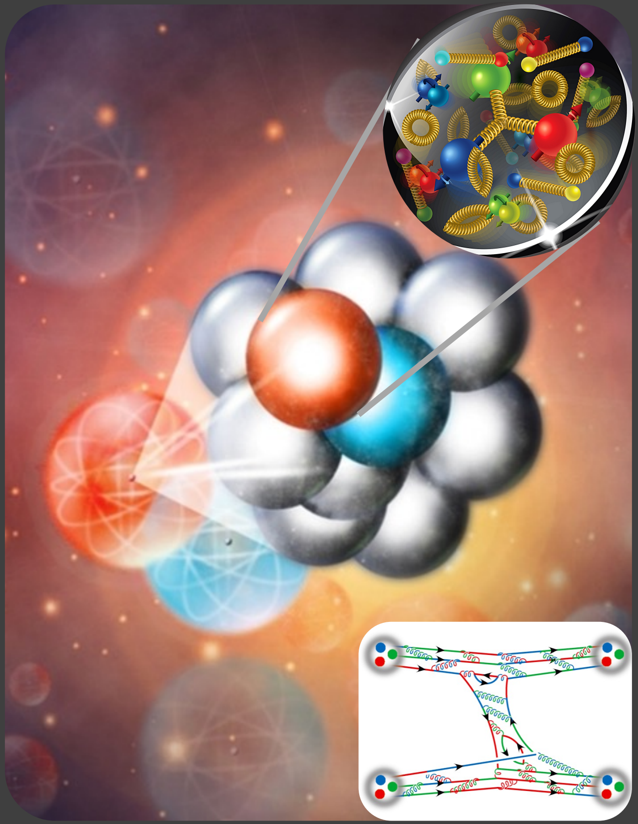
Transparent Virtual Nucleons and Short-Range Correlations

Or Hen - MIT

The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond, June 7th, 2021

Understanding nuclei from QCD is a monumental challenge for the 20th century

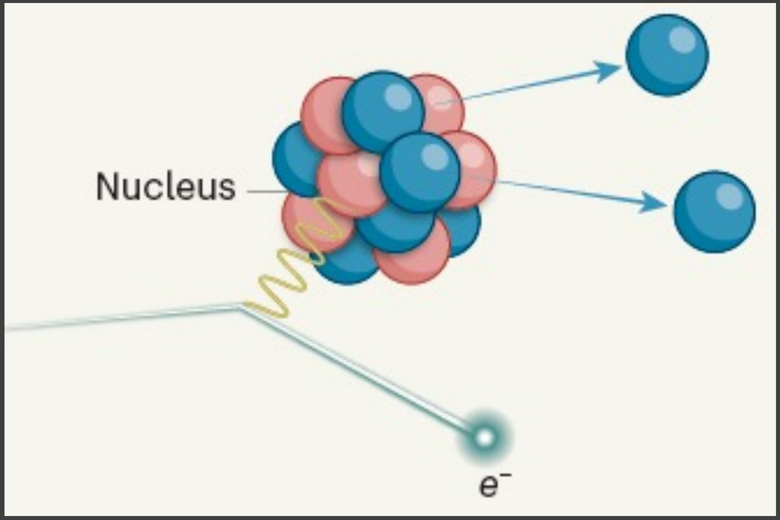
1. Many-body problem.
2. Traditional mean-field approximations challenged by strong many-particle correlations.
3. *Fundamental interaction extremely complex*.
4. *High density*.



Understanding nuclei from QCD is a monumental challenge for the 20th century

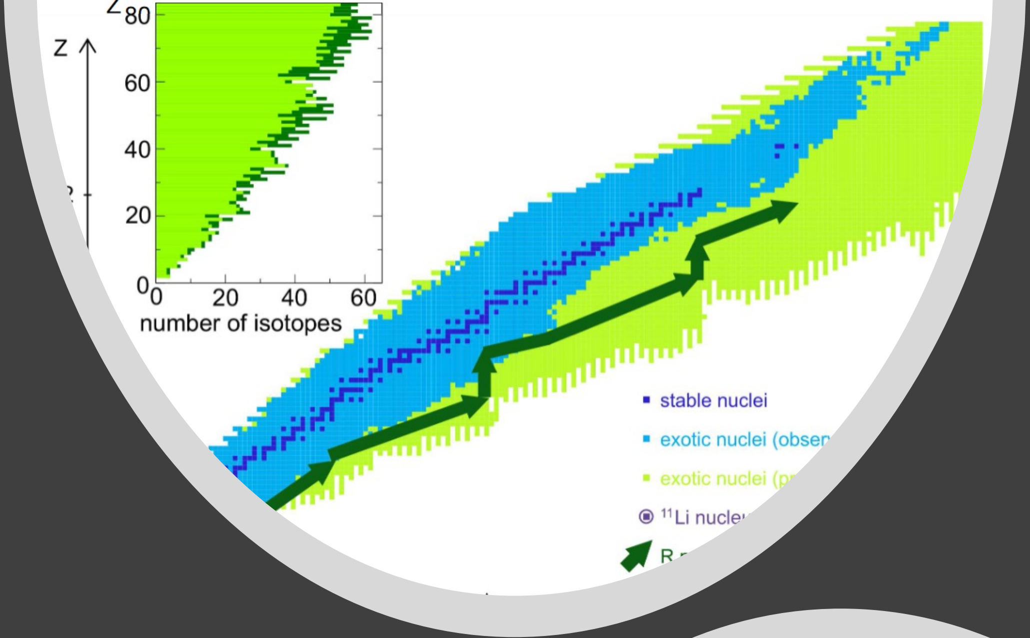
(scattering) Ground-state measurements complicated by strong initial- & final-state interactions.

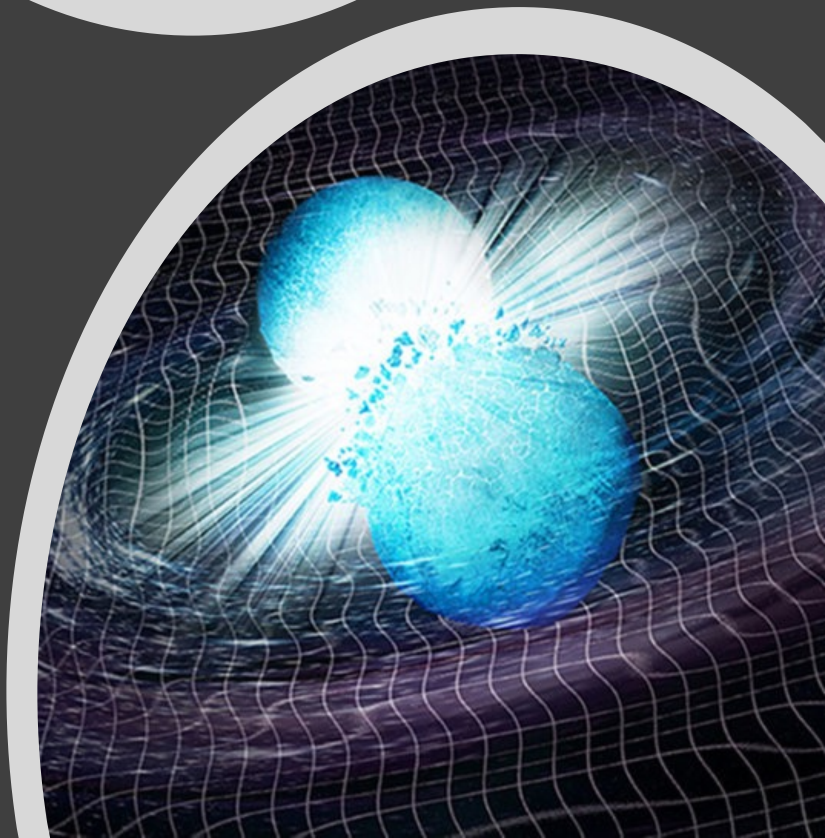
High-energy scattering

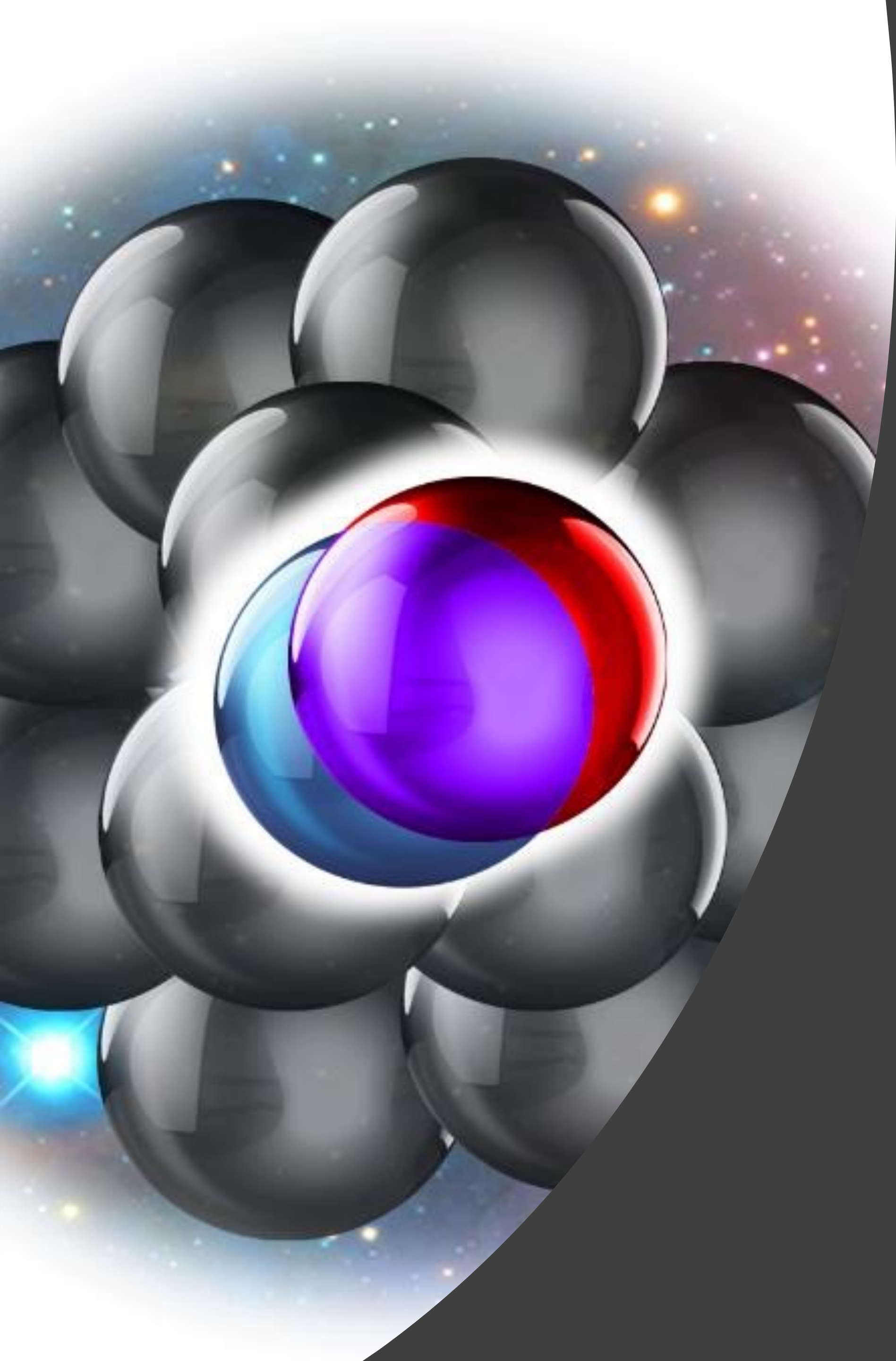


Understanding nuclei is very important

- Most of the visible mass in the universe.
- Formation of the elements.
- Burning of stars and formation of galactic structures
- Lab for (new) interactions.



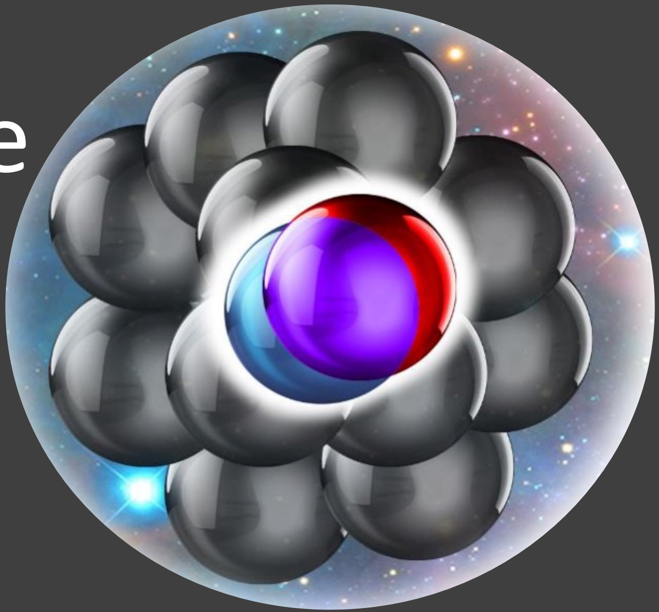


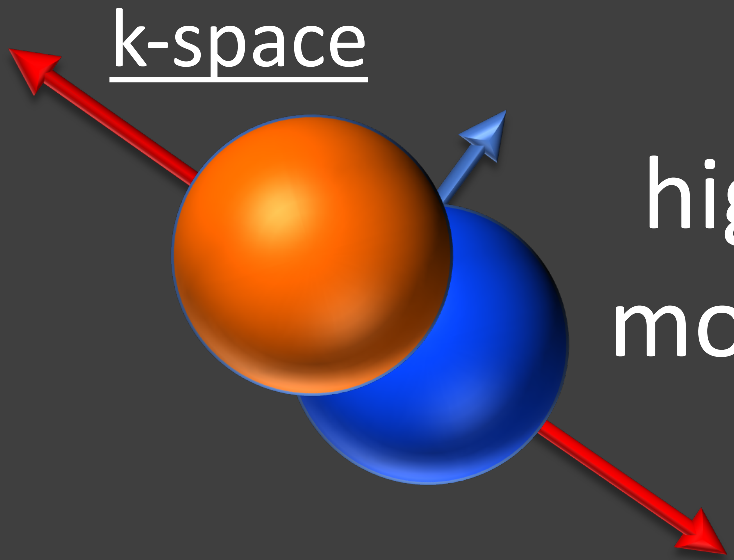


Short-Range Correlations (SRC)

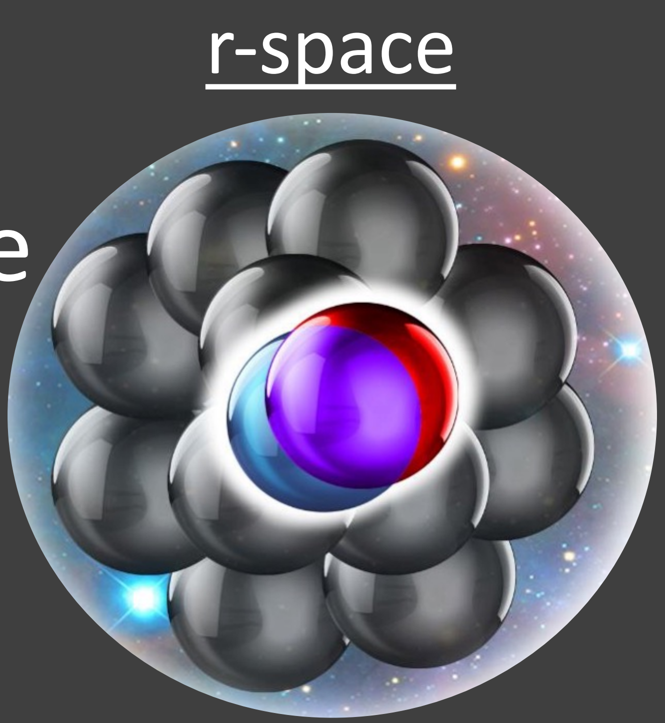
Nucleon pairs that are close together in the nucleus

r-space





high ***relative*** and low ***c.m.*** momentum compared to k_F

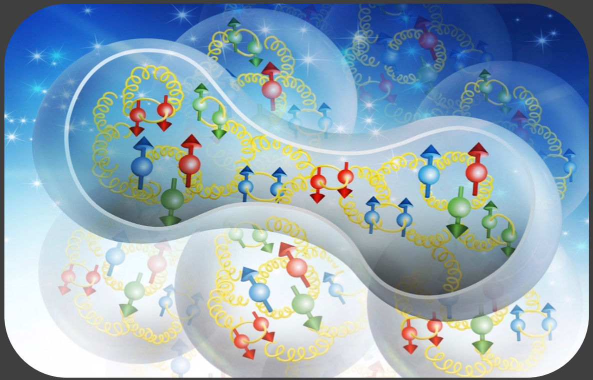


Nucleon pairs that are close together in the nucleus

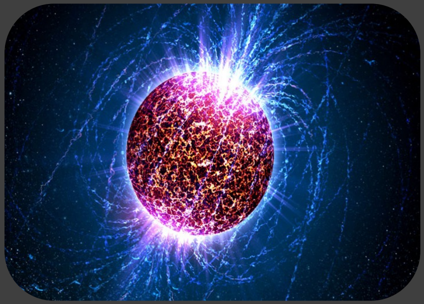
Why SRC?

Required for a high-resolution, first principle, description of nuclear systems & processes.

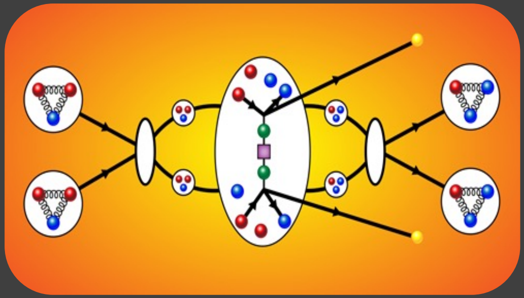
NN interaction from QCD & QCD in nuclei



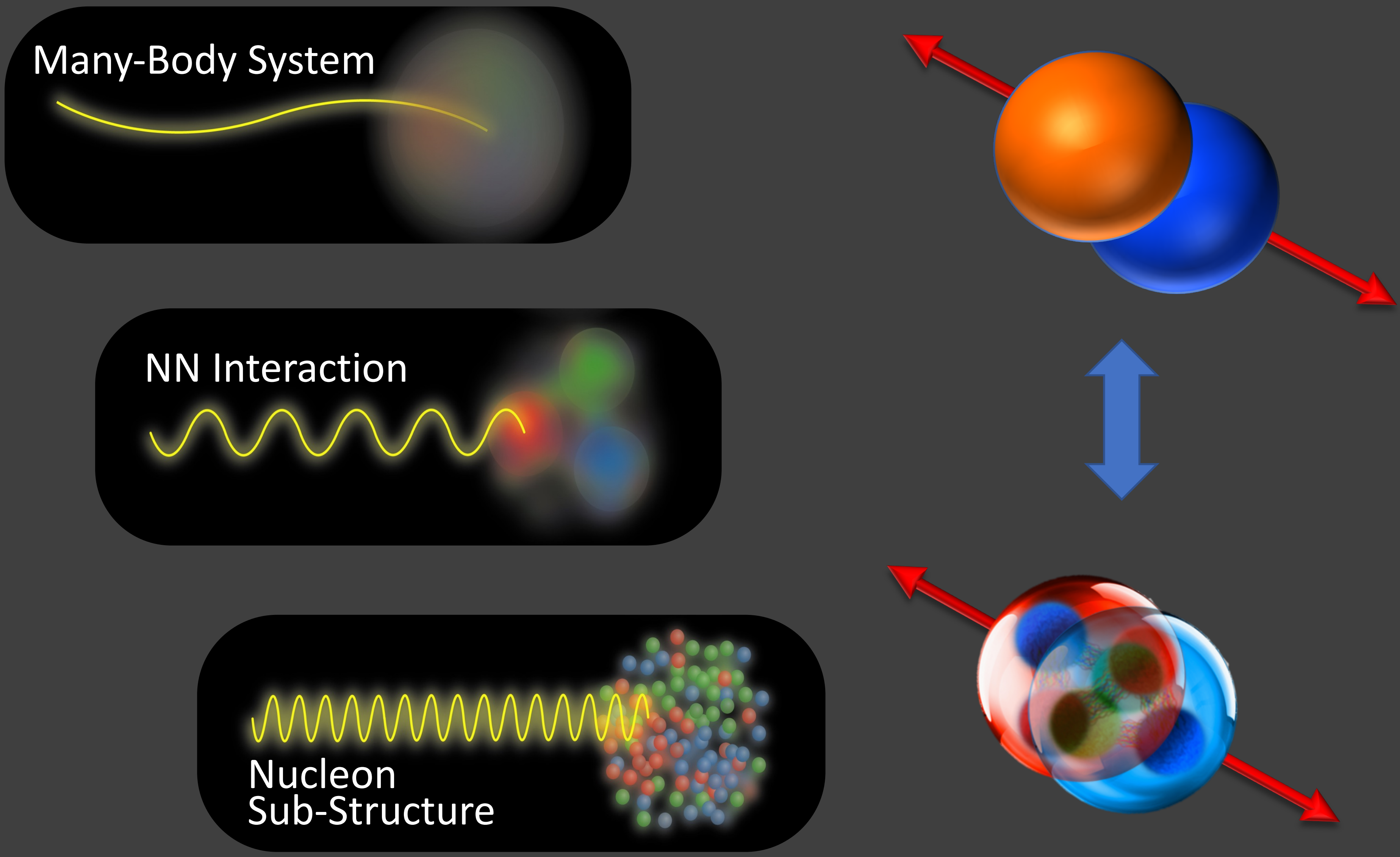
High-density systems

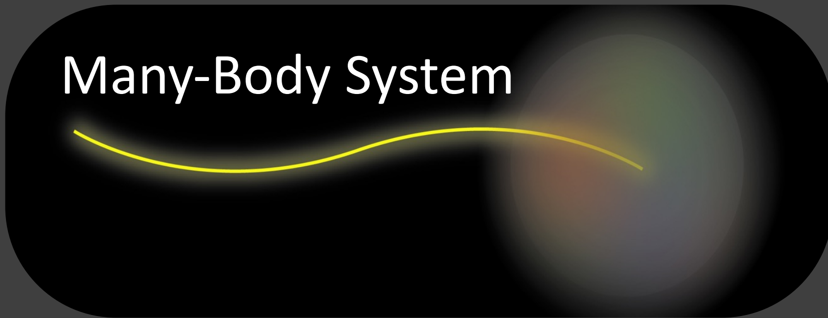


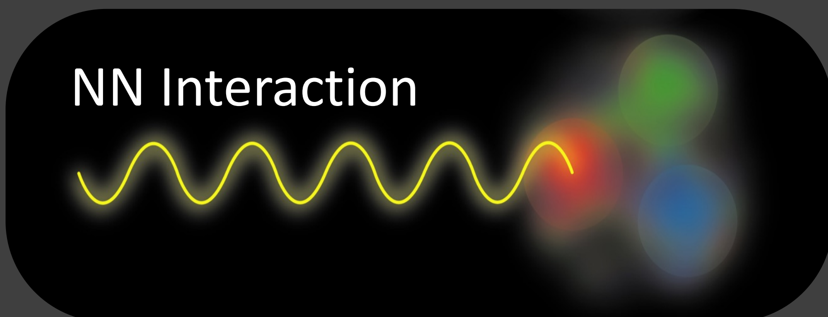
High-q processes
(e.g. $0\nu\beta\beta$ decay)

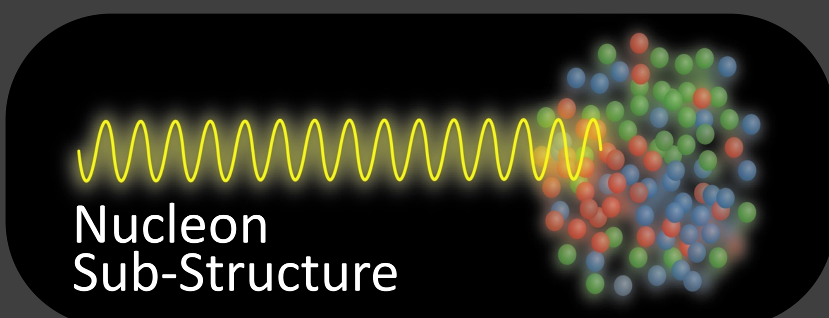


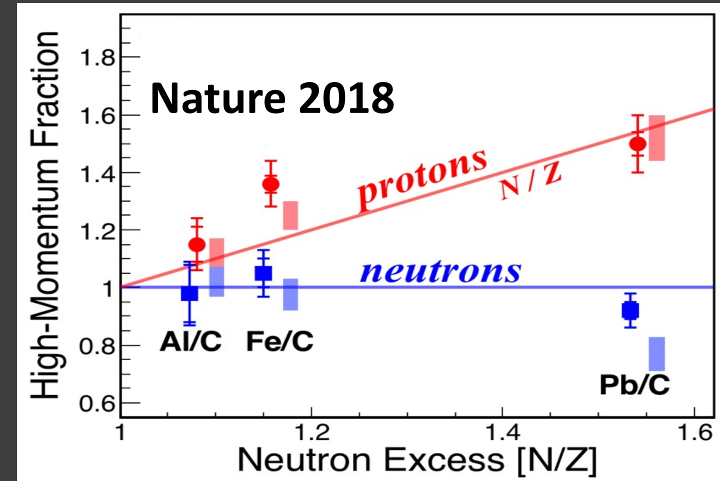
SRCs Across Scales

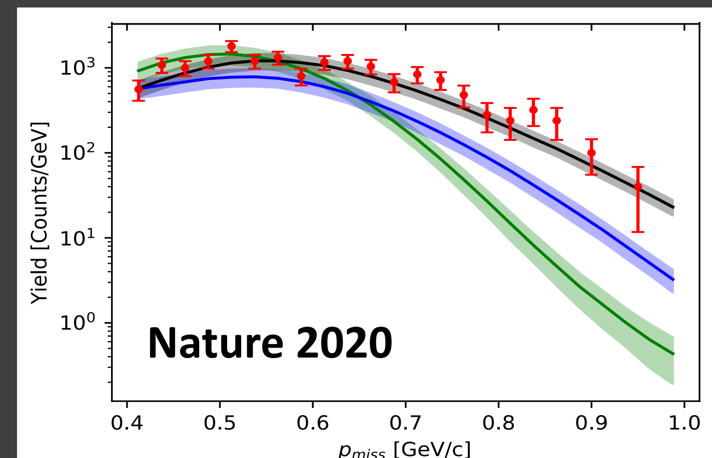


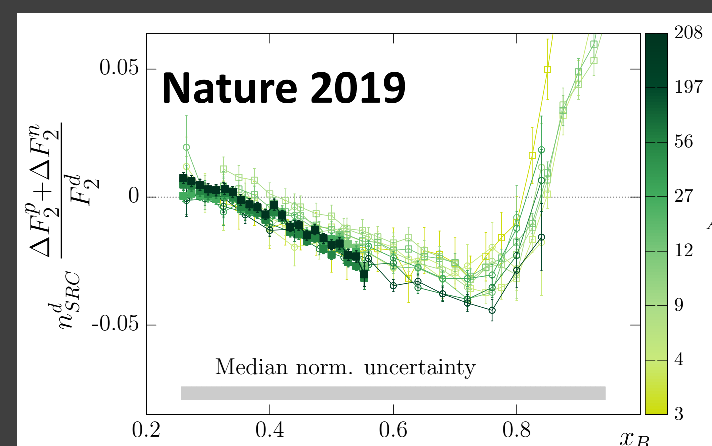

Many-Body System

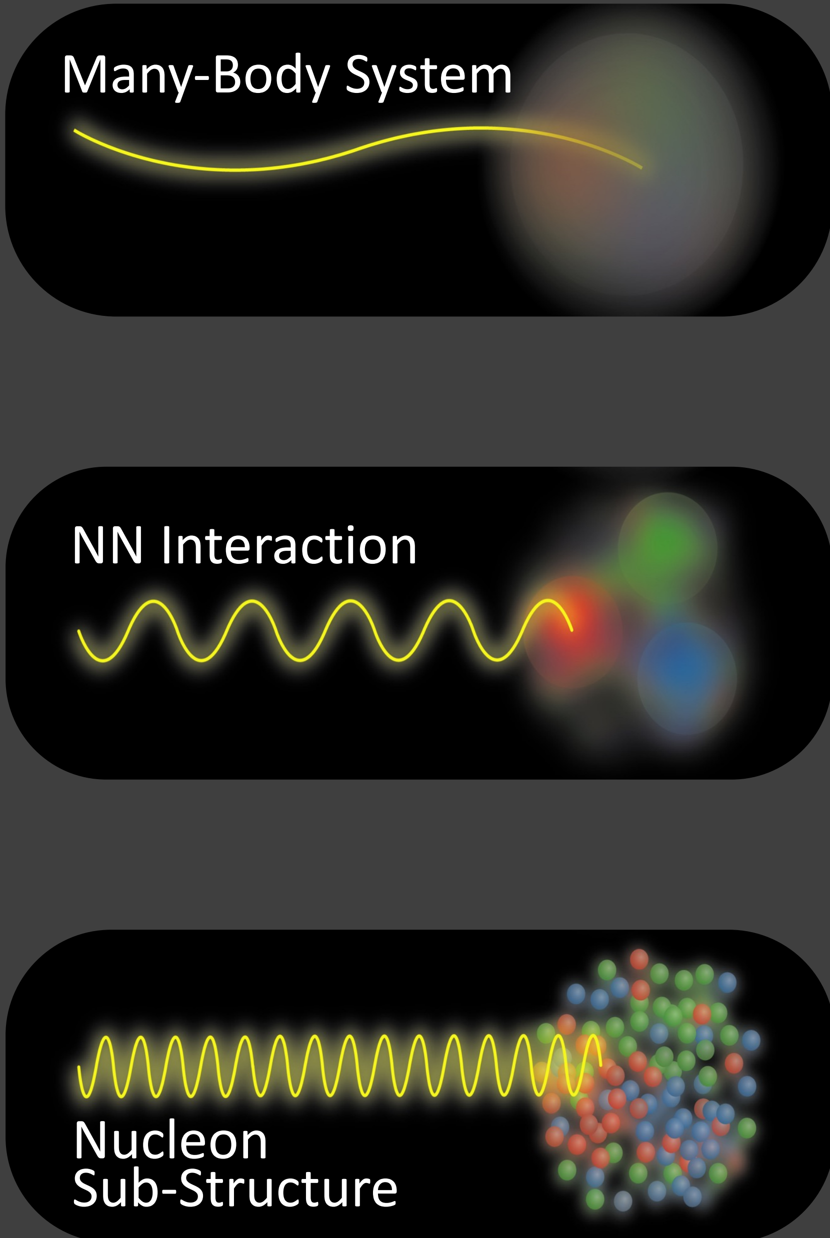

NN Interaction


Nucleon
Sub-Structure


Nature 2018
High-Momentum Fraction
Neutron Excess [N/Z]
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
0.6
0.8
1
1.2
1.4
1.6
1.8
1
1.2
1.4
1.6


Nature 2020
Yield [Counts/GeV]
p_{miss} [GeV/c]
10^3
10^2
10^1
10^0
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Nature 2019
$n^d_{SRC} \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$
x_B
Median norm. uncertainty
A
0.05
0
-0.05
0.2
0.4
0.6
0.8
208
197
56
27
12
9
4
3

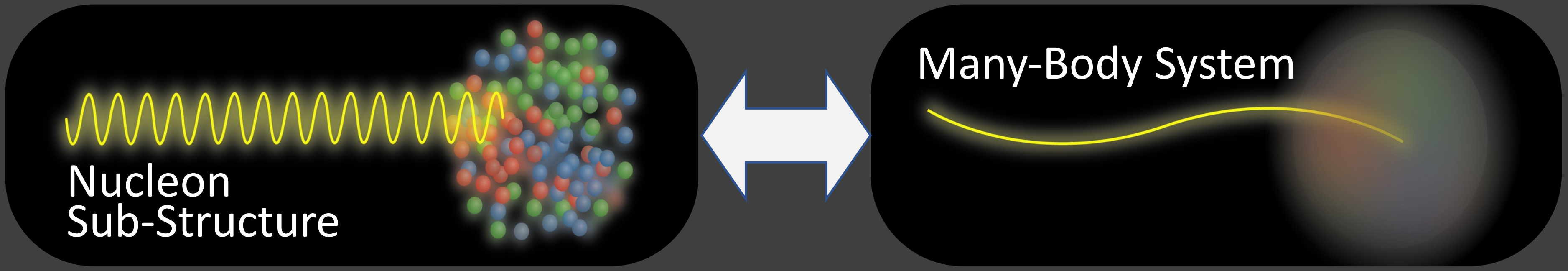


2018-21 SRC Publications:

- Nature 578, 540 (2020)
- Nature 566, 354 (2019)
- Nature 560, 617 (2018)
- Nature Physics, In-Print (2020)
- Nature Physics, In-Print (2021)
- PRL 124, 212501 (2020)
- PRL 124, 092002 (2020)
- PRL 122, 172502 (2019)
- PRL 121, 092501 (2018)
- Phys. Lett. B 811, 135877 (2020)
- Phys. Lett. B 805, 135429 (2020)
- Phys. Lett. B 800, 135110 (2020)
- Phys. Lett. B 797, 134890 (2019)
- Phys. Lett. B 797, 134792 (2019)
- Phys. Lett. B 791, 242 (2019)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 785, 304 (2018)
- Phys. Lett. B 780, 211 (2018)
- Phys. Rev. C (lett.), In-Print (2021)

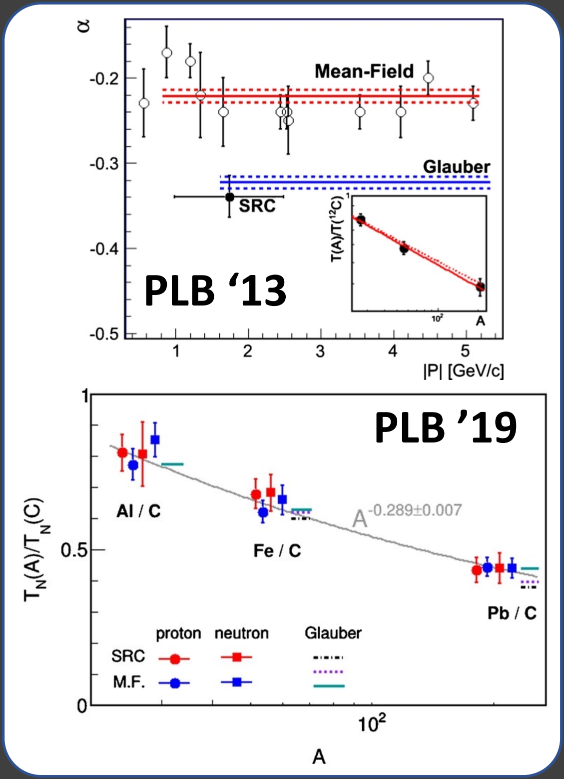
arXiv: 2006.10249; 2004.07304.

Today: SRCs & CT

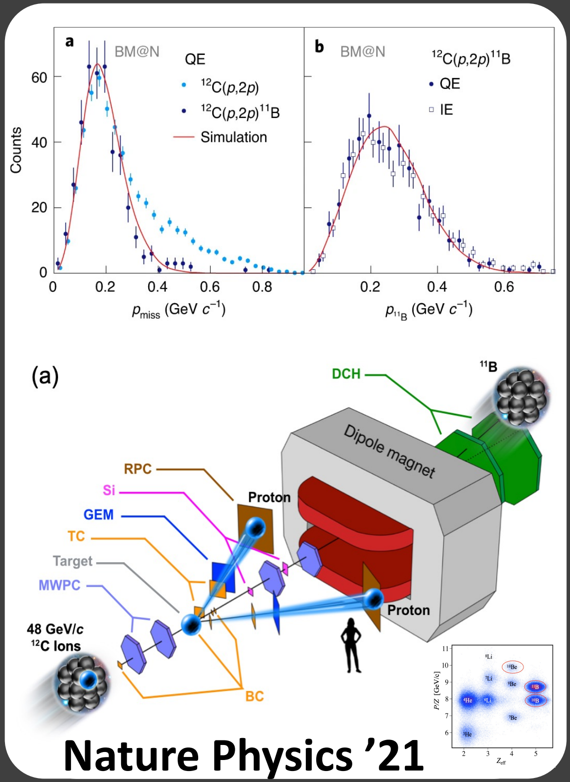


Today: SRCs & CT

JLab (USA)



JINR (Russia)

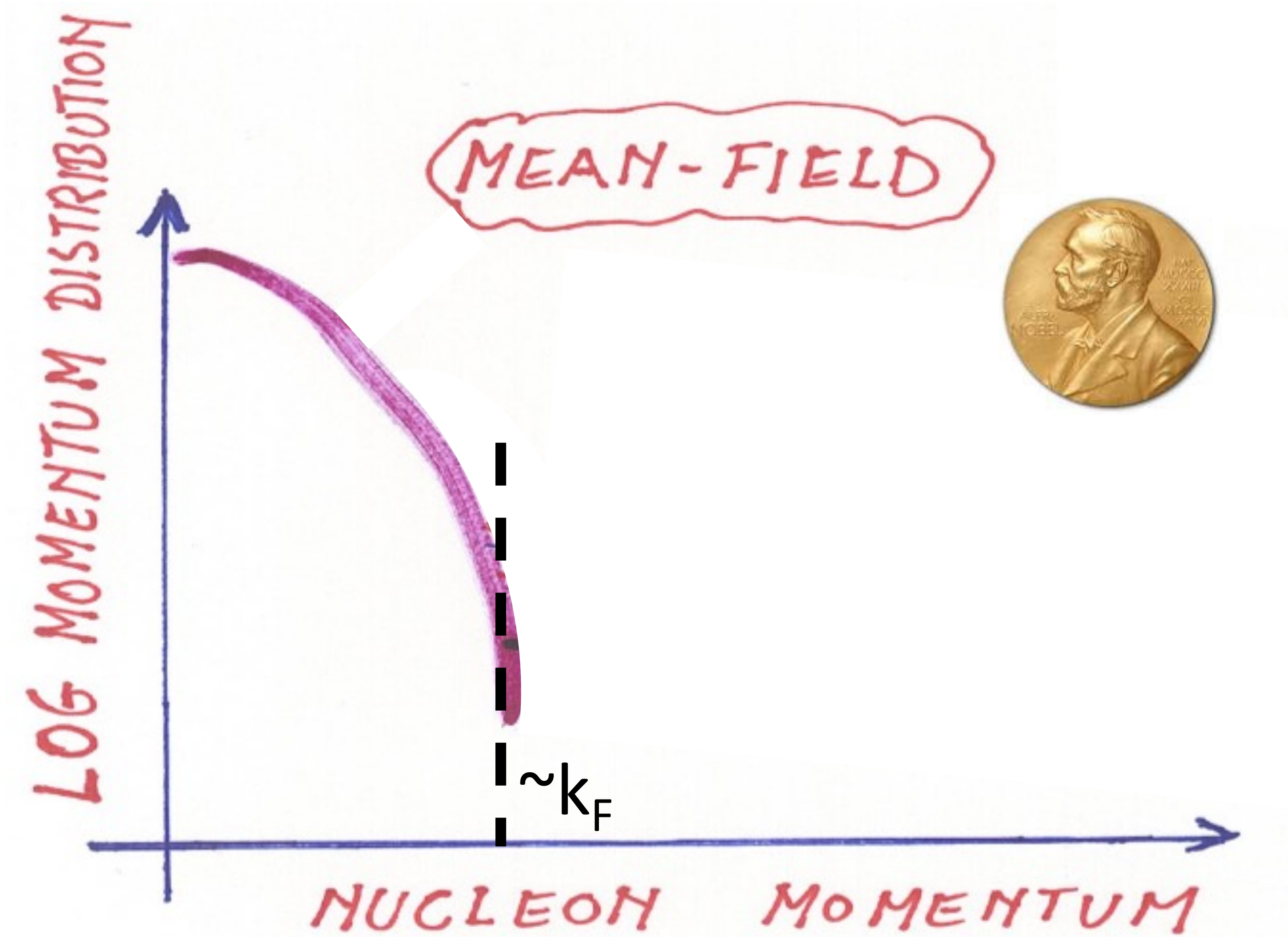


Nuclear Transparency

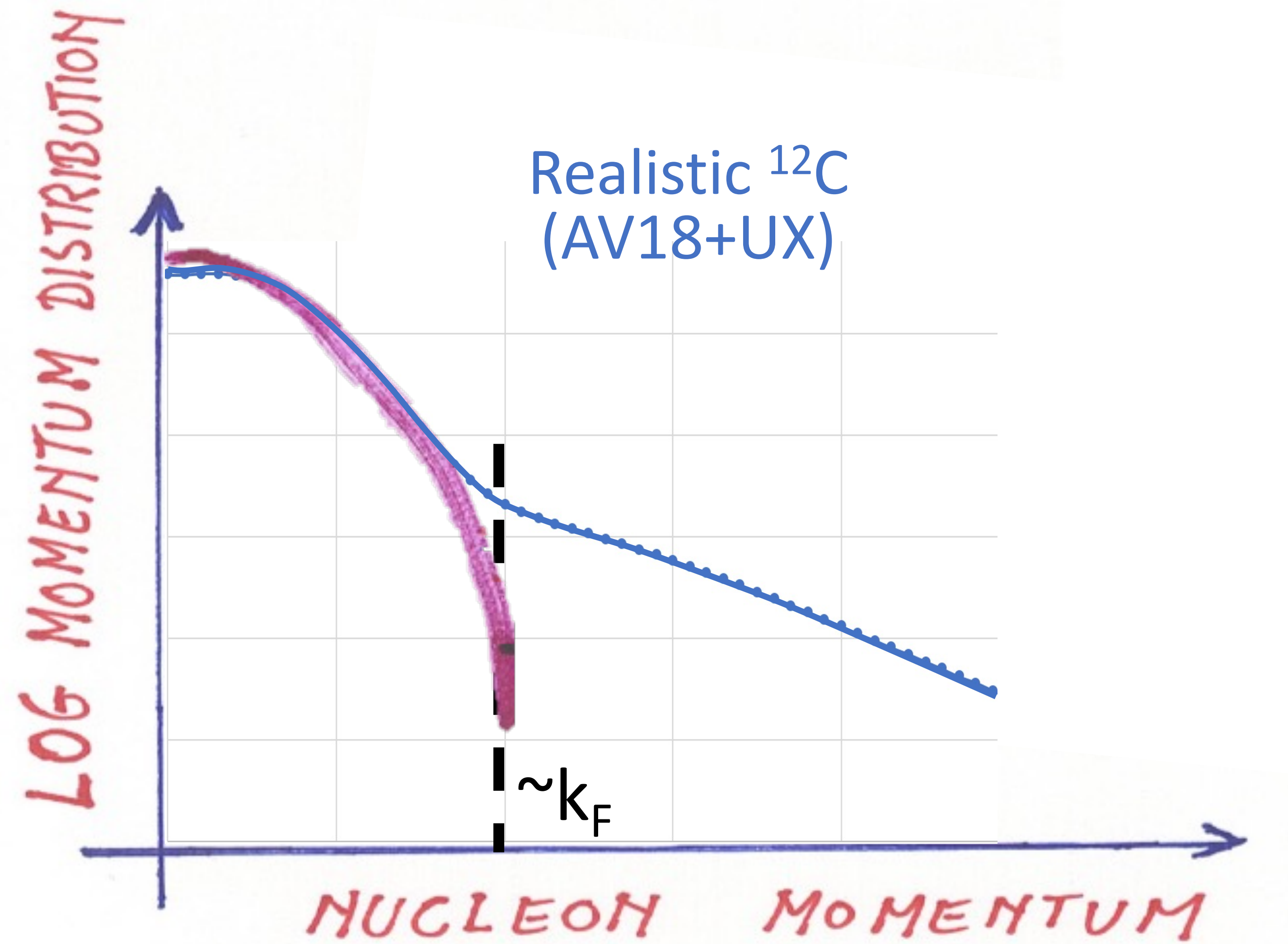
$$T(A) = \frac{\sigma_{exp}(e, e'p)}{\sigma_{PWIA}(e, e'p)}$$

$$\sigma_{PWIA} = \frac{d^6\sigma}{dE'_e d\Omega_{e'} dE'_p d\Omega_{p'}} = p' E'_p \sigma_1^{cc} S(p, E_s)$$

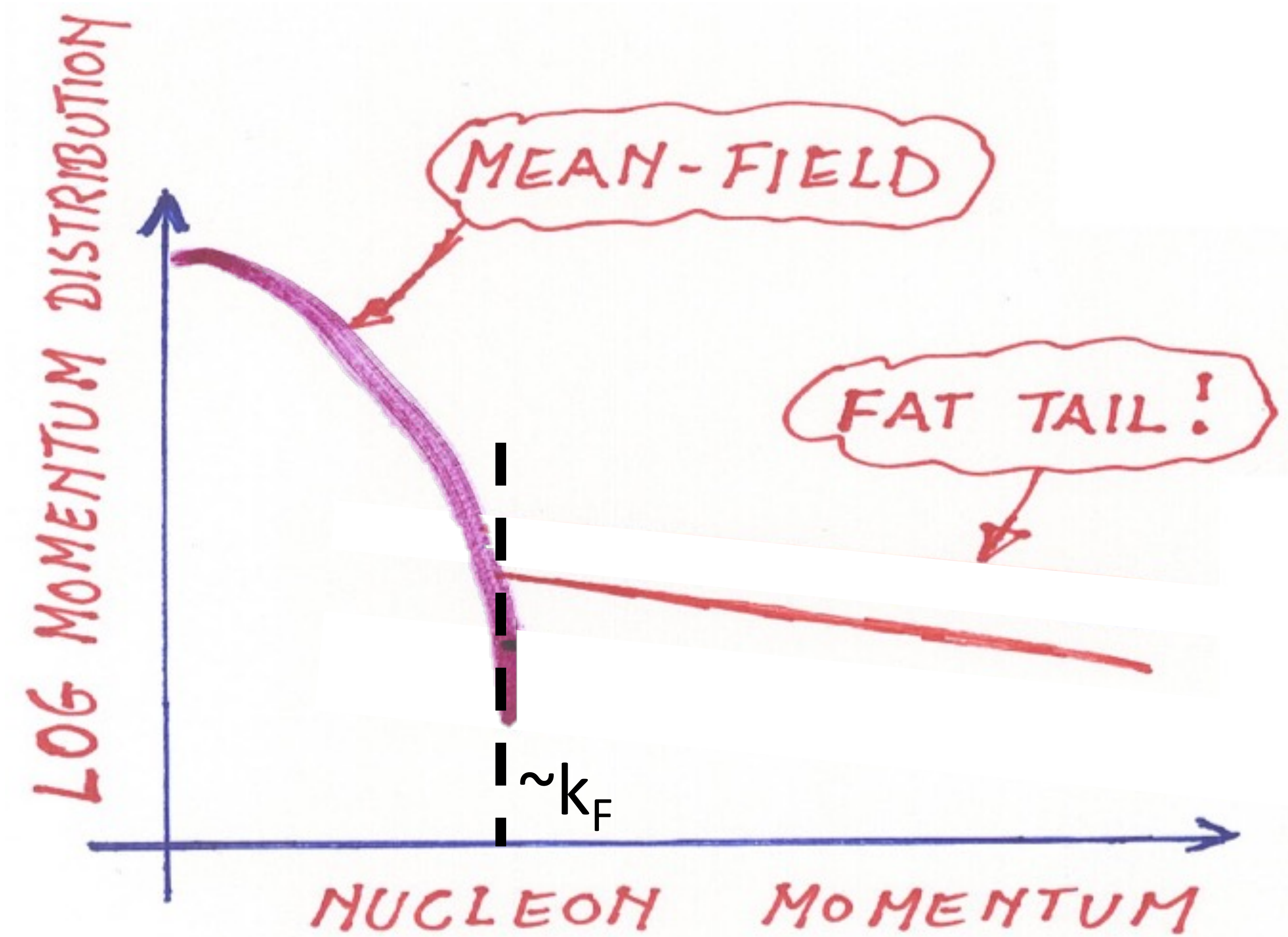
Ratio of experiment / theory → Transparency measurements really depend on our understanding of the nuclear wave function!



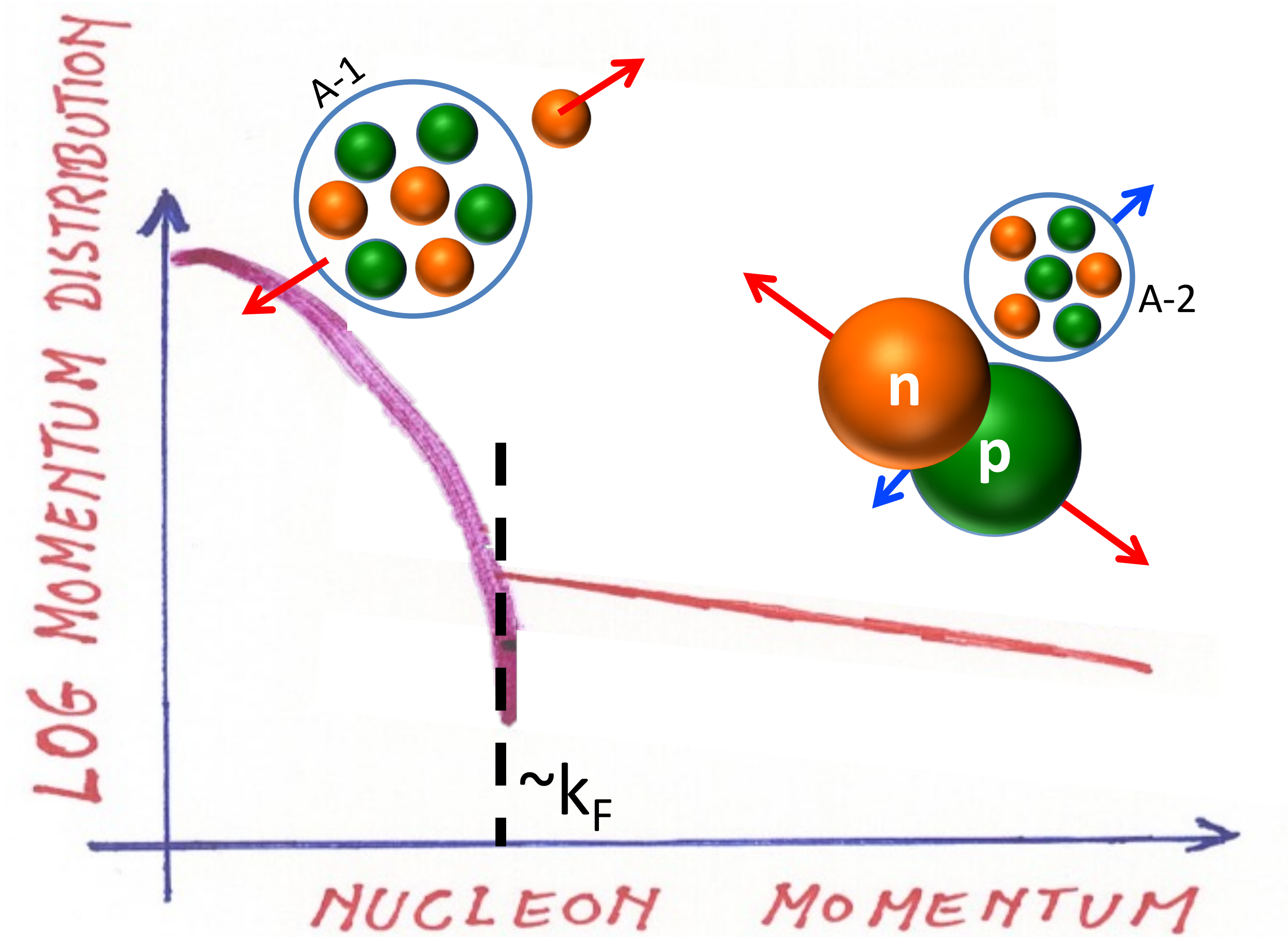
LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
~k_F
NUCLEON MOMENTUM



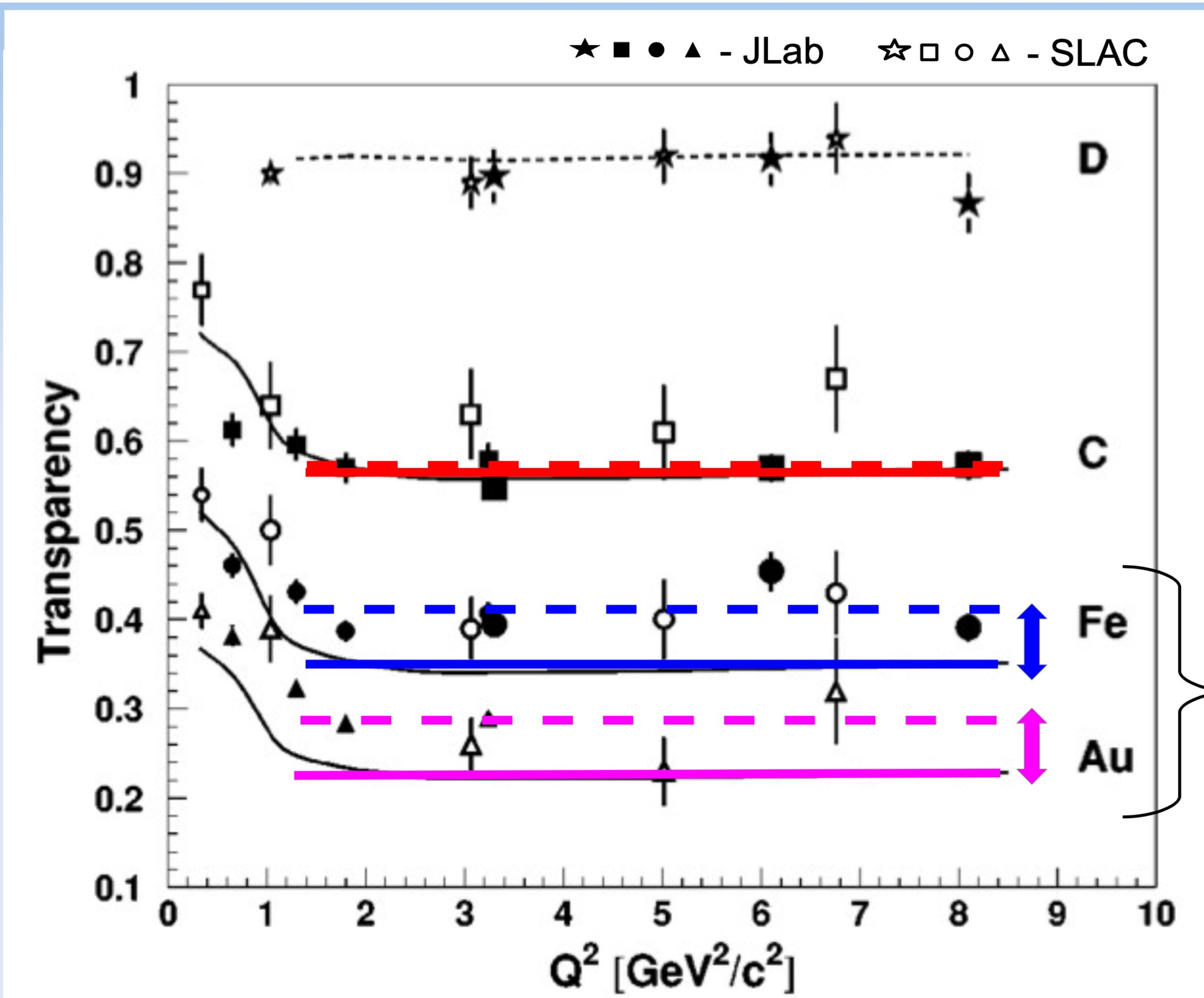
Wiringa, PRC (2014); Carlson, RMP (2015); …



MEAN-FIELD
FAT TAIL!
LOG MOMENTUM DISTRIBUTION
~k_F
NUCLEON MOMENTUM


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

Mean-Field Transparency



~20% discrepancy between data and Glauber calculations

T. G. O'Neill et al. Phys. Lett. B **87**, 351 (1995) K. Garrow et al. Phys. Rev. C. **66**, 044613 (2002)
G. Garino et al. Phys. Rev. C **45**, 780 (1992) D. Abbott et al. Phys. Rev. Lett. **80**, 5072 (1998)

Reduced Correlation Contribution in Transverse Kinematics

$$\sigma_{pwia} = F_{kin}\sigma^{ep}_{cc1} \int S(\mathbf{k}, E)\, d^3k\, d\, E,$$

Independent Particle Shell Model:

$$\int S(\mathbf{k}, E)\, d\, E\, d^3\, k = f(A) \int S_{IPSM}(\mathbf{k}, E) d\, E\, d^3\, k.$$

Correlation correction factor
=> Q^2 (+kinematics) dependent

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Transverse Kinematics:

$$S(k_3 = 0) \equiv \int S(\mathbf{k}_t, k_3 = 0, E) d^2 k_t dE$$

$$S(k_3 = 0) = \frac{1}{2}\int S(\mathbf{k},E)\frac{d^3k}{k} dE,$$

Reduced sensitivity to high momenta

P. Lava et al., Phys. Lett. B. **595**, 117 (2004)

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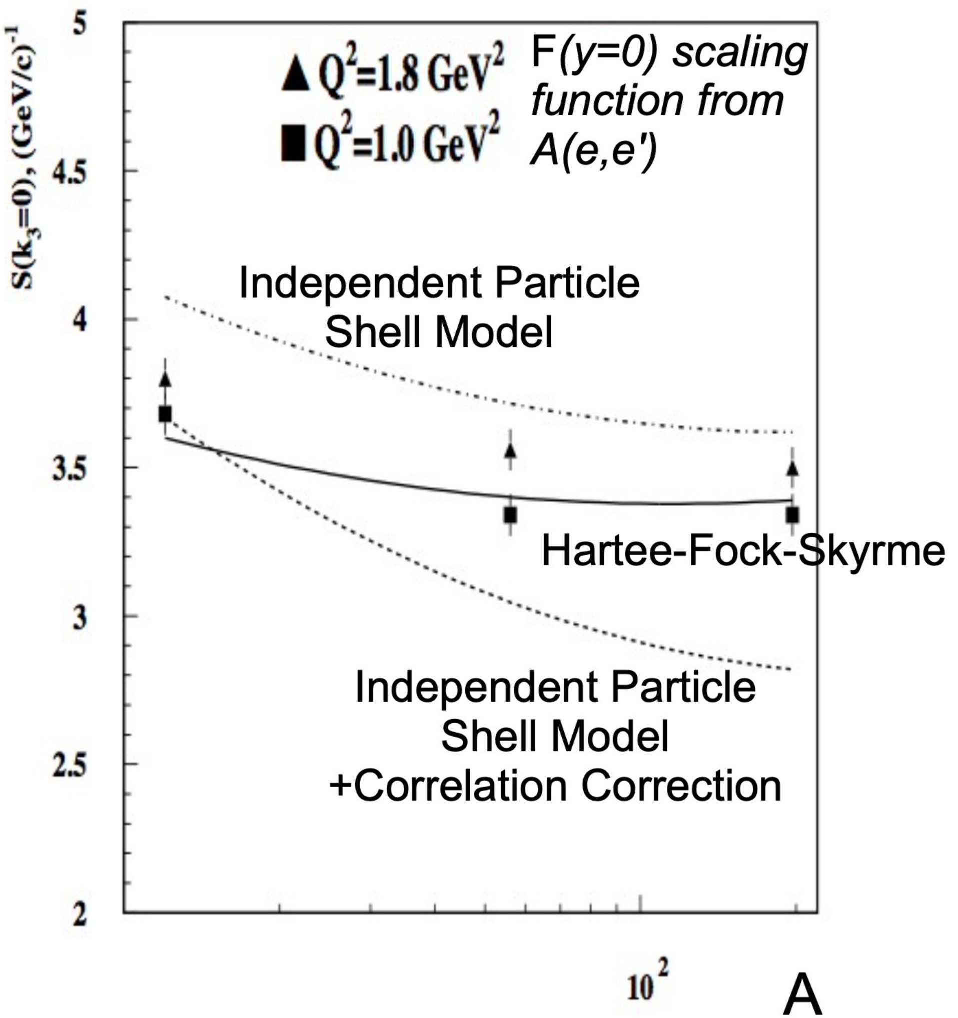
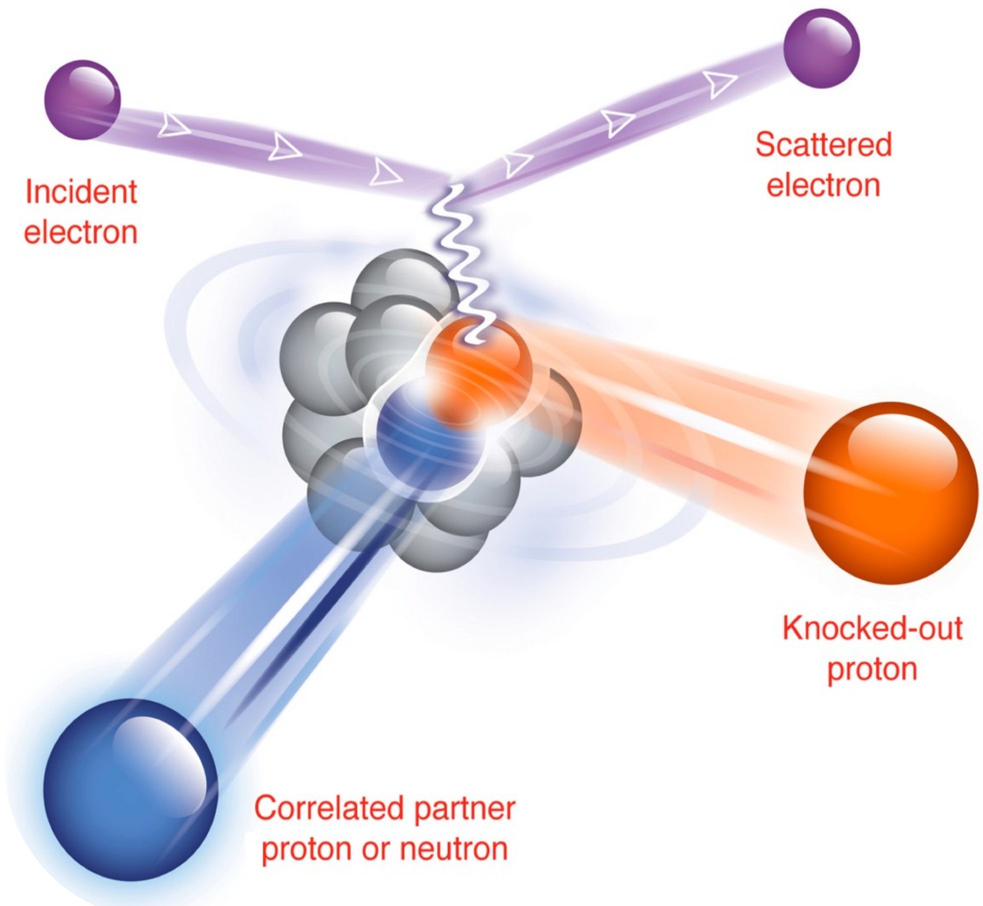


P. Lava et al., Phys. Lett. B. **595**, 117 (2004)

L. L. Frankfurt et al., Phys. Lett. B. **503**, 73 (2001)

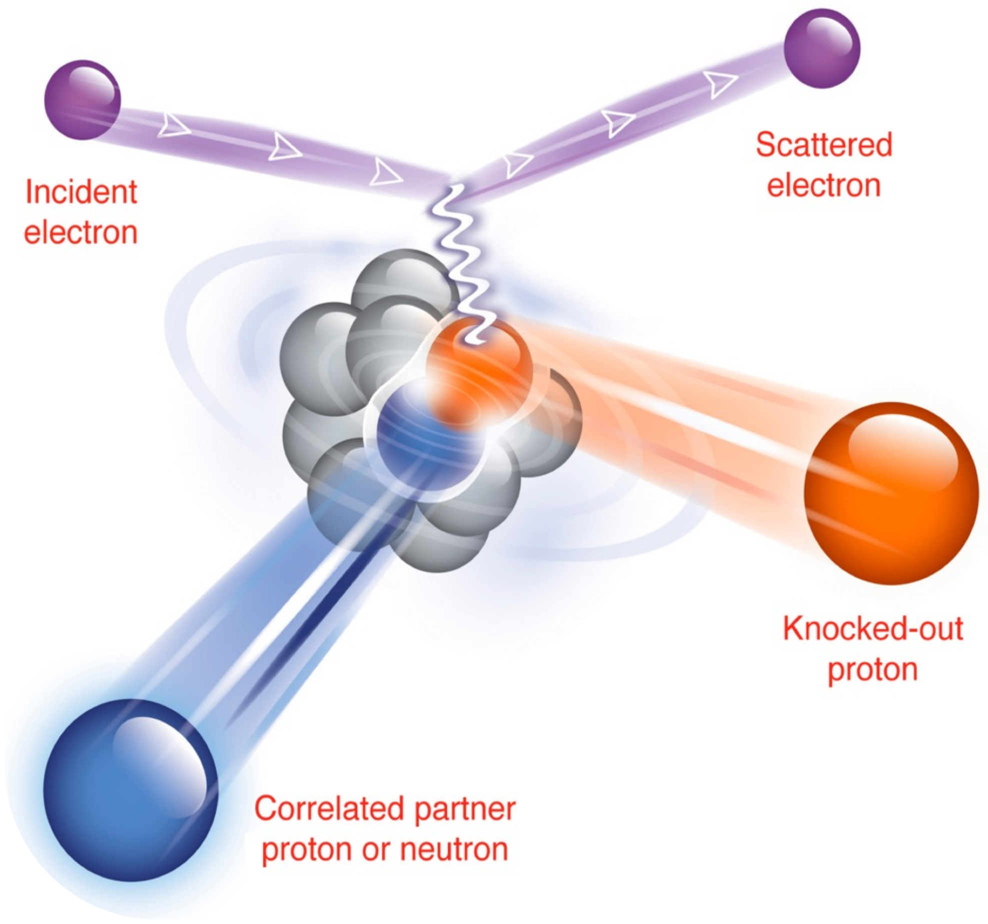
<u>Inverting the problem:</u> Focus on SRCs instead of correcting for them!



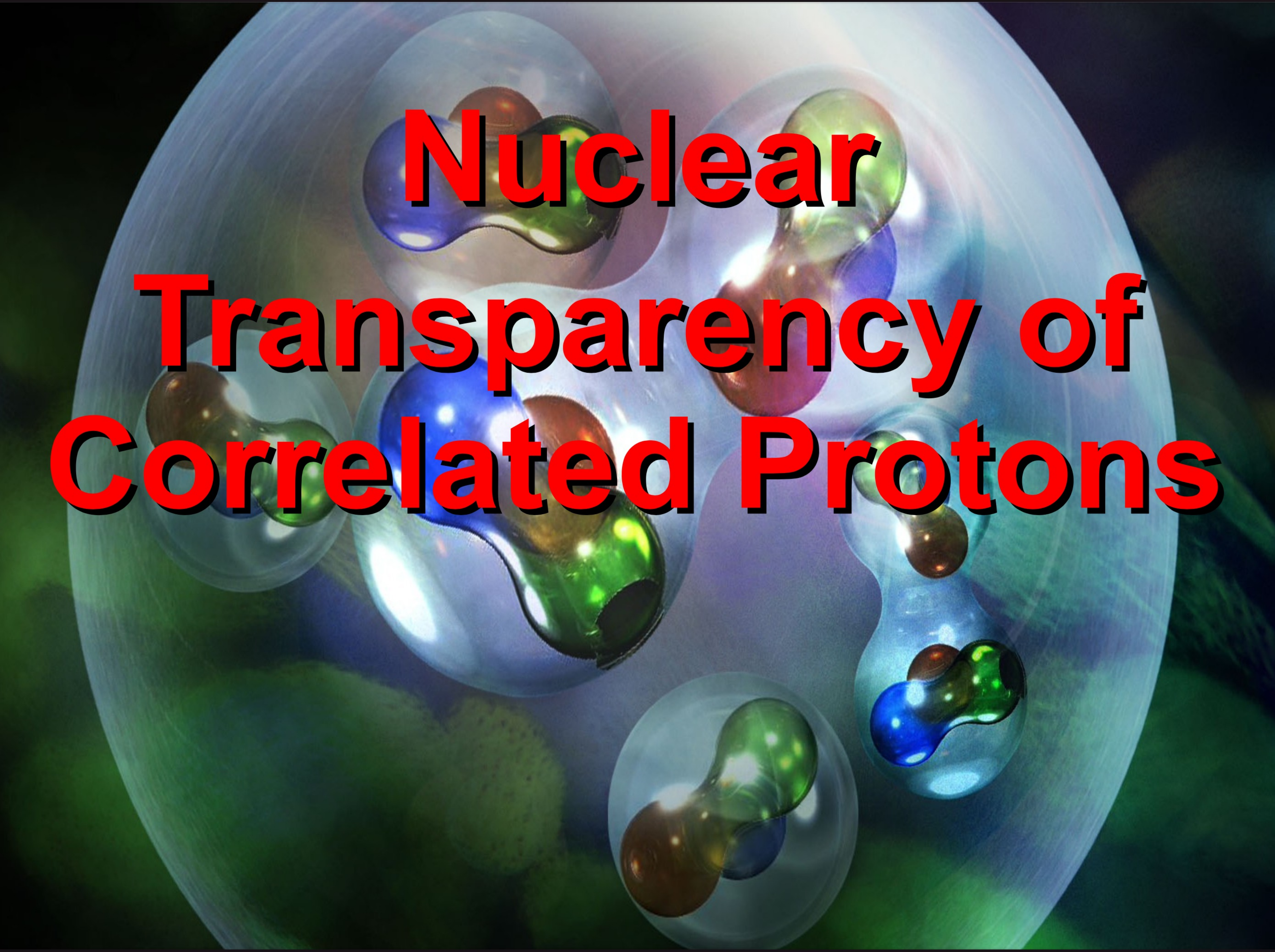
Breakup the pair =>

Detect ***both*** nucleons =>

Reconstruct 'initial' state



Nuclear Transparency of Correlated Protons



A(e,e'p) Transparency in SRC Dominated Kinematics

- Large Q^2, x_B>1 region dominated by 2N-SRC pairs
- Spectral function scales according to the number of 2N-SRC pairs.

  Transparency ratio of SRC protons in nuclei can be expressed as:

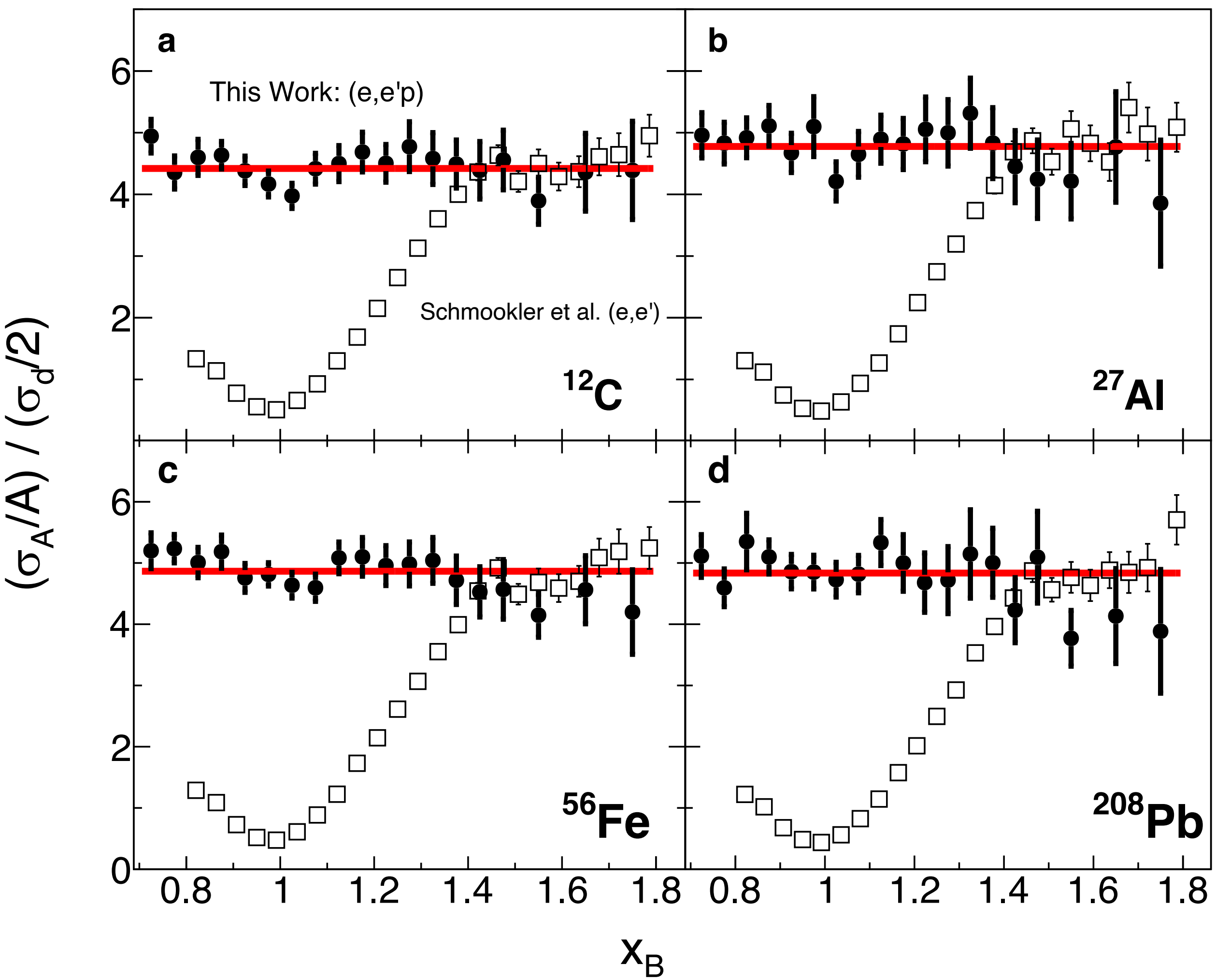
$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(\#np \cdot \sigma_{ep} + 2\#pp \cdot \sigma_{ep})_{A_1}}{\sigma_{A_2(e,e'p)}/(\#np \cdot \sigma_{ep} + 2\#pp \cdot \sigma_{ep})_{A_2}}$$

number of np-SRC pairs

ep→ep off-shell cross section

number of pp-SRC pairs

Scaling Data Can Constrain Relative SRC Abundances

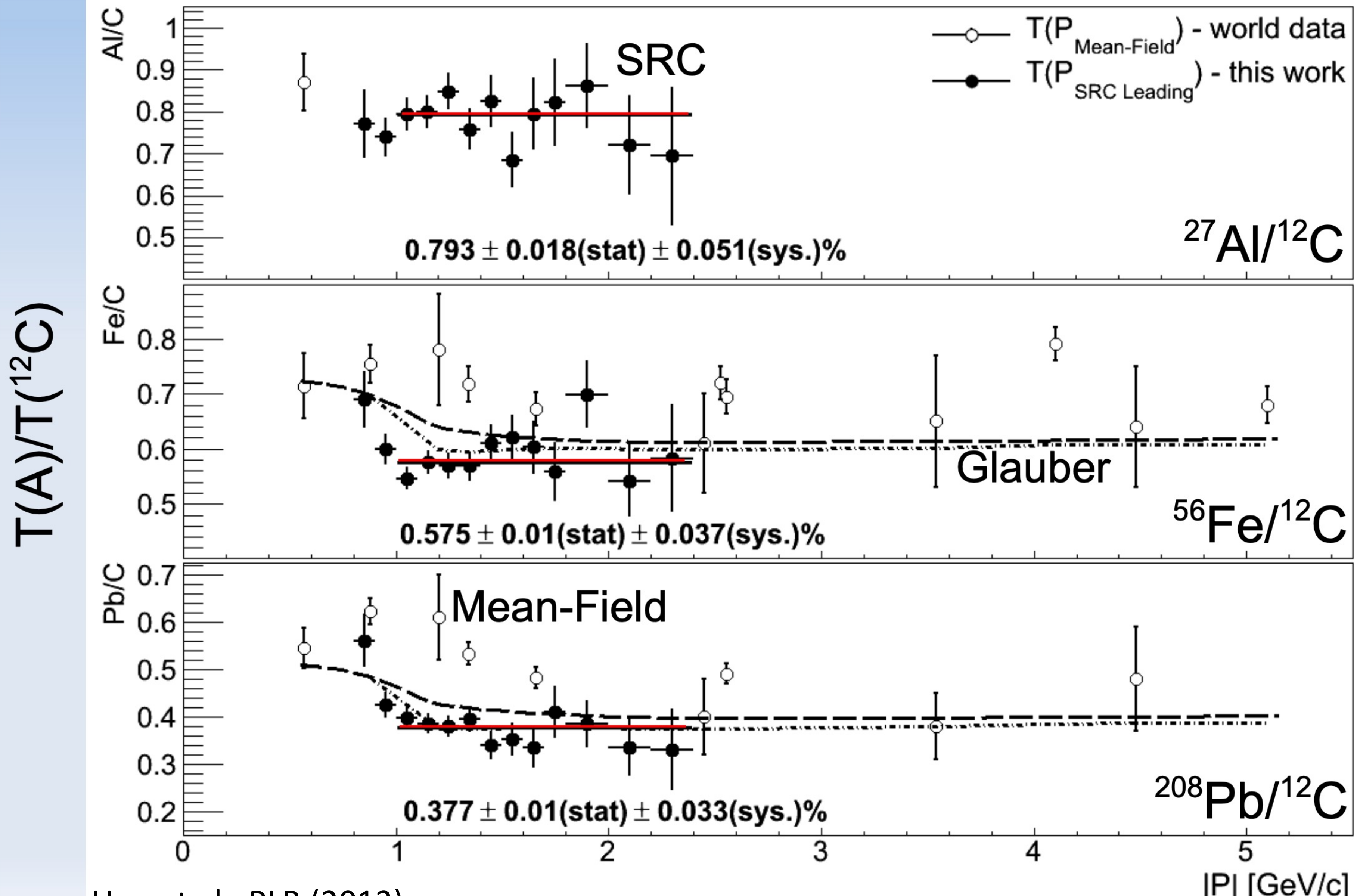


Transparency in SRC Dominated Kinematics

$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(A_1 \cdot a_2(A_1))}{\sigma_{A_2(e,e'p)}/(A_2 \cdot a_2(A_2))} = \boxed{a_2(A_2/A_1) \cdot \frac{\sigma_{A_1(e,e'p)}/A_1}{\sigma_{A_2(e,e'p)}/A_2}}$$

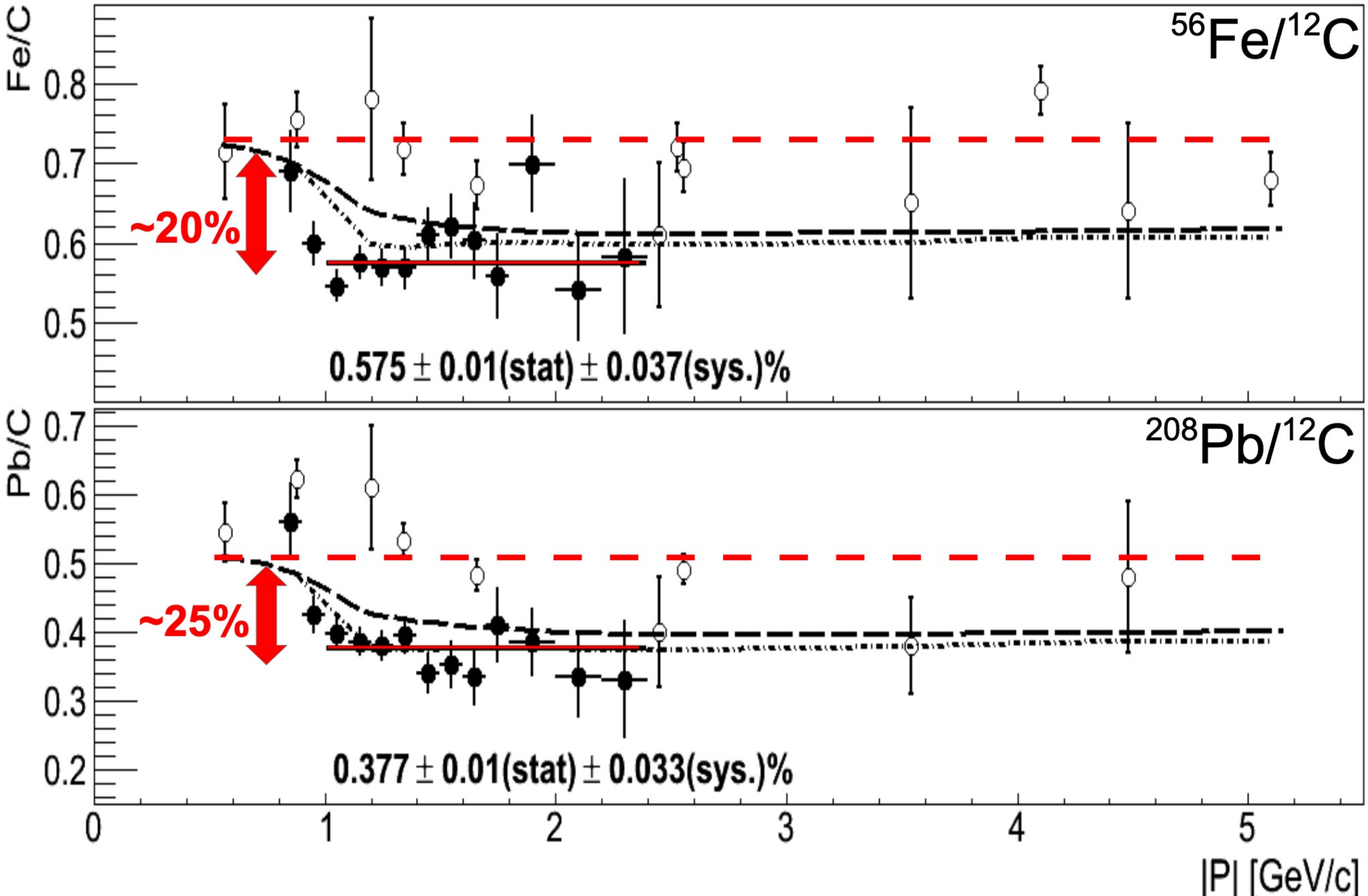
<u>Theory Independent Observable!</u>

SRC Transparency Ratios



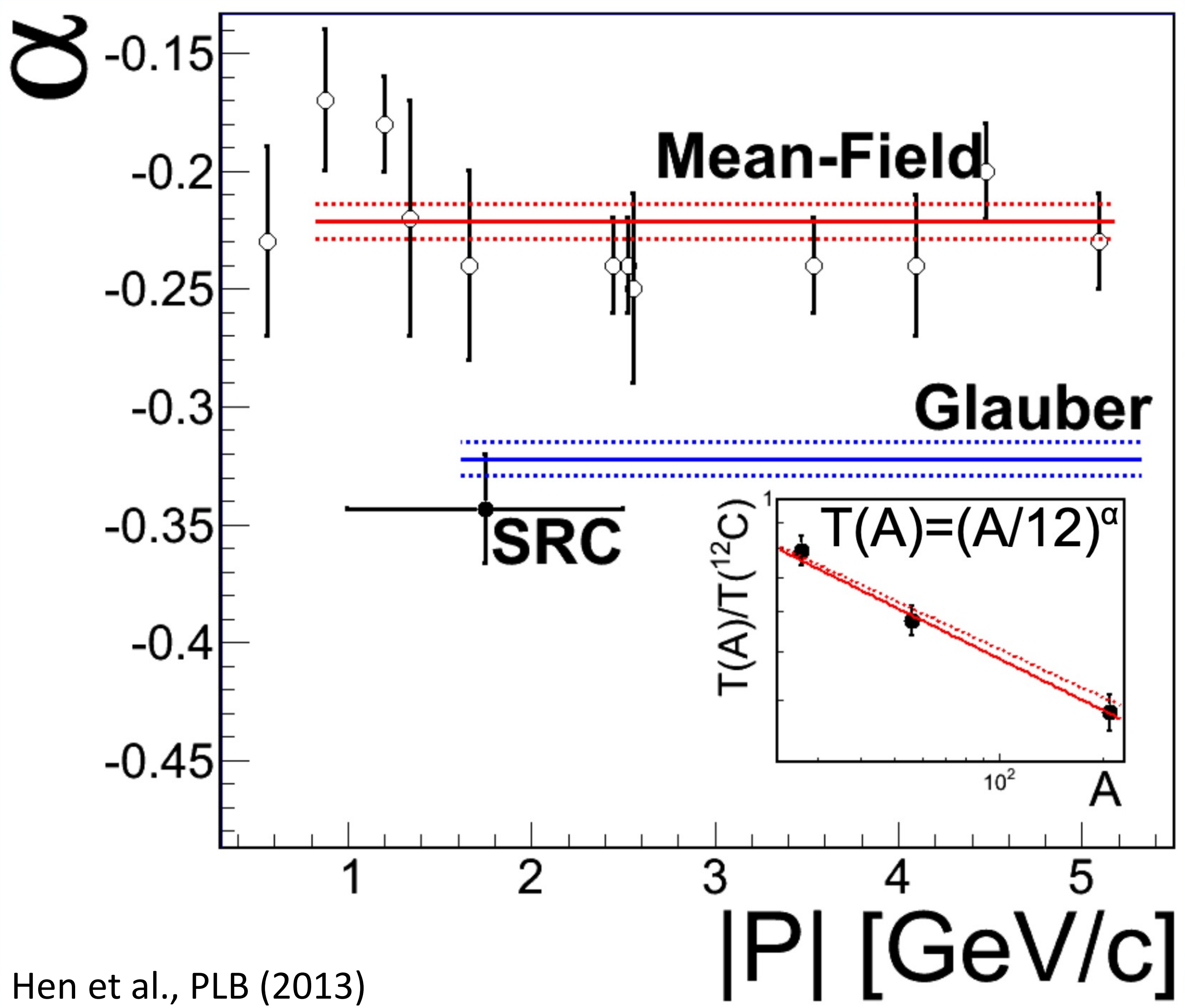
Hen et al., PLB (2013)

Difference Between Mean-Field and SRC Transparencies



Hen et al., PLB (2013)

A dependence
[$T(A) = A^{\alpha}$ Parametrization]



Hen et al., PLB (2013)

A dependence
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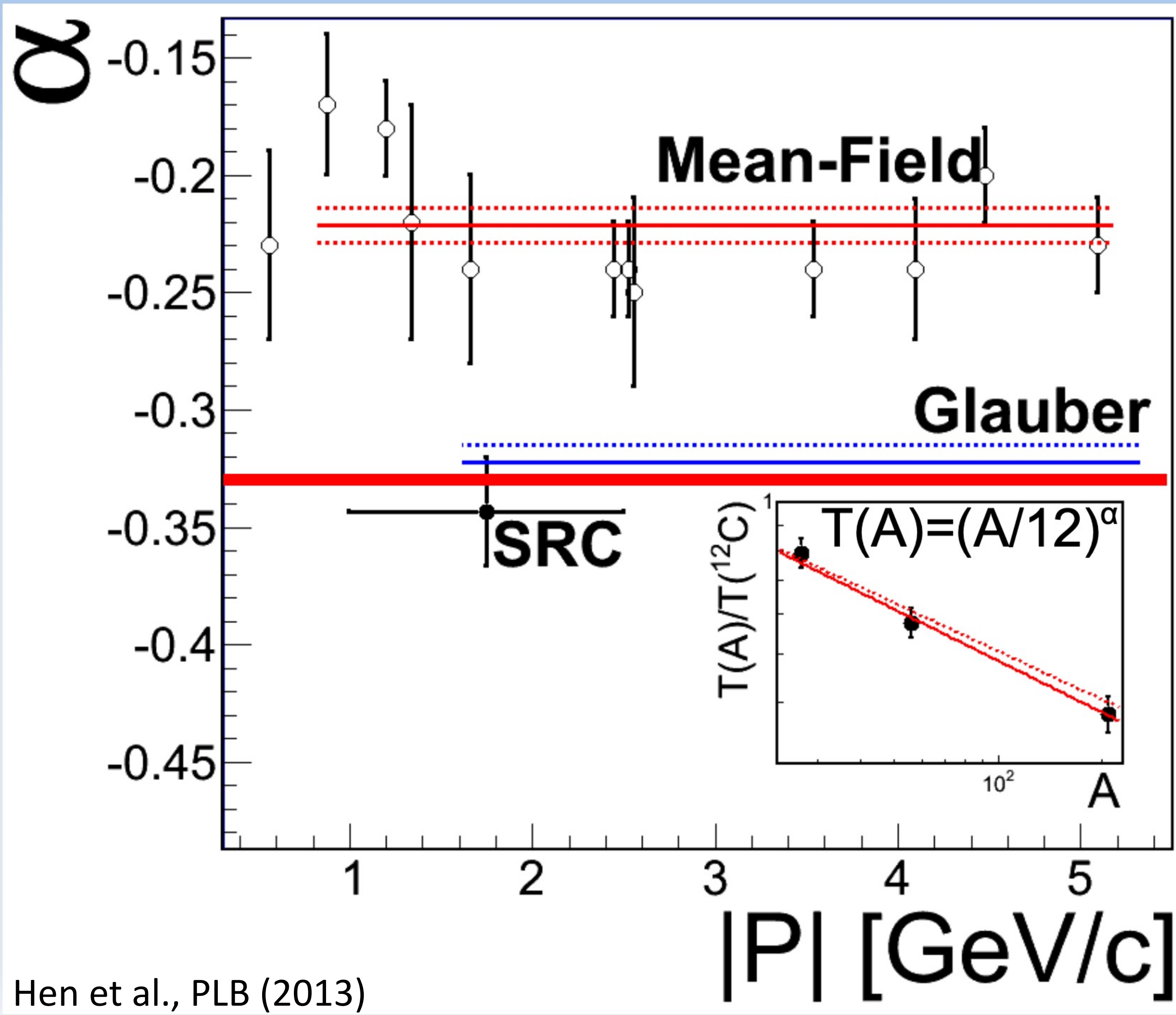
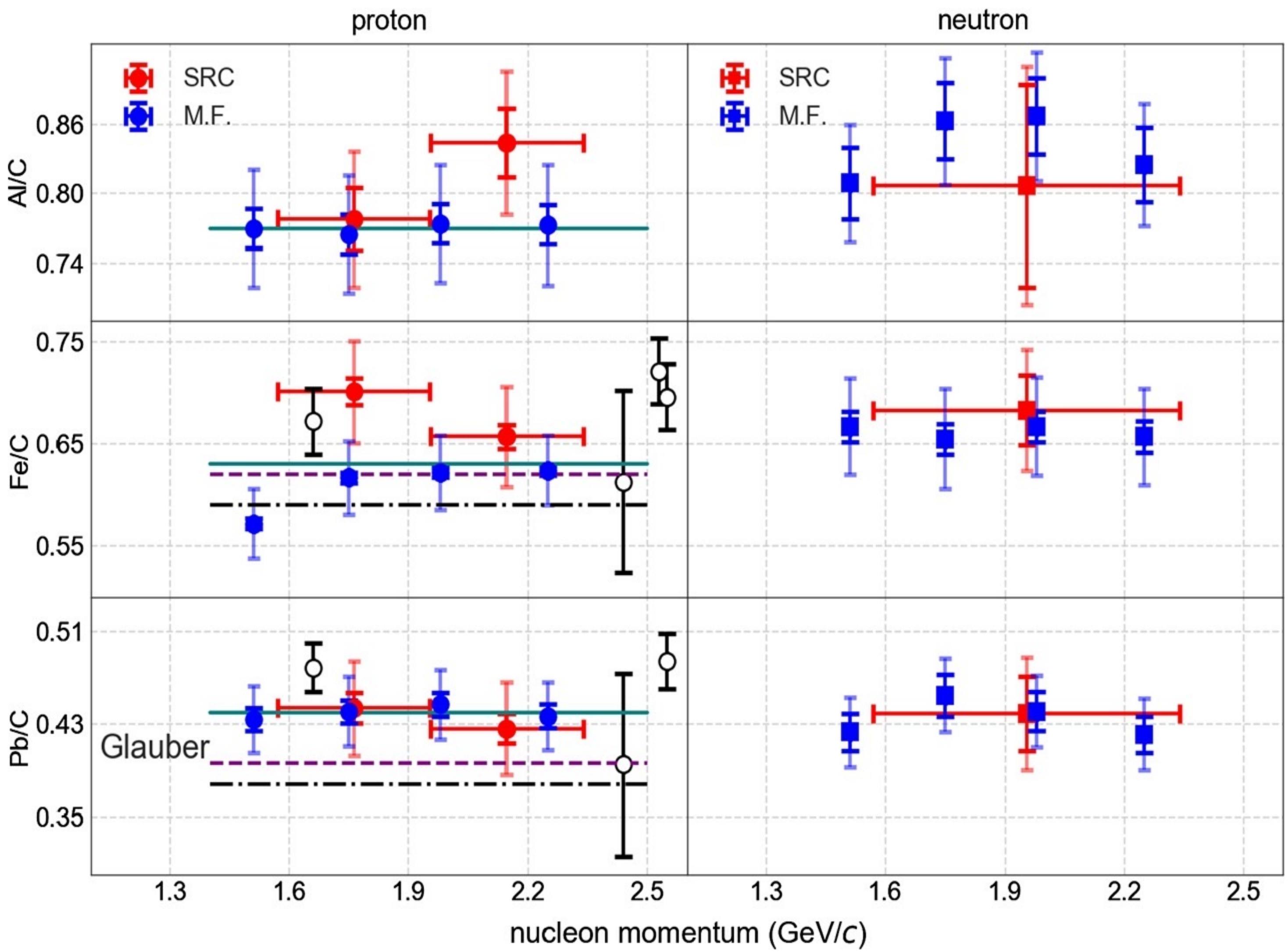


1/r dependence => Surface dominance

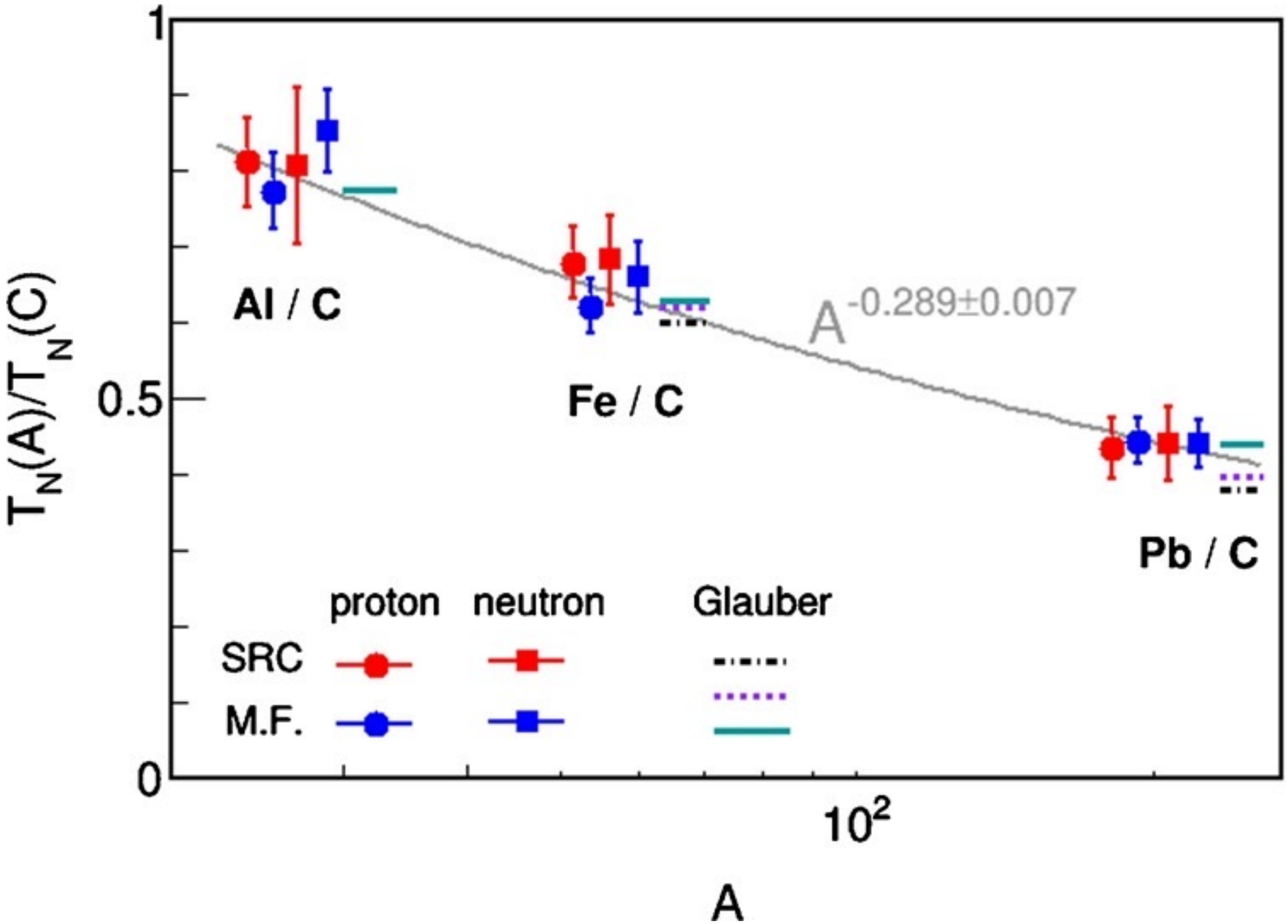
Hen et al., PLB (2013)

Full Understanding \w SRC Guidance



Duer et al., PLB (2019)

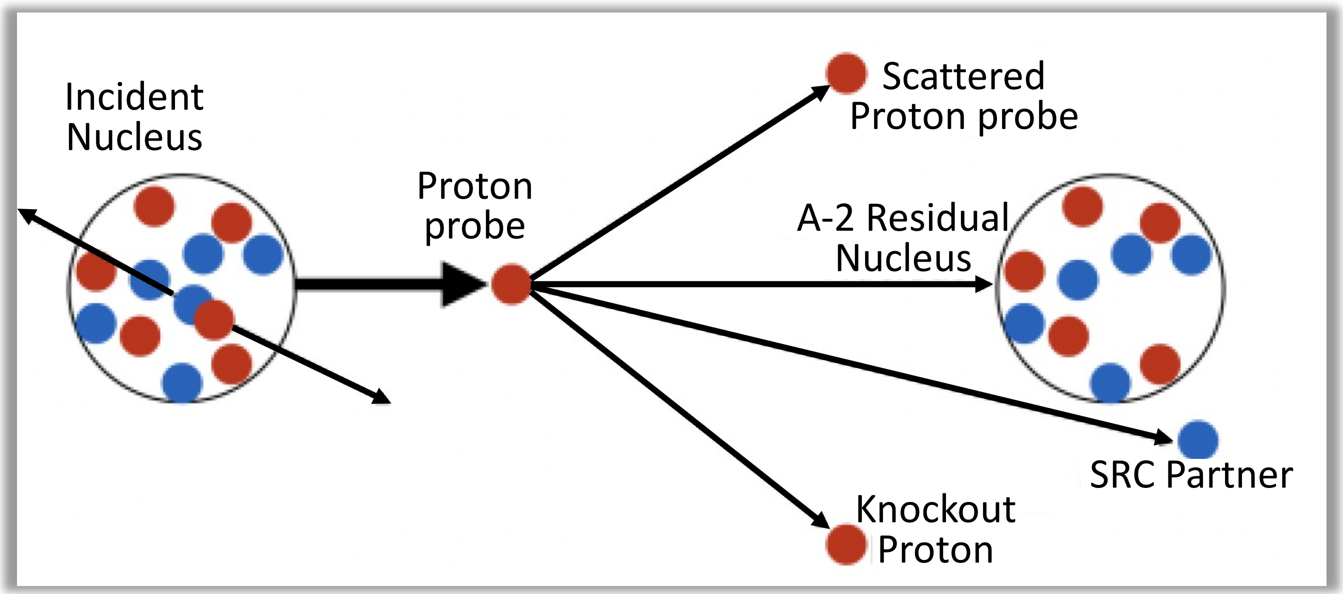
Full Understanding \w SRC Guidance



Duer et al., PLB (2019)

Going Inverse:

Towards Colliders & Radioactive Beams



TEL AVIV UNIVERSITY אוניברסיטת תל אביב

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

DE LA RECHERCHE À L'INDUSTRIE cea

JINR

Key: Suppress Final State Interactions

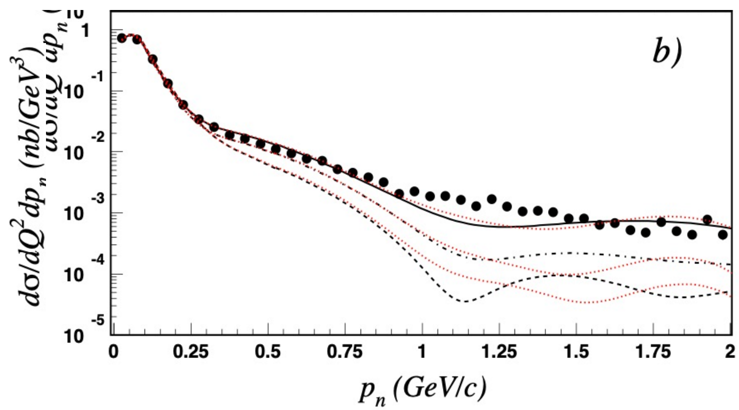
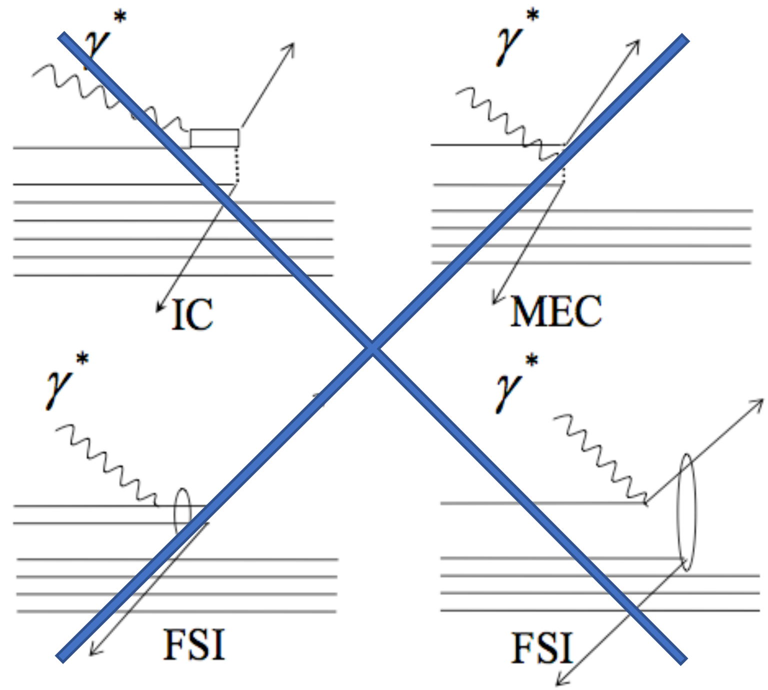
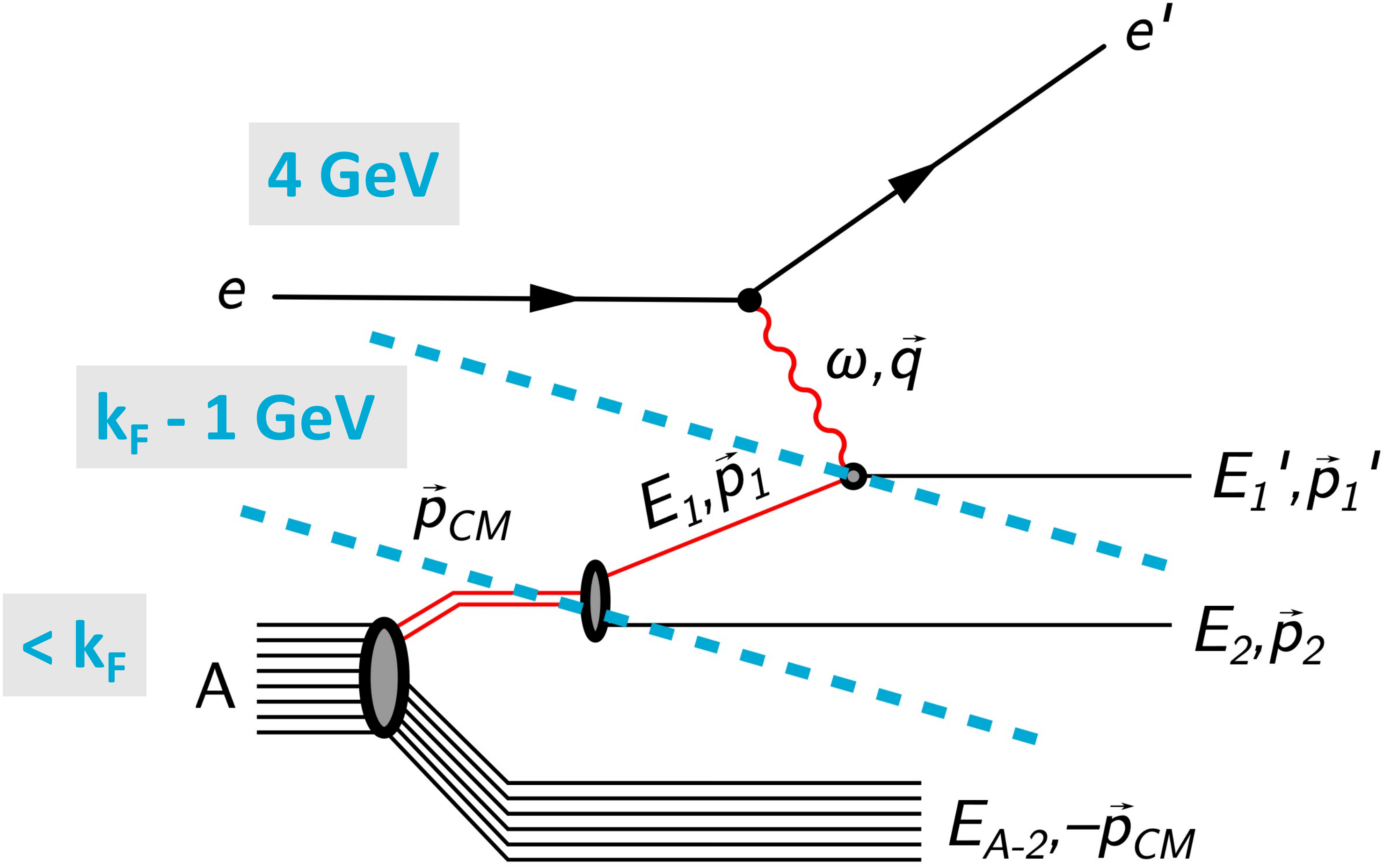


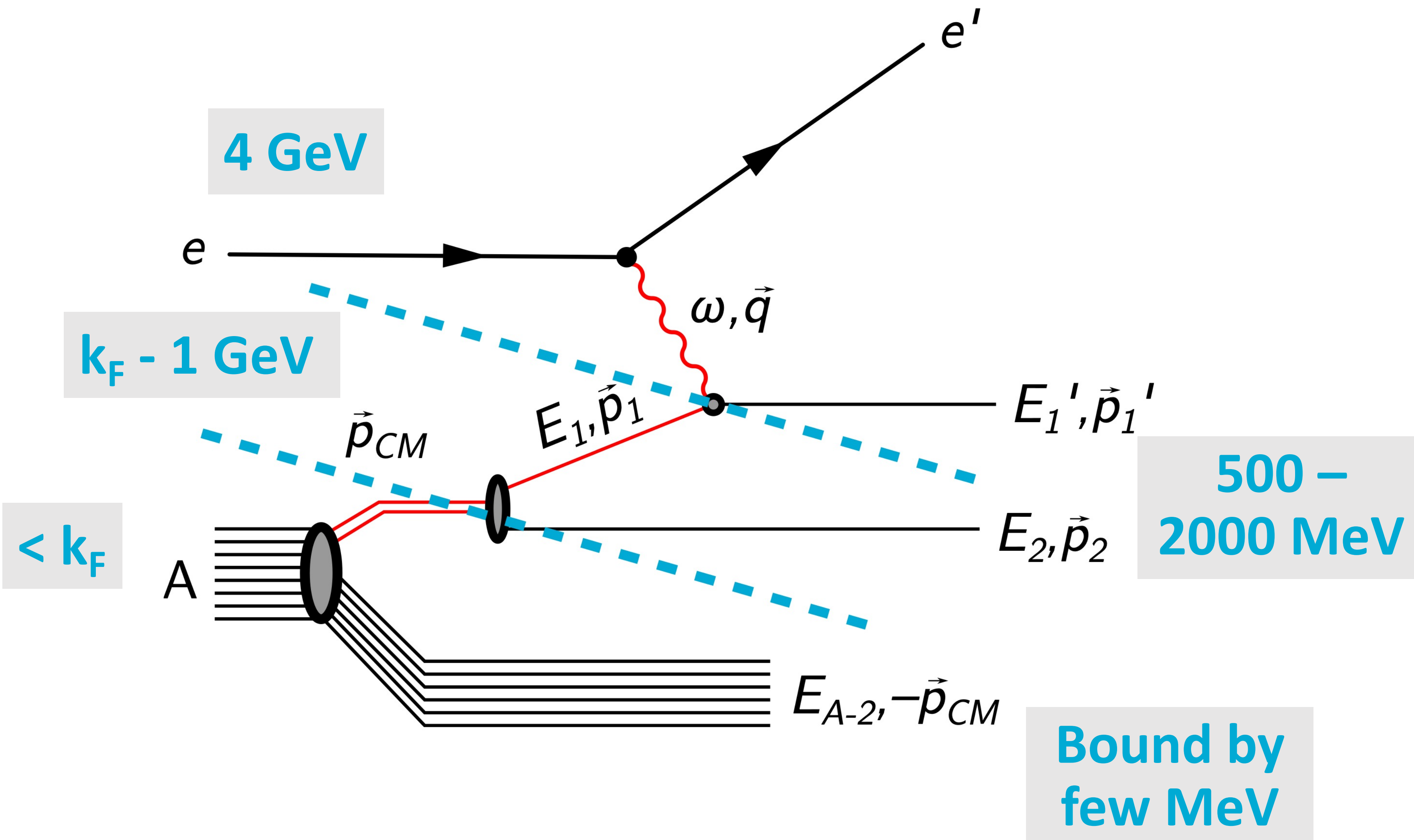
FIG. 1: Color online. The recoil neutron momentum distribution for (a) $Q^2 = 2 \pm 0.25$ GeV^2 and (b) $Q^2 = 3 \pm 0.5$ GeV^2. Dashed, dash-dotted and solid curves are calculations with the Paris potential for PWIA, PWIA+FSI and PWIA+FSI+MEC+NΔ, respectively. Dotted (red) curves are calculations with the AV18 potential.



Scale Separation and re-interactions



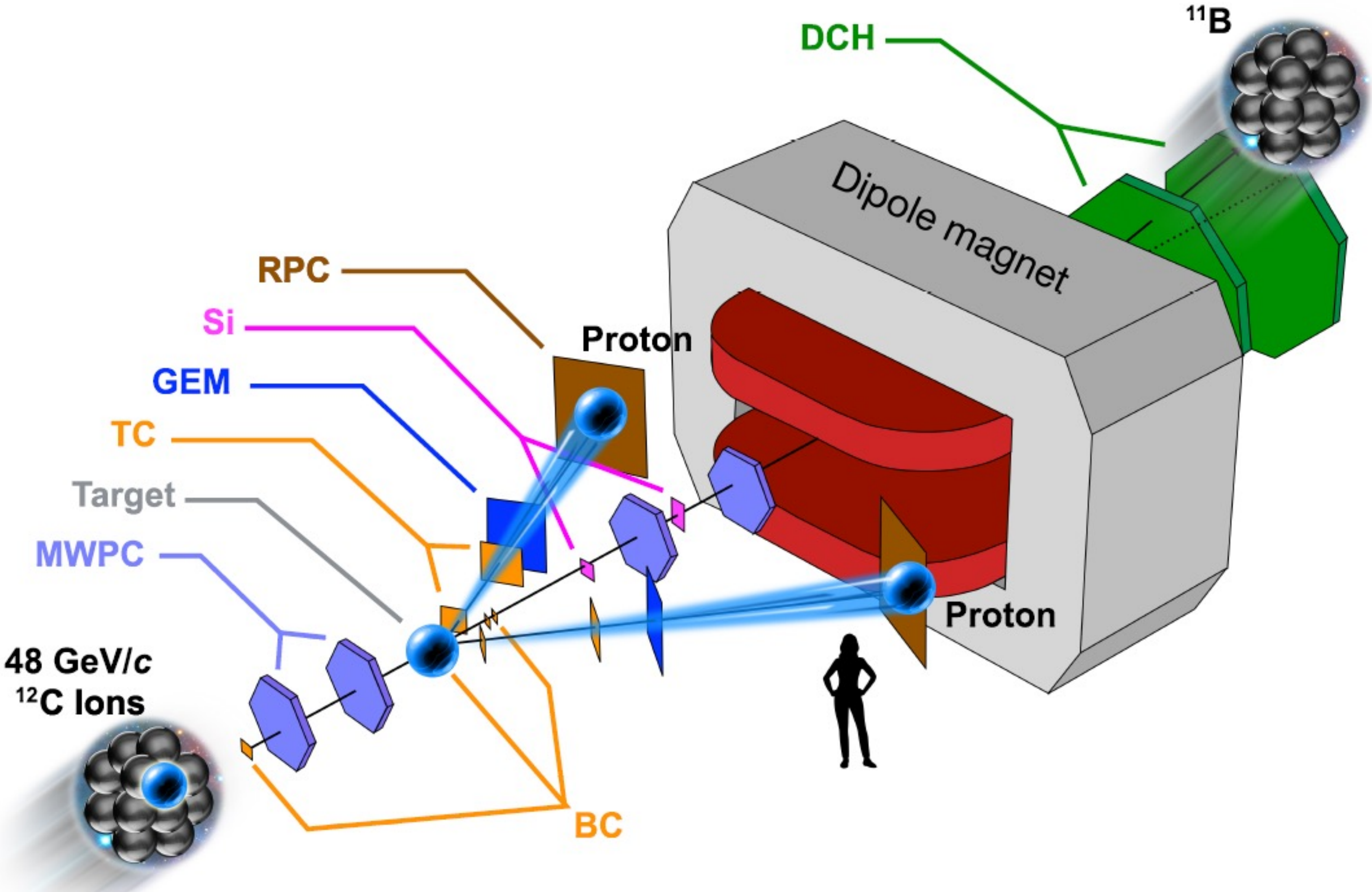
Scale Separation and re-interactions



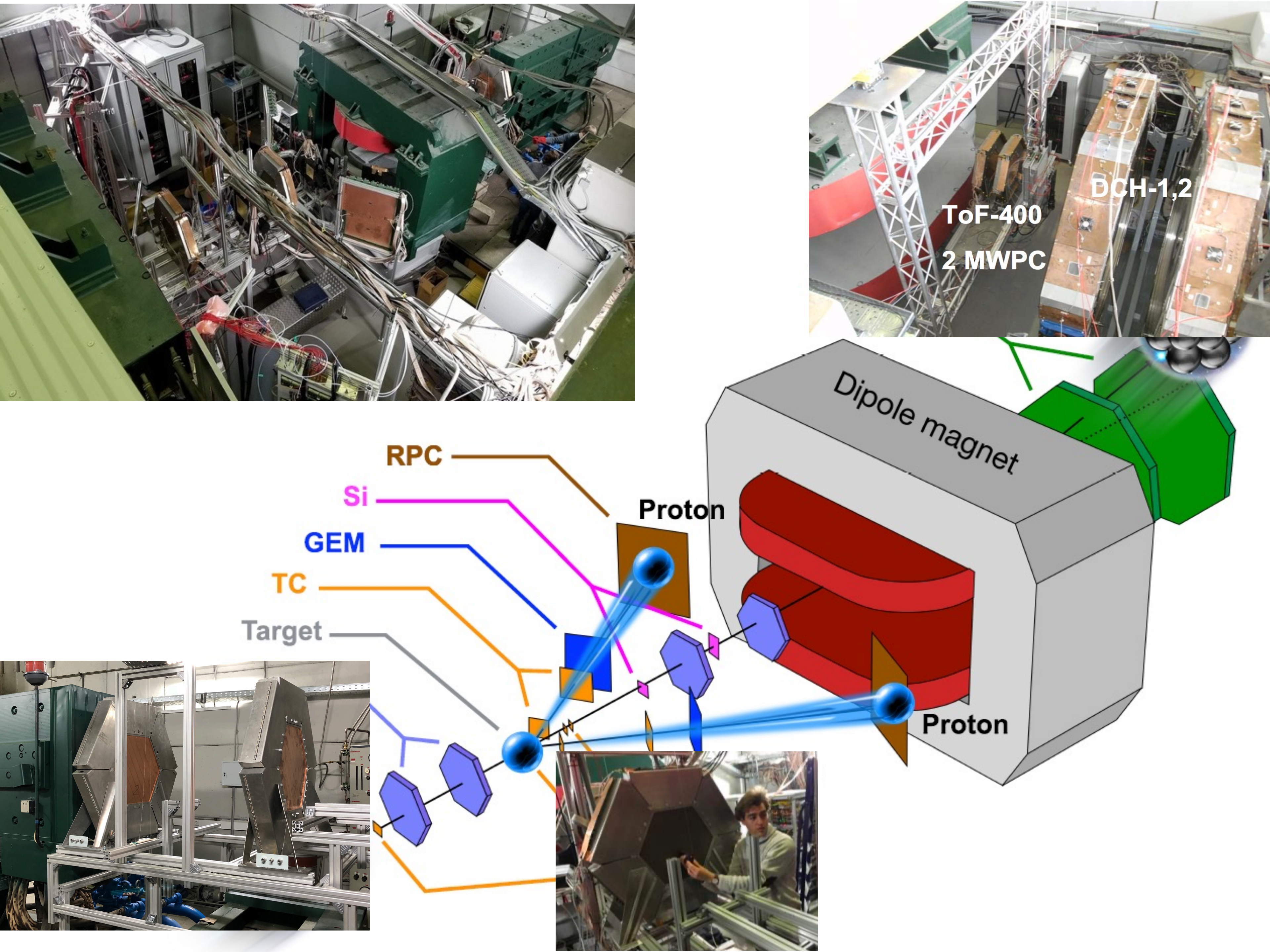
High-Energy Ion Beam @ JINR Nuclotron

High-Energy Ion Beam @ JINR Nuclotron

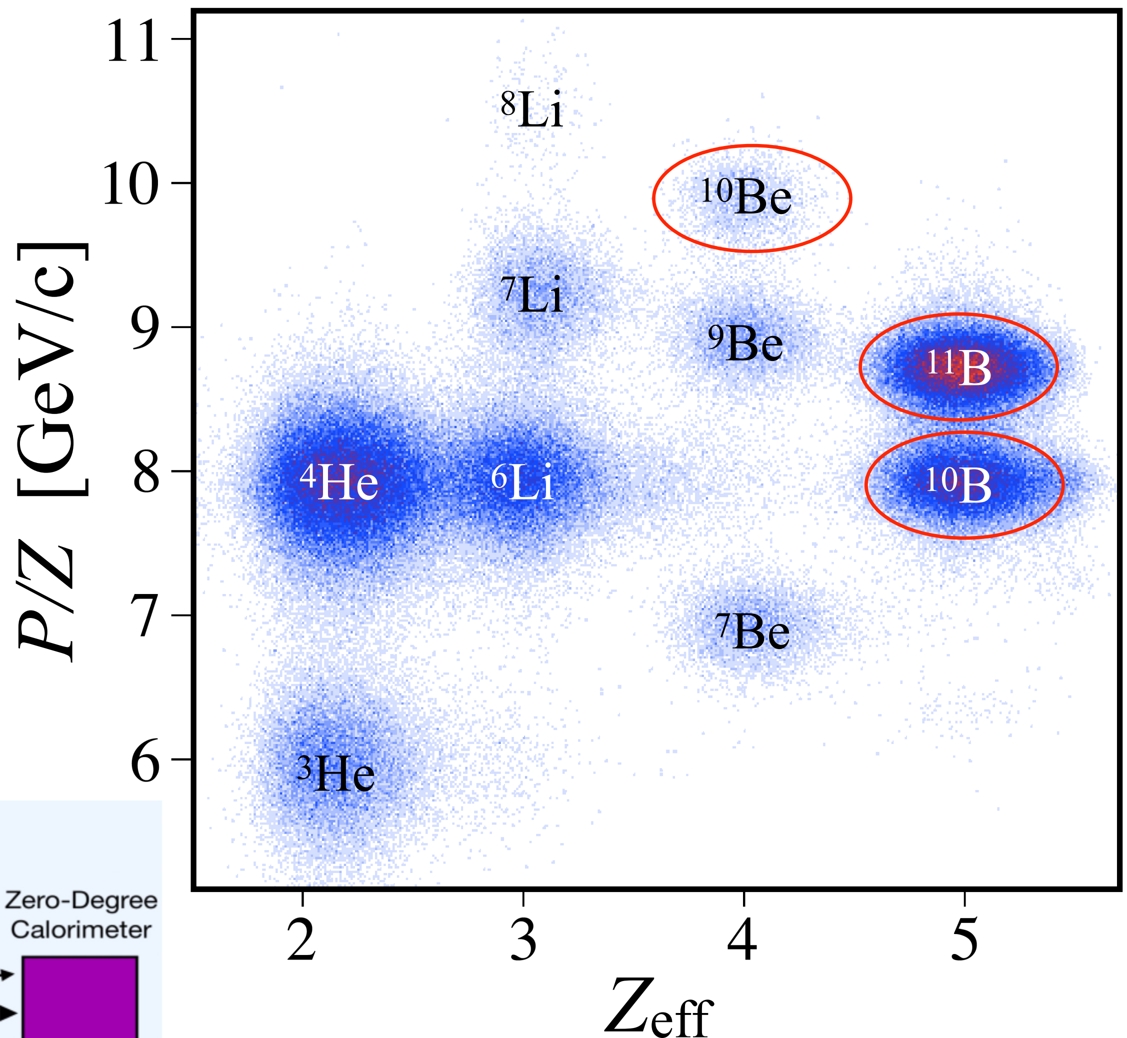
SRC @ BM@N

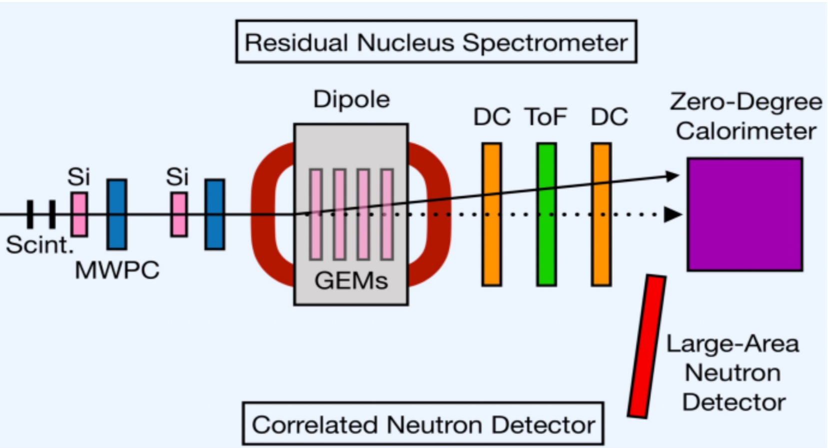


^{11}B
DCH
Dipole magnet
RPC
Si
GEM
TC
Target
MWPC
Proton
Proton
48 GeV/c
^{12}C Ions
BC

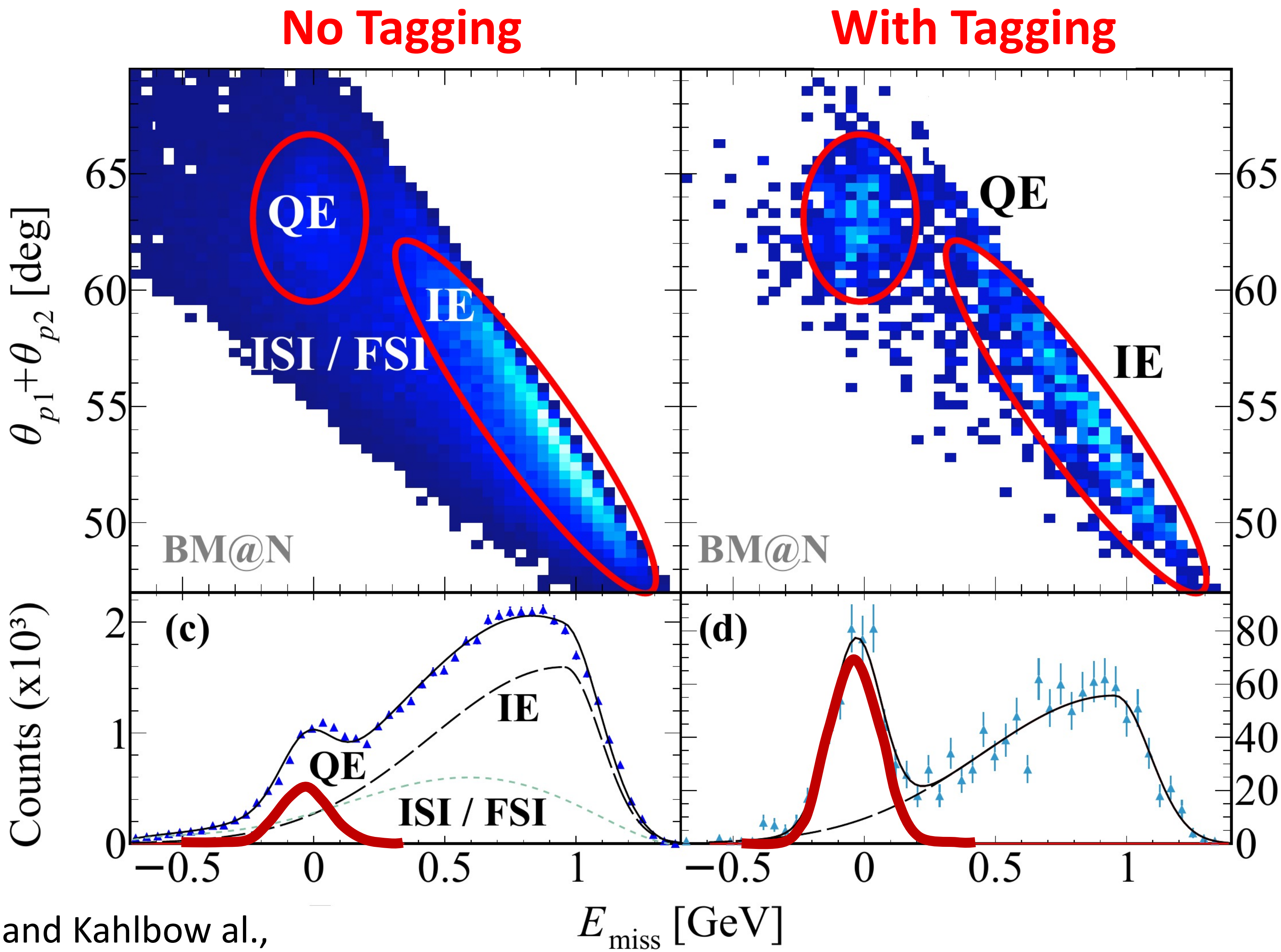

DCH-1,2
ToF-400
2 MWPC
Dipole magnet
RPC
Si
GEM
TC
Target
Proton
Proton

SRC @ BM@N: Fragment



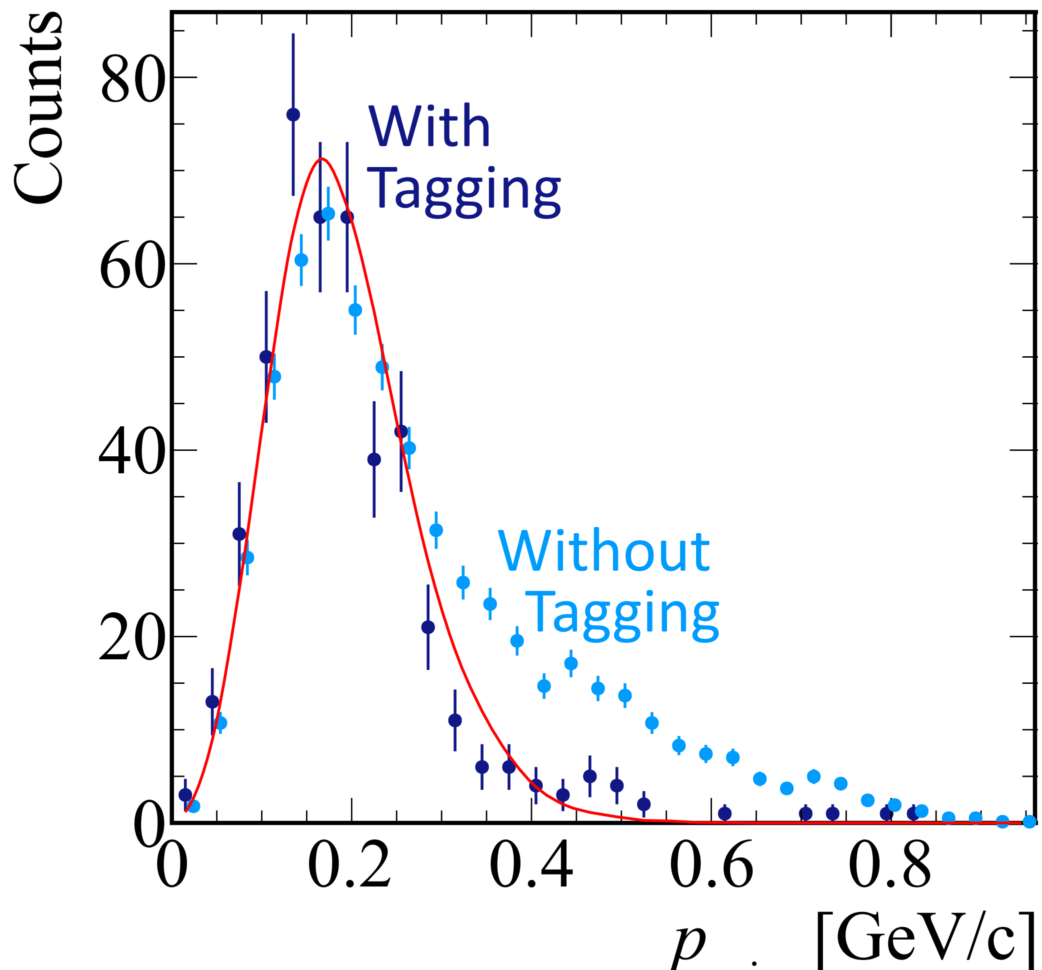


Fragment Tagging Suppress FSI



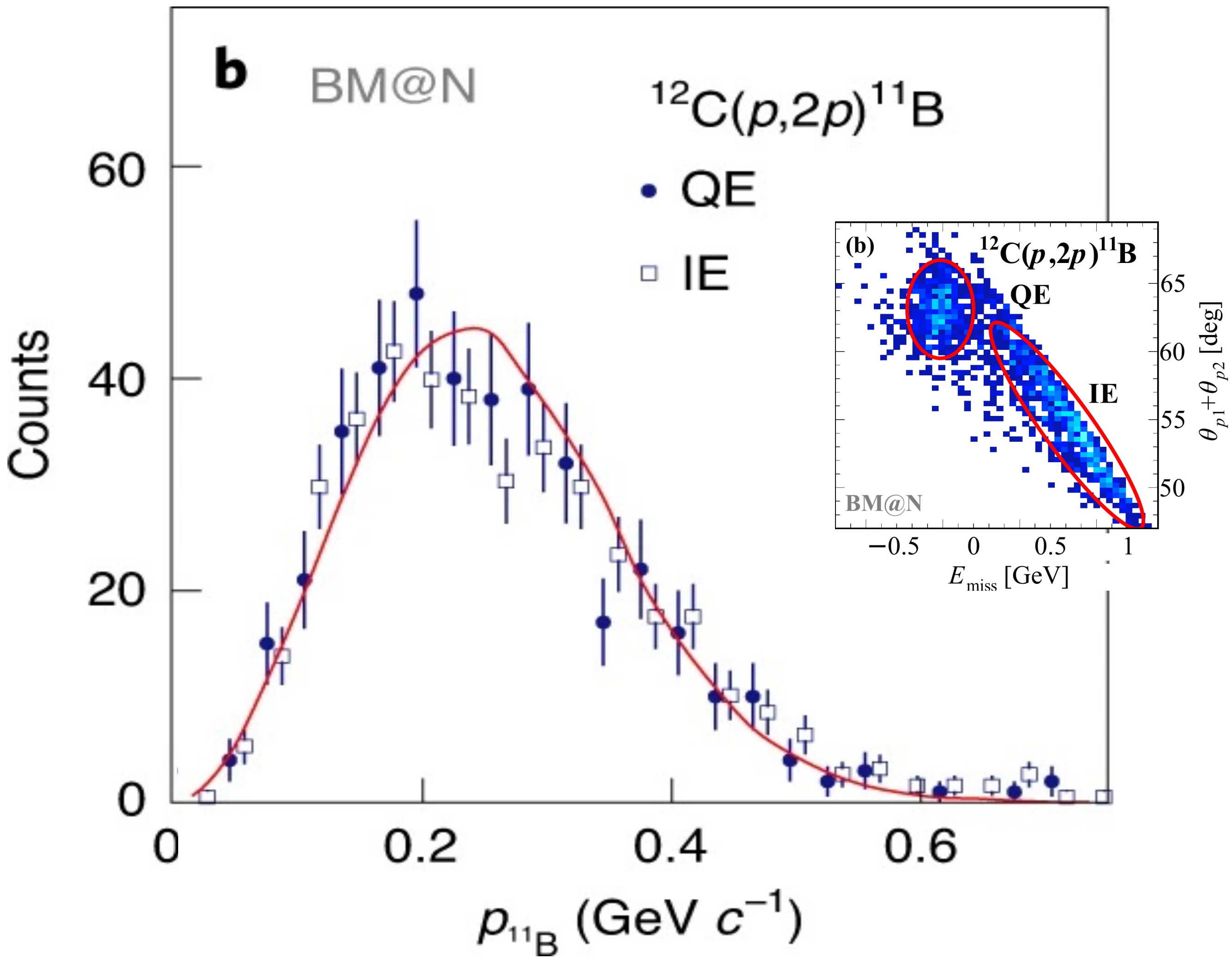
Patsyuk and Kahlbow al., Nature Physics (2021)

^{12}C p-shell measurement



Patsyuk and Kahlbow al., Nature Physics (2021)

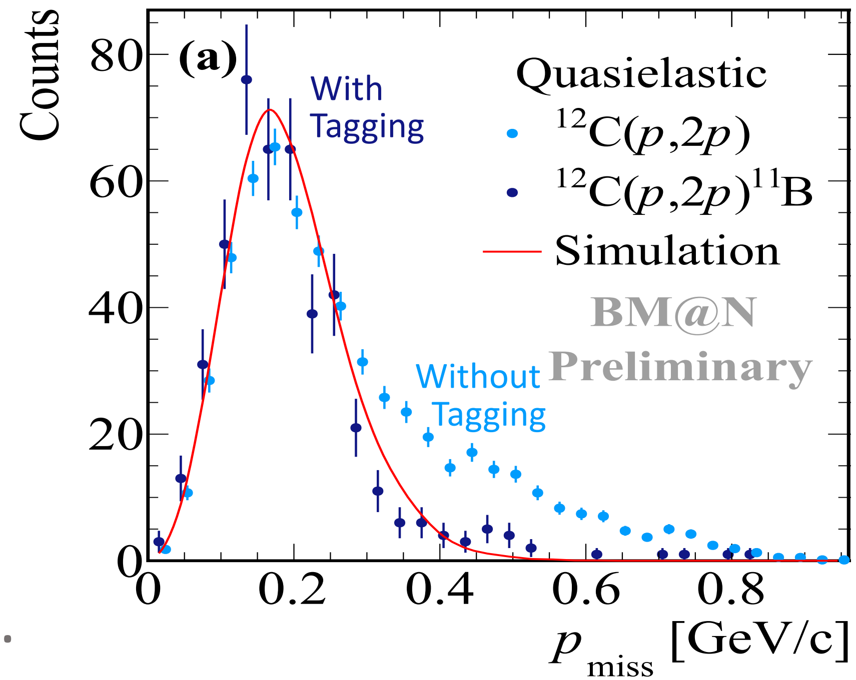
^{12}C p-shell measurement



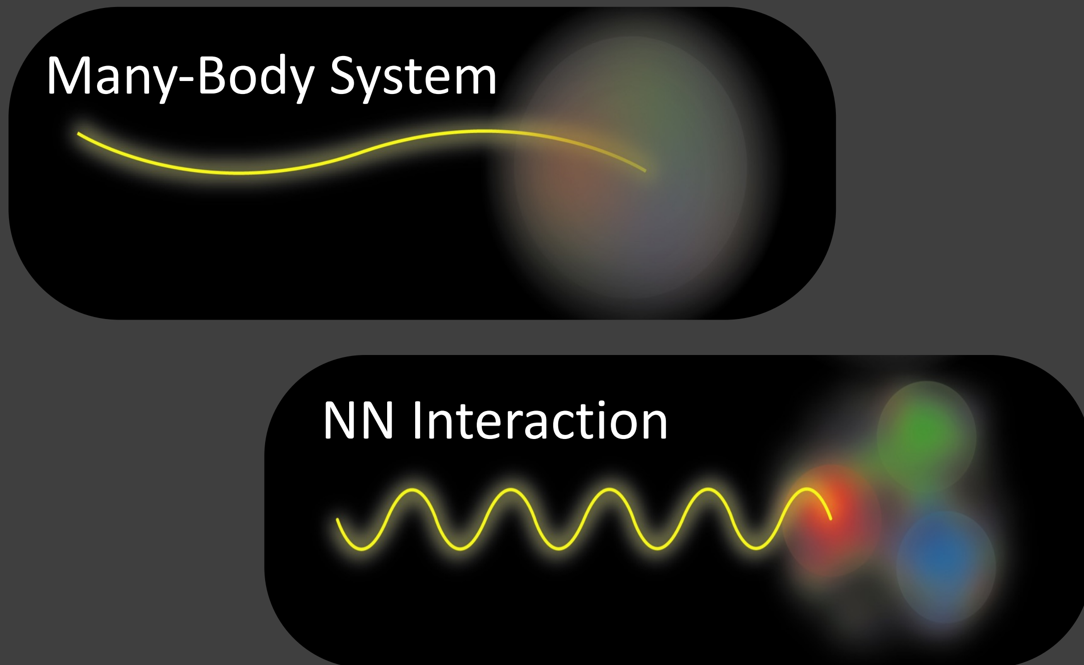
Patsyuk and Kahlbow al.,
Nature Physics (2021)

JINR Results

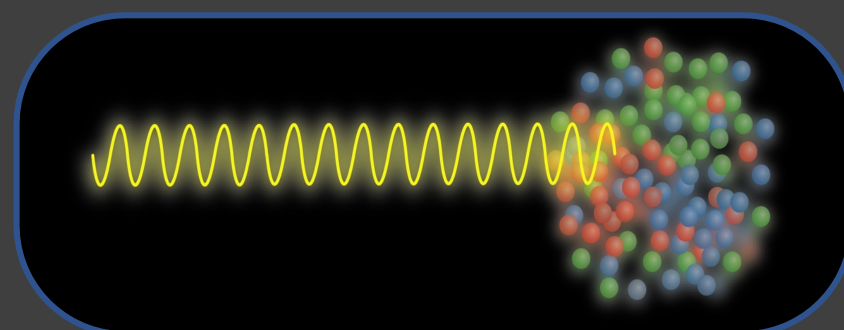
- First observation of ISI/FSI suppression using fragment detection.
- First observation of SRCs with bound residual A-2 system:
  - ➢ Direct measurement of pair c.m. motion
  - ➢ **Establishment of factorization!**



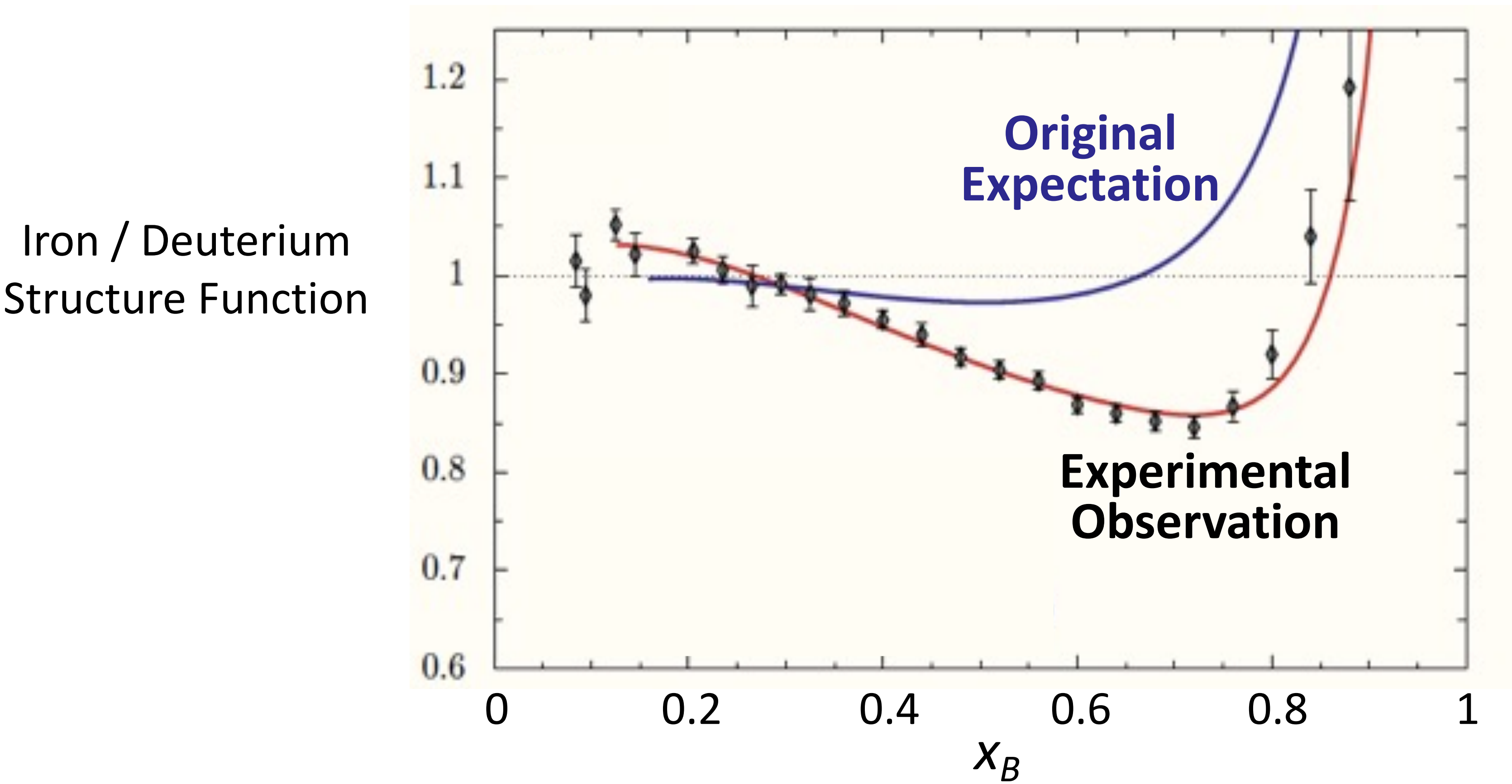
Patsyuk and Kahlbow al.,
Nature Physics (2021)



Quarks in the Nucleus



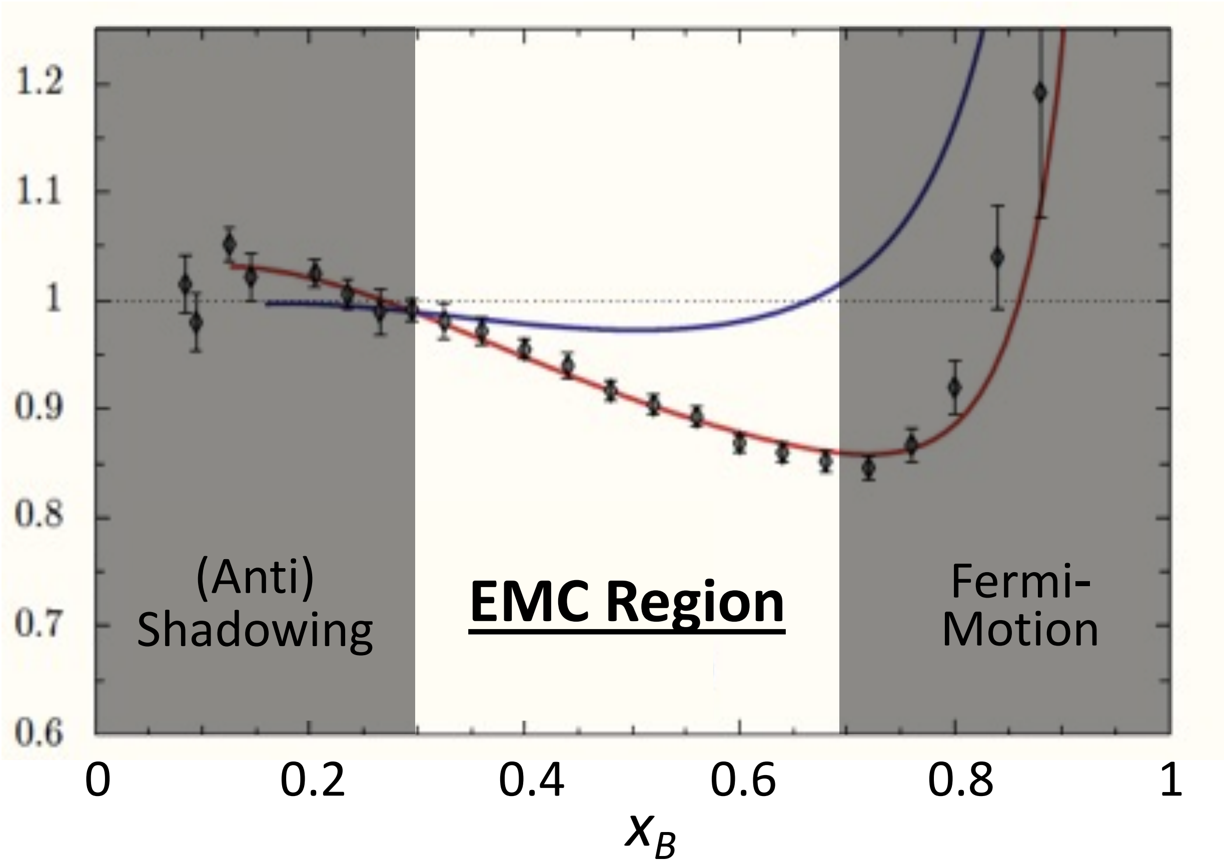
EMC Effect:



Aubert et al., PLB (**<u>1983</u>**); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Nature (**<u>2019</u>**)

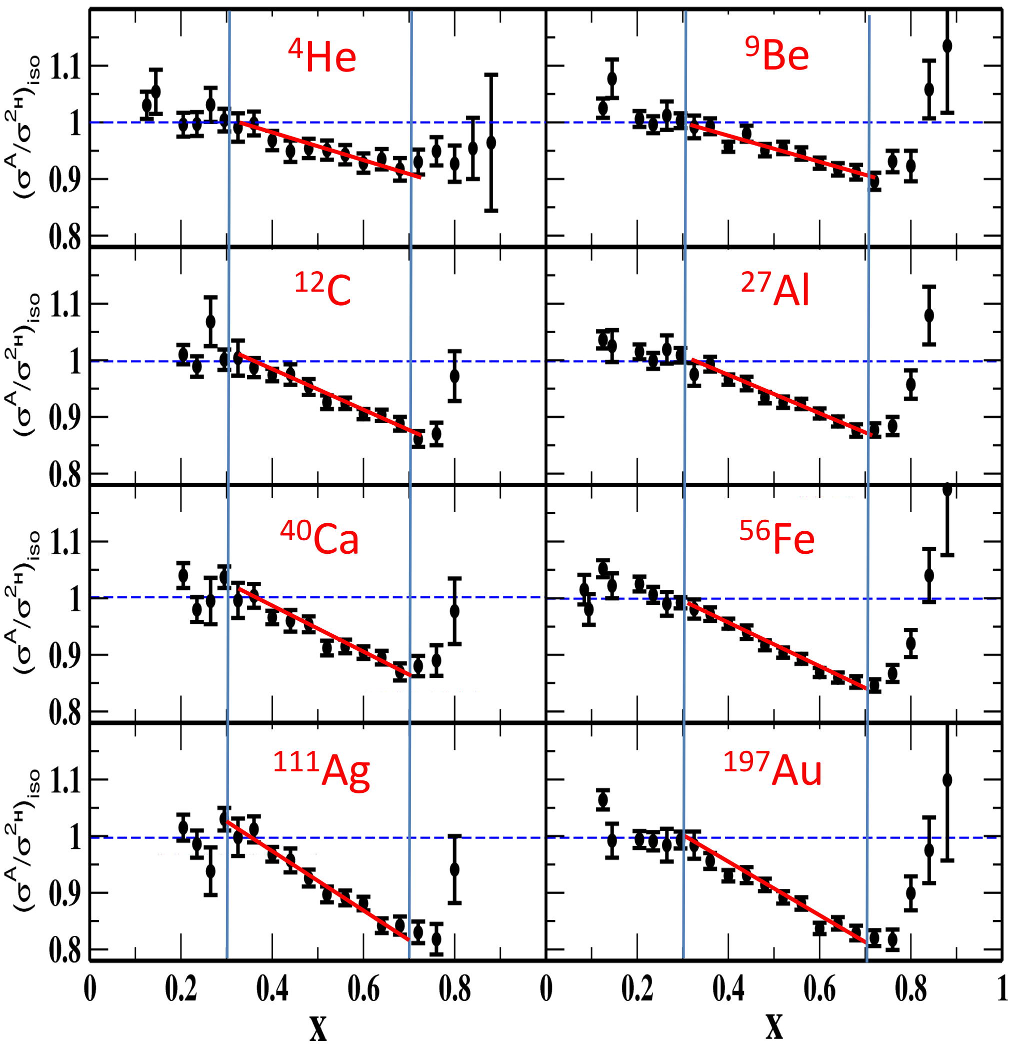
EMC Effect:

Iron / Deuterium Structure Function



Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Nature (2019)

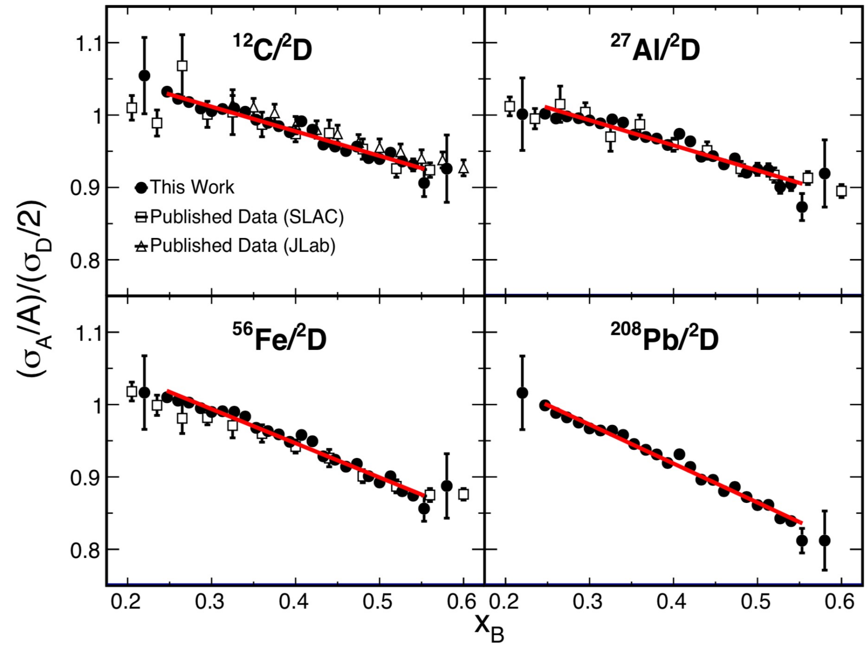
‘Global’ EMC Data



Gomez PRD (1994)

SLAC (1994)

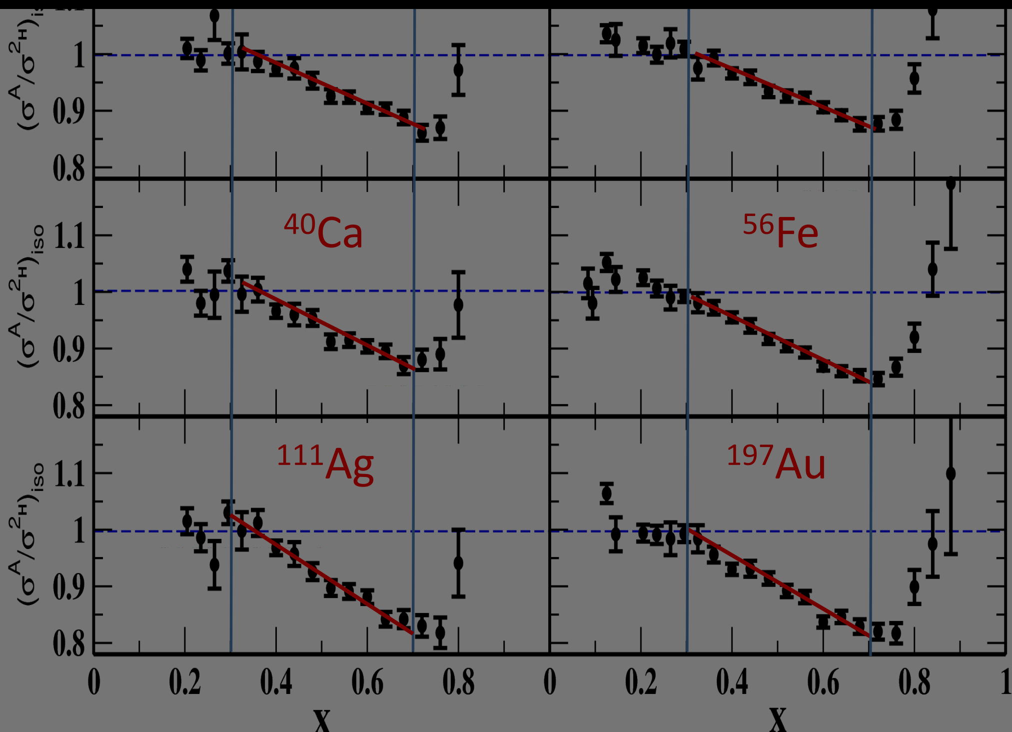
JLab (2019)



Schmookler,
Nature (2019)

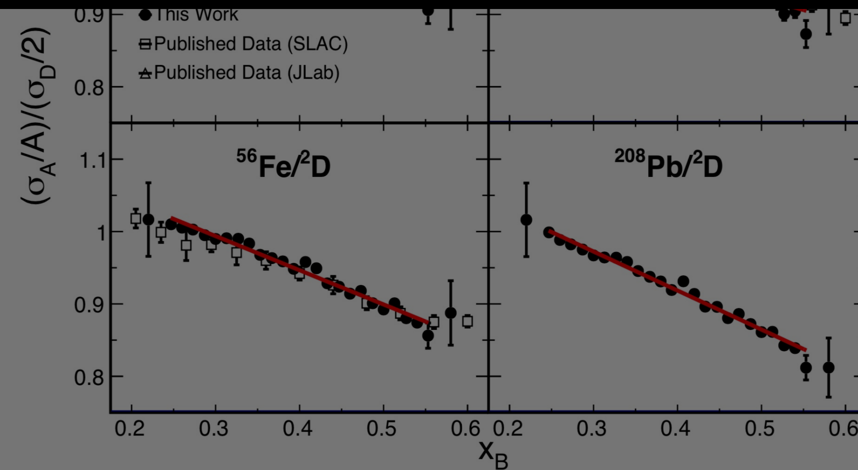
‘Global’ EMC Data

Effect driven by nuclear structure & dynamics



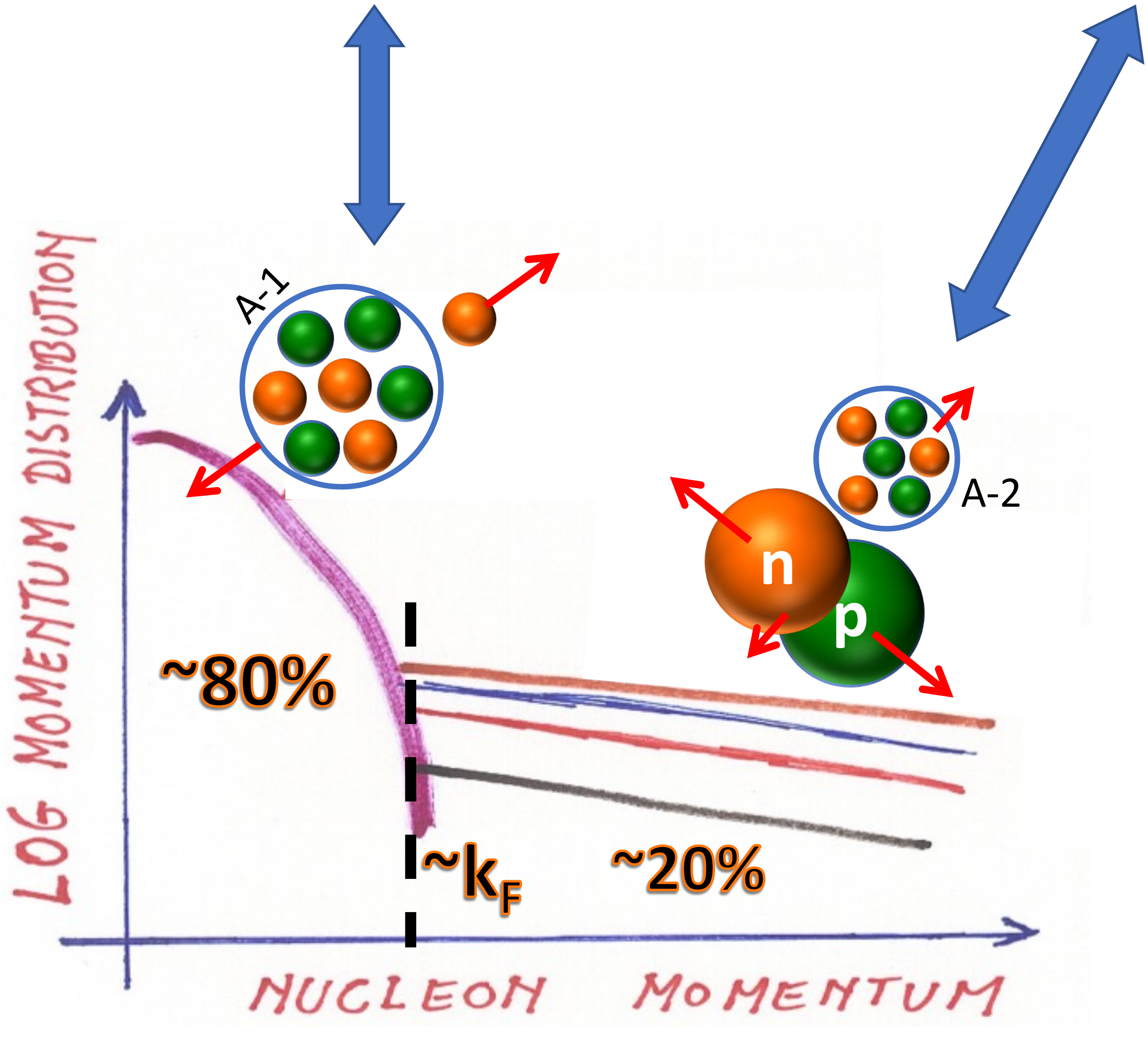
Gomez PRD (1994)

SLAC (1994)



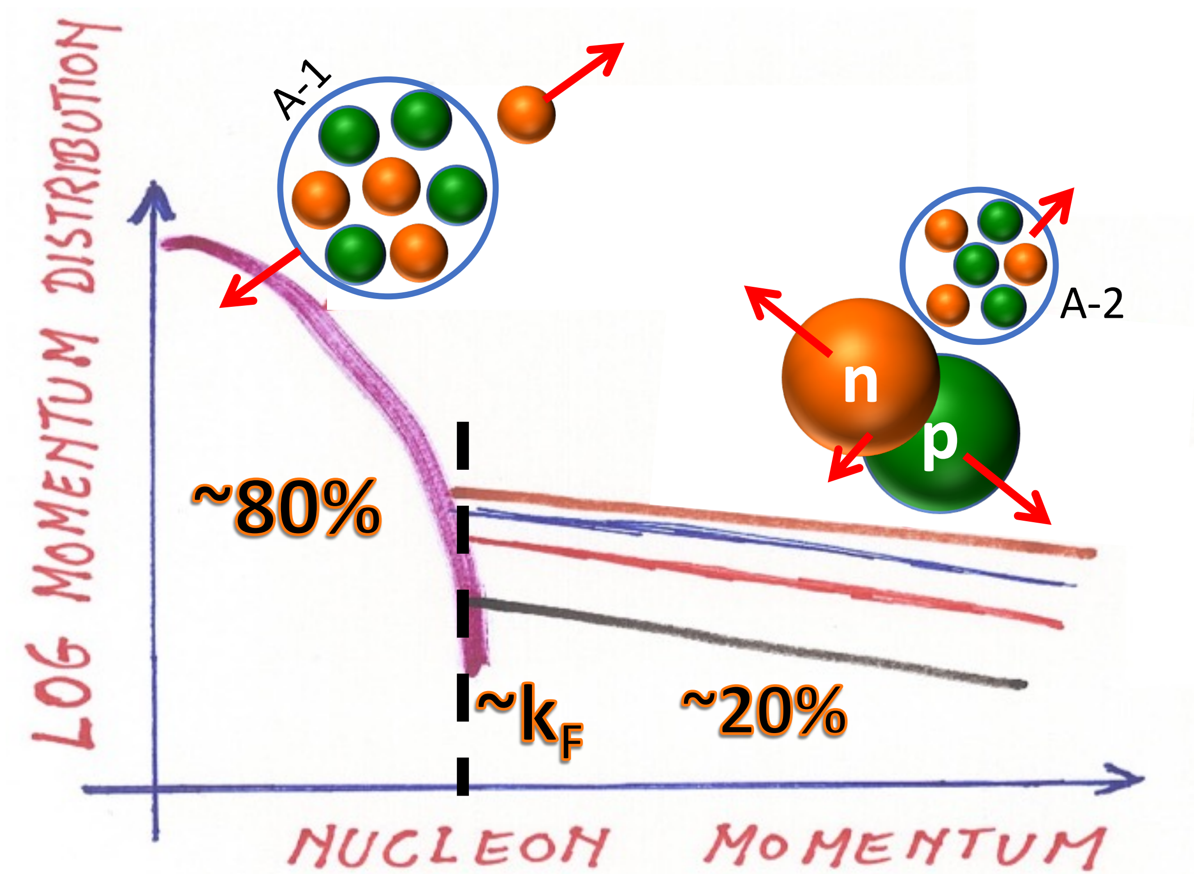
Schmookler, Nature (2019)

Bound = 'quasi Free' + Modified SRCs



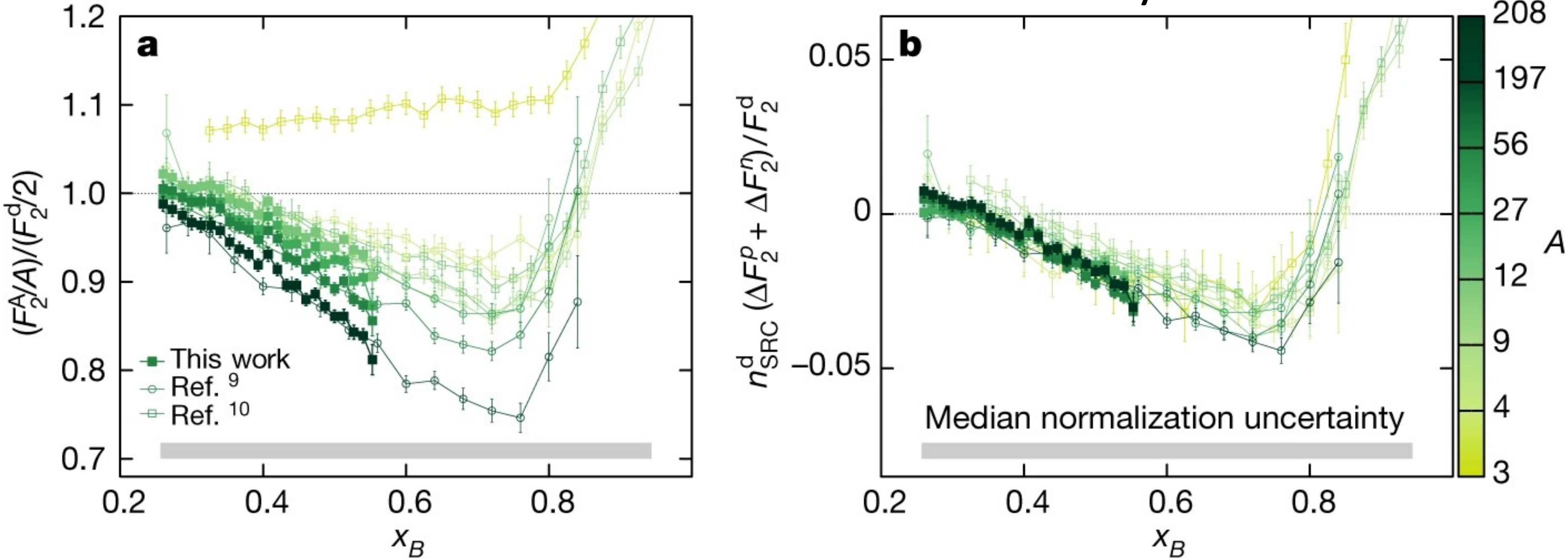
Bound = 'quasi Free' + Modified SRCs

➔ SRC = Bound - 'quasi Free'

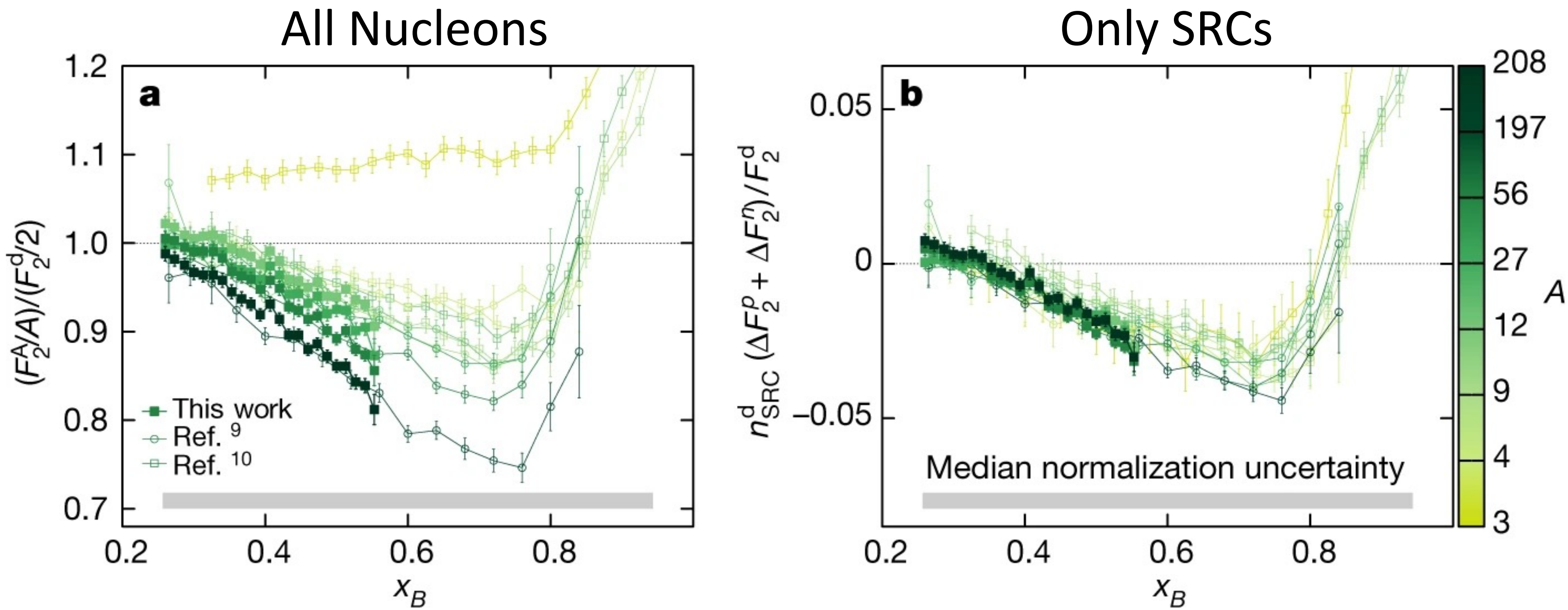


All Nucleons

Only SRCs

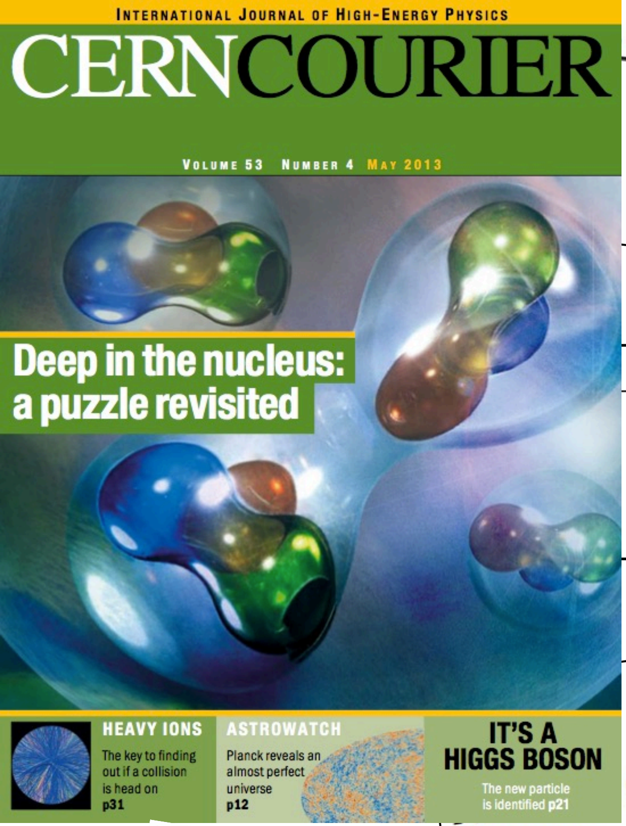


Schmookler, Nature (2019)



SRC Universality!

Schmookler, Nature (2019)



052301 (2011) PHYSICAL REVIEW LETTERS wee 4 FEBR

Short Range Correlations and the EMC Effect

L. B. Weinstein,[1,*] E. Piasetzky,[2] D. W. Higinbotham,[3] J. Gomez,[3] O. Hen,[2] and R. Shneor[2]

PHYSICAL REVIEW LETTERS **124**, 092002 (2020)

Neutron Valence Structure from Nuclear Deep Inelastic Scattering

E. P. Segarra,[1] A. Schmidt,[1,2] T. Kutz,[1,2] D. W. Higinbotham,[3] E. Piasetzky,[4] M. Strikman,[5] L. B. Weinstein,[6] and O. Hen[1,*]

PHYSICAL REVIEW C **85**, 047301 (2012)

strengthen the connection between short range correlations and the EMC

O. Hen,[1] E. Piasetzky,[1] and L. B. Weinstein[2]

PHYSICAL REVIEW D **84**, 117501 (2011)

Constraints on the large-x d/u ratio from electron-nucleus scattering at $x > 1$

O. Hen,[1] A. Accardi,[2,3] W. Melnitchouk,[3] and E. Piasetzky[1]

NUCLEAR PHYSICS A

Short range correlations and the EMC effect

etzky[a], L.B. Weinstein[b], D.W. Higinbotham[c], J. Gomez[c], O. Hen[a]

International Journal of Modern Physics E
Vol. 22, No. 7 (2013) 1330017 (30 pages)

THE EMC EFFECT AND HIG NUCLEONS IN NU

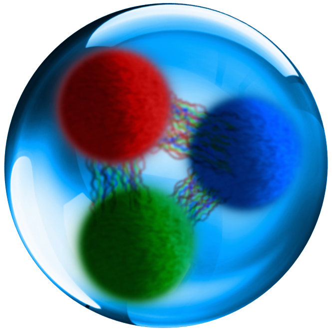
REVIEWS OF MODERN PHYSICS, VOLUME 89, OCTOBER–DECEMBER

Nucleon-nucleon correlations, short-lived excitations, and the quarks within

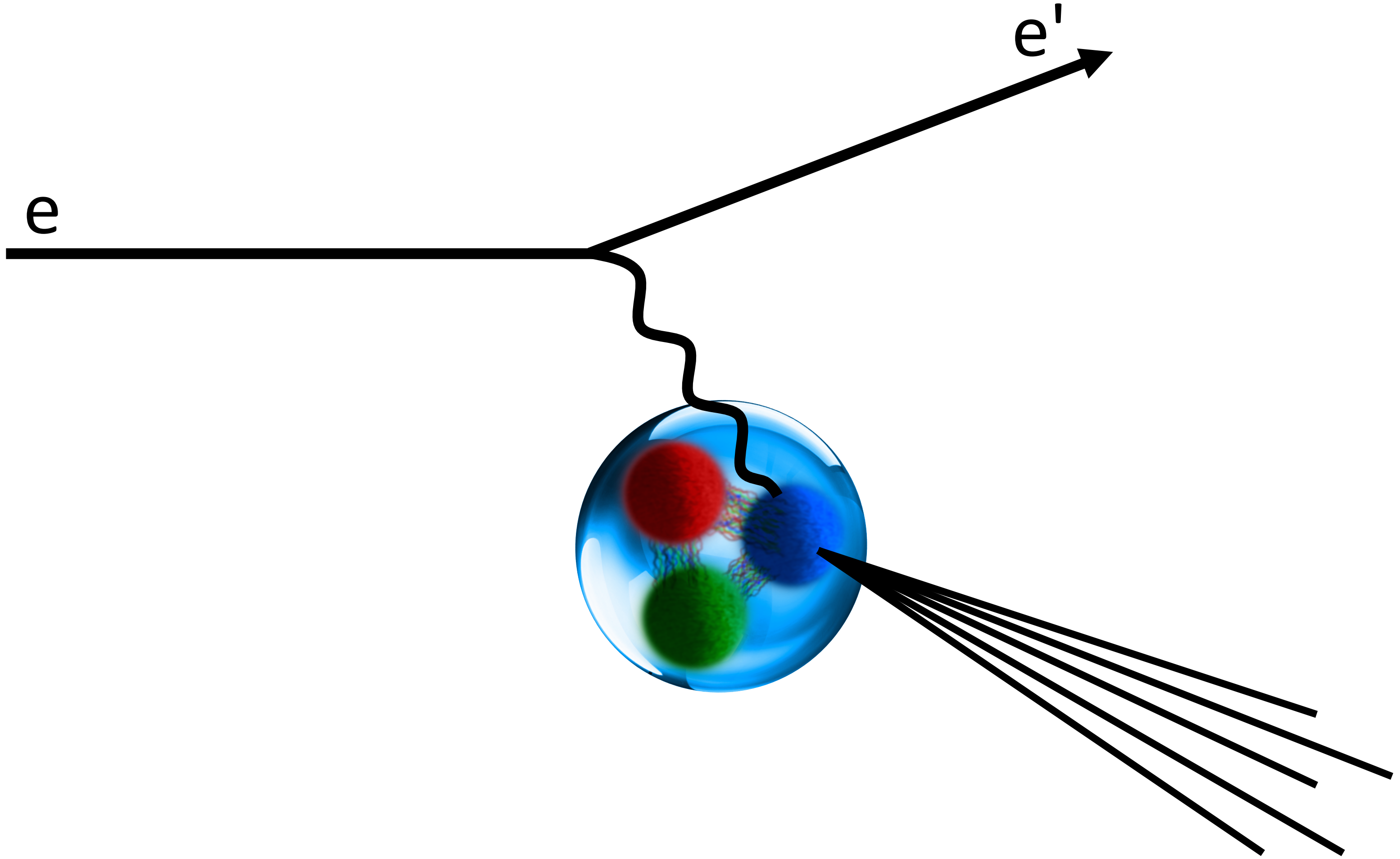
Or Hen Gerald A. Miller Eli Piasetzky Lawrence B. Weinstein

O. Hen, D.W. Higinbotham, G.A. Miller, Piasetzky and Weinstein

SRC quark-gluon structure



SRC quark-gluon structure



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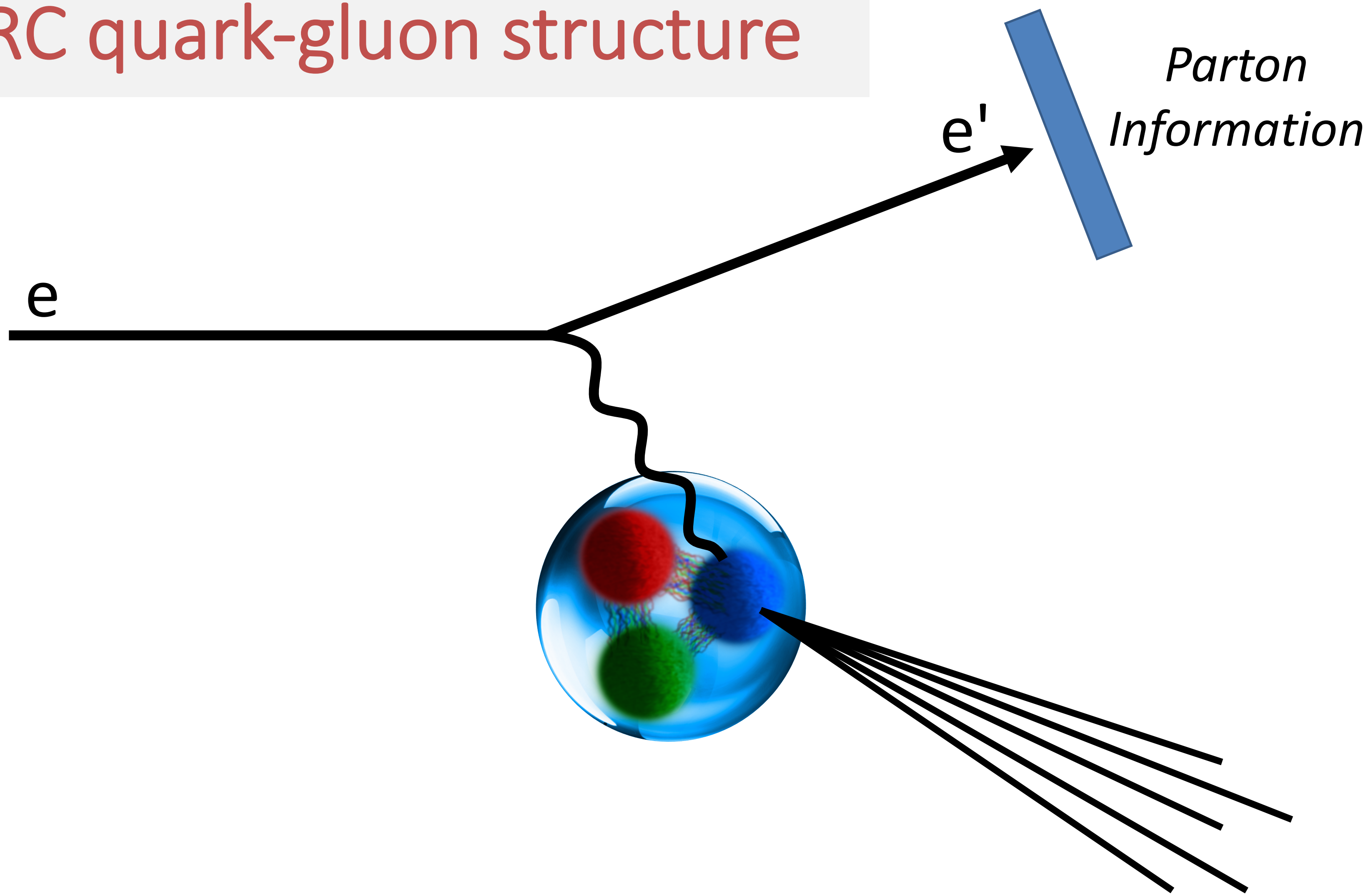

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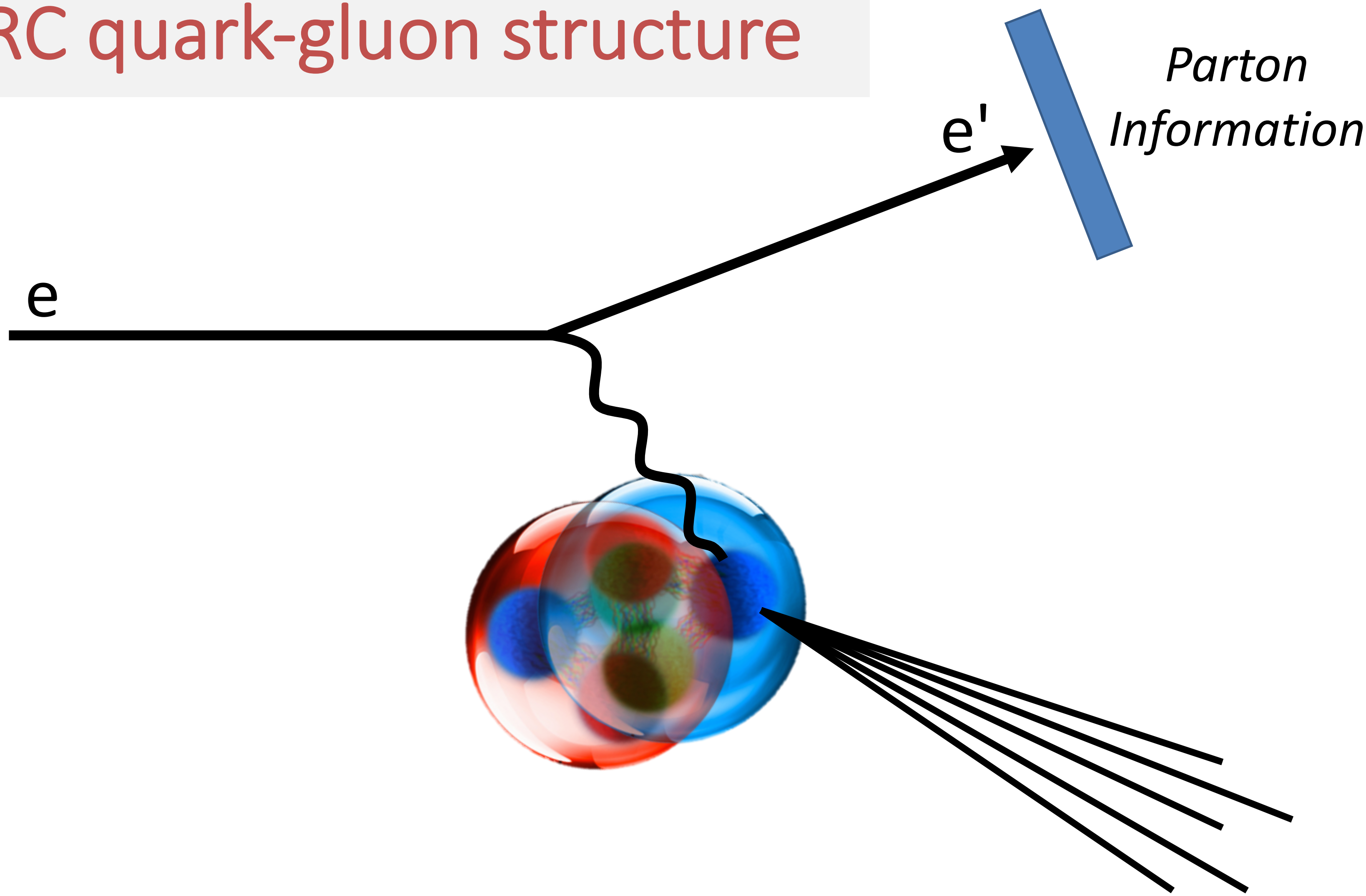
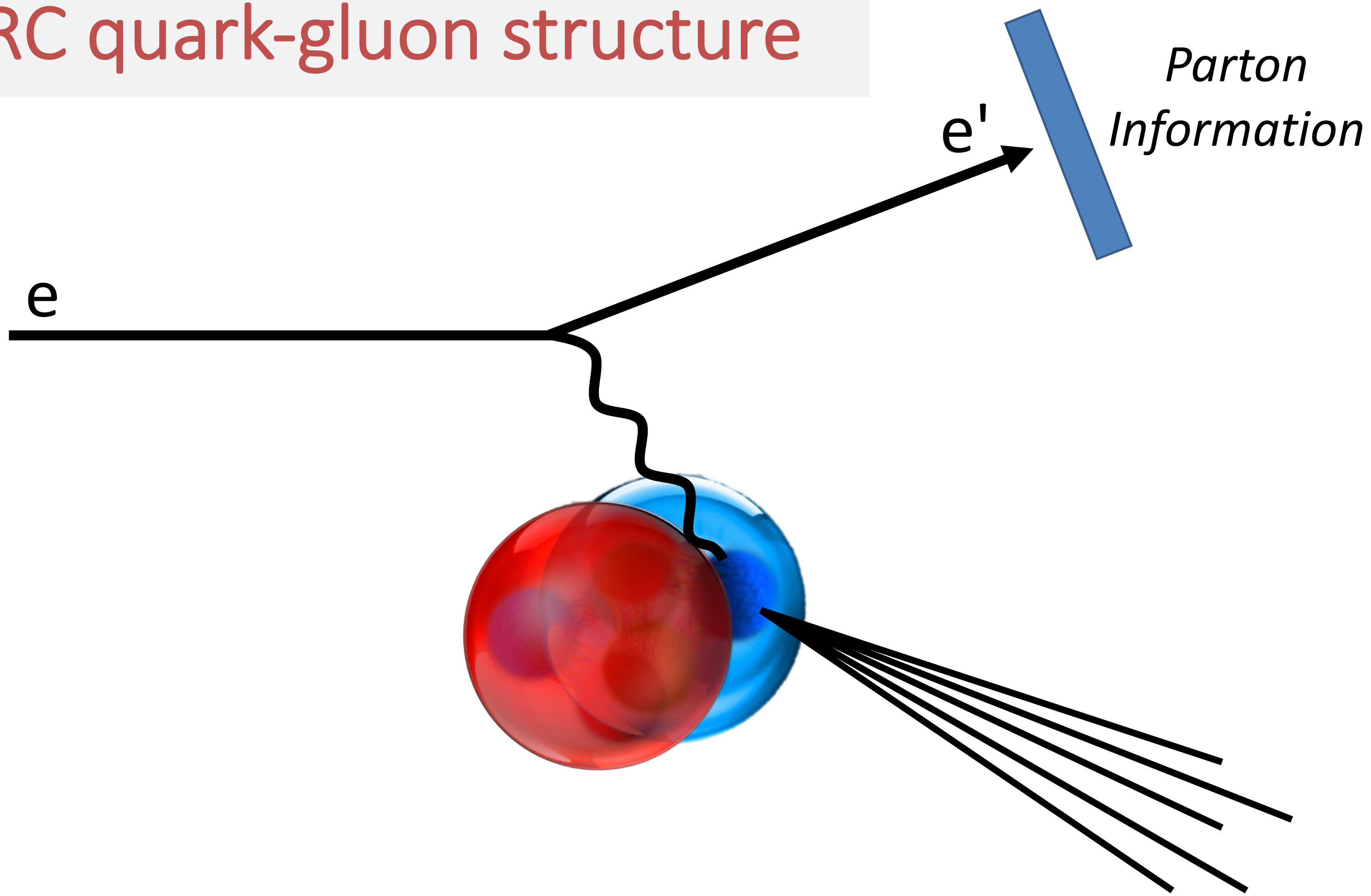
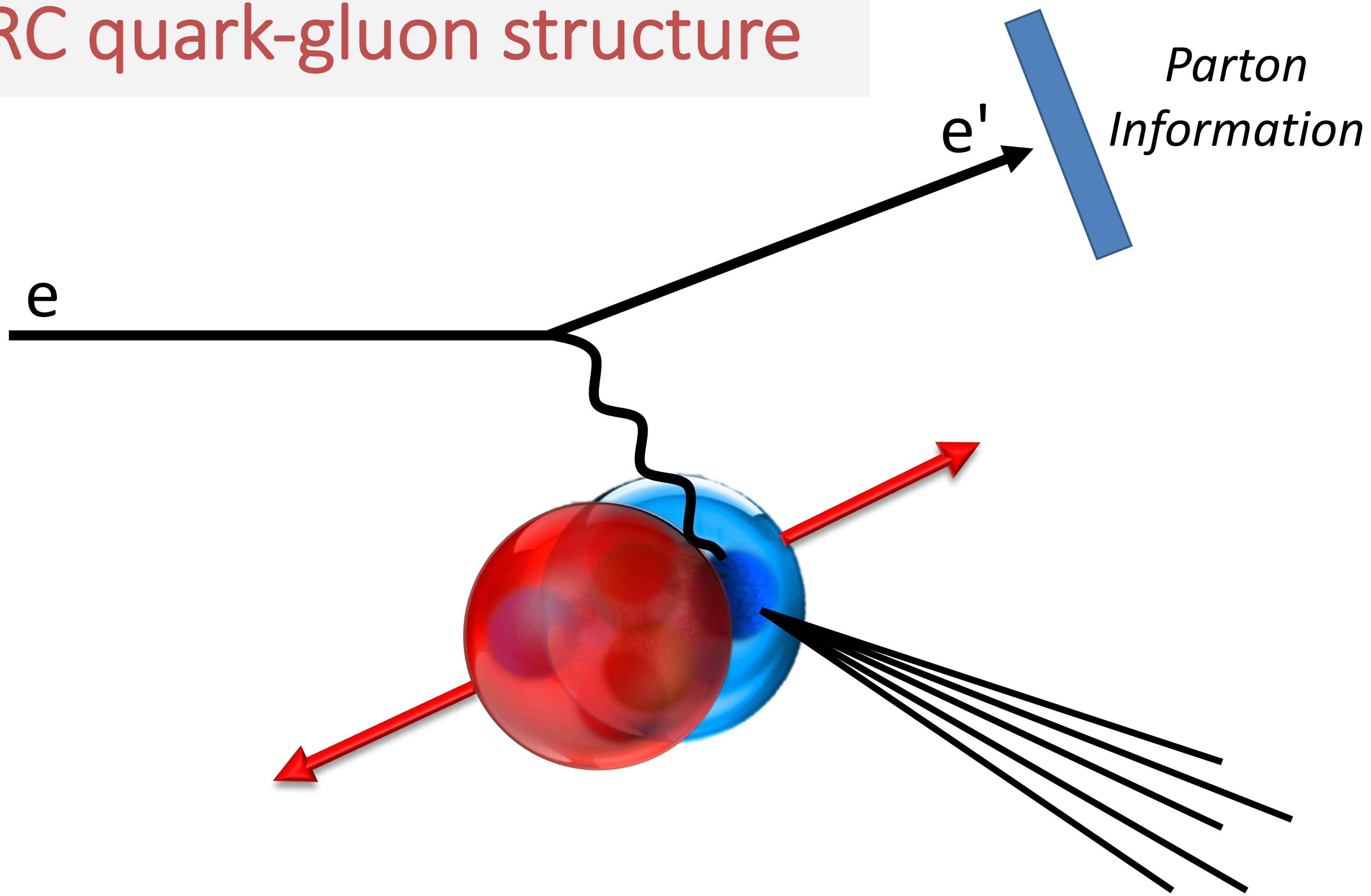


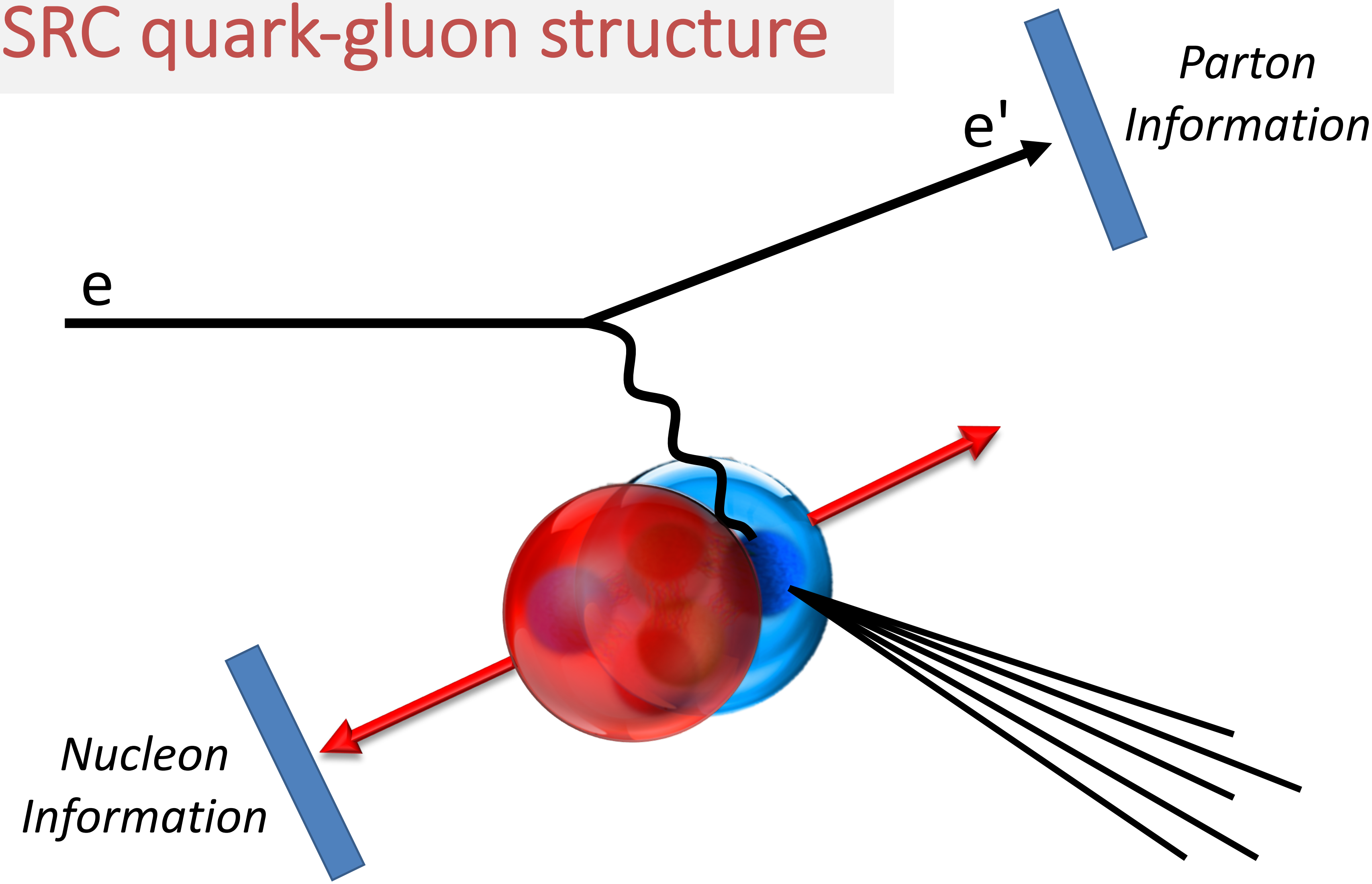
SRC quark-gluon structure



SRC quark-gluon structure



SRC quark-gluon structure



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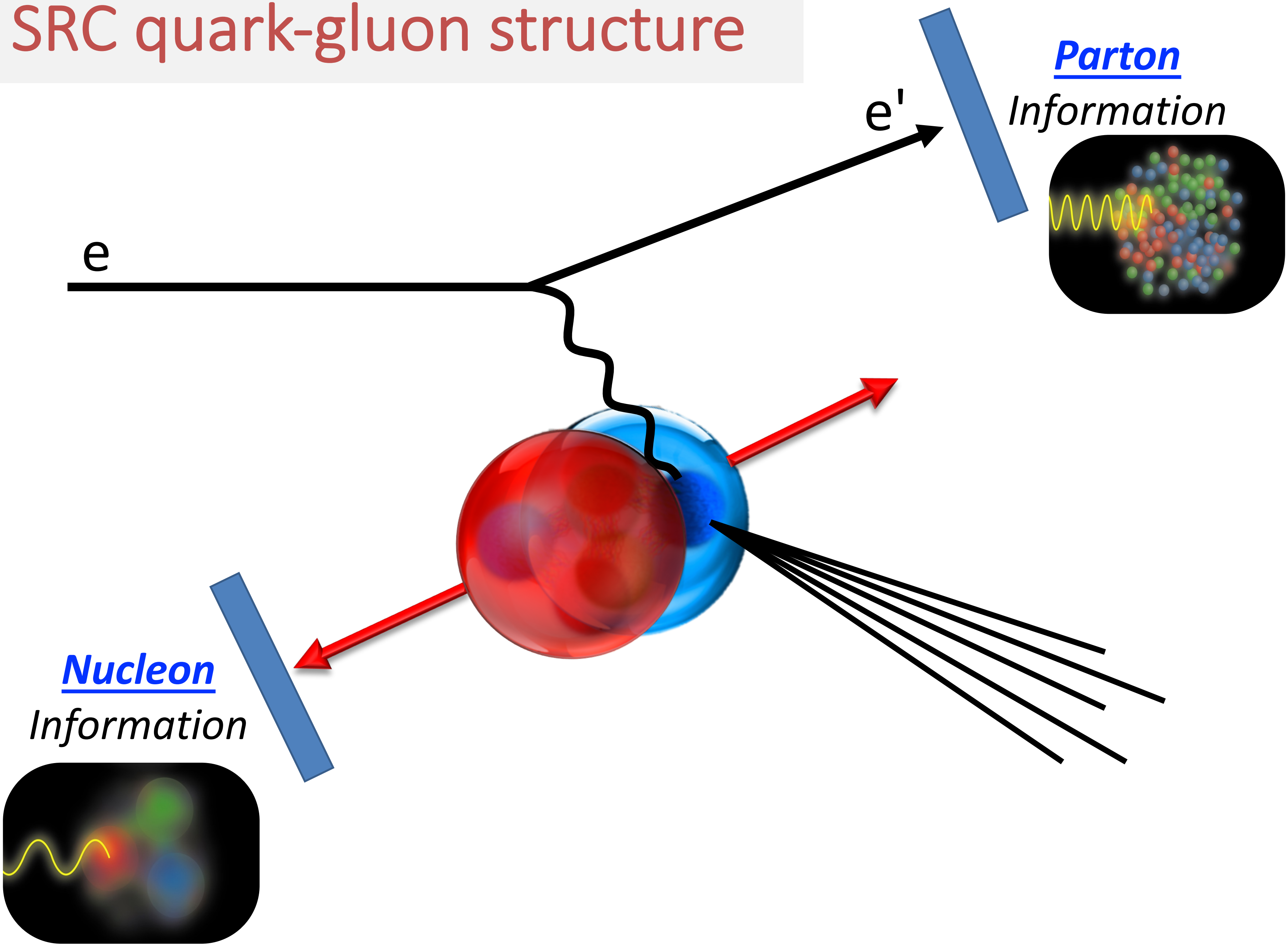
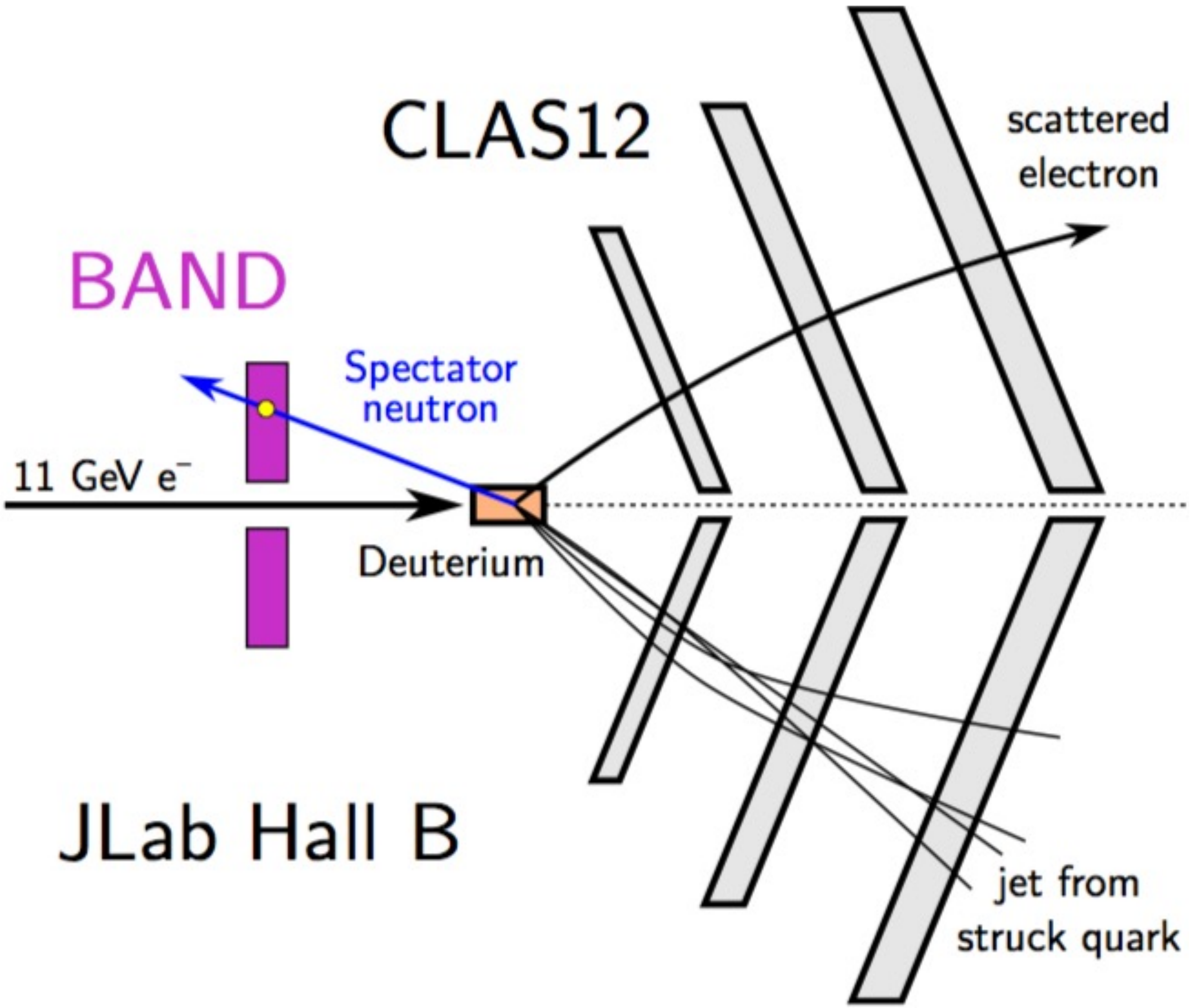
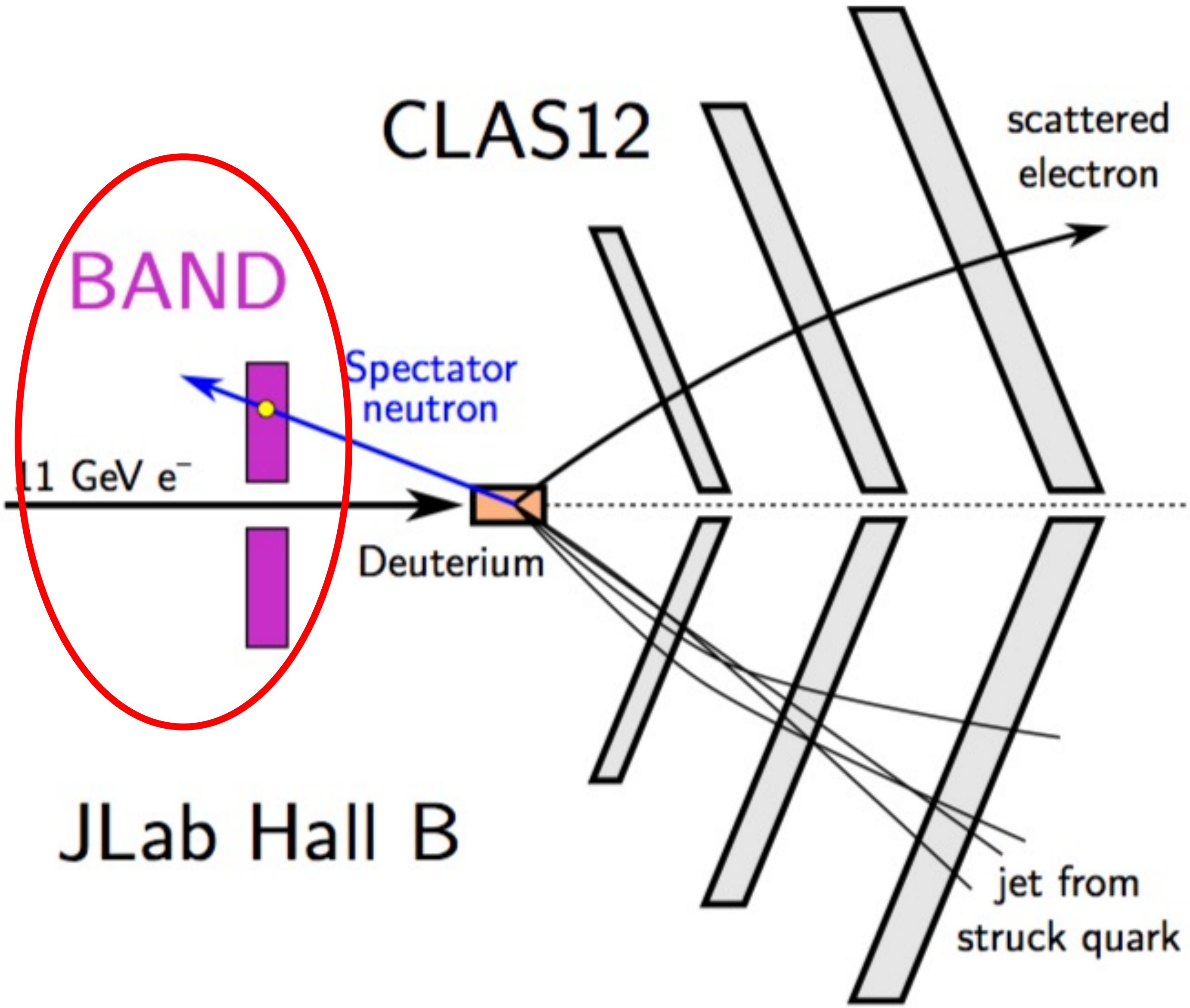



CLAS12
scattered
electron
BAND
Spectator
neutron
11 GeV e⁻
Deuterium
JLab Hall B
jet from
struck quark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Massachusetts Institute of Technology

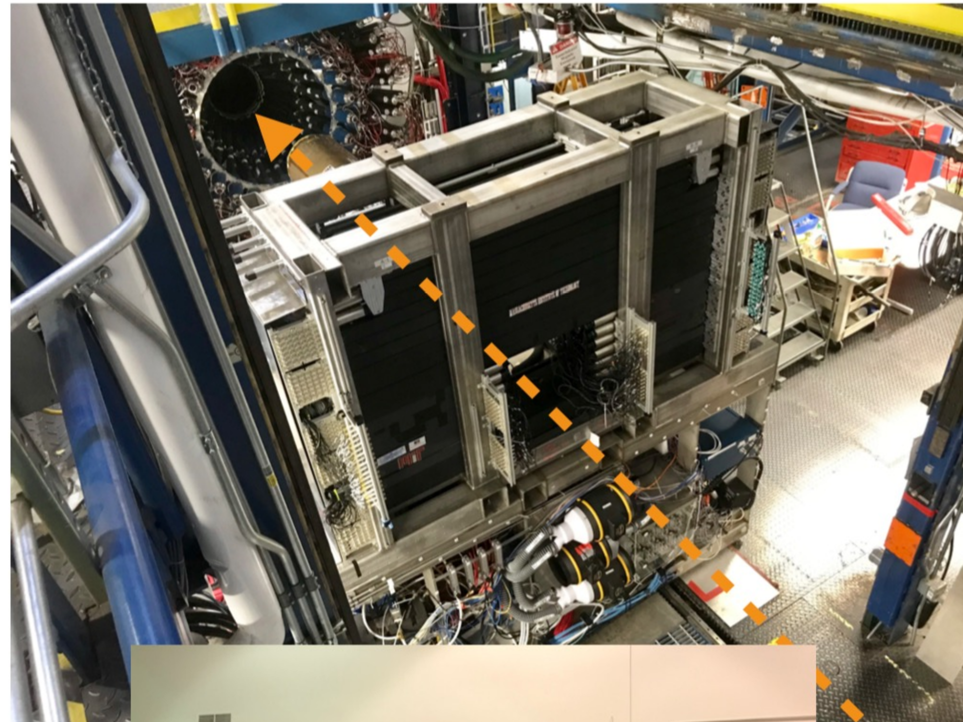
UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

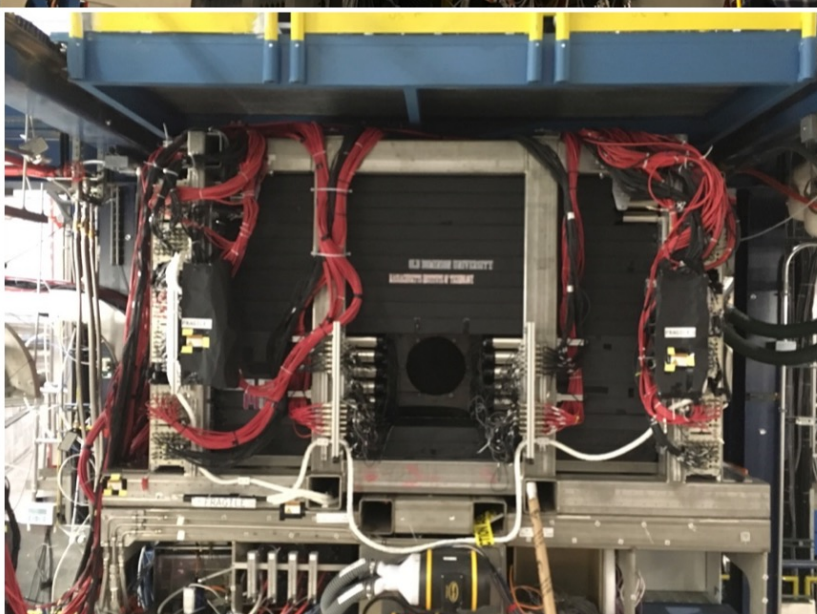
OLD DOMINION UNIVERSITY

TEL AVIV UNIVERSITY

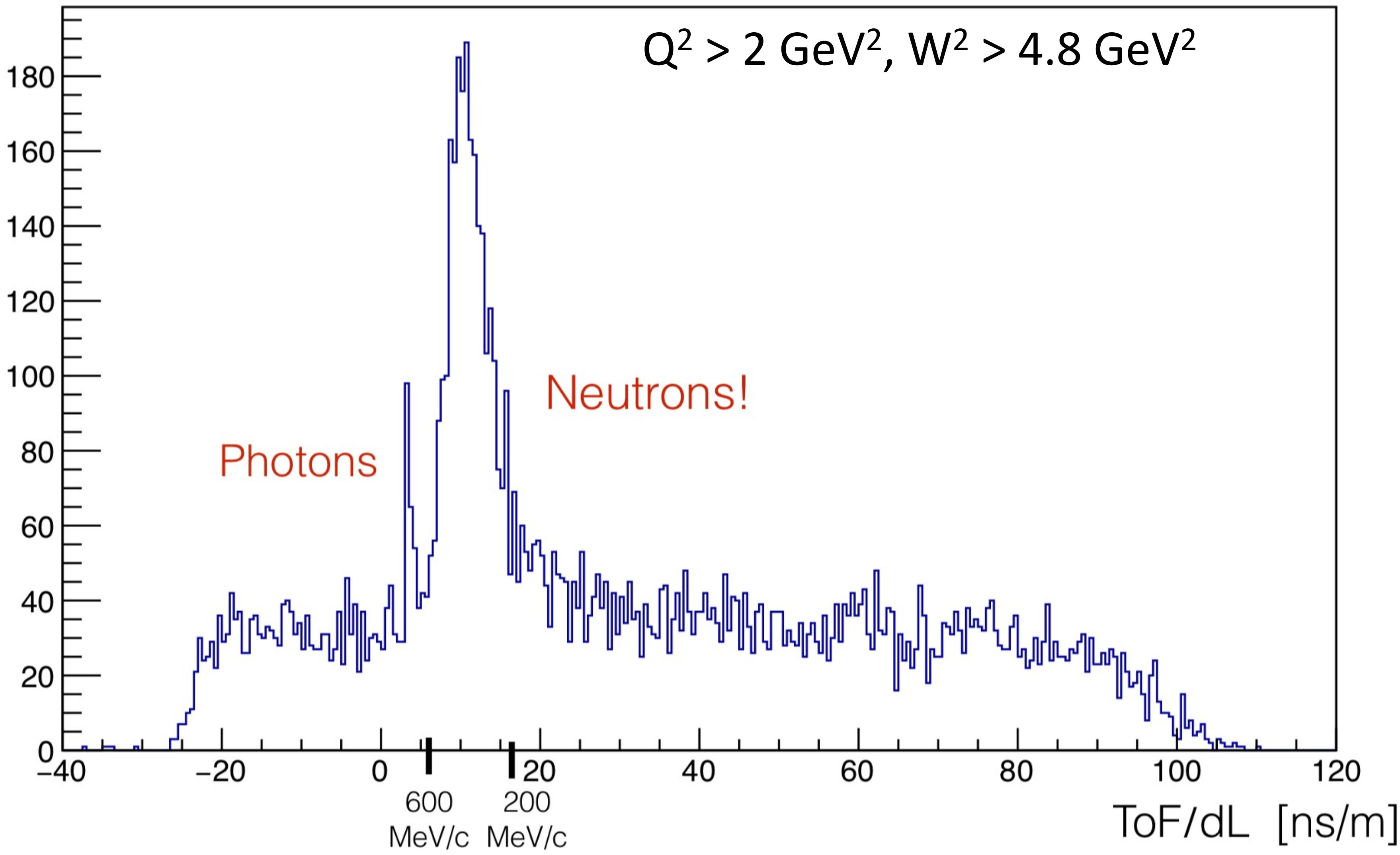

The 3rd Annual
Harvard-Yale
Blood Drive Challenge 2007
American Red Cross
GREEN SPOT

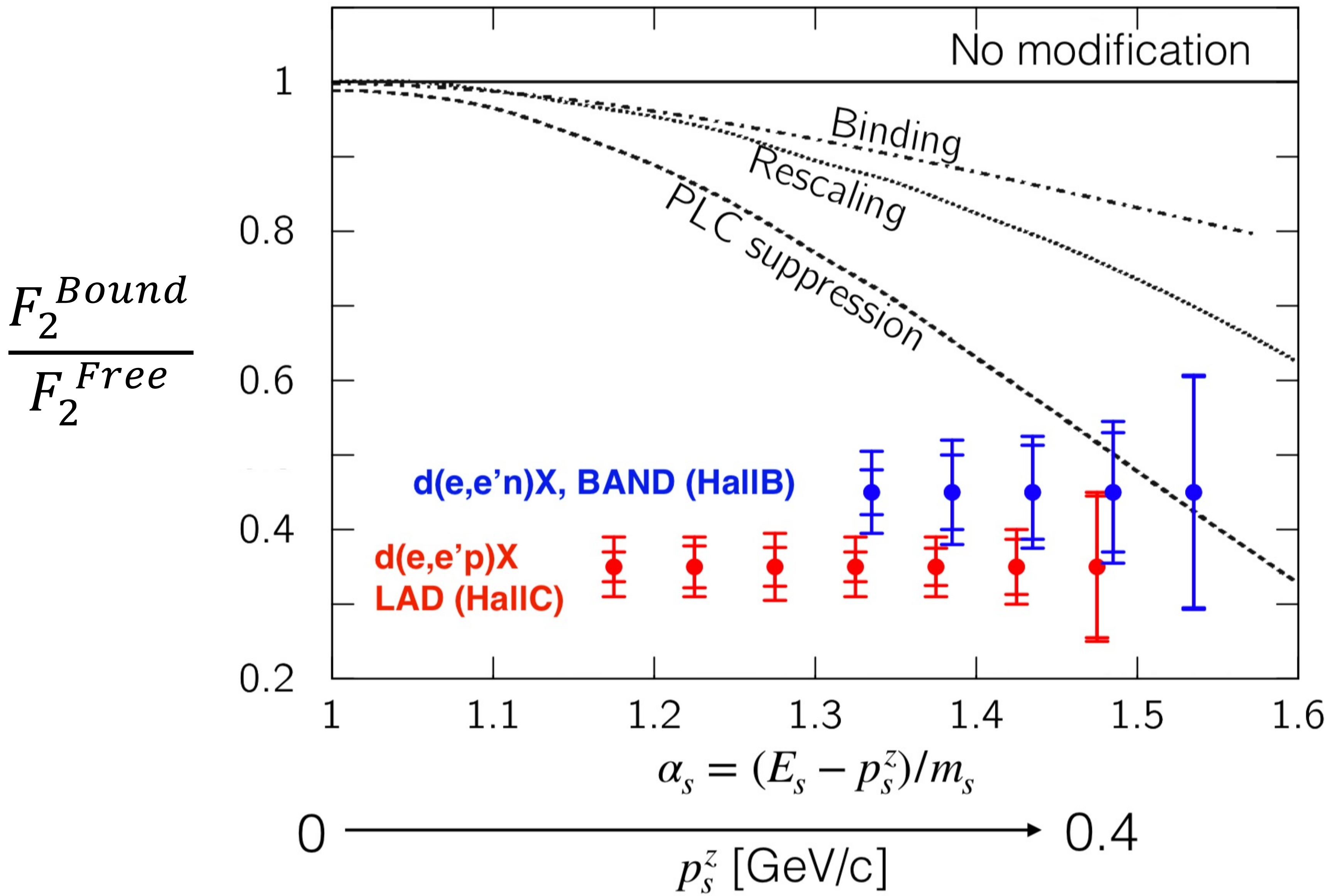
BAND @ JLab Hall B





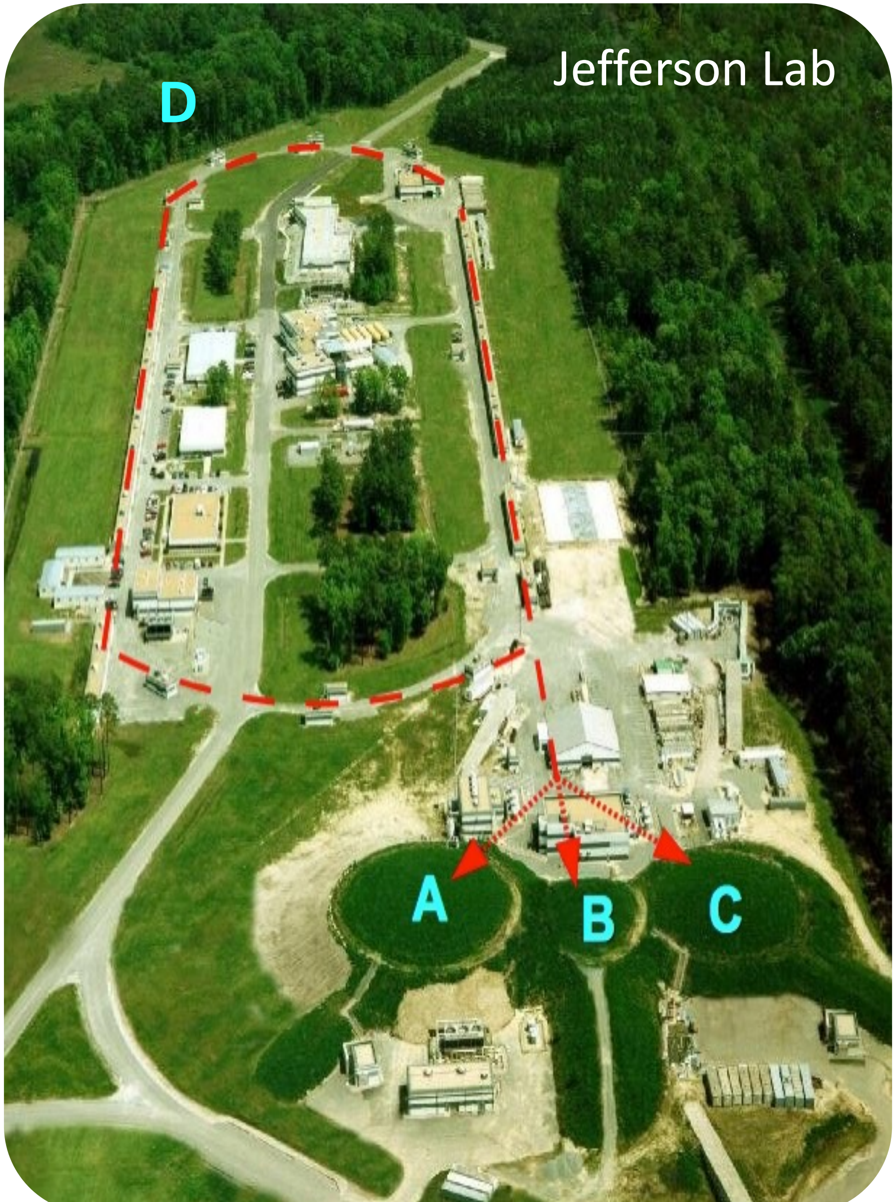
CLAS12+BAND: DIS \w Tagged Neutrons!!

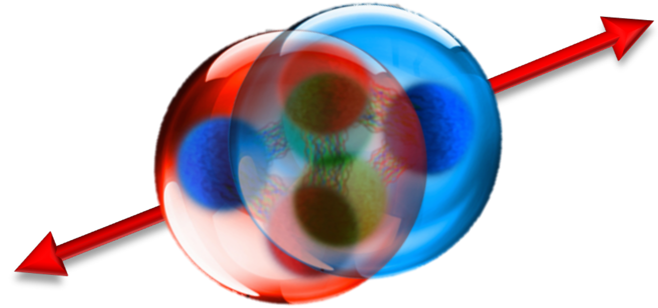


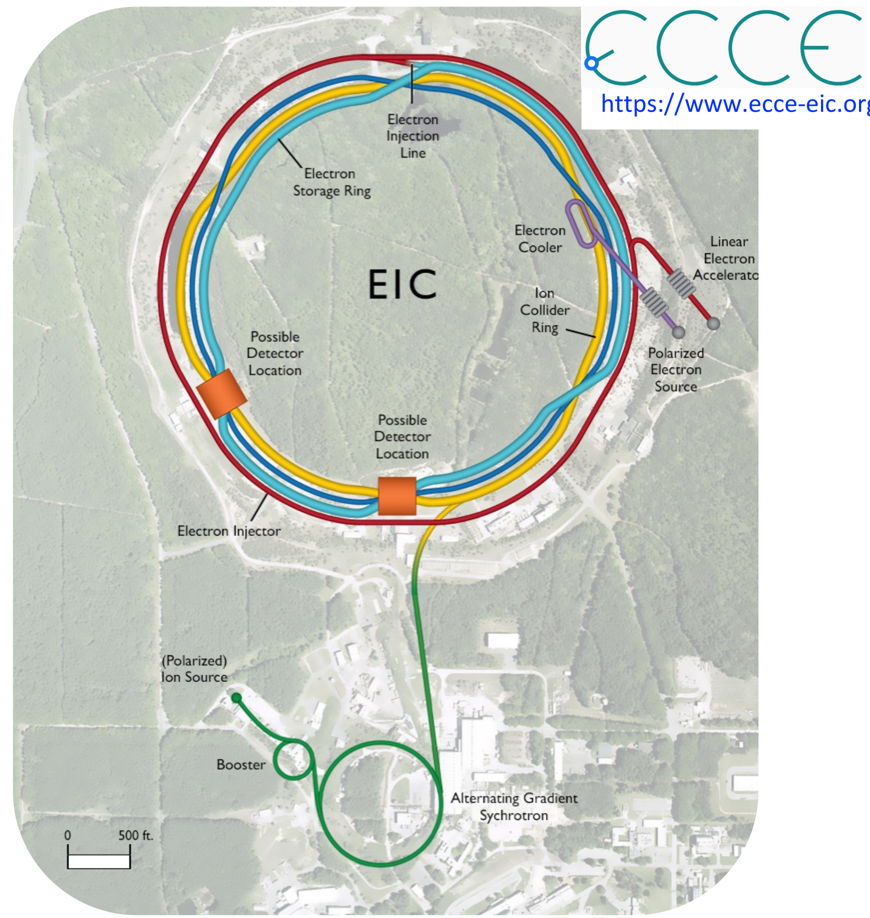


$\frac{F_2^{Bound}}{F_2^{Free}}$
No modification
Binding
Rescaling
PLC suppression
d(e,e'n)X, BAND (HallB)
d(e,e'p)X
LAD (HallC)
1
0.8
0.6
0.4
0.2
1
1.1
1.2
1.3
1.4
1.5
1.6
$\alpha_s = (E_s - p_s^z)/m_s$
0
0.4
p_s^z [GeV/c]

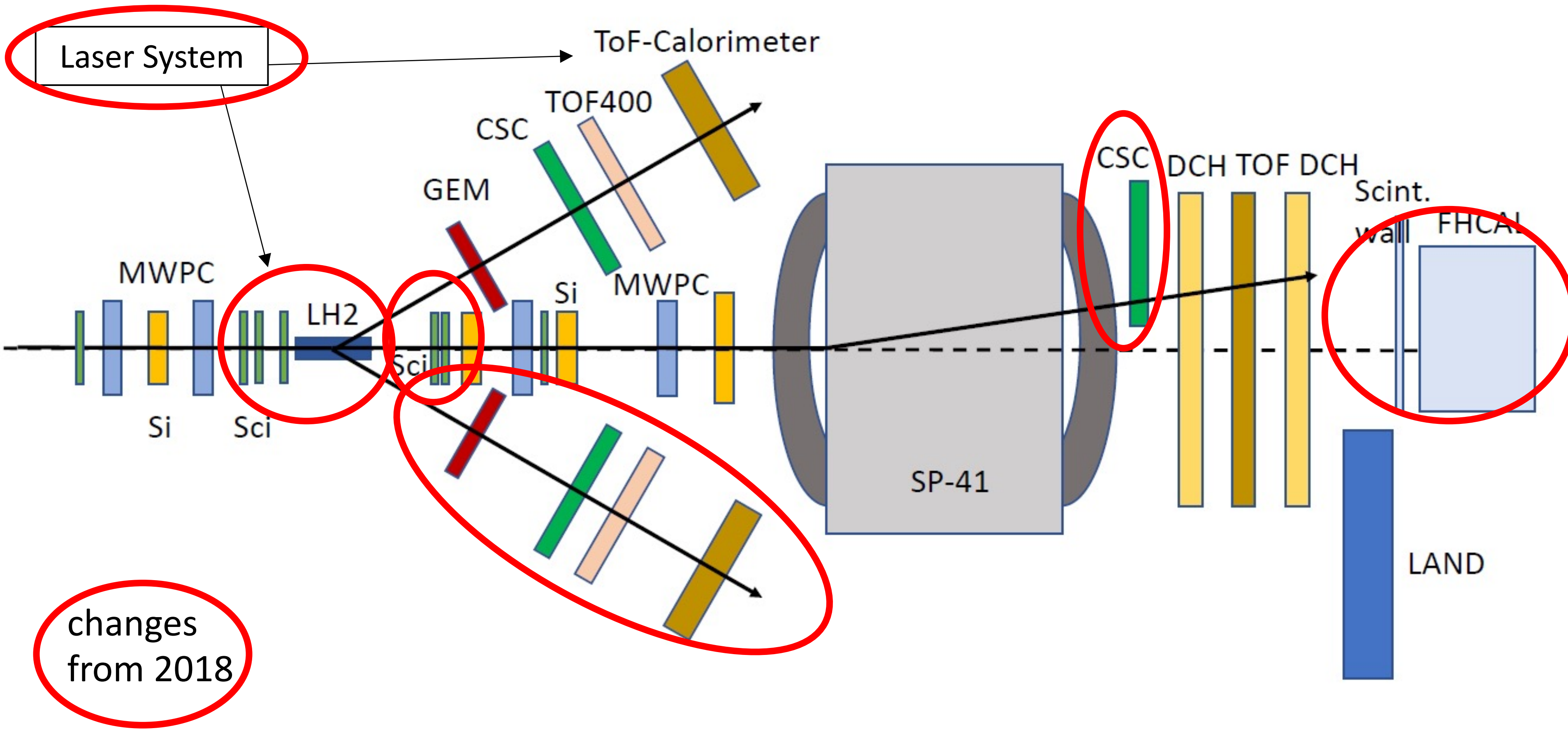
Next Steps in SRC studies \w electrons







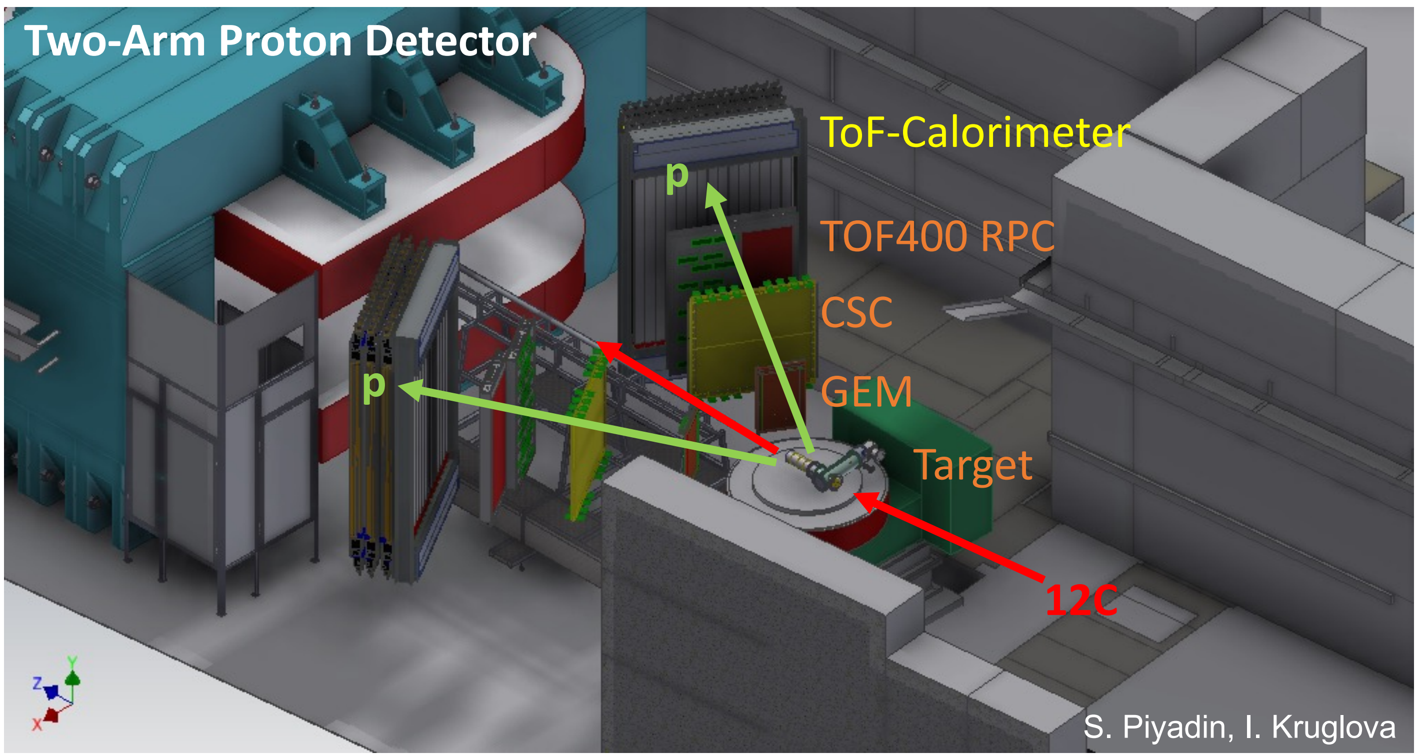
JINR 2021: New Setup

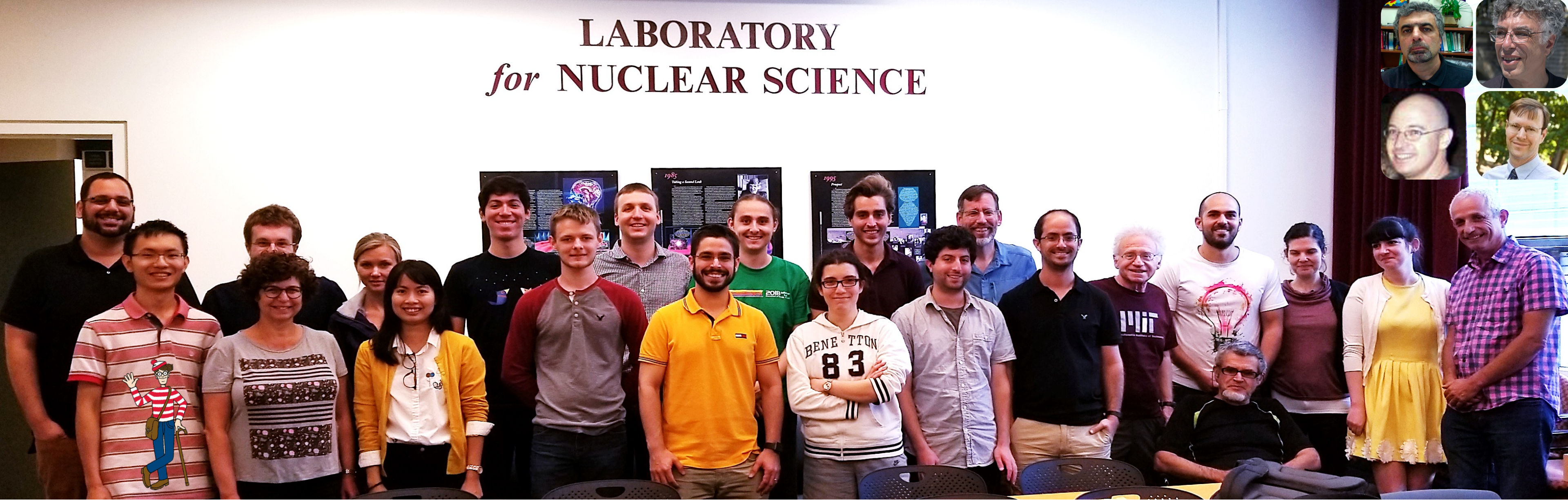


$^{12}C(p,2p)X$ at 3.5 GeV/c/u

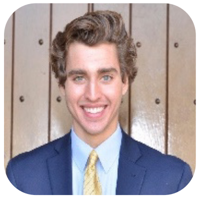
- increased statistics: x20
- improved missing-momentum resolution (60 -> 25 MeV/c)
- direct proton/pion ID
- increased (multi) fragment detection efficiency

$\left.\right\}$ New ToF-Calorimeter






Afroditi Papadopoulou


Efrain Segarra


Jackson Pybus


Andrew Denniston


Hang Qi


Natalie Wright


Dr. Justin Estee


Dr. Tyler Kutz


Dr. Natalie Santiestebn


Dr. Florian Hauenstein


Dr. Julian Kahlbow


Dr. Igor Korover

Thank You!