12th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

EINN2017

TEL AVIV UNIVERSITY

A pre-workshop Pedagogical Talk

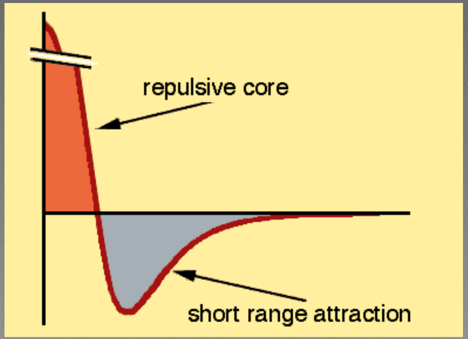
"Nuclear Matter at Short Range"

Paphos, Cyprus

29 October 2017

Eli Piasetzky Tel Aviv University, Israel

Nuclear Physics 101

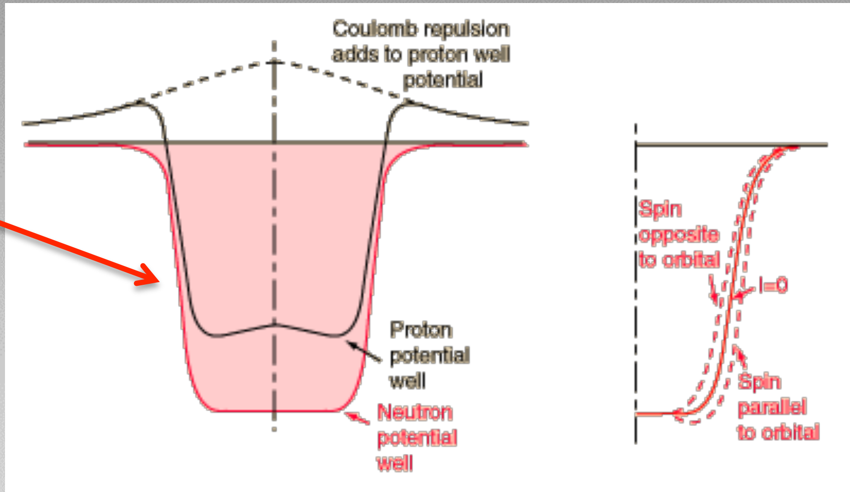


- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} V_{2N}(i,j) + \sum_{i<j<k=1}^{A} V_{3N}(i,j,k) + $$

- Mean-Field Approximation:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i=1}^{A} V(i)$$



Results in an "atom-like" shell model:

- Ground state energies
- Excitation Spectrum
- …

E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize

Beyond the Mean Field: NN Correlations

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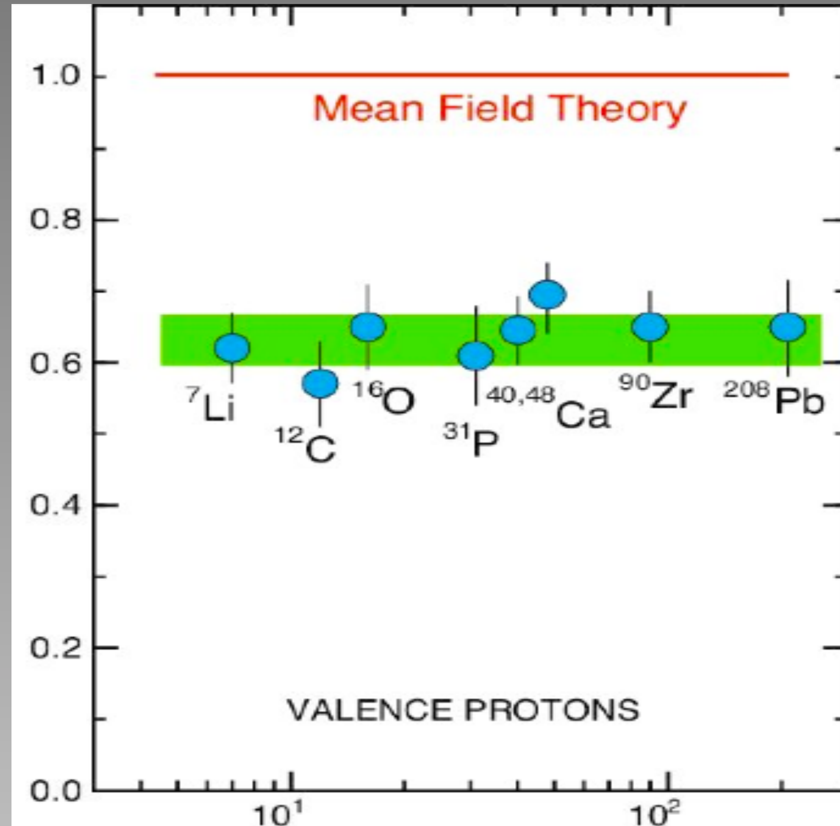
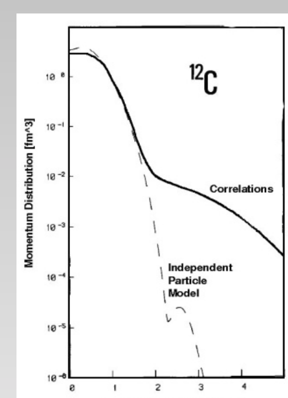
Spectroscopic factors for (e, e'p) reactions

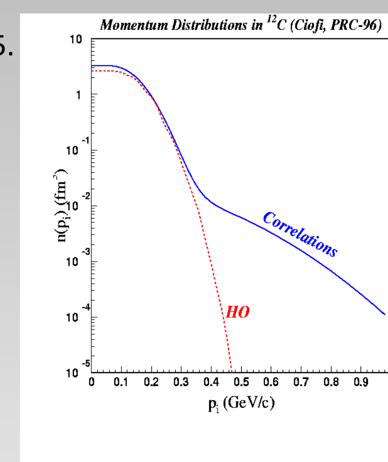
show only 60-70% of the expected single-particle strength.



L. Lapikas, Nucl. Phys. A553, 297c (1993)

Benhar et al., Phys. Lett. **B** 177 (1986) 135.





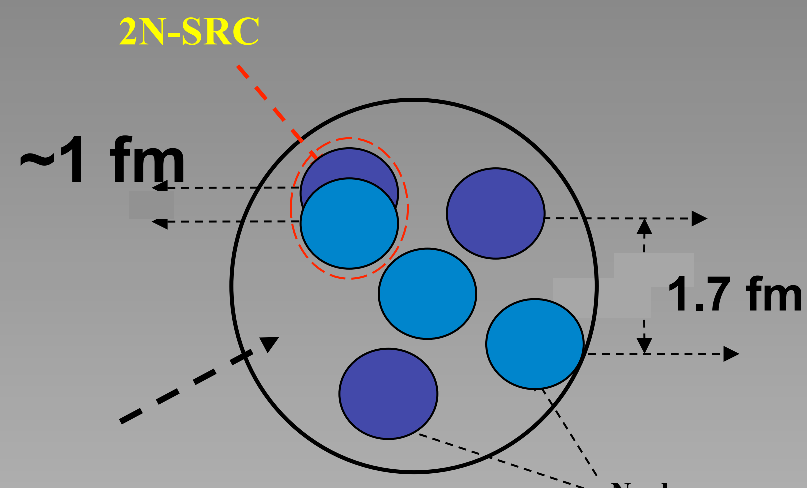
MISSING :

Correlations Between Nucleons

SRC ~R_N LRC ~R_A

What are Short Range Correlations in nuclei ?

SRC ~R_N LRC ~R_A

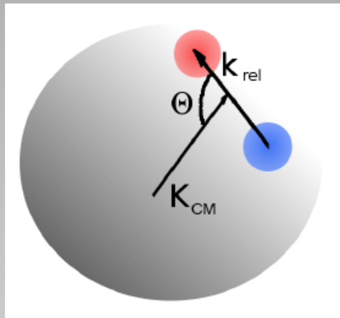


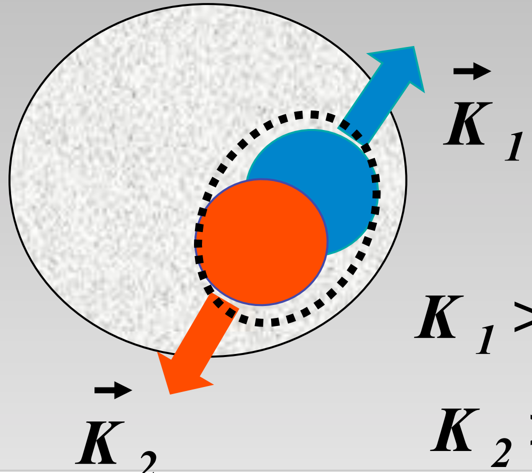
$\rho_o = 0.16\ GeV/fm^3$

In momentum space:

$K_{rel} > K_F$

$K_{CM} < K_F$





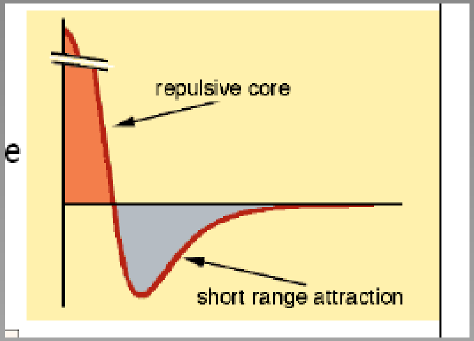
$\cong \vec{K}_1 \quad \vec{K}_2$

$K_1 > K_F ,$

$K_2 > K_F$

A pair with large relative momentum between the nucleons and small CM momentum.

A description of nuclei at distance scales small compared to the radius of the constituent nucleons needs to take into account,

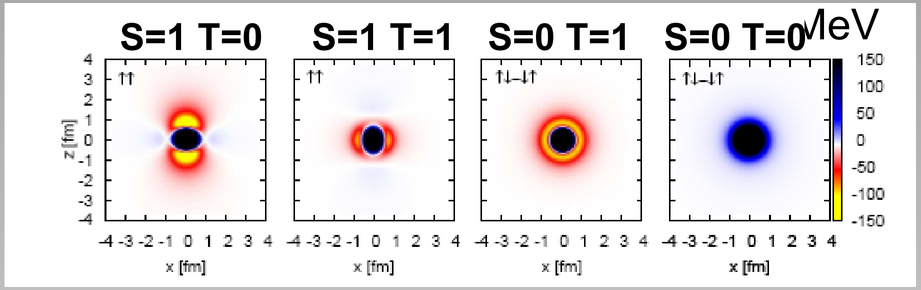


Short range repulsion

(common to many other systems)

Intermediate- to long-range tensor attraction

(unique to nuclei)



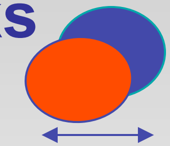
Argonne V8 potential

ArXiv 1107.4956

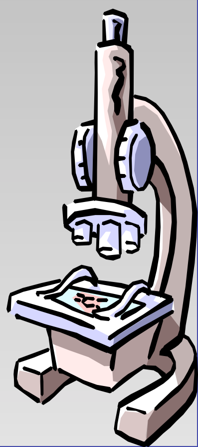
Very difficult many-body problem

presents a challenge to both experiment and theory

This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high energy and large momentum transfer reached by present facilities.



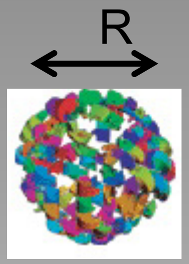
~1 fm

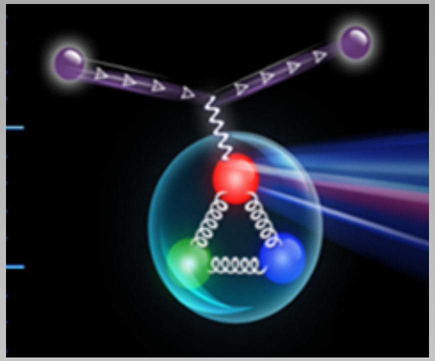


Hard scattering :

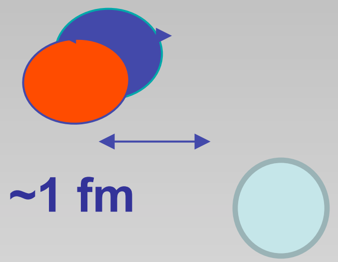
High-energy (small de Broglie wavelength λ) and large-momentum transfer q)

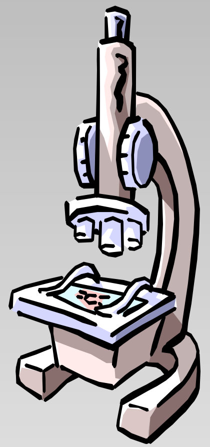
$$\lambda < R \qquad\qquad q \cdot R < 1$$

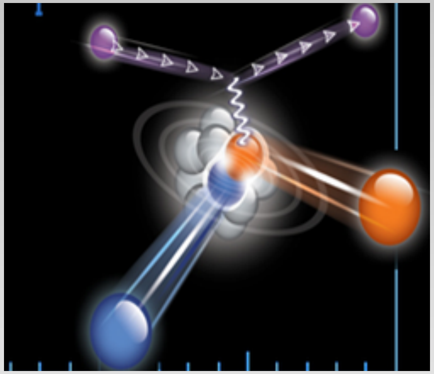




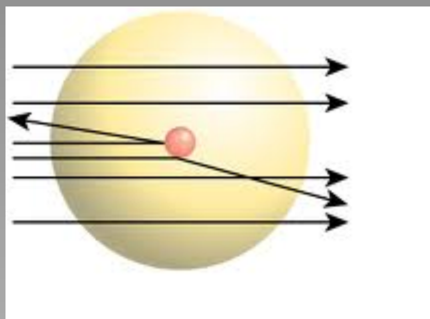
Hard scattering has the resolving power required to probe the internal (partonic) structure of a complex target





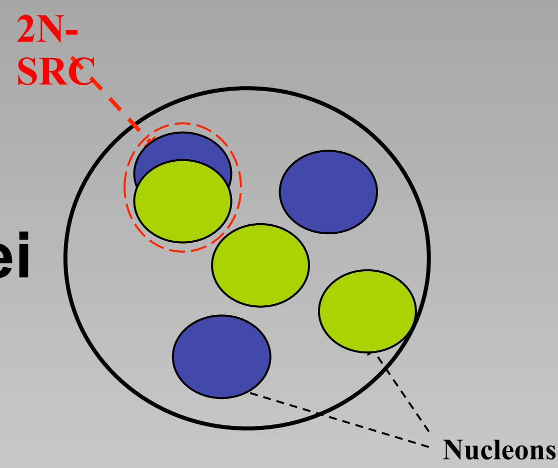


Hard scattering has the resolving power required to probe the internal (partonic) structure of a complex target



Rutherford scattering

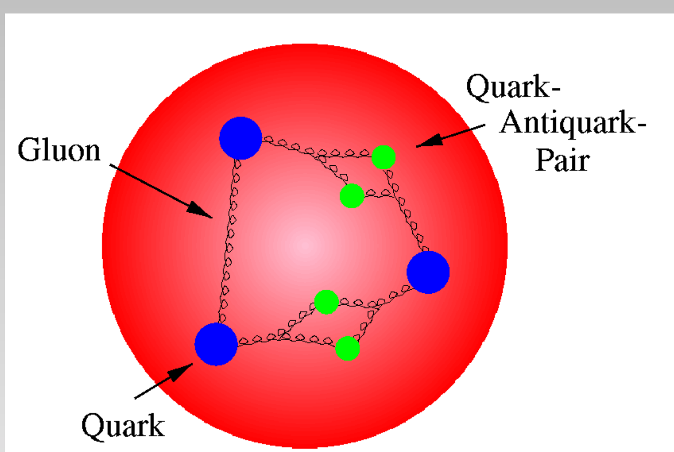
structure of atoms



Hard nuclear reactions

hadronic structure of nuclei

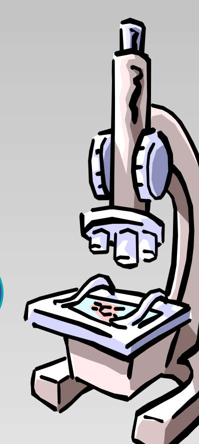
Scale:
several GeV

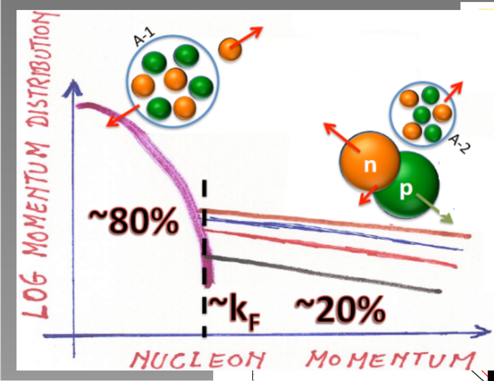


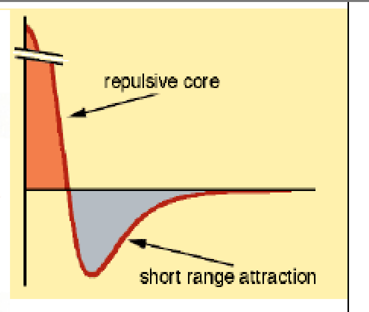
DIS

Scale:
several tens of GeV

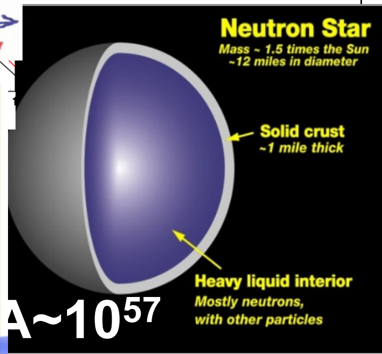
partonic structure
of hadrons

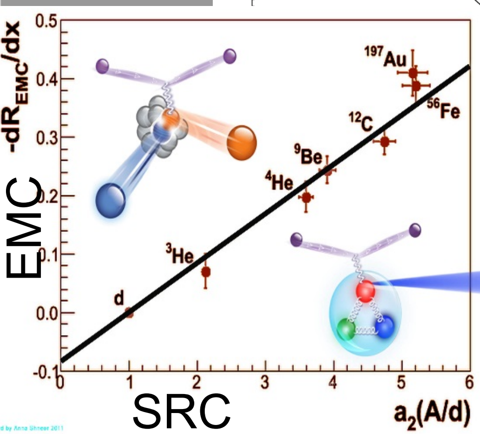


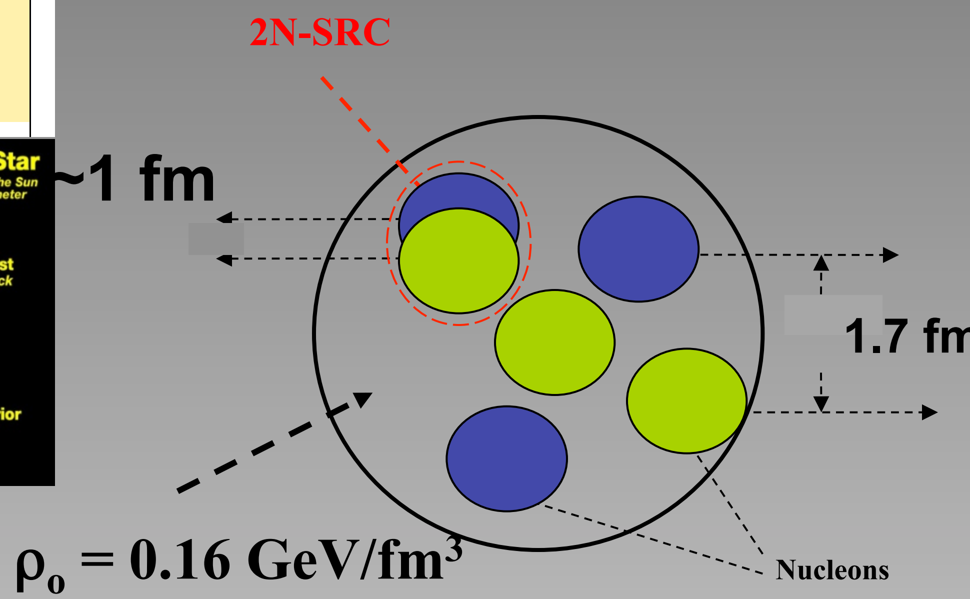




What SRC in nuclei can tell us about:







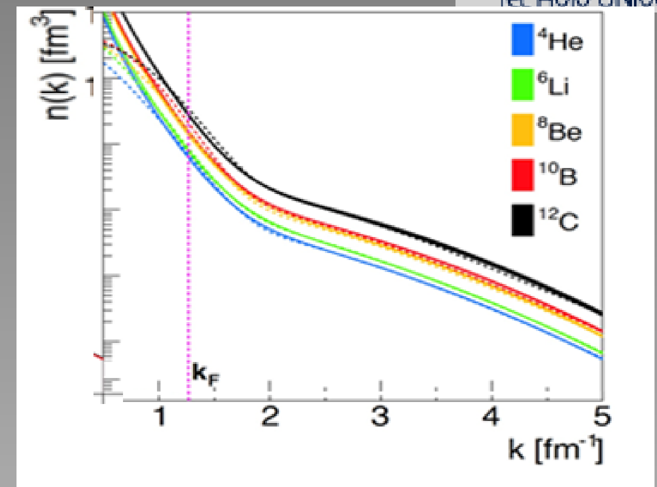
- **High – Momentum Component of the Nuclear Wave Function.**
- **The Strong Short-Range Force Between Nucleons.**

  tensor force, repulsive core, 3N forces
- **Cold-Dense Nuclear Matter (from deuteron to neutron-stars).**
- **Nucleon structure modification in the medium ?**

  EMC and SRC

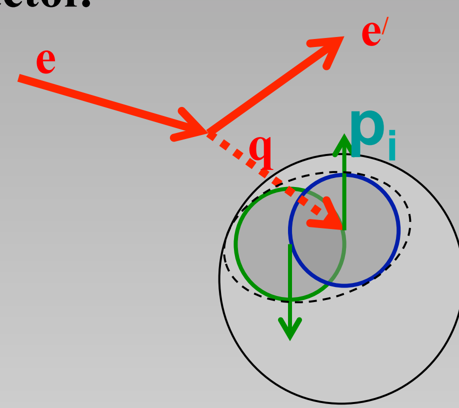
- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.

ab-initio VMC calculations



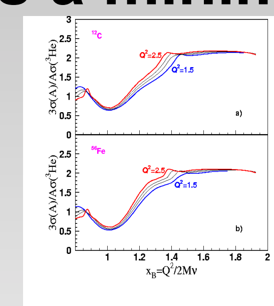
- Can be explained by 2N-SRC dominance.
- Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.

In A(e,e') the momentum of the struck proton (p_i) is unknown.



But: For fixed high Q^2 and $x_B>1$, x_B determines a minimum p_i

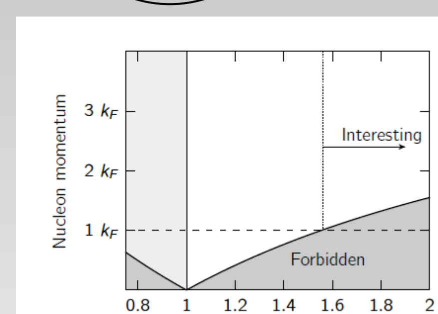
Prediction by Frankfurt, Sargsian, and Strikman:



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega}$$



Inclusive scattering results from data mining (EG2c)

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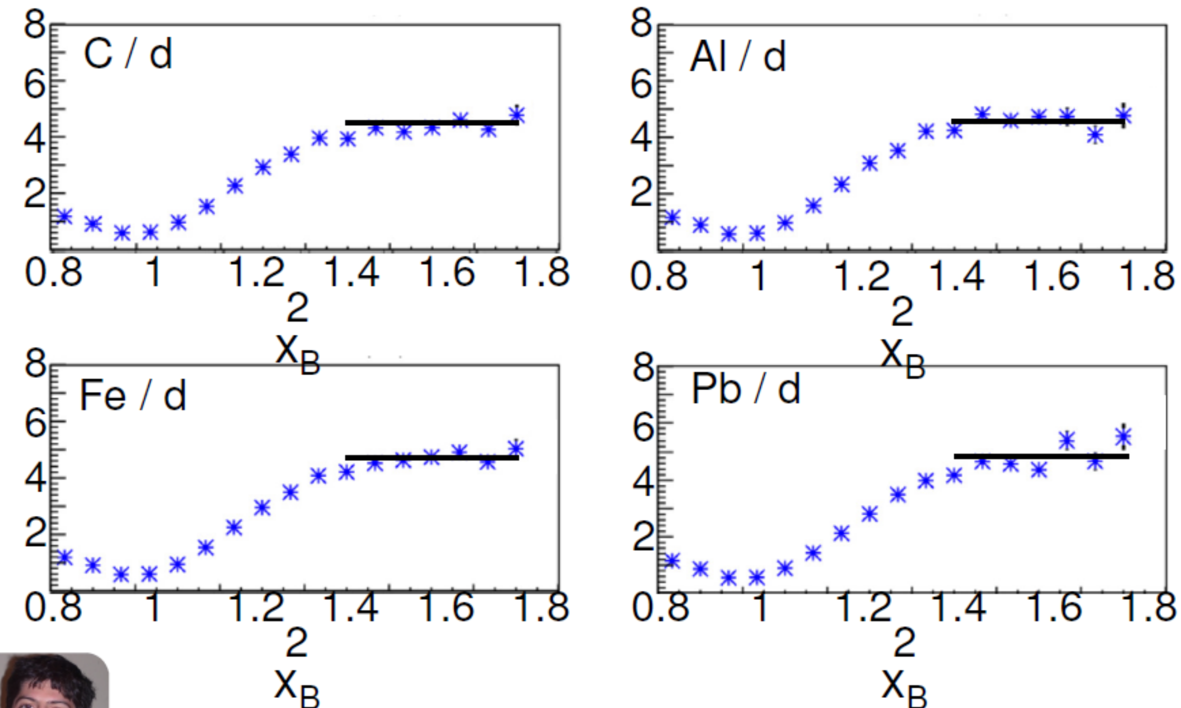
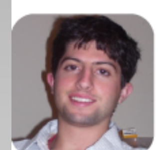
Q^2=1.55 GeV^2

a_{2N}(A/d)

	Fomin *et al.*	Fomin *et al.* [excluding the CM motion correction]
	5	6
^{3}He	1.93 ± 0.10	2.13 ± 0.04
^{4}He	3.02 ± 0.17	3.60 ± 0.09
^{9}Be	3.37 ± 0.17	3.91 ± 0.12
^{12}C	4.00 ± 0.24	4.75 ± 0.16
^{56}Fe	4.33 ± 0.28	5.21 ± 0.19
^{197}Au	4.26 ± 0.29	5.16 ± 0.21





Barak Schmookler (MIT)

Jlab /Hall B: K. Sh. Egiyan et al. PRC 68, 014313 (2003)

K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

Jlab/Hall C: N. Fomin et al. PRL. 108:092502, 2012.

More r(A,d) data:

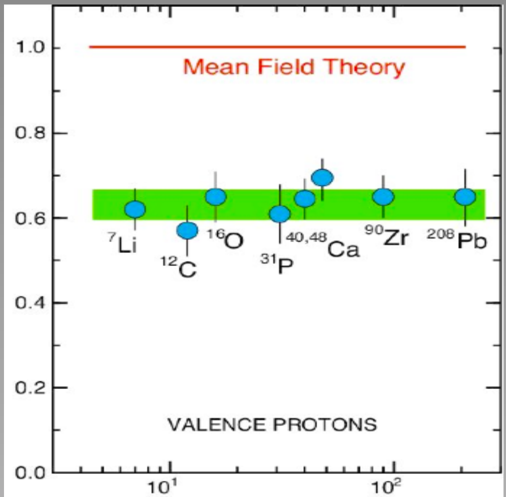
SLAC D. Day et al. PRL 59,427(1987)

Summary

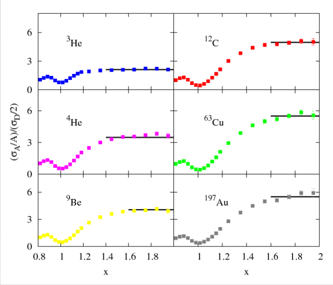
Hard Semi inclusive scattering
A(e, e'p)

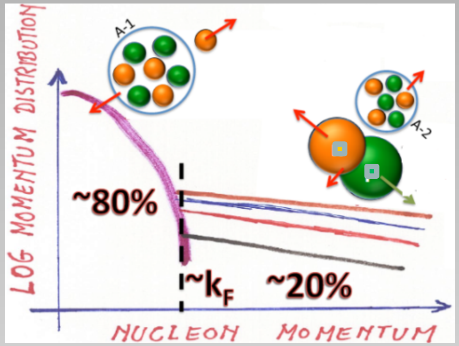
Only 60-70% of the expected single-particle strength.

SRC and LRC



Hard inclusive scattering
A(e, e')

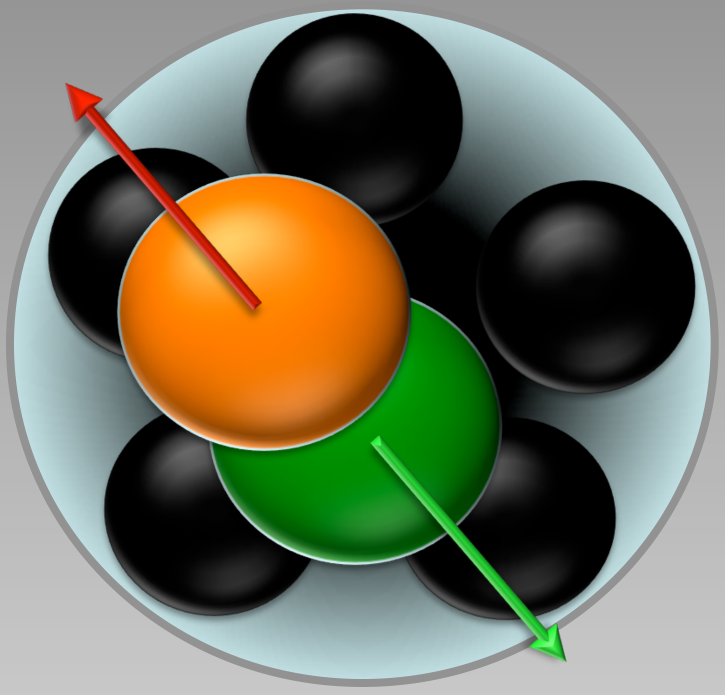




This ~20% includes all three isotopic compositions (pn, pp, or nn) for the 2N-SRC phase in ^{12}C.

Hard exclusive scattering
A(e, e'pp) and A(e, e'pn)

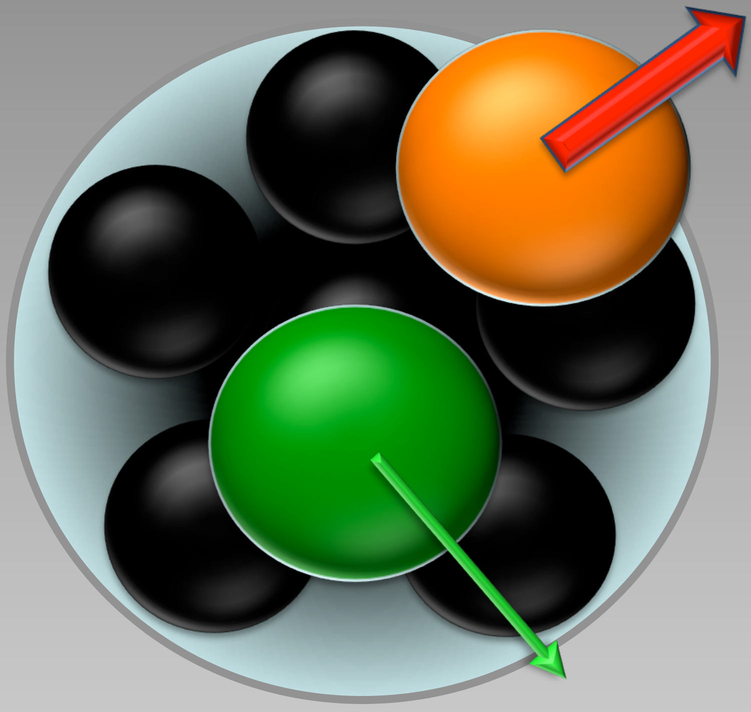
Hard exclusive triple – coincidence measurements



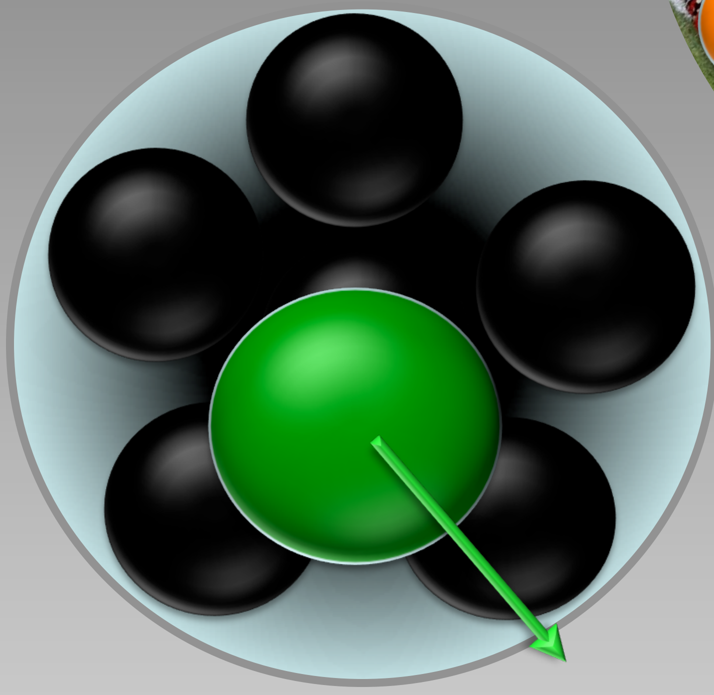
Quasi-Free scattering off a nucleon in a short range correlated pair

triple – coincidence measurements

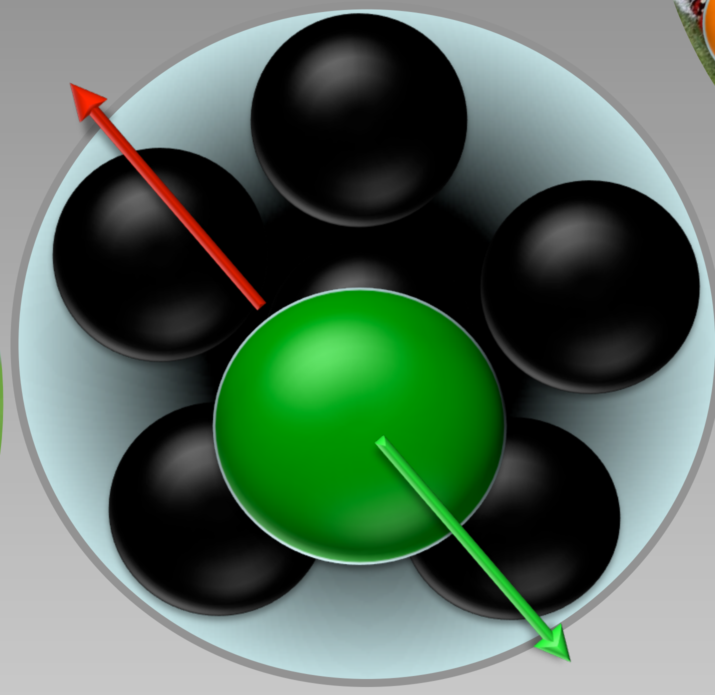
triple – coincidence measurements



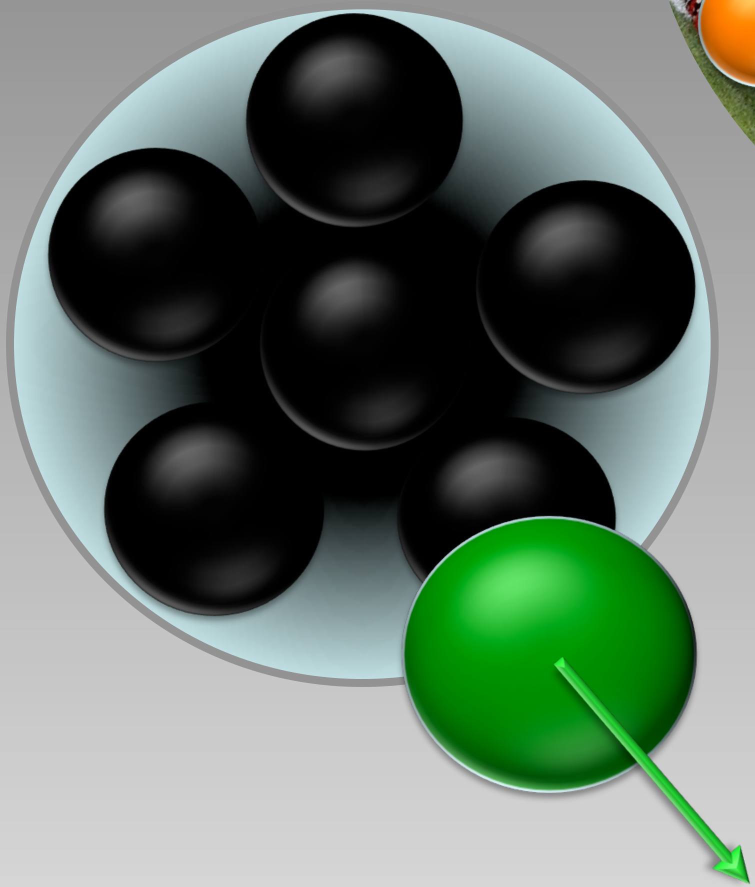
triple – coincidence measurements



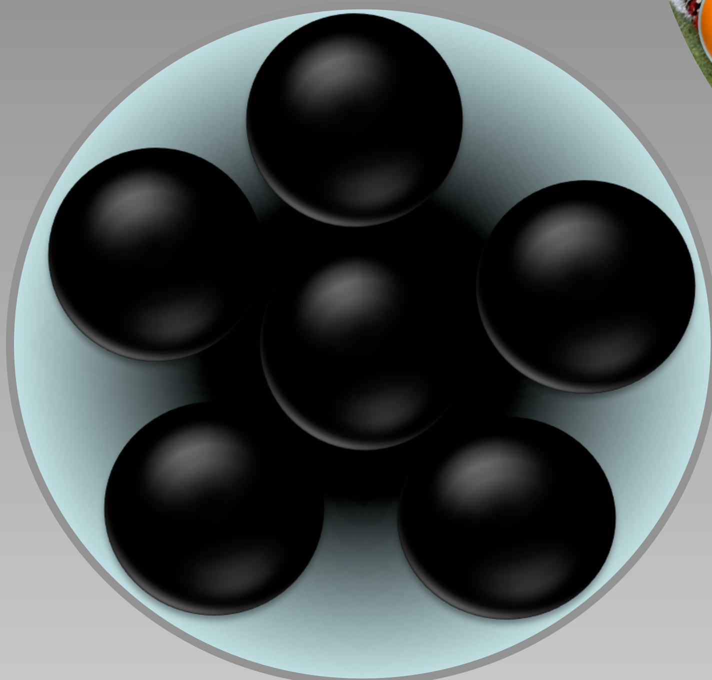
triple – coincidence measurements



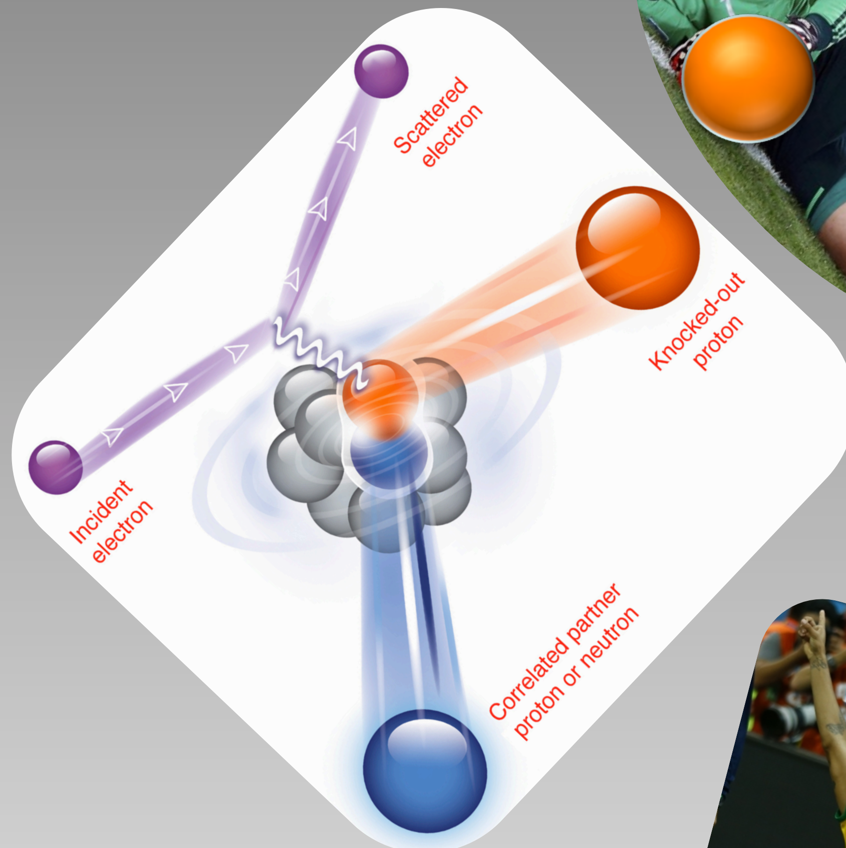
triple – coincidence measurements



triple – coincidence measurements

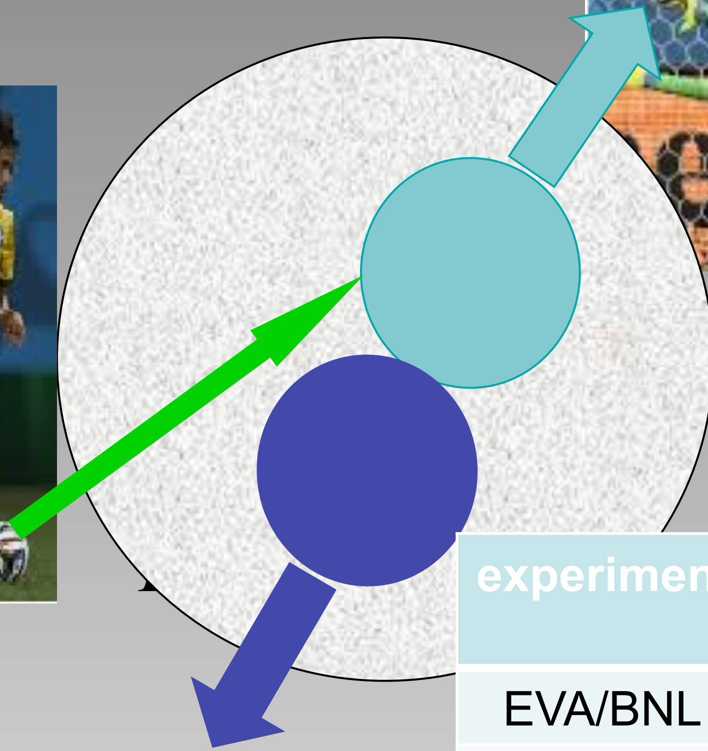


triple – coincidence measurements



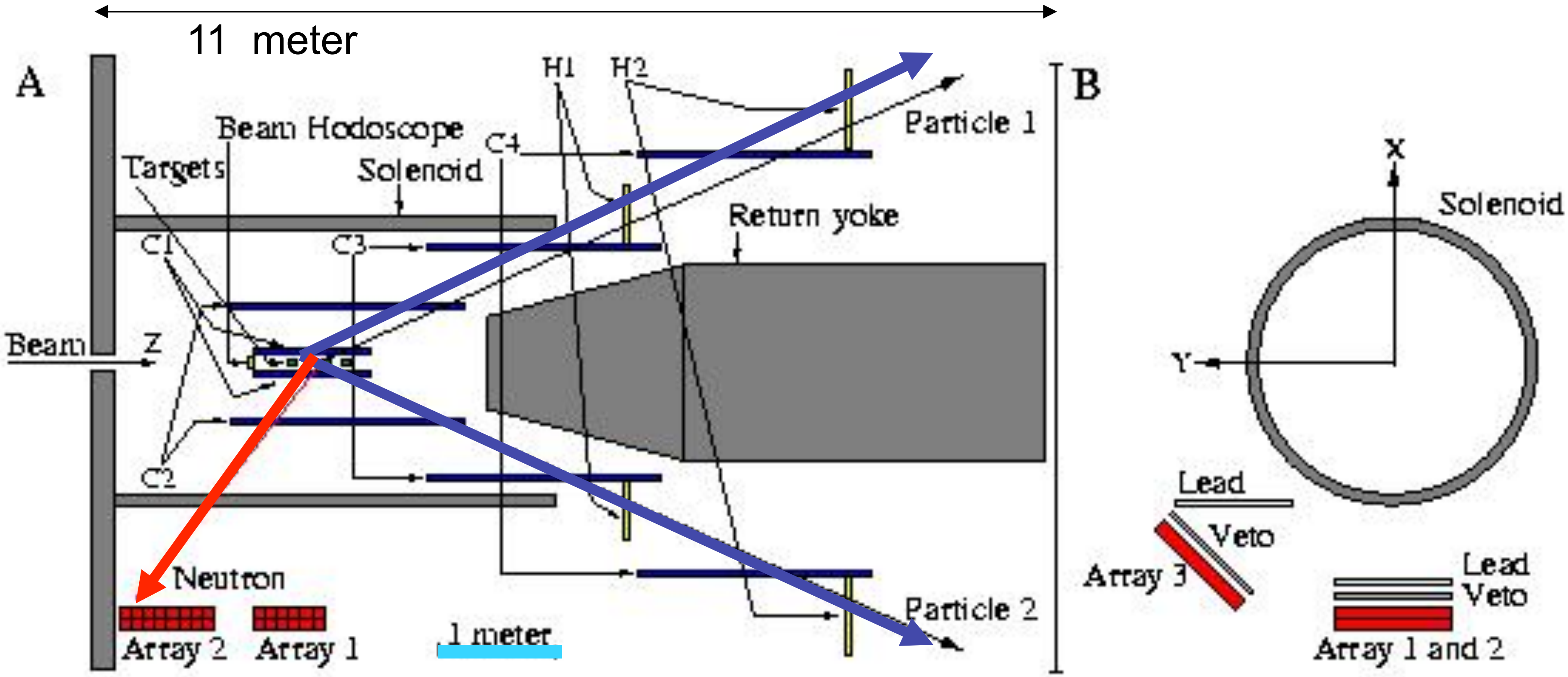
Quasi-Free scattering off a nucleon in a short range correlated pair

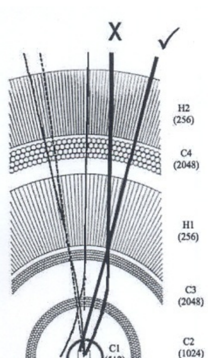
Hard exclusive triple – coincidence measurements

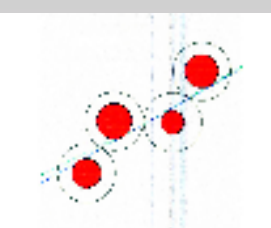


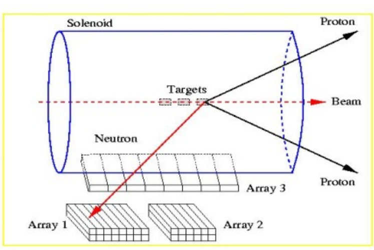
experiment	nuclei	pairs	Pmiss [MeV/c]
EVA/BNL	^{12}C	pn only	300-600
E01-015/ Jlab	^{12}C	pp and np	300-600
E07-006/ JLab	^{4}He	pp and np	400-850
CLAS/JLab	C, Al, Fe, Pb	pp and np	300-700

The EVA spectrometer and the n-counters at BNL









Array 1: total area 0.6×1.0 m², 12 counters, 2 layers 0.125 m

Simultaneous measurements of the (e,e' p) , (e, e' p p), and (e, e' p n) reactions.

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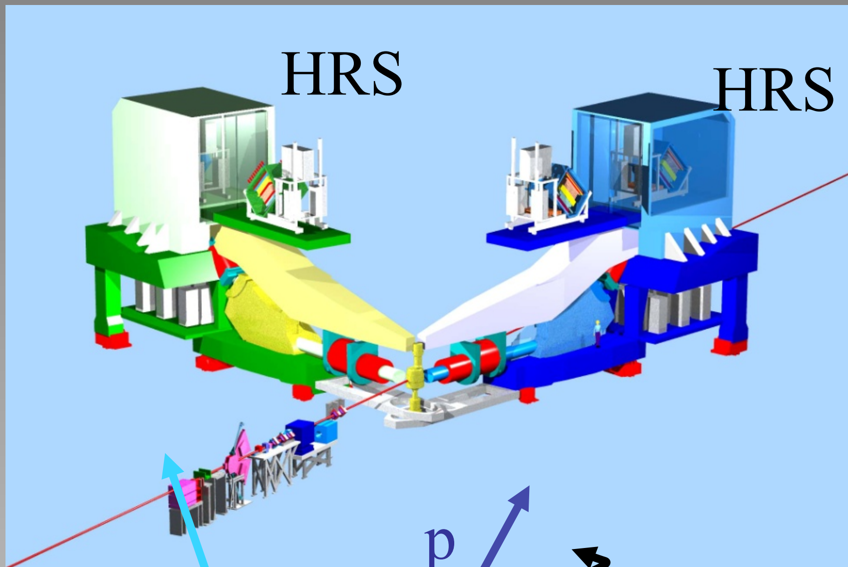
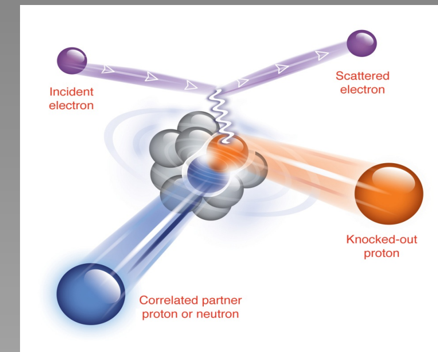
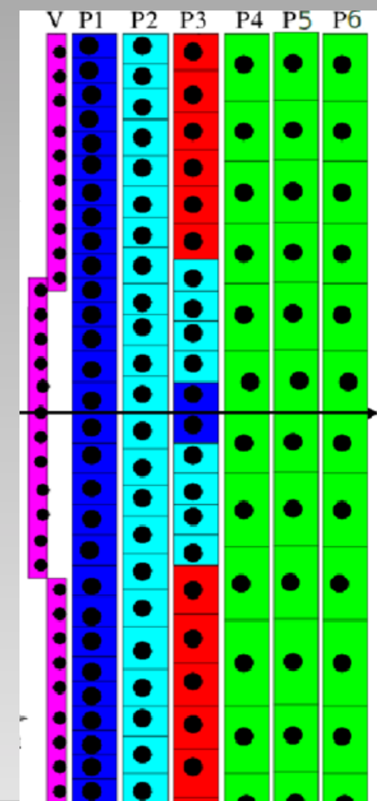


EXP 01-015
and
EXP 07-006
Hall A JLab



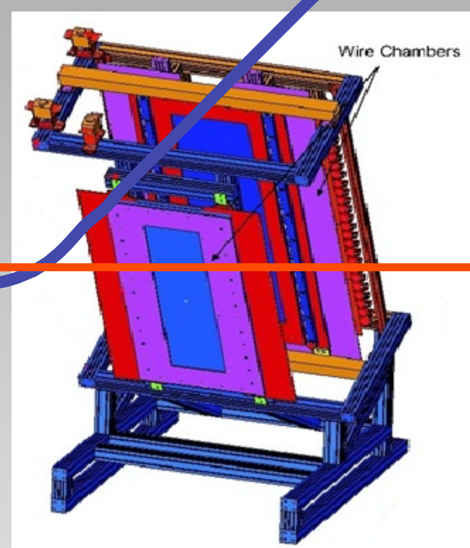
n array

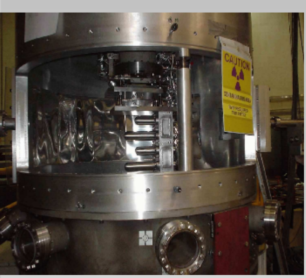


e

p

p



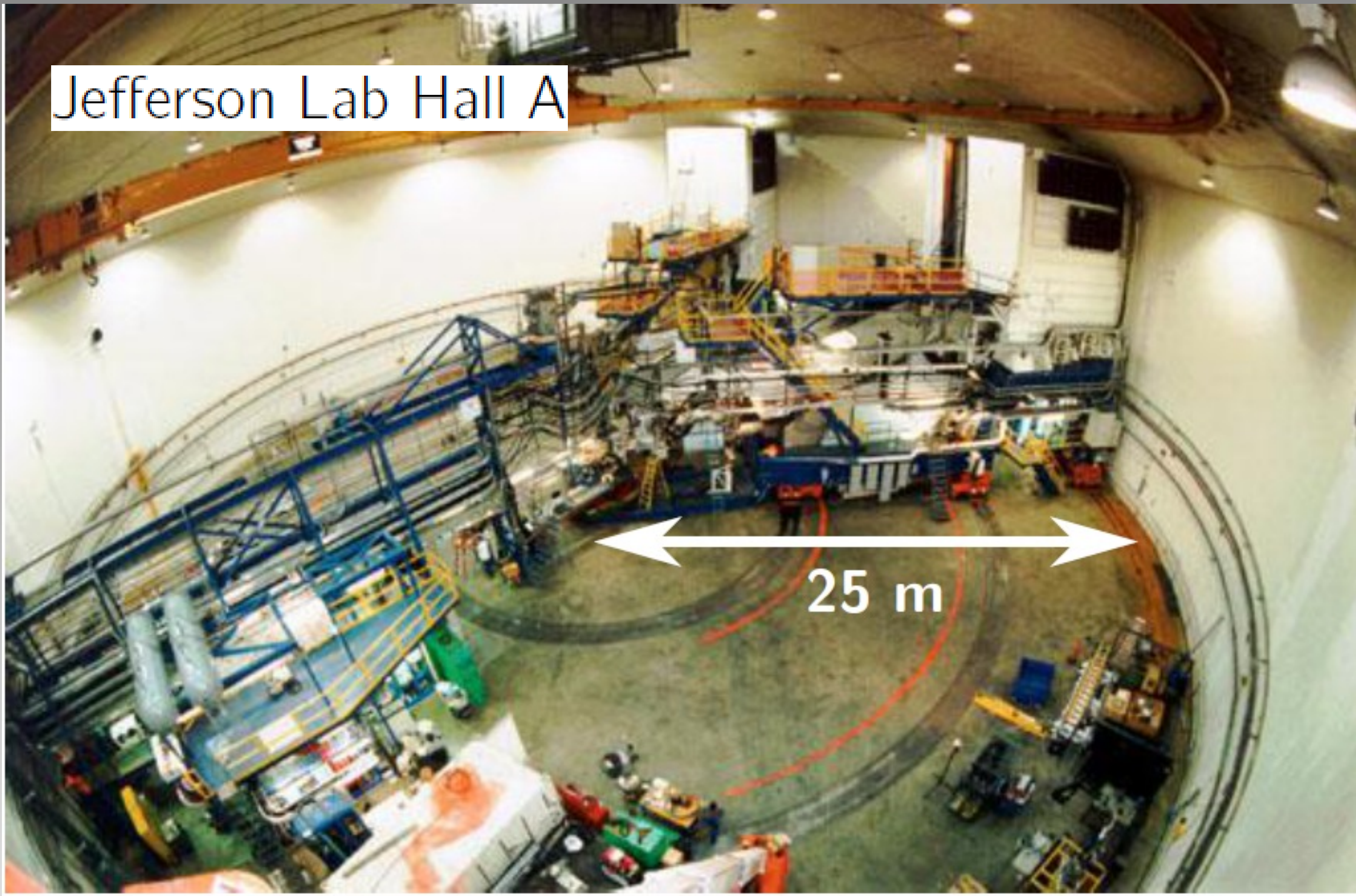


Aluminum cylinder

20 cm long
2.5 " diameter

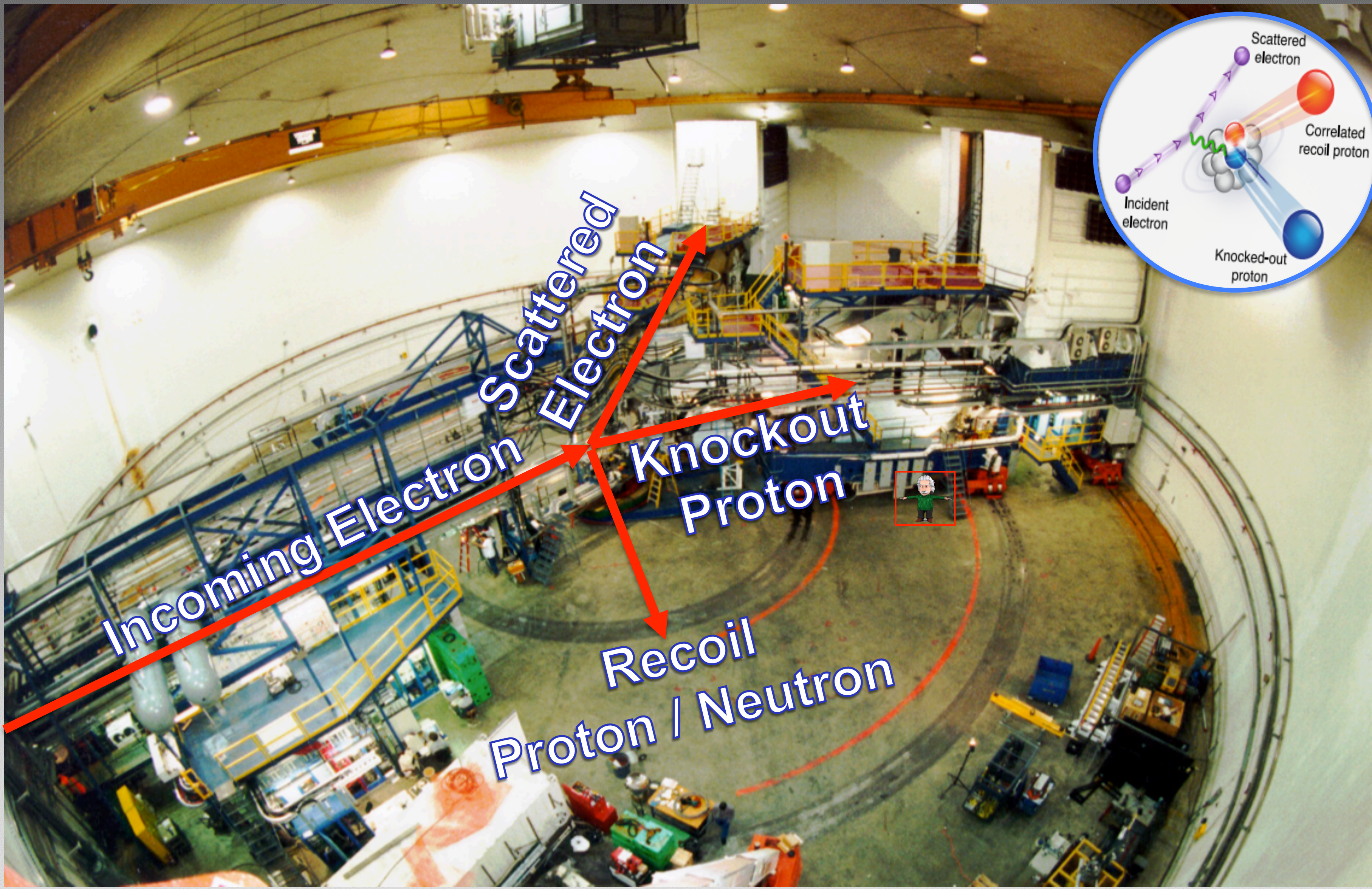
Big Bite

Lead wall



Jefferson Lab Hall A
25 m

Jefferson Lab Hall A



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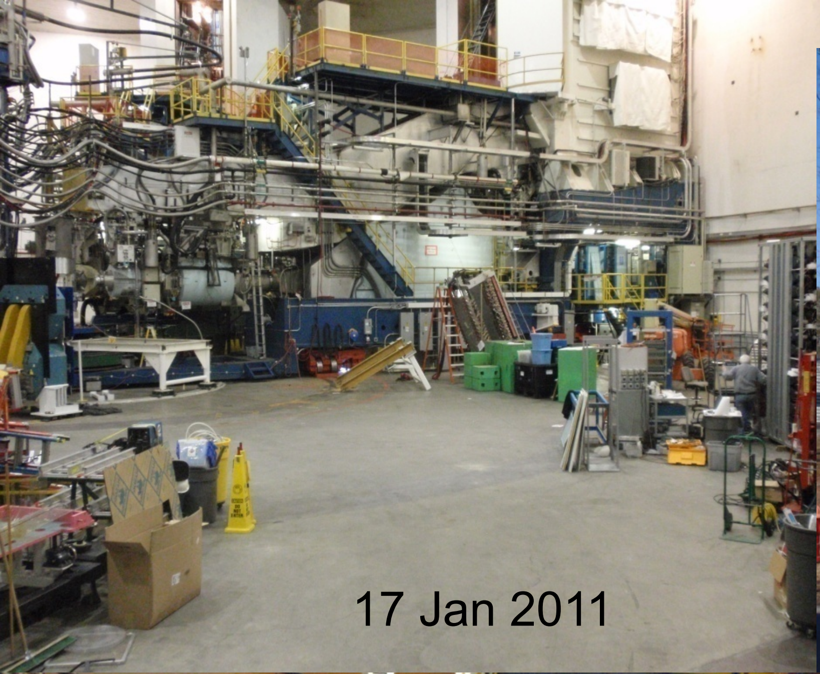
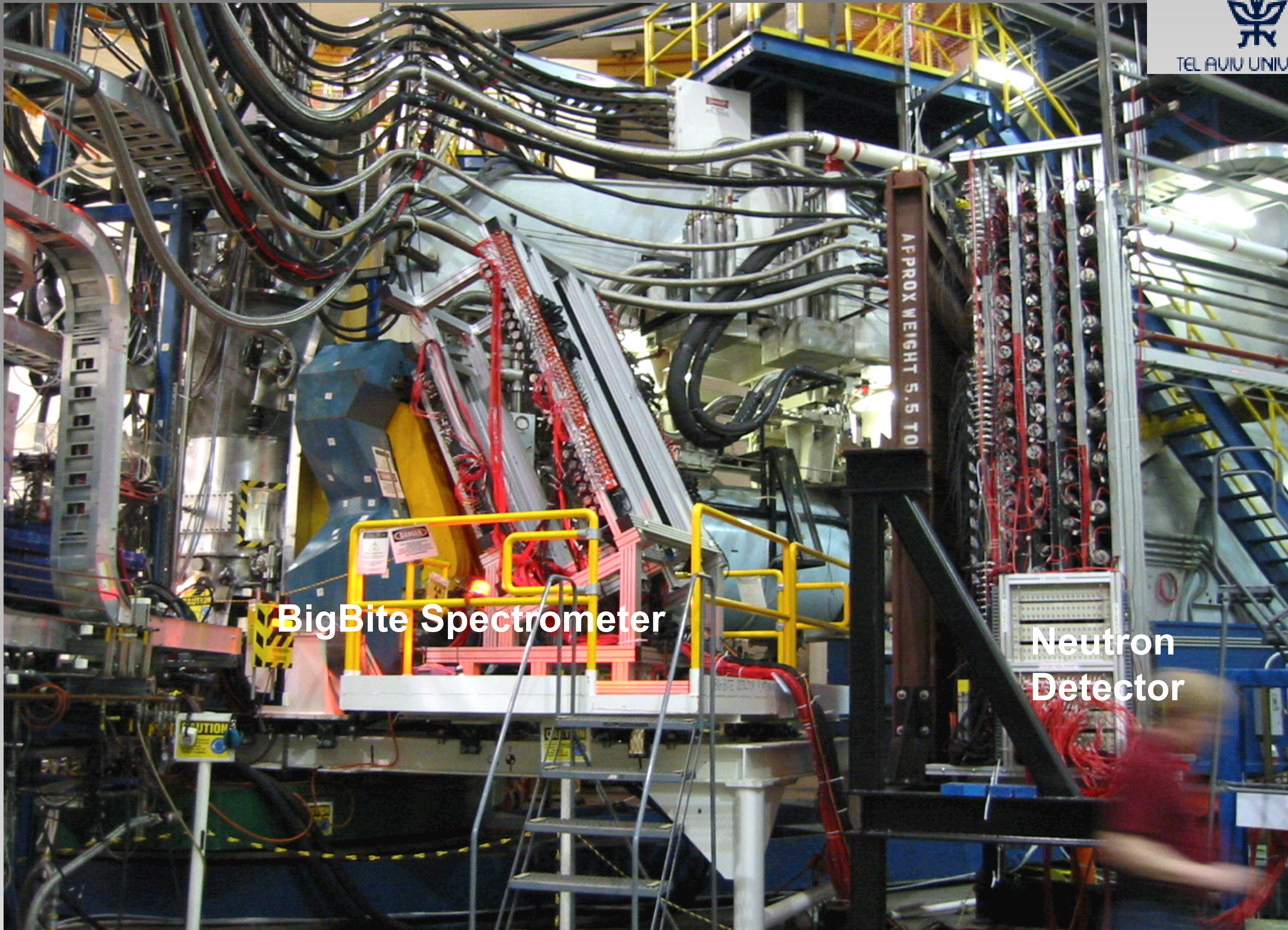


17 Jan 2011

12 Jan 2011

7 Jan 2011



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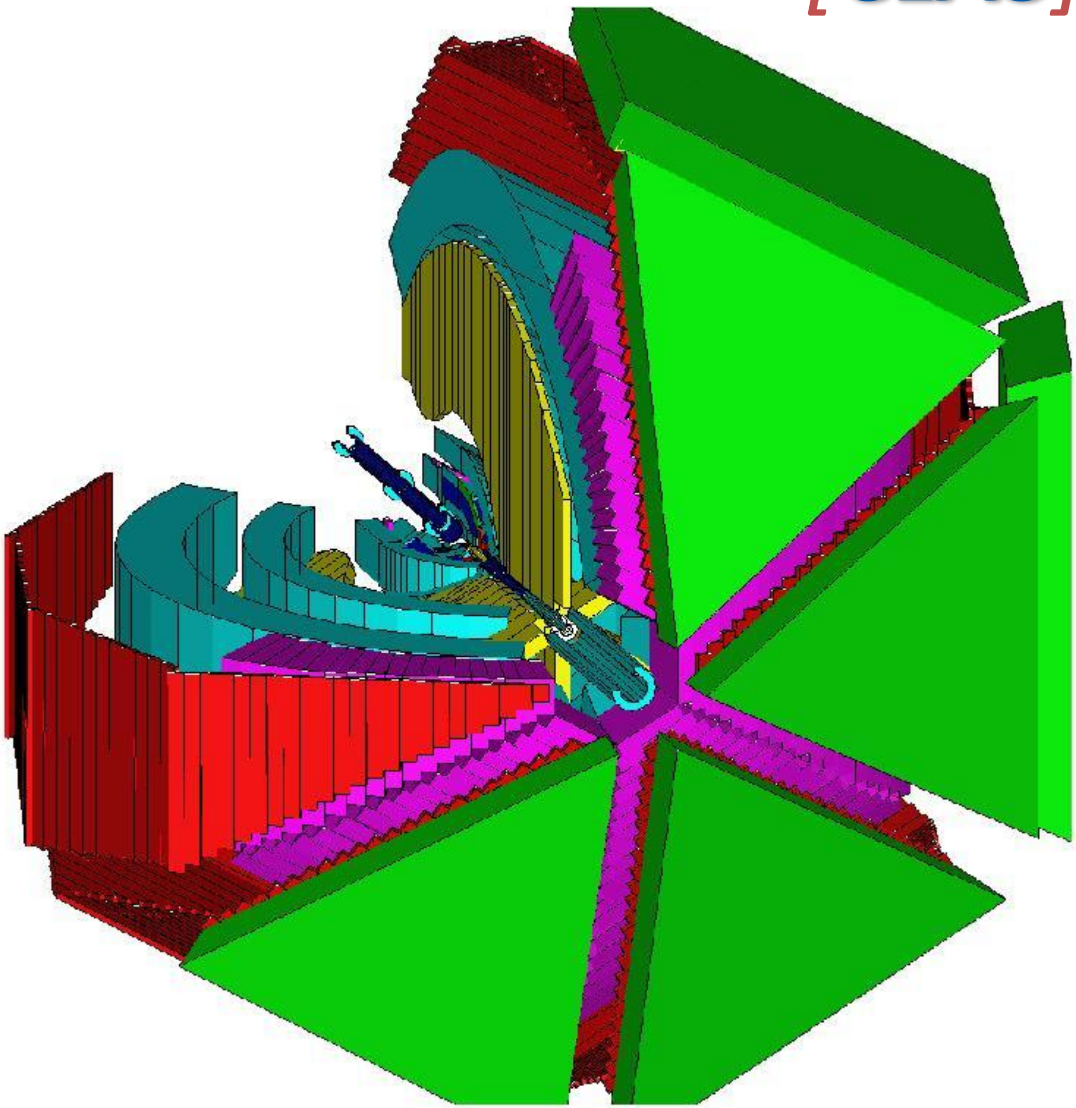
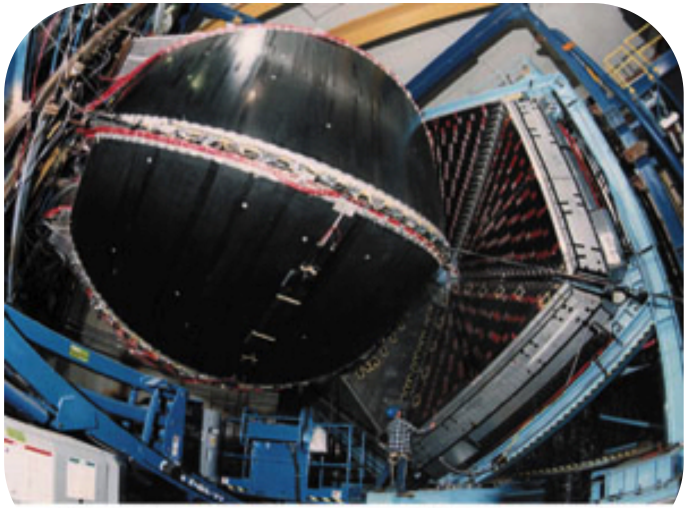
EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

CEBAF Large Acceptance Spectrometer
[CLAS]

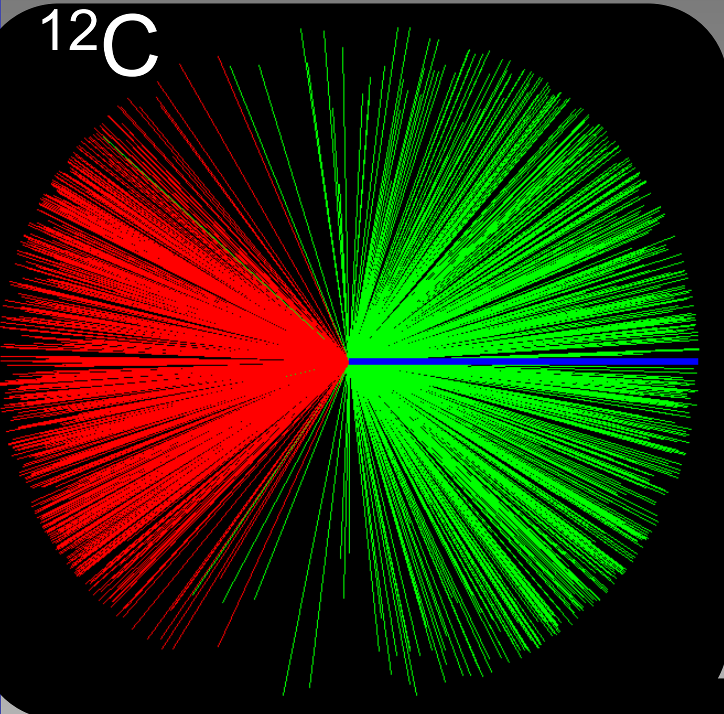




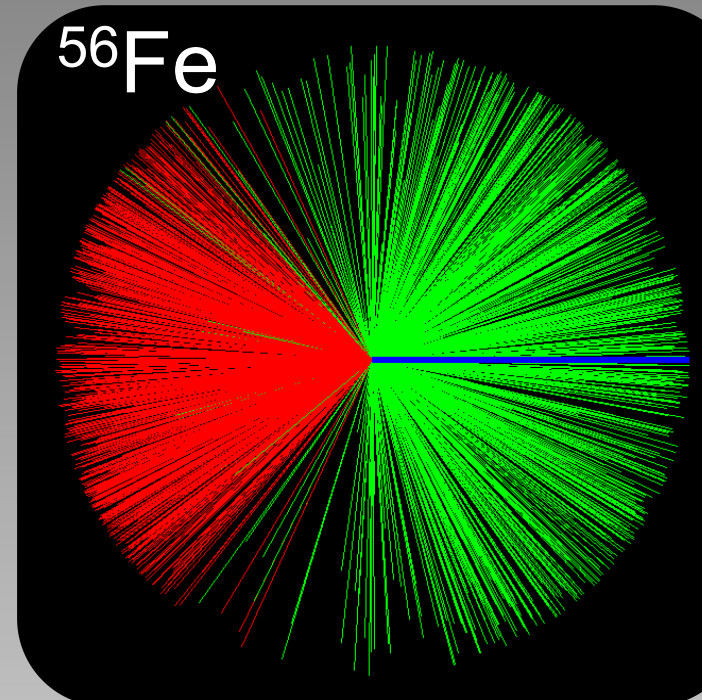
Hall B Large Acceptance Spectrometer

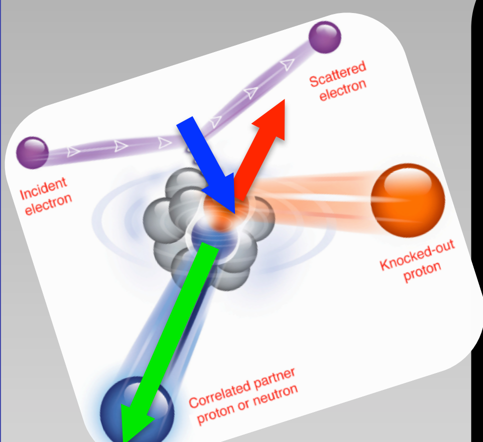
Open (e,e') trigger, Large-Acceptance, Low luminosity (~10^{34} cm^{-2}

JLab / CLAS, Data Mining, EG2 data set

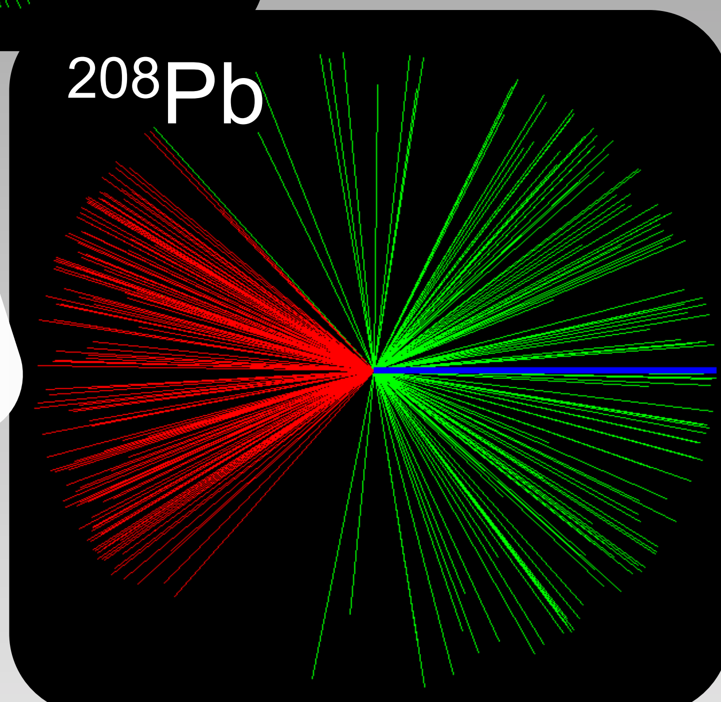


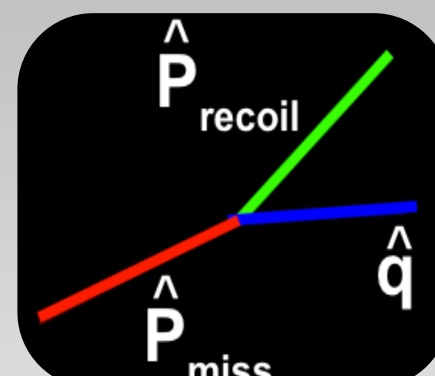
A(e.e' pp)





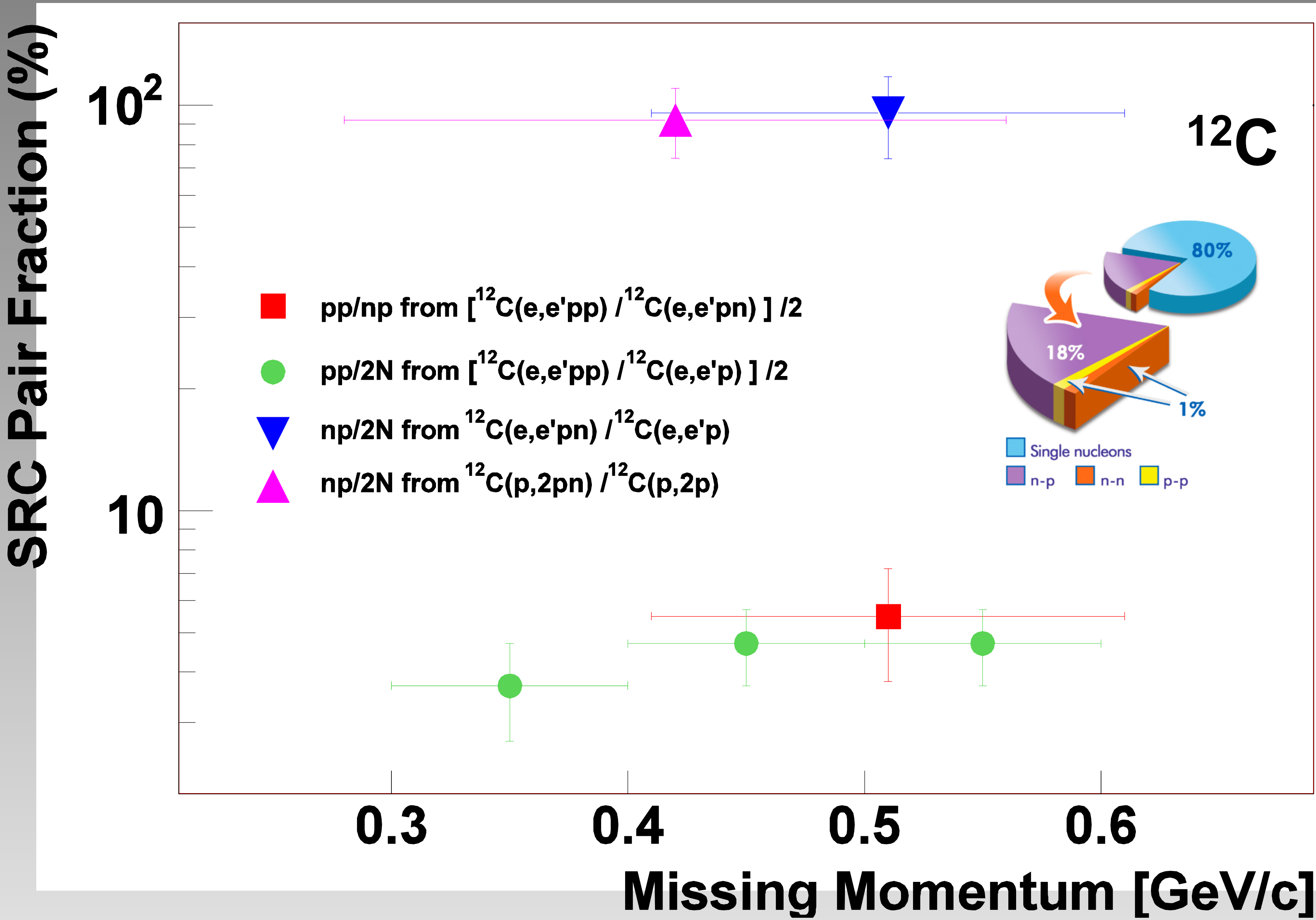
Back-to-back = SRC pairs!



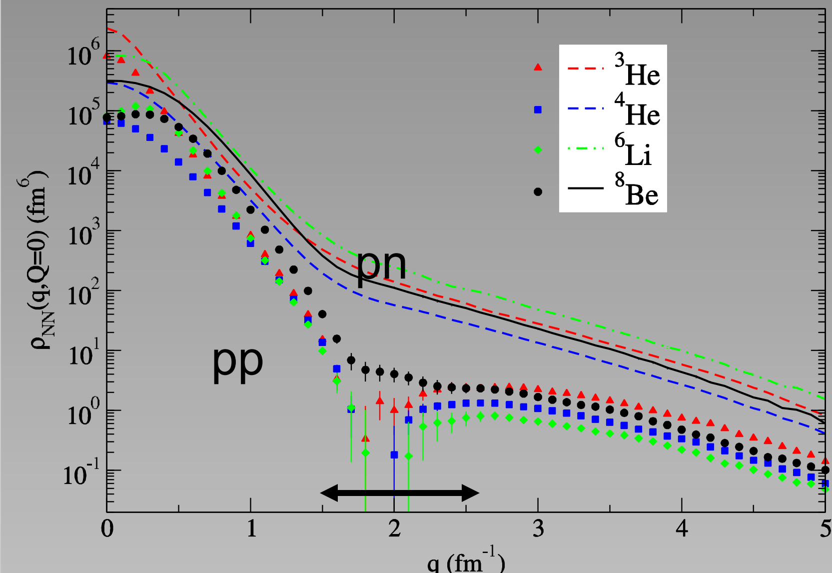


3D Reconstruction

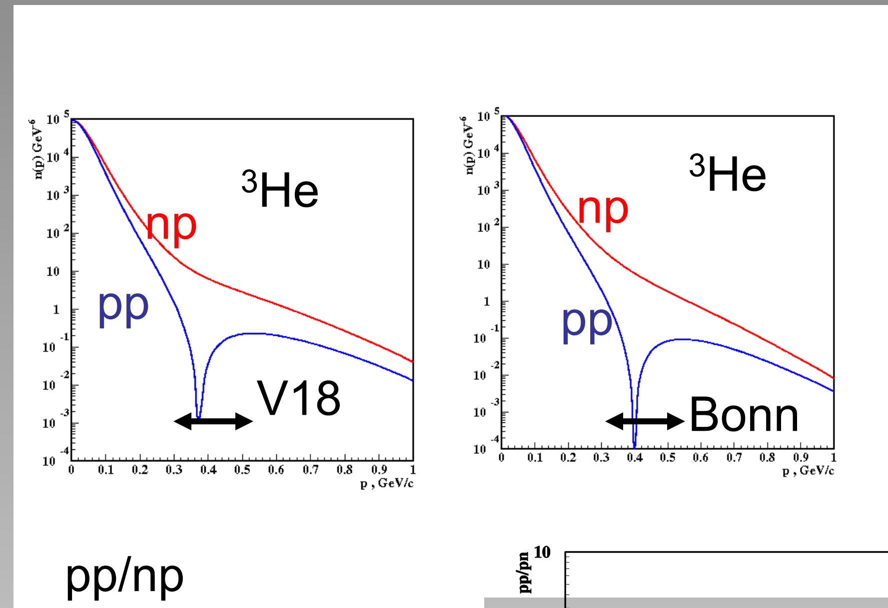
R. Subedi et al., Science 320, 1476 (2008).

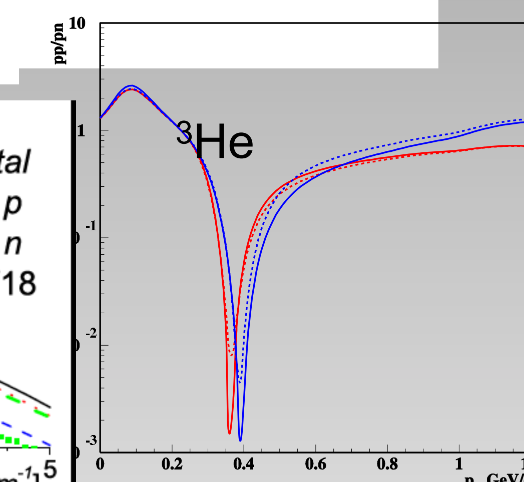


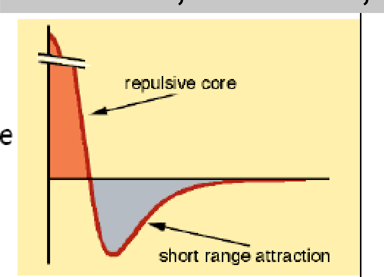
At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.

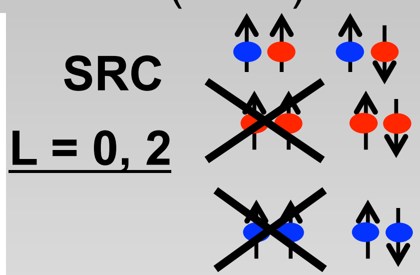


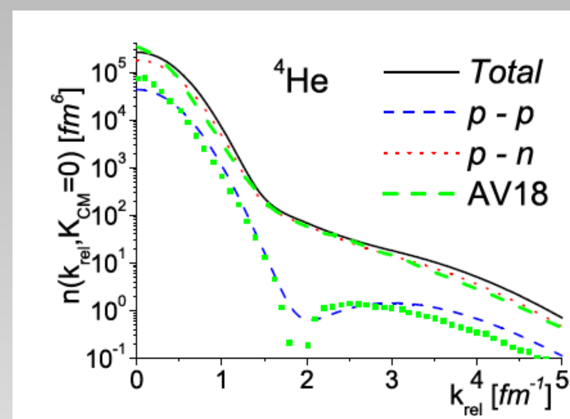
Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).







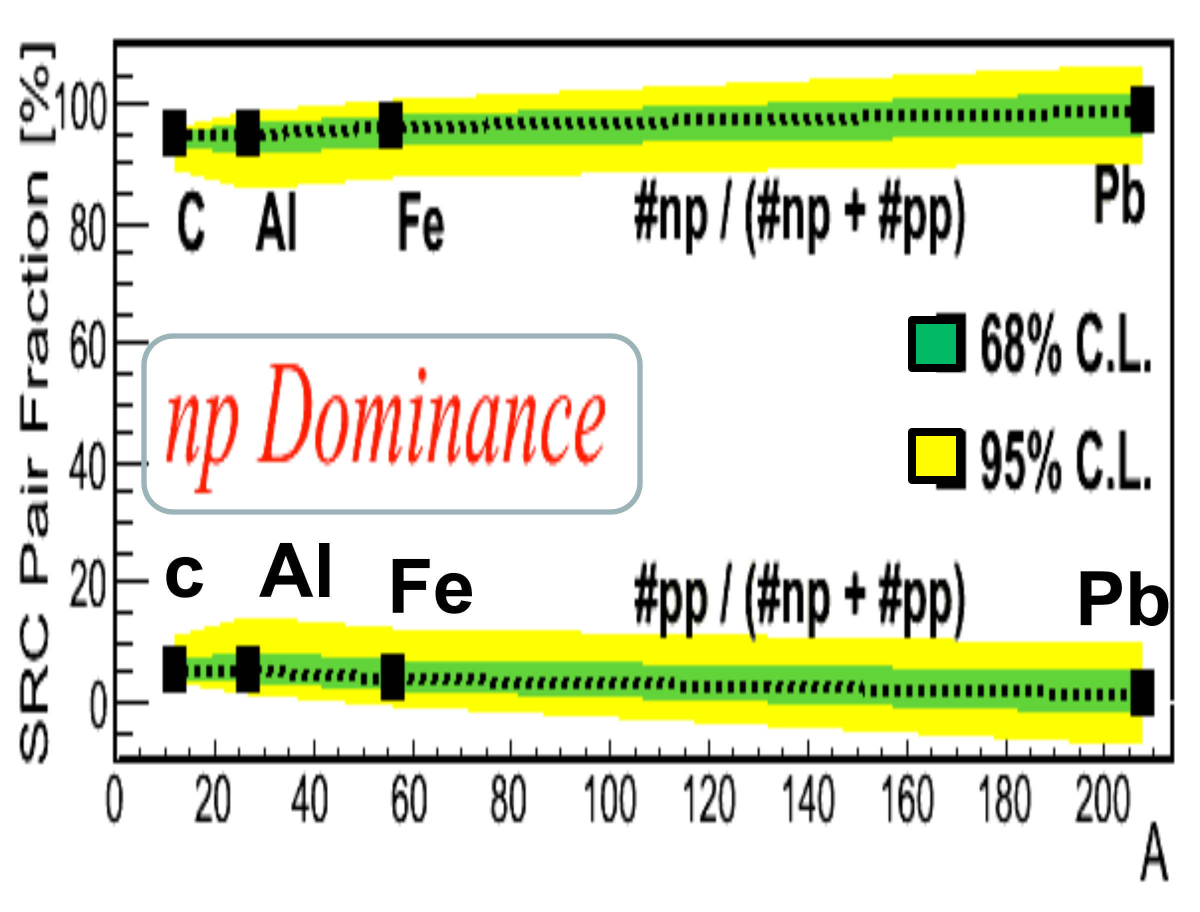




Ciofi and Alvioli PRL 100, 162503 (2008).

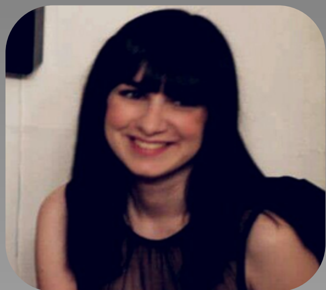
Sargsian, Abrahamyan, Strikman Frankfurt PR C71 044615 (2005

np / pp SRC pairs ratio



O. Hen et al., Science 346, 614 (2014).

New preliminary data mining data - see Meytal Duer talk



Parallel Workshops

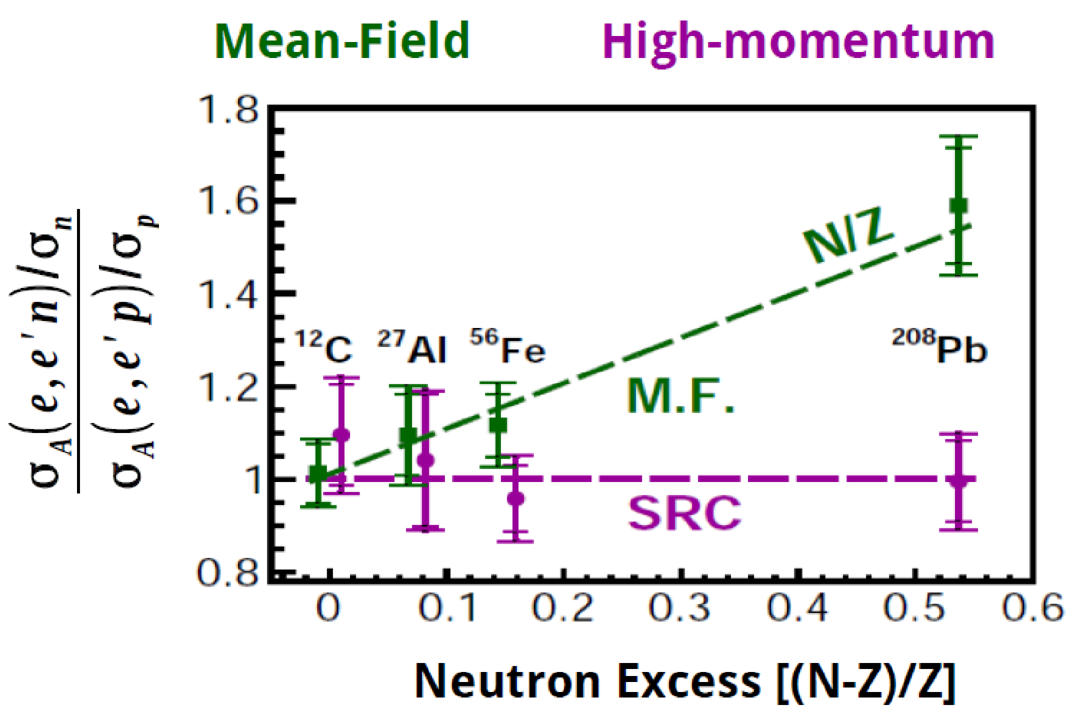
2. New Avenues in Lepton Scattering

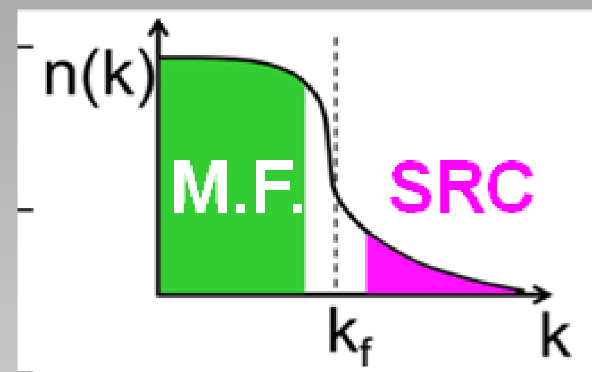
Wednesday, November 01

Session I: Nuclear & Nucleon Structure

N-N correlations in nuclei	Meytal Duer (Tel-Aviv)

A(e,e'n)/A(e,e'p) ratios



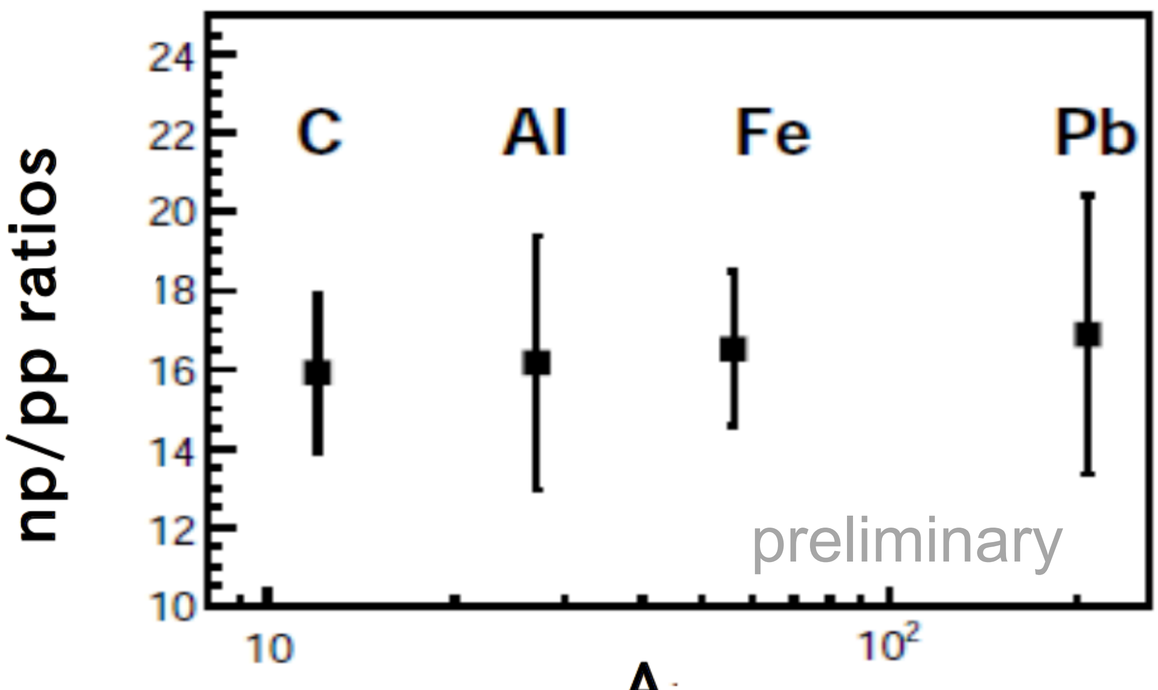


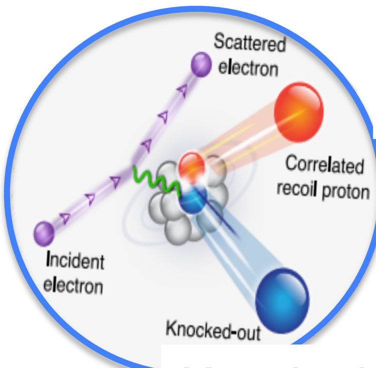
New preliminary data mining data - see Meytal Duer talk

Parallel Workshops	Wednesday, November 01
2. New Avenues in Lepton Scattering	Session I: Nuclear & Nucleon Structure

15:00-15:30	N-N correlations in nuclei	Meytal Duer (Tel-Aviv)

A(e,e'np)/A(e,e'pp)





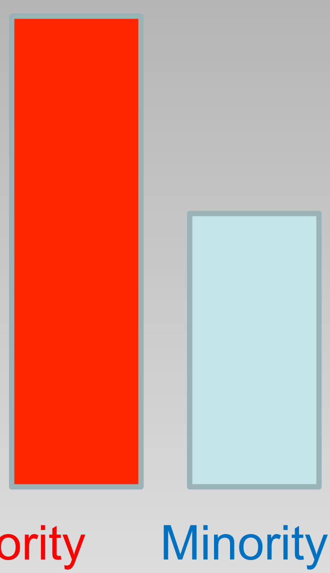
Recoil neutron / proton

Knocked-out neutron

Momentum sharing in Asymmetric (imbalanced) two components Fermi systems

non interacting Fermions

Pauli exclusion principle →

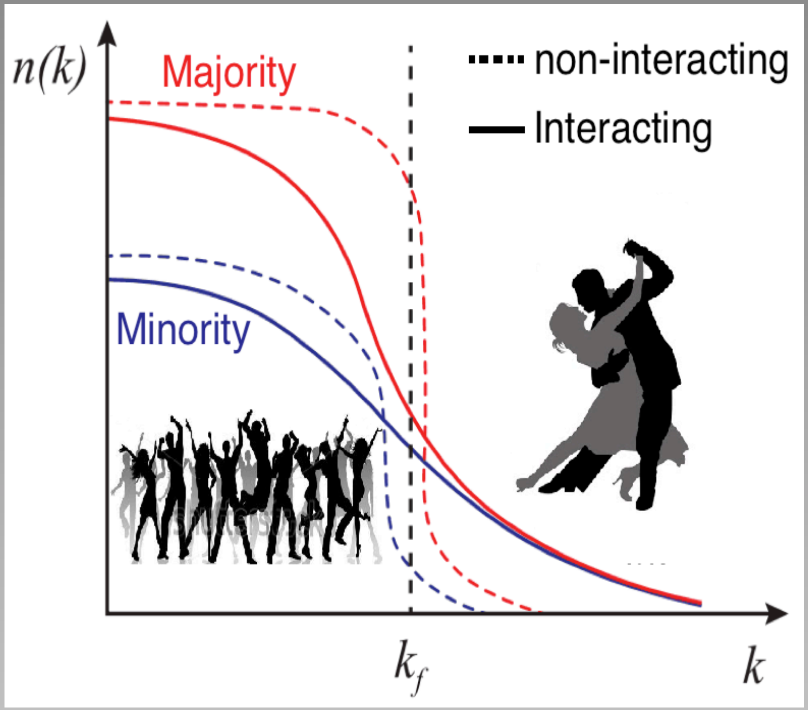


$$k_F^{Majority} > k_F^{Minority}$$

$$\left\langle E^{kin}{}_{Majotiry} \right\rangle > \left\langle E^{kin}{}_{Minority} \right\rangle$$

In a neutron-rich nuclei $<T_n> > <T_p>$

with short-range interaction : strong between unlike fermions, weak between same kind.



Universal property

A minority fermion have a greater probability than a majority fermion to be above the Fermi sea $k > k_F$

Possible inversion of the momentum sharing :

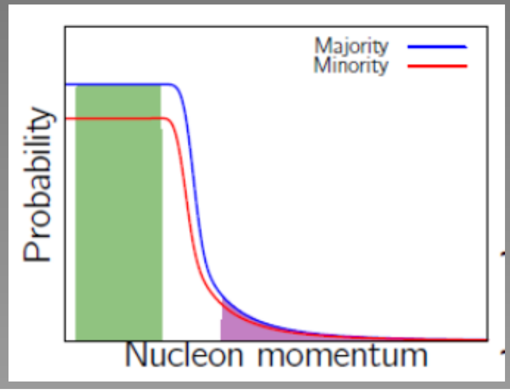
In a neutron-rich nuclei $<T_p> > <T_n>$

np-dominance in asymmetric nuclei

Simple np-dominance model

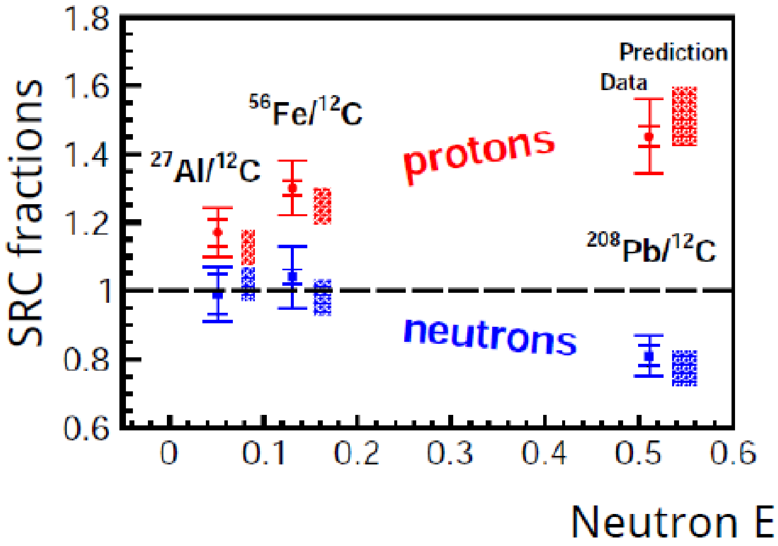
$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k < k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k > k_0 \end{cases}$$

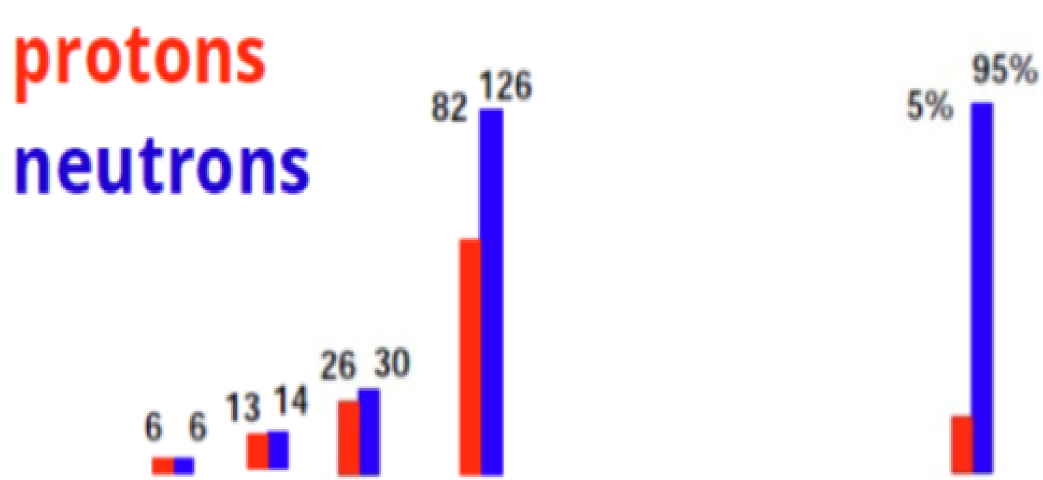
(for neutrons: Z → N)



$$\frac{A(e,e'N)_{high} / A(e,e'N)_{low}}{^{12}C(e,e'N)_{high} / ^{12}C(e,e'N)_{low}}$$

n stars ?

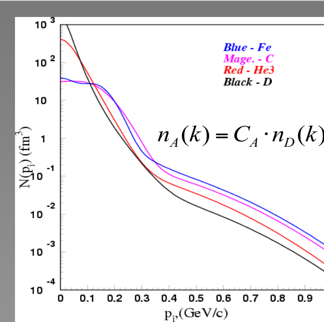




Protons move faster than neutrons in N>Z nuclei

$$\langle T_p \rangle > \langle T_n \rangle$$

- **At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.**



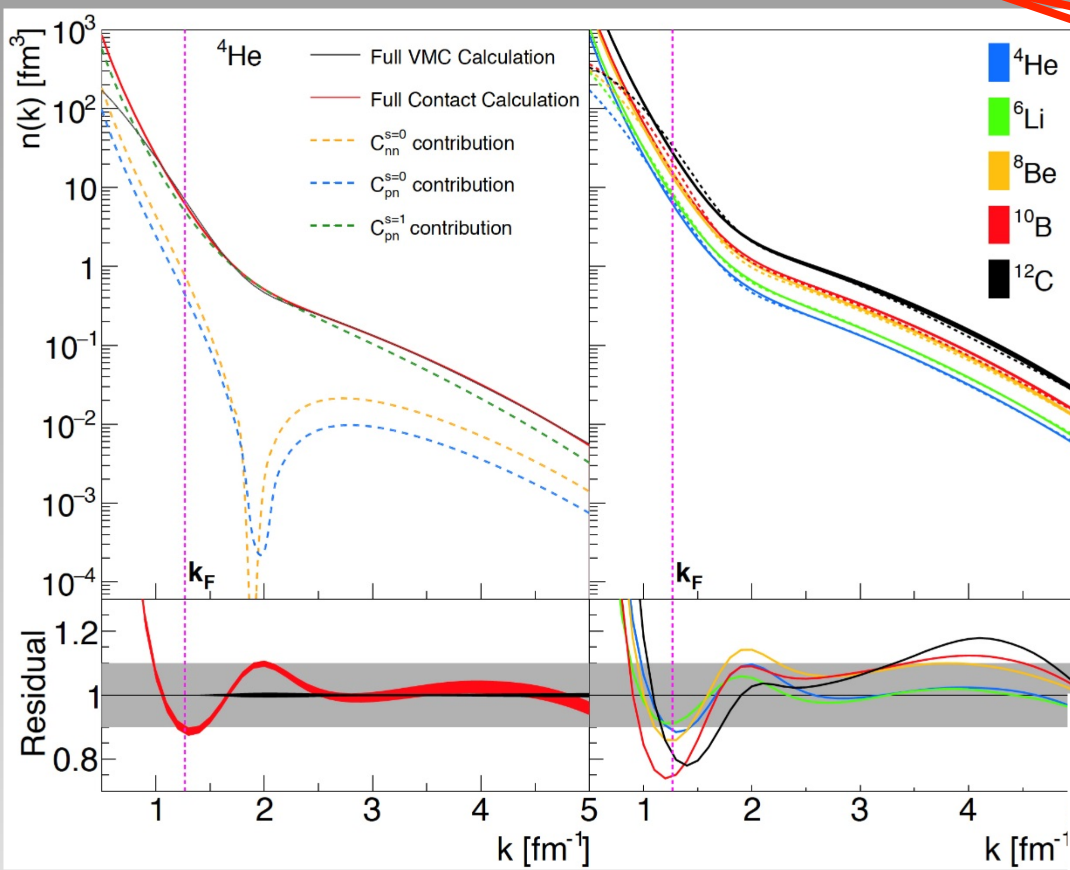
Adapted from
Ciofi degli Atti

Nuclear contact calculations

$$n_p(k) \xrightarrow[k\to\infty]{} C^d_{pn}\left|\varphi^d_{pn}(k)\right|^2 + C^0_{pn}\left|\varphi^0_{pn}(k)\right|^2 + 2C^0_{pp}\left|\varphi^0_{pp}(k)\right|^2$$

$l = 0,2 \; s = 1 \; j = 1$
np pairs

$l = s = j = 0$
pp, nn, np pairs



The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

arXiv:1612.00923

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_\alpha(\boldsymbol{r}_{ij}) A^\alpha_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

a factorized ansatz

Nuclei (Athenaeum Ballroom)		Axel Schmidt
Session chair: **Fabienne Kunne**		
11:30-12:00	New Insights into Nucleon-Nucleon Correlations	Or Hen (MIT)

Compering ab-initio VMC and nuclear contact calculations

Scale-Separated Nuclear Structure

1. **Use a factorized ansatz for the short-distance (high-momentum) part of the many-body wave function:**

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

2. Test by comparing to many-body calculations *and* data from hard knockout measurements

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2017)

Short distance structure of nuclei

1

The probability for a nucleon to have momentum ≥ 300 MeV / c in medium nuclei is 20-25%

2

More than ~90% of all nucleons with momentum ≥ 300 MeV / c belong to 2N-SRC.

1 2

Most of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

3

Probability for a nucleon with momentum 300-600 MeV / c to belong to np-SRC is ~18 times larger than to belong to pp-SRC.

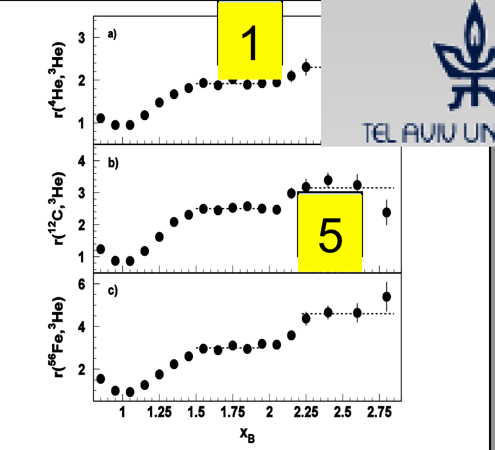
1 3 2

In neutron - rich nuclei: $<T_p> \; > \; <T_n>$

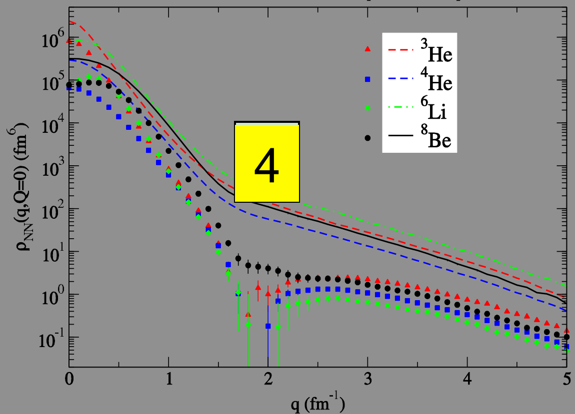
4

Dominant NN force in the 2N-SRC is tensor force.

CLAS / HALL B

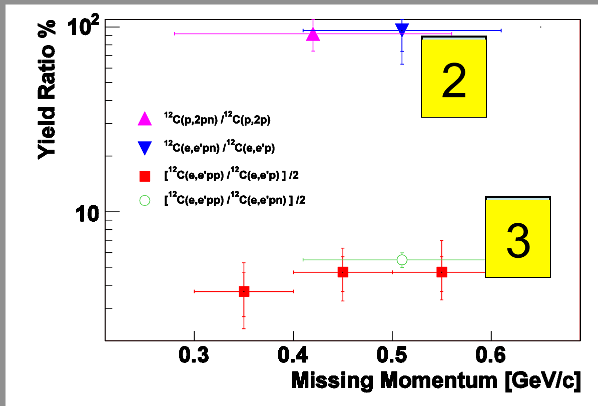


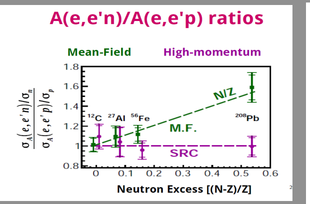
PRL. 96, 082501 (2006)

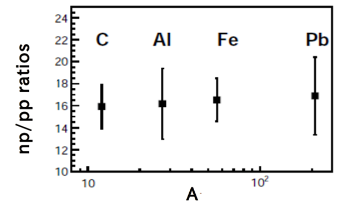


PRL 98,132501 (2007).

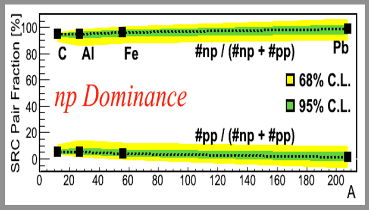
EVA / BNL and Jlab / HALL A







3



Duer et al.

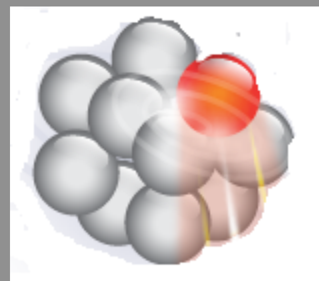
Science 346, 614 (2014).

PRL 162504(2006); Science 320, 1476 (2008).

Are nucleons being modified in the nuclear medium ?

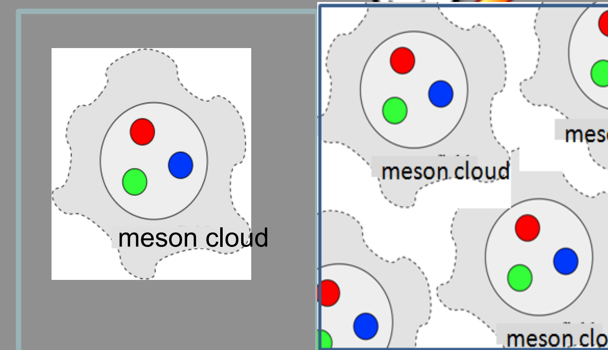
Free neutron

Bound neutron



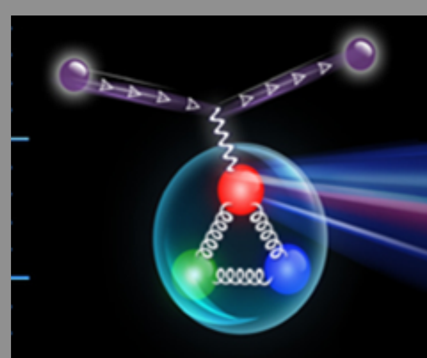
$\tau_n = 15\,\mathrm{min}$

$\tau_{n*} = \infty$



Do nucleons change their quark-gluon structure in the nuclear medium ?

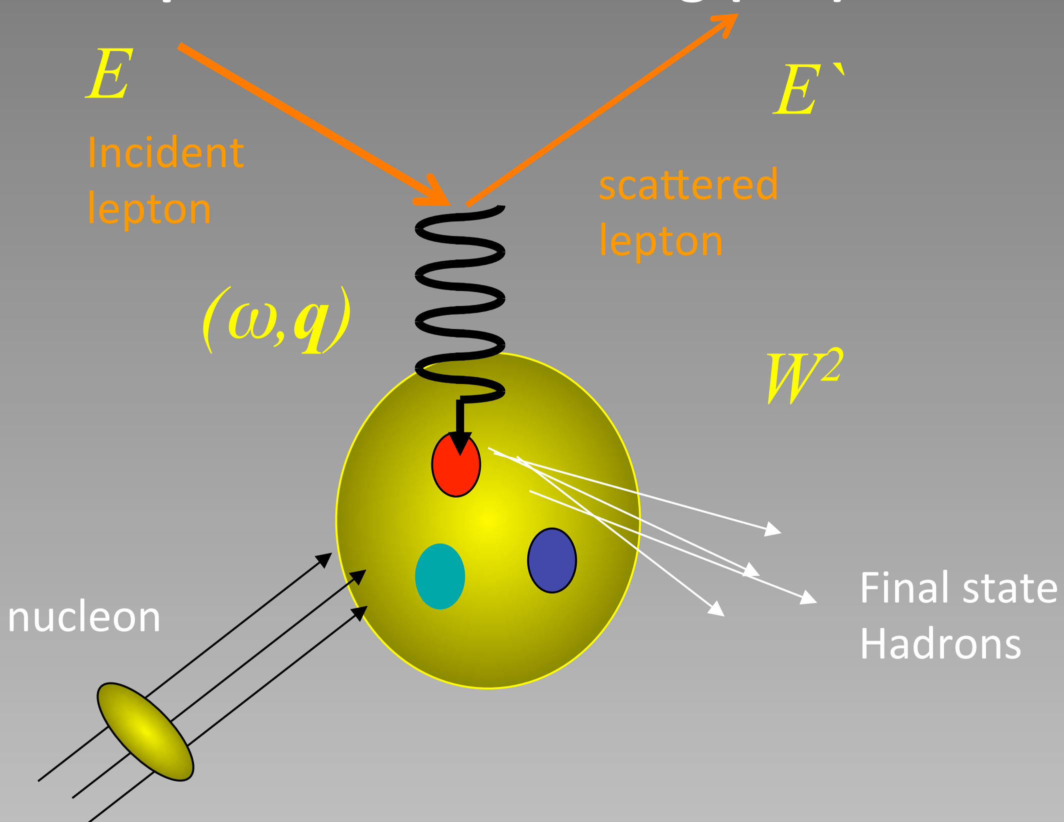
Deep Inelastic Scattering (DIS)



In-Medium vs. Free

Structure Function

Deep Inelastic Scattering (DIS)



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \quad \left(= \frac{Q^2}{2(q \cdot p_T)}\right)$$

$$0 \le x_B \le 1$$

Electrons, muons, neutrinos

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

Q^2 5-50 GeV^2

w^2 >4 GeV^2

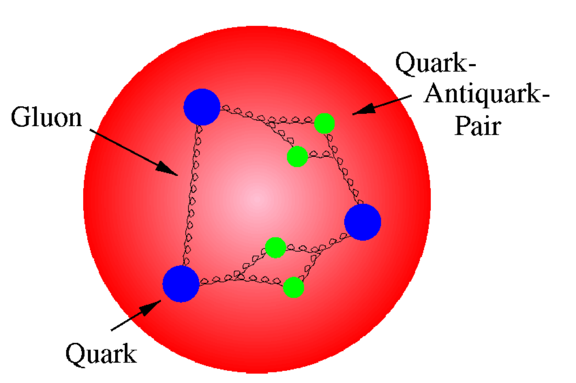
$0 \le X_B \le 1$

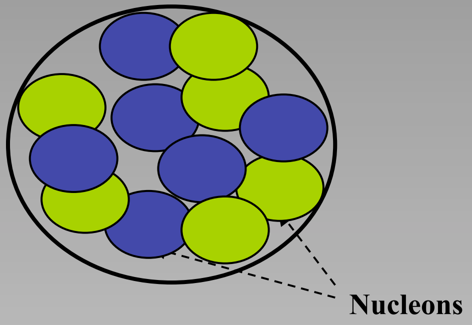
X_B gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions

DIS scale: several tens of GeV

Nucleon in nuclei are bound by ~MeV

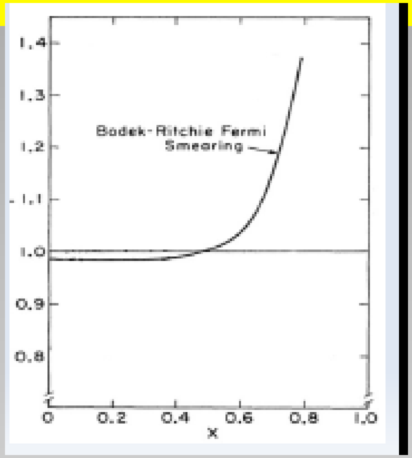


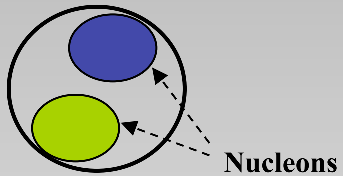


(My) Naive expectations :

DIS off a bound nucleon = DIS off a free nucleon

(Except for small Fermi momentum corrections)





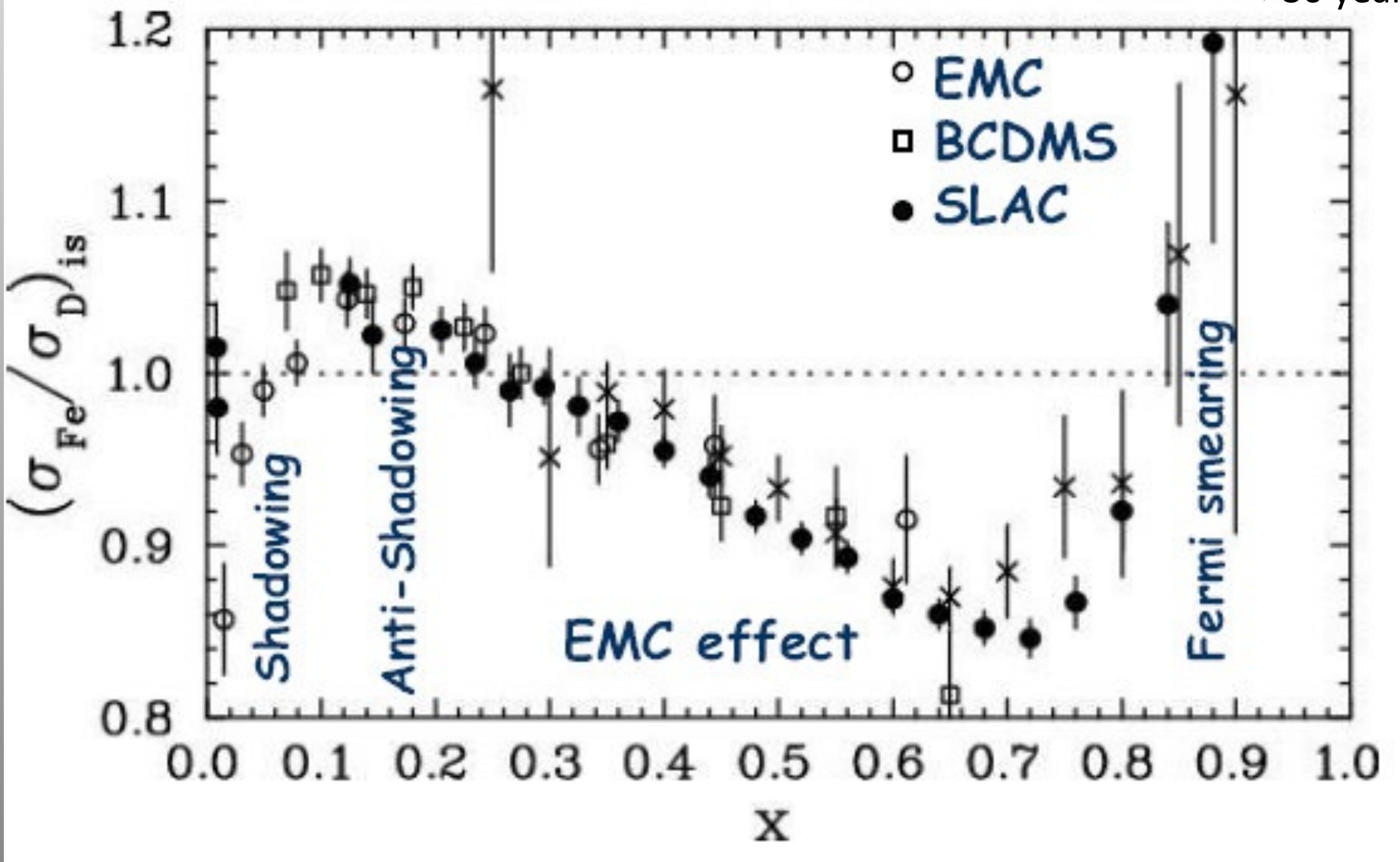
Deuteron: binding energy ~2 MeV

Average nucleons separation ~2 fm

DIS off a deuteron = DIS off a free proton neutron pair

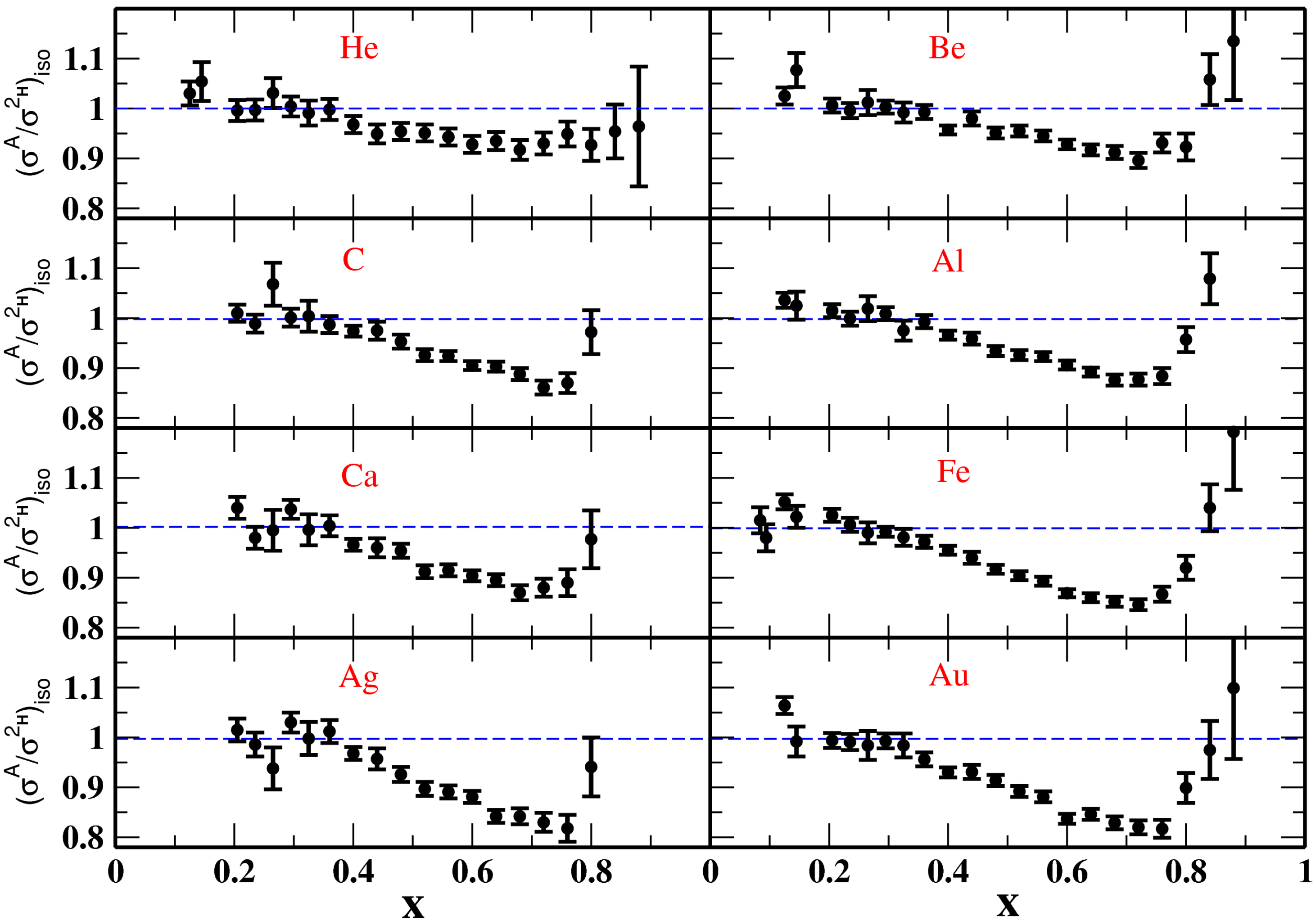
The European Muon Collaboration (EMC) effect

>30 years old



σ^{DIS} per nucleon in nuclei $\neq$ σ^{DIS} per nucleon in deuteron

SLAC E139

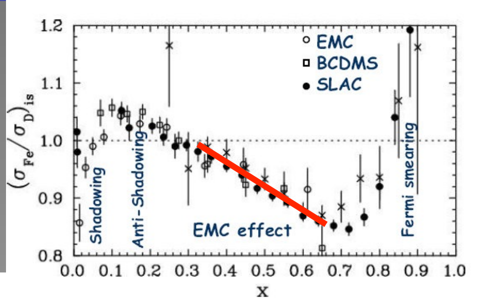


Data from CERN SLAC JLab 1983- 2009

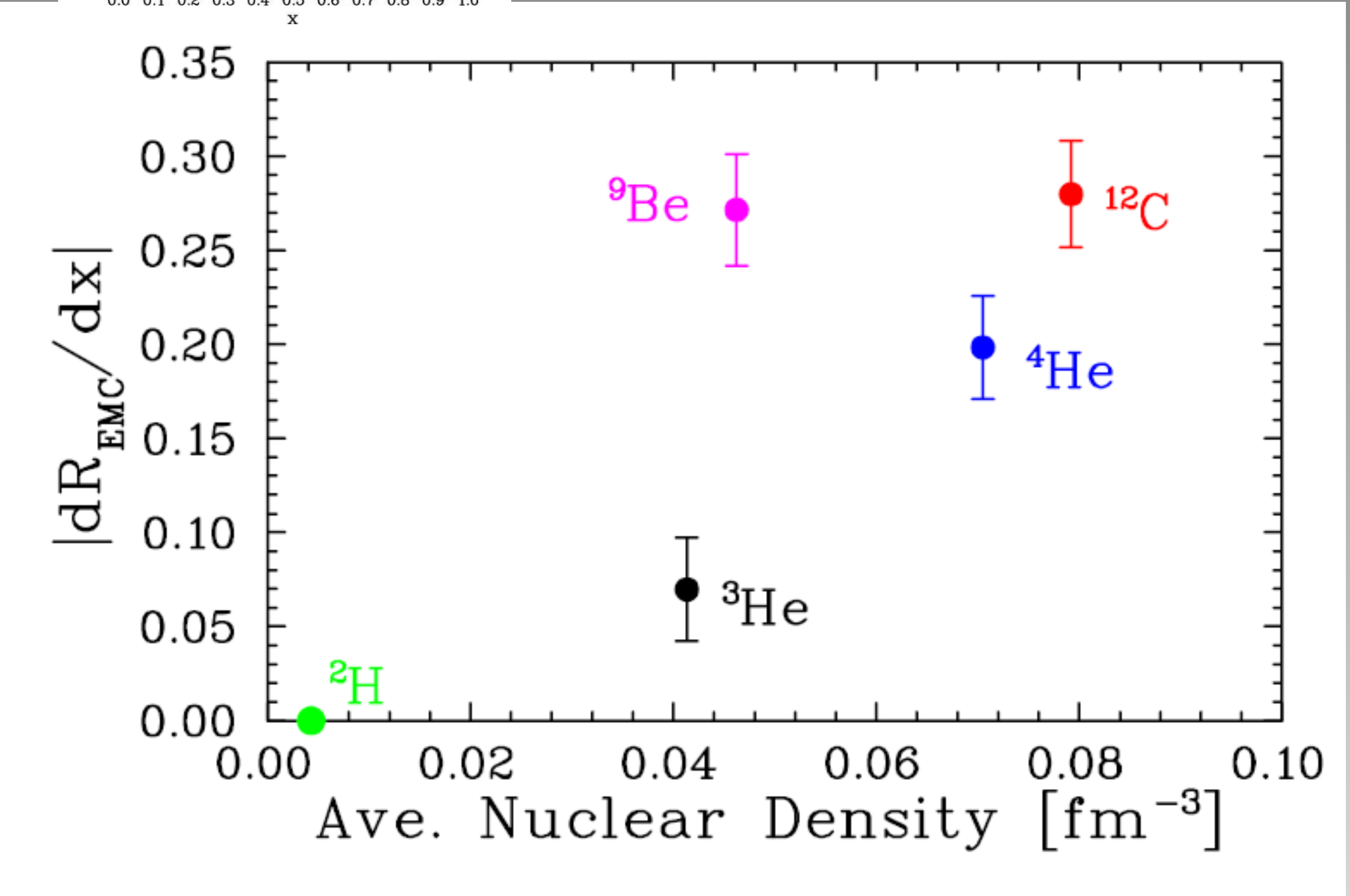
EMC collaboration, Aubert et al. PL B 123,275 (1983)

SLAC Gomez et al., Phys Rev. D49,4348 (1994)

A review of data collected during first decade, Arneodo, Phys. Rep. 240,301(1994)



EMC is a not a bulk property of nuclear medium



JLab / Hall C

. Seely et al. PRL 103, 202301 (2009)

Scaled nuclear density = $(A-1)/A \langle\rho\rangle$
→ remove contribution from struck nucleon

$\langle\rho\rangle$ from ab initio few-body calculations
→ [**S.C. Pieper and R.B. Wiringa**, *Ann. Rev. Nucl. Part. Sci 51, 53 (2001)*]

The European Muon Collaboration (EMC) effect

30 years old

Well established measured effect with no consensus as to its origin

Models of the EMC effect

TEL AVIV UNIVERSITY

Drell-Yan data

Binding effects
Fermi motion
…

Pions
Vector mesons
Δs
Multiquak clusters
'Photons'
…

Nucleus ≠nucleons

bound N ≠ free N

M*≠M
R*≠R
Dynamical rescaling
Confinement changes
Quark w,f. modification in mean field
…

Global changes

Rare configurations

Suppression of PLC
…

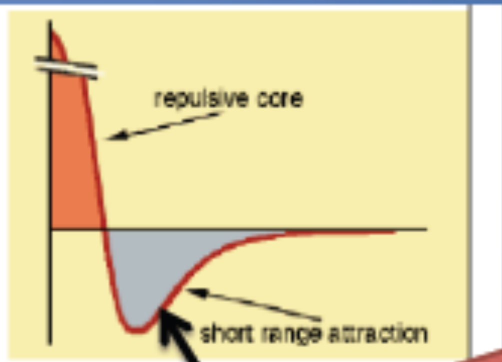
review papers:

Gessman, Saito,Thomas, Annu. Rev. Nucl. Part. Sci. 45:337(1995).

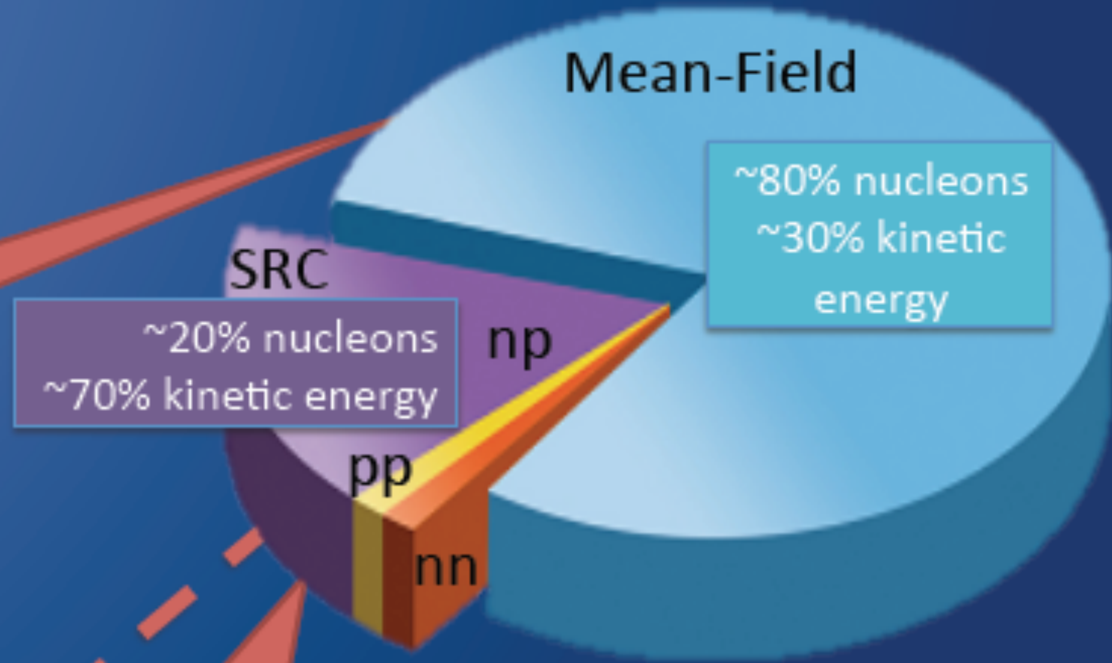
P.R. Norton , Rep Prog. 66 (2003).

Frankfurt and Strikman (2012)

Where is the EMC Effect?



Largest attractive force



Mean-Field

High local nuclear matter density, large momentum, large off shell, large virtuality

SRC

$$\upsilon = p^2 - m^2$$

Inclusive electron scattering A(e,e')

Deep Inelastic Scattering

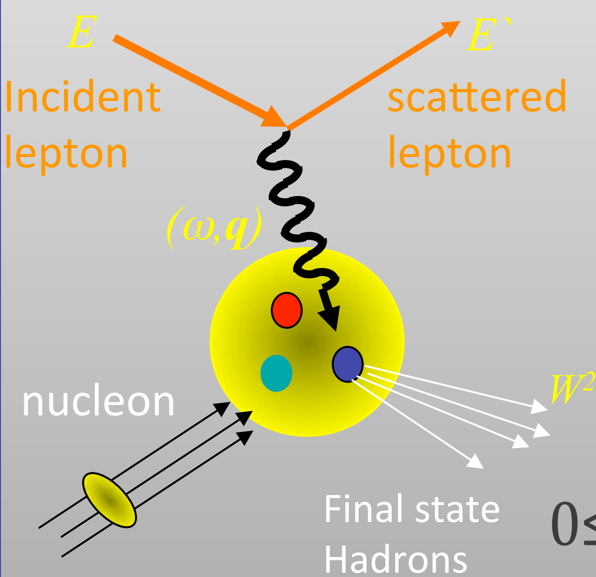
→ Partonic (quark) Structure of **Hadrons**

Inclusive Scattering at $X_B > 1$ A(e,e')

→ Partonic (nucleon) Structure of **Nucleus**

Inclusive electron scattering A(e,e’)

DIS off nucleons | **DIS off nuclei**



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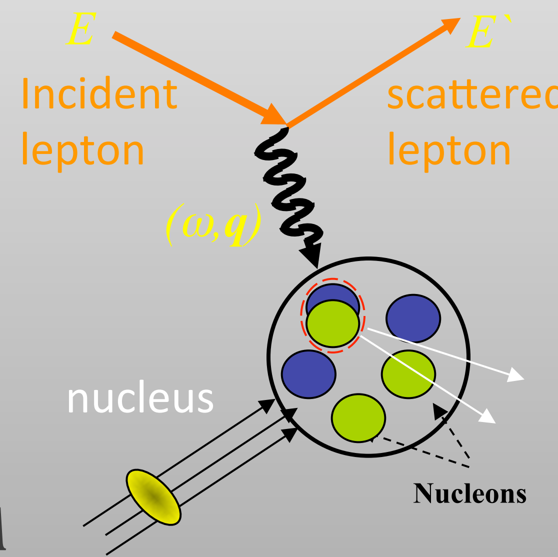
$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad \left(x_B' = \frac{Q^2}{2(q \cdot p_T)}\right)$$

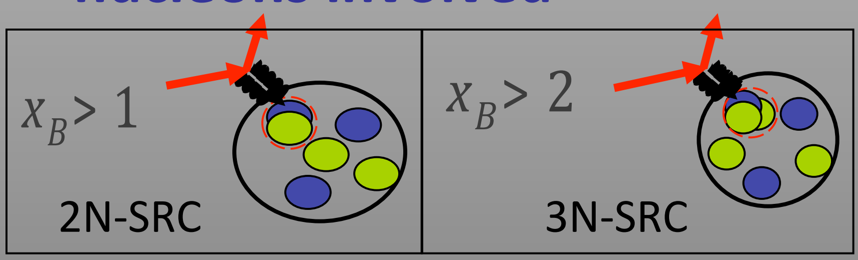
$0 \leq x_B \leq 1$

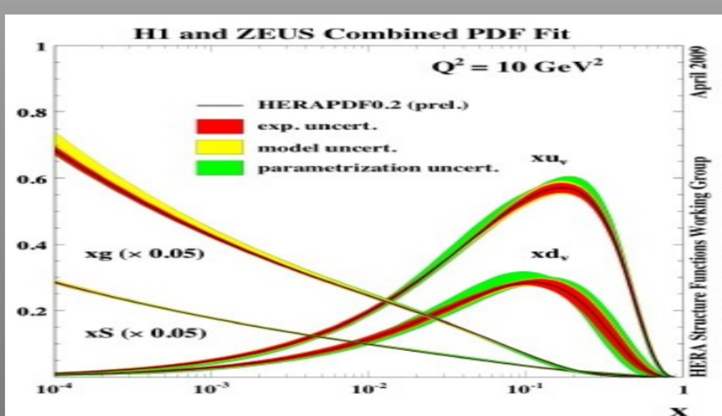


$0 \leq x_B \leq A$

x_B gives the fraction of nucleon momentum carried by the struck parton

x_B counts the number of nucleons involved

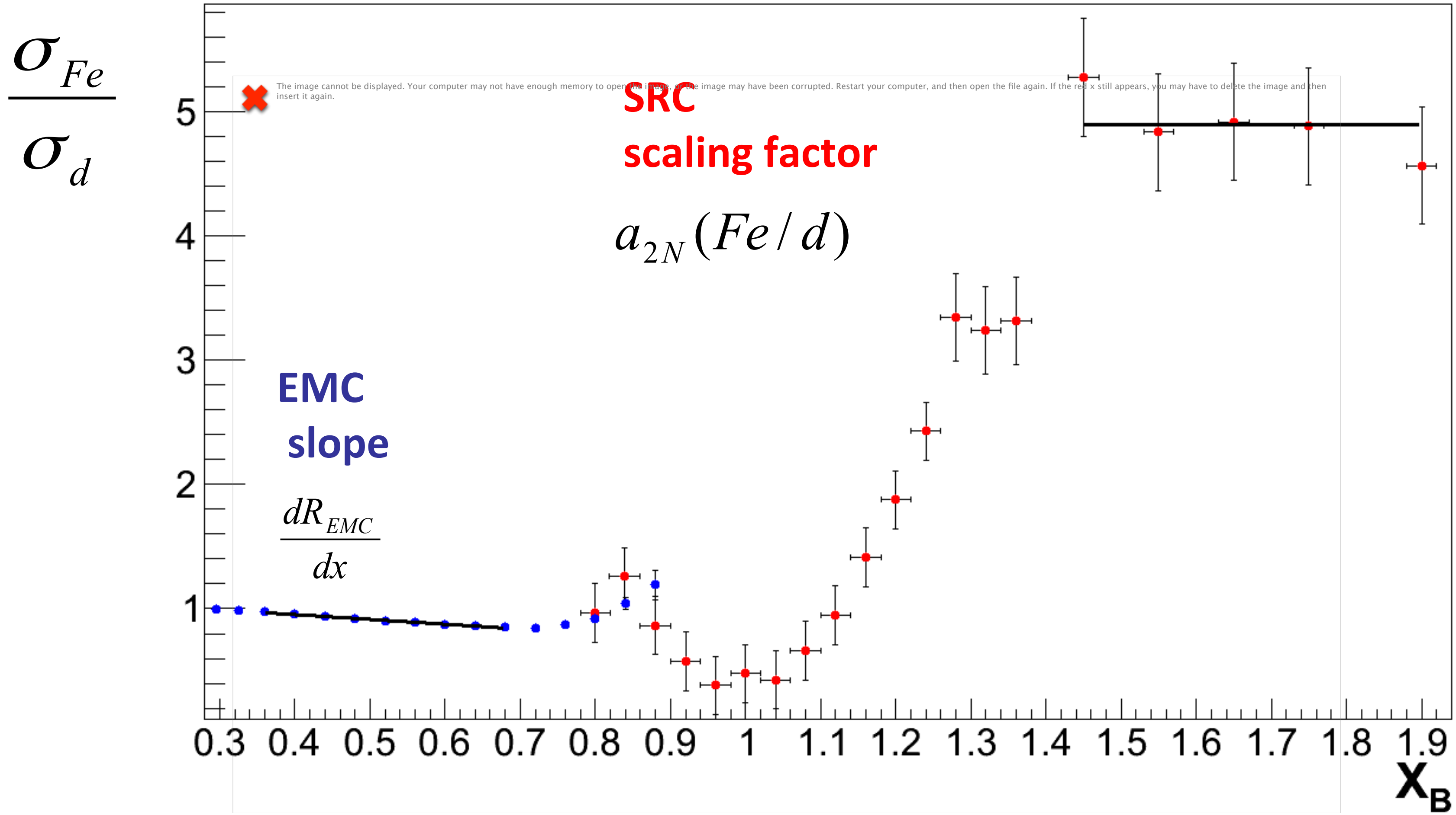




--> scaling

--> Counting the number of SRC clusters in nuclei

Comparing magnitude of EMC effect and SRC scaling factors



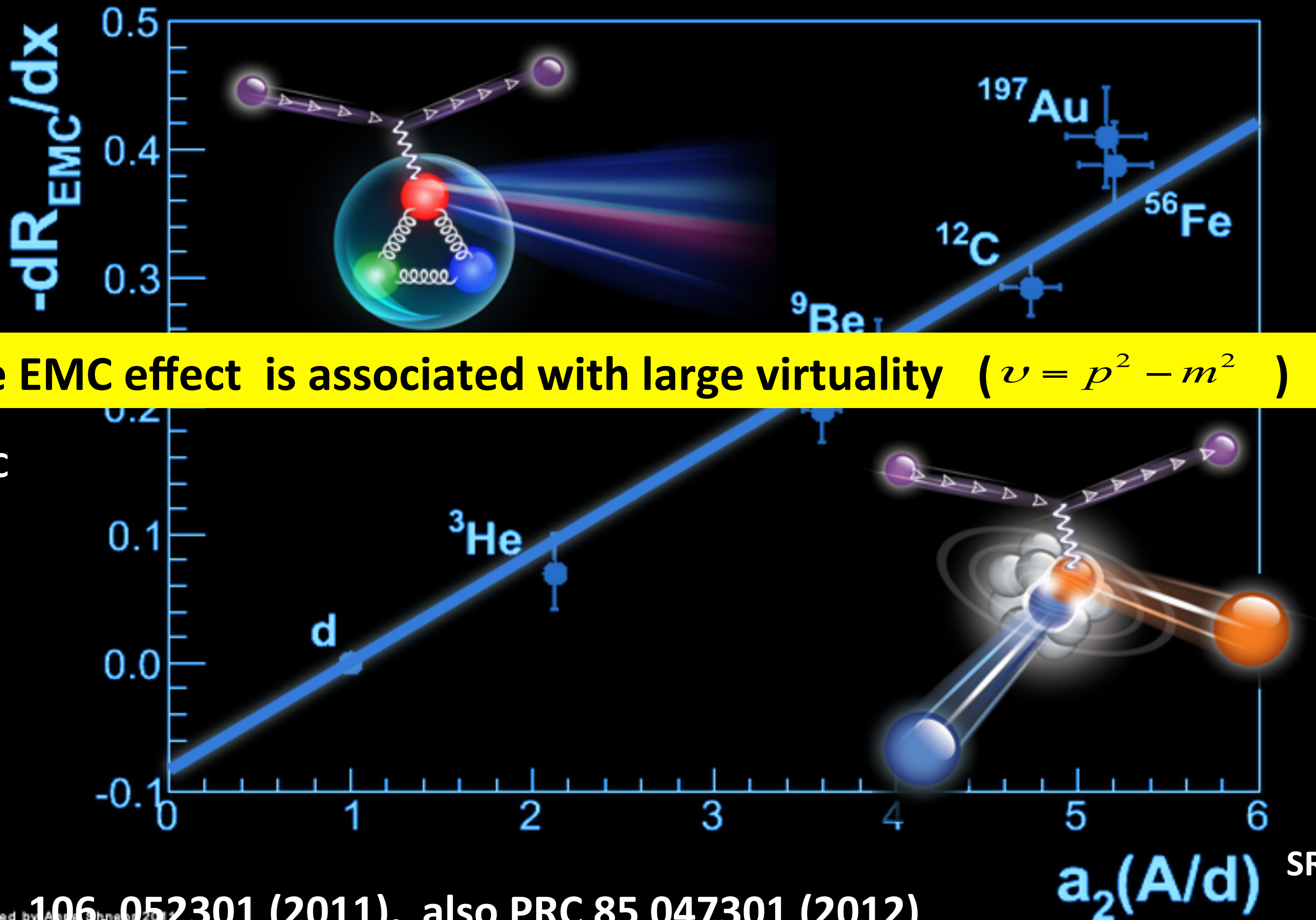
SLAC data:

Gomez et al., Phys. Rev. D49, 4348 (1983).

Q^2=2, 5, 10, 15 GeV/c^2 (averaged)

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451.

Q^2=2.3 GeV/c^2



the EMC effect is associated with large virtuality ($\upsilon = p^2 - m^2$)

EMC

SRC

PRL 106, 052301 (2011), also PRC 85 047301 (2012)

Is the EMC effect associated with large virtuality ?

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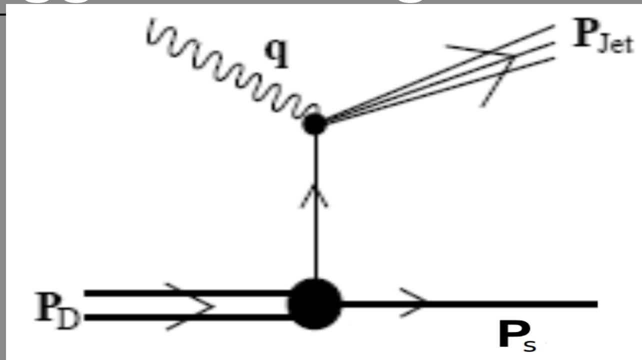
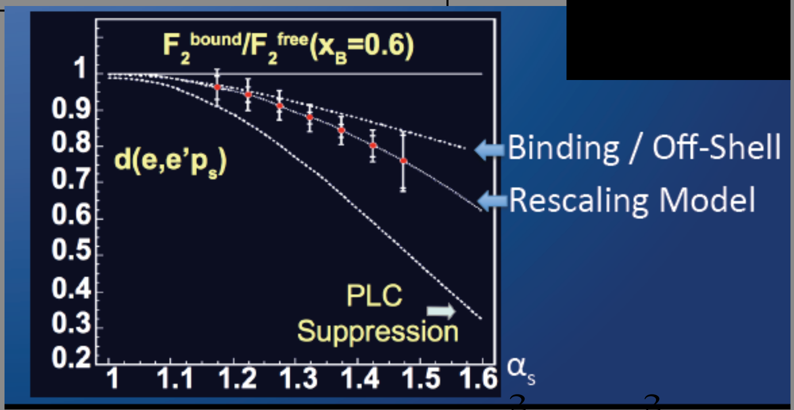
Hypothesis can be verified by measuring DIS off Deuteron tagged with high momentum recoil nucleon

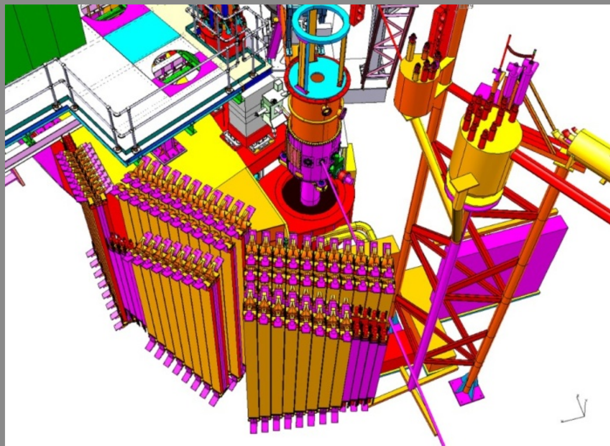




$$v = p^2 - m^2$$

12 GeV JLab/ Hall C approved experiment E 12-11-107

Tagged recoil proton measure neutron structure function

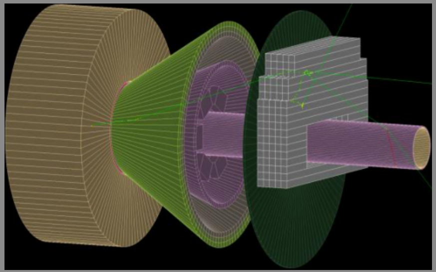


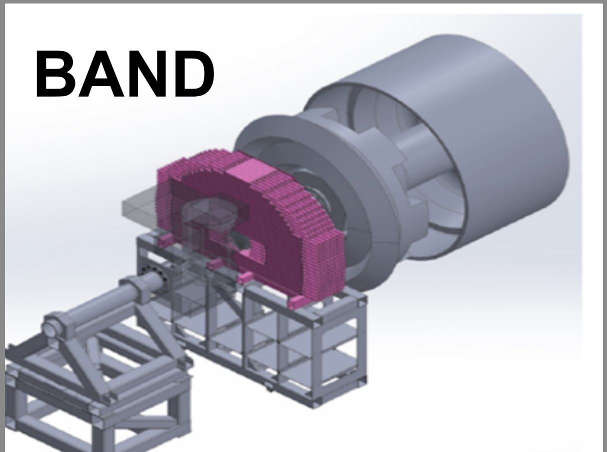
LAND

12 GeV JLab/ Hall B approved experiment

E12-11-003a

Tagged recoil neutron measure in the proton structure function





Summary – relevant of Correlations

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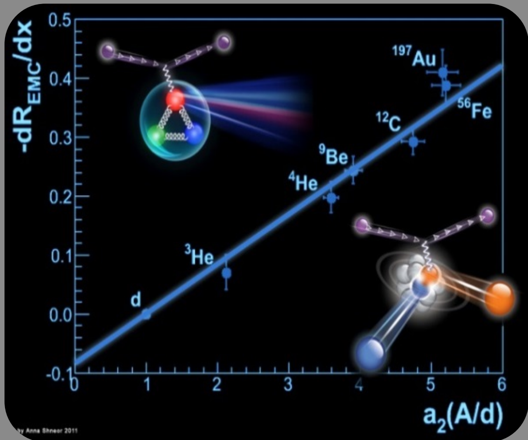
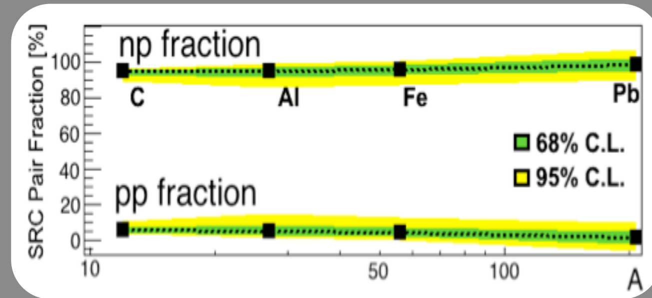
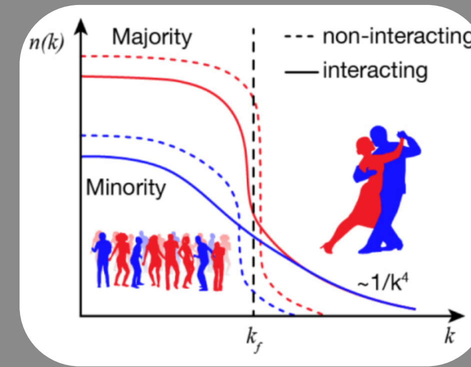
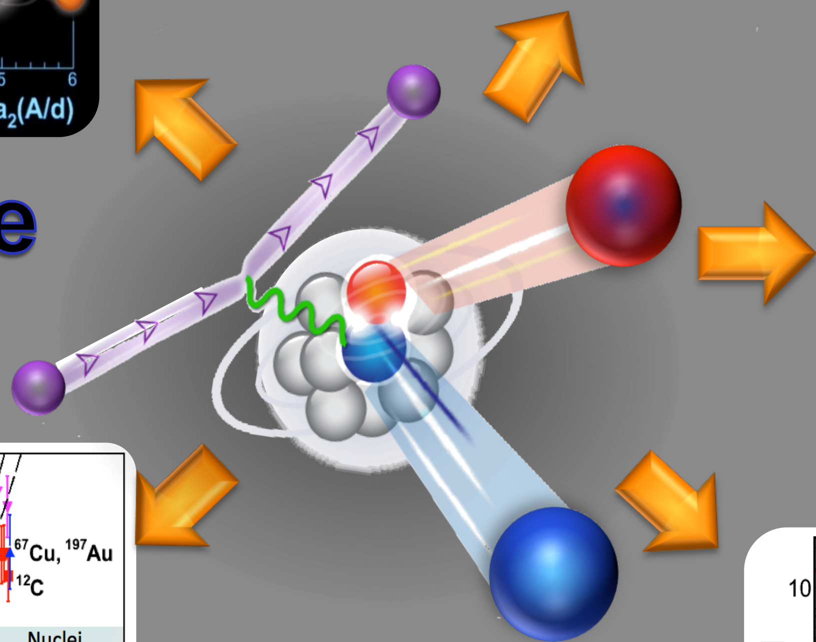


Particle



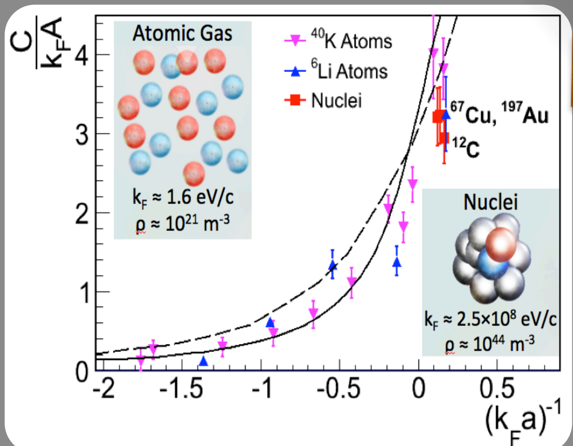
Nuclear





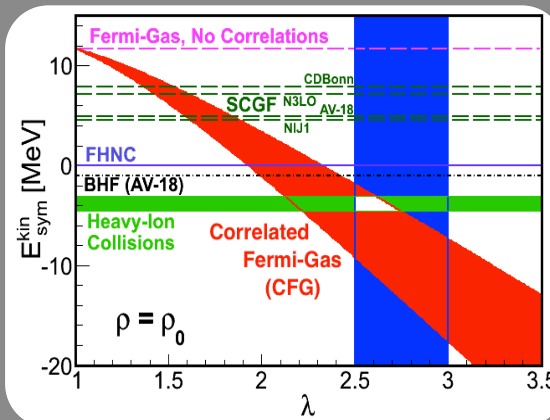
3N-SRC

Atomic



Contact term

Astro



Symmetry energy

Summary – proposed experiments

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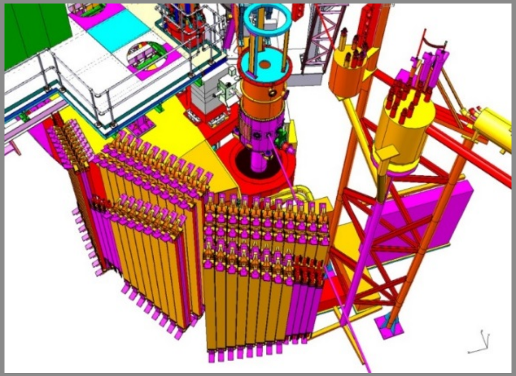
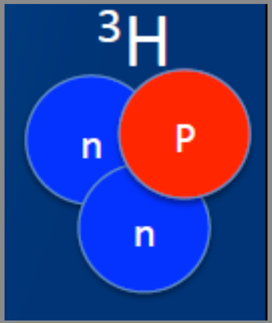
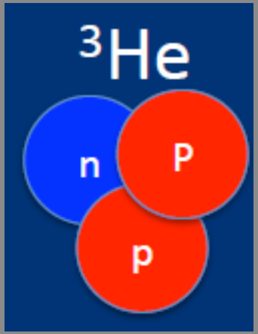
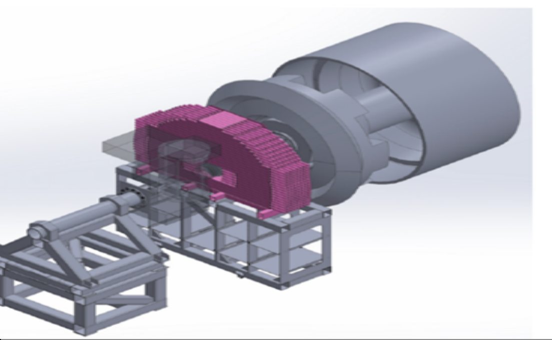


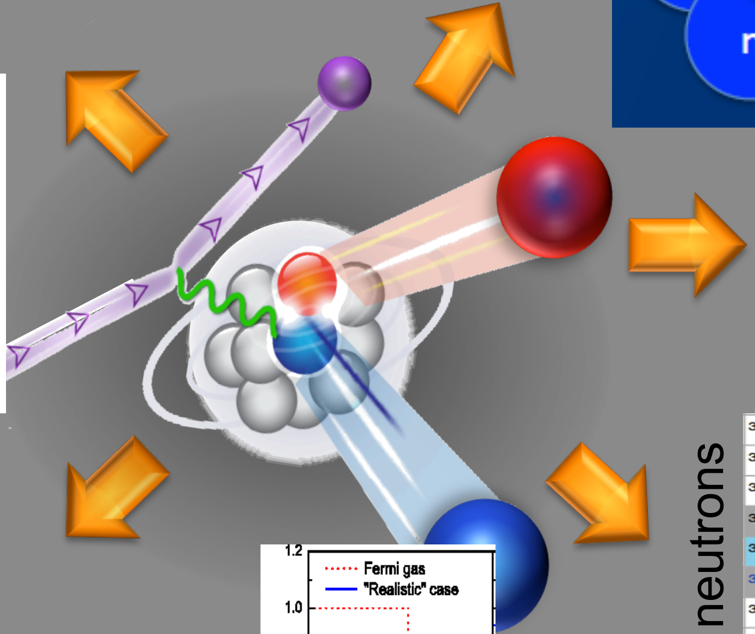
JLab Hall C:
E12-11-107

JLab









JLab Hall A:
E12-14-011

JLab Hall B:
E12-11-003a

Add 8 f7/2 neutrons

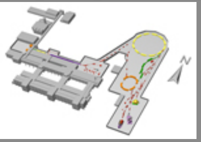
Z

N

^{32}Cl	^{33}Ar		Ca							
^{33}Cl	^{34}Ar	^{35}K		21						
^{34}Cl	^{35}Ar	^{36}K	^{37}Ca	Sc	22					
^{35}Cl	^{36}Ar	^{37}K	^{38}Ca		Ti	23				
^{36}Cl	^{37}Ar	^{38}K	^{39}Ca	^{40}Sc	^{41}Ti	V	24			
^{37}Cl	^{38}Ar	^{39}K	$\boxed{^{40}\text{Ca}}$	^{41}Sc	^{42}Ti		Cr	25		
^{38}Cl	^{39}Ar	^{40}K	^{41}Ca	^{42}Sc	^{43}Ti	^{44}V	^{45}Cr	Mn	26	
^{39}Cl	^{40}Ar	^{41}K	^{42}Ca	^{43}Sc	^{44}Ti	^{45}V	^{46}Cr		Fe	27
^{40}Cl	^{41}Ar	^{42}K	^{43}Ca	^{44}Sc	^{45}Ti	^{46}V	^{47}Cr	^{48}Mn	^{49}Fe	Co
^{41}Cl	^{42}Ar	^{43}K	^{44}Ca	^{45}Sc	^{46}Ti	^{47}V	^{48}Cr	^{49}Mn	^{50}Fe	^{51}Co
^{42}Cl	^{43}Ar	^{44}K	^{45}Ca	^{46}Sc	^{47}Ti	^{48}V	^{49}Cr	^{50}Mn	^{51}Fe	^{52}Co
^{43}Cl	^{44}Ar	^{45}K	^{46}Ca	^{47}Sc	^{48}Ti	^{49}V	^{50}Cr	^{51}Mn	^{52}Fe	^{53}Co
^{44}Cl	^{45}Ar	^{46}K	^{47}Ca	^{48}Sc	^{49}Ti	^{50}V	^{51}Cr	^{52}Mn	^{53}Fe	^{54}Co
28	^{46}Ar	^{47}K	$\boxed{^{48}\text{Ca}}$	^{49}Sc	^{50}Ti	^{51}V	^{52}Cr	^{53}Mn	$\boxed{^{54}\text{Fe}}$	^{55}Co
	29	^{48}K	^{49}Ca	^{50}Sc	^{51}Ti	^{52}V	^{53}Cr	^{54}Mn	^{55}Fe	^{56}Co

Add 8 protons

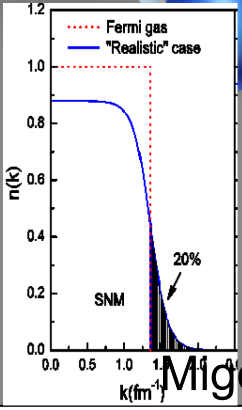
Hadron facilities



GSI / FAIR

Dubna

Nuclotron



Migdal jump

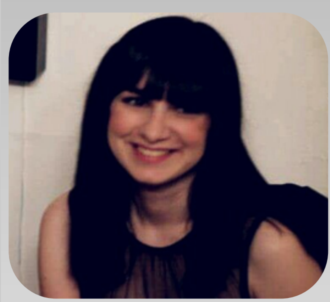
SRC talks

Thursday, November 02

Nuclei (Athenaeum Ballroom)

Session chair: **Fabienne Kunne**

11:30-12:00	New Insights into Nucleon-Nucleon Correlations	Axel Schmidt (MIT)



Parallel Workshops

2. New Avenues in Lepton Scattering

Wednesday, November 01 15:00-15:30

Session I: Nuclear & Nucleon Structure

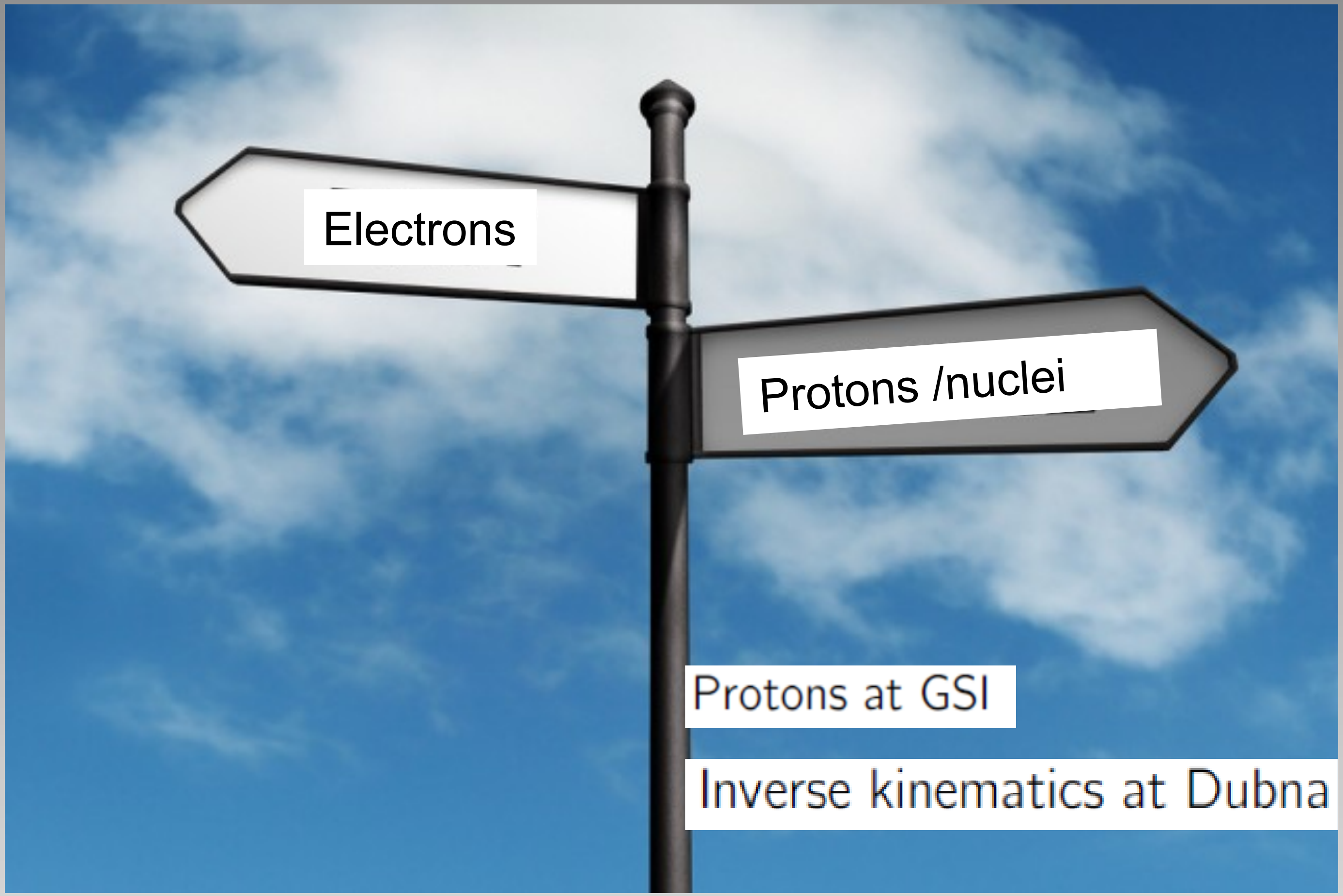
N-N correlations in nuclei	Meytal Duer (Tel-Aviv)

Acknowledgment

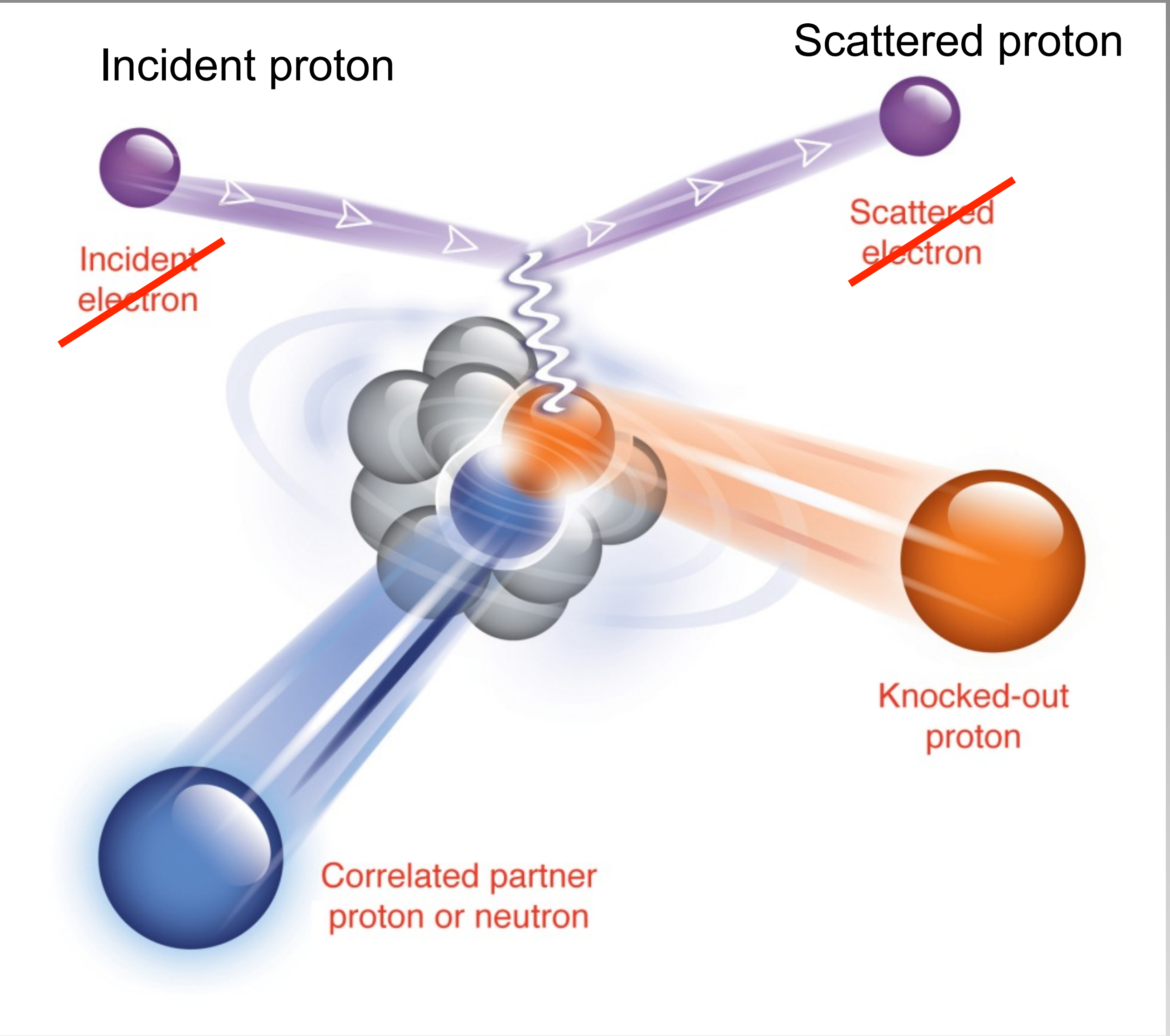
I would like to thank the organizers for the invitation.

Erez Cohen

Axel Schmidt


Electrons
Protons /nuclei
Protons at GSI
Inverse kinematics at Dubna

Triple coincidence A (p, p p N) measurements complementary to JLab



Complementary to JLab study with electrons

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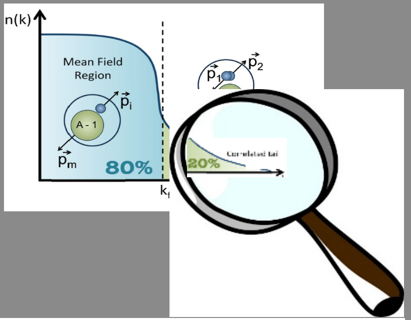
Why H.E. protons are good probes of SRC ?



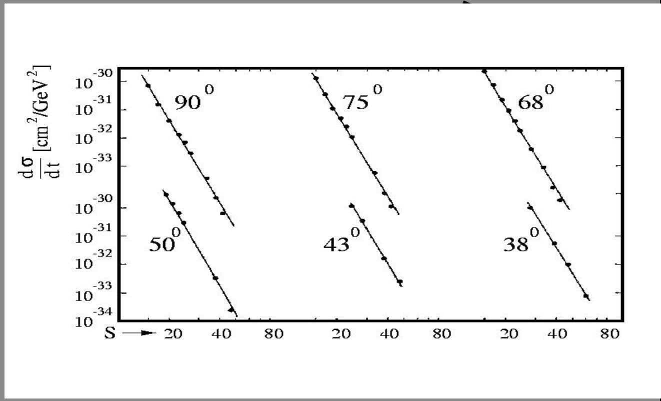
selective attention to SRC

Psychology Wiki

Selective attention. A type of attention which involves focusing on a specific aspect of a scene while ignoring other aspects.

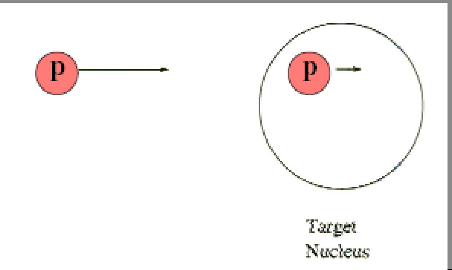
p p → pp elastic scattering near 90^0 c.m

$$\frac{d\sigma}{dt} \propto s^{-10}$$



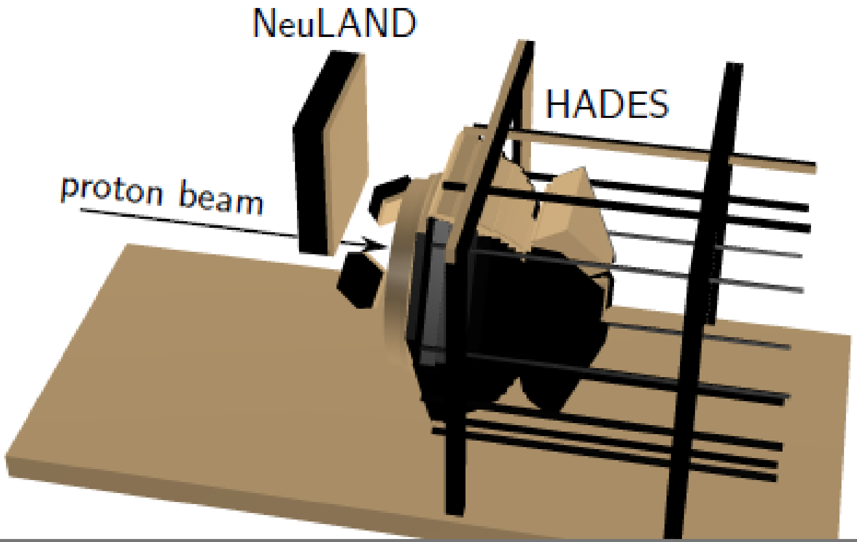
Constituent Counting Rules

QE pp scattering have a very strong preference for reacting with forward going high momentum nuclear protons

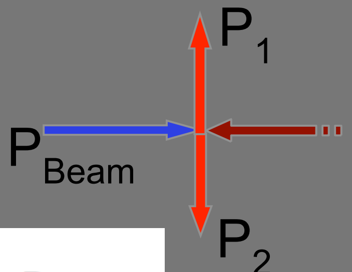


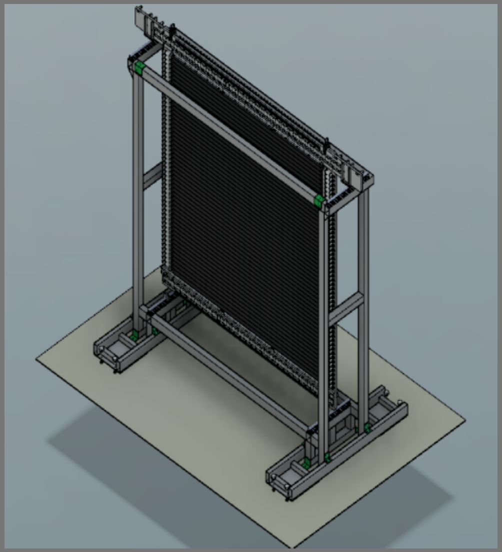
A new proton scattering experiment at GSI can yield

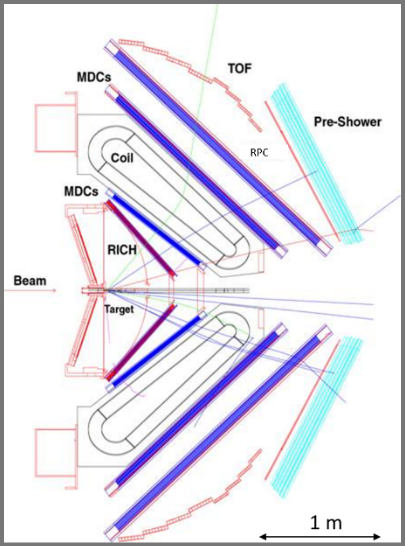
- Proton scattering enhances SRC cross section
- Use existing HADES, NeuLAND detectors
- Chance to look at 3-nucleon correlations

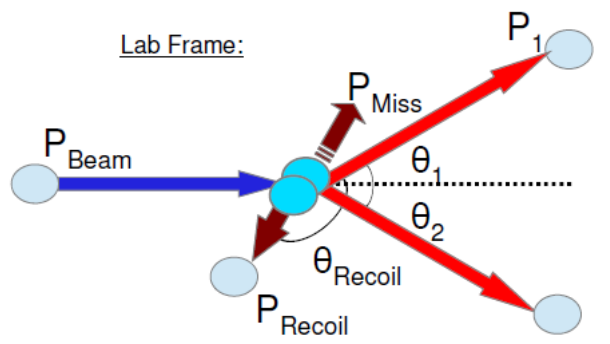


C.M. Frame :

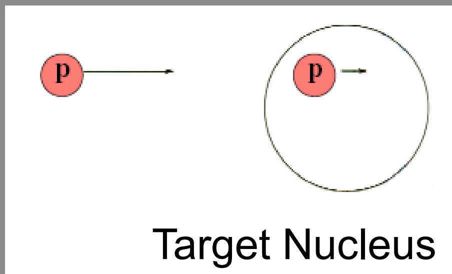


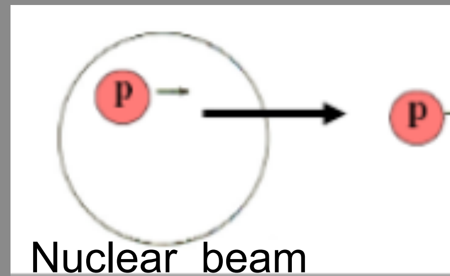


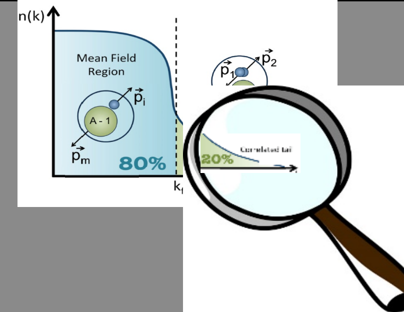




Inverse kinematics at Dubna



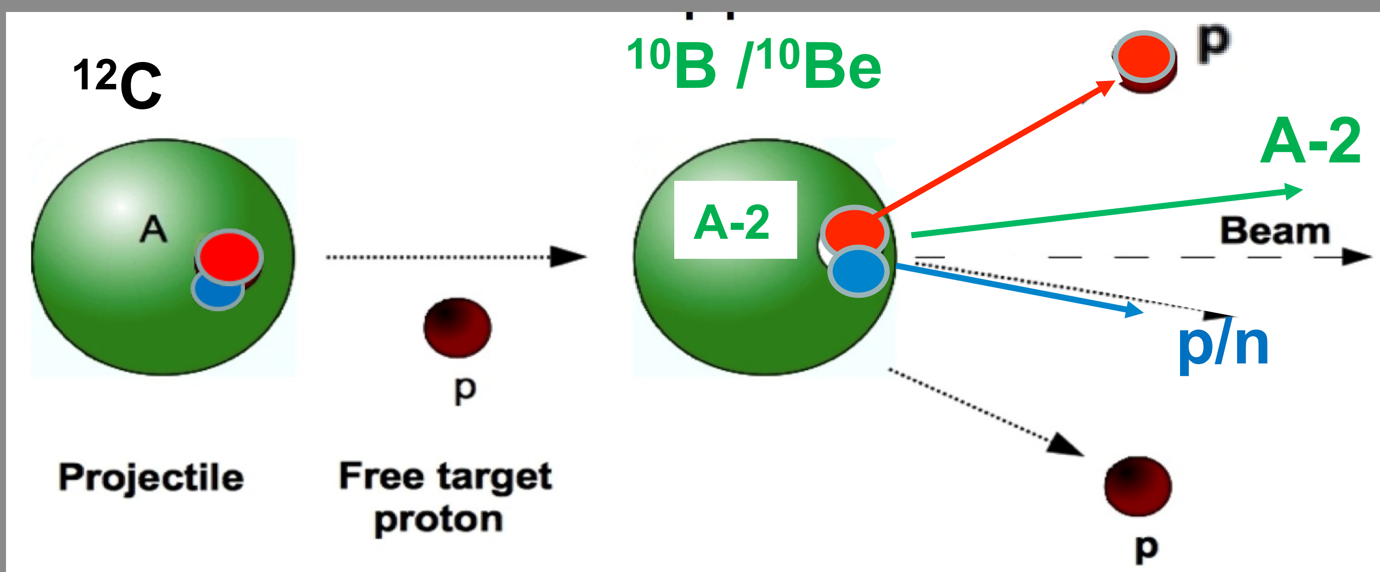




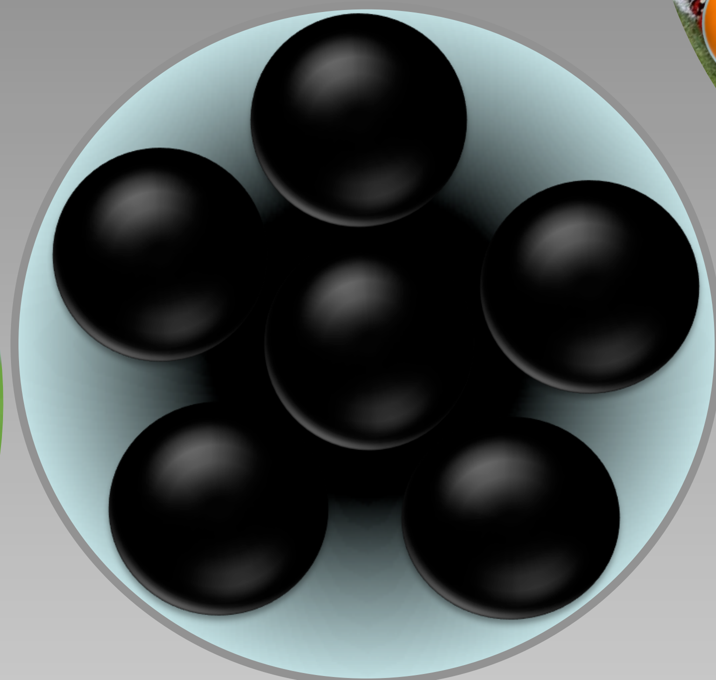
Same selective attention to SRC

A proposal for a BM@N experiment

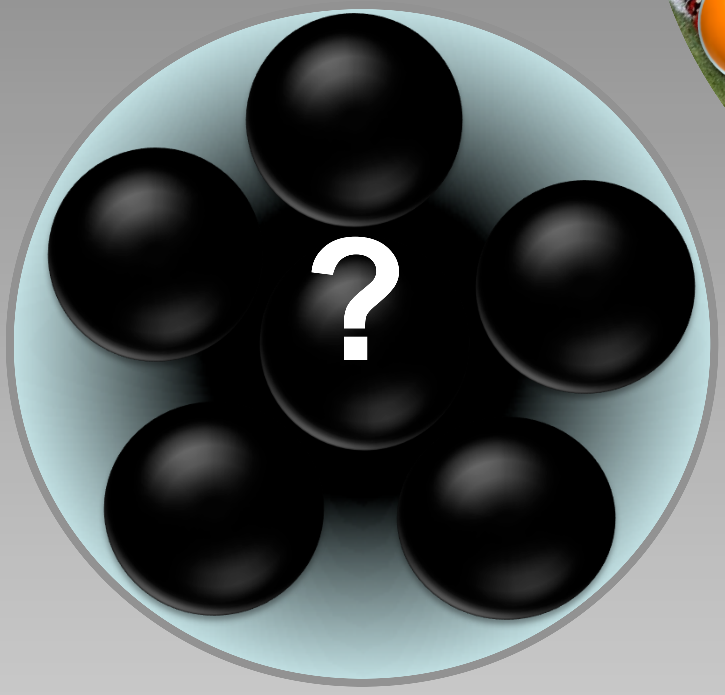
To study the NN Repulsive Core with Hard inverse kinematic reactions



triple – coincidence measurements

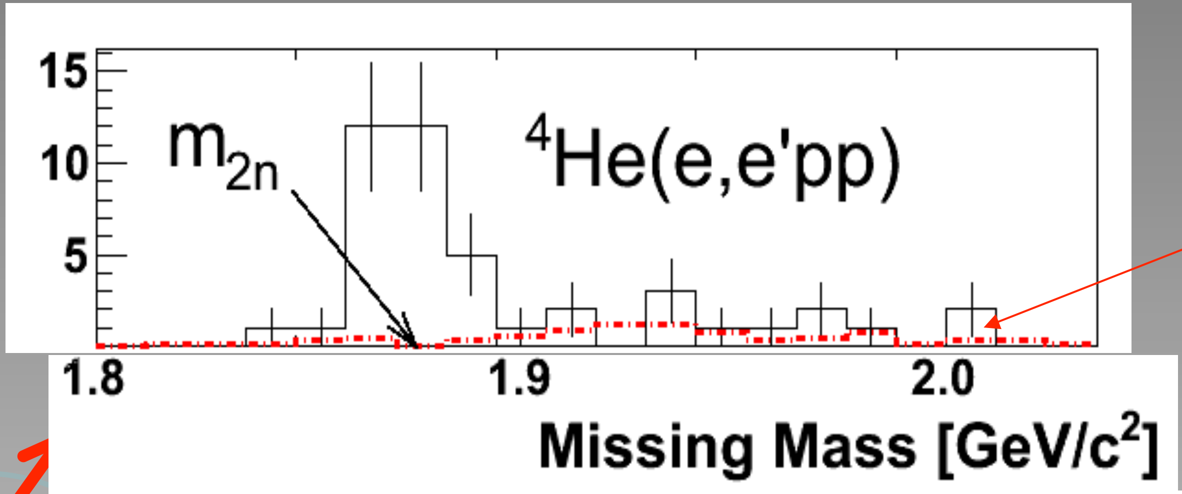


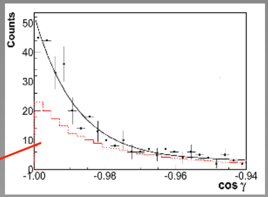
triple – coincidence measurements



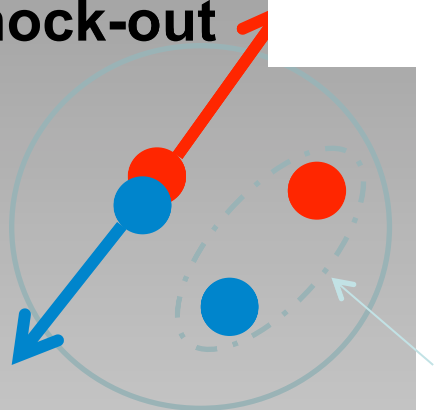
Inverse kinematics

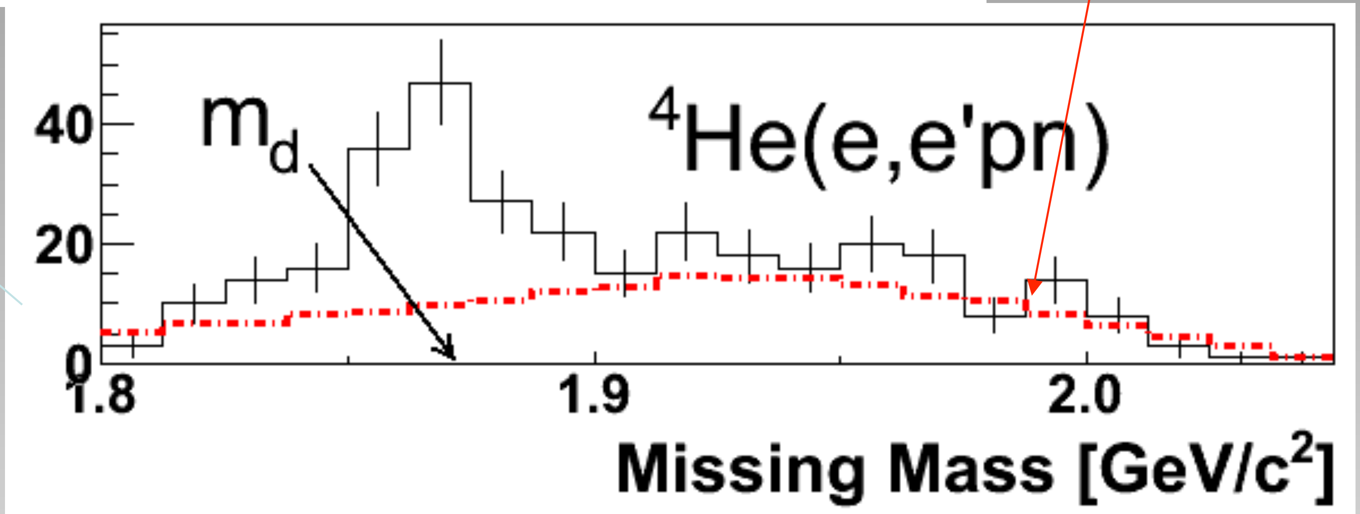
E07-006 (2011) ^{4}He (^{12} C)





background



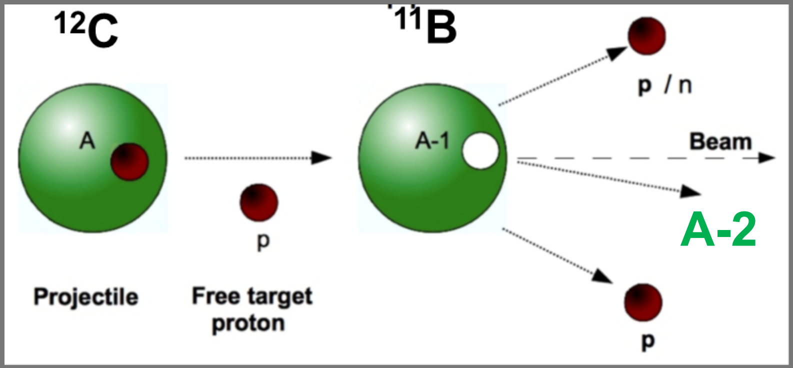


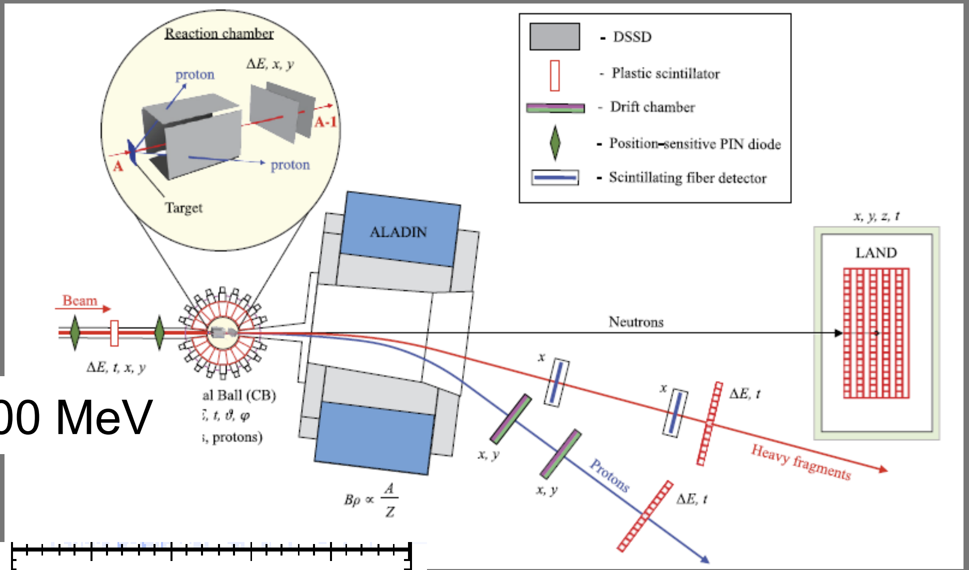
Jlab Hall A experiment

I. Korover et al. Phys. Rev. Let. 113, 022501 (2014).

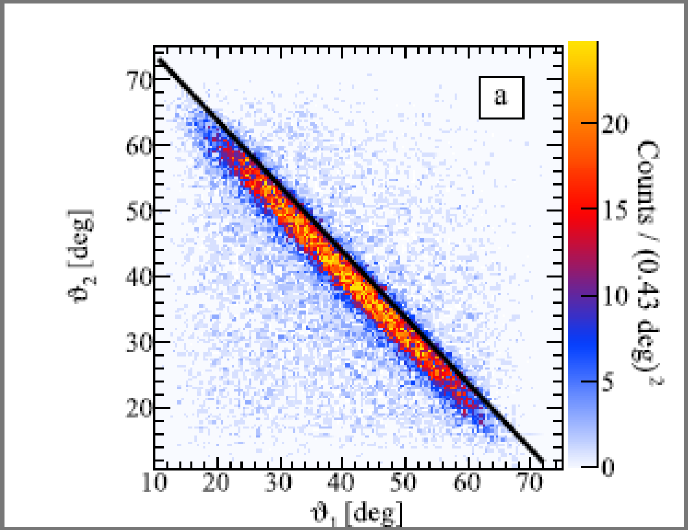
QE measurement with LAND/R3B@GSI

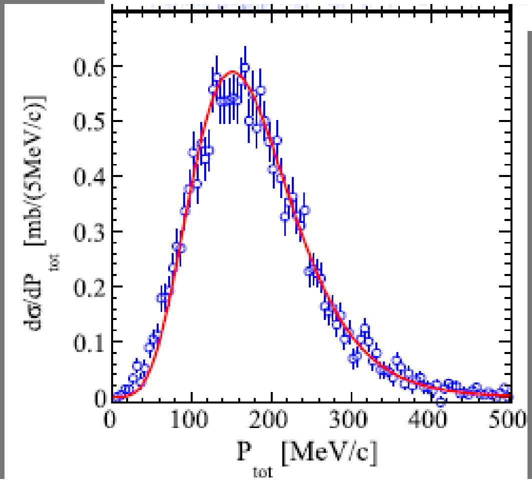
V. Panin et al. PLB 753 (2016) 204.





~400 MeV



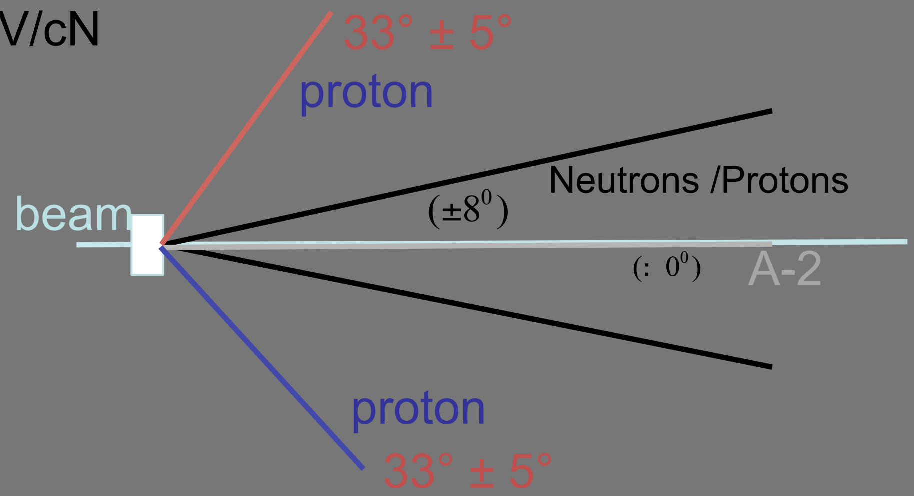


Energy limit at R3B around 1 GeV/nucleon due to maximum rigidity of Super-FRS of 20 Tm

SRC @ Dubna

Carbon beam with momentum of 4 GeV/cN

${}^{12}C + p \rightarrow 2p + {}^{11}_{5}B$	QE
${}^{12}C + p \rightarrow 2p + {}^{10}_{5}B + n$	np SRC
${}^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p$	pp SRC



Get the ratios:

$$np - SRC \big/ pp - SRC$$

$$\#({}^{10}_{5}B + n) \big/ \#({}^{10}_{4}Be + p)$$

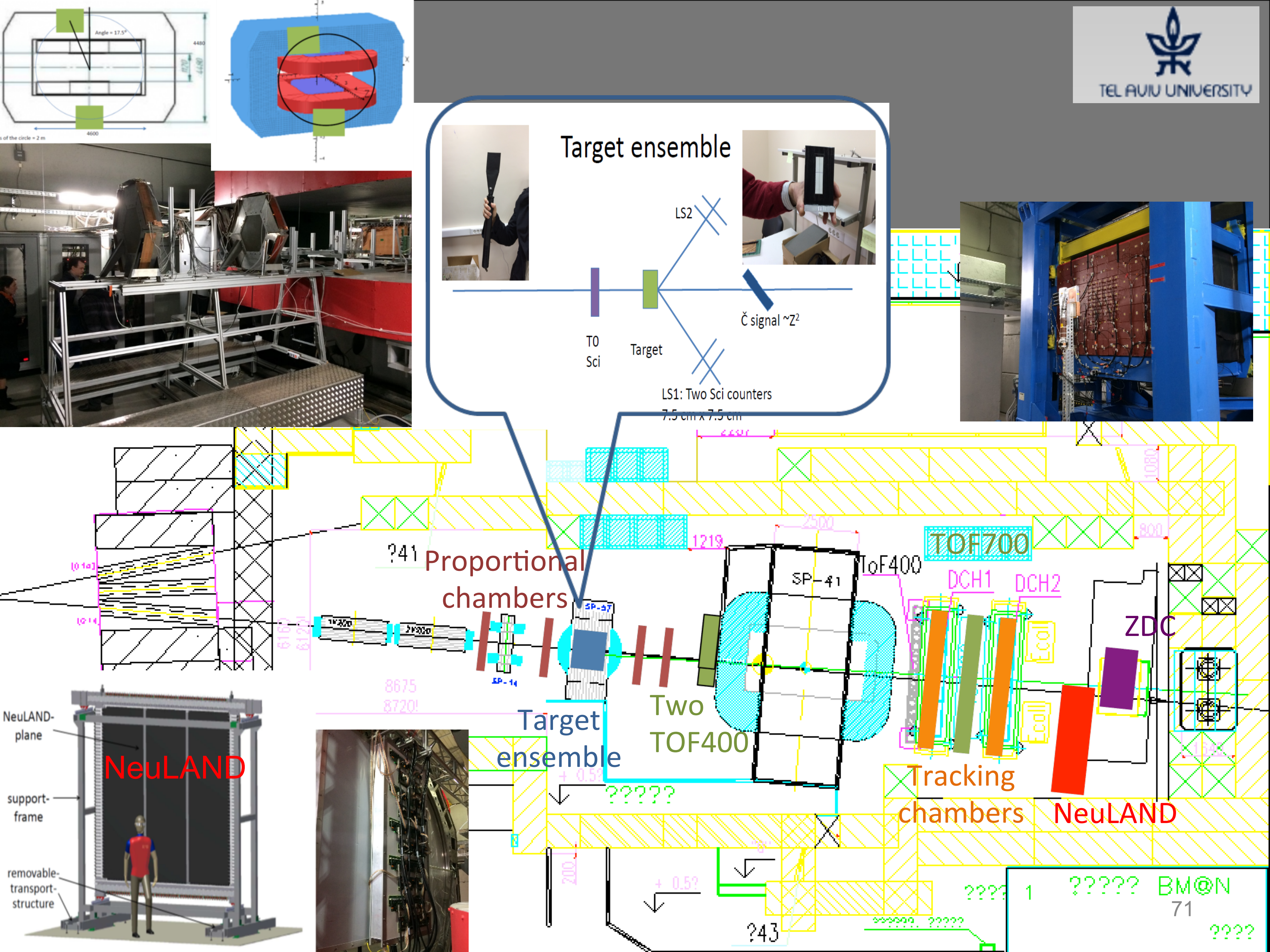
$$np - SRC \big/ p$$

$$\#({}^{10}_{5}B + n) \big/ \#(p, 2p)$$

$$pp - SRC \big/ p$$

$$\#({}^{10}_{4}Be + p) \big/ \#(p, 2p)$$

$$\#({}^{11}_{5}B) \big/ \#(p, 2p)$$



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Target ensemble
LS2
Č signal ~Z²
T0
Sci
Target
LS1: Two Sci counters
7.5 cm x 7.5 cm
Proportional
chambers
Target
ensemble
Two
TOF400
TOF700
ToF400
SP-41
DCH1
DCH2
ZDC
Tracking
chambers
NeuLAND
NeuLAND-
plane
support-
frame
removable-
transport-
structure
NeuLAND
?41
1219
2500
800
8675
8720
?????
?43
????? BM@N
71

LH_2 Vs. CH_2

LH_2:

- Length: 15 cm
- Interaction probability: ~3%

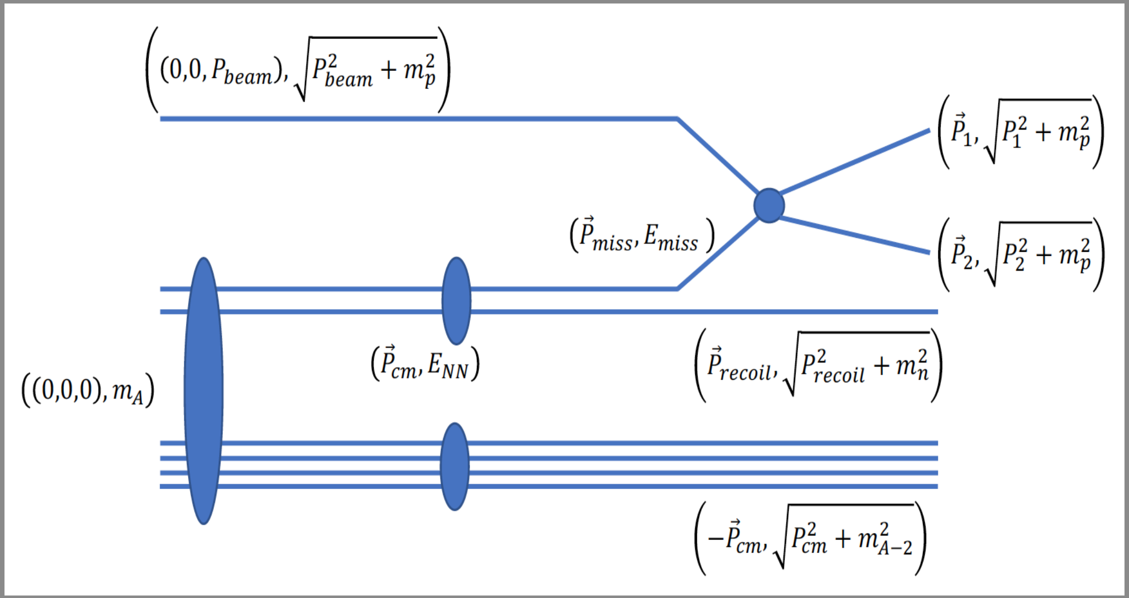
CH_2:

- Length: ~9 cm [equal hydrogen areal density]
- Interaction probability: ~10% [7% with C, 3% with H_2]

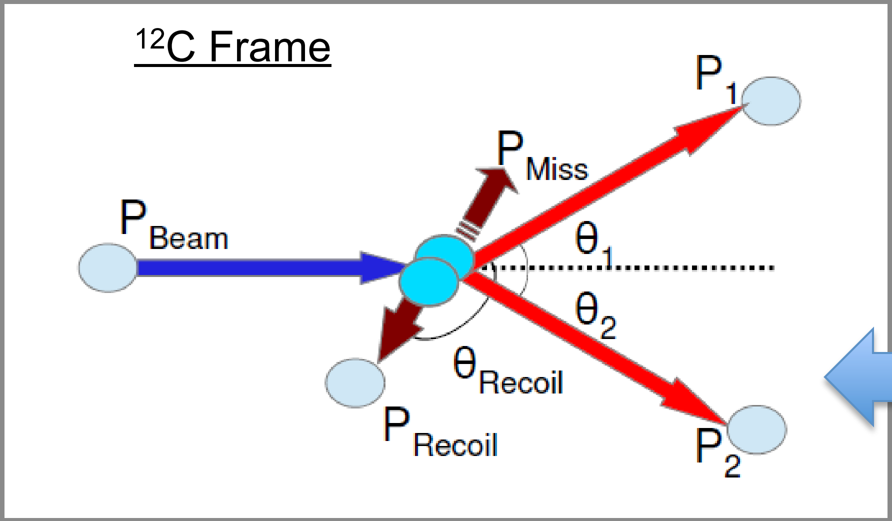
Other considerations:

- CH_2 has increased BG from C-C interactions.
- CH_2 requires extra time for C subtraction.
- CH_2 maintenance free.
- LH_2 requires safety approval for used in BM@N area.

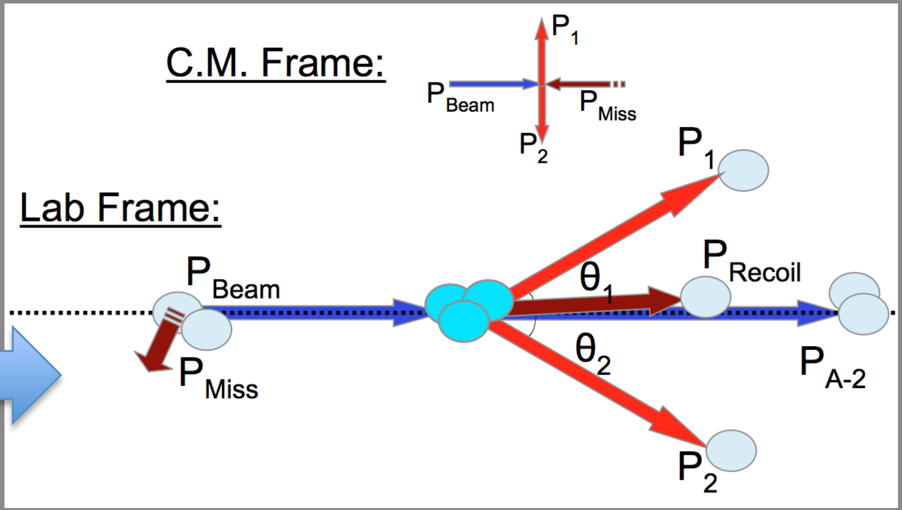
simulation



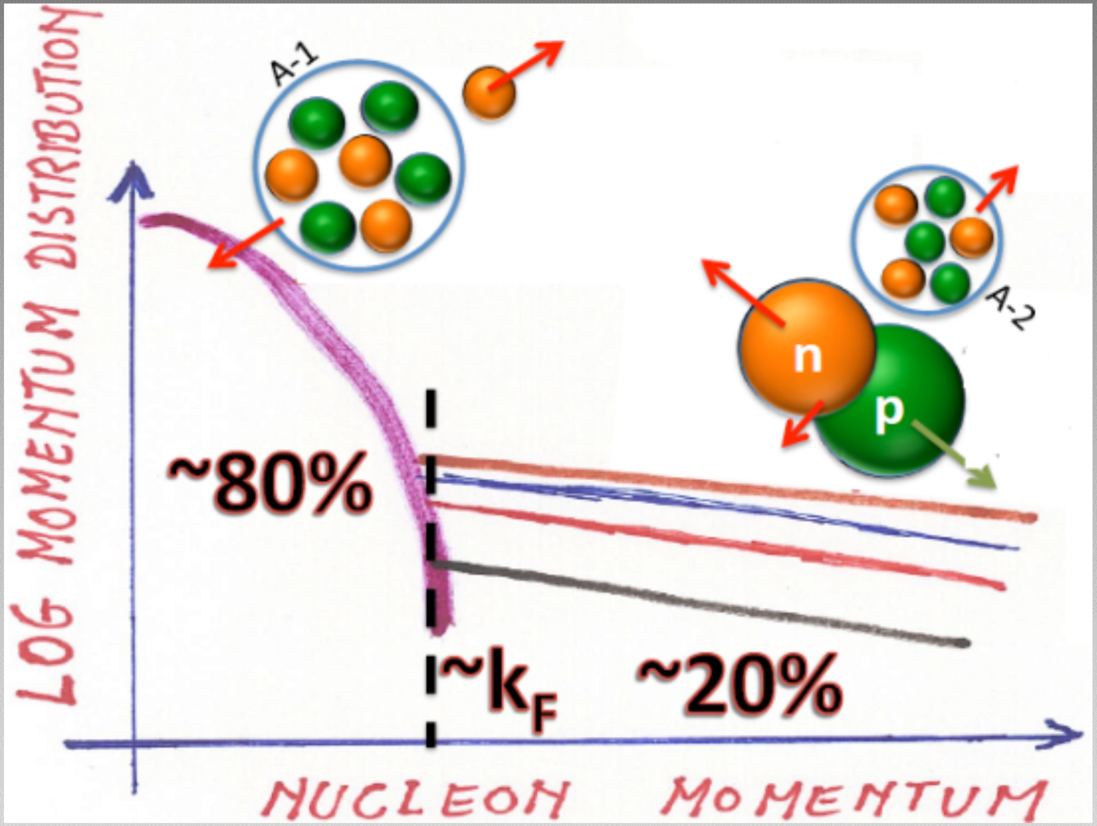
$\left((0,0,P_{beam}), \sqrt{P_{beam}^2 + m_p^2}\right)$
$\left(\vec{P}_1, \sqrt{P_1^2 + m_p^2}\right)$
$\left(\vec{P}_{miss}, E_{miss}\right)$
$\left(\vec{P}_2, \sqrt{P_2^2 + m_p^2}\right)$
$\left((0,0,0), m_A\right)$
$\left(\vec{P}_{cm}, E_{NN}\right)$
$\left(\vec{P}_{recoil}, \sqrt{P_{recoil}^2 + m_n^2}\right)$
$\left(-\vec{P}_{cm}, \sqrt{P_{cm}^2 + m_{A-2}^2}\right)$



^{12}C Frame
P_1
P_{Miss}
P_{Beam}
θ_1
θ_2
θ_{Recoil}
P_{Recoil}
P_2



C.M. Frame:
P_1
P_{Beam}
P_{Miss}
P_2
Lab Frame:
P_1
P_{Beam}
θ_1
P_{Recoil}
θ_2
P_{Miss}
P_{A-2}
P_2



LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
~80%
~k_F
~20%
NUCLEON MOMENTUM

$$\psi_{2N}^{SRC}(\vec{k}_{rel},\vec{K}_{c.m.}) \to \sum_{\alpha} \varphi_{2N}(\vec{k}_{rel}) \cdot A_{2N}(\vec{K}_{c.m.},\{k_\alpha\}_{\alpha\neq 2N})$$

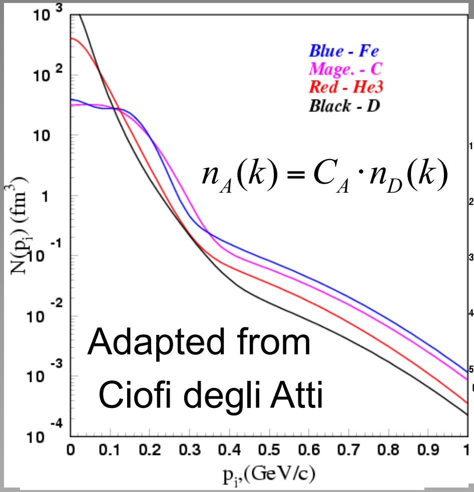
(Factorization) [R. Weiss et al. arXiv:1612.00923]

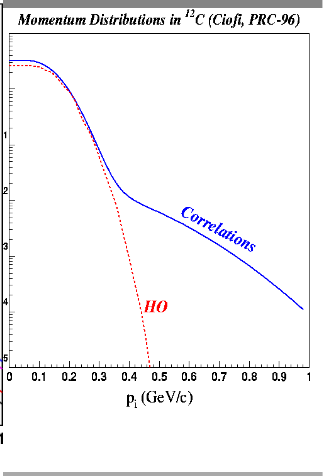
In this work we will consider only the main channels contributing to SRCs, namely, the pn deuteron channel ($\ell = 0, 2$ and $s = 1$ coupled to $j = 1$) and the singlet pp, pn, and nn s-wave channel ($\ell = s = j = 0$). Using Eq. (2), asymptotic expressions for the one- and two-body momentum densities can be derived [38]:

$$\begin{aligned} n_p(\boldsymbol{k}) =& 2C_{pp}^{s=0}|\tilde{\varphi}_{pp}^{s=0}(\boldsymbol{k})|^2 + C_{pn}^{s=0}|\tilde{\varphi}_{pn}^{s=0}(\boldsymbol{k})|^2 \\ &+ C_{pn}^{s=1}|\tilde{\varphi}_{pn}^{s=1}(\boldsymbol{k})|^2 \end{aligned} \tag{3}$$

The inclusive A(e,e') measurements

- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: **SCALING**.

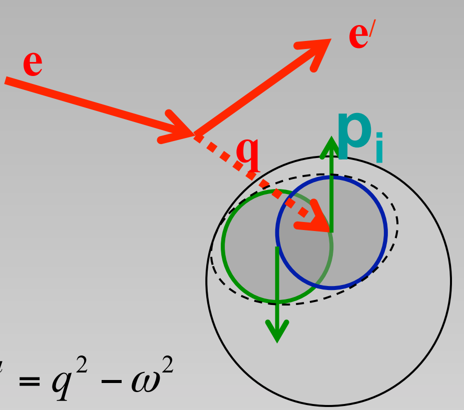




- Can be explained by 2N-SRC dominance.

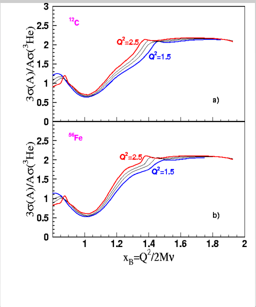
- Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.

In A(e,e') the momentum of the struck proton (p_i) is unknown.



But: For fixed high Q^2 and $x_B>1$, x_B determines a minimum p_i

Prediction by Frankfurt, Sargsian, and Strikman:



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega}$$

Kinematics optimized to minimize the competing processes

FSI

FSI with the A-2 system:

★ Small (10-20%) .

- Kinematics with a large component of p_{miss} in the virtual photon direction.
- Pauli blocking for the recoil particle.
- Geometry, (e, e'p) selects the surface.

★ Can be treated in Glauber approximation.

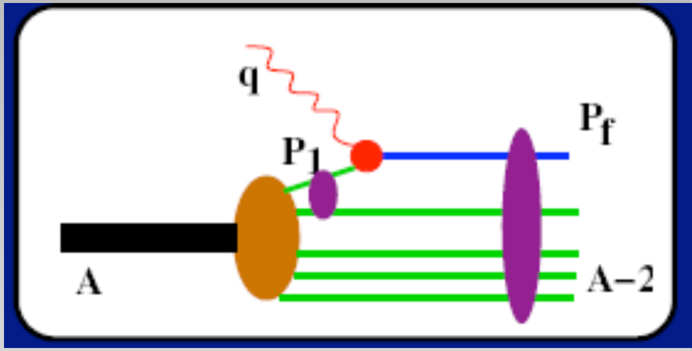
★ Canceled in some of the measured ratios.

FSI in the SRC pair:

These are not necessarily small, BUT:

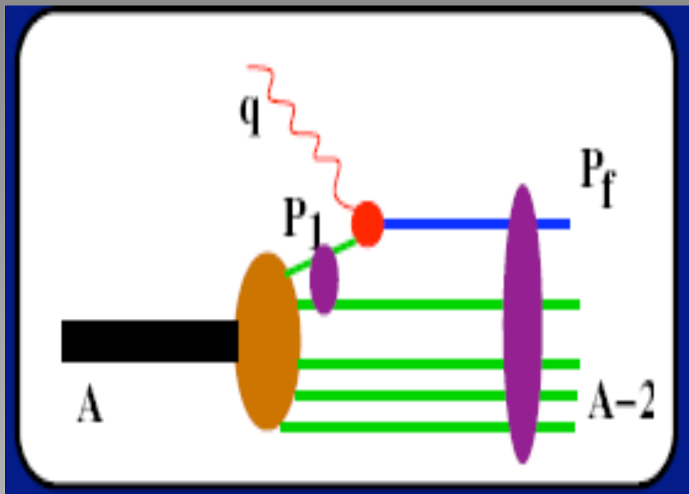
★ Conserve the isospin structure of the pair .

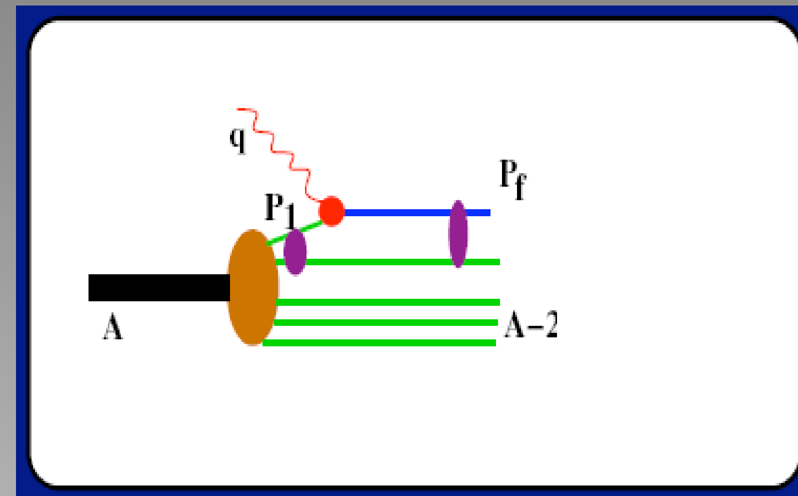
★ Conserve the CM momentum of the pair.



Why FSI do not destroy the 2N-SRC signature ?

For large Q^2 and x>1 FSI is confined within the SRC





distances that highly virtual struck nucleon propagates

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

$$r \approx \frac{1}{\Delta E v} \leq 1 \text{ fm}$$

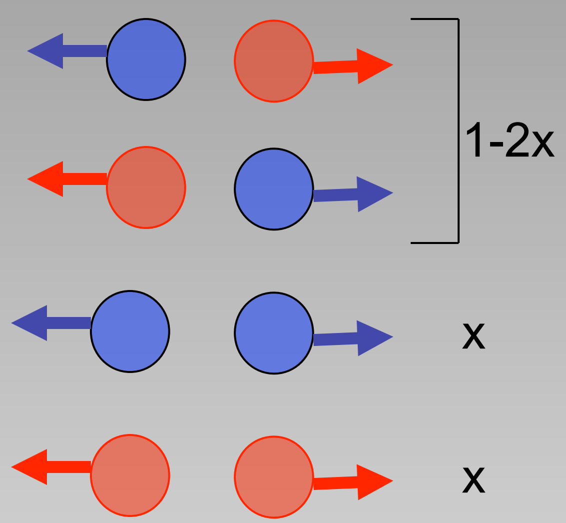
for x > 1.3

FSI in the SRC pair:

- Conserve the isospin structure of the pair .
- Conserve the CM momentum of the pair.

$$\frac{(e,e'pp)}{(e,e'p)} = 9.5 \pm 2\% \quad \Rightarrow \quad \frac{\text{pp-SRC}}{2N-SRC} = 4.75 \pm 1\%$$

Assuming in ^{12}C nn-SRC = pp-SRC and 2N-SRC=100%



A virtual photon with x_B >1 "sees" all the pp pairs but only 50% of the np pairs.

$$\frac{(e,e'pp)}{(e,e'p)} = \frac{x}{x+(1-2x)/2} = 2x$$

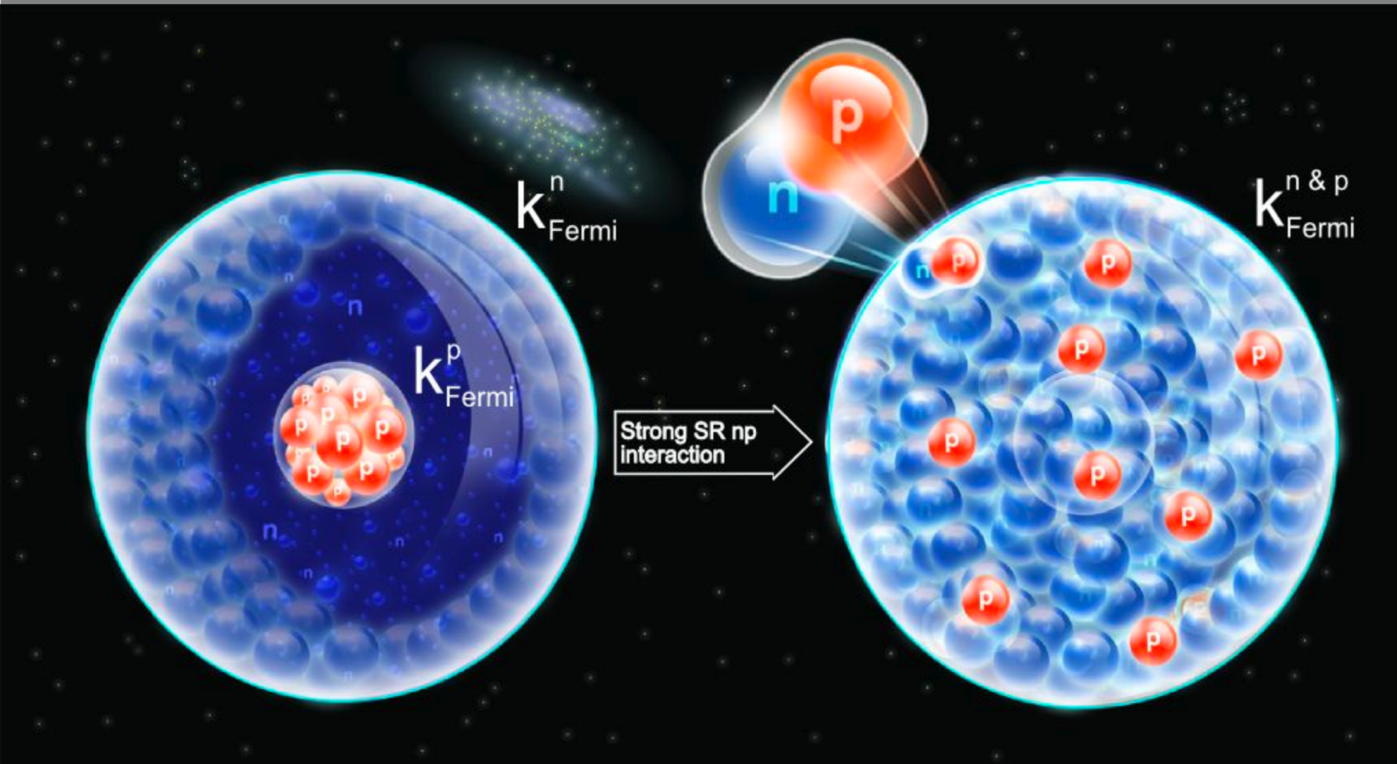
$$BNL \quad \frac{(\mathrm{p,2pn})}{(\mathrm{p,2p})} = \frac{\mathrm{np\text{ - }SRC}}{\mathrm{np\text{ - }SRC+2\ (pp\text{ - }SRC)}} = \frac{\mathrm{np\text{ - }SRC}}{\mathrm{2N\text{ - }SRC}} = (74\text{-}100)\ \%$$

$$Jlab \quad \frac{(\mathrm{e,e'pn})}{(\mathrm{e,e'p})} = \frac{np - SRC}{2N - SRC} = (84\text{ - }100)\%$$

$$Jlab \quad \frac{(\mathrm{e,e'pp})}{(\mathrm{e,e'p})} = (9.5 \pm 2)\ \% \quad \text{i.e} \quad \frac{\mathrm{pp\text{-}SRC}}{\mathrm{2N\text{-}SRC}} = \frac{nn - SRC}{2N - SRC} = (5 \pm 1)\%$$

$$\Rightarrow \qquad \frac{np - SRC}{2N - SRC} = (84\text{ - }92)\%$$

Implications for Neutron Stars



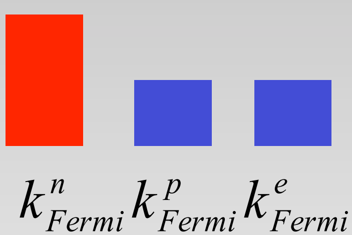
Adapted from: D.Higinbotham, E. Piasetzky, M. Strikman CERN Courier 49N1 (2009) 22

•At the core of neutron stars, most accepted models assume :

~95% neutrons, ~5% protons and ~5% electrons (β-stability).

•Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).

• strong np interaction → the n-gas heats the p-gas.



See estimates in Frankfurt and Strikman : Int.J.Mod.Phys.A23:2991-3055,2008.

SRC in nuclei: implication for neutron stars

TEL AVIV UNIVERSITY

•**At the core of neutron stars, most accepted models assume :**

~95% neutrons, ~5% protons and ~5% electrons (β-stability).

•**Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

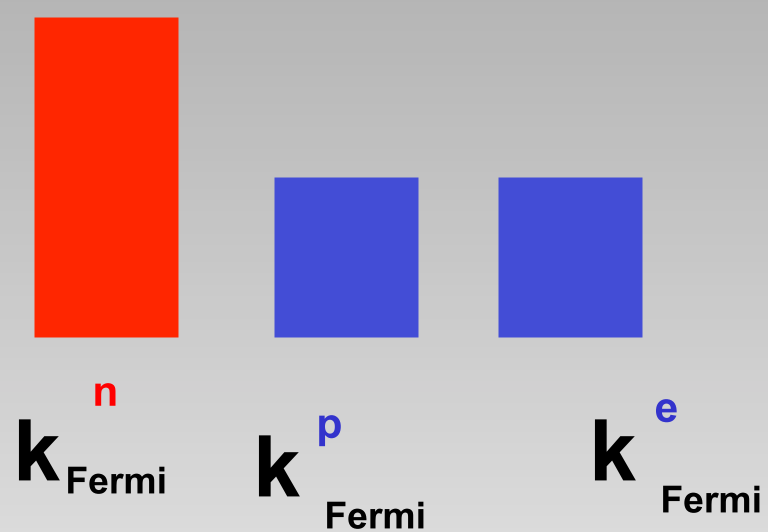
At T=0 $$k^n_{Fermi} = k^p_{Fermi} + k^e_{Fermi}$$

$$k^p_{Fermi} = k^e_{Fermi} = \left(\frac{N_p}{N_n}\right)^{1/3} k^n_{Fermi}$$

For $\rho = 5\rho_0,\ k^n_{Fermi} \approx 500\,\mathrm{MeV/c},\ k^p_{Fermi} = k^e_{Fermi} \approx 250\,\mathrm{MeV/c}$

Pauli blocking prevent direct n decay

$$n \rightarrow p + \mathrm{e} + \bar{\nu}_\mathrm{e}$$



Strong SR np interaction

THE MEAN FIELD APPROXIMATION

$$\left[-\frac{\hbar^2}{2\,m}\sum_i \hat{\nabla}_i^2 + \sum_{i<j} \hat{v}_{ij}\right]\Psi_o = E_o\,\Psi_o$$

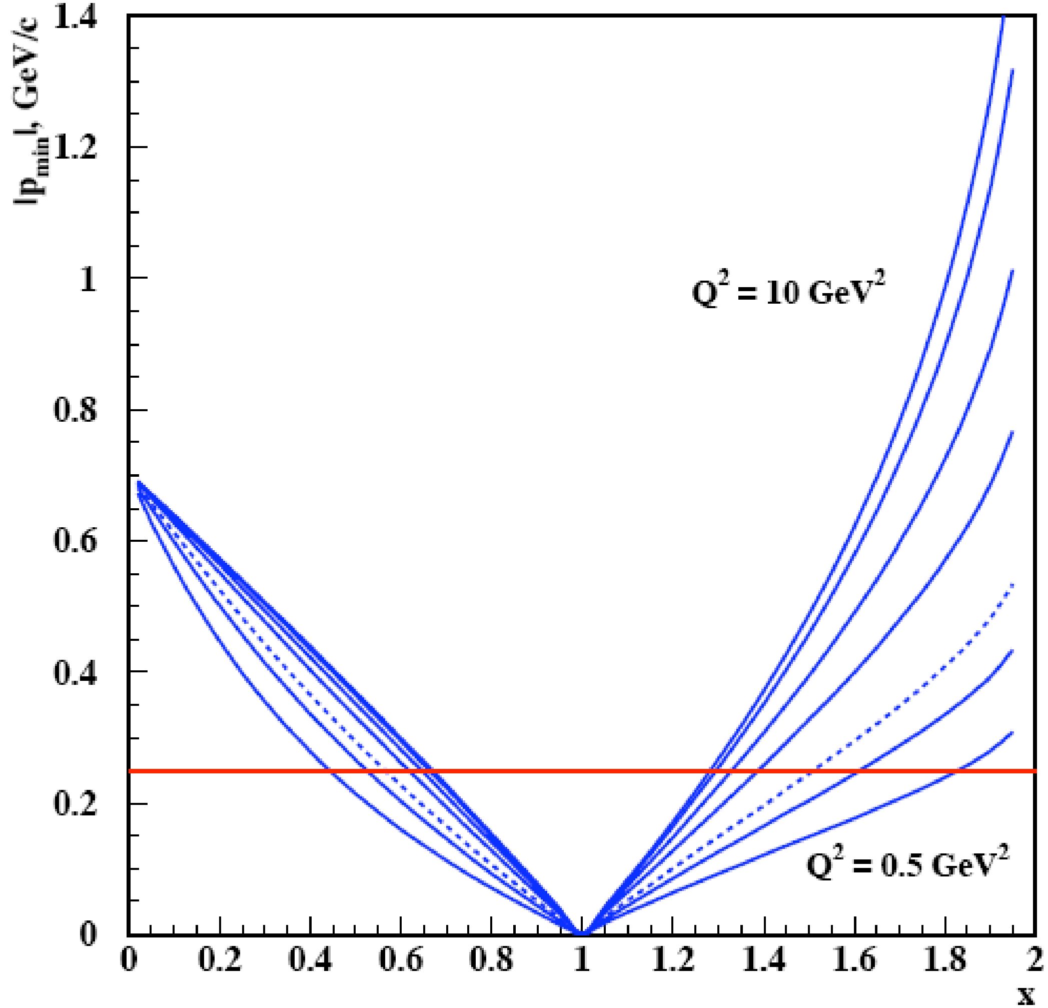
$$\Downarrow$$

$$\left[-\frac{\hbar^2}{2\,m}\sum_i \hat{\nabla}_i^2 + \sum_i V(r_i)\right]\Phi_o = \epsilon_o\,\Phi_o$$

Variational monte carlo (Urbana Group)

Cluster expansion techniques (Ciofi, Alvioli, Cda, Morita)

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



$Q^2 \uparrow$

$q_+ \gg$

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

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

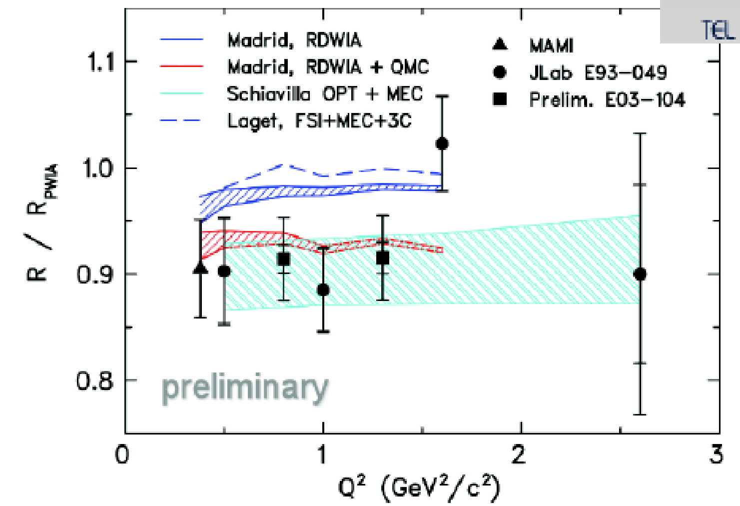
relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

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

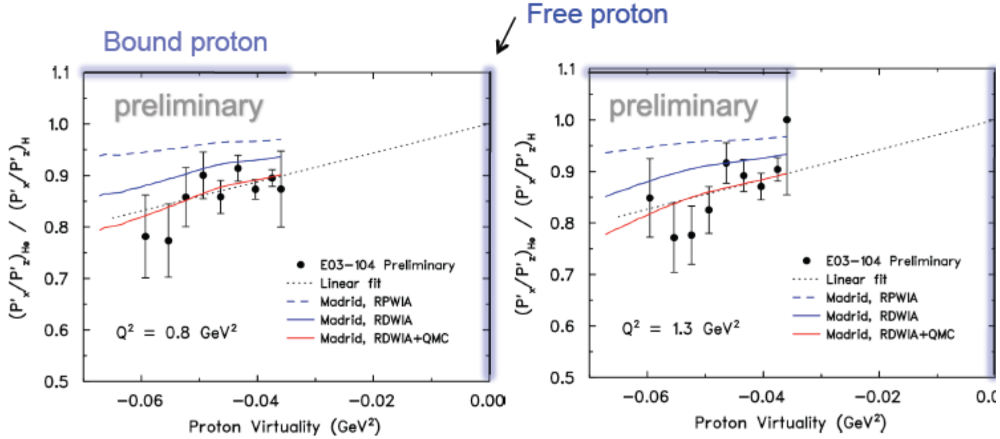
$$ {}^{4}He(\vec{e},e'\vec{p}) $$

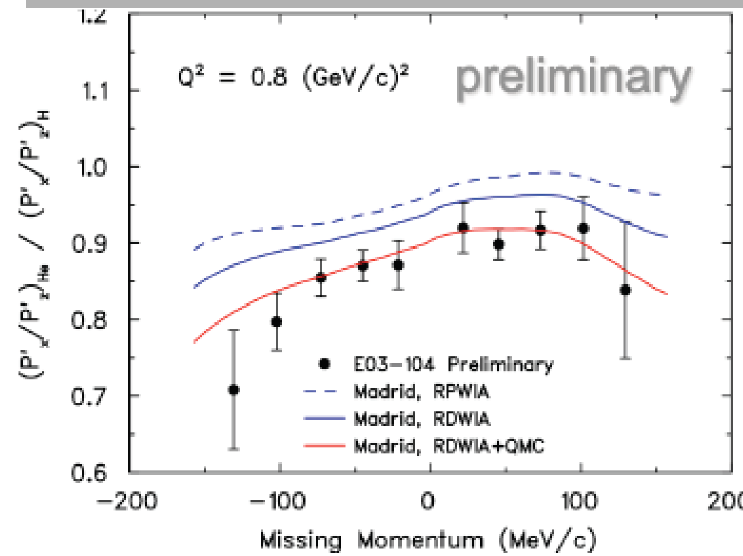
Polariztion Transfer

Copied from S. Strauch talk



Proton Virtuality: $v = p^2 - m_P{}^2$

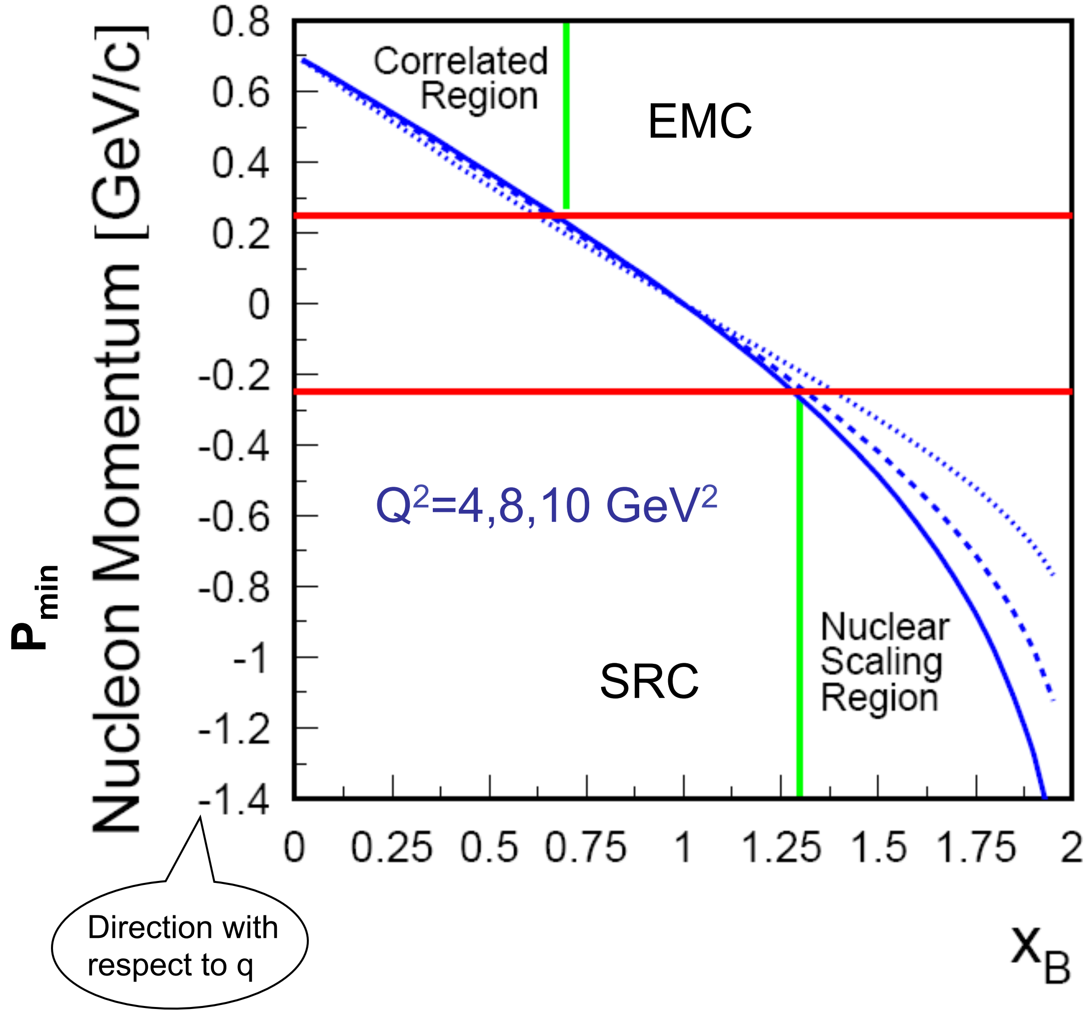




- Polarization-transfer double-ratio data and calculations show dependence on proton virtuality with the trend of R ≈ 1 for $p^2 = m_P{}^2$; as it should be.
- Excellent description of preliminary E03-104 data with the RDWIA + QMC (in-medium form factors) model.

see: C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

M. Paolone at al. PRL 105,072001,(1020)



The minimum missing momentum of the D(e,e')pn reaction from

conservation of energy and momentum for quasi-elestic scattering

$$(q + p_d - p_n)^2 = m_p^2$$

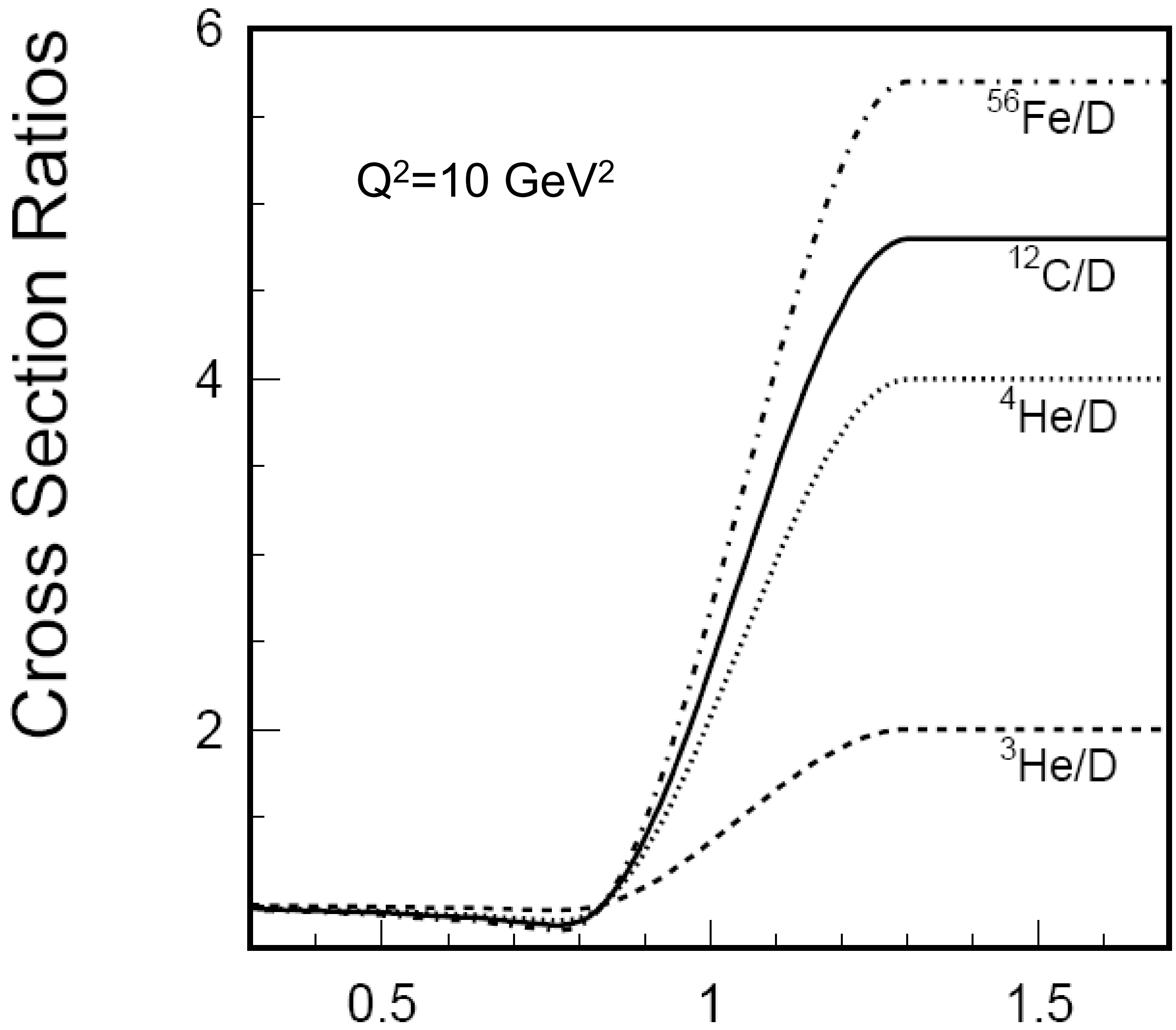
$$P_d(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_d(p) \cdot dp$$

$$n_A(p) = n_d(p) \cdot a_2(A/d)$$

$$P_A(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_A(p) \cdot dp$$

$$\frac{\sigma_A}{\sigma_d} = \frac{1 - P_A(x_B)}{1 - P_d(x_B)}$$

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]



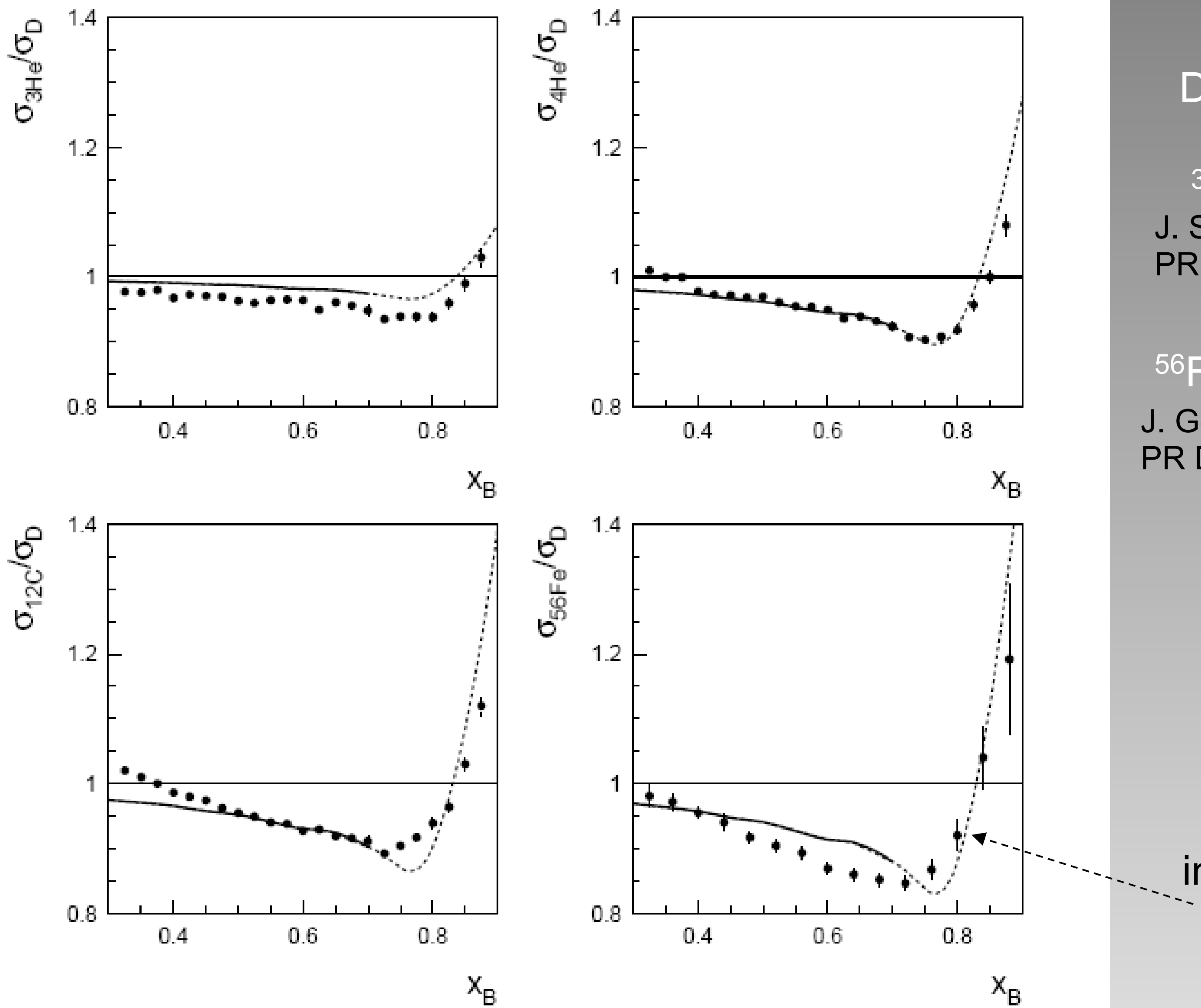
$$\frac{\sigma_A}{\sigma_d} = \frac{1 - P_A(x_B)}{1 - P_d(x_B)}$$

interpolation

$a_2(A/d)$

x_B

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]



Data:

$^{3}He, ^{4}He, ^{12}C$

J. Seely et al.
PRL 103, 202301 (2009).

^{56}Fe

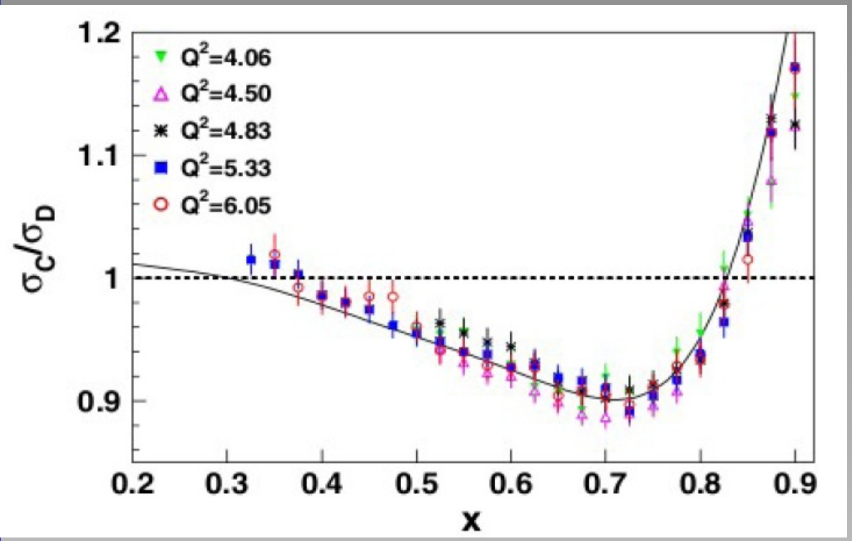
J. Gomez et al.
PR D49, 4348 (1994).

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]

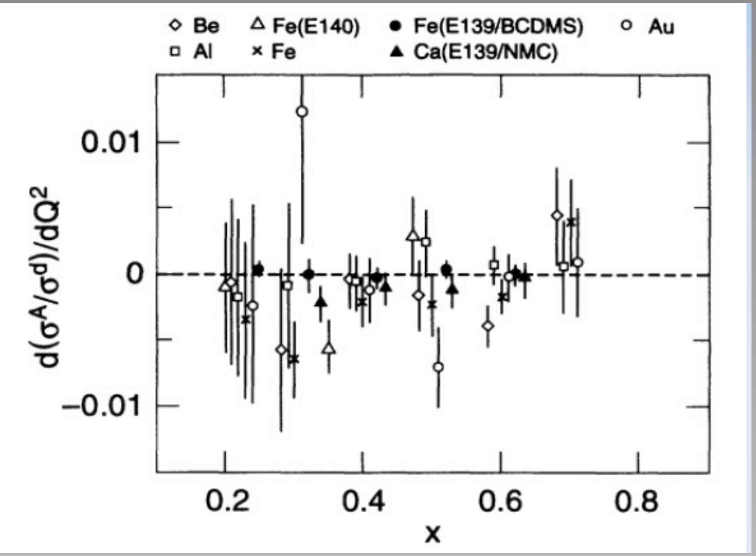
Very weak Q^2 dependence

EMC

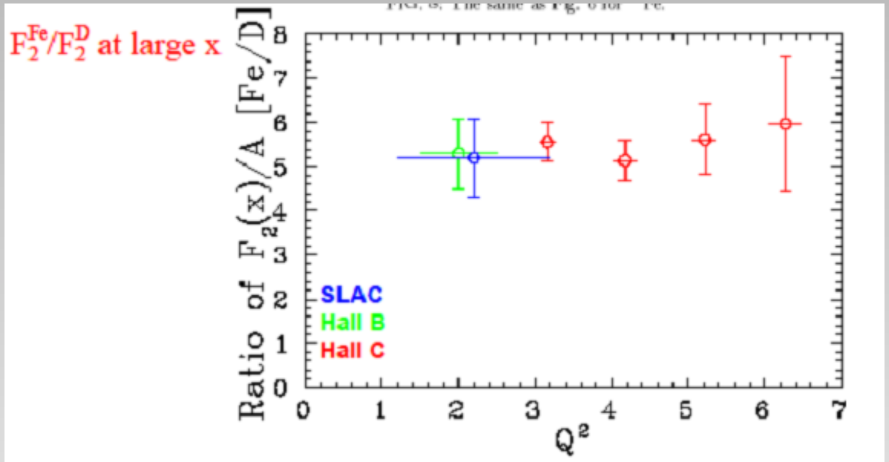
JLab J. Seely et al.



SLAC J. Gomez et al.



SRC



J. Arrington talk, Minami 2010.

E01-015: A customized Experiment to study 2N-SRC

$Q^2 = 2$ GeV/c , $x_B \sim 1.2$, P_m=300-600 MeV/c, E_{2m}<140 MeV

Luminosity ~ $10^{37\text{-}38}$ $cm^{-2}s^{-1}$

Kinematics optimized to minimize the competing processes

High energy, Large Q^2

The large Q^2 is required to probe the small size SRC configuration.

MEC are reduced as $1/Q^2$.

Large Q^2 is required to probe high P_{miss} with x_B>1.

FSI can treated in Glauber approximation.

x_B>1

Reduced contribution from isobar currents.

Large p_{miss}, and $E_{miss} \sim p^2_{miss}/2M$

Large P_{miss_z}

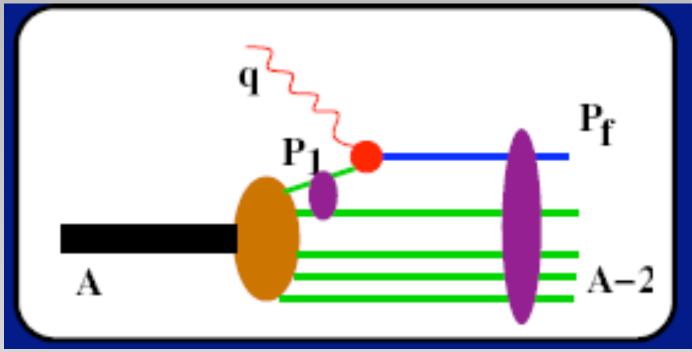
Kinematics optimized to minimize the competing processes

FSI

FSI with the A-2 system:

- ★ Small (10-20%) .
  - Kinematics with a large component of p_{miss} in the virtual photon direction.
  - Pauli blocking for the recoil particle.
  - Geometry, (e, e'p) selects the surface.
- ★ Can be treated in Glauber approximation.
- ★ Canceled in some of the measured ratios.

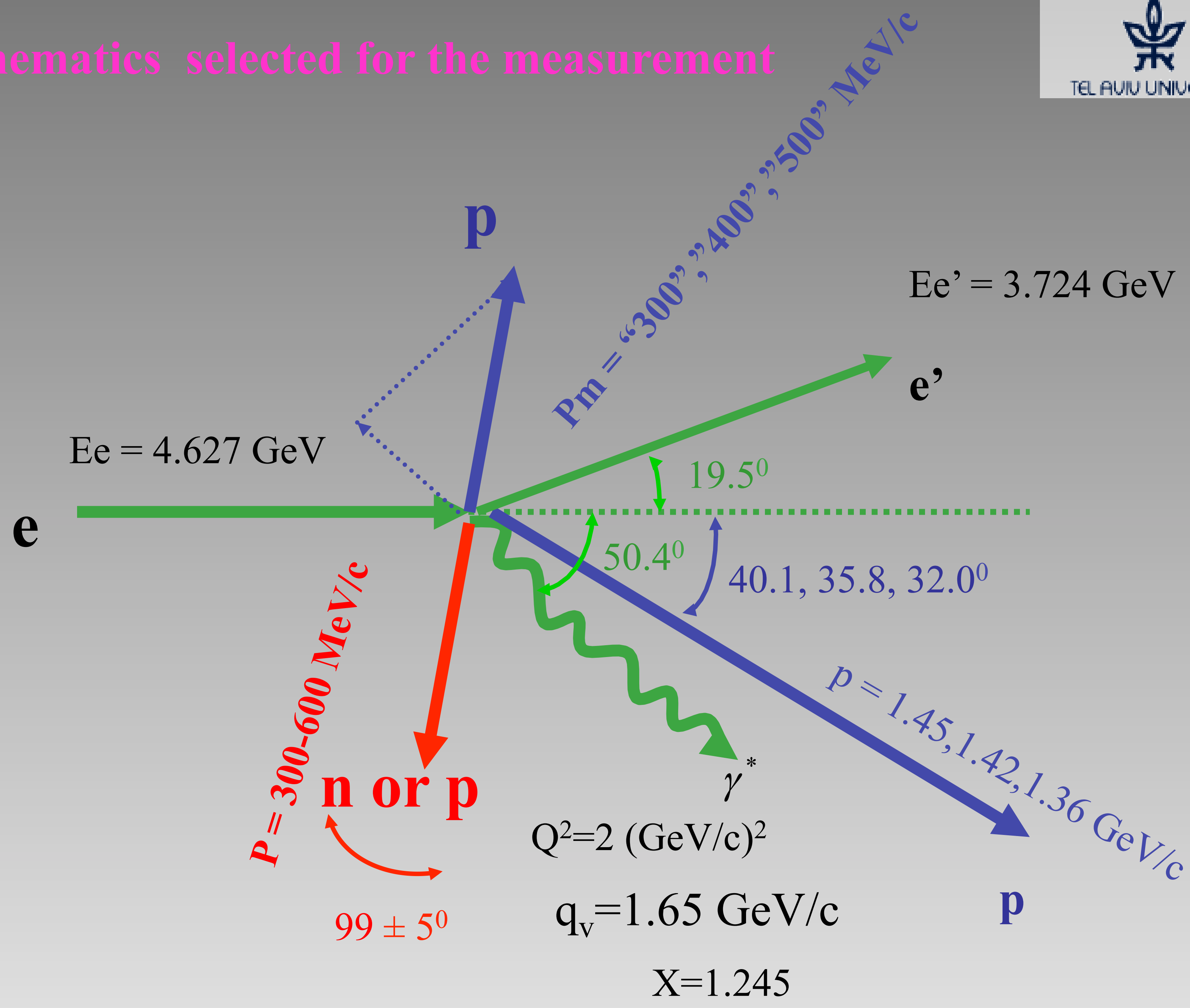
FSI in the SRC pair:



These are not necessarily small,   BUT:

- ★ Conserve the isospin structure of the pair .
- ★ Conserve the CM momentum of the pair.

The kinematics selected for the measurement



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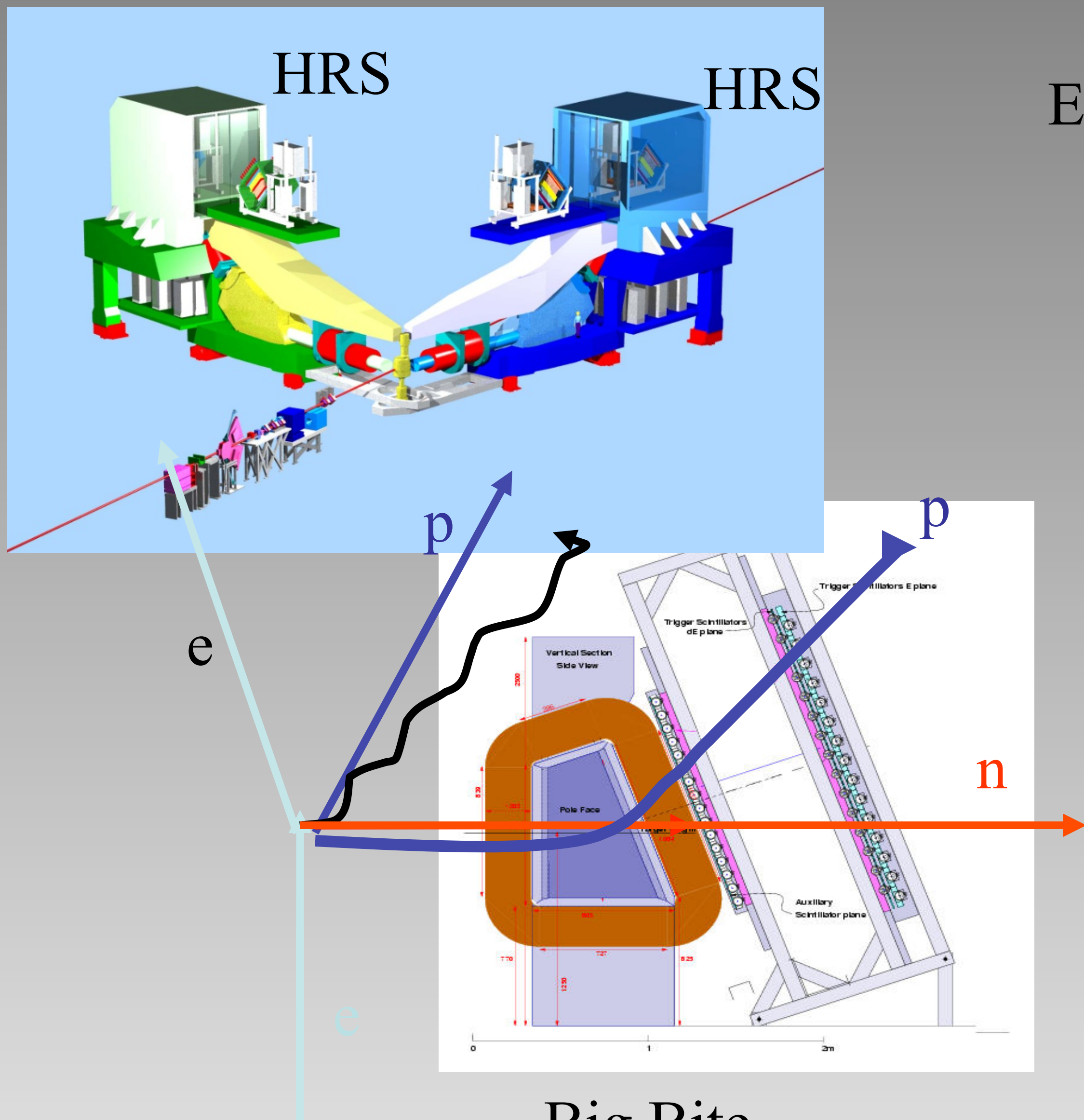
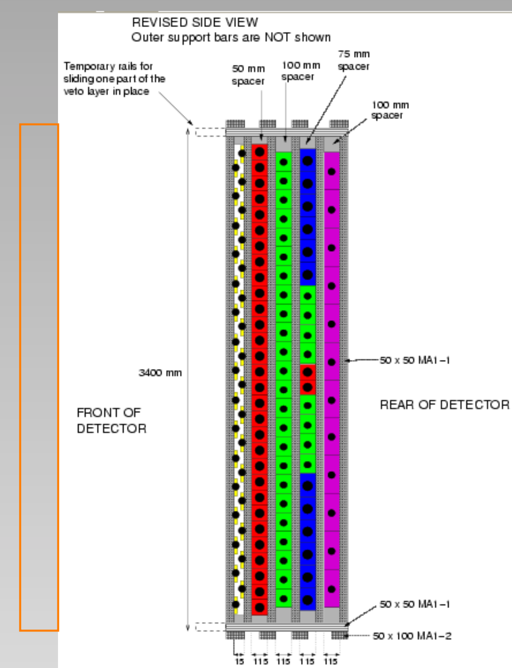
Experimental setup

EXP 01-015 / Jlab

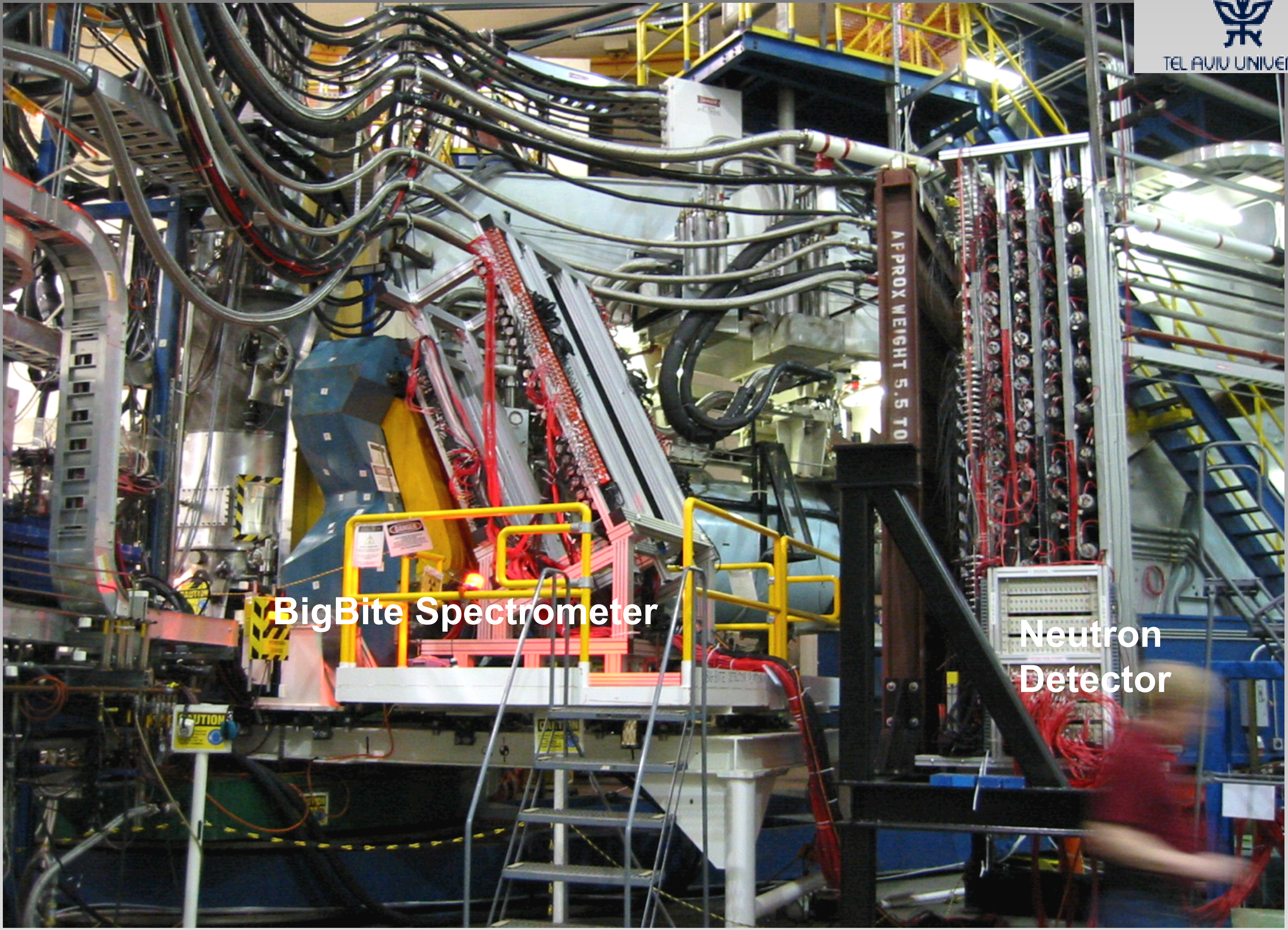


Big Bite

n array



Lead wall



EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

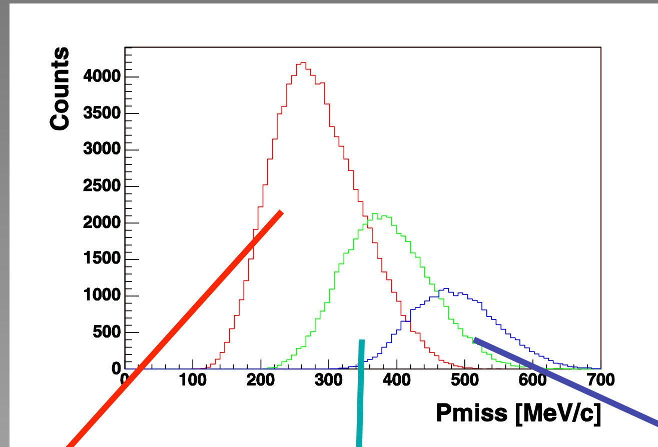
$^{12}C(e,e'p)$

$x_B>1$

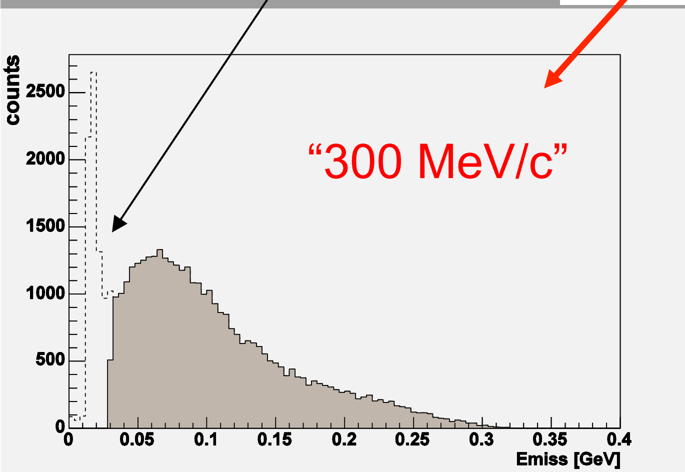
“300 MeV/c”

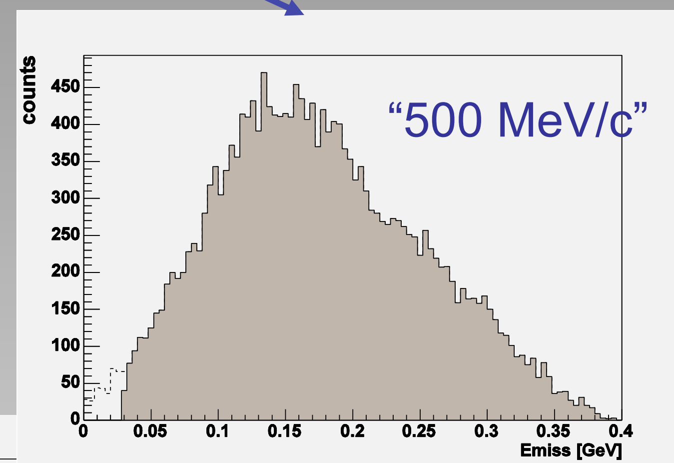
“400 MeV/c”

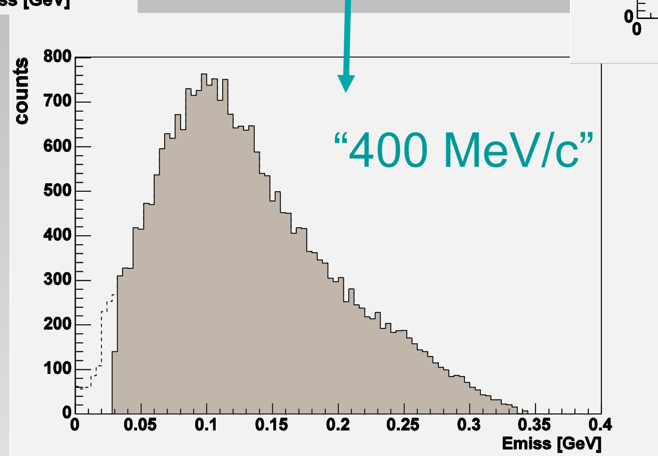
“500 MeV/c”



$^{12}C(e,e'p)^{11}B$







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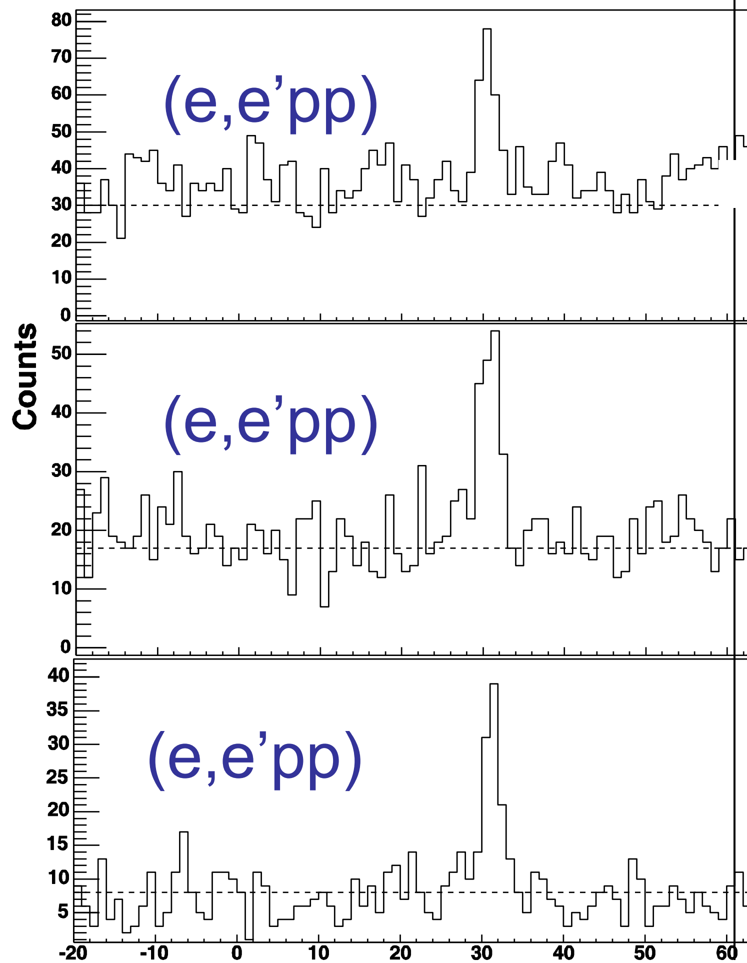


P_{mis}=“300” MeV/c

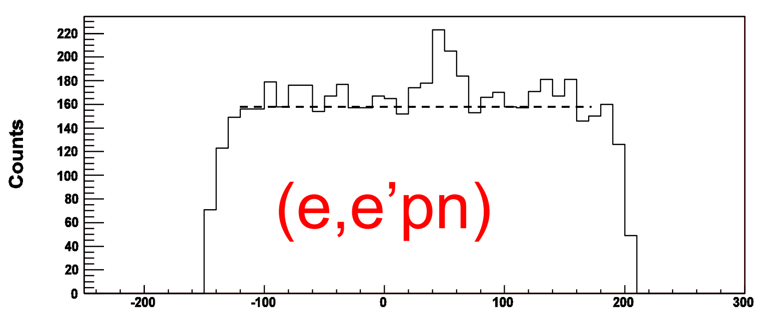
(Signal : BG= 1.5:1)

P_{mis}=“400” MeV/c

(Signal : BG= 2.3:1)

P_{mis}=“500” MeV/c

(Signal : BG= 4:1)



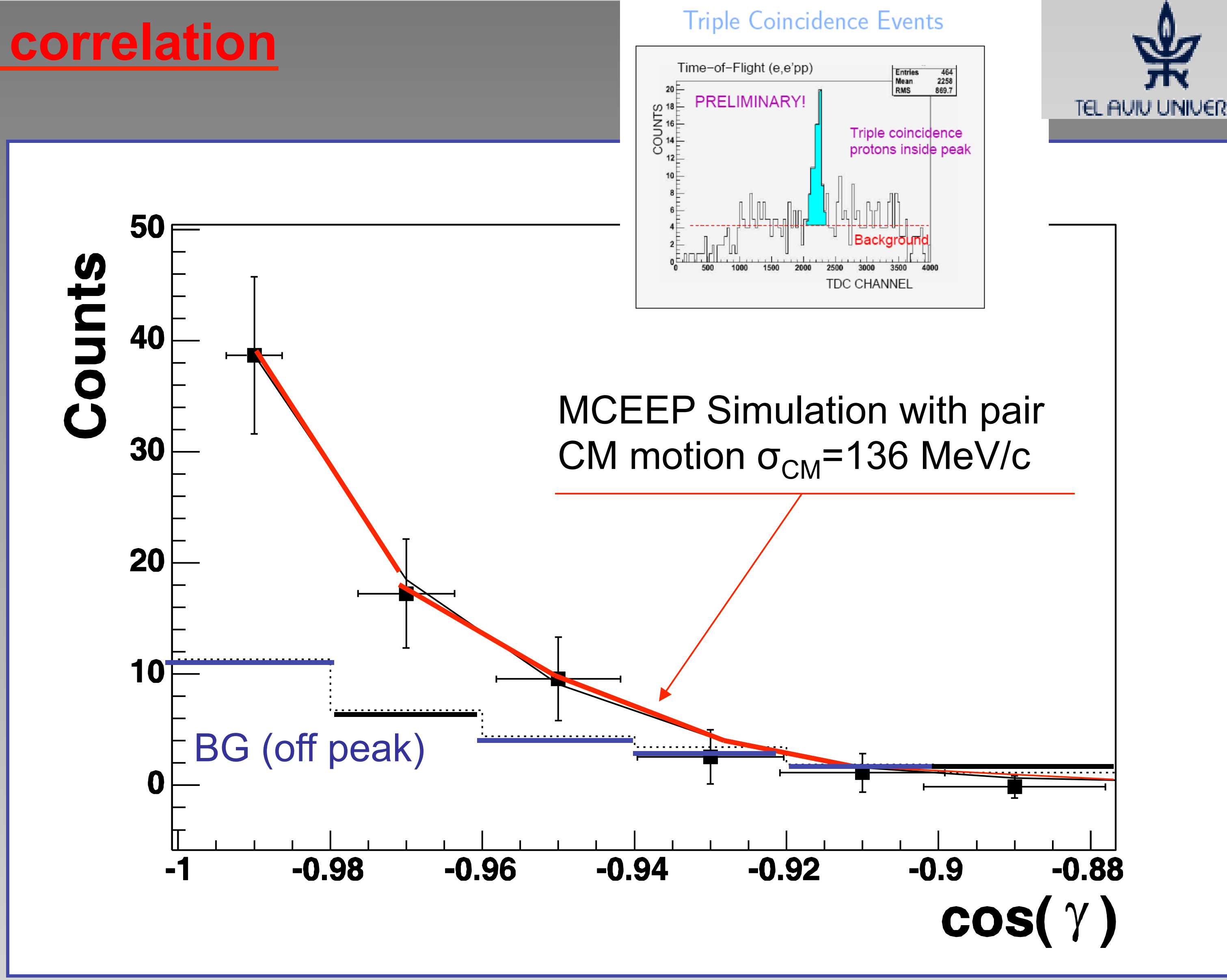
P_{mis}=“500” MeV/c

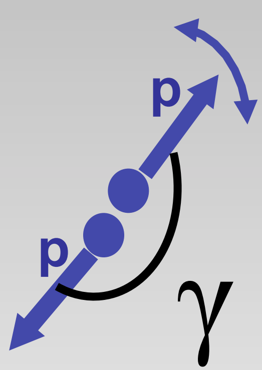
(Signal : BG= 1:7)

TOF [ns]

Directional correlation

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





Directional correlation

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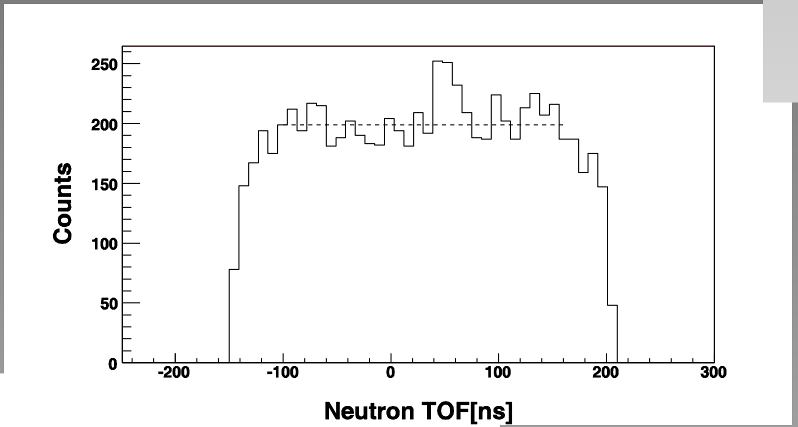
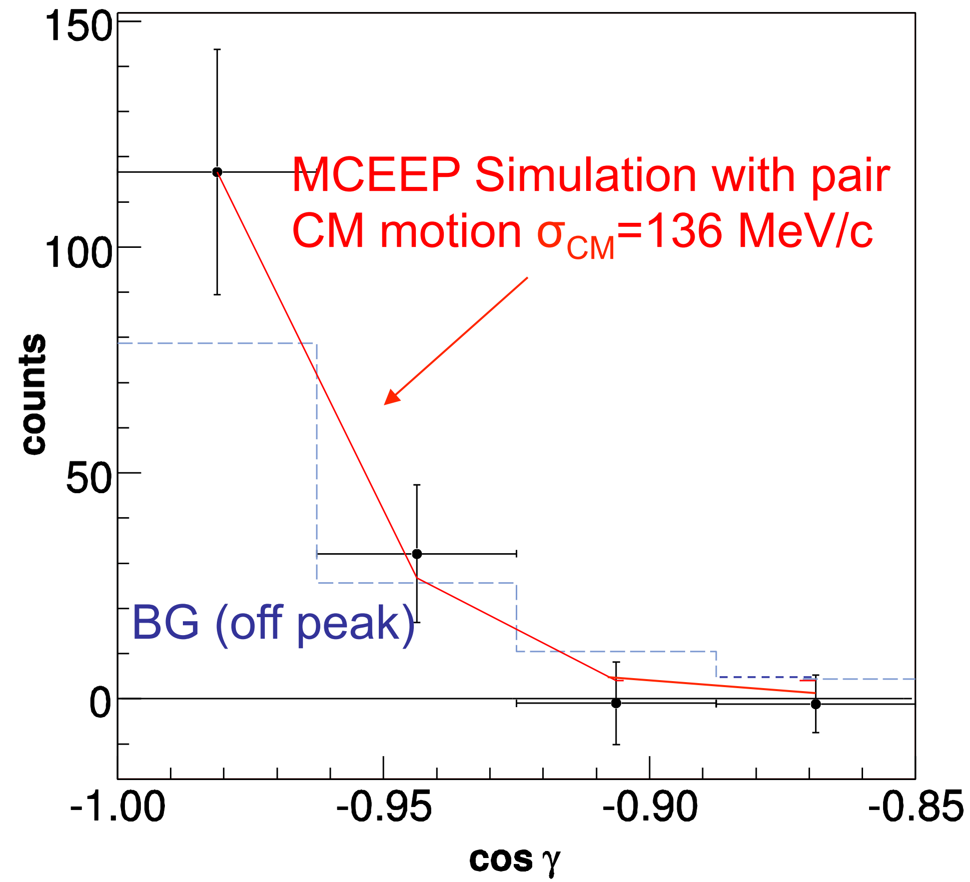
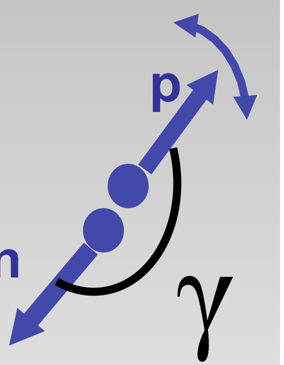
$^{12}C(e,e'pn)$

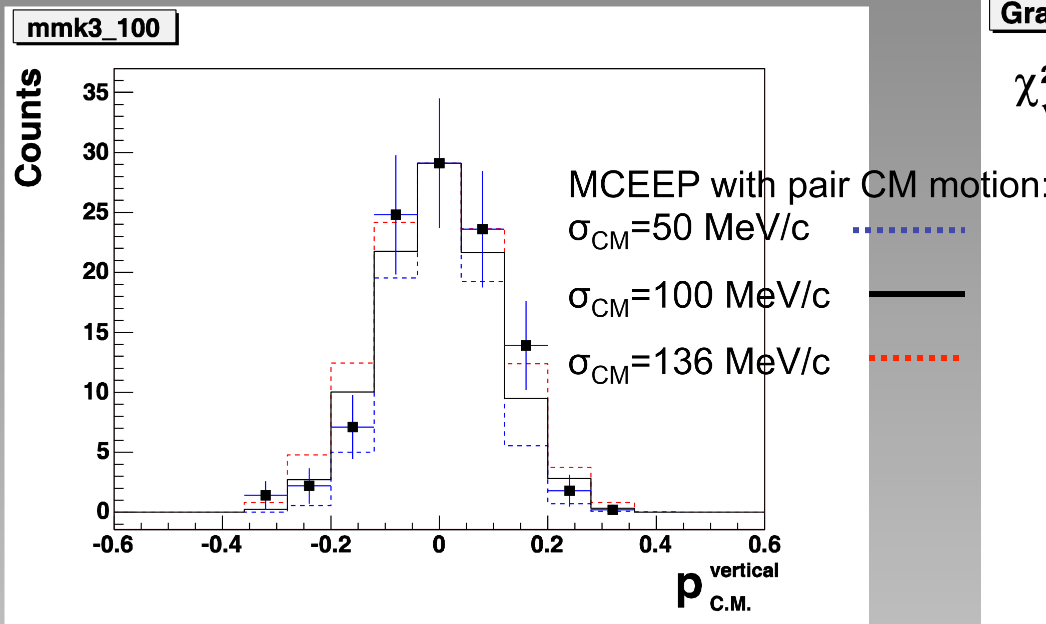


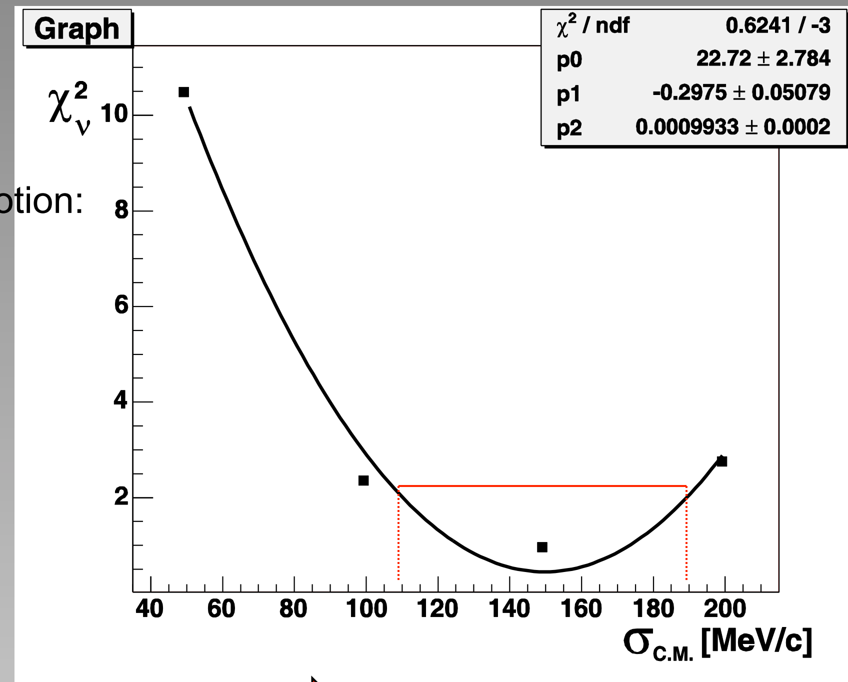




CM motion of the pair:

$P_{c.m}^{vertical}$, “500 MeV/c “ setup





2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

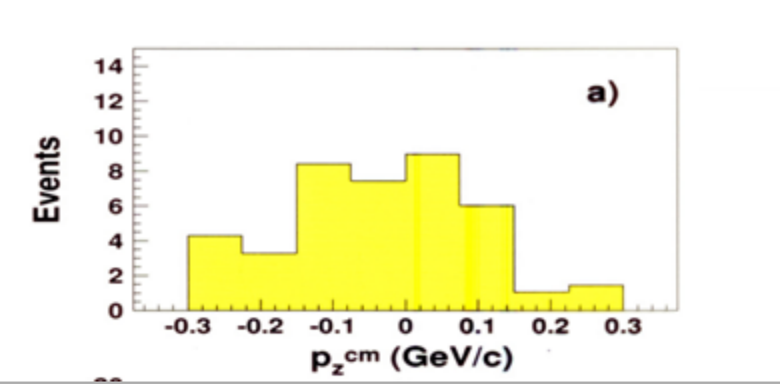
This experiment : σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

CM motion of the pair ("old" data)

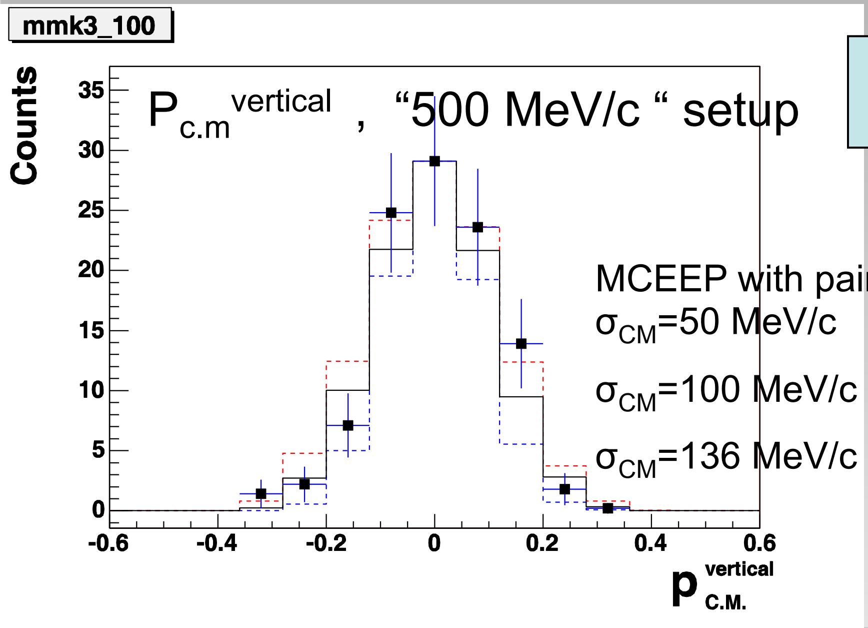
(p,2pn) experiment at BNL : σ_{CM}=143 ± 17 MeV/c



$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

A. Tang et al.
B. Phys. Rev. Lett. 90 ,042301 (2003)

(e,e'pp) JLab/E01-15 : σ_{CM}=136 ± 20 MeV/c



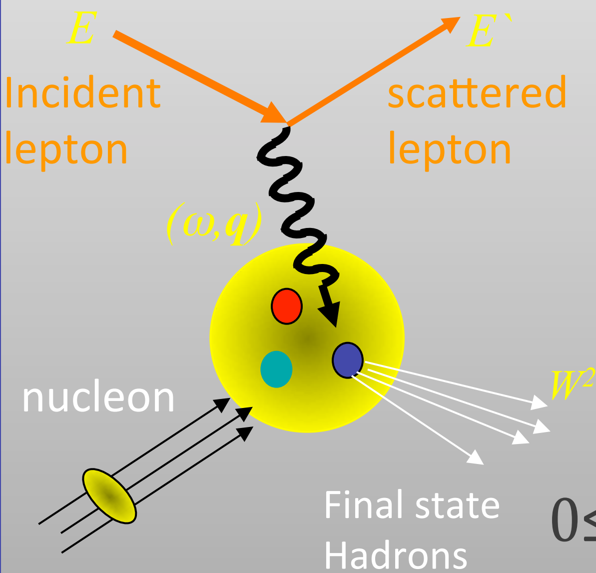
2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

R. Shneor et al.,

PRL 99, 072501 (2007)

Inclusive electron scattering A(e,e')

Deep Inelastic Scattering (DIS)



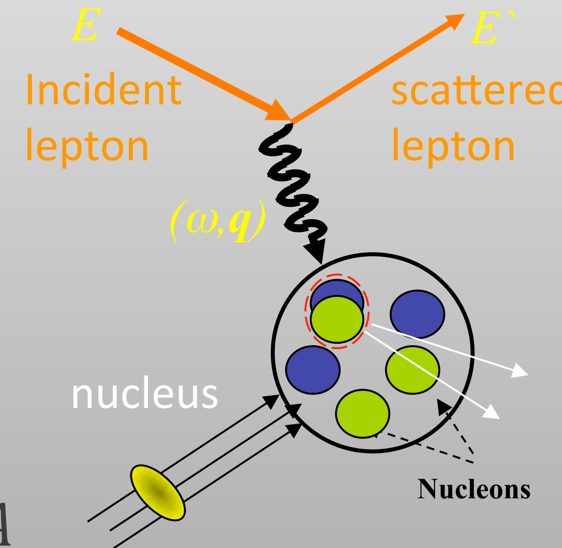
$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad \left(x_B' = \frac{Q^2}{2(q \cdot p_T)}\right)$$

$0 \leq x_B \leq 1$

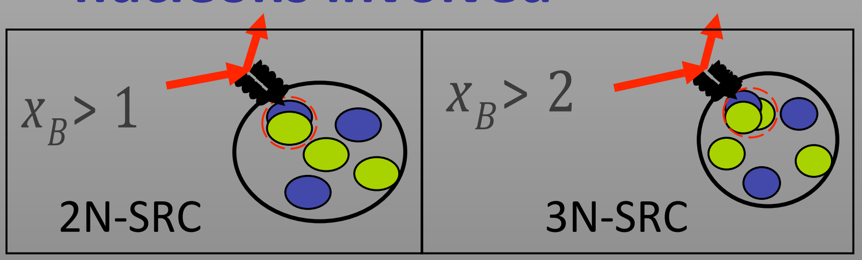
Hard knockout reaction

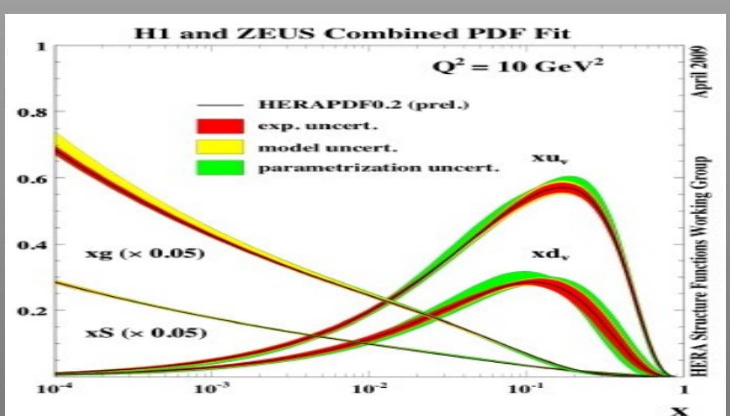


$0 \leq x_B \leq A$

x_B gives the fraction of nucleon momentum carried by the struck parton

x_B counts the number of nucleons involved





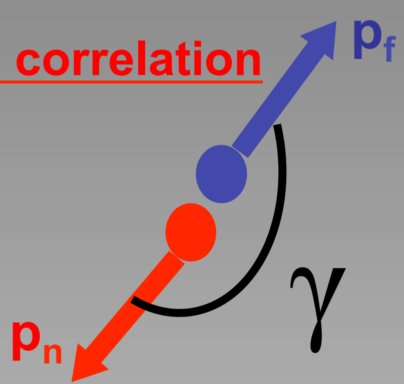
--> scaling

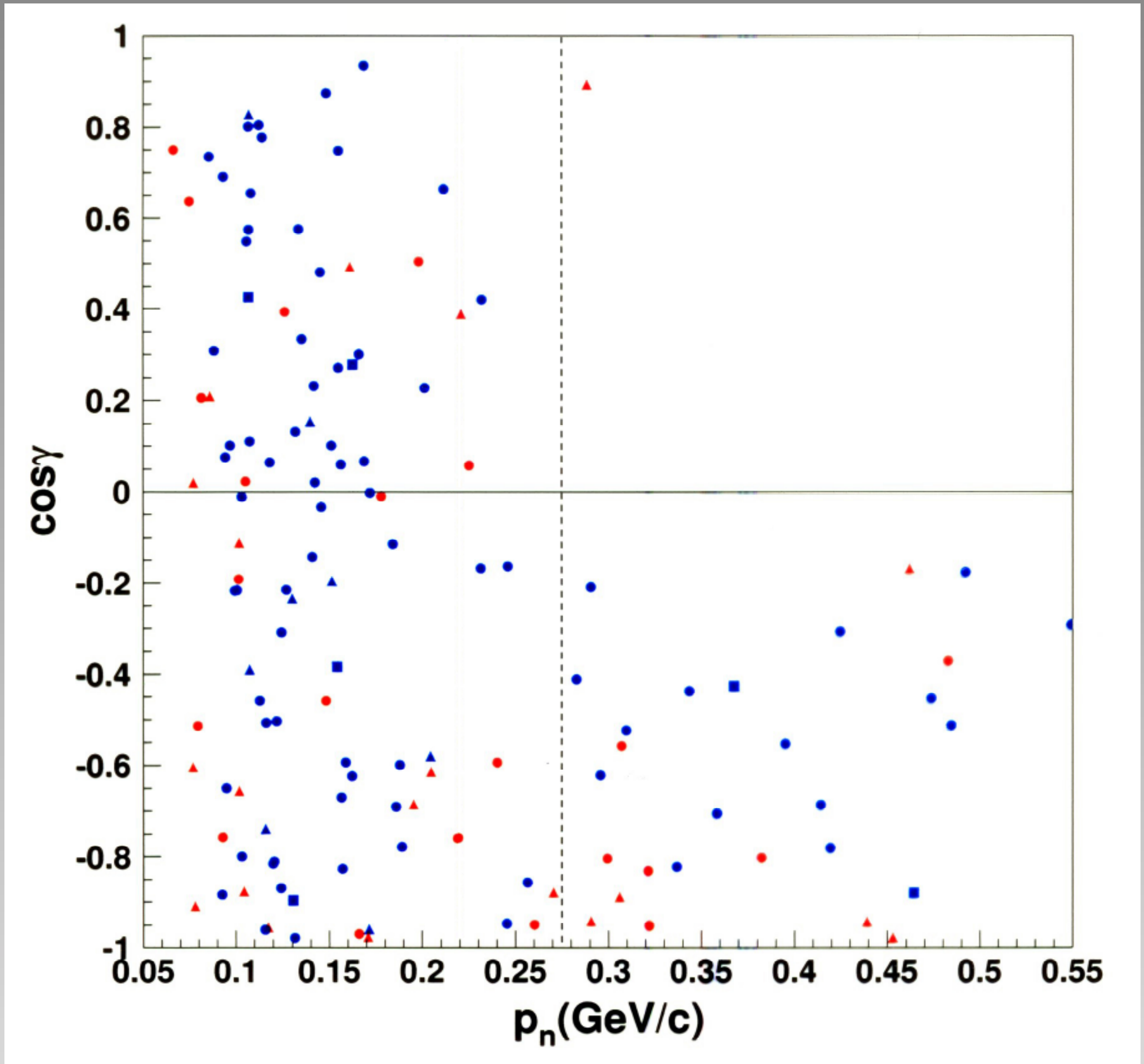
--> Counting the number of SRC clusters in nuclei

$^{12}C(p, p'pn)$ measurements at EVA / BNL

A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

Directional correlation



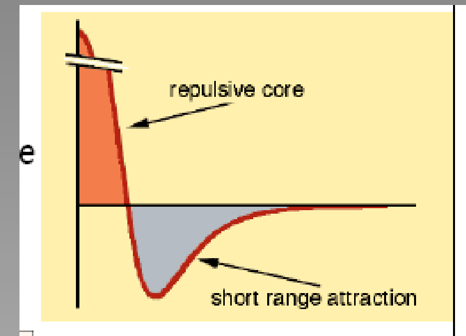


Piasetzky, Sargsian, Frankfurt, Strikman, Watson **PRL 162504(2006).**

Removal of a proton with momentum above 275 MeV/c from ^{12}C is **$92\pm^{8}_{18}$ %** accompanied by the emission of a neutron with momentum equal and opposite to the missing momentum.

σ_{CM}=0.143±0.017 GeV/c

A description of nuclei at distance scales small compared to the radius of the constituent nucleons is needed to take into account,

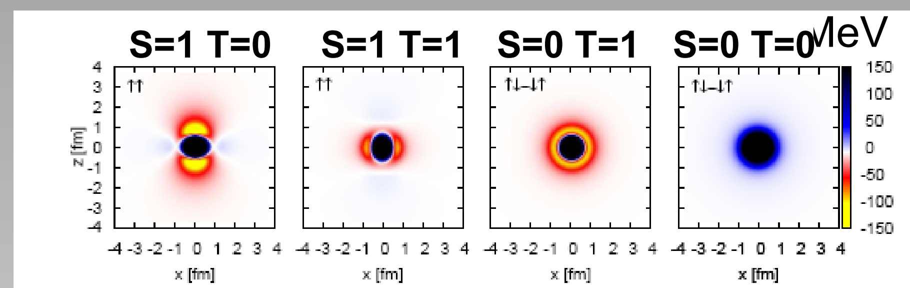


Short- range repulsion

(common to many other systems)

Intermediate-range tensor attraction

(unique to nuclei)



Argonne V8 potential

ArXiv 1107.4956

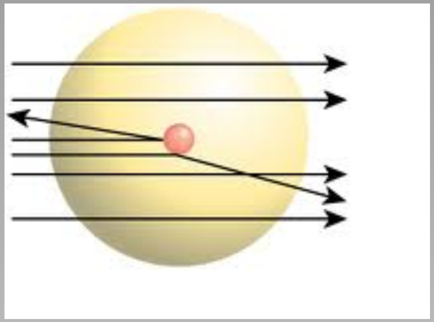
long- range attraction

Very difficult many-body problem

presents a challenge to both experiment and theory

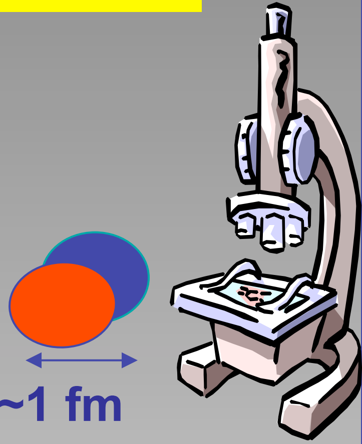
This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high energy and large momentum-transfer (hard scattering) reached by present facilities.

Hard processes

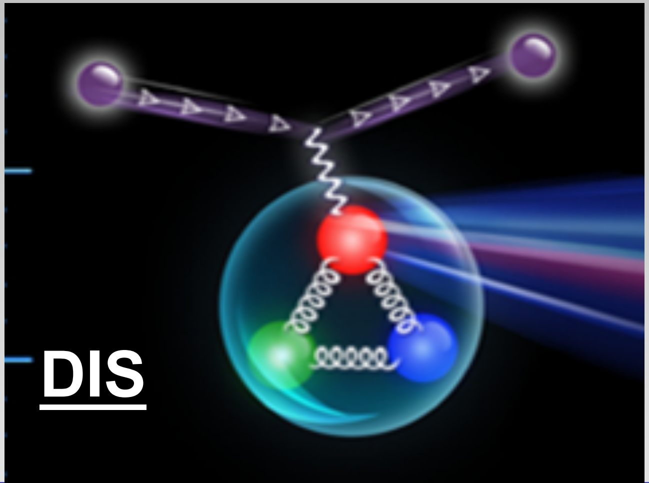


structure of atoms

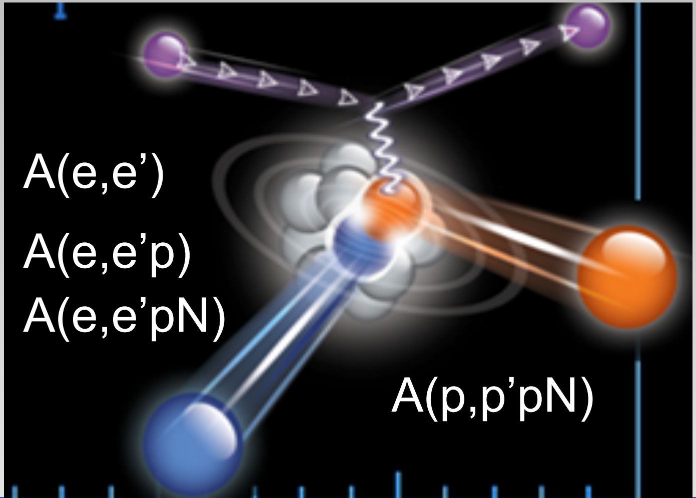
Rutherford scattering



structure of nucleons

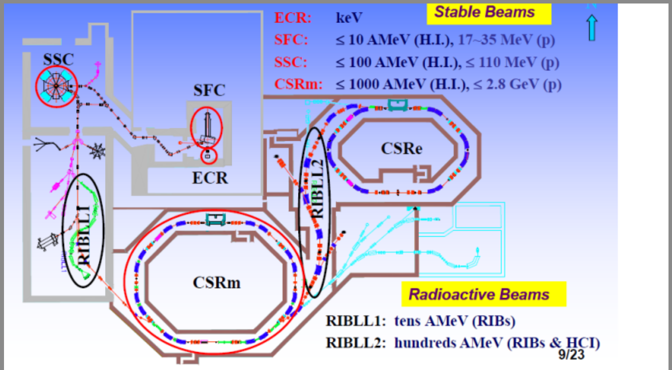


structure of nuclei

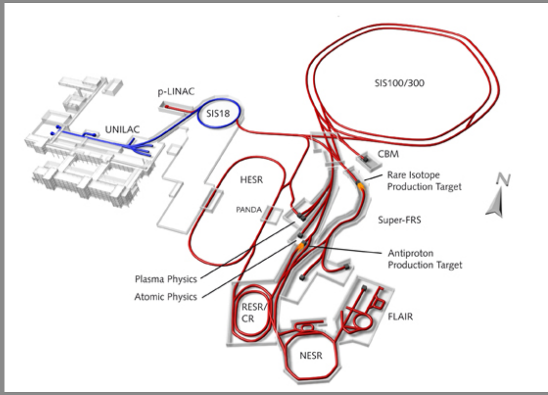


The new facilities:

CSR, Lanzhou



up to 3.6 GeV/c



GSI ->FAIR / PANDA

1.5-15 GeV/c

30 GeV/c

J-PARC
Japan Proton Acce

pA@RICH BNL

100 GeV protons on
100 GeV/nucleon heavy ions

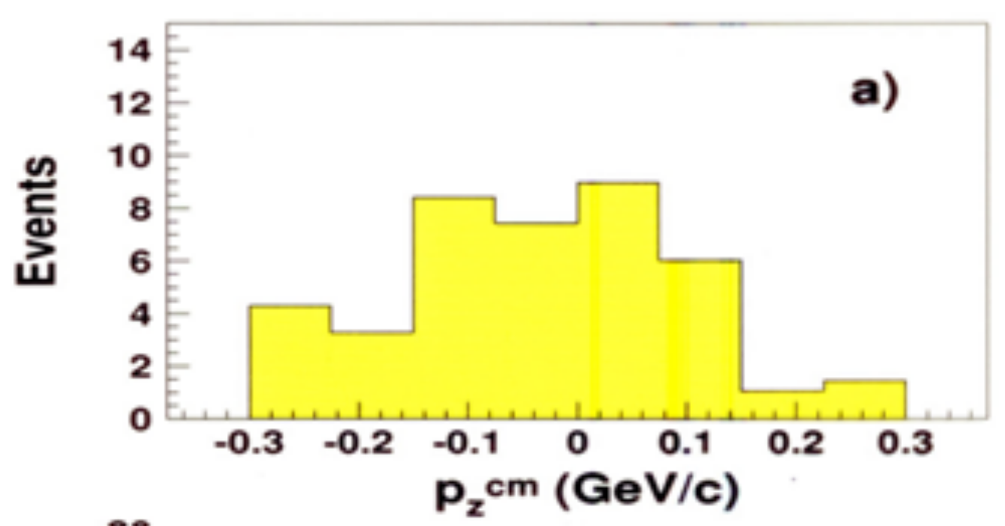
CM motion of the pair ("old" data)

$^{12}C(p,2pn)$ experiment at BNL : σ_{CM}=143 ± 17 MeV/c

$$p_z^{cm} = 2m\left(1 - \frac{\alpha_p + \alpha_n}{2}\right),$$

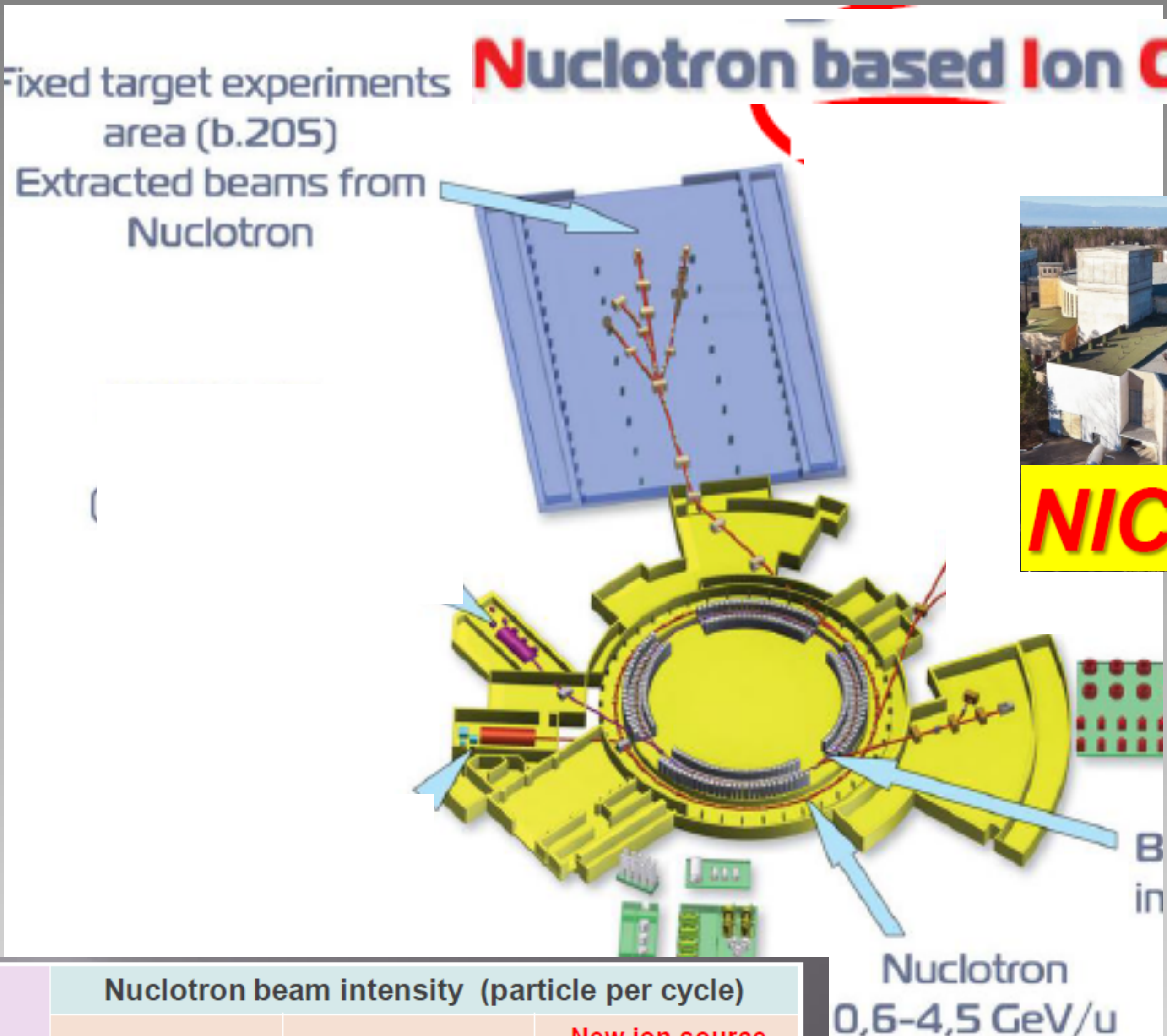
A. Tang et al.
B. Phys. Rev. Lett. 90 ,042301 (2003)

Theoretical prediction (Ciofi and Simula) :
σ_{CM}=0.139 GeV/c PRC 53 (1996) 1689.



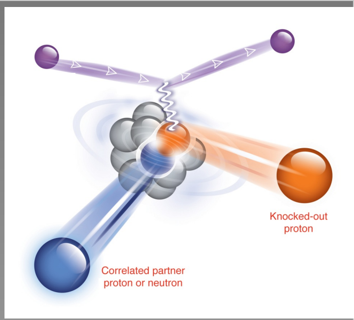
Only ~20 $^{12}C(p,2p+n)$ events with $p_n > k_F$

Study of SRC at JINR



Beam	Nuclotron beam intensity (particle per cycle)		
	Current	Ion source type	New ion source + booster
p	$3 \cdot 10^{10}$	Duoplasmotron	$5 \cdot 10^{12}$

Number of hard triple coincidence events (World data)



experiment	pp pairs	np pairs	nn pairs
EVA/BNL	-	18	-
E01-015/JLab	263	179	-
E07-006/JLab	50	223	-
CLAS/JLab	1533	-	-
Total	<2000	<450	0

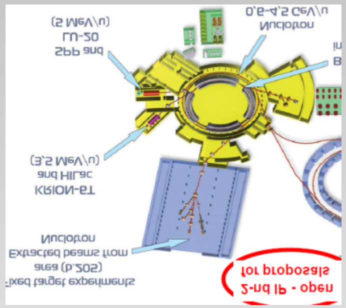
$^{12}C(p,2pn)$

$^{12}C(e,e'pn)$ $^{12}C(e,e'pp)$

$^{4}He(e,e'pn)$ $^{4}He(e,e'pp)$

$\mathrm{C, Al, Fe, Pb}\,(e,e'pp)$

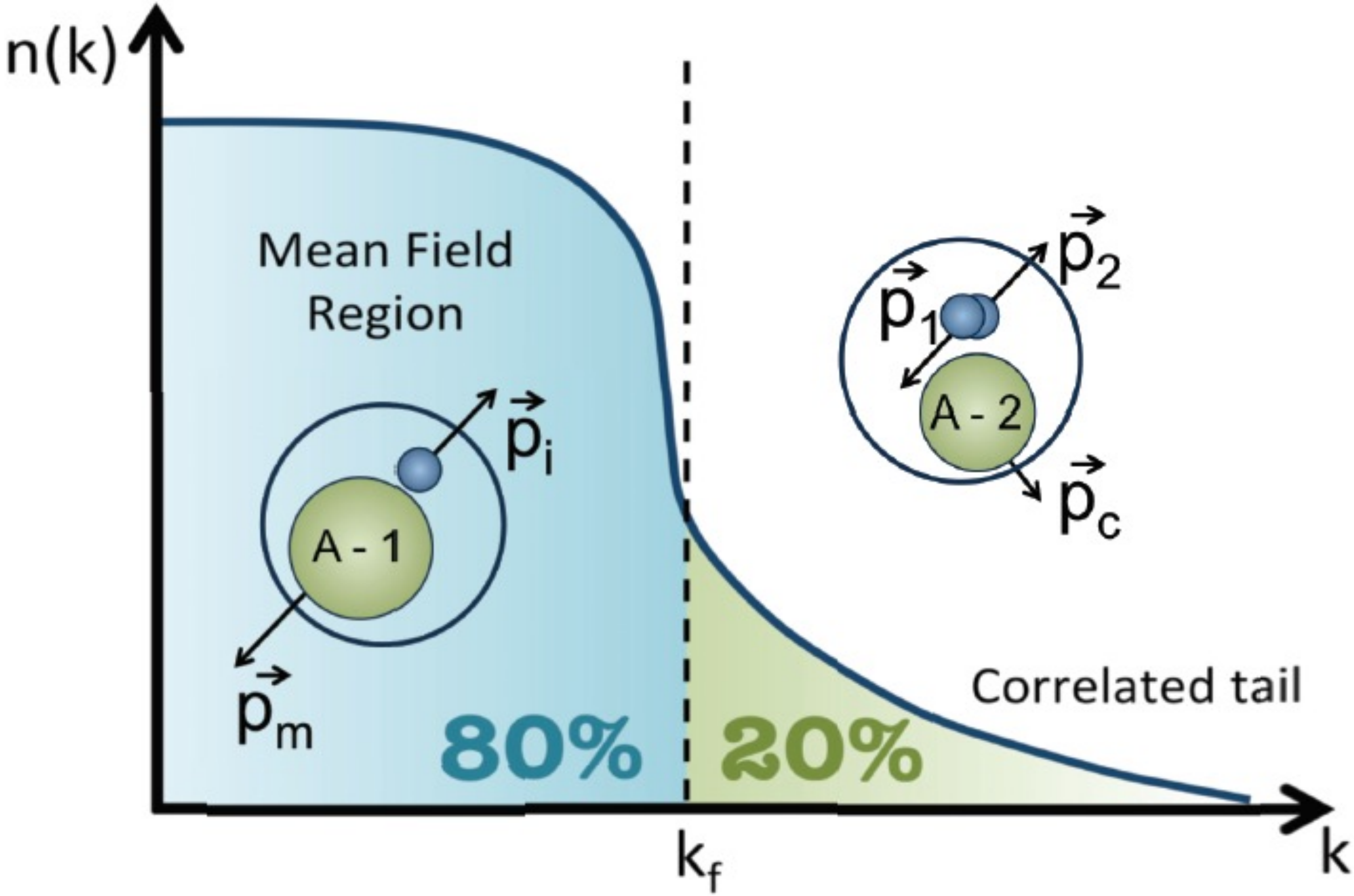
Why are we here ?



Nuclotron

➔ >10k events Before 2018

5 GeV/c 10^9 protons/sec fixed target



n(k)
Mean Field Region
$\vec{p}_i$
A - 1
$\vec{p}_m$
80%
$\vec{p}_2$
$\vec{p}_1$
A - 2
$\vec{p}_c$
20%
Correlated tail
k_f
k

We want to investigate SRCs with new probes.

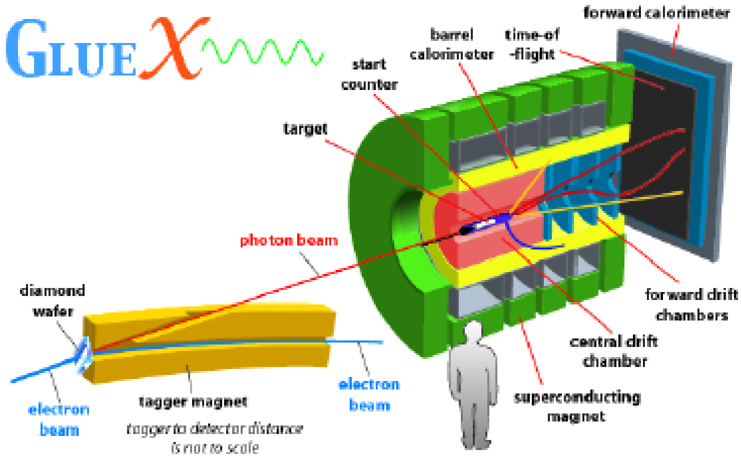
Proposals:

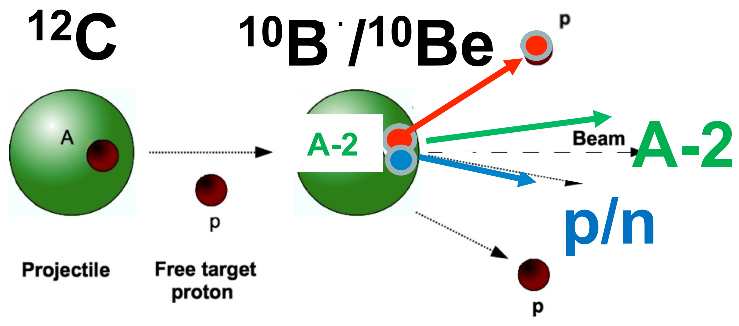
1. Inverse kinematics at Dubna
2. Protons at GSI
3. Photons at GlueX

Glue-X: study SRC pairs with real photons.

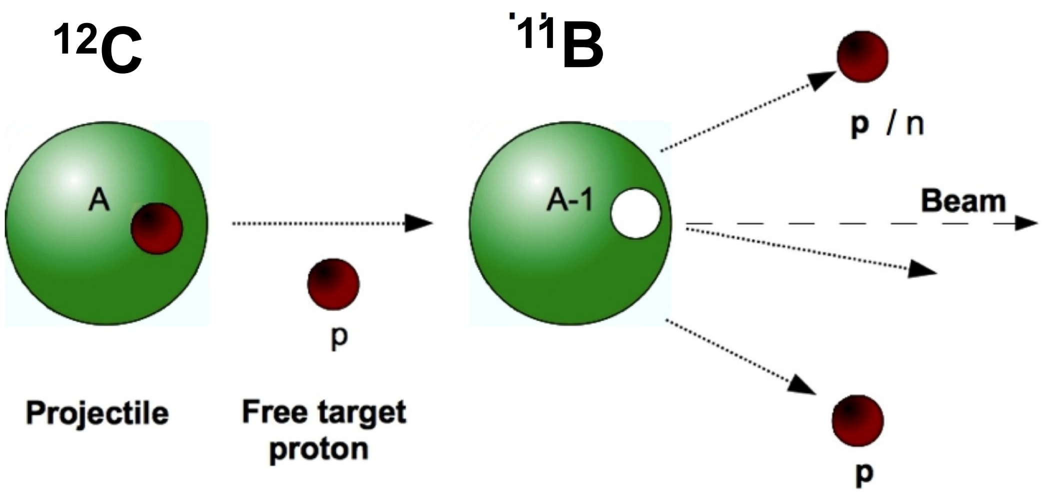
- Glue-X detector at JLab Hall D
- Study neutrons with charged final states:
  - $\gamma n \longrightarrow \pi^- p$
- Tests of vector meson dominance and transparency

For details talk with Maria Patsyuk





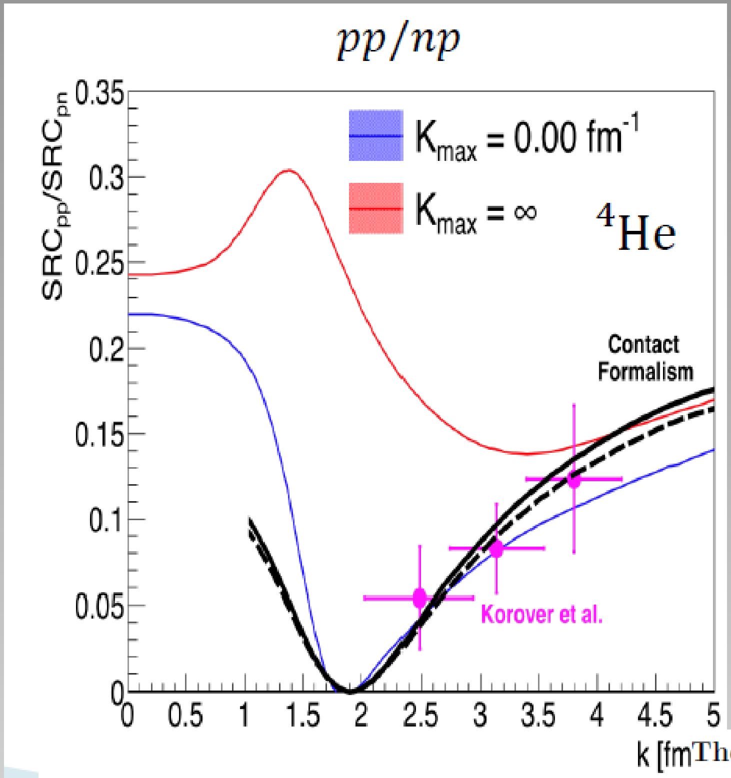
^{12}C
^{10}B / ^{10}Be
A
A-2
p
Beam
A-2
p/n
Projectile
Free target proton

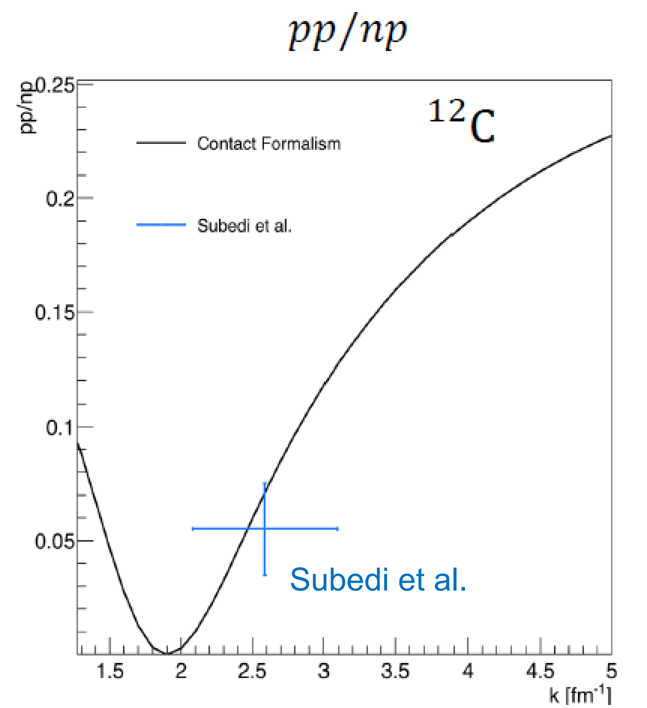


^{12}C
^{11}B
A
A-1
p
p / n
Beam
p
Projectile
Free target proton

Nuclear contact calculations

(Weiss, Cruz-Torres, Barnea, Piasetzky, Hen)



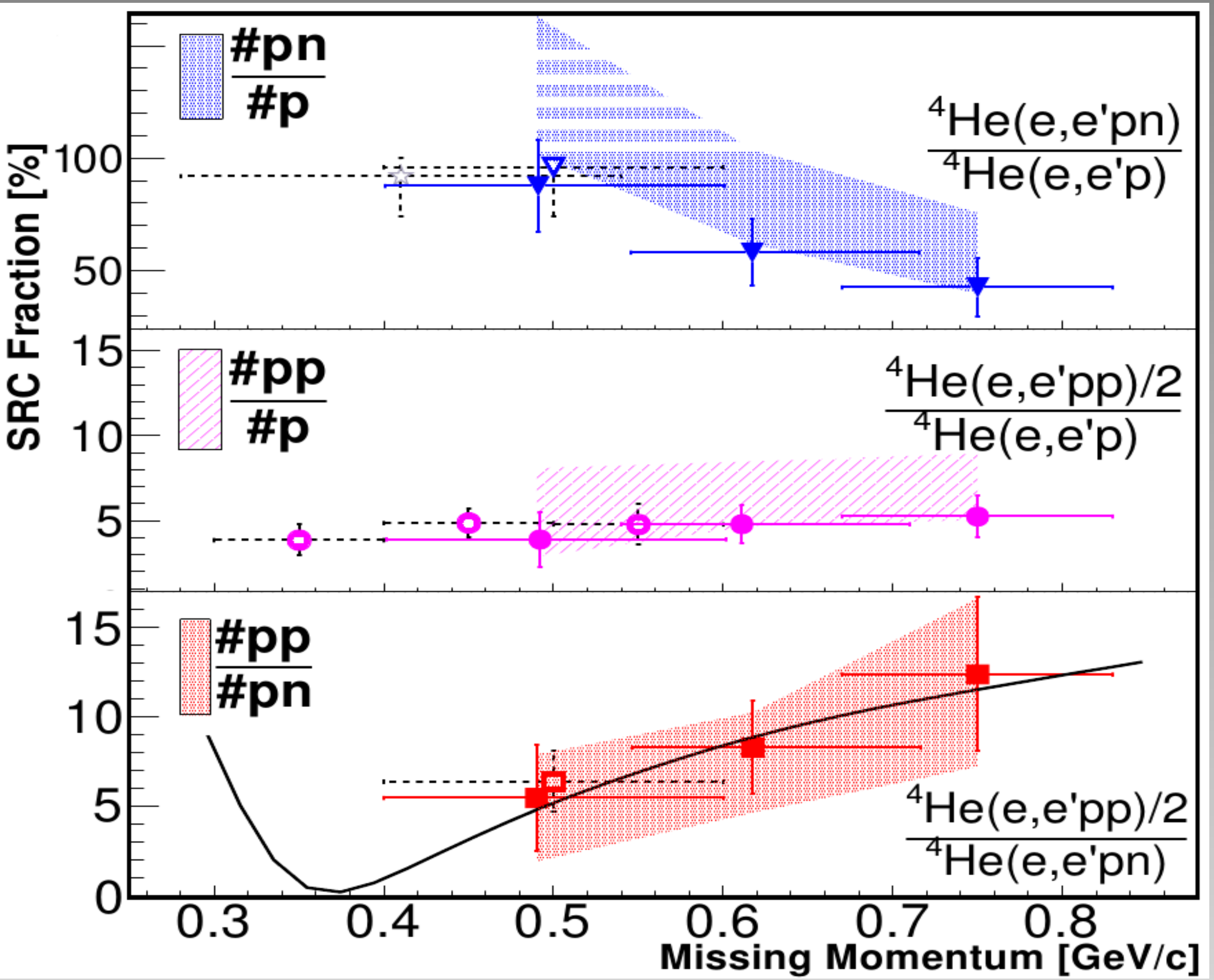


The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

E07-006 (2011) ^{4}He (^{12} C)

New Jlab experiment extend the SRC measurement to **P_{miss}=850 MeV/c**

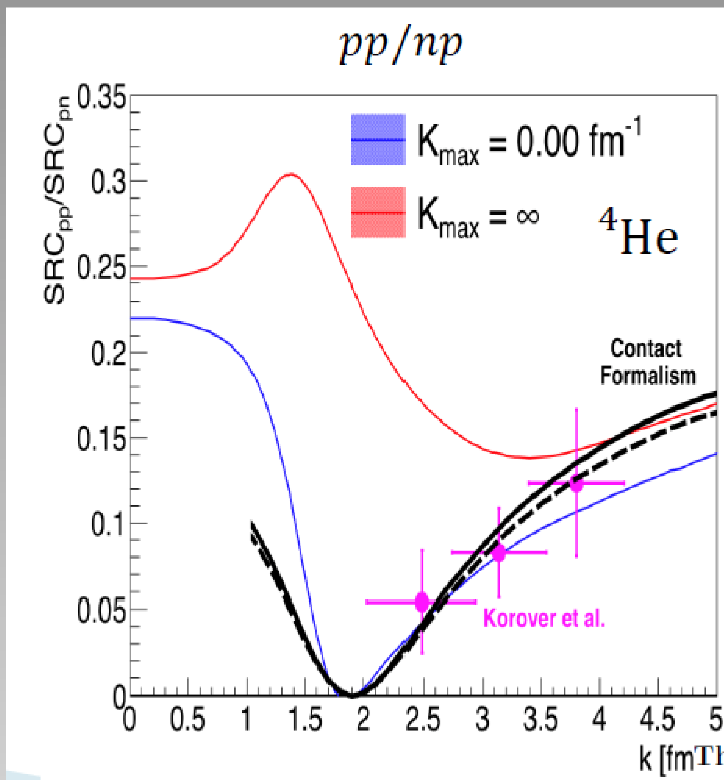


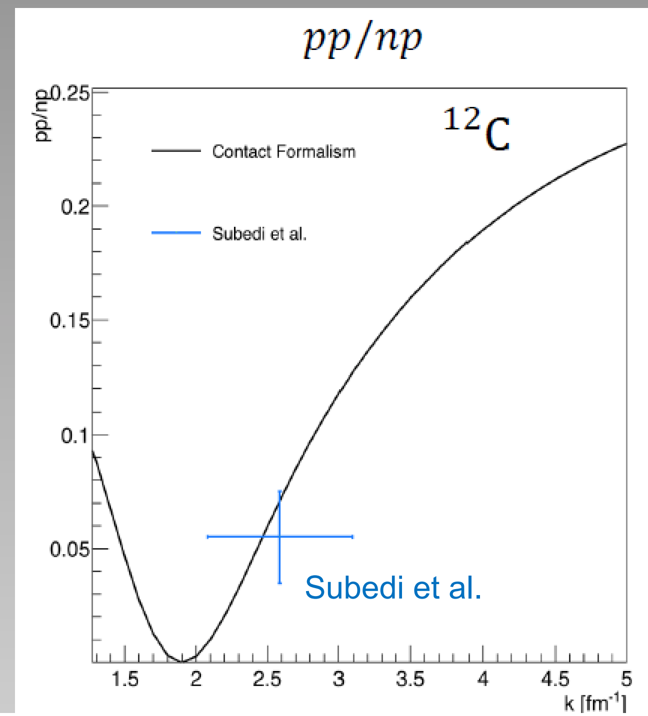
I. Korover et al. Phys. Rev. Let. 113, 022501 (201

Nuclear contact calculations

TEL AVIV UNIVERSITY

(Weiss, Cruz-Torres, Barnea, Piasetzky, Hen)





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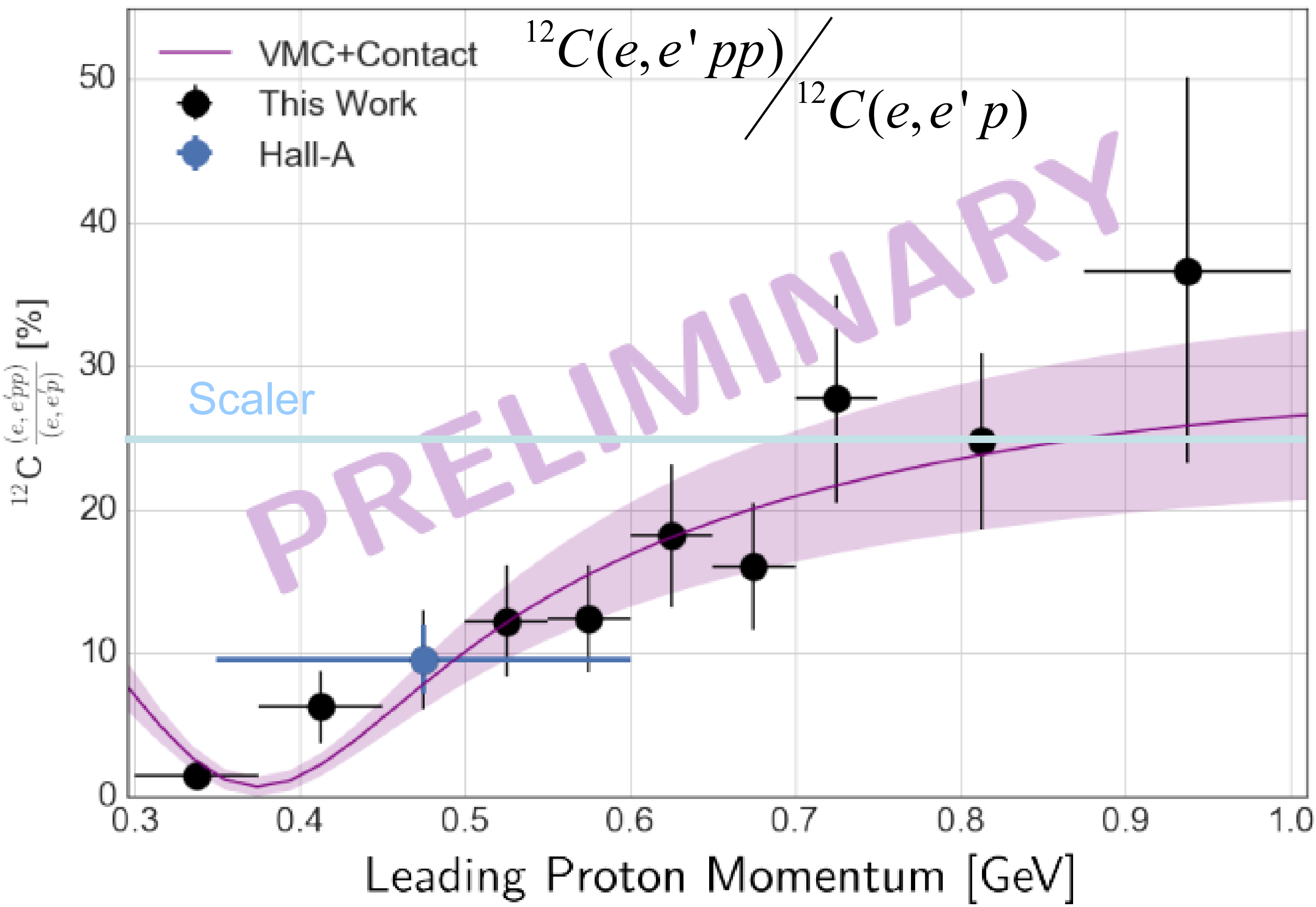

Data mining , CLAS/Jlab, analysis by Erez Cohen (TAU)