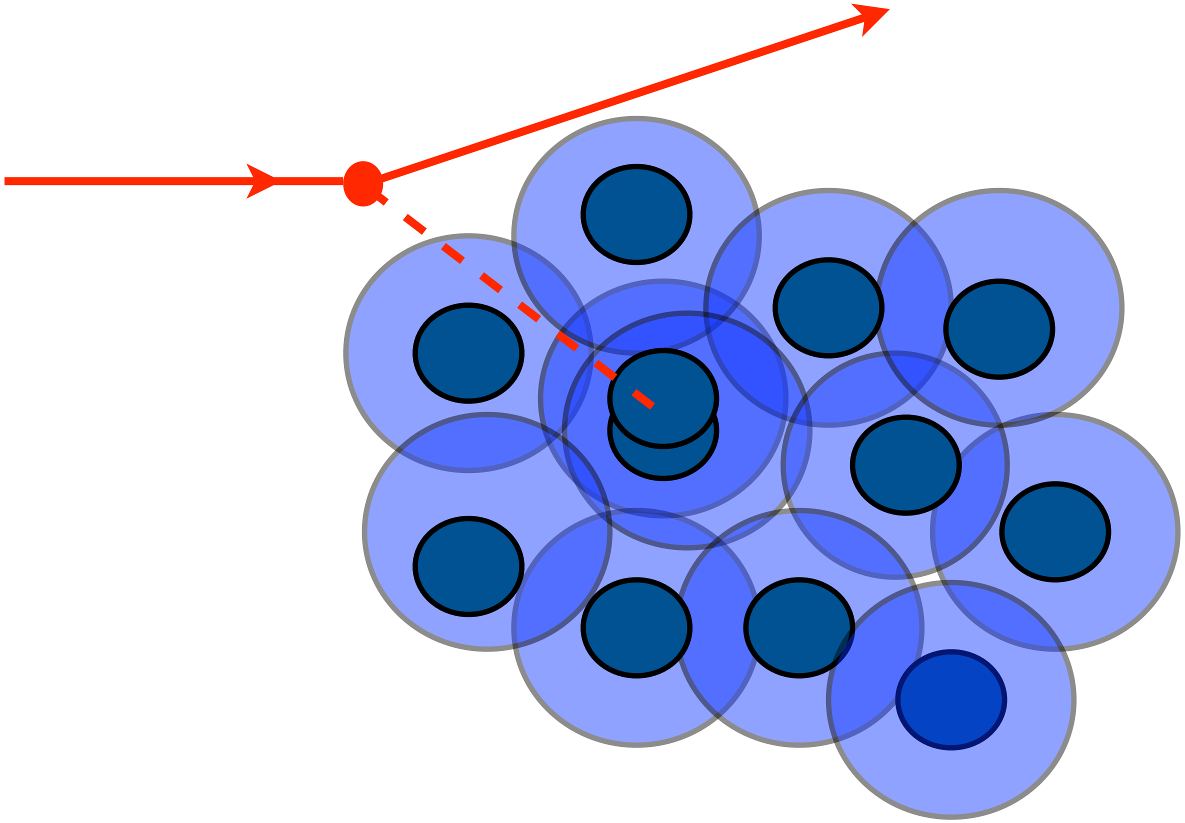
$x > 2$ if only 3 nucleons then $\frac{\sigma_A}{\sigma_{A=3}}$ scales

$x > j$ if only j+1 nucleons then $\frac{\sigma_A}{\sigma_{j+1}}$ scales

x> 1 is not automatically means 2N SRC one needs also large Q2



$q_+ \gg q_-$

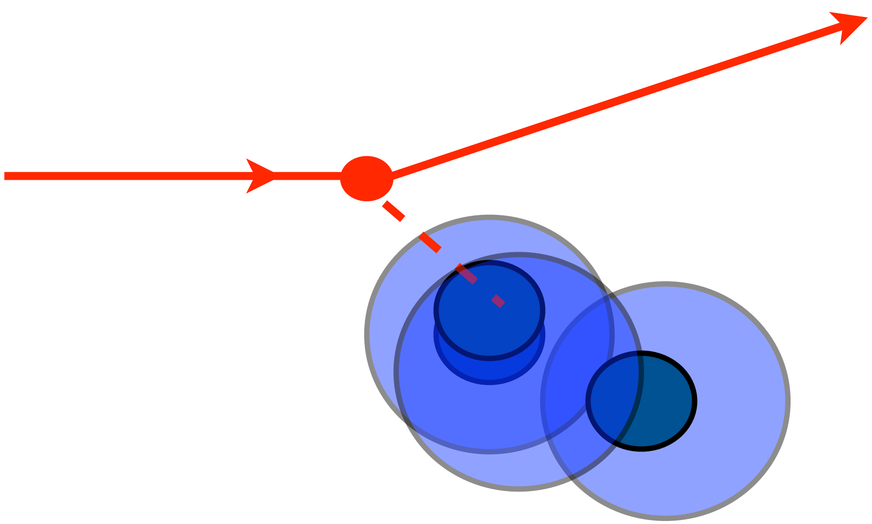


$p_1 \geq 300 - 350 MeV/c$

$x_{Bj} > 1.5 \quad Q^2 \geq 1.4 GeV^2$

$$^{12}C(e,e')X$$

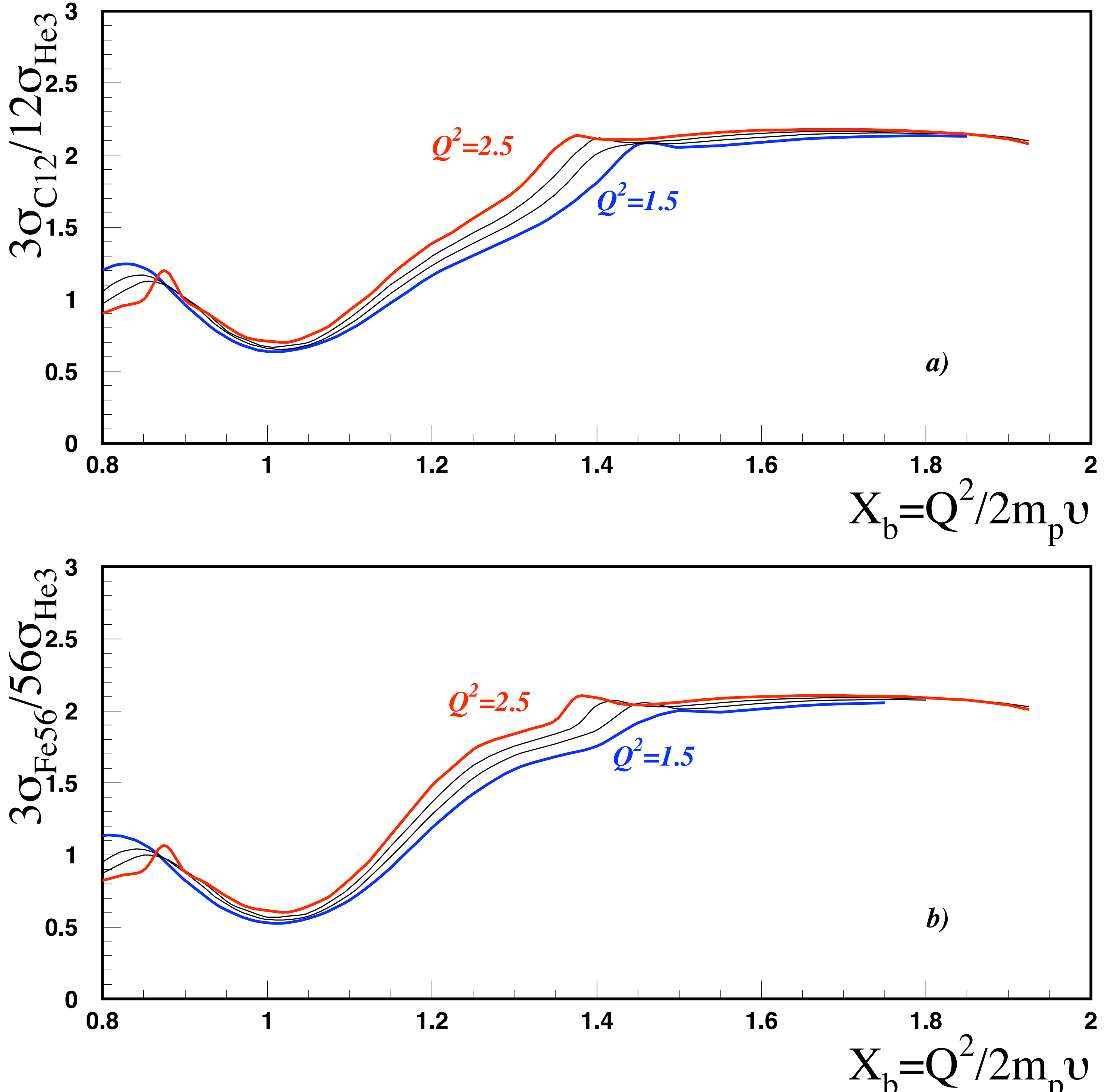
$$\frac{\sigma_{^{12}C}}{12}$$



$$^{3}He(e,e')X$$

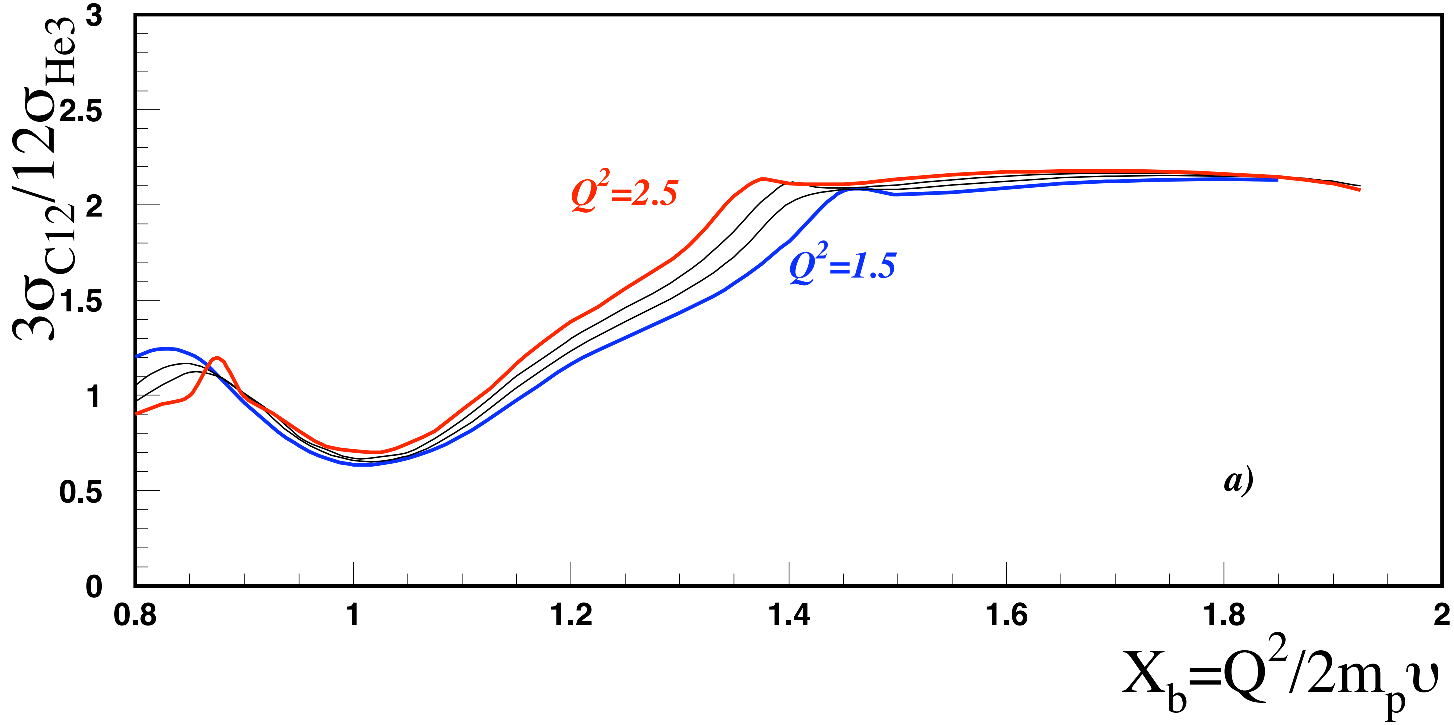
$$\frac{\sigma_{^{3}He}}{3}$$

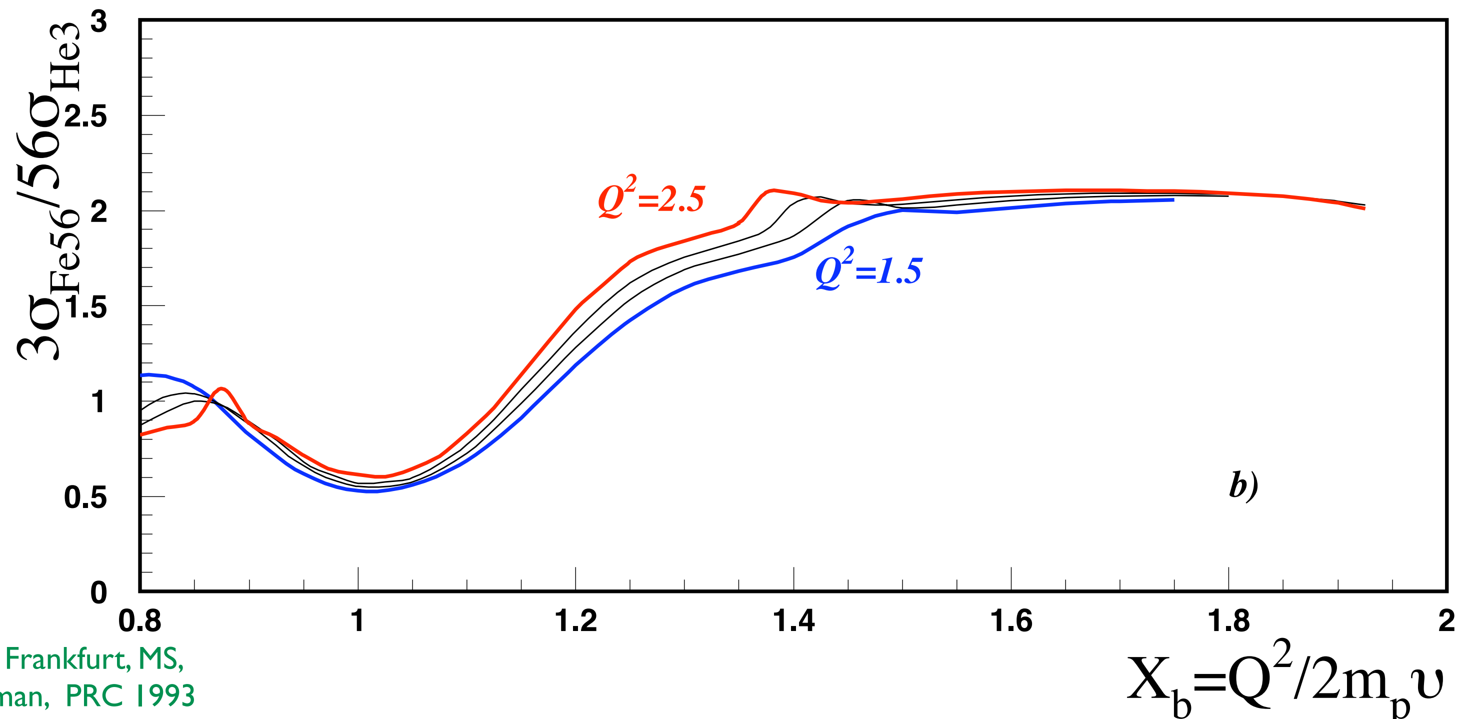
$A(e,e')$



$3\sigma_{C12}/12\sigma_{He3}$
Q^2=2.5
Q^2=1.5
a)
$X_b=Q^2/2m_p\upsilon$
$3\sigma_{Fe56}/56\sigma_{He3}$
Q^2=2.5
Q^2=1.5
b)
$X_b=Q^2/2m_p\upsilon$

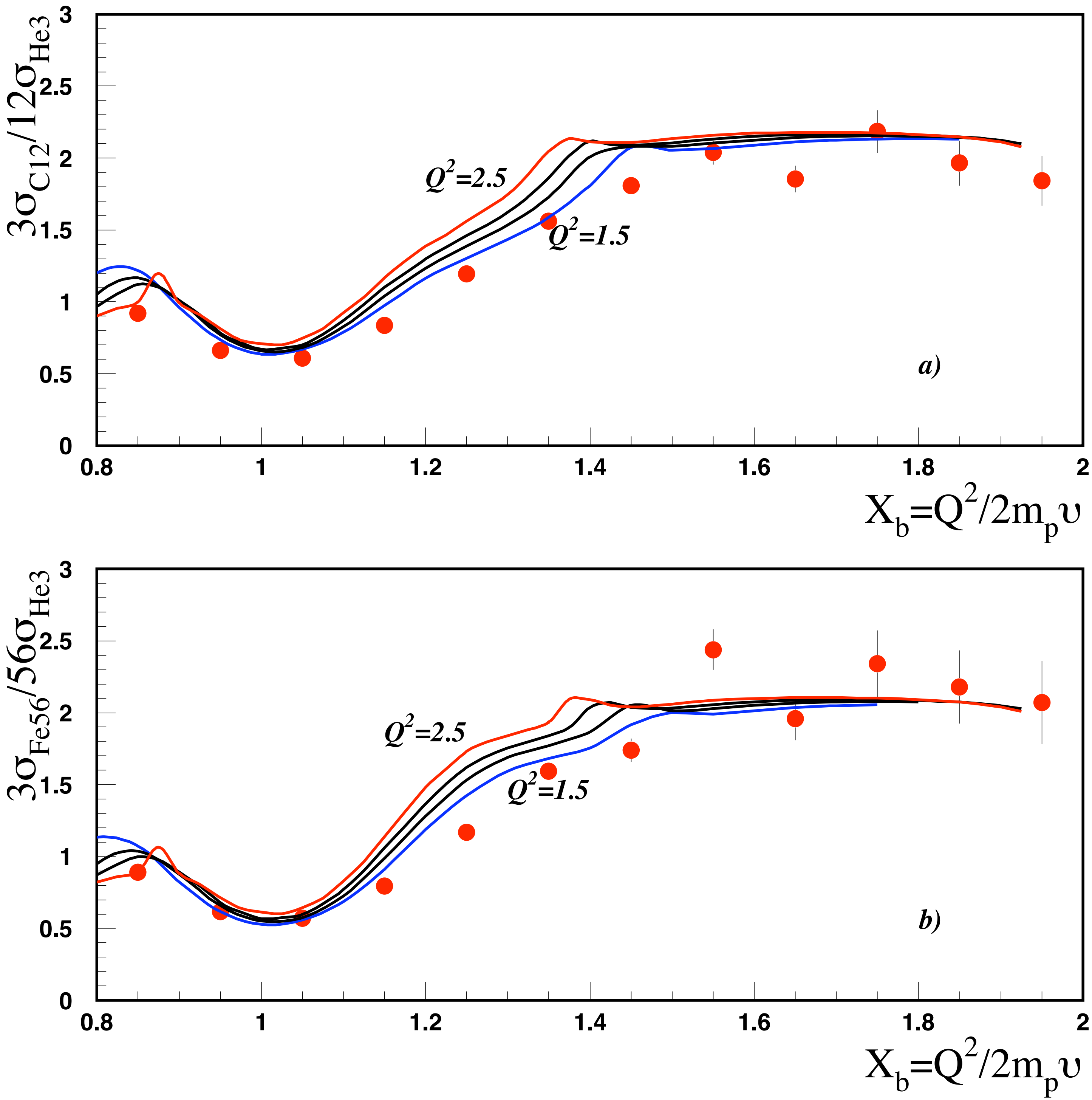
$A(e,e')$





Day, Frankfurt, MS,
Strikman, PRC 1993

$A(e,e')$



3
2.5
2
1.5
1
0.5
0
0.8
1
1.2
1.4
1.6
1.8
2
$3\sigma_{C12}/12\sigma_{He3}$
Q^2=2.5
Q^2=1.5
a)
$X_b=Q^2/2m_p\upsilon$
3
2.5
2
1.5
1
0.5
0
0.8
1
1.2
1.4
1.6
1.8
2
$3\sigma_{Fe56}/56\sigma_{He3}$
Q^2=2.5
Q^2=1.5
b)
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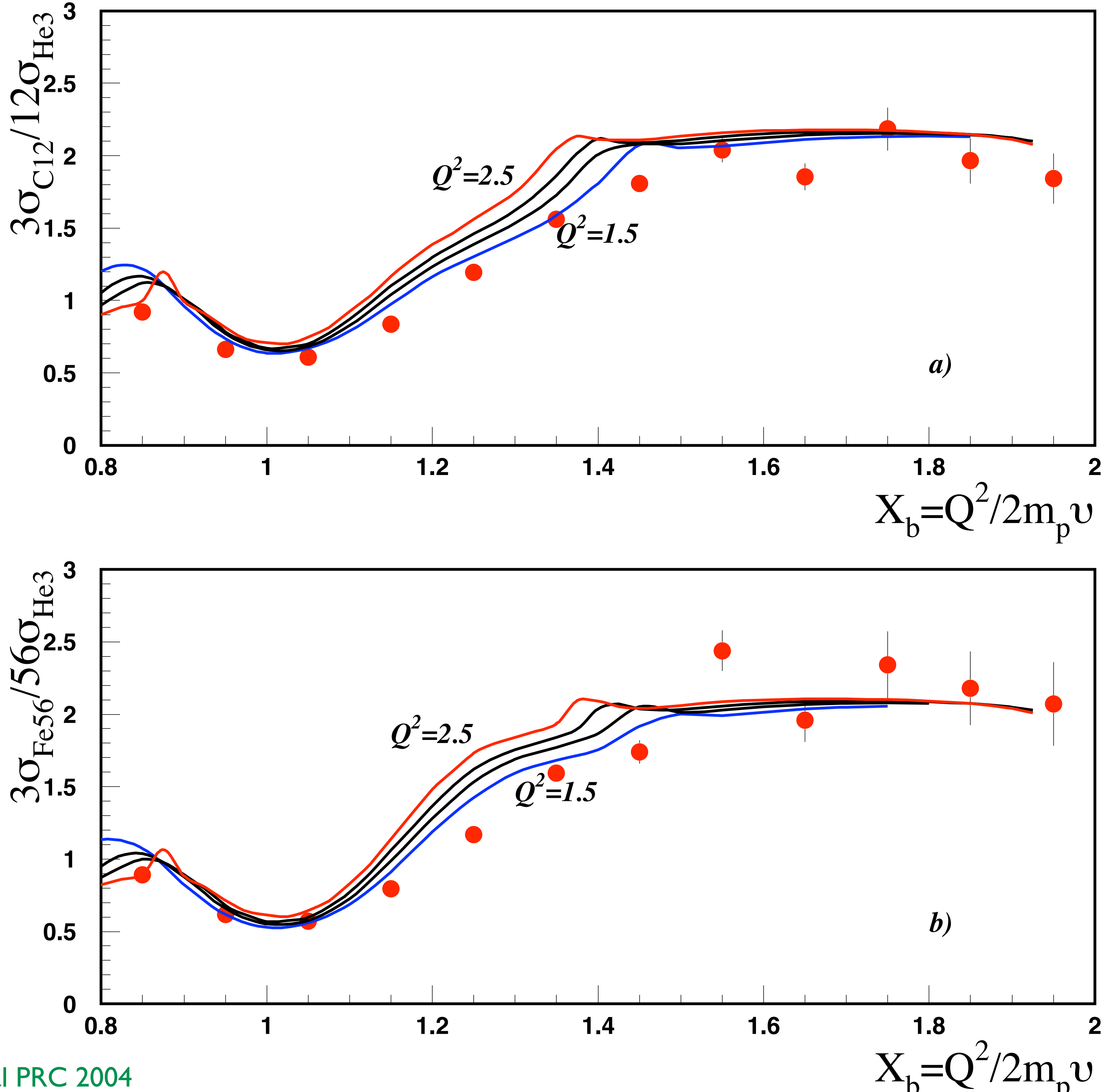
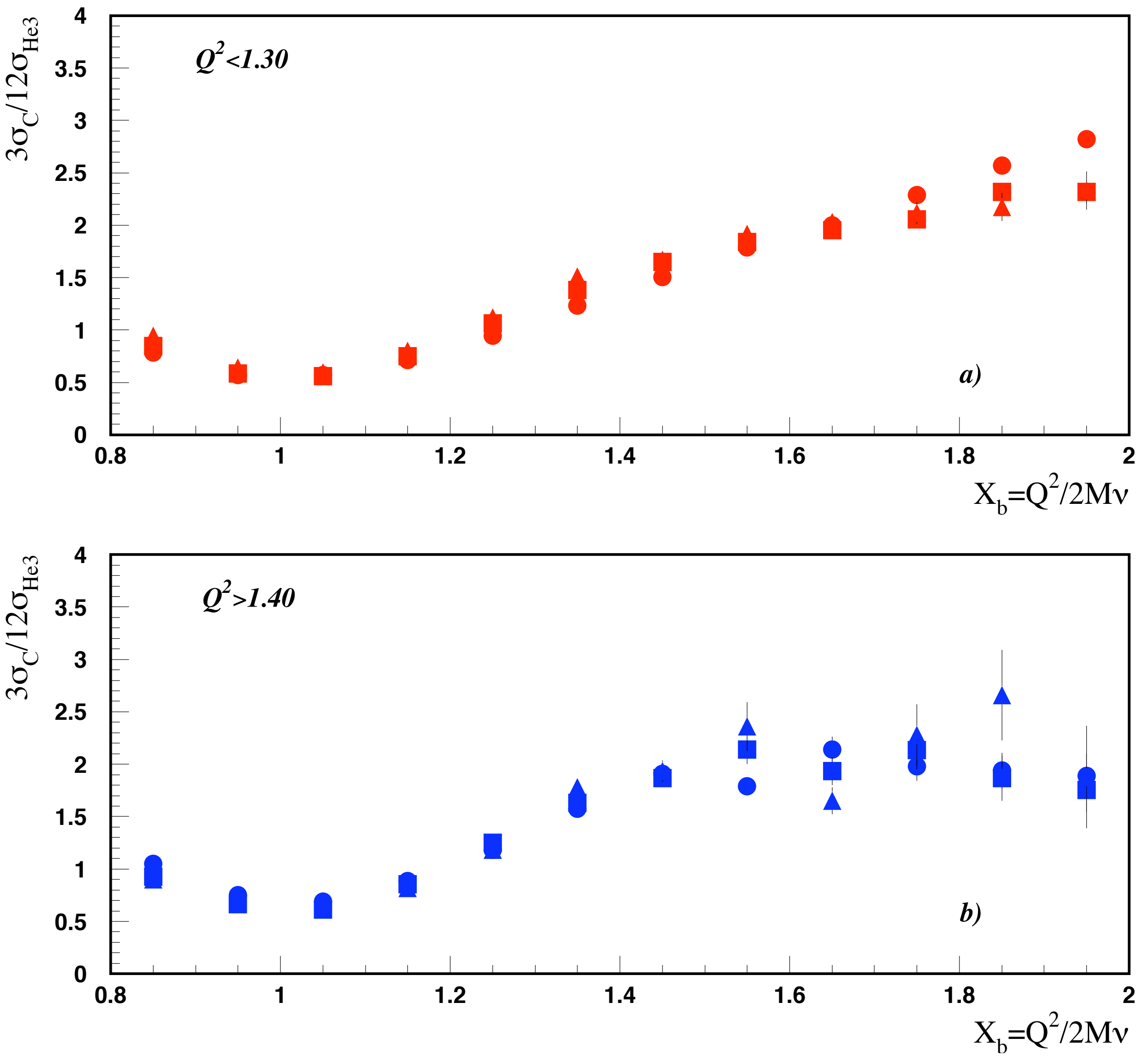
A(e,e')



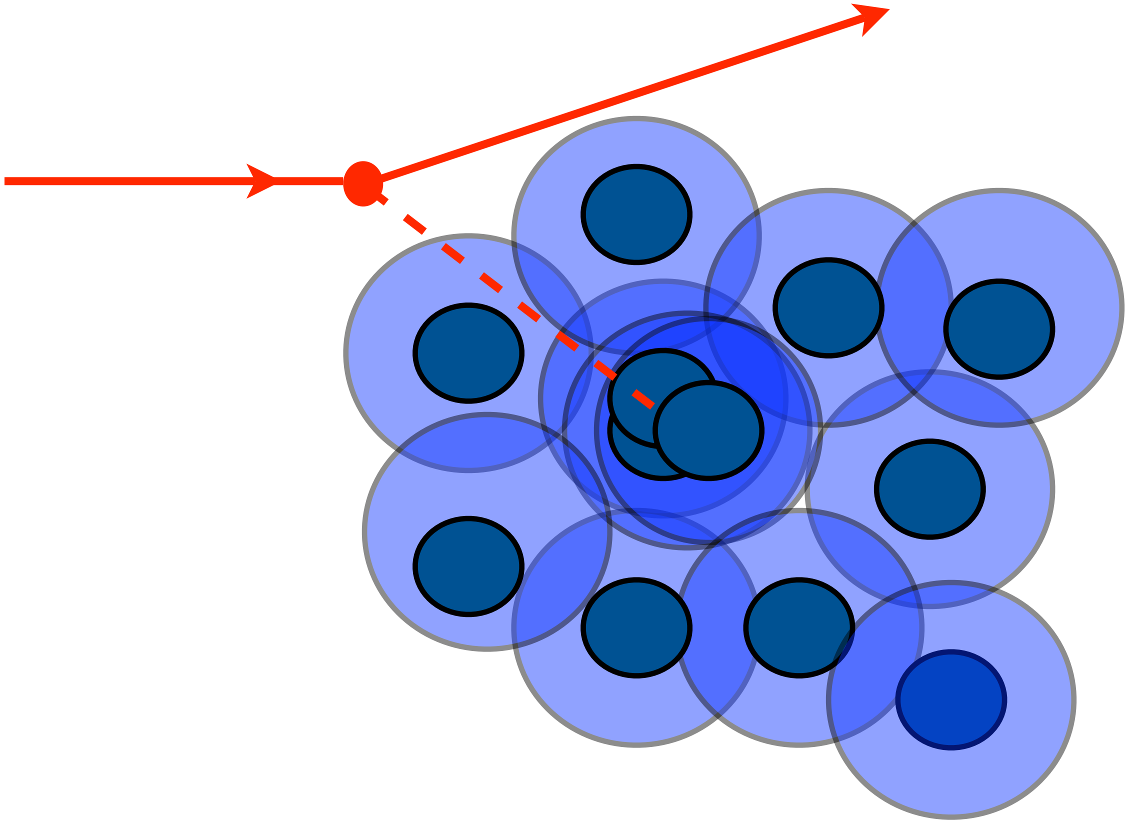
Egiyan, et al PRC 2004

$A(e,e')$



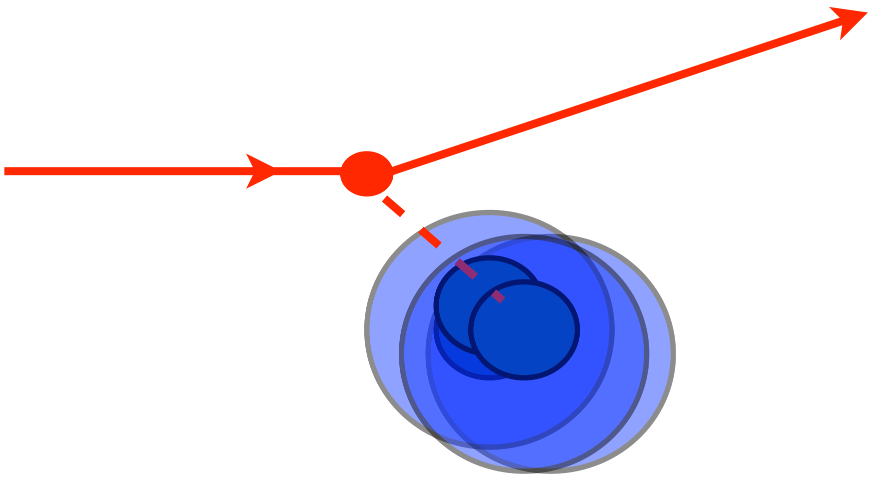
$3\sigma_C/12\sigma_{He3}$
$Q^2<1.30$
a)
$X_b=Q^2/2M\nu$
$3\sigma_C/12\sigma_{He3}$
$Q^2>1.40$
b)
$X_b=Q^2/2M\nu$

$x_{Bj} > 2$



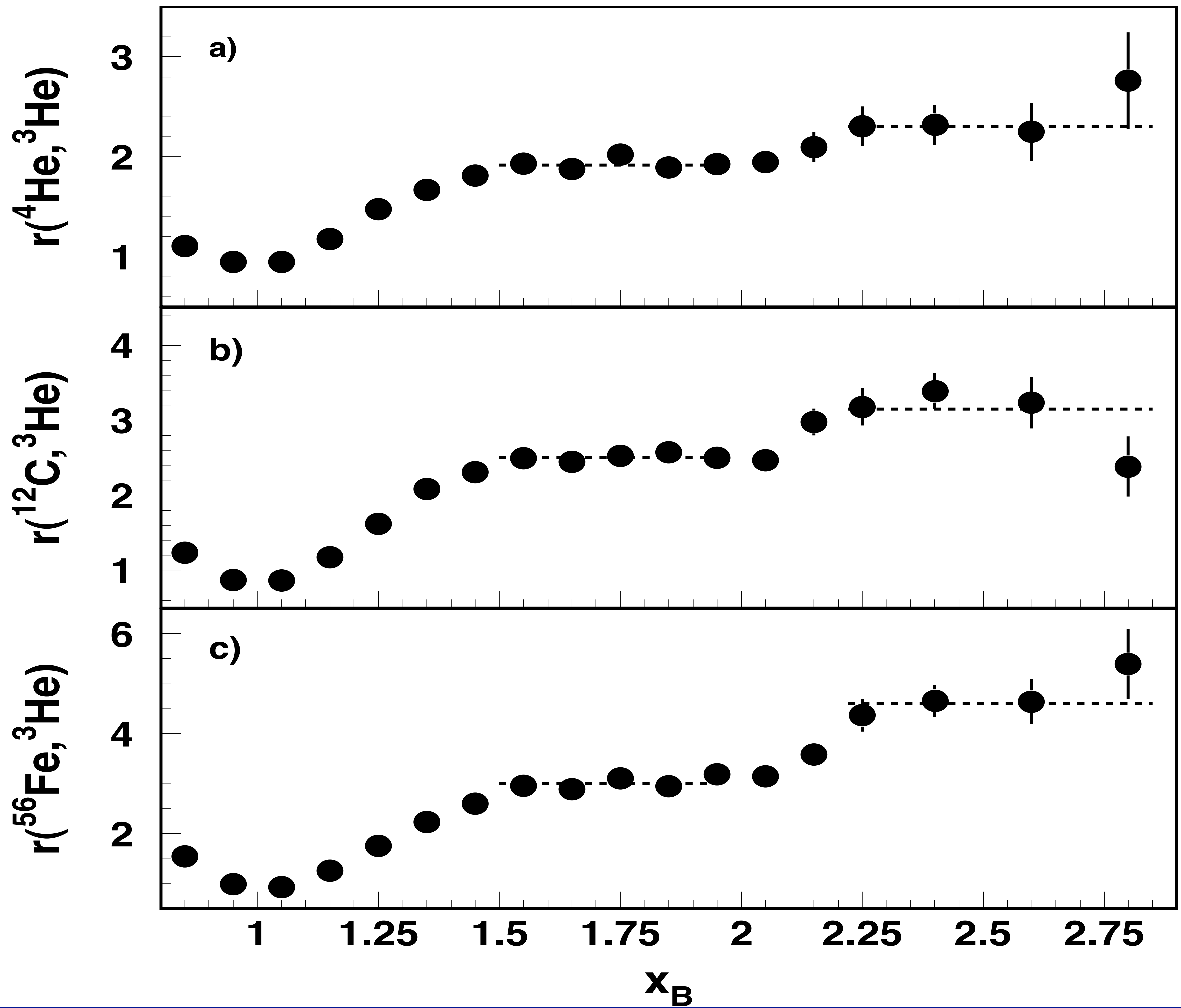
$^{12}C(e,e')X$

$$\frac{\sigma_{^{12}C}}{12}$$



$^{3}He(e,e')X$

$$\frac{\sigma_{^{3}He}}{3}$$



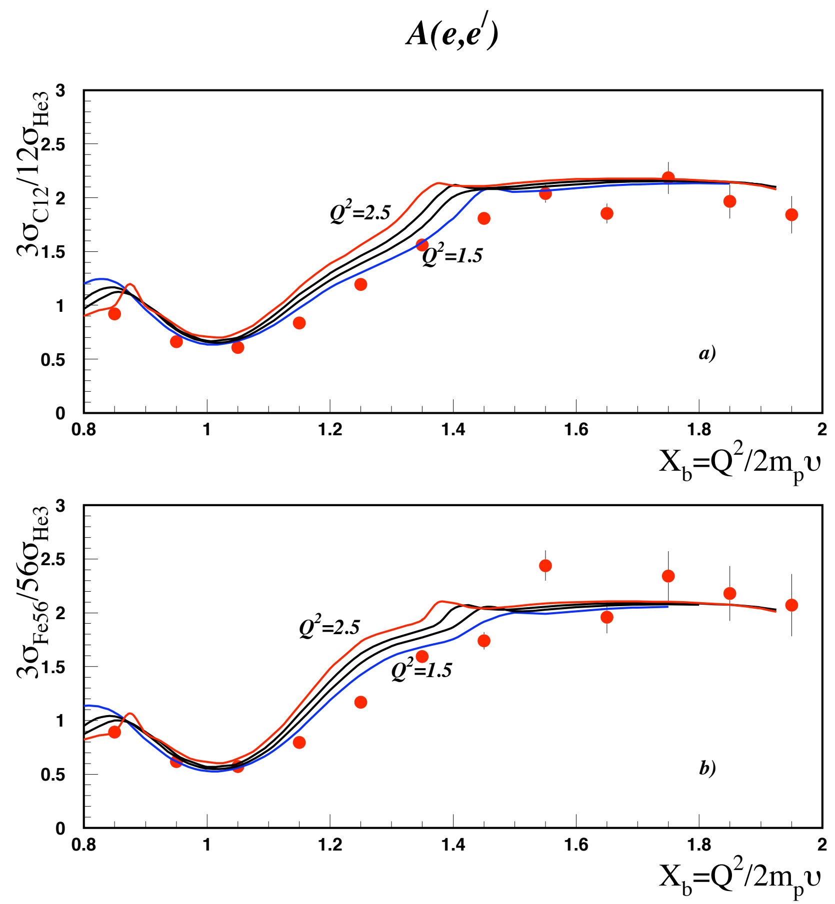
a)
b)
c)
r(^{4}He,^{3}He)
r(^{12}C,^{3}He)
r(^{56}Fe,^{3}He)
1
2
3
4
6
1.25
1.5
1.75
2.25
2.5
2.75
x_B

Meaning of the scaling values

Day, Frankfurt, MS, Strikman, PRC 1993

Frankfurt, MS, Strikman, IJMP A 2008

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



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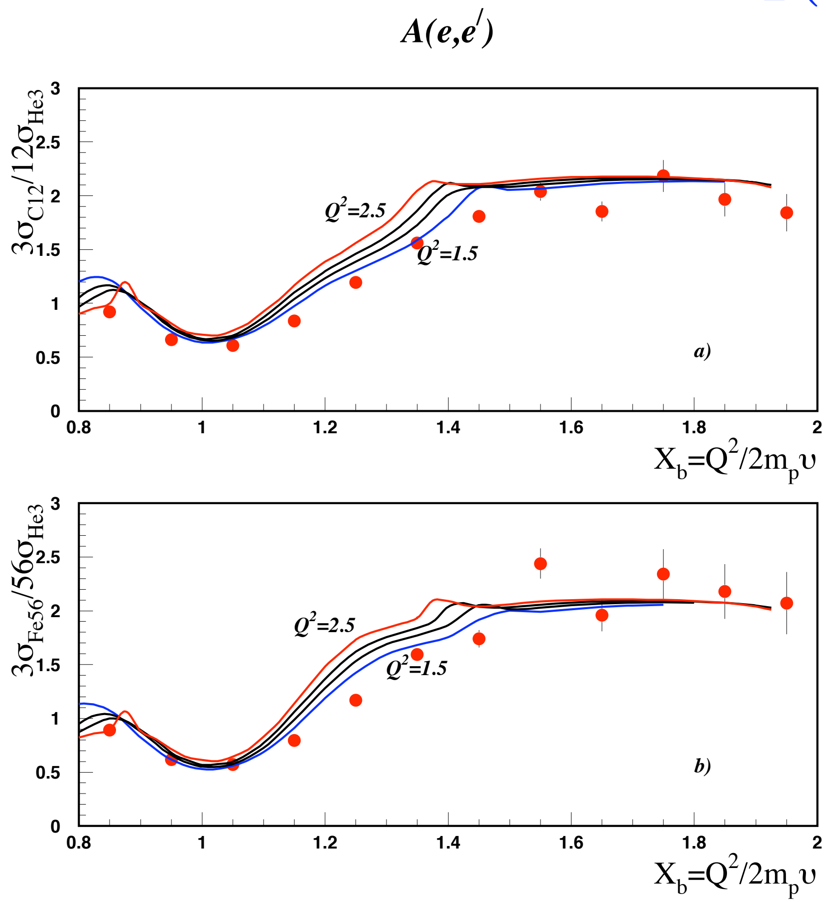
$$R = \frac{A_2 \sigma[A_1(e,e')X]}{A_1 \sigma[A_2(e,e')X]}$$

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



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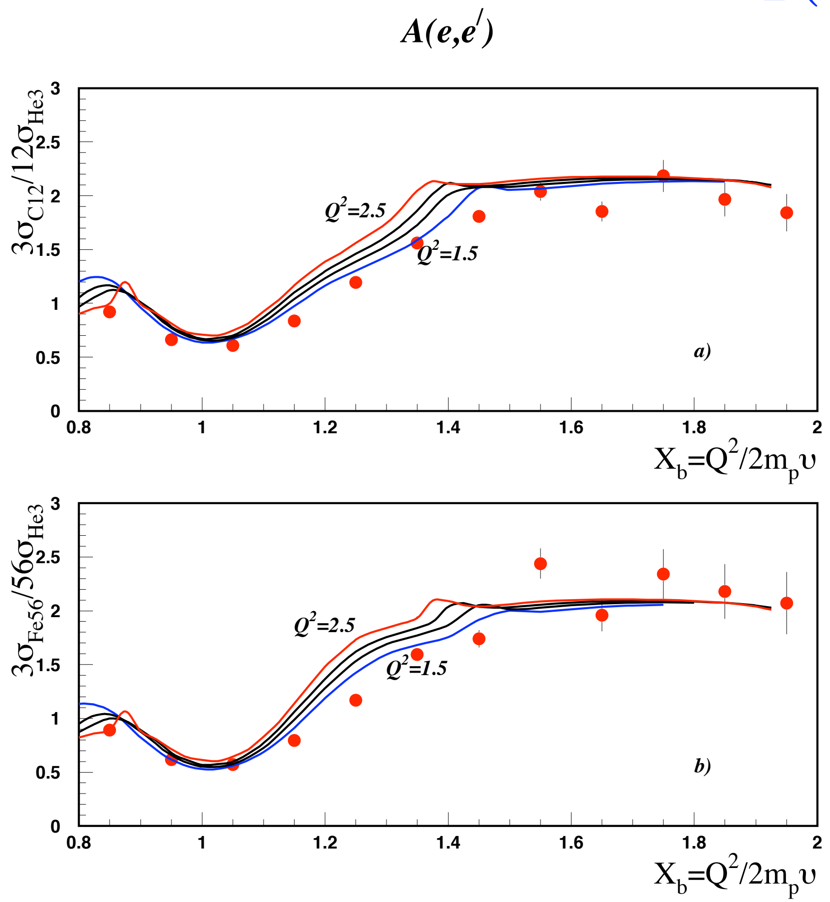

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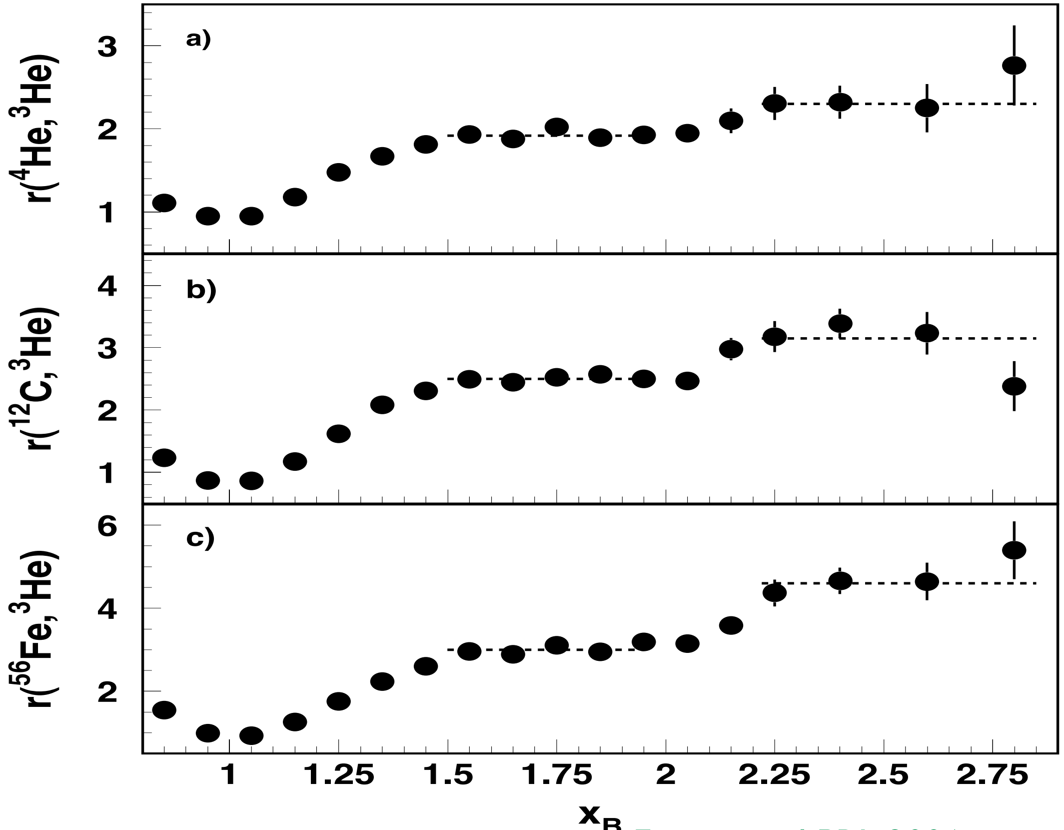
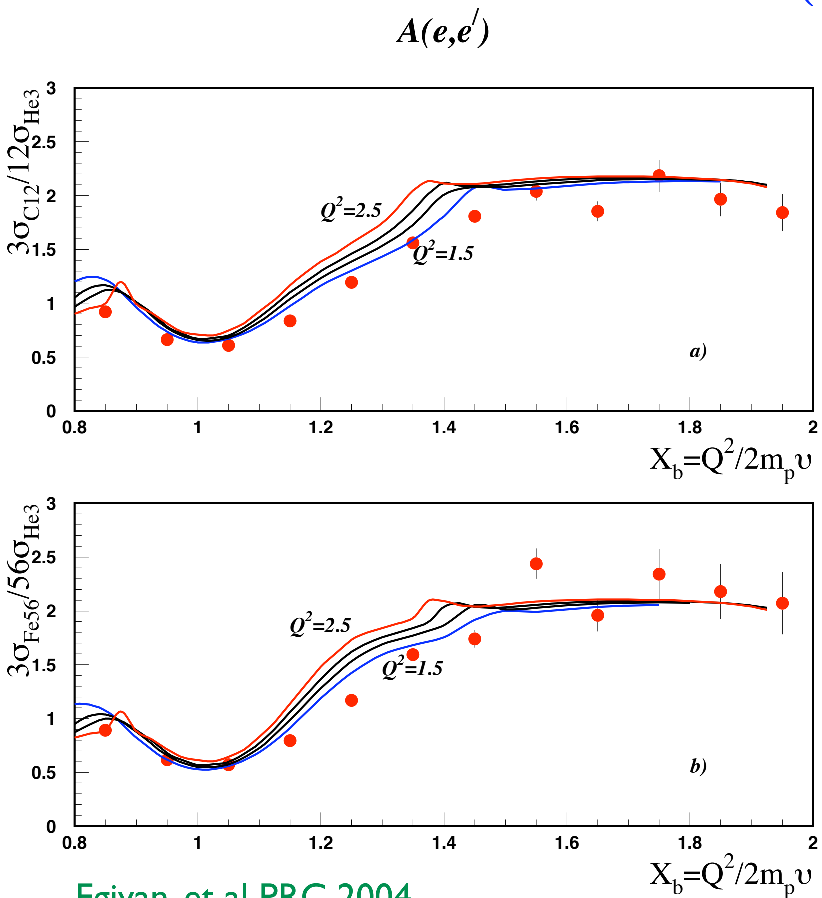


Egiyan, et al PRL 2006



Egiyan, et al PRC 2004

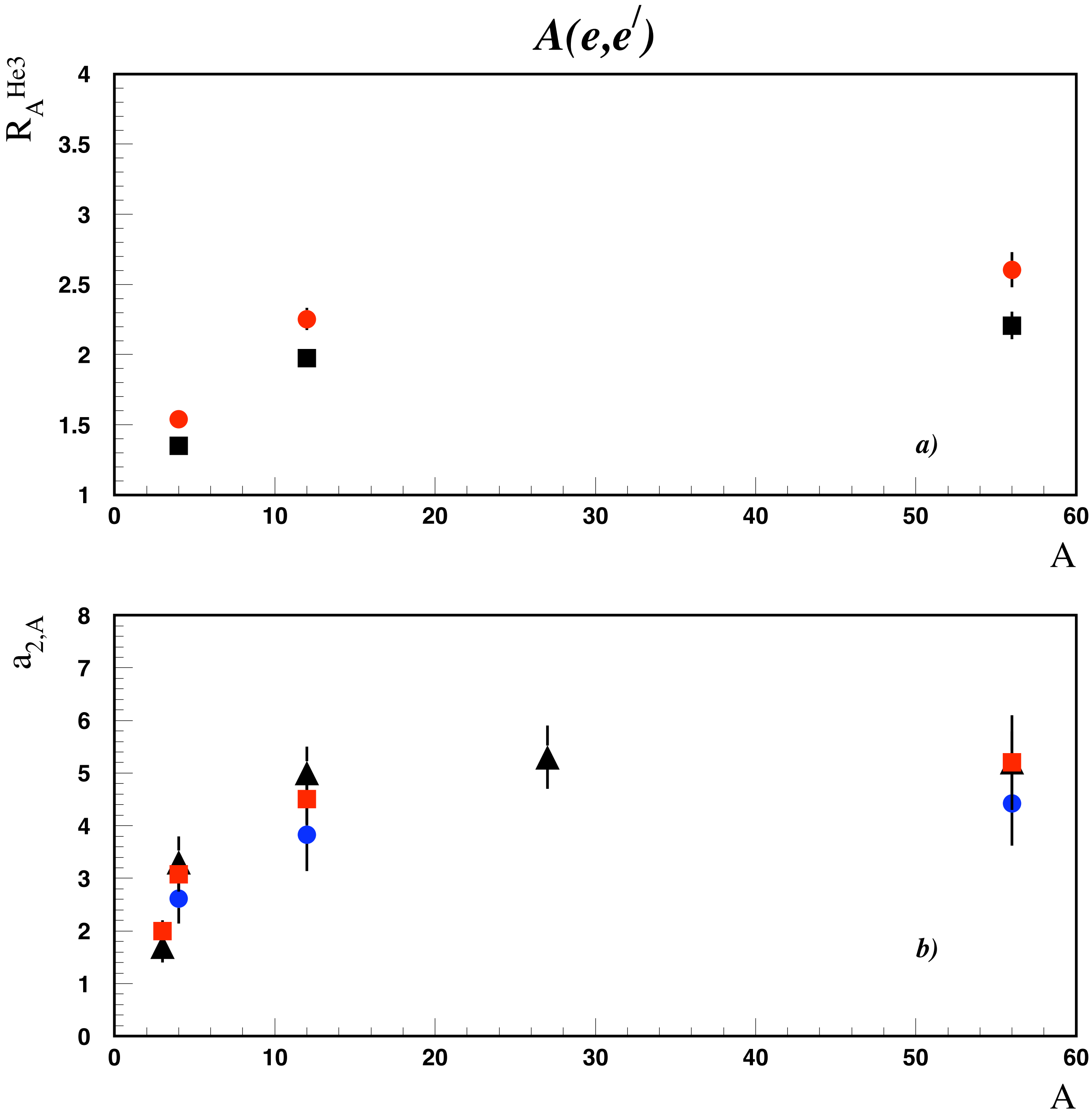
What we Learned from A(e,e')X Reactions

	$a_{2N}(A)$
^{3}He	0.080±0.000± 0.004
^{4}He	0.154±0.002± 0.033
^{12}C	0.193±0.002± 0.041
^{56}Fe	0.227±0.002± 0.047

$a_{3N}(A)$
0.0018±0.0000±0.0006
0.0042±0.0002±0.0014
0.0055±0.0003±0.0017
0.0079±0.0003±0.0025

$$a_2(^{12}C) = 0.194\%$$
$$a_3(^{12}C) = 0.0055\%$$

$$a_2(^{56}Fe) = 0.227\%$$
$$a_3(^{56}Fe) = 0.0079\%$$



A(e,e')
R_A^{He3}
a)
A
$a_{2,A}$
b)
A

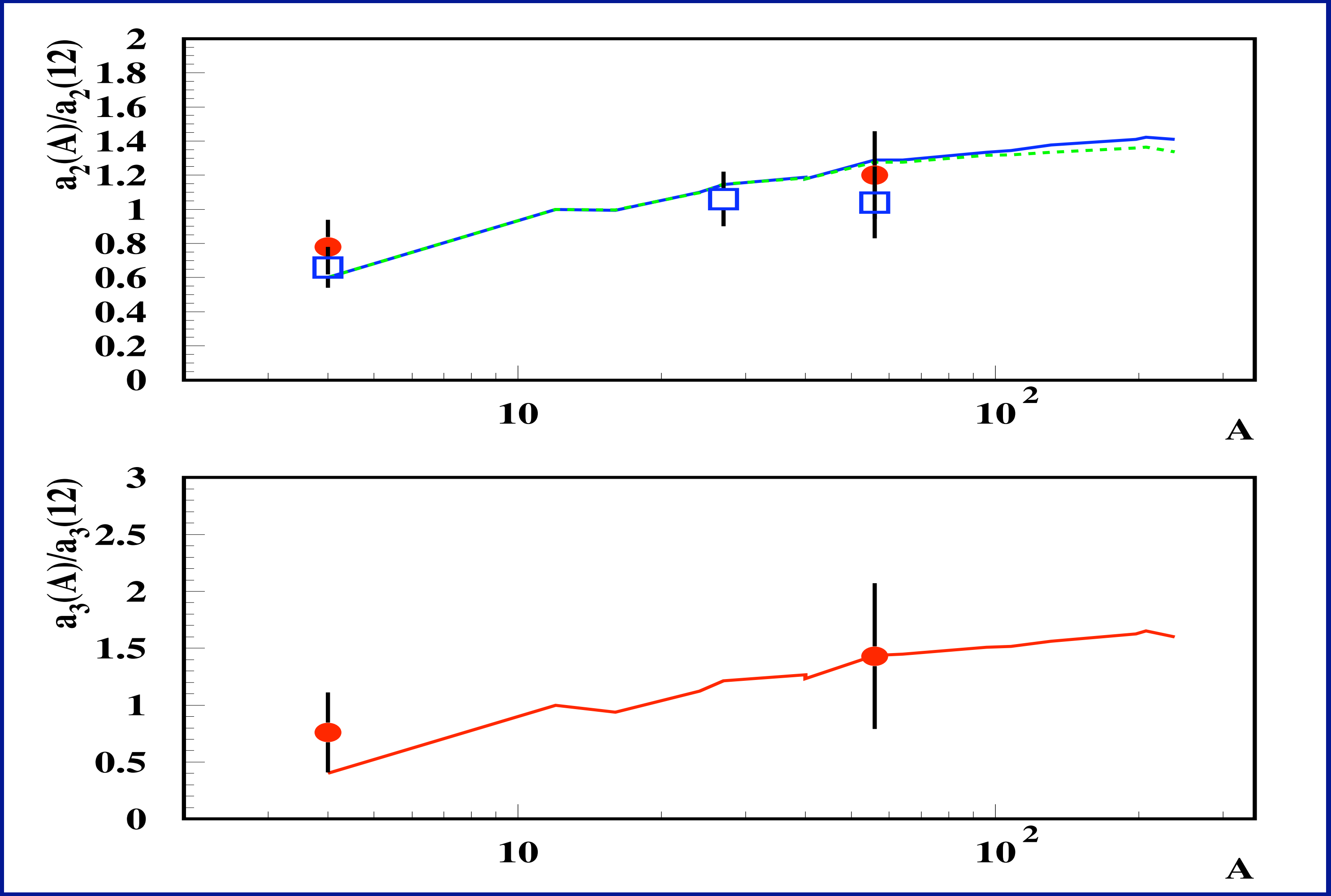
What $a_2(A)$ and $a_3(A)$ can tell us

are they really fluctuations?

Estimating density fluctuations

Frankfurt, MS, Strikman
IJMA review, 2008

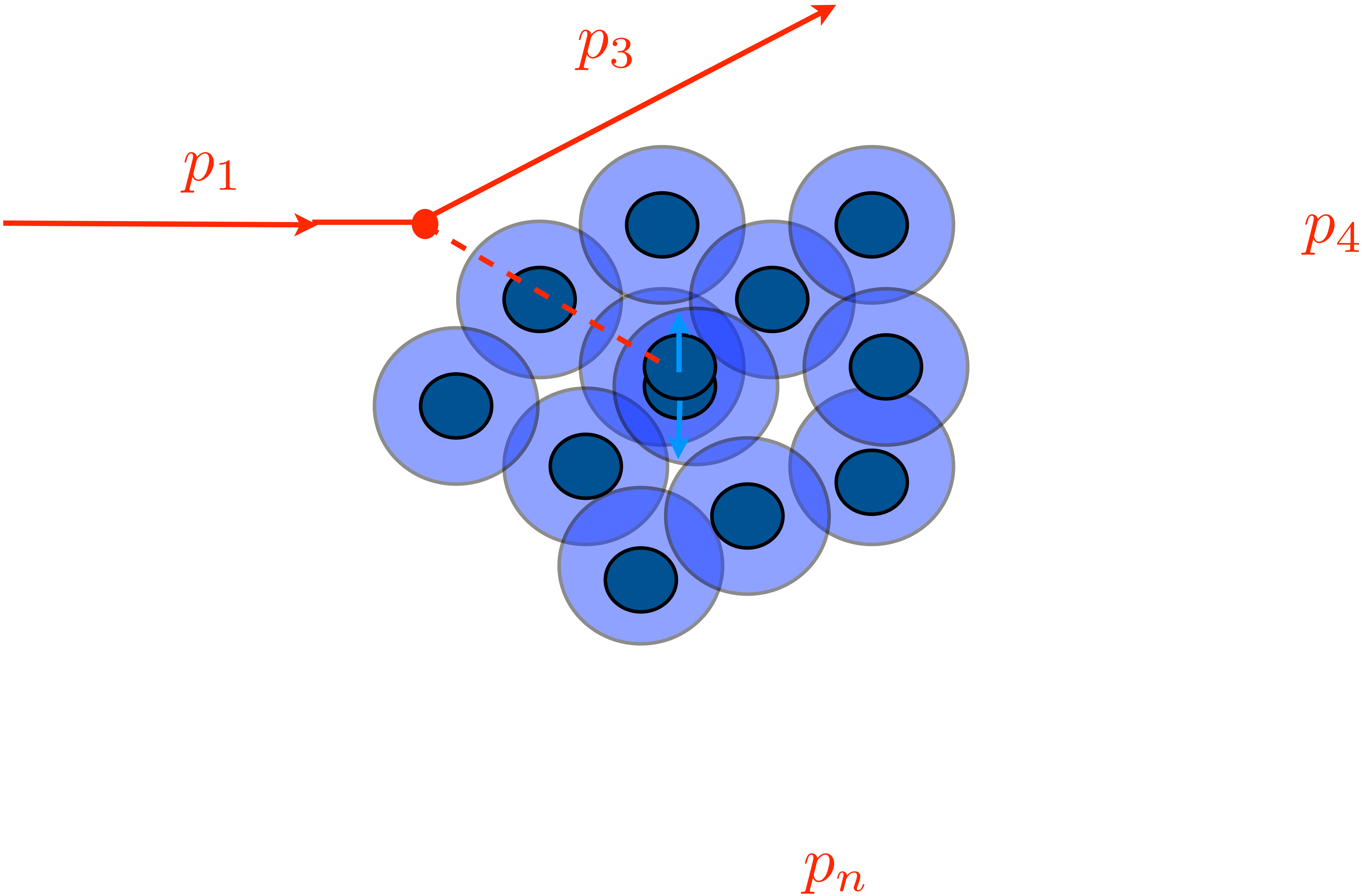
$$a_j(A) \propto \int \rho_A(r)^j d^3r \approx \int \rho^j_{A,mf}(1 + j\frac{\rho_{A,src}}{\rho_{A,mf}})d^3r$$



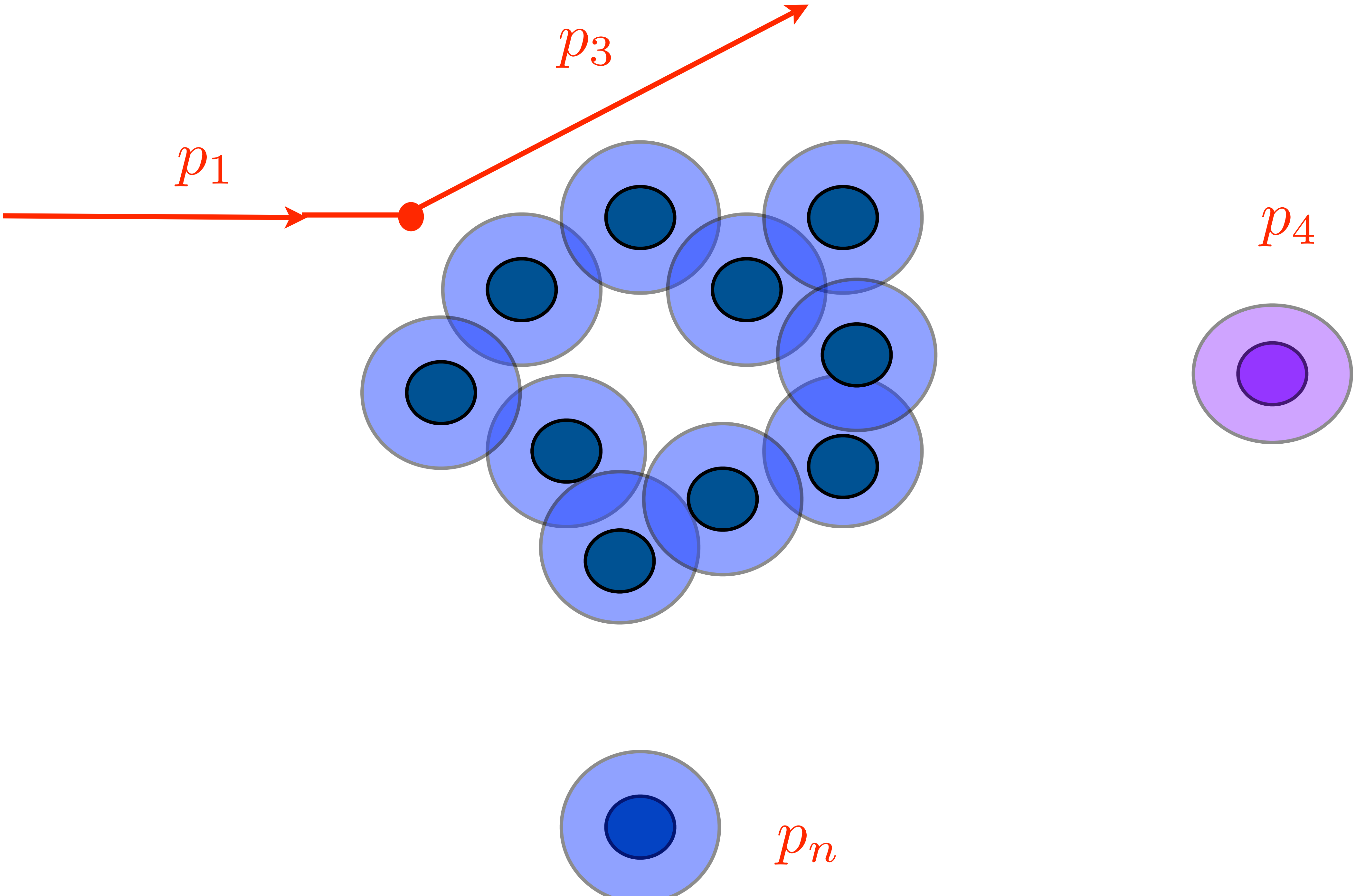
- high energy inclusive probe at x>1 and large Q2 can detect high density fluctuations

- and measure their probabilities $a_2(A)\ a_3(A)$

What are these correlations/fluctuations made of



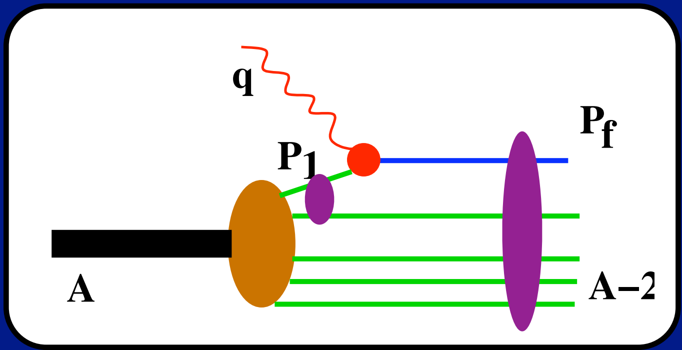
What are these correlations/fluctuations made of



We made this observation based on the estimates of the characteristic distances that highly virtual struck nucleon propagates

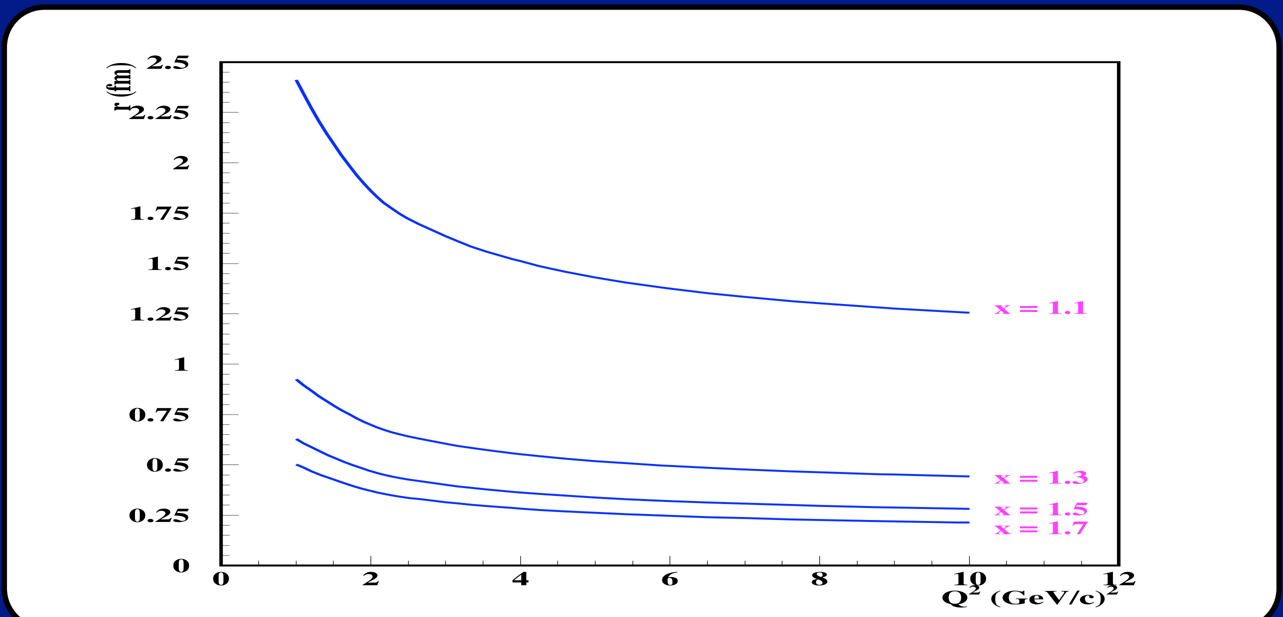
Day, Frankfurt, MS, Strikman, PRC 1993

Frankfurt, MS, Strikman IJMA review, 2008



$$r \sim \frac{v}{\Delta E}$$

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

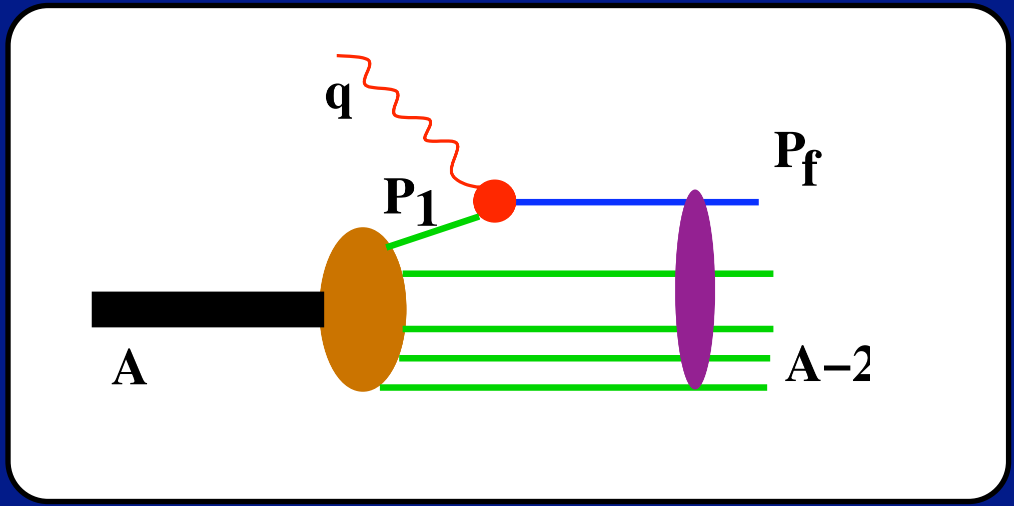


Generalized Eikonal Approximation

Frankfurt, Greenberg, Miller, MS, Strikman, ZPhys 1995 ,

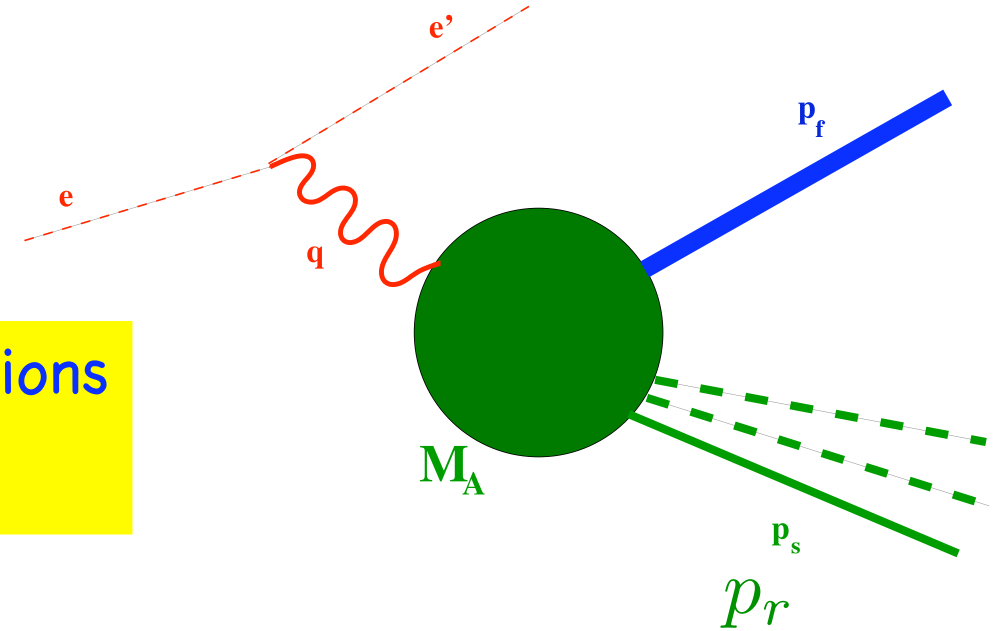
Frankfurt, MS, Strikman, PRC1997 ,

MS, Int. J. Mod. Phys 2001,



High Energy Photo/Electro-Nuclear Reactions

Kinematics



I. Momenta involved in the reactions
$q \approx p_f >$ few GeV/c.

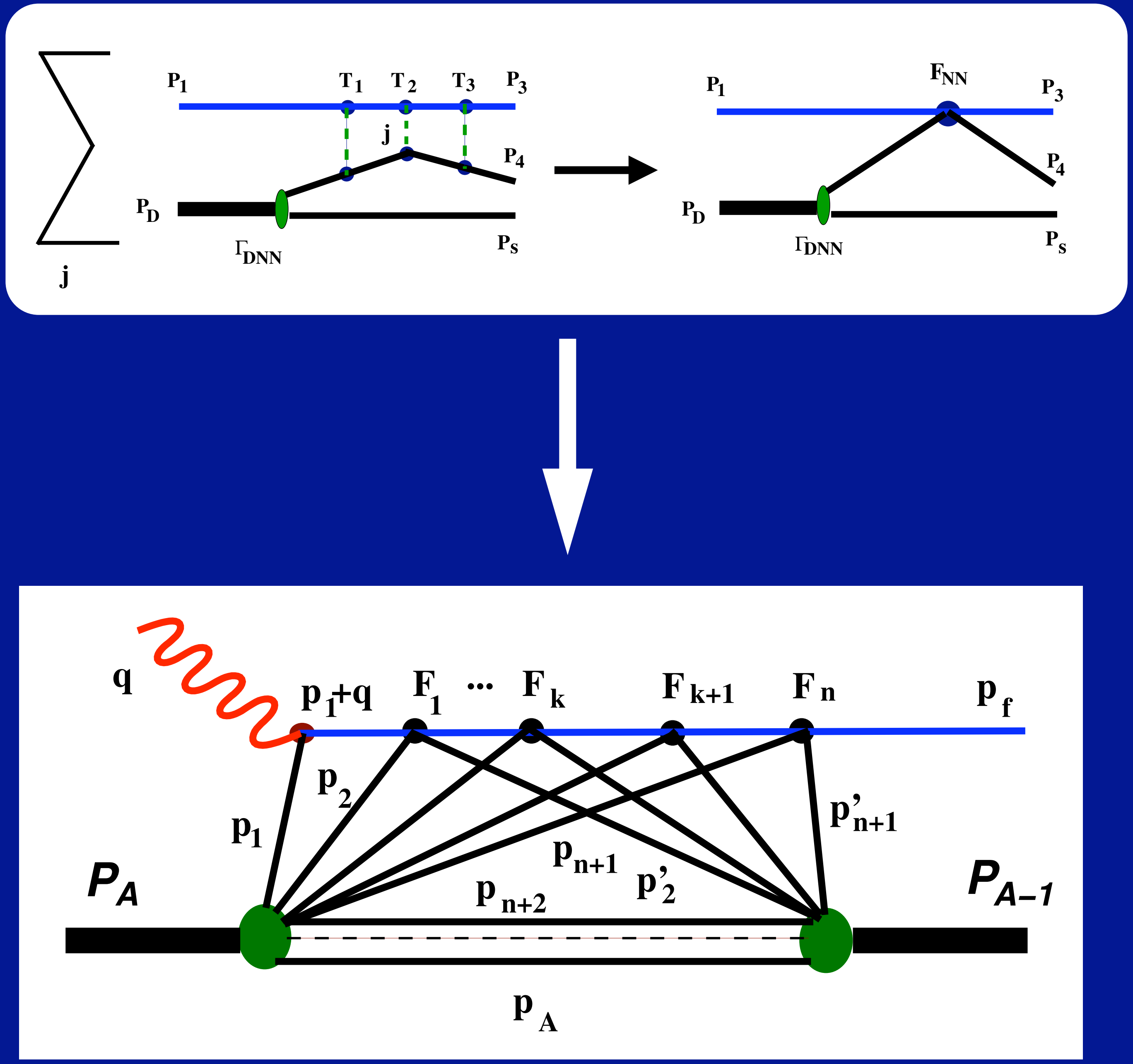
A new small parameter

$$\frac{p_-^f}{p_+^f} \equiv \frac{E^f - p_z^f}{E^f + p_z^f} \approx \frac{m^2}{4p_z^f} \ll 1$$

$$\frac{q_-}{q_+} \approx \frac{x_{Bj}^2 m^2}{Q^2} \ll 1$$

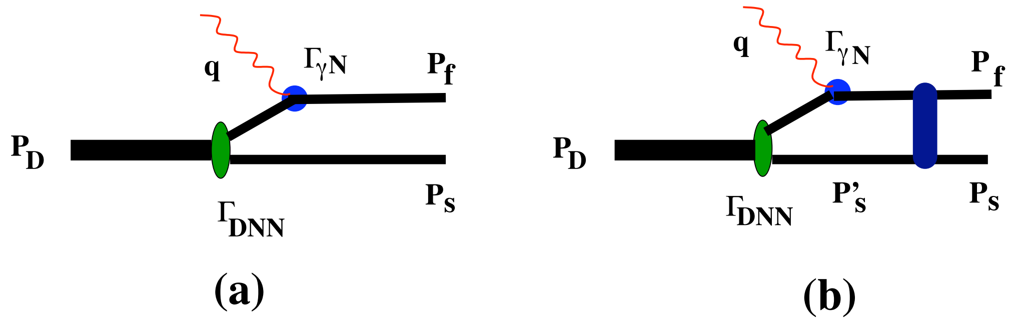
For inclusive (e,e') reaction

$$\sqrt{\frac{Q^2(2-x)}{x}} \geq \frac{1}{2}$$

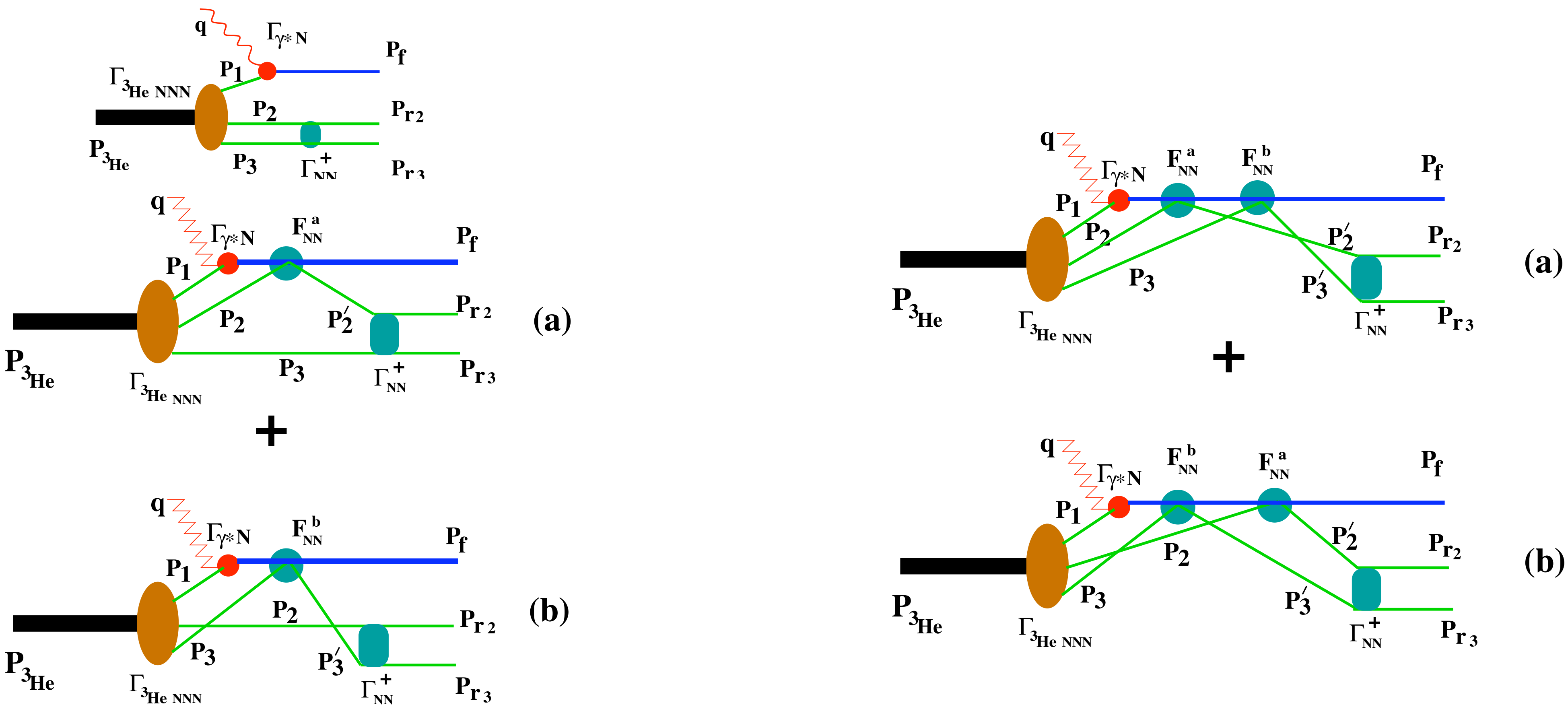


j
P1
T1
T2
T3
P3
j
P4
PD
ΓDNN
Ps
P1
FNN
P3
P4
PD
ΓDNN
Ps
q
p1+q
F1
...
Fk
Fk+1
Fn
pf
p2
p1
p'n+1
pn+1
p'2
PA
pn+2
PA−1
pA

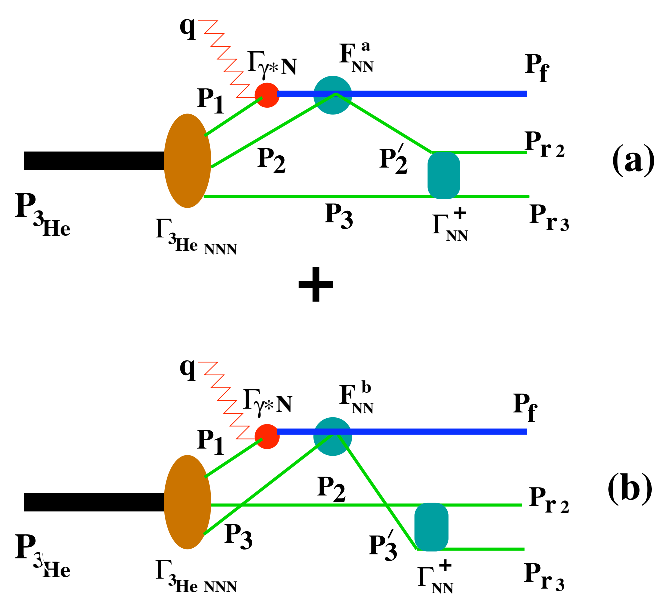
$e + d \longrightarrow e' + p + n$



$e + {}^3He \longrightarrow e' + p + p + n$



Single Rescattering

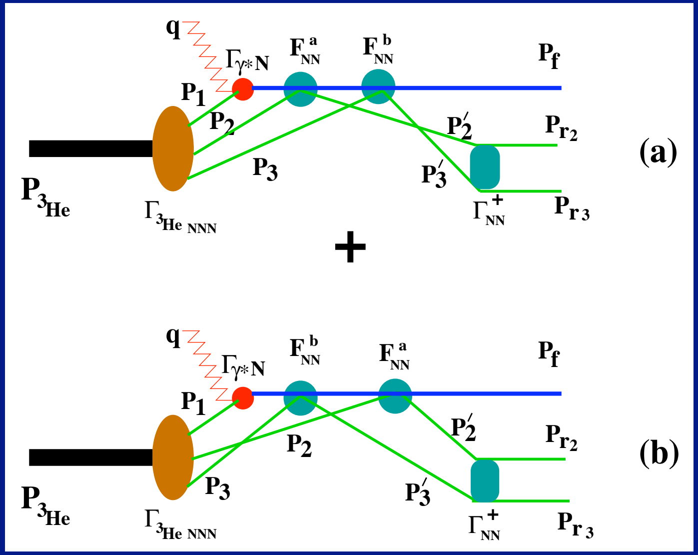


$$
\begin{aligned}
A^\mu_{1\mathrm{a}} &= -\int \frac{d^4p_2}{i(2\pi)^4}\frac{d^4p_3}{i(2\pi)^4}\bar{u}(p_{r3})\bar{u}(p_{r2})\bar{u}(p_f)\frac{\Gamma^+_{NN}(p_2', p_3)(\hat{p}_2' + m)}{p_2'^2 - m^2 + i\varepsilon} \times \\
&\times \frac{F^{\mathrm{a}}_{NN}(p_2' - p_2)(\hat{p}_1 + \hat{q} + m)}{(p_1+q)^2 - m^2 + i\varepsilon} \cdot \Gamma^\mu_{\gamma^* N} \cdot \frac{\hat{p}_3 + m}{p_3^2 - m^2 + i\varepsilon} \times \\
&\times \frac{\hat{p}_2 + m}{p_2^2 - m^2 + i\varepsilon} \cdot \frac{\hat{p}_1 + m}{p_1^2 - m^2 + i\varepsilon} \cdot \Gamma_{^3\mathrm{He}NNN}(p_1, p_2, p_3)\,\chi^A.
\end{aligned}
$$

$$
\begin{aligned}
A^\mu_{1a} &= -\frac{F}{2}\sum_{s_{1'},s_{2'},s_1,s_2,s_3}\ \sum_{t_1,t_{2'},t_2,t_3}\int \frac{d^3p_2}{(2\pi)^3}d^3p_3 \Psi^{\dagger p_{r2},s_{r2},t_{r2};p_{r3},s_{r3},t_{r3}}_{NN}(p_2', s_{2'}, t_{2'}; p_3, s_3, t_3) \\
&\times \frac{\sqrt{s_2^{NN}(s_2^{NN} - 4m^2)}}{2qm}\frac{f_{NN}(p_2', s_{2'}, t_{2'}, p_f, s_f, t_f; |p_2, s_2, t_2, p_1 + q, s_{1'}, t_1)}{p_{mz} + \Delta^0 - p_{1z} + i\varepsilon} \\
&\times j^\mu_{t_1}(p_1 + q, s_{1'}; p_1, s_1) \cdot \Psi^{s_A}_A(p_1, s_1, t_1; p_2, s_2, t_2; p_3, s_3, t_3).
\end{aligned}
$$

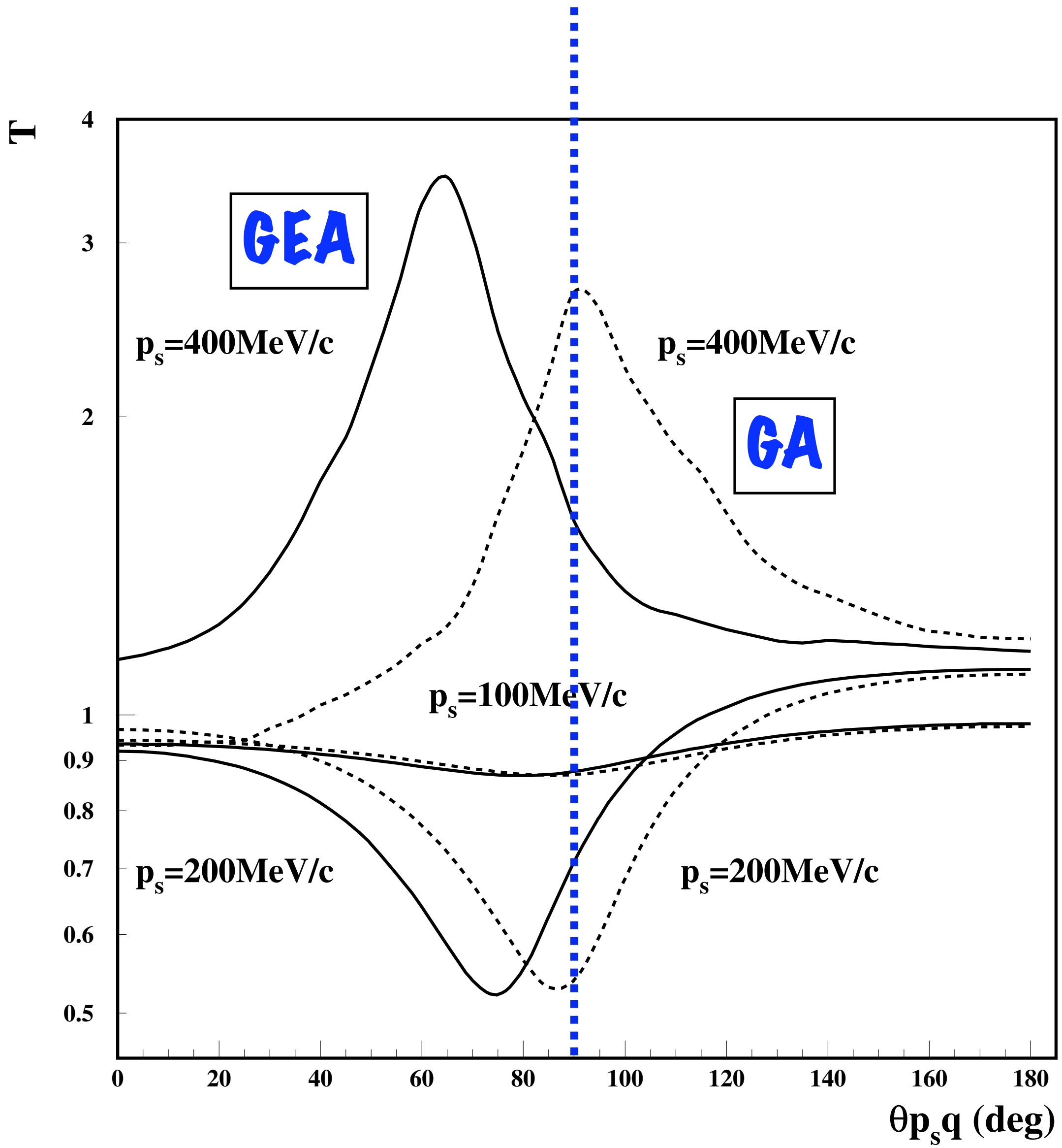
$$
\Delta^0 = \frac{q_0}{q}(T_{r2} + T_{r3} + |\epsilon_A|)
$$

Double Rescattering



$$
\begin{aligned}
A^{\mu}_{2a} \;=\;& \frac{F}{4} \sum_{s_1,s_2,s_3} \sum_{t_1,t_2,t_3,t_{1'},t_{2'},t_{3'}} \int \frac{d^3p'_3}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} d^3p_3 \Psi^{\dagger p_{r2},s_{r2},t_{r2};p_{r3},s_{r3},t_{r3}}_{NN}(p'_2, s_2, t_{2'}; p'_3, s_3, t_{3'}) \times \\
\times\;& \frac{\chi_2(s^{NN}_{b3}) f^{t_{3'},t_f|t_3,t_{1'}}_{NN}(p'_{3\perp} - p_{3\perp})}{\Delta_3 + p'_{3z} - p_{3z} + i\varepsilon} \frac{\chi_1(s^{NN}_{a2}) f^{t_{2'},t_{1'}|t_2,t_1}_{NN}(p'_{2\perp} - p_{2\perp})}{\Delta^0 + p_{mz} - p_{1z} + i\varepsilon} \\
\times\;& j^{\mu}_{t1}(p_1 + q, s_f; p_1, s_1) \cdot \Psi^{s_A}_{A}(p_1, s_1, t_1; p_2, s_2, t_2; p_3, s_3, t_3),
\end{aligned}
$$

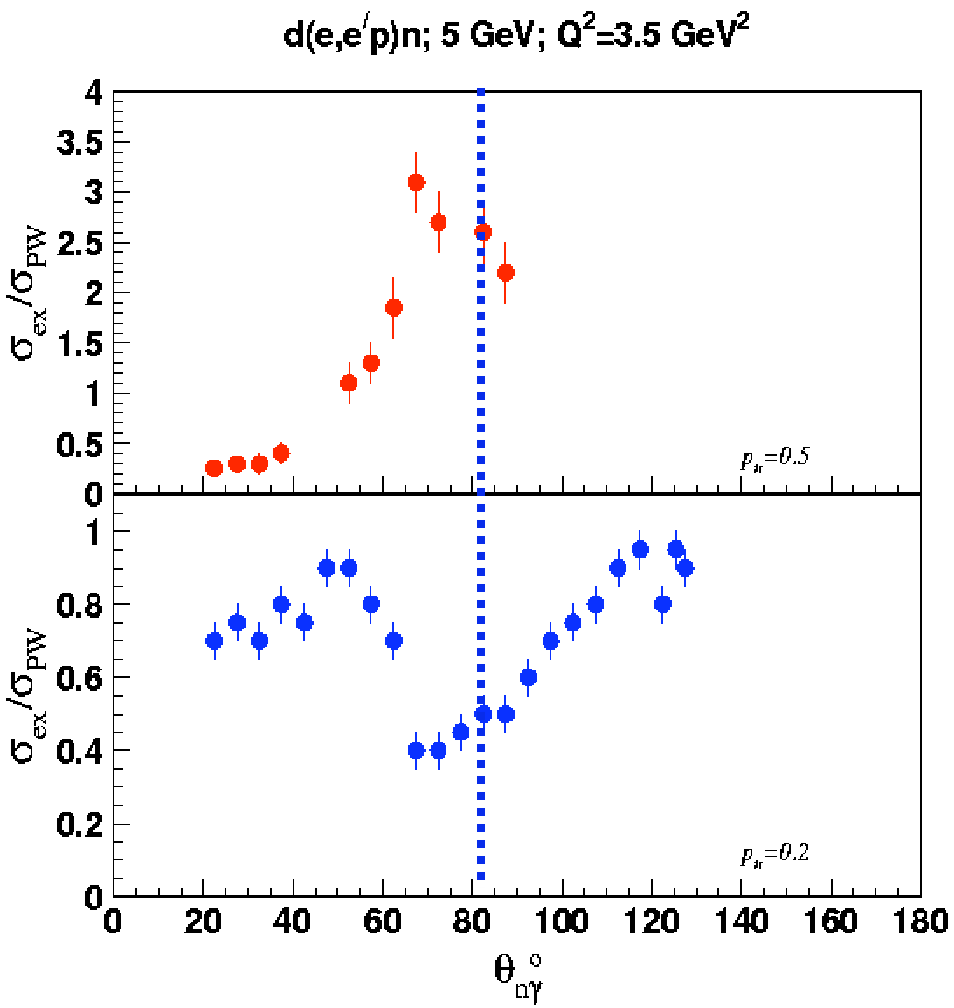
$$
\Delta^3 \approx \frac{E_f}{p_{fz}} T_{r3}
$$



Frankfurt, MS,
Strikman, PRC1997 ,

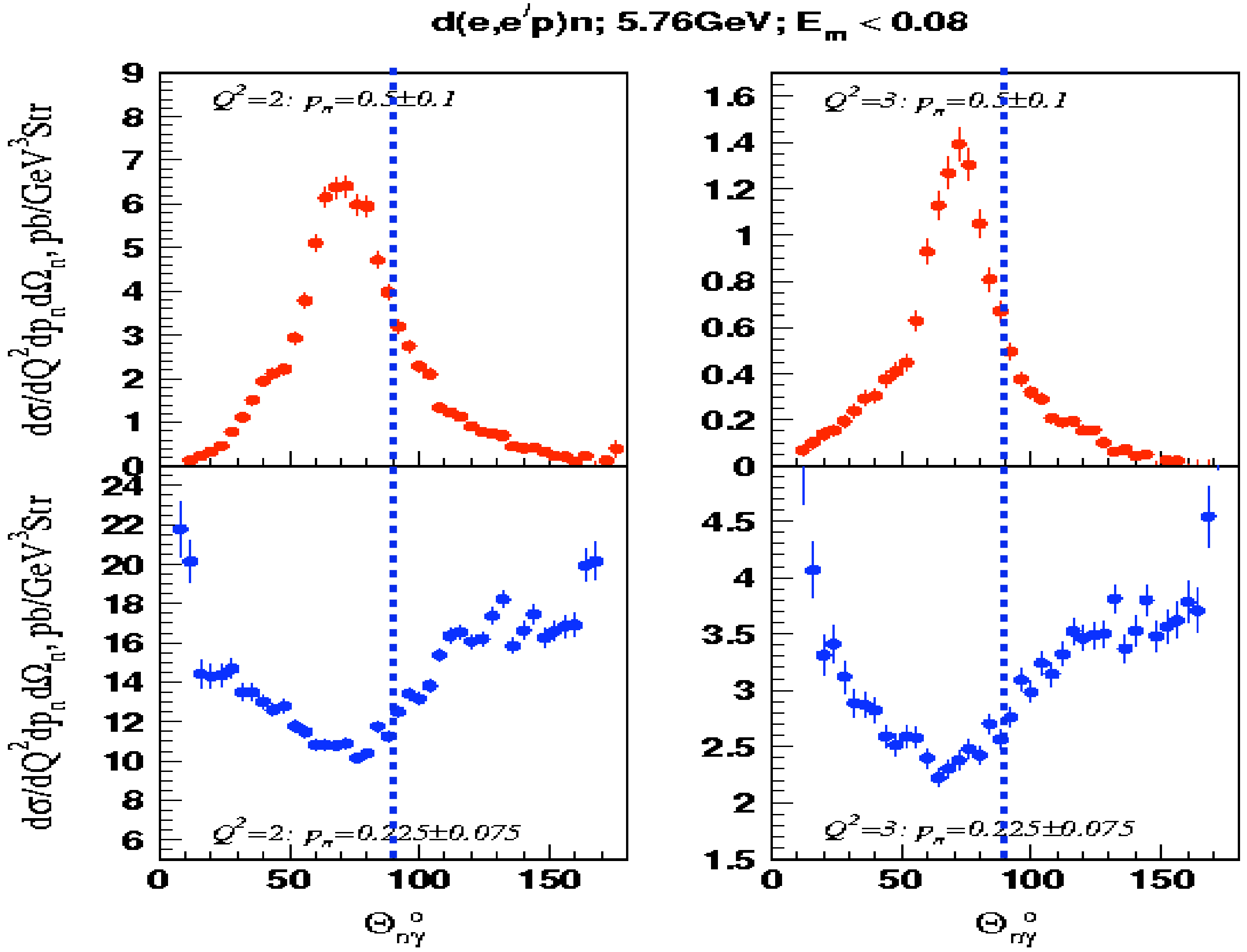
Recoil-Neutron Angular Distributions; Hall A Exp.

Werner Boeglin
Luminita Coman, PhD 2007



PRELIMINARY

Recoil-Neutron's Angular Distributions - I



K. Egiyan et al, PRL07

Dynamics of Reinteraction within GEA

Comparing with Glauber theory - Single Rescattering

GEA in coordinate space

$$A_1^\mu \sim \int d^3r \psi^\dagger_{A-1} e^{-ip_i r} \Theta(z) \Gamma^{NN}_{GEA}(\Delta_0, z, b) \Psi_A(r)$$

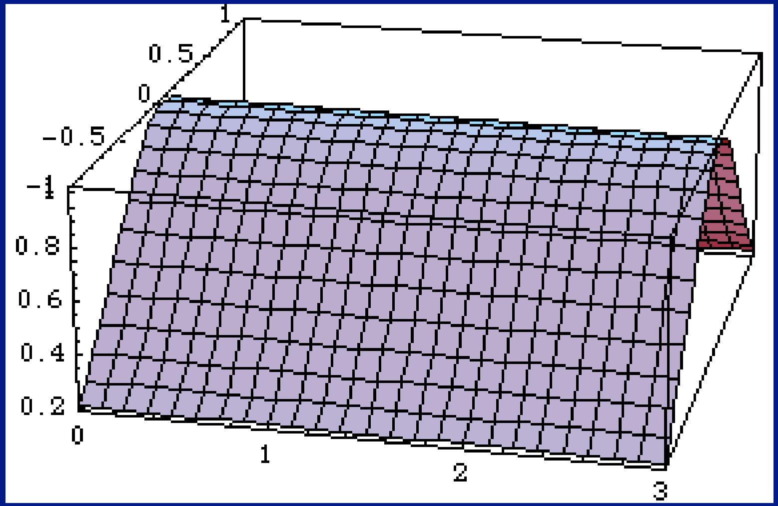
$$\Gamma^{NN}_{GEA}(\Delta_0, z, b) = e^{i\Delta_0 z} \Gamma^{NN}_{Glauber}(z, b)$$

$$\Gamma^{NN}_{Glauber}(z, b) = \frac{1}{2i} \int f^{NN}(k_\perp) e^{-ik_\perp b} \frac{d^2k_\perp}{(2\pi)^2}$$

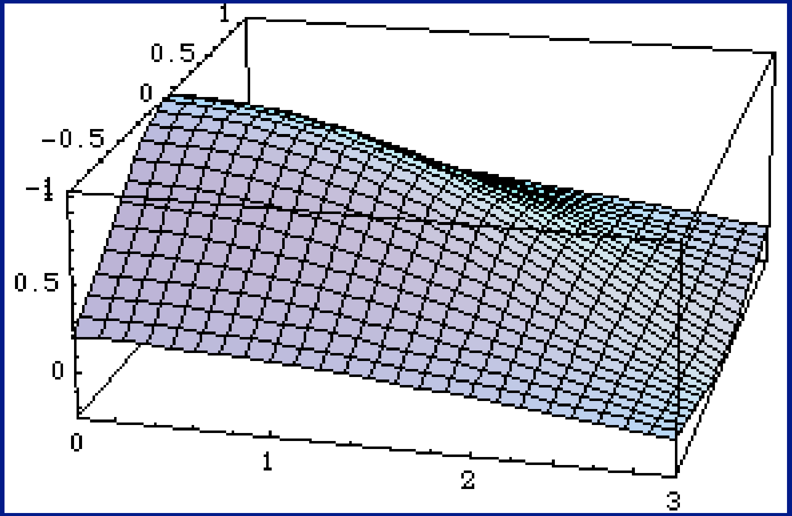
$$\Delta^0 = \frac{q_0}{q}(T_{r2} + T_{r3} + |\epsilon_A|)$$

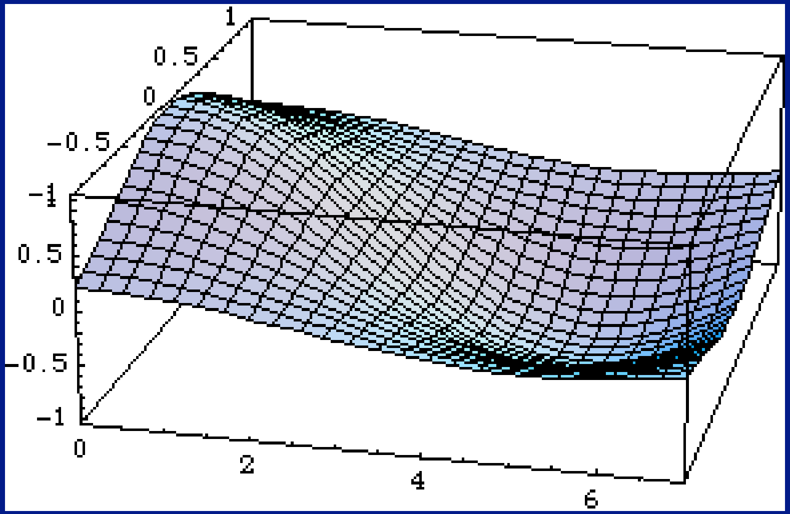
Impulse Approximation

$$\Gamma_{Glauber}(z,b)$$



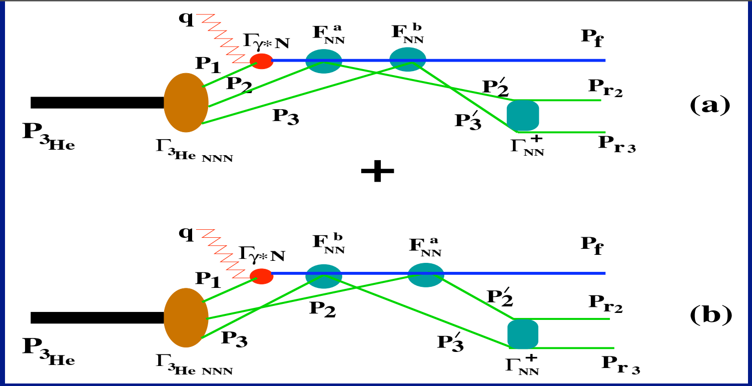
$$\Gamma_{GEA}(\Delta_0,z,b)$$





$$\Gamma_{GEA}(\Delta_0,z,b)$$

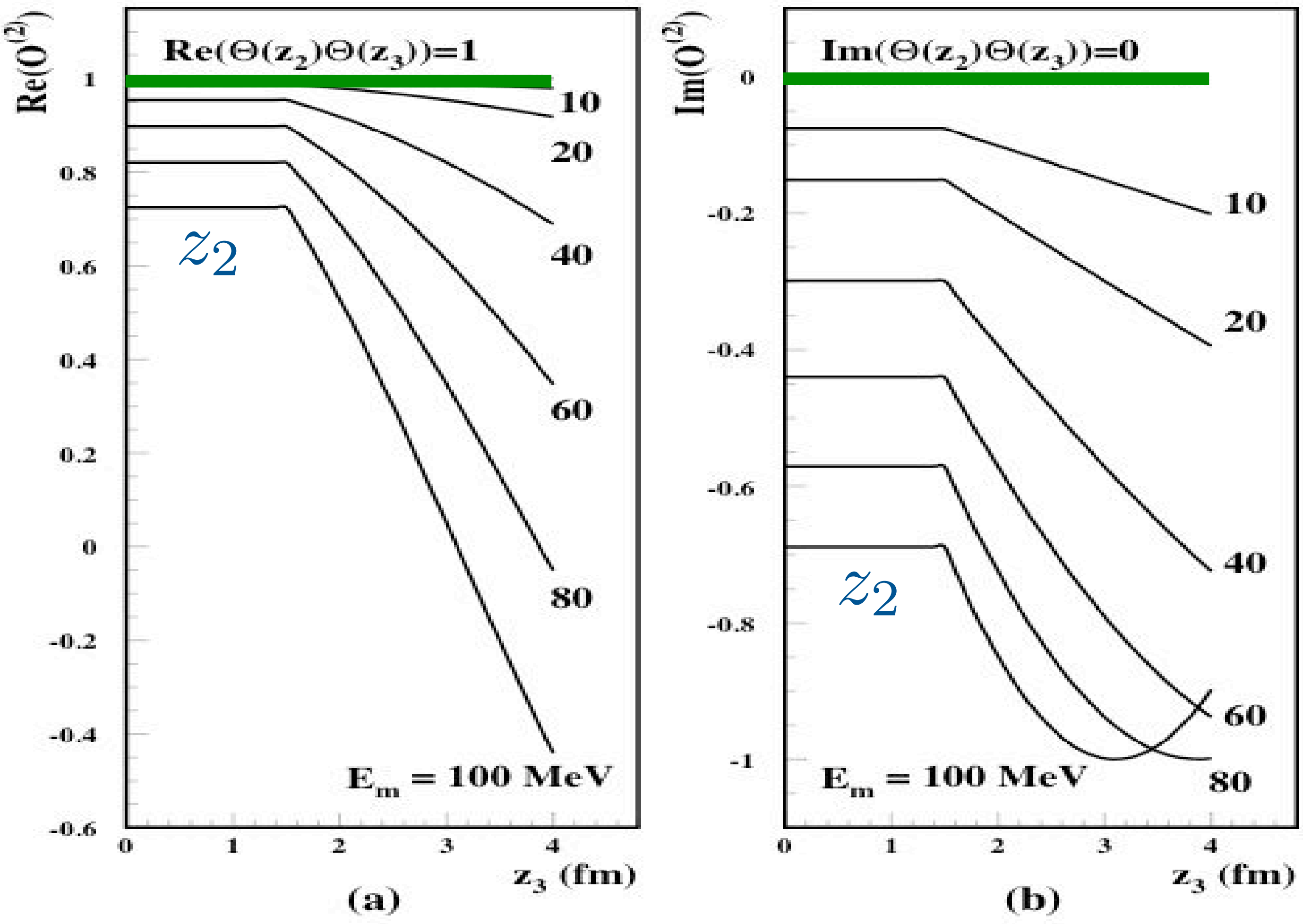
Double Rescattering



$$A_2^\mu \sim \int d^3x_1 d^3x_2 d^3x_3 \psi^\dagger(x_2 - x_3), \mathcal{O}^{(2)}(z_1, z_2, z_3, \Delta_0, \Delta_2, \Delta_3)$$
$$\Gamma^{NN}(x_2 - x_1, \Delta_0)\Gamma^{NN}(x_3 - x_1, \Delta_0) e^{-i\vec{r}_1\cdot\vec{p}_m}\psi_A(x_1, x_2, x_3)$$

$$\mathcal{O}^{(2)}(z_1, z_2, z_3, \Delta_0, \Delta_2, \Delta_3) = \Theta(z_2 - z_1)\Theta(z_3 - z_2)e^{-i\Delta_3(z_2-z_1)}e^{i(\Delta_3-\Delta_0)(z_3-z_1)} + \Theta(z_3 - z_1)\Theta(z_2 - z_3)e^{-i\Delta_2(z_3-z_1)}e^{i(\Delta_2-\Delta_0)(z_2-z_1)}. \quad (1)$$

$$\mathcal{O}|_{\Delta,\Delta_2,\Delta_3\to 0} \to \Theta(z_2 - z_1)\Theta(z_3 - z_1)$$



Re(O^(2))
Re(Θ(z2)Θ(z3))=1
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
10
20
40
60
80
z_2
E_m = 100 MeV
0 1 2 3 4
z3 (fm)
(a)
Im(O^(2))
Im(Θ(z2)Θ(z3))=0
0
-0.2
-0.4
-0.6
-0.8
-1
10
20
40
60
80
z_2
E_m = 100 MeV
0 1 2 3 4
z3 (fm)
(b)

FSI Conserves α

$$A^{\mu}_{1a} = -\frac{F}{2}\sum_{s_{1'},s_{2'},s_1,s_2,s_3}\sum_{t_1,t_{2'},t_2,t_3}\int\frac{d^3p_2}{(2\pi)^3}d^3p_3\Psi^{\dagger p_{r2},s_{r2},t_{r2};p_{r3},s_{r3},t_{r3}}_{NN}(p'_2,s_{2'},t_{2'};p_3,s_3,t_3)$$

$$\times\ \frac{\sqrt{s_2^{NN}(s_2^{NN}-4m^2)}}{2qm}\frac{f_{NN}(p'_2,s_{2'},t_{2'},p_f,s_f,t_f;|p_2,s_2,t_2,p_1+q,s_{1'},t_1)}{\underline{p_{mz}+\Delta^0-p_{1z}+i\varepsilon}}$$

$$\times\ j^{\mu}_{t_1}(p_1+q,s_{1'};p_1,s_1)\cdot\Psi^{s_A}_A(p_1,s_1,t_1;p_2,s_2,t_2;p_3,s_3,t_3). \quad (1)$$

$$\frac{1}{[p^m_z+\Delta_0-p_{1z}+i\epsilon]} = \frac{1}{m[\alpha_1-\alpha_i-\frac{Q^2}{2q^2}\frac{E_m}{m}+i\epsilon]}.$$

$$E_m = q_0 - T_f$$

$$\alpha_i = \alpha_f - \frac{q_-}{m}$$

$$\frac{Q^2}{2|q|^2}\frac{E_m}{m} = \frac{1}{2(1+\frac{q_0}{2mx})}\frac{E_m}{m} \to 0$$

Conservation of α

$$A_1^\mu \sim -\int \psi_A(\alpha_1, p_{1t}, \alpha_2, p_{2t}, \alpha_3, p_{3t}) J_1^{em,\mu}(Q^2) \frac{f^{NN}}{[\alpha_1 - \alpha_m - \frac{Q^2}{2q^2}\frac{E_m}{m} + i\epsilon]}$$

$$\psi_{A-1}(\alpha_2', p_{2t}', \alpha_3, p_{3t}) \frac{d\alpha_1 d^2 p_{1t}}{(2\pi)^3} \frac{d\alpha_3 d^2 p_{3t}}{(2\pi)^3}.$$

$$A_2^\mu \sim \int \psi_A(\alpha_1, p_{1t}, \alpha_2, p_{2t}, \alpha_3, p_{3t}) J^{em,\mu}(Q^2) \times$$

$$\frac{f^{NN}(p_{1t} - p_{mt} - (p_{3t}' - p_{3t}))}{[\alpha_1 - \alpha_m - \frac{Q^2}{2q^2}\frac{E_m}{m} + i\epsilon]} \frac{f^{NN}(p_{3t}' - p_{3t})}{[\alpha_3 - \alpha_3' - \frac{Q^2}{2q^2}\frac{k_{3t}^2}{2m^2} + i\epsilon]} \psi_{A-1}(\alpha_2, p_{2t}', \alpha_3, p_{3t}')$$

$$\frac{d\alpha d^2 p_{1t}}{(2\pi)^3} \frac{d\alpha_3 d^2 p_{3t}}{(2\pi)^3} \frac{d\alpha_3' d^2 p_{3t}'}{(2\pi)^3}. \qquad (1)$$

Conservation of α

Therefore if the kinematics is chosen such that $\alpha_i = \alpha_f - \frac{q_-}{m} > j$

The α_1 which inters in FSI amplitude is also $\alpha_1 \geq j$

and therefore FSI amplitude will be dominated by SRC

Which experimental signatures will indicate the suppression of long-range FSI ?

- Naturally will explain the scaling at x>1

- $E_m \approx \frac{p_m^2}{2m}$ - relation survives FSI

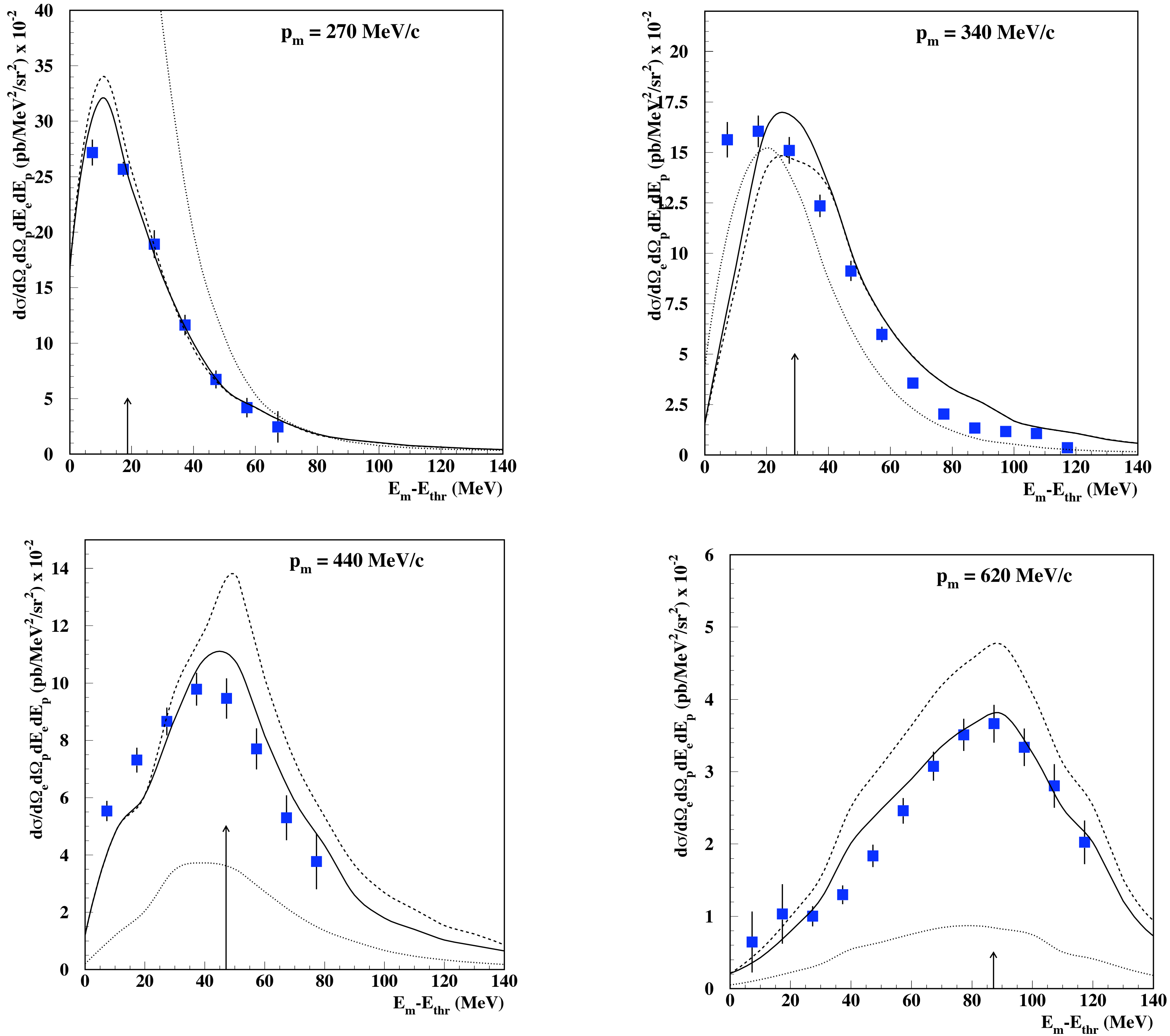
- CM momentum distribution of SRC is not affected by FSI

Three Body Break-up He3(e,e'p)pn Reaction

$Q^2 = 1.55\ \mathrm{GeV}^2$

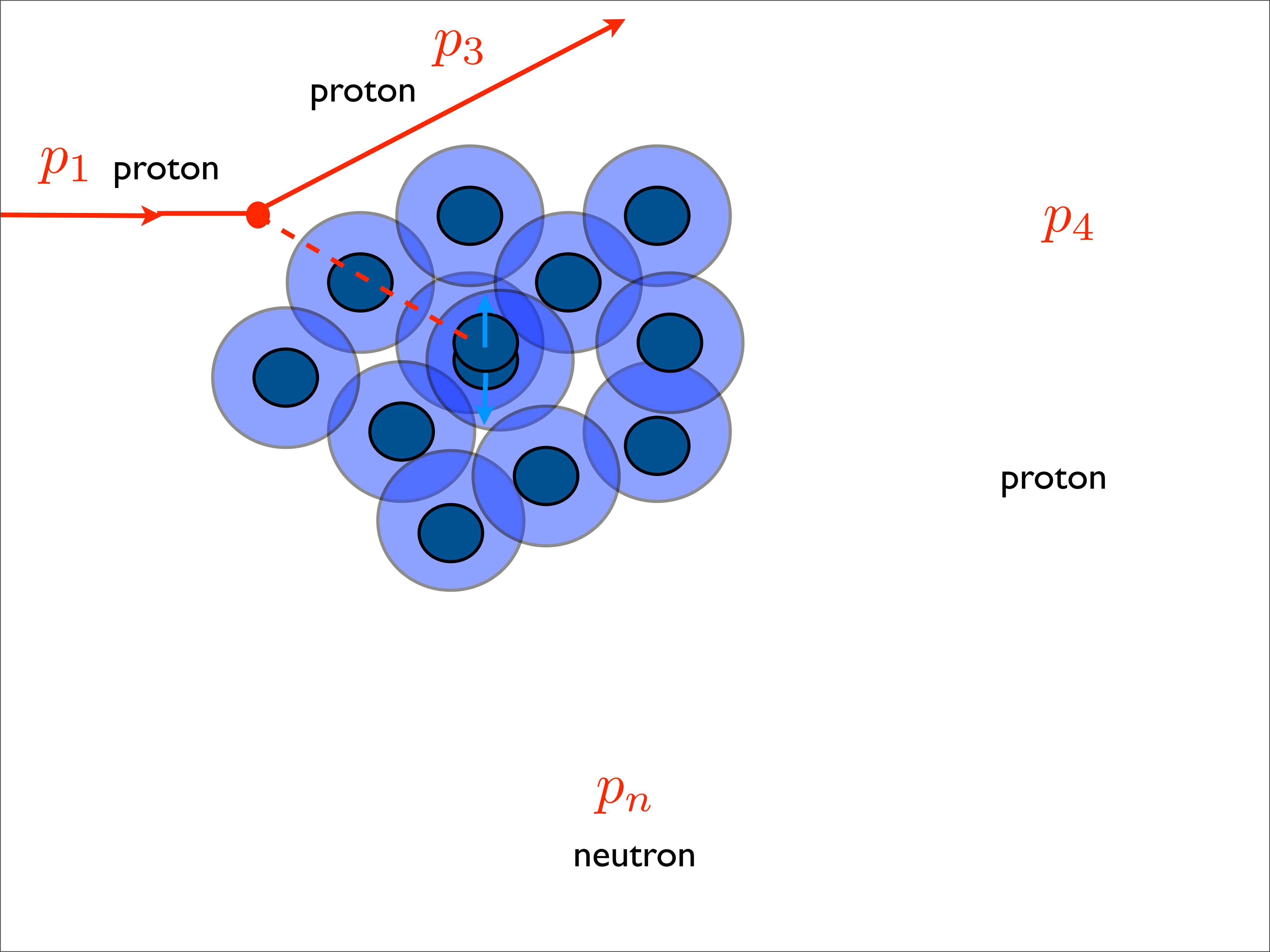
Benmokhtar, et al PRL 2005

$$E_m \approx \frac{p_m^2}{2m}$$

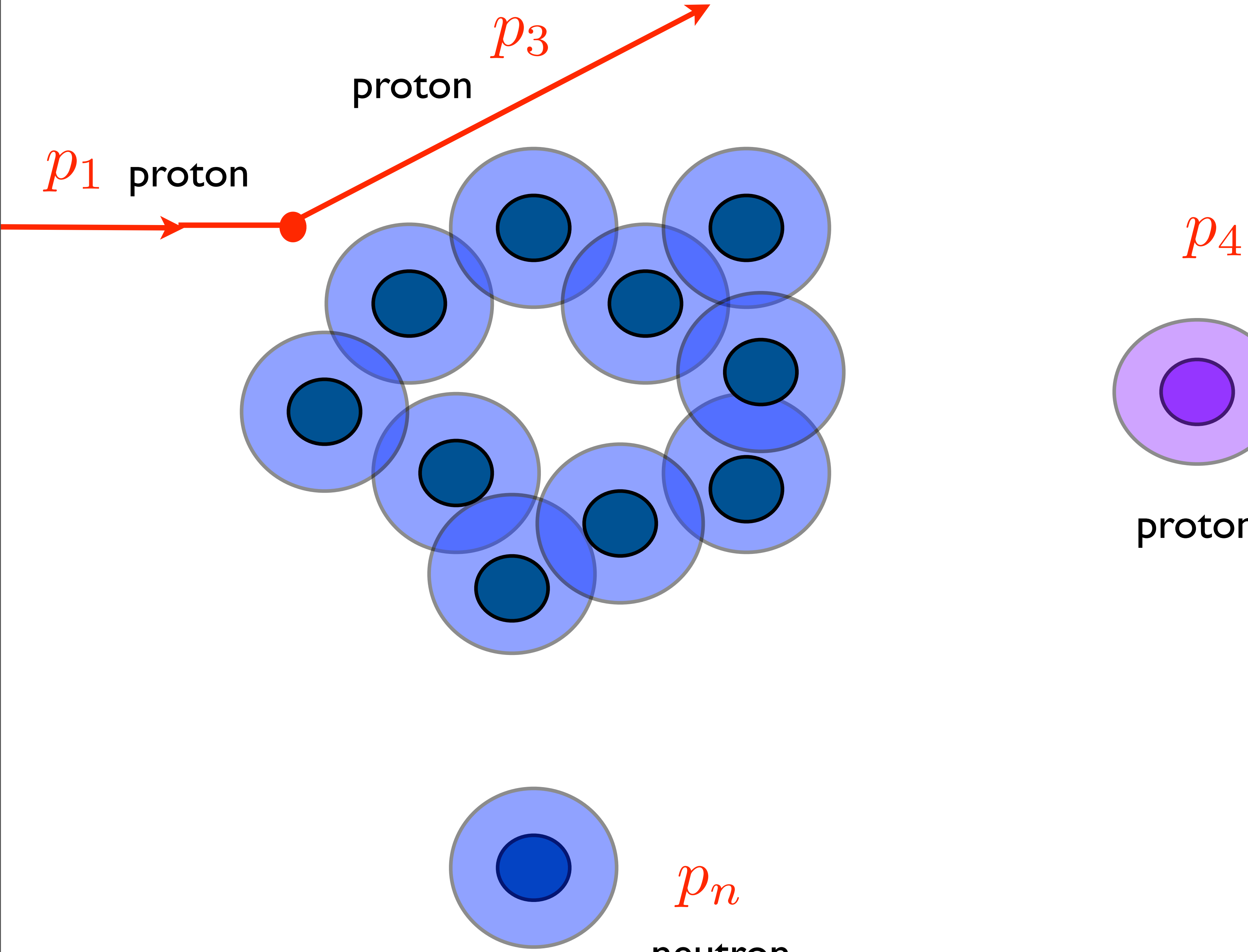


MS. , Abrahamyan, Frankfurt, Strikman, et al PRC 2005

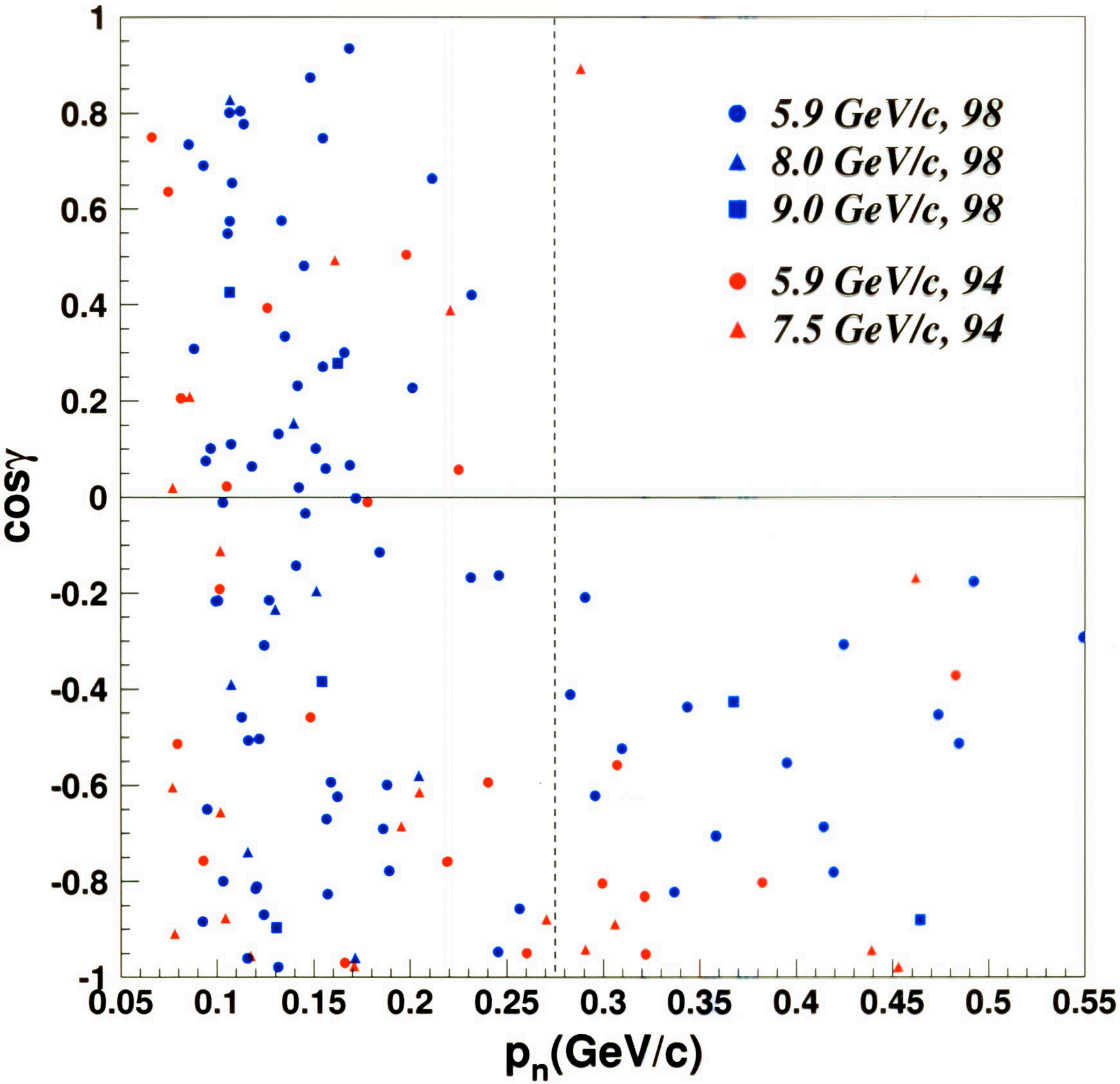
He3 WF
Bochum Group
Andreas Nogga



p_3
proton
p_1
proton
p_4
proton
p_n
neutron



p_3
proton
p_1 proton
p_4
proton
p_n
neutron



A. Tang et al, PRL 2003

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \leq p_i, p_n \leq 550 \text{ MeV/c}$$

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Theoretical Analysis

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A. Tang et al, PRL 2003

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Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

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Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

Brookhaven Experiment

A. Tang et al, PRL 2003

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Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

relative probability of finding pn SRC in the "pX" configuration that contains a proton with

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \le p_i, p_n \le 550 \text{ MeV/c}$$

Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

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Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

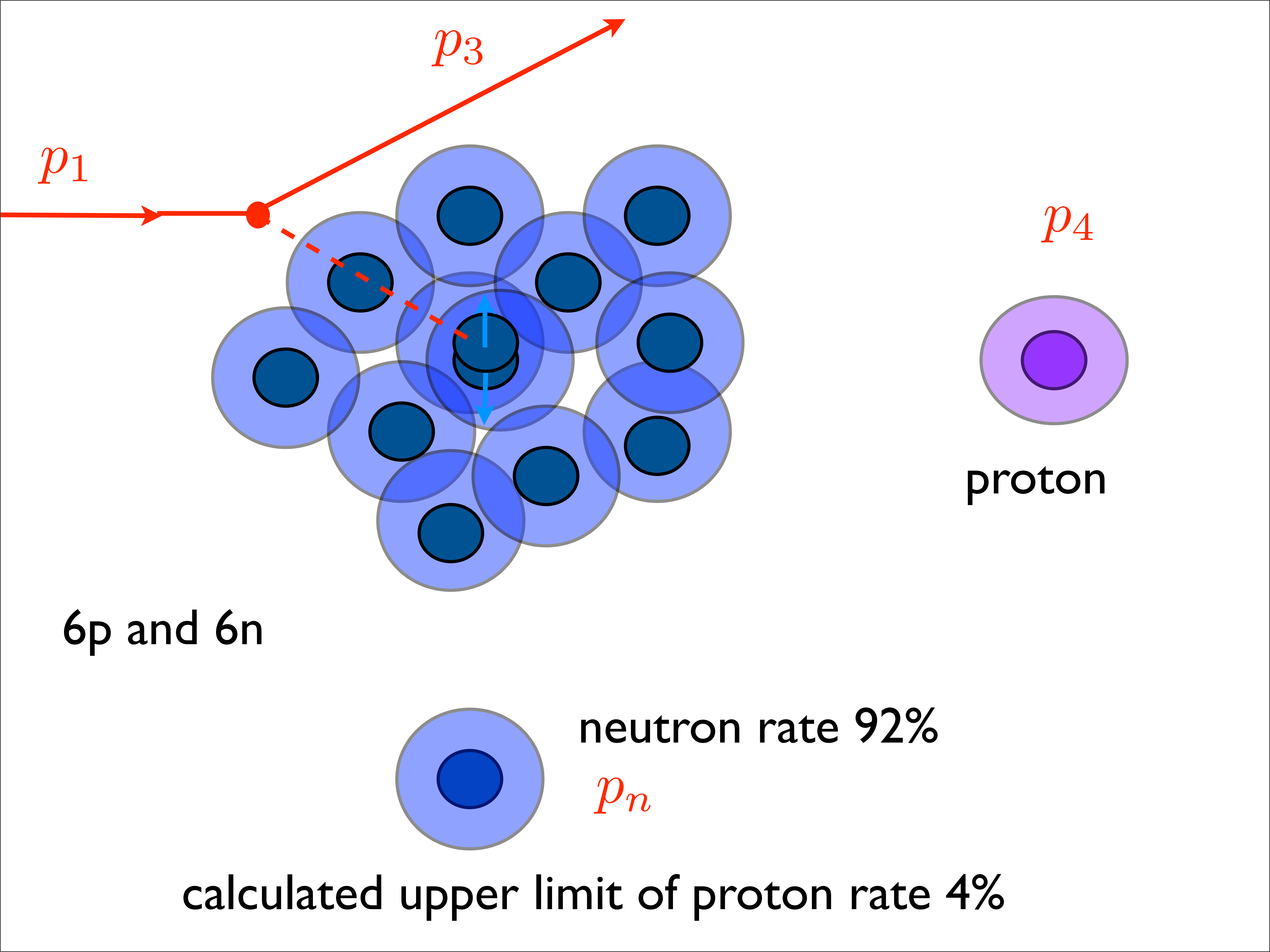
relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

$$R \equiv \frac{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} \int\limits_{\alpha_n^{min}}^{\alpha_n^{max}} \int\limits_{p_{tn}^{min}}^{p_{tn}^{max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t \frac{d\alpha_n}{\alpha_n} d^2p_{tn} dP_{R+}}{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} S^{pn}((\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t dP_{R+}}.$$

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

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

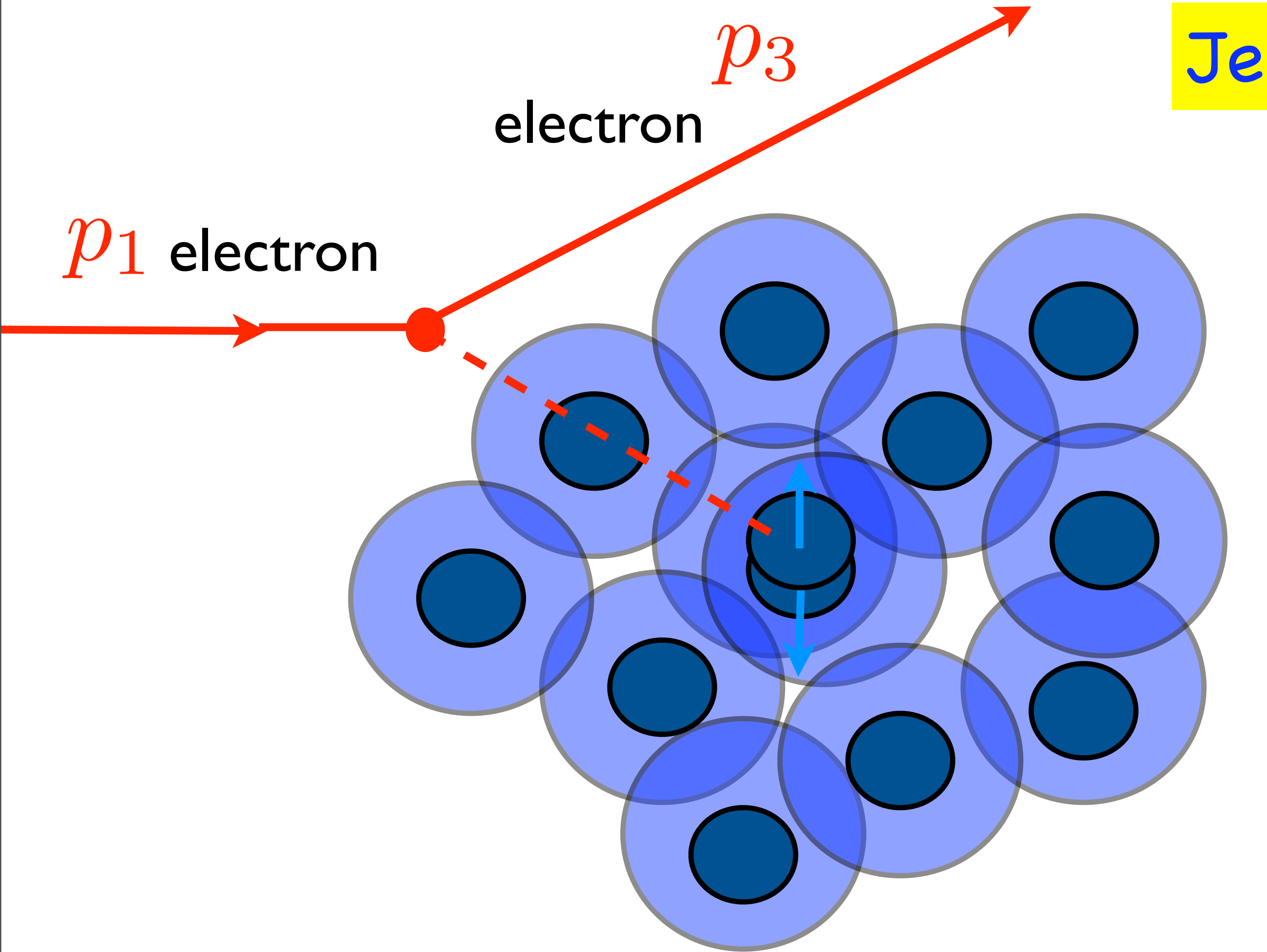
- 92% of the time two-nucleon high density fluctuations are proton and neutron
- at most 4% of the time proton-proton or neutron-neutron



p_3
p_1
p_4
proton
6p and 6n
neutron rate 92%
p_n
calculated upper limit of proton rate 4%

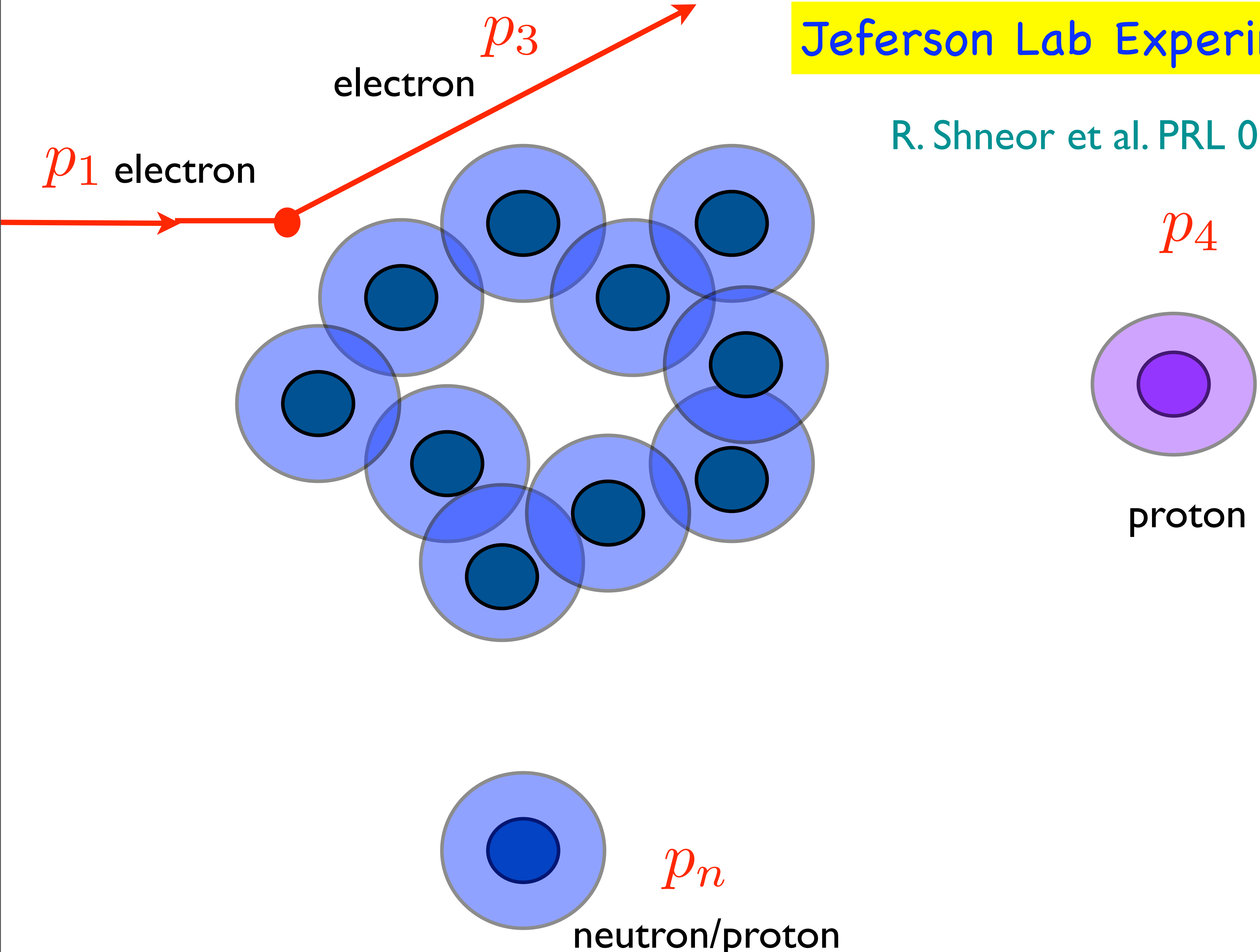
Jeferson Lab Experiment

R. Shneor et al. PRL 07



Jeferson Lab Experiment

R. Shneor et al. PRL 07



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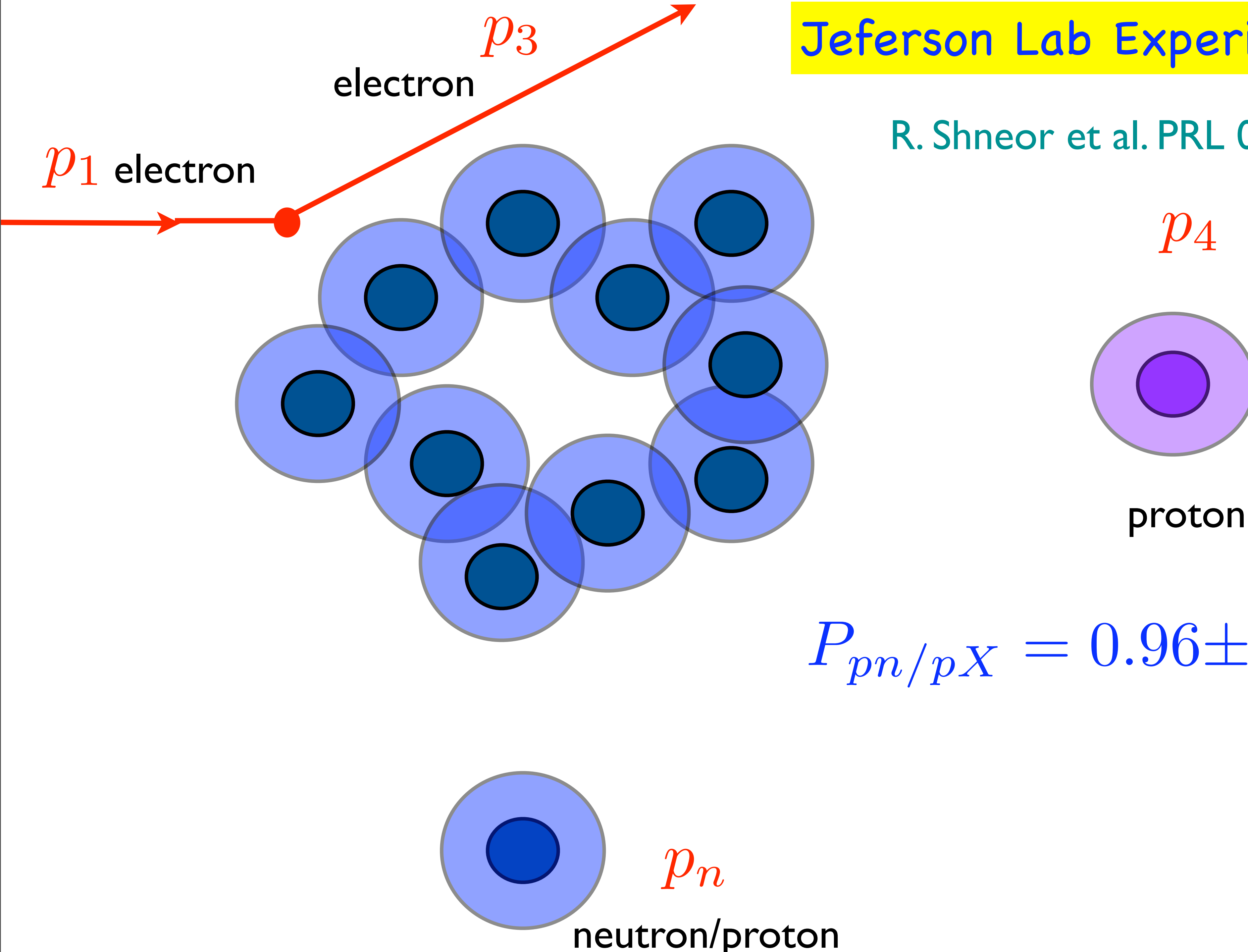
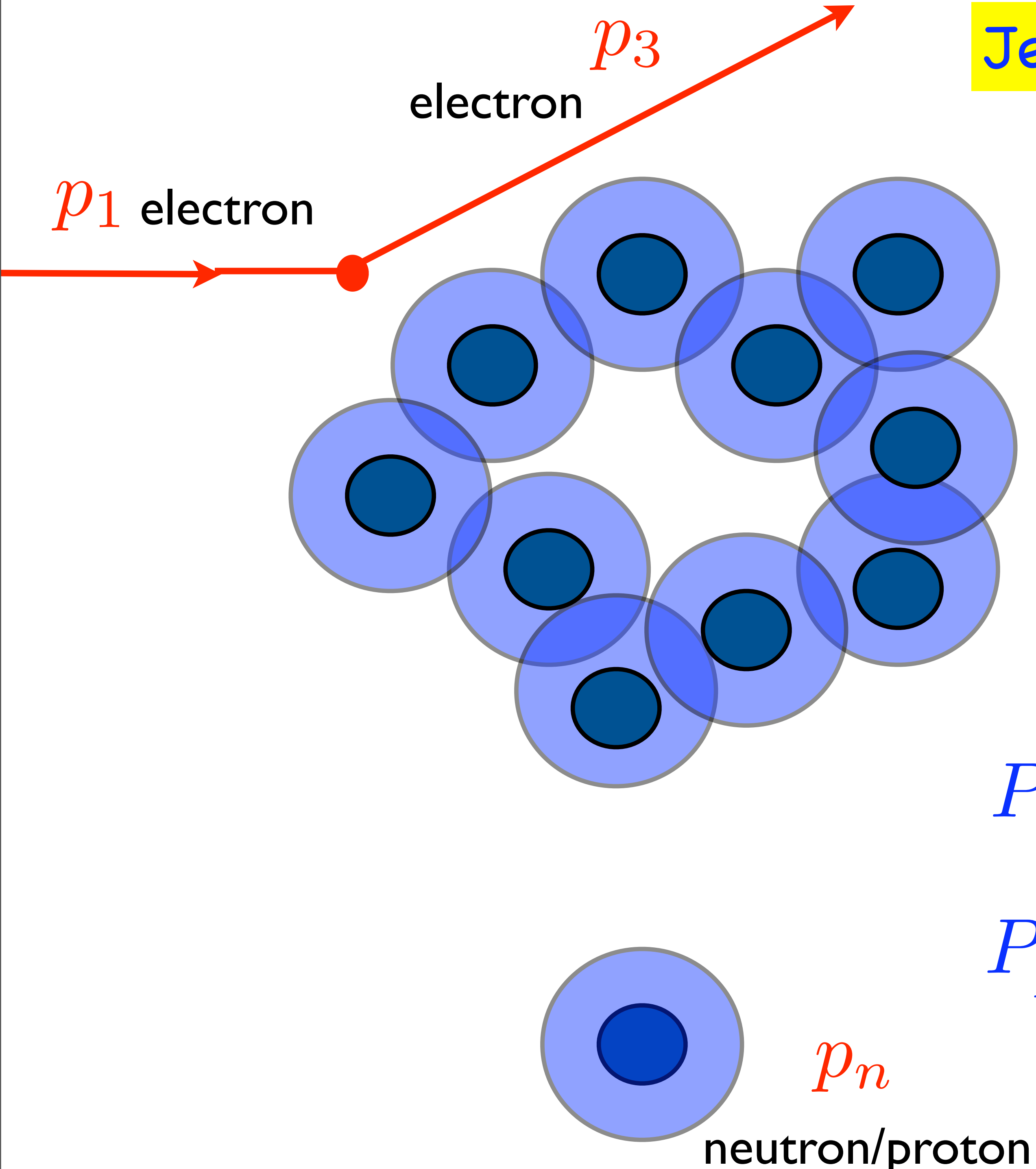
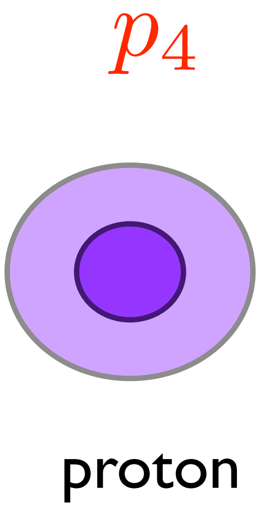


$$P_{pn/pX} = 0.96 \pm 0.22$$

Jeferson Lab Experiment

R. Shneor et al. PRL 07

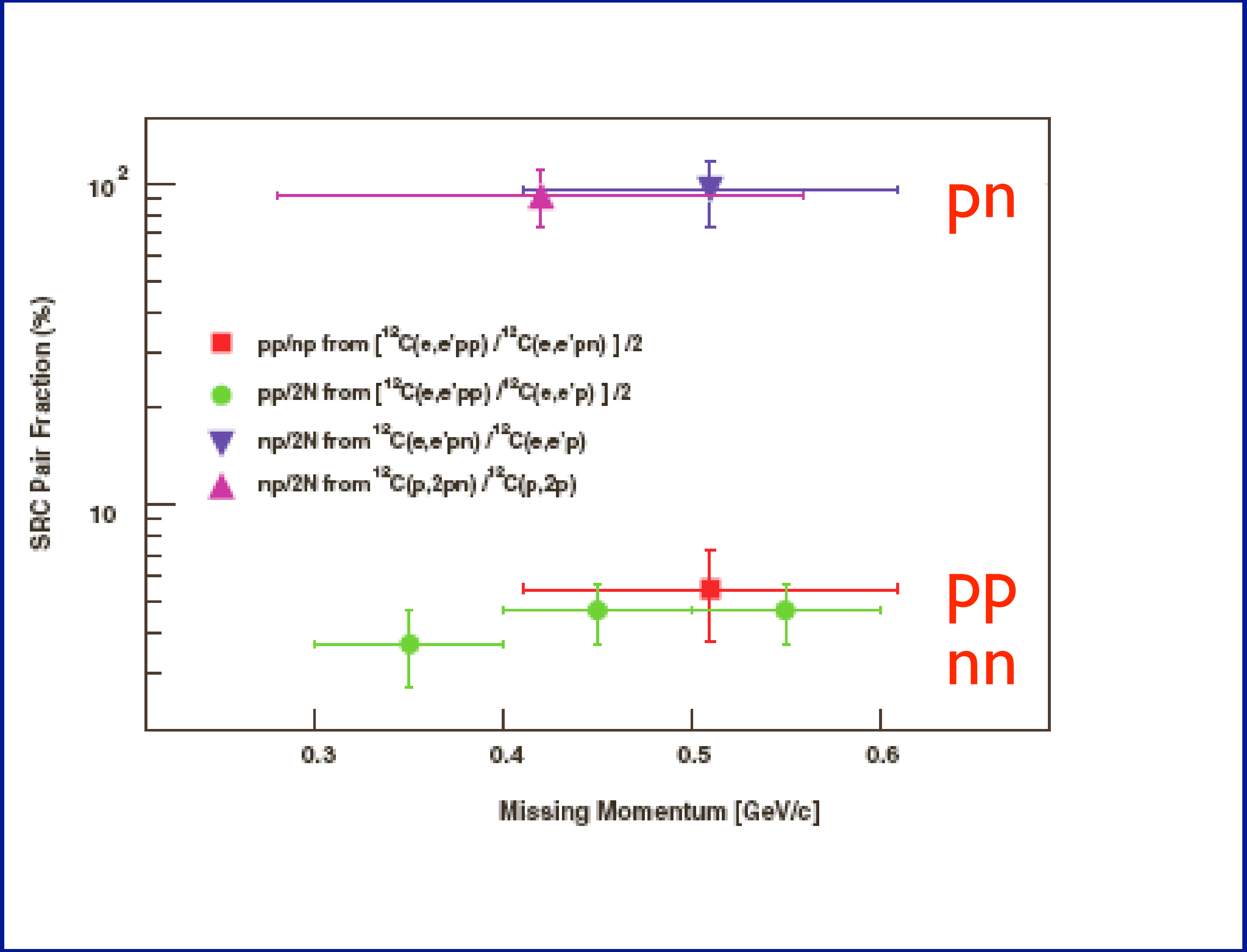




$$P_{pn/pX} = 0.96 \pm 0.22$$

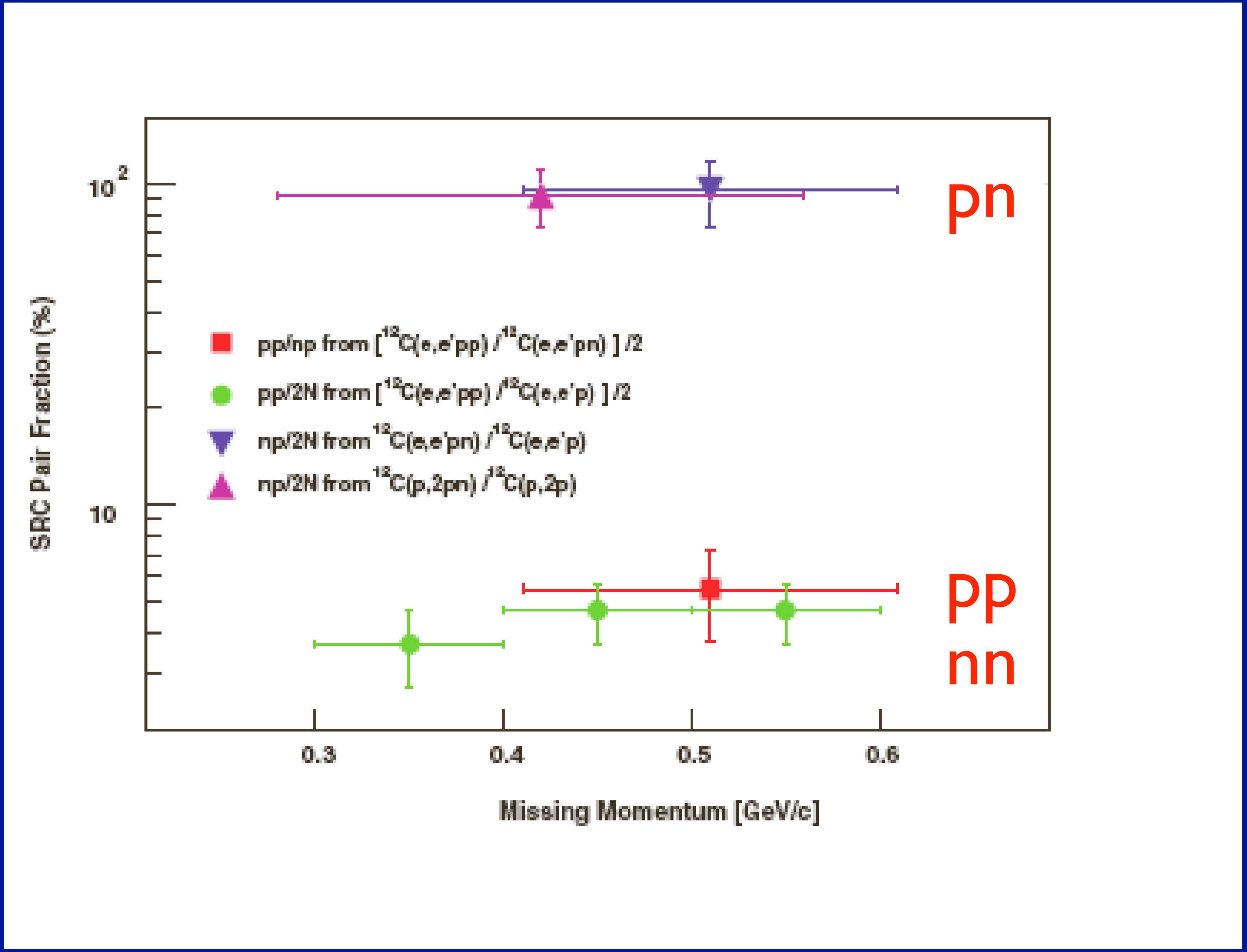
$$P_{pp/pn} = 0.056 \pm 0.018$$

Combined Analysis

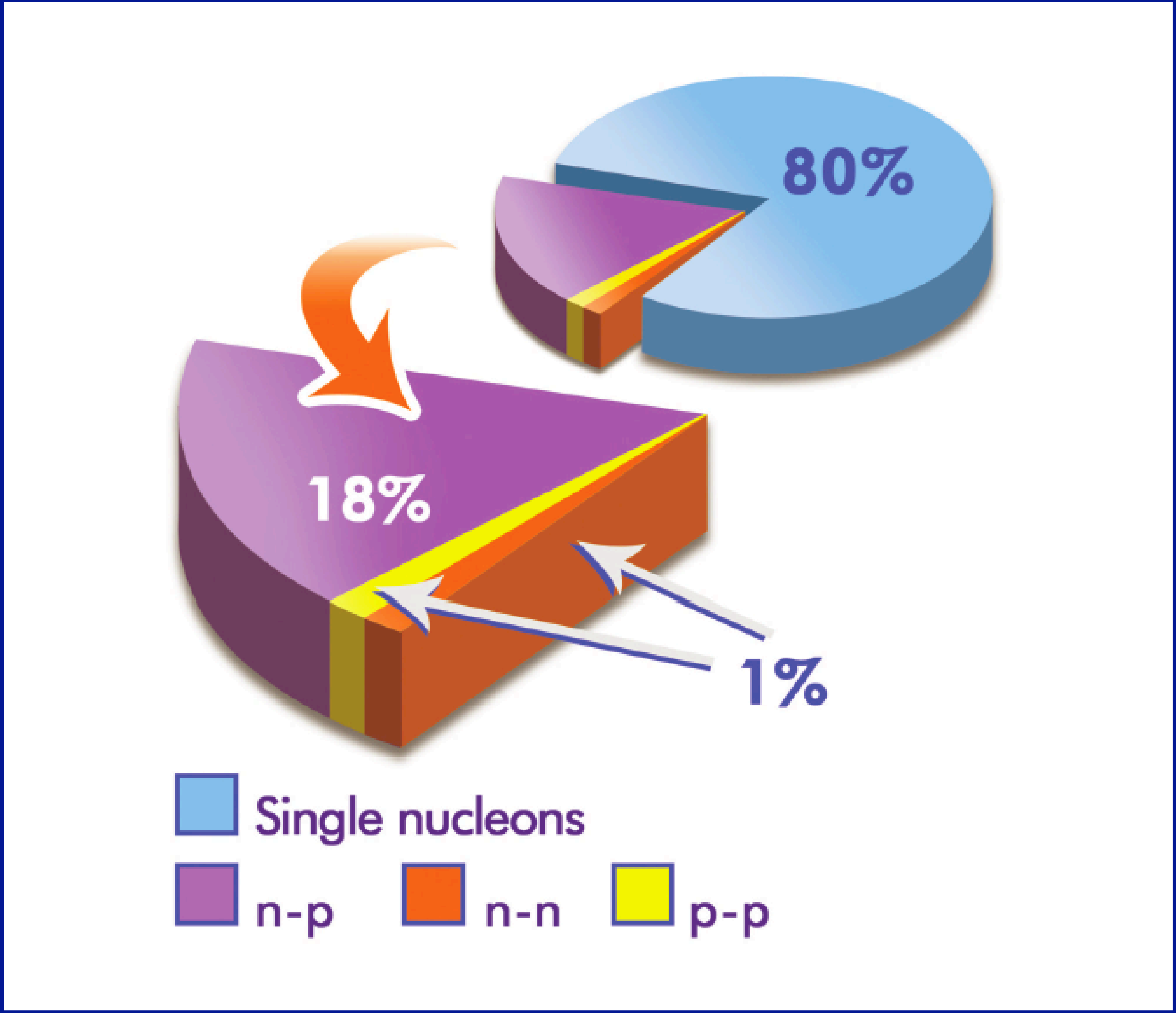


Combined Analysis

R.Subdei, et al Science , 2008



Combined Analysis



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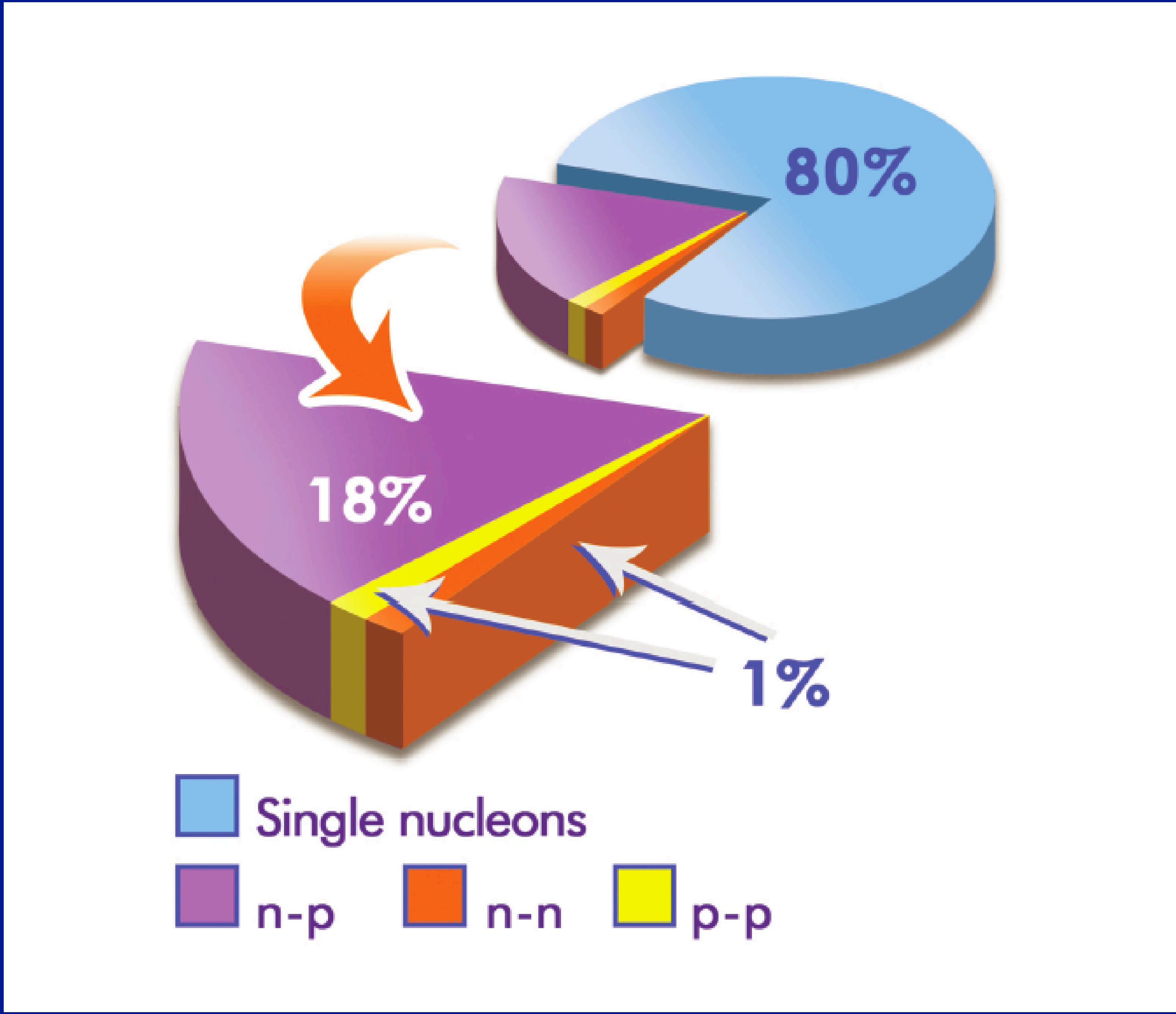
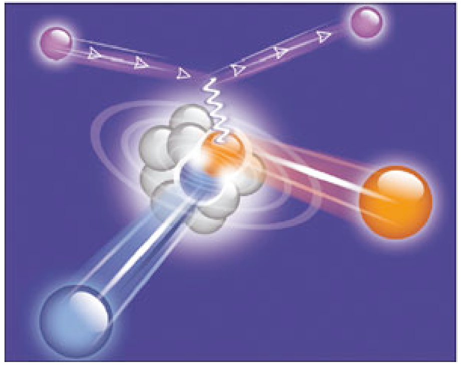


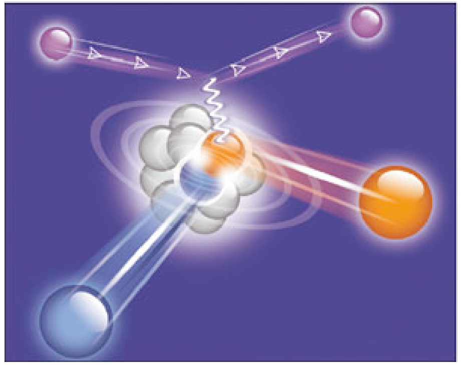


Press releases on SRC:

protonSRCfinal.pdf
EVA-SRC-discoverbnl.pdf
Protons Pair Up with Neutrons (from BNL News, pdf)
Science Magazine: Probing Cold Dense Nuclear Matter (pdf)
Nature Physics (Research Highlights: Unequal pairs (pdf))
Protons Pair Up With Neutrons, EurekAlert, May 29, 2008
Jefferson Lab in the News: Nuclear Pairs
Brookhaven National News: Protons Pair Up with Neutrons
Press release from Kent State University
ScienceDaily (Penn State University)
ScienceDaily (Penn State University)
ScientistLive (Penn State University)
On Target
Physics Today (July, 2008)
PHYSORG.com
NFC (in hebrew)
Tel Aviv University Press (in hebrew)
CERN Courier article (July, 2008)

R&D magazine
The A to Z of Nanotechnology
analitica-world
Matter News
Softpedia
News @ Old Dominion

from http://tauphy.tau.ac.il/eip



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Jefferson Lab in the News: Nuclear Pairs
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ScientistLive (Penn State University)
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NFC (in hebrew)
Tel Aviv University Press (in hebrew)
CERN Courier article (July, 2008)

R&D magazine
The A to Z of Nanotechnology
analitica-world
Matter News
Softpedia
News @ Old Dominion

from http://tauphy.tau.ac.il/eip

Some Conclusions

- We learned to probe directly the short range correlations in nuclei with relative momenta up to 600 MeV/c

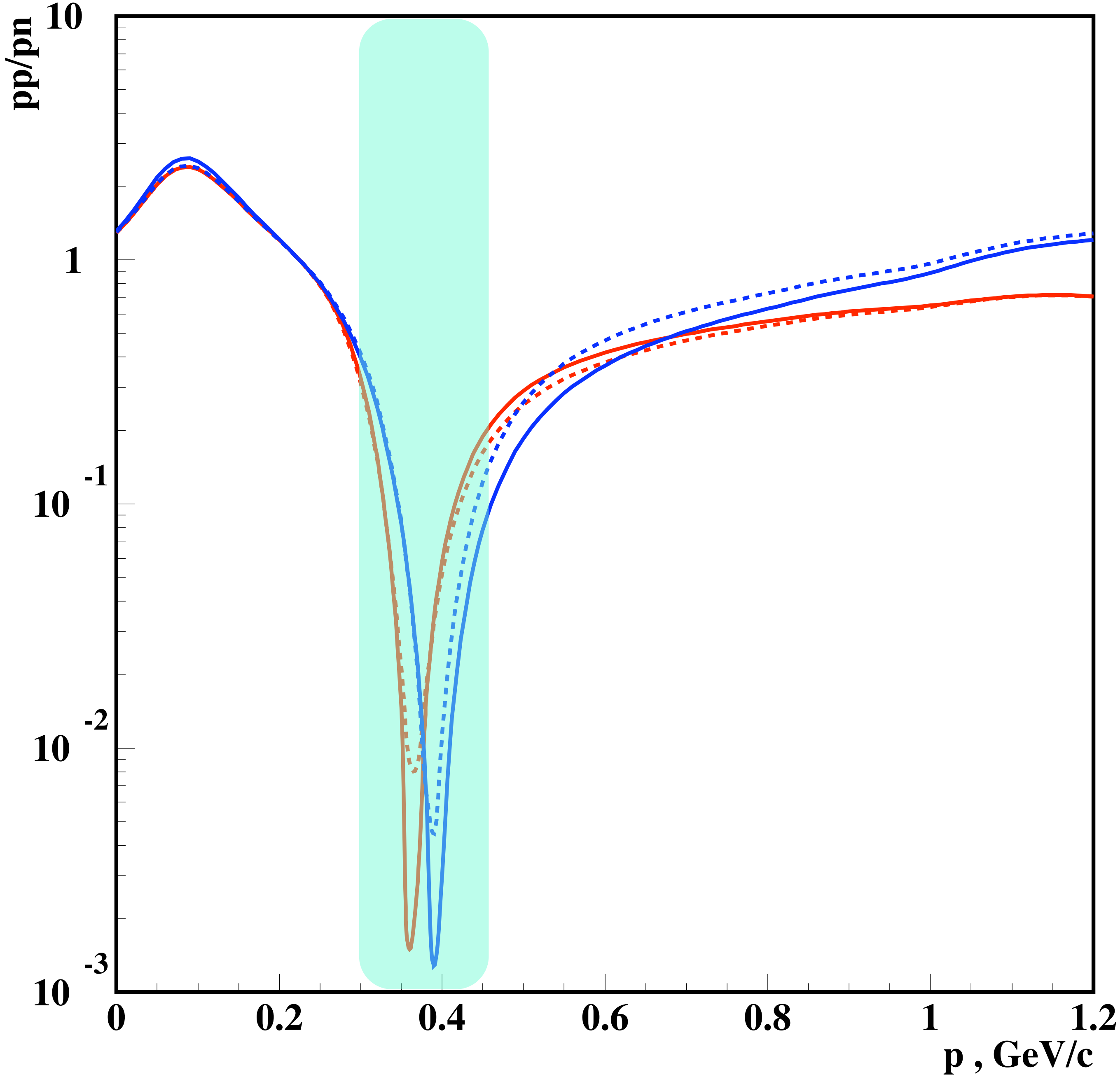
- SRC's are dynamically high-density fluctuations

- Final State Interactions are localized in SRCs

- There is a strong suppression (factor of 20) of pp and nn SRCs as compared to pn SRCs

- this disparity is related to the dominance of the strong tensor force at intermediate to short distances

Relativism and core of the NN interaction



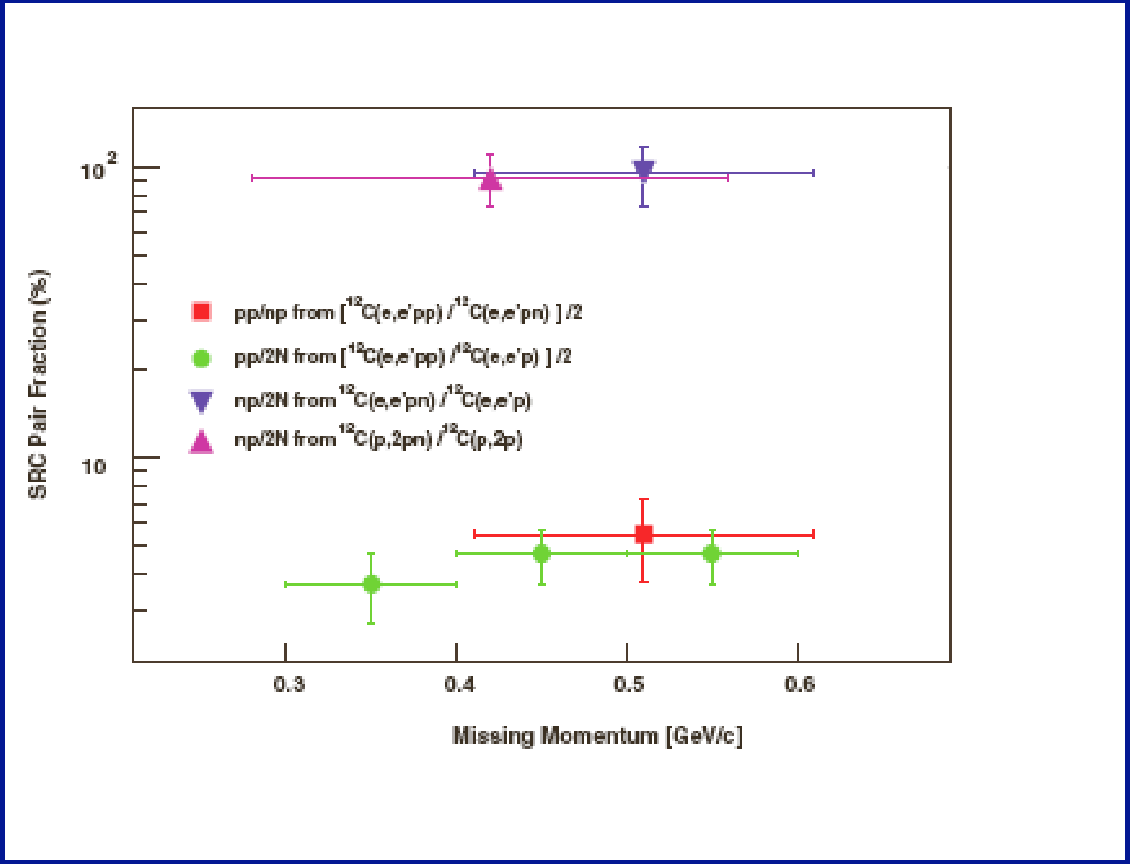
Dominance of T=0 channel of NN interaction

What these studies can tell us about structure of Neutron Stars ?

- Transition from hadronic to quark degrees of freedom in high density nuclear matter

- Role of the protons in highly asymmetric nuclear matter

Transition from hadronic to quark degrees of freedom in high density nuclear matter



$$P_{pn} + P_{pp} + P_{nn} = 1$$

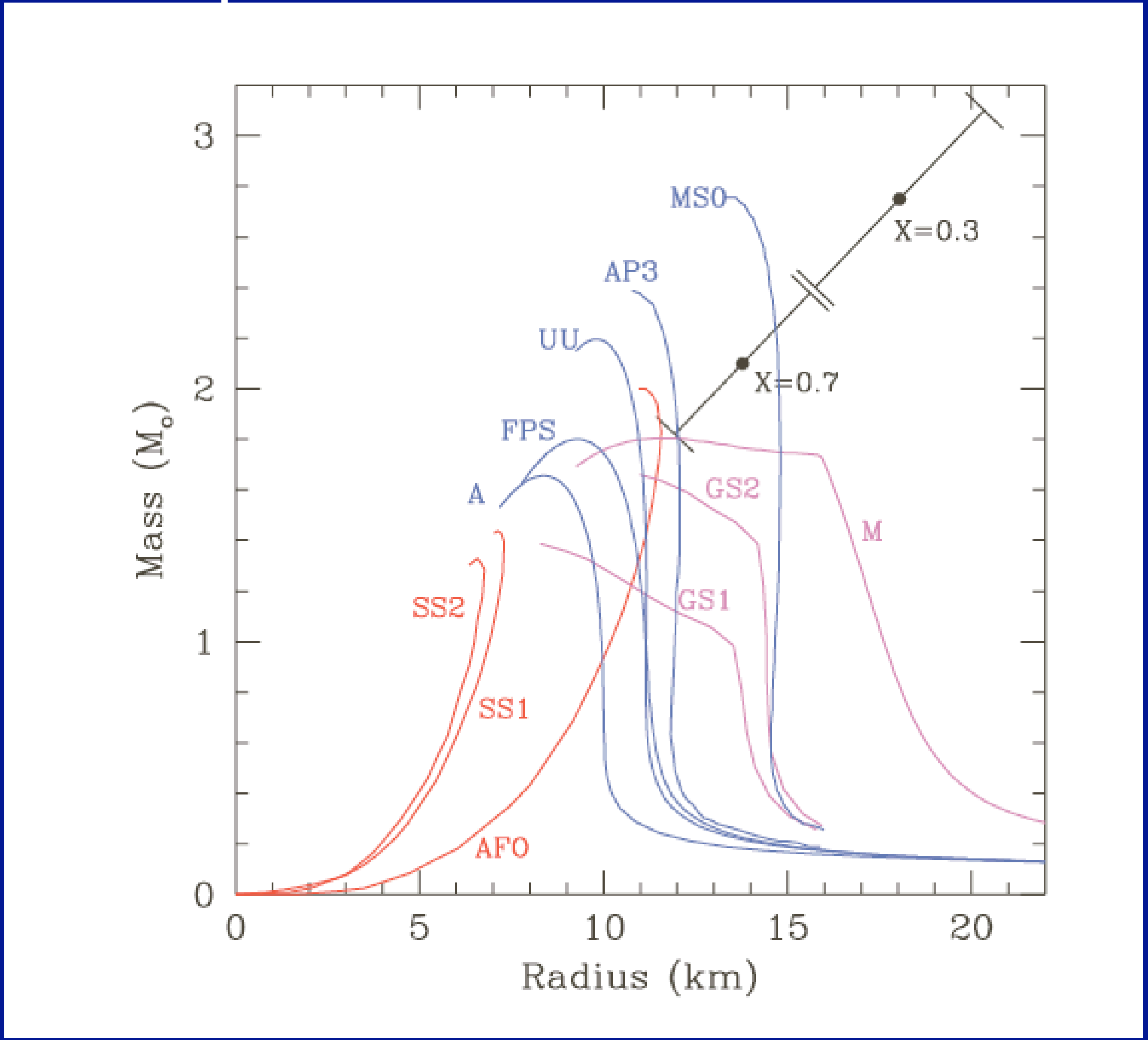
for internal momenta up to 600 MeV/c

nucleonic degrees freedom are dominant for up to $\sim (4-5)\rho_0$

T=0 is dominant: inelasticities appear at $2(M_\Delta - M_N) \approx 300 MeV$

$k \sim 700 MeV/c$

- This my support the phenomenological observation that equation of state is rather stiff



The Mass and Radius estimate of EXO-0748-676 provides the evidence for stiff Equation of State

Strong Modification of Proton momentum distribution in asymmetric nuclear matter

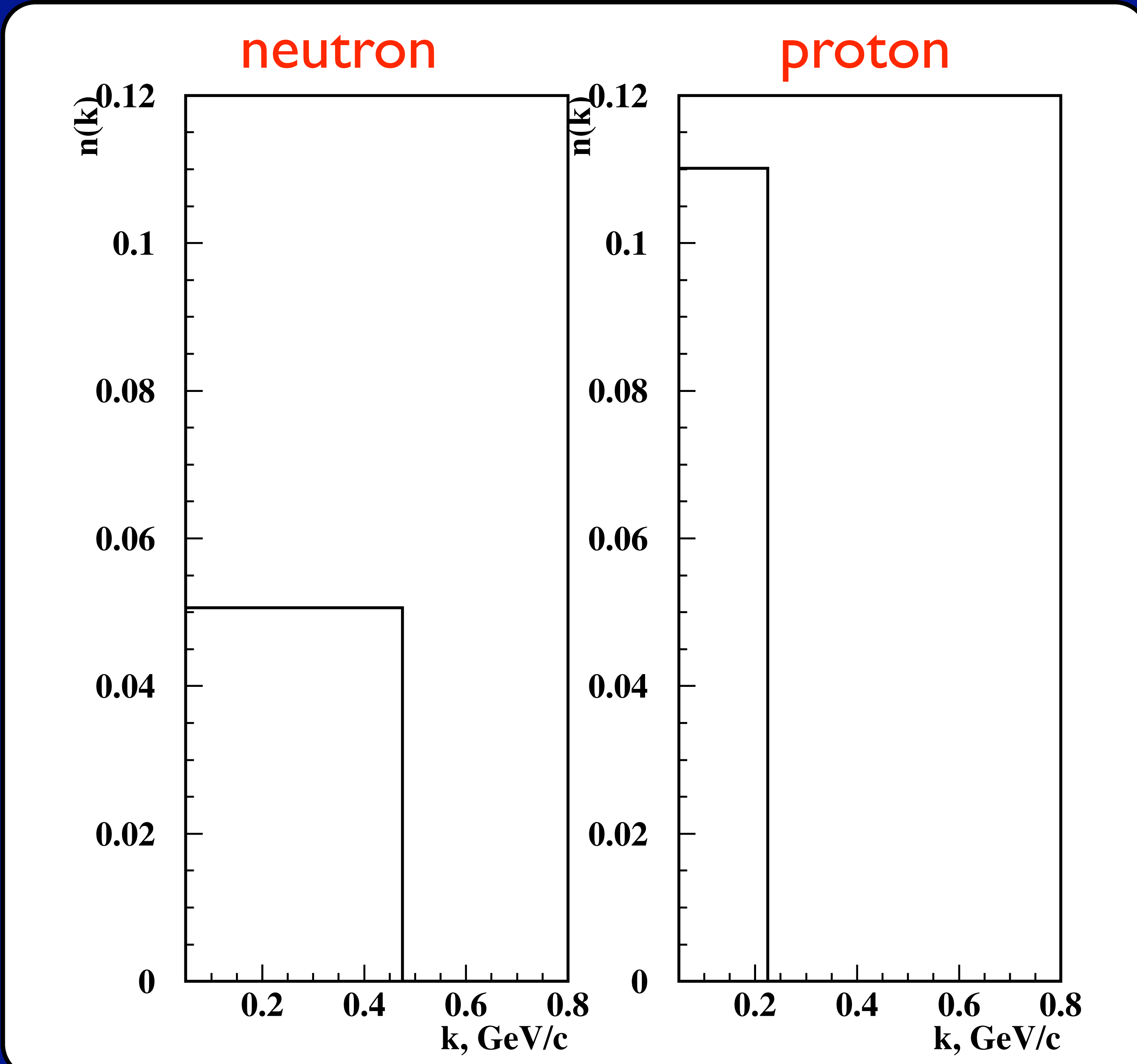
neutron proton

- consider asymmetric mixture of noninteracting neutron and proton fermi gases

$$x_p = \frac{n_p}{n_n}$$

$$(x_p)^{\frac{1}{3}} k_F(n) = k_F(p)$$

Strong Modification of Proton momentum distribution in asymmetric nuclear matter



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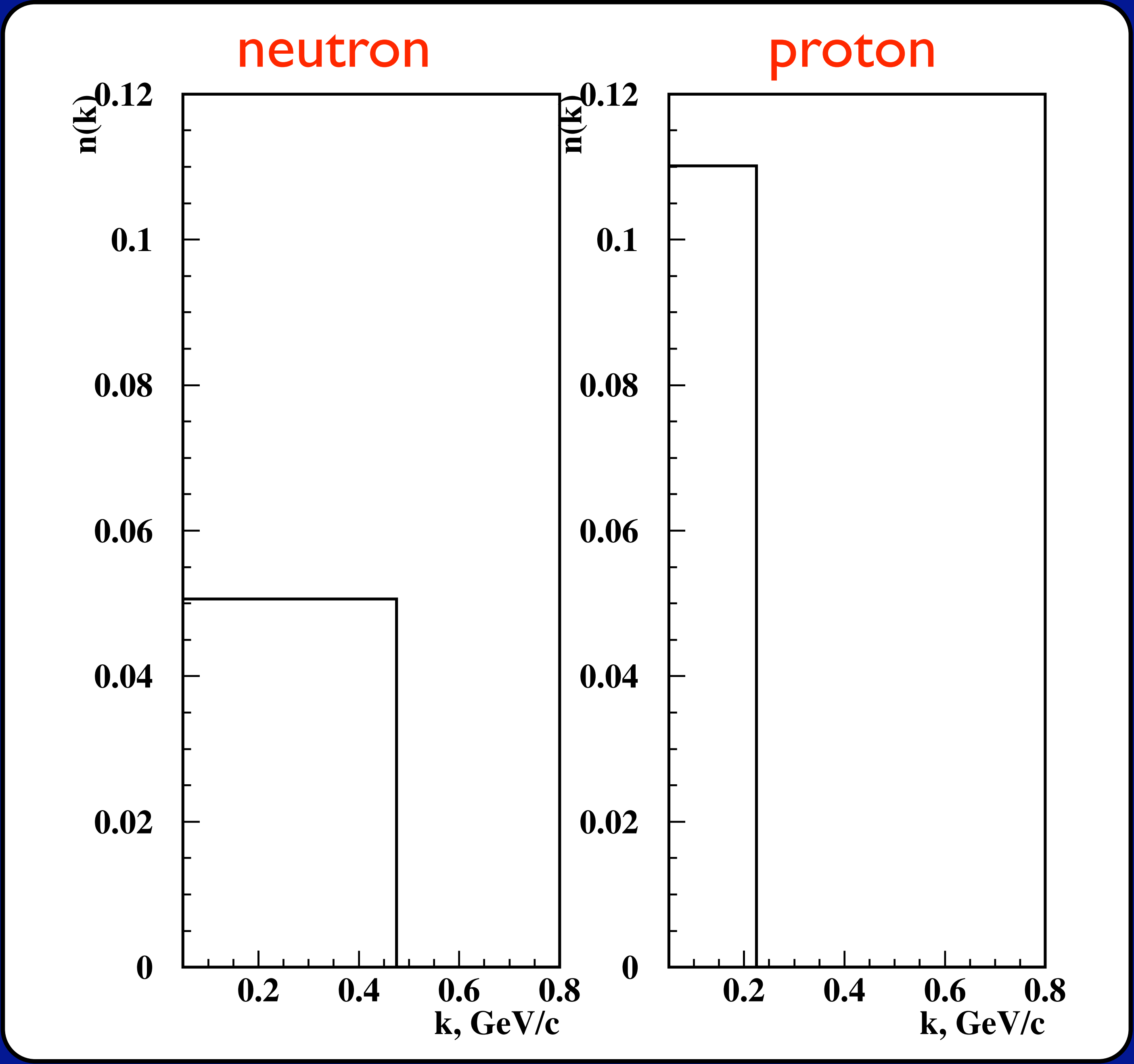

- consider asymmetric mixture of noninteracting neutron and proton fermi gases

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-switch the pn interaction

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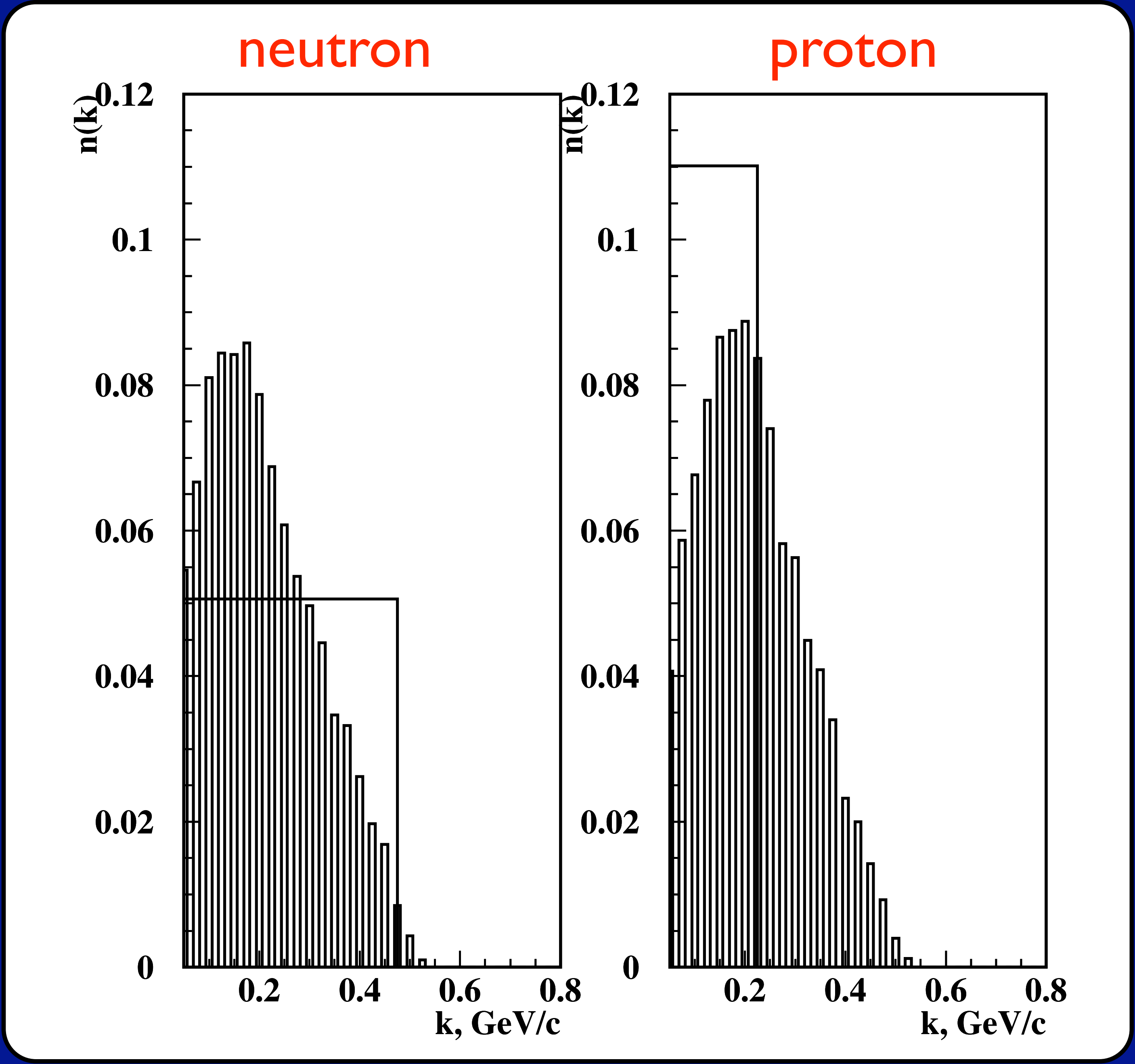


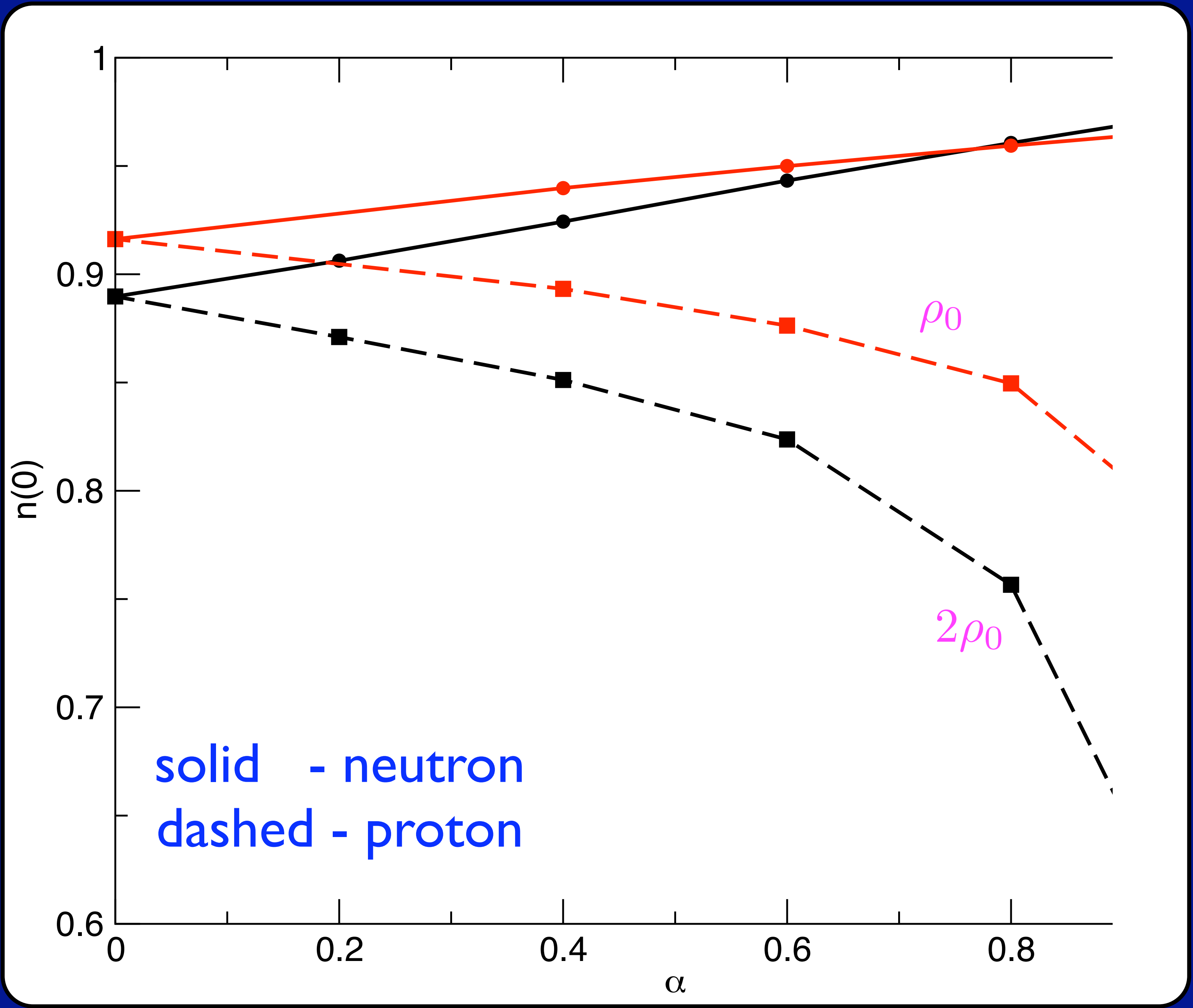
- consider asymmetric mixture of noninteracting neutron and proton fermi gases

$$x_p = \frac{n_p}{n_n}$$

$$(x_p)^{\frac{1}{3}} k_F(n) = k_F(p)$$

-switch the pn interaction

More realistic case
Self-Consistent Green-Function Method
(for finite T= 5MeV)



Frick, Muether, Rios, Polls, Ramos PRC 2005

One Possible Effect of Proton Momentum Modifcation

Continuos cooling of the Neutron Stars due to
Direct URCA Processes even for $x_p < \frac{1}{9}$,
which follows from the condition for $2k_F(p) > k_F(n)$.

for noninteracting degenerate gas distributions for p and n

Lattimer, Pethic, Prakash, Haensel PRL 1991

$$p + e^- \rightarrow n + \nu_e$$

Conclusions

- High Energy Nuclear Physics may become an earthbound lab for studies several dynamical aspects of dense nuclear matter

- the available data from high-energy nuclear reactions allow to put a limit for quark degrees of freedom for up to 600 MeV/c relative momentum between two nucleons

- Analysis also strongly indicates on the dominance of T = 0 isosinglet states in 2N SRCs in 300-600 MeV/c region

- There is a strong evidence that due to dominant tensor part at short distance, proton spectrum is strongly modified in highly asymmetric nuclear matter