Short-Range Correlations and Nuclear Universality

Or Hen – MIT

R^3B Collaboration Meeting,
April 5th 2017, Darmstadt, Germany.

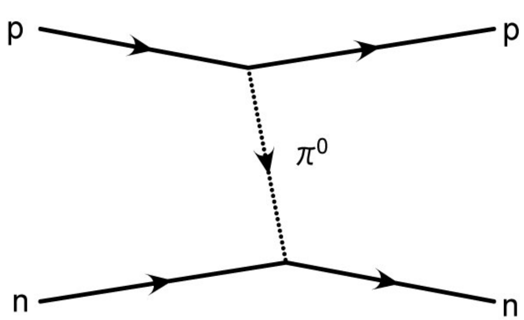
Nuclear Many-Body Challenge

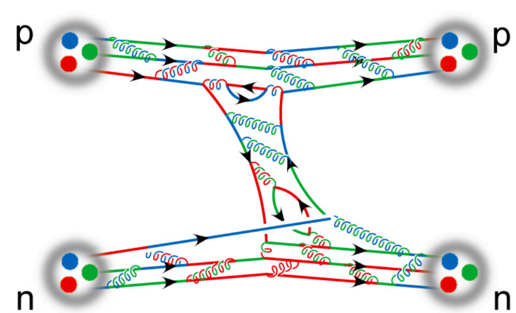
Many-body Schrödinger Equation

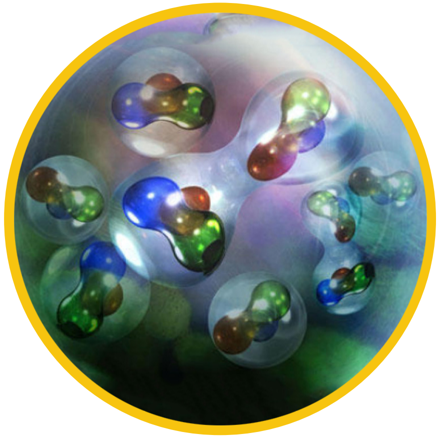
$$\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, \dots, \vec{r}_N, t) \right\} + U(\vec{r}_1, \dots, \vec{r}_N)\Psi(\vec{r}_1, \dots, \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \dots, \vec{r}_N, t)$$

Main Challenges:

1. No 'fundamental' Interaction.
2. Complex phenomenological parametrizations (e.g. over 18 operators)

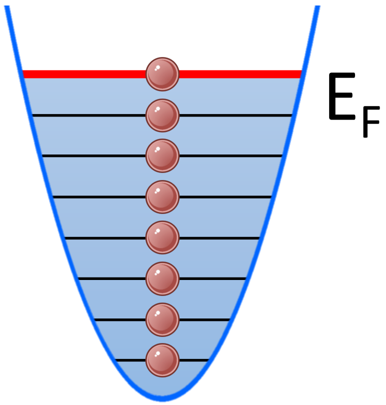






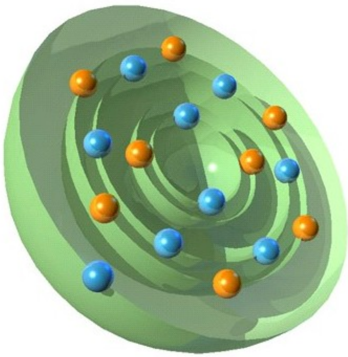
Solution: Effective Theories

Fermi Gas Model

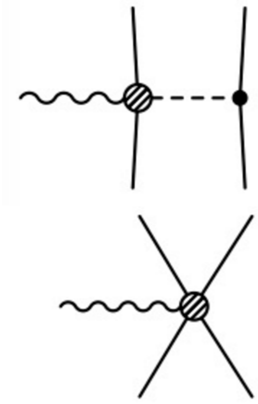


Liquid Drop Model

Shell Model

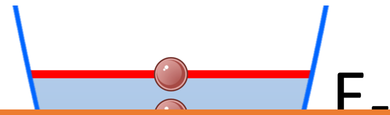


Chiral Perturbation Theory

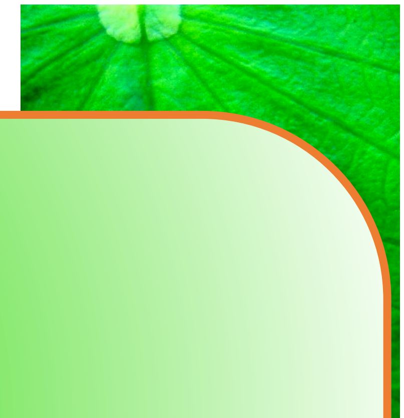


Solution: Effective Theories

Fermi



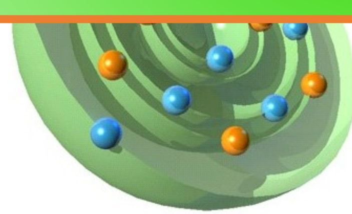
Liquid



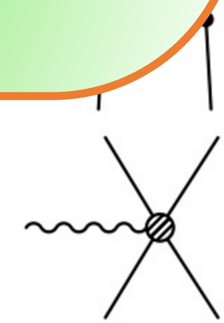
Common idea:

Scale separation of *long* and *short* range dynamics

Model

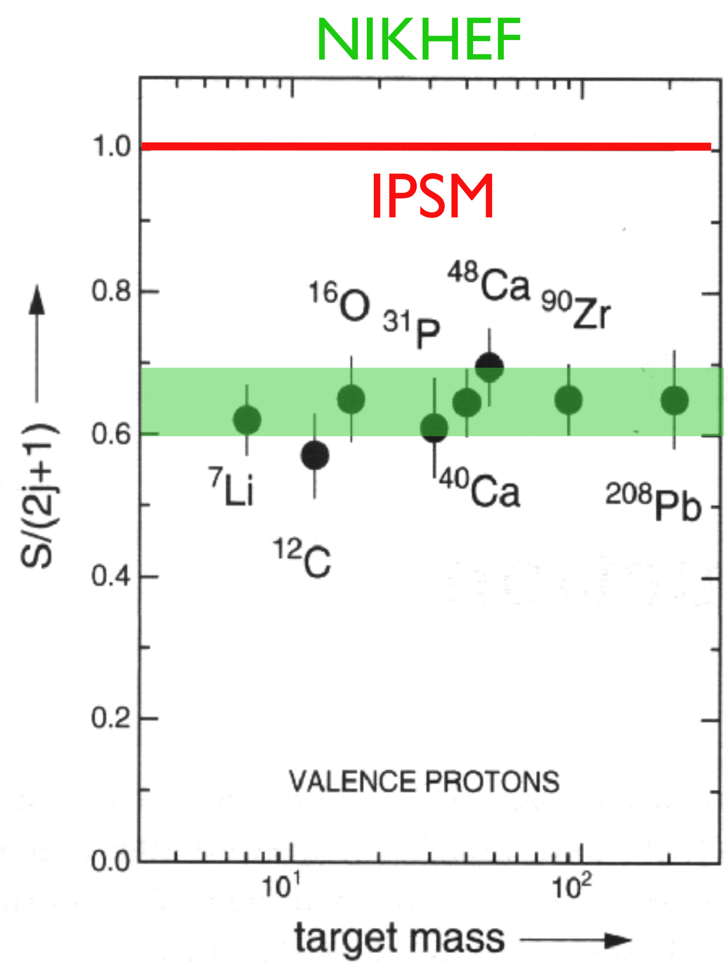


Perturbation Theory



Universality of long-range dynamics

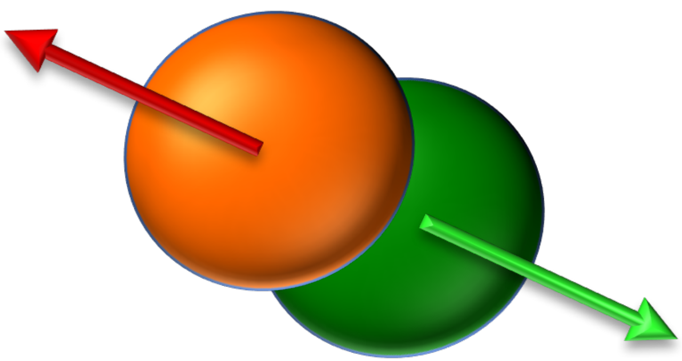
- Long-range (low-momentum) structure of nuclei studied for many years.
- Mean-field models give good description of this part of the ground state.
- Two big questions:
  - How important are of the short-range dynamics?
  - Is there an effective, *universal*, way to include them?

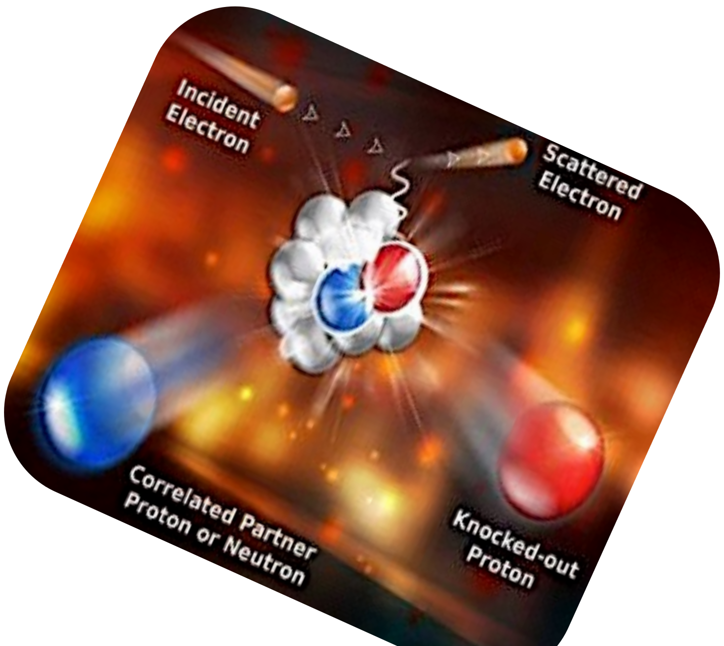


What Are SRC?

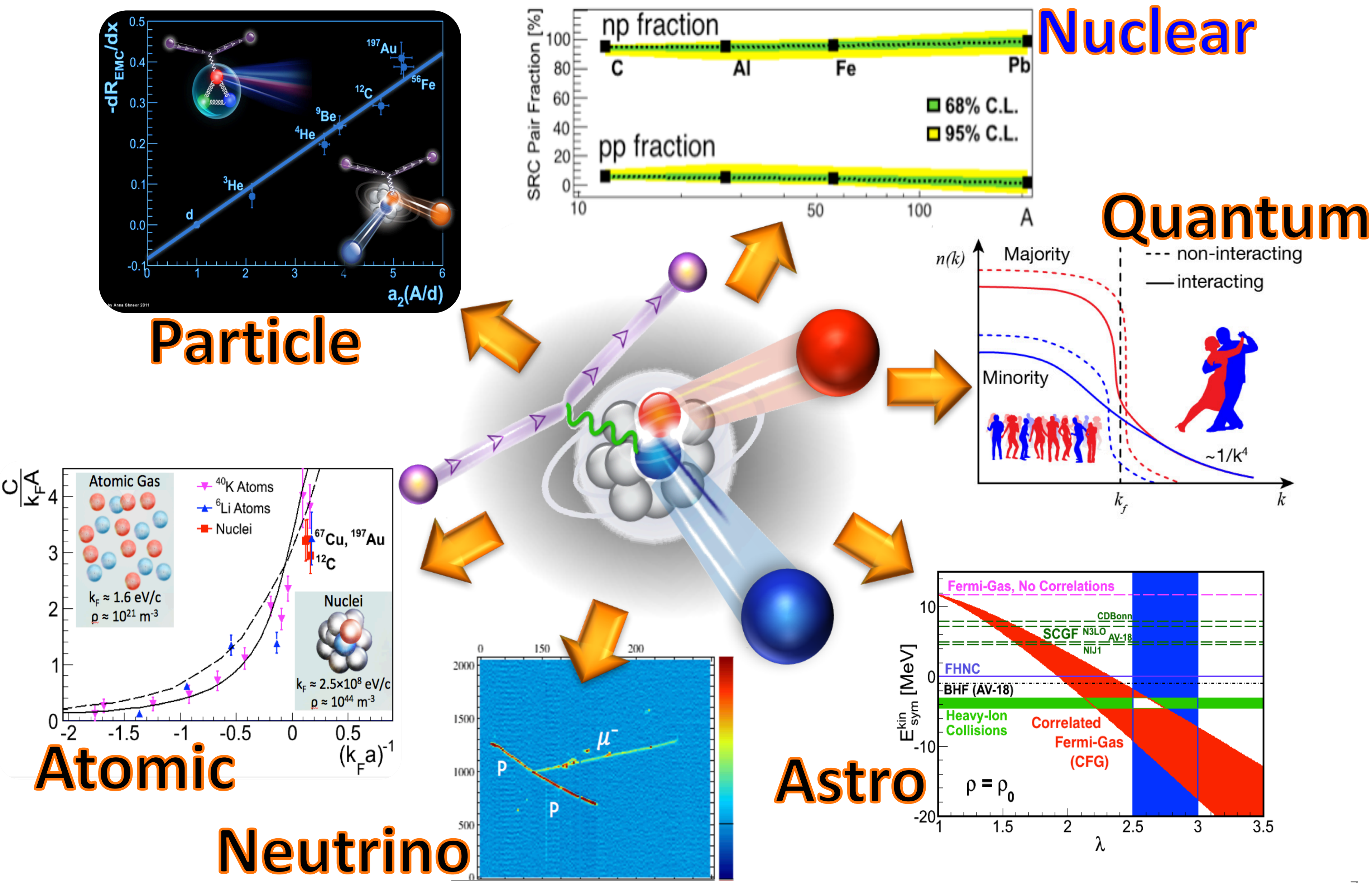
SRC are pairs of nucleon that are close together in the nucleus (wave functions overlap)

=> Momentum space: pairs with *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)



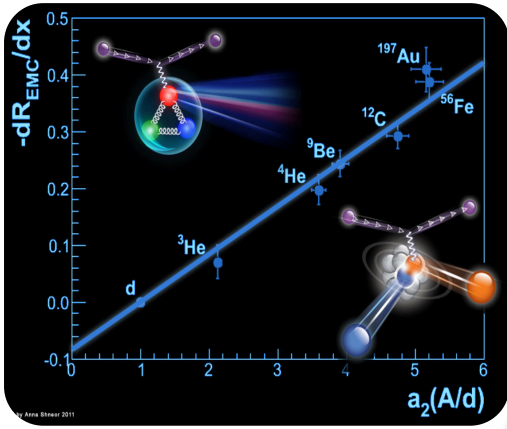


Why SRC?


Nuclear
np fraction
pp fraction
SRC Pair Fraction [%]
C
Al
Fe
Pb
68% C.L.
95% C.L.
A
Quantum
Majority
Minority
non-interacting
interacting
n(k)
k
k_f
~1/k^4
Particle
$-dR_{EMC}/dx$
$a_2(A/d)$
d
^{3}He
^{4}He
^{9}Be
^{12}C
^{56}Fe
^{197}Au
Atomic
Atomic Gas
$k_F \approx 1.6$ eV/c
$\rho \approx 10^{21}$ m^{-3}
^{40}K Atoms
^{6}Li Atoms
Nuclei
^{67}Cu, ^{197}Au
^{12}C
$k_F \approx 2.5\times10^8$ eV/c
$\rho \approx 10^{44}$ m^{-3}
$\frac{C}{k_F A}$
$(k_F a)^{-1}$
Neutrino
μ^-
P
P
Astro
Fermi-Gas, No Correlations
CDBonn
SCGF
N3LO
AV-18
NIJ1
FHNC
BHF (AV-18)
Heavy-Ion Collisions
Correlated Fermi-Gas (CFG)
$\rho = \rho_0$
E^{kin}_{sym} [MeV]
λ

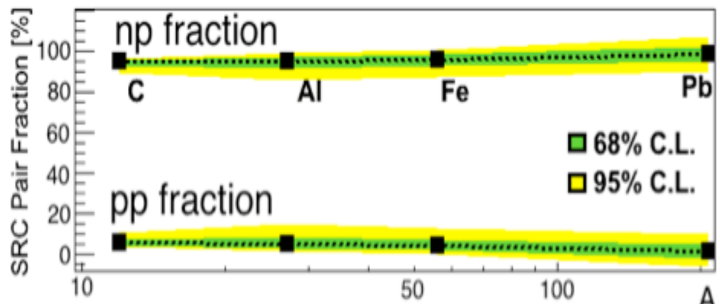
Why SRC?

Particle

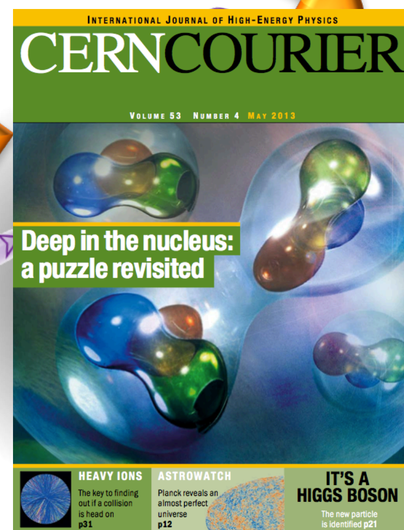


PRL **106**, 052301 (2011),
PRD **84**, 117501(2011),
PRC **85**, 047301(2012),
IJMPE **22**, 1330017 (2013),
arXiv 1607.03065 (2016).

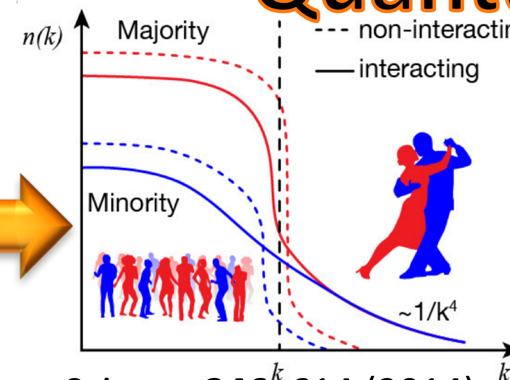
Nuclear



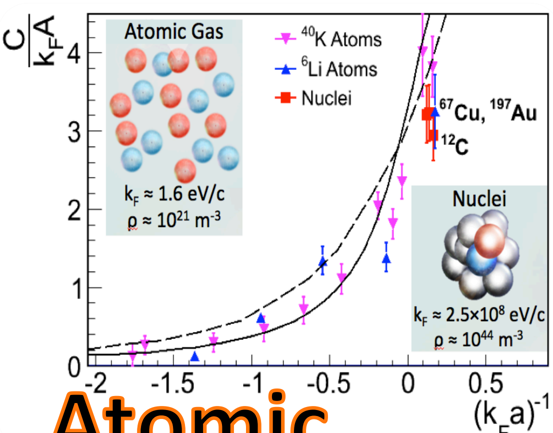
Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB 772, **63** (2013),
PRL **113**, 022501 (2014),
PRC **92**, 024604 (2015).



Quantum

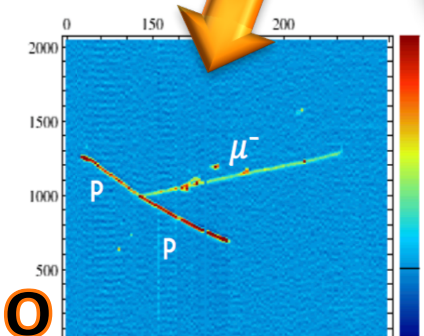


Science **346**, 614 (2014).



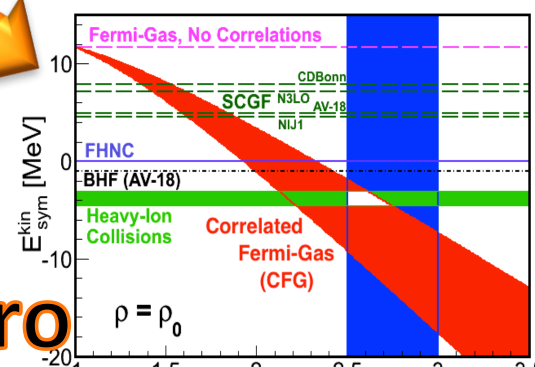
Atomic

PRC **92**, 045205 (2015).



Neutrino

PRD **90**, 012008 (2014); PRC **94**, 045501 (2016)



Astro

PRC **91**, 025803 (2015), PRC **93**, 044610 (2016),
PRC **91**, 044601 (2015), PRC **93**, 014619 (2016),
PRC **92**, 011601 (2015), PLB **759**, 79 (2016),
arXiv: 1608.00487 (2016); 1606.08045 (2016)

Why SRC?

You can't do nuclei without correlations!

Today:

What? (do we know)

How? (do we know it)

Where? (do we go from here)

You can’t do nuclei without correlations!

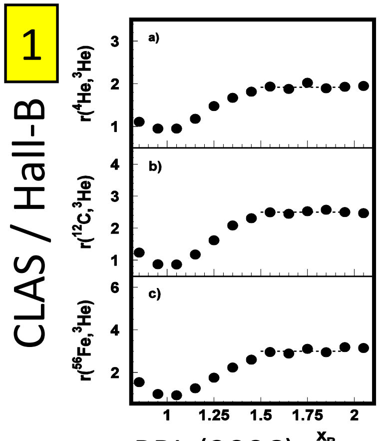
What? (do we know about SRC)

1 Account for ~ 25% of nucleons in nuclei.

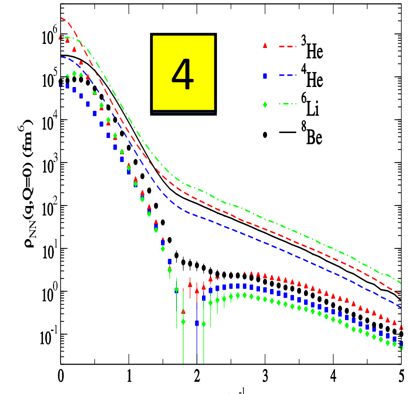
2 Dominate the momentum distribution for k ≥ 300 MeV/c.

3 Probability for np-SRC is ~18 times larger than pp-SRC. Also true for heavy asymmetric nuclei.

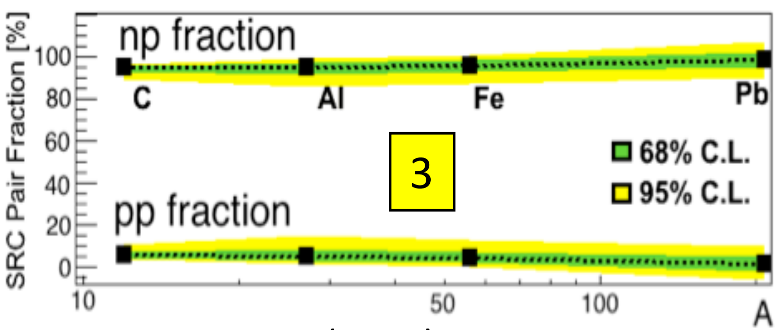
4 Dominant NN force in the 2N-SRC is tensor force.
High momentum tail (300-600 MeV/c)
dominated by L=0,2 S=1 np-SRC pairs.



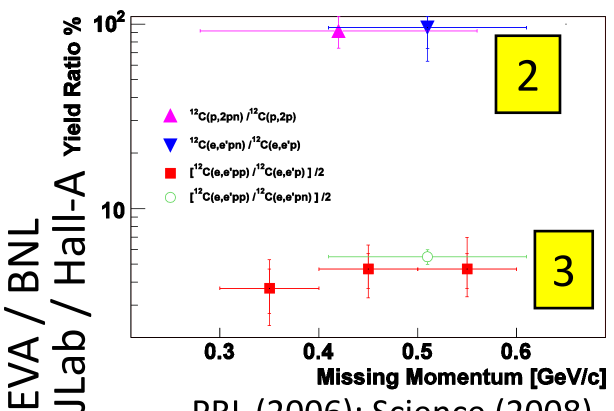
PRL (2006)



PRL (2007)

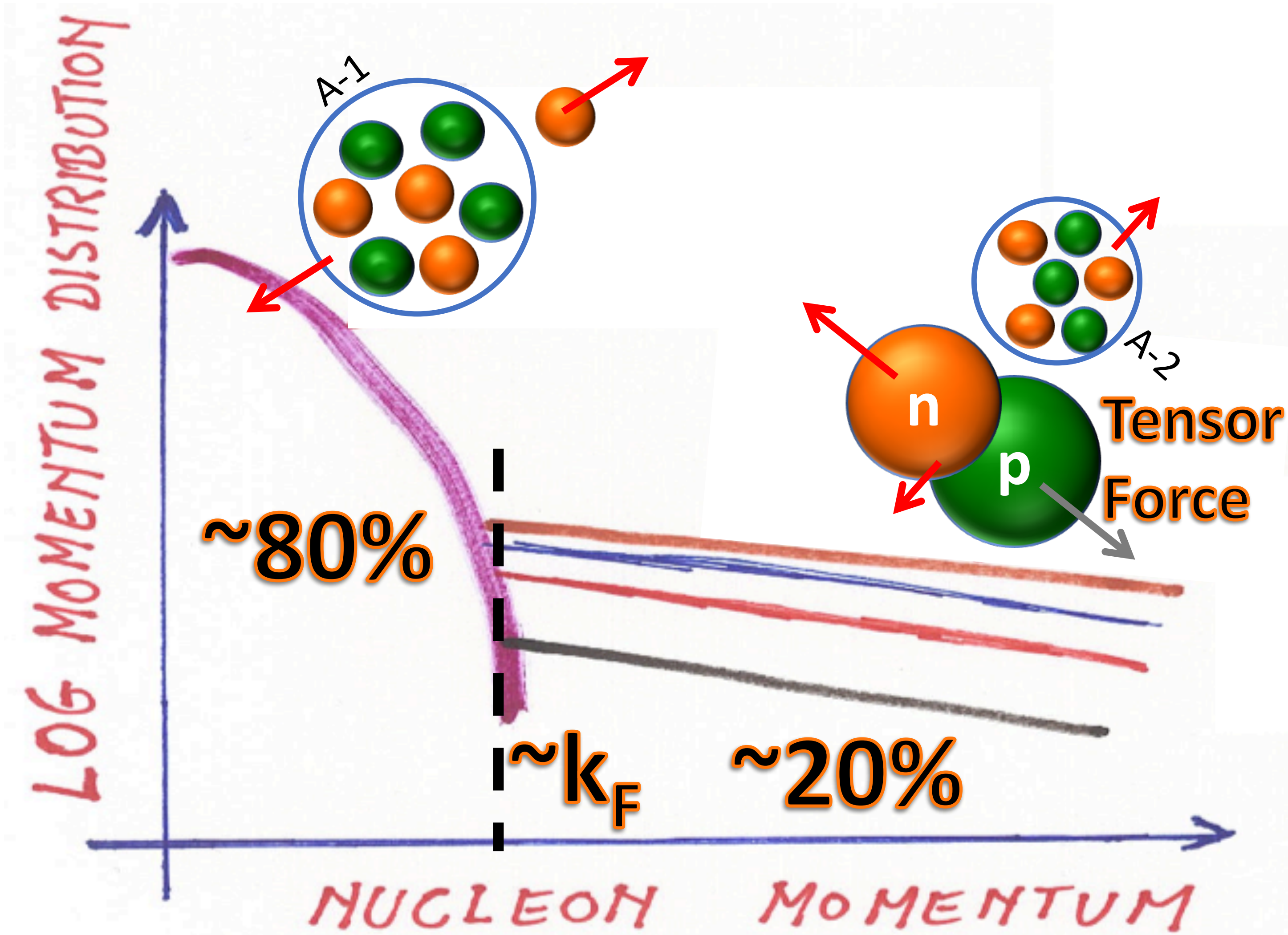


Science 346, 614 (2014)



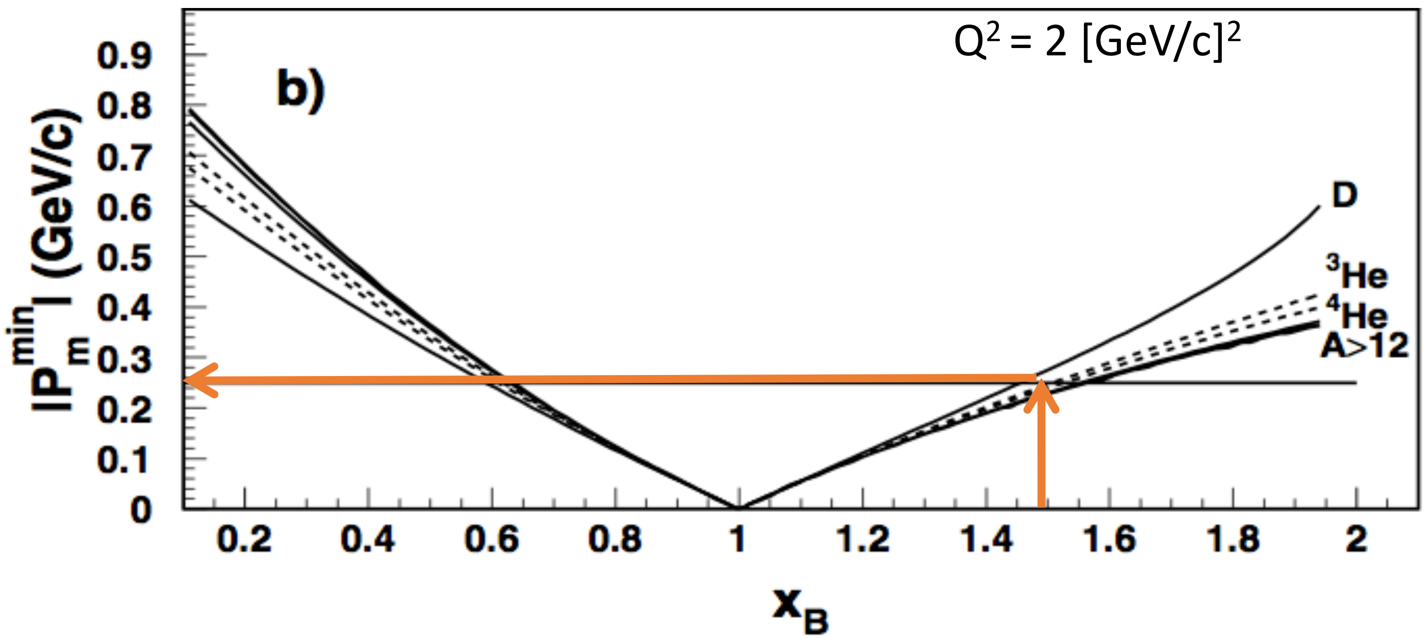
PRL (2006); Science (2008).

What? (do we know about SRC)



How? (do we get 25%)

(e,e') cross section at different kinematics is sensitive to different 'parts' of the nuclear momentum distribution.



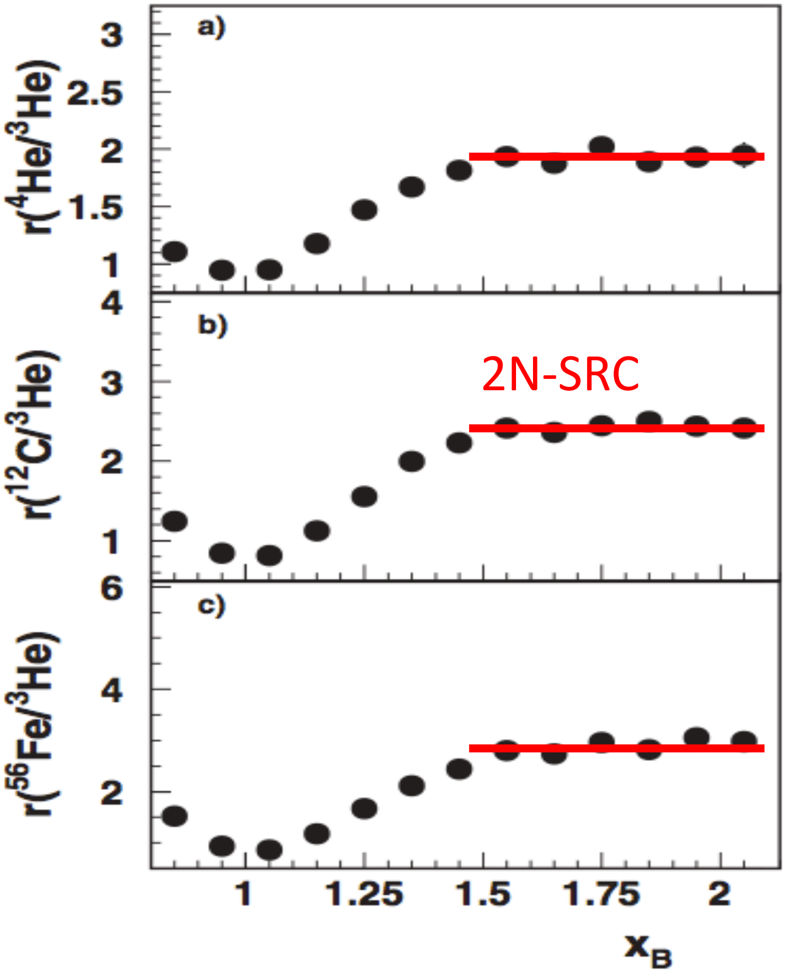
$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2$$

How? (do we get 25%)

- A/d (e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$

- Observed scaling in for $x_B \geq 1.5$.

=> $n_A(k>k_F) = a_2(A) \times n_d(k)$



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

L. Frankfurt et al. , Phys. Rev. C **48**, 2451 (1993).
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003). N. Fomin et al., Phys. Rev. Lett. **108**, 092502 (2012).

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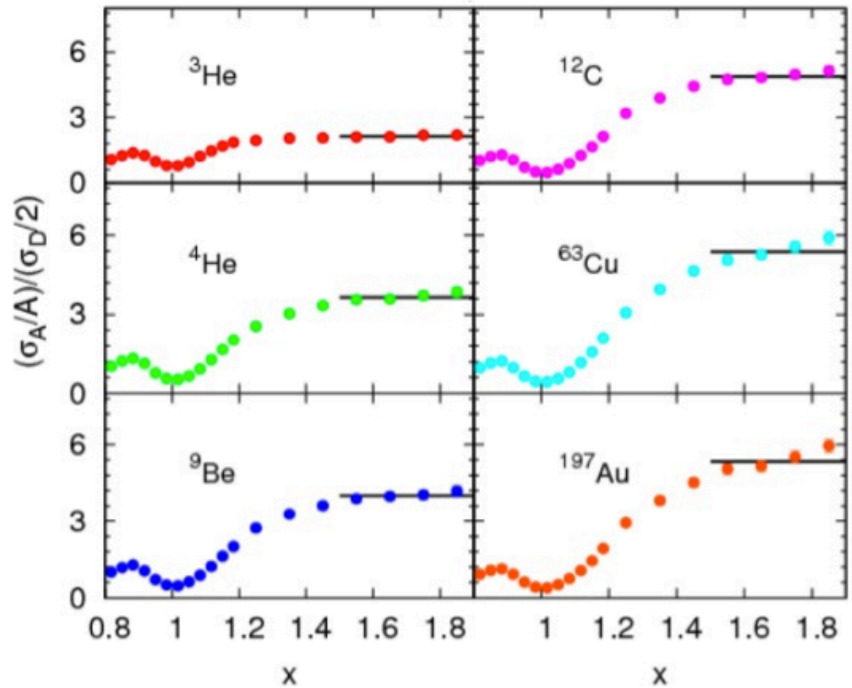
$$\Rightarrow n_A(k>k_F) = a_2(A) \times n_d(k)$$



N. Fomin et al., PRL **108**, 092502 (2012)

A	a_2(A/D)	A	a_2(A/D)
^{3}He	2.1 ± 0.1	^{12}C	4.7 ± 0.2
^{4}He	3.6 ± 0.1	^{63}Cu	5.2 ± 0.2
^{9}Be	3.9 ± 0.1	^{197}Au	5.1 ± 0.2

O. Hen et al., PRC **85**, 047301 (2012)

L. Frankfurt et al. , Phys. Rev. C **48**, 2451 (1993).
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003).

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

How? (do we get 25%)

Nuclei have a high-momentum tail!

1. It scales: $n_A(k>k_F) = a_2(A/d) \times n_d(k)$
2. Scale factor, a_2, determined experimentally
3. In A ≥ 12 nuclei, 20 – 25% of the nucleons have high-momentum ($k>k_F$).

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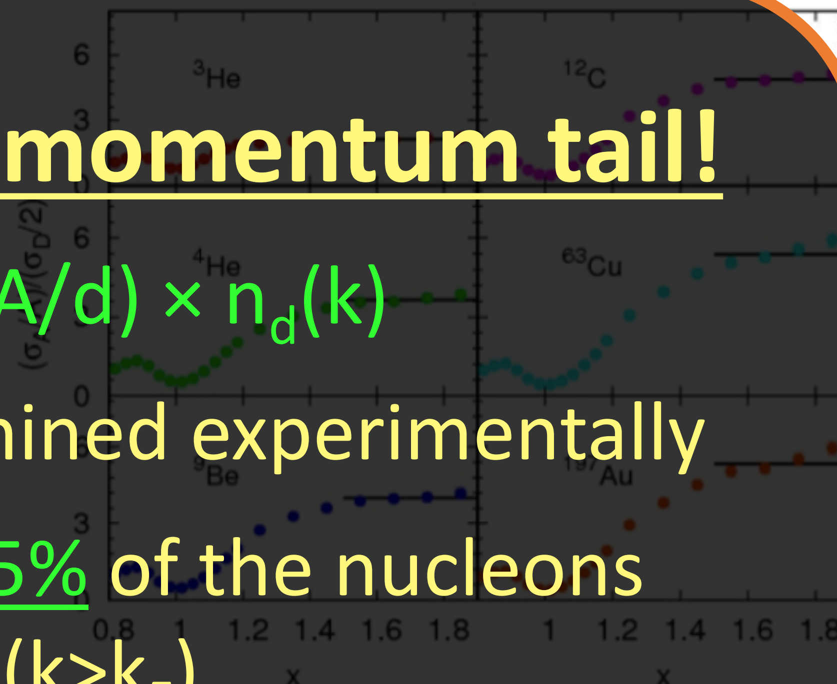
$=> n_A(k>k_F) = a_2(A) \times n_d(k)$



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

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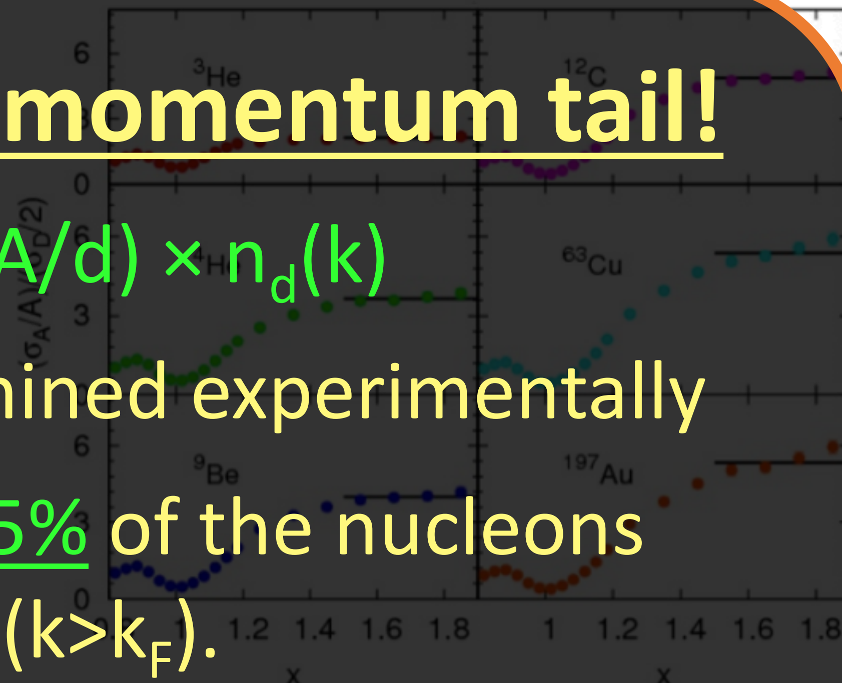
3. In A ≥ 12 nuclei, 20 – 25% of the nucleons have high-momentum ($k>k_F$).

Do ALL high-momentum nucleons come in pairs? What kind of pairs?



N. Fomin et al., PRL **108**, 092502 (2012)

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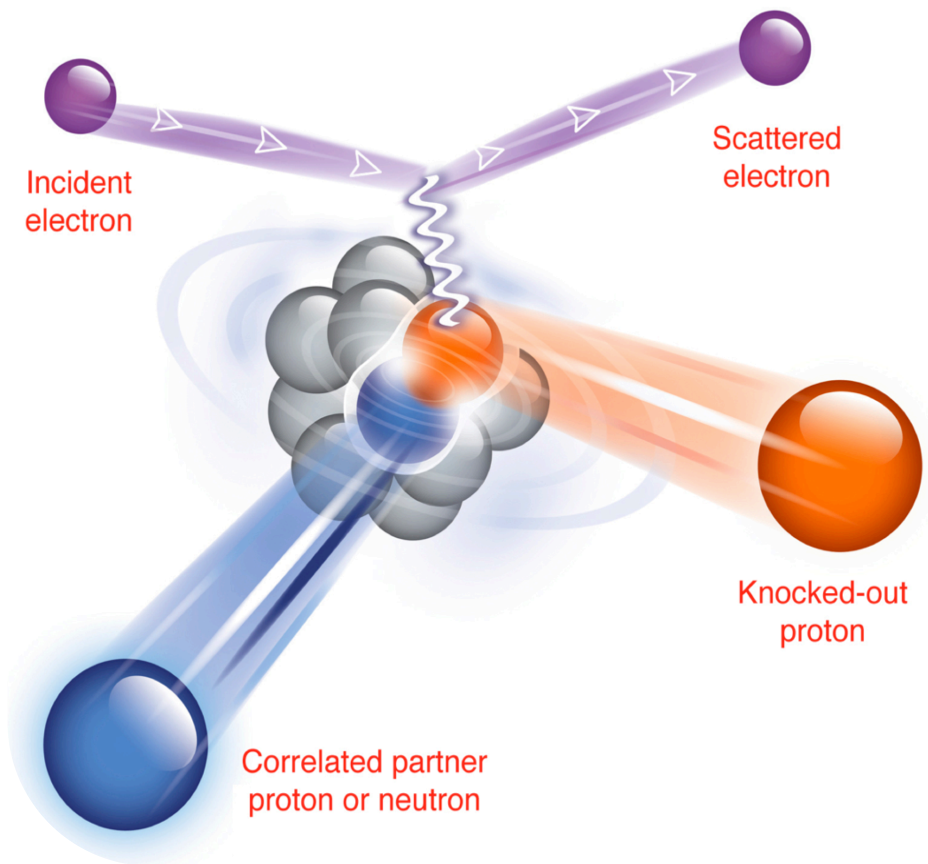
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003).

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

How? (do we get np dominance)

Breakup the pair =>
Detect both nucleons =>
Reconstruct ‘initial’ state



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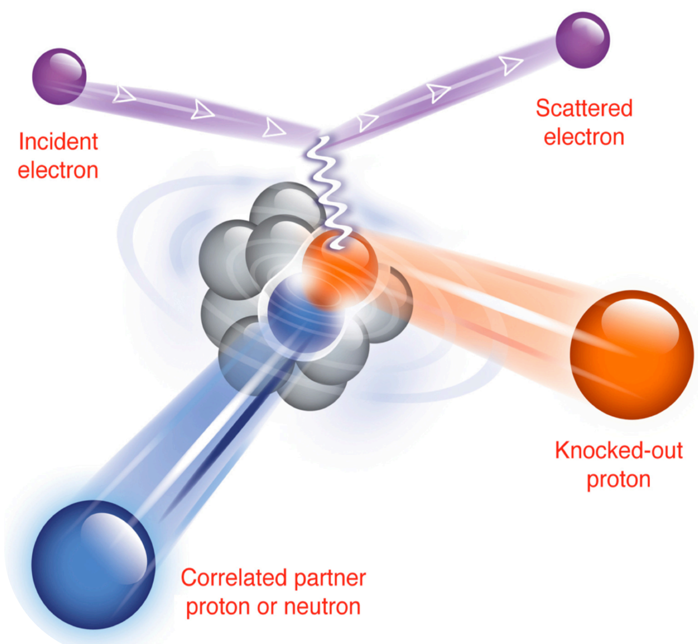
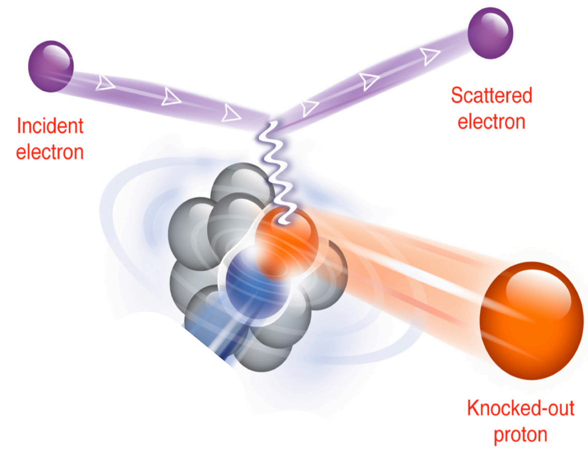
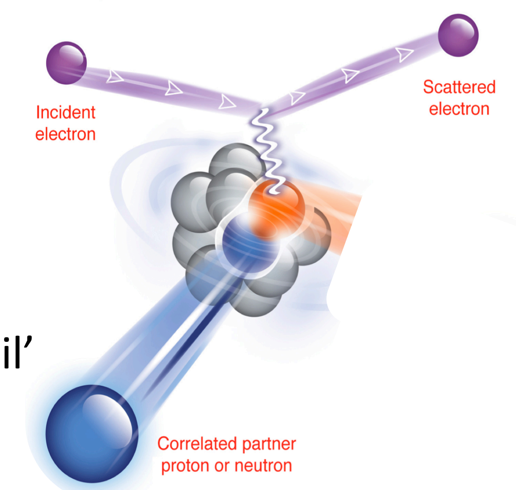




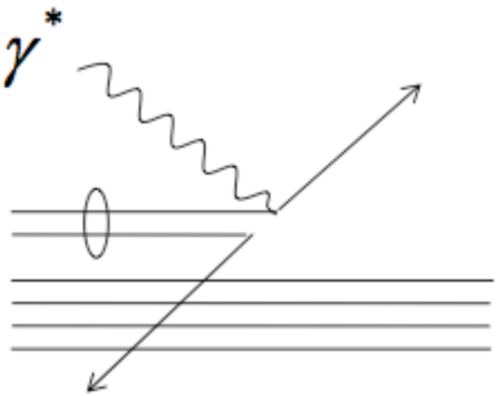
'leading'



'recoil'

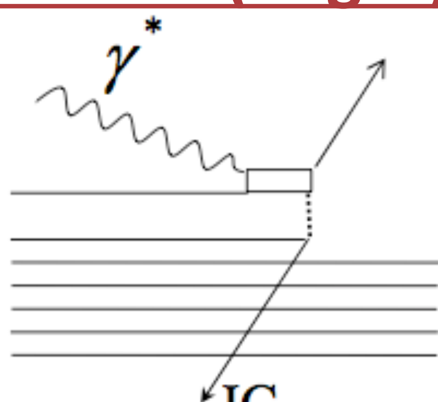
Issue: Reaction Mechanisms

What we want:

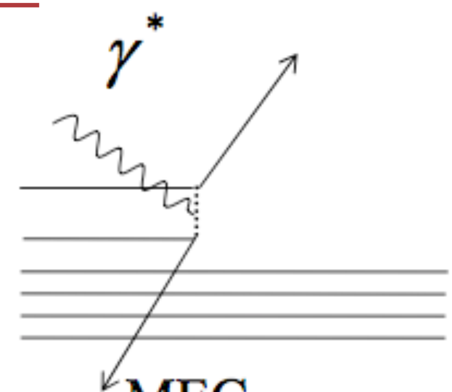


SRC

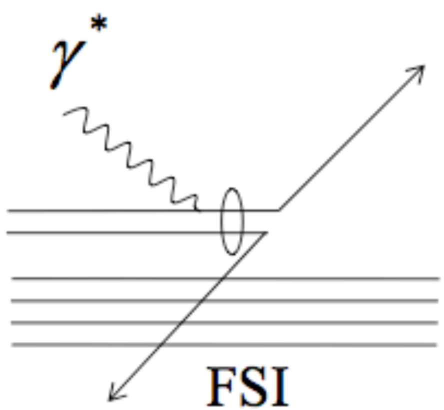
What we (might) get:



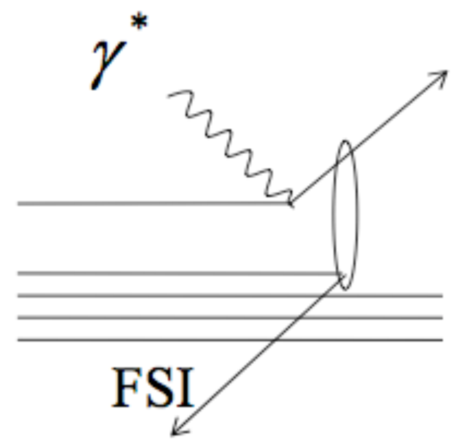
IC



MEC



FSI

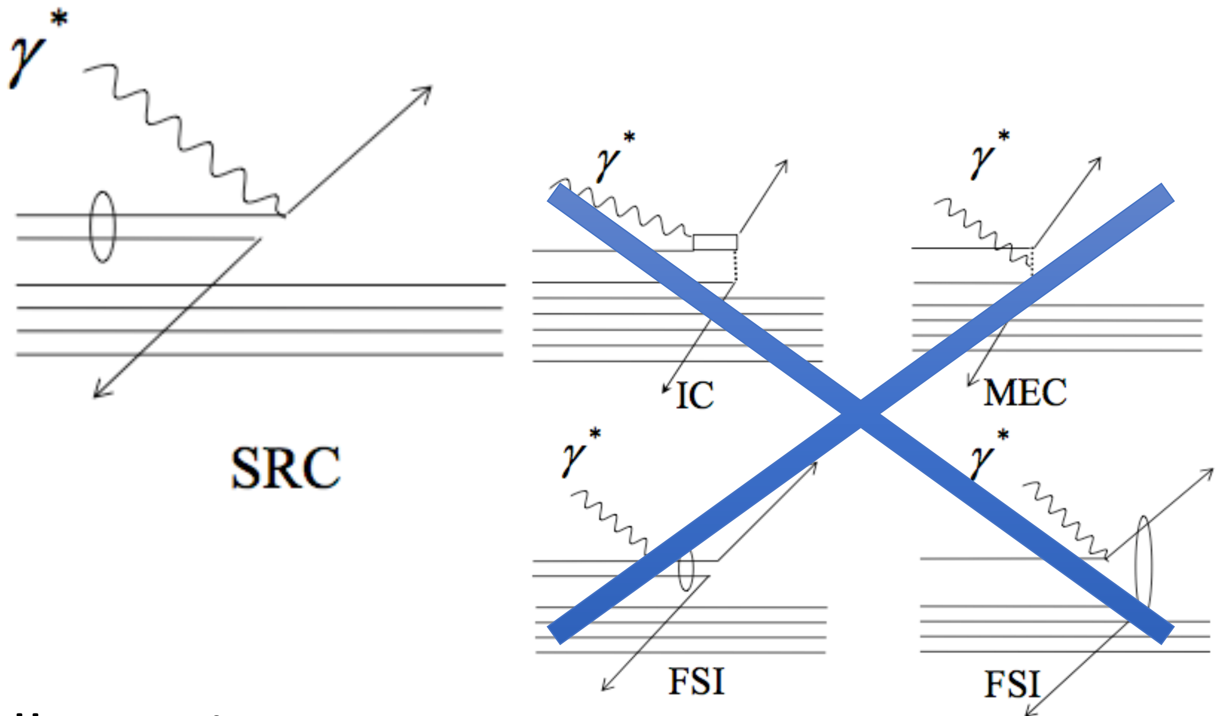


FSI

Solution: Hard Knockout Reactions!

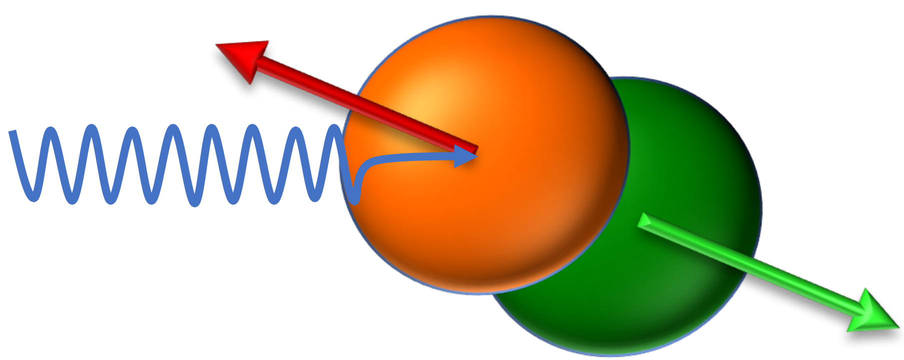
Trick: choose 'good' kinematics!

- $x_B > 1.2$
- $Q^2 \sim 2\ (GeV/c^2)$
- Anti-Parallel Kinematics

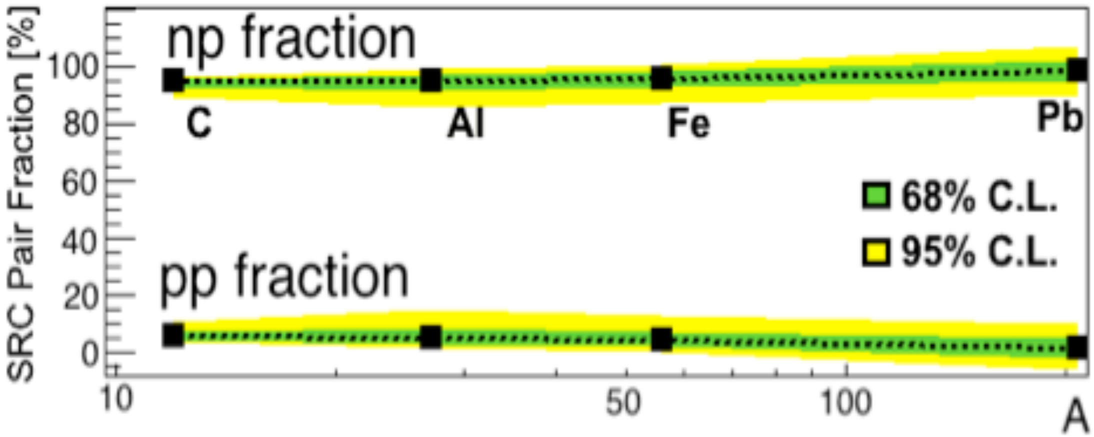


A word on FSI:

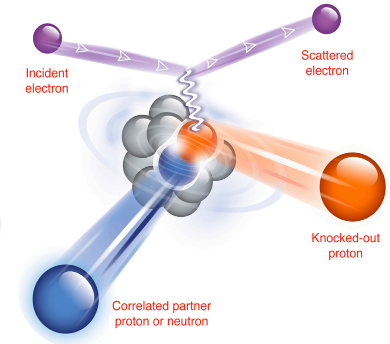
- Large-Q^2 (/ $|t,u,s|$) allow using the Eikonal approximation for FSI calculations.
- Combines with $x_B>1$ ensures FSI are confined to within the nucleons of the pair.

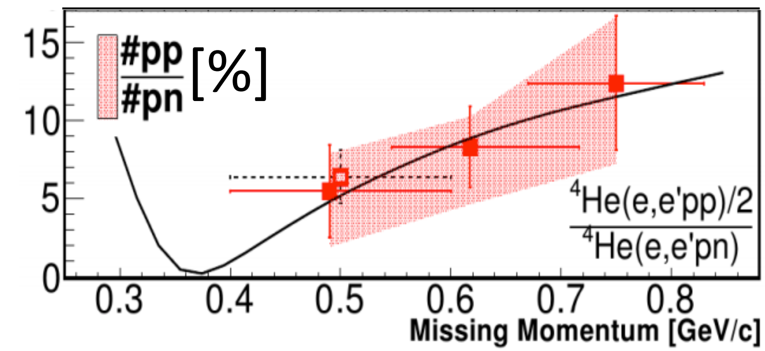


How? (do we get np dominance)



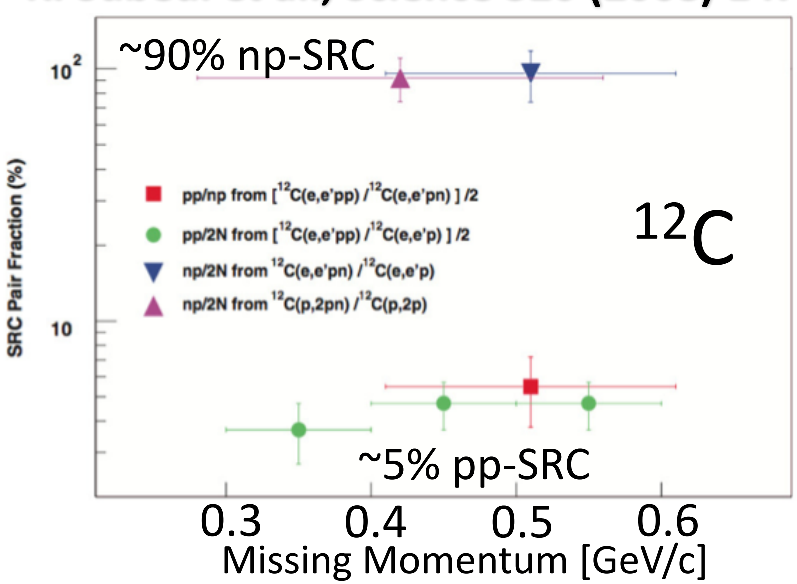
O. Hen et al., Science 364 (2014) 614

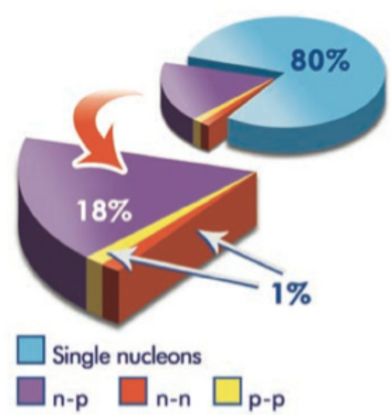


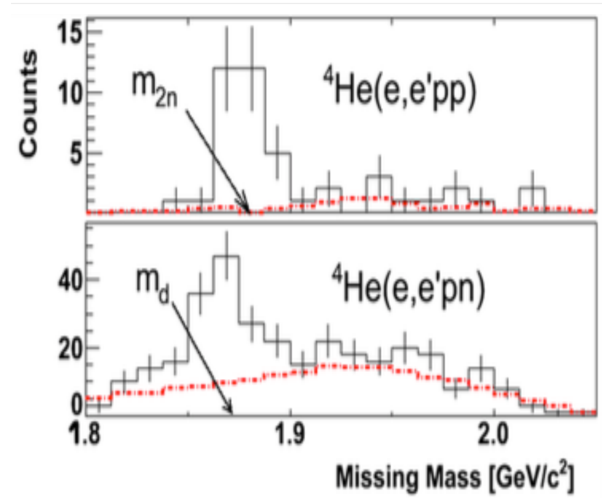


R. Subedi et al., Science 320 (2008) 1476

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



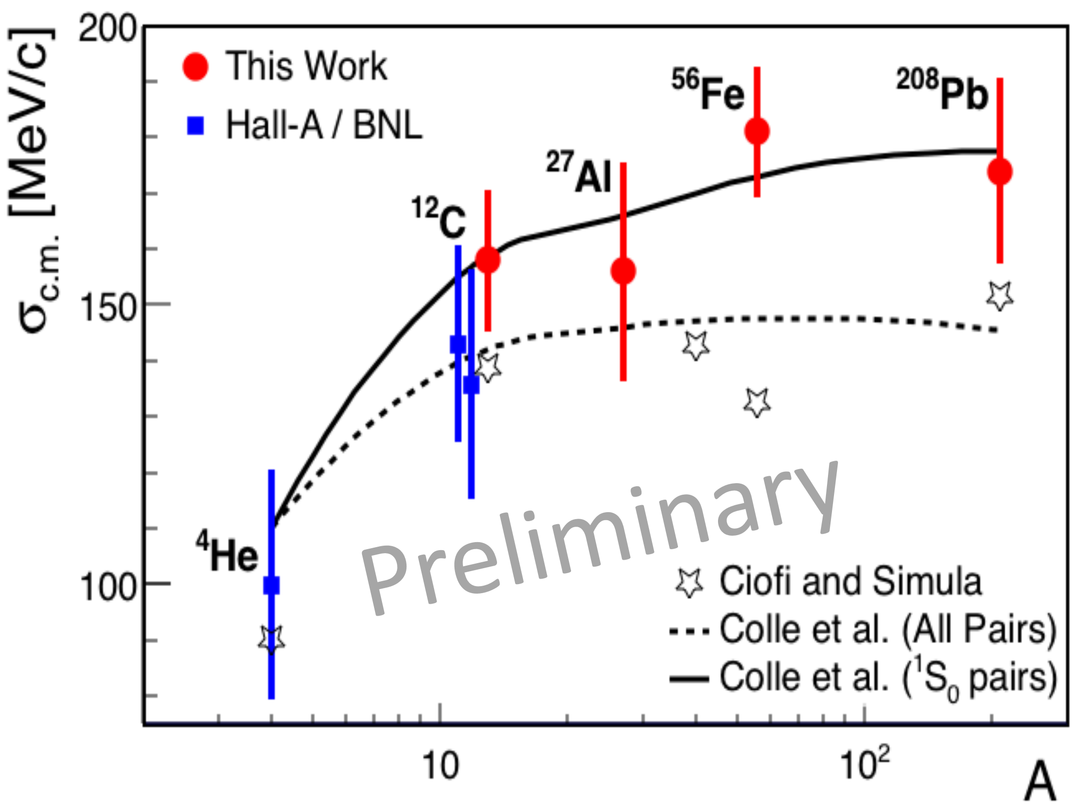


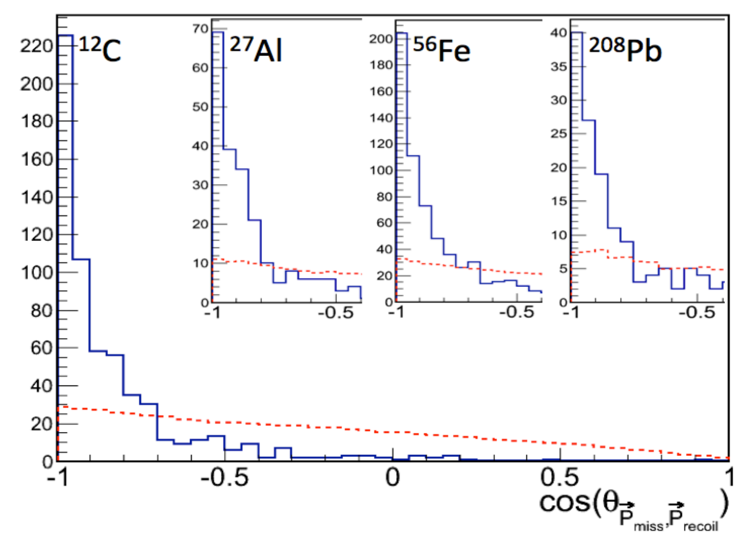


A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

How? (do we know its properties)

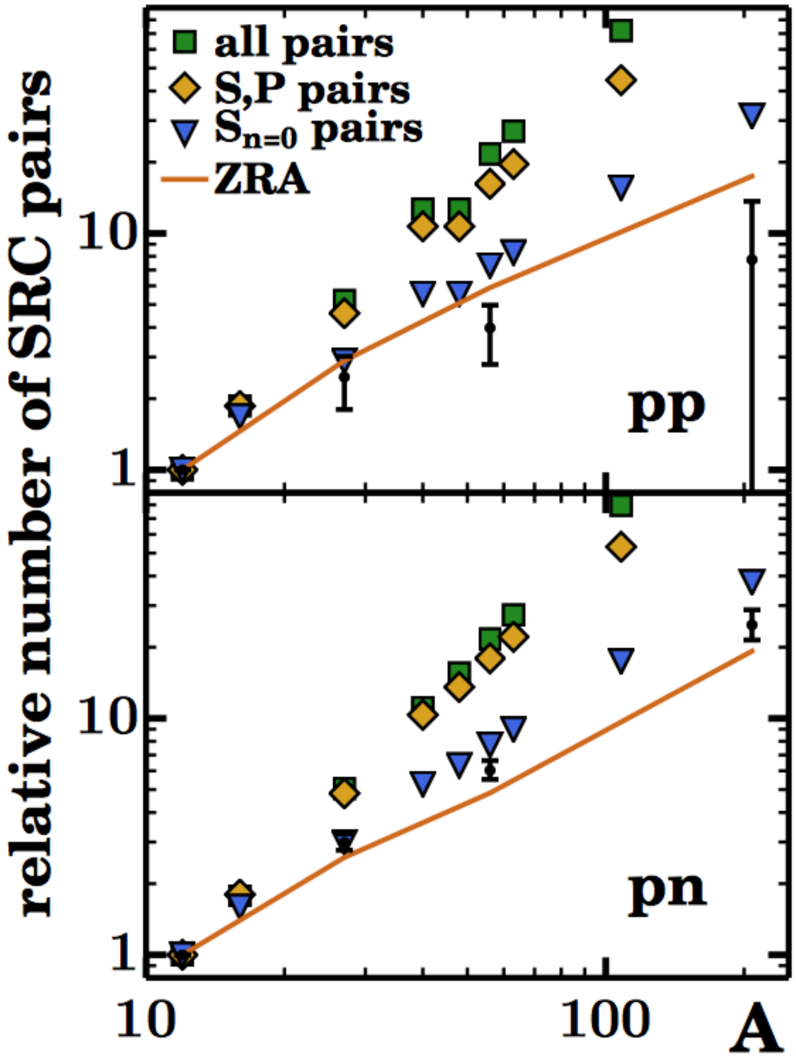
"… *high relative momentum* and ***low c.m. momentum*** compared to the Fermi momentum (k_F)"



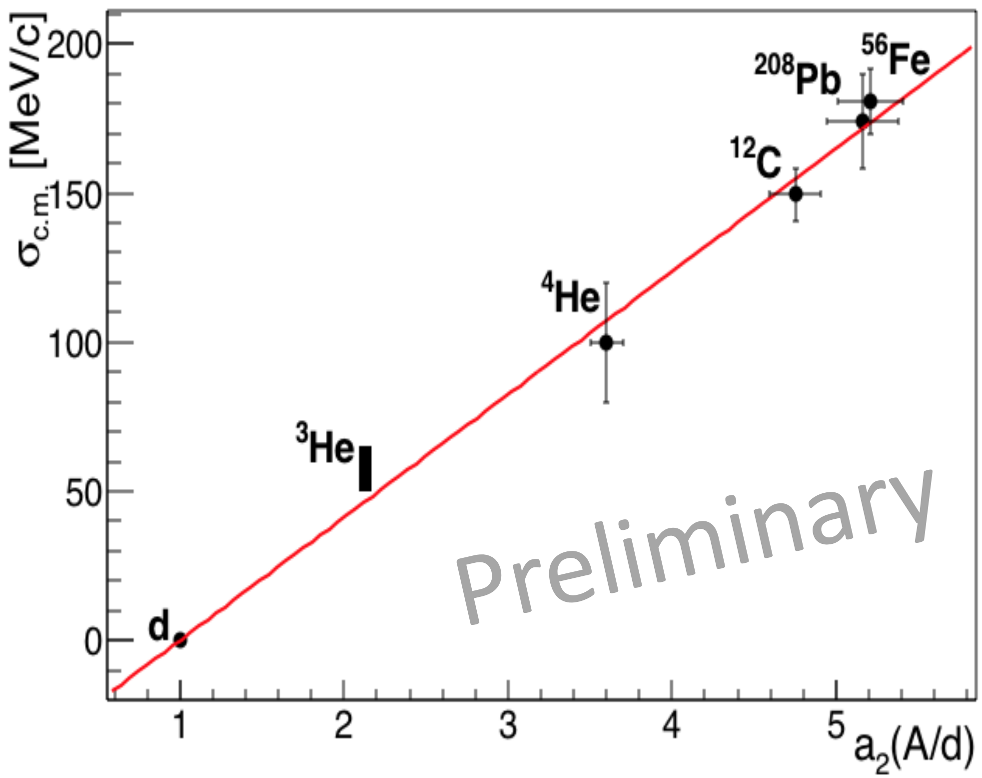


E. Cohen et al. (CLAS Collaboration)

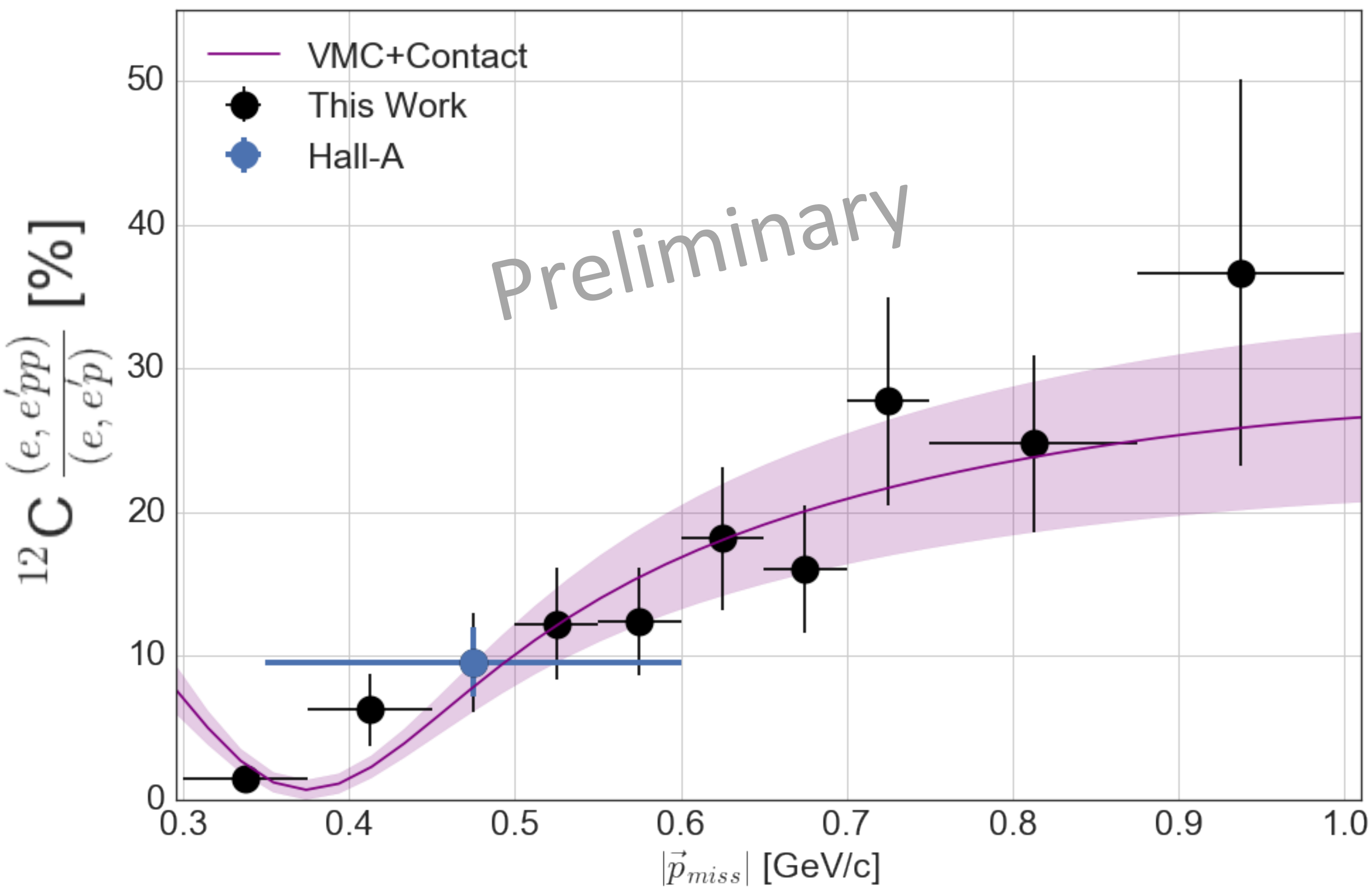
How? (do we know its properties)



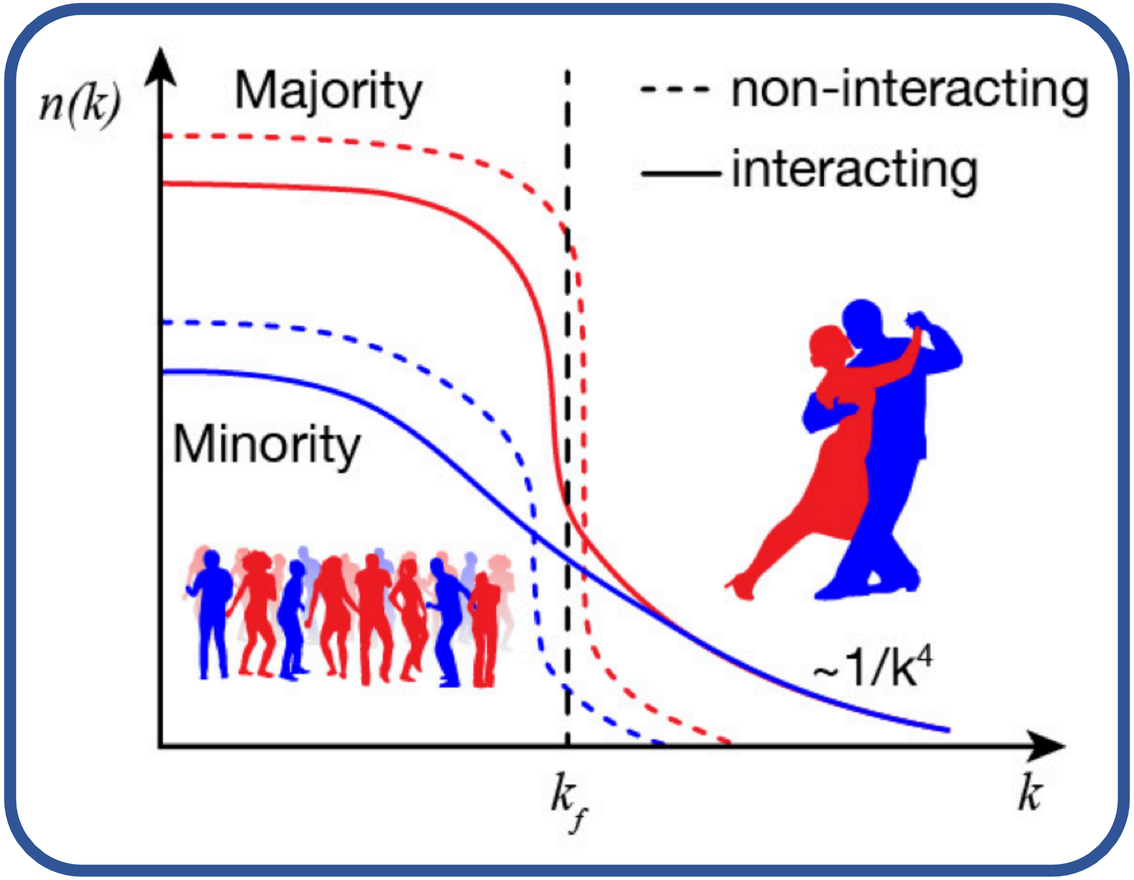
C. Colle et al., PRC (2015)

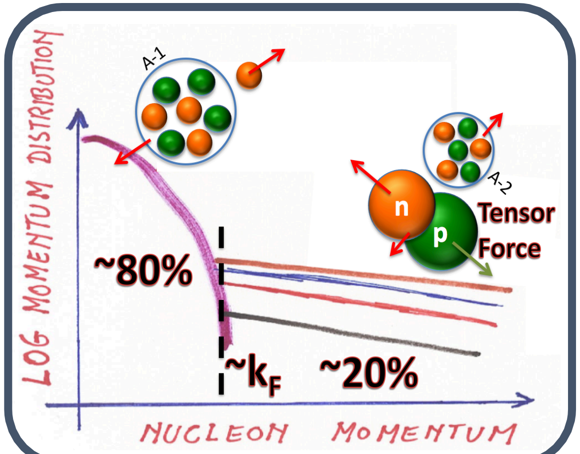


How? (do we probe the repulsive core)



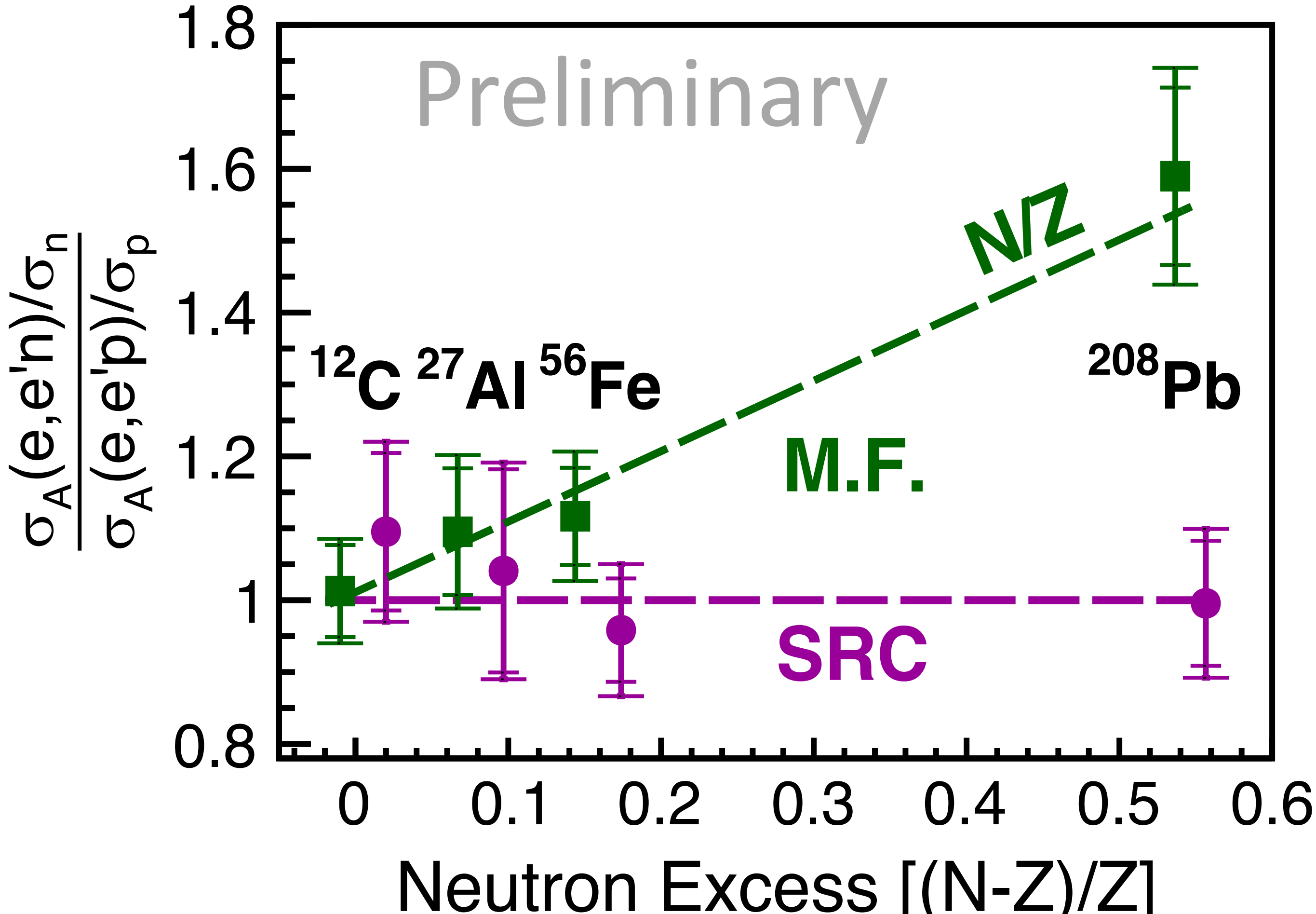
How? (do we study asymmetry dependence)





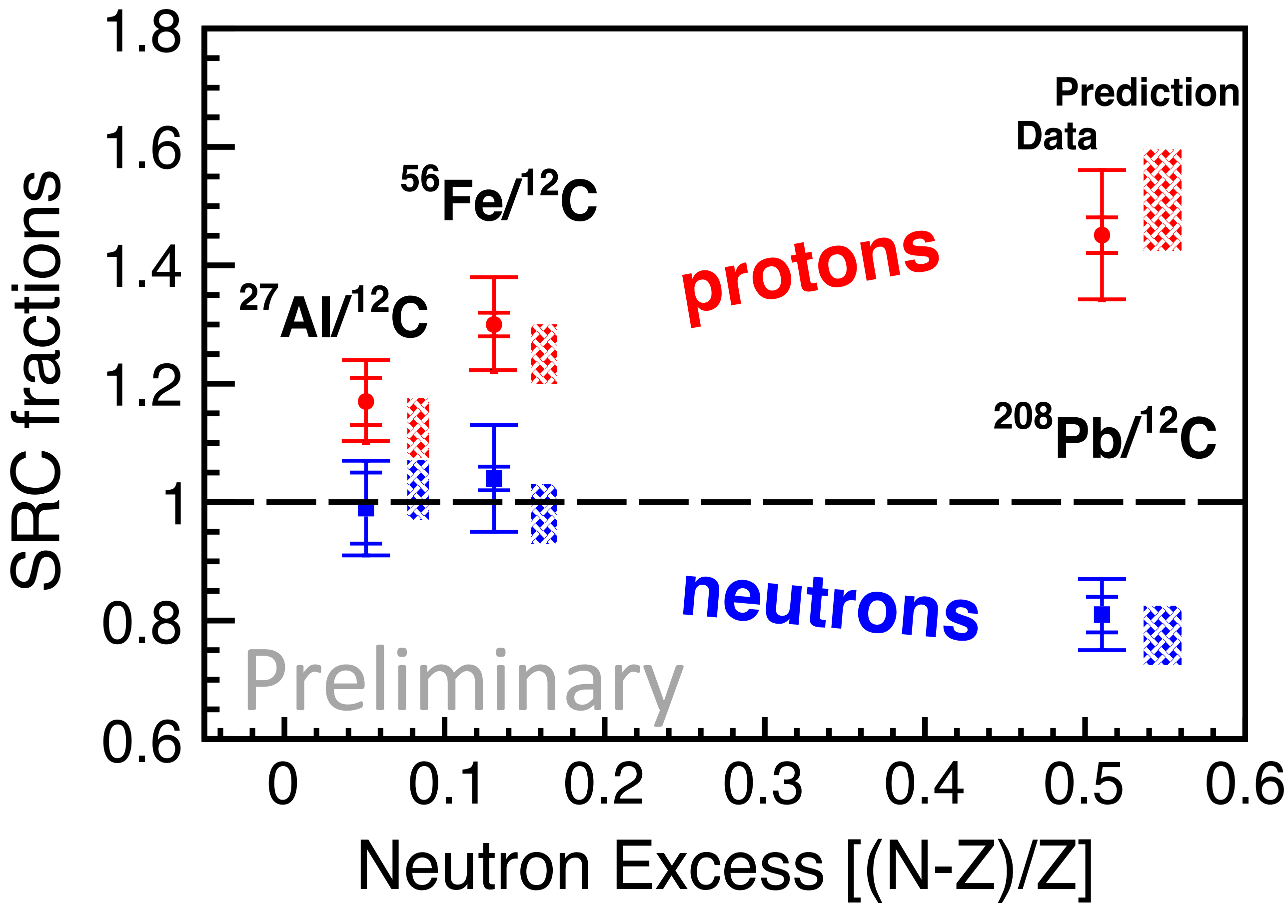
How? (do we study asymmetry dependence)

Same number of high-momentum protons and neutrons, even in neutron rich nuclei!



How? (do we study asymmetry dependence)

Protons are more correlated in neutrons rich nuclei!



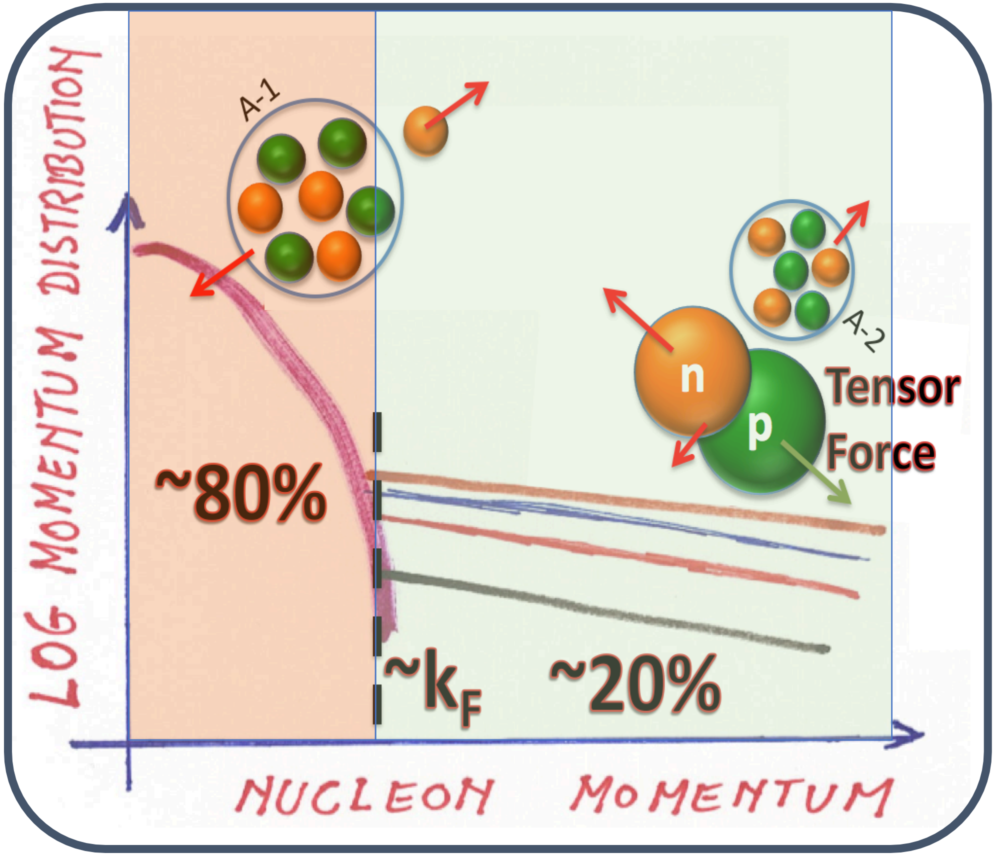
New Era in SRC Research!

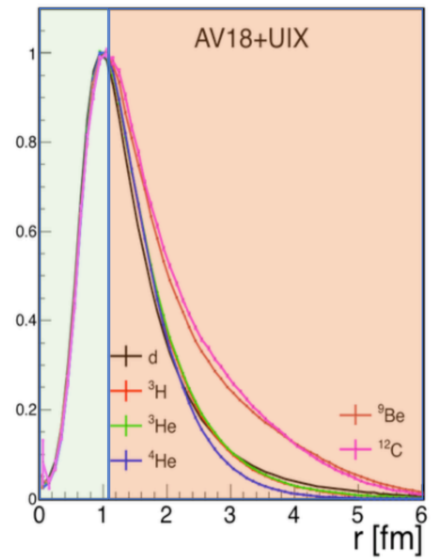
Consistent set of (e,e’), (e,e’p), (e,e’pN) and (p,2pn) measurements, on a variety of nuclei, allow quantifying SRCs with unprecedented accuracy!

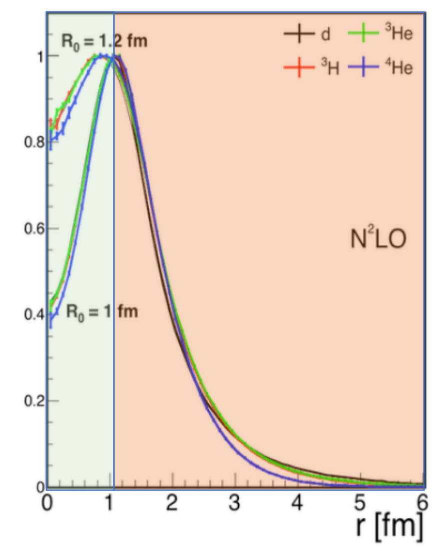
1. SRC Exist in Nuclei (!) and account for:
   - ~ 20% of the nucleons in nuclei.
   - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
2. Have large relative momentum and low c.m. momentum.
3. Predominantly due to np-SRC.
4. Universal for A = 4 – 208 nuclei.
5. np-SRC create a larger fraction of high-momentum protons in neutron rich nuclei!
6. **Tensor force** dominance at short distance.

Universal Nuclear Structure?

Can we formulate a universal description of the SRC phase (in both coordinate and momentum space) WITHOUT relaying on many-body calculations? (YES)

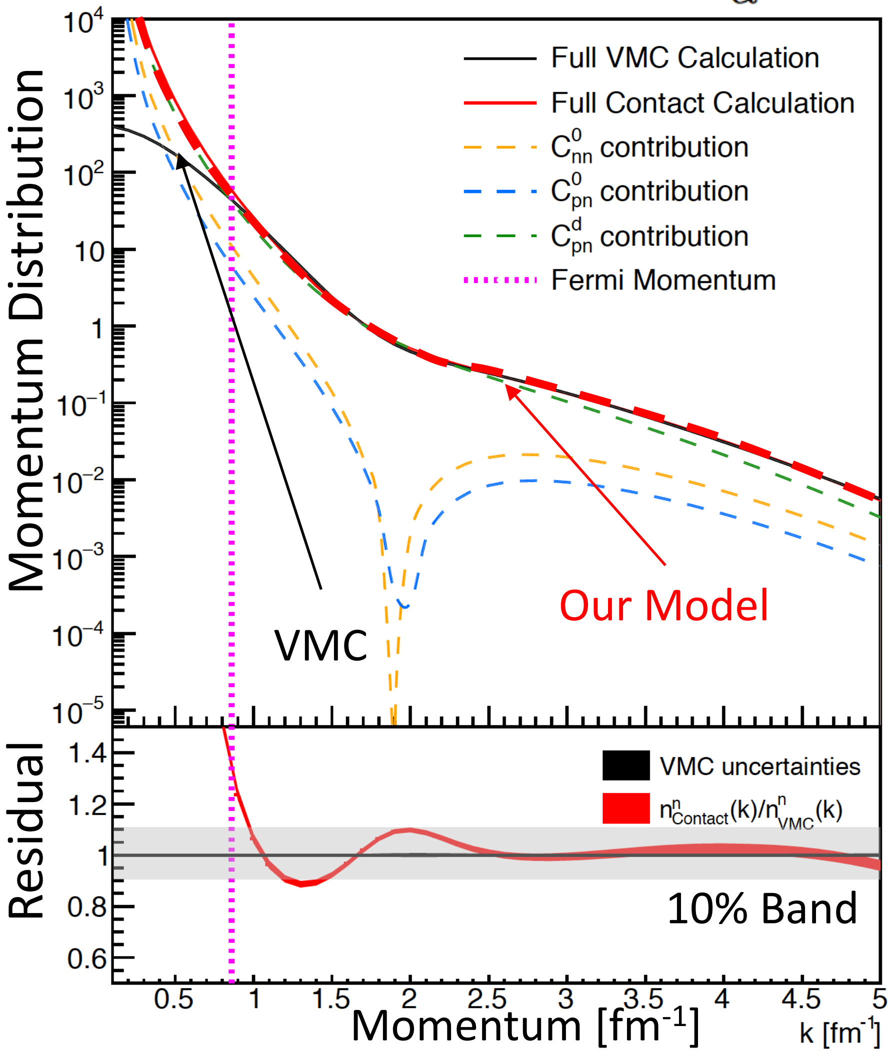


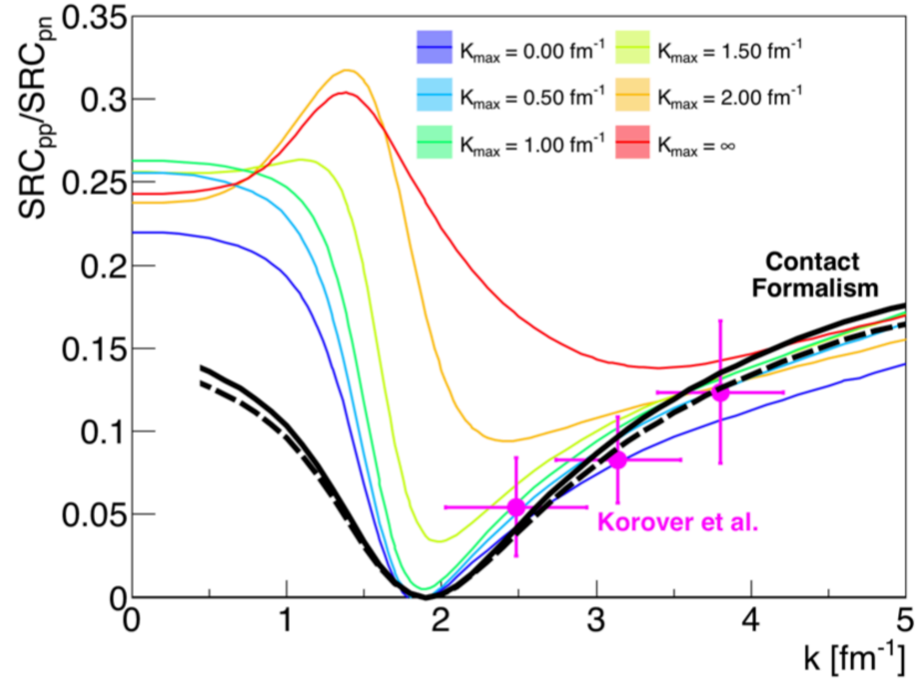




Universal Nuclear Structure!

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



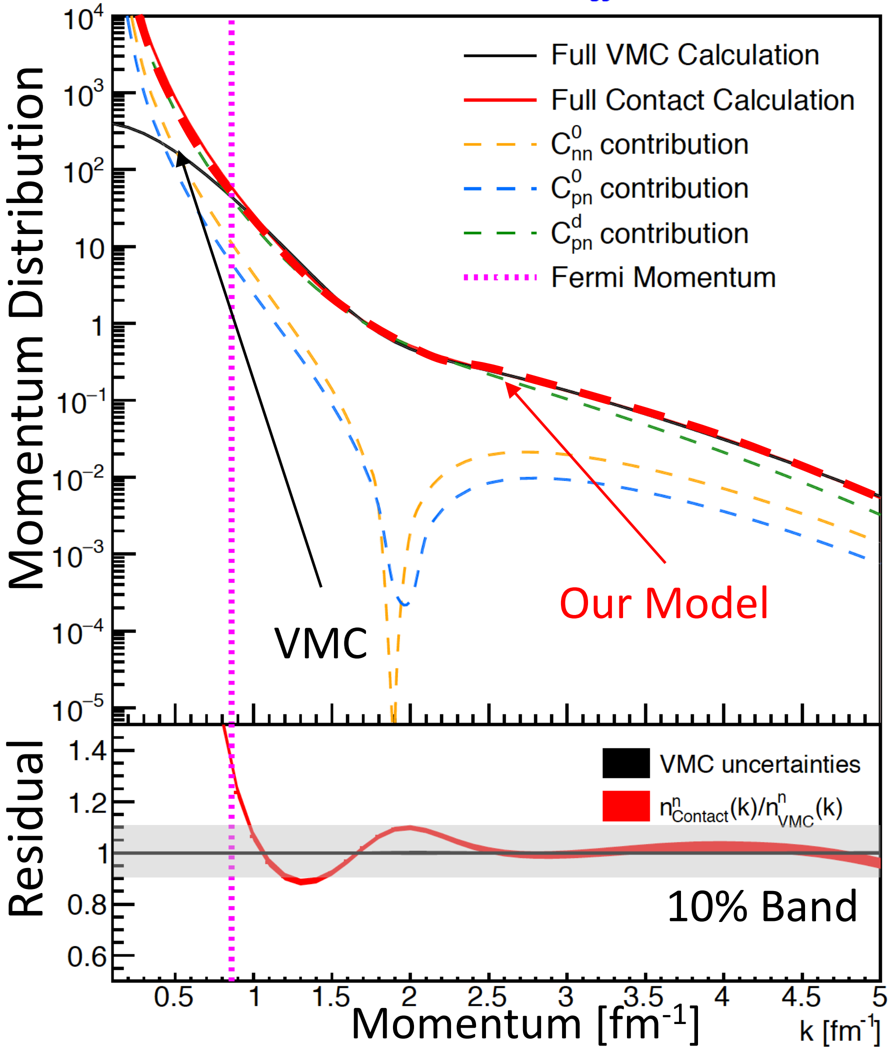


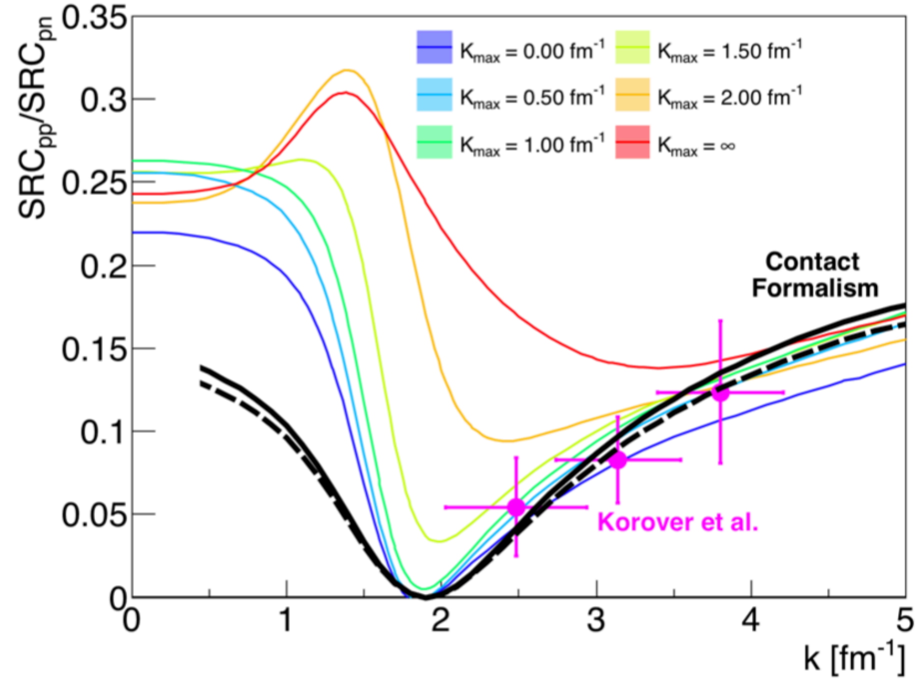
Nuclear contacts can also be extracted from experiment!

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

Universal Nuclear Structure!

$$n_p(k) = \sum_\alpha \left|\tilde{\varphi}^\alpha_{pp}(k)\right|^2 2C^\alpha_{pp} + \sum_\alpha \left|\tilde{\varphi}^\alpha_{pn}(k)\right|^2 C^\alpha_{pn}$$





Nuclear contacts can also be extracted from experiment!

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Short Range Correlations and the EMC Effect in Effective Field Theory

Jiunn-Wei Chen,[1,2,*] William Detmold,[2,†] Joel E. Lynn,[3,4,‡] and Achim Schwenk[3,4,5,§]

[1] *Department of Physics, CTS and LeCosPA, National Taiwan University, Taipei 10617, Taiwan*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[4] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[5] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

arXiv: 1607.03065 (2016)

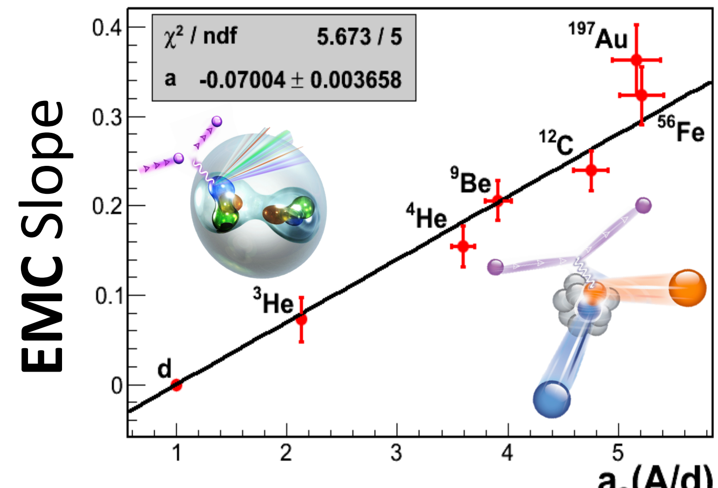
EFT description of bound nucleon structure:

$$F_2^A(x,Q^2)/A = F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda)$$

$$g_2(A,\Lambda) = \underbrace{\frac{1}{A}\langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda}_{\text{SRC contact}}$$

$$a_2(A,x>1) = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

[SRC Scaling Factor]



SRC Scaling factors

RMP Review

Nucleon-Nucleon Correlations and the Quarks Within

Or Hen

Massachusetts Institute of Technology, Cambridge, MA 02139

Gerald A. Miller

Department of Physics,
University of Washington, Seattle,
WA 98195

Eli Piasetzky

School of Physics and Astronomy,
Tel Aviv University, Tel Aviv 69978,
Israel

Lawrence B. Weinstein

Department of Physics,
Old Dominion University, Norfolk,
VA 23529

(Dated: November 2, 2016)

- conventional (non-quark) nuclear physics cannot account for the EMC effect
- models need to include nucleon modification to account for the EMC effect. These models can modify the structure of either:
  - mean field nucleons, or
  - nucleons belonging to SRC pairs.
- there is a phenomenological connection between the strength of the EMC effect and the probability that a nucleon belongs to a two-nucleon SRC pair ($a_2(A)$), see Fig. 33.
- the influence of SRC pairs can account for the EMC-SRC correlation because both effects are driven by high virtuality nucleons with $p^2 \neq M^2$,
- the connection between the EMC effect and the coefficients $a_2(A)$ has been derived using two completely different theories, so that this connection is no accident
- nuclei must contain a small percentage of baryons that are not nucleons. Such baryons exist in the short-ranged correlations and are the source of the EMC effect.

Where? (do we go from here)

- **Probe universality and Factorization breakdown.**
- SRC formation process.
- Proton dynamics in neutron rich nuclei
- Nuclear Interaction at *very* short distances – NN repulsive core
- Direct observation (discovery) of 3N-SRC
- Non-nucleonic degreed of freedom in SRCs

SRC Studies Hit a Statistic Wall

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

=> Need 1-2 orders of magnitude improvement to address next generation BIG questions

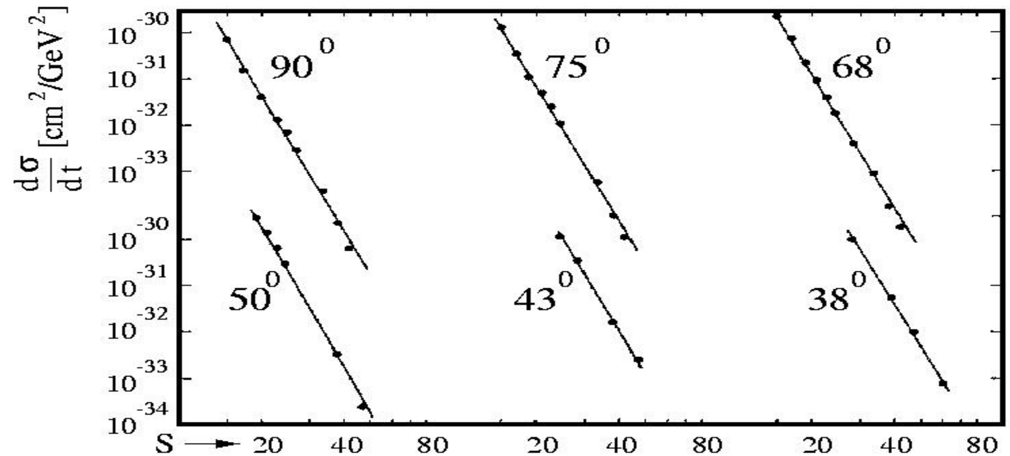
Proton beam advantage:

Selective Attention!

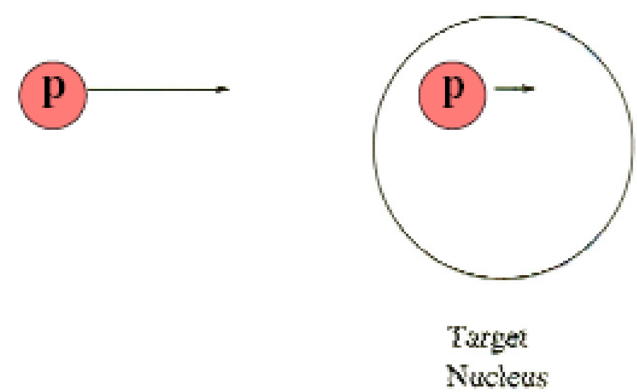
pp → pp elastic scattering near 90^0 c.m:

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

Constituent Counting Rules



Incident proton prefers to interact with forward going high momentum nuclear protons



Proton beam advantage:

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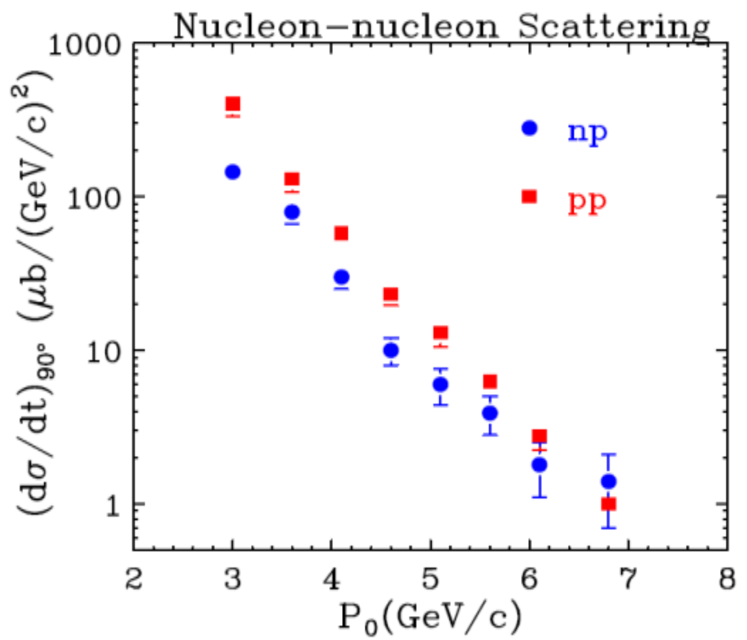
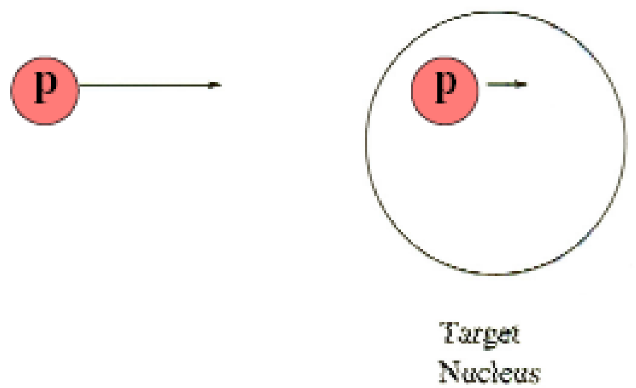


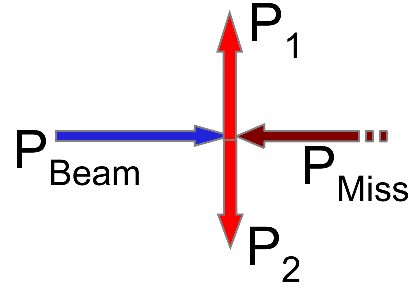
Lower energy increase the cross-section and the sensitivity to SRC via S weighting. But… **need to keep a hard process (s,t,u > 2 GeV^2)**.



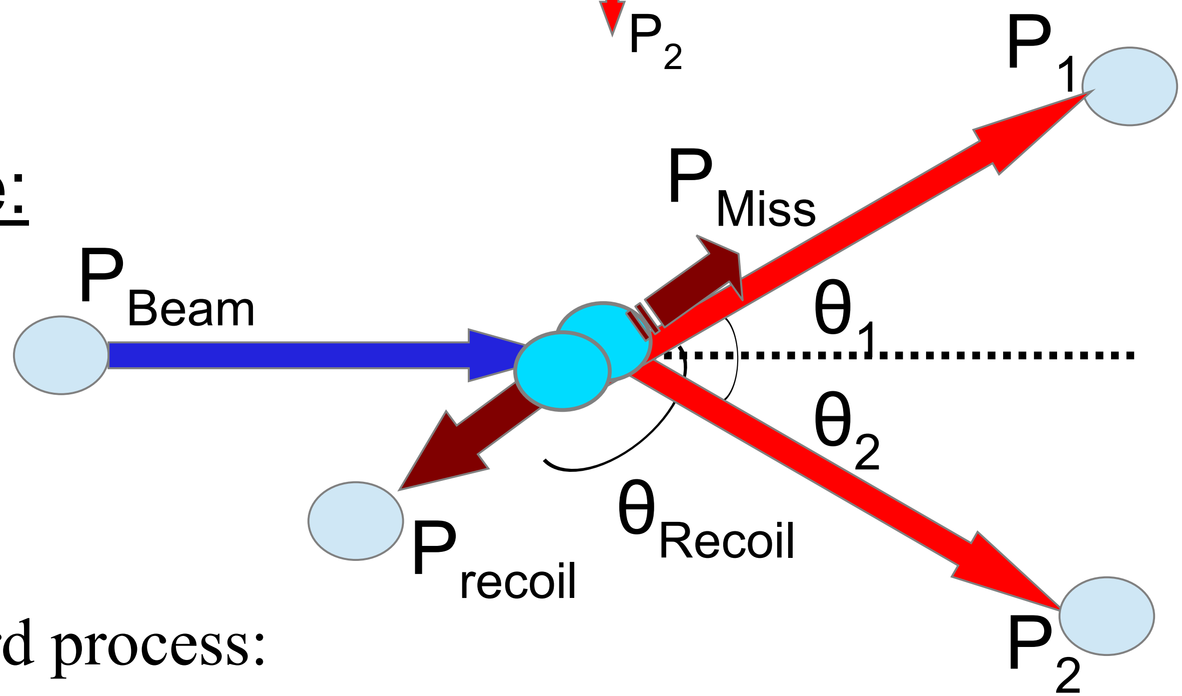
3.5 – 5 GeV beams are ideal!

SRC Kinematics: 2N-SRC

C.M. Frame (90°±10° scattering):



Lab Frame:



- SRC dominance:

$$|p_{recoil}| \geq 250 MeV/c$$

- Hard process:

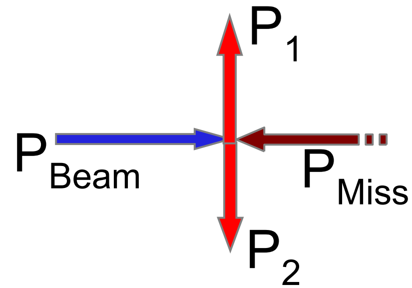
$$-t = -(pb - p1)^2 > 2(GeV/c)^2$$

$$-u = -(pb - p2)^2 > 2(GeV/c)^2$$

$$s = (p1 + p2)^2 > 2(GeV/c)^2$$

SRC Kinematics: 3N-SRC

C.M. Frame (90°±10° scattering):



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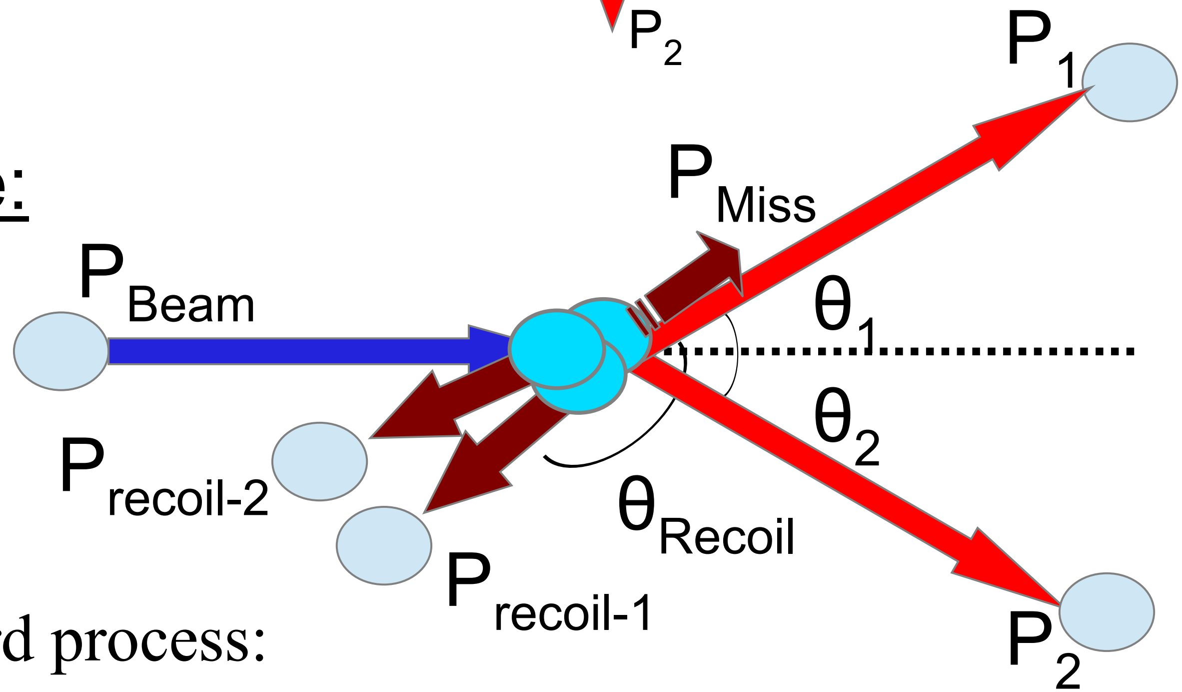

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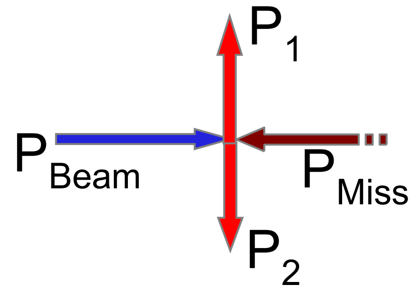

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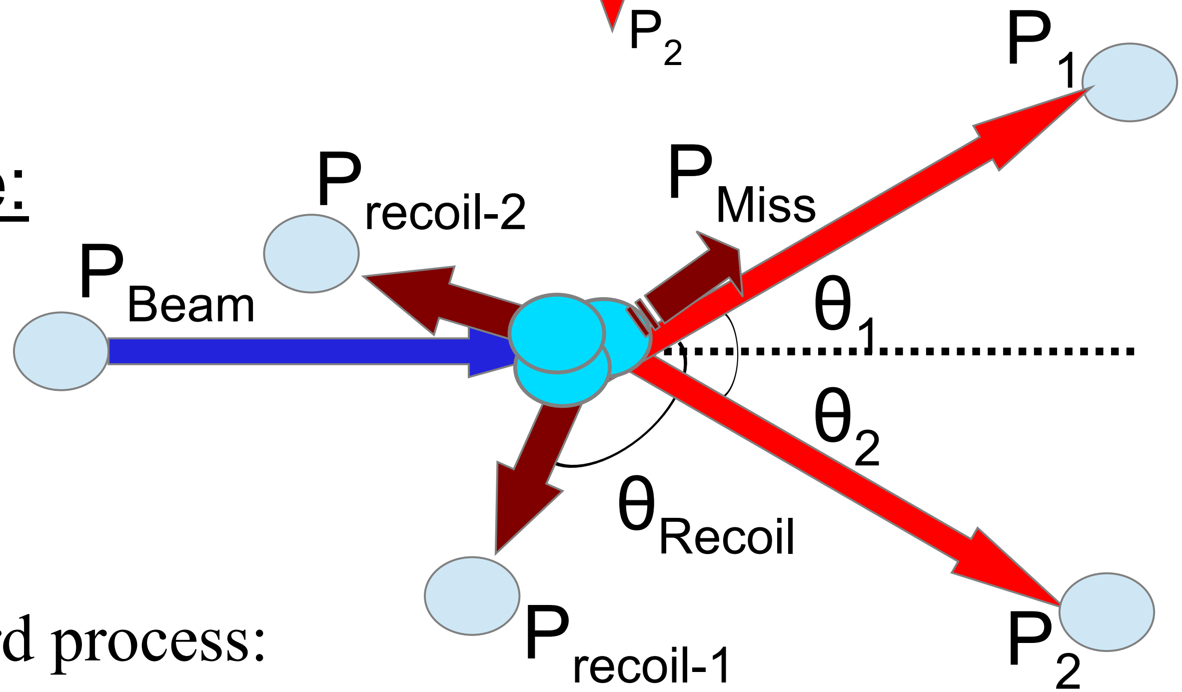

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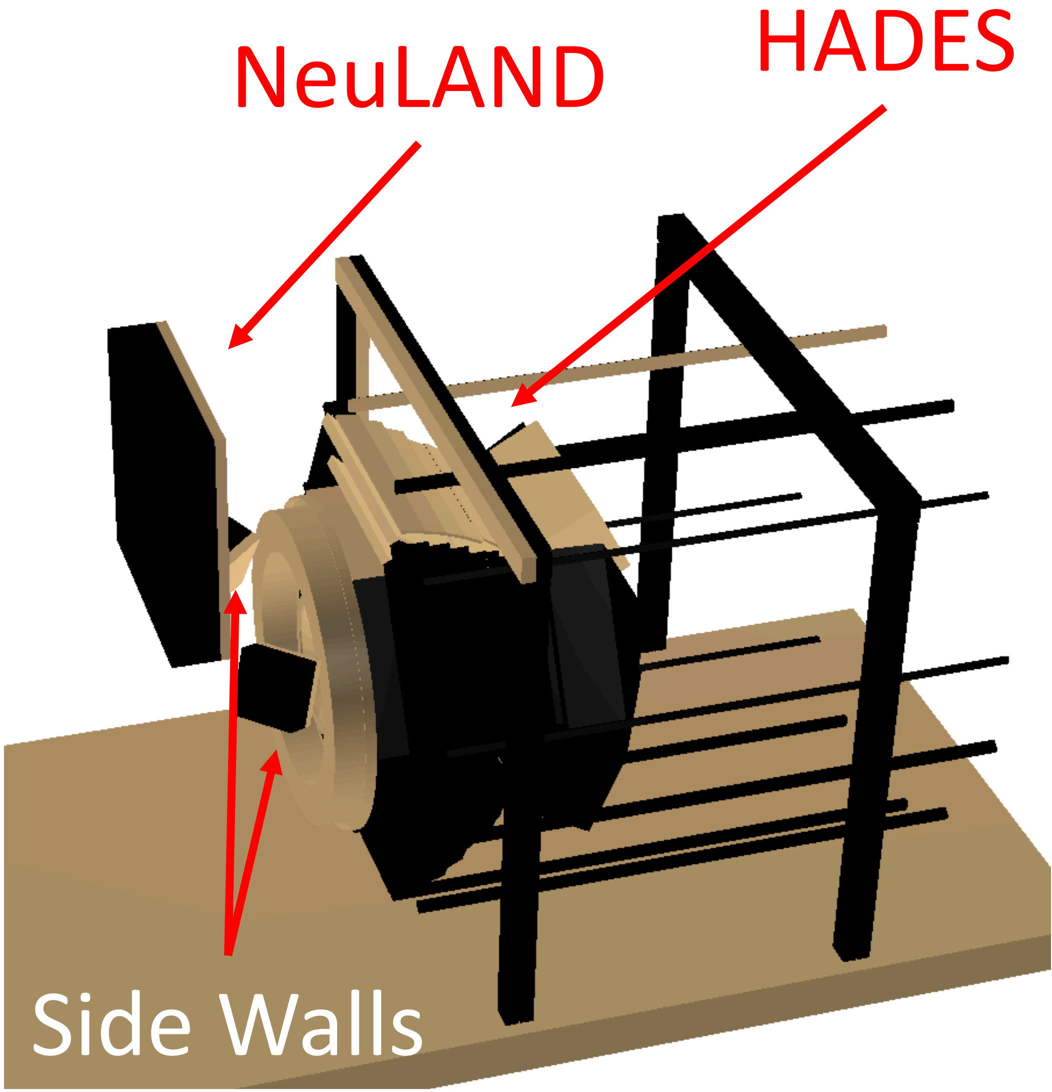
$$s = (p1 + p2)^2 > 2(GeV/c)^2$$

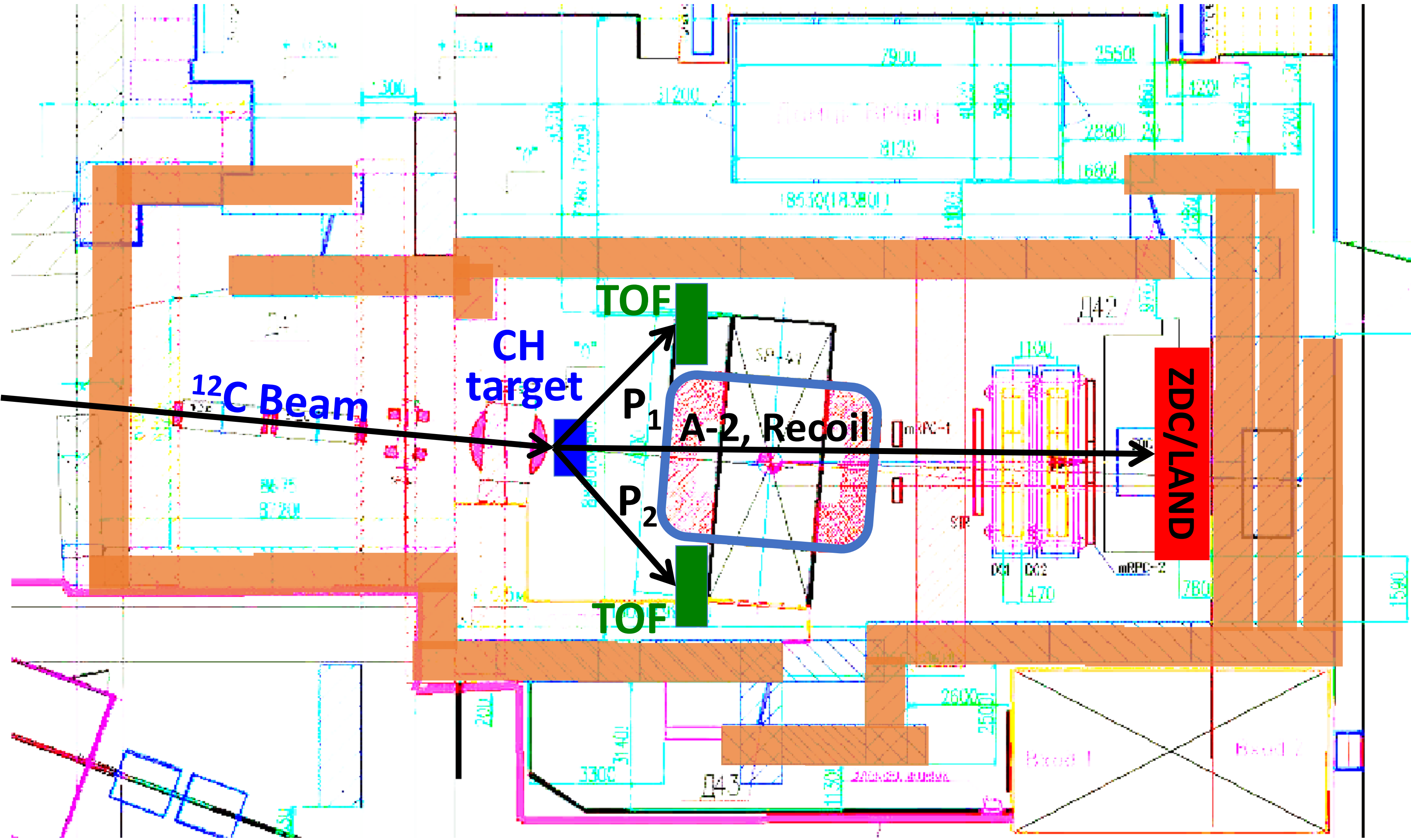
HADES + NeuLAND

<u>Central Wall (NeuLAND)</u>
- $250 x 250 x 60\ cm^3$
- 6 planes 10 cm thick
- 2 cm veto plane

<u>Side Walls:</u>
- $70 x 70 x 40\ cm^3$
- 4 planes 10 cm thick
- 2 cm veto plane



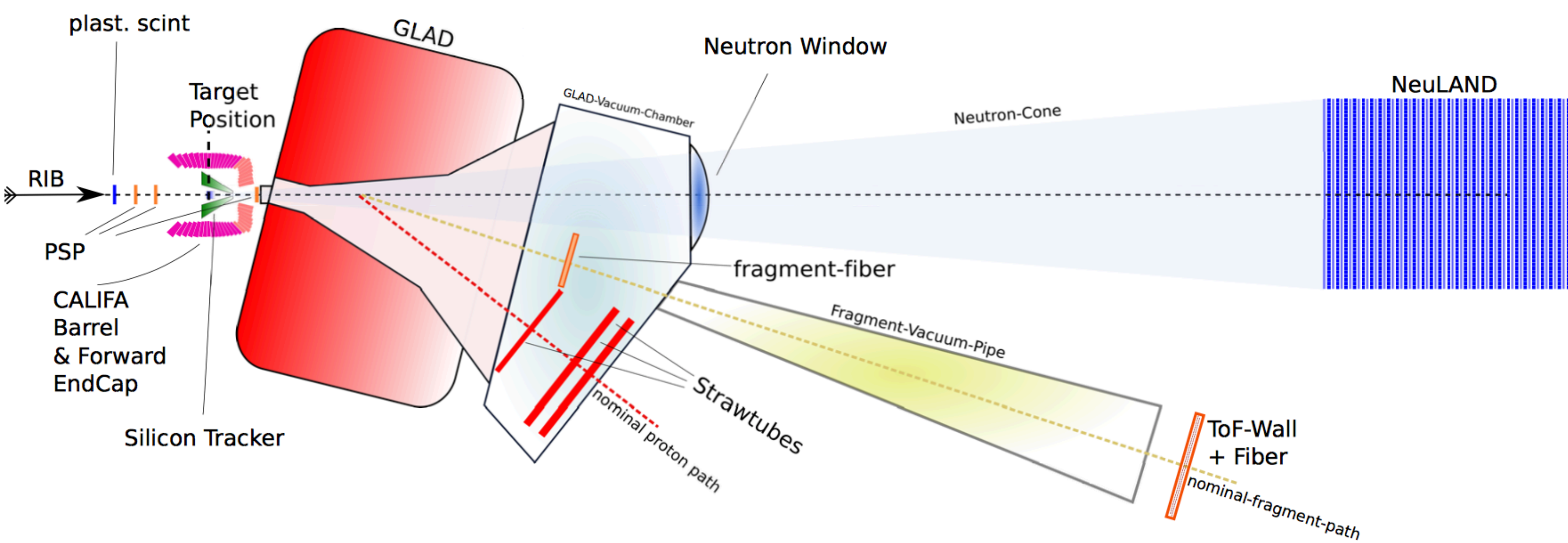
Inverse Kinematics @ DUBNA (Nov. 2017!?!)



Inverse Kinematics @ GSI

R3B Phase 1

TECHNISCHE UNIVERSITÄT DARMSTADT



GLAD: 0 – 40 degree, +/-80 mrad, 5 Tm bending power

Relative momentum resolution: 10^{-3}

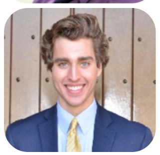
Neutrons: +/- 80 mrad at 15 m distance

The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou

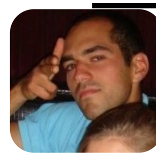

Axel Schmidt


George Laskaris

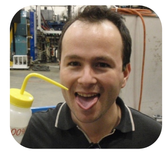

Maria Patsyuk


Taofeng Wang

- **TAU (Eli Piasetzky):**


Erez Cohen


Meytal Duer


Igor Korover


Adi Ashkenazy

- **ODU (Larry Weinstein):**


Mariana Khachatryan

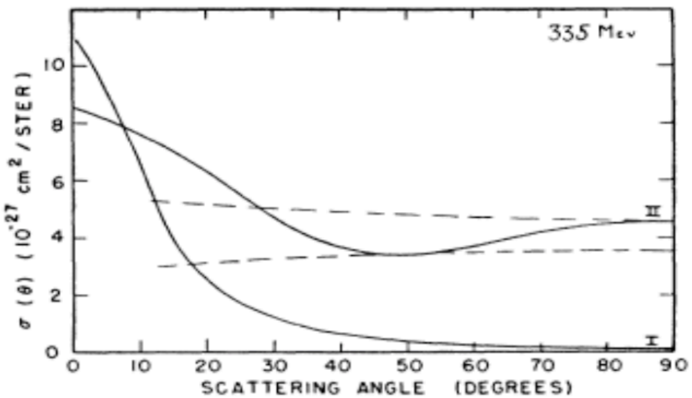

Florian Hauenstein

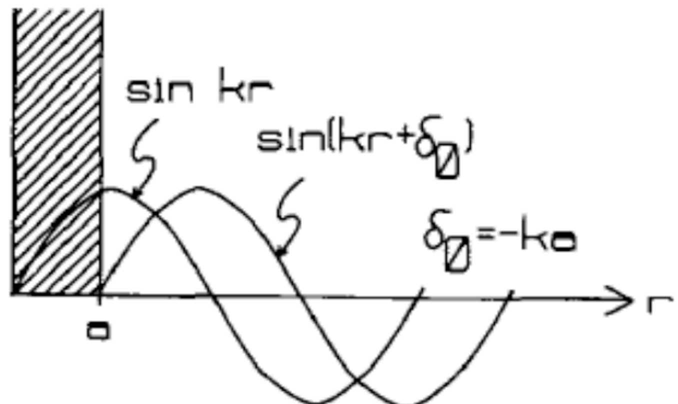
- **Theory Collaborators** (lots!)

Repulsive Core

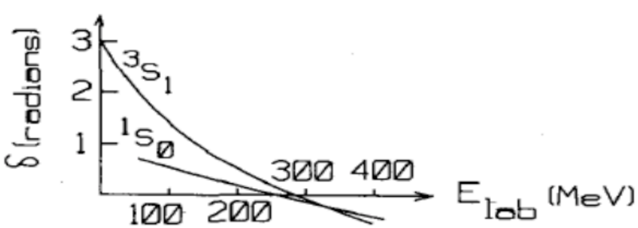
- **Nuclear Forces at Short Distances:** **NN repulsive core**

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



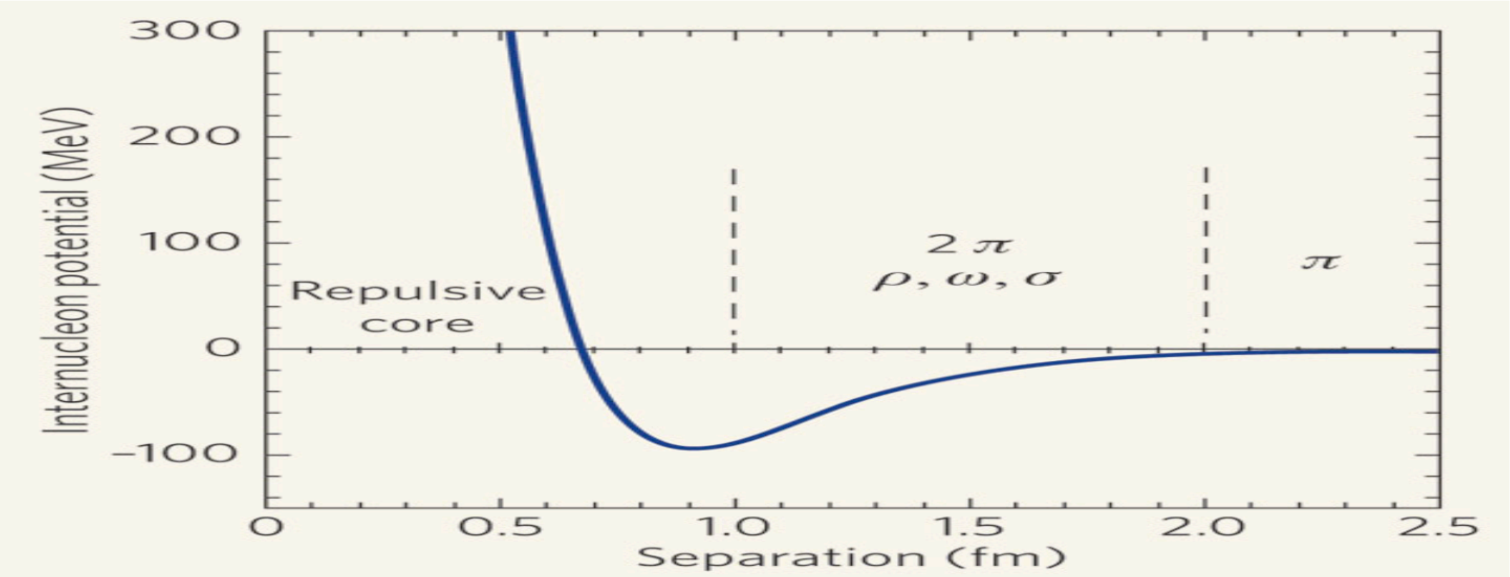


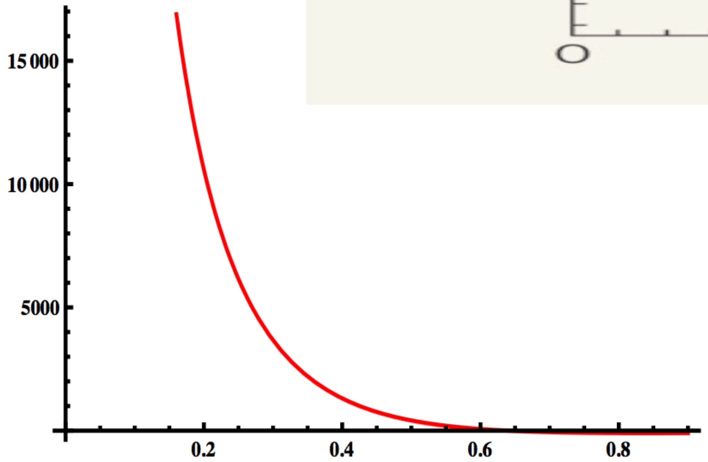
r_0 = 0.4fm



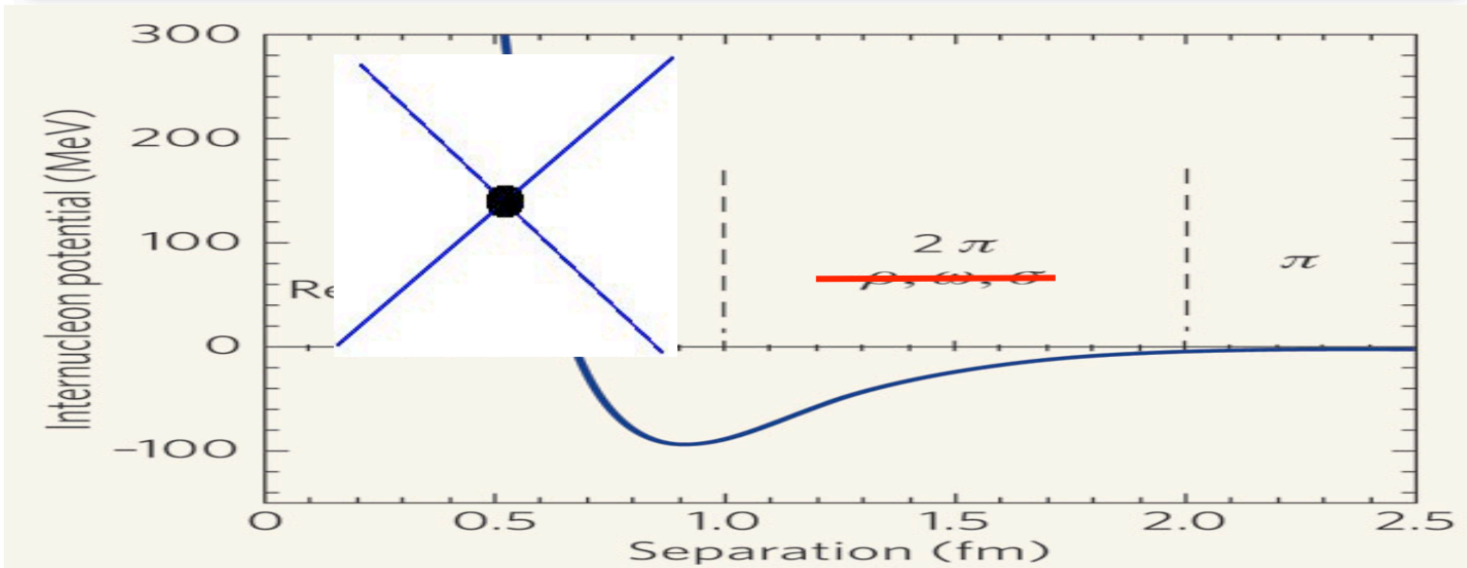
Stability Theorem: Nuclei will Collapse without Repulsive interaction 1950s Weisskopf, Blatt

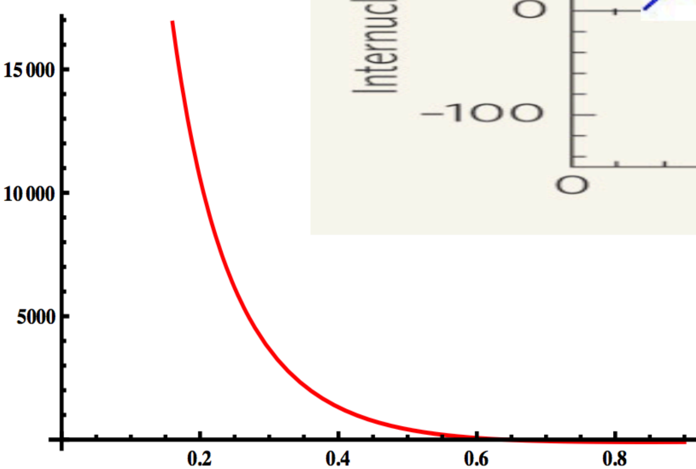
Repulsive Core



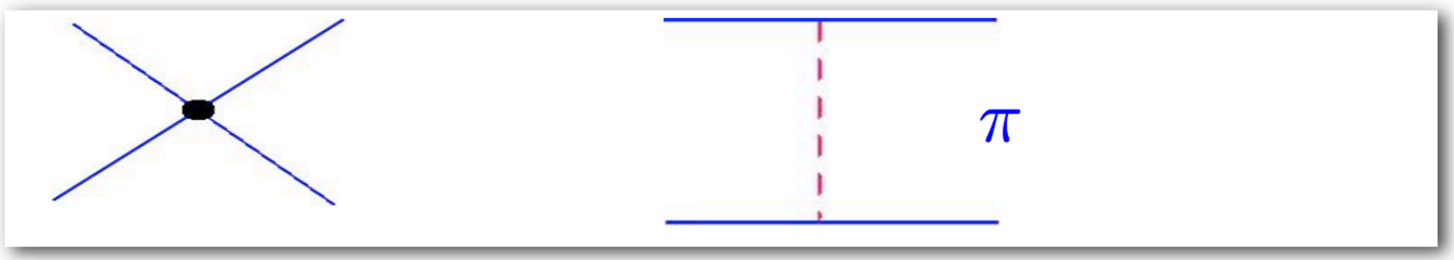


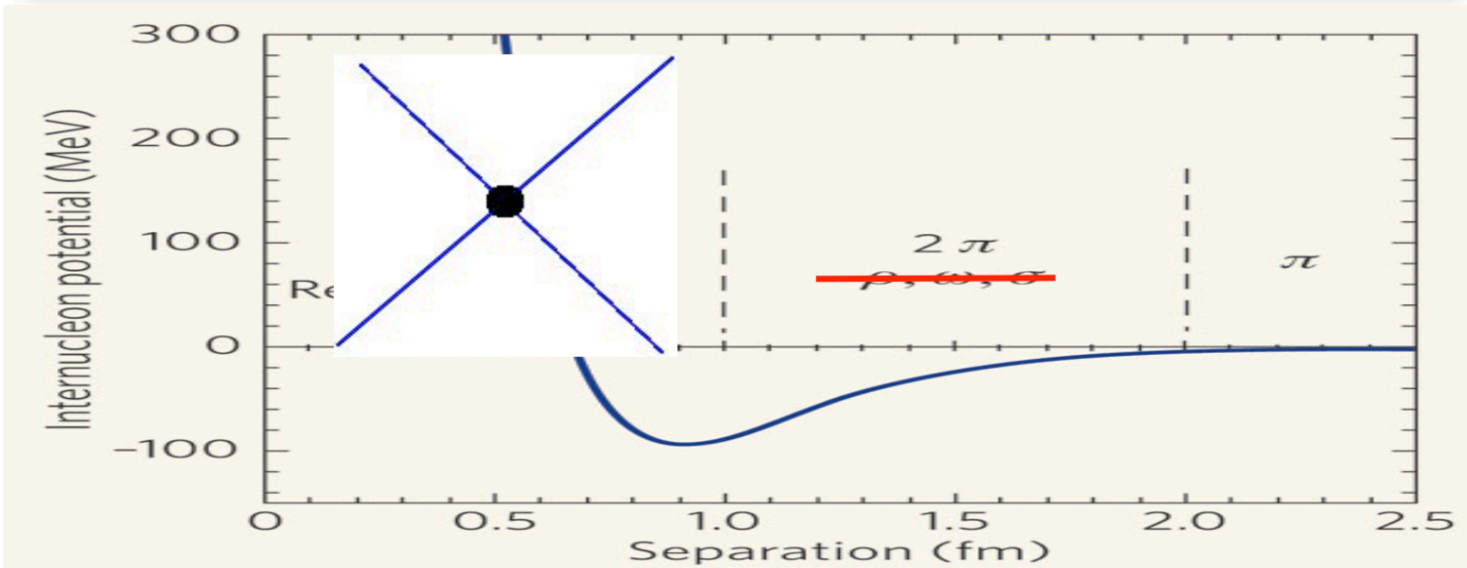
Repulsive Core

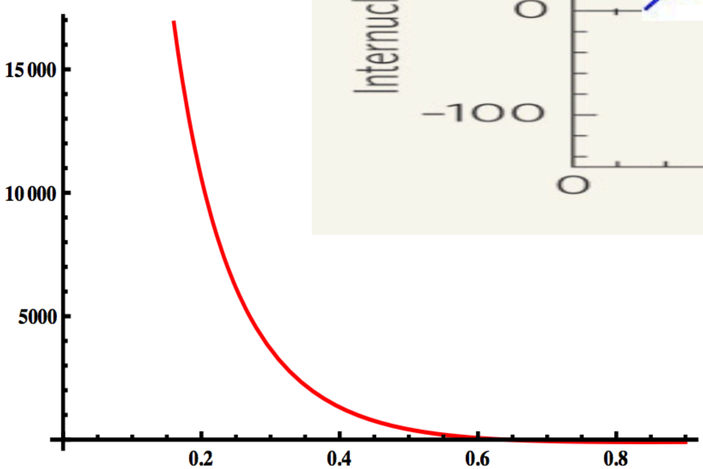




Repulsive Core



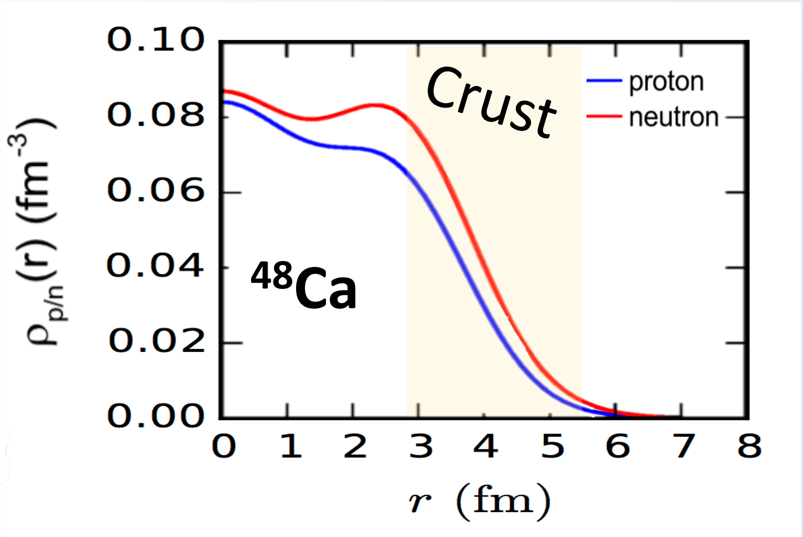




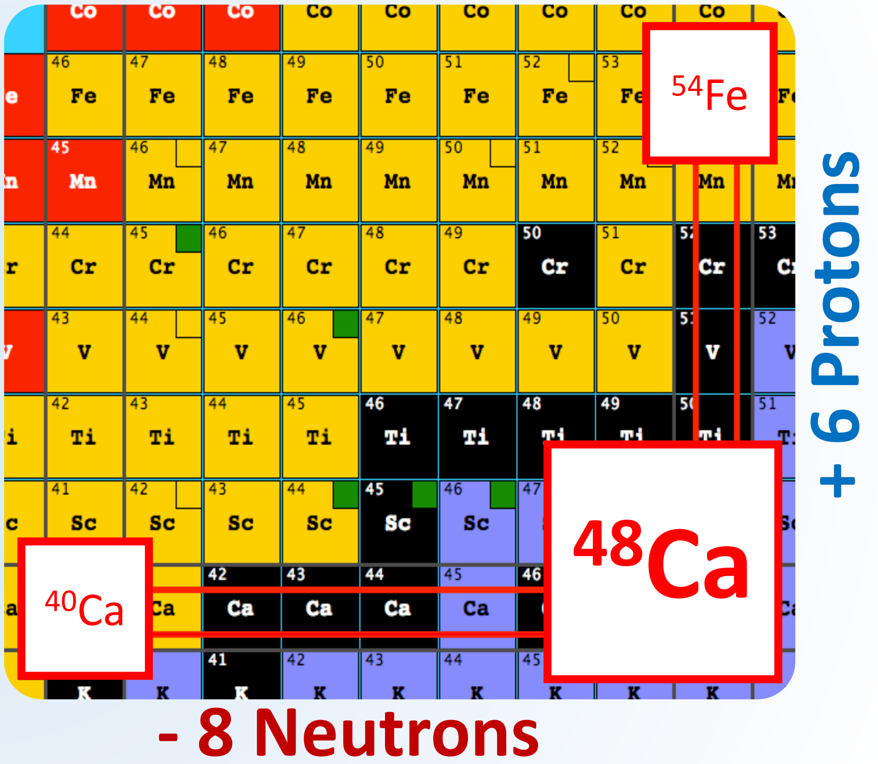
"Repulsive core has to be large to support neutron stars > 1 solar mass"

Protons Dynamics in Neutron Rich Nuclei

Focused Study of SRC dynamics in ^{48}Ca by comparing to the CaFe triplet.



G. Hagen et al., Nature Physics 12, 186 (2016)



3N-SRC (Terra Incognita!)