PREX, CREX and Short-Range Correlations

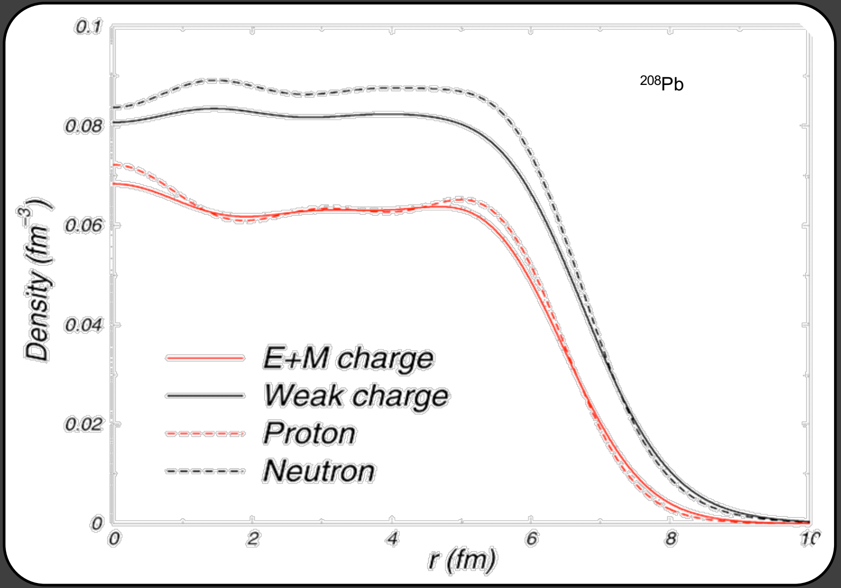
Or Hen

Low-Energy Nuclear Physics Community
Town Meeting, ANL, November 14th (2022)

PREX-2 and CREX : Neutron Skin in ^{208}Pb and ^{48}Ca

Nuclear theory predicts a neutron "skin" on heavy nuclei

Very clean interpretation makes this a crucial calibration for equation-of-state of heavy, neutron rich nuclei



At the measured Q^2, Fw is primarily sensitive to the density dependence of the nuclear equation of state

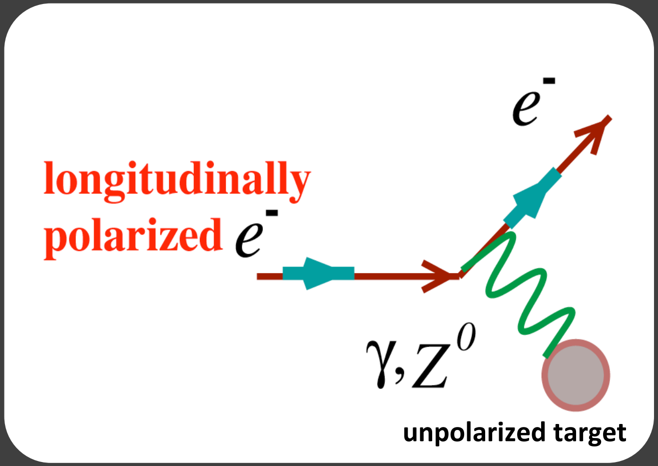
PREX-2 and CREX : Neutron Skin in ^{208}Pb and ^{48}Ca

Electron Scattering: γ vs Z^0

$$\frac{d\sigma}{d\theta dE} \Leftrightarrow F_{\text{ch}}(Q^2)$$

$$A_{\text{PV}} \Leftrightarrow F_{\text{W}}(Q^2)$$

parity-violating asymmetry



$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z F_{\text{ch}}(Q^2)}$$

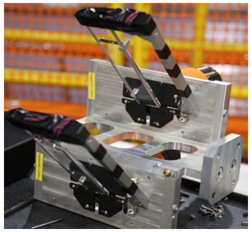
F_{W} - F_{ch} : negligible model dependence

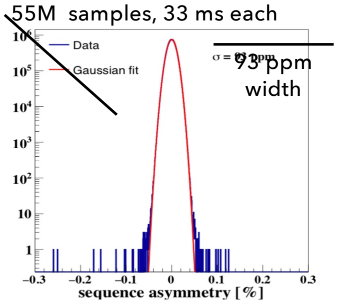
+ well-known R_{ch} and ρ shape model

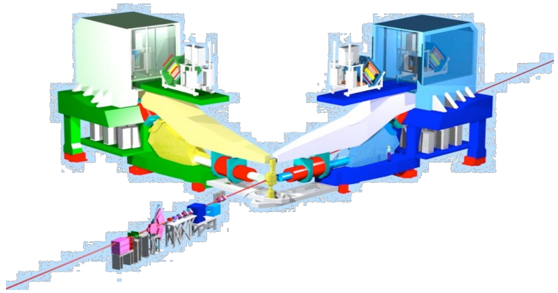
$\longrightarrow R_{\text{W}},\ R_{\text{n}},\ R_{\text{n}} - R_{\text{p}},\ \rho_0^{\text{W}}$

Challenging Measurement!

- High luminosity, >4 GHz detected rate (PREX-2)
- Precise calibration & polarimetry
- Careful control of beam asymmetries, backgrounds, noise, false ...asymmetries





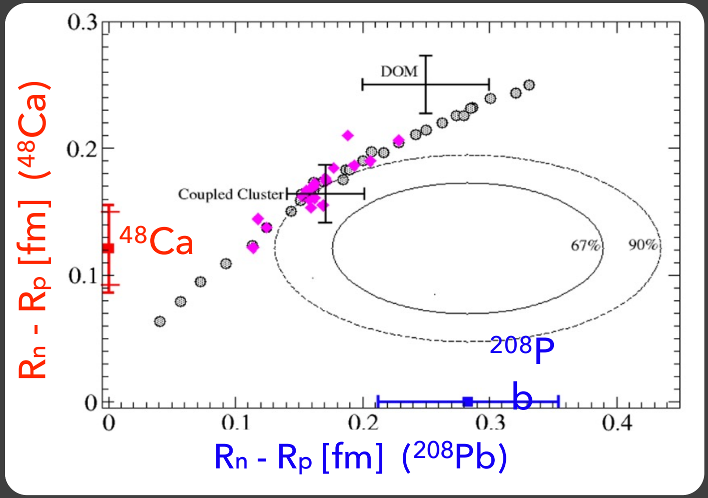


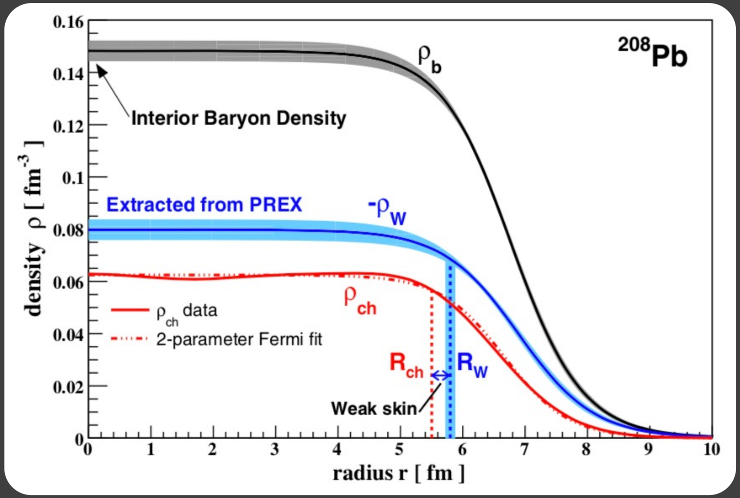
PRL 126, 172502 (2021)
PRL 129, 042501 (2022)

^{208}Pb and ^{48}Ca Results

PREX-2: ^{208}Pb A_{PV} = 550 ± 16 (stat) ± 8 (syst) ppb
CREX: ^{48}Ca A_{PV} = 2668 ± 106 (stat) ± 40 (syst) ppb

Determine neutron skins with small model dependence:
PREX: ^{208}Pb $R_n - R_p$ = **0.278 fm** ± 0.071 (exp) ± 0.012 (model)
CREX: ^{48}Ca $R_n - R_p$ = **0.121 fm** ± 0.026 (exp) ± 0.024 (model)



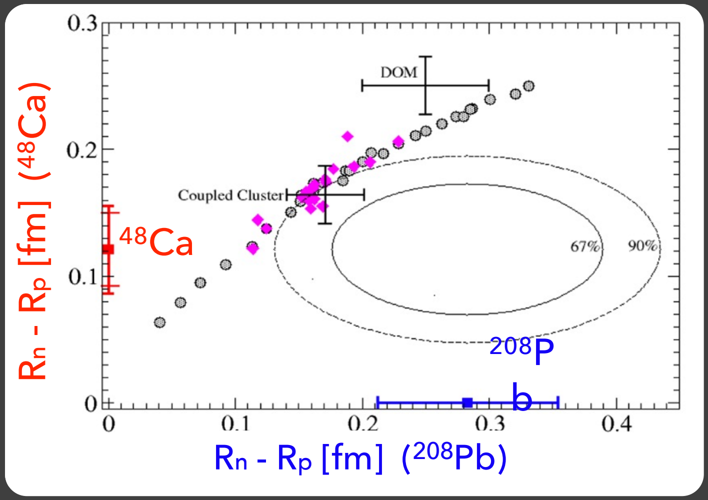


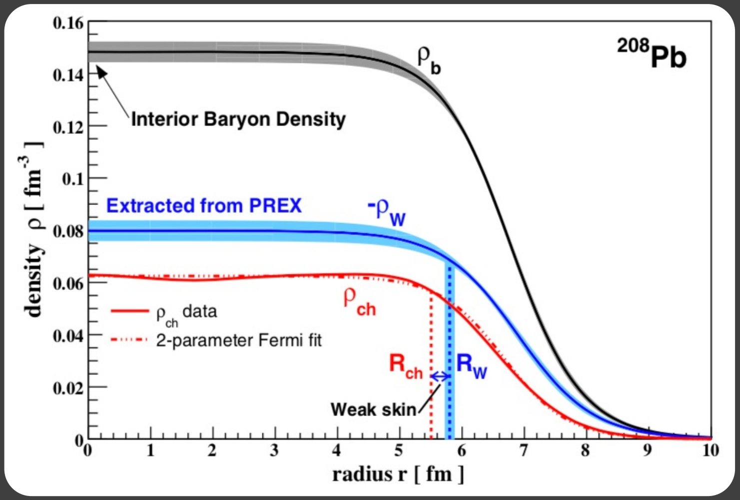
^{208}Pb and ^{48}Ca Results

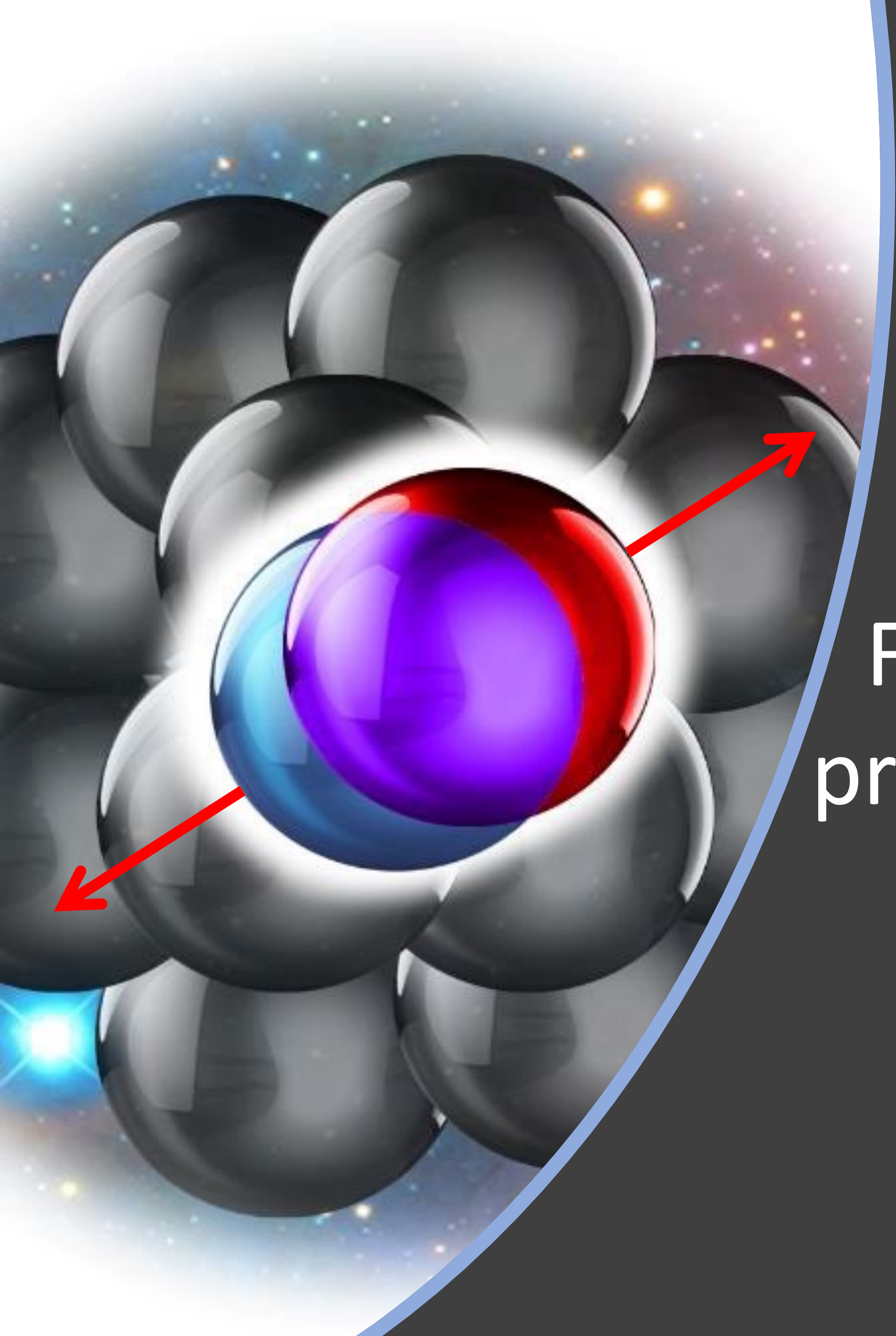
PREX indicate a large skin, with low nuclear baryon density ρ_b
CREX indicate a smaller skin than most models

Generally, models expect both skins large or both small;
The results presents an important empirical test

Unique, valuable contribution to the nuclear structure data set, as a cleanly interpretable measurement of an isovector nuclear property



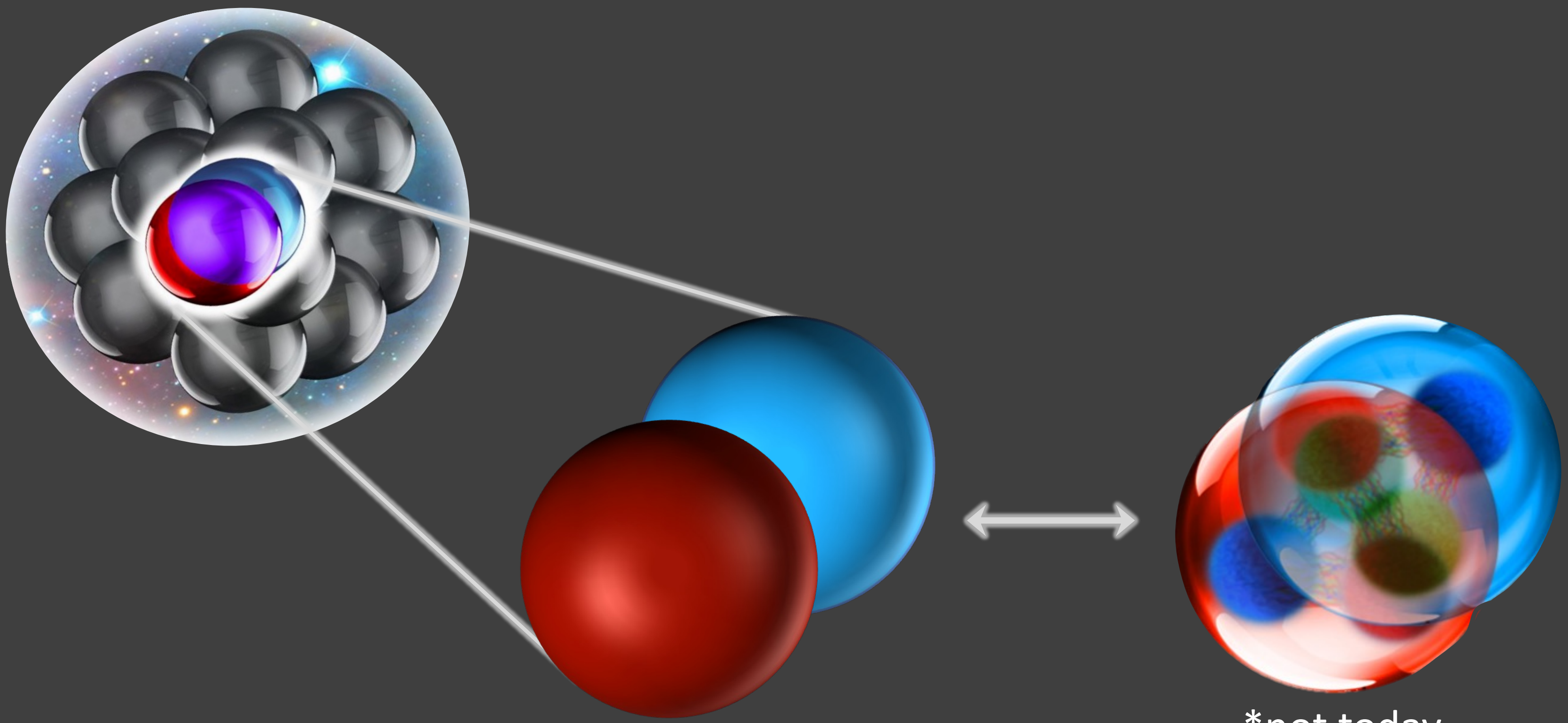




Short-Range Correlations (SRC)

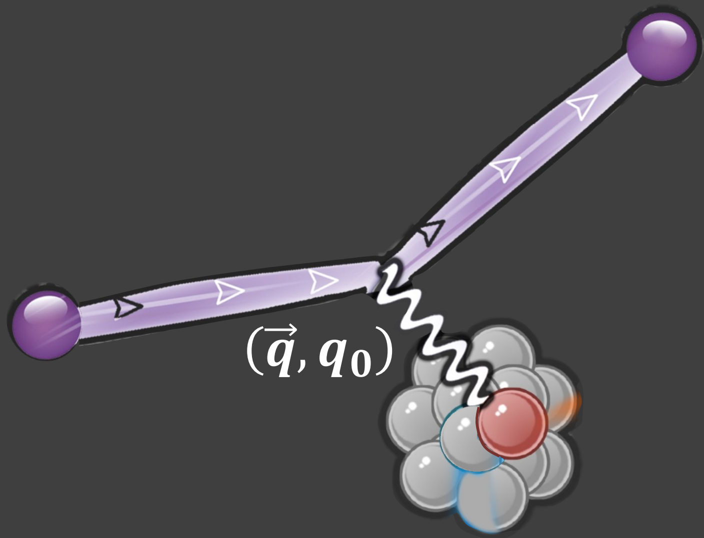
Fluctuations of close-proximity nucleon pairs

SRCs Across Nuclear Scales



*not today

High Res. Electromagnetic Probe



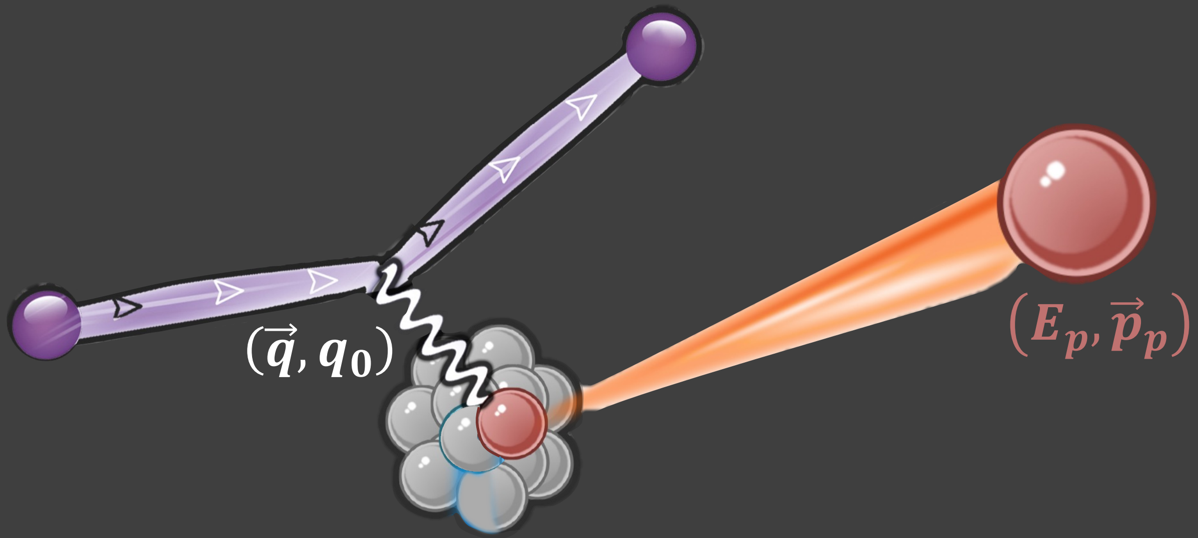
Reaction Scale: $Q^2 = |\vec{q}|^2 - q_0^2$

Reaction scale >> Nuclear energy scale

$$Q^2 > 1.5 - 2\ GeV^2$$

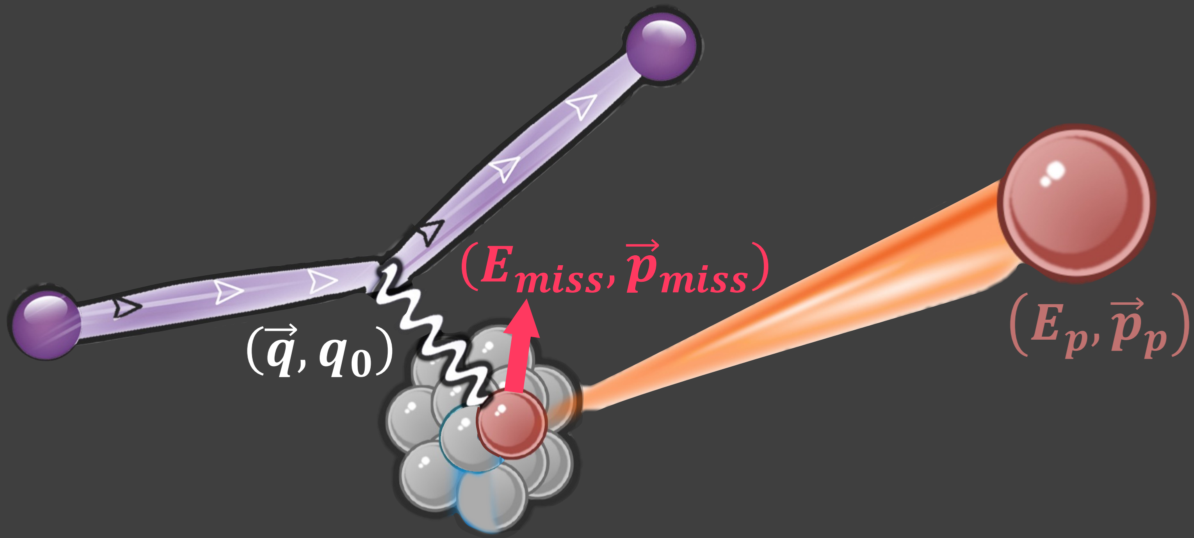
$$(q_0, \vec{q} > 1GeV \gg |V_{NN}|, 2\ k_F)$$

High Res. Electromagnetic Probe



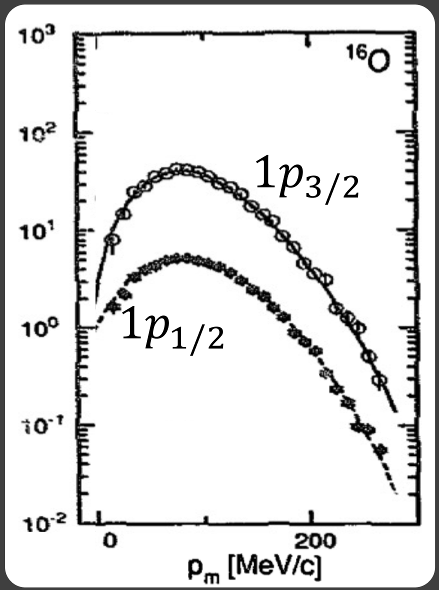
Proton carries large fraction of $(\vec{q}, q_0)$

High Res. Electromagnetic Probe



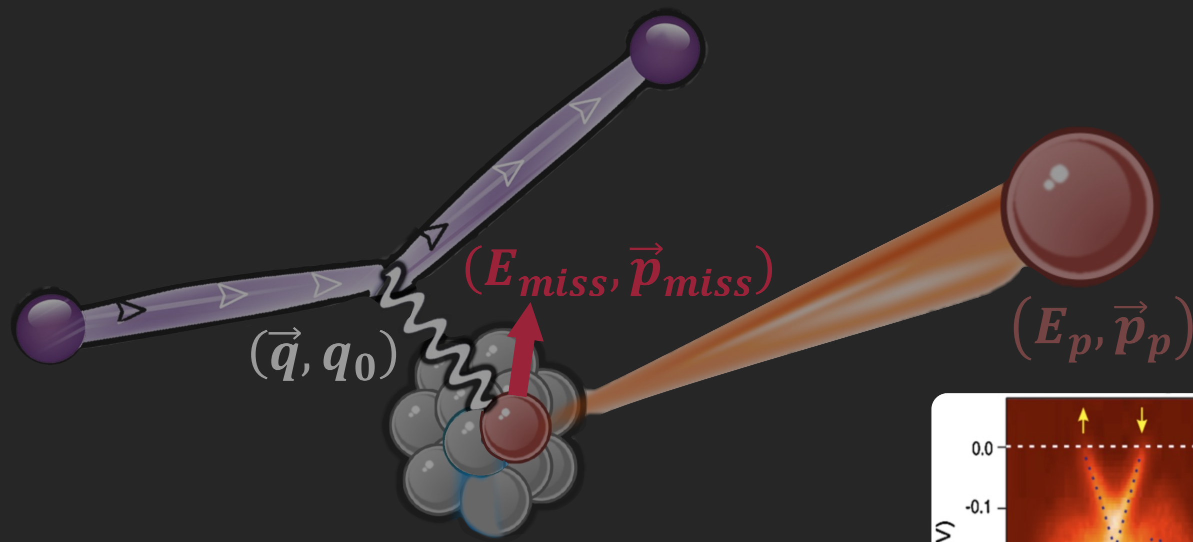
4-Momentum Conservation: $\vec{p}_{miss} = \vec{p}_p - \vec{q}$

$E_{miss} = E_p - q_0$



Lapikas Nuc. Phys. A '93

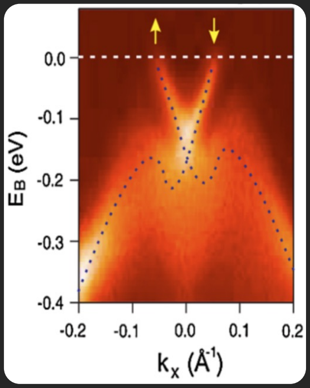
High Res. Electromagnetic Probe



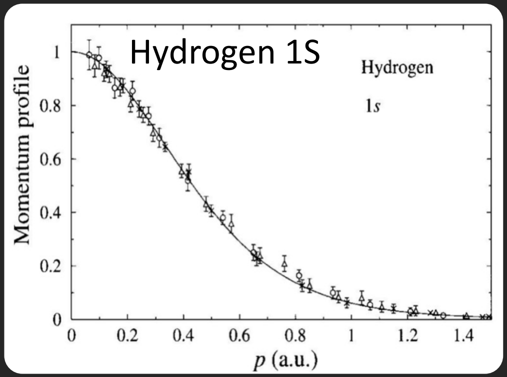
4-Momentum Conservation: $\vec{p}_{miss} = \vec{p}_p - \vec{q}$

$E_{miss} = E_p - q_0$

(γ,e) ARPES: surface state bands (2009)

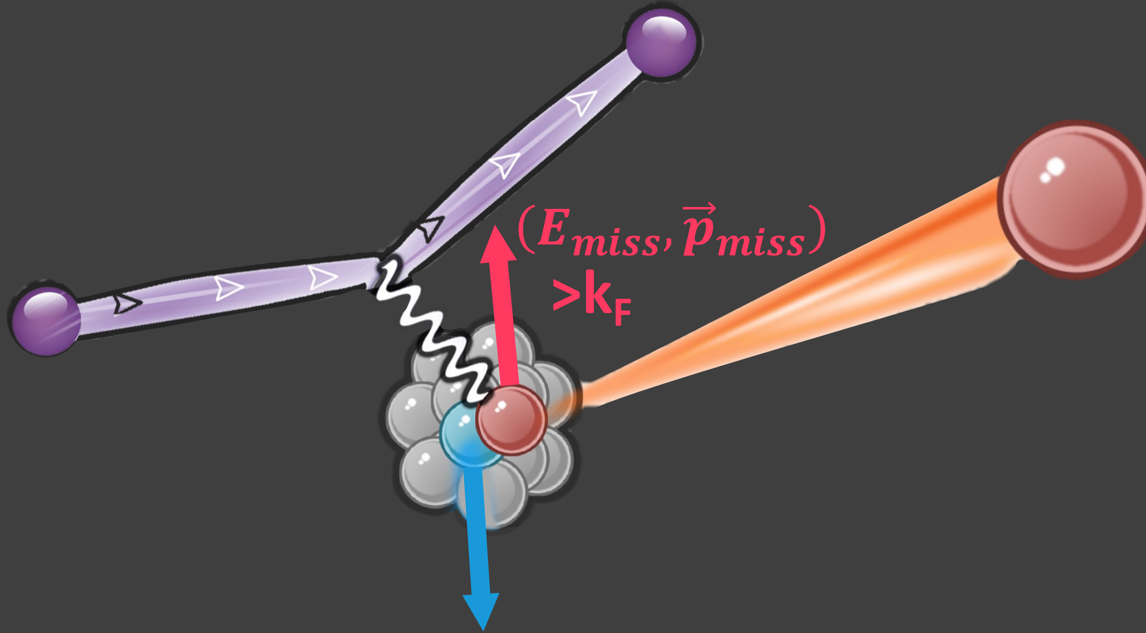


Similar to atomic / condensed matter spectral function extractions

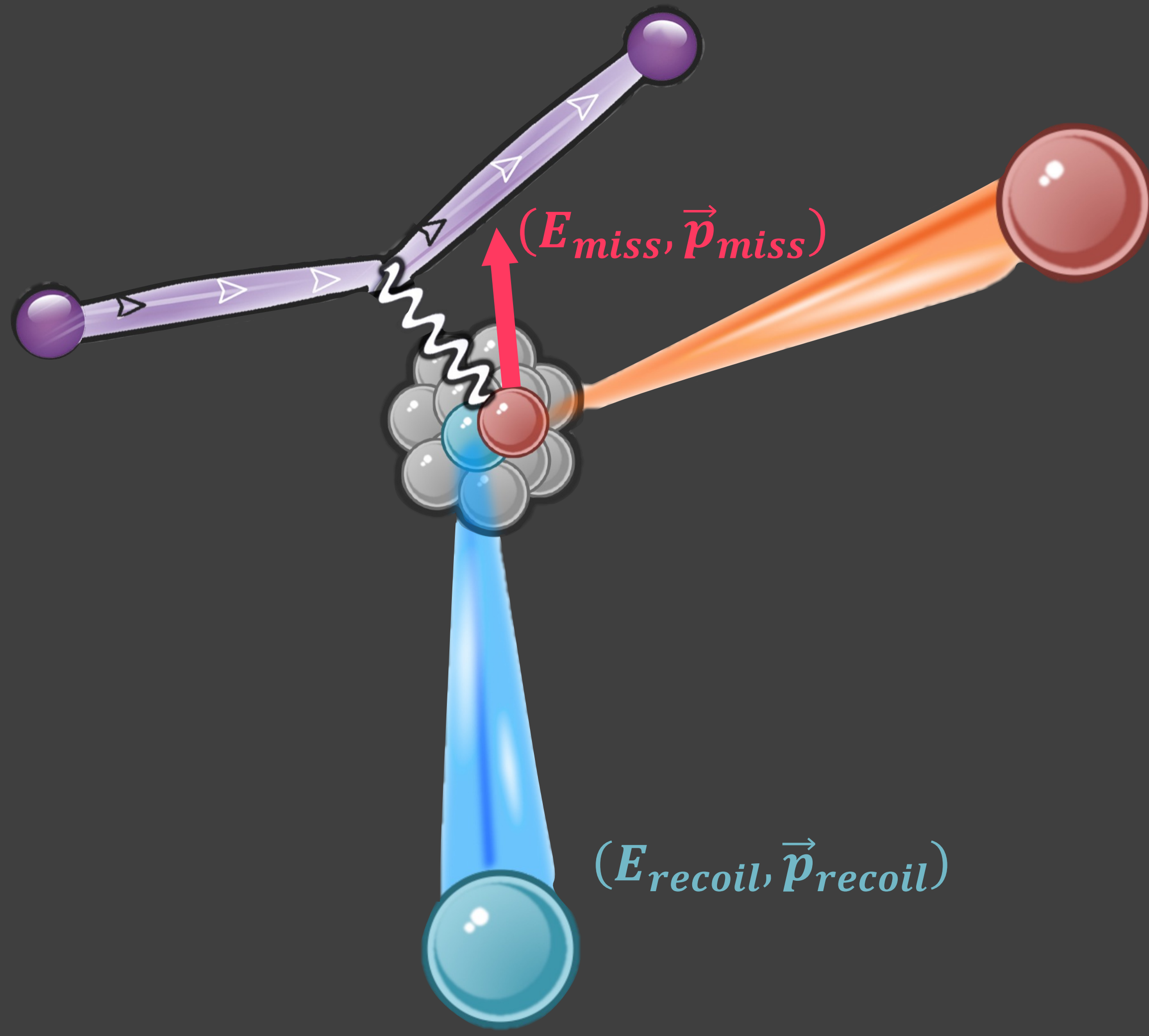


(e,2e) reduced cross-section (1981)

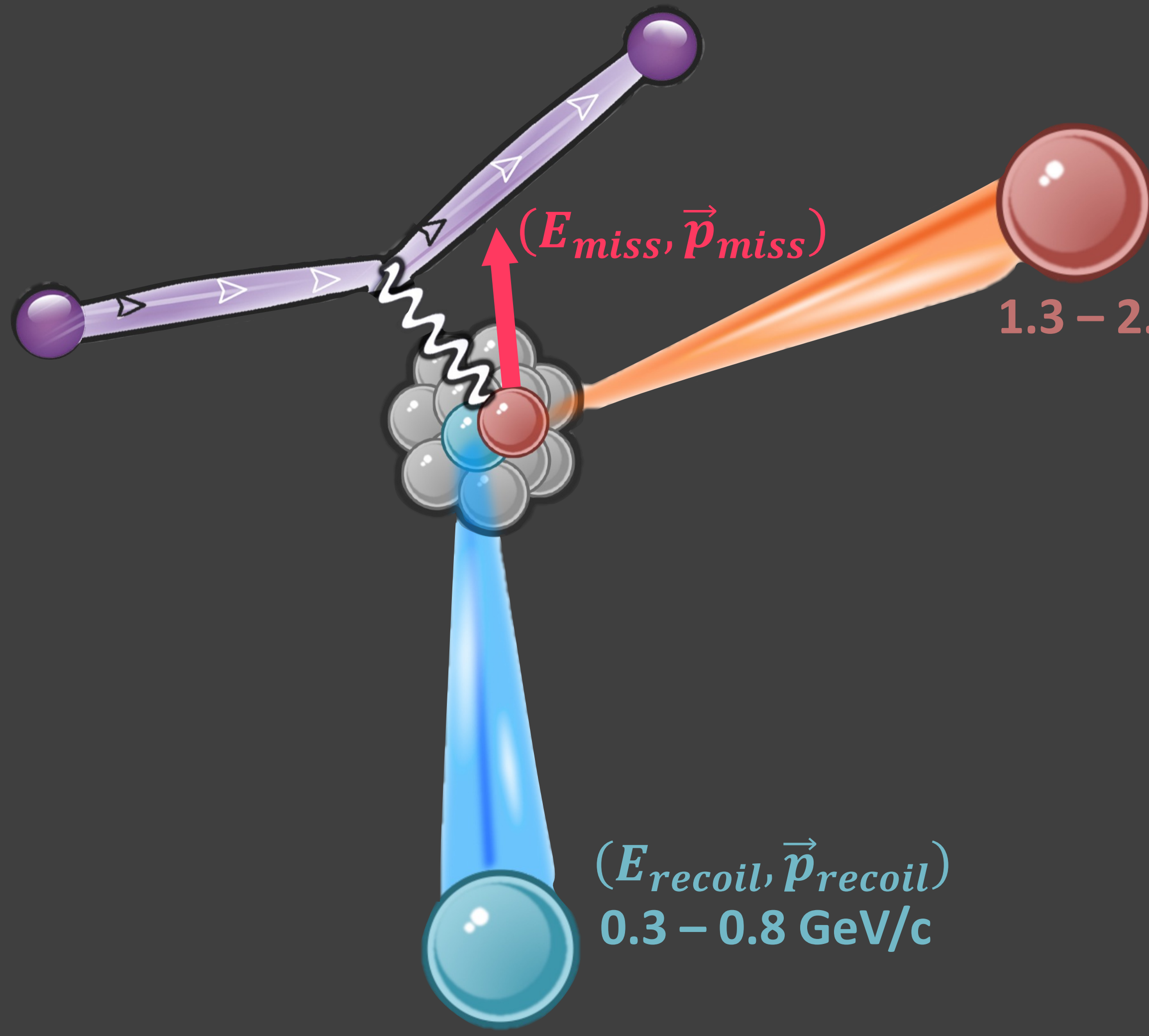
Probing Short-Range Correlations



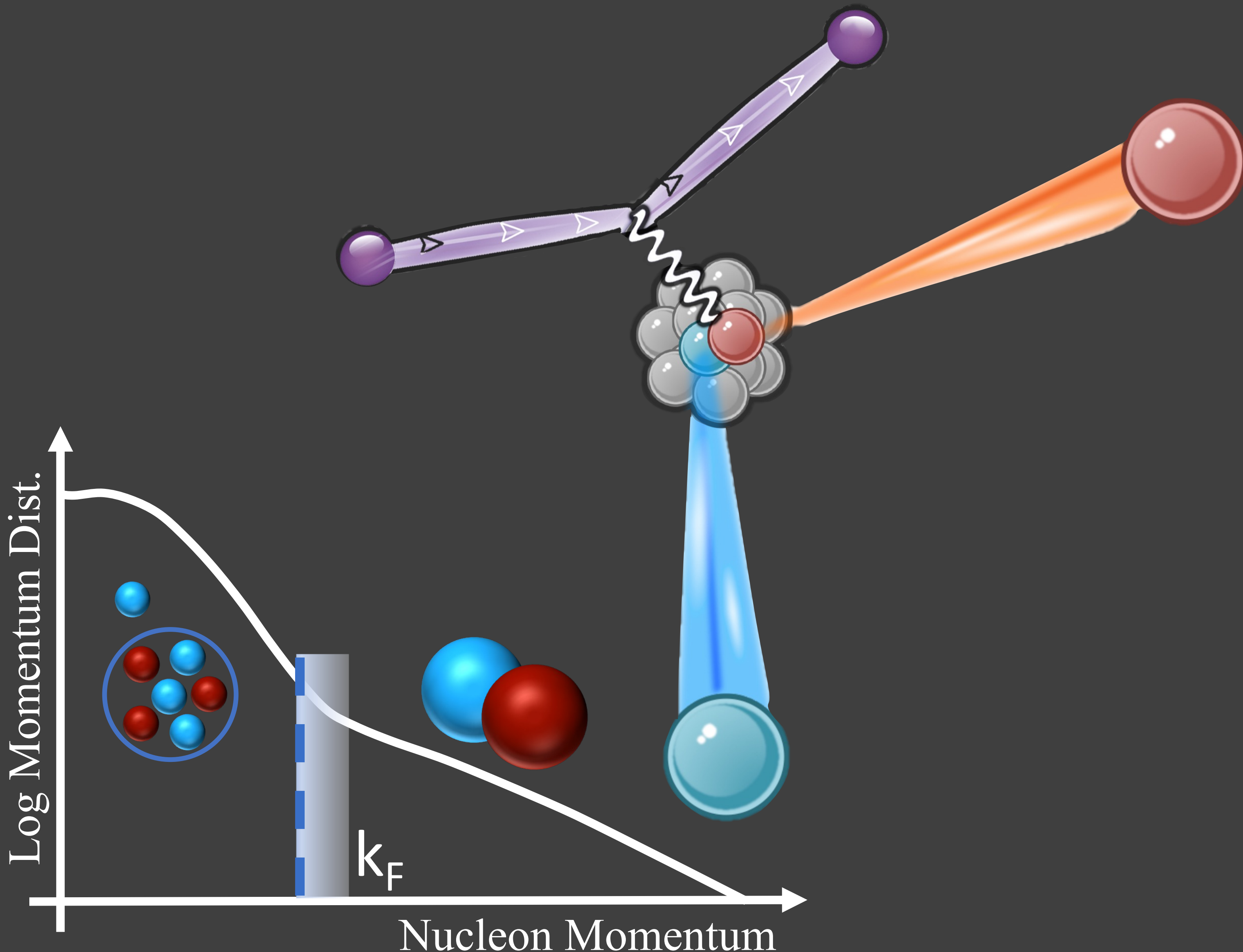
Probing Short-Range Correlations



Probing Short-Range Correlations



Probing Short-Range Correlations



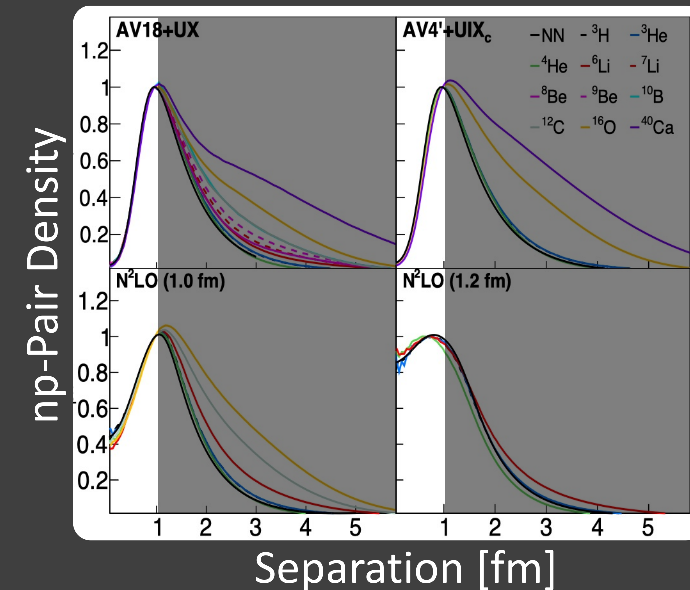
Scale Separation and Factorization

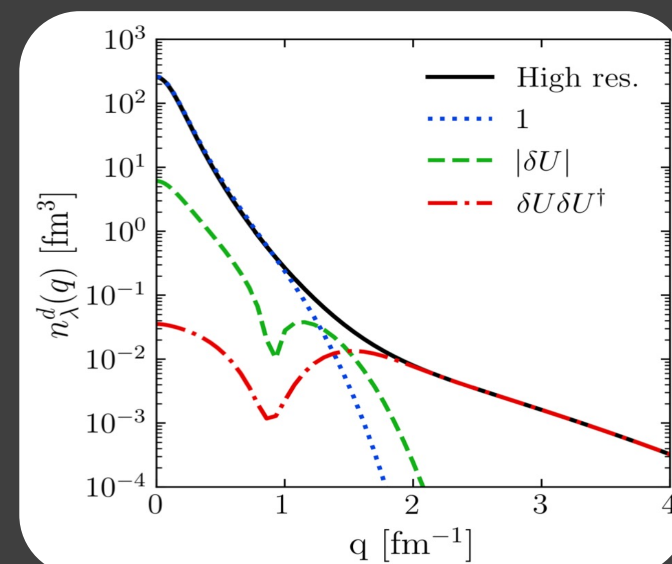
$$\rho_A^{NN,\alpha}(r) \underset{r<1\text{ fm}}{\cong} C_A^{NN,\alpha} \times |\psi_{NN}^{\alpha}(r)|^2$$

Total Dist. = Constant x Two-body

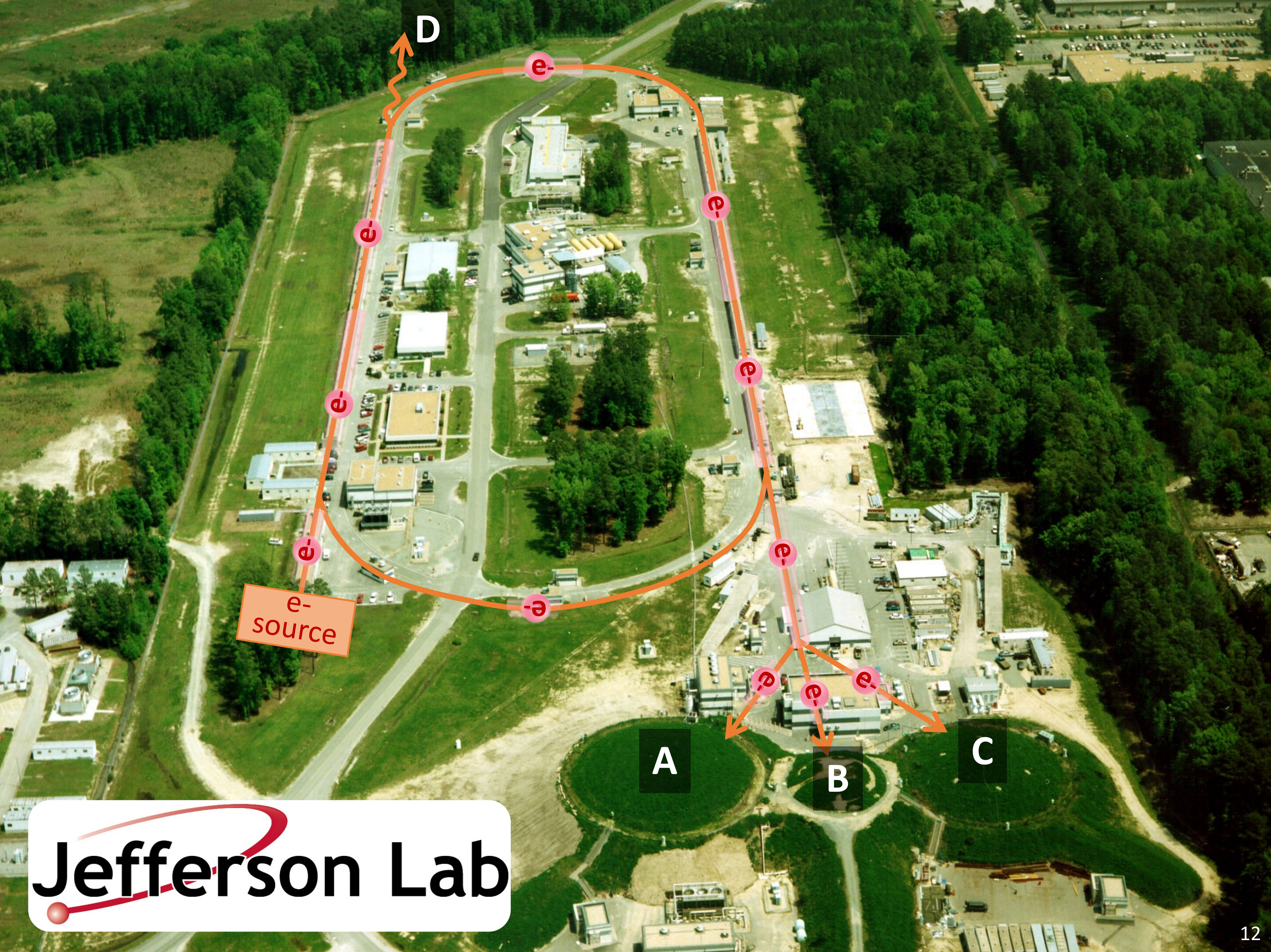
(Low-Energy) (High-Energy)

$$\sigma^A \cong \mathrm{K} \times \sigma^N \times \sum_{NN,\alpha} C_A^{NN,\alpha} |\psi_{NN}^{\alpha}|^2$$





Cruz-Torres et al., Nature Physics (2021)
Weiss et al., Phys. Lett. B 780 (2018)
Weiss, Bazak, Barnea, Phys. Rev. C 92 (2015)
Tropiano et al., Phys. Rev. C 104, 034311 (2021)
Lynn et al., JPG 47, 045109 (2020)
Chen, Detmold, Lynn, Schwenk, PRL 119 (2017)
Ryckebusch et al., Phys. Lett. B 792, 21 (2019)
…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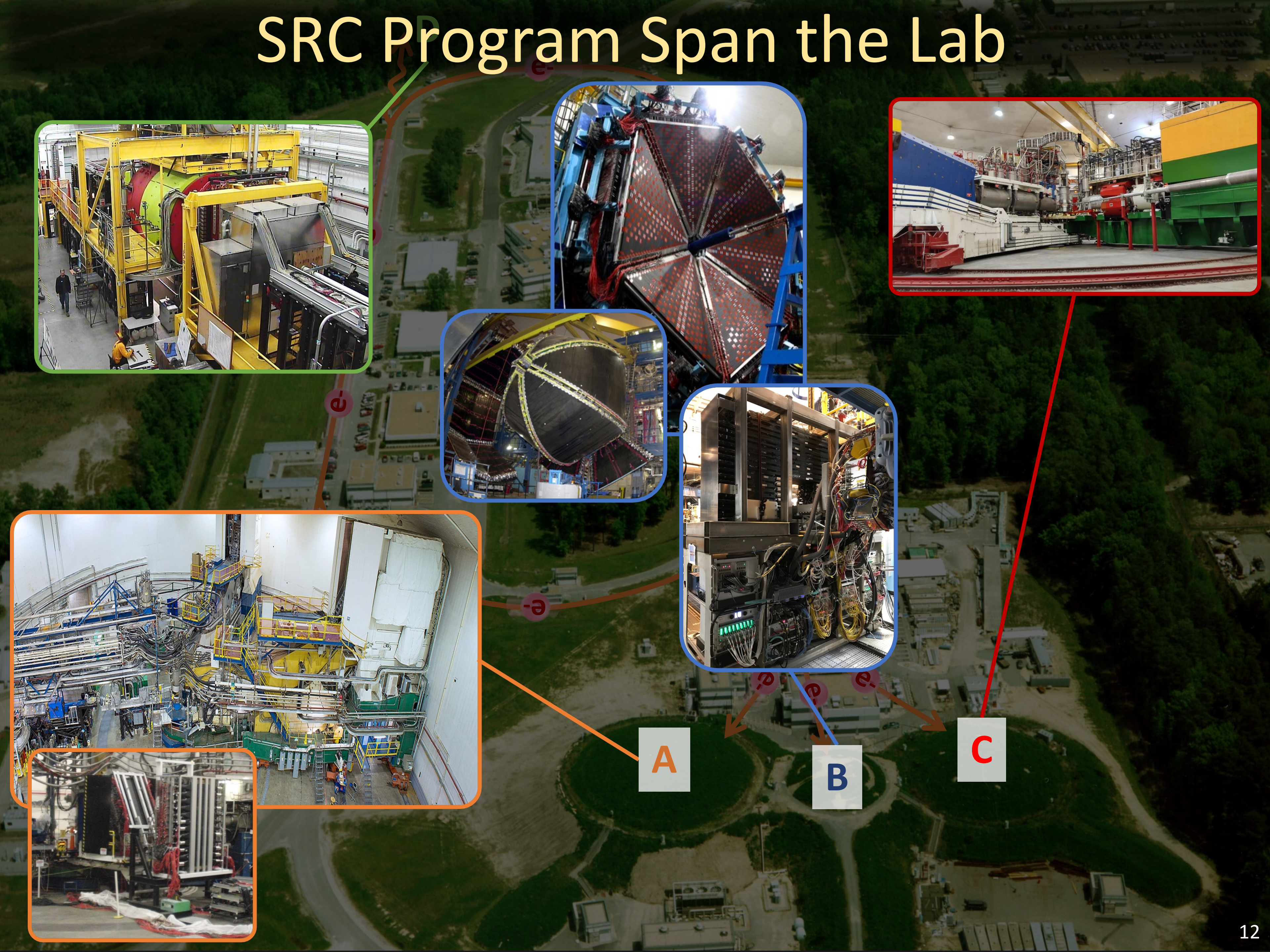
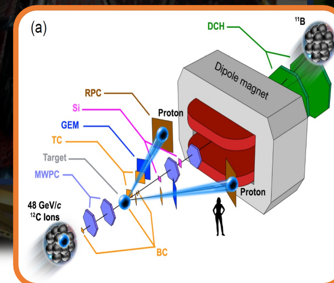
Jefferson Lab

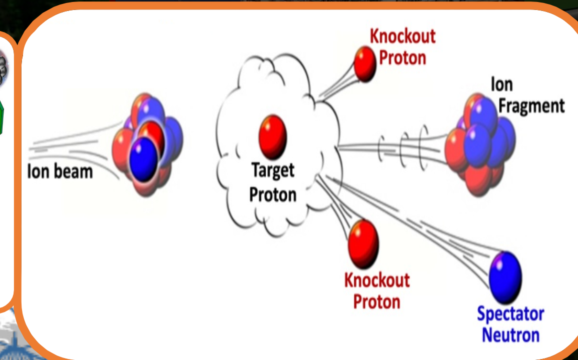
SRC Program Span the Lab

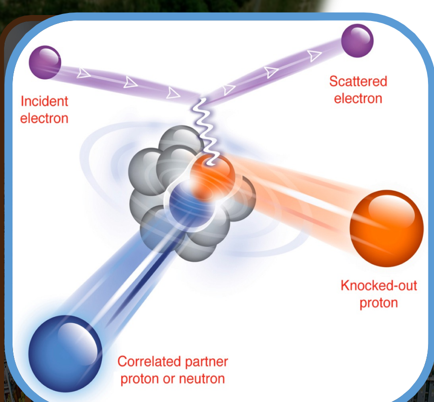


SRC Program Span the world 🤪

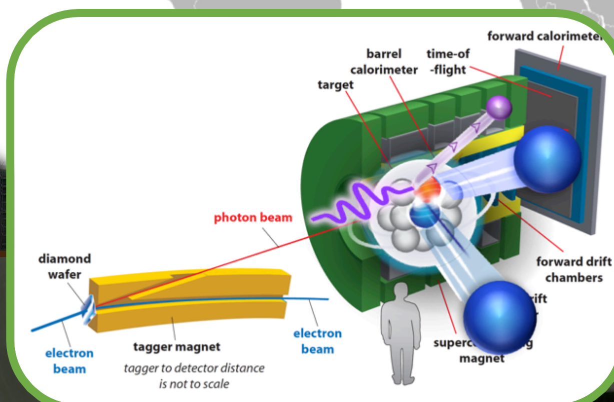
$(p, 2p\ N\ A-2)$





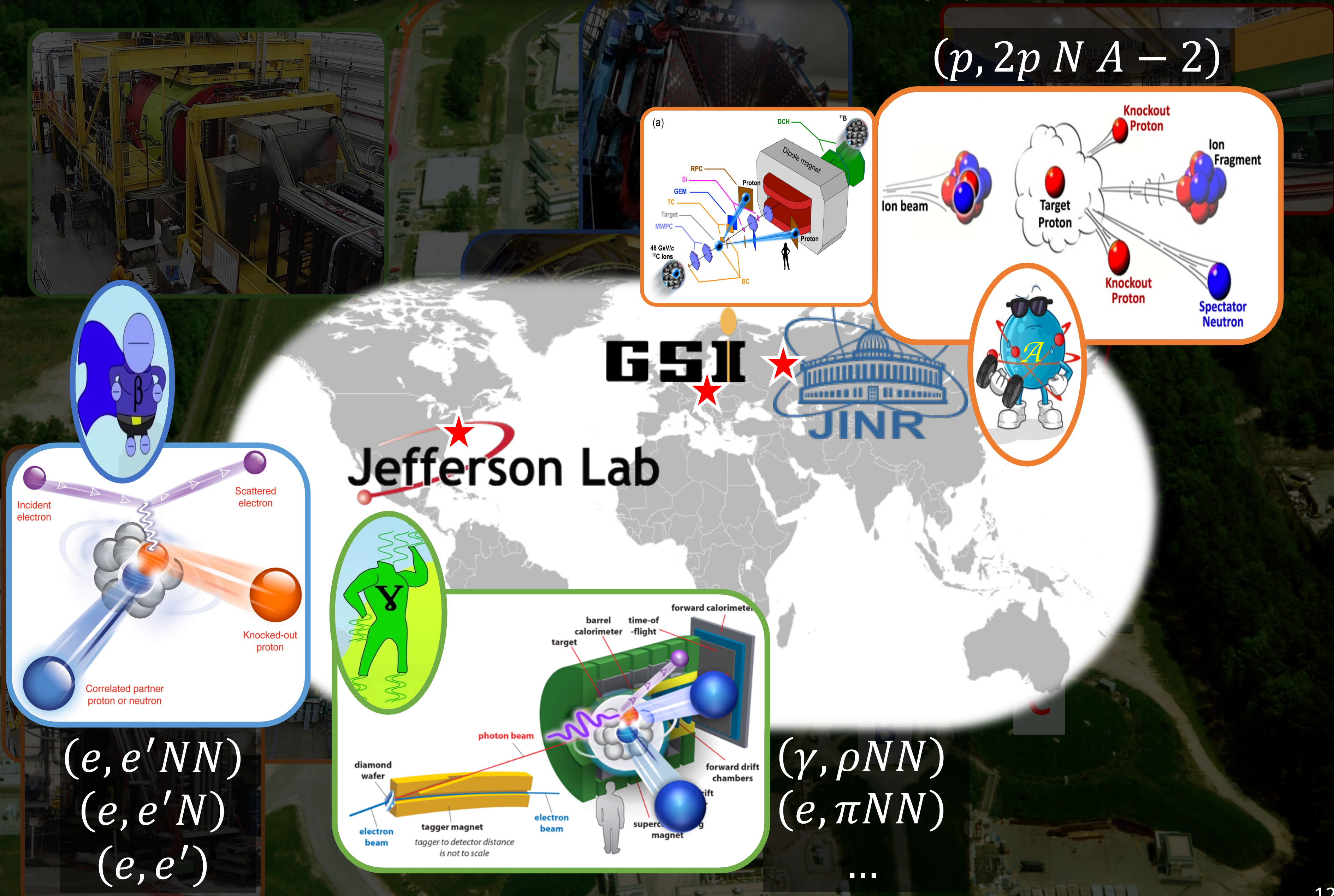


$(e, e'NN)$
$(e, e'N)$
(e, e')



$(\gamma, \rho NN)$
$(e, \pi NN)$
…

Multi-probe / Reaction Approach



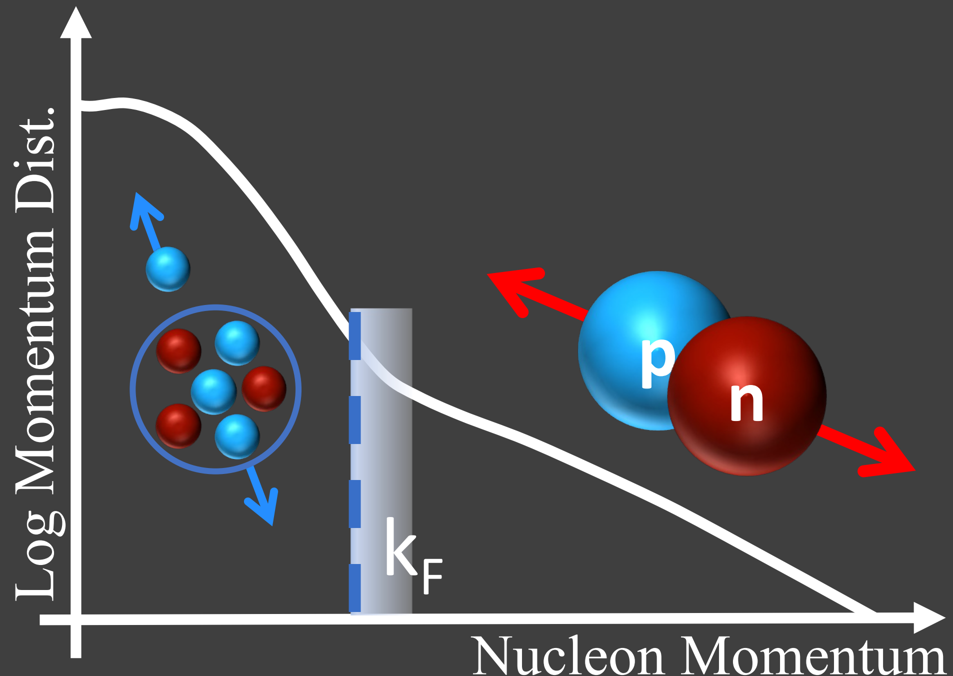
$(p, 2p\ N\ A-2)$

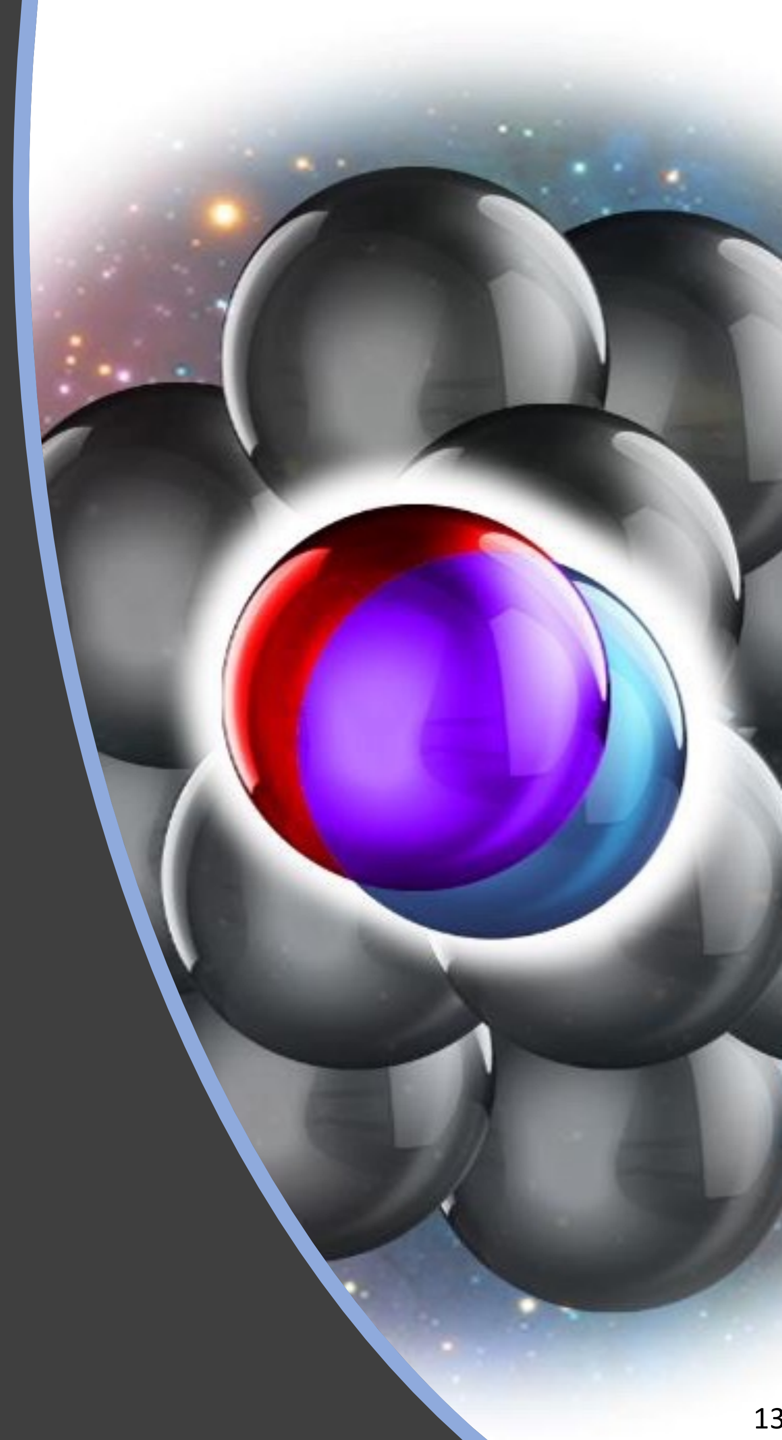
$(e, e'NN)$
$(e, e'N)$
(e, e')

$(\gamma, \rho NN)$
$(e, \pi NN)$
…

Short-Range Correlations (SRC)

- Produce high missing-momentum ($>k_F$)
- Predominantly neutron-proton pairs
- Universal Deuteron-like Scaling
- Scale separated from residual system





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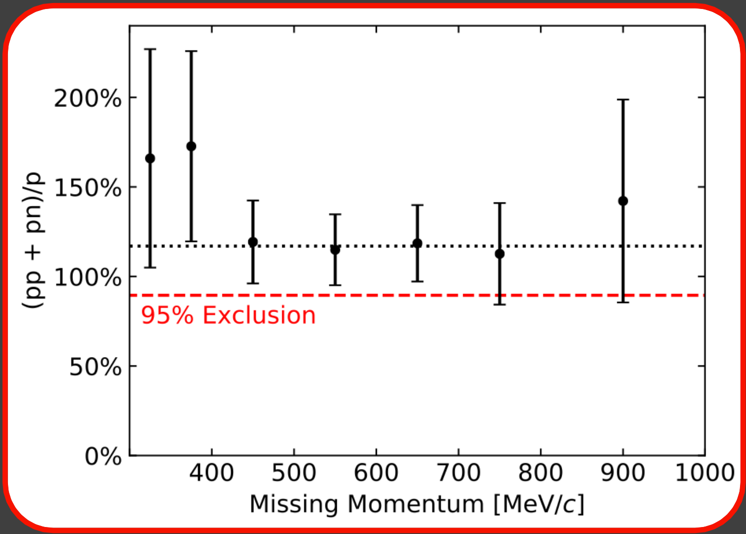
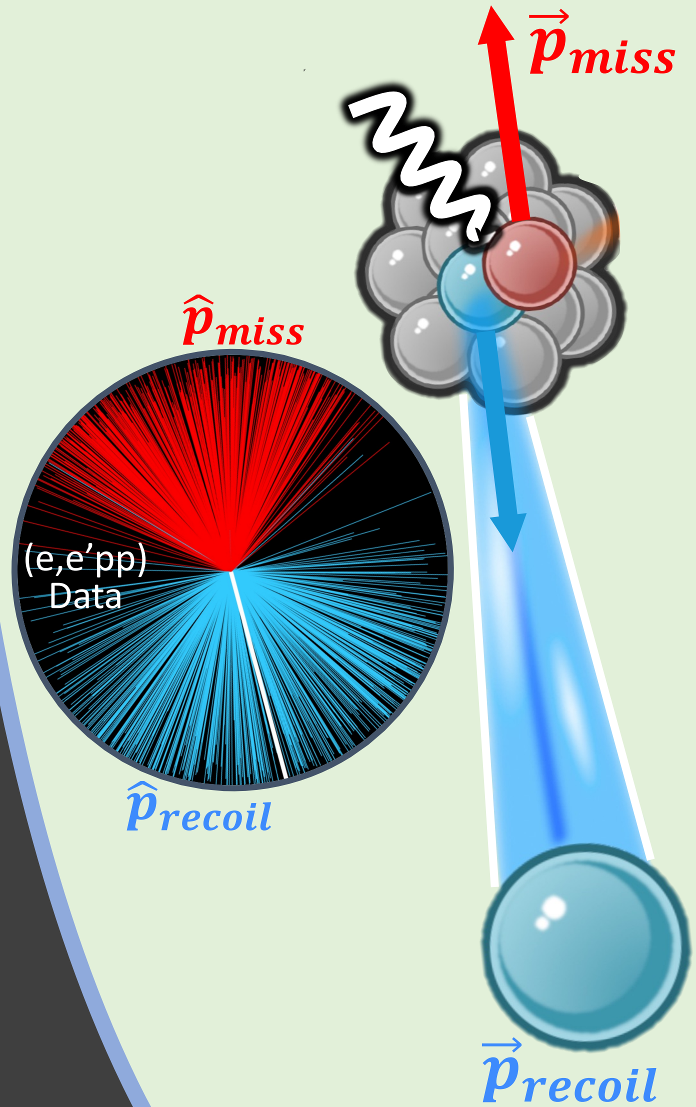


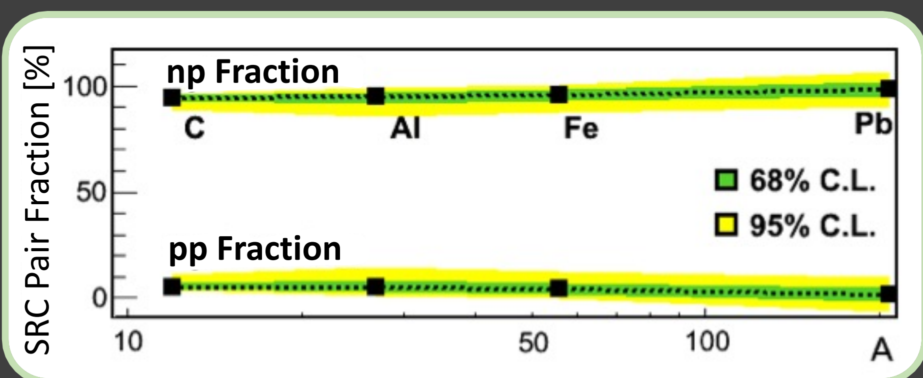
Korover et al., Phys. Lett. B (2021)

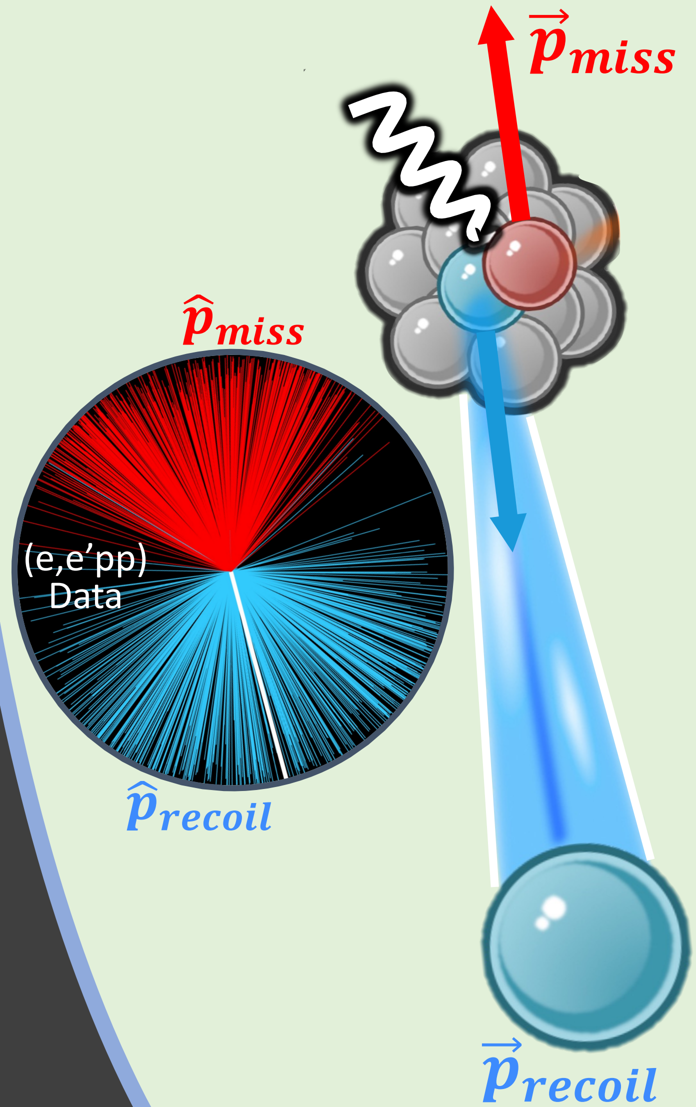


Hen et al., Science (2014)

Short-Range Correlations (SRC)

- Produce high missing-momentum (>k_F)
- Predominantly neutron-proton pairs
- Universal Deuteron-like Scaling
- Scale separated from residual system





Korover PLB '21; Duer PRL '19; Duer Nature '18; Hen Science '14; Korover PRL '14;
Subedi Science '08; Shneor PRL '07; Piasetzky PRL '06; Tang PRL '03; Review: Hen RMP '17

Short-Range Correlations (SRC)

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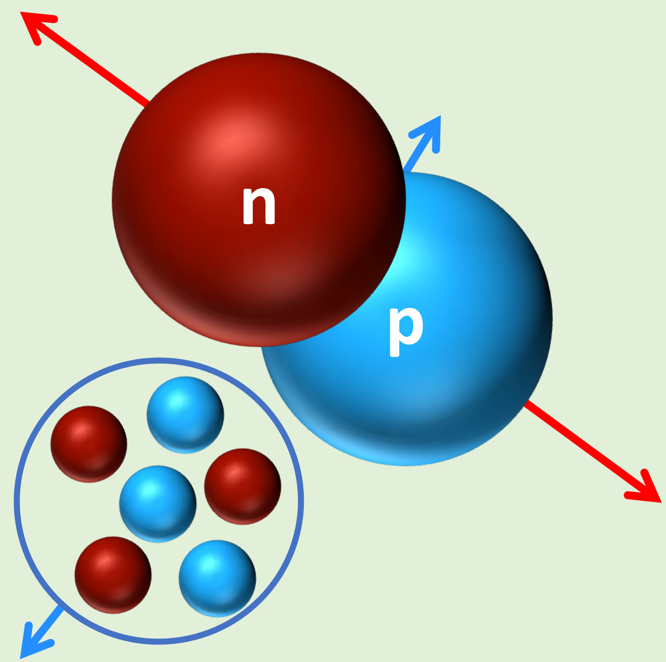
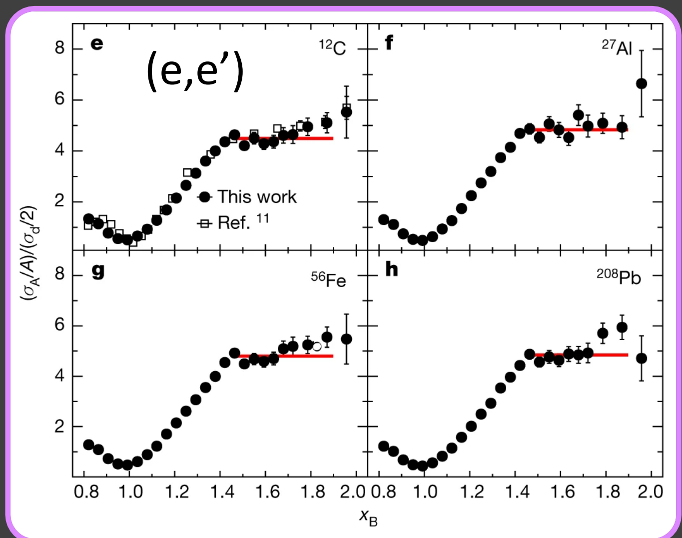
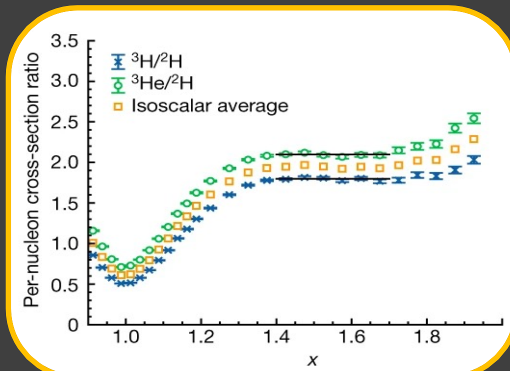
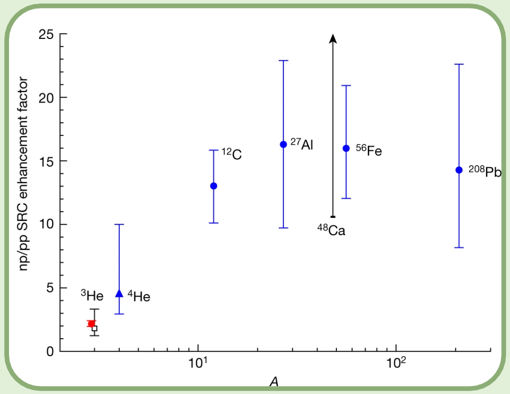


Ratio to Deuterium









Exp: Li Nature '22, Nguyen PRC '20; Schmookler Nature '19; Fomin PRL '12; …

Theory example: Weiss et al., PRC Lett '21

Short-Range Correlations (SRC)

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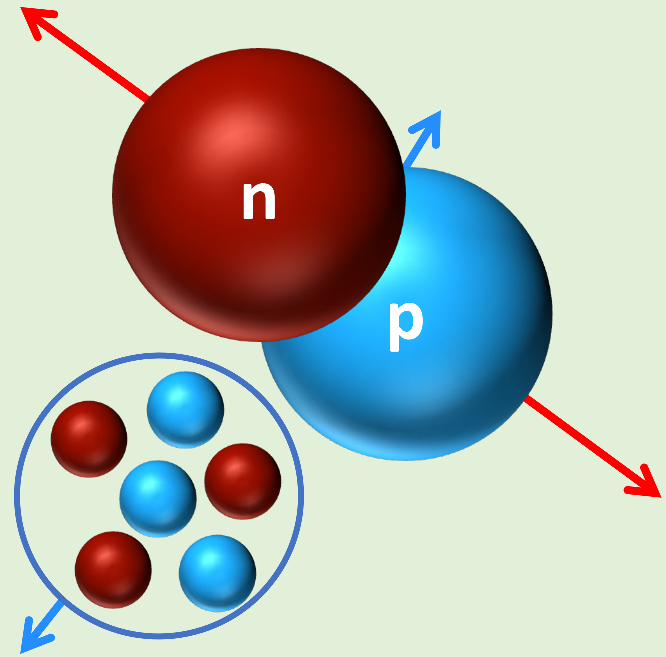

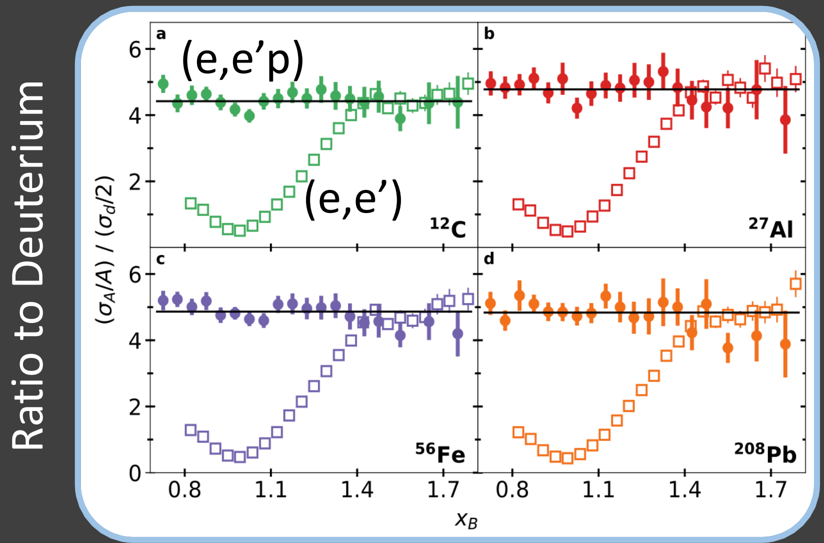

Korover and Denniston et al., Submitted (2022)

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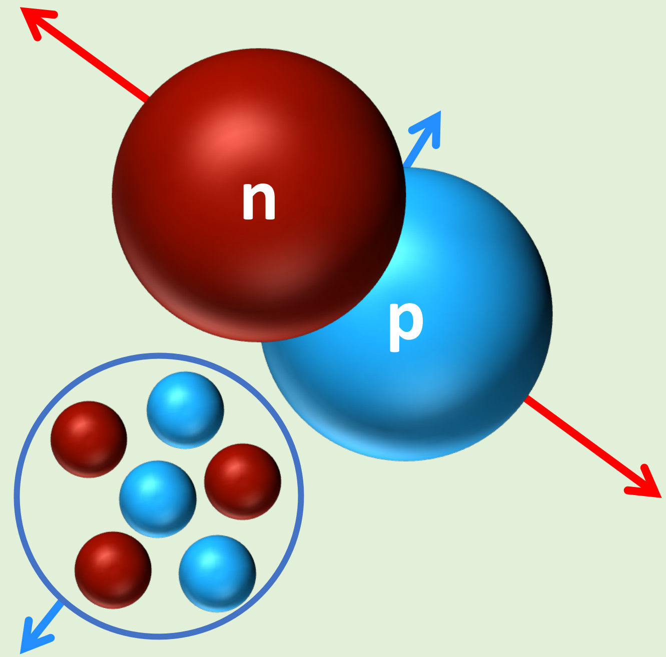

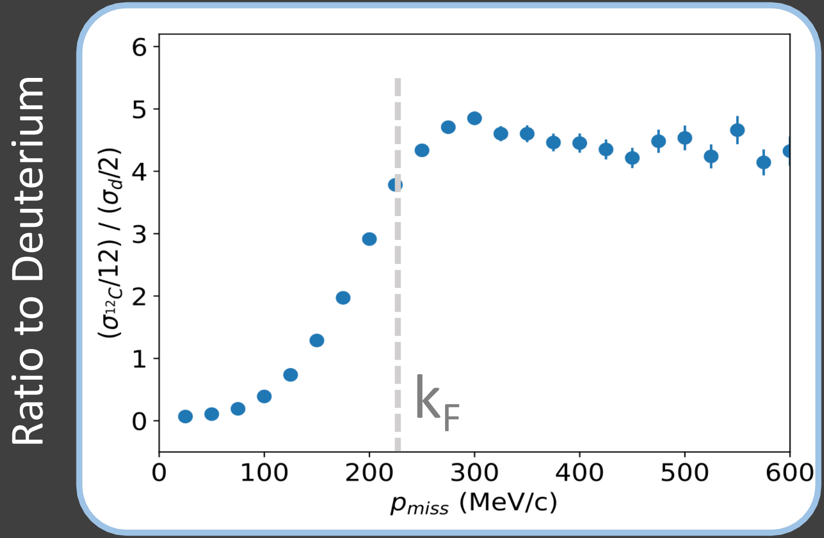

Korover and Denniston et al., Submitted (2022)

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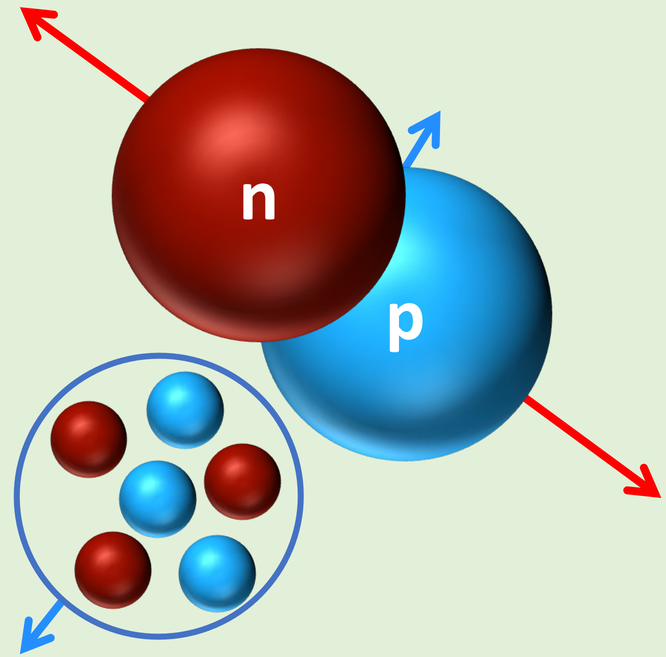

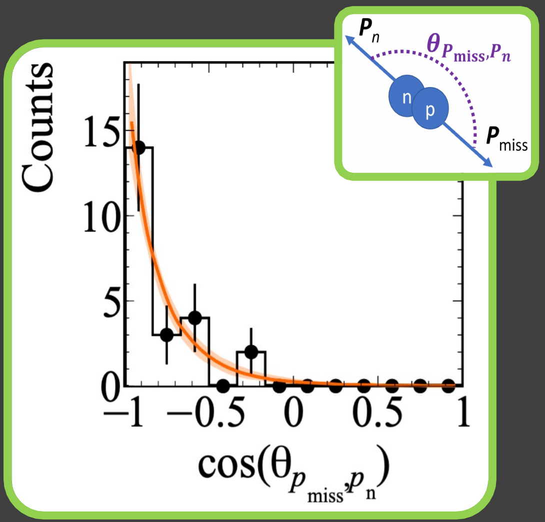

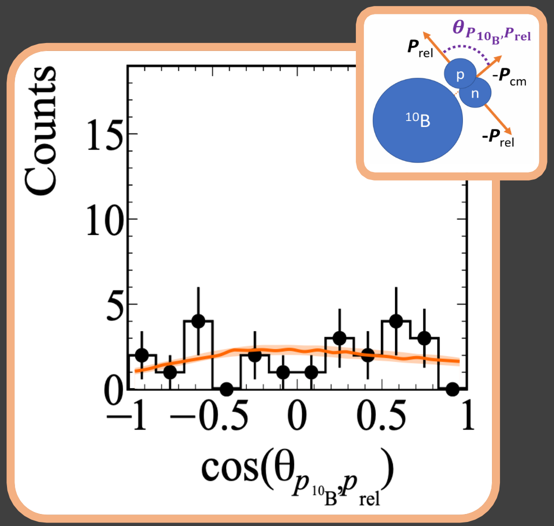

Patsyuk and Kahlbow et al., Nature Physics (2021)

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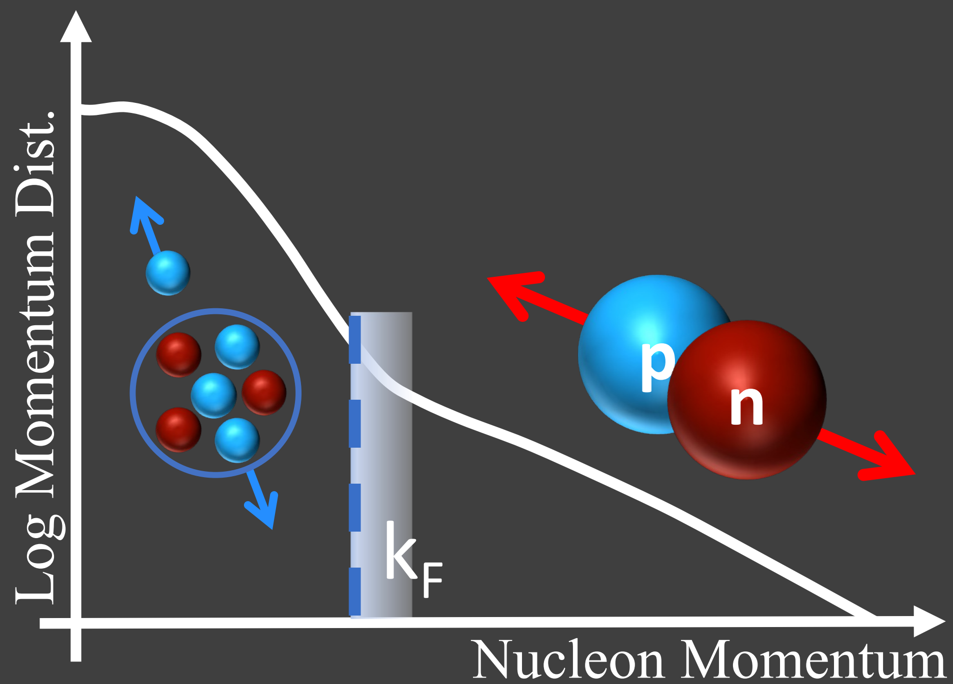


Isospin Structure:

Nature 609, 41 (2022)
Phys. Rev. C 102, 0644004 (2020)
Phys. Rev. Lett. 122, 172502 (2019)
Nature 560, 617 (2018)
Science 346, 614 (2014)
Phys. Rev. Lett. 113, 022501 (2014)

C.M. Motion:

Phys. Rev. Lett. 121, 092501 (2018)

Hard-Reaction Dynamics:

Nature Physics 17, 693 (2021)
Phys. Lett. B 797, 134792 (2019)
Phys. Lett. B 722, 63 (2013)

Nuclei / Nuclear Matter Properties:

Phys. Lett. B 800, 135110 (2020)
Phys. Lett. B 793, 360 (2019)
Phys. Lett. B 785, 304 (2018)
Phys. Rev. C 91, 025803 (2015)

Effective Theory:

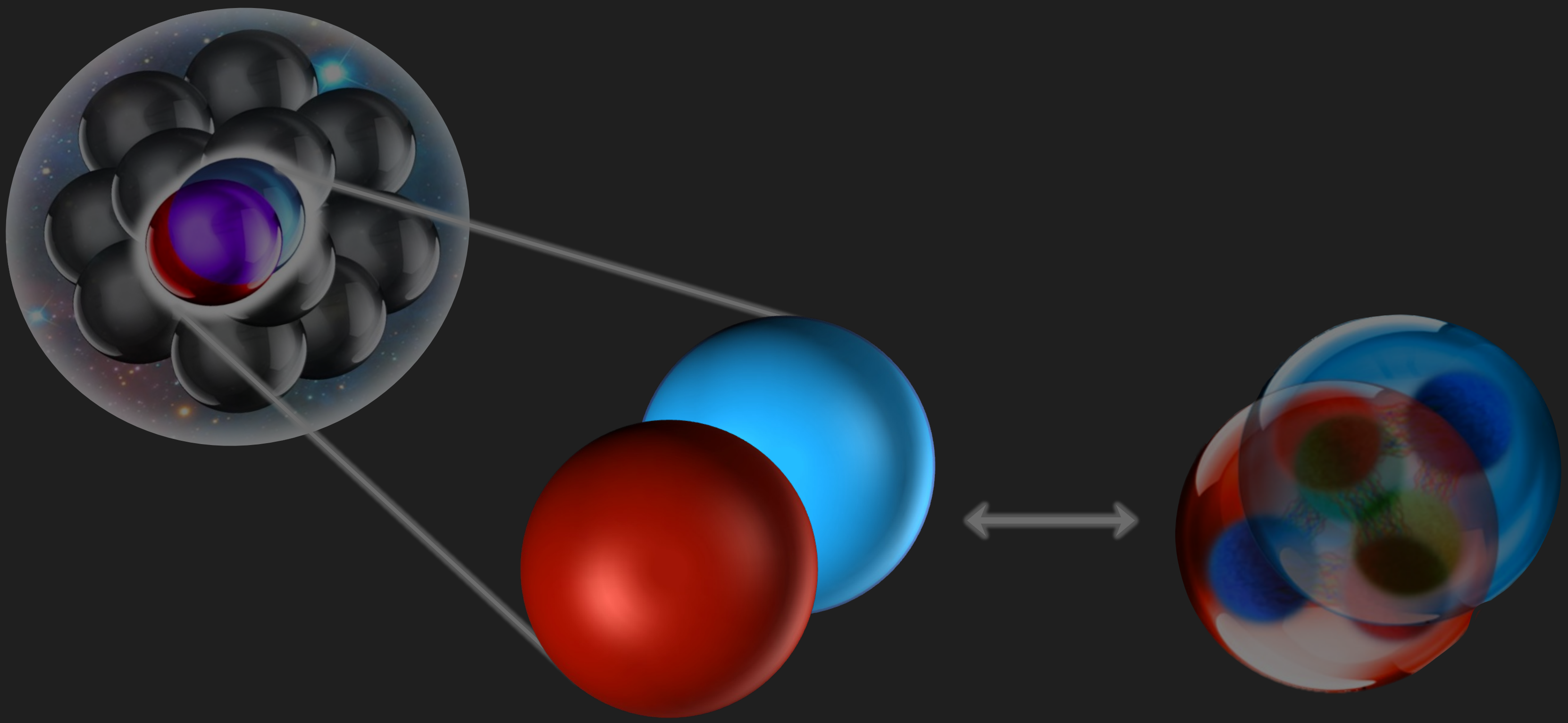
Nature Physics 17, 306 (2021)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 791, 242 (2019)
Phys. Rev. C 104, 034311 (2021)
Phys. Lett. B 792, 21 (2019)

Quantum Numbers, Mass, Asymmetry Dependence:

Phys. Rev. C 103, L031301 (2021)
Phys. Lett. B 780, 211 (2018)
PRC 92, 024604 (2015)
PRC 92, 045205 (2015)

^^partial list

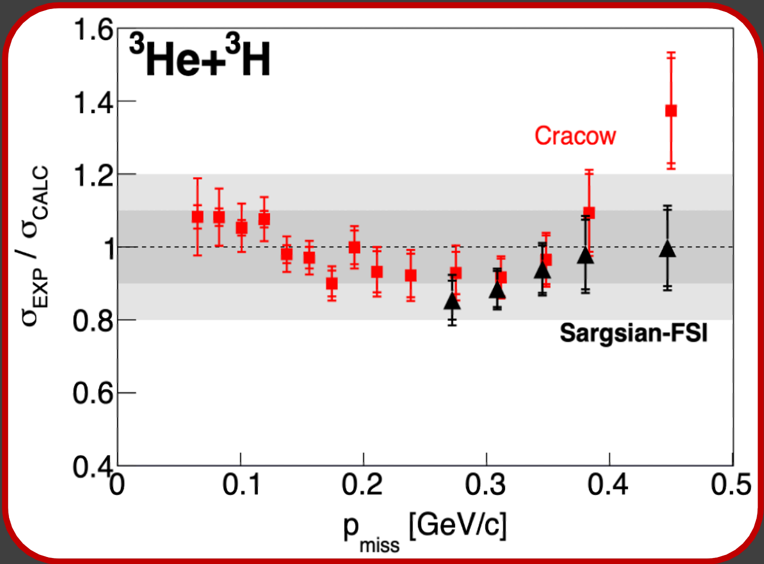
High-resolution Interactions



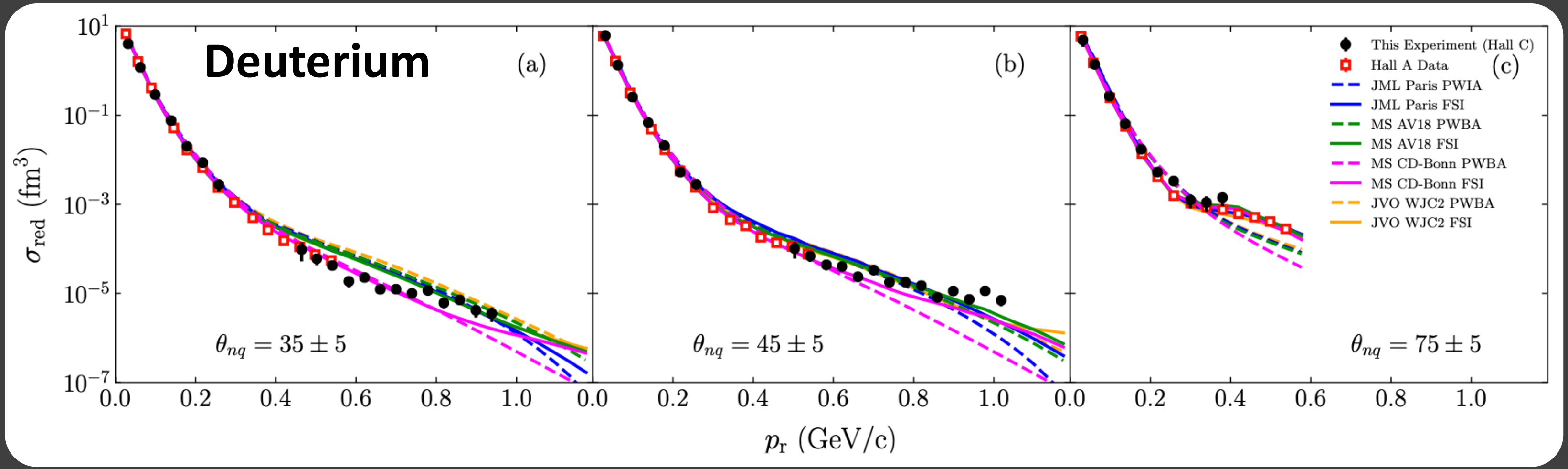
(e,e'p) Few-Body Cross-Sections


Editors' Suggestion

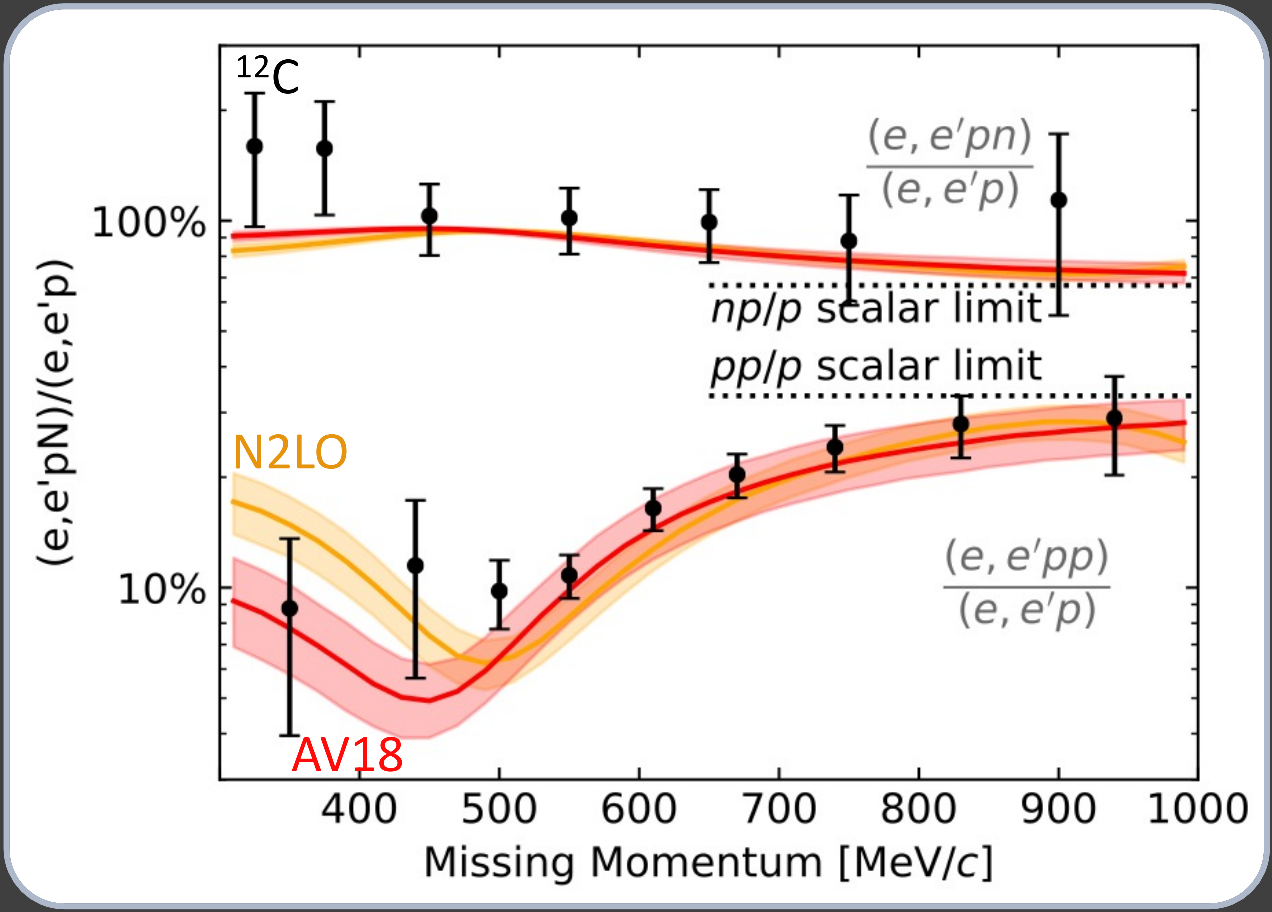
Cruz Torres and Nguyen et al., Phys. Rev. Lett (2020)



Yero et al., Phys. Rev. Lett (2020)



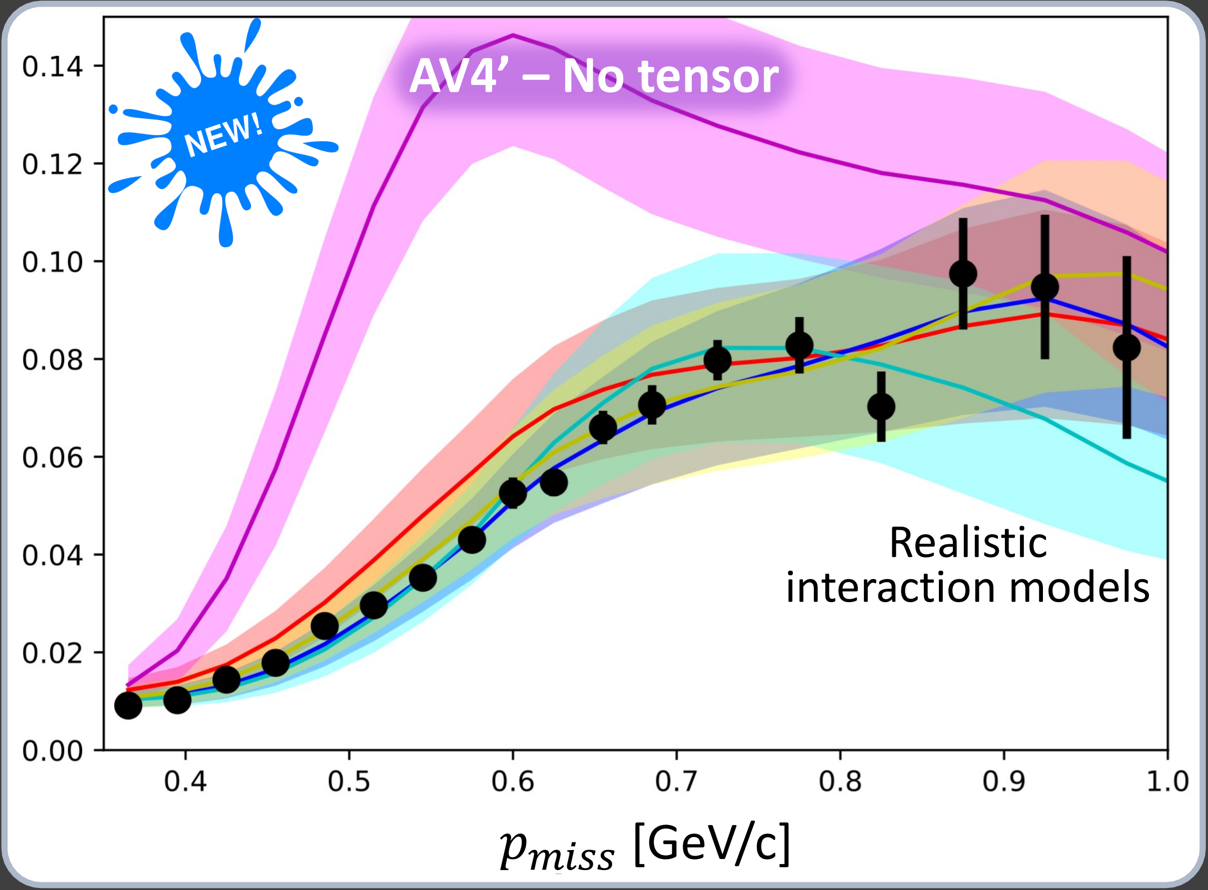
pp-SRC Fraction Increase



Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

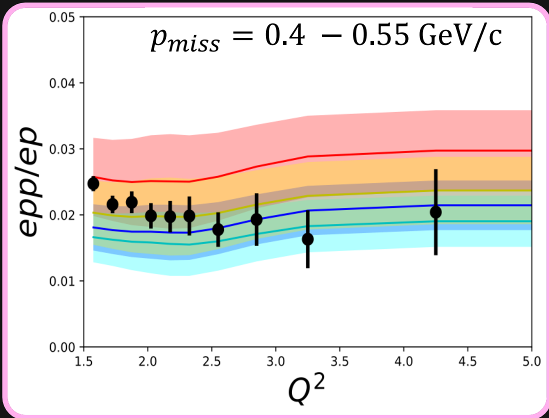
New: High-Precision Data

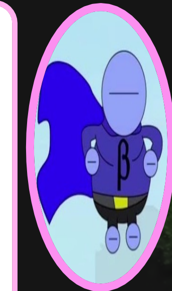
$$\frac{^4He(e,e'pp)}{^4He(e,e'p)}$$



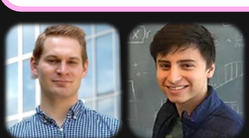
*40% of collected data

Scale Independence



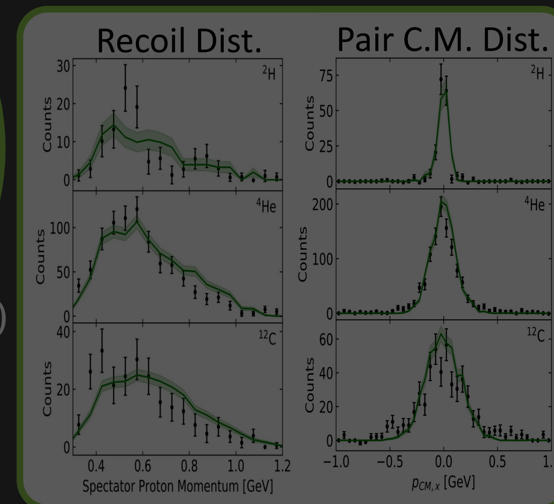


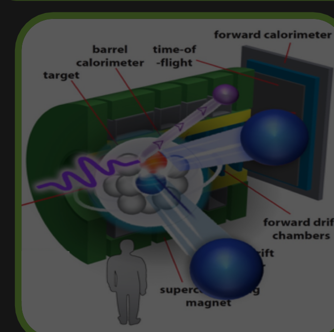
$(e, e'pN)$



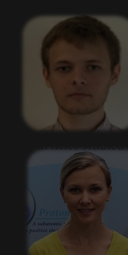
*40% of collected data

$(\gamma, \rho^- pp)$

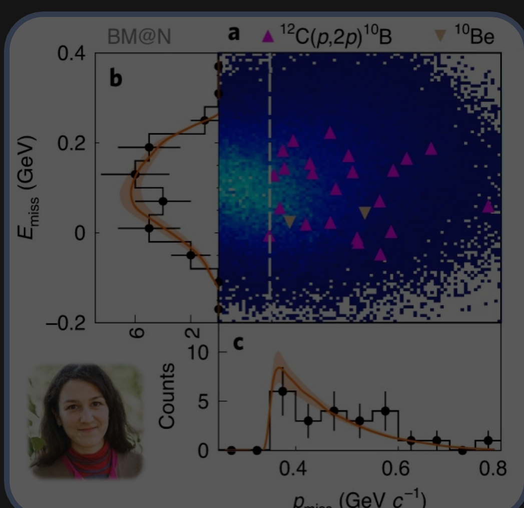


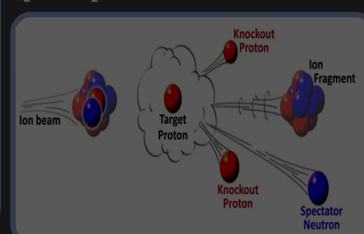


<20% of collected data



$(p, 2p\ \text{A}{-}2)N$



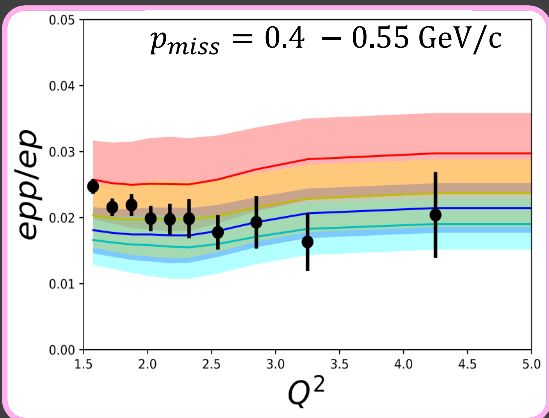


Patsyuk and Kahlbow et al., Nature Physics (2021)

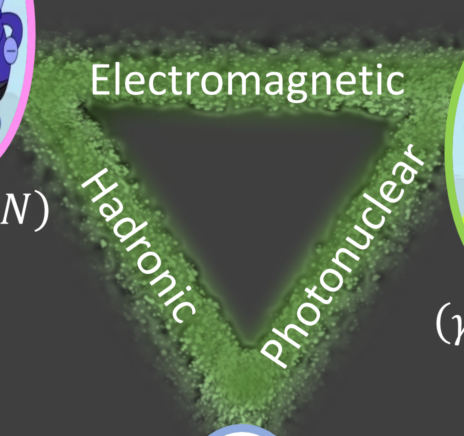
Scale and Probe Independence

NEW!

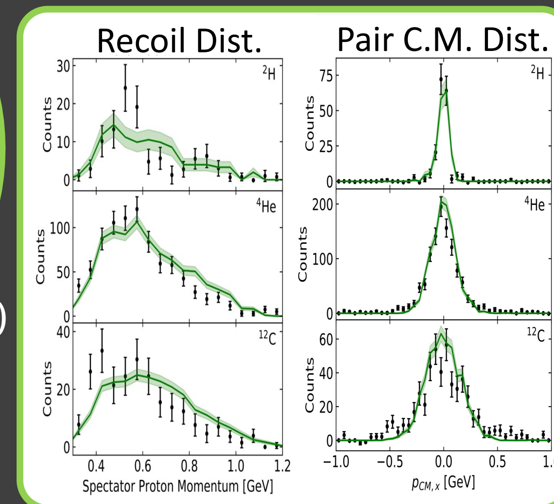
$$\sigma^{A}_{probe} = K \times \sigma^{N}_{probe} \times \sum_{NN,\alpha} C^{A}_{NN,\alpha} \left|\psi_{NN,\alpha}\right|^2$$

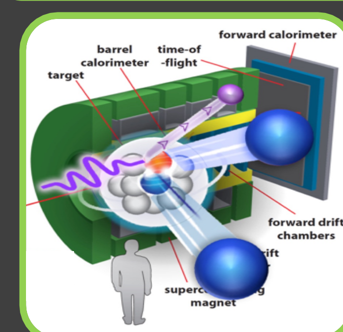


$(e, e'pN)$

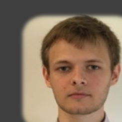


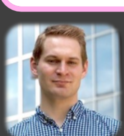
$(\gamma, \rho^- pp)$

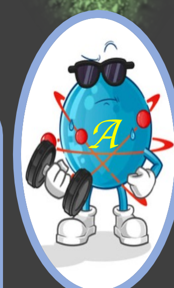


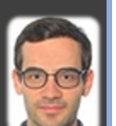


<20% of collected data

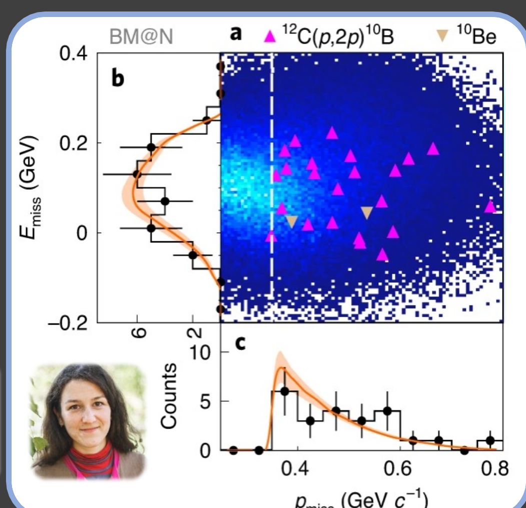


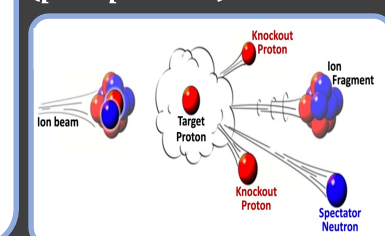





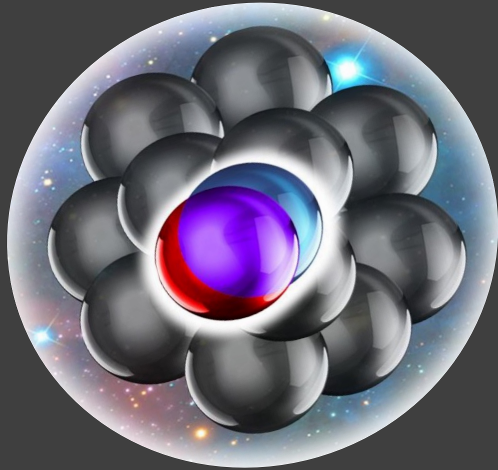


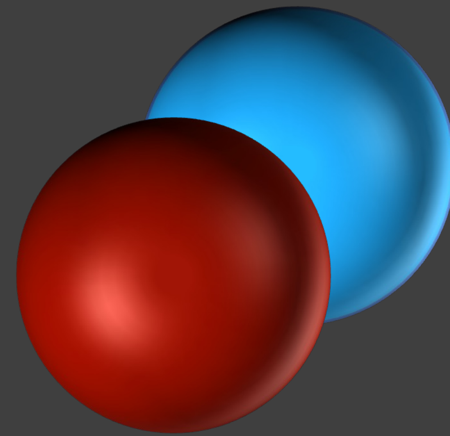
$(p, 2p\ A{-}2)N$

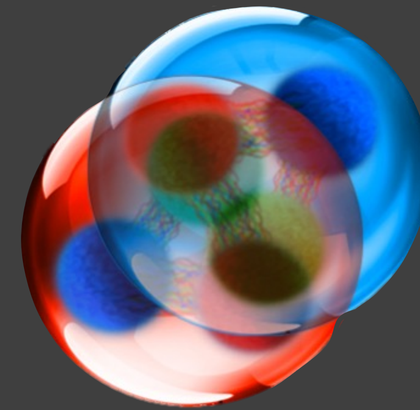




Patsyuk and Kahlbow et al., Nature Physics (2021)



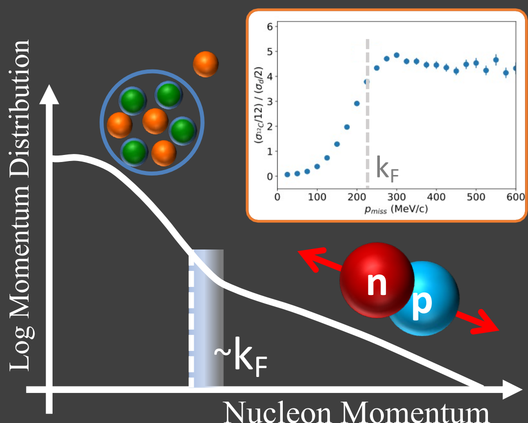


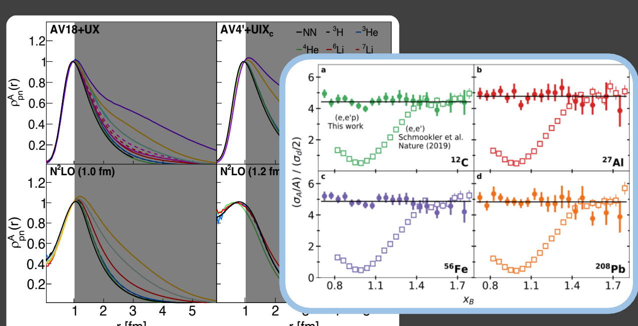


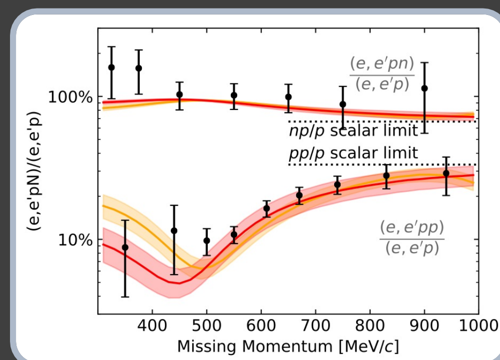
High-resolution nuclear structure

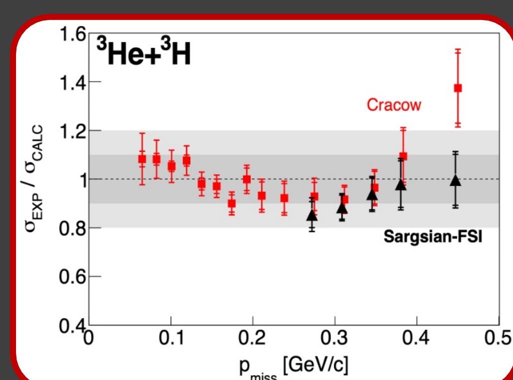
Nucleon-nucleon interaction

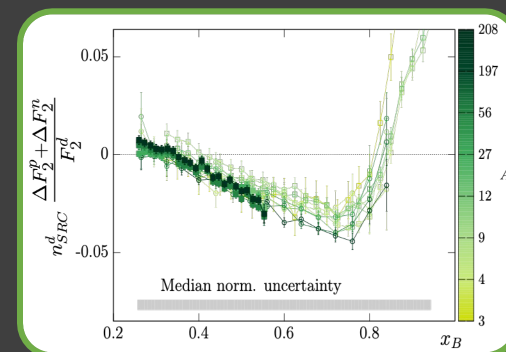
Quark-gluon structure of nuclei

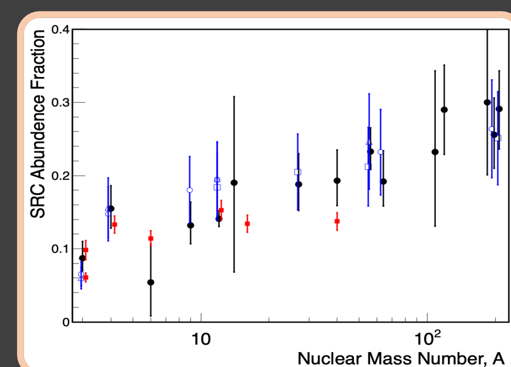


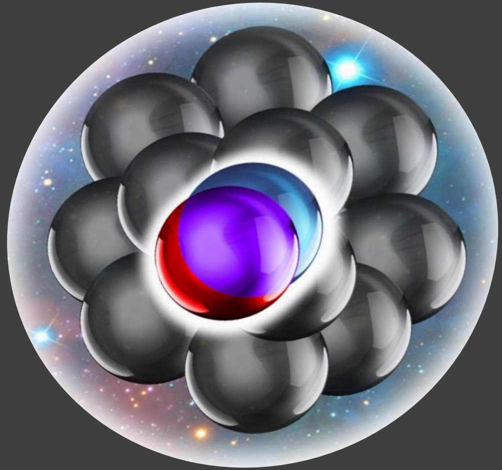




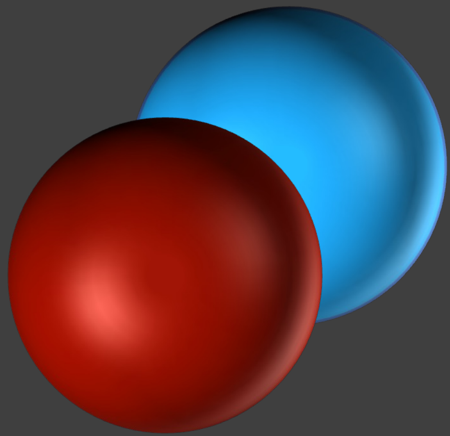




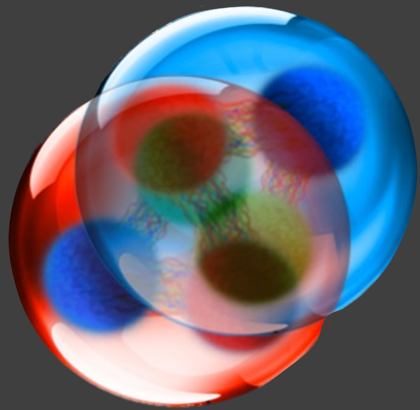




High-resolution
nuclear structure

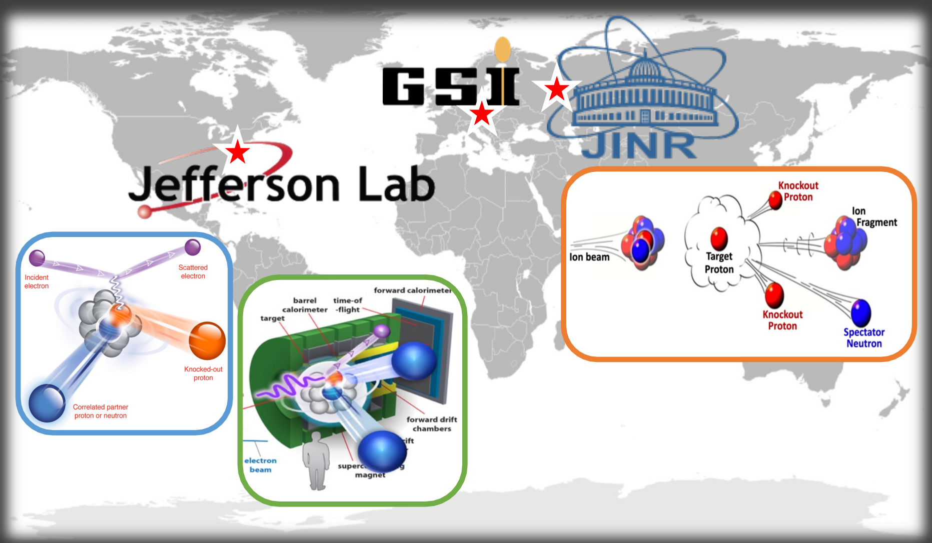


Nucleon-nucleon
interaction



Quark-gluon
structure of nuclei

Growing International Effort + Forthcoming Electron-Ion Collider



What's Coming?

JLab – electron:

- d(e,e'p): Precision data at high missing-momentum
- High-statistics (e,e'), (e,e'N) and (e,e'Np) on ^{3}He-^{3}H mirror nuclei
- (e,e') and (e,e'p): stable light- and medium-mass asymmetric nuclei
- High-statistic (e,e'NN) spanning light (^{4}He) to heavy (^{120}Sn) nuclei

JLab – photon:

- Wide array of photonuclear reactions with d, ^{4}He, and ^{12}C

GSI:

- (p,2p A-2 N): ~1.5 GeV/u Carbon 12 & 16
- (p,d) SRC study

JINR:

- (p,2p A-2 N): high-stat. + PID with ~3 GeV/u Carbon 12

Your ideas here!

Thank you!

Exciting
Times Ahead!

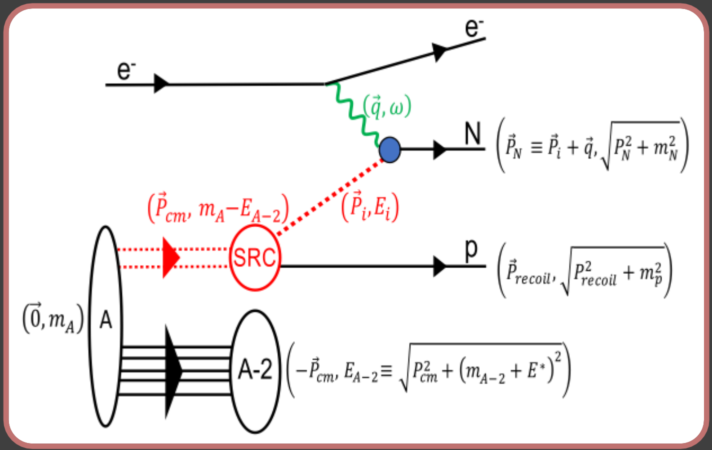
Backup

Using Hard Reactions

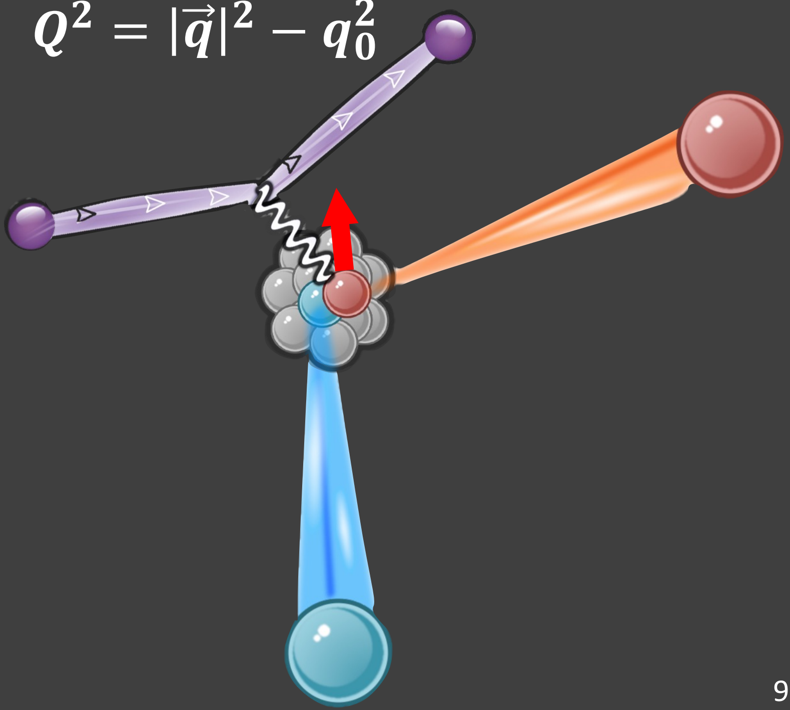
Probe energy >> Nuclear energy scale

$$q_0, \vec{q} > 1GeV \gg |V_{NN}|, 2\, k_F$$

- Provides resolving power



$$\boldsymbol{Q^2 = |\vec{q}|^2 - q_0^2}$$



Ciofi degli Atti, Physics Reports (2015)
Sargsian+, Phys. Rev. C (2005)
Frankfurt, Sargsian, and Strikman, Phys. Rev. C (1997)
Frankfurt and Strikman, Physics Reports (1981)

Using Hard Reactions

Probe energy >> Nuclear energy scale

$$q_0, \vec{q} > 1GeV \gg |V_{NN}|, 2\ k_F$$

- Provides resolving power
- Use verifiable Glauber calculations for Final State Interaction (FSI) assessment and correction

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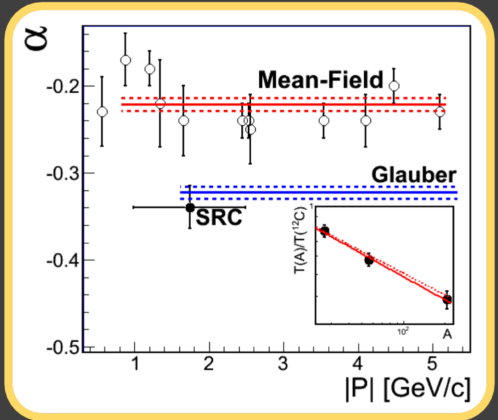
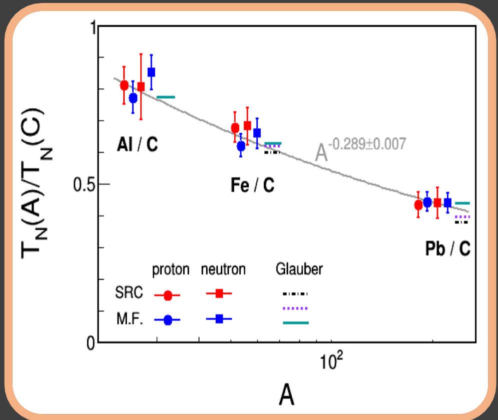
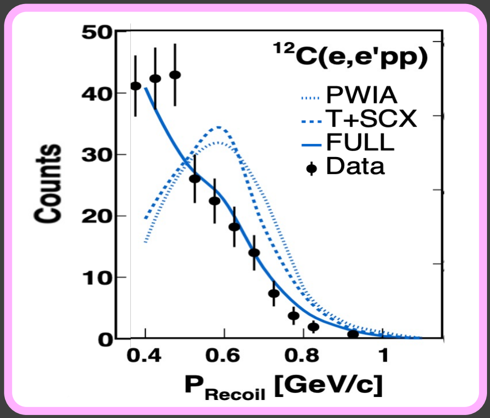


Hen+ Phys. Lett. B (2013)



Duer+ Phys. Lett. B (2019)



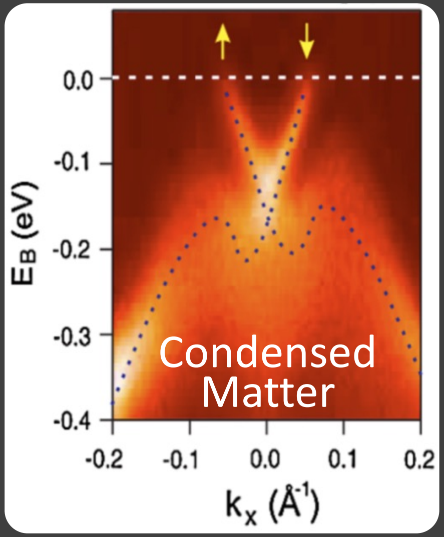
Wright+ arXiv (2022)

Using Hard Reactions

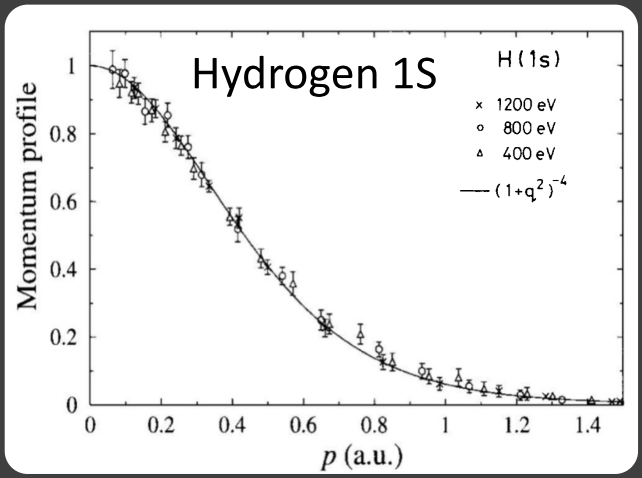
Probe energy >> Nuclear energy scale

$$q_0, \vec{q} > 1GeV \gg |V_{NN}|, 2\, k_F$$

- Provides resolving power
- Use verifiable Glauber calculations for Final State Interaction (FSI) assessment and correction
- Similar to atomic / condensed matter spectral function extractions

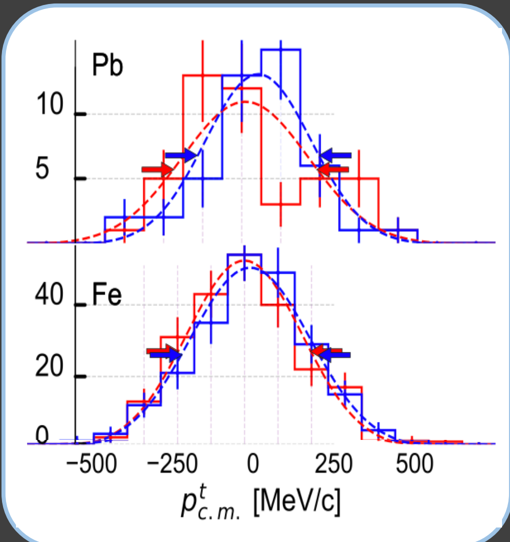


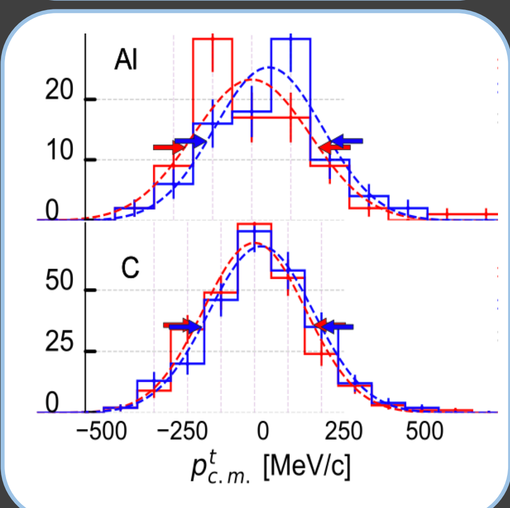
(γ,e) ARPES: surface state bands in $Bi_{2-x}Mn_xTe_3$ (2009)

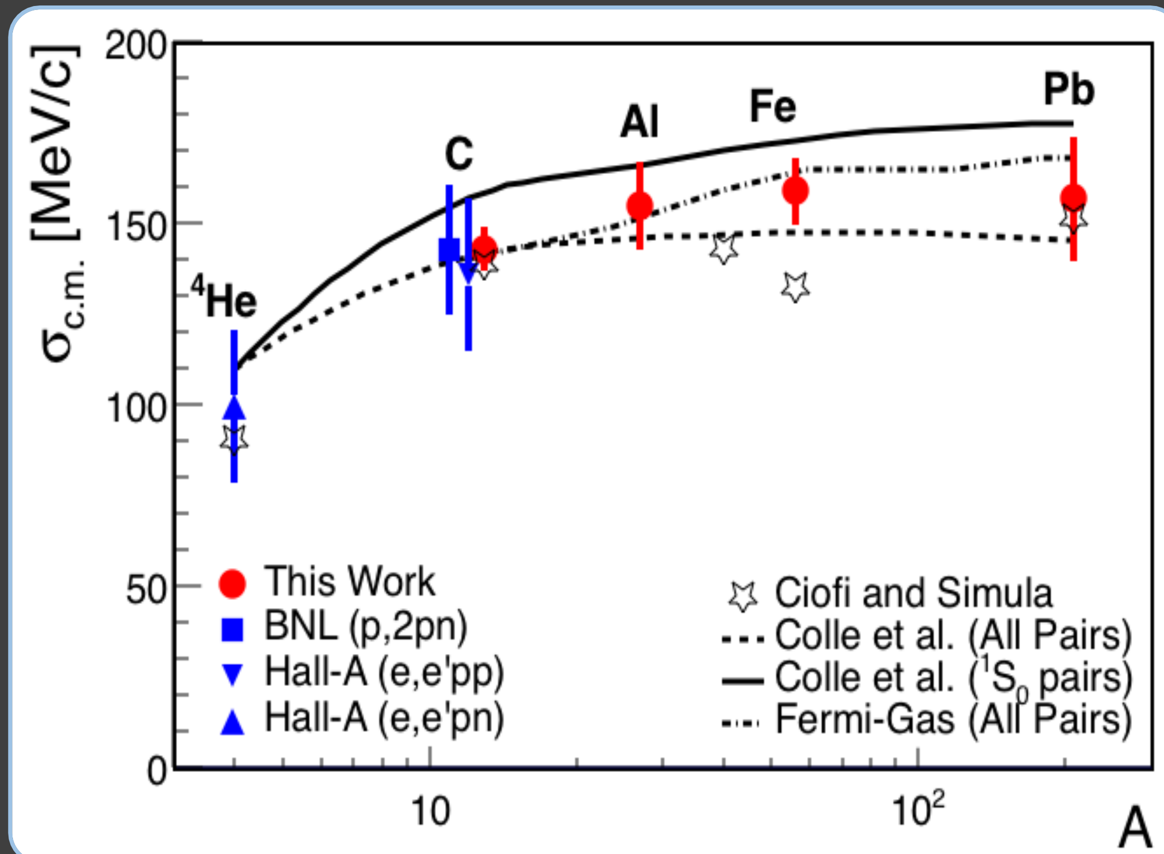


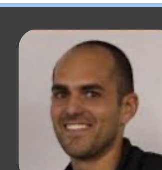
(e,2e) reduced cross-section (1981)

Strongly correlated? Yes! low pair c.m. motion



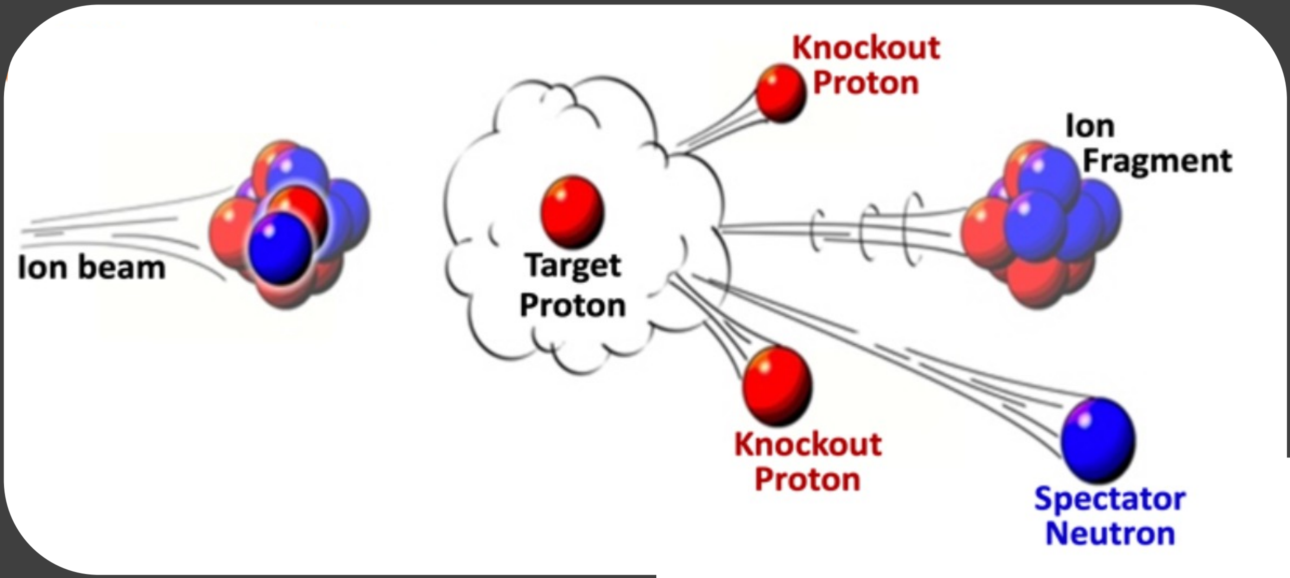


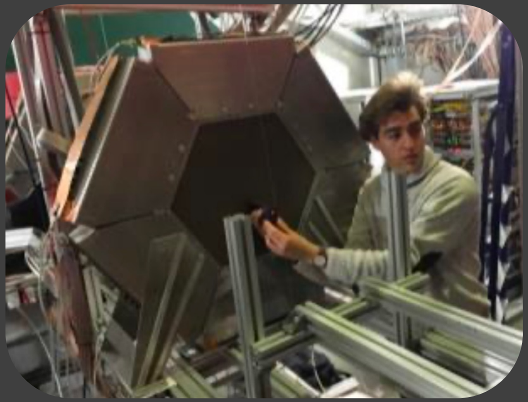


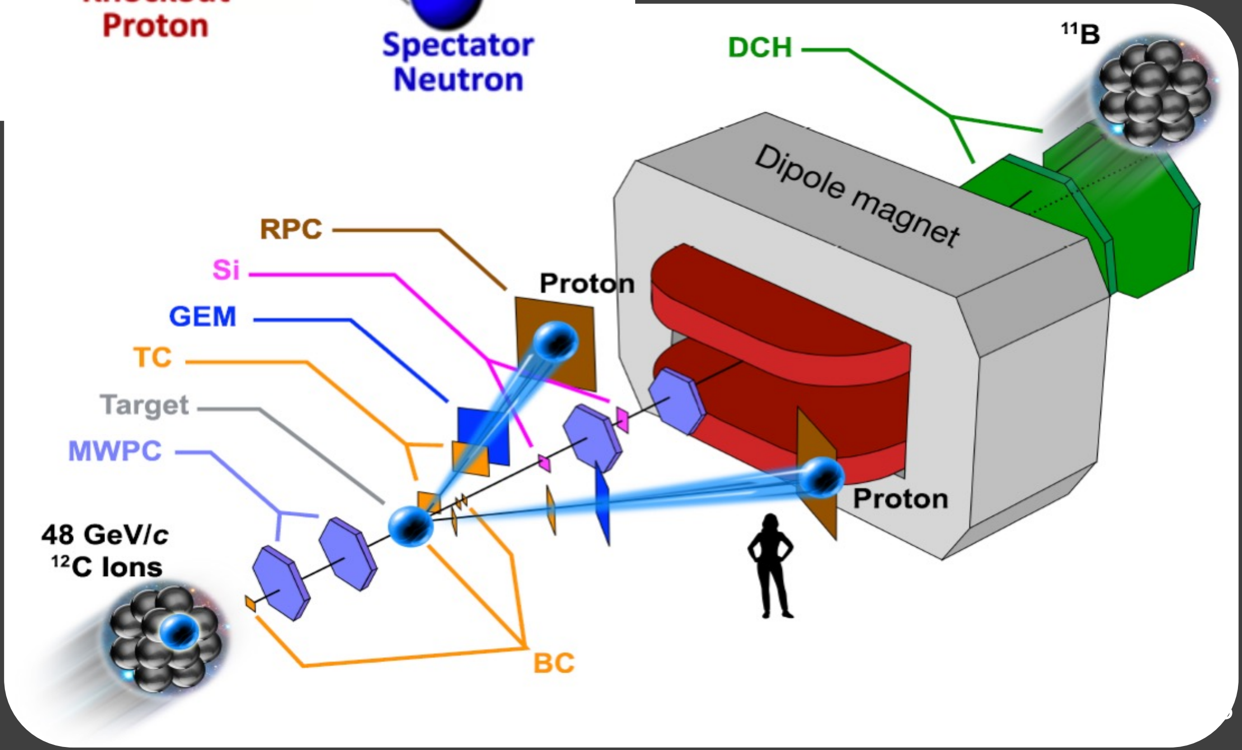


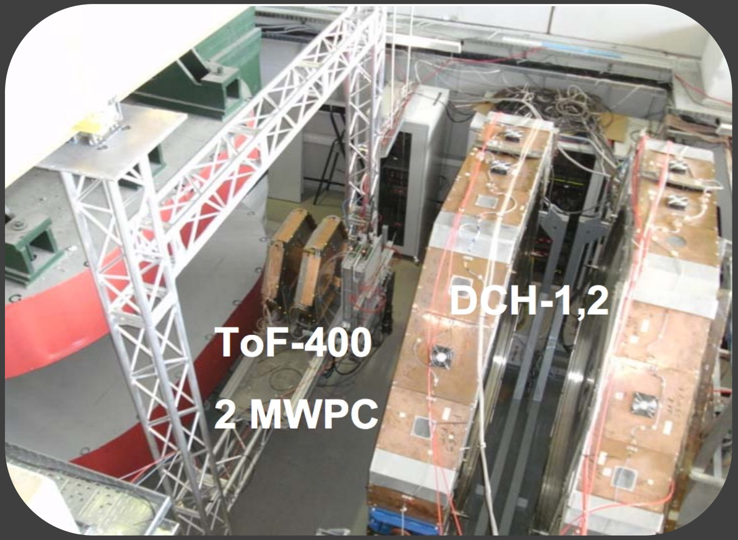
Cohen et al., PRL (2018)

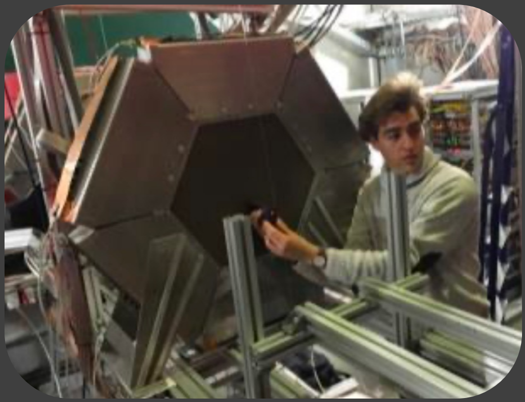
Inverse Kinematics Measurement

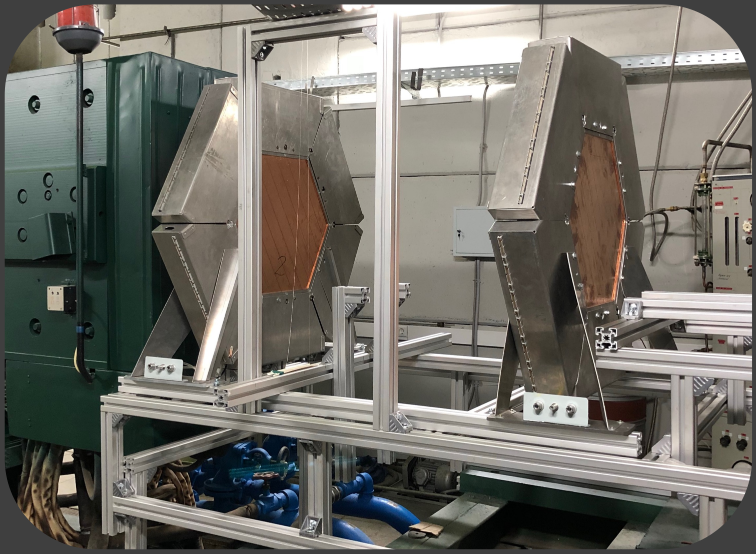




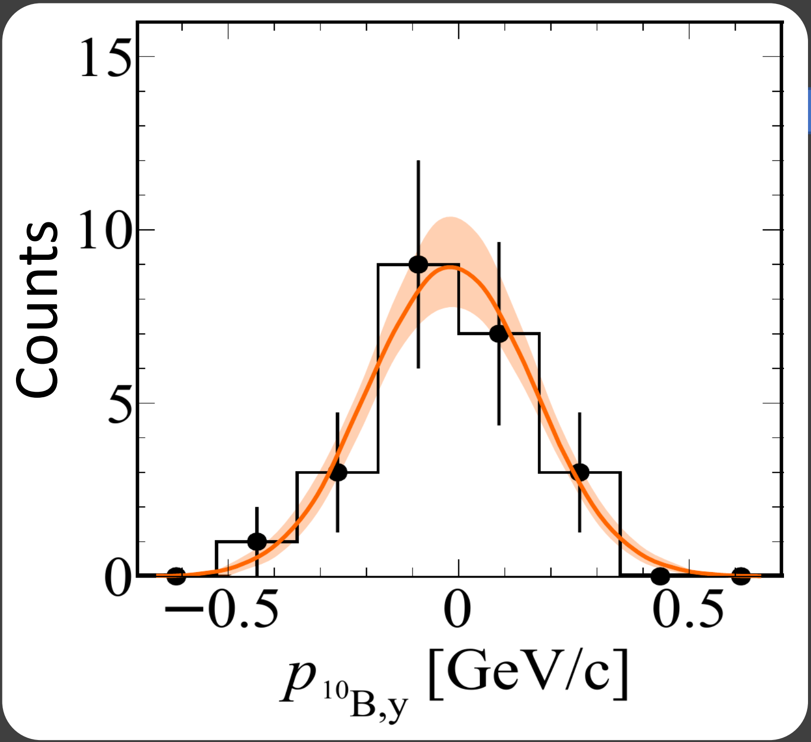


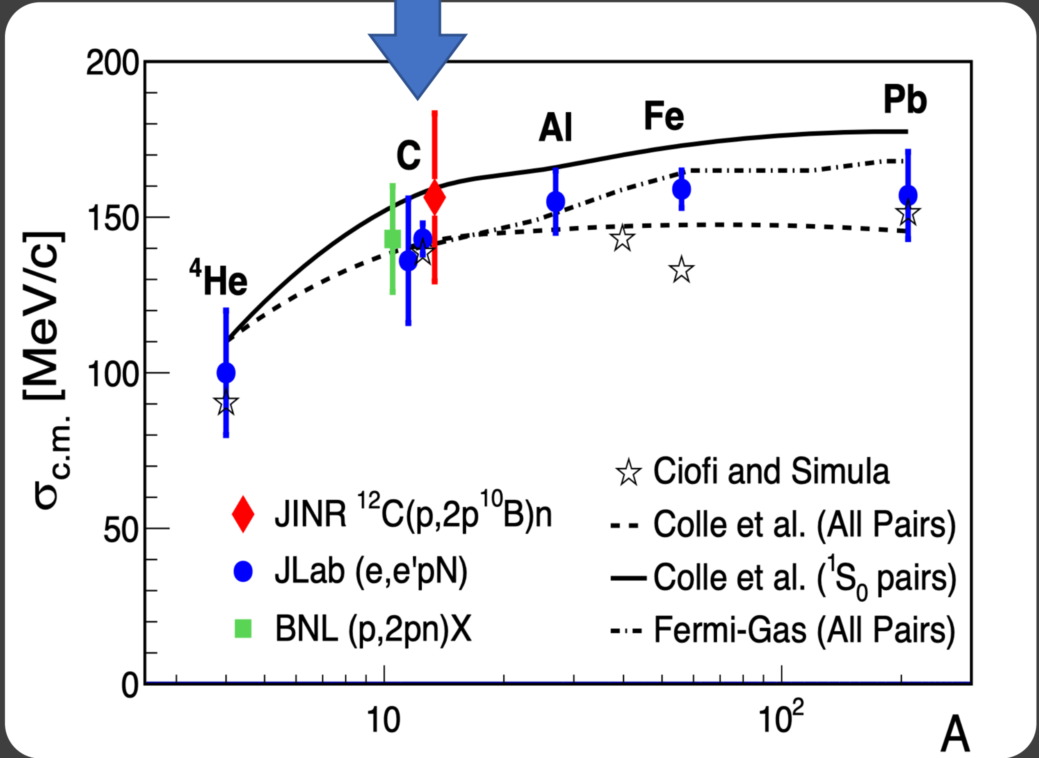

DCH-1,2
ToF-400
2 MWPC





Pair Motion from ^{10}B
(Agree \w JLab data)

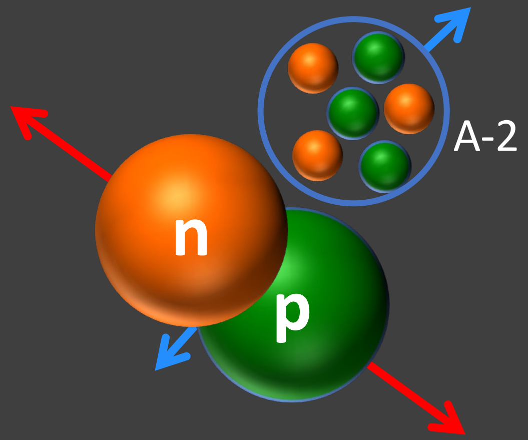




Patsyuk and Kahlbow et al.,
Nature Physics 17, 693 (2021)

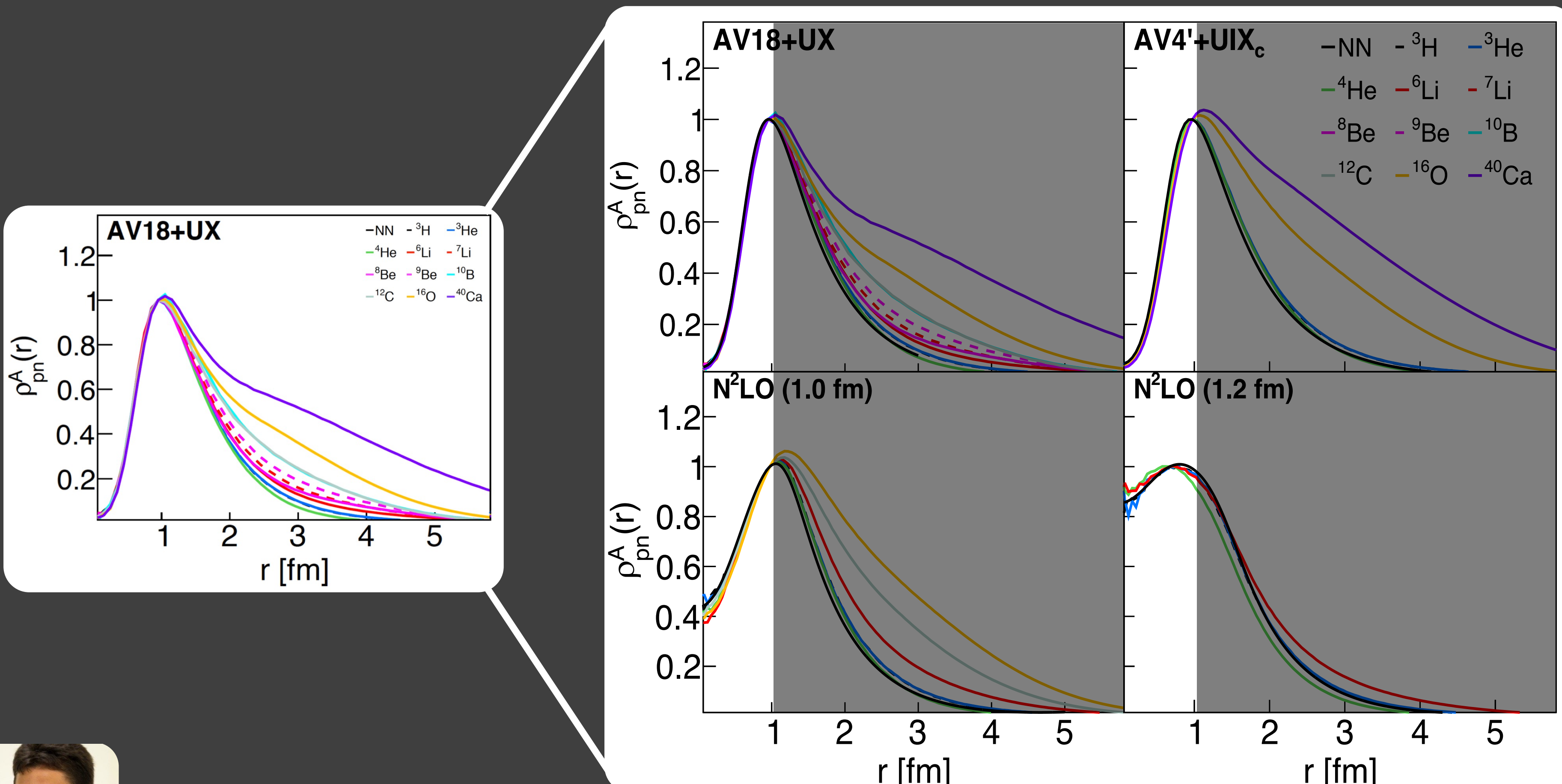
Experimental Signature: no correlation between relative & c.m. motions

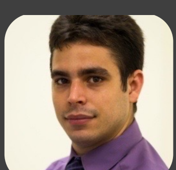
$$f\left(p_{rel}, p_{c.m.}, \theta_{rel,c.m.}\right) \approx C\left(p_{c.m.}\right) \times \varphi\left(p_{rel}\right)$$



How model dependent is all of this?
i.e., changing scale / scheme changes conclusions?

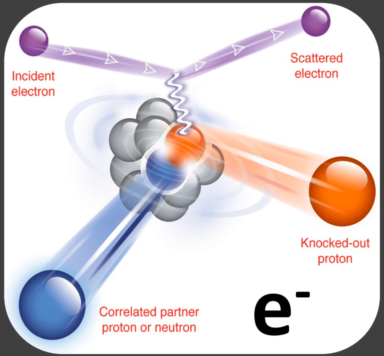
Short-distance factorization is model independent!

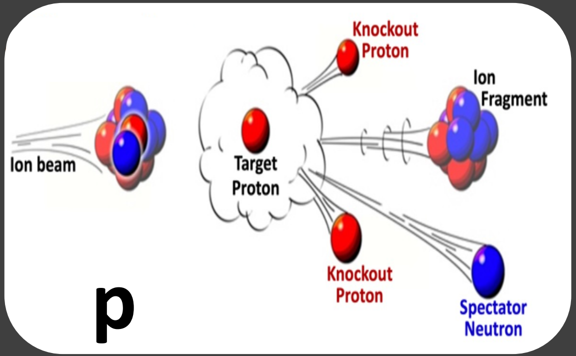


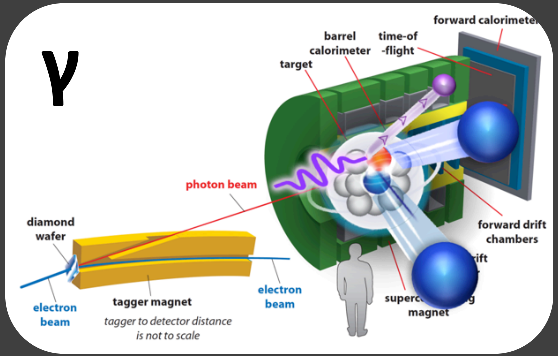


Cruz Torres et al.,
Nature Physics (2021)

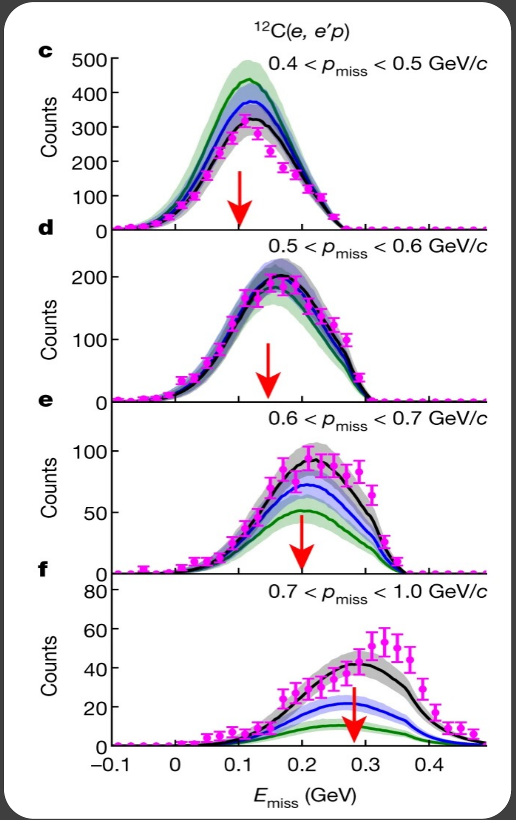
Results Independent of probe type



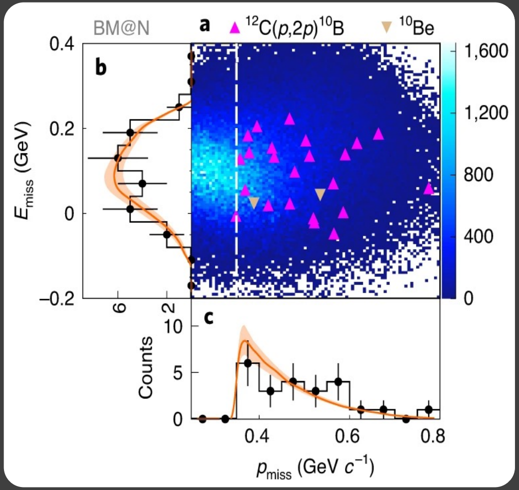


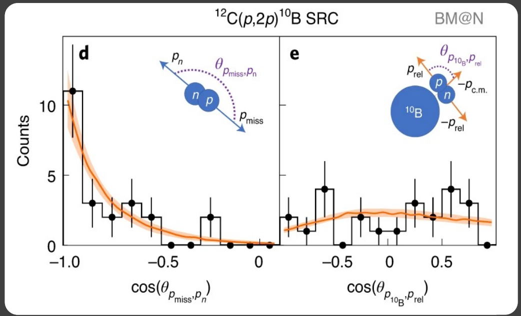


Nature '20

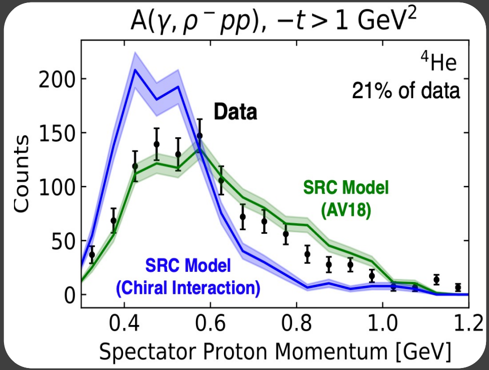


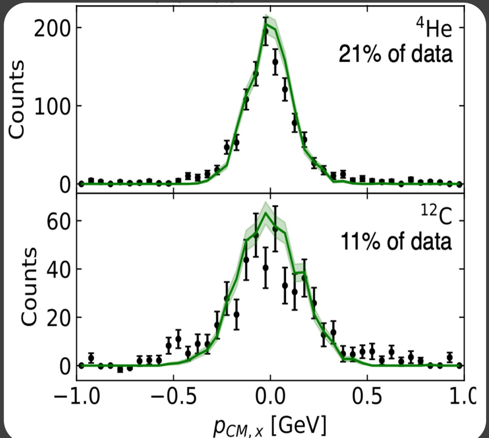
Nature Physics '21



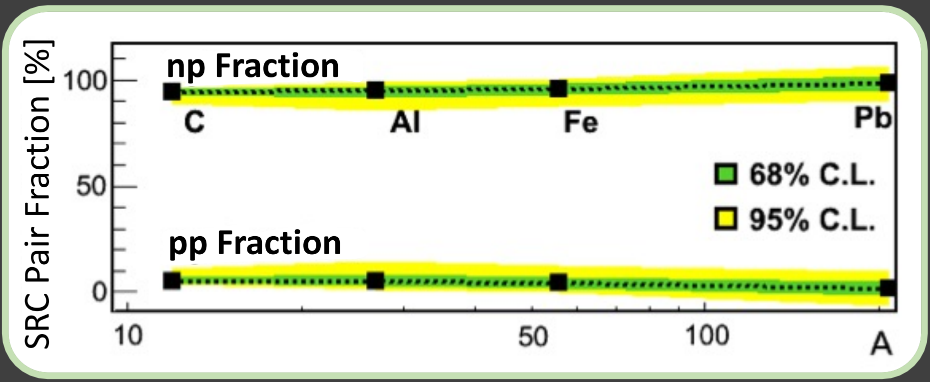


Brand new data!

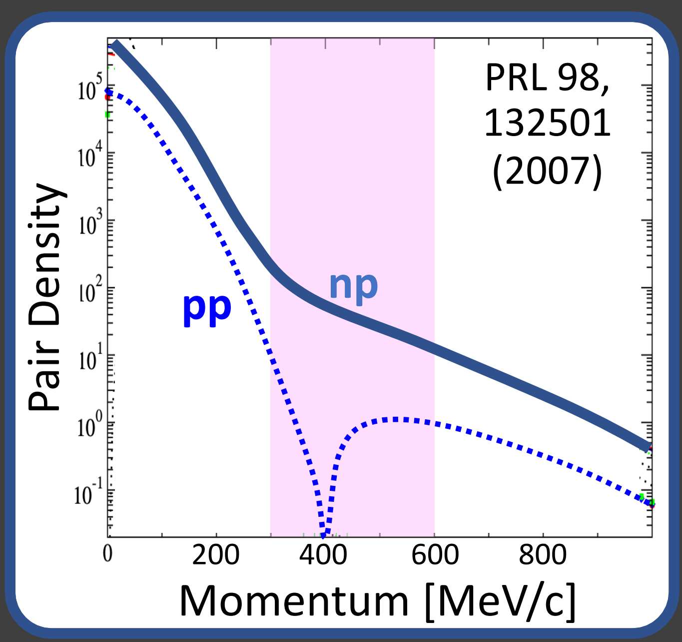




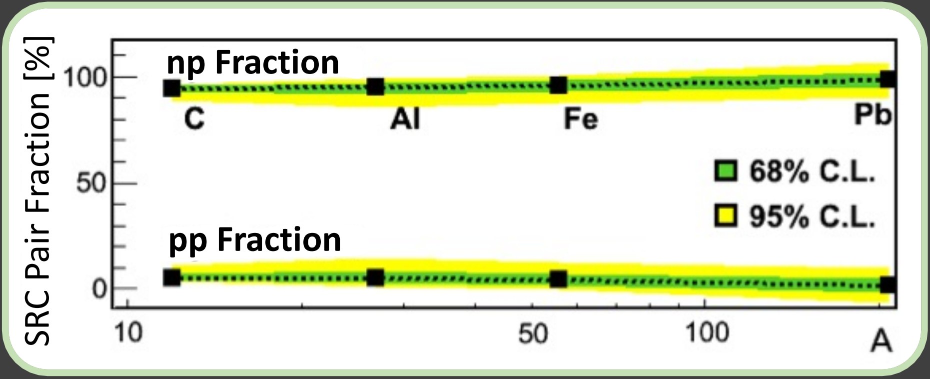
Short-Ranged Interactions



np pairs = Tensor force dominance (spin-dependent)



Short-Ranged Interactions



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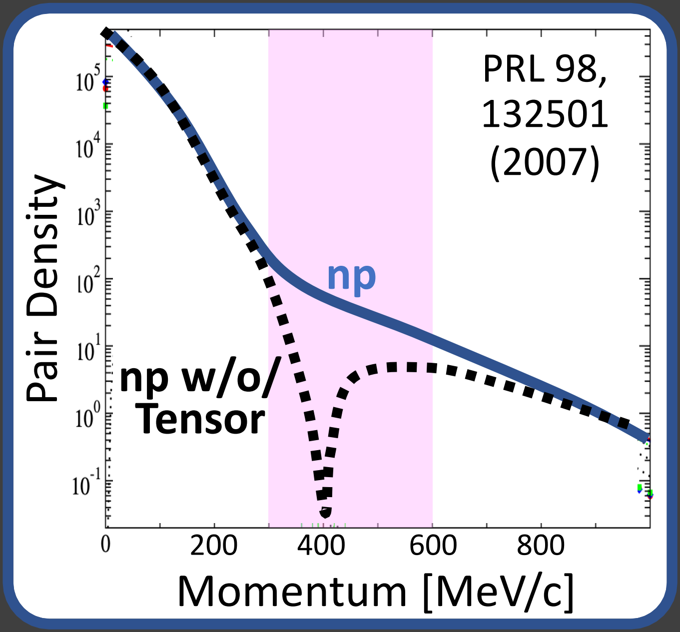
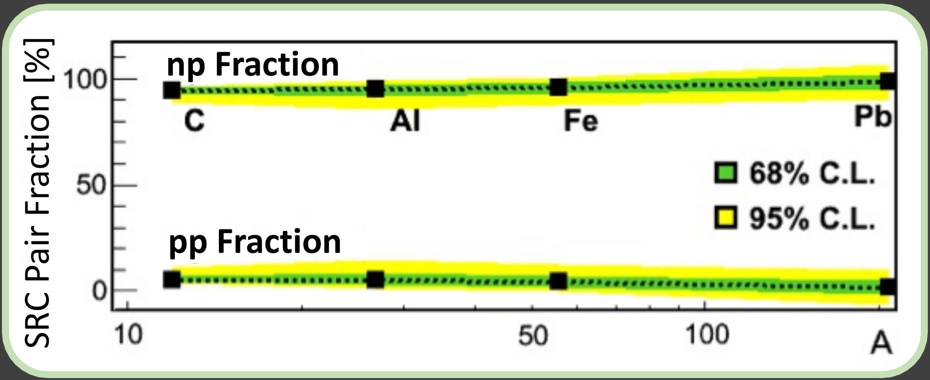
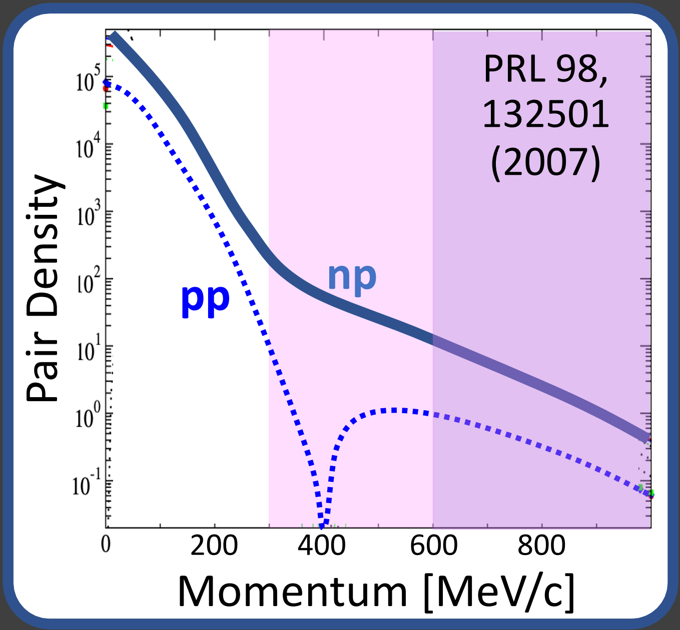


Short-Ranged Interactions



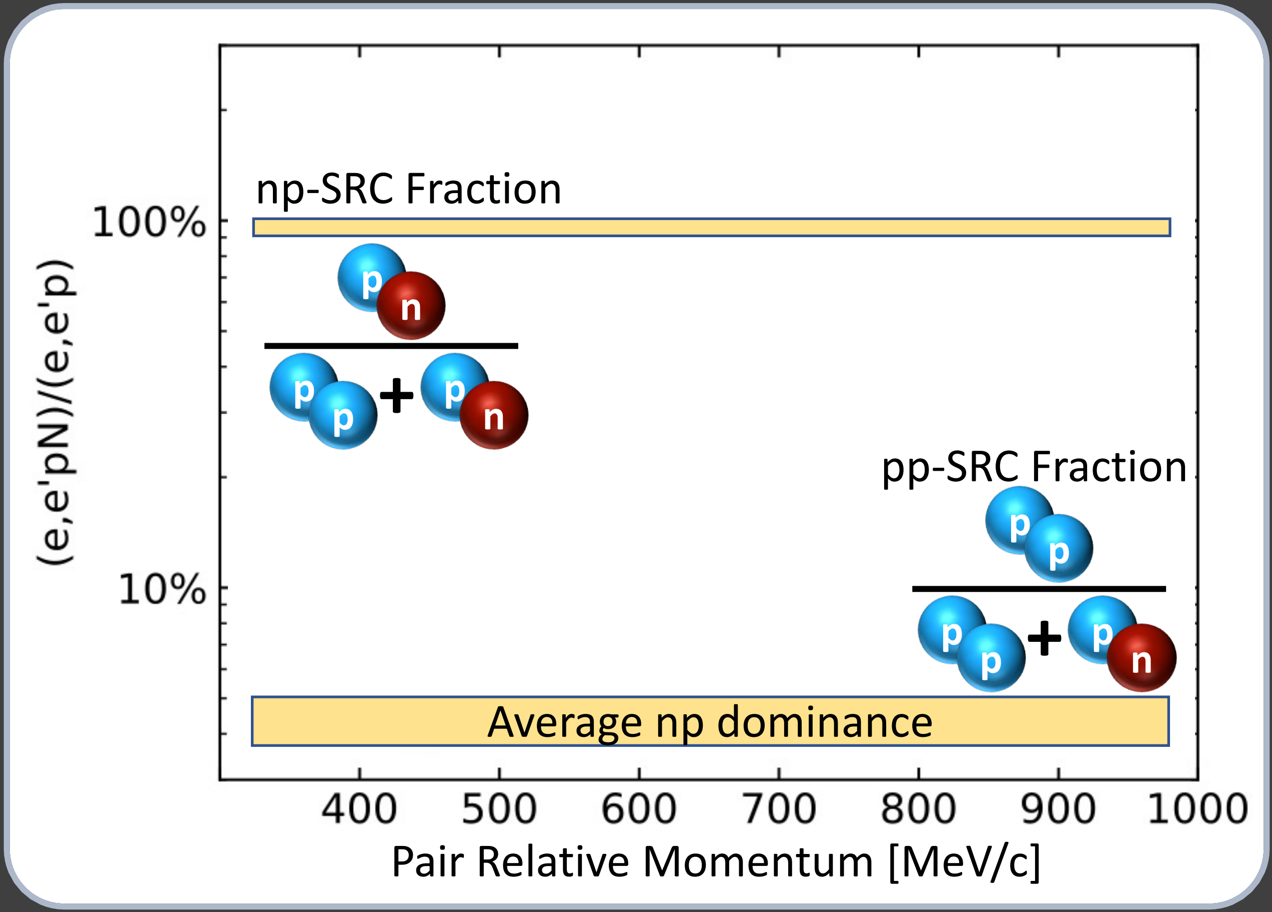
np pairs = Tensor force dominance (spin-dependent)



Repulsive core transition:

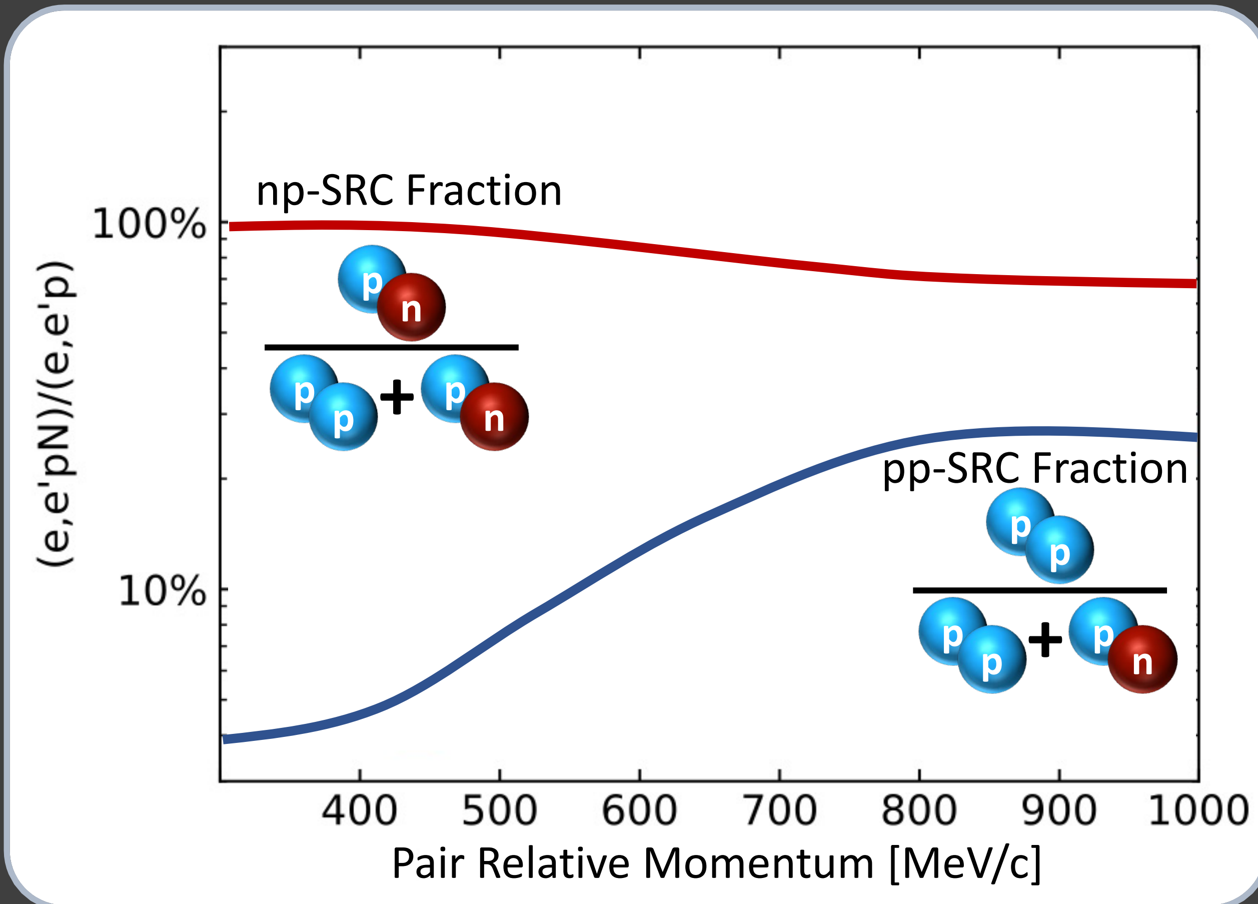
Scalar (spin-independent) core produces more pp pairs

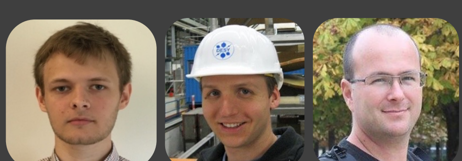
Probing the Repulsive Core



Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

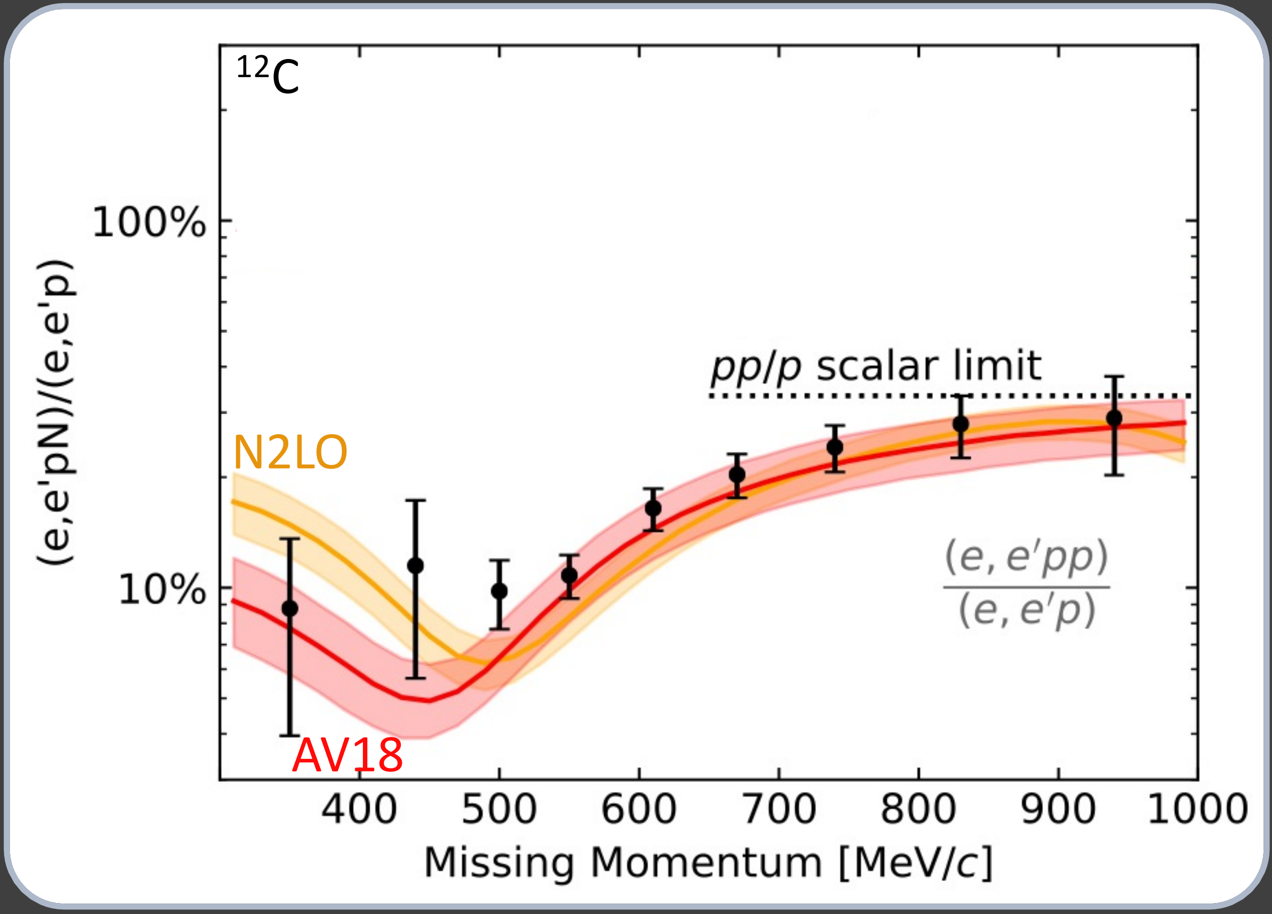
Probing the Repulsive Core





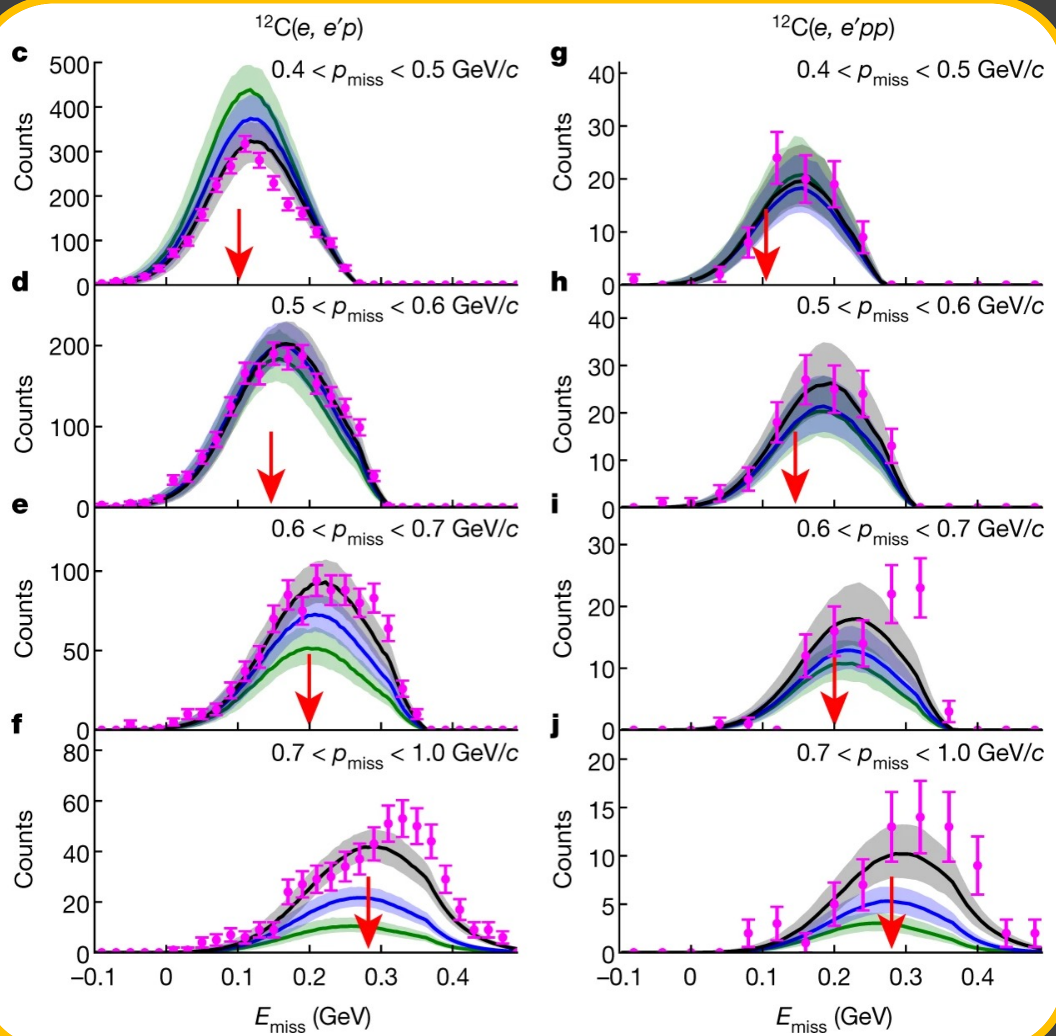
Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

Probing the Repulsive Core



Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

First Spectral Function Mapping



Momentum

400 – 500 MeV/c

500 – 600 MeV/c

600 – 700 MeV/c

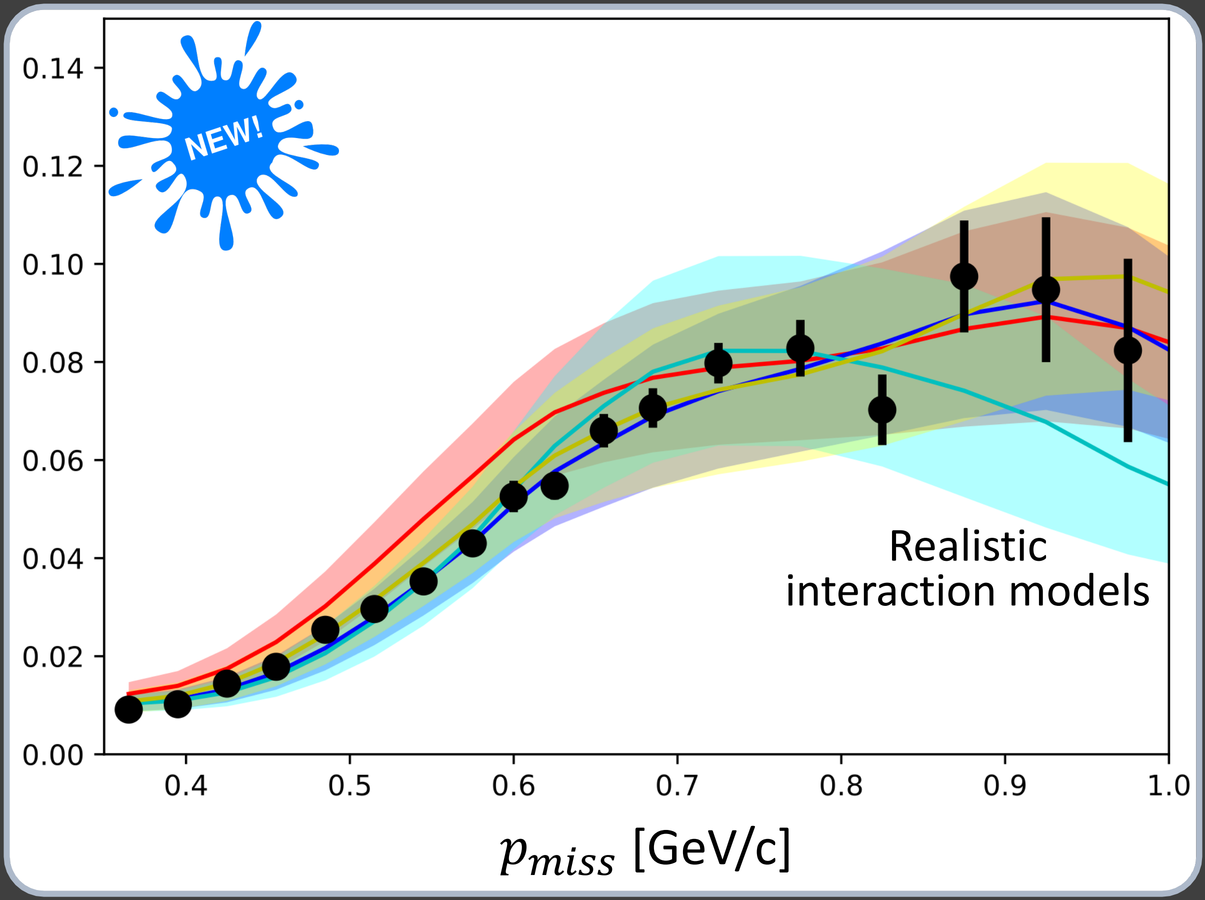
700 – 1000 MeV/c

Energy

Schmidt and Pybus
et al., Nature (2020)

New: High-Precision Data

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



<u>Nature 2020:</u> ~500 pp-SRC events

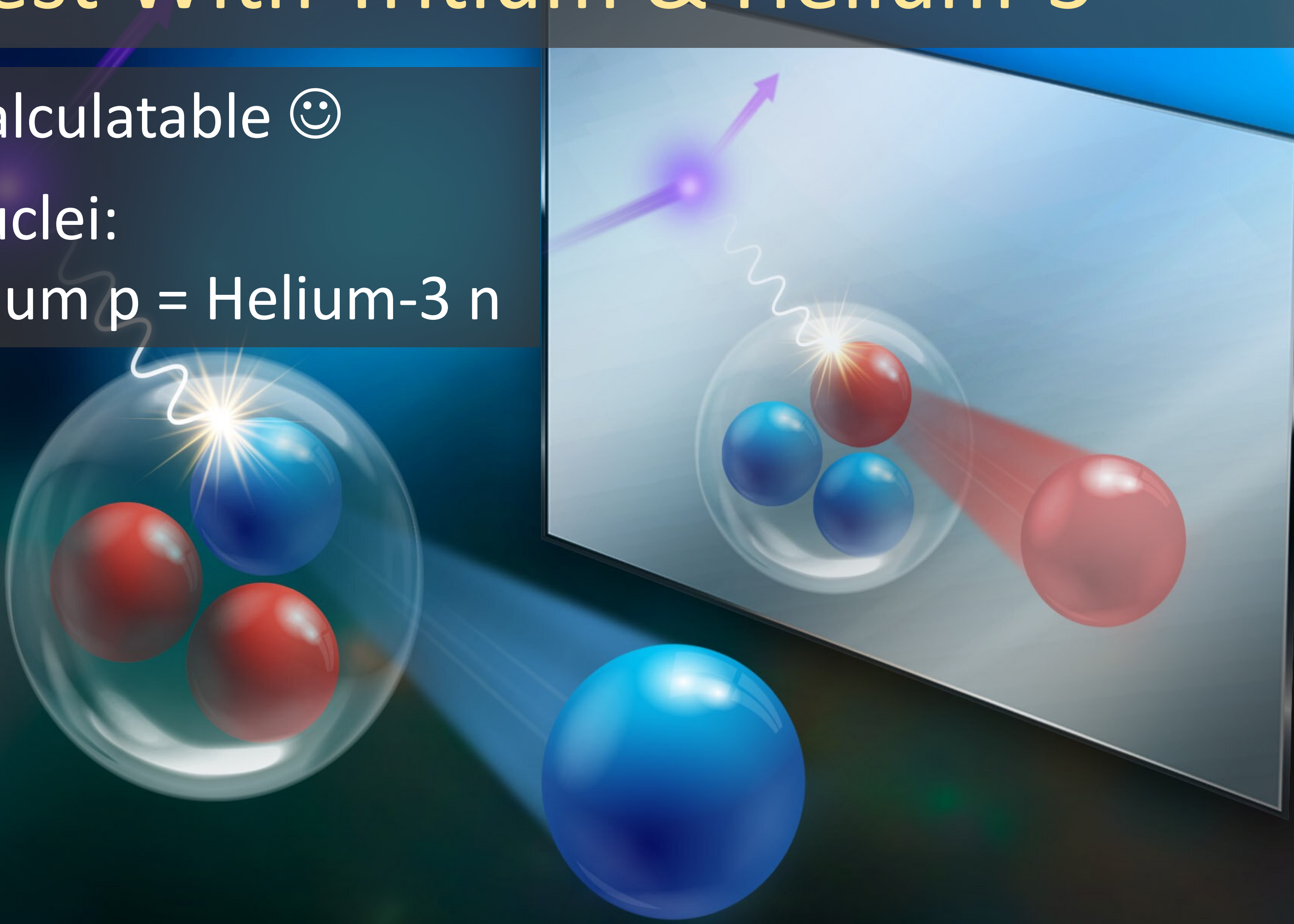
<u>New data:</u> x20 higher stat (4,000 events used above)!

Test With Tritium & Helium-3

Exactly calculatable ☺

Mirror nuclei:

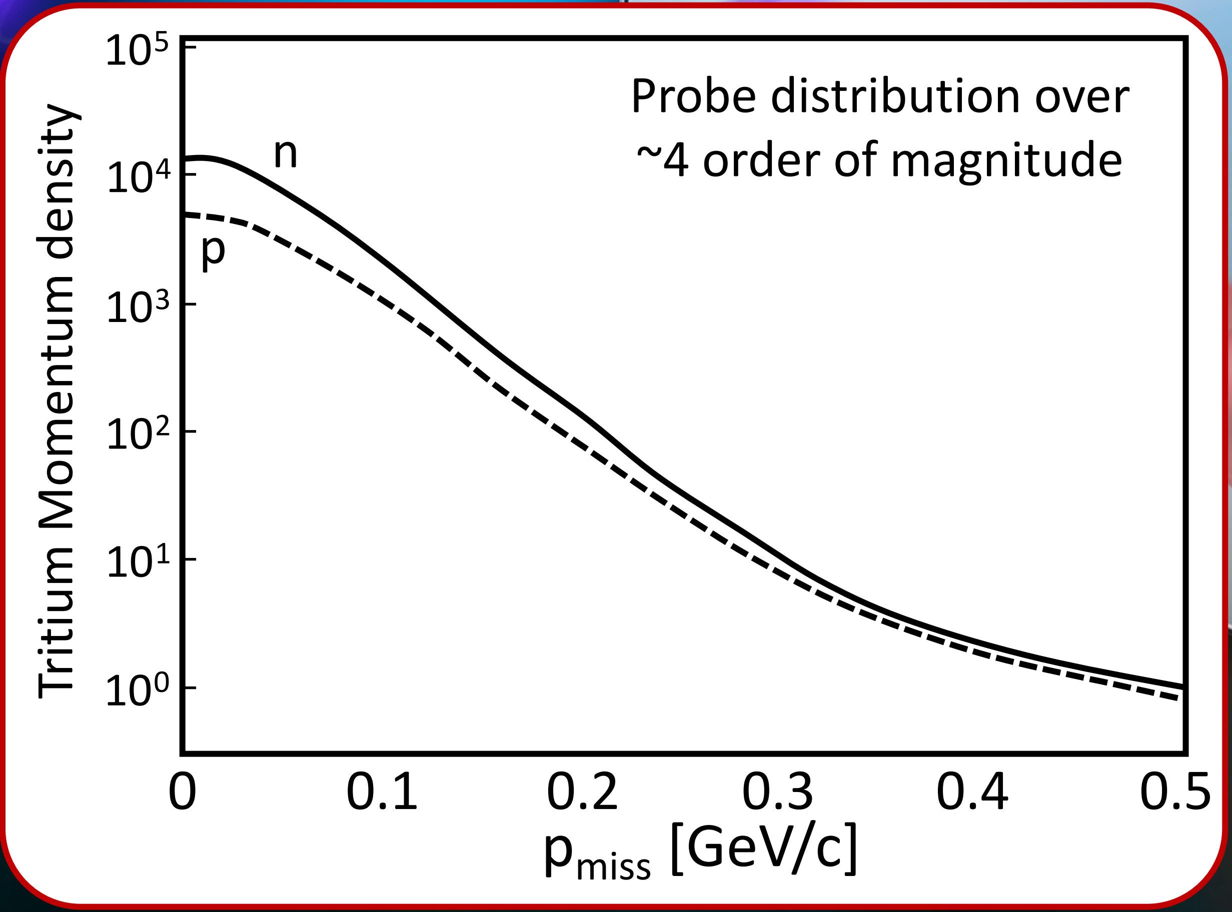
Tritium p = Helium-3 n



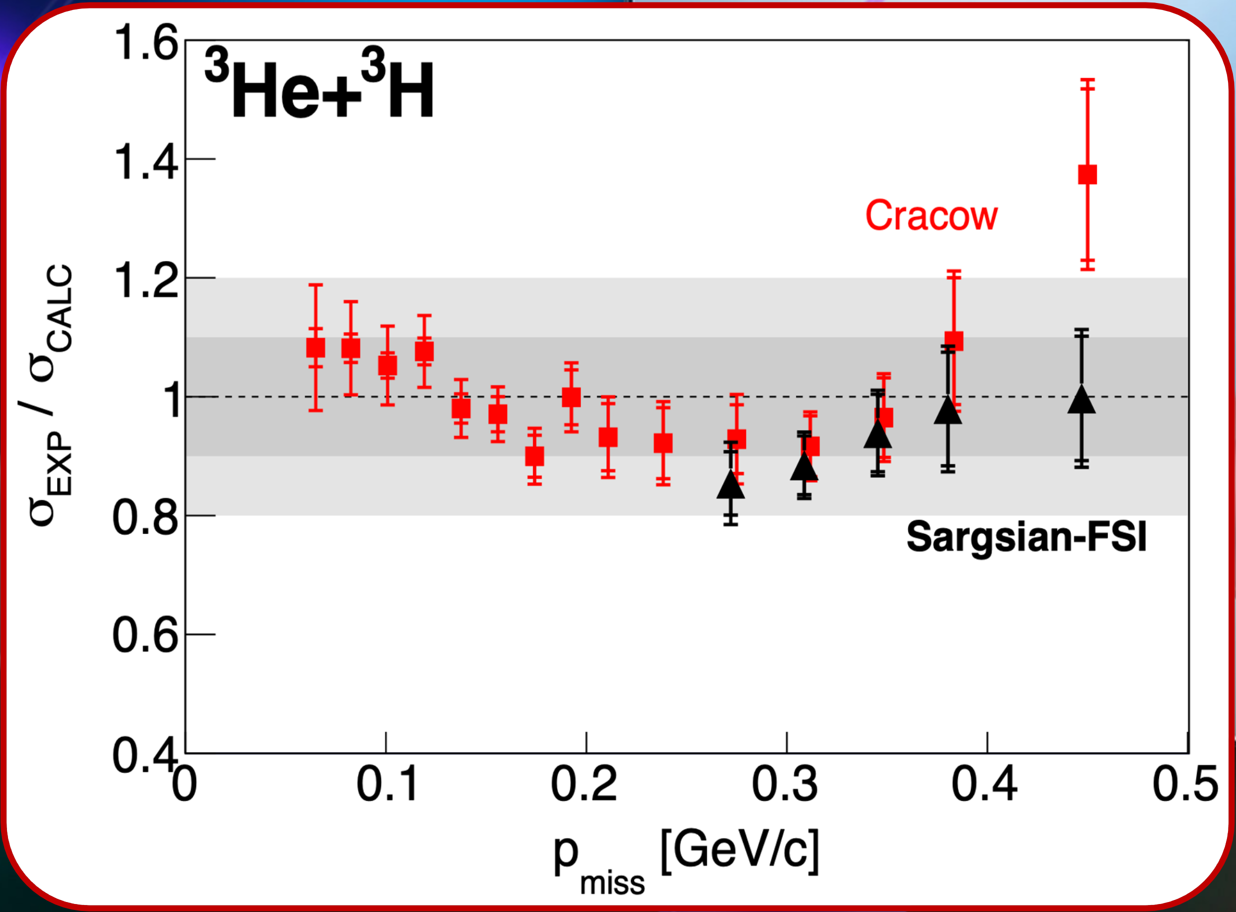
Editors' Suggestion

Cruz Torres and Nguyen et al., Phys. Rev. Lett (2020)

Challenges: Tritium Radioactivity
Low High-p States Density



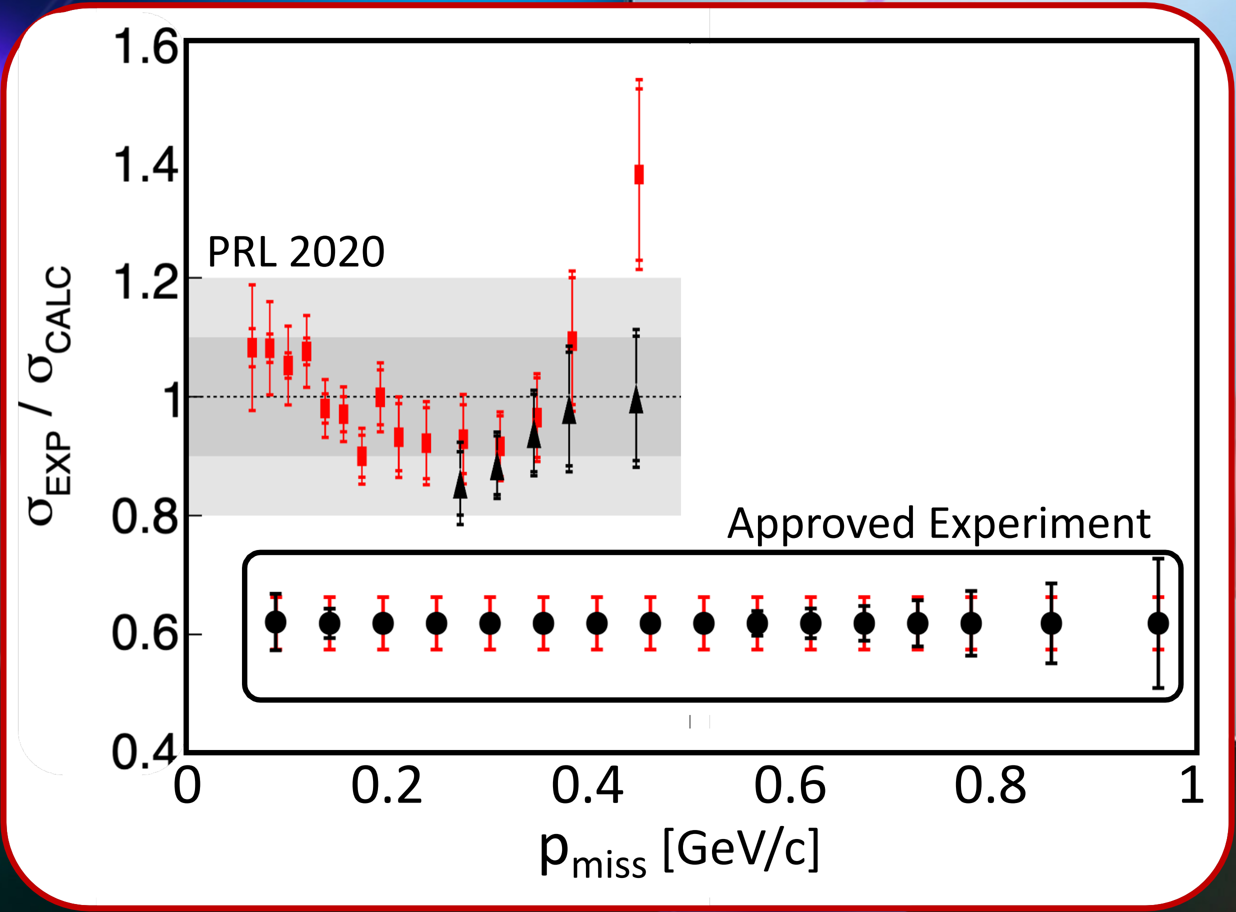
✓ Agreement Over 4 Orders of Magnitude



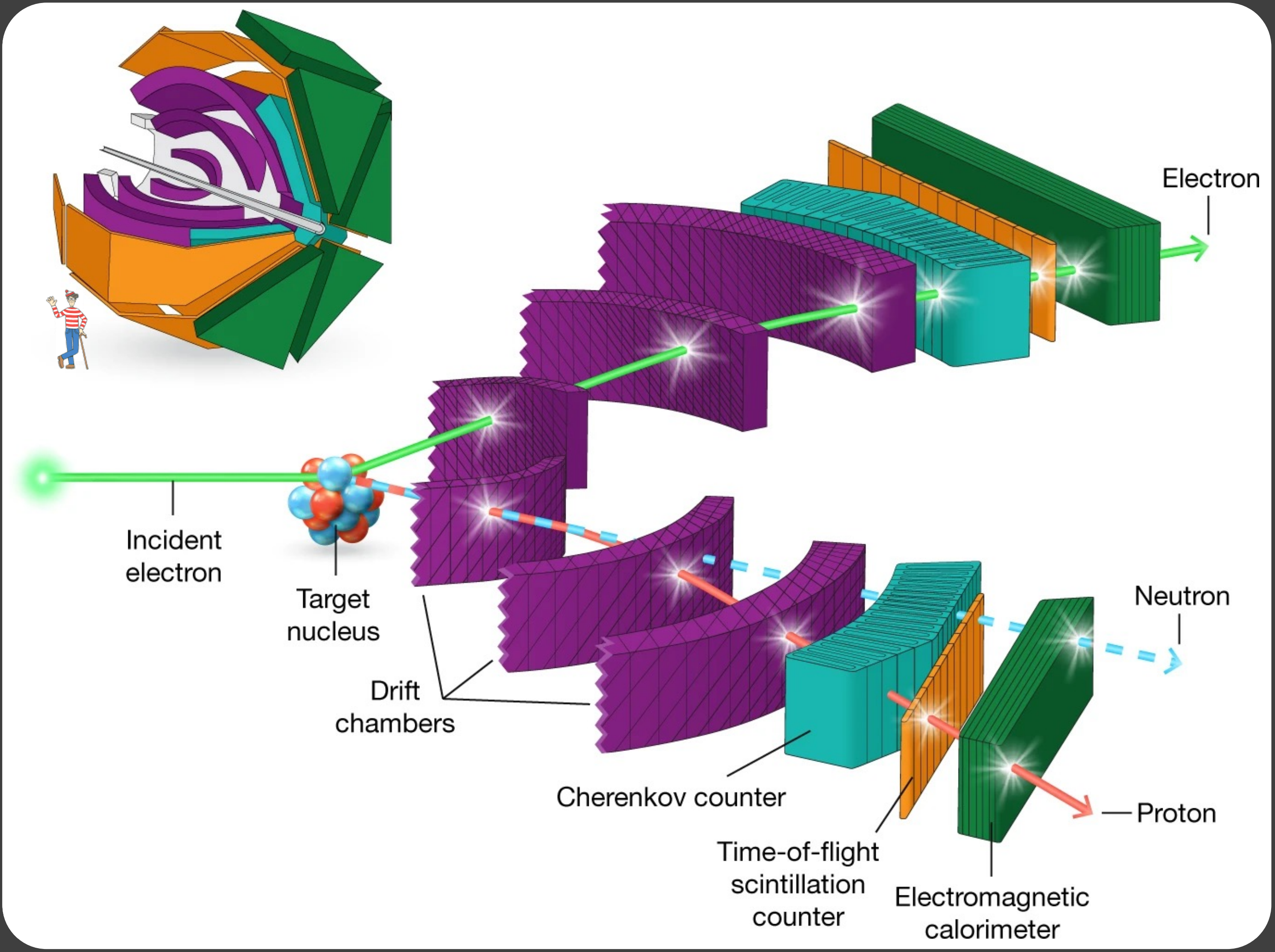
Editors' Suggestion

Cruz Torres and Nguyen et al., Phys. Rev. Lett (2020)

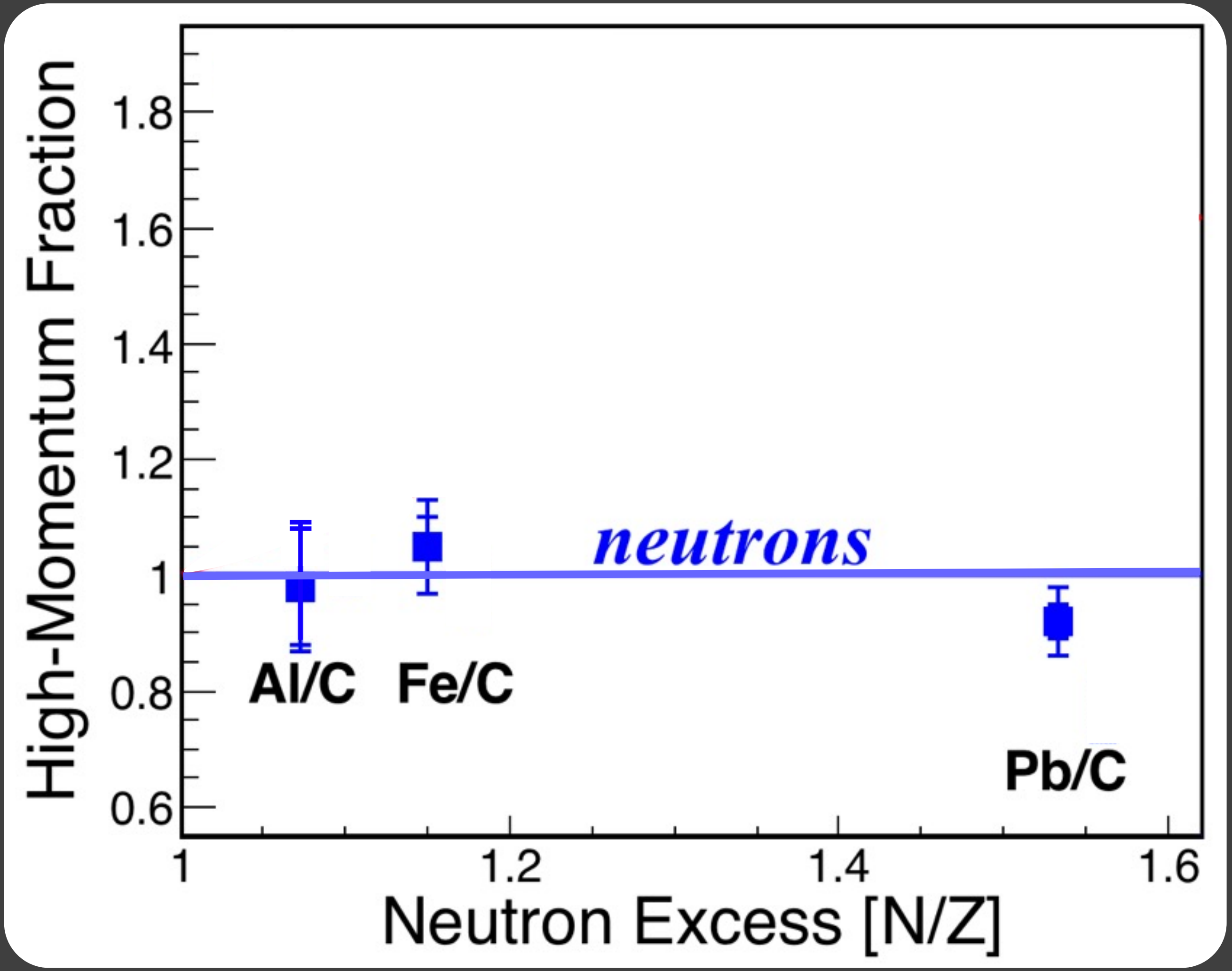
Next Step: Double the Reach



Comparing Proton & Neutron Dynamics

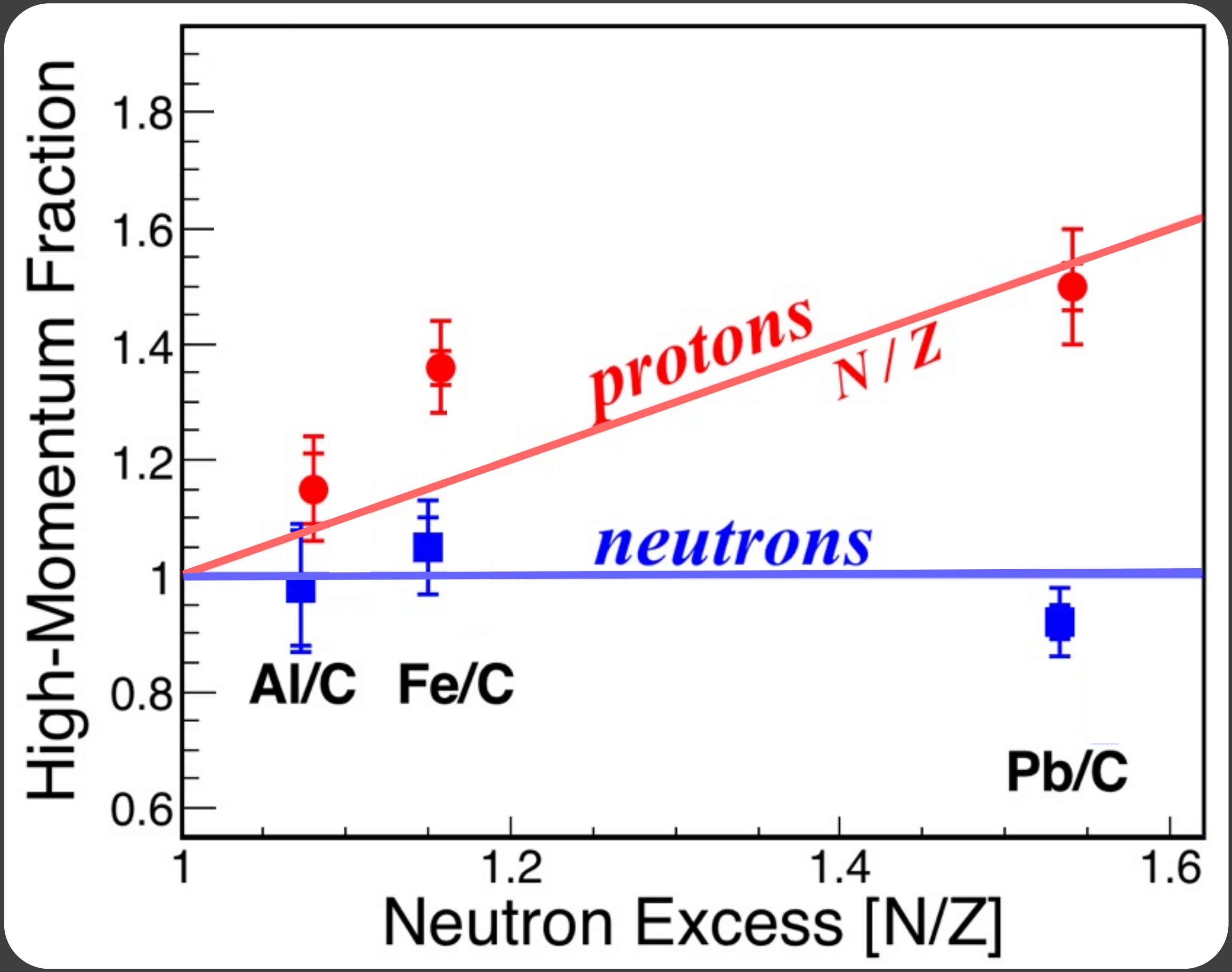


Correlation Probability:
Neutrons saturate



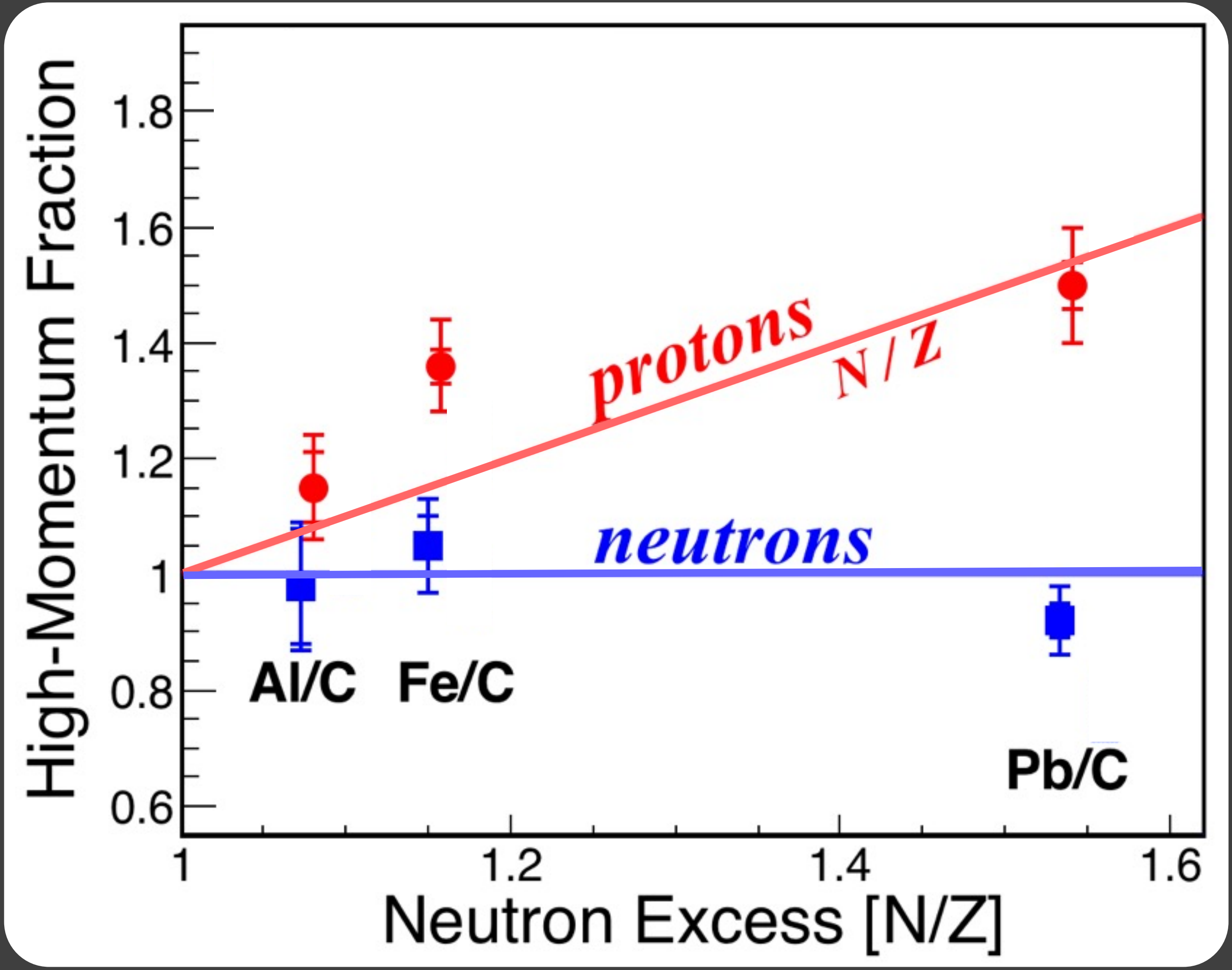
Duer Nature (2018)

Correlation Probability:
Neutrons saturate Protons grow



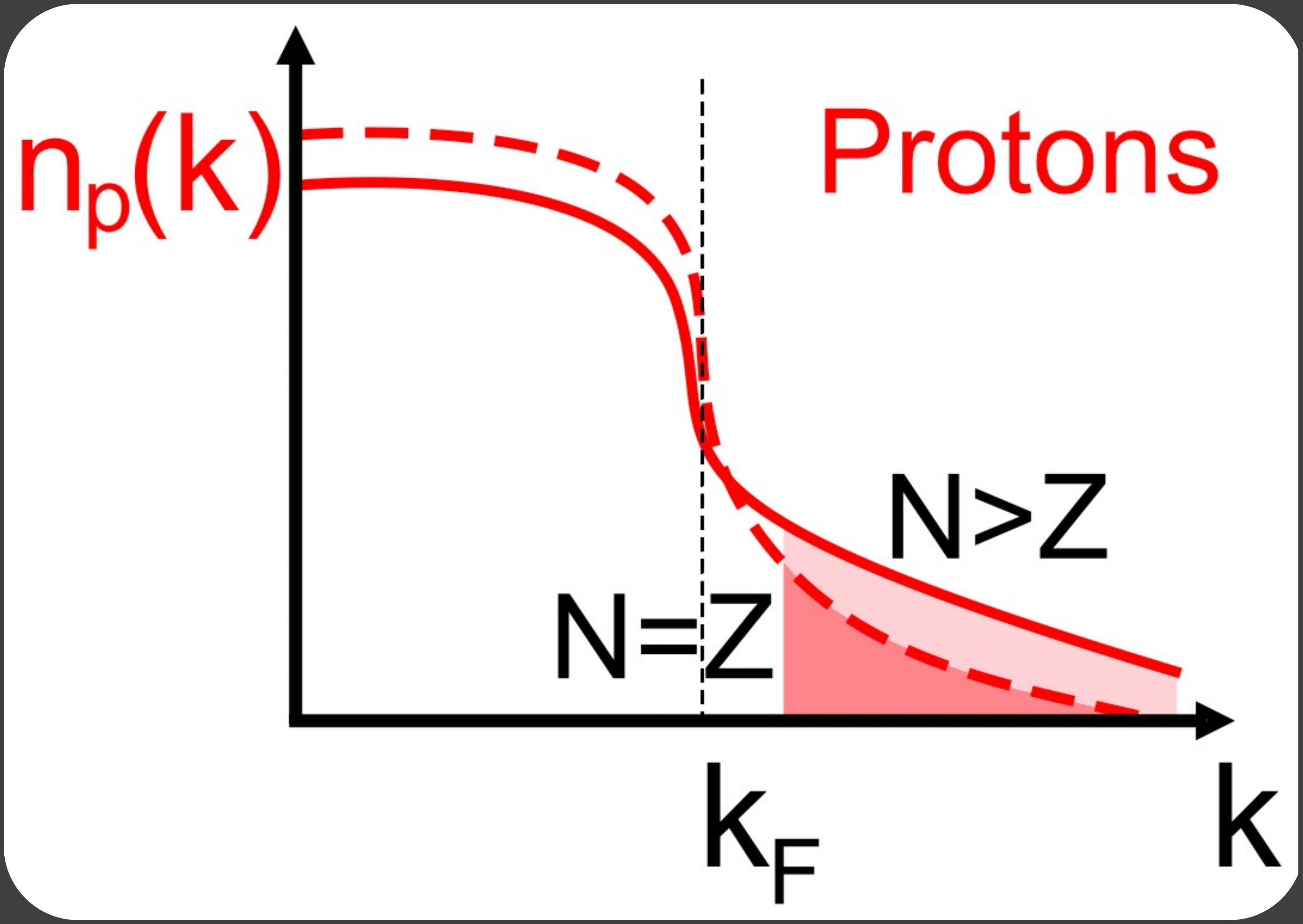
Duer Nature (2018)

Protons 'Speed-Up' In Neutron-Rich Nuclei



Duer Nature (2018)

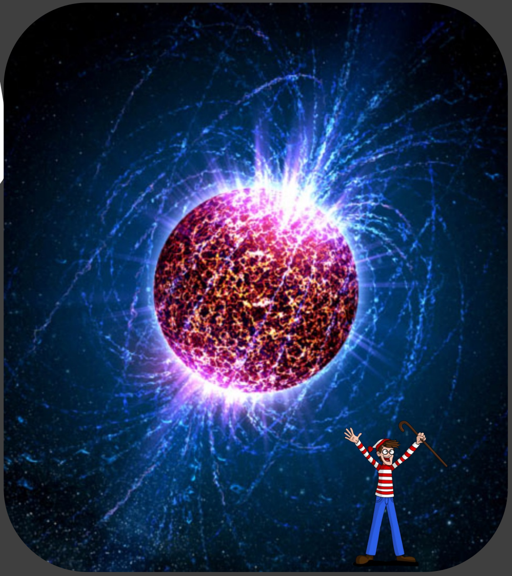
Protons 'Speed-Up' In Neutron-Rich Nuclei



Duer Nature (2018)

Daily Press

Jefferson Lab breaks new ground, from nucleons to neutron stars

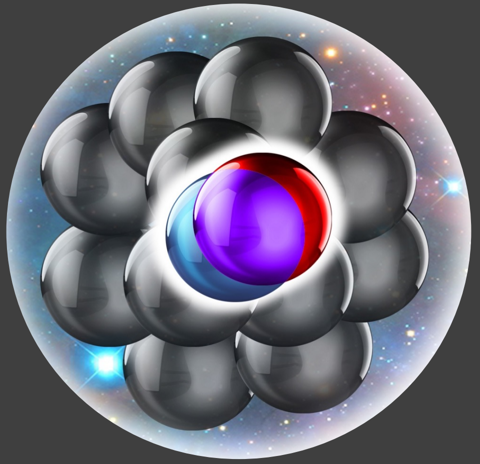


PHYS ORG

Protons may have an outsize influence on the properties of neutron stars and other neutron-rich objects

Space Answers

Protons strongly influence the behaviour of neutron stars



Astronomy Now

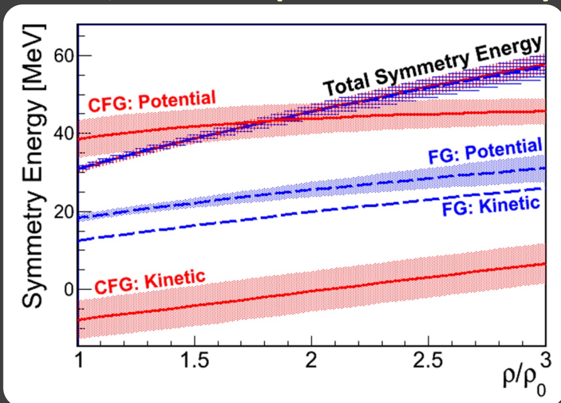
physicsworld

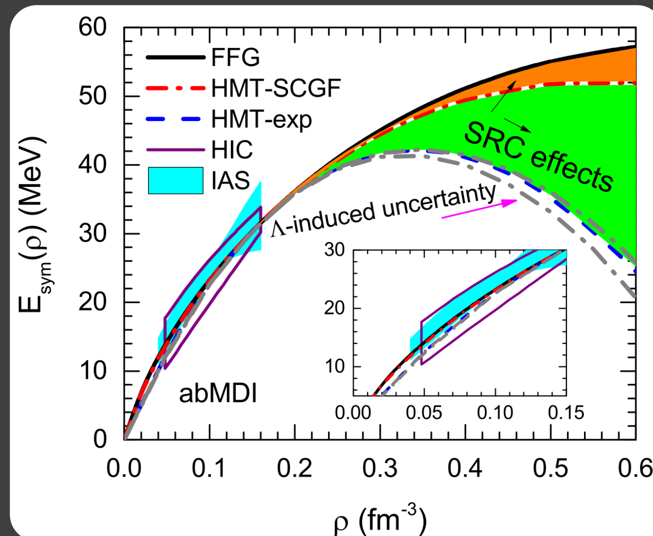
GIZMODO

Surprising Accelerator Finding Could Change the Way We Think About Neutron Stars

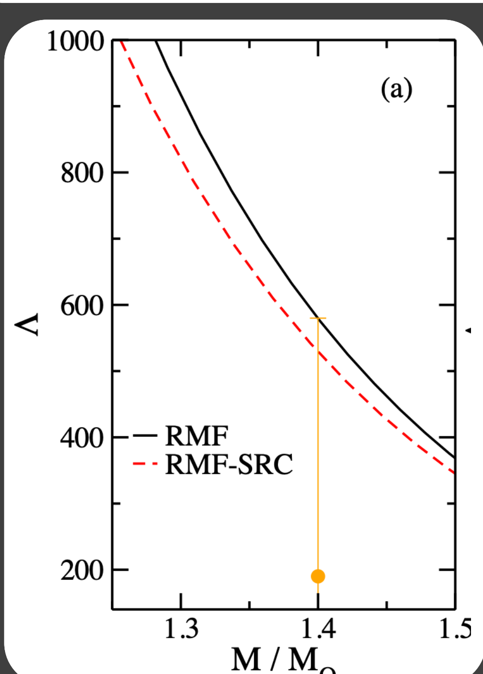
Affects neutron star calculations

Hen+, PRC '15 (>100 citations)

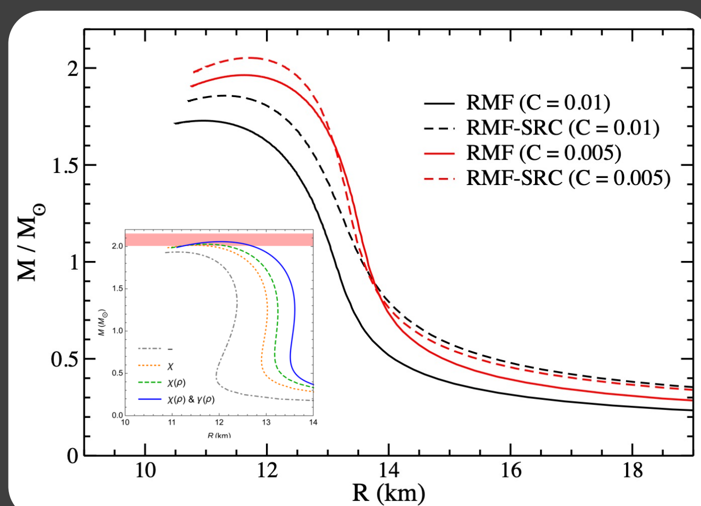


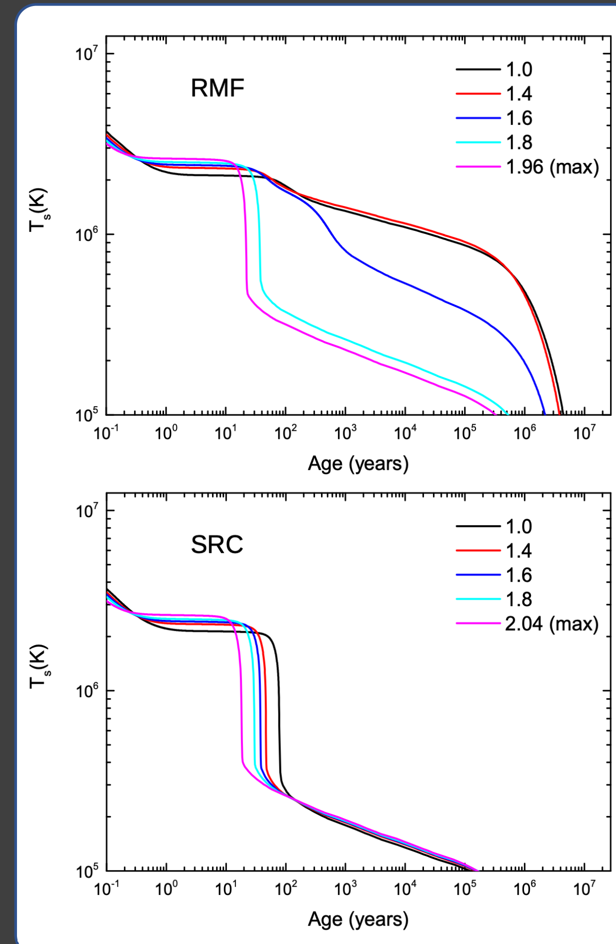


Prog. Part. Nucl. Phys. 99, 29 (2018)
Eur. Phys. J. A 55, 117 (2015)



PRC 101, 065202 (2020)
NPA 990, 118 (2019)



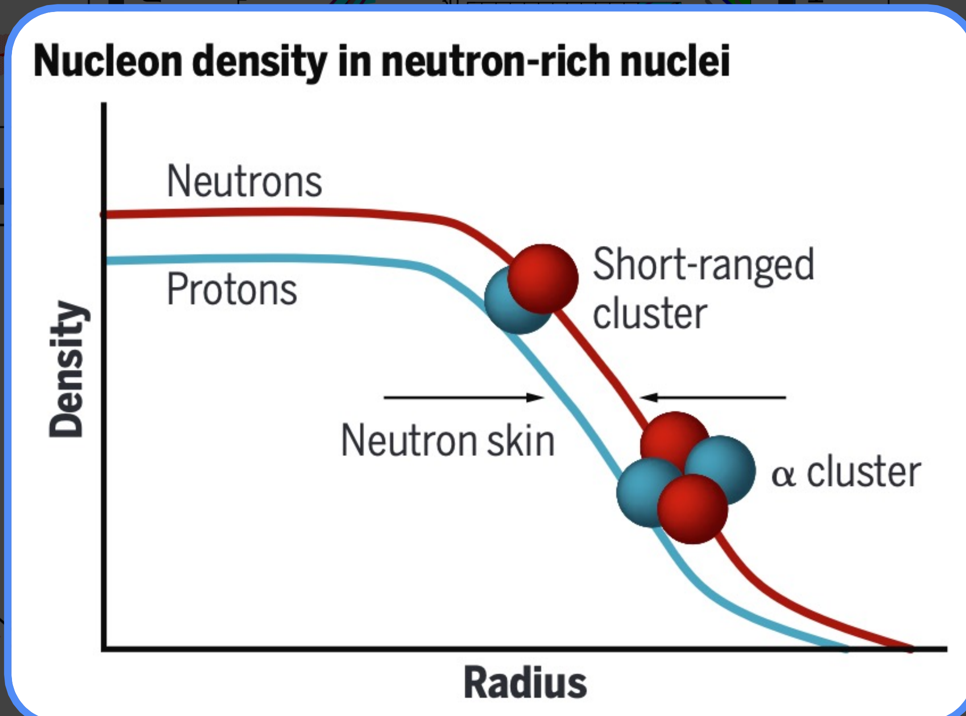


arXiv 2004.10309

INSIGHTS | PERSPECTIVES
Science AAAS

NUCLEAR PHYSICS

From nuclear clusters to neutron stars



arXiv 2004.10309

Hen, Science 371, 232 (2021)
Tanaka et al., Science 371, 260 (2021)
Miller et al., Phys. Lett. B 793, 360 (2019)