Next generation nuclear physics with JLab12 and EIC

10-13 February 2016 *Florida International University*
US/Eastern timezone

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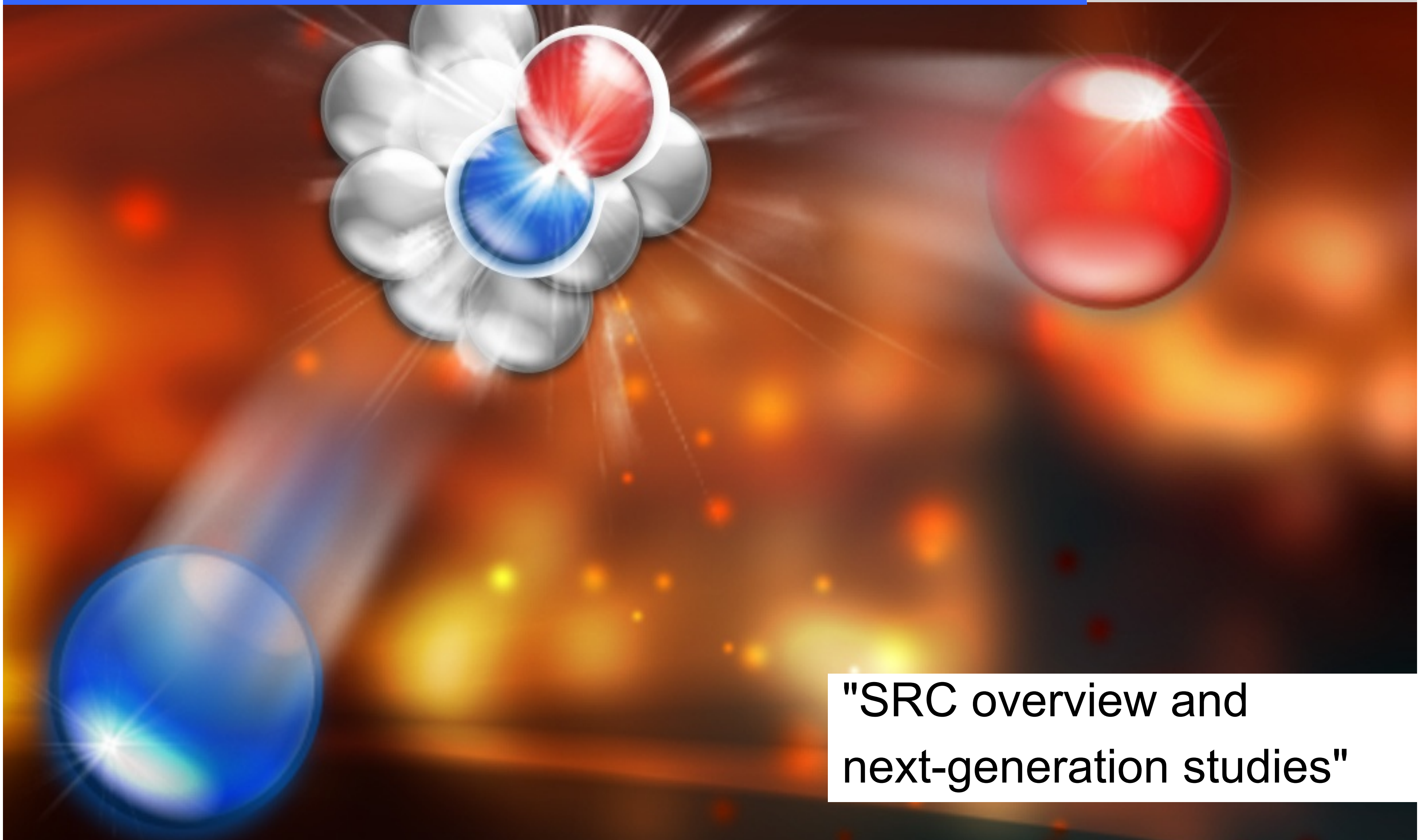


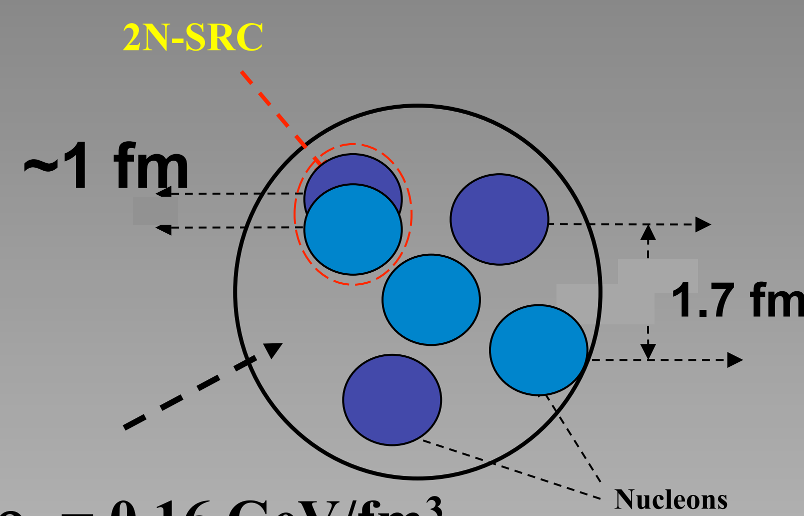
"SRC overview and next-generation studies"

Eli Piasetzky Tel Aviv University, Israel

11 February 2016

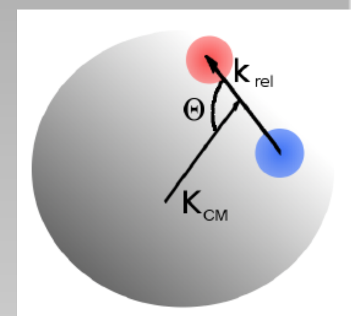
What are Short (intermediate) Range Correlations in nuclei ? (tensor)

SRC ~R_N LRC ~R_A



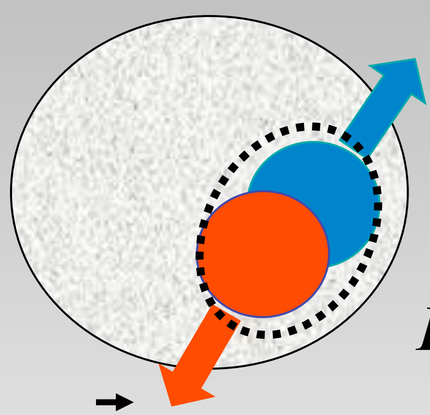
$\rho_o = 0.16\ GeV/fm^3$

In momentum space:



$K_{rel} > K_F$

$K_{CM} < K_F$



$\vec{K}_1$

$\vec{K}_2$

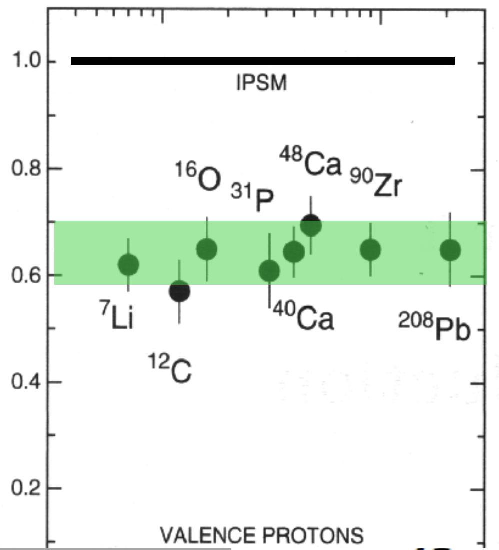
$\cong \vec{K}_1 \quad \vec{K}_2$

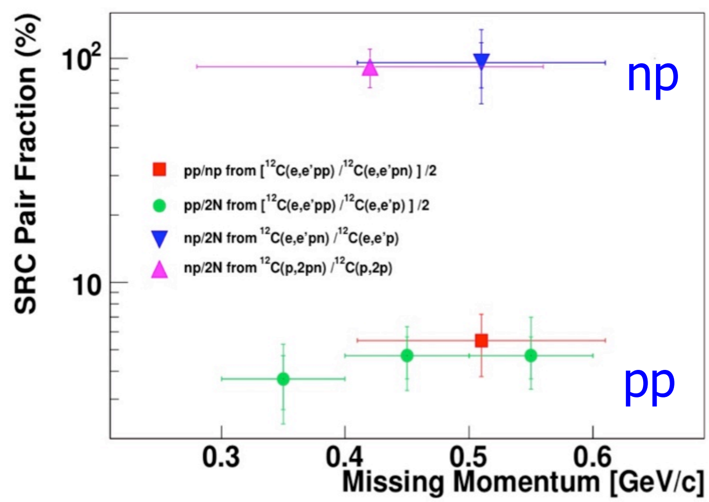
$K_1 > K_F$,

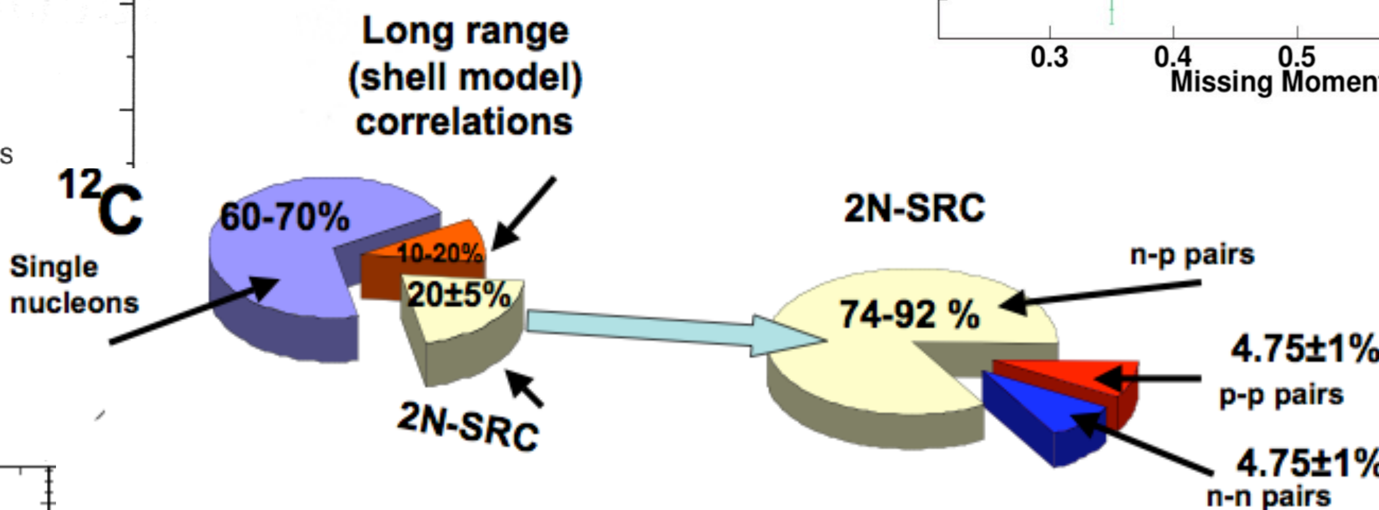
$K_2 > K_F$

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

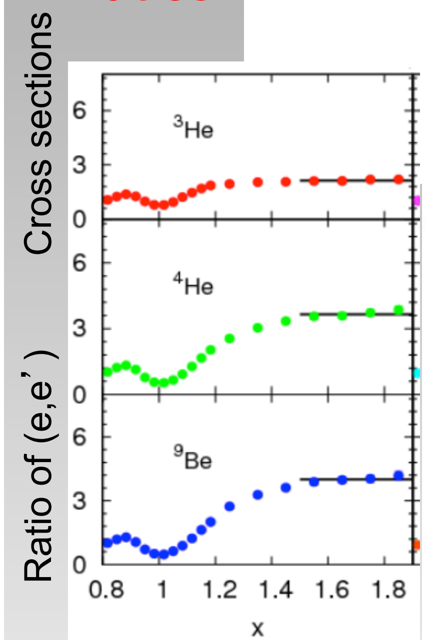
(e,e’ p)
Shell
occ

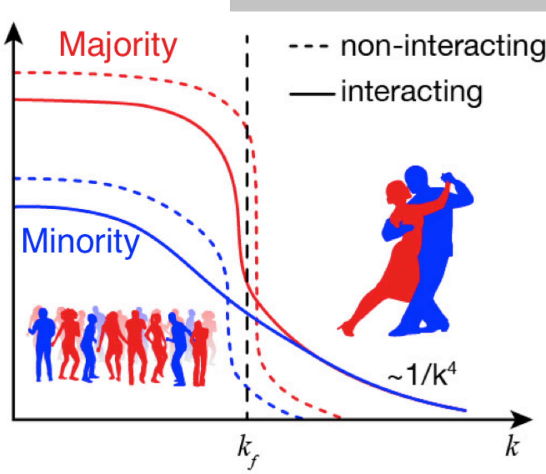


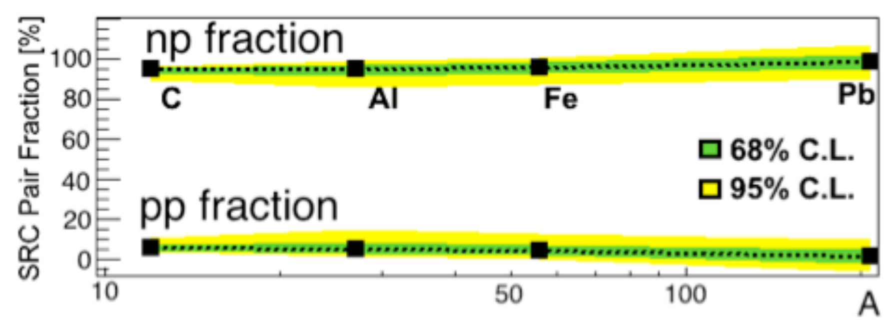




A(e,e’)
ratios

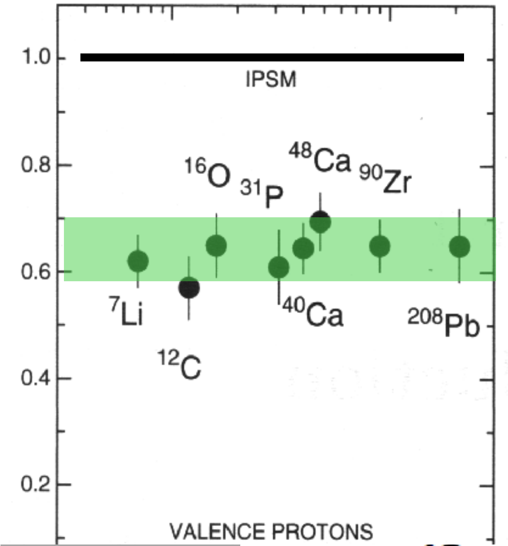


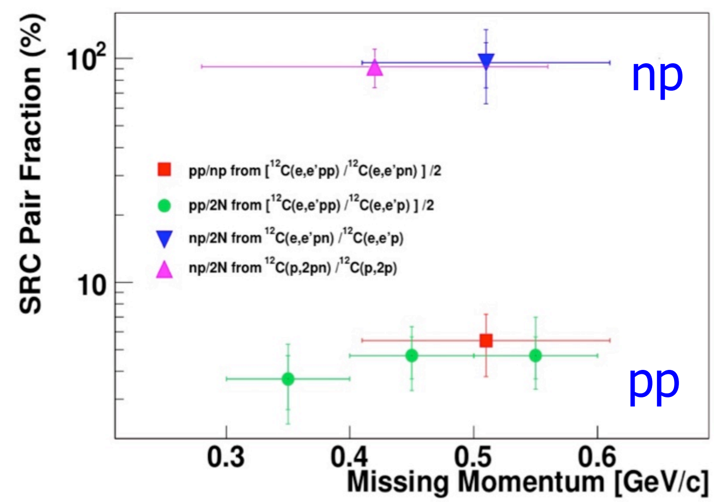


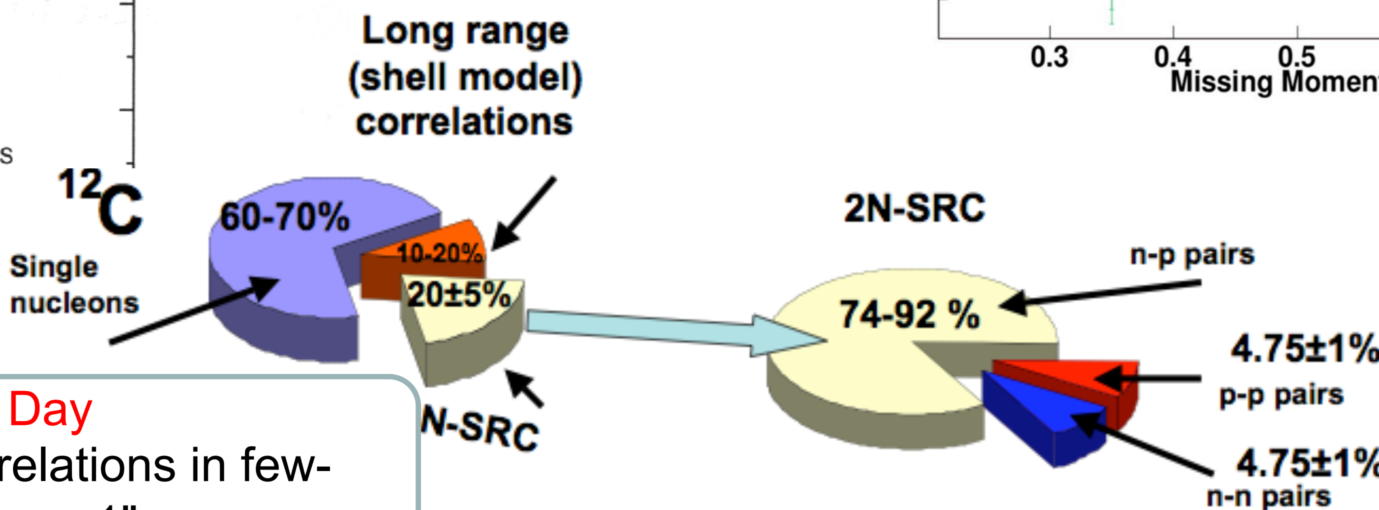


20-25% SRC pairs
- ~90% np pairs

(e,e' p)
Shell
occ

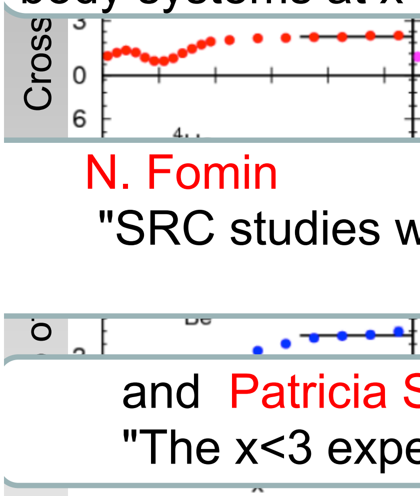






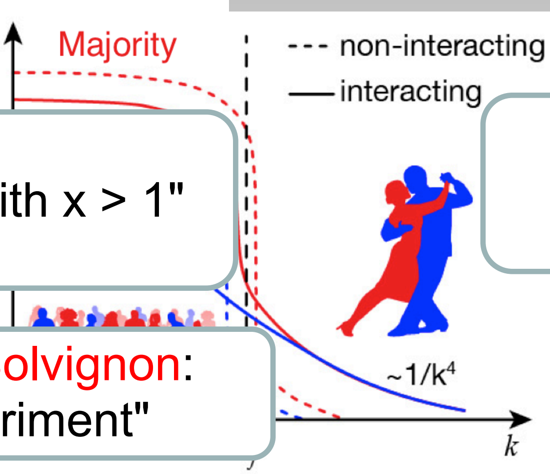
A(e,e')
ratios

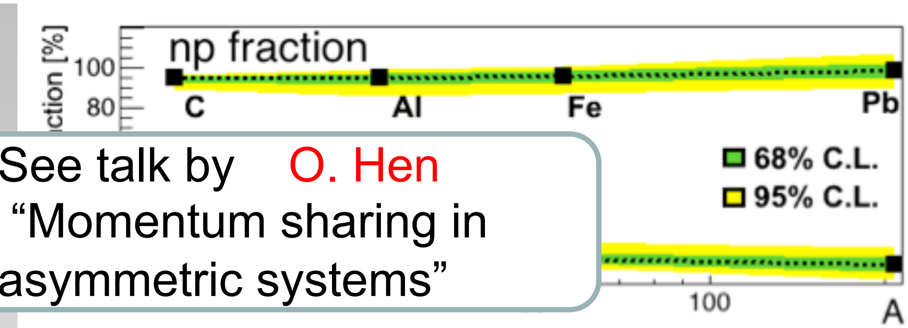
See talk by D. Day
"2N and 3N correlations in few-body systems at x > 1"



N. Fomin
"SRC studies with x > 1"

and Patricia Solvignon:
"The x<3 experiment"





See talk by O. Hen
"Momentum sharing in asymmetric systems"

20-25% SRC pairs
- ~90% np pairs

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.

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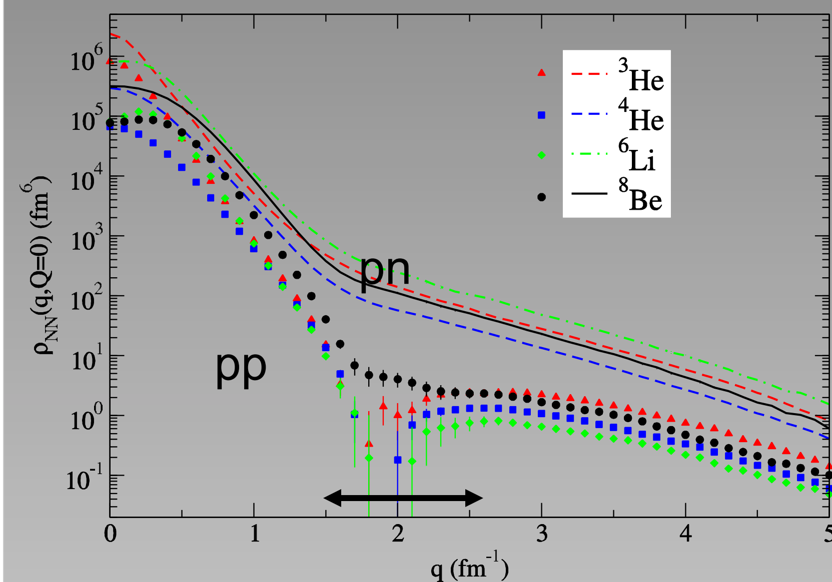
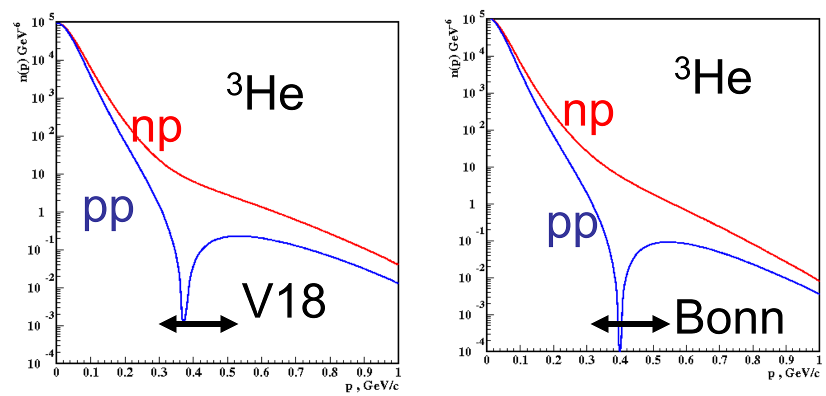
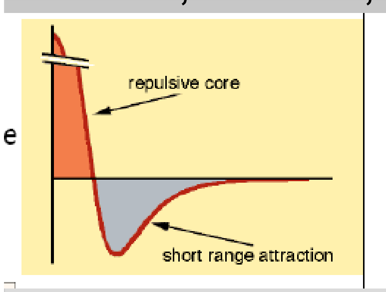


Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

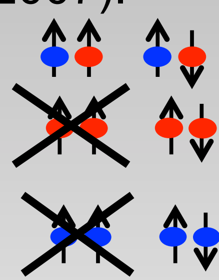


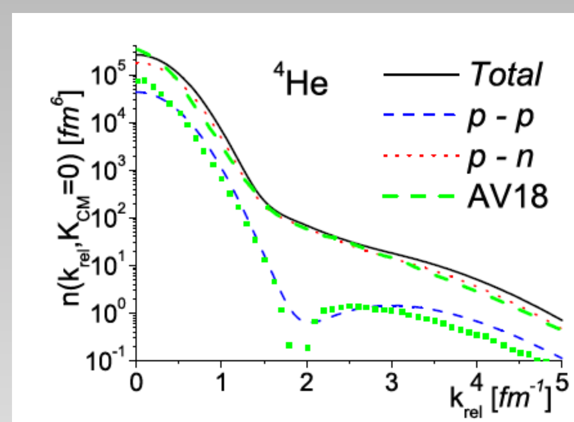
pp/np

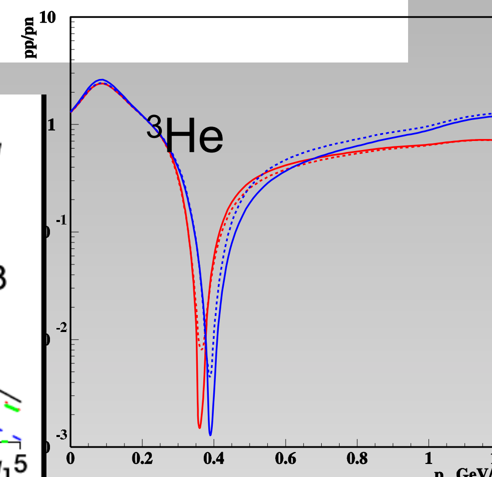


SRC

L = 0, 2



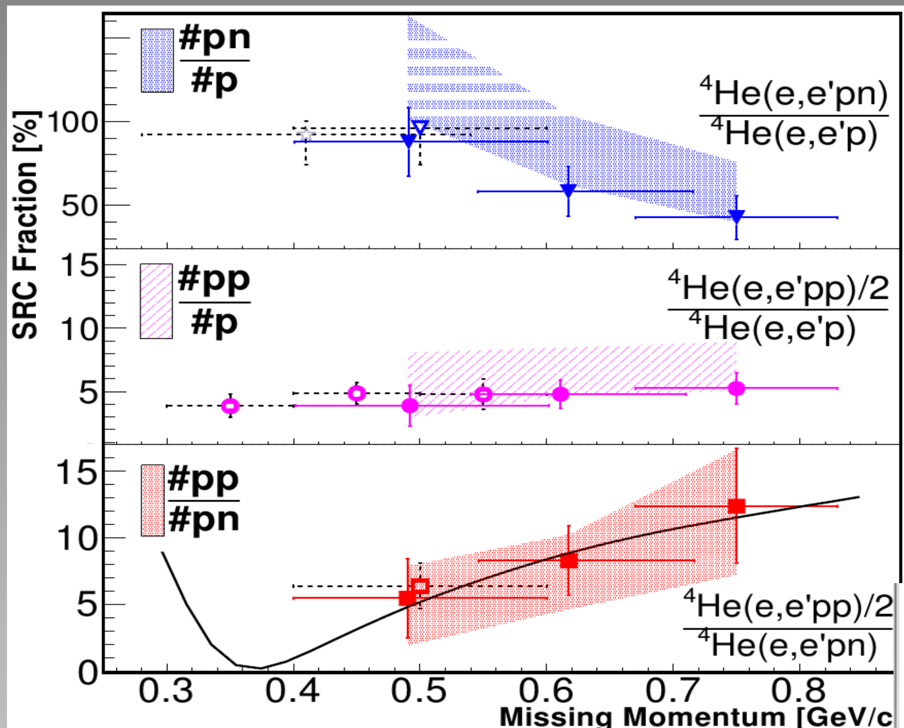




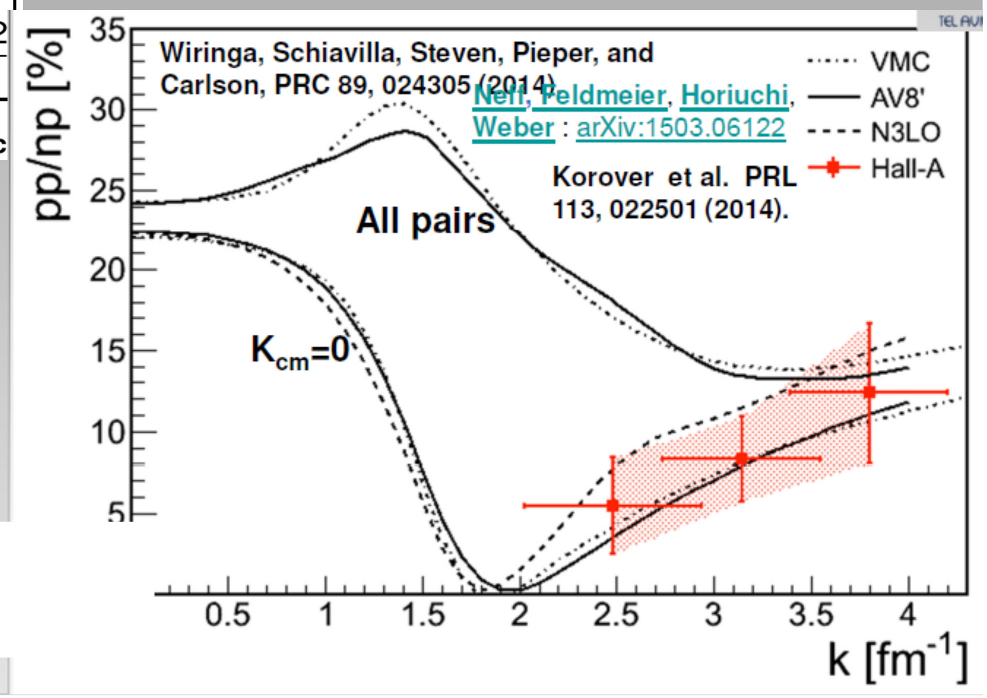
Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikmar Frankfurt PR C71 044615 (2005

E07-006 (2011) ^{4}He

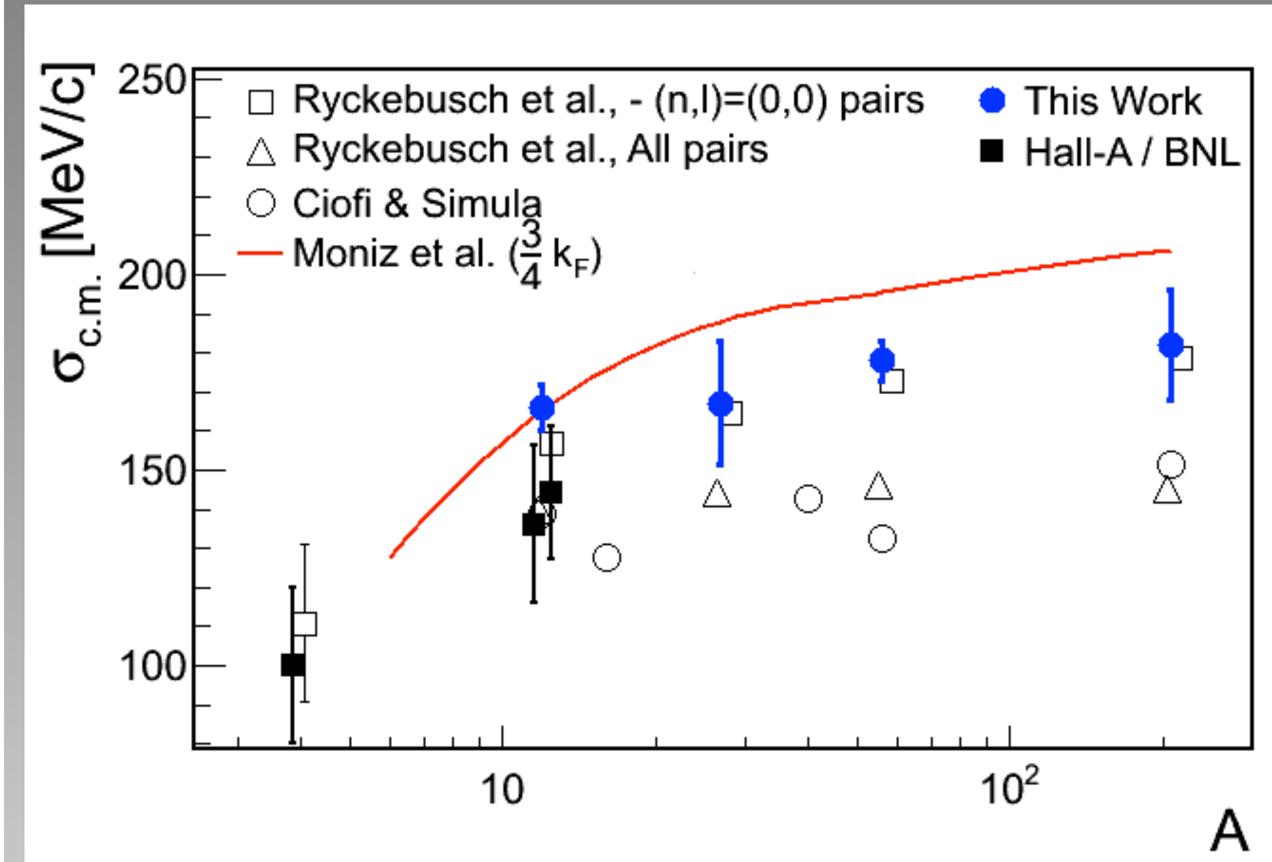


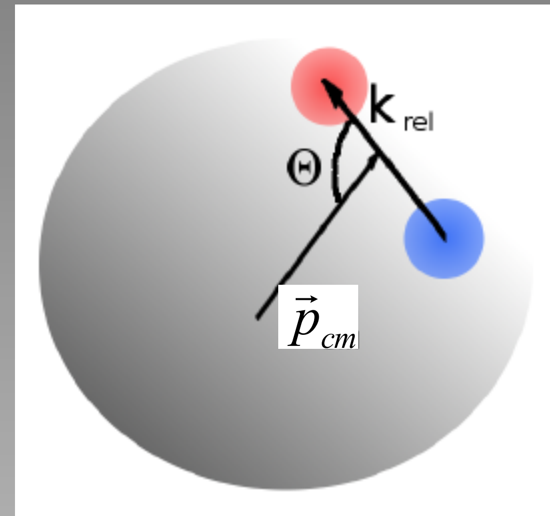
I. Korover et al.
PRL 113, 022501 (2014).



See talk by Thomas Neff
"Nuclear structure calculations with SRCs"

C.M. motion of the pair





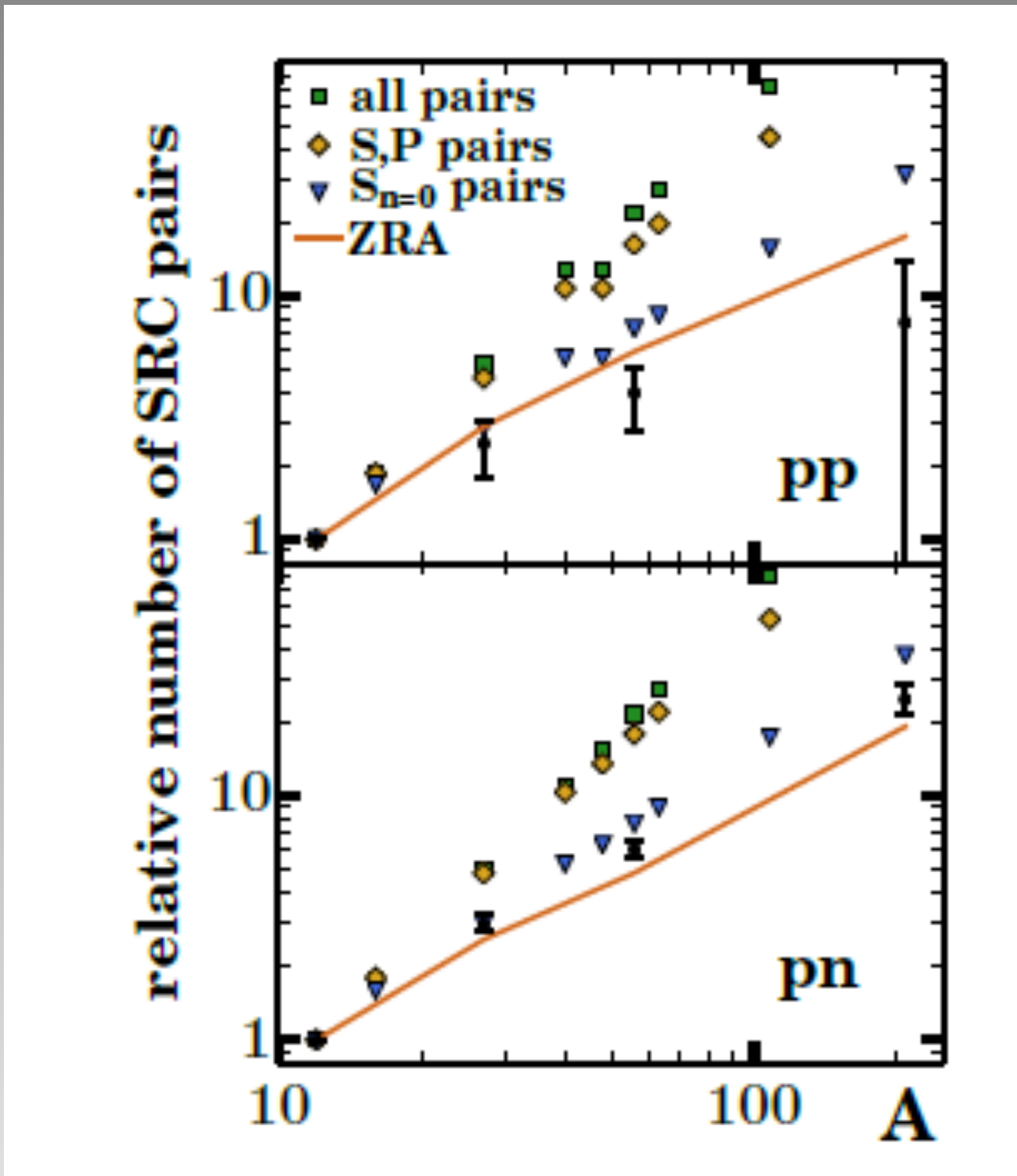
$$\vec{p}_{cm} = \vec{p}_{miss} + \vec{p}_{recoil}$$

$$P_{CM} < P_F$$

PRELIMINARY

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

The mass dependence of the SRC pairs



N=0 (nodeless) L=o IPM pairs

Predominantly:

L=0,2 T=0 S=1

(deuteron like) **pairs**

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

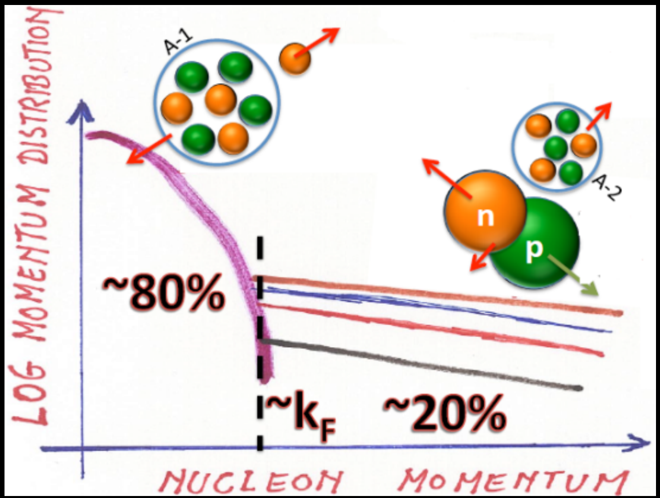
C. Colle,[1] O. Hen,[2] W. Cosyn,[3] I. Korover,[3] E. Piasetzky,[3] J. Ryckebusch,[3] and L.B. Weinstein[3]

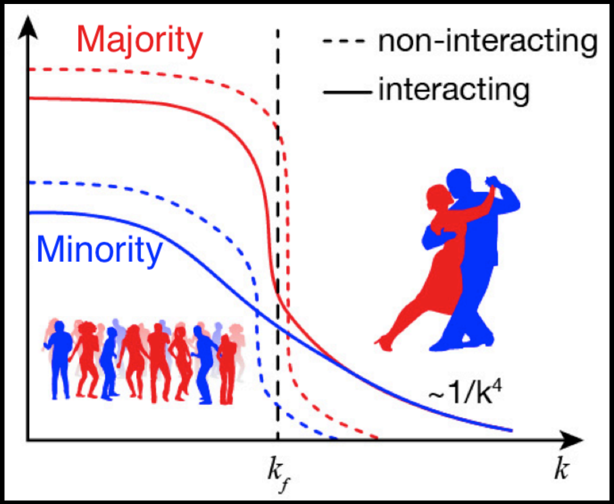
Phys. Rev. C 92, 024604 (2015)

Universal High momentum tail In all nuclei:

Identified triple coincidence SRC pairs in: (^{3}He,) ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb

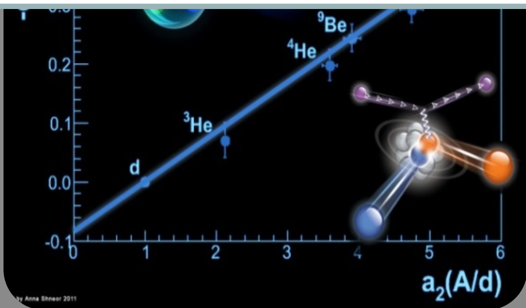
High momentum tail is dominated by np- SRC pairs

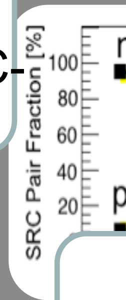




Summary – SRC outreach

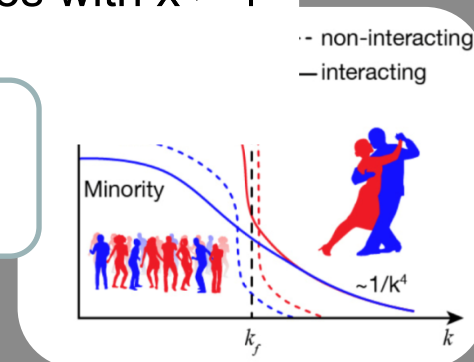
See talk by D. Higinbotham
“Tagged EMC effect and EMC-SRC connection”





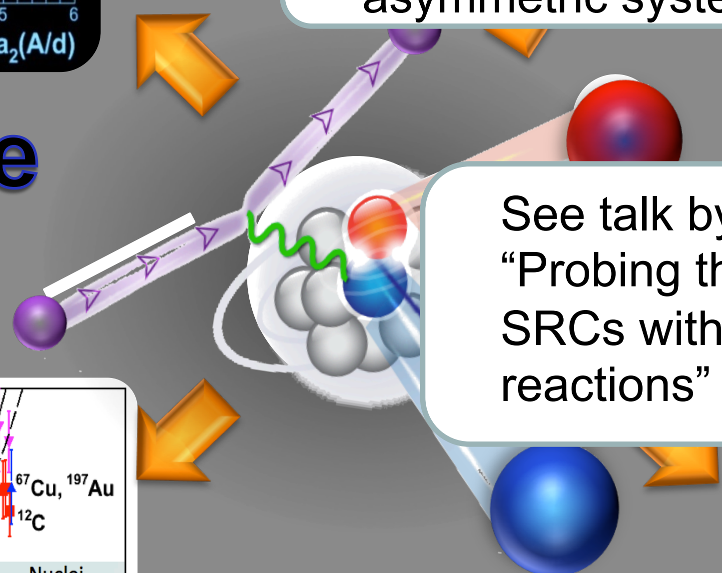
See also talks by Donal Day, “2N and 3N correlations at x > 1“ and Nadia Fomin: "SRC studies with x > 1"

Nuclear

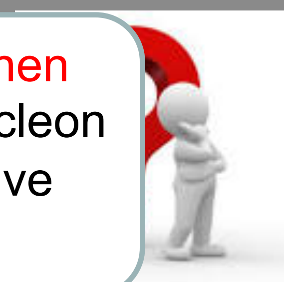


See talk by O. Hen
“Momentum sharing in asymmetric systems”

Particle

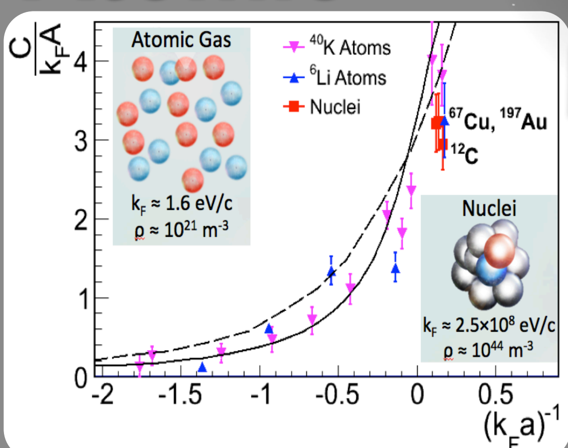


See talk by E. Cohen
“Probing three-nucleon SRCs with exclusive reactions”



3N-SRC

Atomic

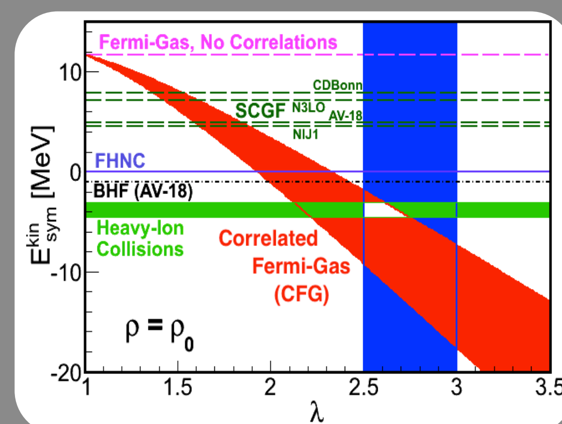


Contact term

Astro

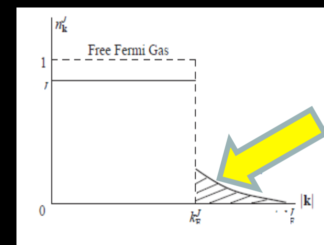
Symmetry energy

Neutron stars



Tensor correlations (np - dominace):

Breaks the Fermi Gas picture



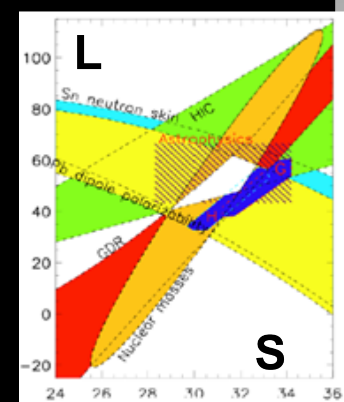
?

in SNM (np- pairs) in PNM (nn- pairs)

in n-stars (?)

Reduce the kinetic symmetry Energy (at ρ_0)

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$



Enhance the potential symmetry Energy (at ρ_0)

Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems and HI Reactions ?

For Diluted (d) systems of two different type of fermions with short-range (r_{eff}) strong interaction (a) between different fermions

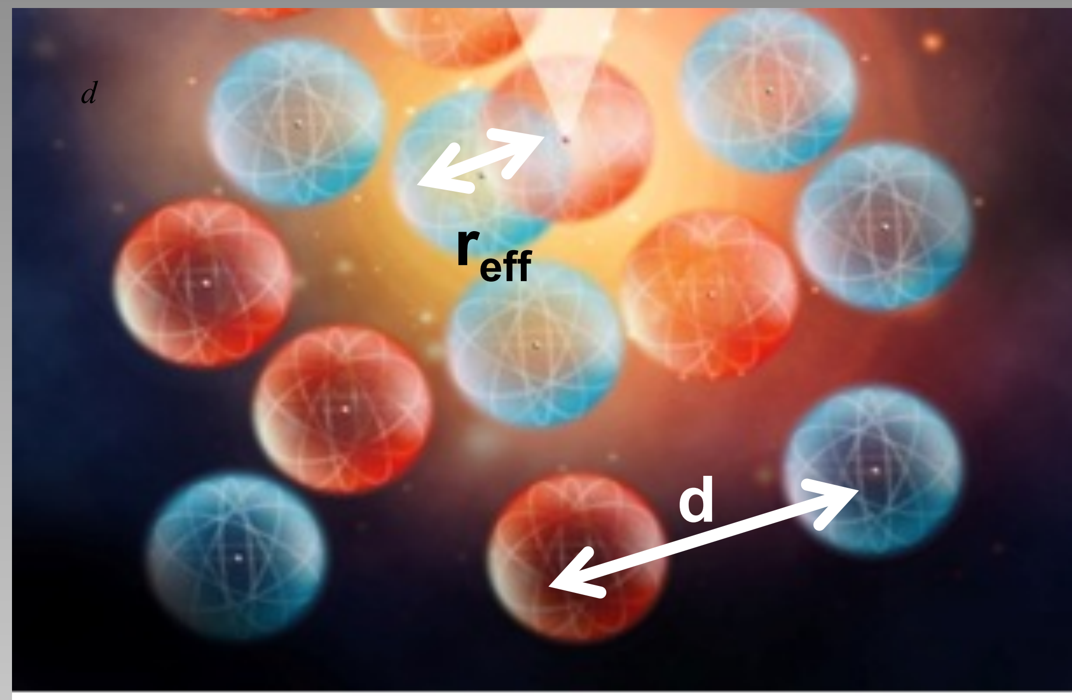
$$a >> d >> r_{eff}$$

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

high- momentum tail:

$$n(k) = C / k^4$$

C is the contact term



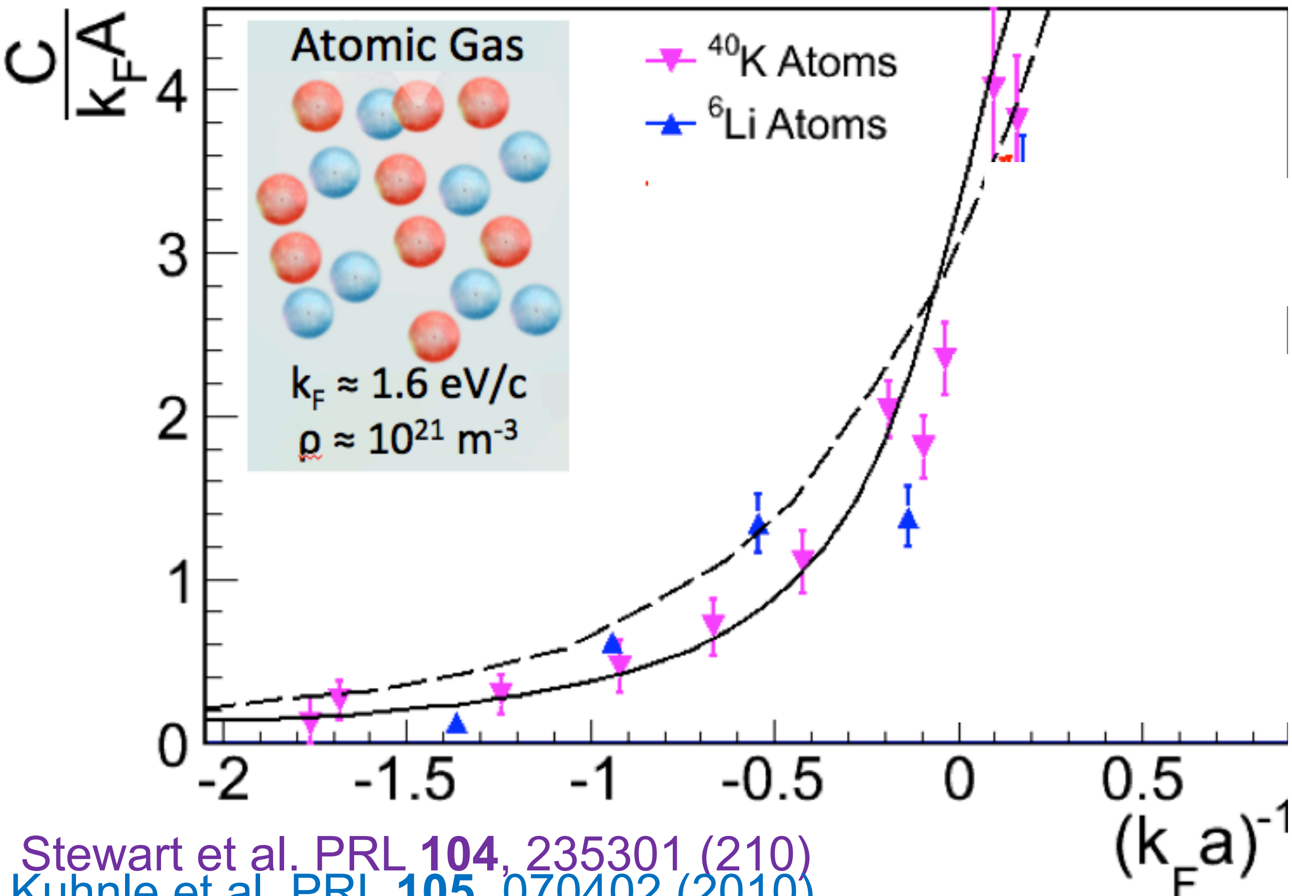
The contact measure the number of close different –fermions pairs

Thermodynamics can be describe by a single parameter: ‘contact’

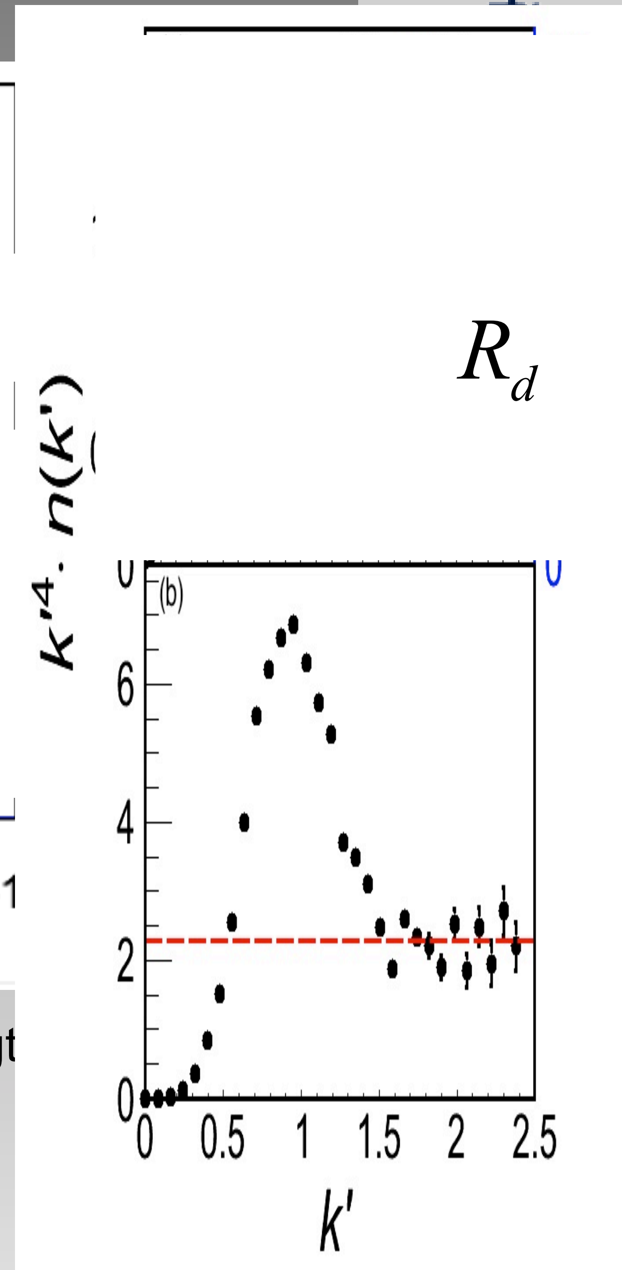
Experiments with two spin-state mixtures of ulta-cold ^{40}K and ^{6}Li atomic gas systems extracted the contact term and verified the universal relations

Correlated Fermion Pairs in Nuclei and Ultracold Atomic Gases

O. Hen,[1,*] L.B. Weinstein,[2] E. Piasetzky,[1] G.A. Miller,[3] M.M. Sargsian,[4] and Y. Sagi[5]



Stewart et al. PRL **104**, 235301 (210)
Kuhnle et al. PRL **105**, 070402 (2010)



Dimensionless interaction strengt

For nuclei
k_F~1.3 fm
A~5.4 fm
$k_F a^{-1}$~0.15

$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

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2016 -2020

High energy Electron beam and fixed target

JLab halls A, B, and C

High energy proton beam and fixed target

Dubna/Nuclotron GSI / HADES
JPARC ?

2020 -

EIC

See talk by O. Hen
"SRC studies with EIC"

Inclusive EMC/SRC Measurements

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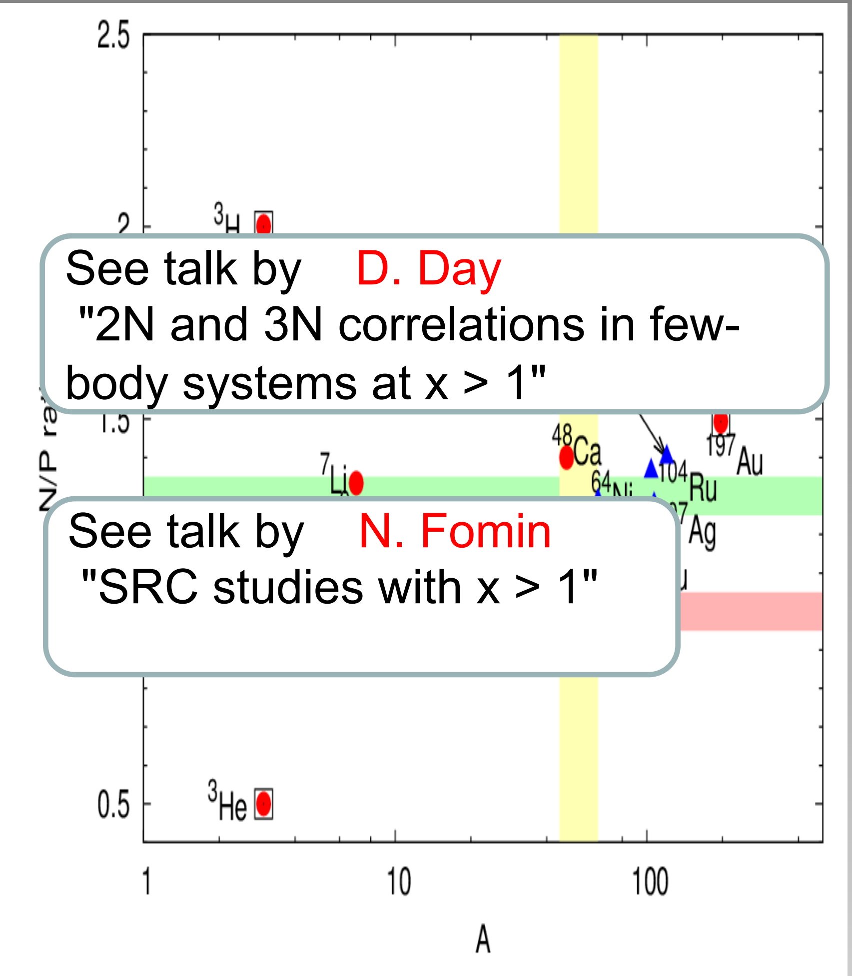
- High precession measurement of both a_2 and EMC slopes in a MANY nuclei.
- Very wide kinematical coverage in x_B and Q^2
- Try to understand underline physics by comparing nuclei with:
  - equal-mass / different asymmetry
  - equal-asymmetry / different mass

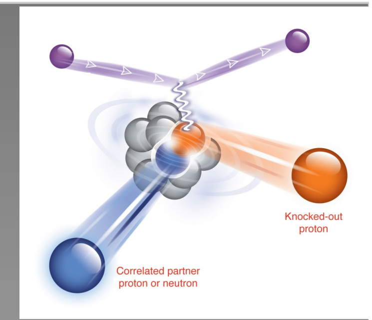


See talk by D. Day
"2N and 3N correlations in few-body systems at x > 1"

See talk by N. Fomin
"SRC studies with x > 1"

+ ^{3}He and ^{3}H already in 2017 (?)

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

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

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

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

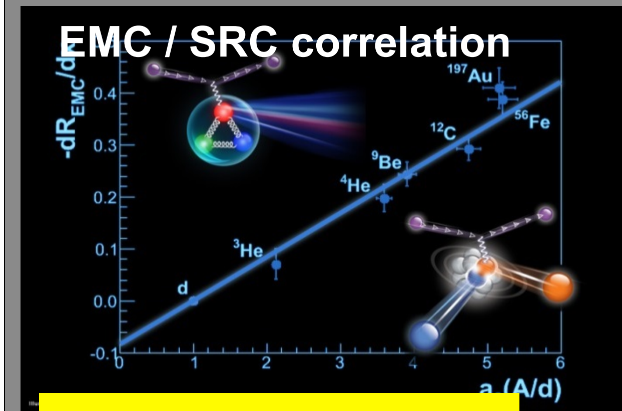
$\mathrm{C, Al, Fe, Pb}\,(e,e'pp)$

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

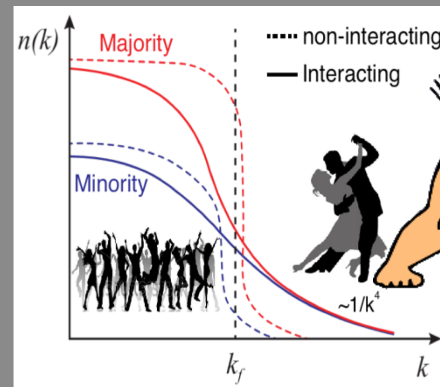
12 GeV JLab: $\frac{\sigma_{MOTT}(12GeV)}{\sigma_{MOTT}(4GeV)} \approx 8$ **Detector acceptance: 5**
(e,e’ p)

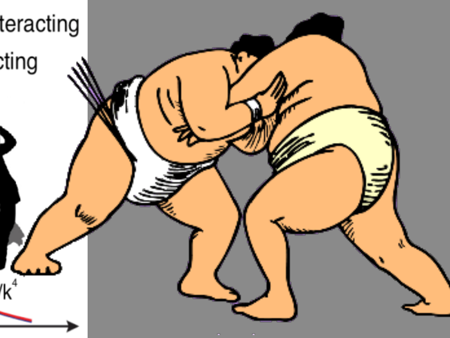
Dubna / GSI : **5-10 GeV/c**
10^9 protons/sec **➔ >10k events Before 2020**

Questions to be addressed (2016-2020)

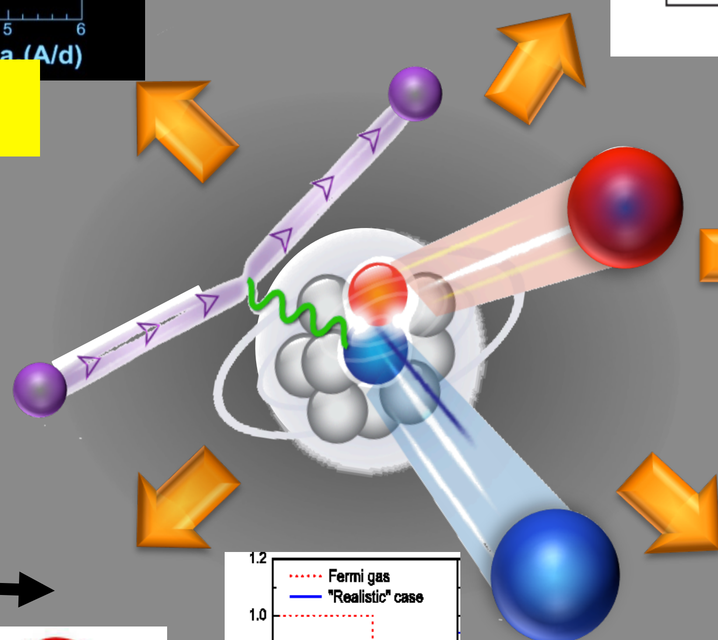


large virtuality?

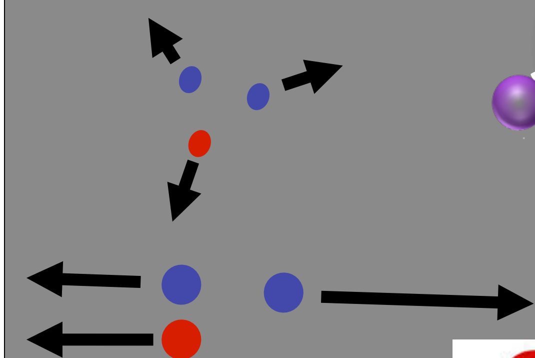




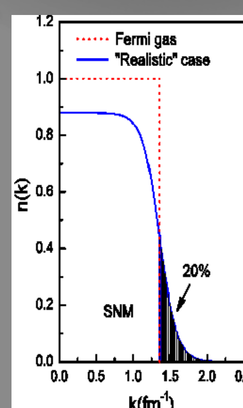
Who wins?



$$\langle k_{minority} \rangle \gtrless ? \langle k_{majority} \rangle$$



more than two nucleons SRC ?



Migdal jump

Add 8 f7/2 neutrons

^{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	^{40}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	^{48}Ca	^{49}Sc	^{50}Ti	^{51}V	^{52}Cr	^{53}Mn	^{54}Fe	^{55}Co
	29	^{48}K	^{49}Ca	^{50}Sc	^{51}Ti	^{52}V	^{53}Cr	^{54}Mn	^{55}Fe	^{56}Co

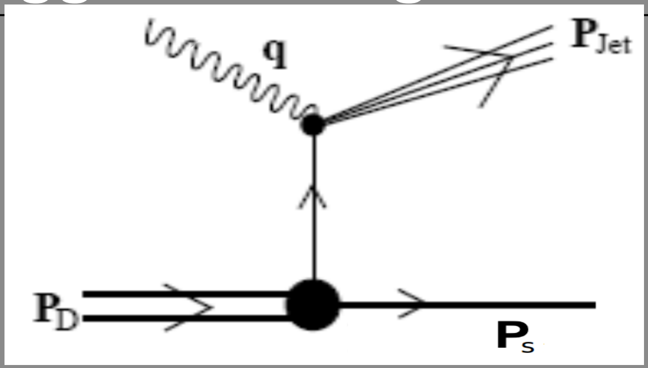
Z

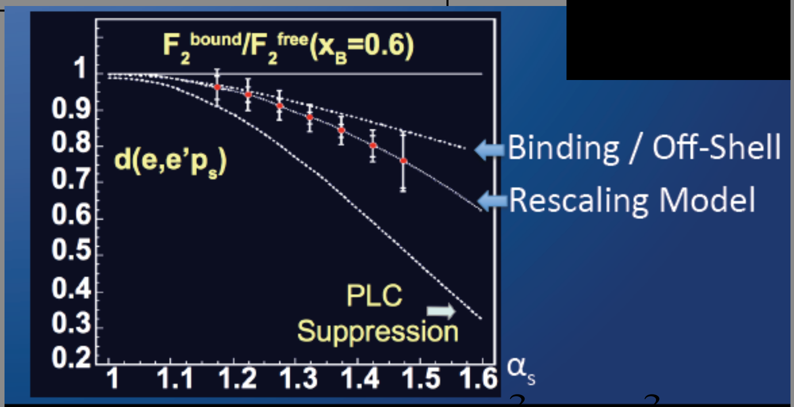
N

Add 8 protons

Is the EMC effect associated with large virtuality ?

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

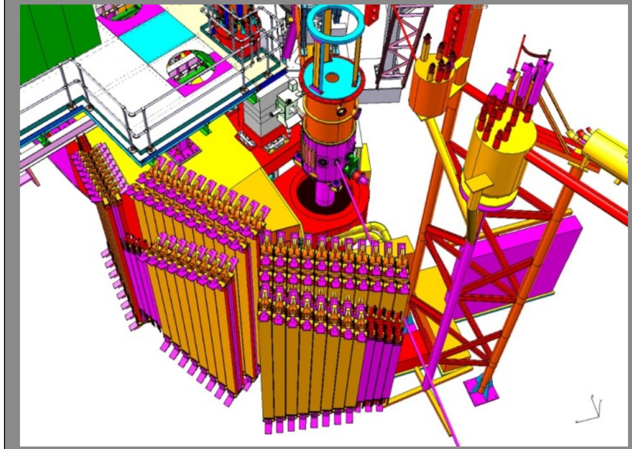




$$v = p^2 - m^2$$

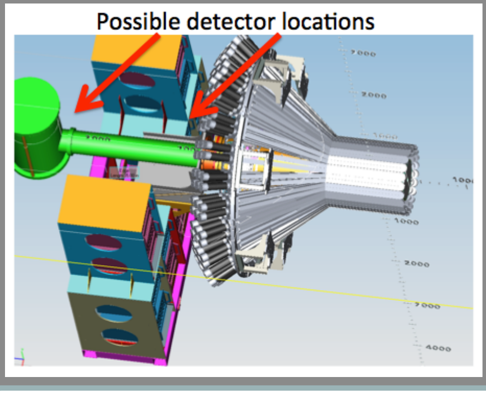
12 GeV JLab/ Hall C approved experiment E 12-11-107

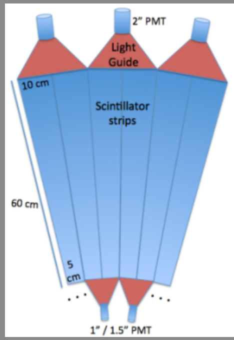
Tagged recoil proton measure neutron structure function



12 GeV JLab/ Hall B approved experiment

Tagged recoil neutron measure in the proton structure function





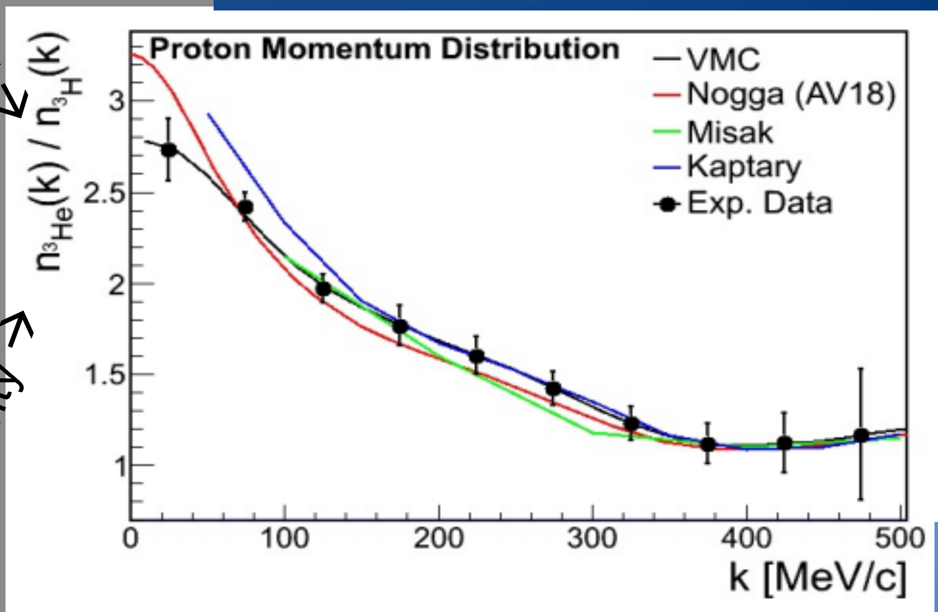
See talk by D. Higinbotham
"Tagged EMC effect and EMC-SRC connection"

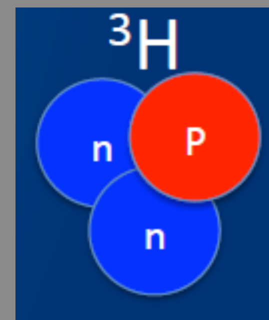
Momentum sharing in the A=3 nuclei

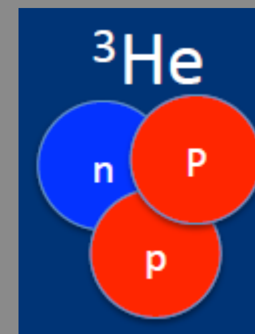
^{3}He and ^{3}H are mirror nuclei: $[p/n]_{3He} = [n/p]_{3H}$

Minority →

Majority →



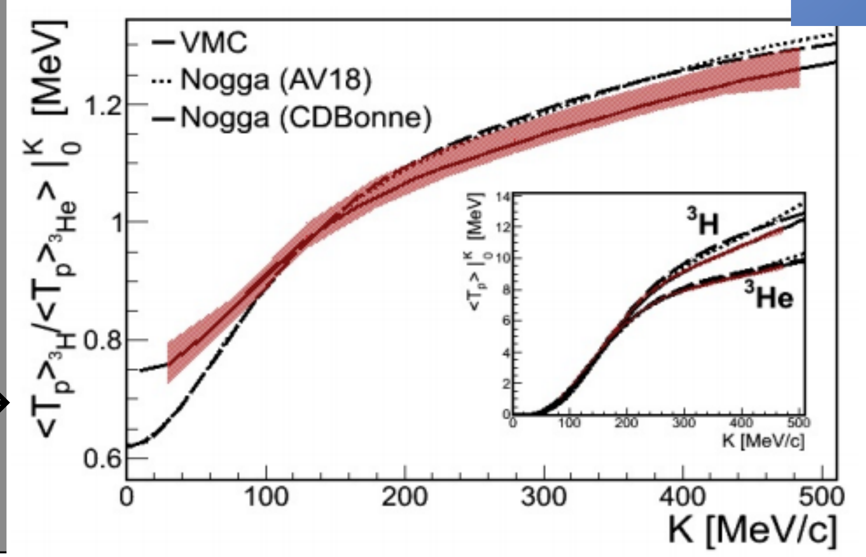




Mapping the Transition from Majority to Minority Dominance

Majority →

Minority →

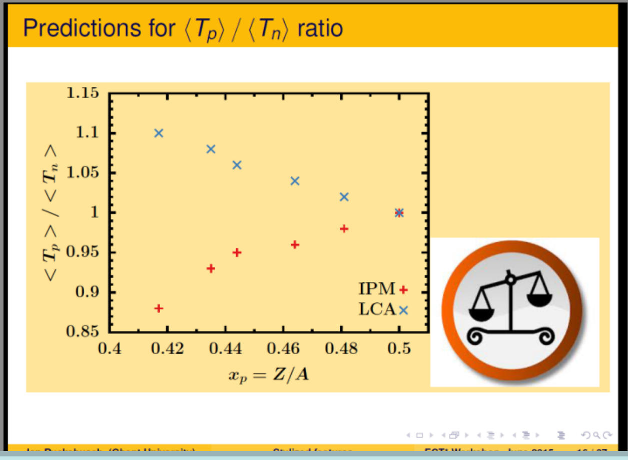


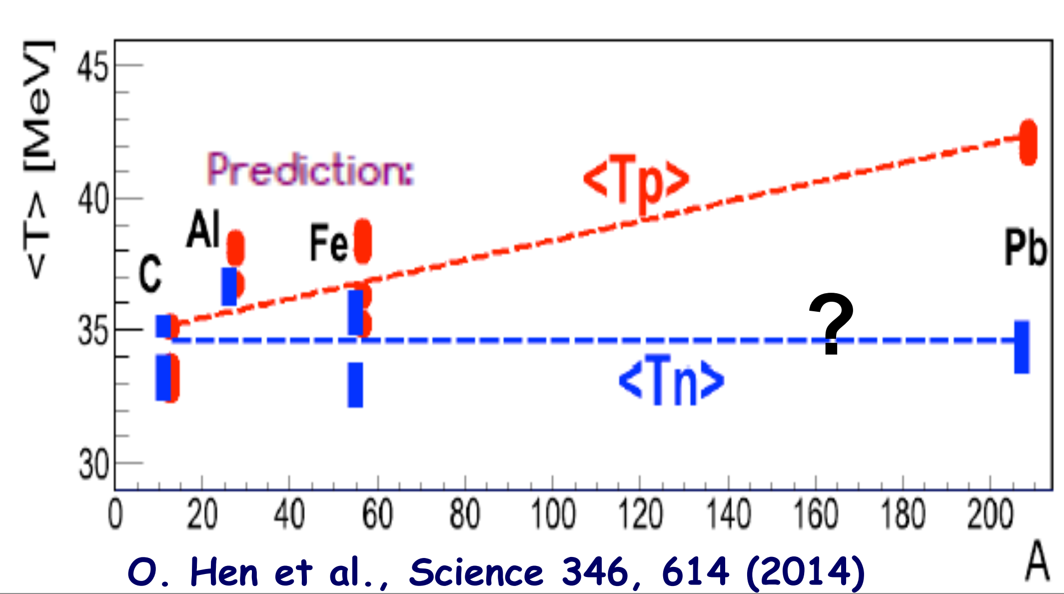
JLab E12-14-011 (e,e'p)
E12-11-112 (e,e')
(Approved experiments)
2016/2017

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

a data mining analysis

Meytal Duer (Tel – Aviv University)





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

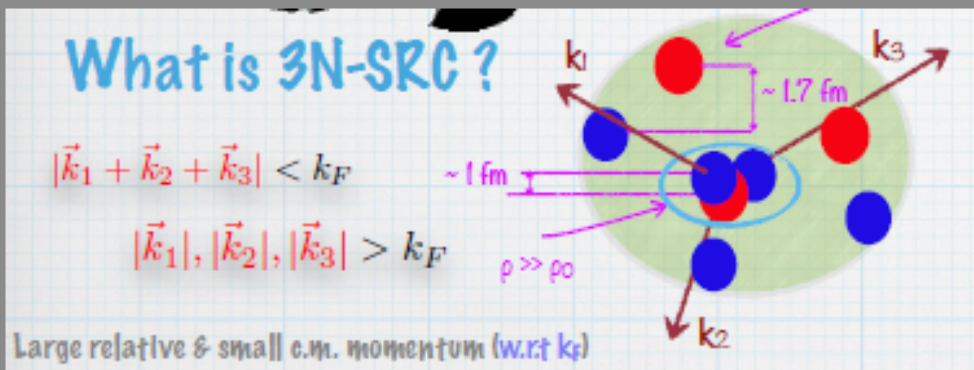
0- 250 MeV/c

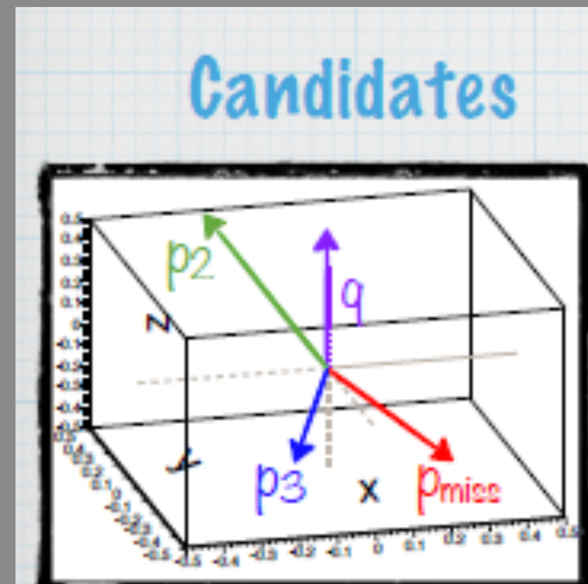
See talk by O. Hen
"Momentum sharing in asymmetric systems"

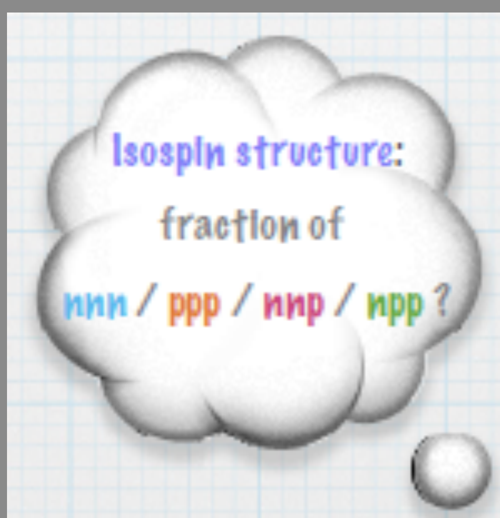
Search for 3N correlation using JLAB – CLAS EG2 data

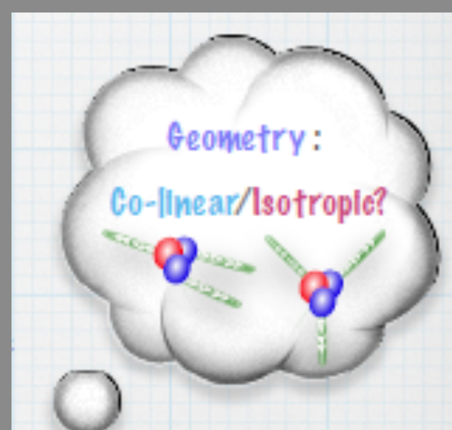
a data mining analysis

Erez Cohen (Tel – Aviv University)



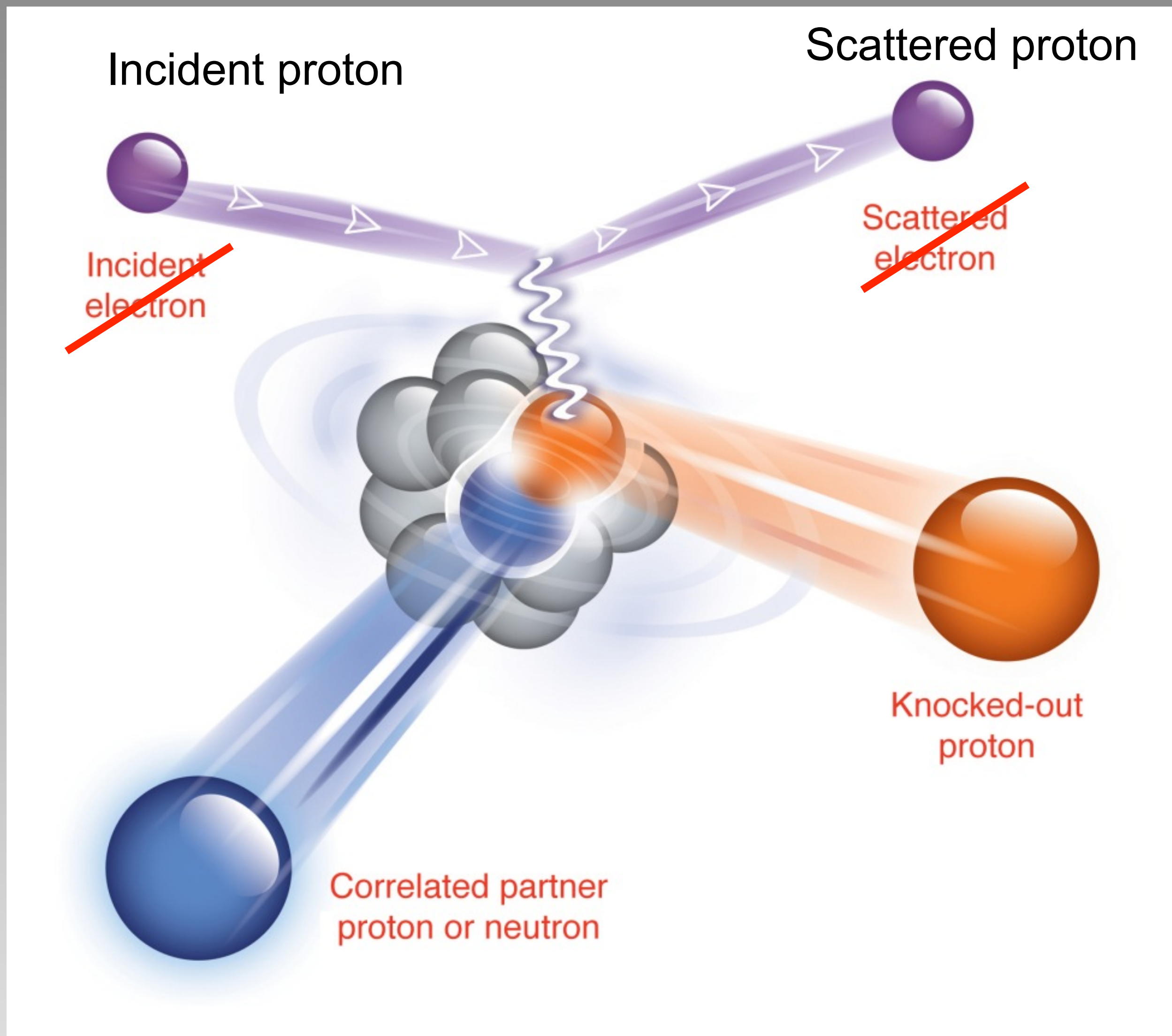






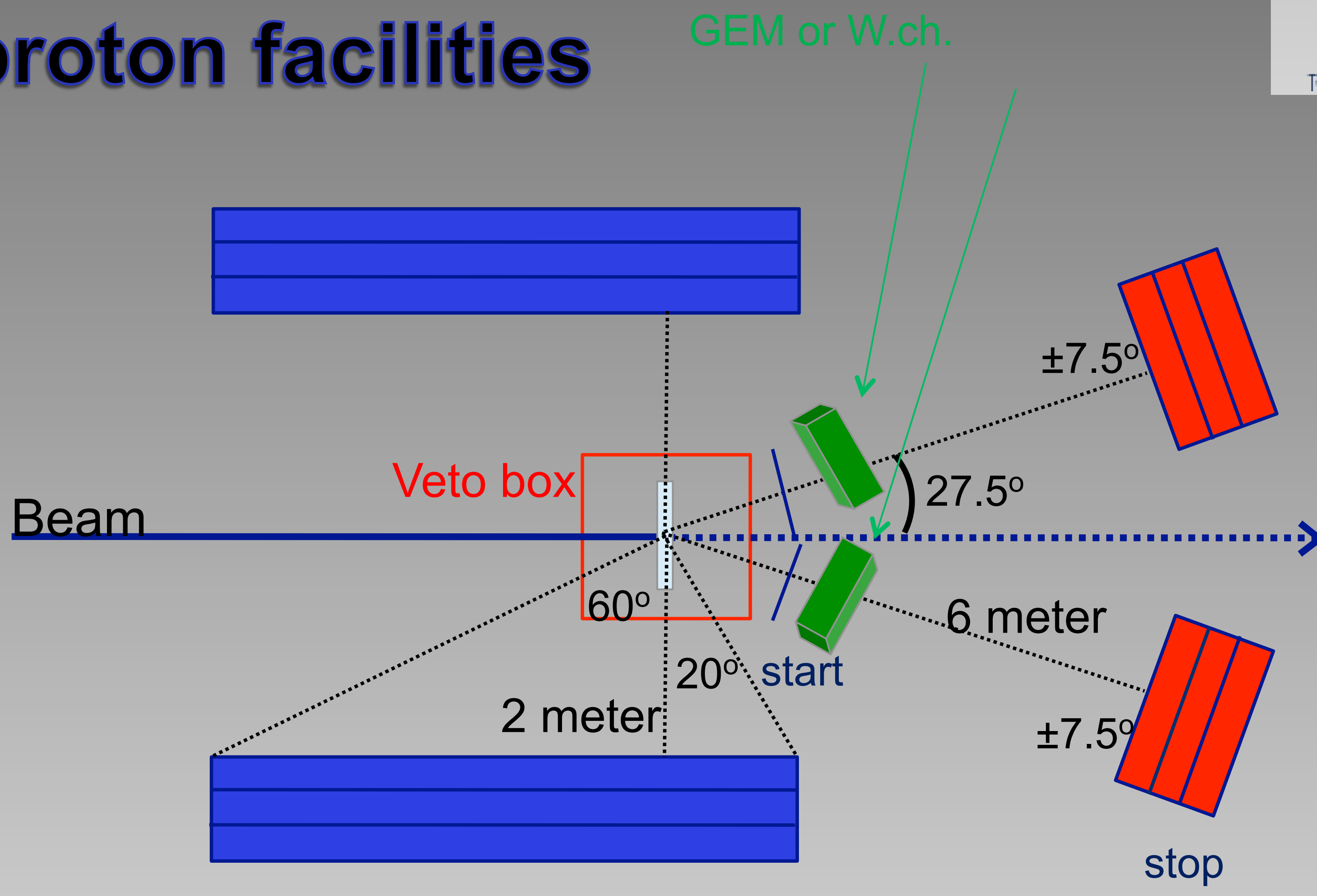
See talk by E. Cohen
“Probing three-nucleon SRCs with exclusive reactions”

Triple coincidence A (p, p p N) measurements



Complementary to JLab study with electrons

At proton facilities



Recoil detector

Array of scintillators

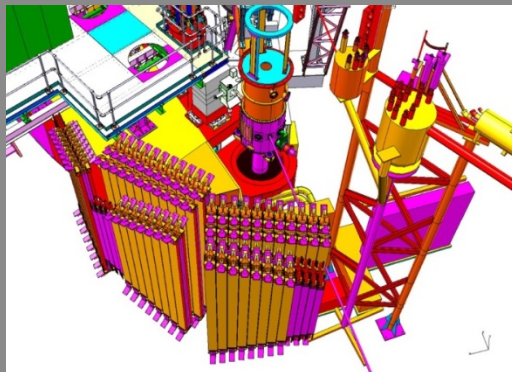
LAND, NeuLAND ?

σ_{TOF}<100ps

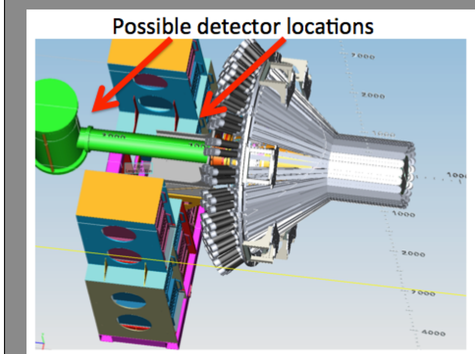
Forward detector

HADES ?

Summary – proposed experiments

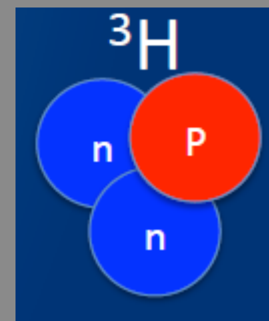


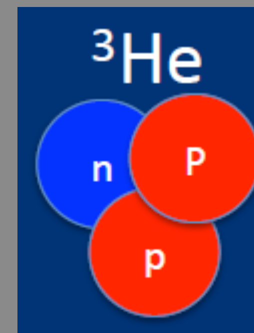
JLab Hall C:
E12-11-107

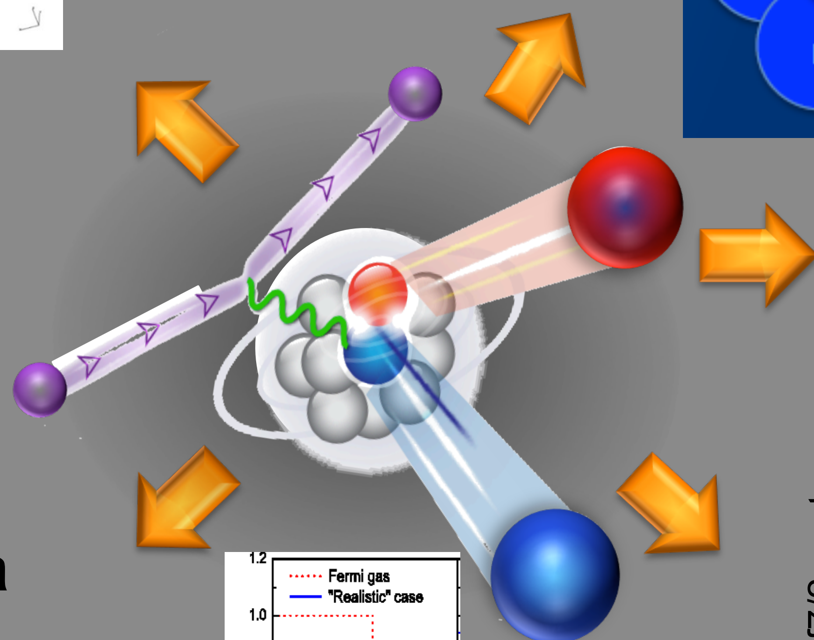


JLab Hall B:
E12-11-003a

JLab

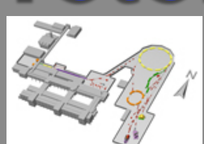






JLab Hall A:
E12-14-011(e,e'p)
E12-11-112 (e,e')

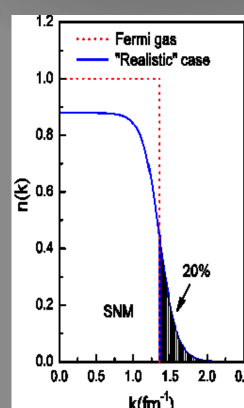
Proton facility



GSI / FAIR

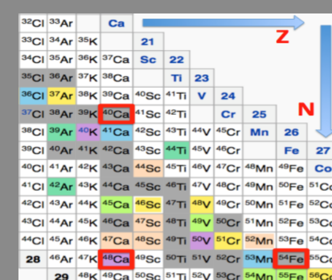
Dubna

Nuclotron



Migdal jump

Add 8 f7/2 neutrons



Add 8 protons

JLab Hall C:
E12-06-105 (e,e')

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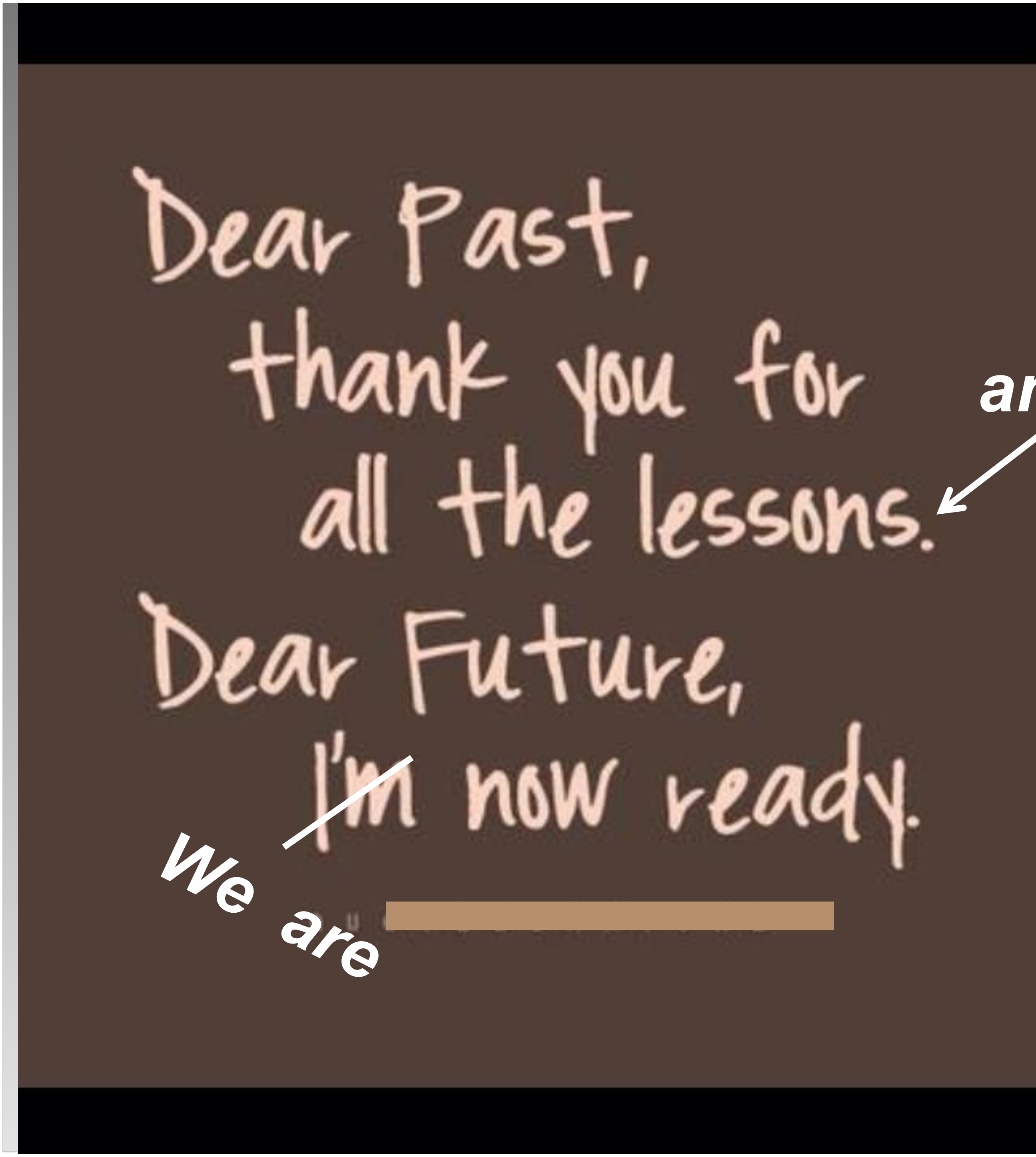


Acknowledgment

I would like to thank the organizers for the invitation.

Will Brooks
Raphael Dupre
Charles Hyde
Misak Sargsian

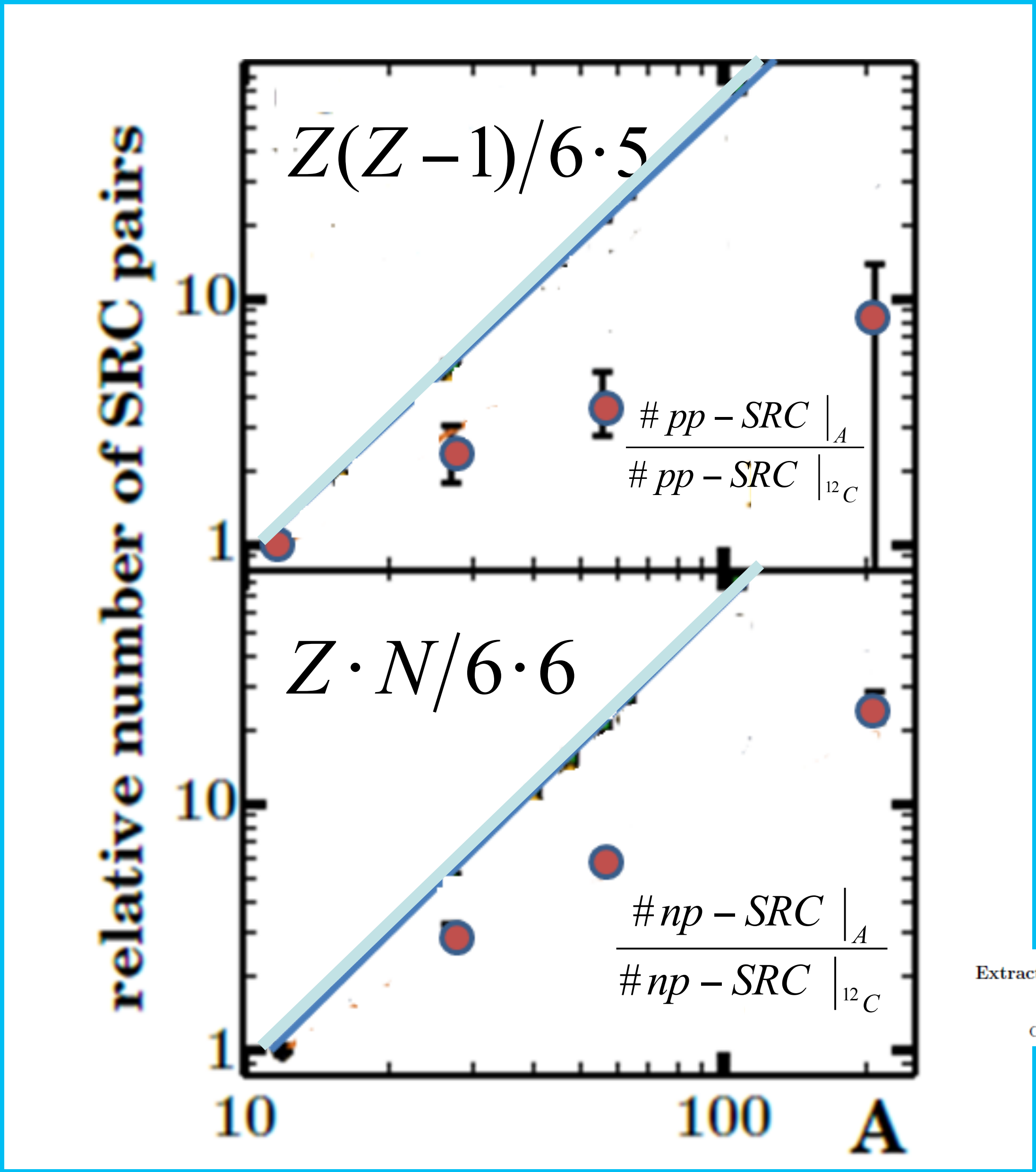
Misak and everyone for the

Collaborators:

Or Hen, Larry Weinstein, Shalev Gilad, Doug Higinbothan, Steve Wood, John Watson

Misak Sargsian, Mark Strikman, Leonid Frankfurt, Gerald Miller

The mass dependence of the SRC pairs

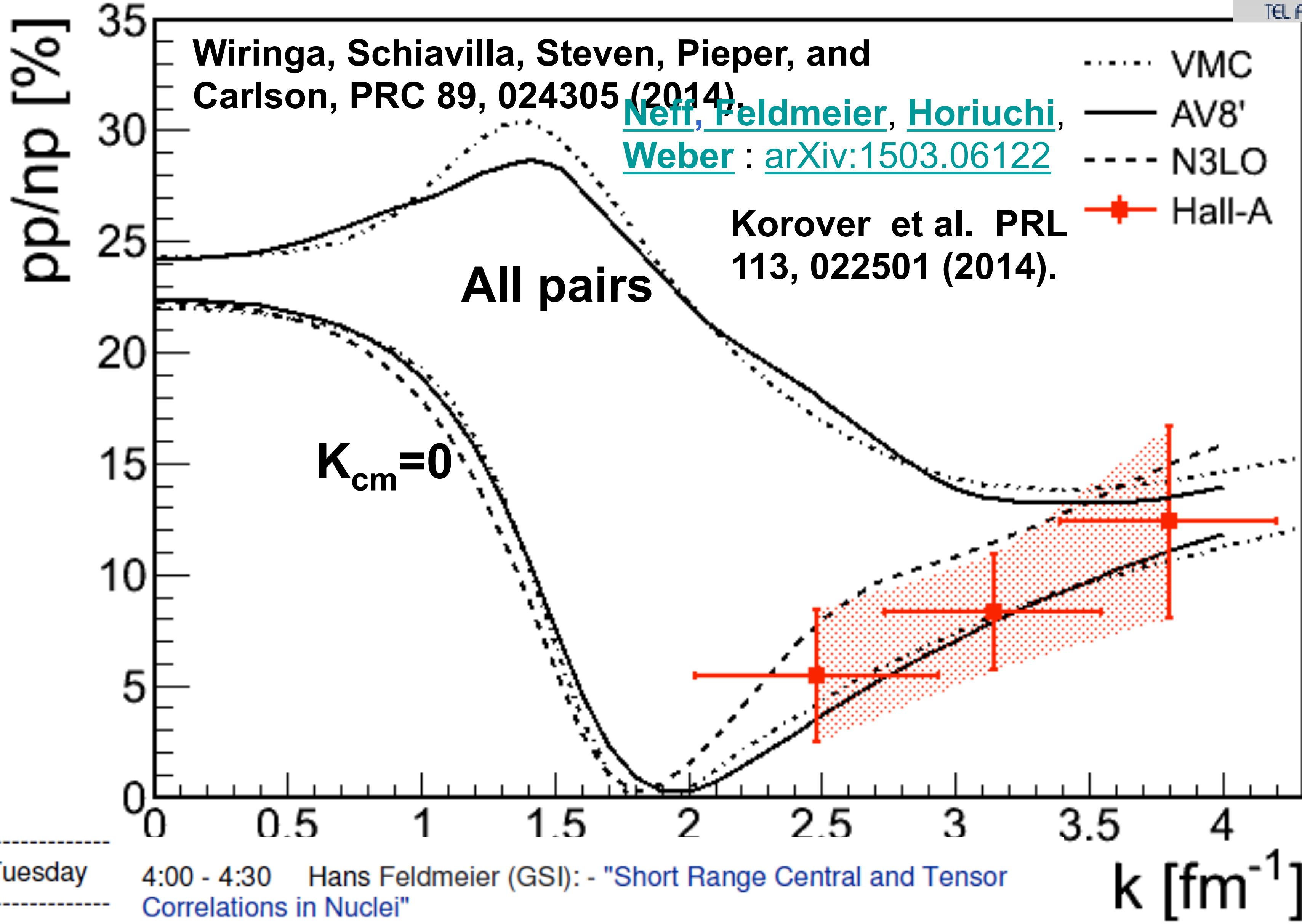


a data mining analysis

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

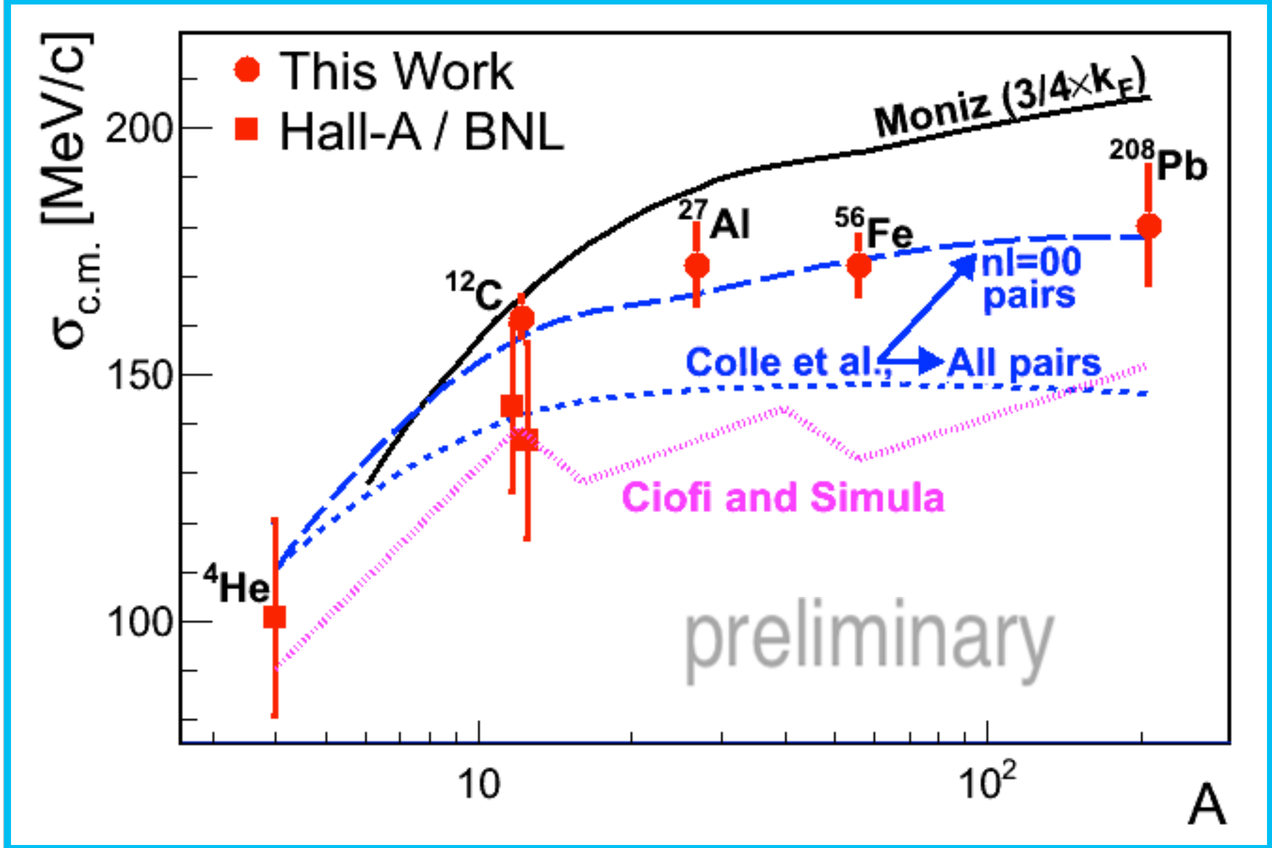
4:00 - 4:30 Hans Feldmeier (GSI): - "Short Range Central and Tensor Correlations in Nuclei"

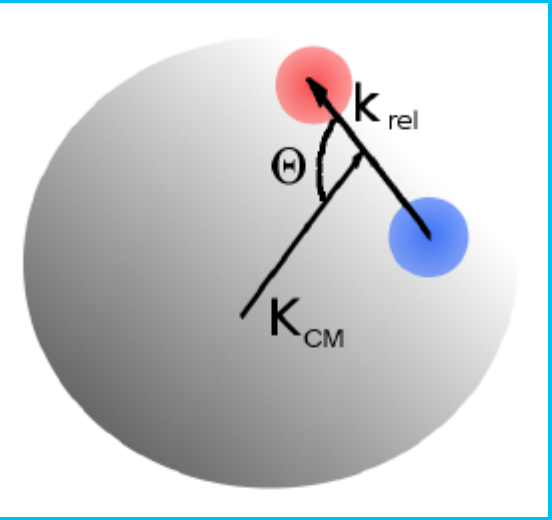
Friday

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

C.M. motion of the pair

a data mining analysis





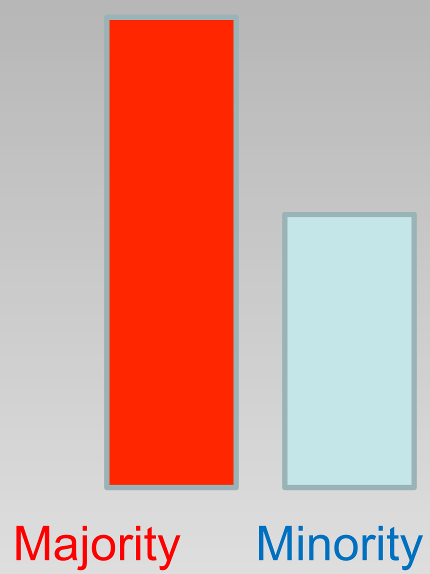
$$\vec{p}_{cm} = \vec{p}_{miss} + \vec{p}_{recoil}$$

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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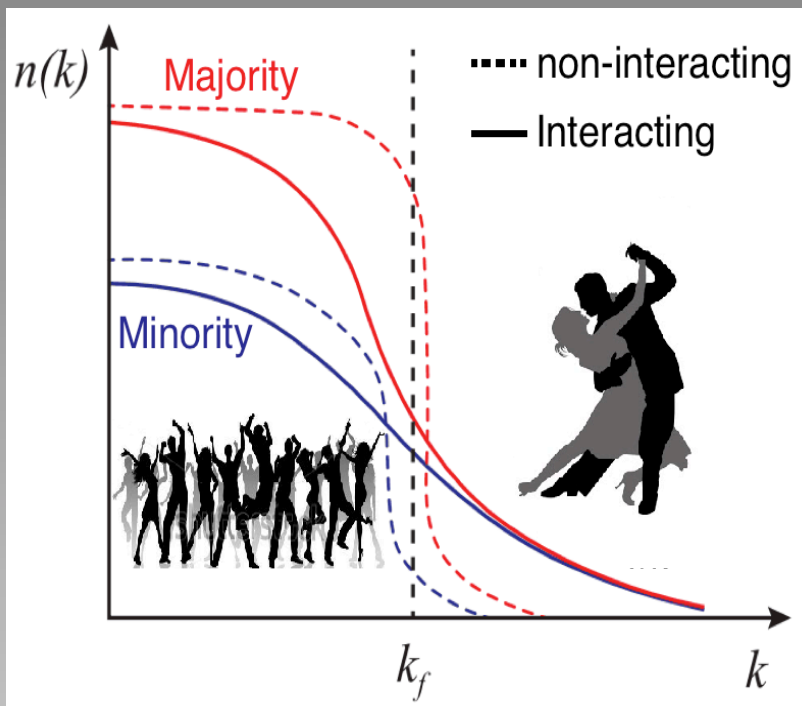
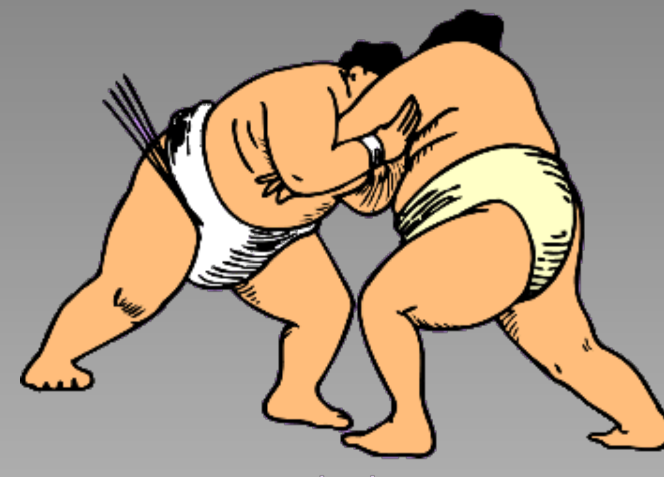




Who wins?

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 :

$$\langle k_{minority} \rangle > \langle k_{majority} \rangle$$

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

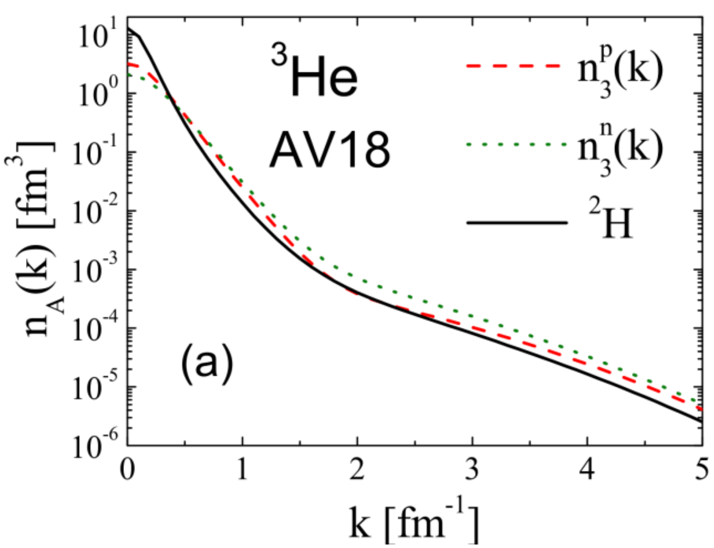
(protons move faster than neutrons in N>Z nuclei)

Light nuclei A<11

Variational Monte Carlo calculations by the Argonne group

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

	$\frac{\|N-Z\|}{A}$	$\langle KE\rangle_p$	$\langle KE\rangle_n$	$\langle KE\rangle_p - \langle KE\rangle_n$
^{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:

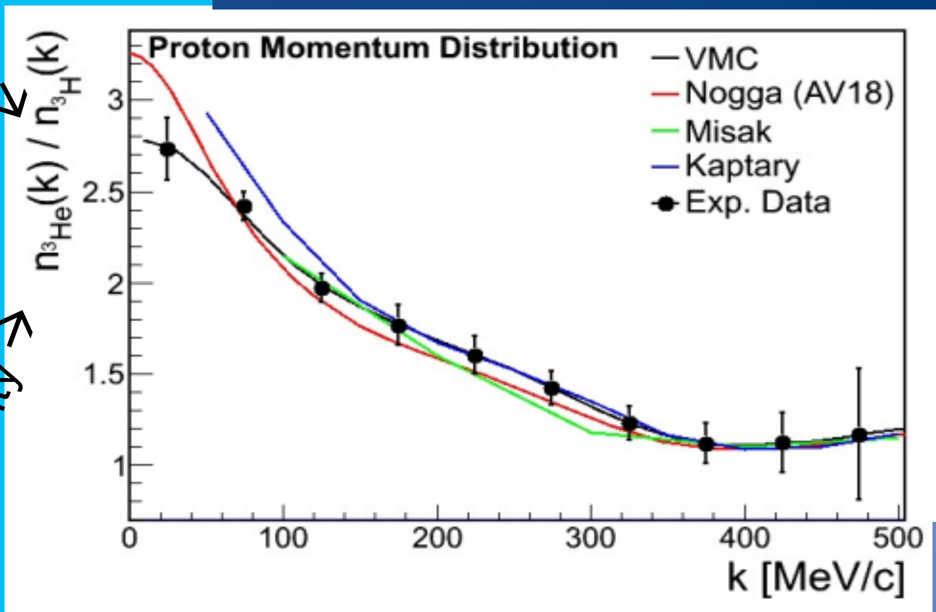
$$\frac{n_n(k>1)}{n_n(k<1)} > \frac{n_p(k>1)}{n_p(k<1)}$$

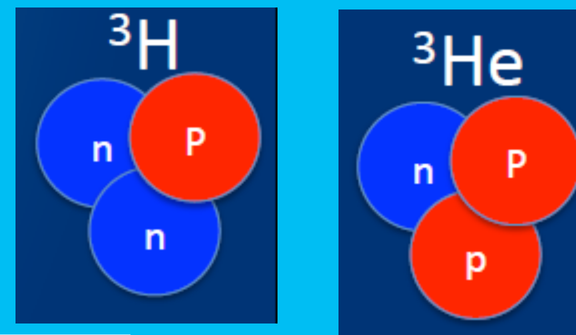
Momentum sharing in the A=3 nuclei

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

Minority →

Majority →





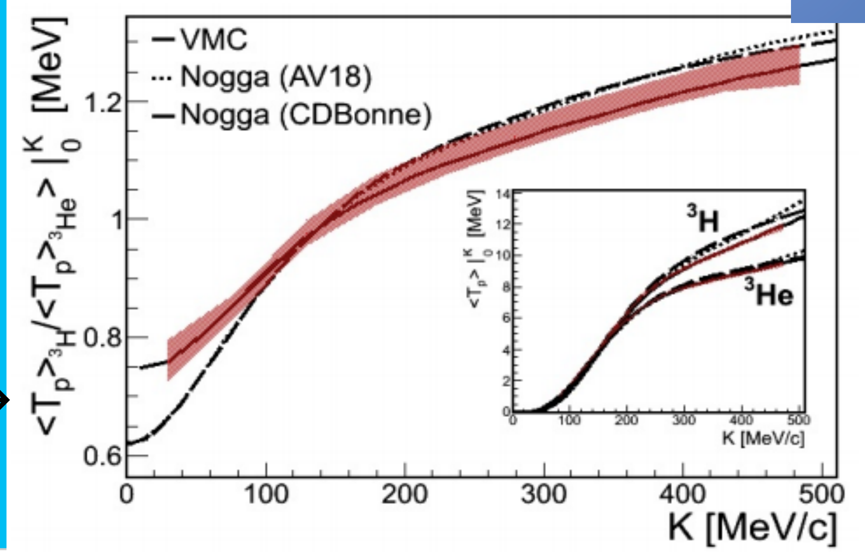
Wednesday

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

Mapping the Transition from Majority to Minority Dominance

Majority →

Minority →

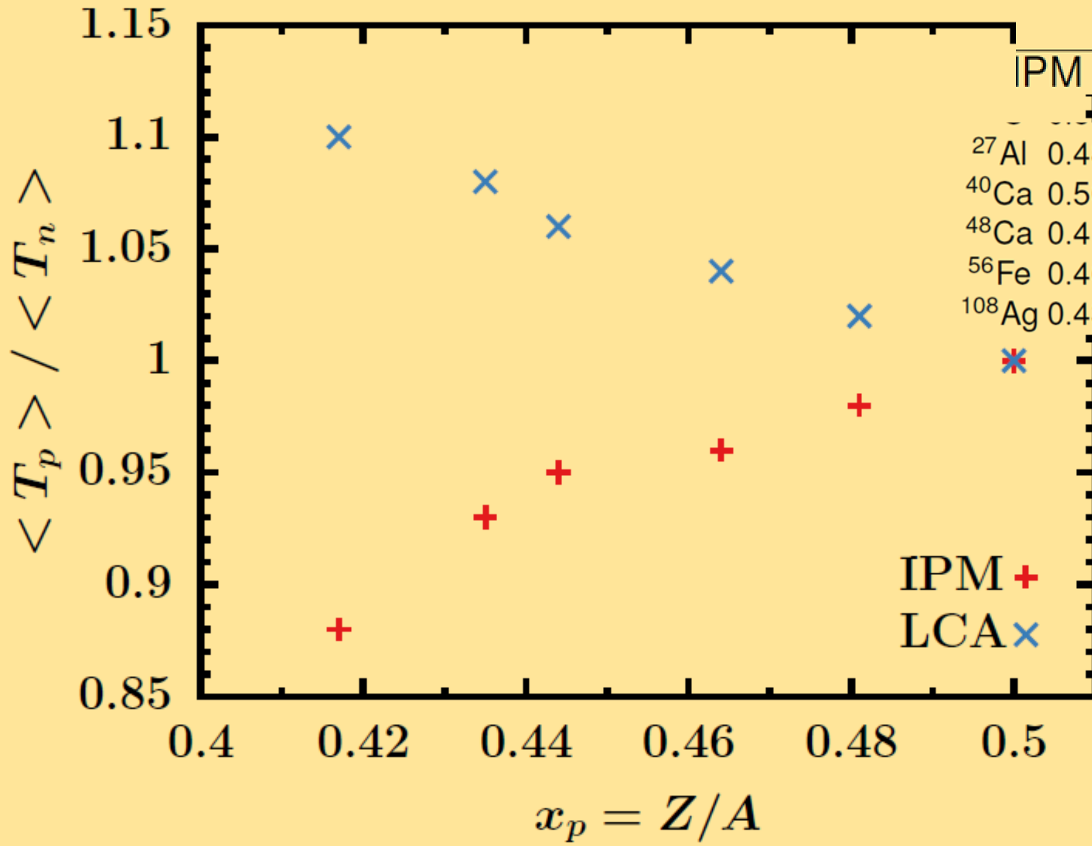


JLab E14-011 (Approved experiment) 2016/2017

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)
^{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

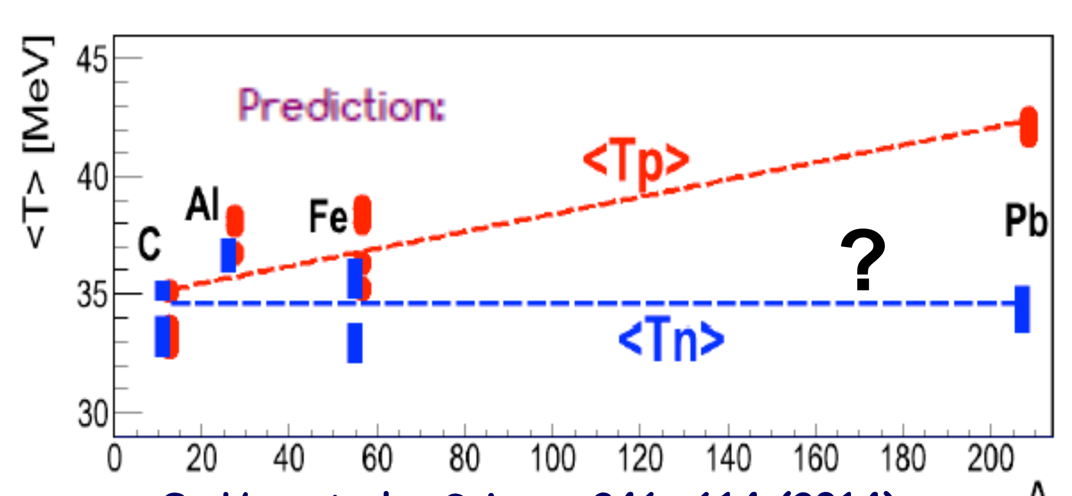
2:00 - 3:00 Jan Ryckebusch (Ghent) " Introduction to Calculational Methods of Medium/Heavy Nuclei:
Stylized features of nuclear momentum distributions and the quest for SRCs"

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

Meytal Duer (Tel – Aviv University)

TEL AVIV UNIVERSITY

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

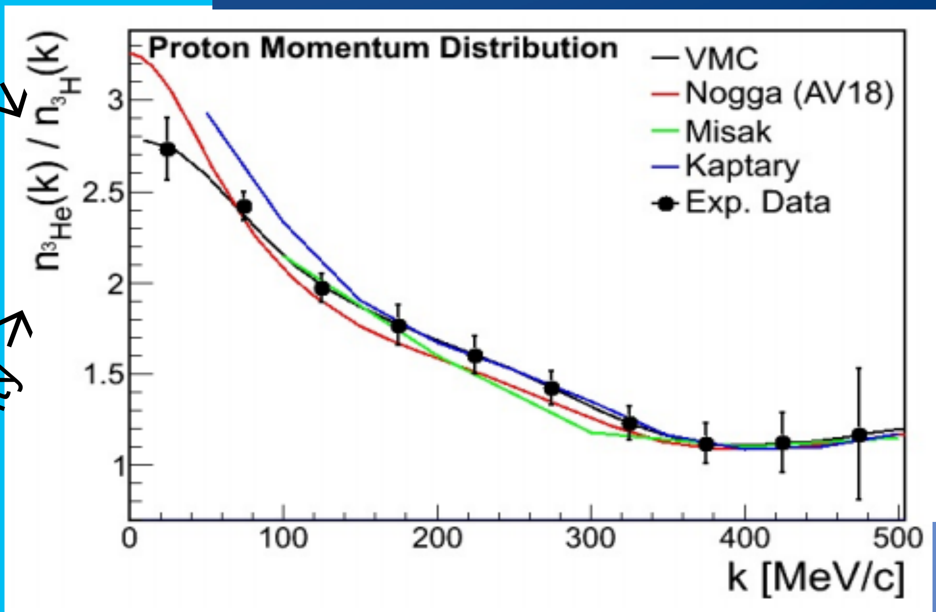
14:20 - 14:40 Meytal Duer(Tel Aviv) "SRCs from Data Mining"

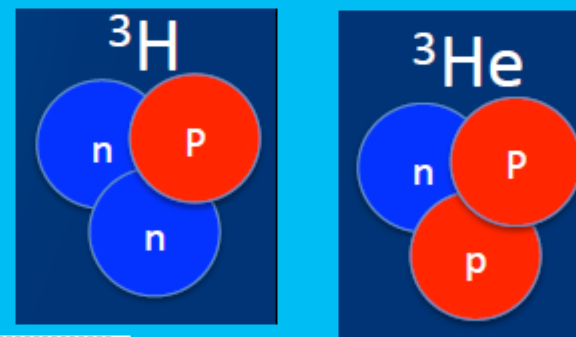
Momentum sharing in the A=3 nuclei

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

Minority →

Majority →





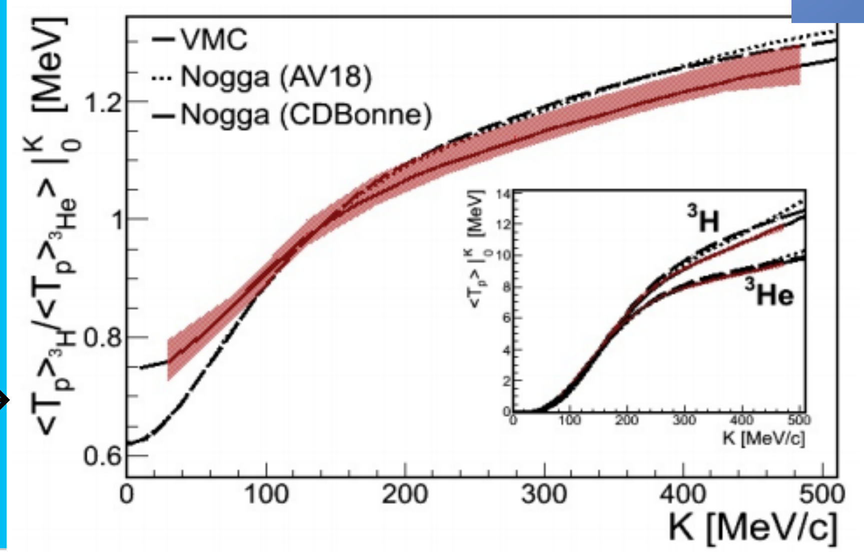
Wednesday

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

Mapping the Transition from Majority to Minority Dominance

Majority →

Minority →

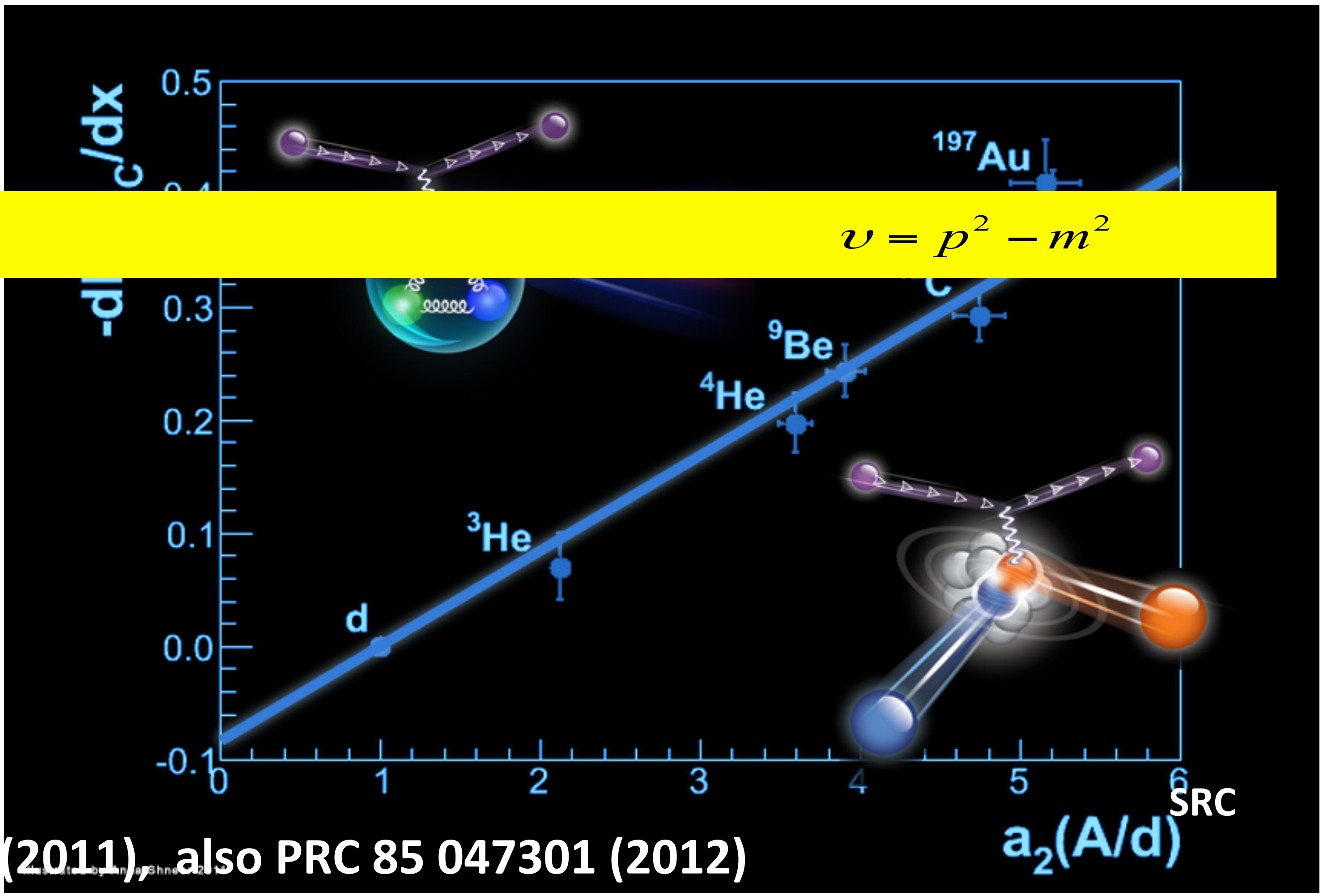


JLab E14-011
(Approved experiment)
2016/2017

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

EMC / SRC correlation

large virtuality? $\upsilon = p^2 - m^2$

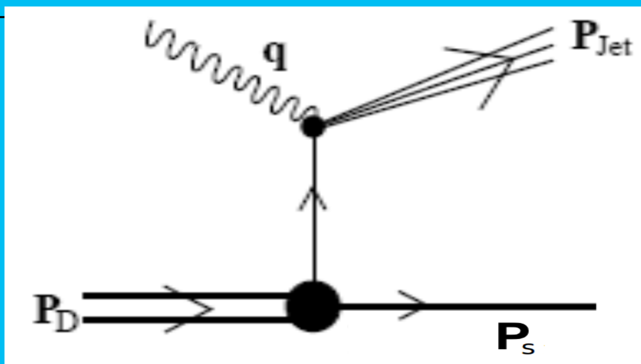


SRC

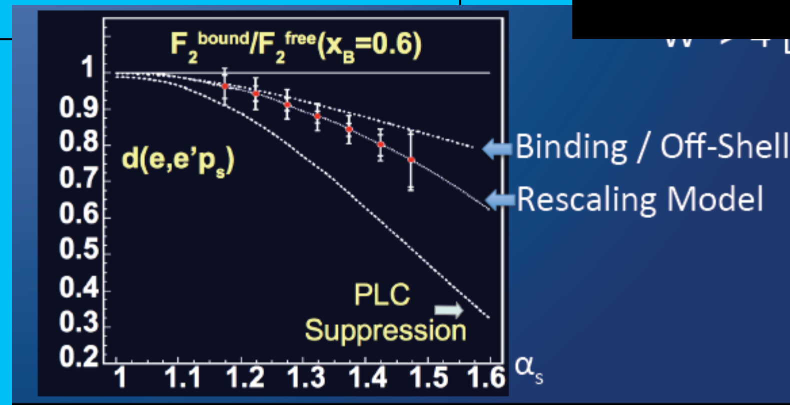
(2011), also PRC 85 047301 (2012)

the EMC effect is associated with large virtuality

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



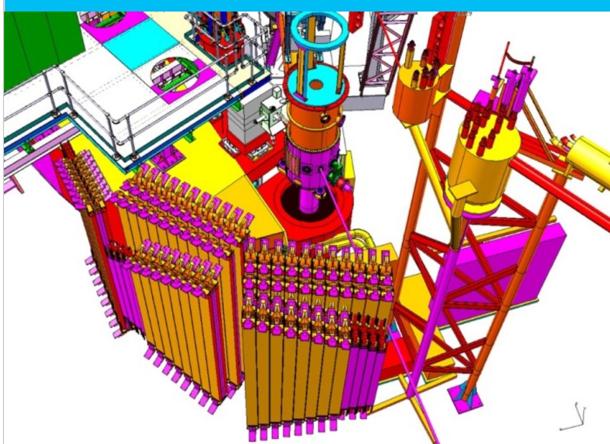
[redacted]



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

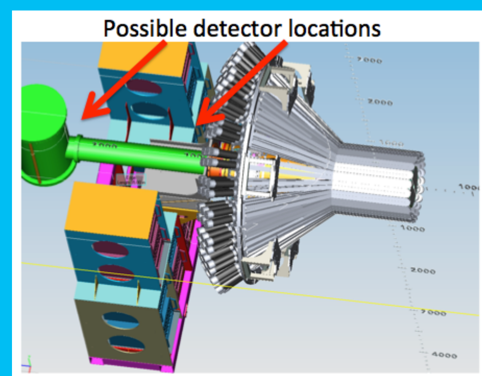
12 GeV JLab/ Hall C approved experiment E 12-11-107

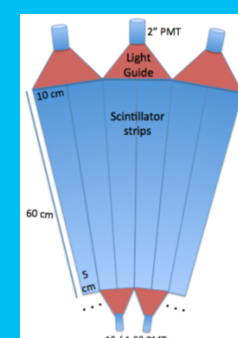
Tagged recoil proton measure neutron structure function



12 GeV JLab/ Hall B approved proposal

Tagged recoil neutron measure in the proton structure function



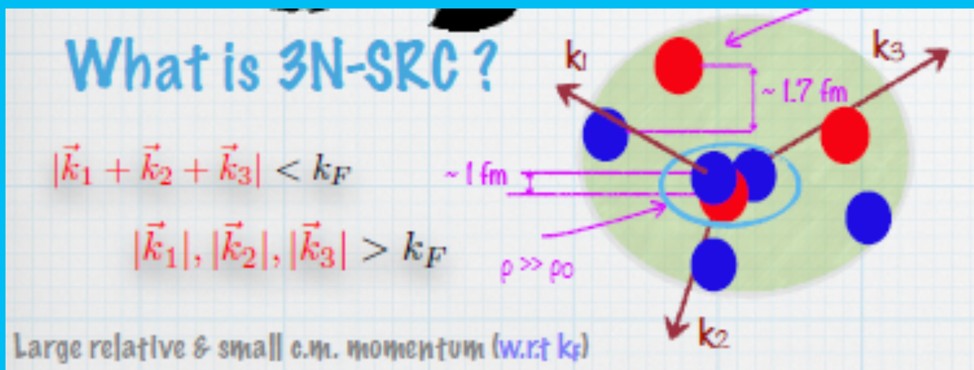


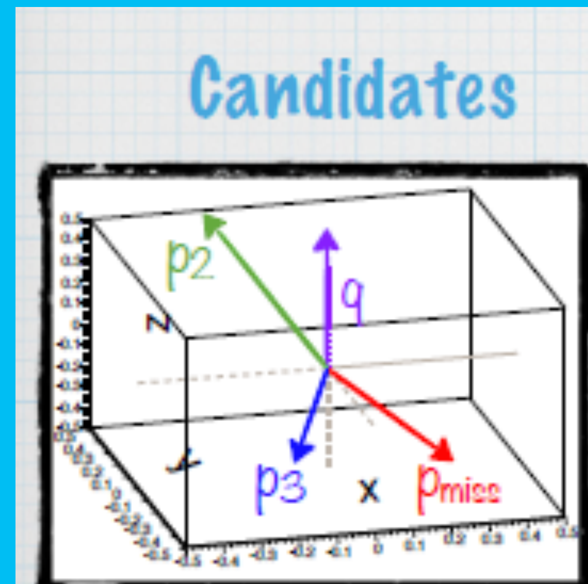
Wednesday 10:00 - 10:30 Or Hen (MIT) - "SRC and EMC effects"

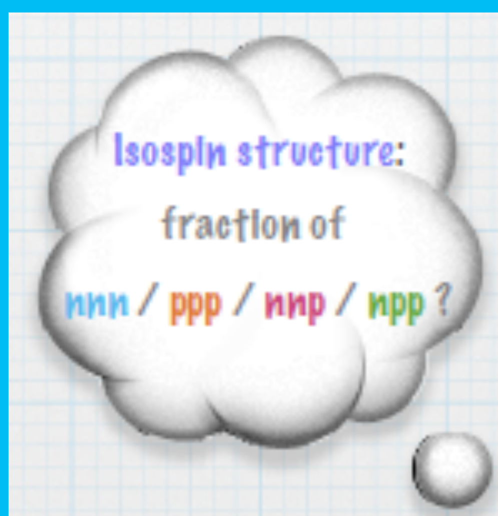
Search for 3N correlation using JLAB – CLAS EG2 data

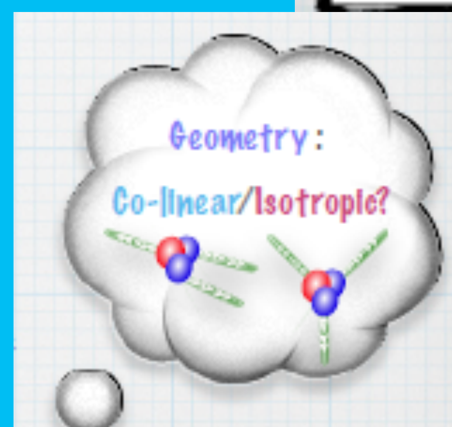
Erez Cohen (Tel – Aviv University)

a data mining analysis





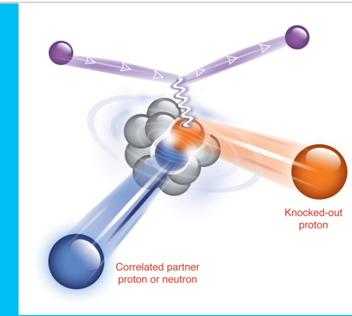




Friday

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

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

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

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

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

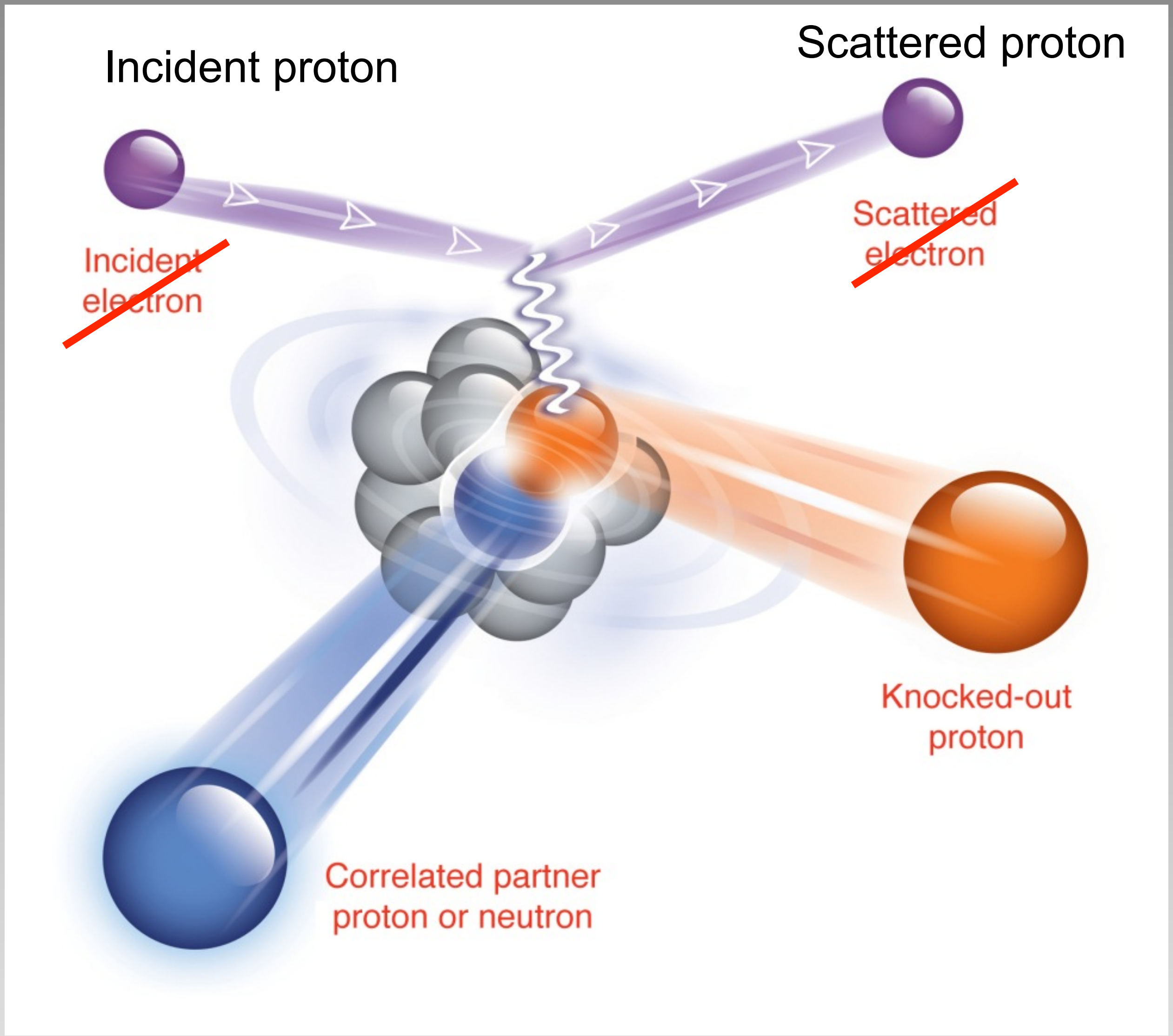
Need high statistic exclusive measurement (>10,000 events)

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 ?

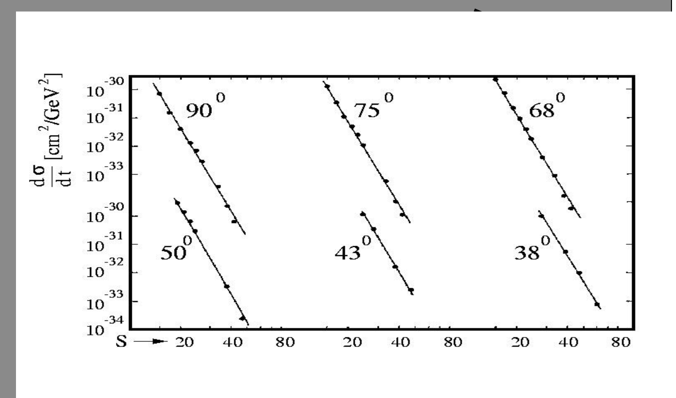
selective attention to SRC

Psychology Wiki

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

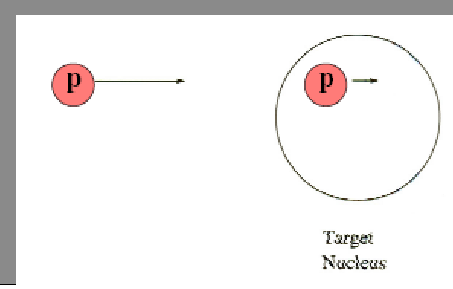
p p → pp elastic scattering near 90^0 c.m

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



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 ?

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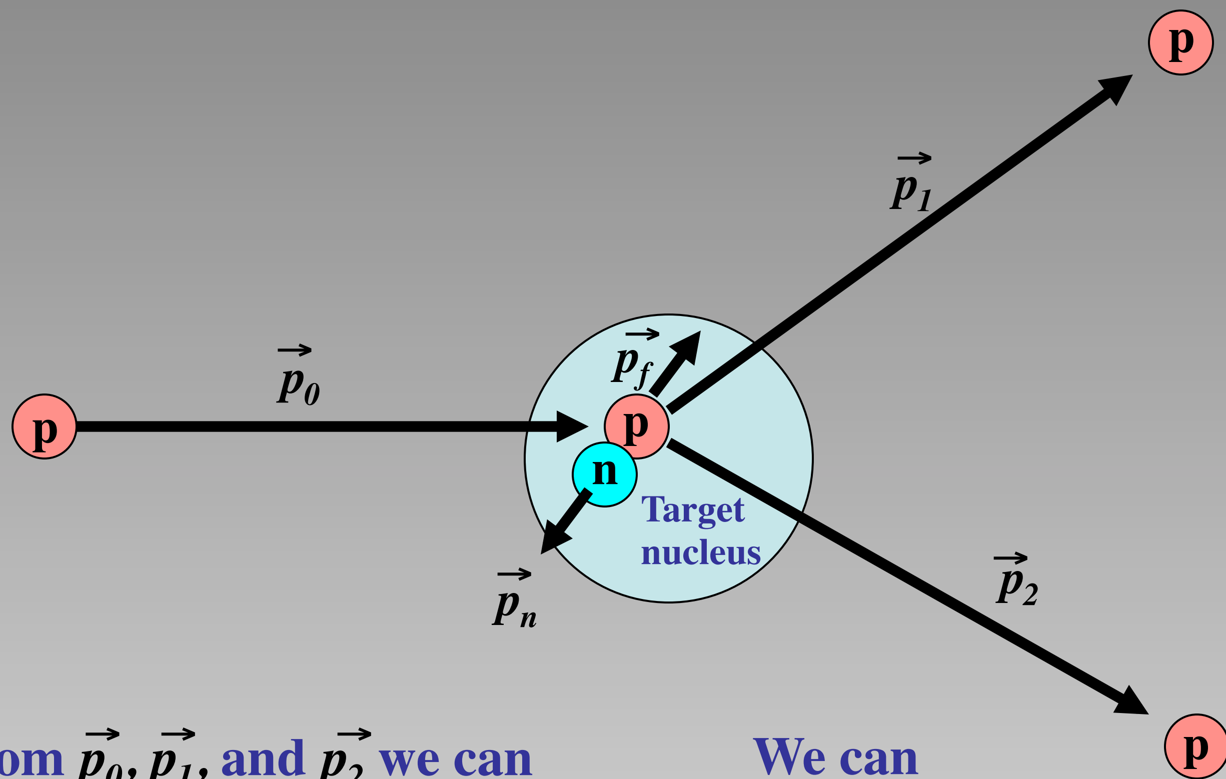
- They have Small deBroglie wavelength:

$\lambda = h/p = hc/pc = 2\pi \cdot 0.197$ GeV-fm/(6 GeV) ≈ 0.2 fm.

- Large momentum transfer is possible with wide angle scattering

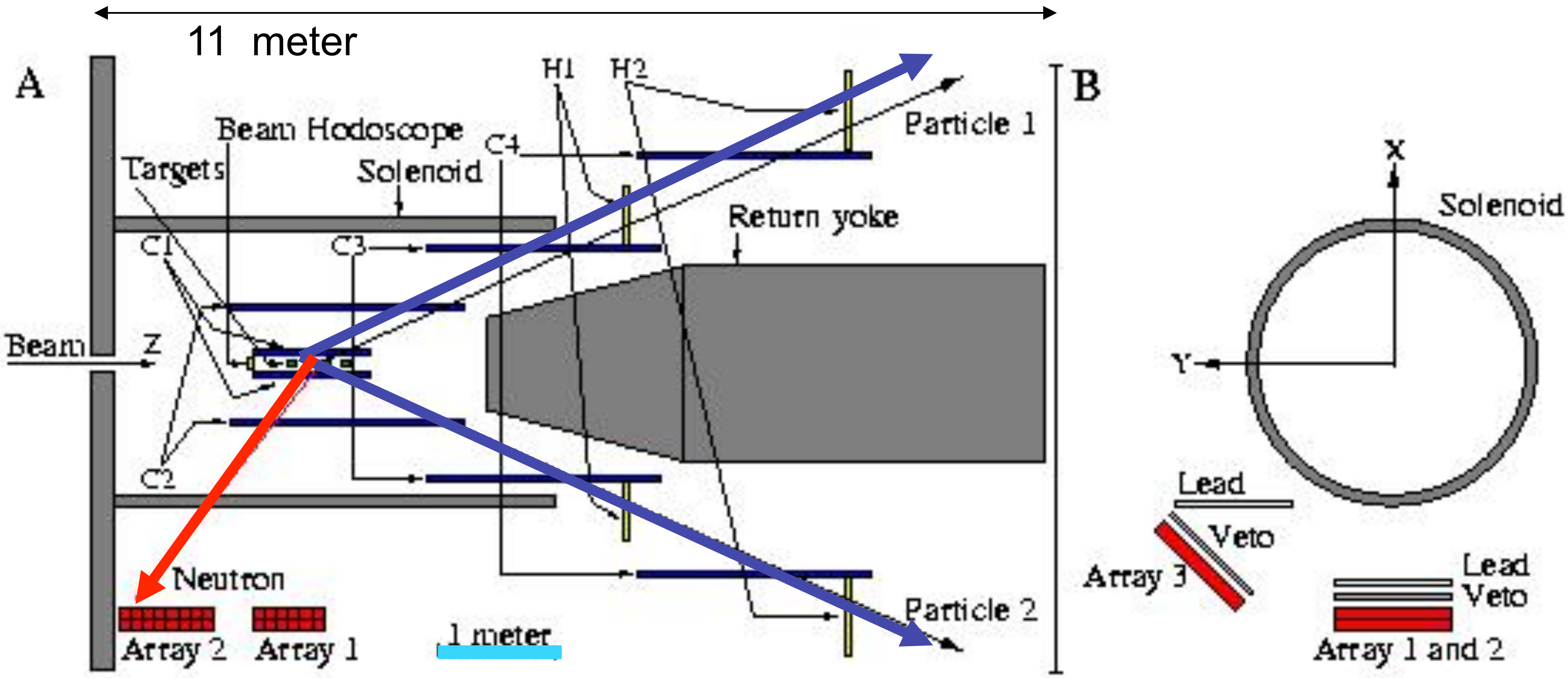
- Cross section is large

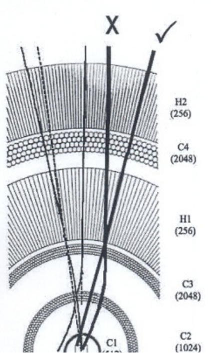


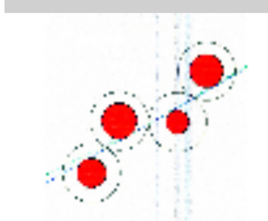
From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

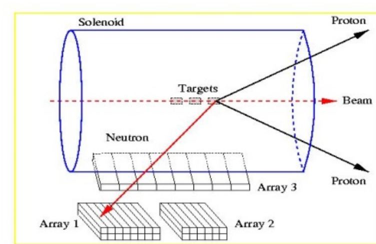
We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly "back to back."

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)

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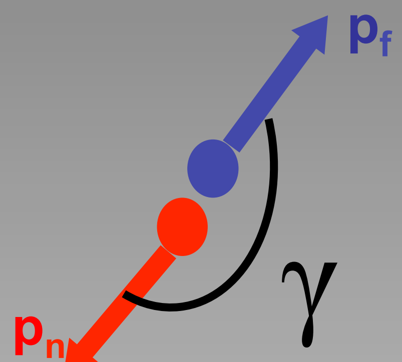
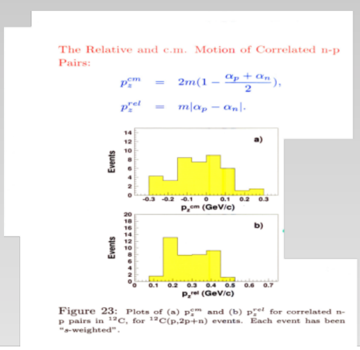


Removal of a proton with momentum above 275 MeV/c from ^{12}C is $92\pm^{8}_{18}$ % accompanied by a recoil high momentum neutron.

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



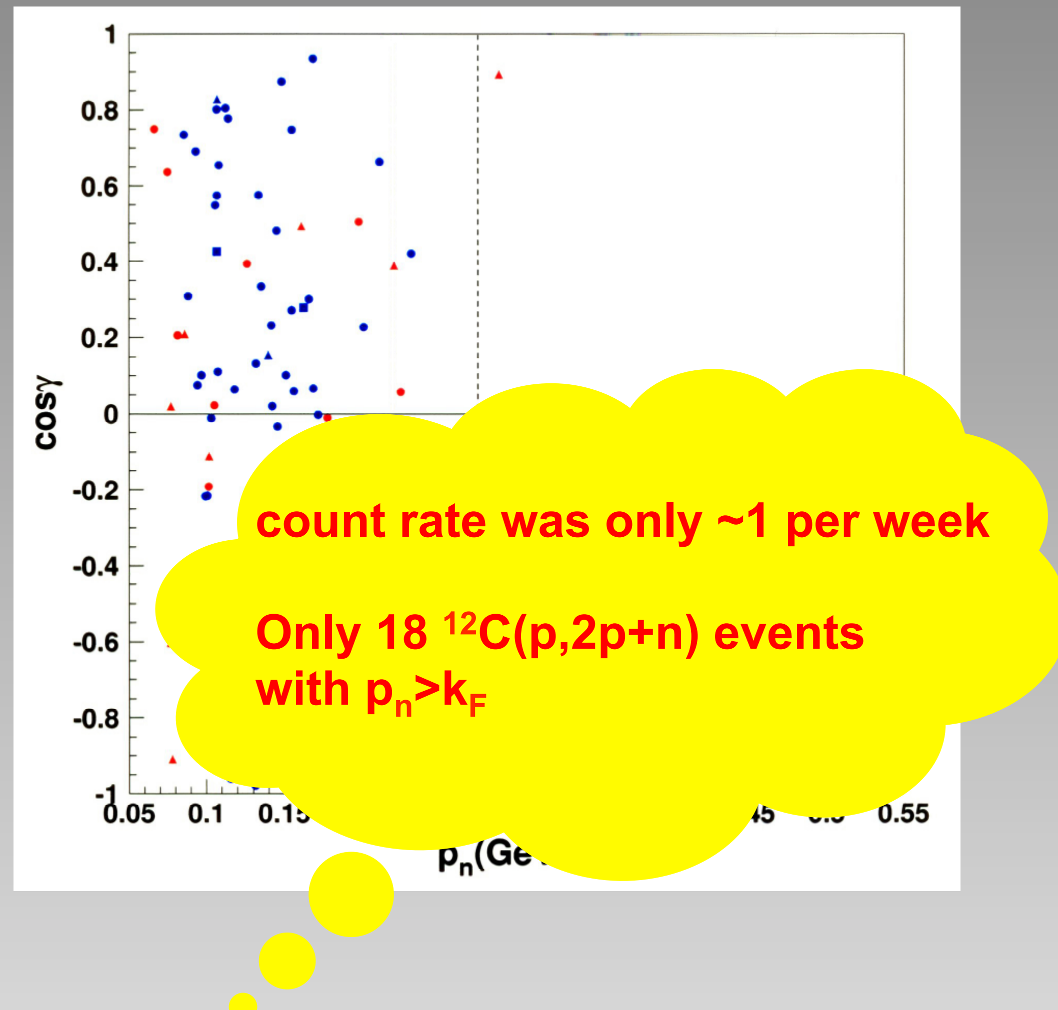
The Relative and c.m. Motion of Correlated n-p Pairs:

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

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

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".

Directional correlation

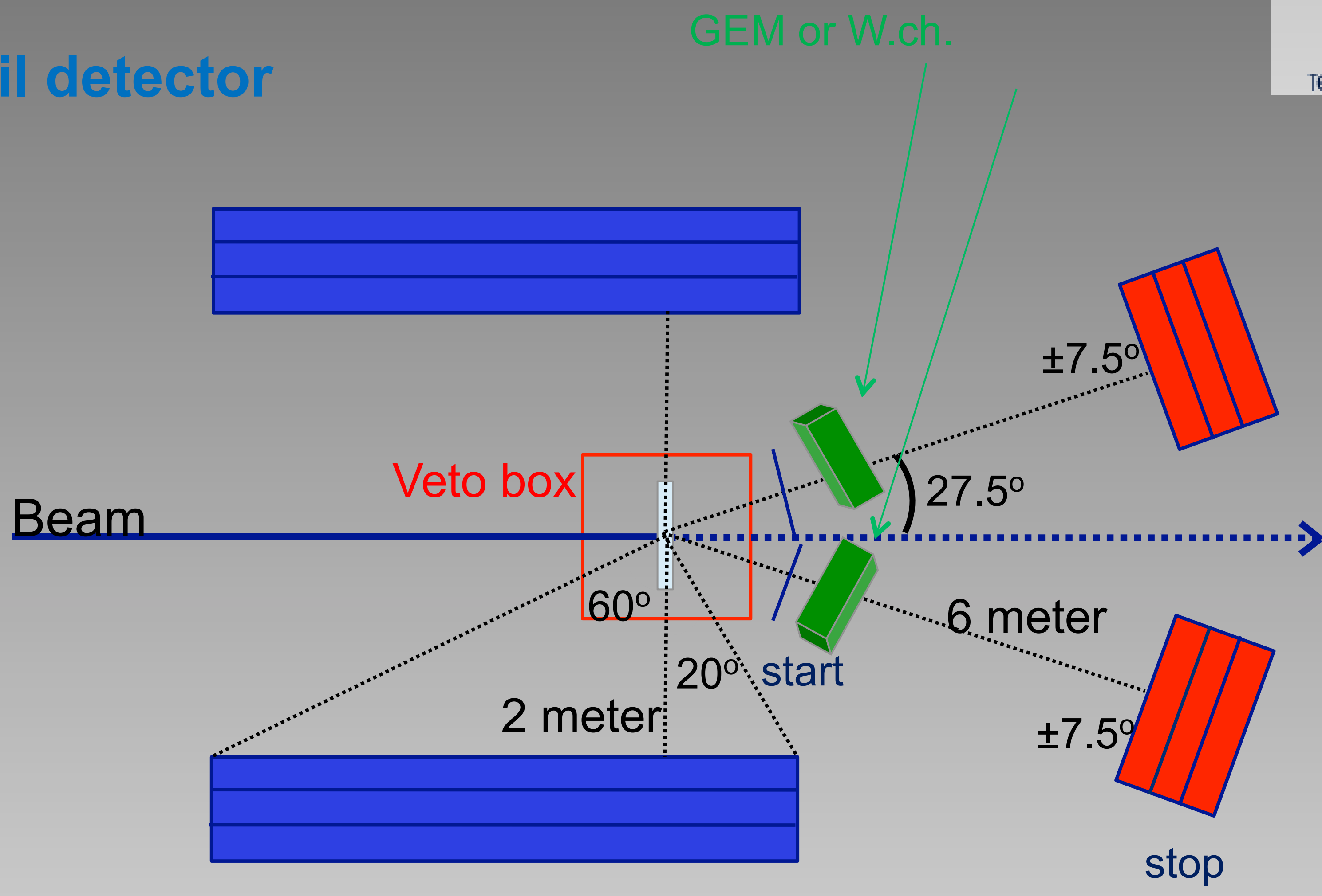


count rate was only ~1 per week

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

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

Recoil detector



Array of scintillators

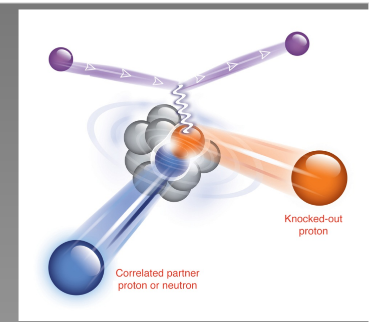
LAND, NeuLAND ?

σ_{TOF}<100ps

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

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

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

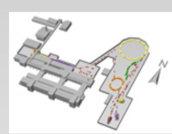
$^{4}He(e,e'pn)$ $^{4}He(e,e'pp)$

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

A window of opportunity:

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

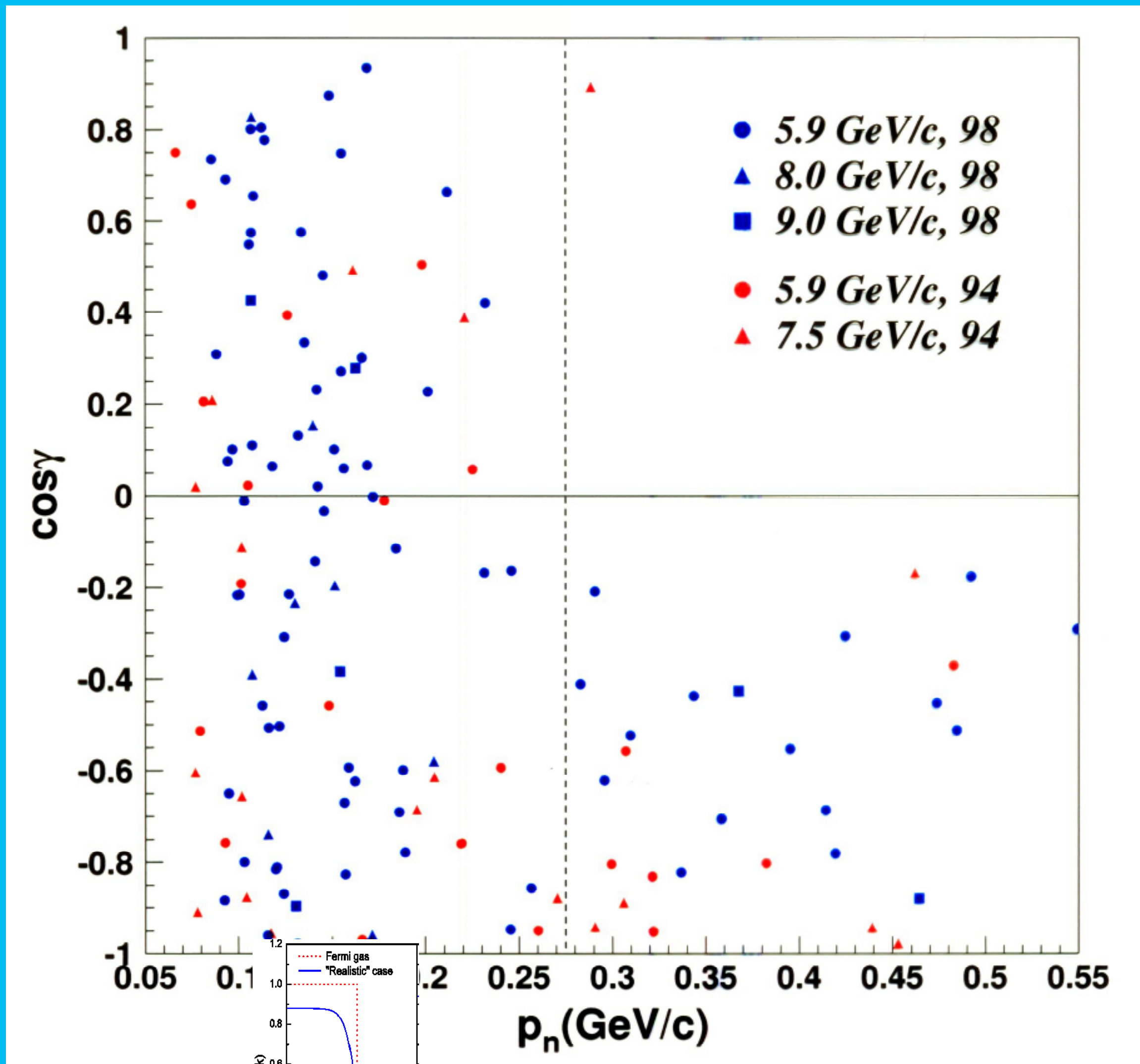
Dubna

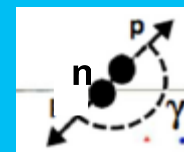


GSI / FAIR

➔ **>10k events Before 2020**

Mapping the transition from mean field to SRC





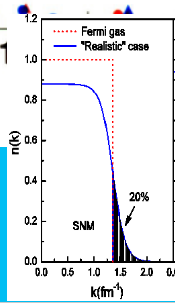
EVA / BNL:

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



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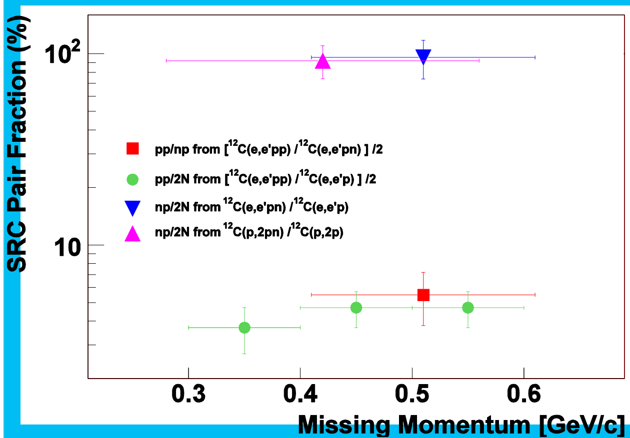
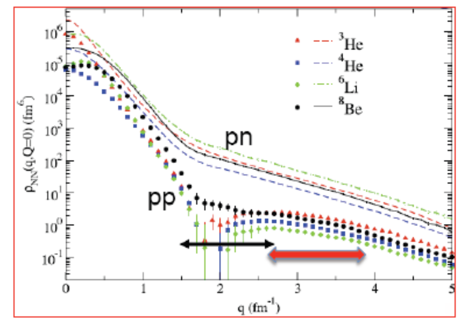
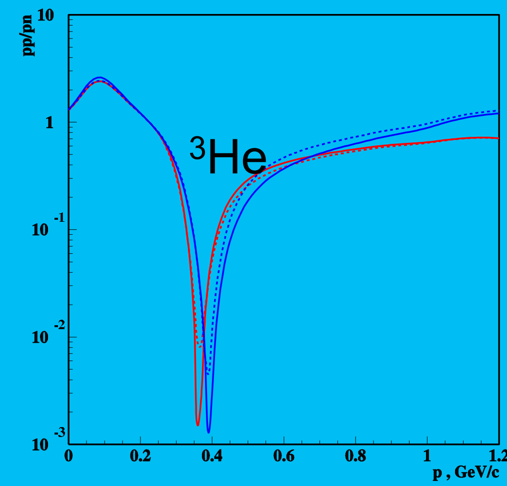
SRC Isospin Structure and the Tensor Force





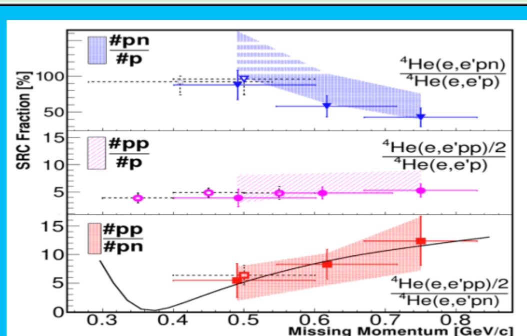
R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Phys. Rev. Lett. **98** (2007) 132501



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 :**

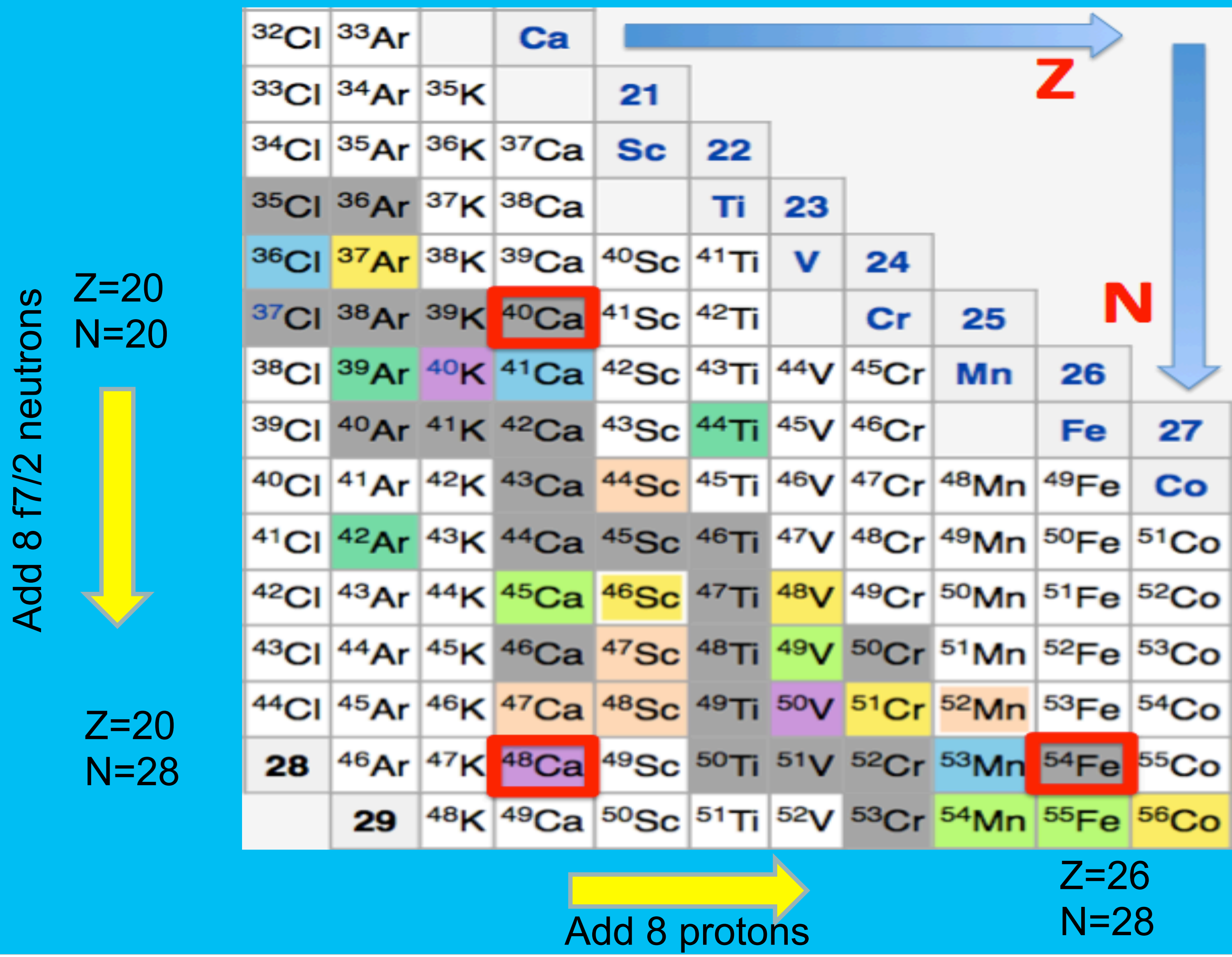
First measurement below 400 MeV/c

Better statistics above 600 MeV/c

****

Asymmetric nuclei N>Z:

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



motion of the pair

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

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

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

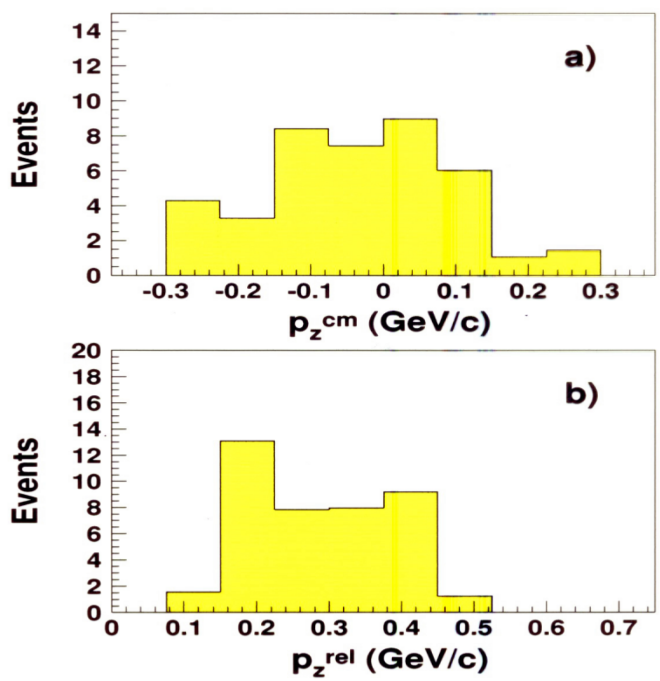


Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p+n)$ events. Each event has been "s-weighted".

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

σ_{CM}=0.143±0.017 GeV/c

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

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

Electron scattering (shneor et al.) : σ_{CM}=0.136±0.02 GeV/c

PRL 99, 072501 (2007).

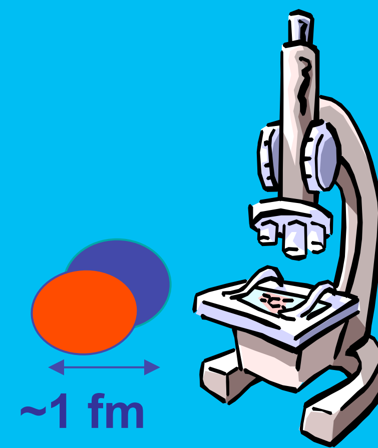
Reaction Mechanism

Hard processes

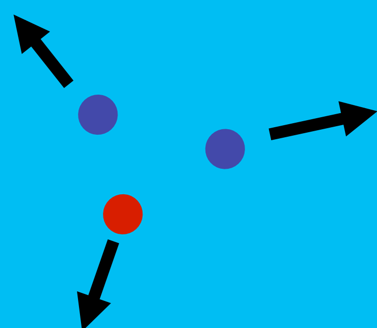
high energy and large momentum-transfer

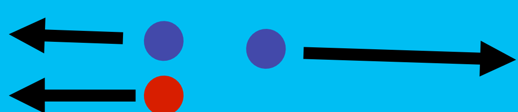
Important practical question:

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



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





Summary – data and analysis

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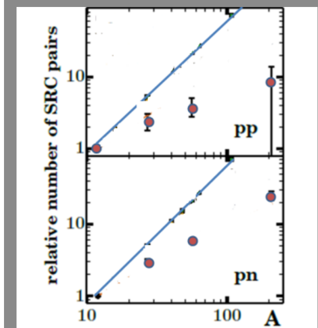
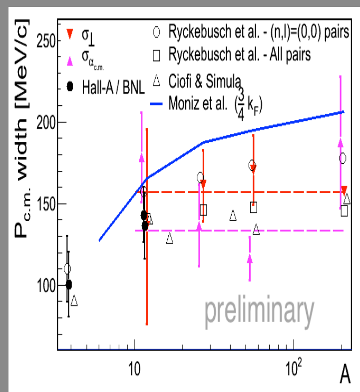
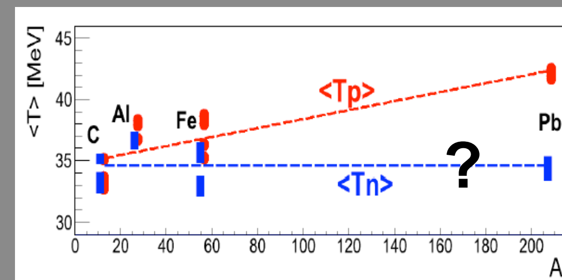
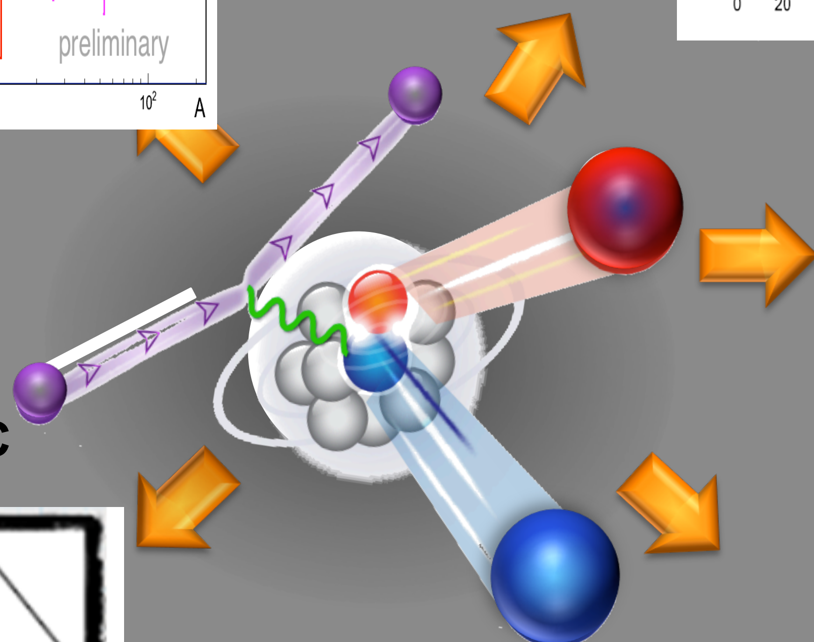
C.M. motion of the pair



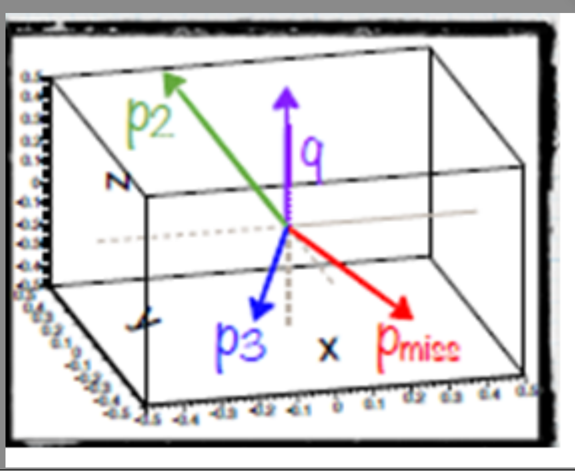


Momentum sharing in asymmetric nuclei





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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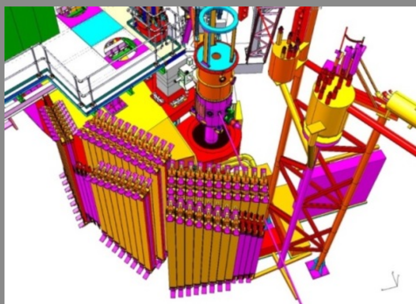
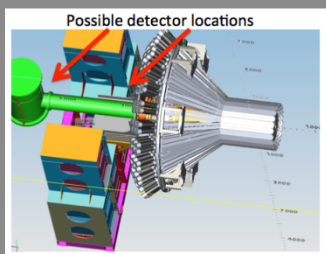
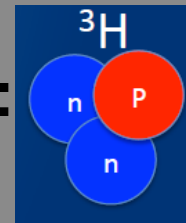
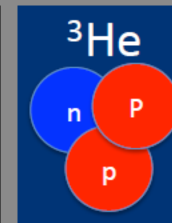


JLab Hall C:
E12-11-107



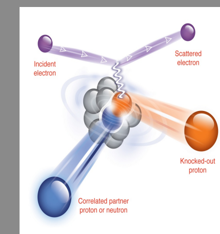
JLab Hall A:
E12-14-011

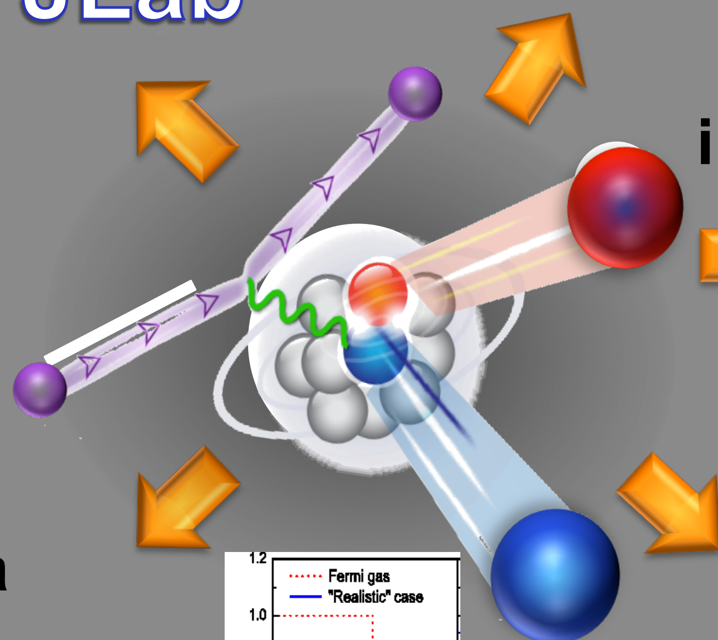




JLab

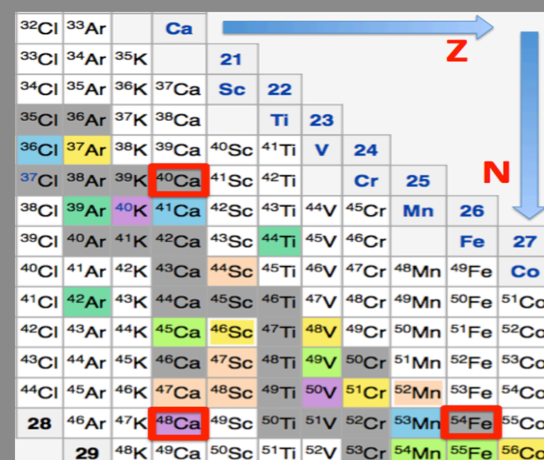
Proposal in preparation





inclusive QE and DIS

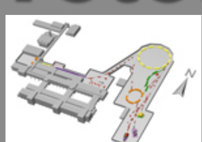
JLab Hall C:
E12-11-112, E12-06-105
E12-08-014



Add 8 protons

JLab Hall B:
E12-11-003a

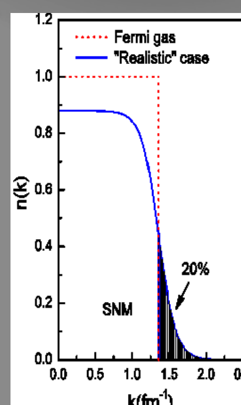
Proton facility



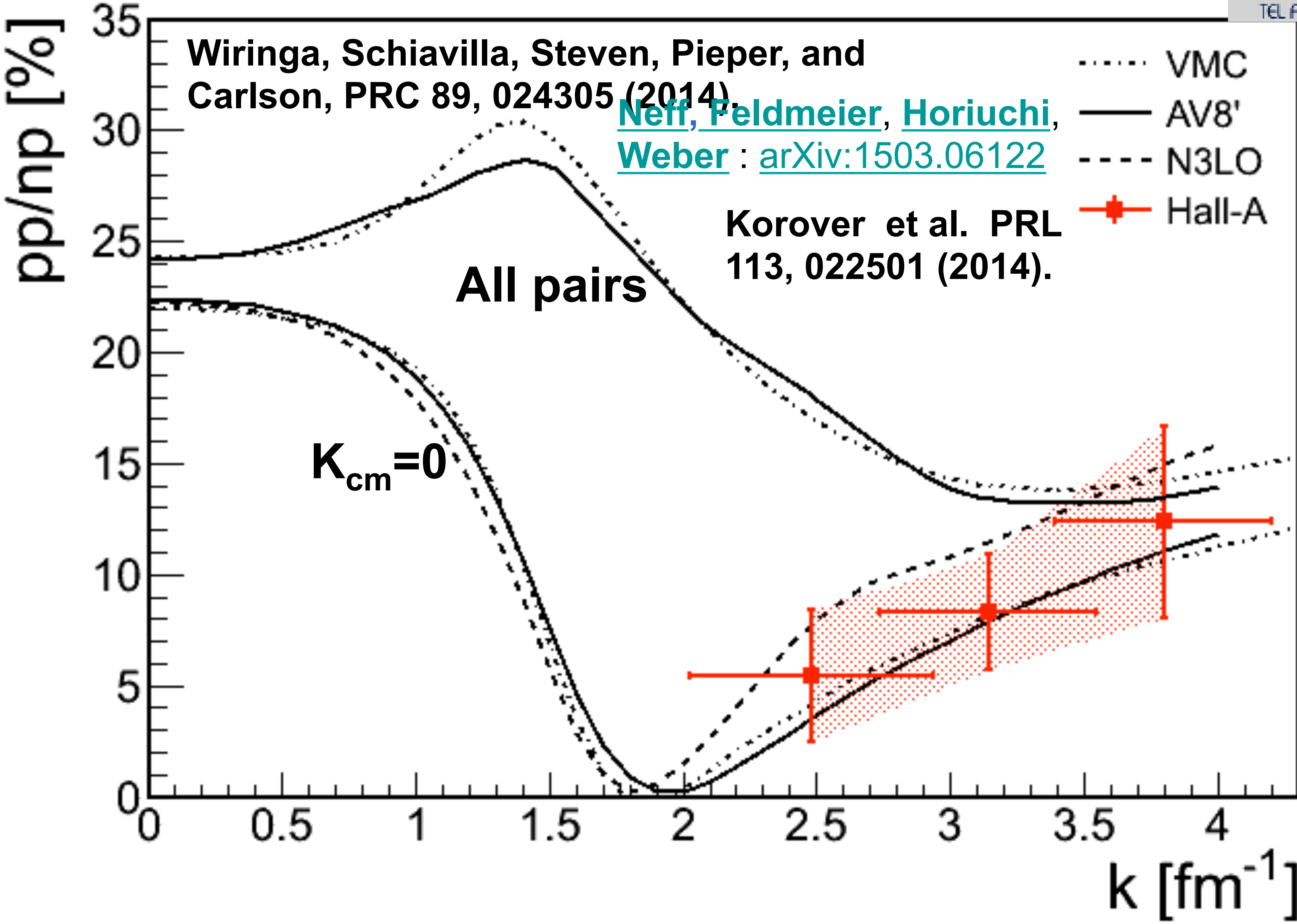
GSI / FAIR

Dubna

Nuclotron



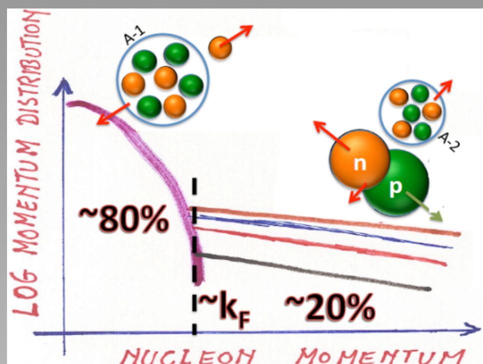
Migdal jump

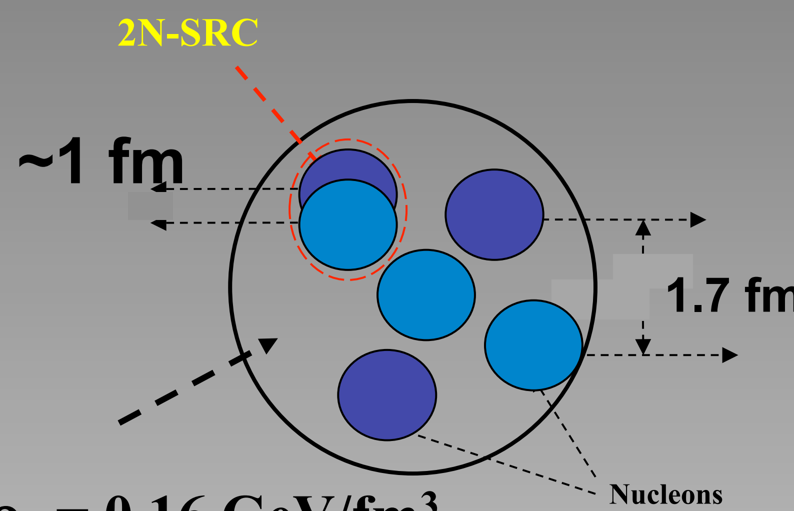


Wiringa, Schiavilla, Steven, Pieper, and Carlson, PRC 89, 024305 (2014).
Neff, Feldmeier, Horiuchi, Weber : arXiv:1503.06122
Korover et al. PRL 113, 022501 (2014).
All pairs
K$_{cm}$=0
VMC
AV8'
N3LO
Hall-A
pp/np [%]
k [fm^{-1}]
0
0.5
1
1.5
2
2.5
3
3.5
4
5
10
15
20
25
30
35

What are Short (intermediate) Range Correlations in nuclei ? (tensor)

SRC ~R_N **LRC ~R_A**



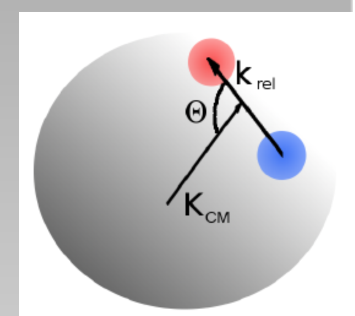


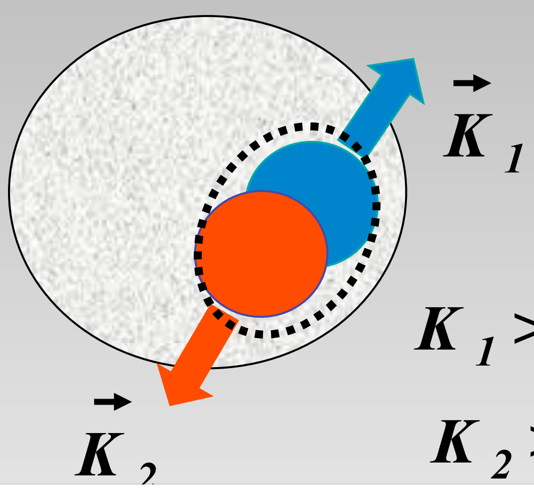
$\rho_o = 0.16\ GeV/fm^3$

In momentum space:

$$K_{rel} > K_F$$

$$K_{CM} < K_F$$





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

$$K_1 > K_F,$$

$$K_2 > K_F$$

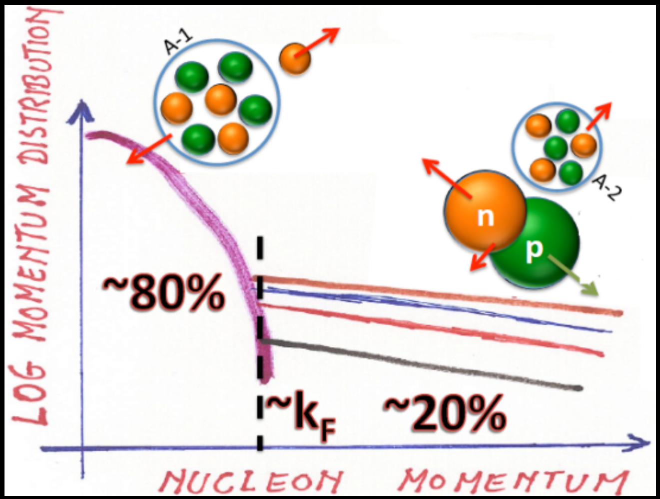
A pair with large relative momentum between the nucleons and small CM momentum.

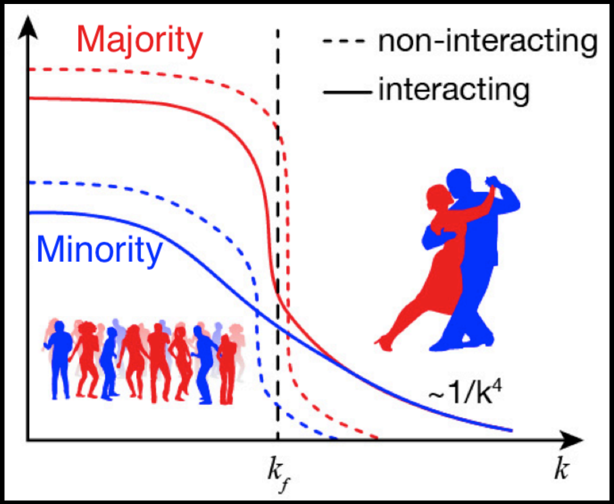
Universality:

Identified triple coincidence SRC pairs in: (^{3}He,) ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb

High momentum tail In nuclei dominated by SRC pairs

np-SRC dominance





Symmetry Energy

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$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) + E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

(Pure Neutron Matter) (Symmetric Nuclear Matter)

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho)$$

Relates to the energy change when replacing n with p

- equation-of-state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesis
- core-collapse supernovae
- more...

with Tensor Correlations:

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$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho)$$

np-SRC dominance ➡

High momentum tail in SNM

(np- pairs)

No high momentum tail in PNM

(nn- pairs)

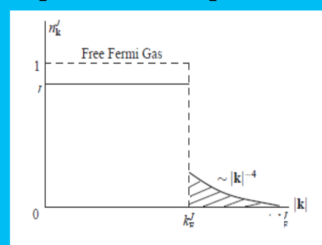
➡ $$E_{sym}^{kin}(with\,\mathrm{SRC}) < E_{sym}^{kin}(no\,\mathrm{SRC})$$

How large is the effect (ρ_0) ?

Free Fermi Gas (FFG)

$$n(k) = \begin{cases} A & k < k_F \\ 0 & k > k_F \end{cases} \quad \Rightarrow \quad E_{sym}^{kin} = (2^{2/3} - 1) \cdot \frac{3}{5} \cdot E_F(\rho_0) \approx 12.5\,\text{MeV}$$

With correlations (CFG)

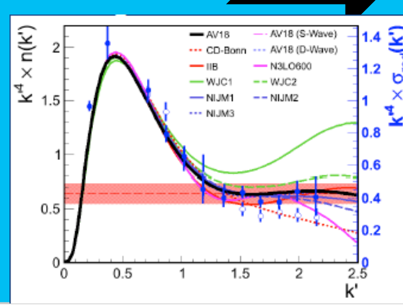


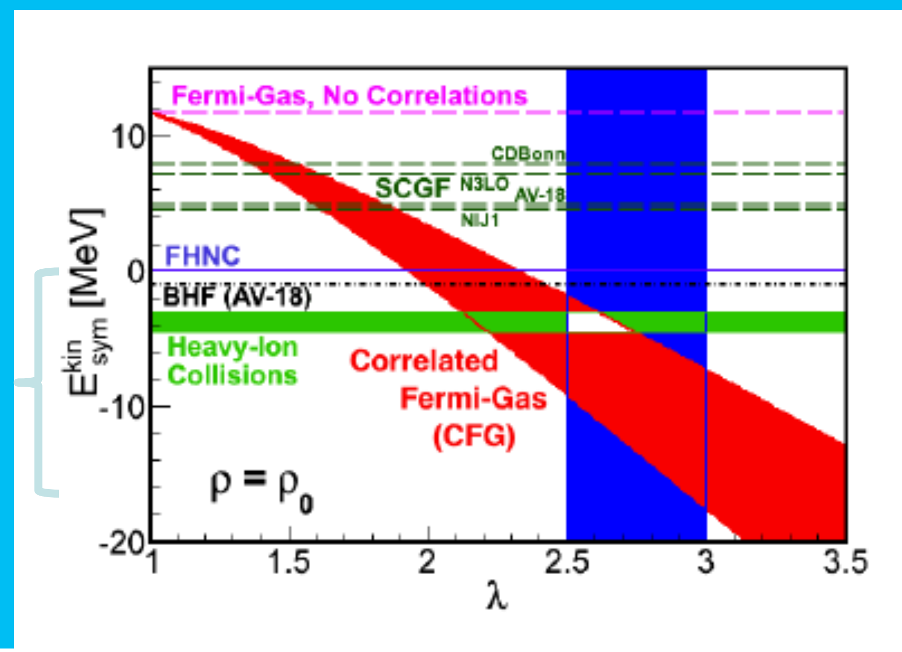
$$n(k) = \begin{cases} A_0 & k < k_F \\ C_0 / k^4 & k_F < k < \lambda k_F \\ 0 & k > \lambda k_F \end{cases}$$

$c_0 = 4.16 \pm 0.95,$

$\lambda \approx 2.75 \pm 0.25$

Phys. Rev. C92, 045205 (2015)





Symmetry energy of nucleonic matter with tensor correlations

Or Hen,[1,*] Bao-An Li,[2] Wen-Jun Guo,[2,3] L.B. Weinstein,[4] and Eli Piasetzky[1]

Phys. Rev. C91, 025803 (2015)

If the potential part is extracted by:

$$E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0)$$

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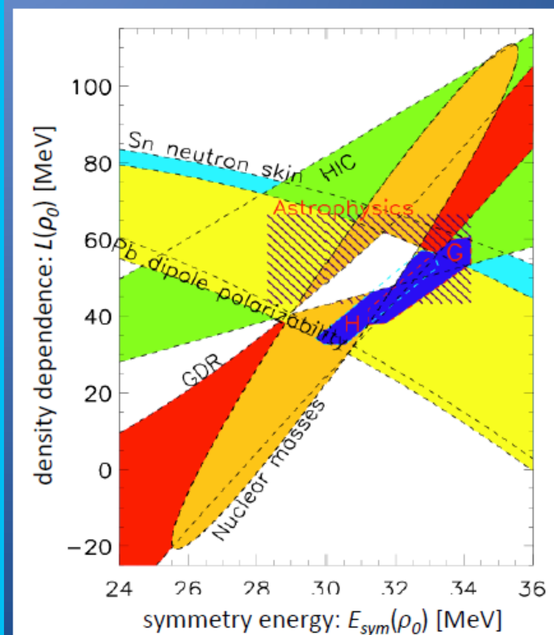
Symmetry Energy @ Saturation Density (ρ_0)



Global analysis of world data:

$28.9 \le E_{sym}(\rho_0) \le 34.1$

$42.4 \le L(\rho_0) \le 74.4$

J. Lattimer and Y. Lim, Astrophys. J. 771, 51 (2013)

$^*L(\rho_0) = 3\rho[dE/d\rho]|_{\rho 0}$

np-SRC dominance

➡

$$E_{sym}^{kin}(with\ \mathrm{SRC}) < E_{sym}^{kin}(no\ \mathrm{SRC})$$

$$E_{sym}^{pot}(with\ \mathrm{SRC}) > E_{sym}^{pot}(no\ \mathrm{SRC})$$

Density dependence of Symmetry Energy

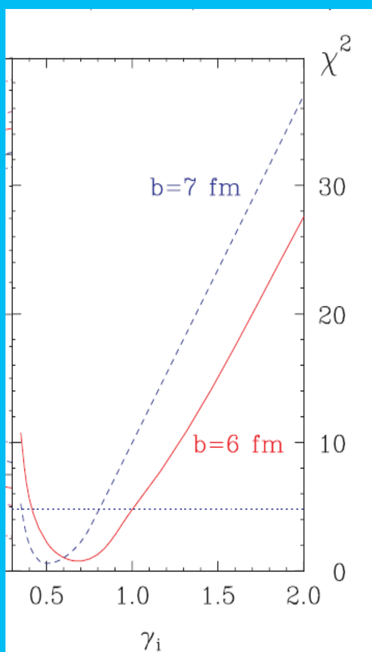
$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

FFG:

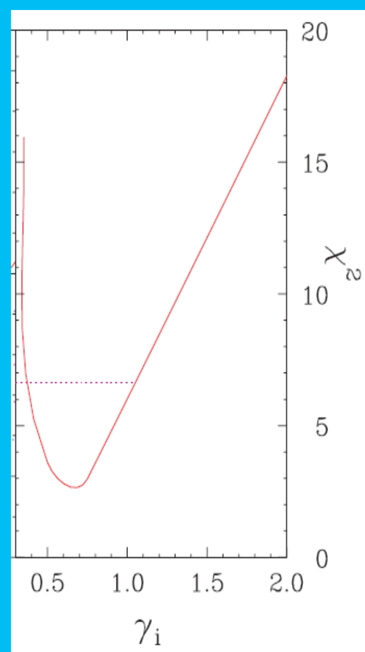
$$E_{sym}^{kin}(\rho_0) = 12.5\,\mathrm{MeV} \qquad \alpha = 2/3 \qquad \gamma = 0.48 \pm 0.1$$

$$s_0 = 31 \pm 1\,\mathrm{MeV},\ \mathrm{L} = 50 \pm 5\,\mathrm{MeV}$$

$$\gamma = \frac{\frac{1}{3}L - \frac{dE_{sym}^{kin}(\rho)}{d\rho}\Big|_{\rho_0}}{E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0)}.$$



isospin transport ratios
data vs. ImQMD calculations



double neutron-proton ratios
data vs. ImQMD calculations

Tsang et al.
PRL. 102, 122701 (2009)

Density dependence of Symmetry Energy

TEL AVIV UNIVERSITY

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

with Tensor Correlations (CFG):

$$E_{\rm sym}^{kin}(\rho) = E_{sym}^{kin}(\rho)|_{\rm FG} - \Delta E_{sym}^{kin}(\rho)$$

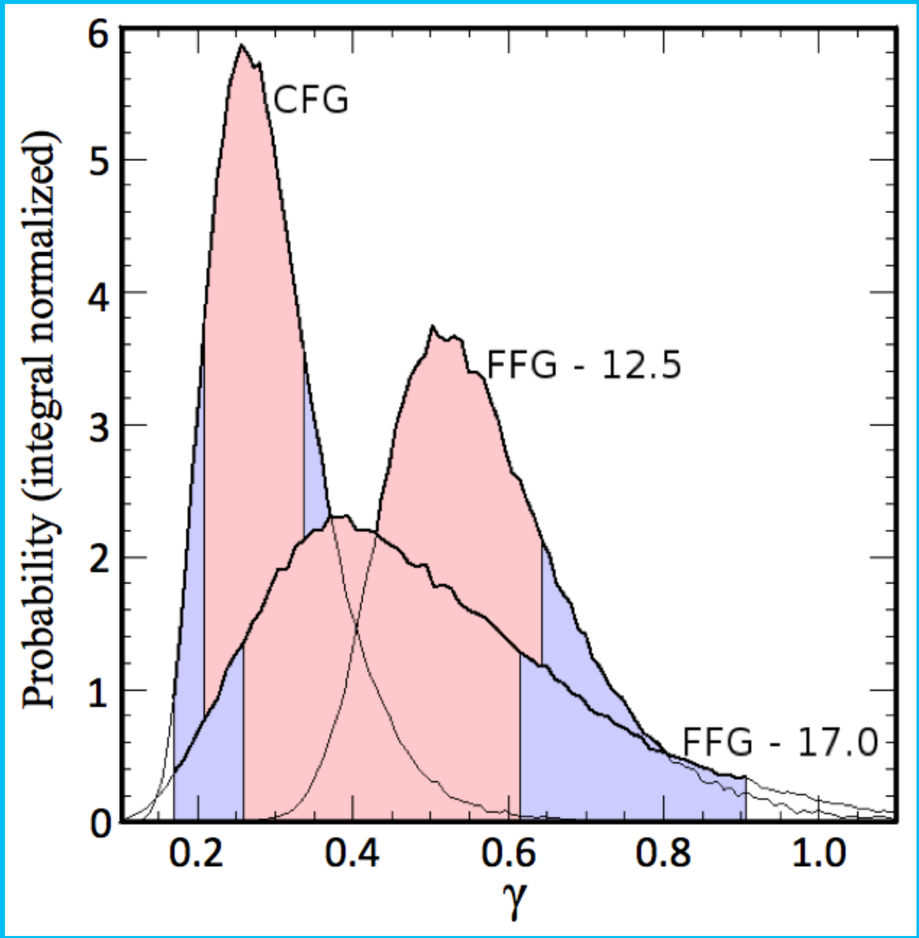
where the SRC correction term is:

$$\Delta E_{sym}^{kin} \equiv \frac{E_F^0}{\pi^2}c_0\left[\lambda(\frac{\rho}{\rho_0})^{1/3} - \frac{8}{5}(\frac{\rho}{\rho_0})^{2/3} + \frac{3}{5}\frac{1}{\lambda}(\frac{\rho}{\rho_0})\right]$$

$$E_{sym}^{kin}(\rho_0) = -10 \pm 3\,\mathrm{MeV}$$

$$\gamma = 0.25 \pm 0.05$$

Bayesian analysis of neutron stars observations lead to the same result



NS EOS

3 energy-density regions

A. W. Steiner, J. M. Lattimer, and E. F. Brown, Astrophys. J. **722**, 33 (2010), 1005.0811.

NS data include:

- high precision mass extractions from Pulsar-timing measurements
- simultaneous mass-radius extractions from photospheric radius expansion (PRE) X-ray burst measurements
- thermal spectra measurement of low-mass X-ray Binaries (LMXB

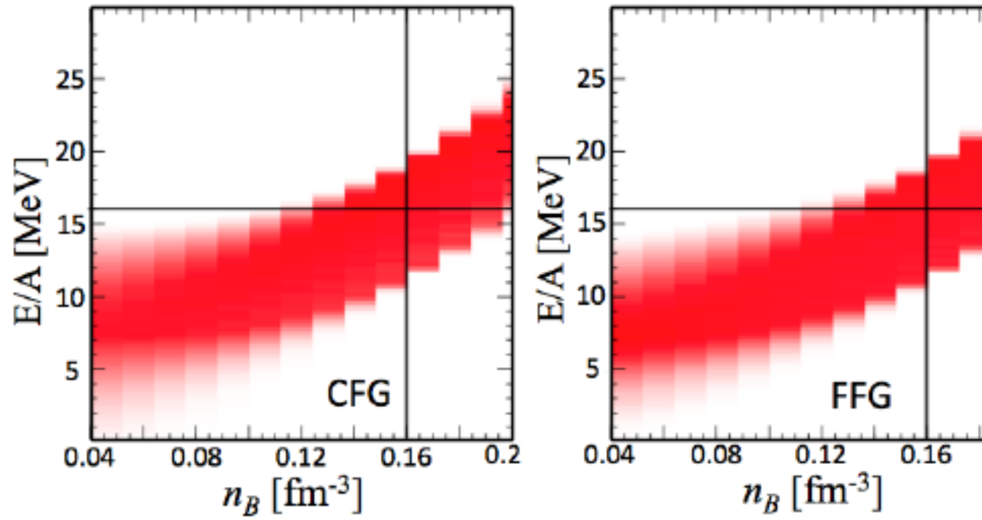
$$E^{pot}_{sym}(\rho/\rho_0) = S_{pot} \cdot (\rho/\rho_0)^{\gamma} = (S_v - S_{kin}) \cdot (\rho/\rho_0)^{\gamma},$$

Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

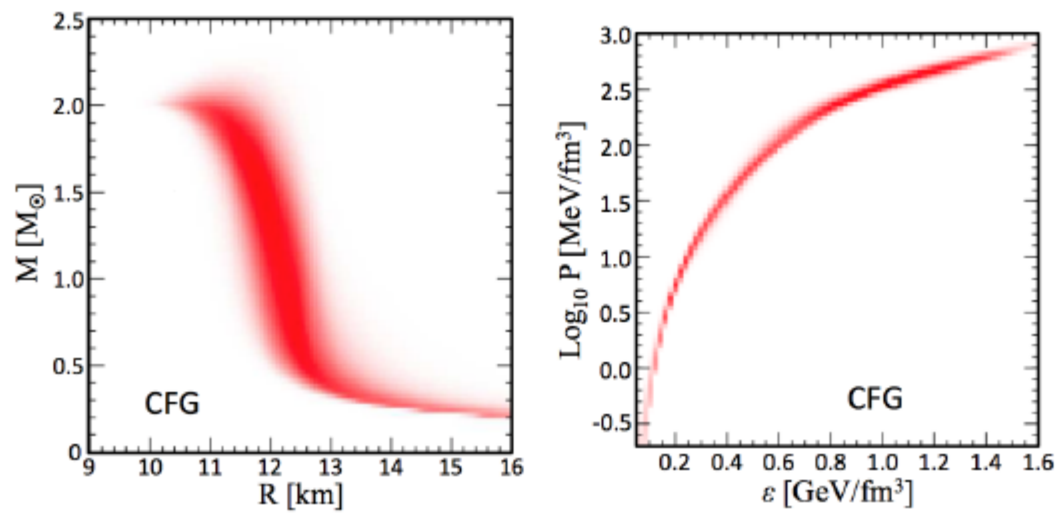
O. Hen,[1] A.W. Steiner,[2,3,4] E. Piasetzky,[1] and L.B. Weinstein[5]

Bayesian analysis of neutron stars observations

TEL AVIV UNIVERSITY



r online) The extracted energy per particle as a

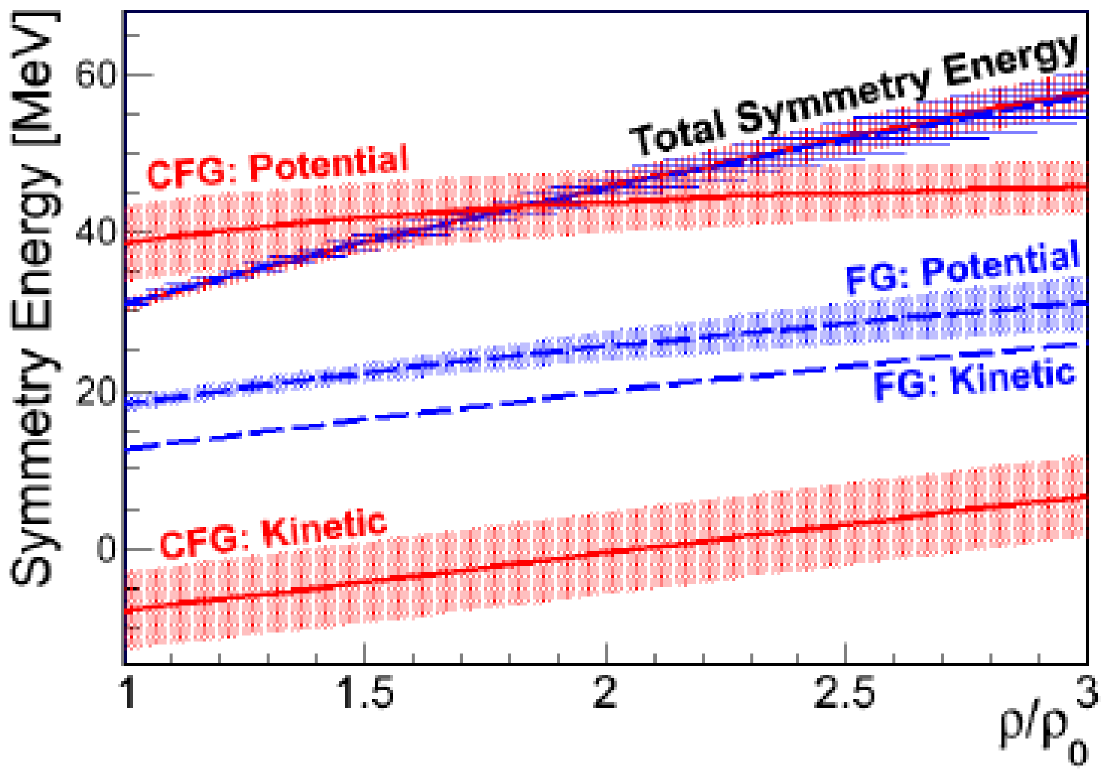


Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

O. Hen,[1] A.W. Steiner,[2,3,4] E. Piasetzky,[1] and L.B. Weinstein[5]

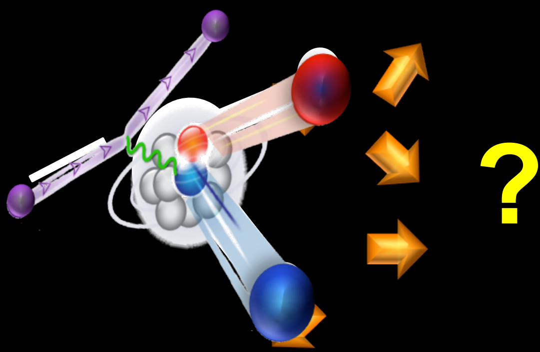
Density dependence of Symmetry Energy

Without Tensor Correlations (FFG) / with (CFG):



	$E^{kin}_{sym}(\rho_0)$ [MeV]	γ $\pm 1\sigma(2\sigma)$
CFG	-10 ± 3	0.25 ± 0.05
FG	-10 ± 3	0.58 ± 0.05
	0	0.55 ± 0.06
	12.5	0.48 ± 0.10
	17.0	0.41 ± 0.13

Need an observable sensitive to the potential (not total) Symmetry Energy



Tensor correlations:

Breaks the Fermi Gas picture

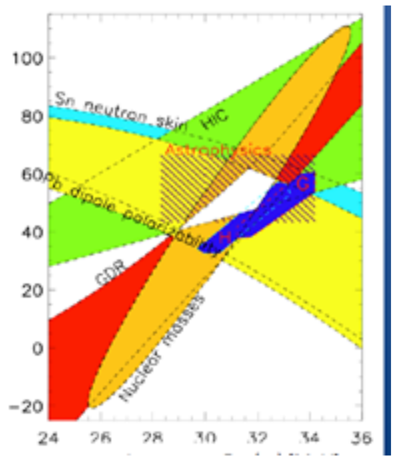
Reduce the kinetic symmetry Energy (at ρ_0)

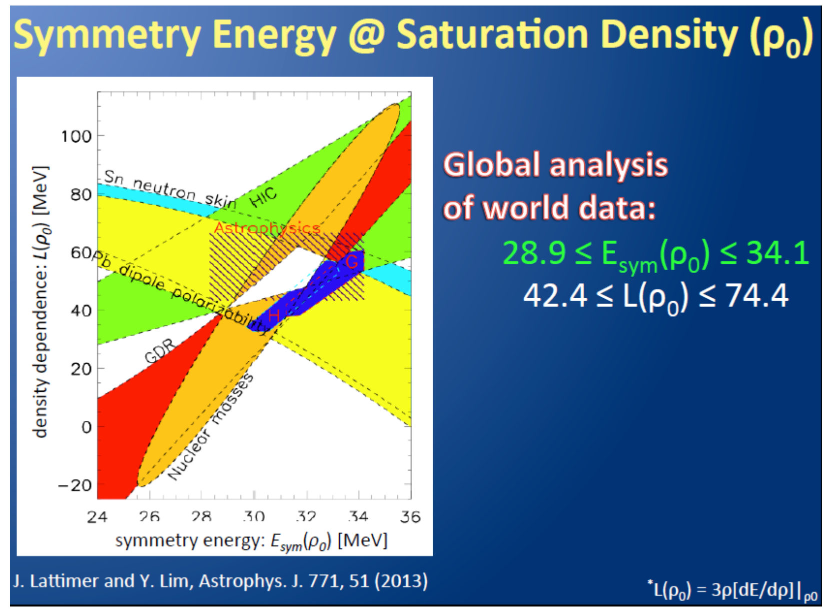
Enhance the potential symmetry Energy (at ρ_0)

Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems and HI Reactions ?

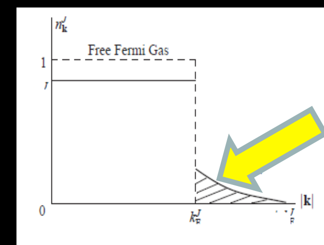
S


100
80
60
40
20
0
−20
24
26
28
30
32
34
36
Sn neutron skin
HIC
Astrophysics
Pb dipole polarizability
GDR
Nuclear masses
H
G


Symmetry Energy @ Saturation Density (ρ0)
Global analysis
of world data:
28.9 ≤ Esym(ρ0) ≤ 34.1
42.4 ≤ L(ρ0) ≤ 74.4
density dependence: L(ρ0) [MeV]
symmetry energy: Esym(ρ0) [MeV]
Sn neutron skin
HIC
Astrophysics
Pb dipole polarizability
GDR
Nuclear masses
H
G
100
80
60
40
20
0
−20
24
26
28
30
32
34
36
J. Lattimer and Y. Lim, Astrophys. J. 771, 51 (2013)
*L(ρ0) = 3ρ[dE/dρ]|ρ0

Tensor correlations (np - dominace):

Breaks the Fermi Gas picture



?

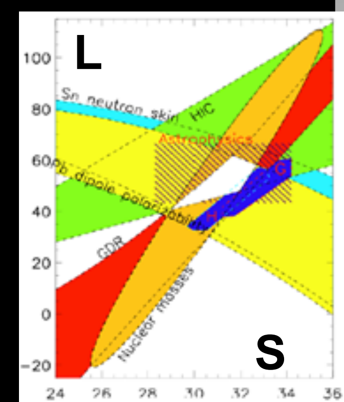
in SNM (np- pairs) in PNM (nn- pairs)

in n-stars (?)

Reduce the kinetic symmetry Energy (at ρ_0)

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

Enhance the potential symmetry Energy (at ρ_0)

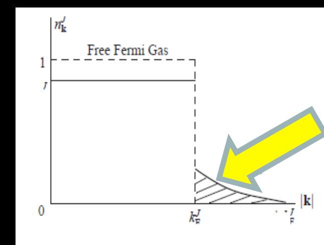


Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems and HI Reactions ?

Tensor correlations (np - dominace):

Breaks the Fermi Gas picture



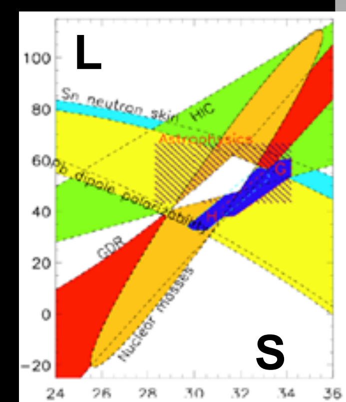
?

in SNM (np- pairs) in PNM (nn- pairs)

in n-stars (?)

Reduce the kinetic symmetry Energy (at ρ_0)

$$E_{sym}(\rho) \approx E(\rho)_{PNM} - E(\rho)_{SNM}$$

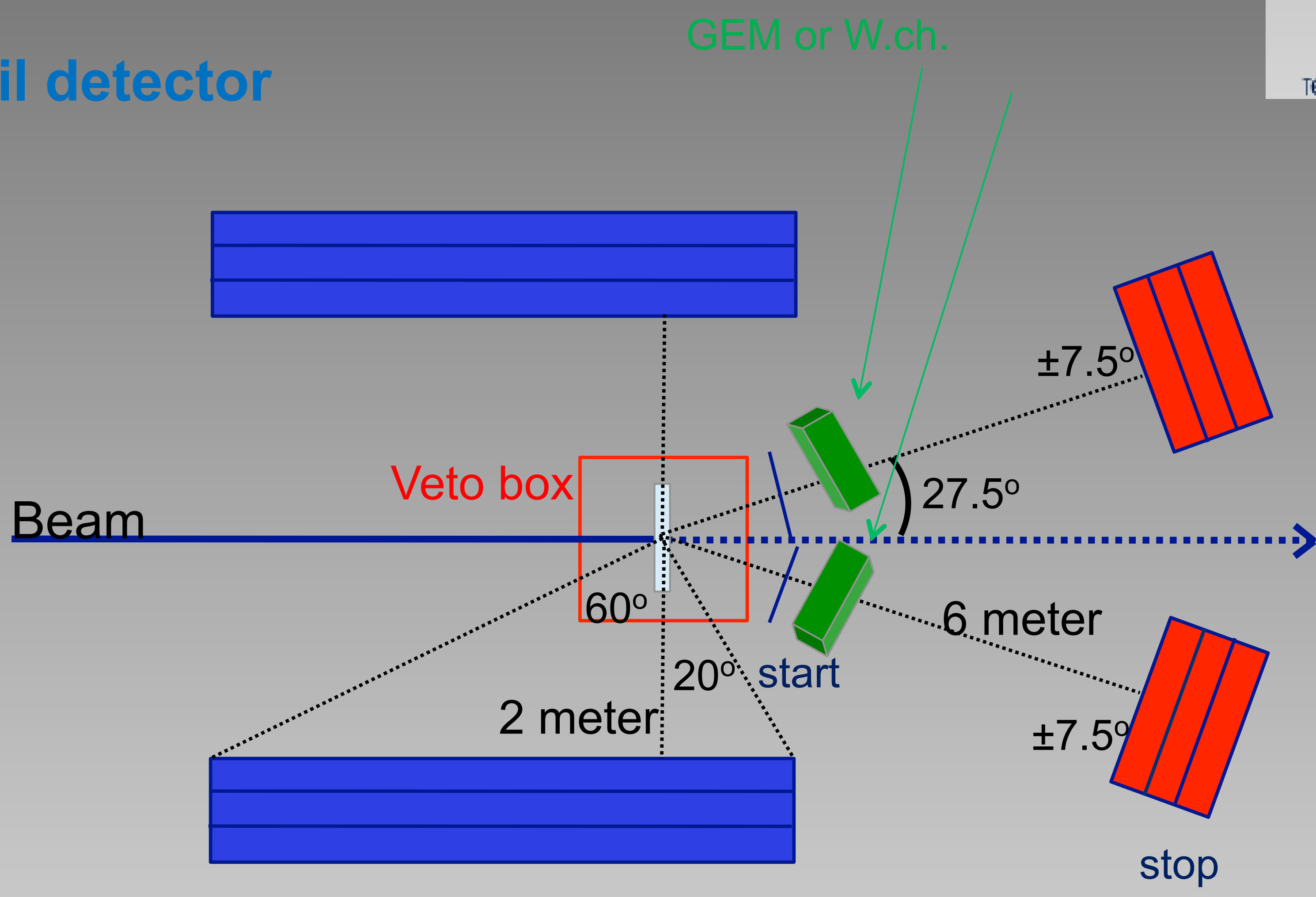


Enhance the potential symmetry Energy (at ρ_0)

Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems and HI Reactions ?

Recoil detector



Array of scintillators

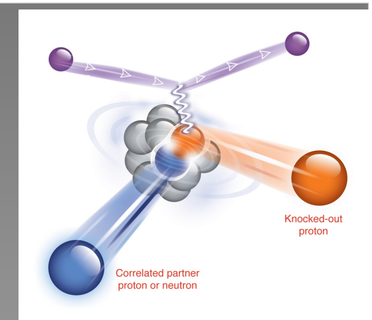
LAND, NeuLAND ?

σ_{TOF}<100ps

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

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

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

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

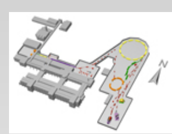
$\mathrm{C, Al, Fe, Pb}\,(e,e'pp)$

A window of opportunity:

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

Nuclotron

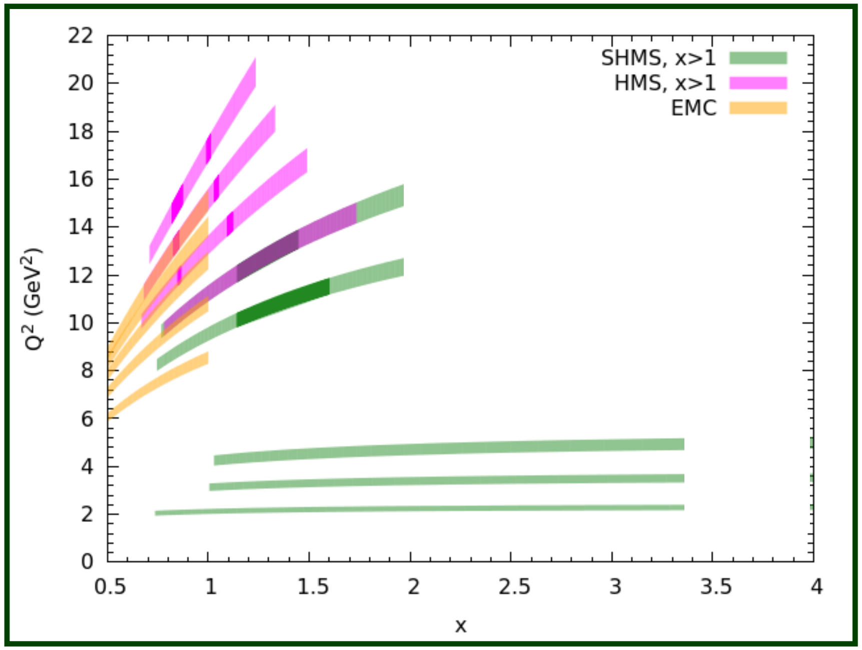
Dubna



GSI / FAIR

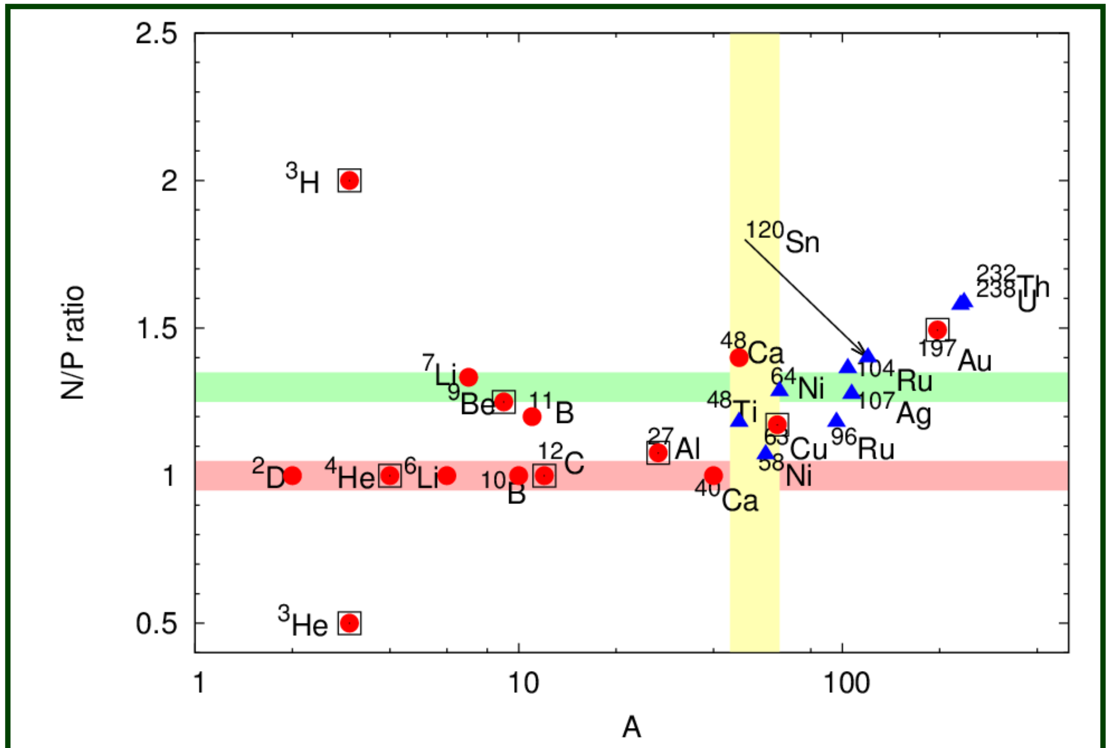
J-PARC

➔ **>10k events Before 2020**



Jlab E12-06-105

- short-range nuclear structure
  - Isospin dependence
  - A-dependence
- Super-fast quarks



Coming very soon: [Jlab E12-11-112]

- Quasielastic electron scattering with ^3H and ^3He
- Study isospin dependence of 2N and 3N correlations
- Test calculations of FSI for well-understood nuclei