EMMI Workshop: Cold dense nuclear matter:
from short-range nuclear correlations to neutron stars

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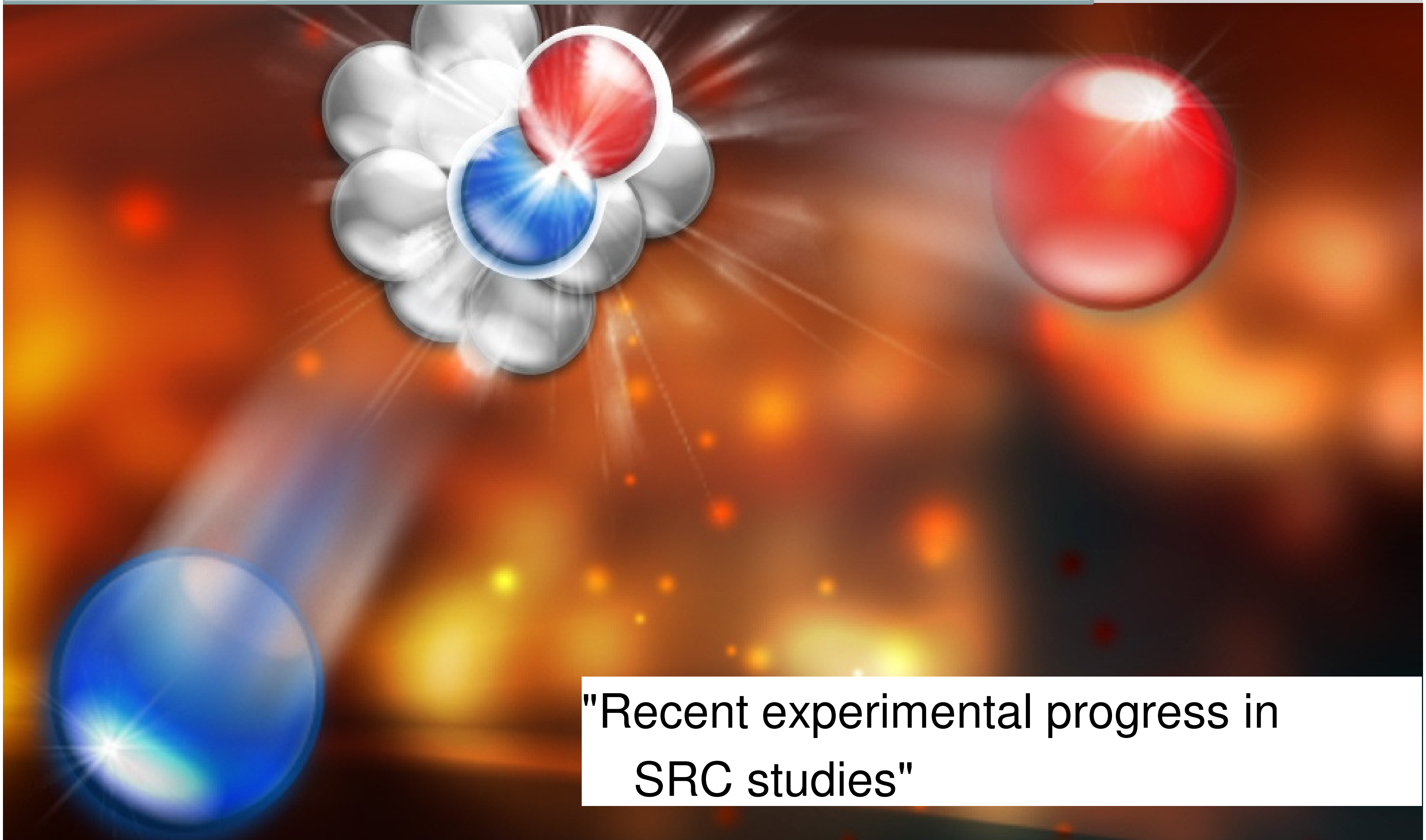
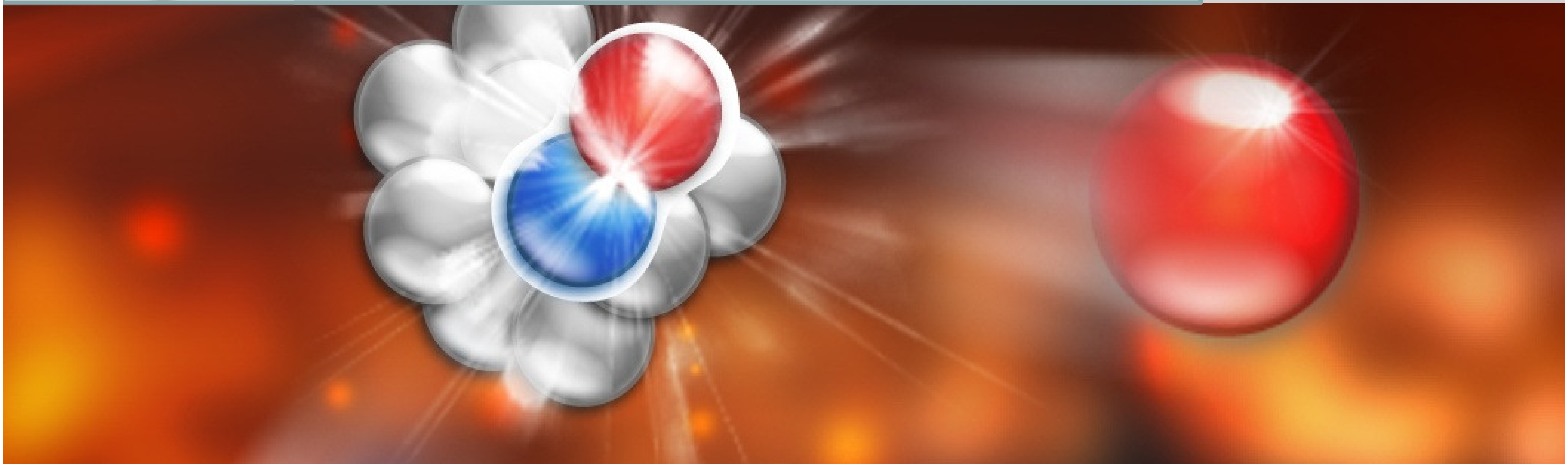


"Recent experimental progress in SRC studies"

Eli Piasetzky Tel Aviv University, Israel

12 October 2015

EMMI Workshop: Cold dense nuclear matter:
from short-range nuclear correlations to neutron stars



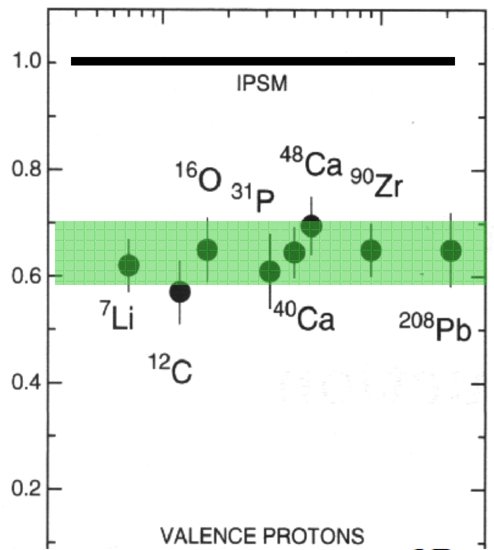
"Recent experimental progress in SRC studies"

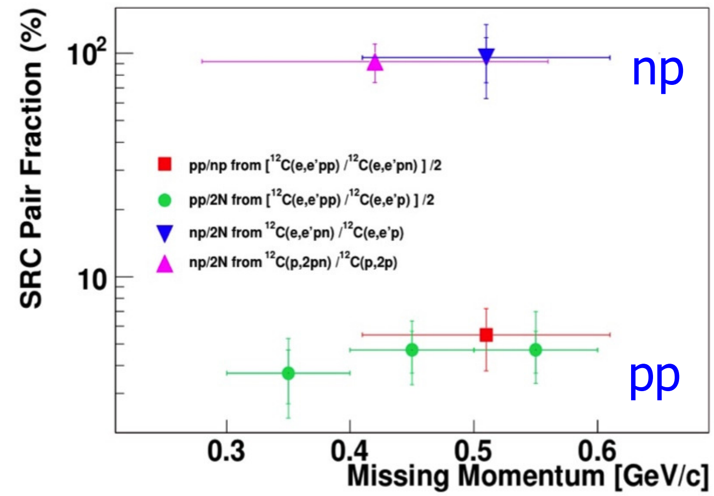
I think that the best way to split our talks is if I talk about electrons up to today and you talk about protons and future experiments. [Larry]

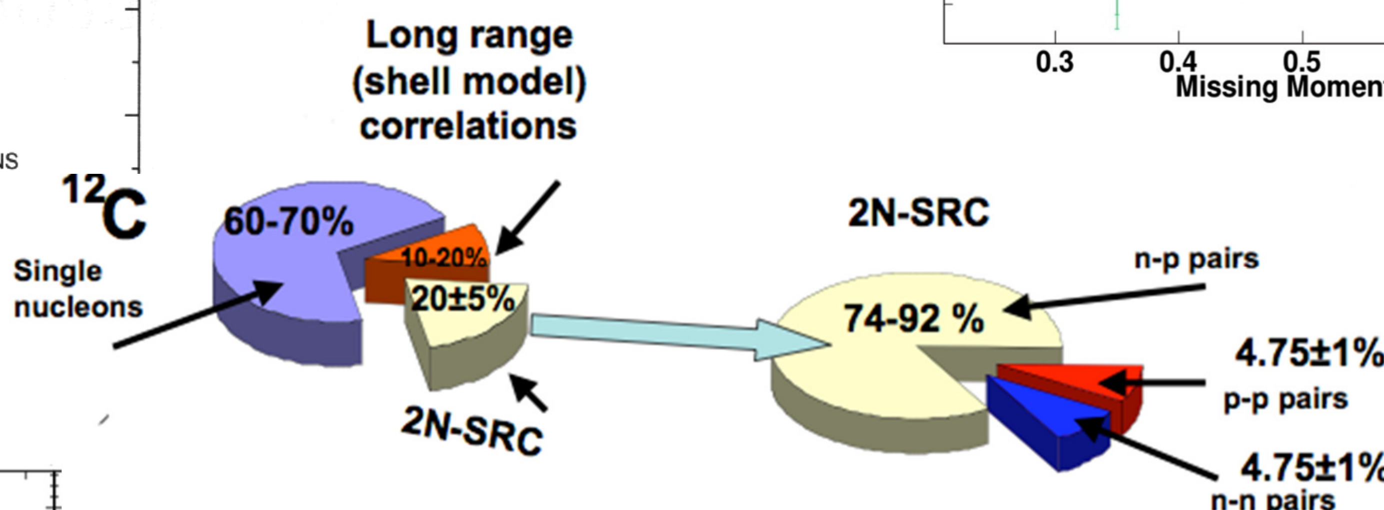
Eli Piasetzky Tel Aviv University, Israel **12 October 2015**

Summary

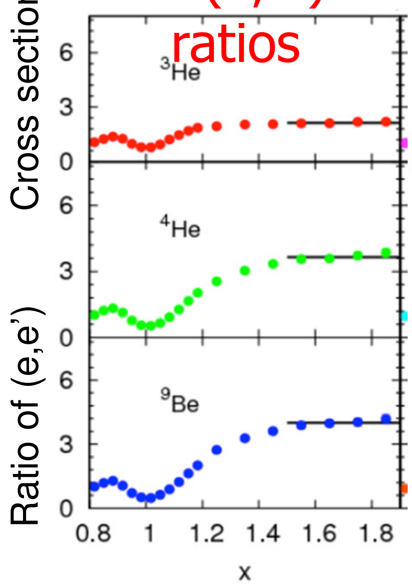
(e,e'p)
Shell
occ

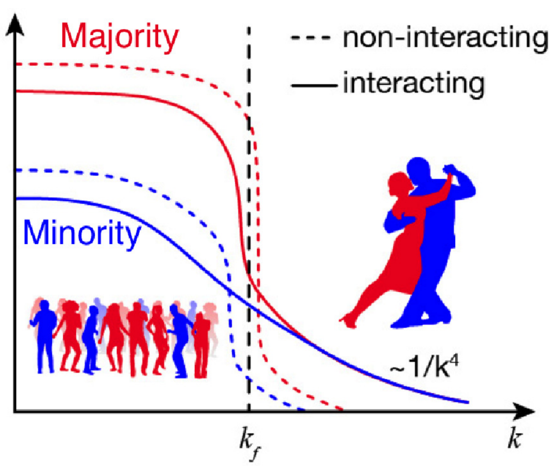


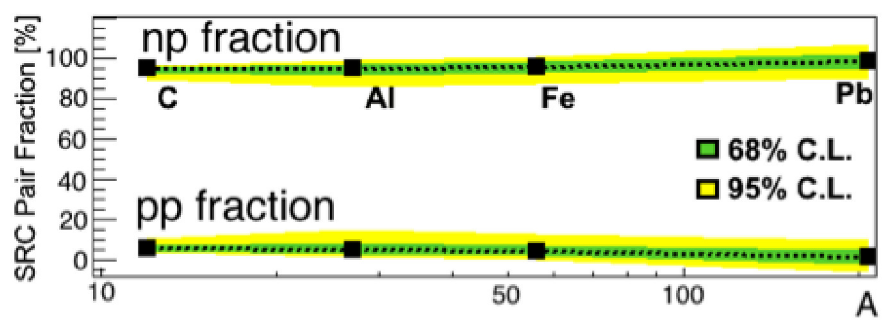




A(e,e')
ratios







~25% SRC pairs
- ~90% tensor correlated np pairs

Summary – SRC outreach

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Wednesday

Morning session: Non-nucleonic degree in nucle

9:00 - 10:00 Mark Strikman (PSU) - "Non-nucleonic degrees of freedom - evidence and constraints"
10:00 - 10:30 Or Hen (MIT) - "SRC and EMC effects"

10:30 - 11:00 Coffee Break

11:00 - 11:30 John Arrington (Argonne)- "Experimental Studies of EMC Effects"
11:30 - 12:00 Shalev Gilad (MIT) - " Medium Modification in Tagged Processes"
12:00 - 12:30 Werner Boeglin (FIU) "Probing the Deuteron Structure at Short Distances"

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p fractio

Tuesday

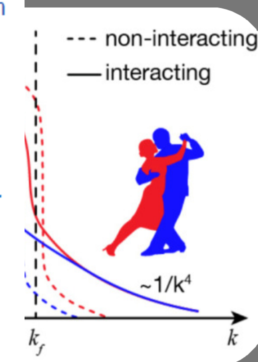
Session: Short Range Structure of Nuclei

2:00 - 3:00 Jan Ryckebusch (Ghent) " Introduction to Calculational Methods of Medium/Heavy Nuclei: Stylized features of nuclear momentum distributions and the quest for SRCs"
3:00- 3:30 Ulrich Mosel (Giessen) "Fundamentals of SRC in spectral functions"

3:30 - 4:00 Coffee Break

4:00 - 4:30 Hans Feldmeier (GSI): - "Short Range Central and Tensor Correlations in Nuclei"
4:30 - 5:00 Nadia Fomin (UTK): - "SRCs at x>1 Inclusive Processes"
5:00 - 5:30 Misak Sargsian(FIU): - "New Results in Short Range Correlation Studies"
5:30 - 6:30 Discussions

clear

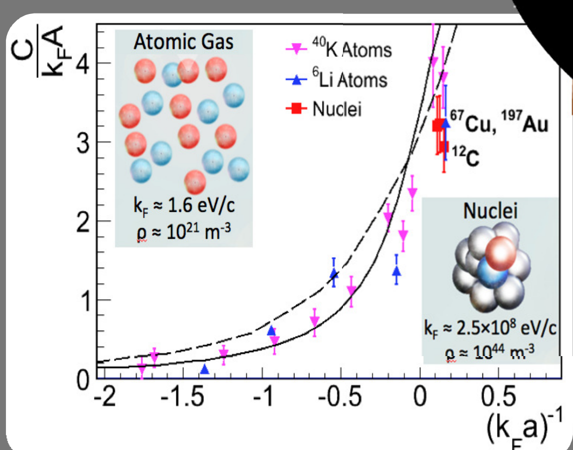


Friday

Session: Multi-Nucleon SRCs

9:00 - 9:30 Arianna Carbone (Tu-Darmstadt) "Self-Consistent Green's Function with 3N Forces"
9:30 - 10:00 Donal Day (UVA) - "Correlations in Few-Body Systems"
10:00 - 10:30 Igor Korover (Tel Aviv) - "Correlations in 4He"
14:00 - 14:20 Erez Cohen(Tel Aviv) "SRCs from Data Mining"

Atomic



Contact term

A

Symme

Thursday:

C

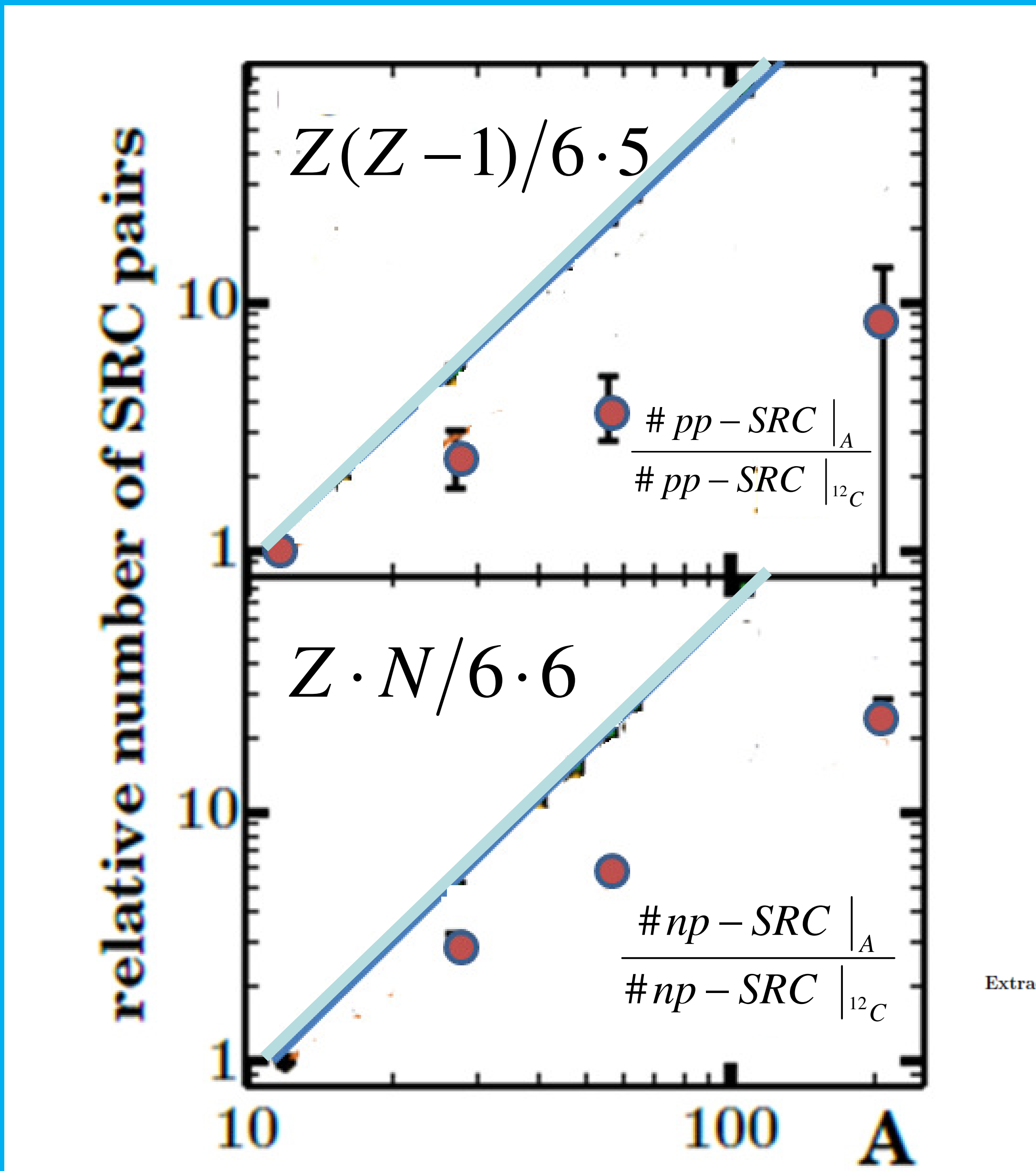
Session: Nuclear Matter and neutron stars

2:00 - 3:00 Sanjay Reddy (Seattle) "Review on Nuclear Matter and Neutron Stars"
3:00 - 3:30 Armen Sedrakian (Frankfurt) "Cooling Processes in Neutron Stars"

3:30 - 4:00 Coffee break

4:00 - 4:30 Arnau Rios (Surrey) "Density and isospin asymmetry dependence of short-range correlations"
4:30 - 5:00 Bao-An Li (Texas A&M) "Nuclear Symmetry Energy"
5:00 - 5:30 Yukinori Sakuragi (Osaka City University) "High-density nuclear matter probed by nucleus-nucleus scattering - its implication to neutron star mass problem -"
5:30 -6:00 Achim Schwenk (TU Darmstadt) "Nuclear forces and their impact on neutron-rich matter",

The mass dependence of the SRC pairs

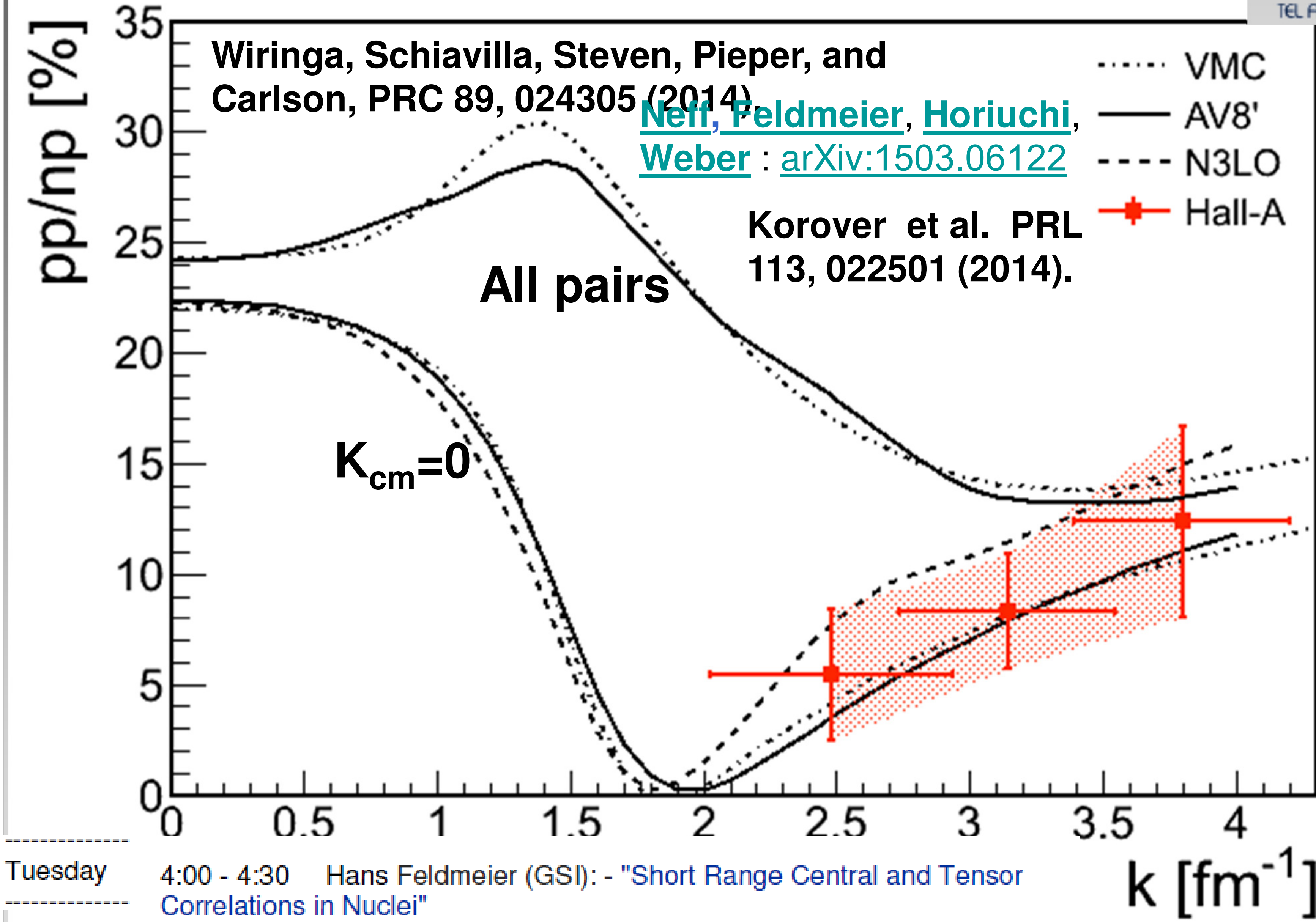


a data mining analysis

Extracting the Mass Dependence and Quantum Numbers of Short-Range Correlated Pairs from A(e, e′p) and A(e, e′pp) Scattering

C. Colle,[1] O. Hen,[2] W. Cosyn,[1] I. Korover,[2] E. Piasetzky,[2] J. Ryckebusch,[1] and L.B. Weinstein[3]

Phy. Rev. C92, 024604 (2015)



Tuesday

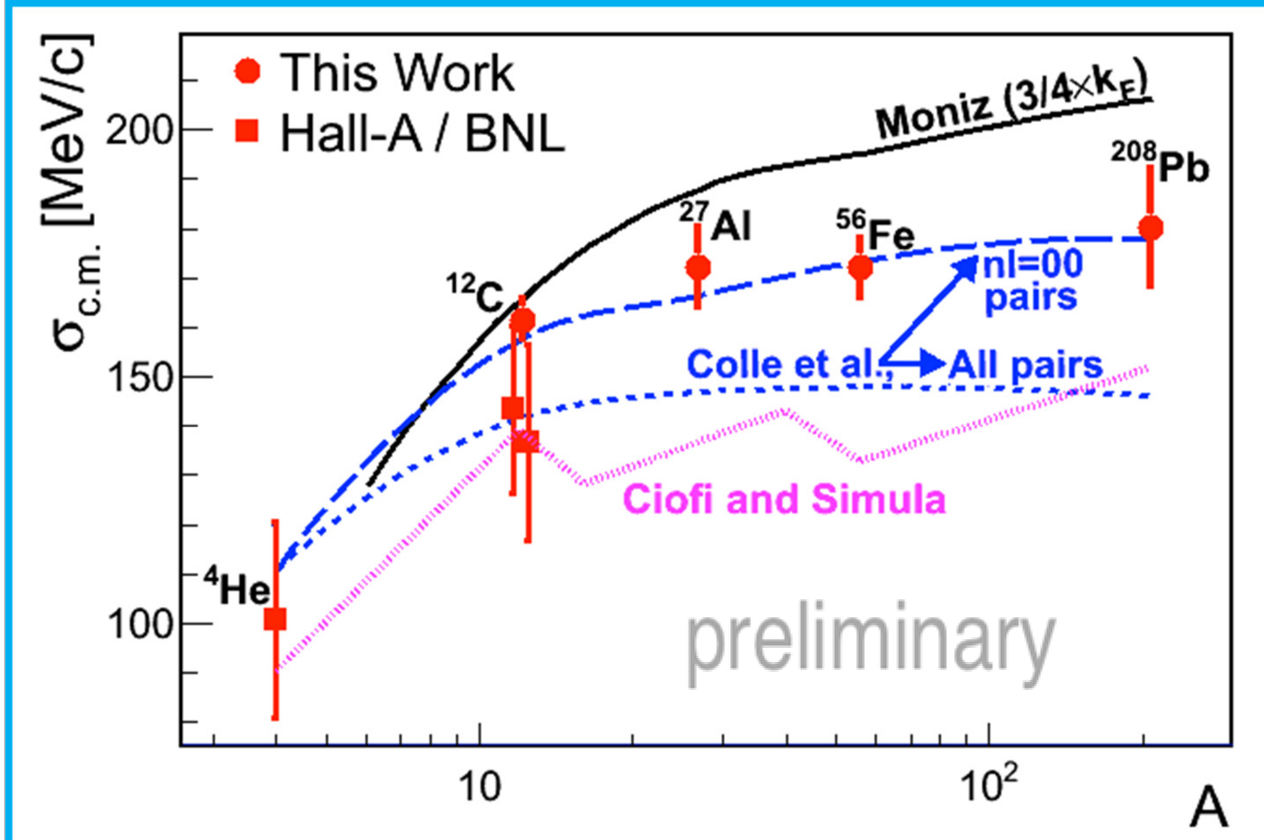
4:00 - 4:30 Hans Feldmeier (GSI): - "Short Range Central and Tensor Correlations in Nuclei"

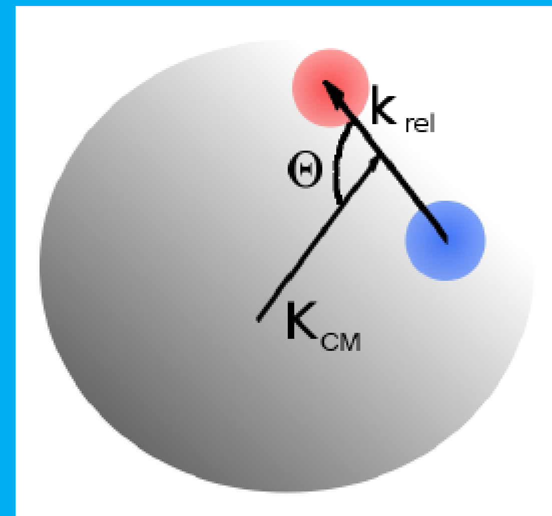
Friday

10:00 - 10:30 Igor Korover (Tel Aviv) - "Correlations in 4He"

C.M. motion of the pair

a data mining analysis





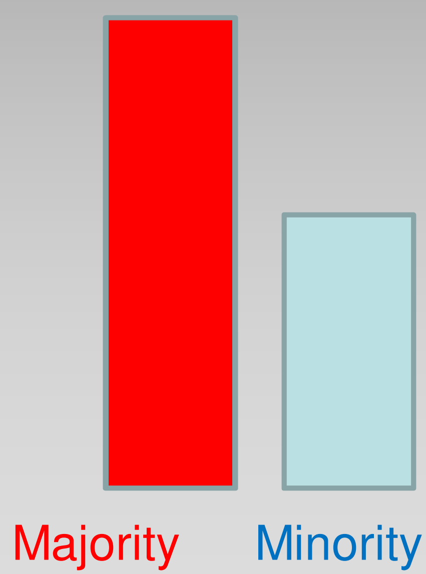
$$\vec{p}_{cm} = \vec{p}_{miss} + \vec{p}_{recoil}$$

O. Hen E. Cohen et al., in preparation

Momentum sharing in Asymmetric (imbalanced) two components Fermi systems

non interacting Fermions

Pauli exclusion principle ➔



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

$$\left\langle T_{Majotiry} \right\rangle > \left\langle T_{Minority} \right\rangle$$

$$\left\langle k_{Majotiry} \right\rangle > \left\langle k_{Minority} \right\rangle$$

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

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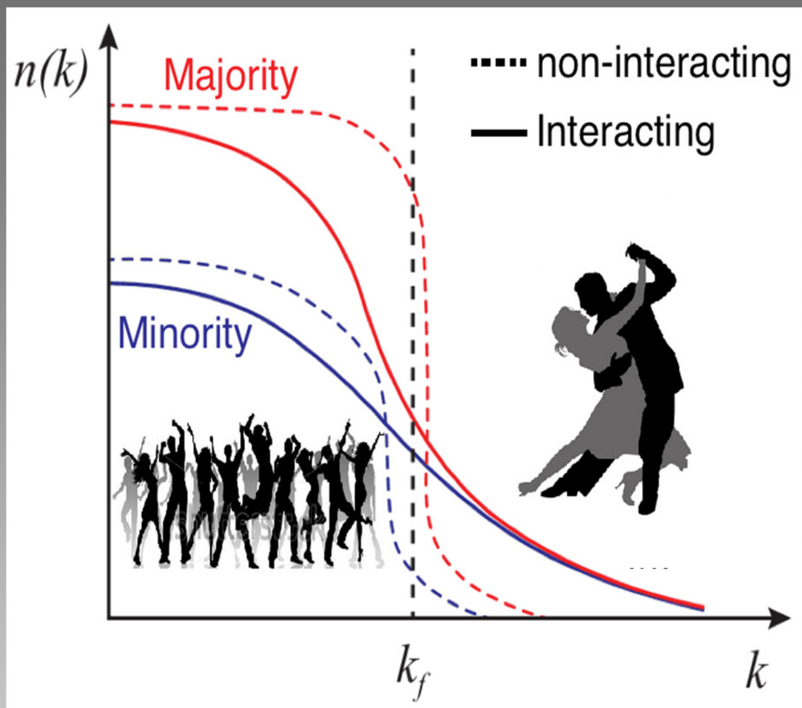
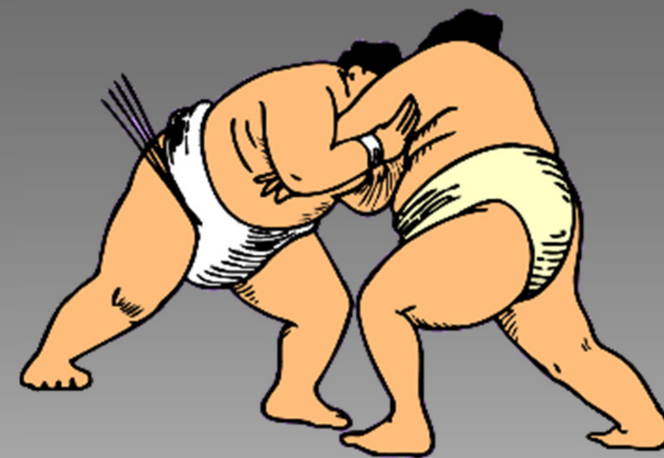




Who wins?

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 :

$$\langle k_{\min ority} \rangle > \langle k_{majority} \rangle$$

M. Sargsian Phys.Rev. C89 (2014) 3, 034305
O. Hen et al., Science 346, 614 (2014).

Protons move faster than neutrons in N>Z nuclei

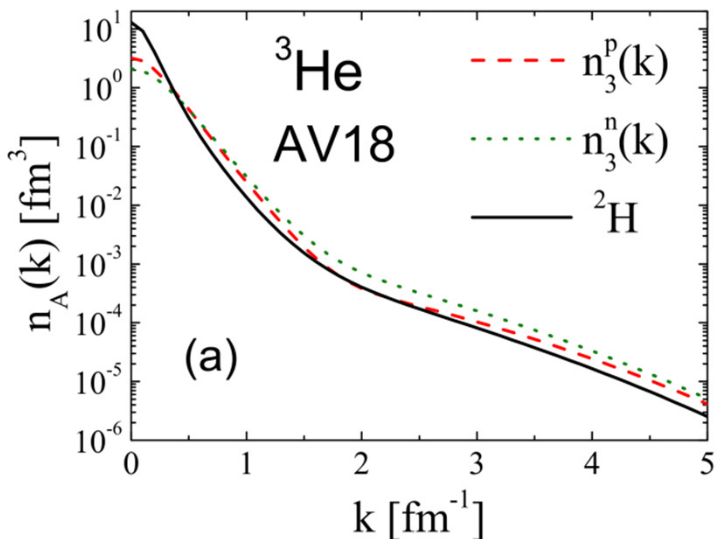
(protons move faster than neutrons in N>Z nuclei)

Light nuclei A<11

Variational Monte Carlo calculations by the Argonne group

Wiringa et al.
Phys. Rev. C89, 034305 (2014).

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



For ^{3}He:

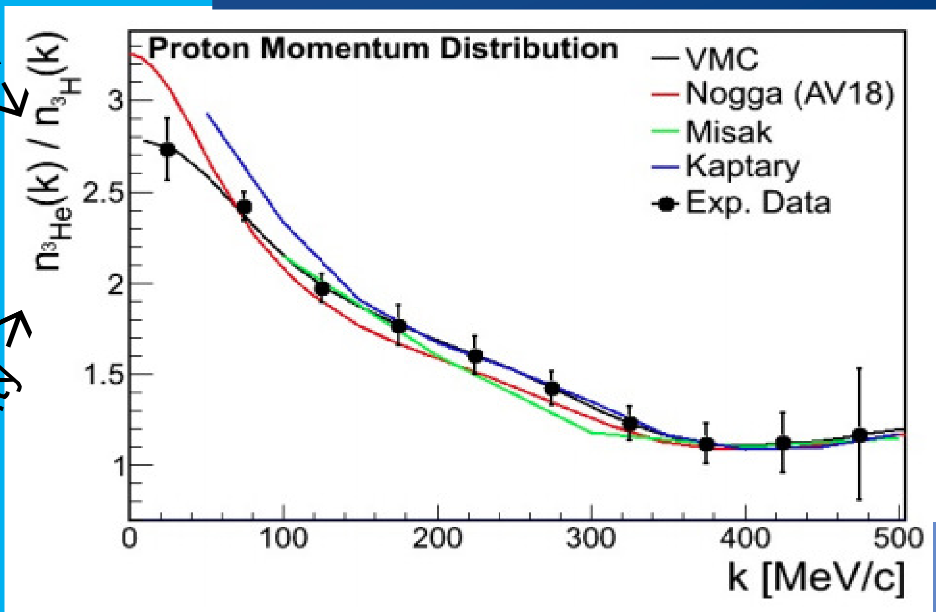
$$\frac{n_n(k>1)}{n_n(k<1)} > \frac{n_p(k>1)}{n_p(k<1)}$$

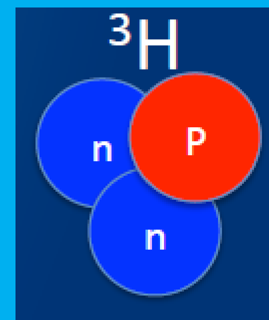
Momentum sharing in the A=3 nuclei

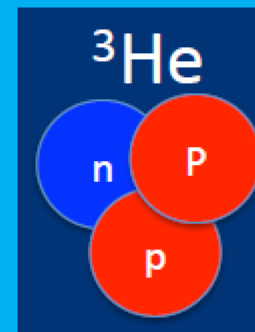
^{3}He and ^{3}H are mirror nuclei: $[p/n]_{3He} = [n/p]_{3H}$

Minority →

Majority →







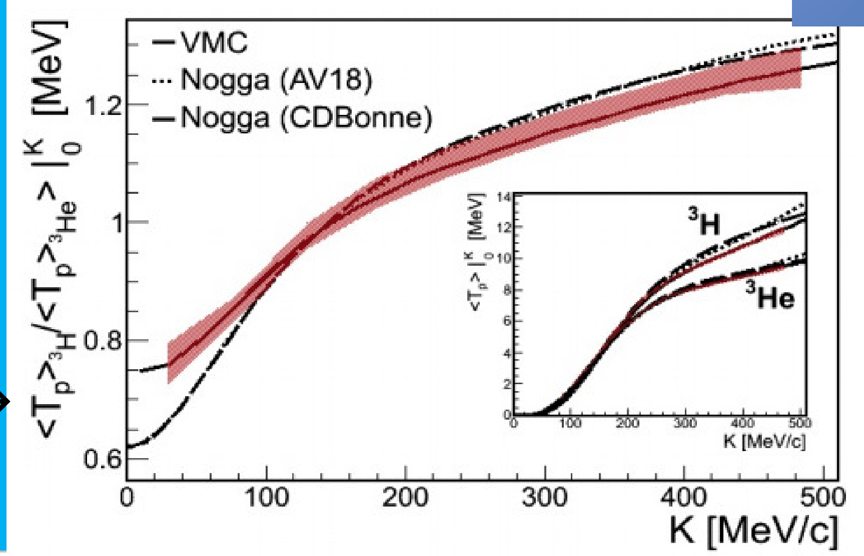
Wednesday

12:00 - 12:30 Werner Boeglin (FIU) "Probing the Deuteron Structure at Short Distances"

Mapping the Transition from Majority to Minority Dominance

Majority →

Minority →

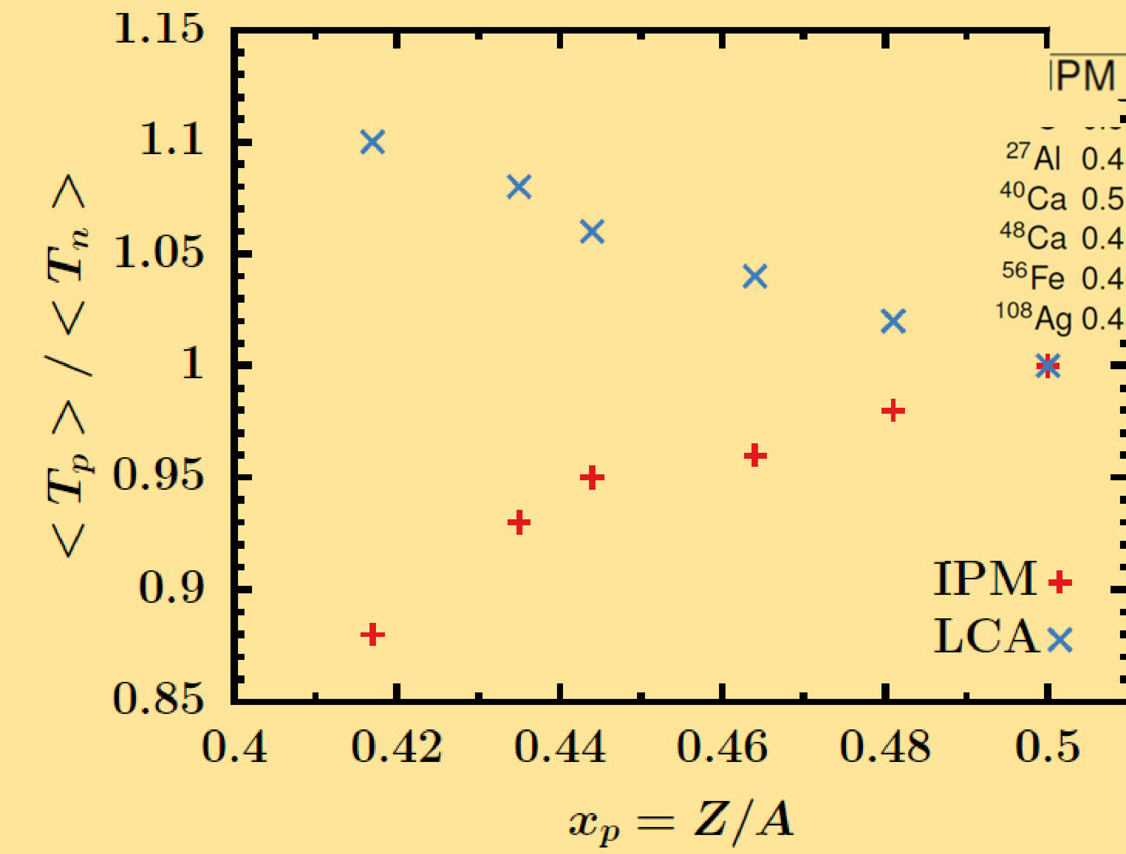


JLab E14-011
(Approved experiment)
2016/2017

Spokespersons: O. Hen, L. Weinstein, S. Gilad, W. Boeglin

Predictions for $\langle T_p \rangle / \langle T_n \rangle$ ratio

Average kinetic energy per nucleon



		$\langle T_N \rangle$ (MeV)			
		IPM (p)	IPM (n)	LCA (p)	LCA(n)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{27}Al	0.481	16.61	16.92	30.93	30.26
^{40}Ca	0.500	16.44	16.42	31.23	31.18
^{48}Ca	0.417	15.64	17.84	33.04	30.06
^{56}Fe	0.464	16.71	17.45	32.33	31.13
^{108}Ag	0.435	16.48	17.81	33.55	31.16

Tuesday

2:00 - 3:00 Jan Ryckebusch (Ghent) " Introduction to Calculational Methods of Medium/Heavy Nuclei: Stylized features of nuclear momentum distributions and the quest for SRCs"

Study of the A(e,e'n) reaction using JLAB – CLAS EG2 data

Meytal Duer (Tel – Aviv University)

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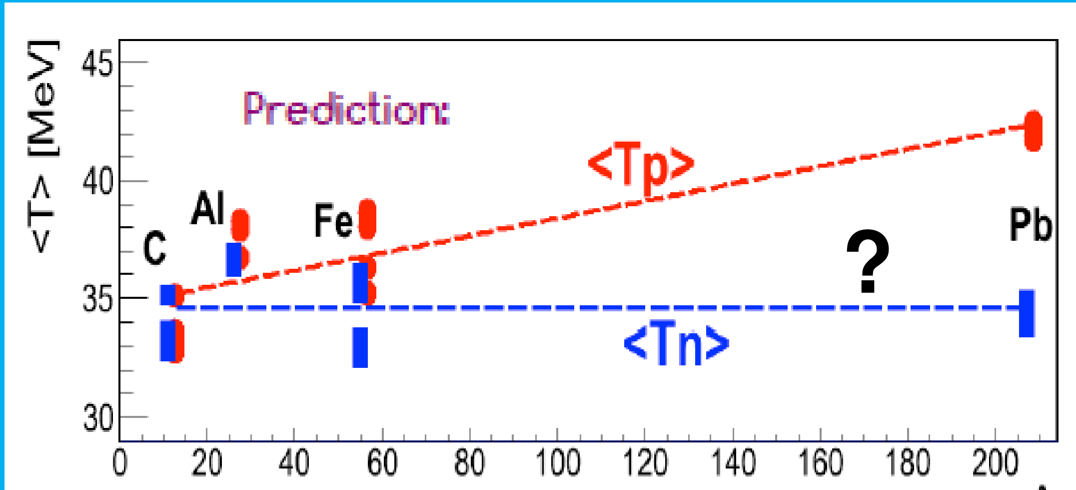
a data mining analysis



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

$$\frac{A(e,e'n)/^{12}C(e,e'n)|high\ Pmiss}{A(e,e'n)/^{12}C(e,e'n)|low\ Pmiss}$$

350-1000 MeV/c

0- 250 MeV/c

$$\frac{A(e,e'p)/^{12}C(e,e'p)|high\ Pmiss}{A(e,e'p)/^{12}C(e,e'p)|low\ Pmiss}$$

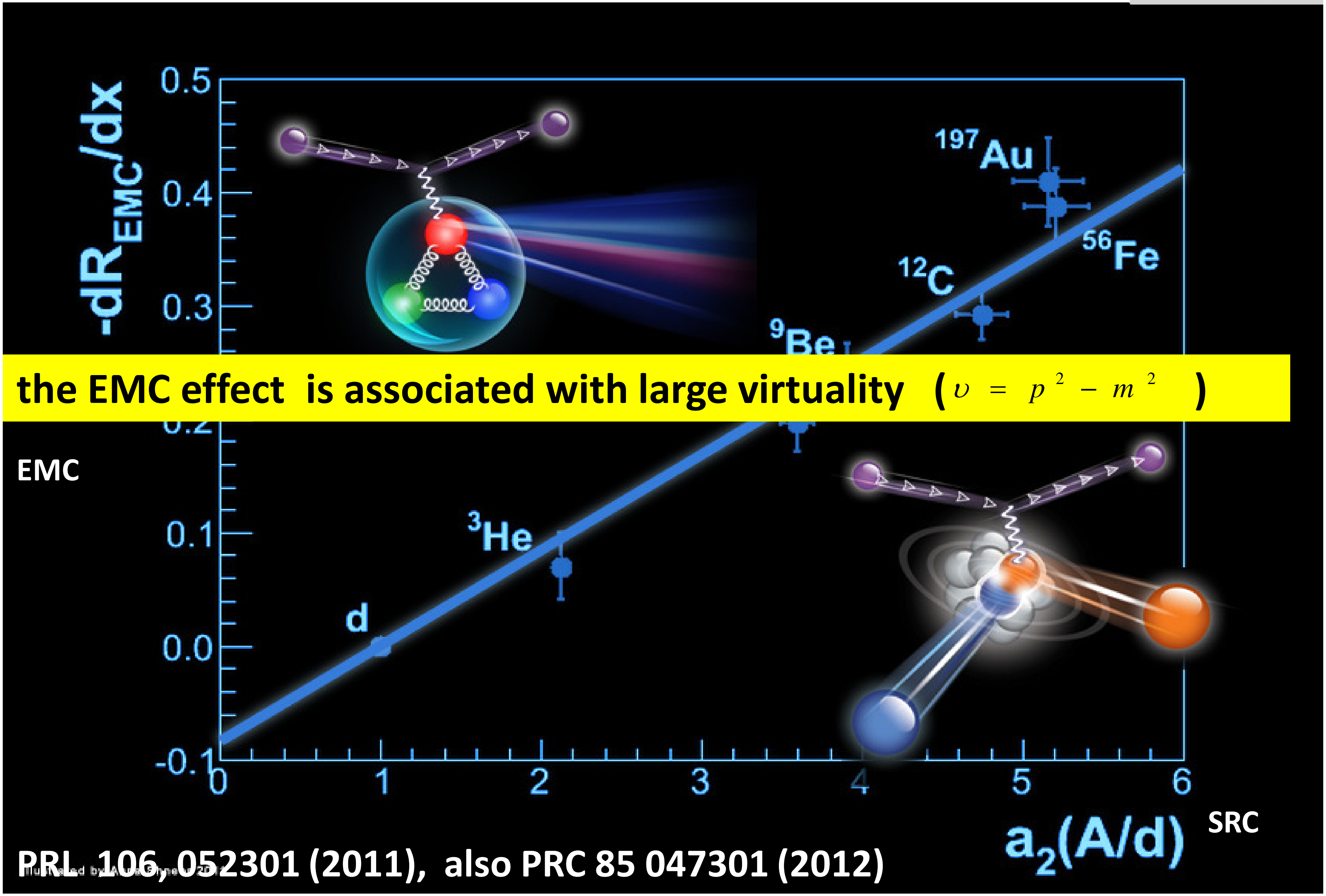
350-1000 MeV/c

0- 250 MeV/c

----------- Friday ------------

14:20 - 14:40 Meytal Duer(Tel Aviv) "SRCs from Data Mining"

EMC / SRC correlation



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

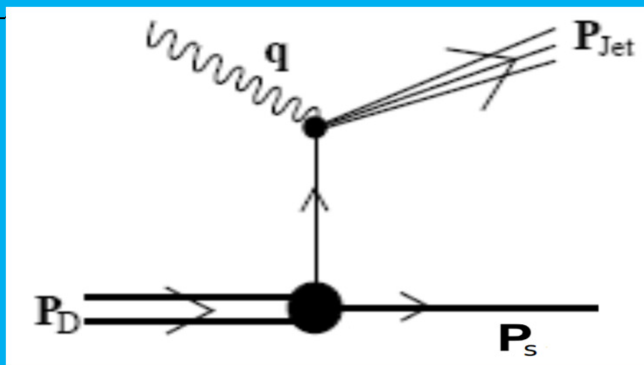
EMC

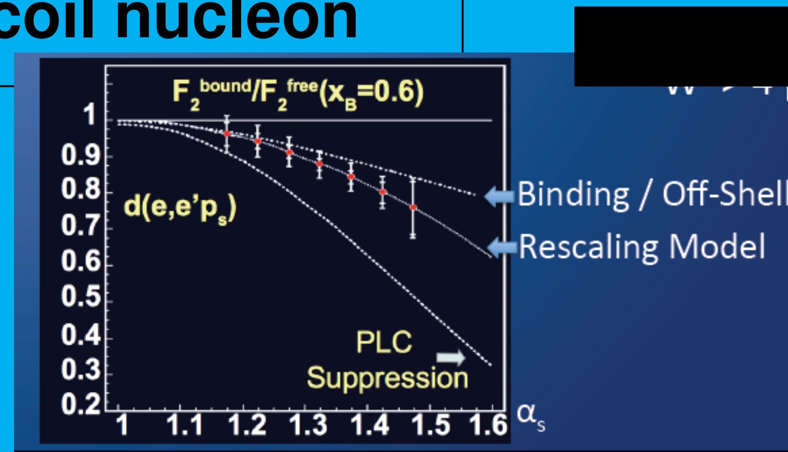
SRC

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

the EMC effect is associated with large virtuality

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





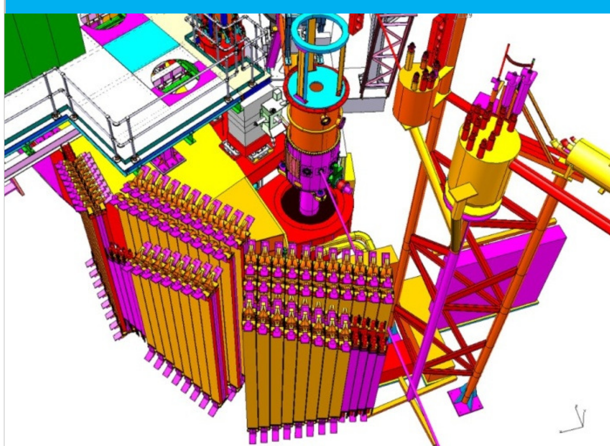
$$\upsilon = p^2 - m^2$$

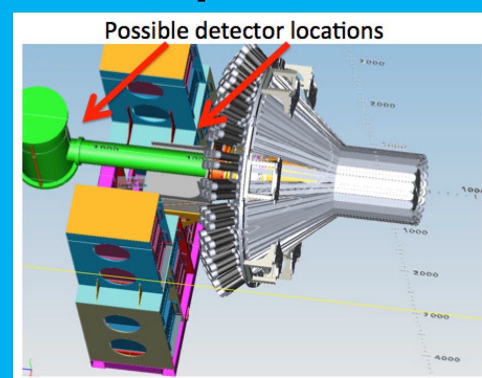
12 GeV JLab/ Hall C approved experiment E 12-11-107

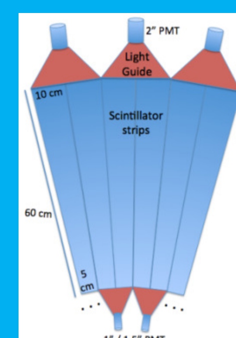
Tagged recoil proton measure neutron structure function

12 GeV JLab/ Hall B approved proposal

Tagged recoil neutron measure in the proton structure function





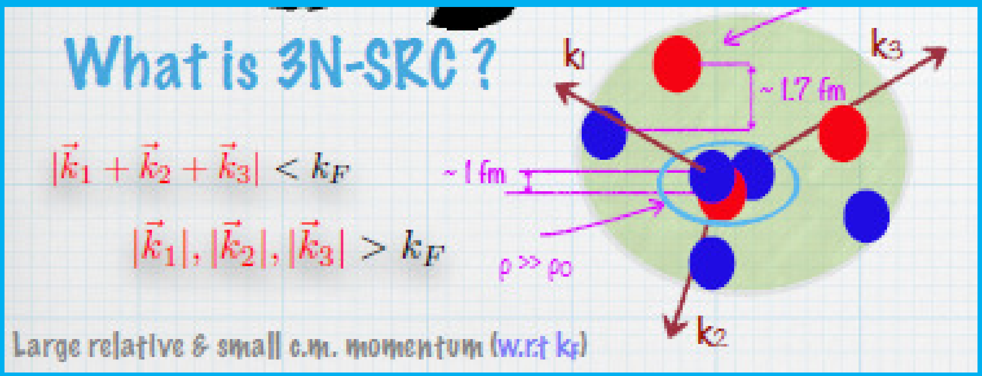


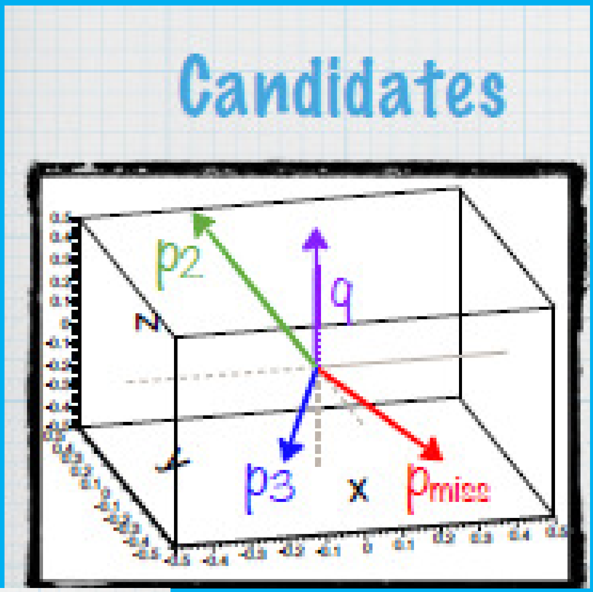
Wednesday 10:00 - 10:30 Or Hen (MIT) - "SRC and EMC effects"

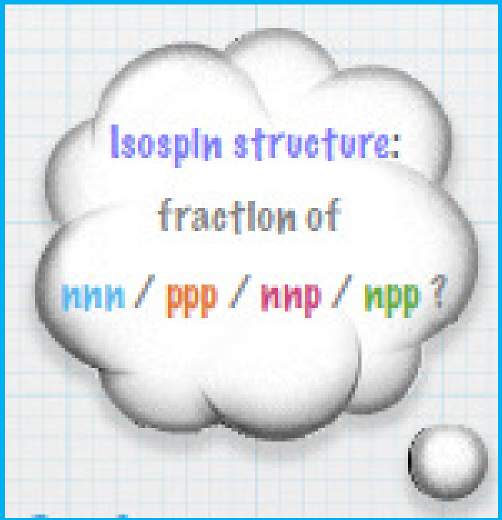
Search for 3N correlation using JLAB – CLAS EG2 data

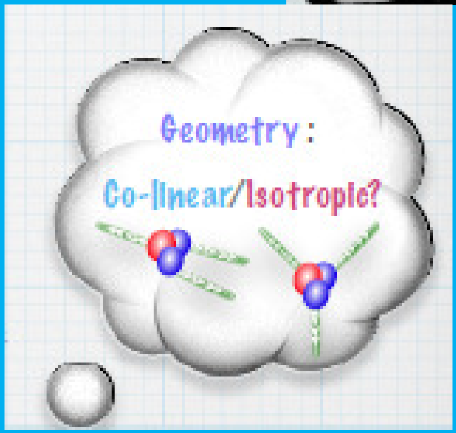
Erez Cohen (Tel – Aviv University)

a data mining analysis





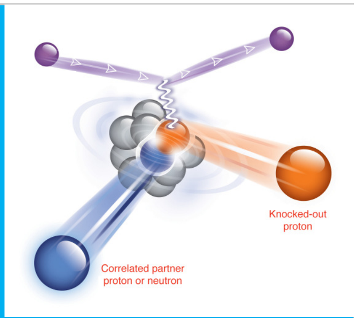




Friday

14:00 - 14:20 Erez Cohen(Tel Aviv) "SRCs from Data Mining"

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

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

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

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

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

Need high statistic exclusive measurement (>10,000 events)

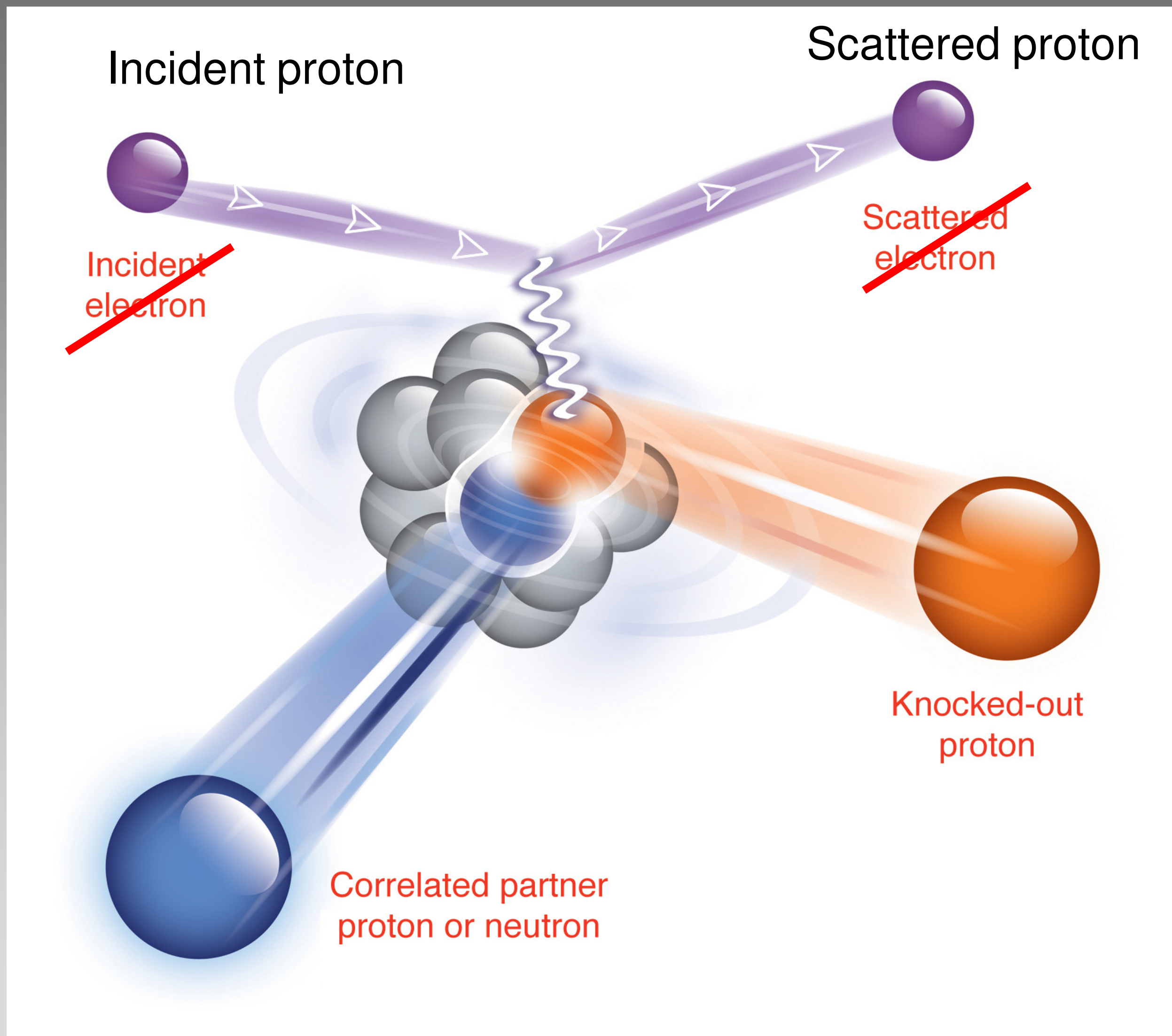
At Jlab after 12 GeV upgrade:

Detector acceptance: 5

(e,e'p)

$$\frac{\sigma_{MOTT}(12GeV)}{\sigma_{MOTT}(4GeV)} \approx 8$$

Triple coincidence A (p, p p N) measurements



Complementary to JLab study with electrons

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

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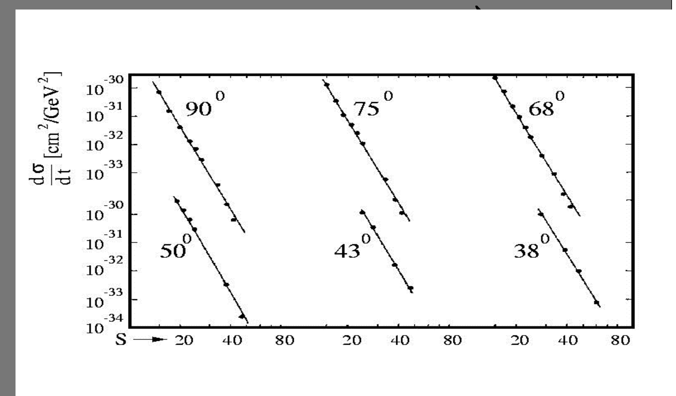
selective attention to SRC

Psychology Wiki

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

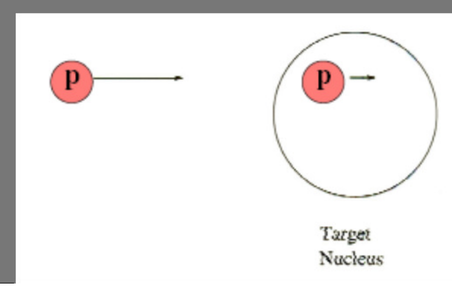
p p → pp elastic scattering near 90^0 c.m

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



Constituent Counting Rules

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



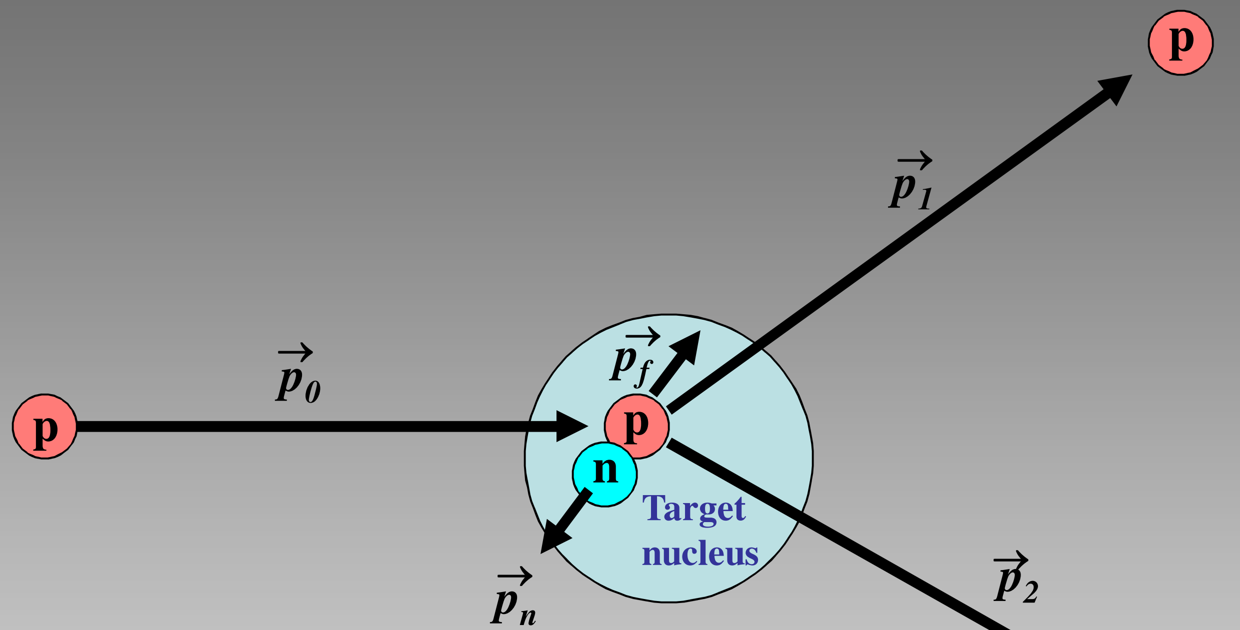
Other reasons Why several GeV and up protons are good probes of SRC ?

- They have Small deBroglie wavelength:

λ = h/p = hc/pc = 2π • 0.197 GeV-fm/(6 GeV) $\approx$ 0.2 fm.

- Large momentum transfer is possible with wide angle scattering

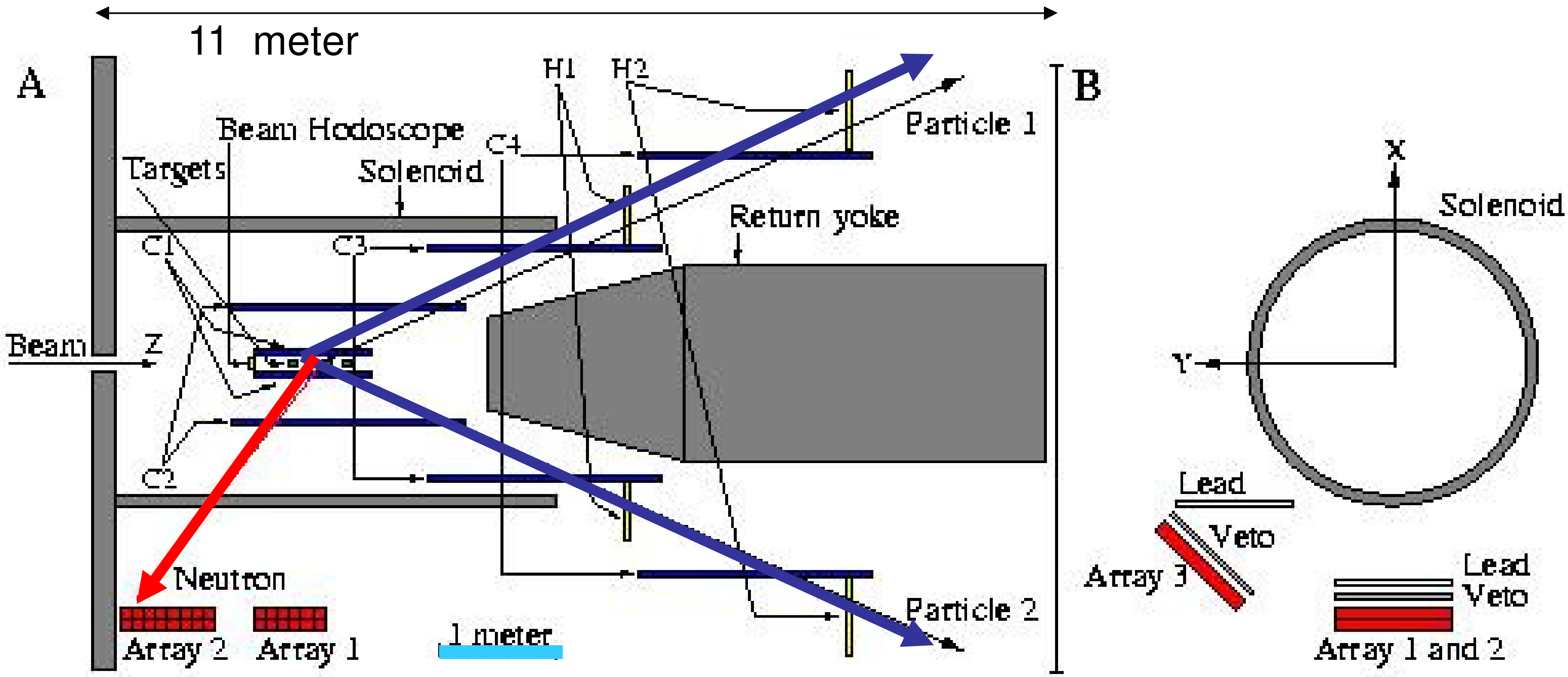
- Cross section is large

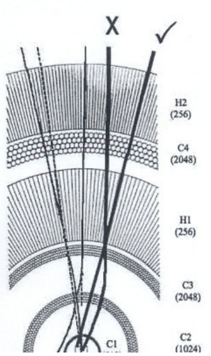


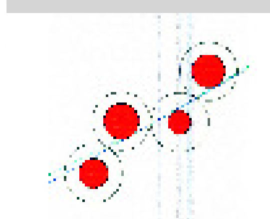
From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

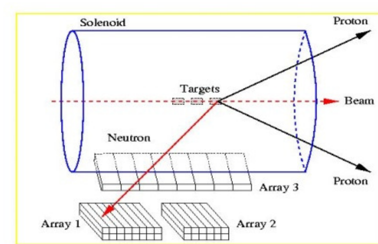
We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly "back to back."

The EVA spectrometer and the n-counters at BNL







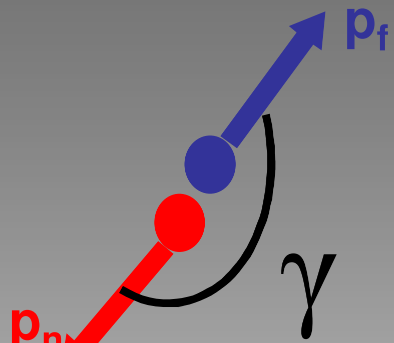


Array 1: total area 0.6×1.0 m^2, 12 counters, 2 layers 0.125 m

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

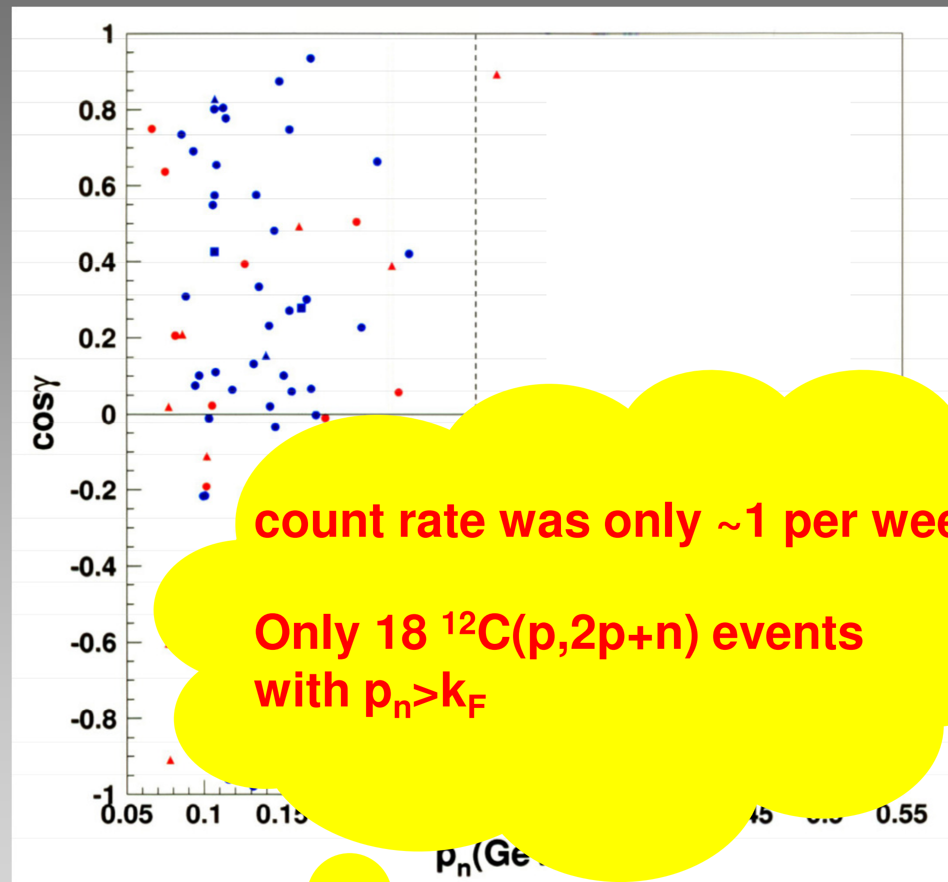
A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

Directional correlation



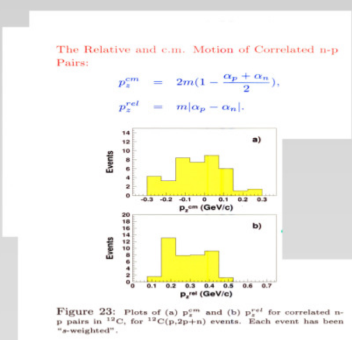
Removal of a proton with momentum above 275 MeV/c from ^{12}C is $\mathbf{92\pm^{8}_{18}}$ **%** accompanied by a recoil high momentum neutron.

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



count rate was only ~1 per week

Only 18 $^{12}C(p,2p+n)$ events with $p_n>k_F$



The Relative and c.m. Motion of Correlated n-p Pairs:

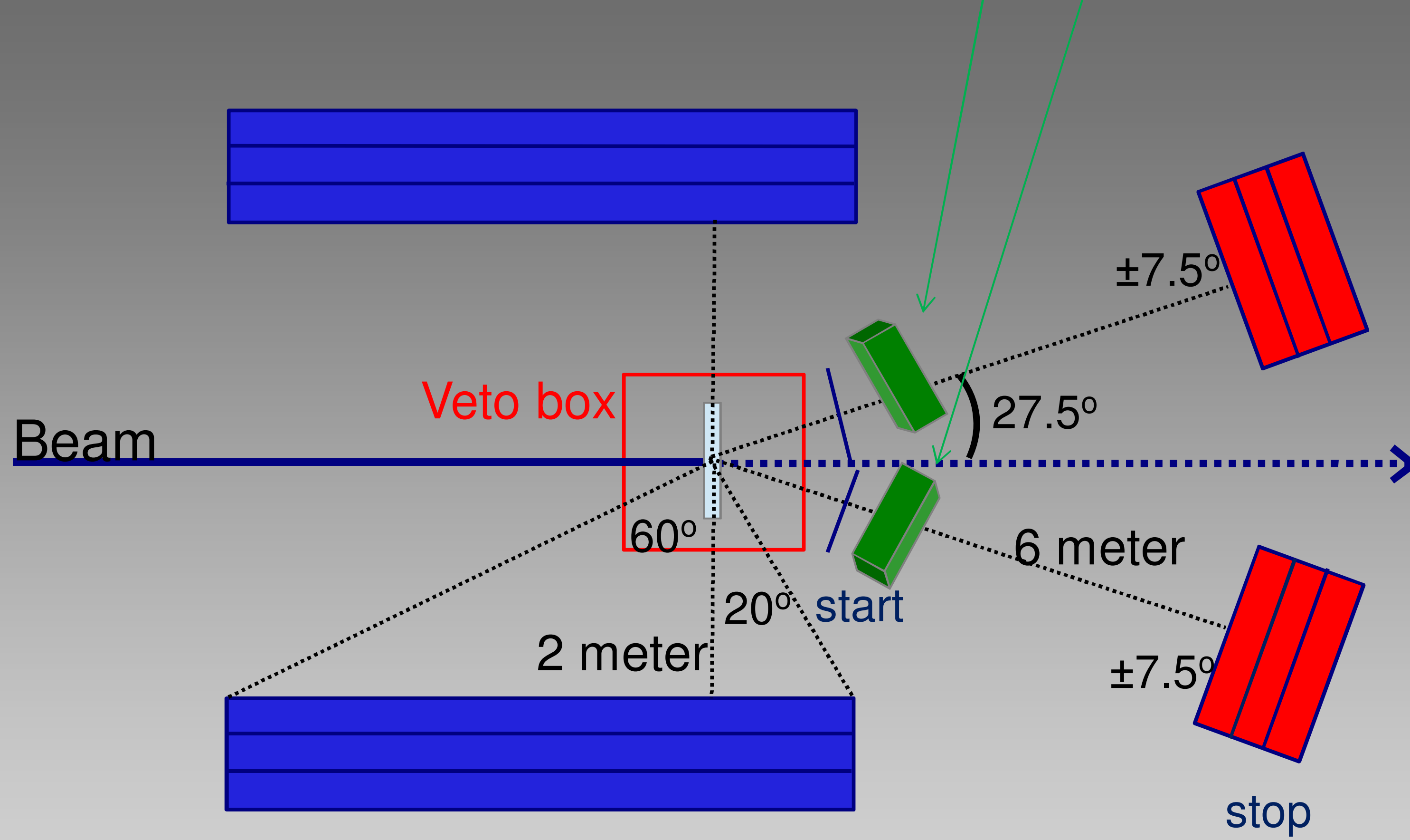
$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$

Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p+n)$ events. Each event has been "s-weighted".

σ_{CM}=0.143±0.017 GeV/c

Recoil detector



σ_{TOF}<100ps

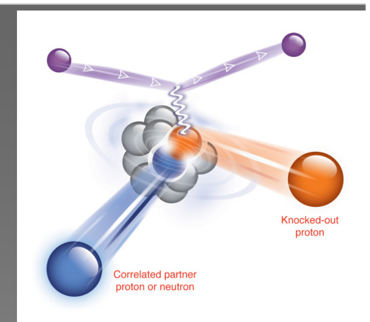
Array of scintillators

LAND, NeuLAND ?

Forward detector

HADES ?

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

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

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

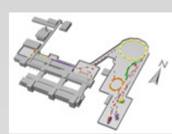
$^{4}He(e,e'\,pn)$ $^{4}He(e,e'\,pp)$

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

A window of opportunity:

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

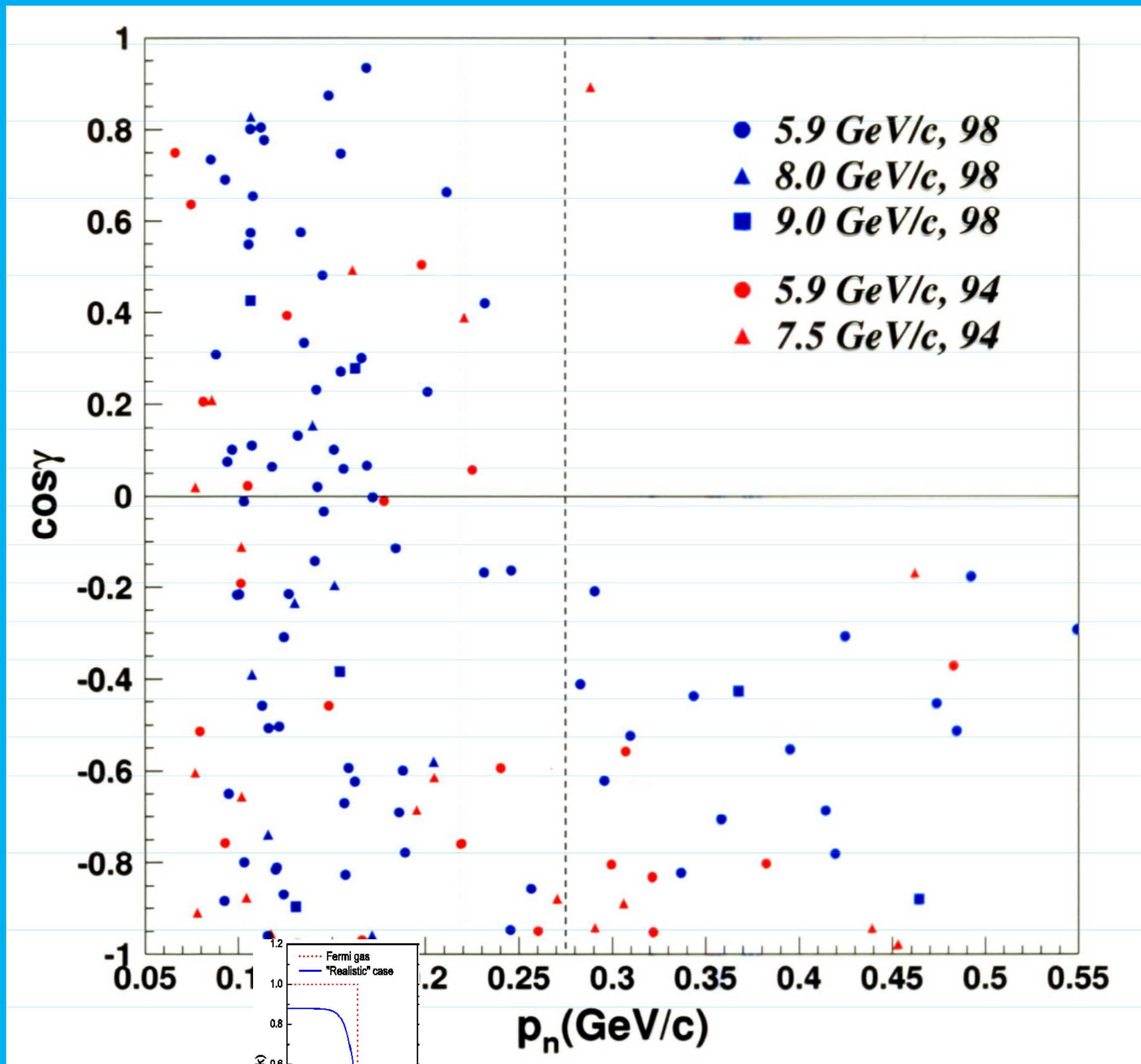
Dubna

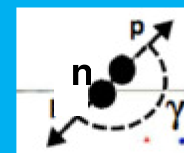


GSI / FAIR

→ >10k events
Before 2020

Mapping the transition from mean field to SRC





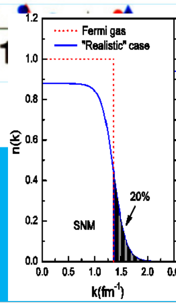
EVA / BNL:

Only 18 $^{12}C(p,2p+n)$ events with $p_n > k_F$

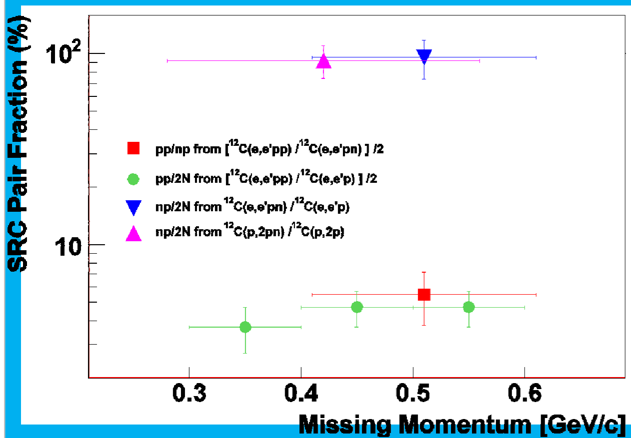
With 100ps TOF resolution:

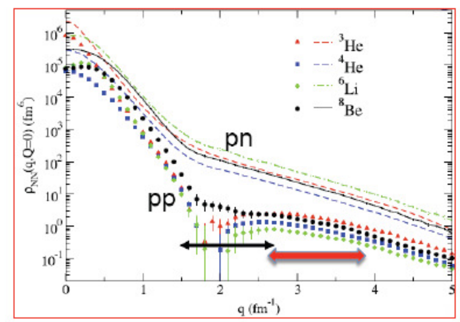
$$\Delta p_{miss} \approx 15 MeV / c$$

Migdal jump

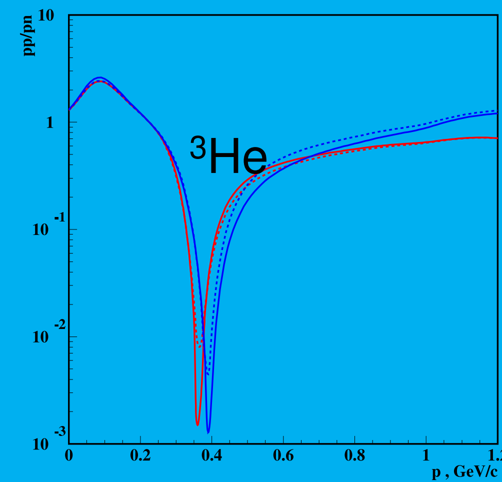


SRC Isospin Structure and the Tensor Force





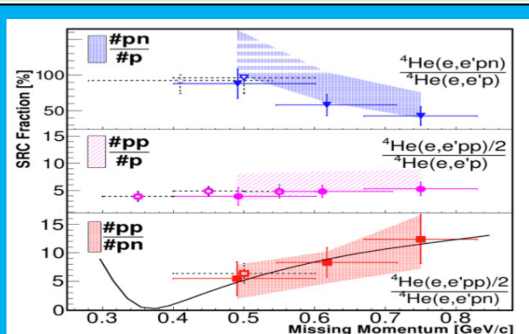
R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Phys. Rev. Lett. **98** (2007) 132501



At 400-600 MeV/c.

np SRC is ~18 times pp (nn) SRC!!!

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).



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

. **We propose :**

First measurement below 400 MeV/c

Better statistics above 600 MeV/c

\

Asymmetric nuclei   N>Z:

Who are the parents of the 2N-SRC pairs ?

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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 f7/2 neutrons

Z=20
N=20

Z=20
N=28

Add 8 protons

Z=26
N=28

motion of the pair

The Relative and c.m. Motion of Correlated n-p Pairs:

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

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$

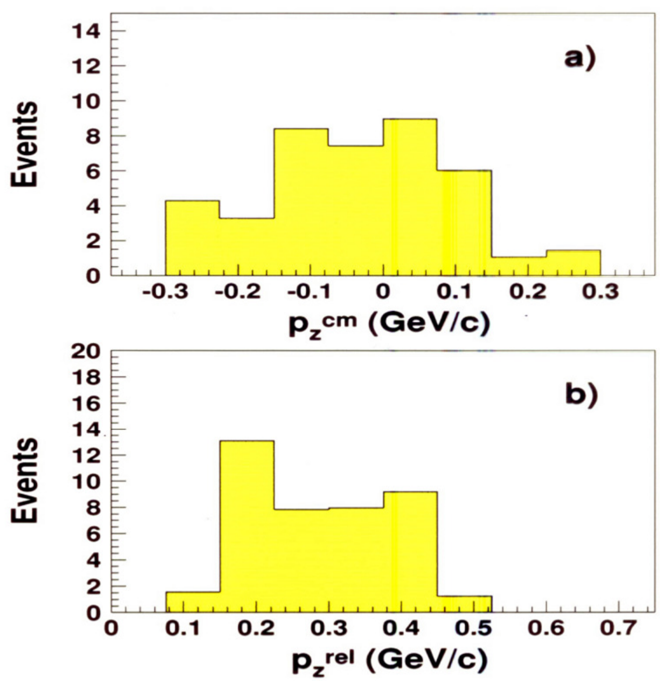

Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p+n)$ events. Each event has been "s-weighted".

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

$\sigma_{CM}=0.143\pm0.017$ GeV/c

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

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

Electron scattering (shneor et al.) : $\sigma_{CM}=0.136\pm0.02$ GeV/c

PRL 99, 072501 (2007).

Reaction Mechanism

Hard processes

high energy and large momentum-transfer

Important practical question:

How low in t, u, Q2 … can we still use the advantages of hard scattering ?

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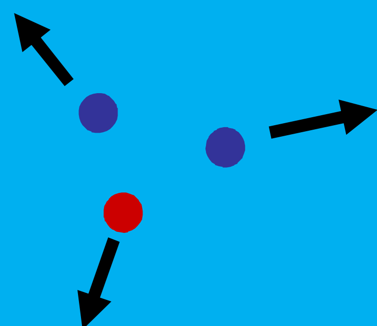
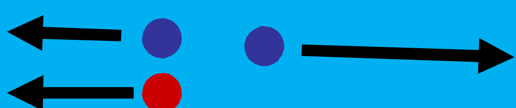
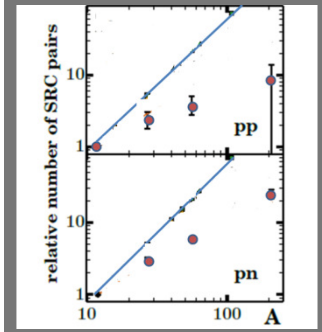
What is the role played by short range correlation of more than two nucleons ?

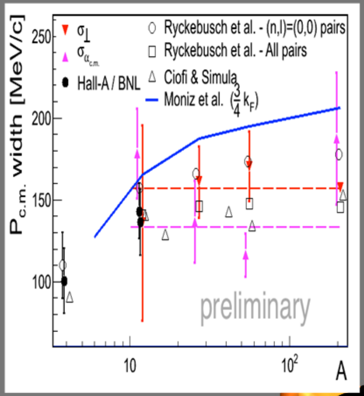




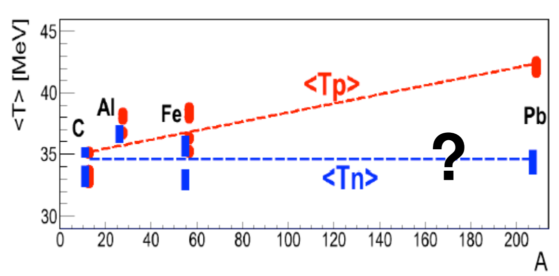
Summary – data and analysis

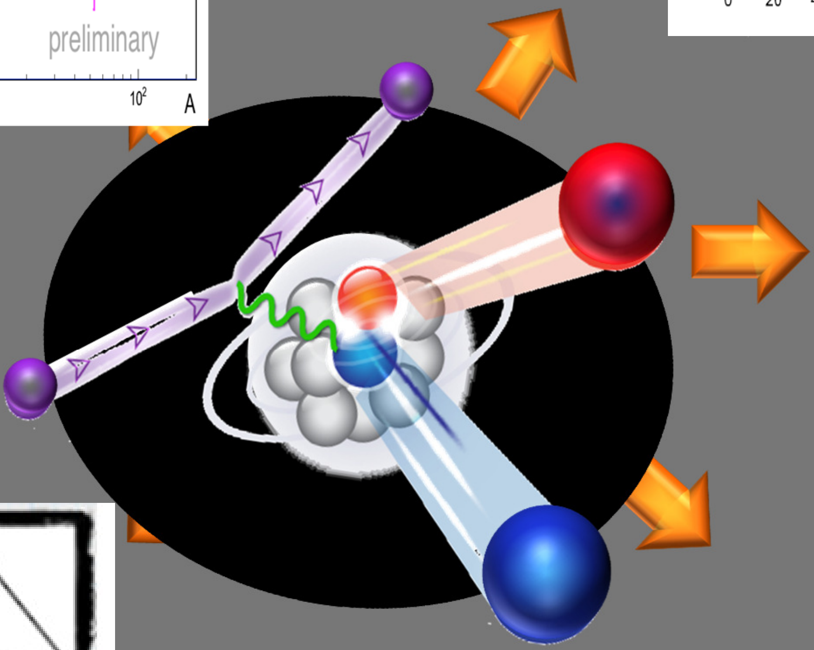
C.M. motion of the pair



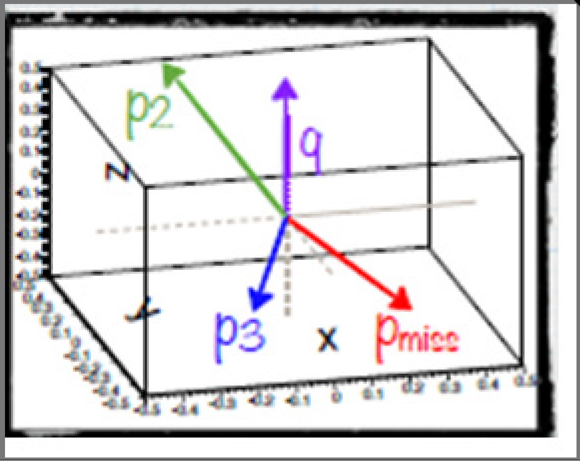


Momentum sharing in asymmetric nuclei





Search for 3N SRC



Isospin dependence of inclusive x>1 (>2)data

Tuesday

4:30 - 5:00 Nadia Fomin (UTK): - "SRCs at x>1 Inclusive Processes"

Summary – future experiments

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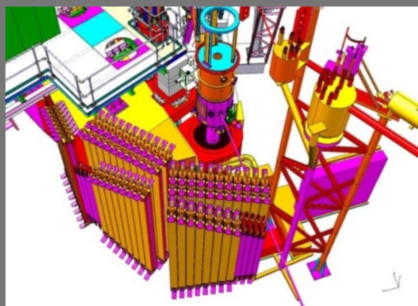
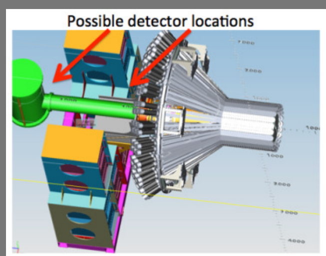
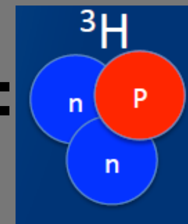
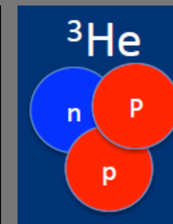




JLab Hall C:
E12-11-107

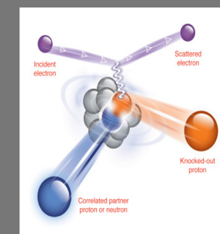
JLab Hall A:
E12-14-011

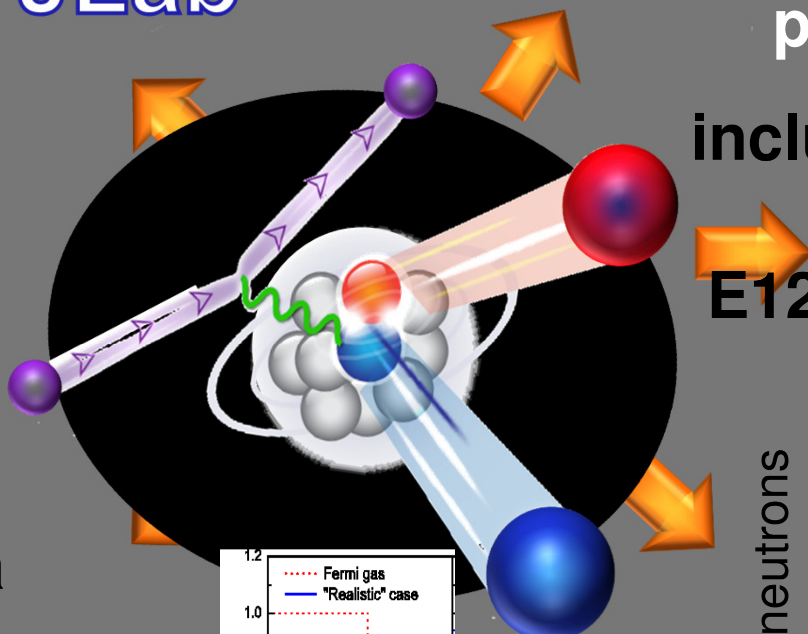




JLab

Proposal in preparation

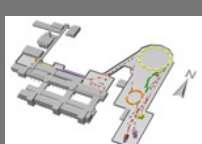




inclusive QE and DIS
JLab Hall C:
E12-11-112, E12-06-105
E12-08-014

JLab Hall B:
E12-11-003a

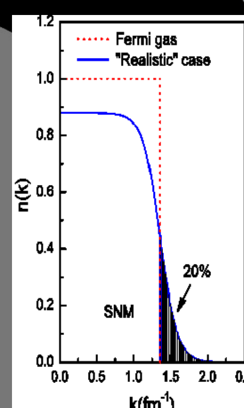
Proton facility



GSI / FAIR

Dubna

Nuclotron



Migdal jump

Add 8 f7/2 neutrons

^{32}Cl	^{33}Ar		Ca							
^{33}Cl	^{34}Ar	^{35}K		21					Z	
^{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	^{40}Ca	^{41}Sc	^{42}Ti		Cr	25	N	
^{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
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	29	^{48}K	^{49}Ca	^{50}Sc	^{51}Ti	^{52}V	^{53}Cr	^{54}Mn	^{55}Fe	^{56}Co

Add 8 protons