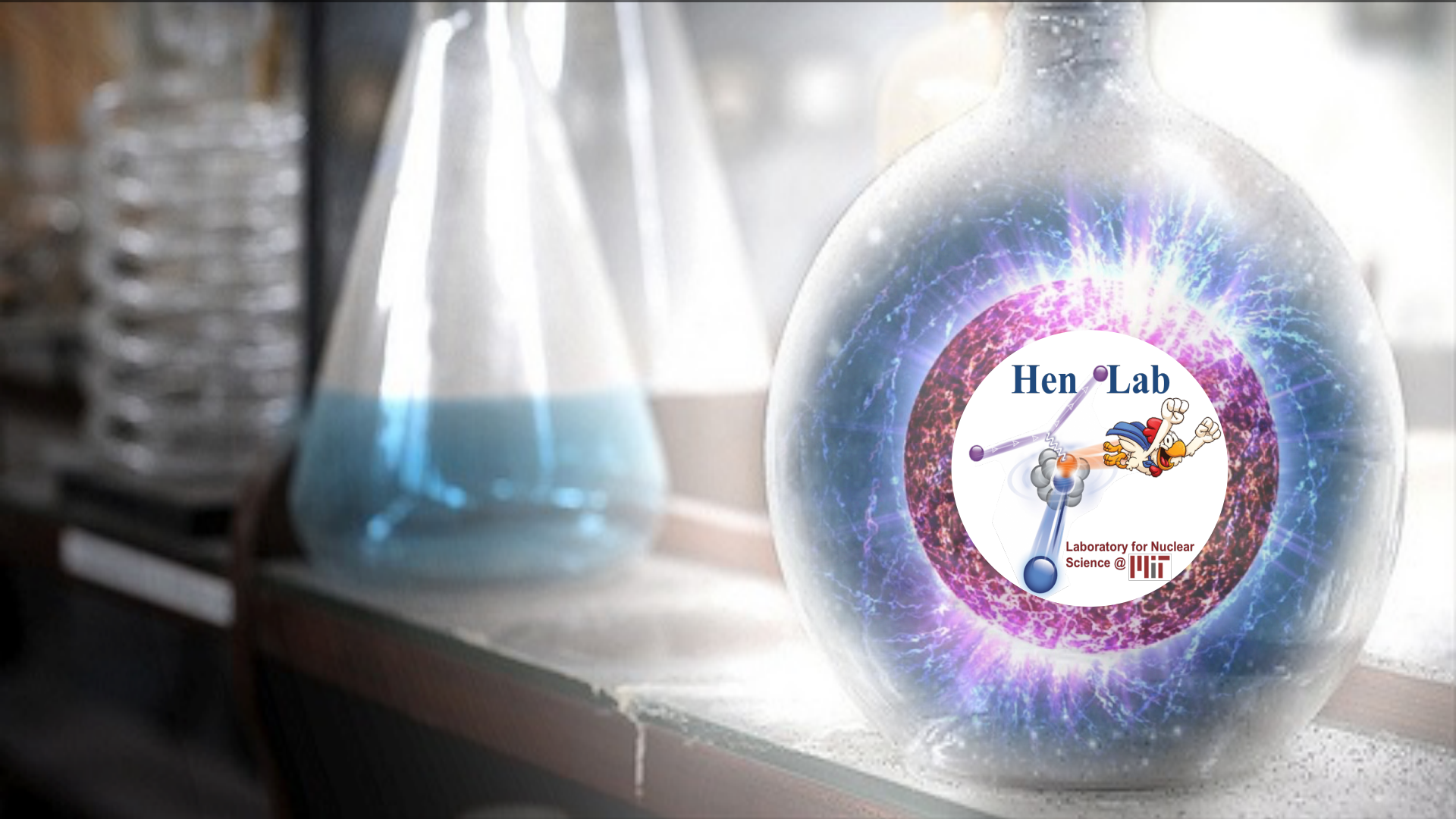


Short-Range Correlations 101

Or Hen – MIT





The Nuclear Many-Body Challenge

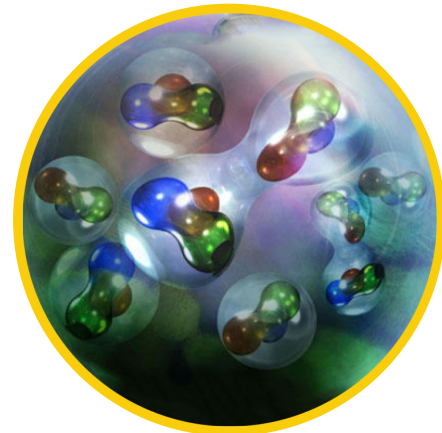
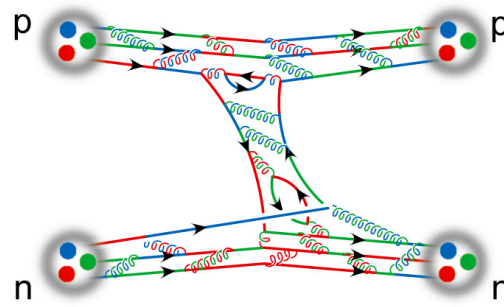
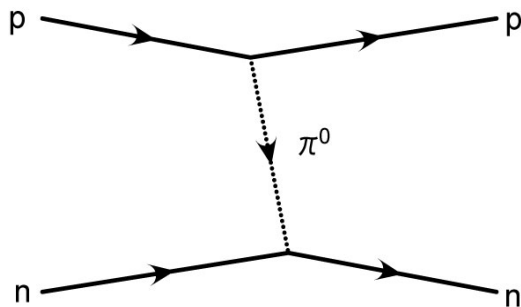


Many-body Schrödinger Equation

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

Main Challenges:

1. No 'fundamental' Interaction => residual interaction between quarks that makeup the nucleons.
2. Phenomenological parametrizations are complex!
(over 18 operators)

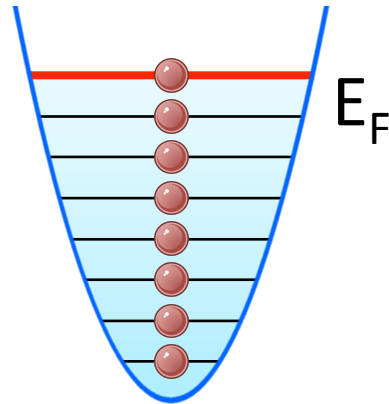




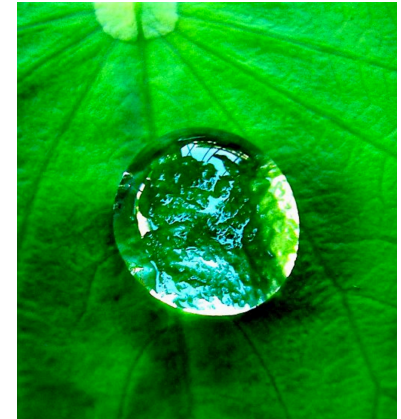
Solution: Effective Theories



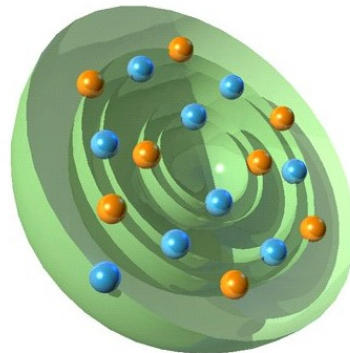
Fermi
Gas
Model



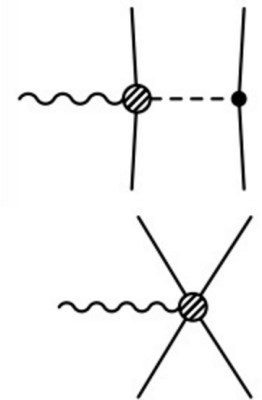
Liquid
Drop
Model



Shell
Model



Chiral
Perturbation
Theory

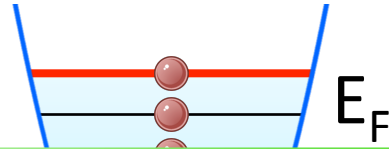




Solution: Effective Theories



Fermi



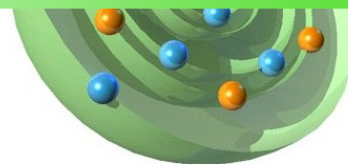
Liquid



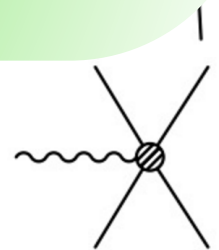
All effective theories relay on the same common idea:

Scale separation of long and short range dynamics in nuclei

Model



Perturbation Theory





Universality of long-range dynamics

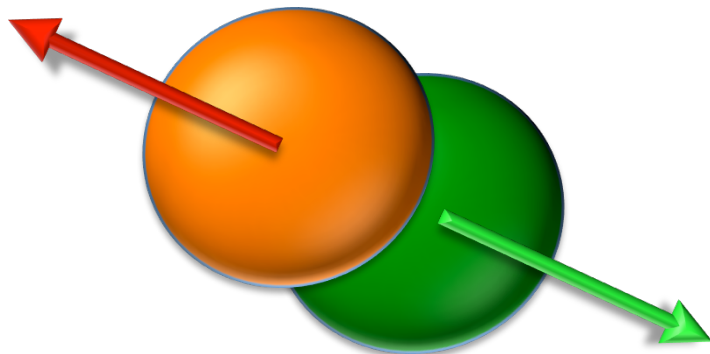
Long-range (low-momentum) structure of nuclei was studied for many years. Mean-field approaches give a good description of this part of the nuclear ground state.

- Two big questions:
 - How important are details of the short-range structure that are neglected / smeared out?
 - Is there an effective, *universal*, way to add the short-range dynamics for a global description?



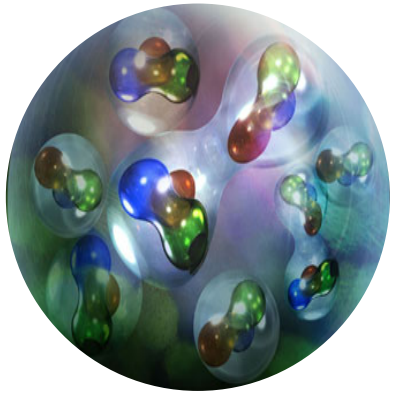
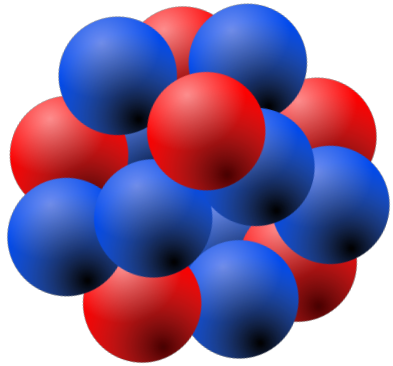
SRC are pairs of nucleon that are close together in the nucleus (wave functions overlap)

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





Nuclear Density Scales

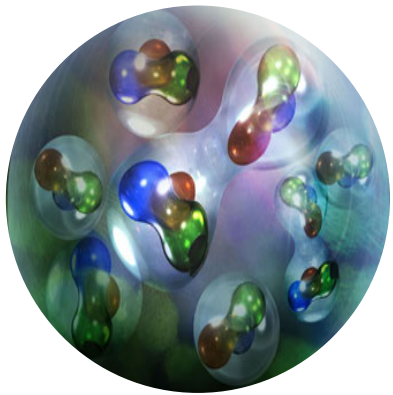
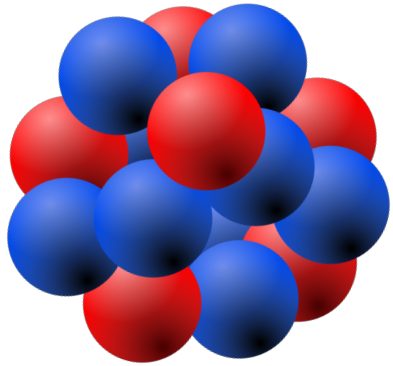


- Nuclear: $0.16 \text{ nucleons/fm}^3$
- Nucleon: $0.36 \text{ nucleons/fm}^3$
- SRC pair: $\sim 0.55 \text{ nucleons/fm}^3$

SRC pairs have $\sim$ **x3.5 larger density** compared to saturation nuclear density!



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SRC pairs probe densities relevant to neutron stars!

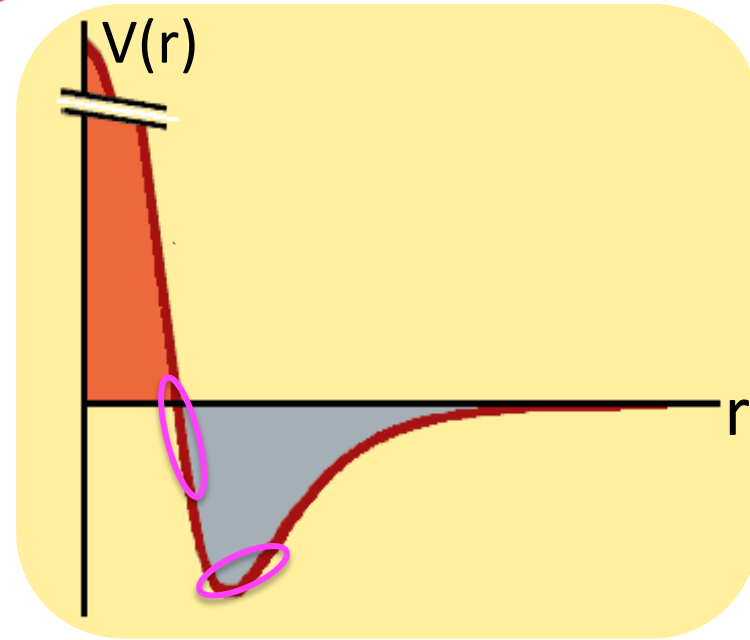


Why SRC?



Nuclear Physics

Better understanding of the
nucleon-nucleon interaction and the
nuclear momentum distribution

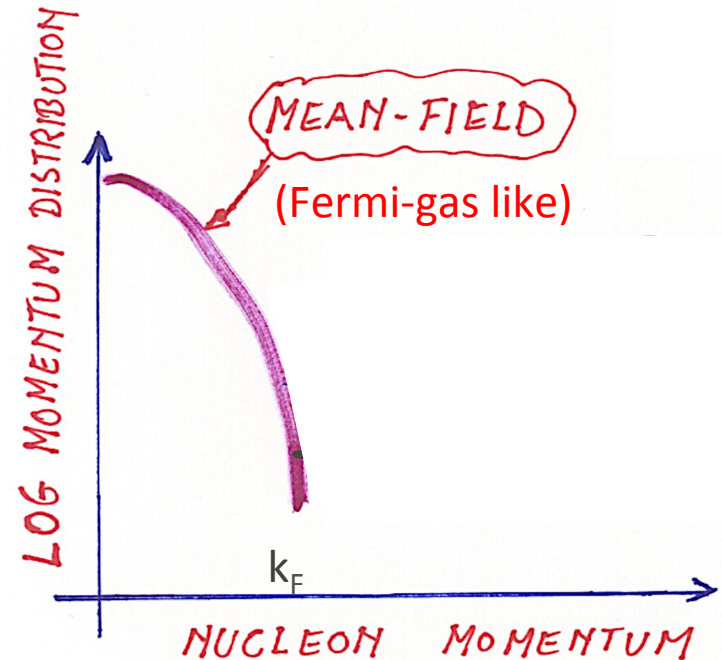
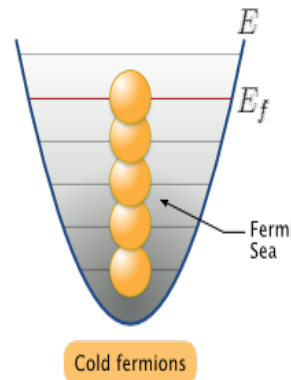




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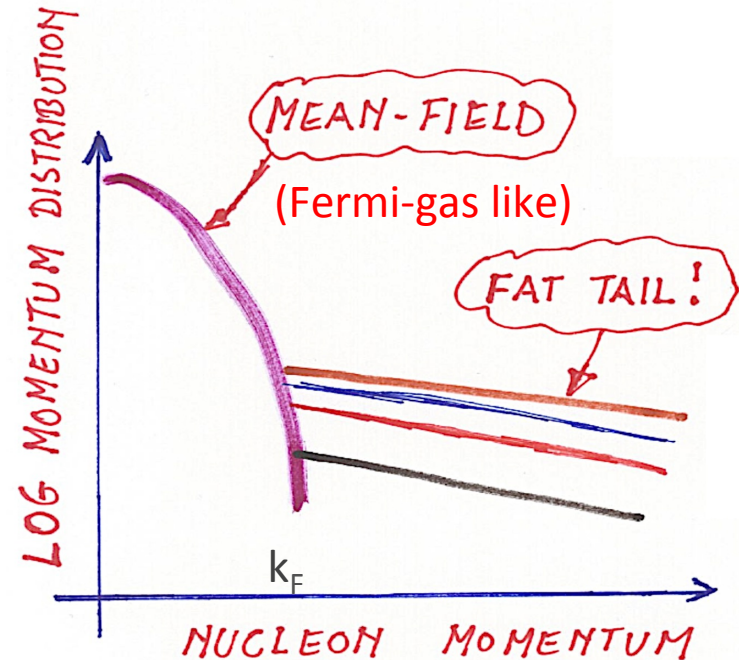
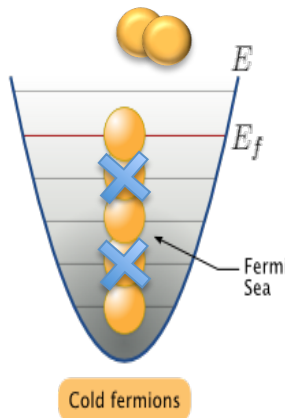


Why SRC?



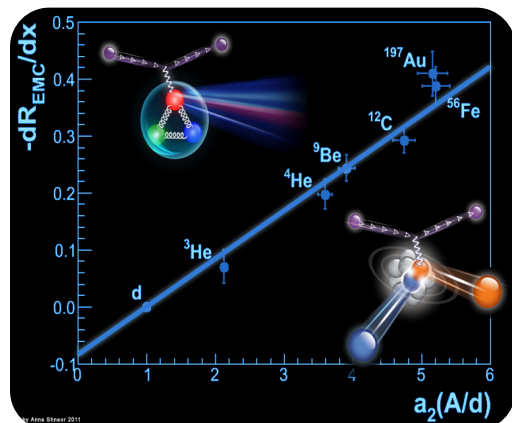
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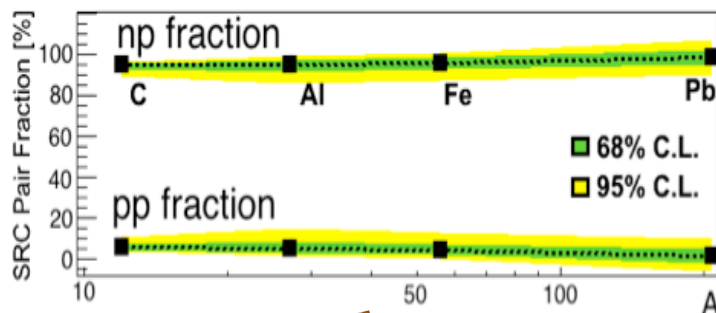




Why SRC?

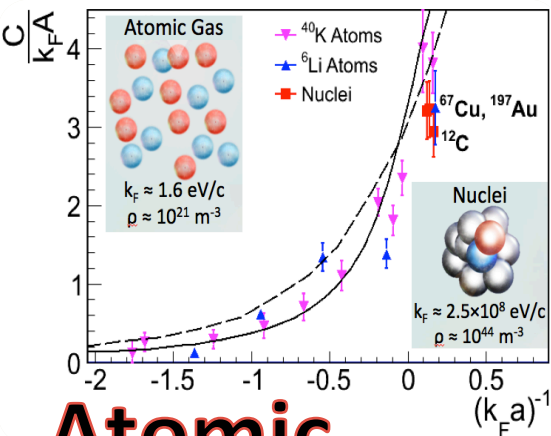
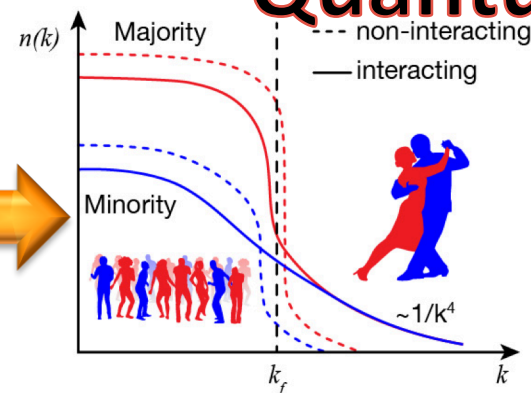


Particle



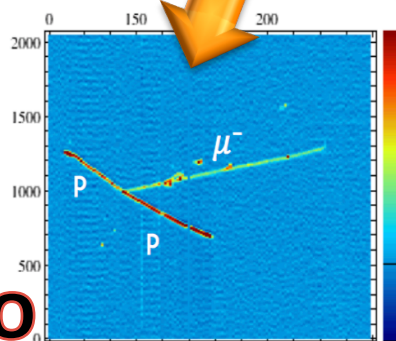
Nuclear

Quantum

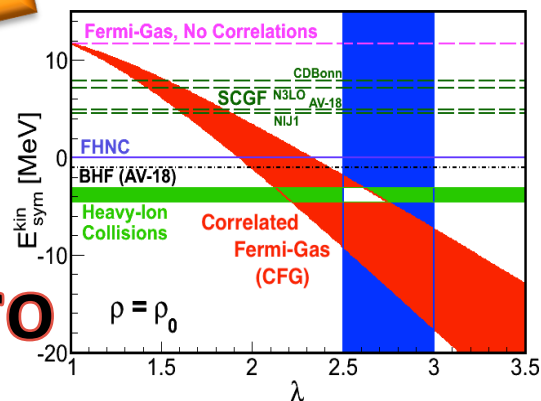


Atomic

Neutrino



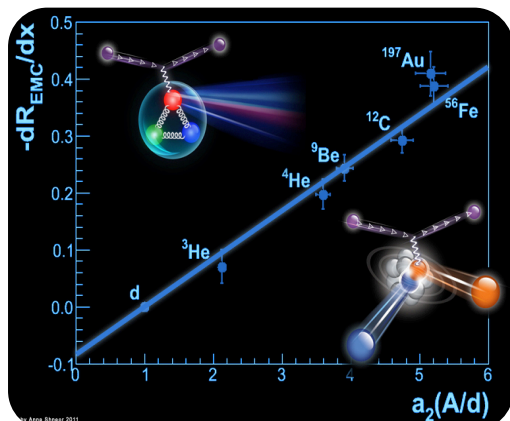
Astro



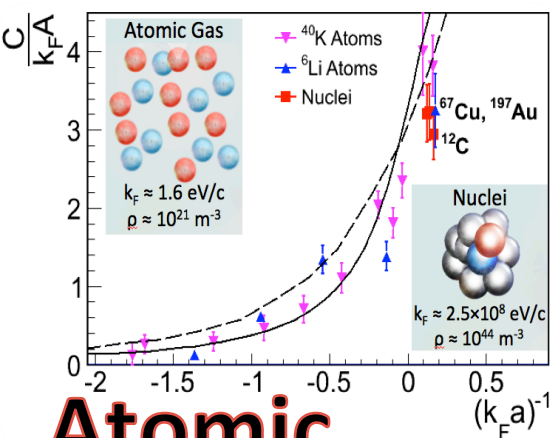


Why SRC?

Particle



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

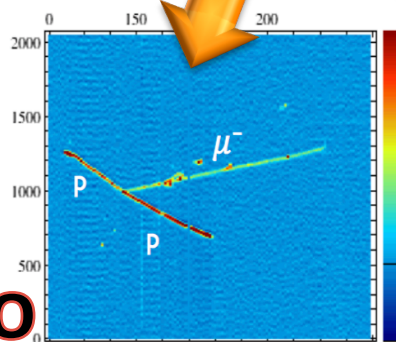
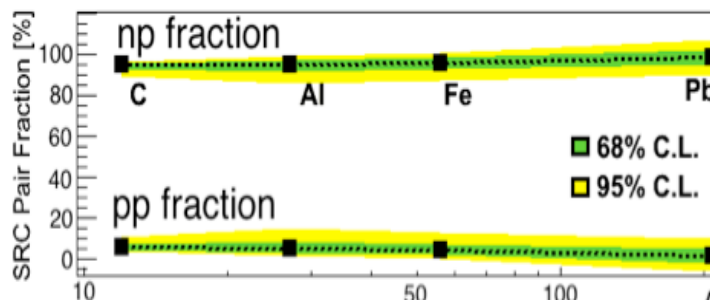


Atomic

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

Neutrino

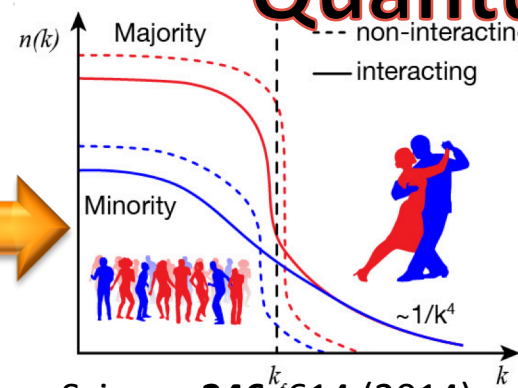
PRD **90**, 012008 (2014); PRC **94**, 045501 (2016)



Nuclear

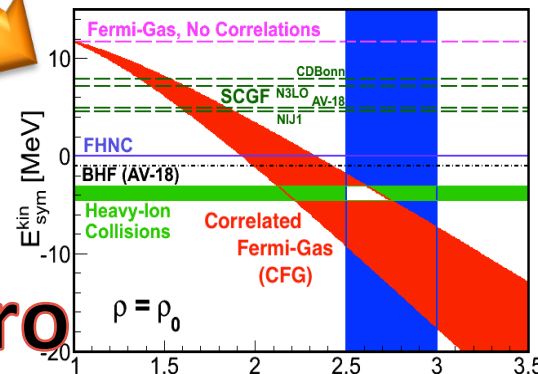
Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB **772**, **63** (2013),
PRL **113**, 022501 (2014),
PRC **92**, 024604 (2015).

Quantum



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

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!



Why SRC?



Today:

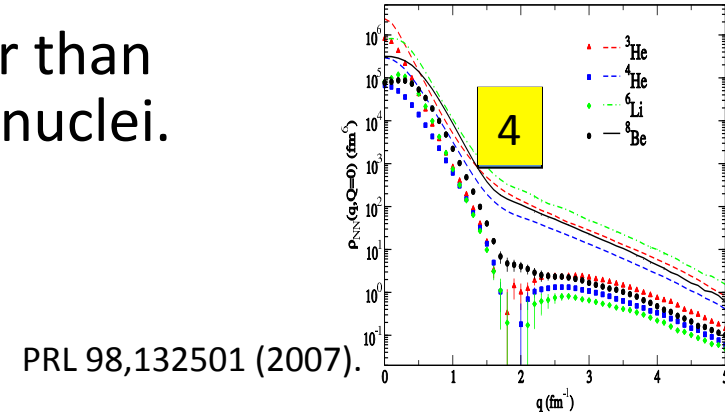
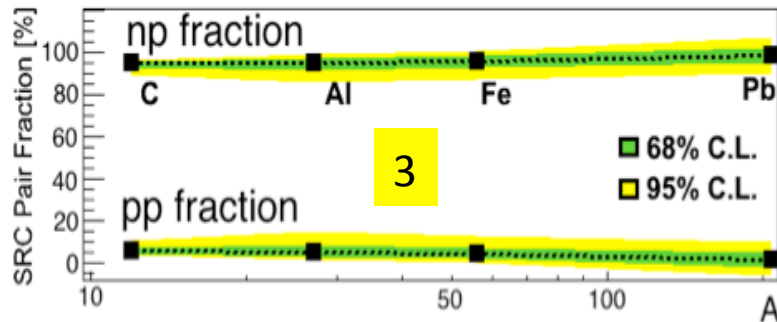
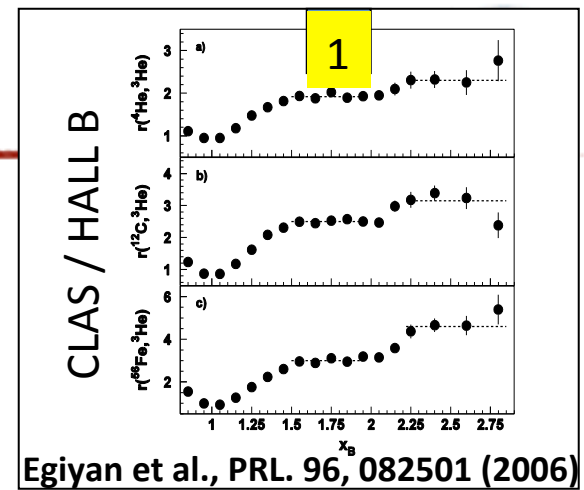
(short) overview of what we know and
what we want to know about SRC with
the help of HADES

You can't do nuclei without
correlations!



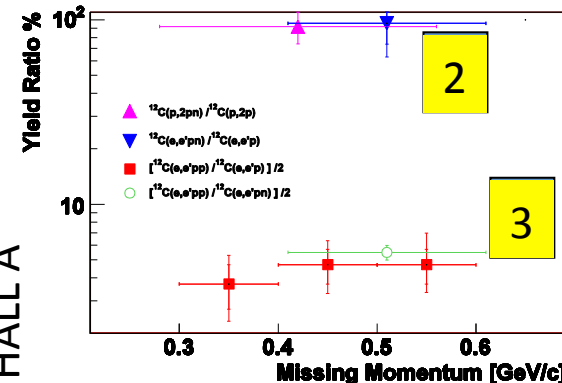
SRC 101

- 1 Account for $\sim 25\%$ of nucleons in nuclei.
- 2 Dominate the momentum distribution for $k \geq 300$ 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.
The high momentum tail (300-600 MeV/c) is dominated by $L=0,2$ $S=1$ np –SRC pairs.



PRL 98,132501 (2007).

EVA / BNL and JLab /
HALL A



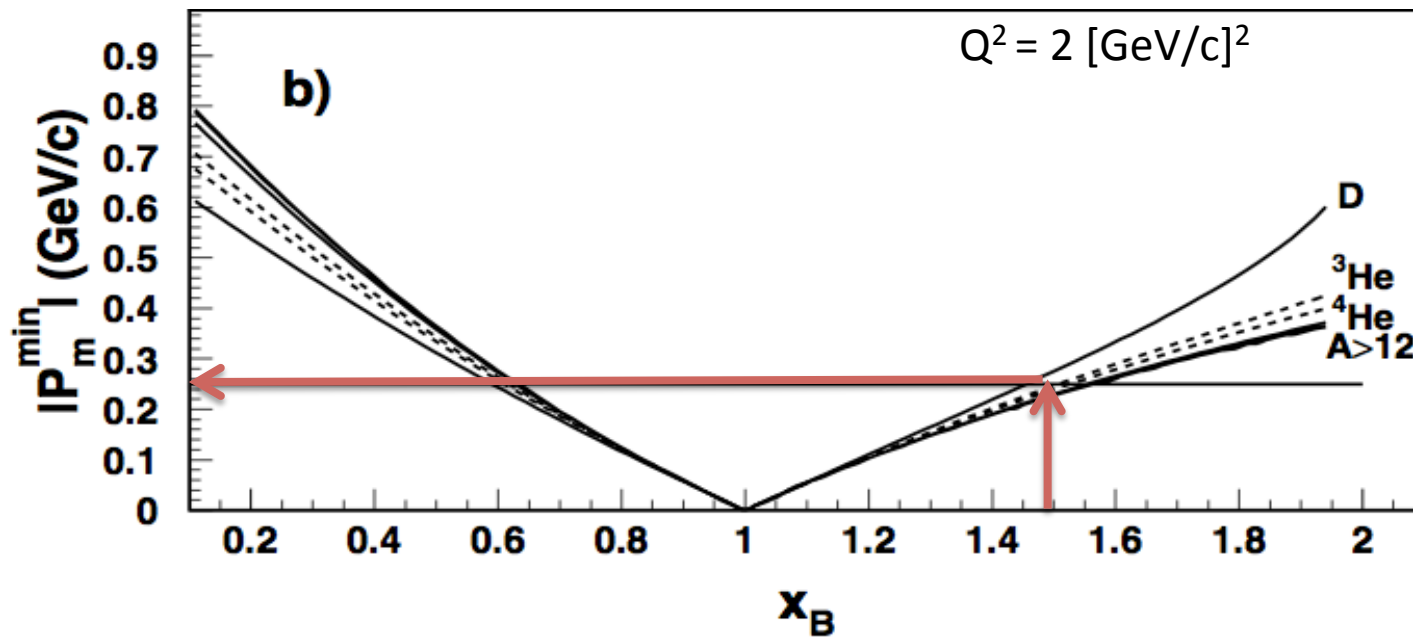
PRL 162504(2006); Science 320, 1476 (2008).



High-Momentum Scaling



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



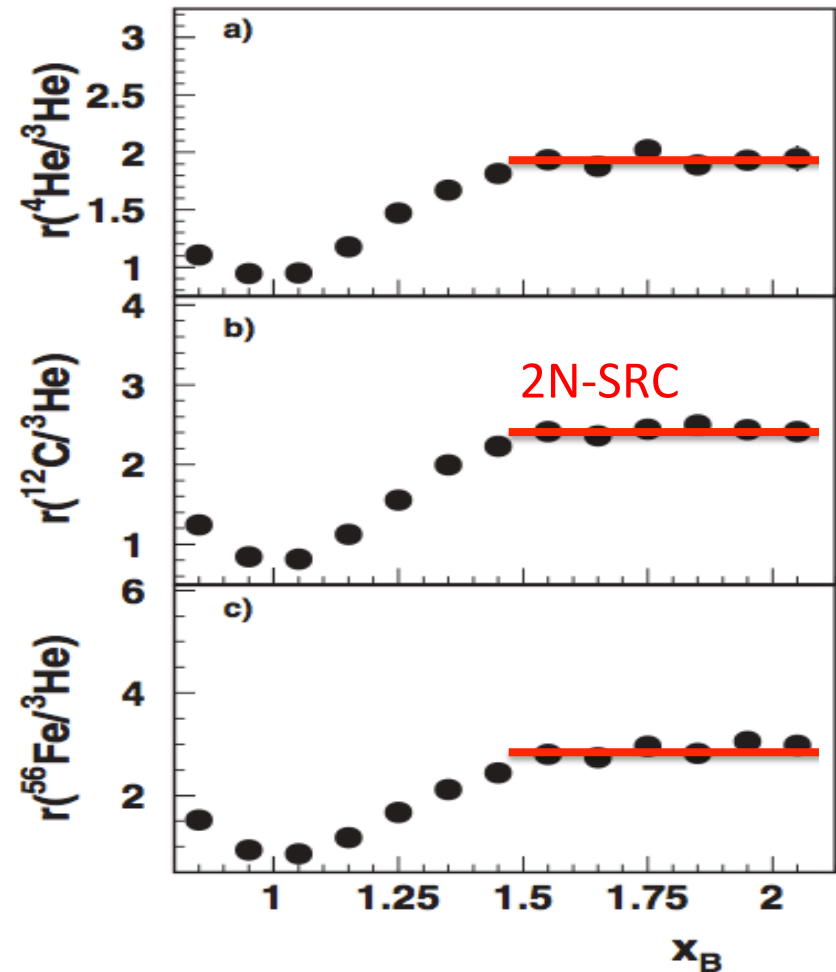


High-Momentum Scaling



- (e,e') cross section ratios sensitive for A/d 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).

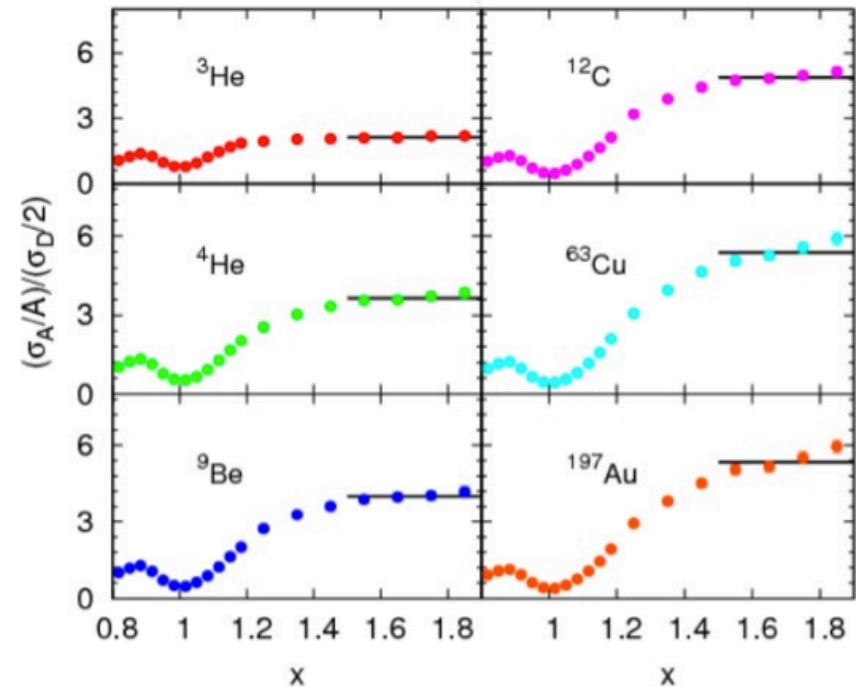


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N. Fomin et al., PRL **108**, 092502 (2012)

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

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



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).



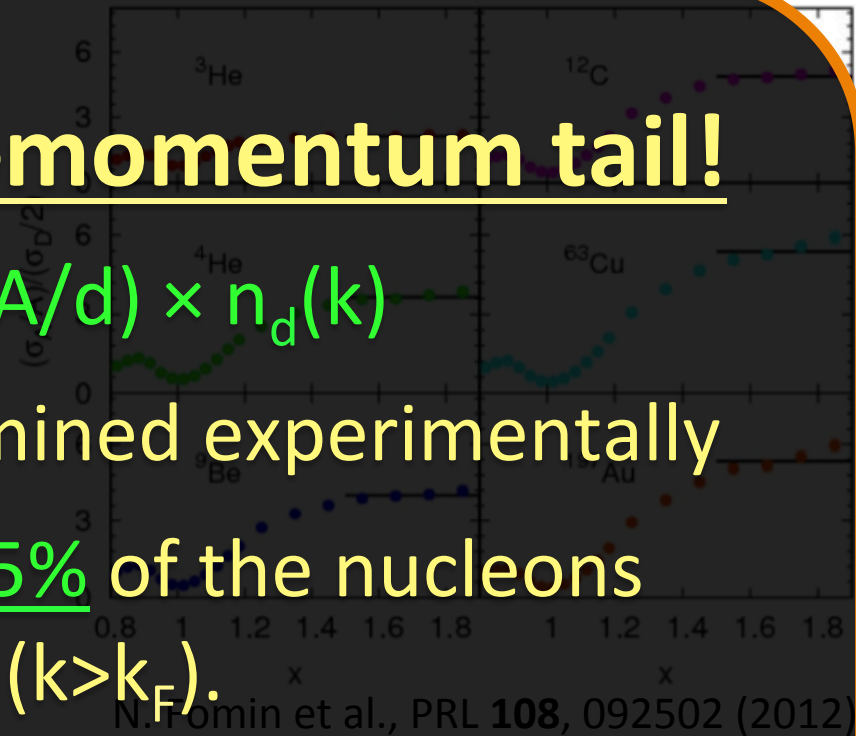
High-Momentum Scaling



- (e,e') cross section

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



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

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



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



High-Momentum Scaling



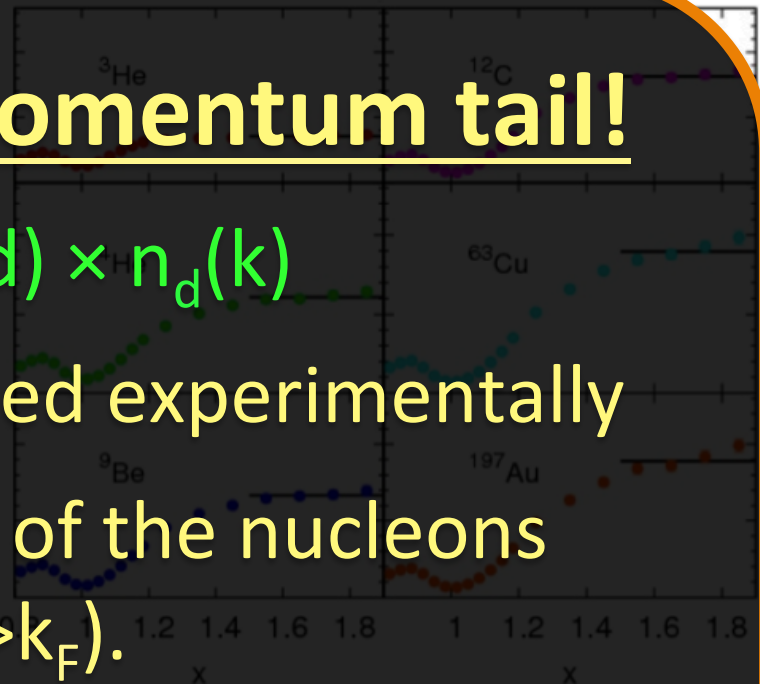
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Do ALL high-momentum nucleons come in pairs? What kind of pairs?



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

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

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



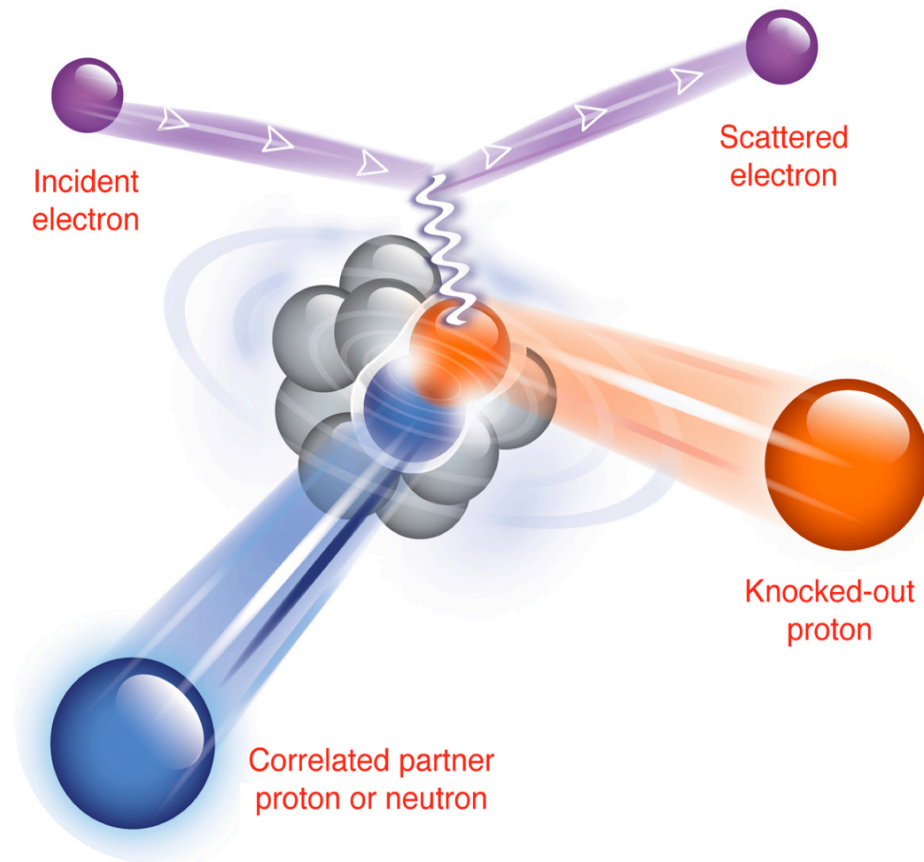
K. Egiyan et al., PRL **96**, 082501 (2006)



Exclusive 2N-SRC Studies



Breakup the pair =>
Detect both nucleons =>
Reconstruct 'initial' state





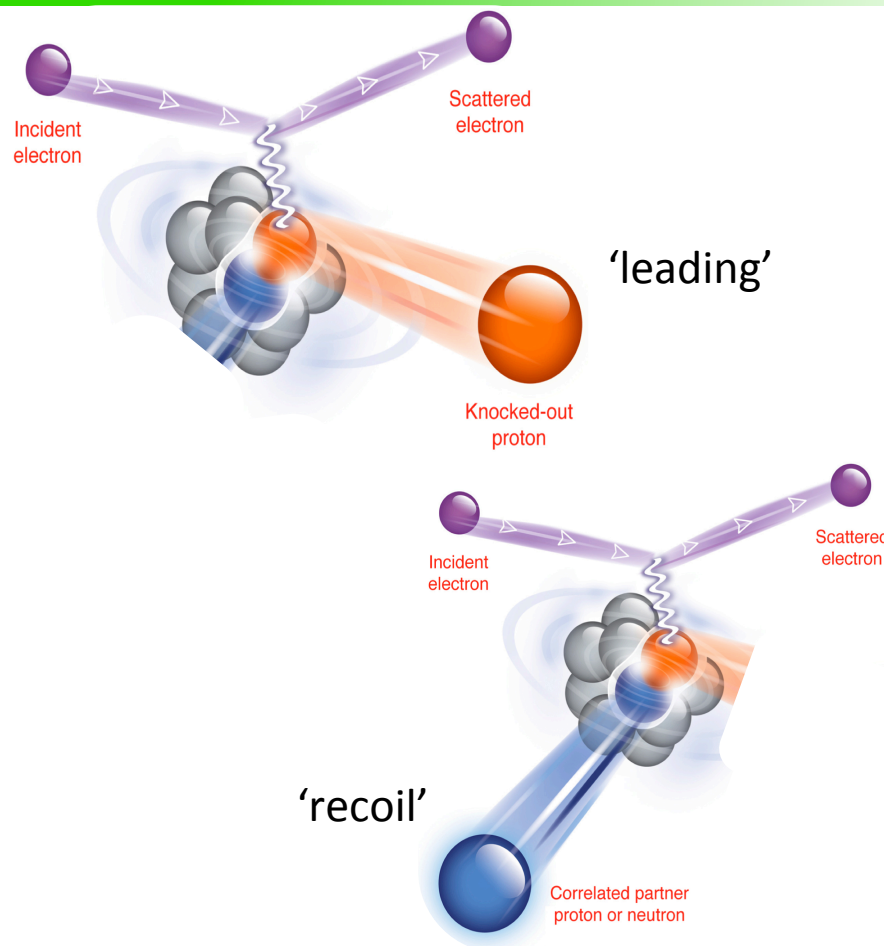
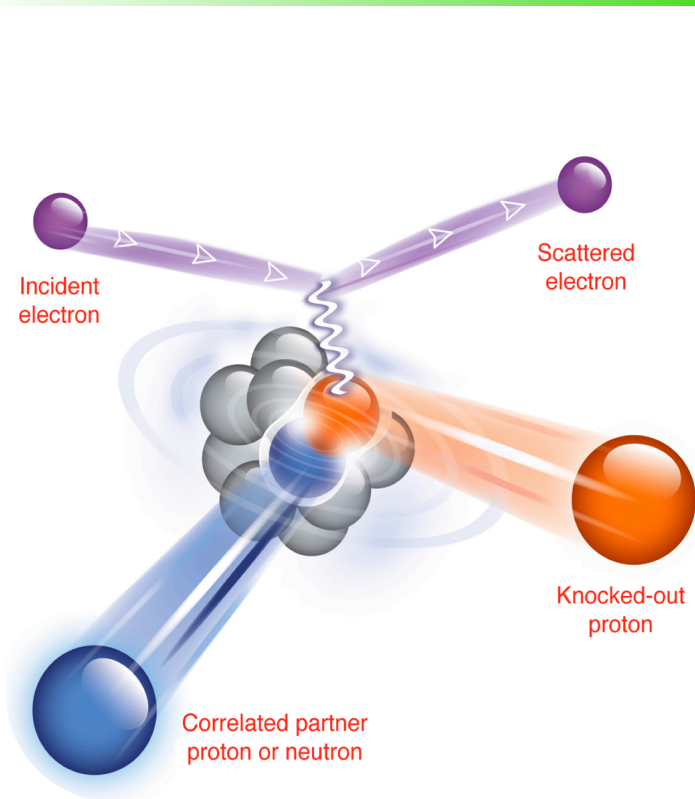
(semi) Exclusive 2N-SRC Studies



Breakup the pair =>

Detect both nucleons =>

Reconstruct 'initial' state



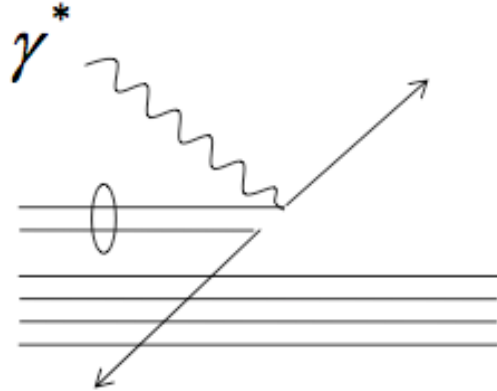


Exclusive 2N-SRC Studies



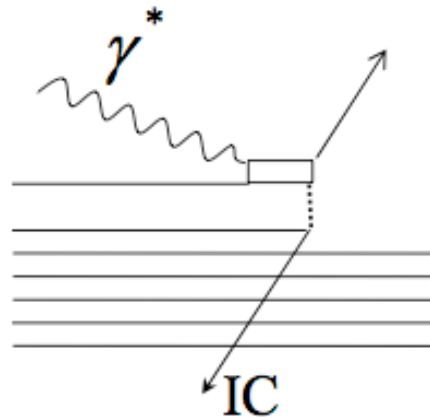
What we want:

=> comment for experts...

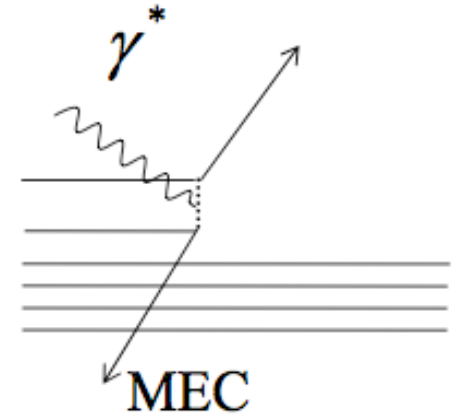


SRC

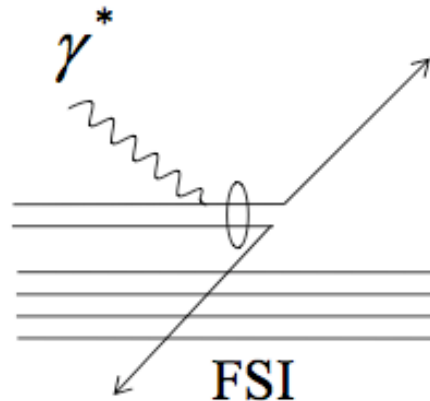
What we (might) get:



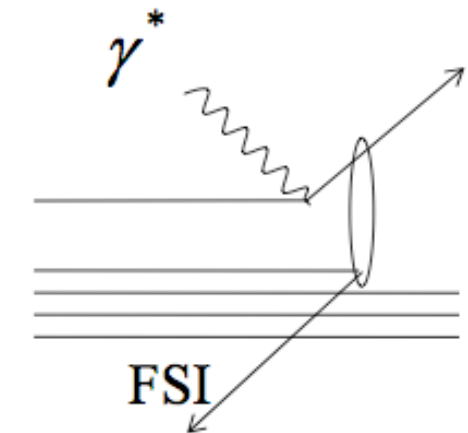
IC



MEC



FSI



FSI

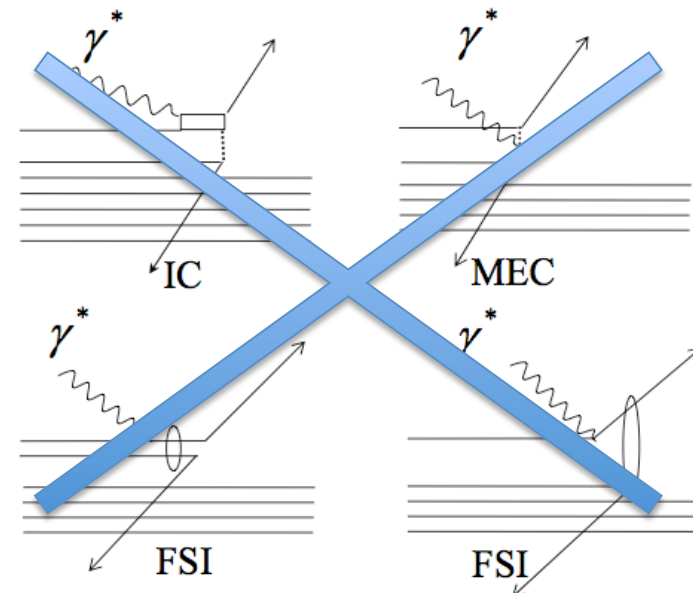
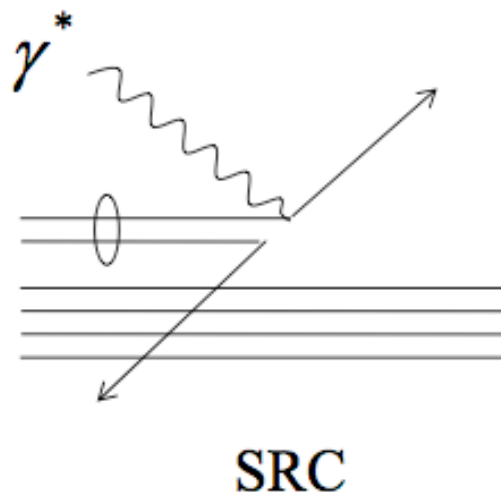


Exclusive 2N-SRC Studies



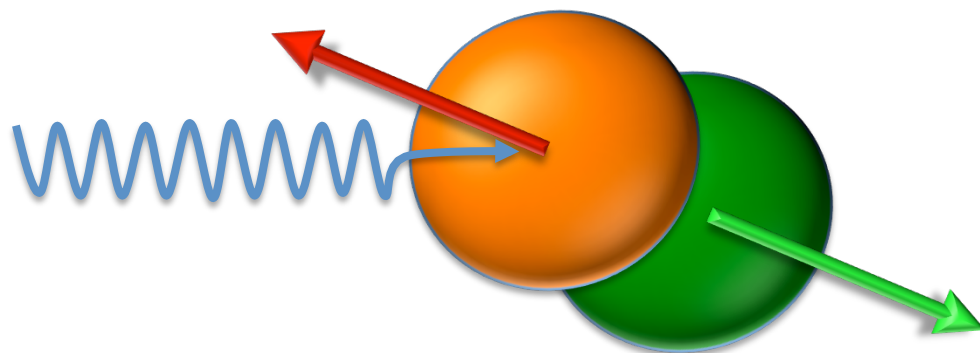
Trick: choose 'good' kinematics!

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



A word on FSI:

Large- Q^2 allows using the Eikonal approximation for FSI calculations. Combines with $x_B > 1$ ensures FSI are confined to within the nucleons of the pair.

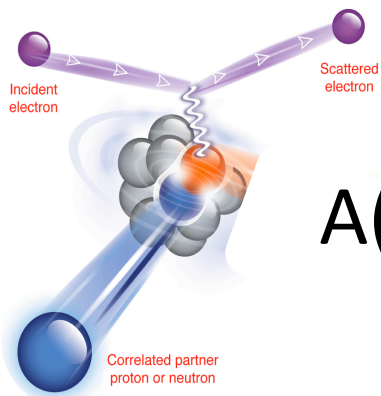




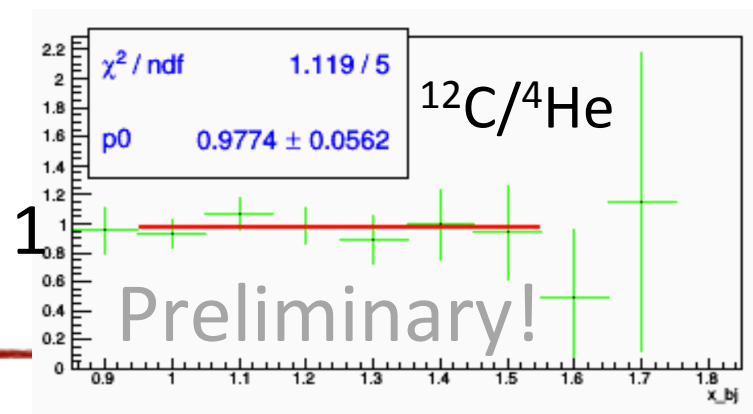
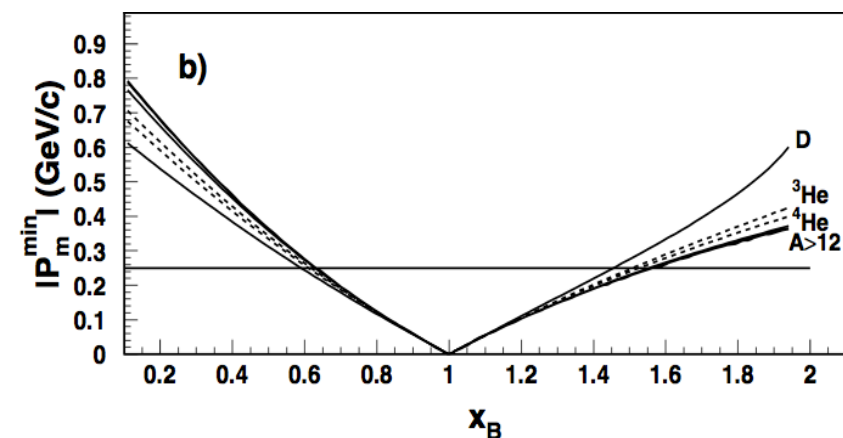
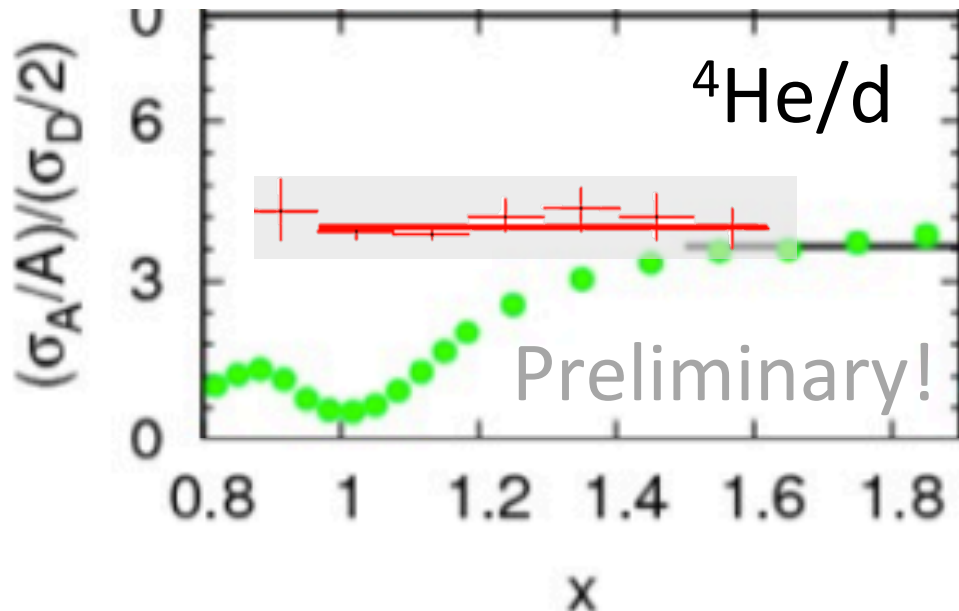
NEW DATA! (1)



Counting SRCs using spectator tagging.

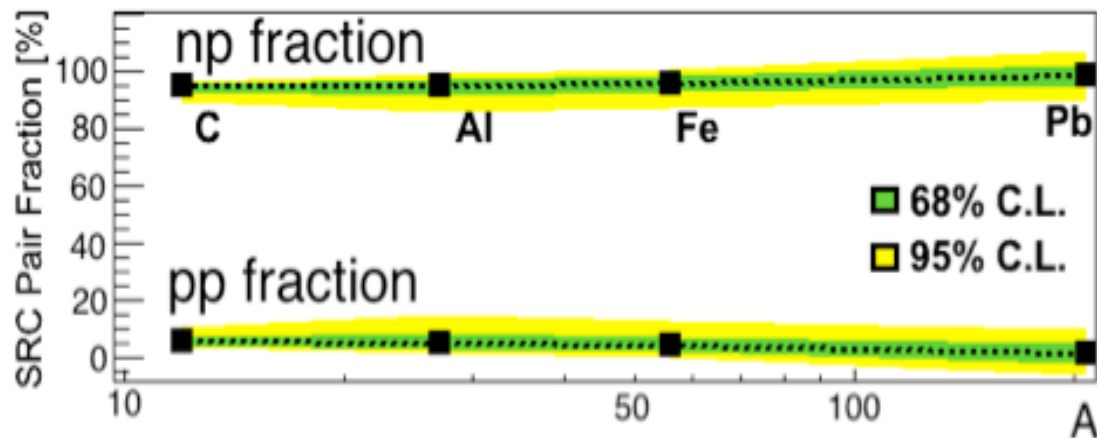
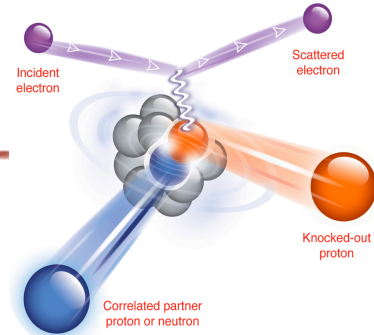


$A(e, e' p_{\text{recoil}})$

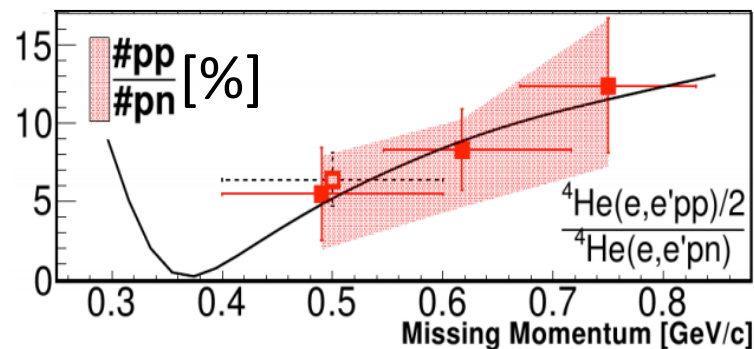




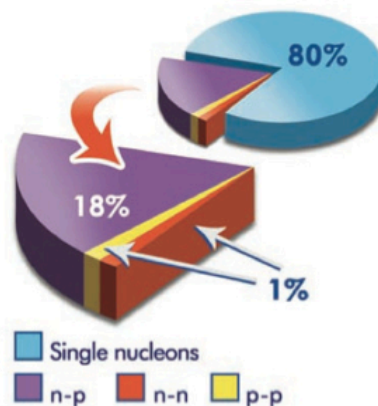
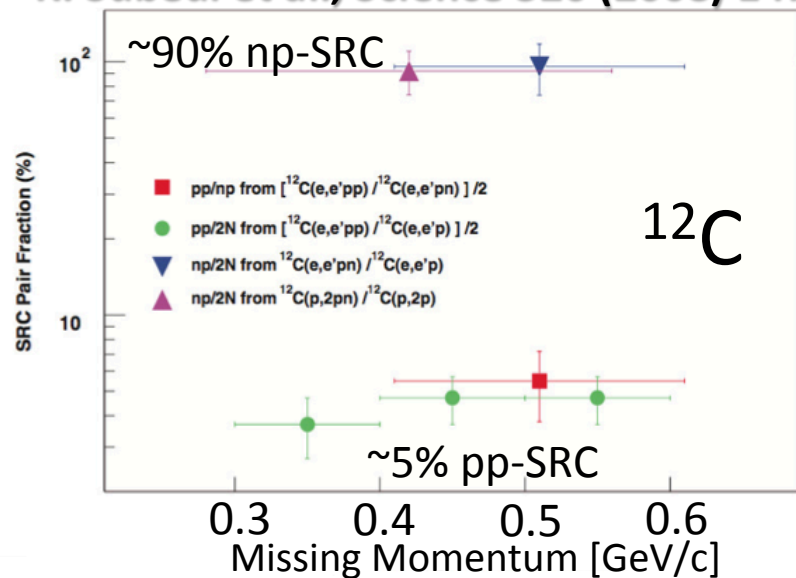
SRC Isospin Structure



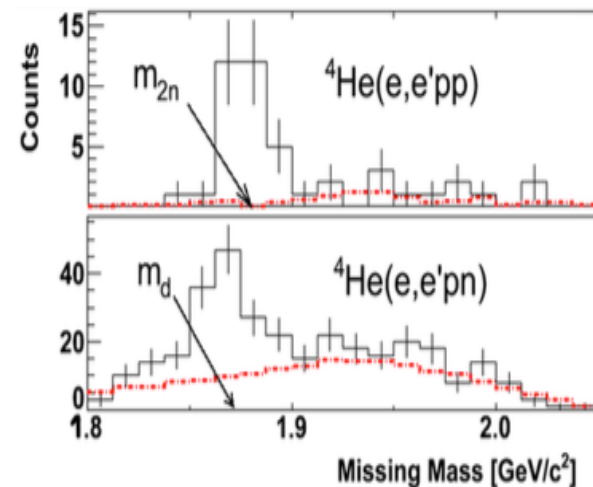
O. Hen et al., Science 364 (2014) 614



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);

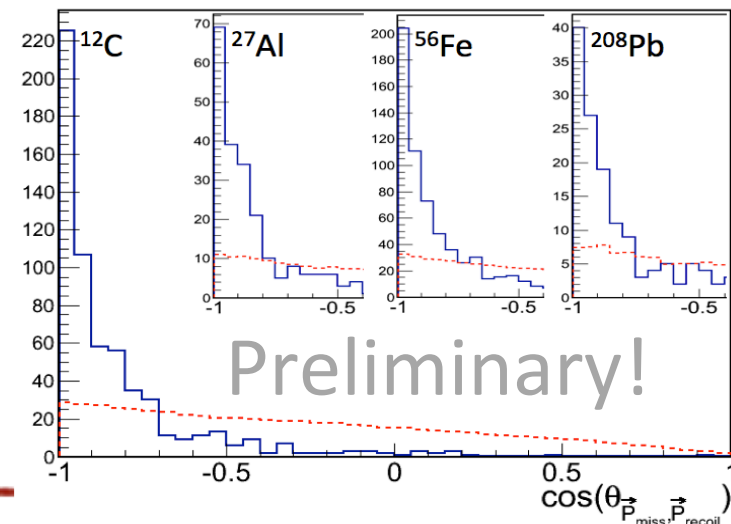
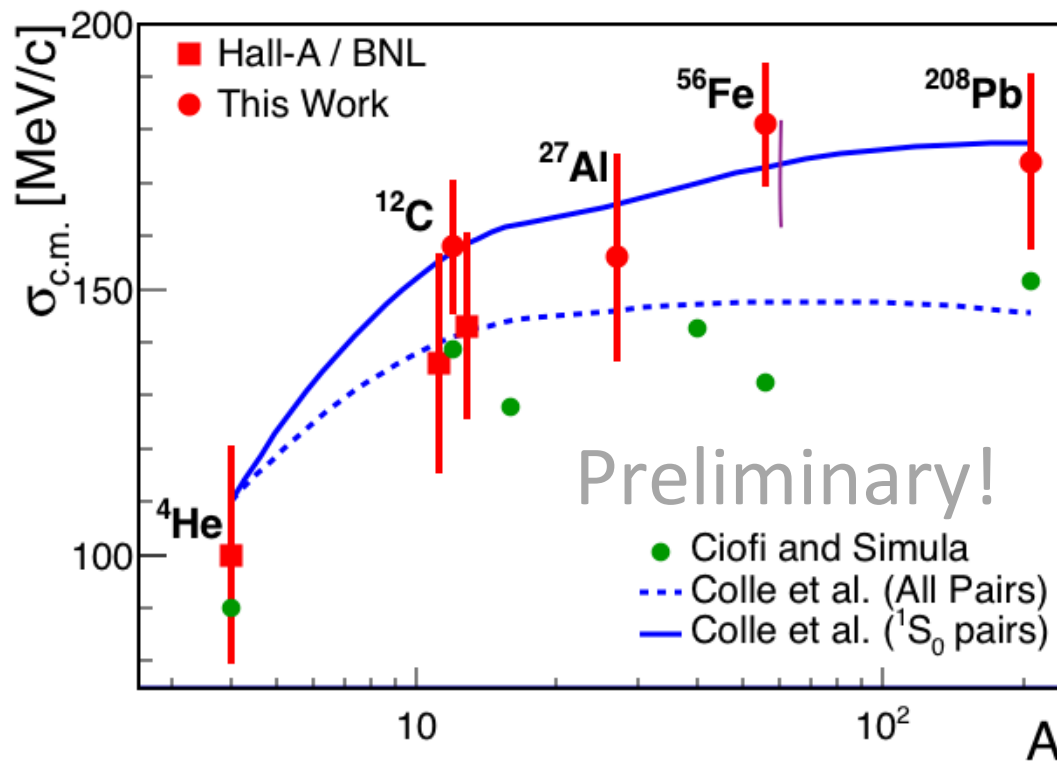
R. Shneor et al., PRL



NEW DATA! (2)



“... high relative momentum and low c.m. momentum compared to the Fermi momentum (k_F)”

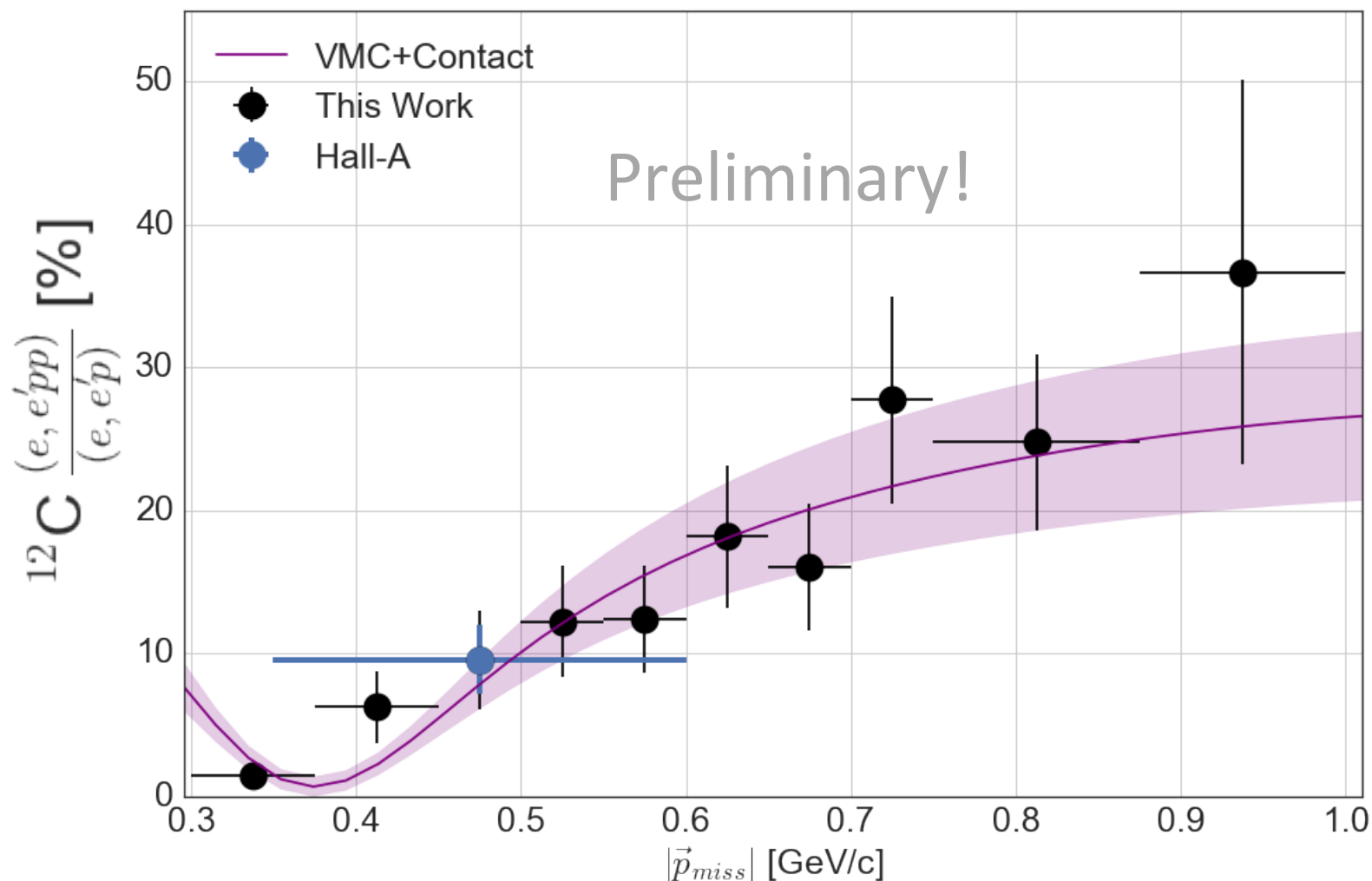




NEW DATA! (3)



Pushing the nuclear wave function to the limit...





SRC Isospin Structure

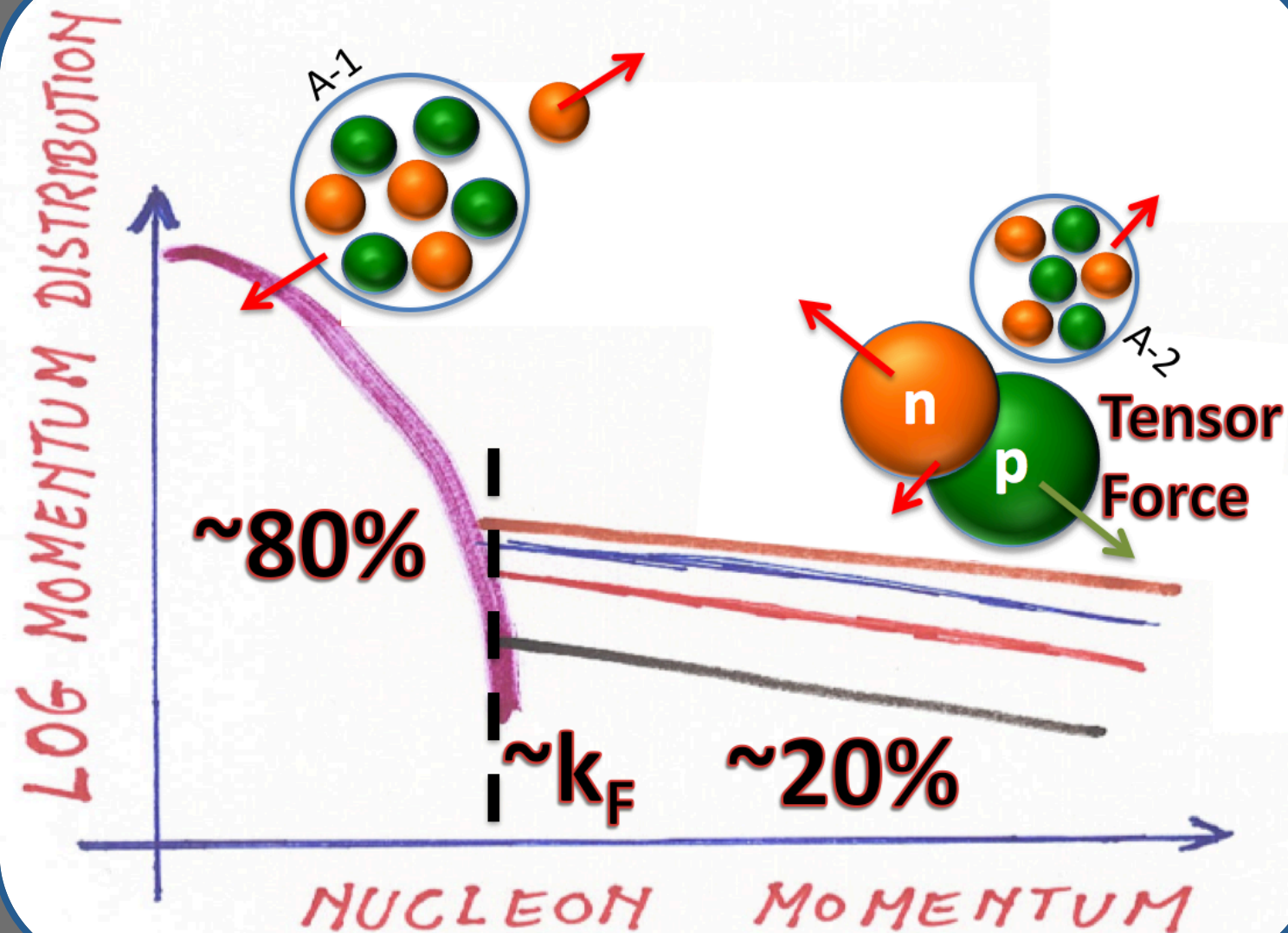


Bottom Line:

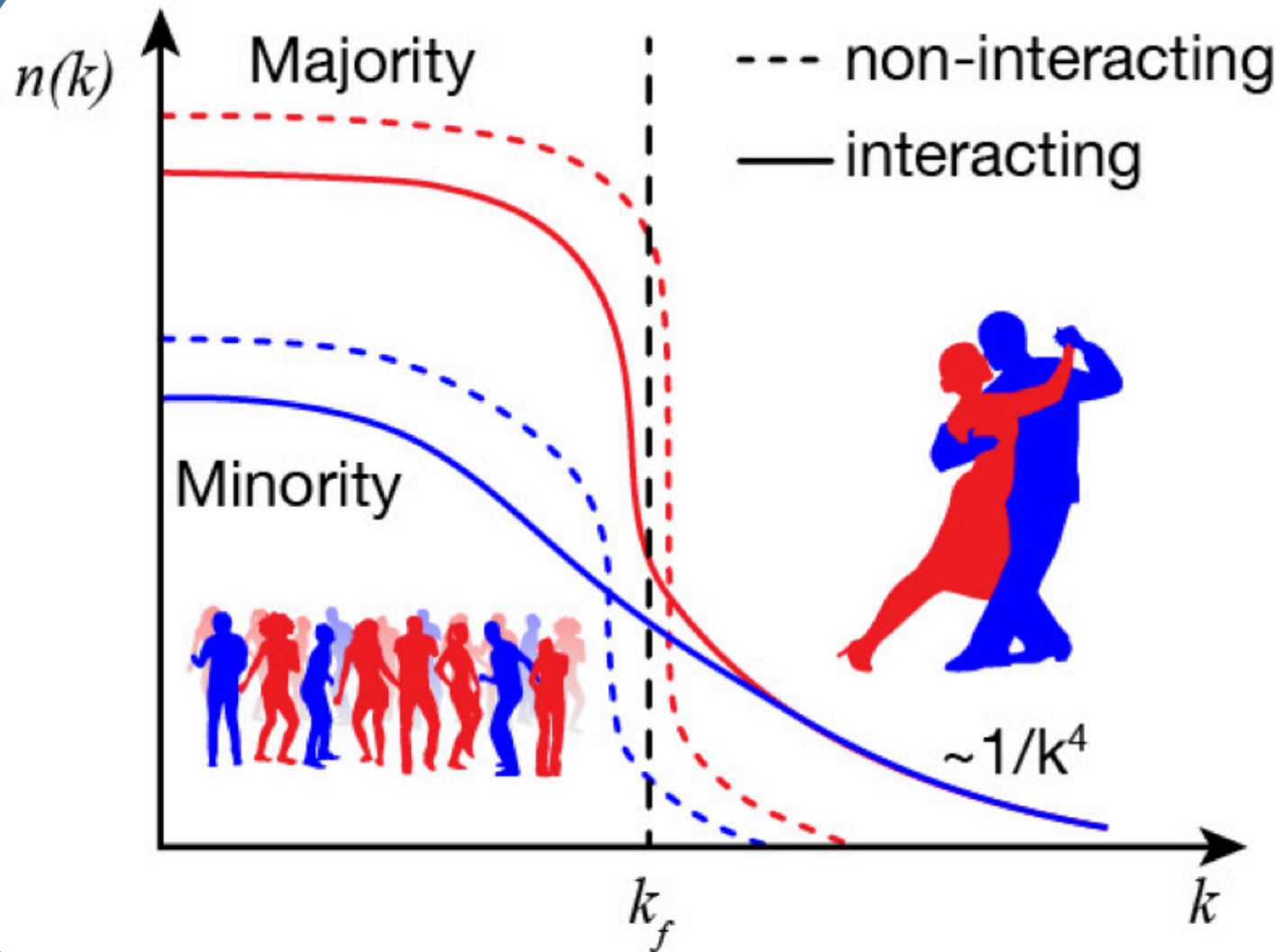
- SRCs account for:
 - ~ 20% of the nucleons in nuclei.
 - ~100% of the high-p ($k > k_F$) nucleons in nuclei.
- Predominantly due to np-SRC.
- Universal for $A = 4 - 208$ nuclei.
- Tensor force dominance at short distance.

0.3 0.4 0.5 0.6
Missing Momentum [GeV/c]

Universal structure of nuclear momentum distributions



Universal structure of nuclear momentum distributions

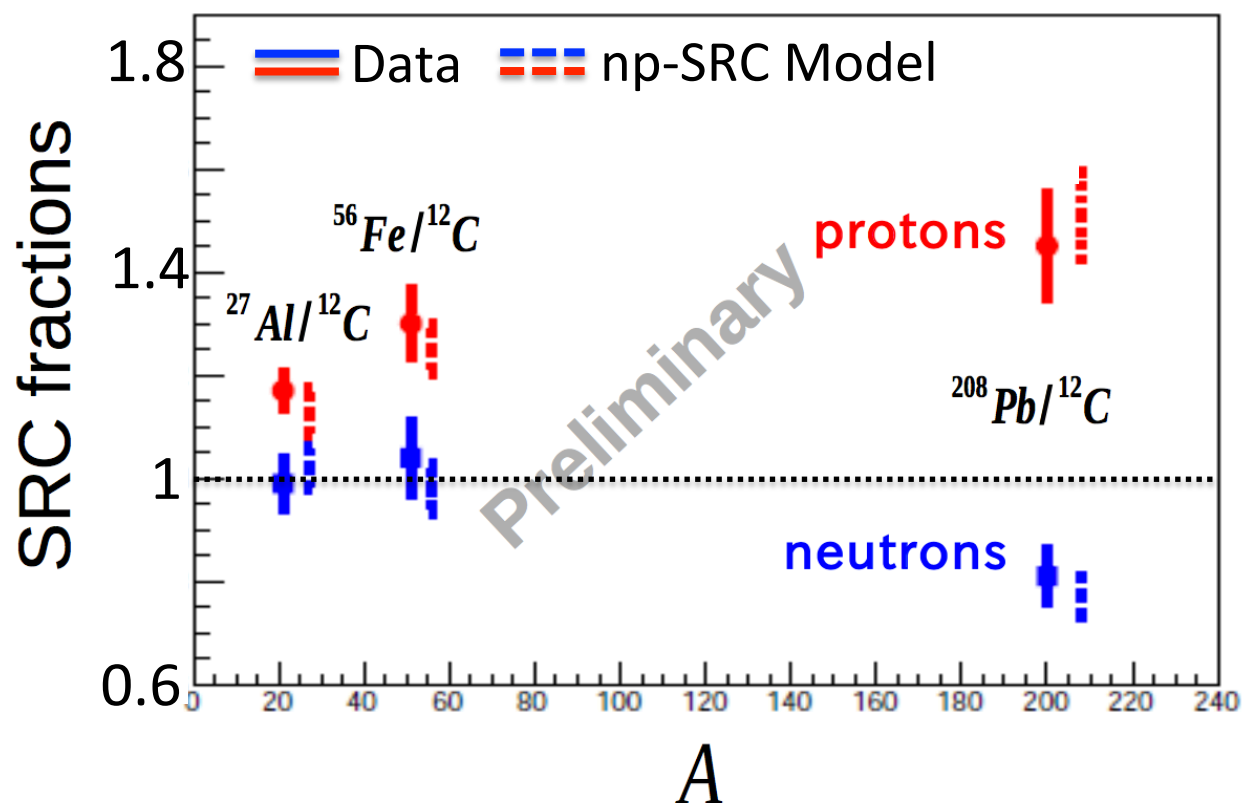




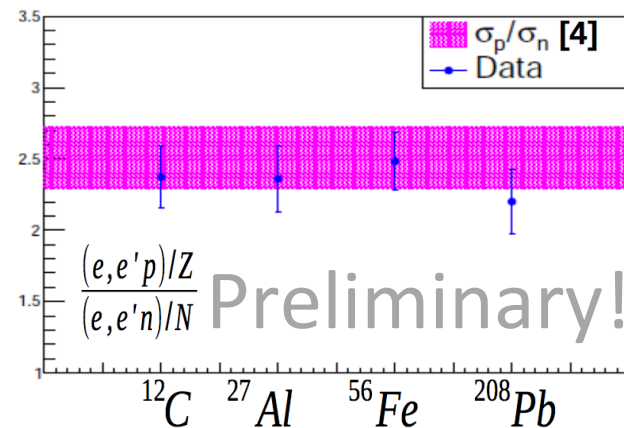
NEW DATA! (4)



Fraction of high-momentum nucleons in asymmetric nuclei



$$\frac{A(e,e'N) [\text{high-}P_m / \text{low-}P_m]}{^{12}\text{C}(e,e'N) [\text{high-}P_m / \text{low-}P_m]}$$



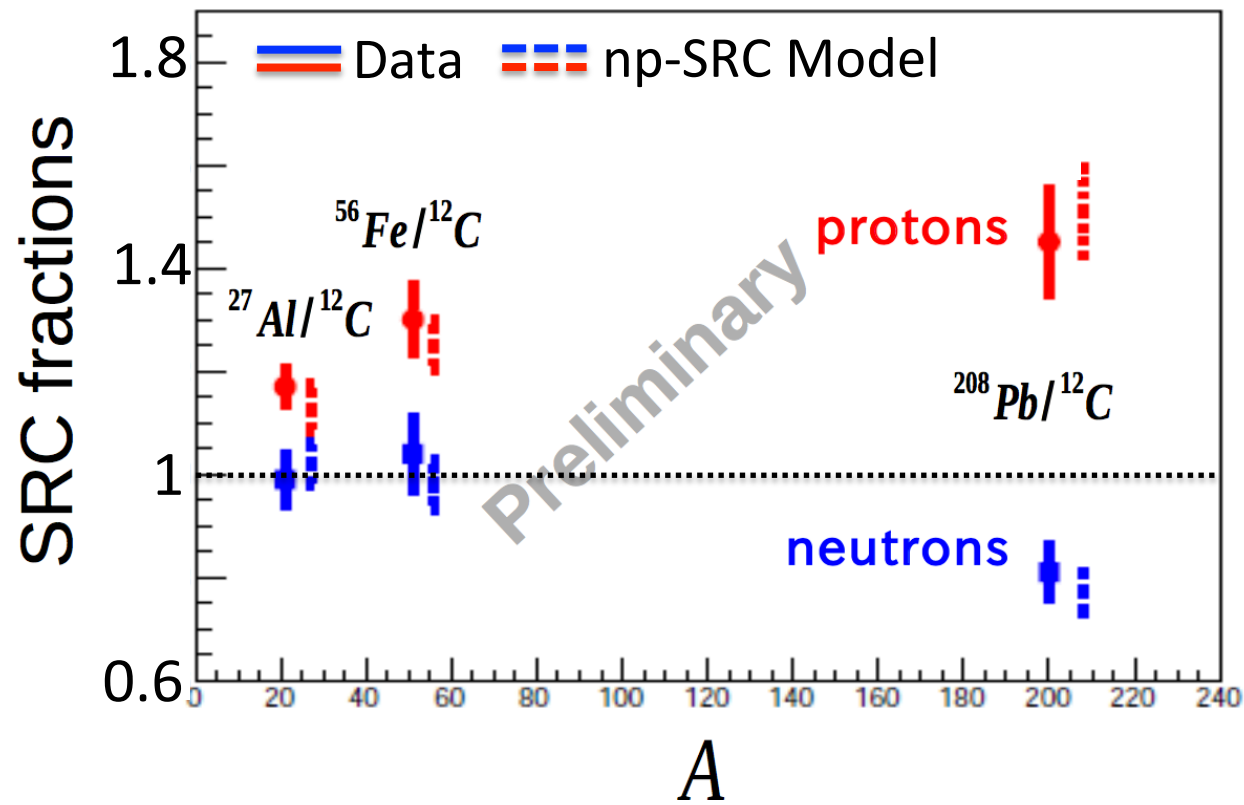
M. Duer et al. (CLAS Collaboration)



NEW DATA! (4)



Fraction of high-momentum nucleons in
asymmetric nuclei



Protons in
neutron rich
nuclei have
higher SRC
probability!!



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!

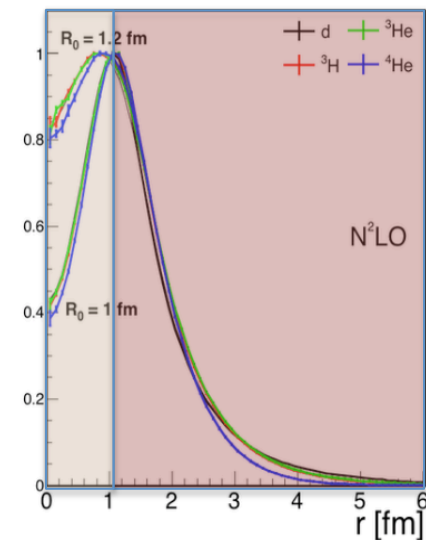
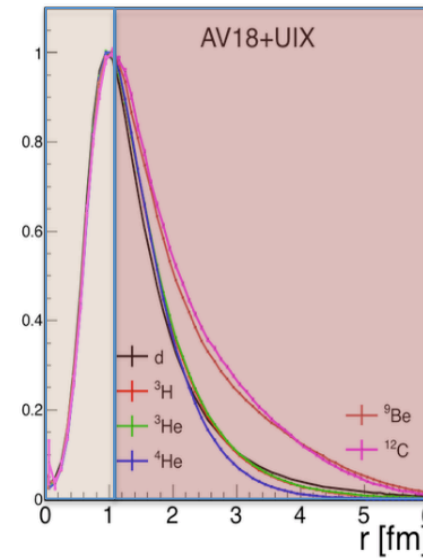
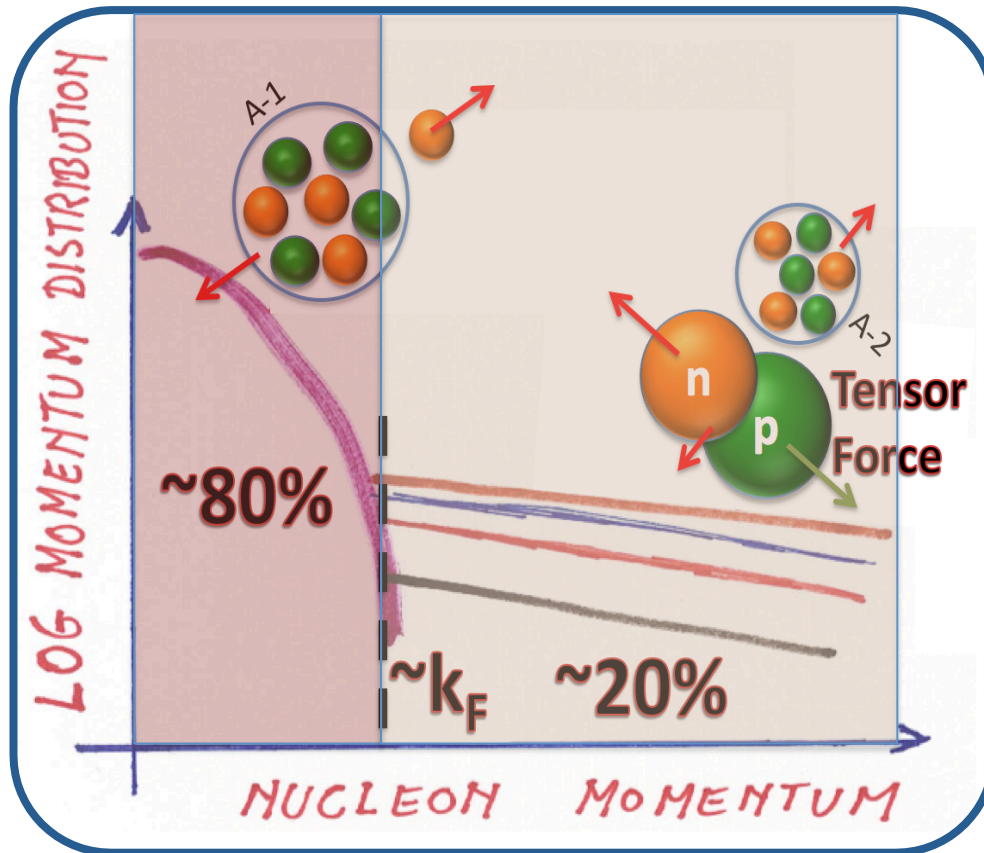
1. SRC Exist in Nuclei (!) and account for:
 - $\sim 20\%$ of the nucleons in nuclei.
 - $\sim 100\%$ of the high- p ($k > k_F$) nucleons in nuclei.
2. Have large relative momentum and low c.m. momentum.
3. Predominantly due to np-SRC.
4. Universal for $A = 4 - 208$ nuclei.
5. np-SRC create a larger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



Universal Nuclear Structure



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

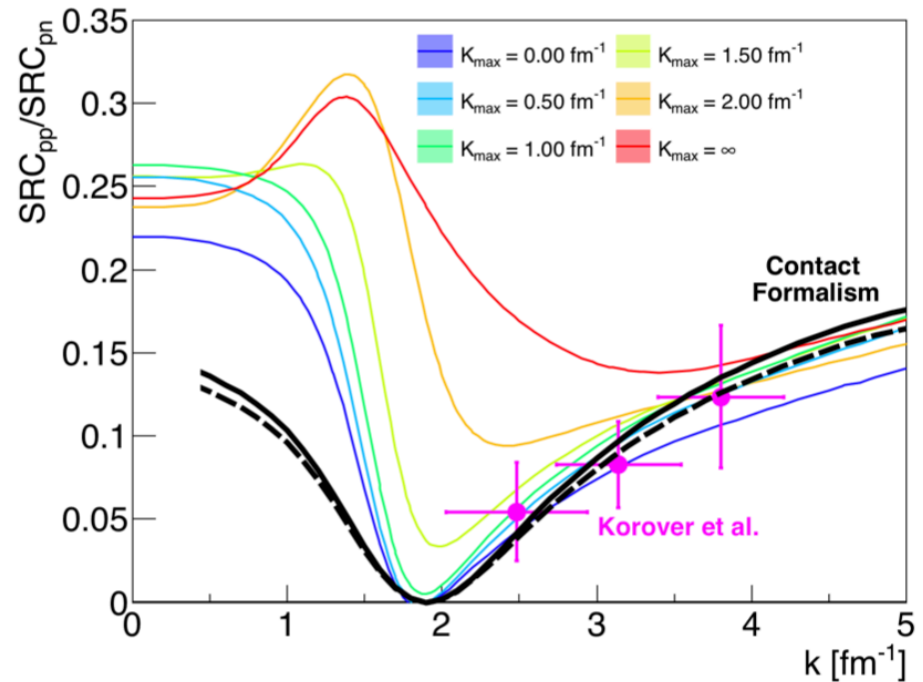
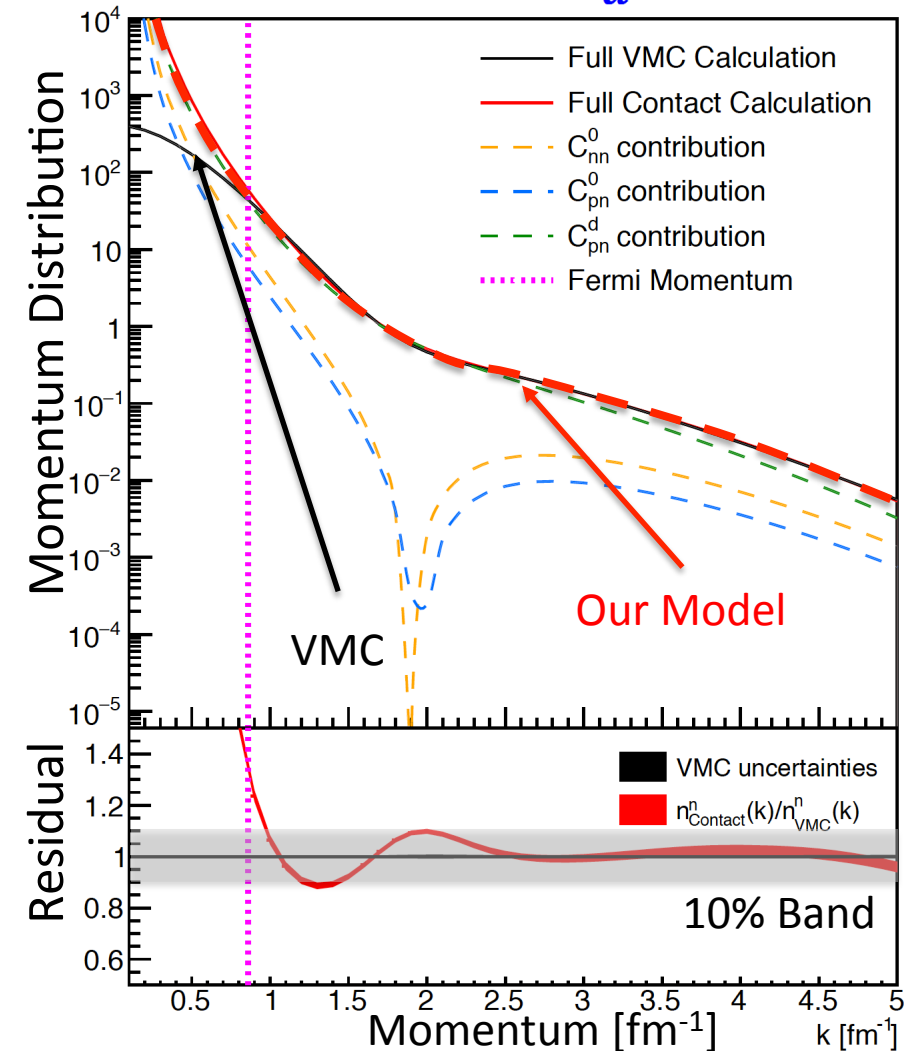




Universal Nuclear Structure



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



=> Need to determine the nuclear contacts from experiment!

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,§}

¹Department of Physics, CTS and LeCosPA, National Taiwan University, Taipei 10617, Taiwan

²Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

³Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

⁴ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

⁵Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Gerald A. Miller

count for the EMC effect
the structure of either

arXiv: 1607.03065 (2016)

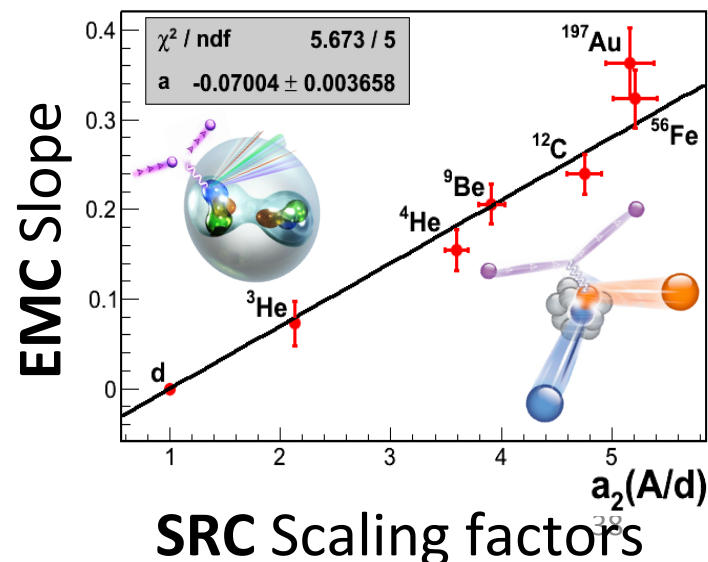
EFT description of bound nucleon structure:

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

$$g_2(A, \Lambda) = \frac{1}{A} \langle A | (N^\dagger N)^2 | A \rangle_\Lambda$$

The contact...

$$a_2(A, x > 1) = \frac{g_2(A, \Lambda)}{[SRC \text{ Scaling Factor}] g_2(2, \Lambda)}$$





Forthcoming 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 Piassetzky

*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)

Hen, Miller, Piassetzky and Weinstein,
arXiv: 1611.09748 (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.



Outstanding Questions in SRC Studies



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



SRC Studies Hit A Atatistic 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

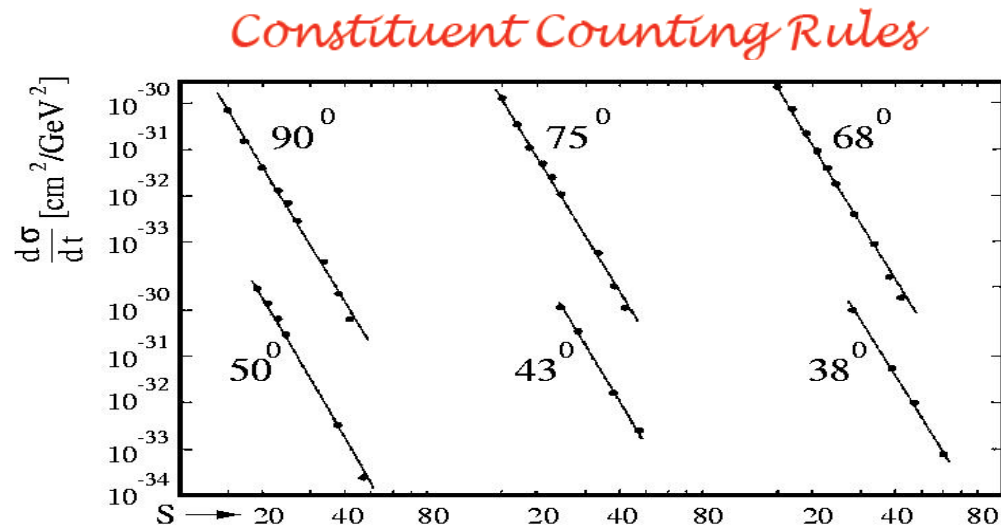


Proton beam advantage:

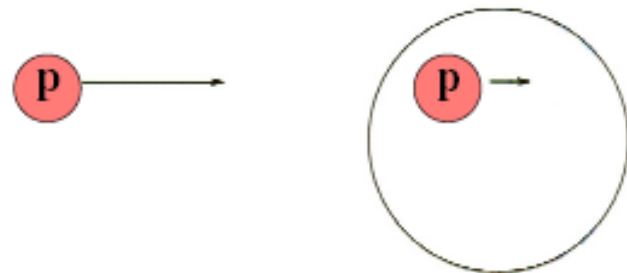
Selective Attention!

pp $\rightarrow$ pp elastic scattering
near 90° c.m:

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



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



Target
Nucleus



Proton beam advantage:

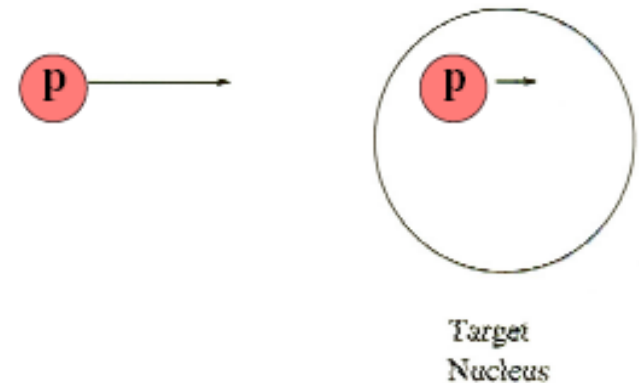
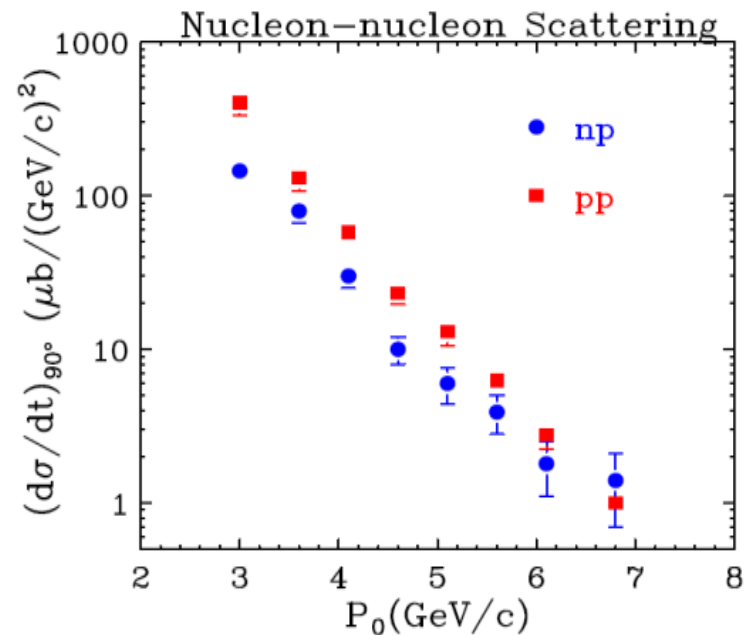
Selective Attention!

pp $\rightarrow$ pp elastic scattering
near 90° c.m:

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

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

3.5 – 5 GeV beams are ideal!

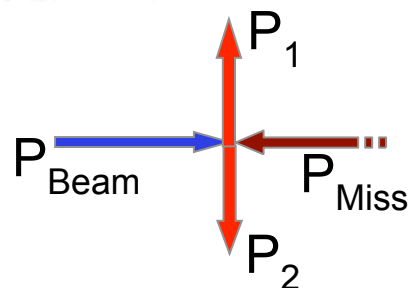




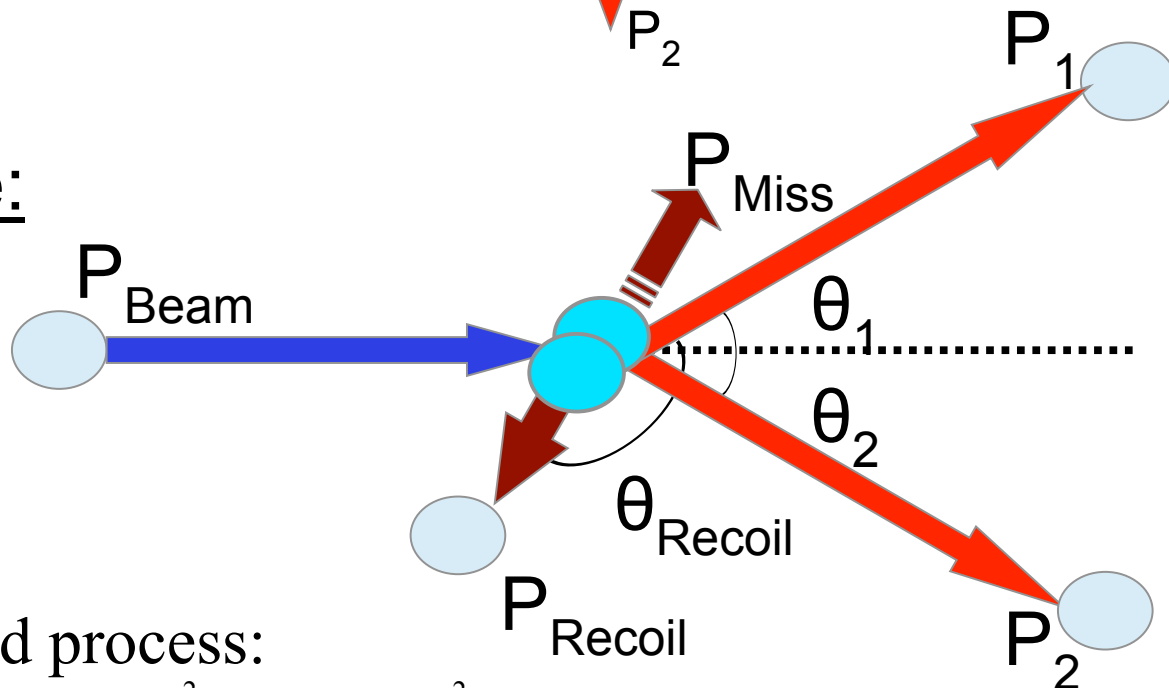
SRC Kinematics



C.M. Frame ($80^\circ \sim 90^\circ$ scattering):



Lab Frame:



• SRC dominance:

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

$$\theta_{\text{recoil}} \geq 90^\circ$$

• Hard process:

$$-t = -(p_1 - p_3)^2 > 2(\text{GeV} / c)^2$$

$$-u = -(p_1 - p_2)^2 > 2(\text{GeV} / c)^2$$

$$s > 7(\text{GeV} / c)^2$$

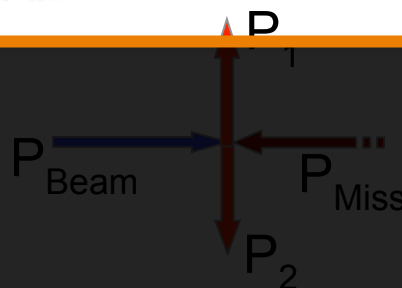
$$\theta_1 = 27.5^\circ \pm 7.5^\circ, \theta_2 = -27.5^\circ \pm 7.5^\circ \quad (\vartheta_{\text{cm}} \approx 90^\circ)$$



SRC Kinematics



C.M. Frame ($80^\circ \sim 90^\circ$ scattering):



**George will talk about exact
(possible) experimental realization
and expected rates...**

• SRC dominance:

$$|P_{\text{recoil}}| \geq 250 \text{ MeV} / c$$

$$\theta_{\text{recoil}} \approx 90^\circ$$

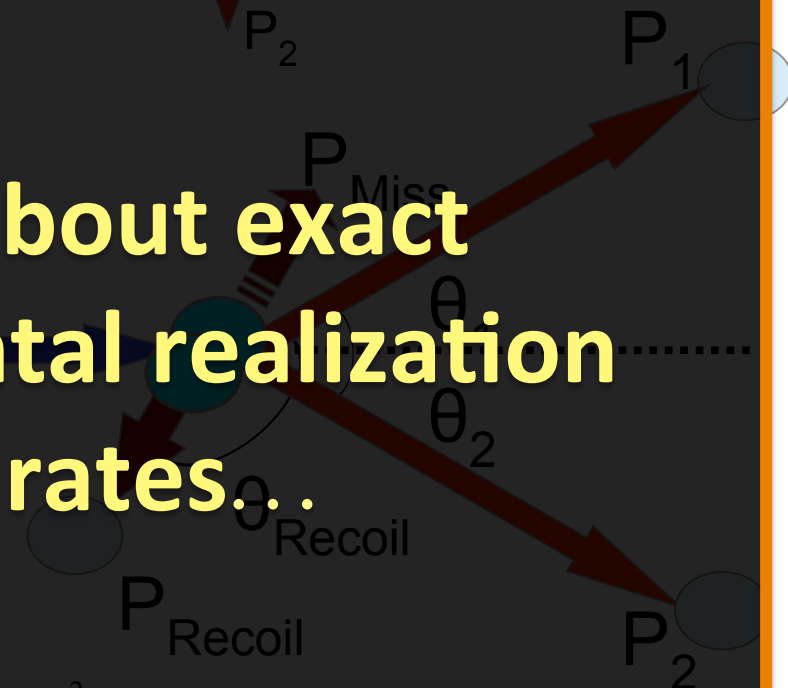
• Hard process:

$$-t = -(p_1 - p_3)^2 > 2(\text{GeV} / c)^2$$

$$-u = -(p_1 - p_2)^2 > 2(\text{GeV} / c)^2$$

$$s > 7(\text{GeV} / c)^2$$

$$\theta_1 = 27.5^\circ \pm 7.5^\circ, \theta_2 = -27.5^\circ \pm 7.5^\circ \quad (\vartheta_{\text{cm}} \approx 90^\circ)$$

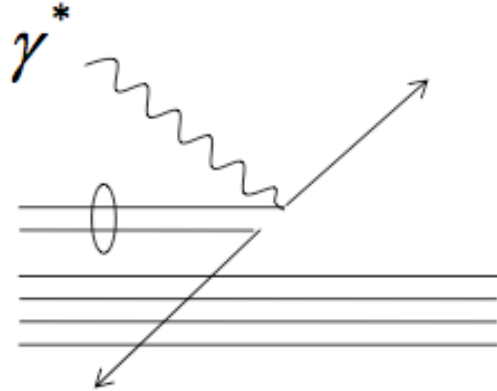




Probe Universality



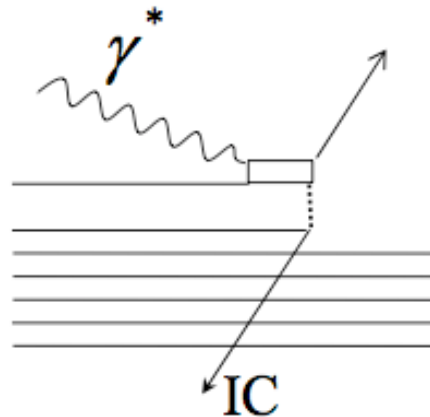
What we want:



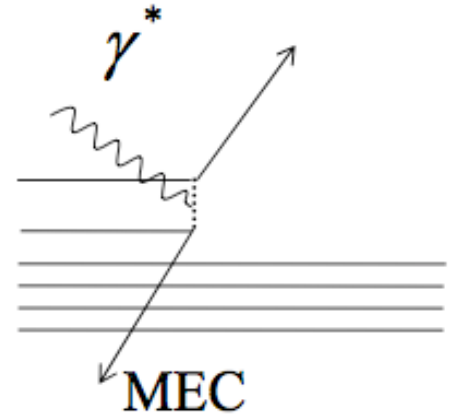
SRC

=> comment for experts...

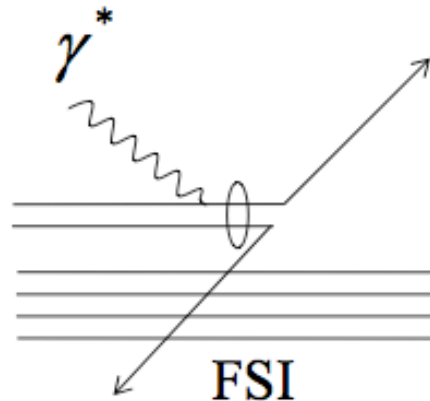
What we (might) get:



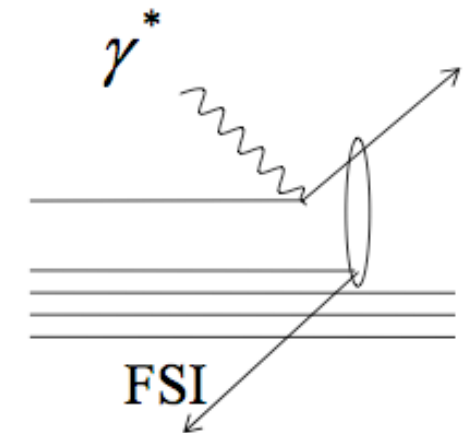
IC



MEC



FSI



FSI

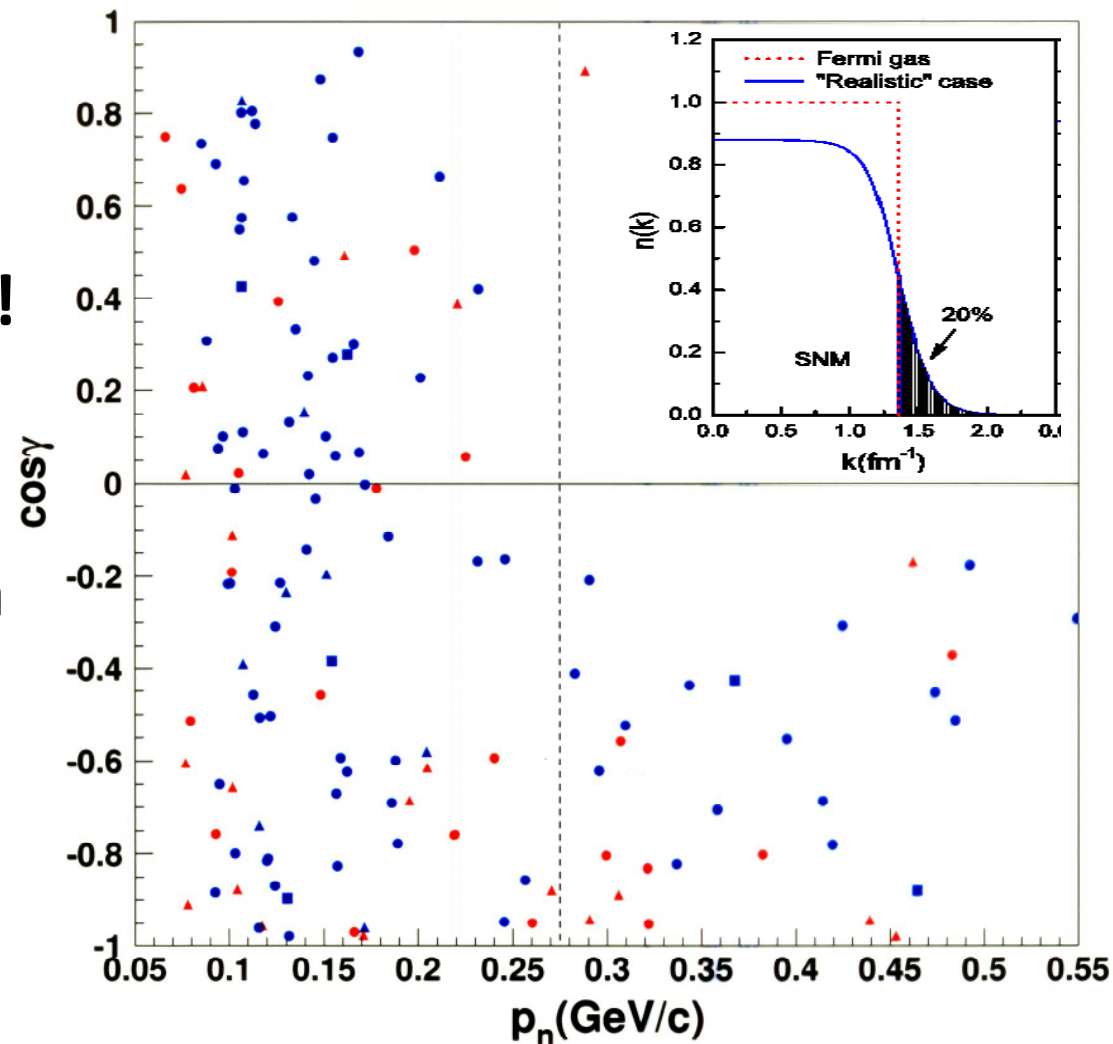


SRC Formation (1) – Migdal jump



- Migdal Jump: transition between mean-field to SRC dominated region.
- **Never observed before!**
- BNL observed clear onset of back-to-back pairs dominance at high recoil momentum.
- But.... Inconclusive (~30 Events).

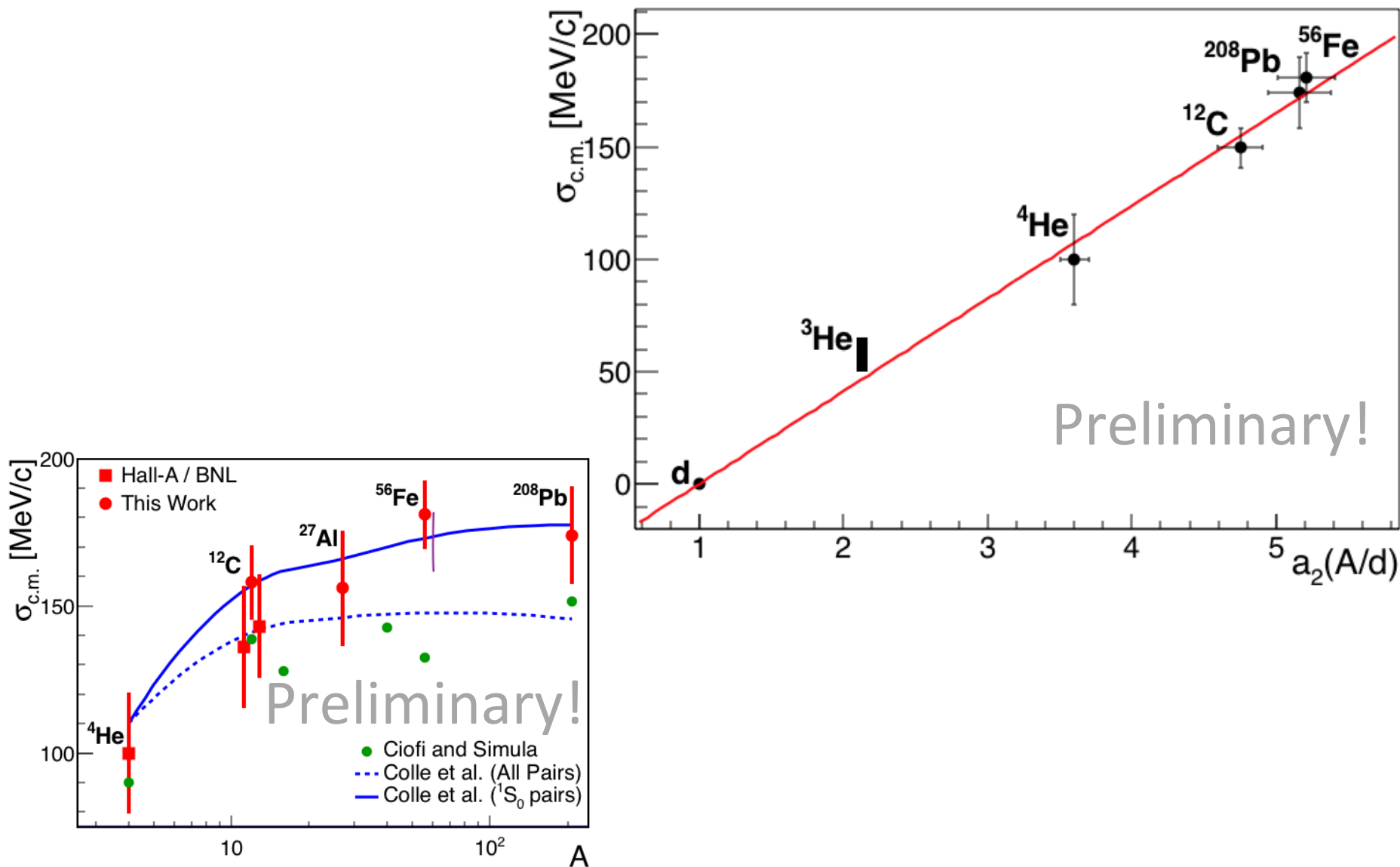
How will it look with
~10k events?



E. Piasetzky *et al.*, PRL 97, 162504 (2006).



SRC Formation (2) – quantum numbers



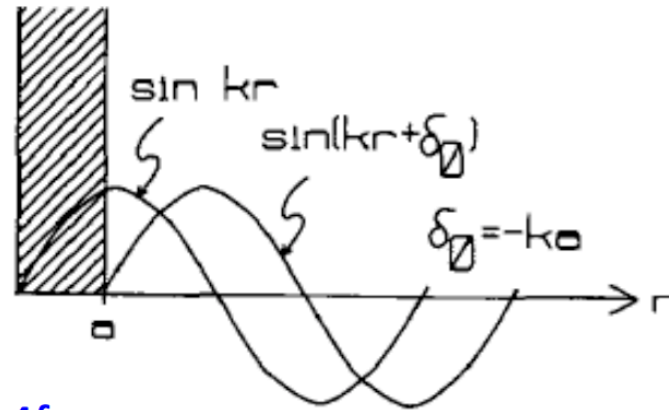
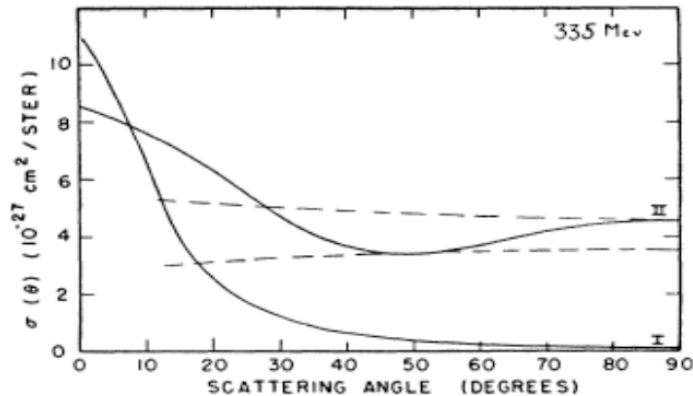


Repulsive Core

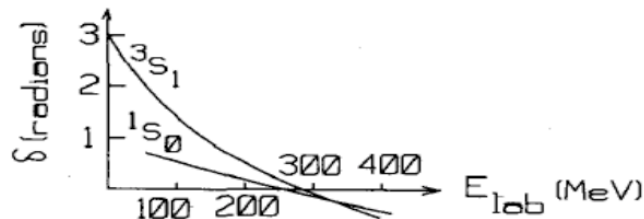


- Nuclear Forces at Short Distances: **NN repulsive core**

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



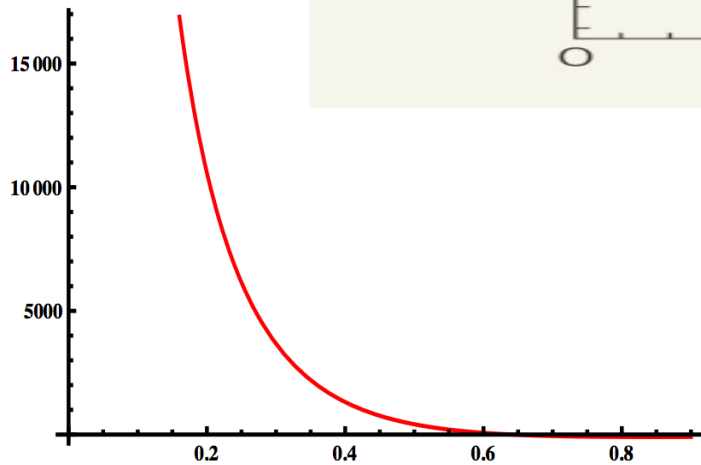
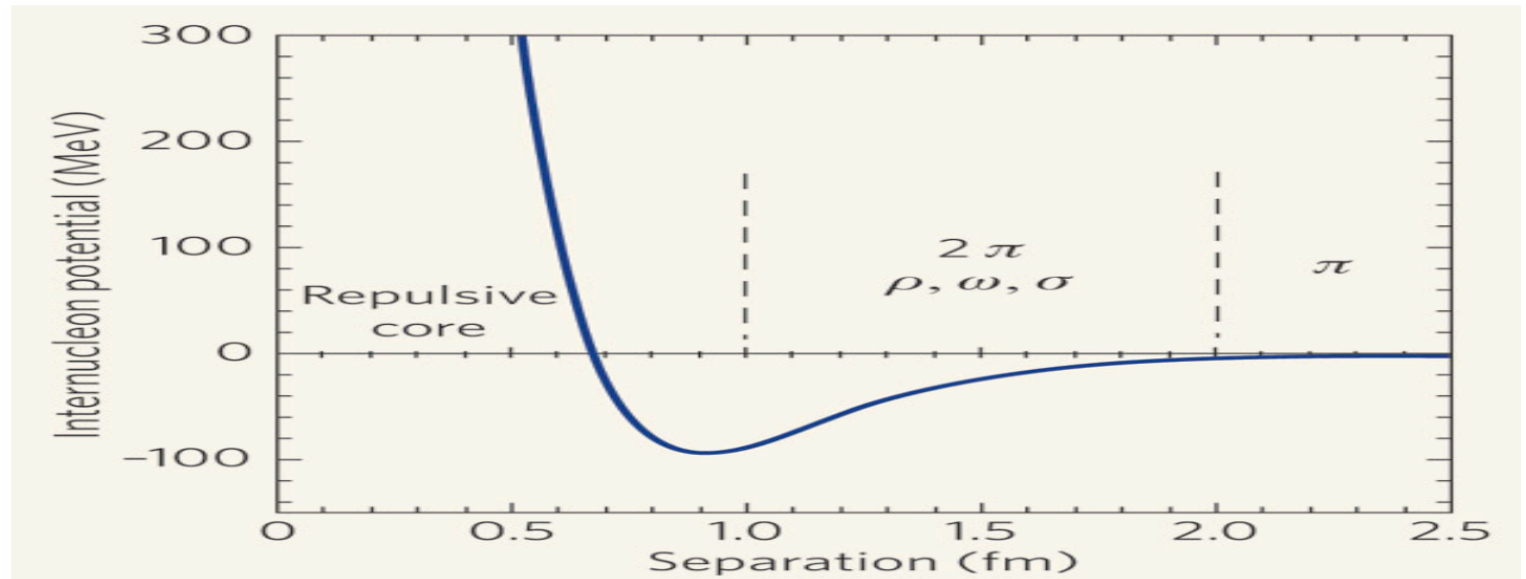
$$r_0 = 0.4\text{fm}$$



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

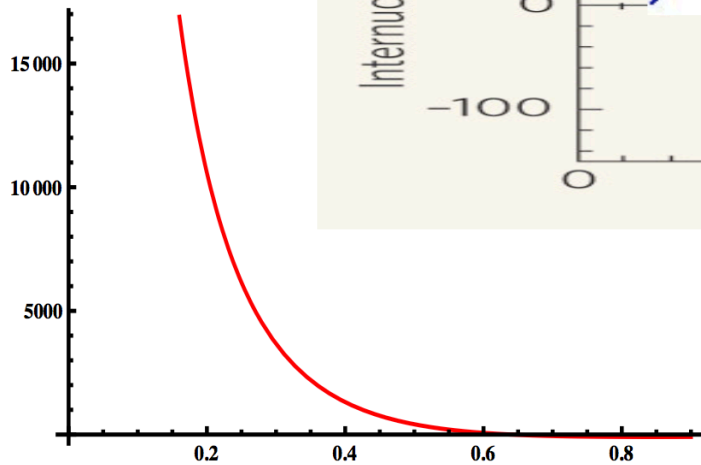
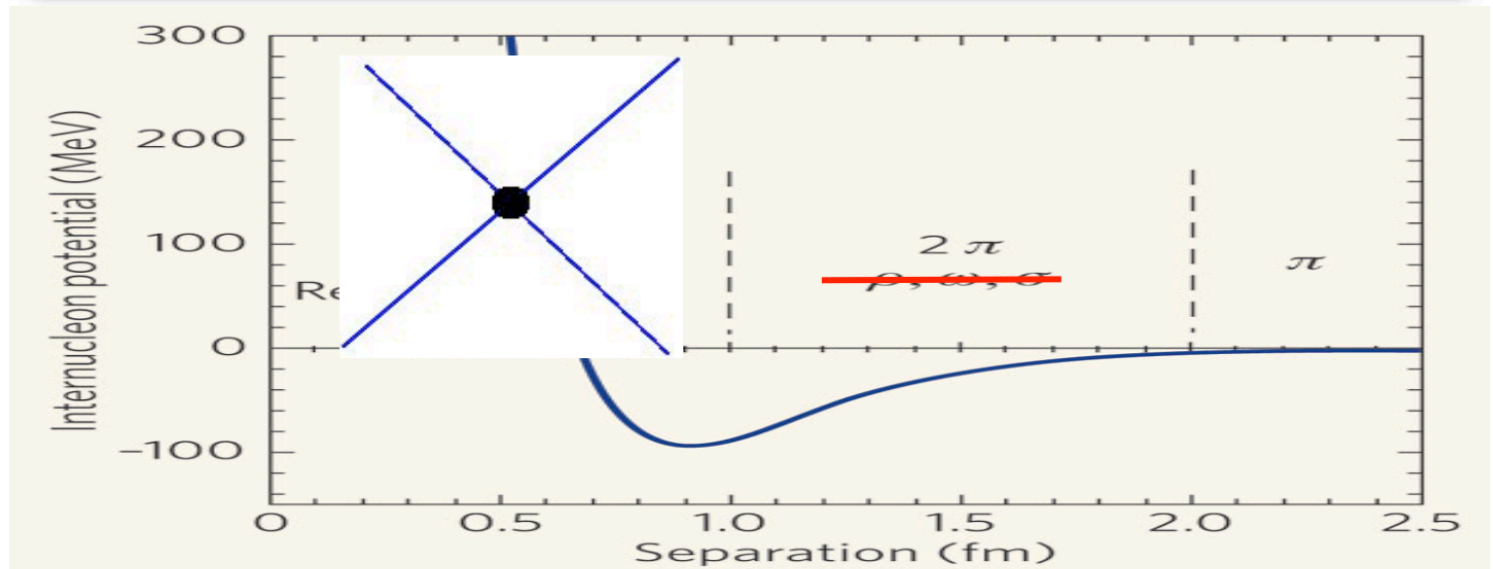
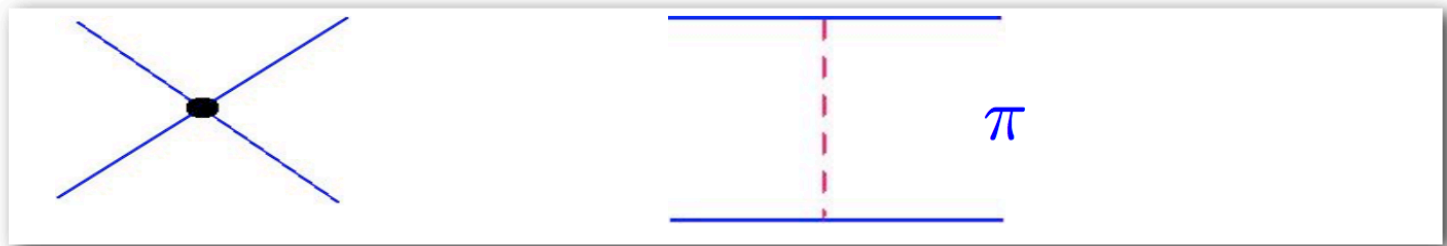


Repulsive Core



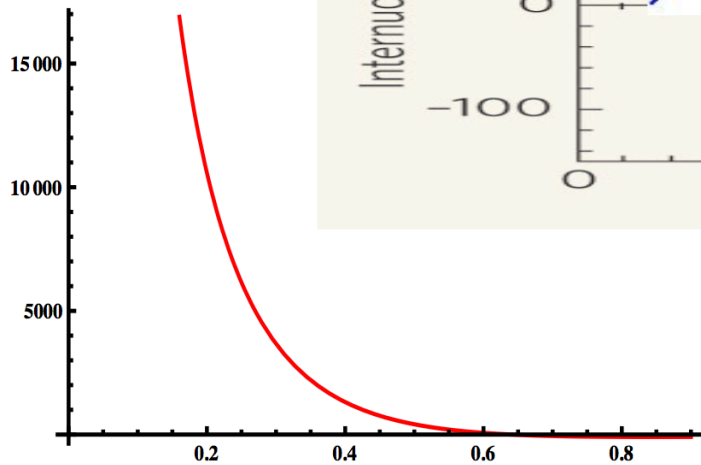
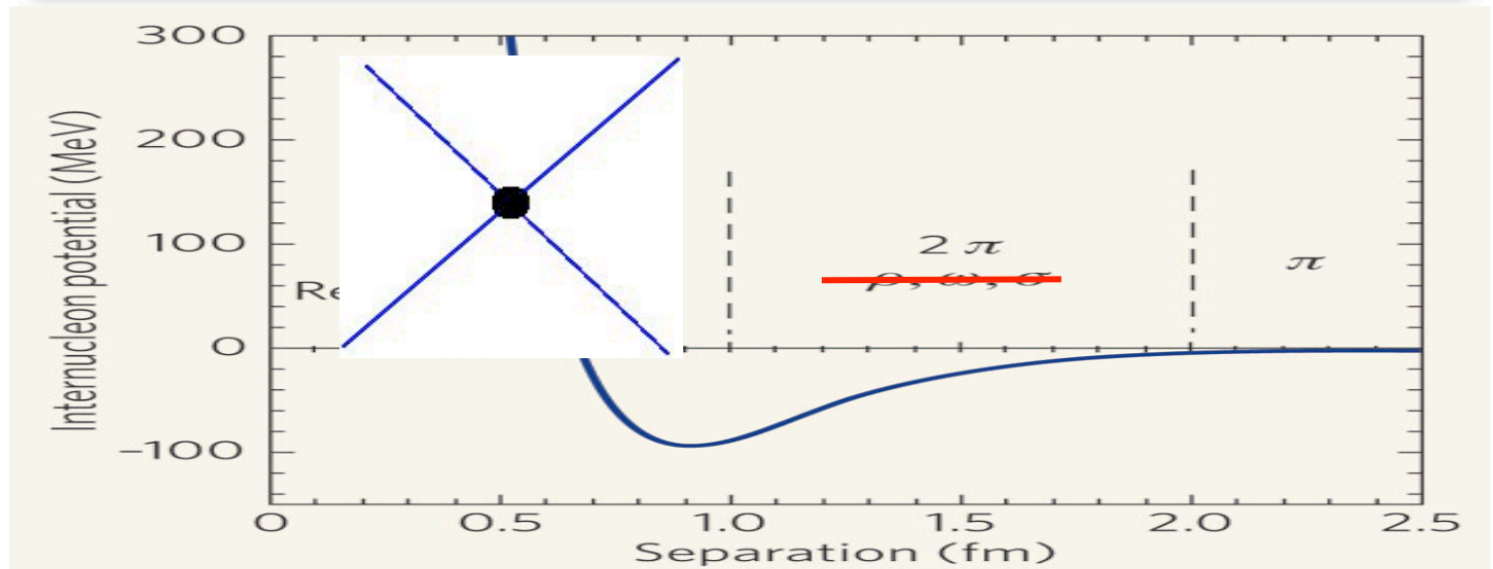
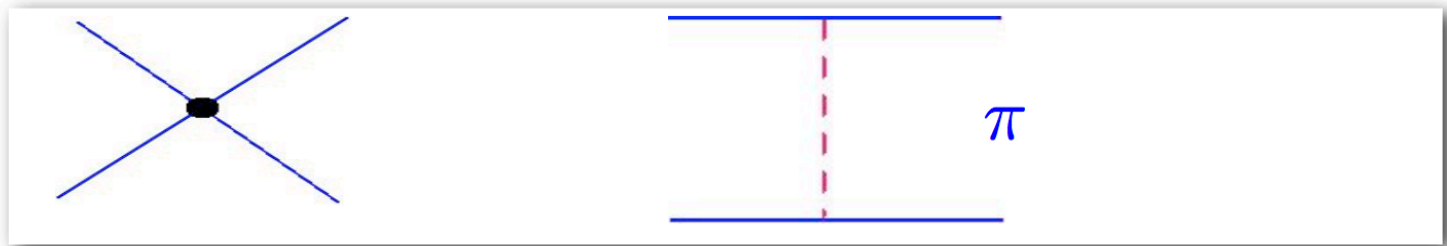


Repulsive Core





Repulsive Core

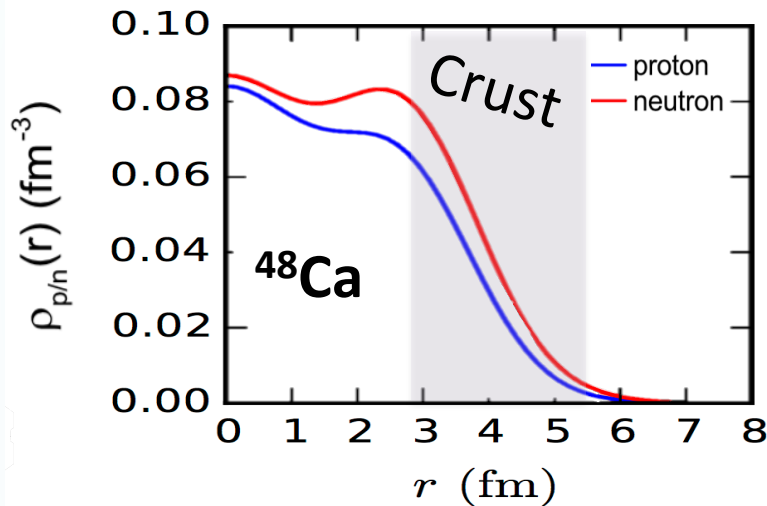


“Repulsive core has to be large to support neutron stars > 1 solar mass”

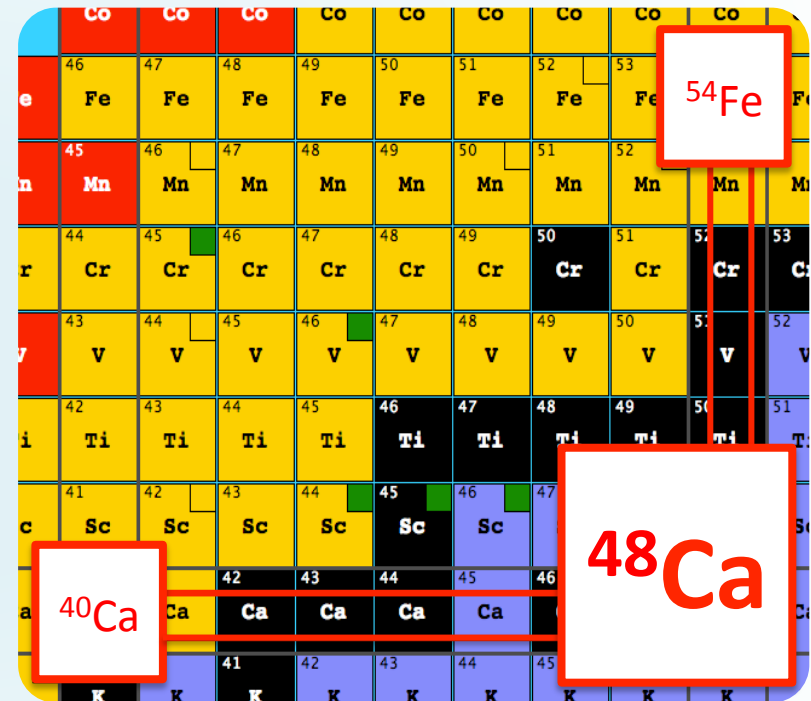


Protons Dynamics in Neutron Rich Nuclei

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



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

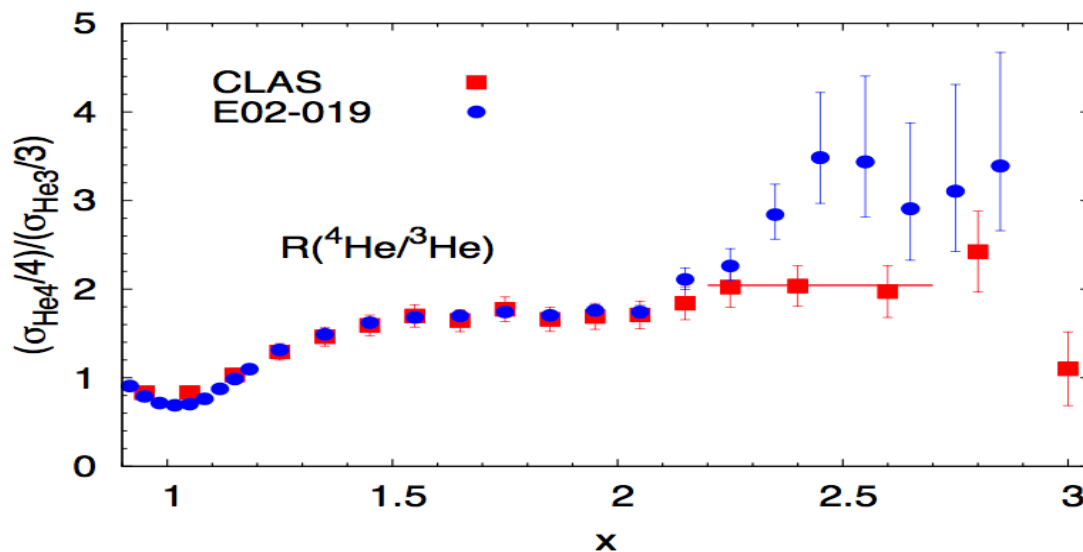
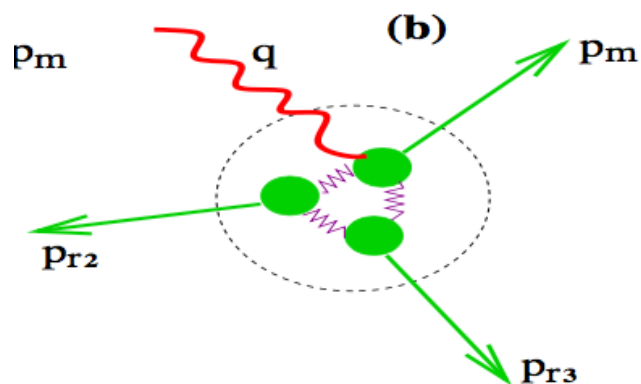
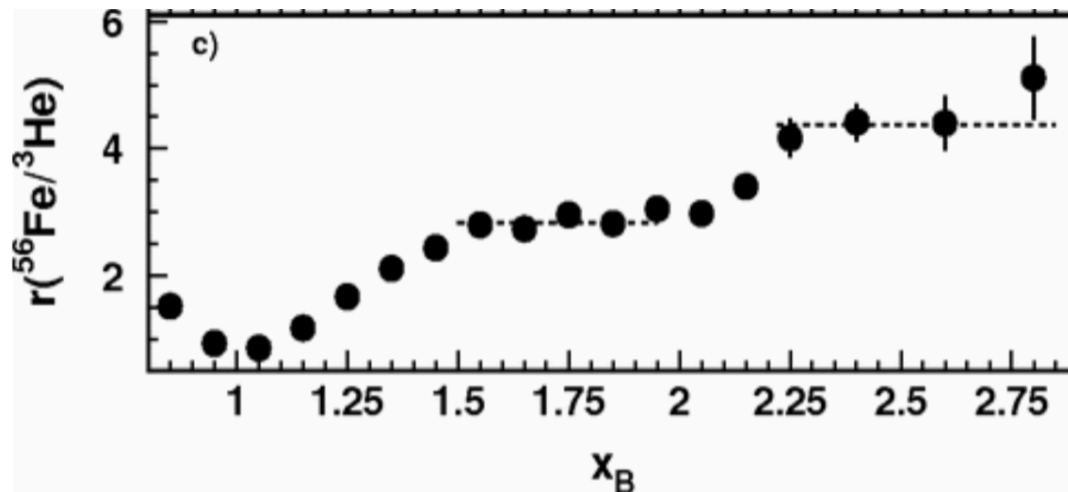
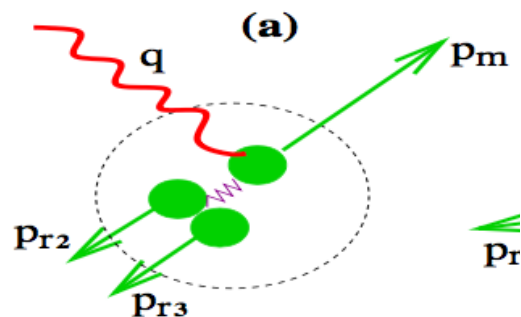


+ 6 Protons

- 8 Neutrons



3N-SRC (Terra Incognita!)





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



The Correlations group



- MIT (Or Hen):



Barak Schmookler



Reynier Torres



Efrain Segarra



Afroditi Papadopoulou



Axel Schmidt



George Laskaris



Maria Patsyuk



Taofeng Wang (*visiting scientist)

- TAU (Eli Piasezky):



Erez Cohen



Meytal Duer



Igor Korover



Adi Ashkenazy

- ODU (Larry Weinstein):



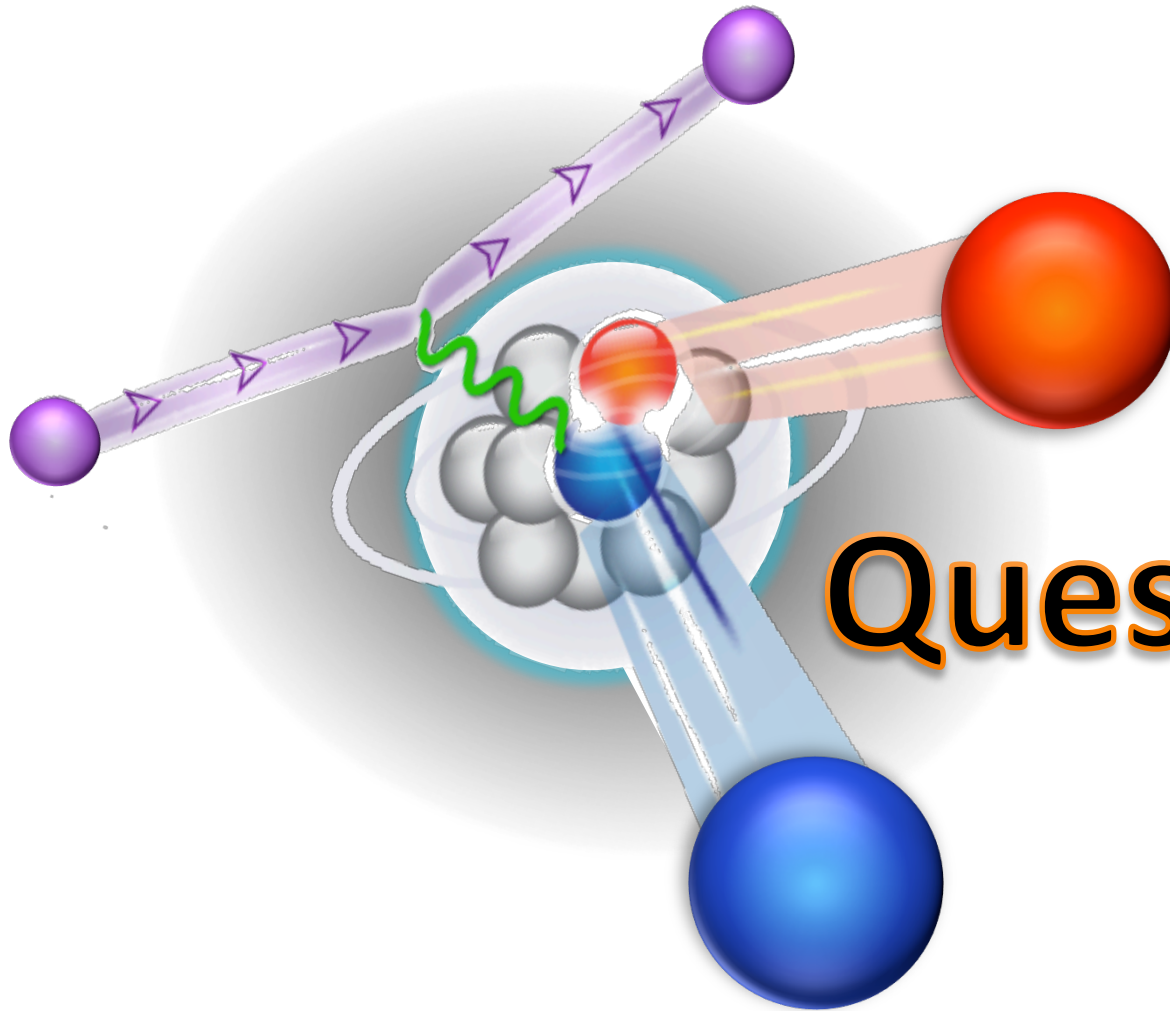
Mariana Khachatryan



Florian Hauenstein

- Theory Collaborators (lots!)

Thank You!



Questions?



Problem: you can't always get what you want...

- SRC trigger is quite exclusive:
 - Can 'handle' high beam current.
 - But.... HADES can't (?)
- Di-lepton trigger is quite inclusive:
 - Can't handle high beam current.
- Detection of recoil protons seems unfeasible without removing the RICH:
 - Incompatible with Di-Lepton.



Solution: Phased approach!

- Phase I (3.5 GeV, parrallel to Di-Lepton):
 - Focus on np-SRC pairs
 - Study rates and backgrounds towards phase II.
 - Extract physics: Migdal jump; 3N-SRC; IsoSpin structure; Repulsive core; Factorization breakdown.
- Phase II (4.5 GeV):
 - Add pp-SRC pairs. Increase statistics. Increase number of nuclei.
 - Complete the full physics program!