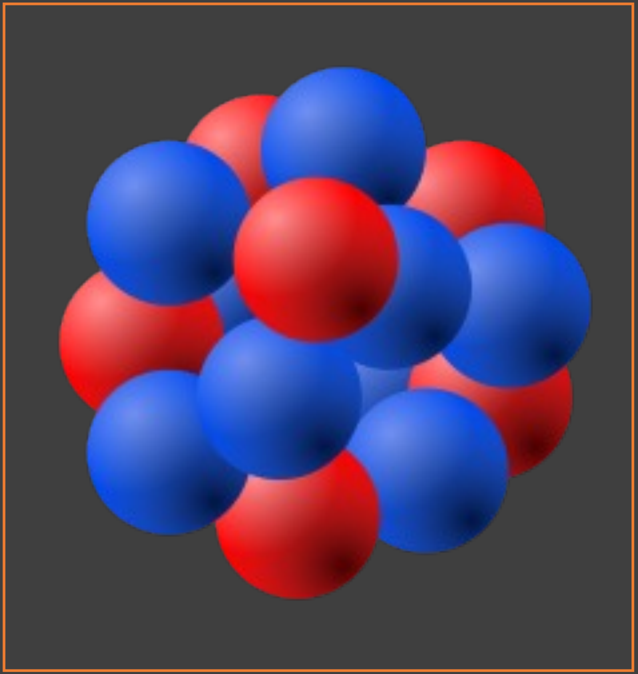
Electron-Nucleus Scattering and Short Range Correlations: Introduction and Overview

Or Hen
(MIT)

4th International Workshop on Quantitative Challenges in SRC & EMC Effect Research, CEA France, Jan 30th (2023)

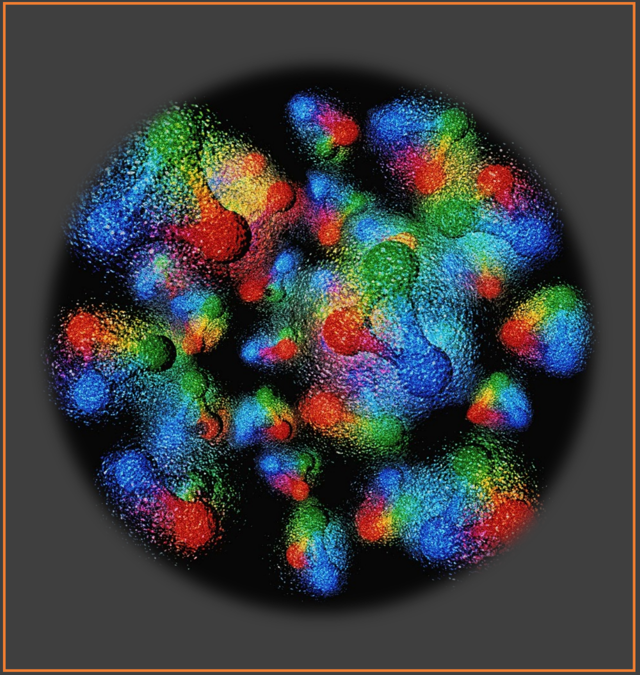
Hen Lab
Laboratory for Nuclear Science @ MIT

Nuclei: At the Heart of Visible Matter



Described by protons and neutrons, but made of quarks and gluons

→ To understand the visible universe from the Standard Model we must understand nuclei from QCD



(one) Challenge: short-distance structure, where distance scales ≤ nucleon radius

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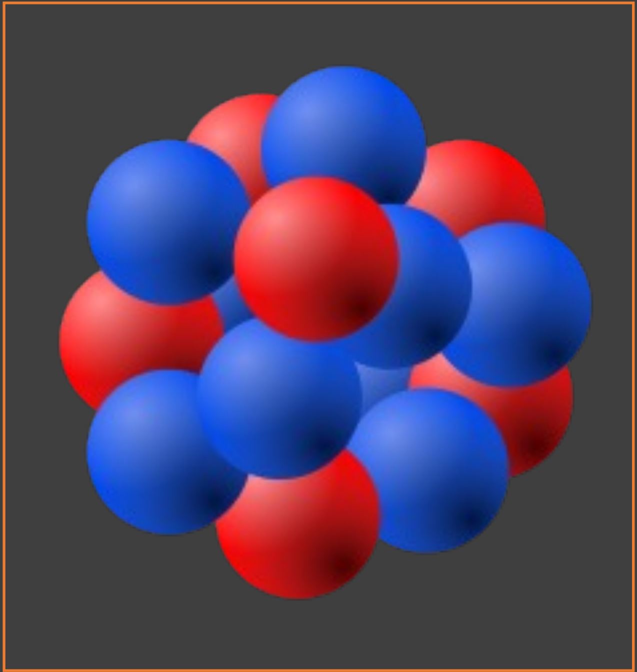

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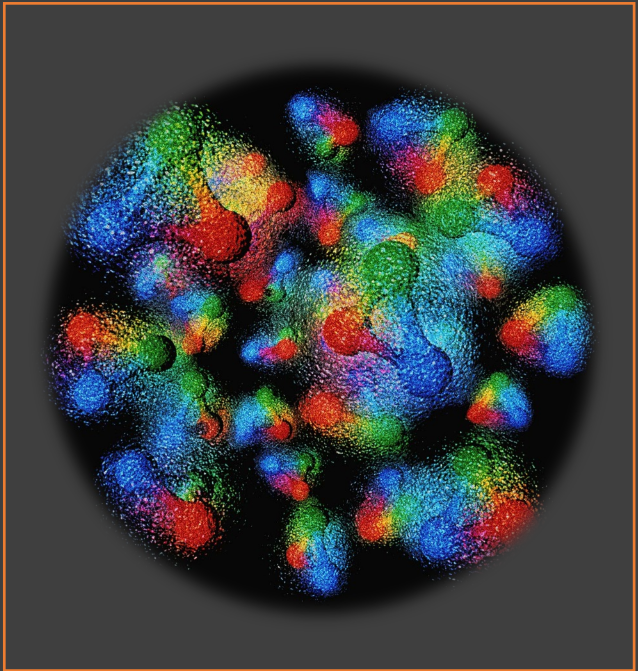

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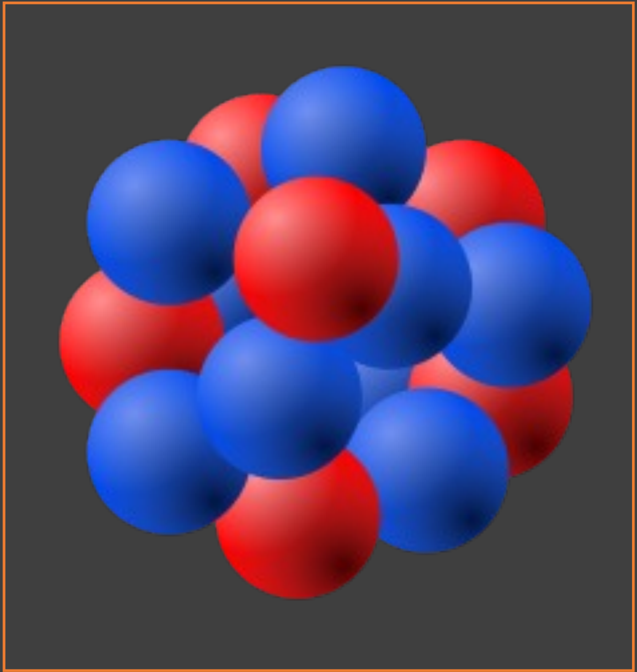

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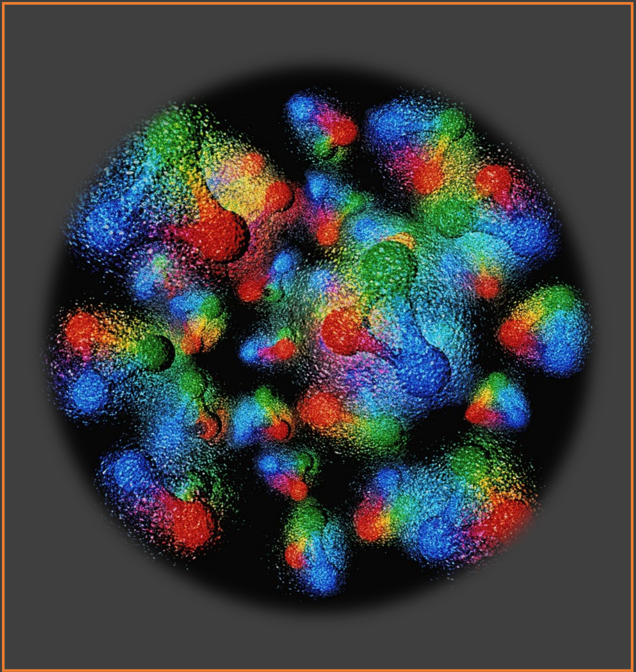

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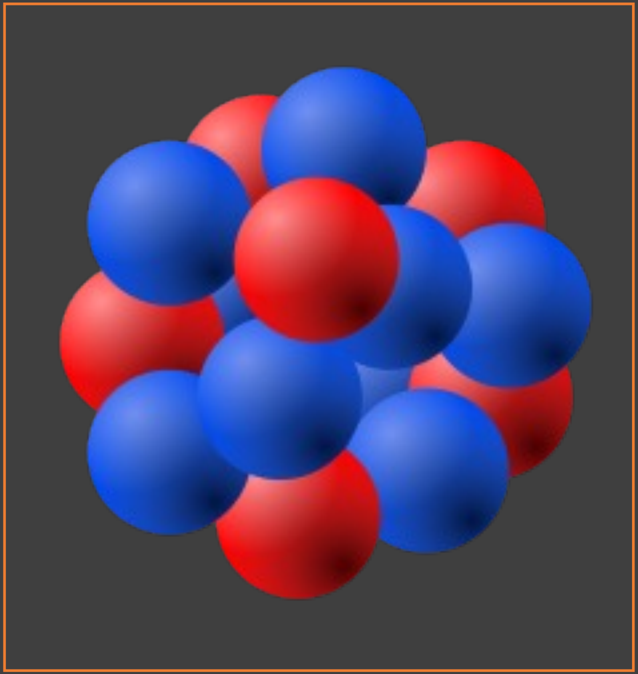

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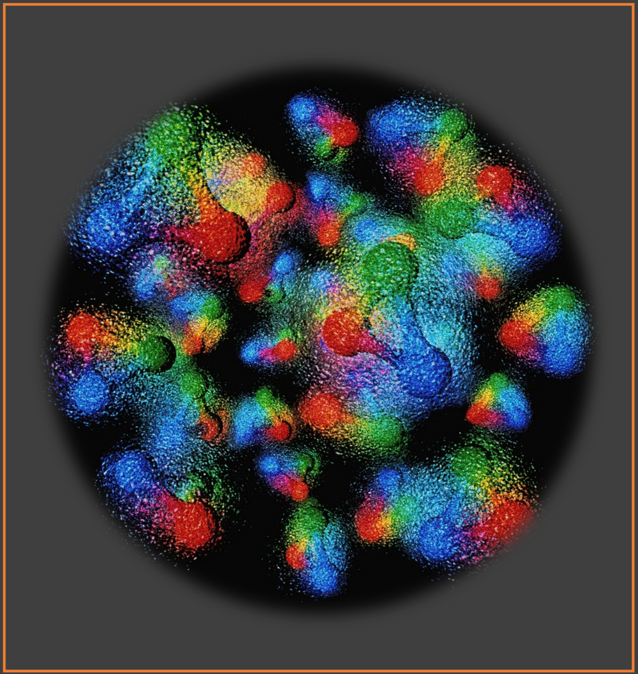

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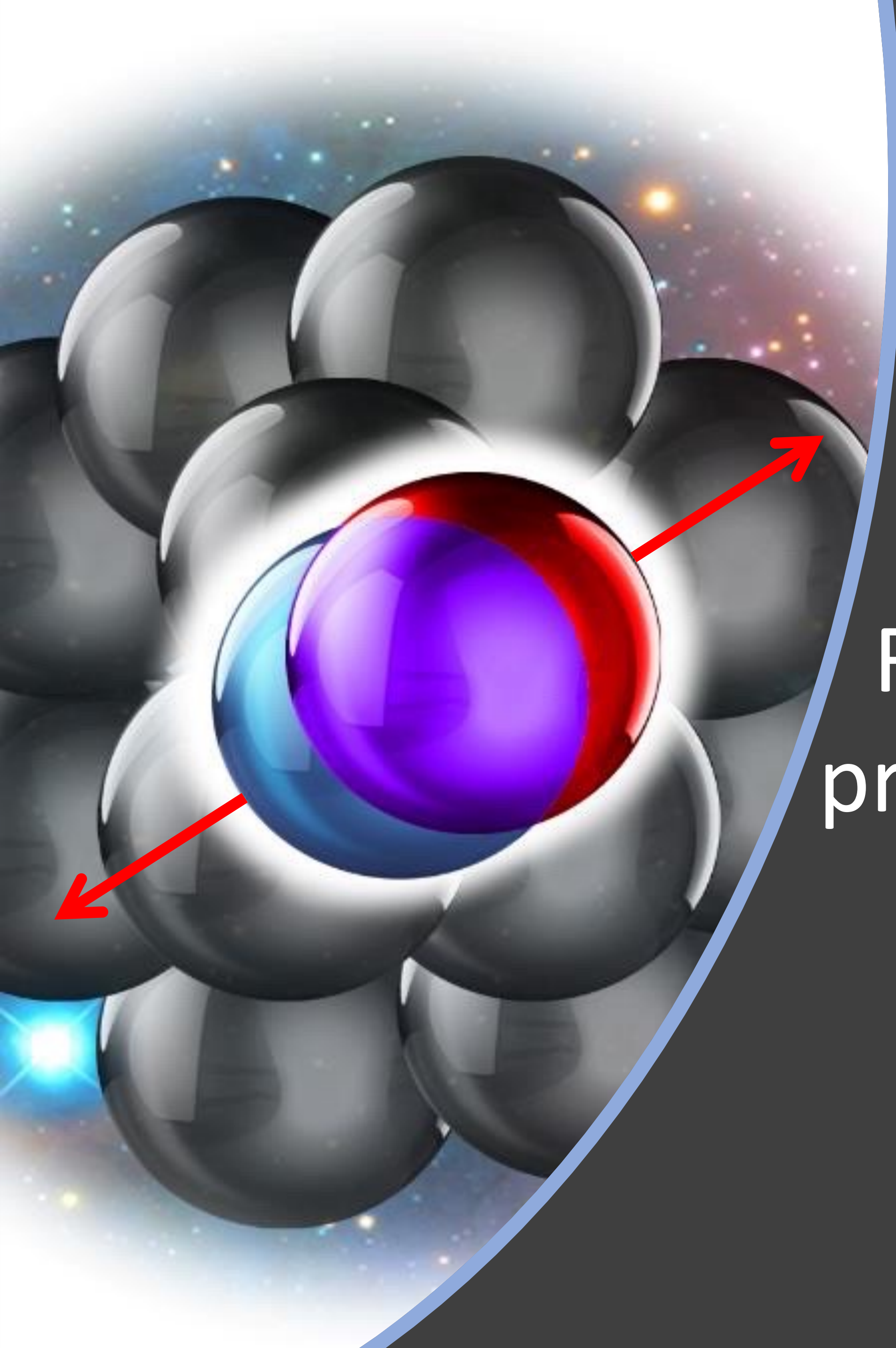
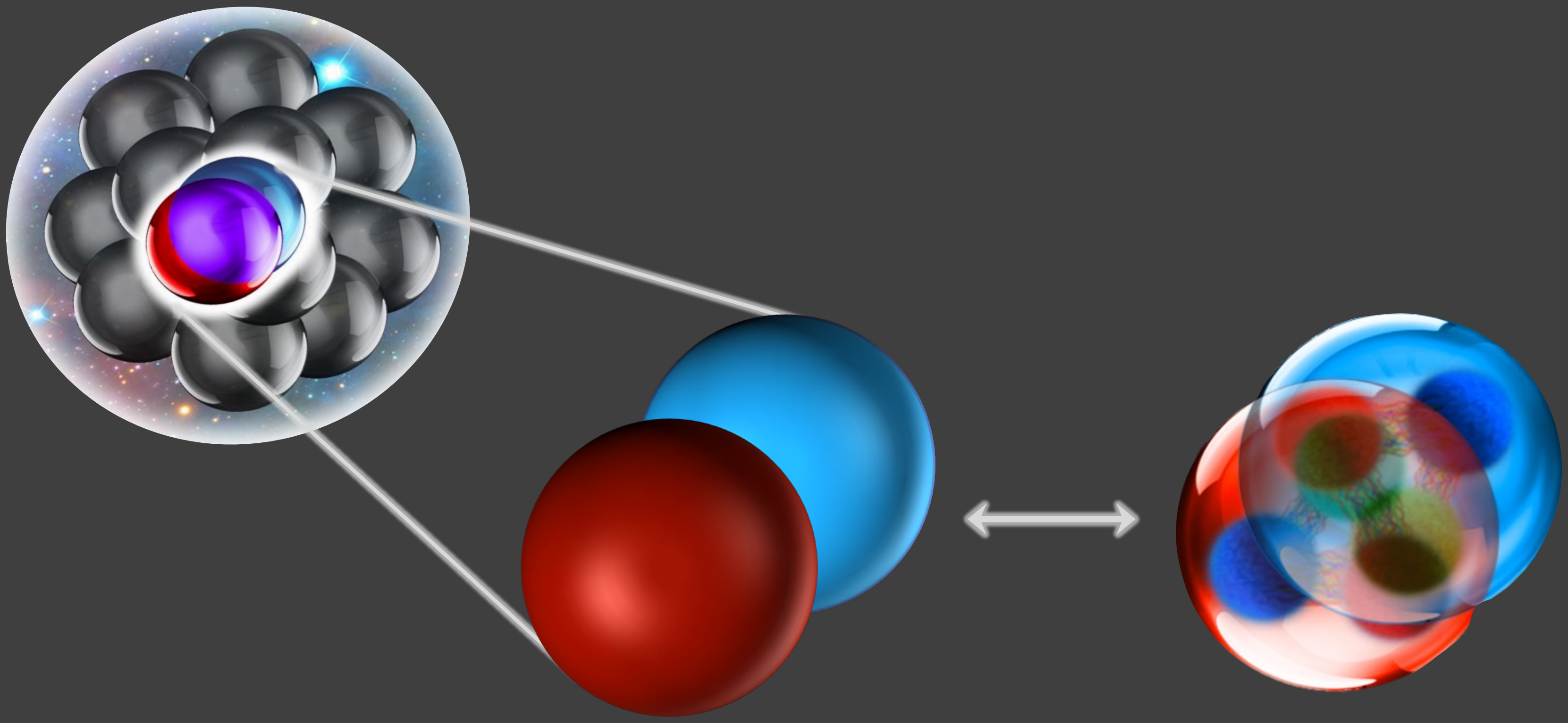


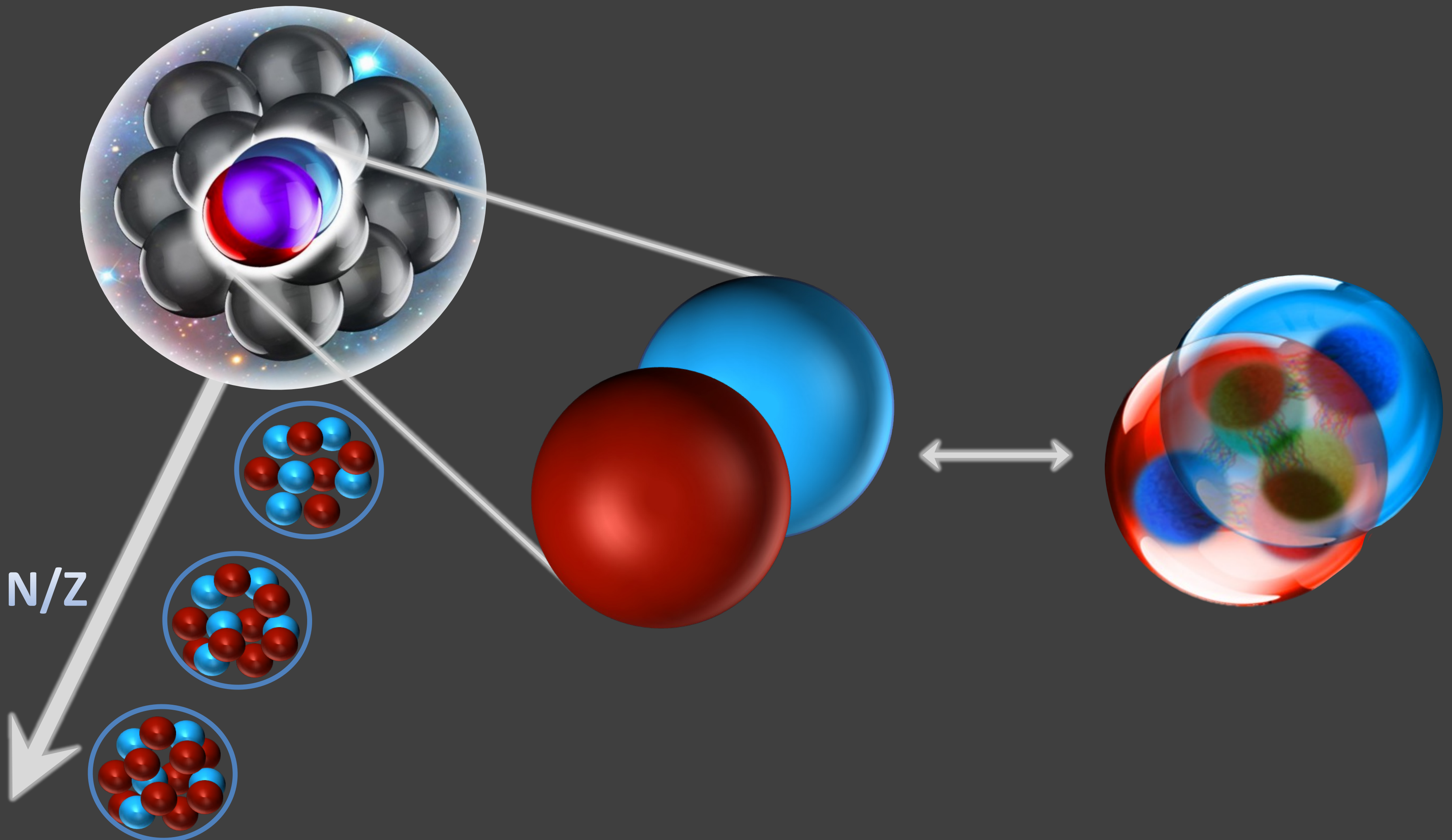
Short-Range Correlations (SRC)

Fluctuations of close-proximity nucleon pairs

Goal: Understand SRCs Across Nuclear Scales



Goal: Understand SRCs Across Nuclear Scales and Along the Nuclear Chart

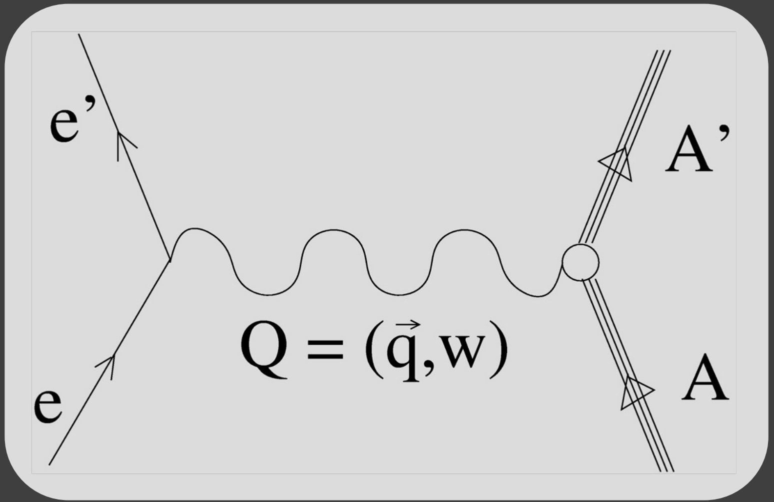


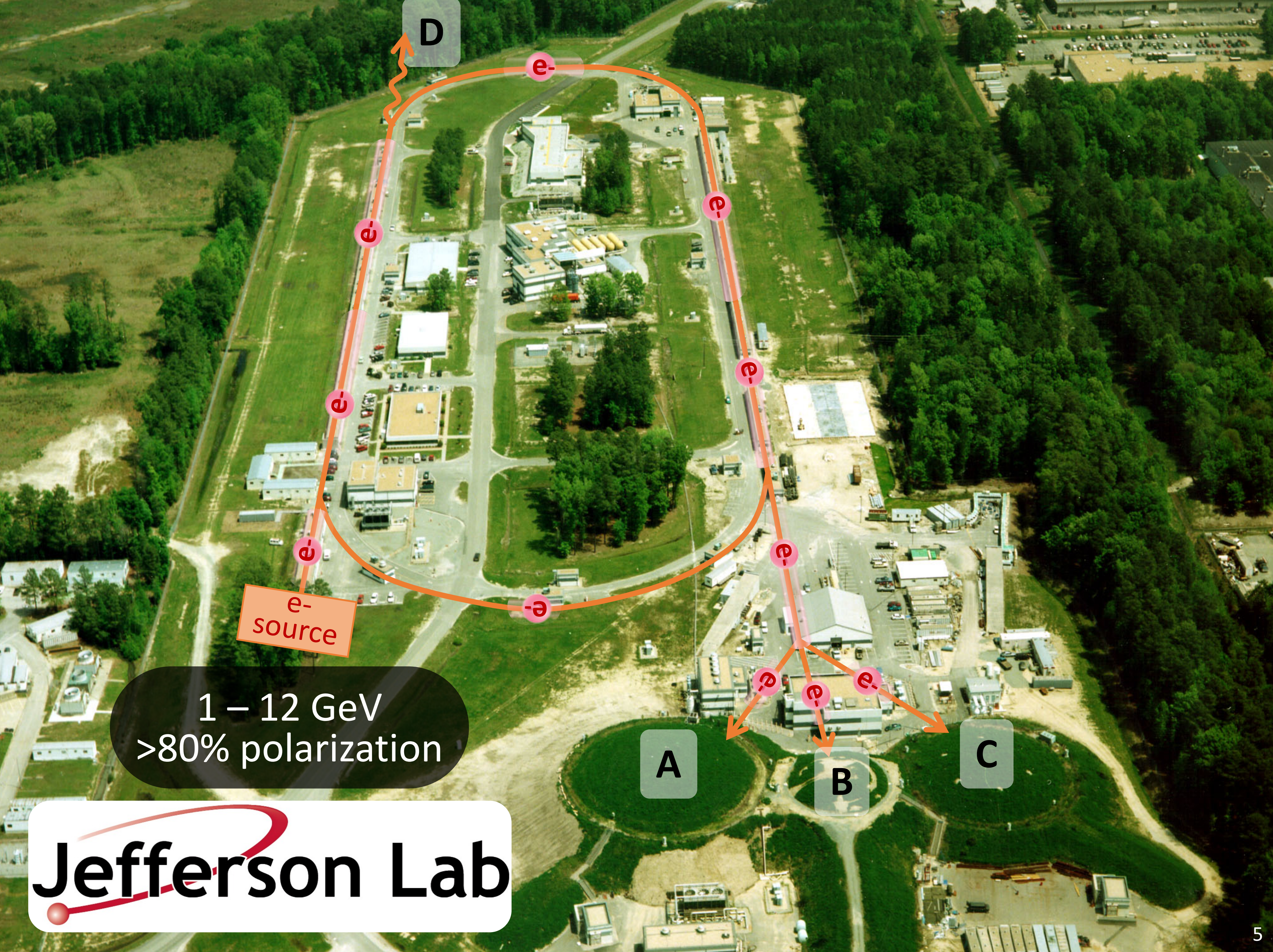
Weapon of Choice: Electron Scattering

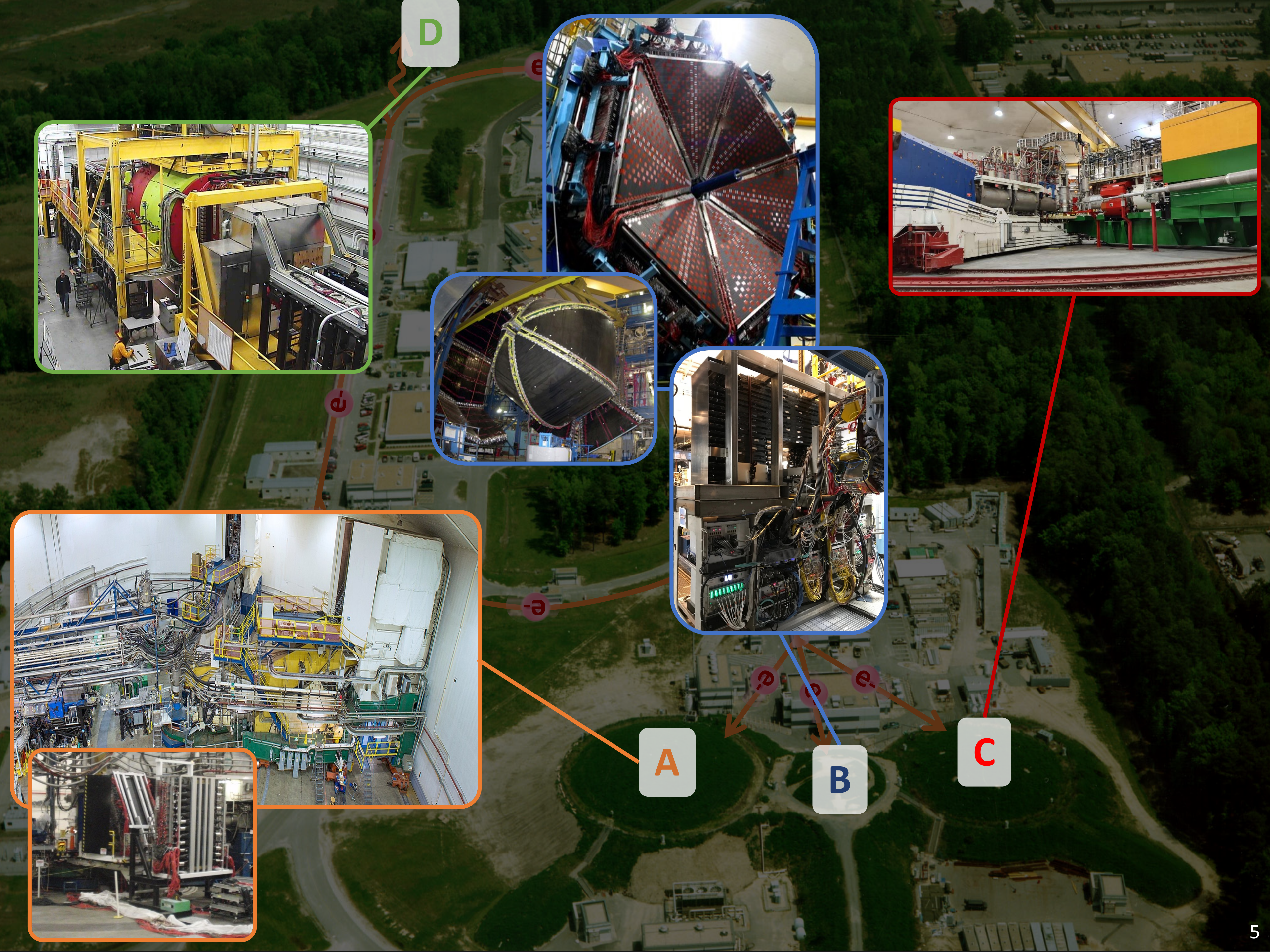
- Probe structure understood (point particle)
- Electromagnetic interaction understood (QED)
- Interaction is weak ($\alpha = 1/137$)
  - Theory works!
    (First Born Approximation / one photon exchange)
  - Probe interacts only once
  - Study the entire nuclear volume

But....

- Small cross section
- Radiative effects

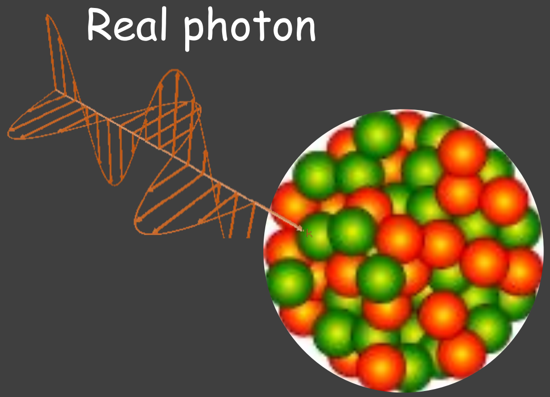


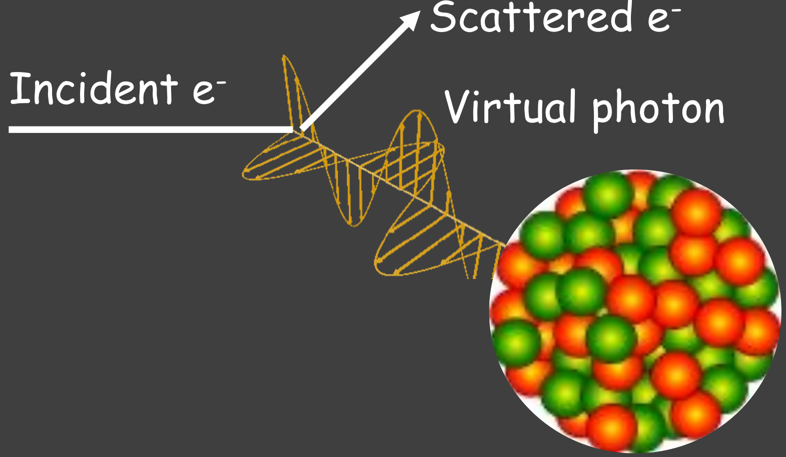

D
e-
e-
source
1 – 12 GeV
>80% polarization
A
B
C
Jefferson Lab


D
A
B
C

Key Point: It’s all photons!

Electrons interacts with nuclei by exchanging a single virtual photon





Real photon:

Momentum (q) = energy (ν)

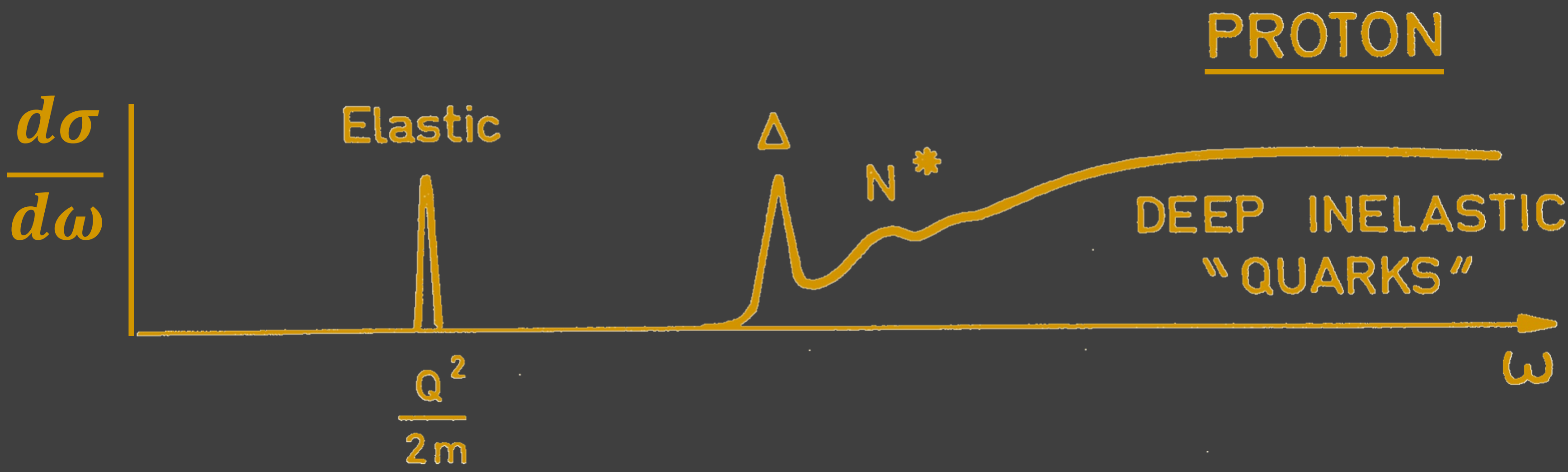
Mass = Q^2 = $|\boldsymbol{q}|^2 - \nu^2 = 0$

Virtual photon:

Momentum $q >$ energy ν

$Q^2 = |\boldsymbol{q}|^2 - \nu^2 > 0$ photon “has mass”!

Kinematics Tell Us A Lot!



(This is just energy conservation
at fixed momentum transfer)

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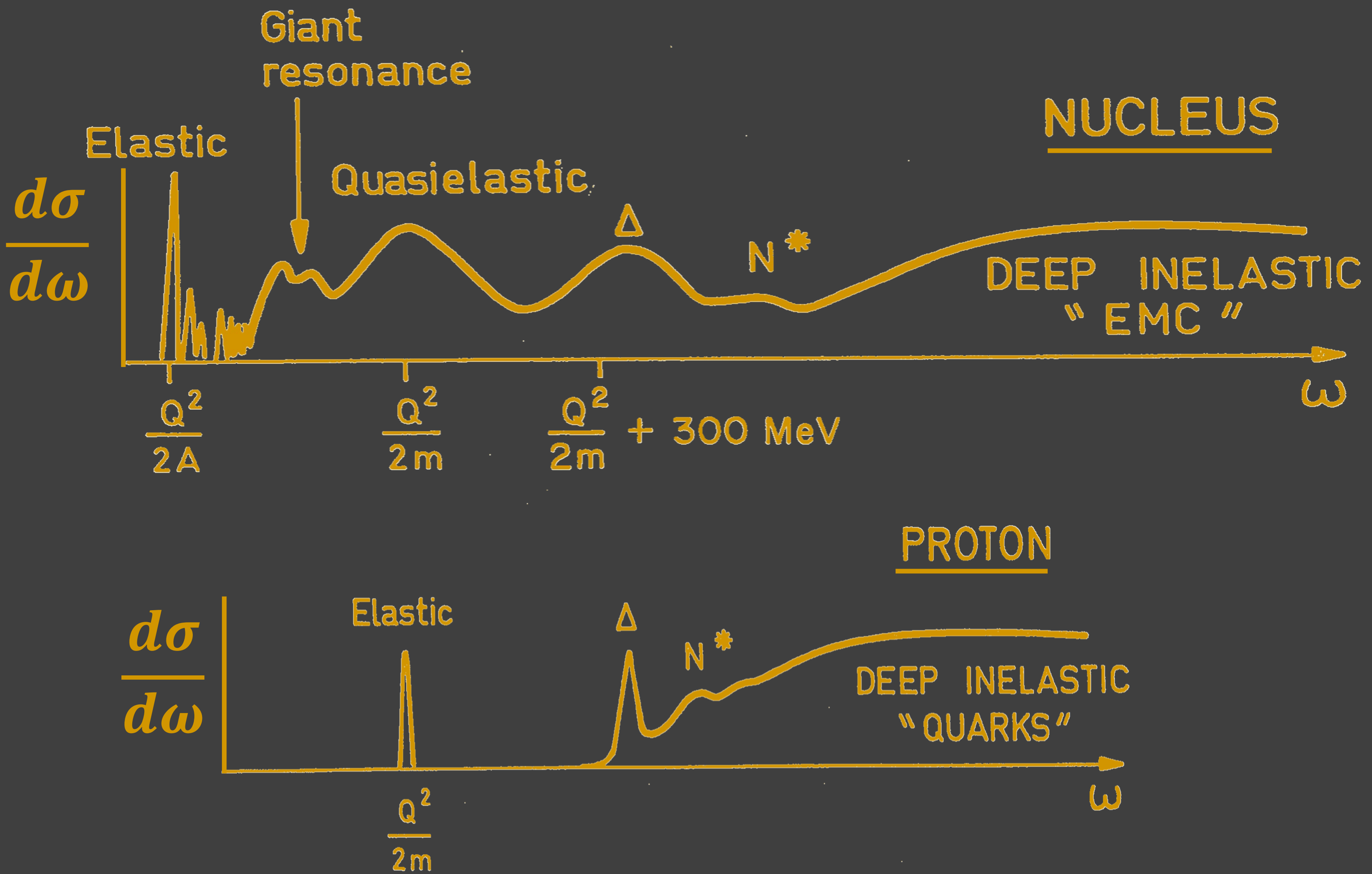
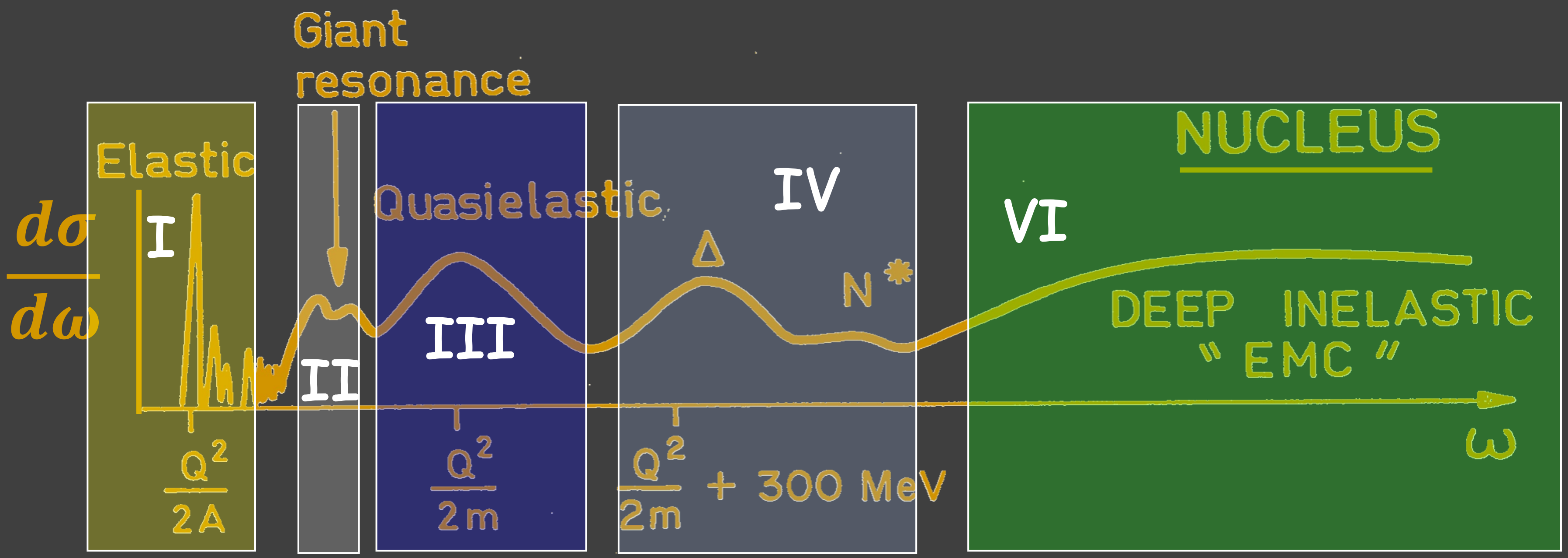
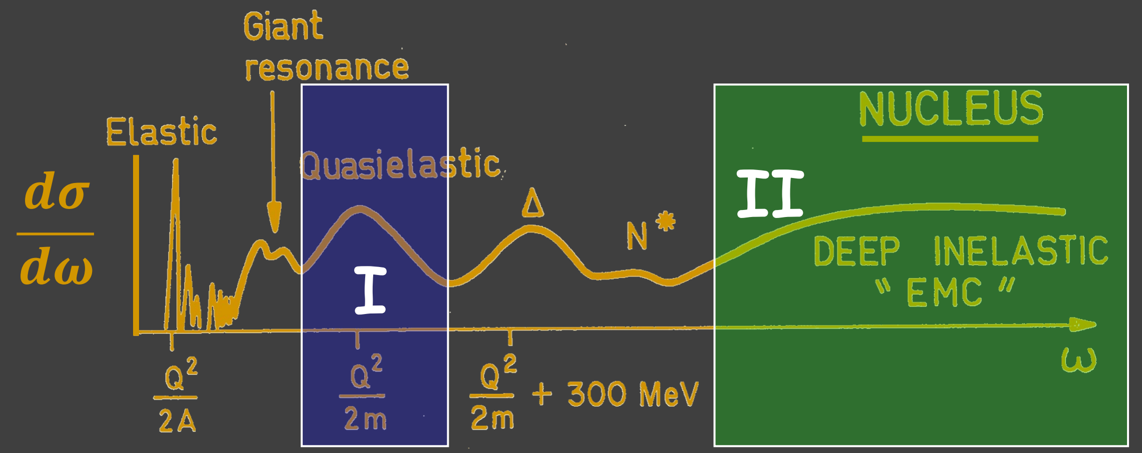


… Everything is Interesting ☺



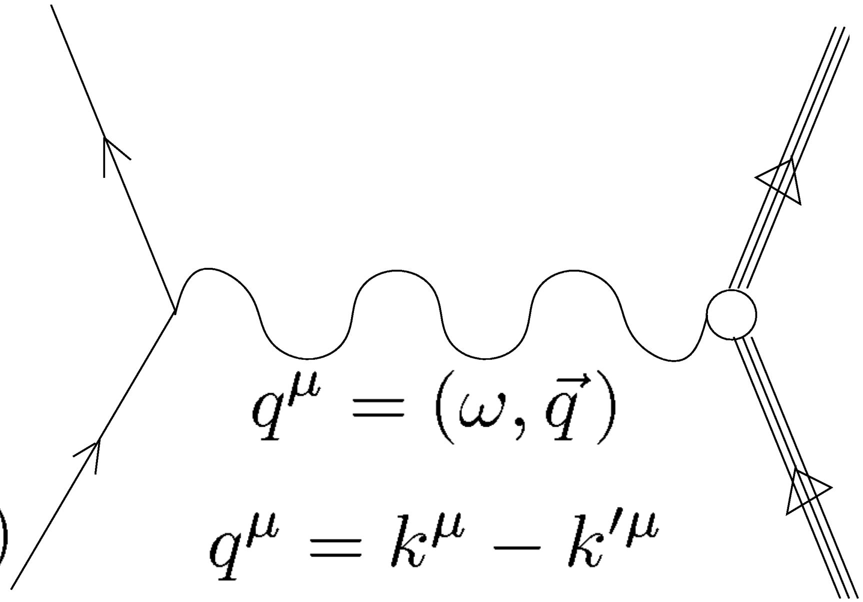
Focus On Two Regimes



1. Quasielastic (QE)
   - Shell structure
     - Momentum distributions
     - Occupancies
   - Short Range Correlations
   - Nuclear transparency and color transparency

2. Deep Inelastic Scattering (DIS)
   - The EMC Effect and Nucleon modification
   - Quark hadronization in color medium

Lab frame kinematics



$k'^\mu = (E', \vec{k}\,')$

$p'^\mu = (E_p, \vec{p}_p)$

(not always detected)

$q^\mu = (\omega, \vec{q}\,)$

$k^\mu = (E, \vec{k}\,)$

$q^\mu = k^\mu - k'^\mu$

$p^\mu = (M, \vec{0}\,)$

Invariants:

$$p^\mu p_\mu = M^2 \qquad\qquad p_\mu q^\mu = M\omega$$

$$Q^2 = -q^\mu q_\mu = |\vec{q}\,|^2 - \omega^2 \qquad W^2 = (q^\mu + p^\mu)^2 = p'_\mu p'^\mu$$

Elastic e-p Scattering

Ignoring polarization, cross-section given by two form-factors and kinematic factors:

$$\frac{d\sigma}{d\Omega} = \sigma_M \frac{E'}{E} \left\{ \left[F_1^2(Q^2) + \frac{Q^2}{4M^2}\kappa^2 F_2^2(Q^2) \right] + \frac{Q^2}{2M^2}[F_1(Q^2) + \kappa F_2(Q^2)]^2 \tan^2\frac{\theta}{2} \right\}$$

Recoil factor

Form factors

Mott cross section:

$$\sigma_M = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$$

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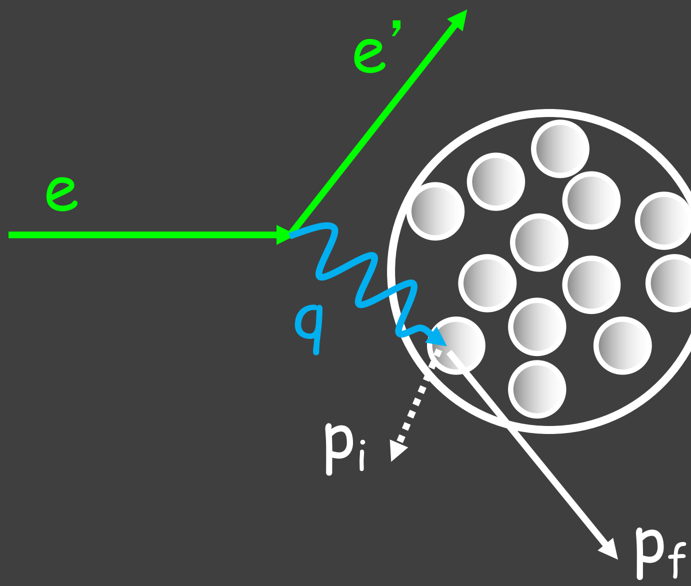
Very interesting physics! But not our focus…

→ We will assume known nucleon form-factors and ask what's going on in the nucleus?

Fermi-distribution from (e,e') data



Expect $\sigma(\nu)$ to:

- Peak at $\nu = q^2/2m_p + \varepsilon$
- With peak width $2qp_{fermi} / m_p$
- And Integral $Z\,\sigma_{ep} + N\,\sigma_{en}$

Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

Final nucleon energy: $KE_f = p_f^2 / 2m_p = (\vec{q} + \vec{p}_i)^2 / 2m_p$

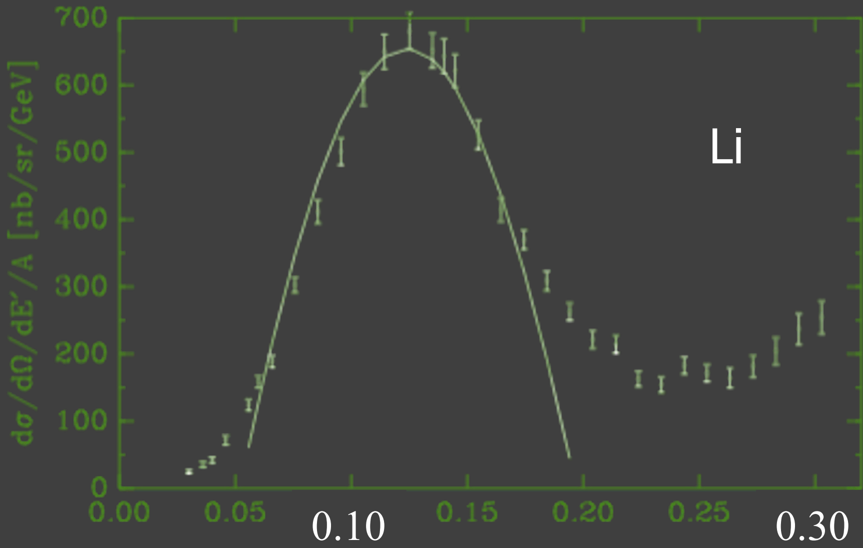
Energy transfer: $\nu = KE_f - KE_i = \dfrac{\vec{q}^2}{2m_p} + \dfrac{\vec{q}\cdot\vec{p}_i}{m_p}$

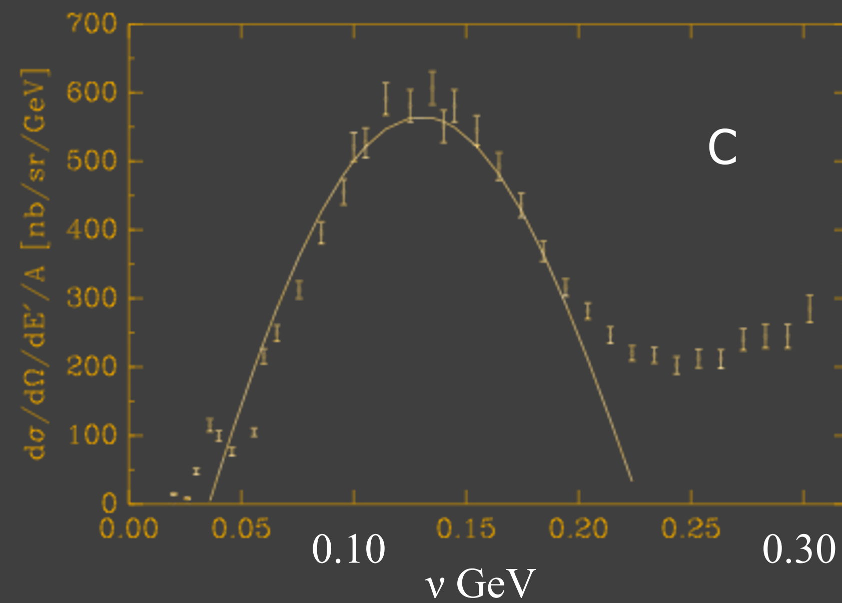
500 MeV, 60°

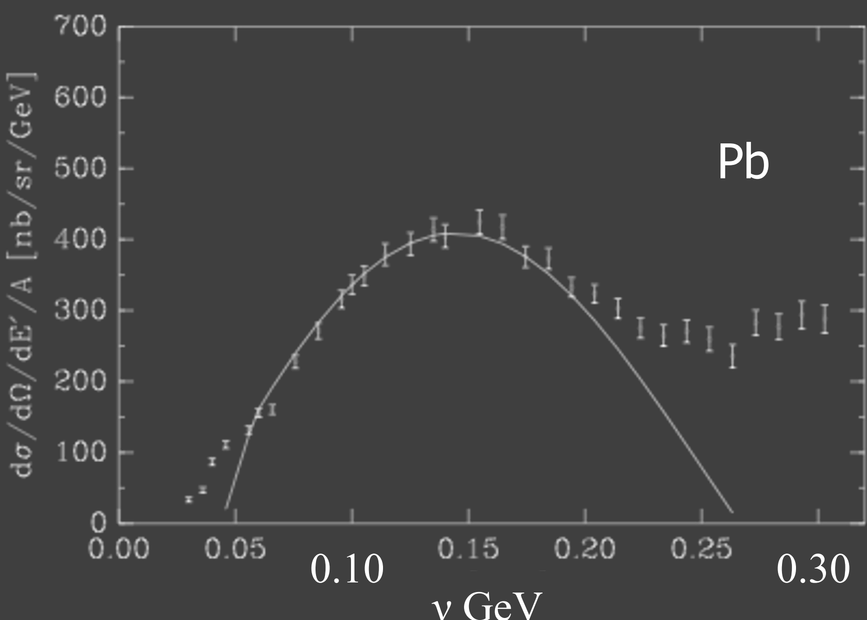
$\vec{q} \simeq 500 MeV/c$

➔ getting the bulk features!

R.R. Whitney et al., PRC 9, 2230 (1974)







Nucleus	k_F	$\bar{\epsilon}$
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44
	MeV/c	MeV

Step Further: y-Scaling

Assuming scattering from a quasi-free nucleon in the nucleus.

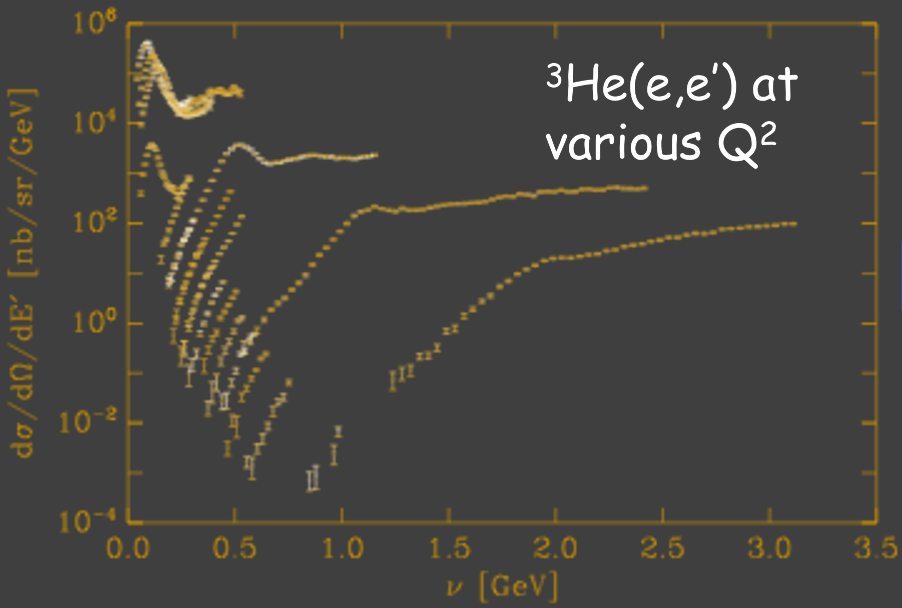
Momentum of struck nucleon in momentum transfer direction:
$y \approx -q/2 + m\nu/q$ (nonrelativistically)

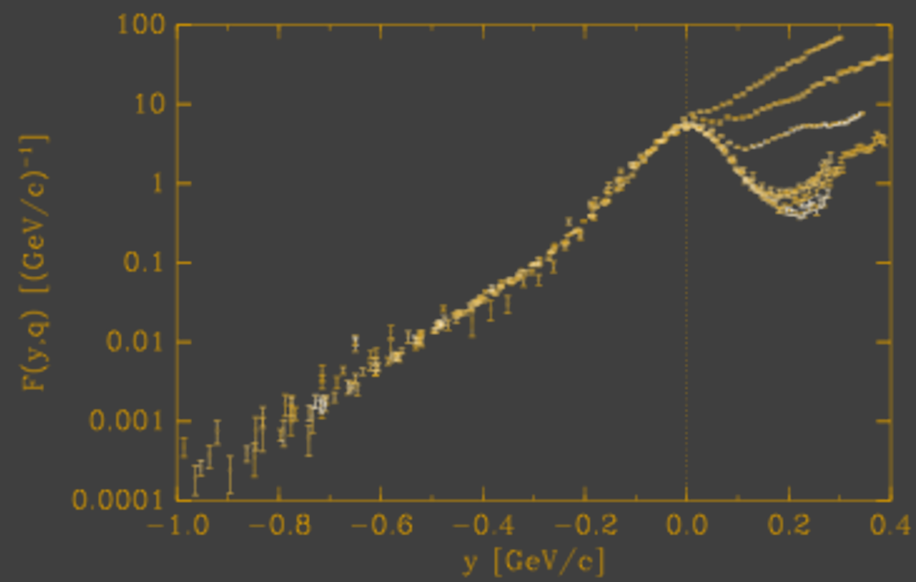
IF the scattering is quasifree, then $F(y)$ is the **integral** over all perpendicular nucleon momenta

$F(y)$ is the integral ➔ we can extract from it the momentum distribution $n(k)$:

$$F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K \qquad n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

It Works Well!

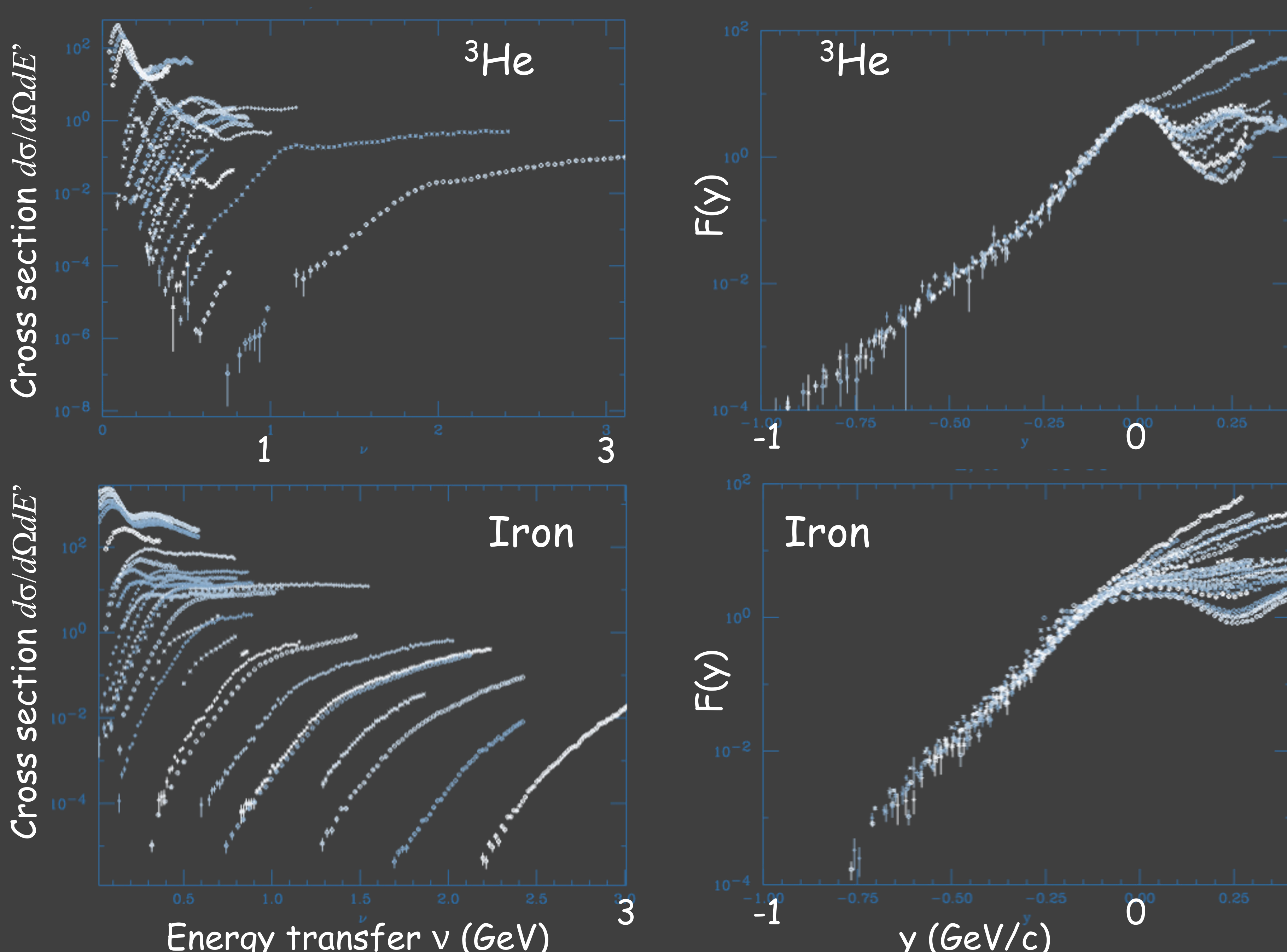




$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

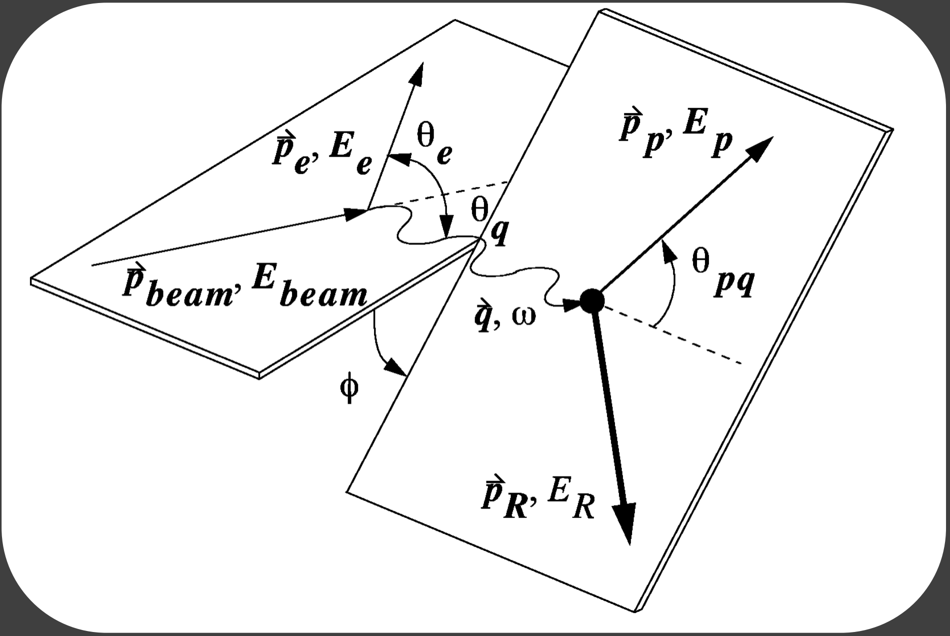
Impressive results for an ‘energy conservation’ formalism! But…

- No Final State Interactions (FSI)
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite *q*
- No inelastic processes (choose y<0)
- No medium modifications



^{3}He
Cross section $d\sigma/d\Omega dE'$
1
3
^{3}He
F(y)
-1
0
Iron
Cross section $d\sigma/d\Omega dE'$
3
Energy transfer ν (GeV)
Iron
F(y)
-1
0
y (GeV/c)

What about the Shell Model? (e,e'p)!



Four response functions

(Including electron and nucleon spin, there are 18!)

(If polarized spin-1 target, there are 41)

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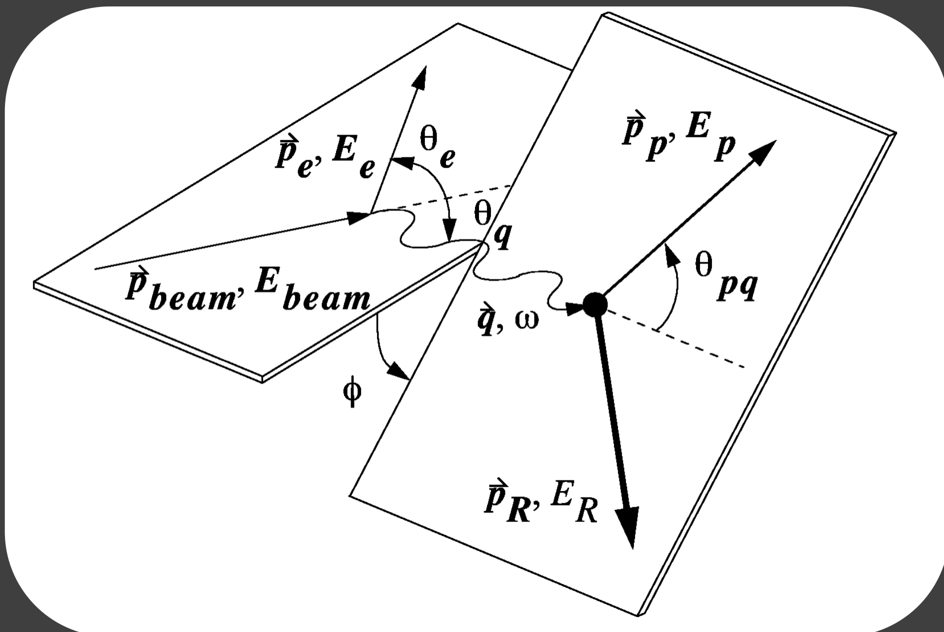

Four response functions

(Including electron and nucleon spin, there are 18!)

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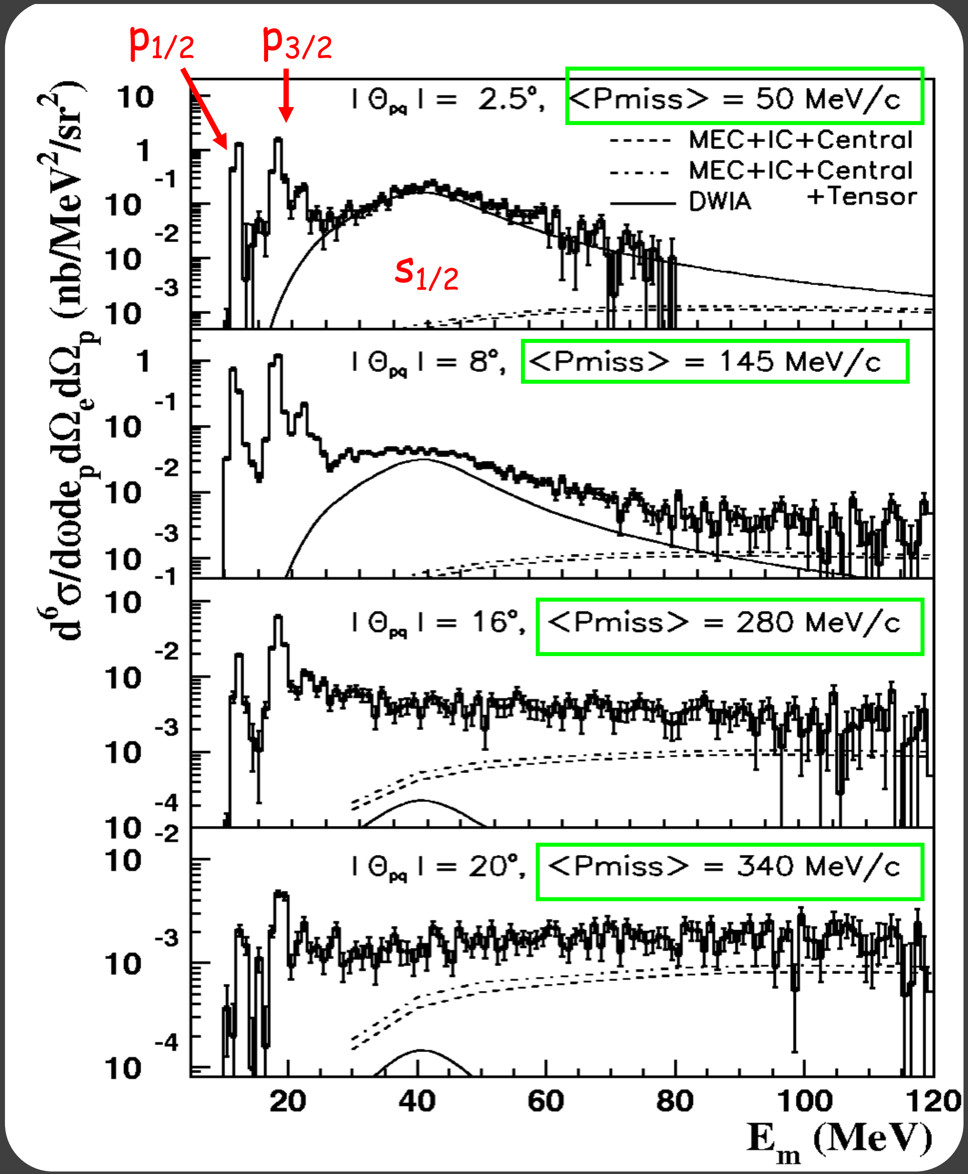
Detecting the proton = complicating the reaction

But… we access new kinematic information!

➔ Missing momentum
➔ Missing energy

Missing Energy Peaks = Shells



$^{16}O(e,e'p)$

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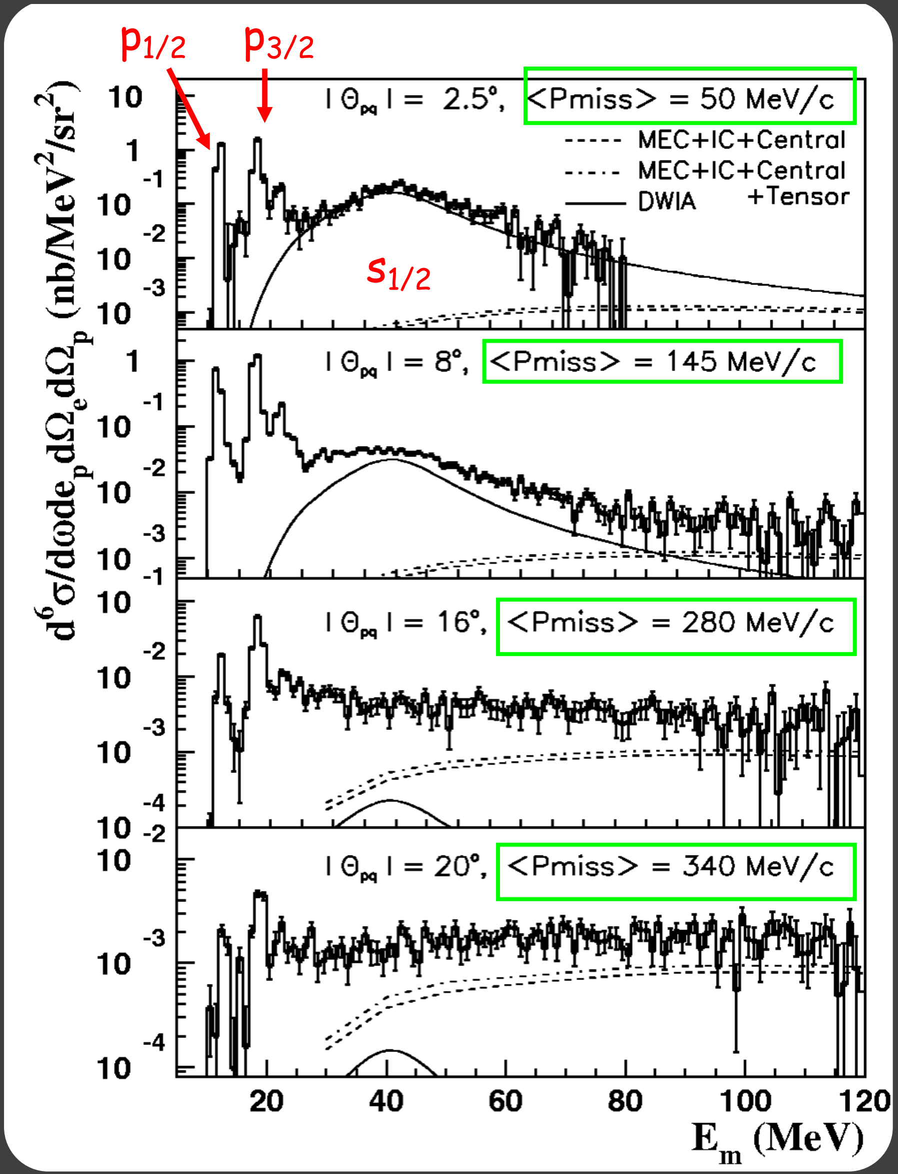
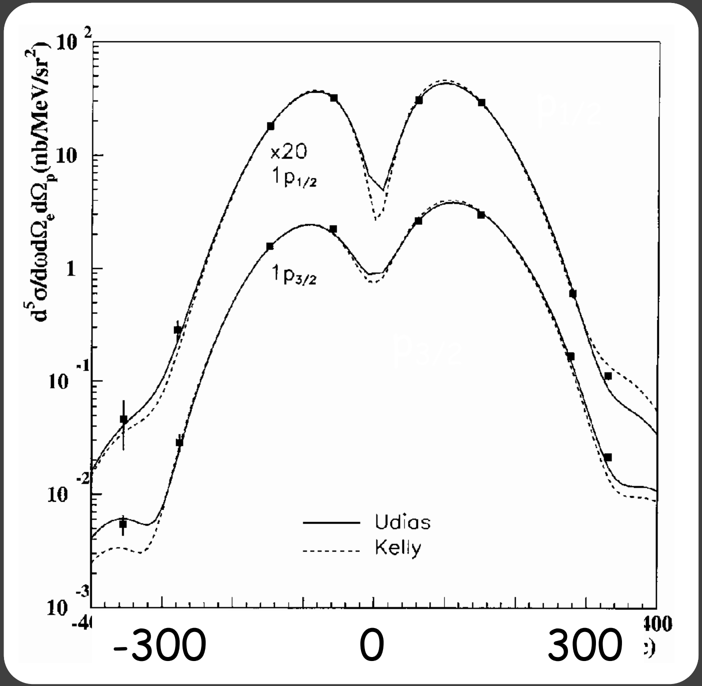




Missing Momentum

$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

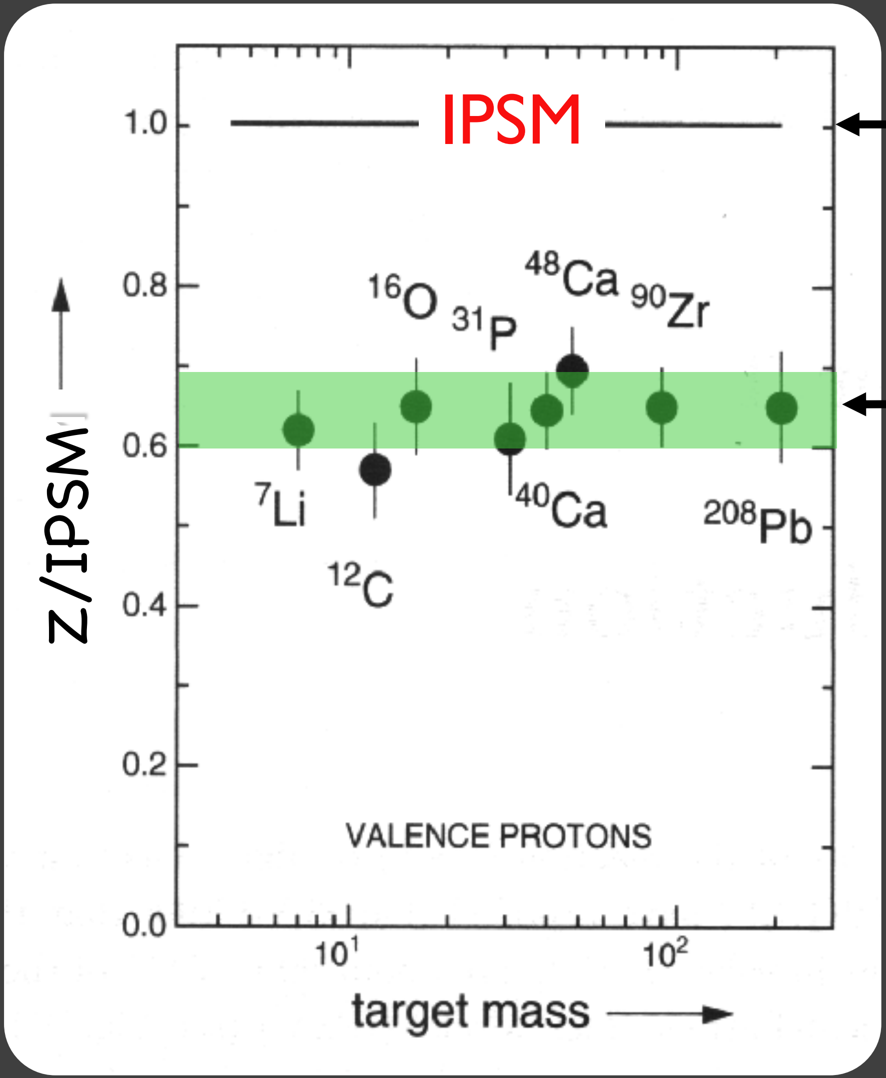
Momentum distribution as expected

Absolute scale is off!

Fissum et al, PRC 70, 034606 (2003)

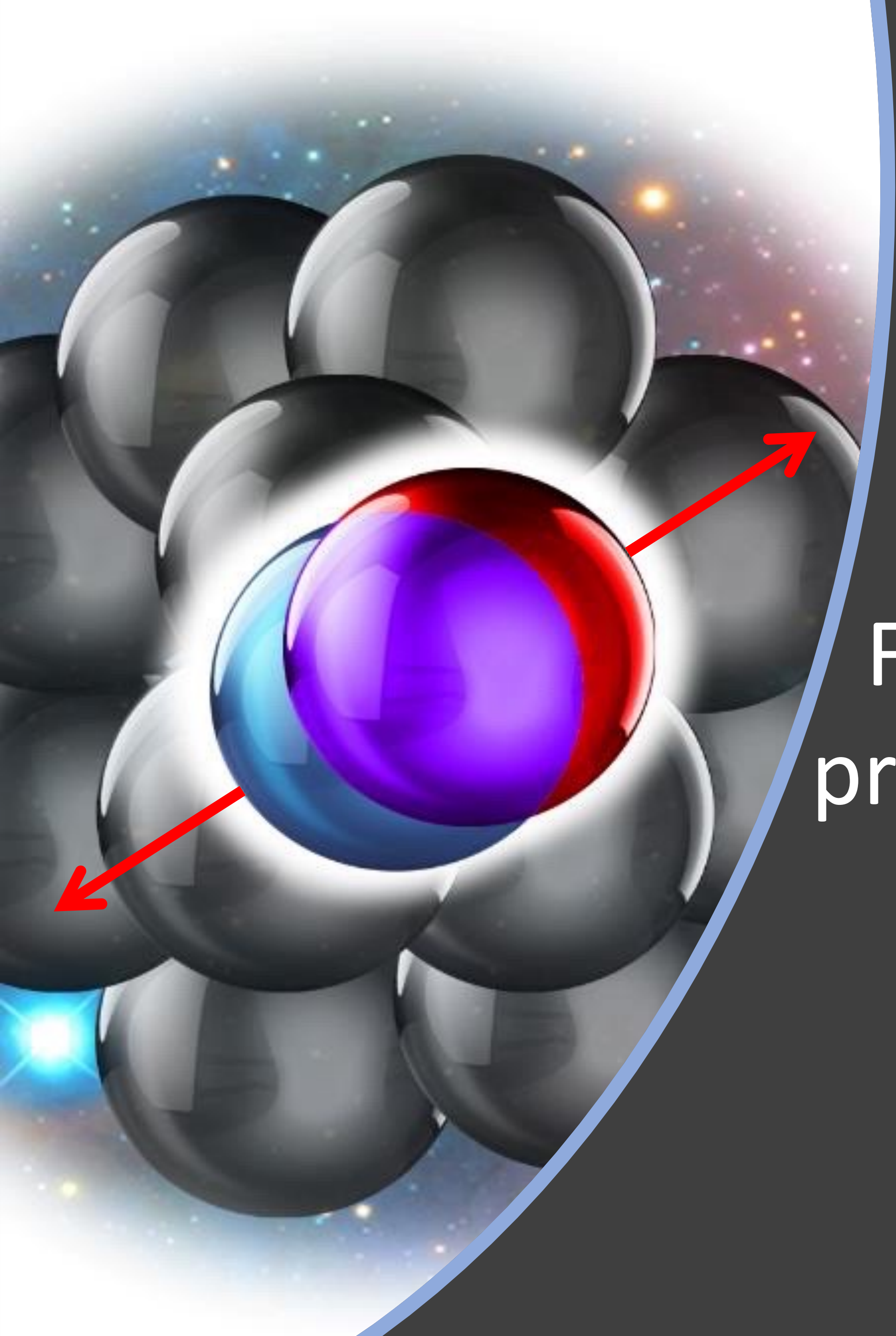
Missing Strength below k_F

NIKHEF



100%

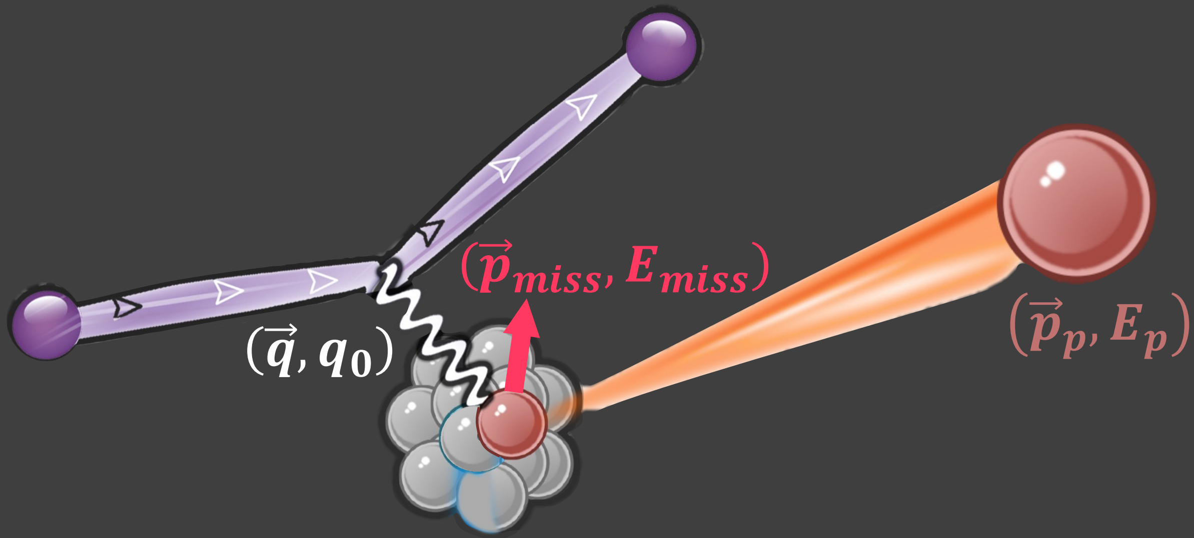
65%



Short-Range Correlations (SRC)

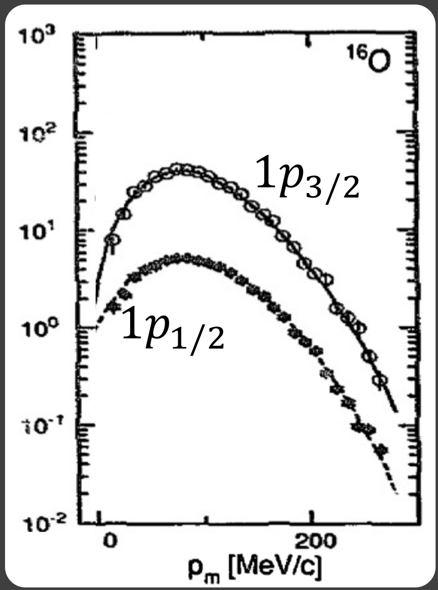
Fluctuations of close-proximity nucleon pairs

From Single-Nucleons to Pairs



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

$E_{miss} = E_p - q_0$



Lapikas Nuc. Phys. A '93

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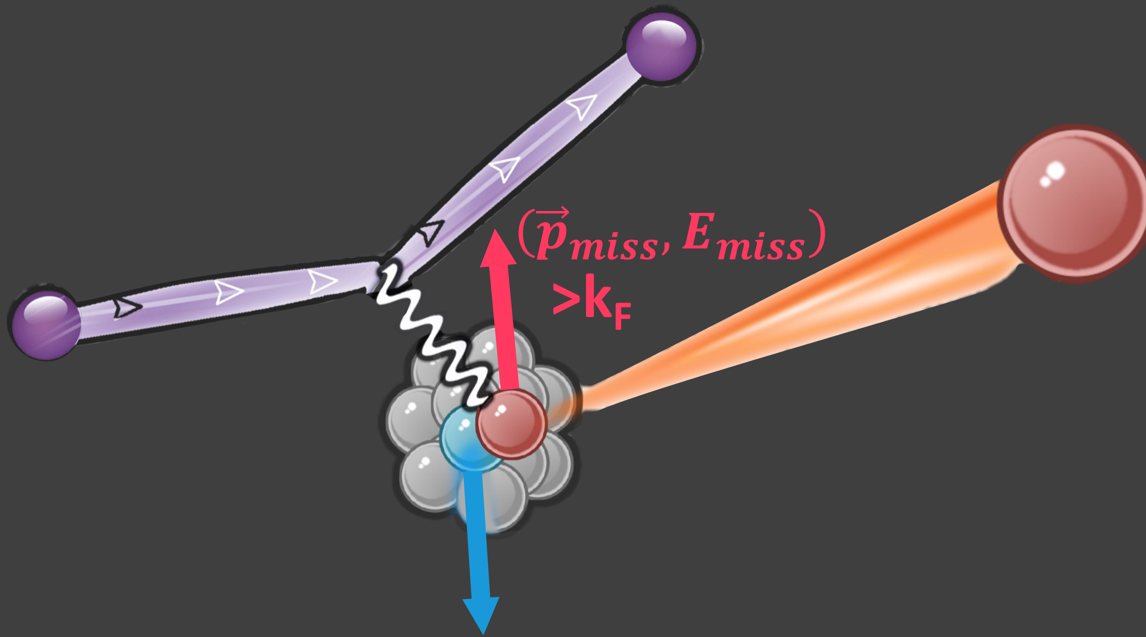
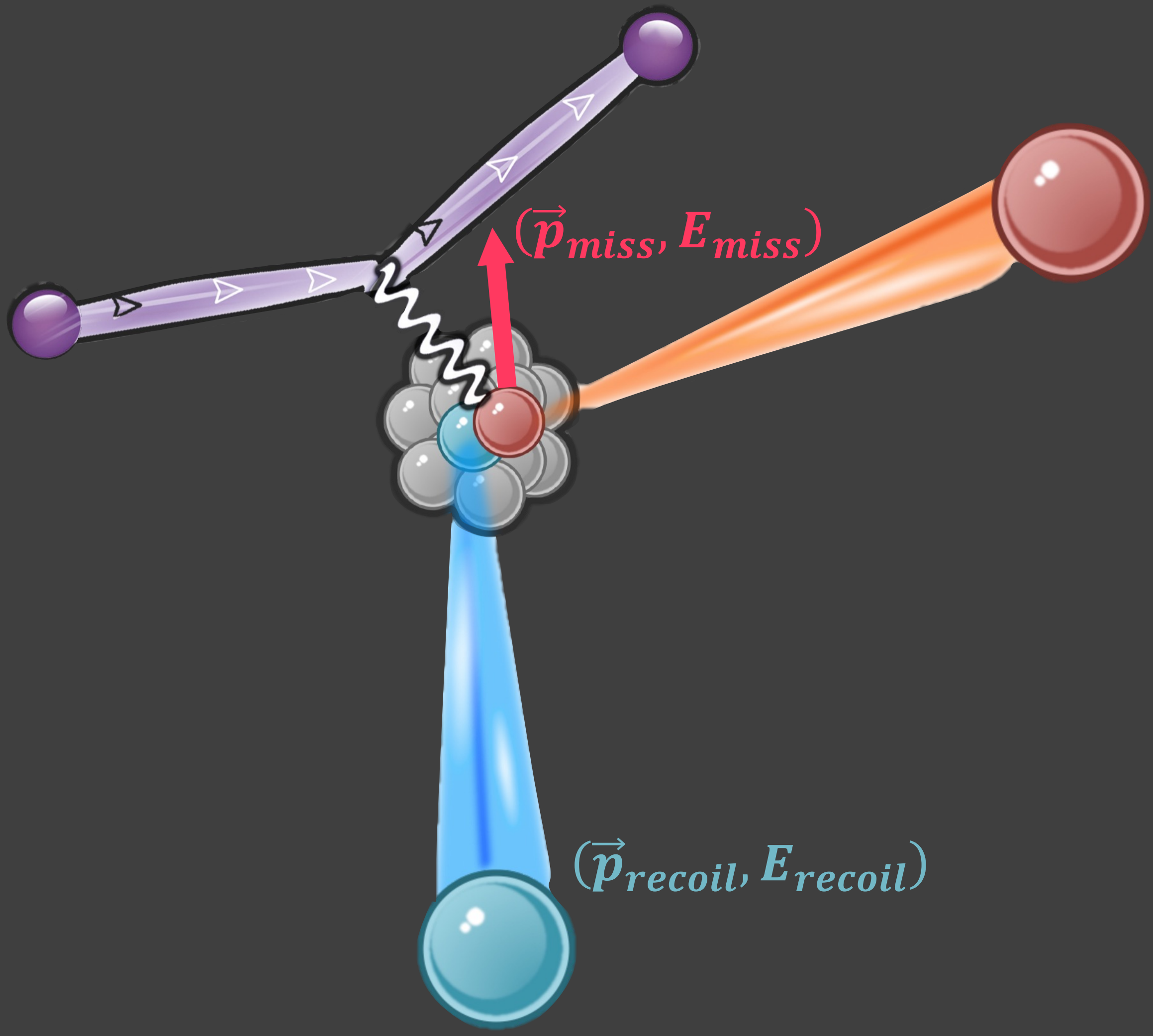


Probing SRCs



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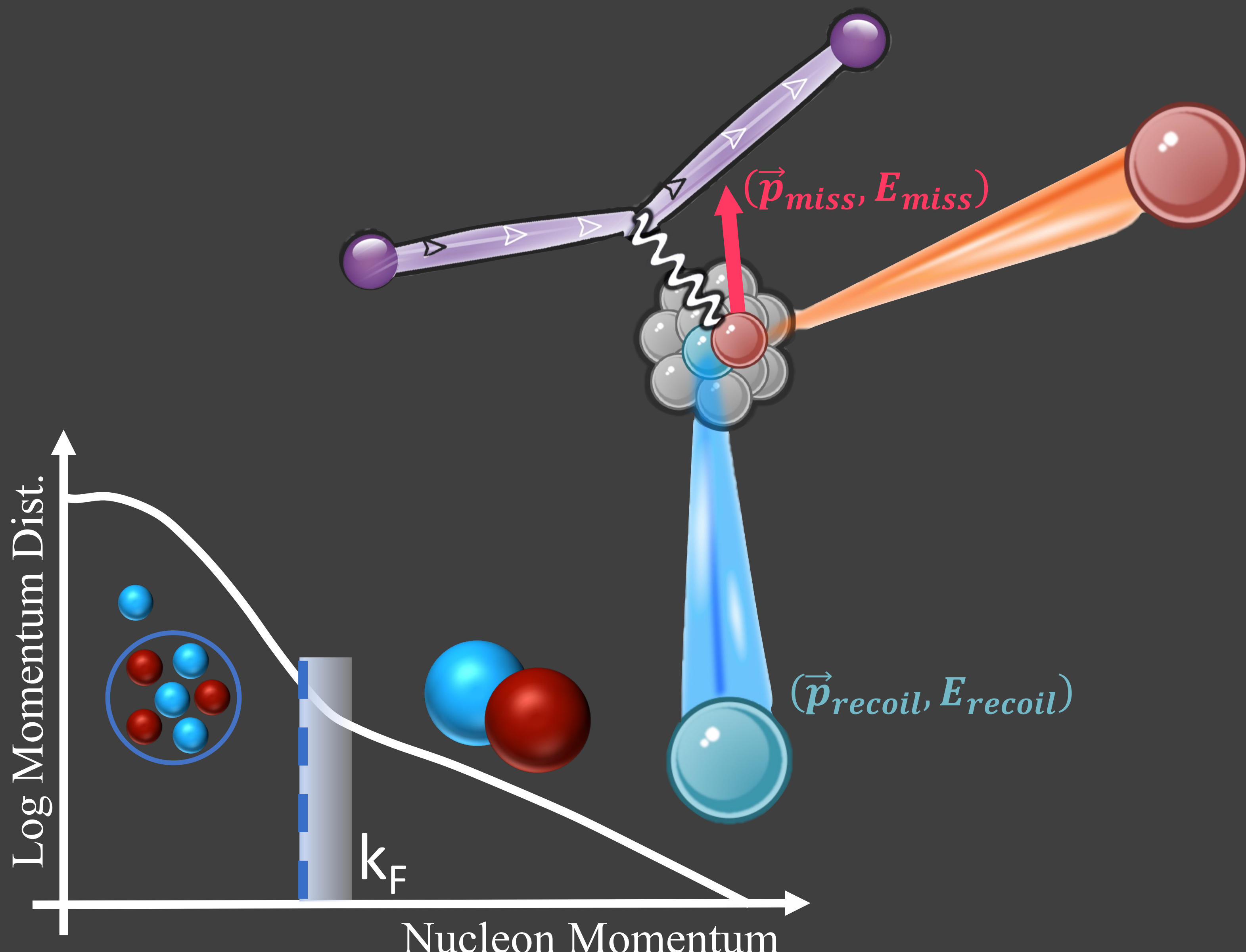
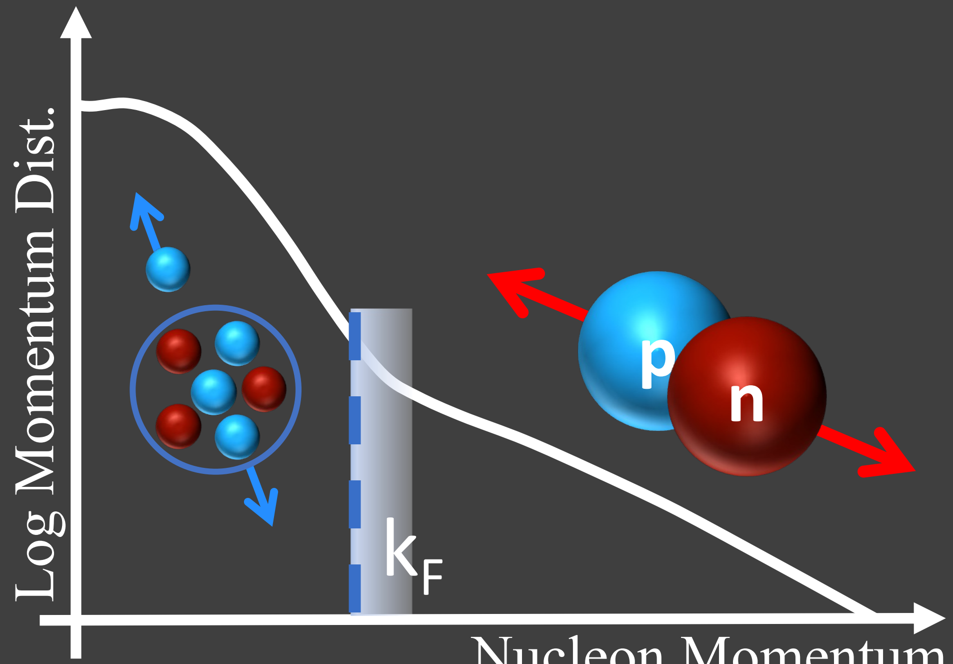
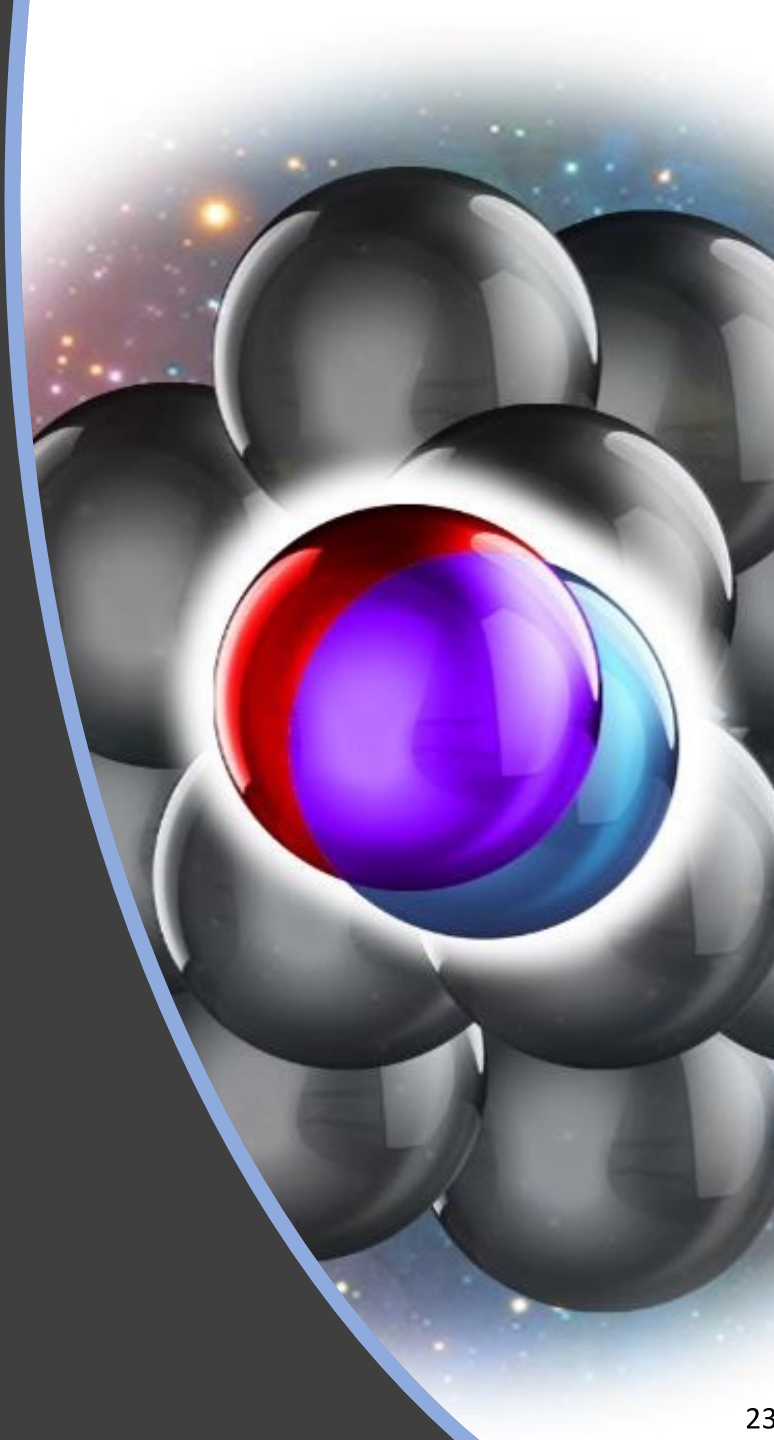


Short-Range Correlations (SRC)

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





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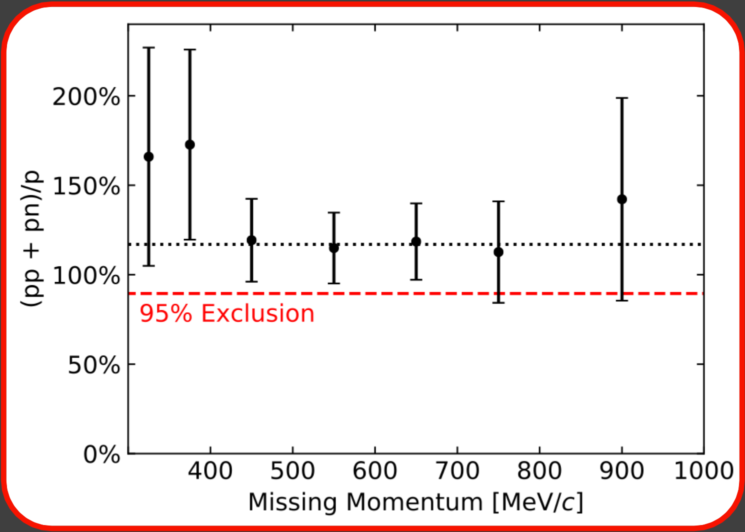
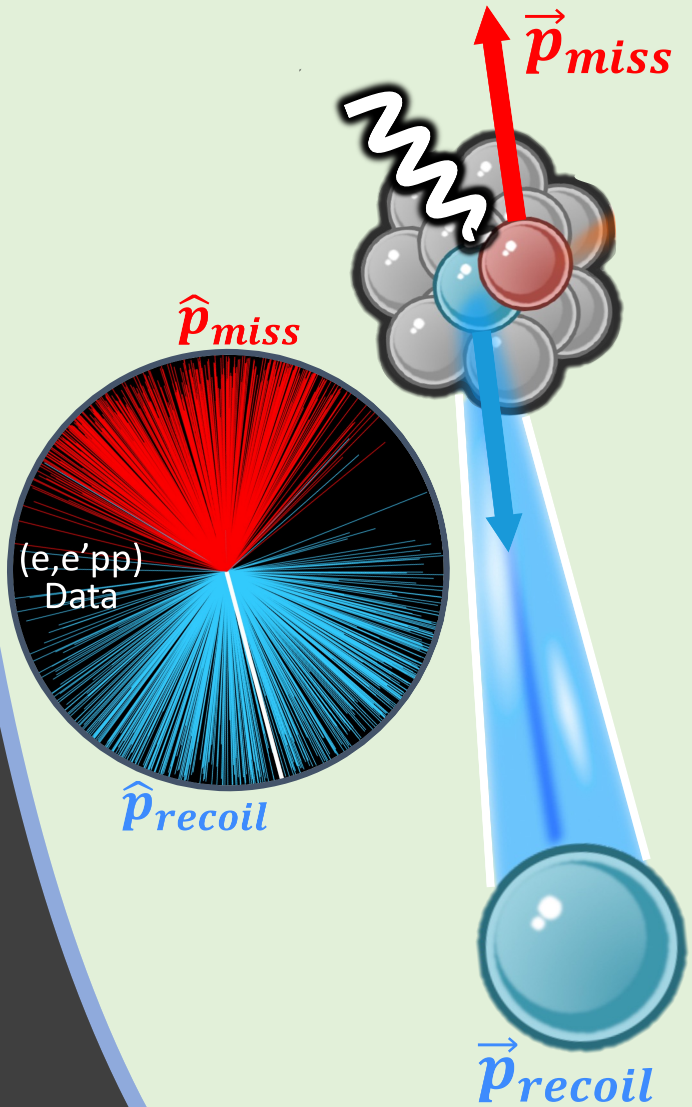


Korover et al., Phys. Lett. B (2021)



Hen et al., Science (2014)

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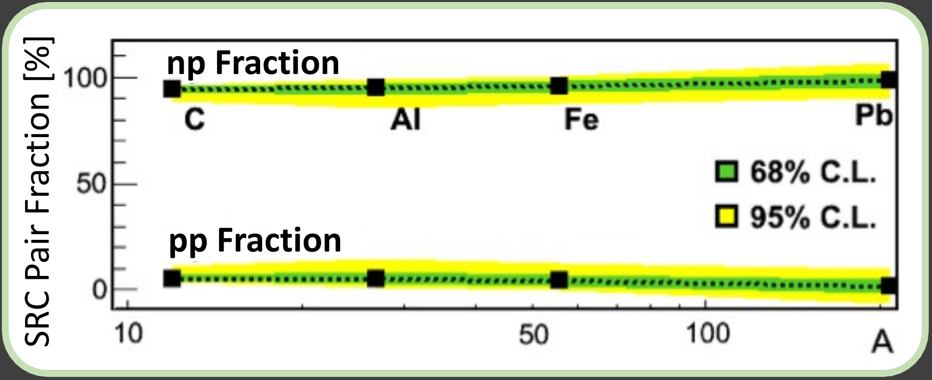

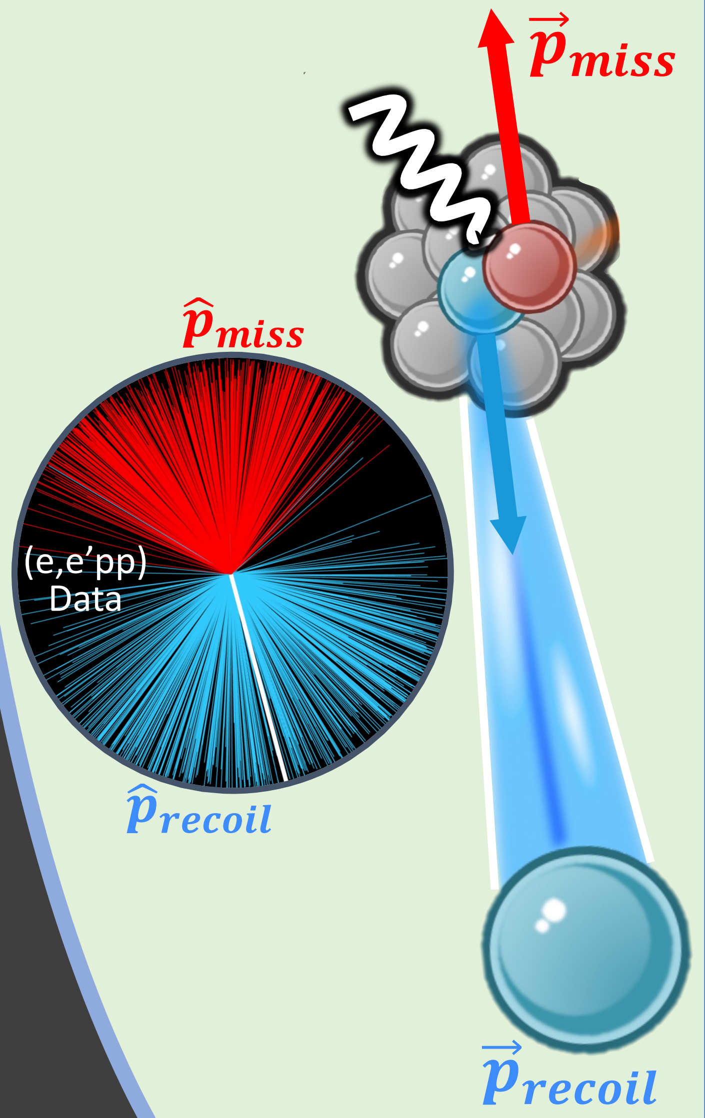

Korover PLB '21; Duer PRL '19; Duer Nature '18; Hen Science '14; Korover PRL '14; Subedi Science '08; Shneor PRL '07; Piasetzky PRL '06; Tang PRL '03; Review: Hen RMP '17

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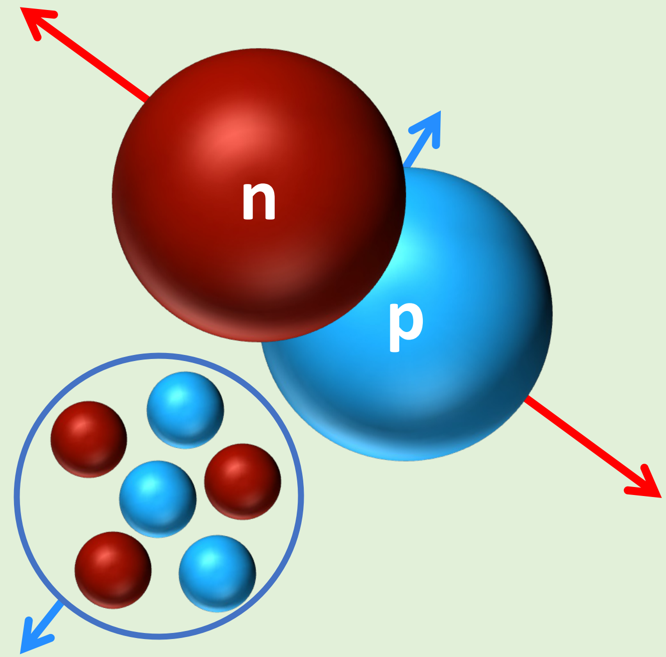

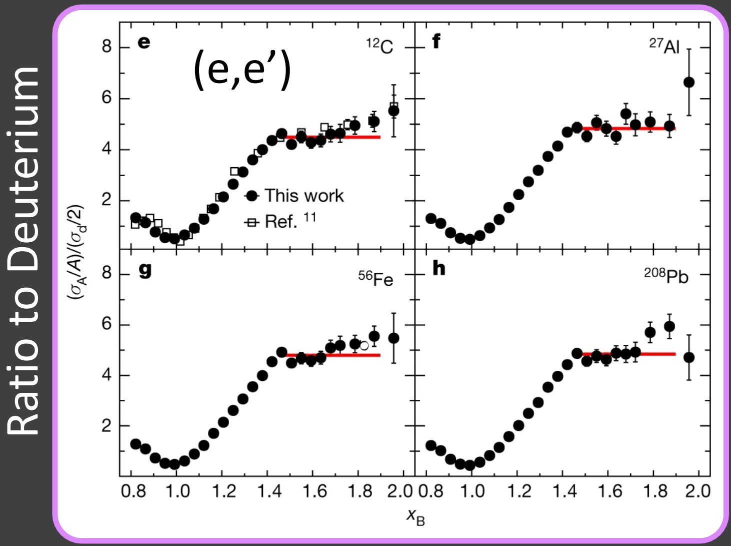

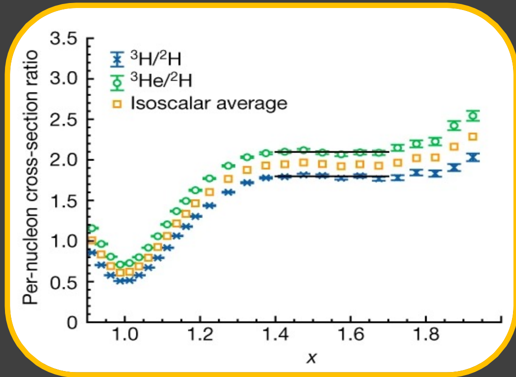



Li Nature '22, Nguyen PRC '20;
Schmookler Nature '19; Fomin PRL '12; …

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

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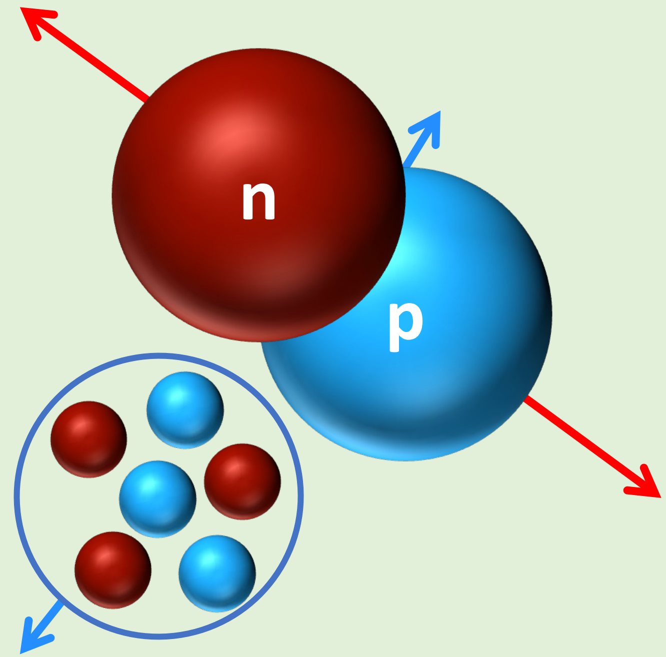
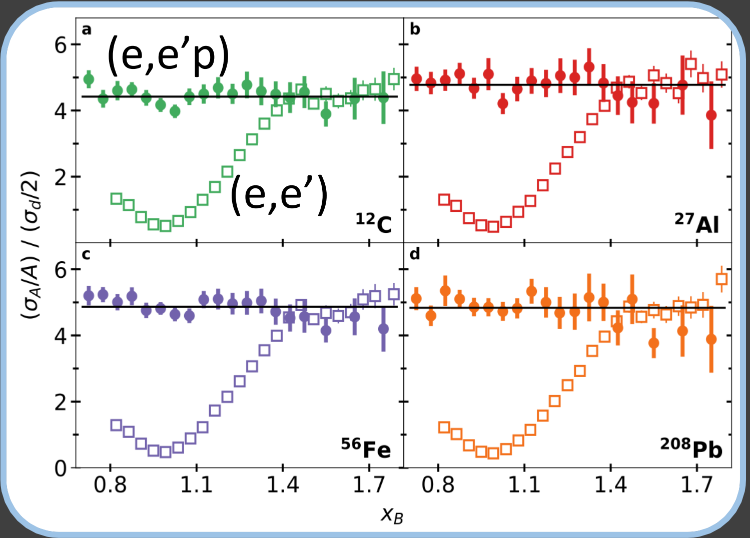


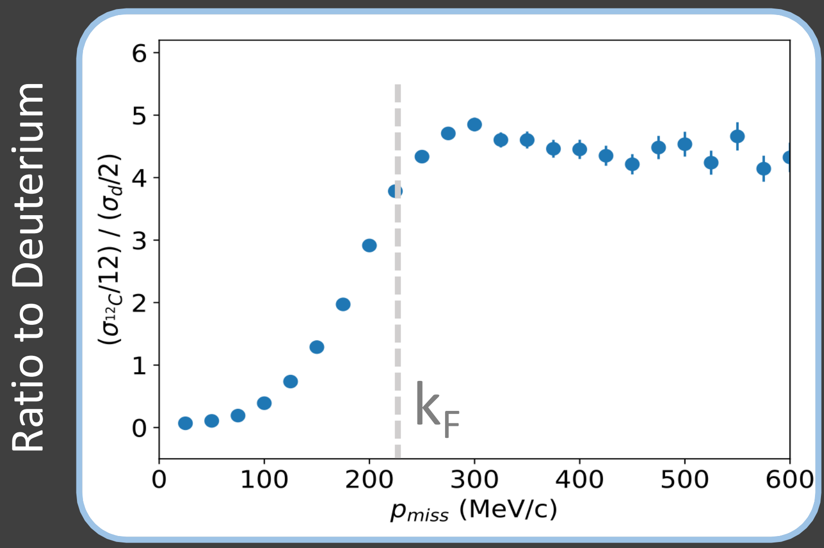
Ratio to Deuterium

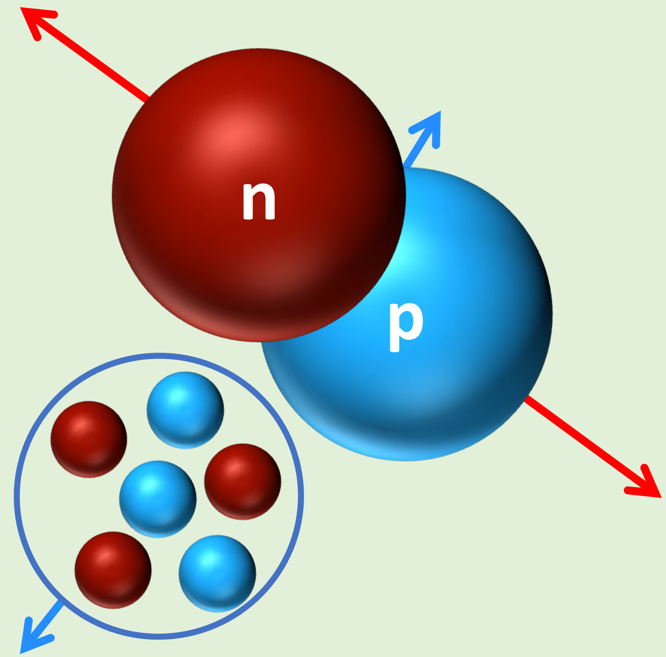


Korover and Denniston et al., Submitted (2022)

Short-Range Correlations (SRC)

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





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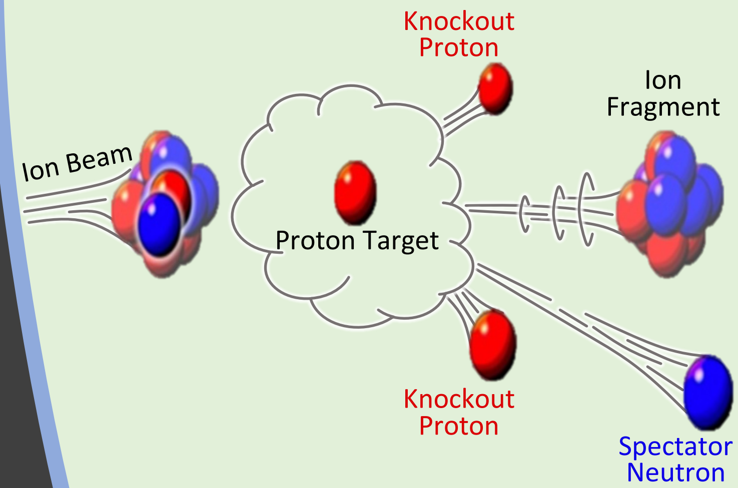

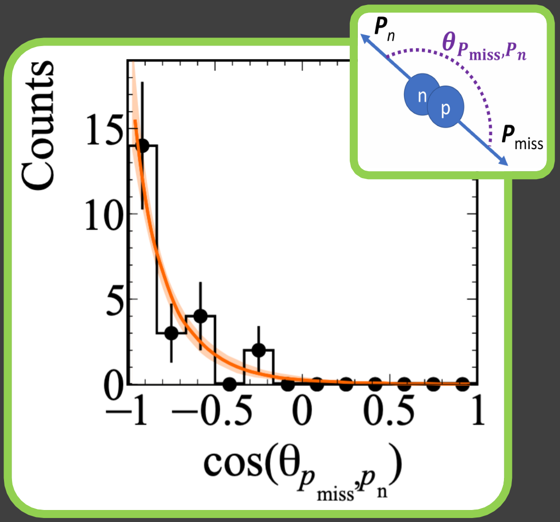

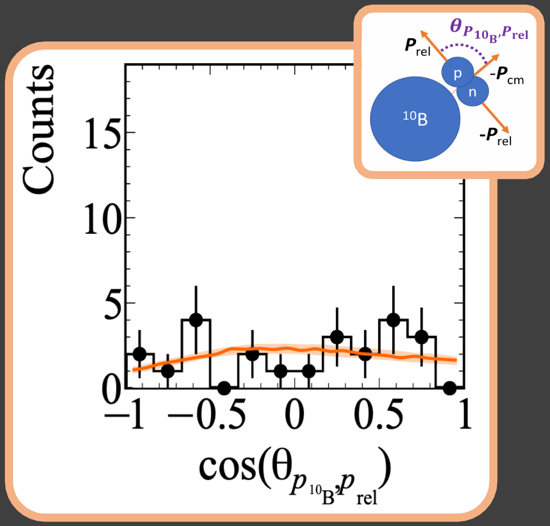

Patsyuk and Kahlbow et al., Nature Physics (2021)

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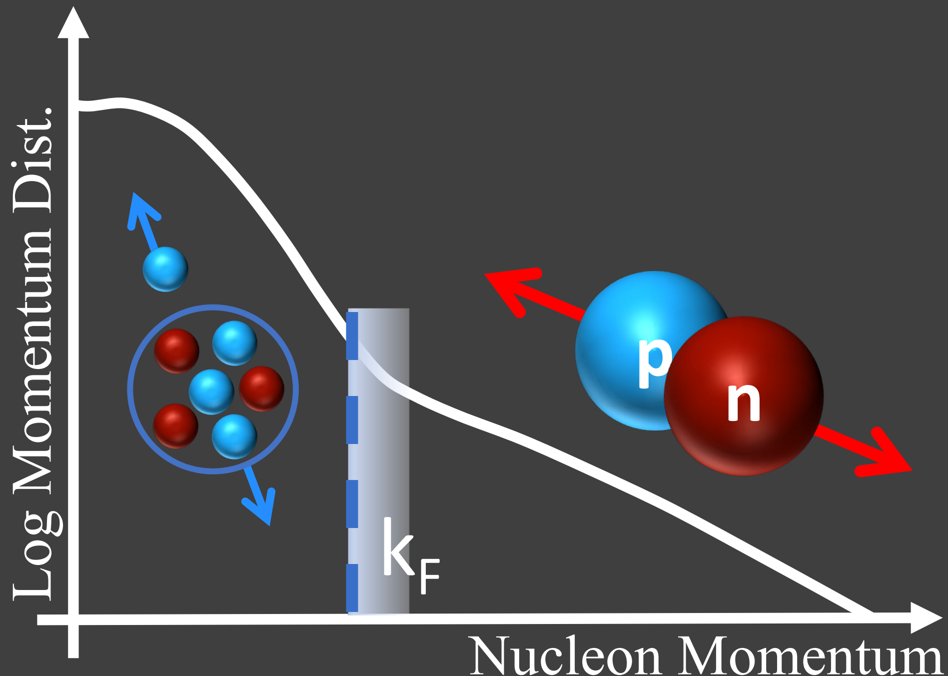


Isospin Structure:

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)

Quantum Numbers, Mass, Asymmetry Dependence:

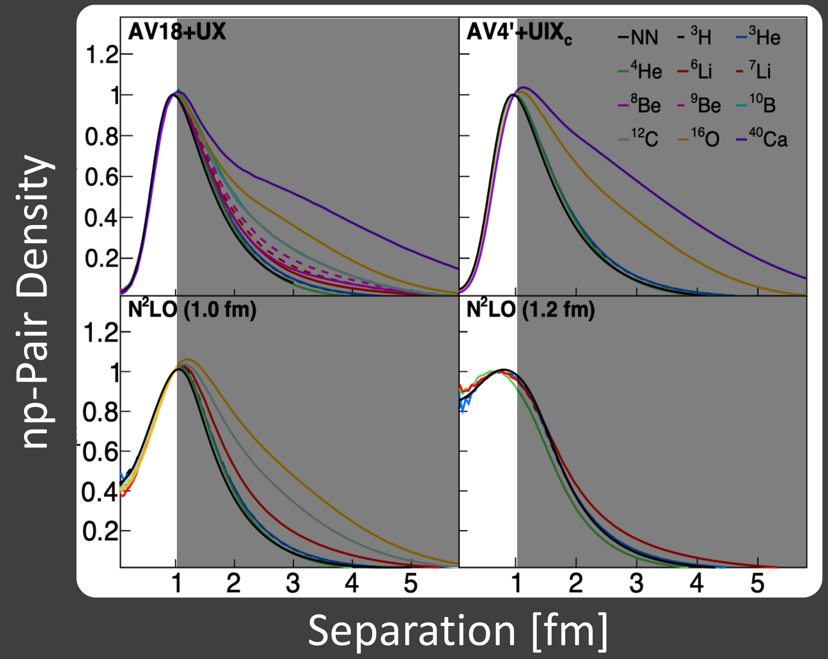
Phys. Rev. C 103, L031301 (2021)
Phys. Lett. B 780, 211 (2018)
PRC 92, 024604 (2015)
PRC 92, 045205 (2015)

Theory: 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)



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)

…

Theory: Scale Separation and Factorization

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

Total Dist. = Constant (Nucleus specific) x Two-body (Universal)

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)
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Ryckebusch et al., Phys. Lett. B 792, 21 (2019)
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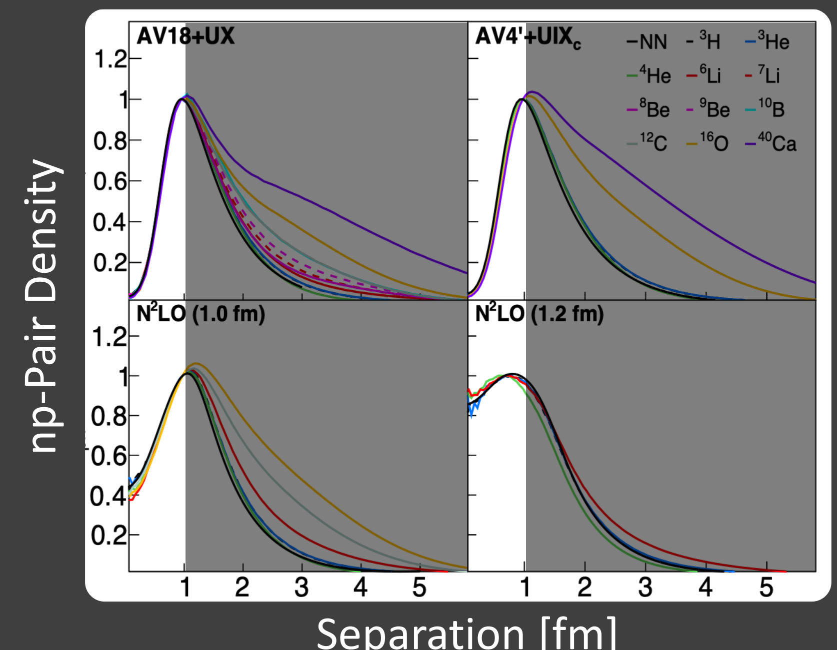
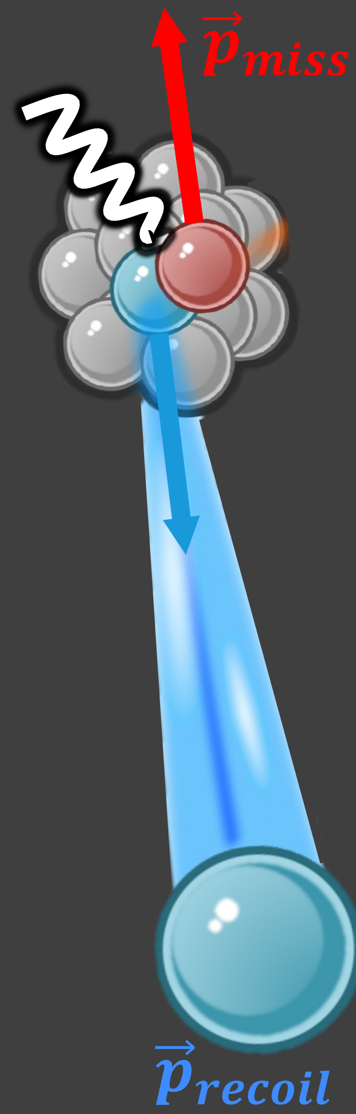


Scale Separation → Cross-Section Models

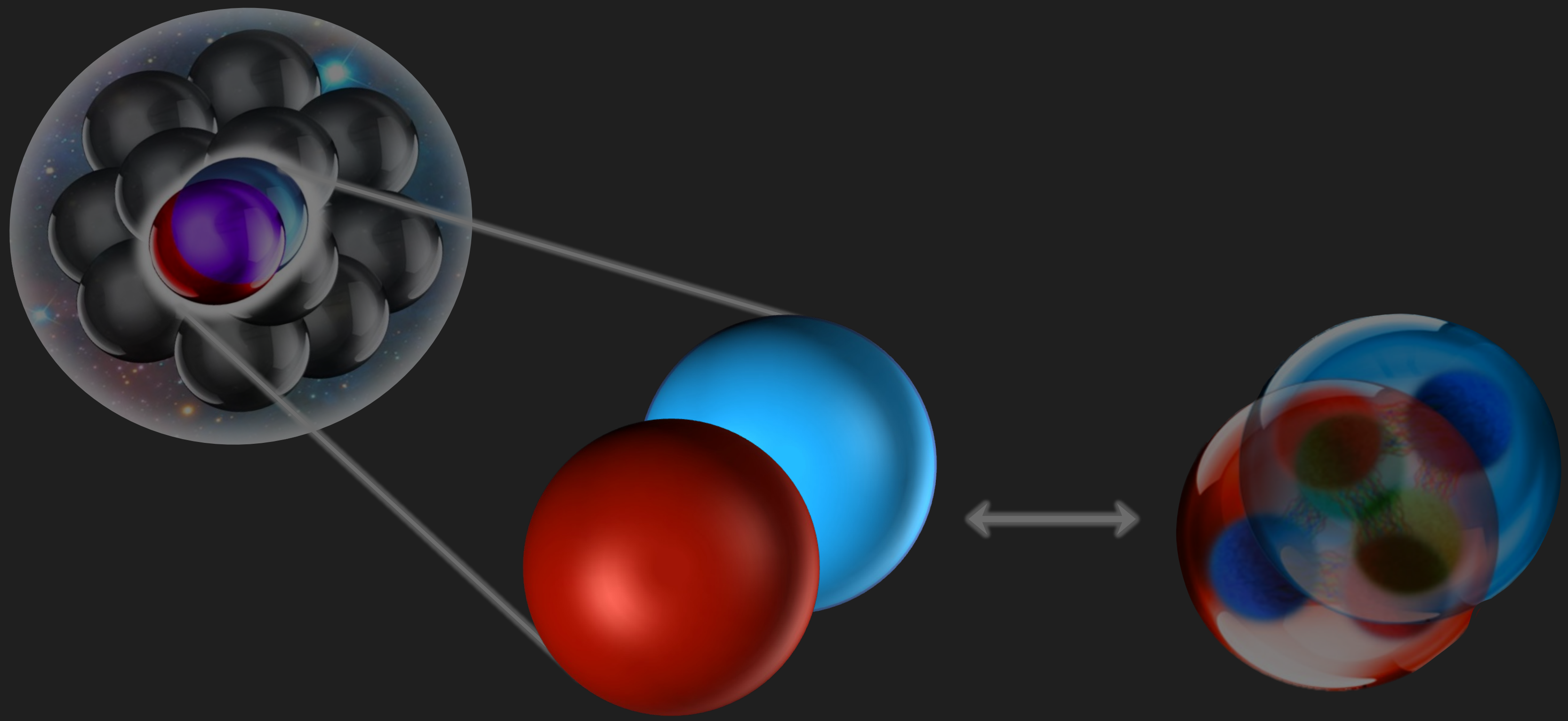
$$\rho_A^{NN,\alpha}(r) \underset{r<1\,\text{fm}}{\cong} C_A^{NN,\alpha} \times |\psi_{NN}^{\alpha}(r)|^2$$

Factorized ground-state →
Factorized reaction model

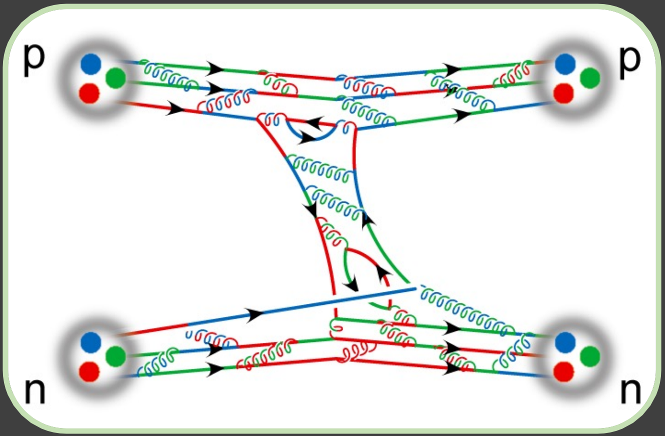
$$\sigma^A \cong \mathrm{K} \times \sigma^N \times \sum_{NN,\alpha} C_A^{NN,\alpha}\, |\psi_{NN}^{\alpha}|^2$$

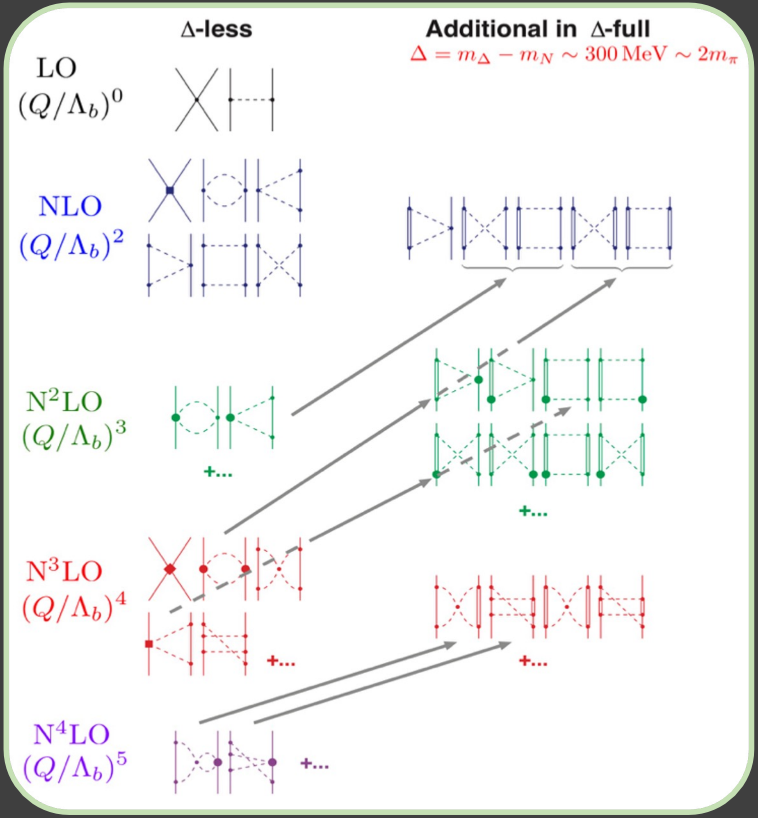


Probing the NN interaction with SRCs



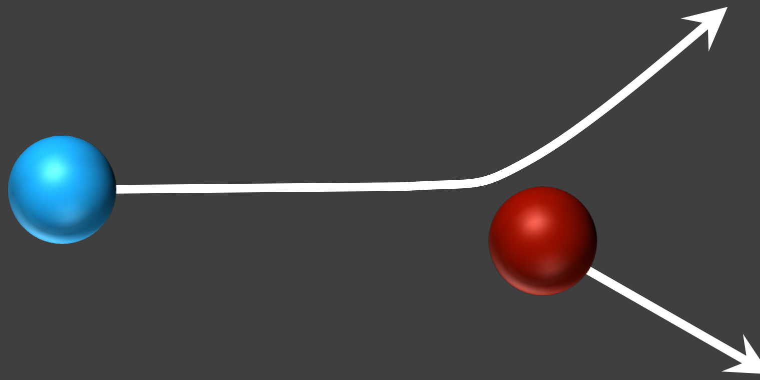
Effective Nucleon-Nucleon Interactions

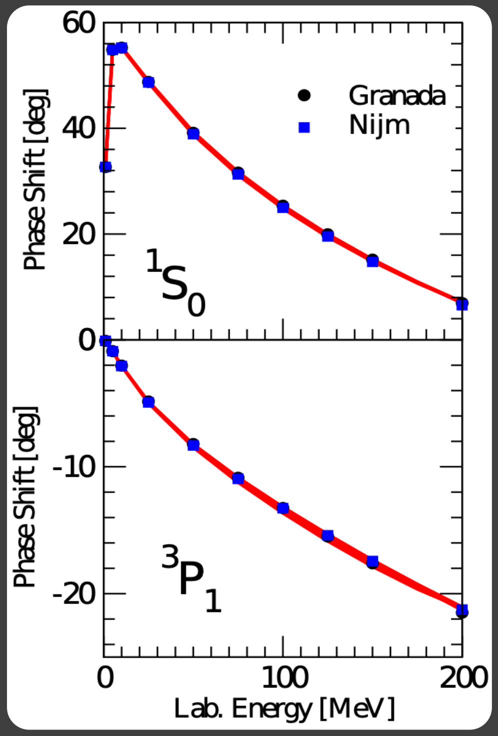




Models Need Experimental Constraints

- Model parameters constrained by data*
- Direct constraints below 400 MeV/c (π threshold)
- Higher momenta (shorter distance) not directly constrained / tested





*Recently also lattice QCD

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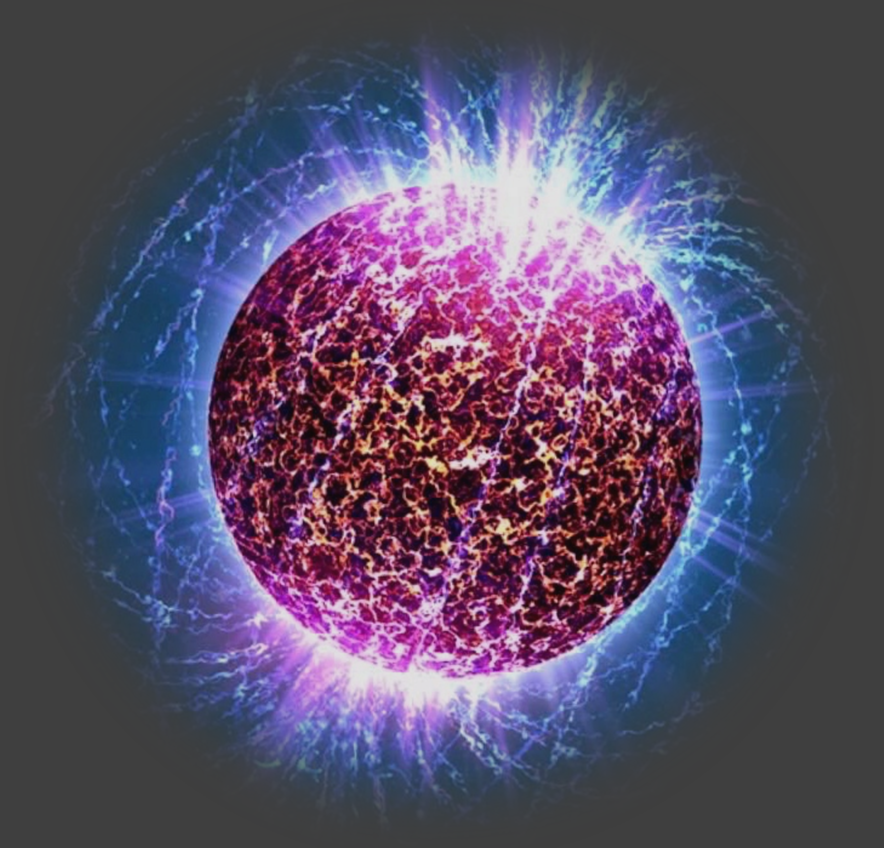


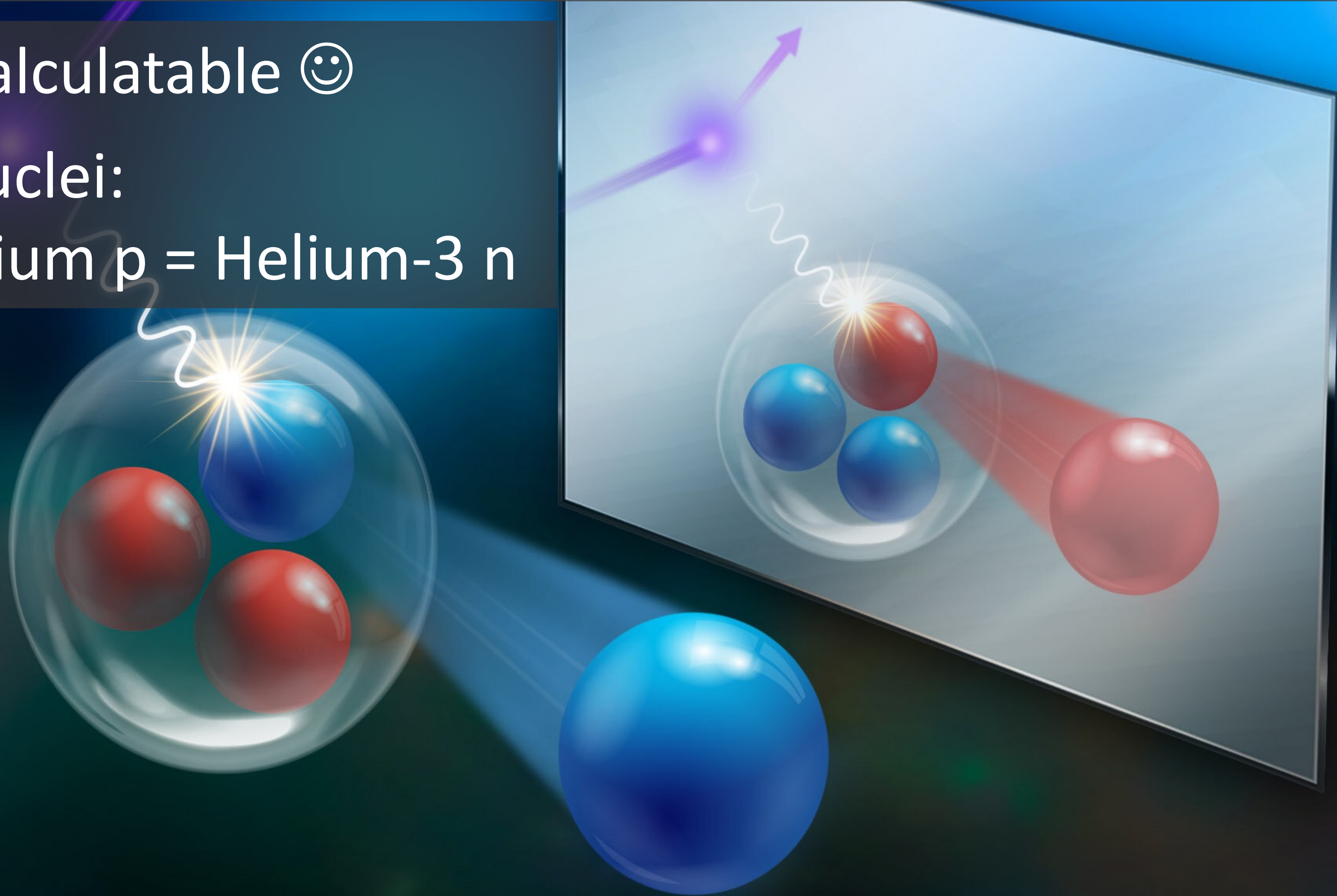
*Recently also lattice QCD

Test With Tritium & Helium-3

Exactly calculatable ☺

Mirror nuclei:

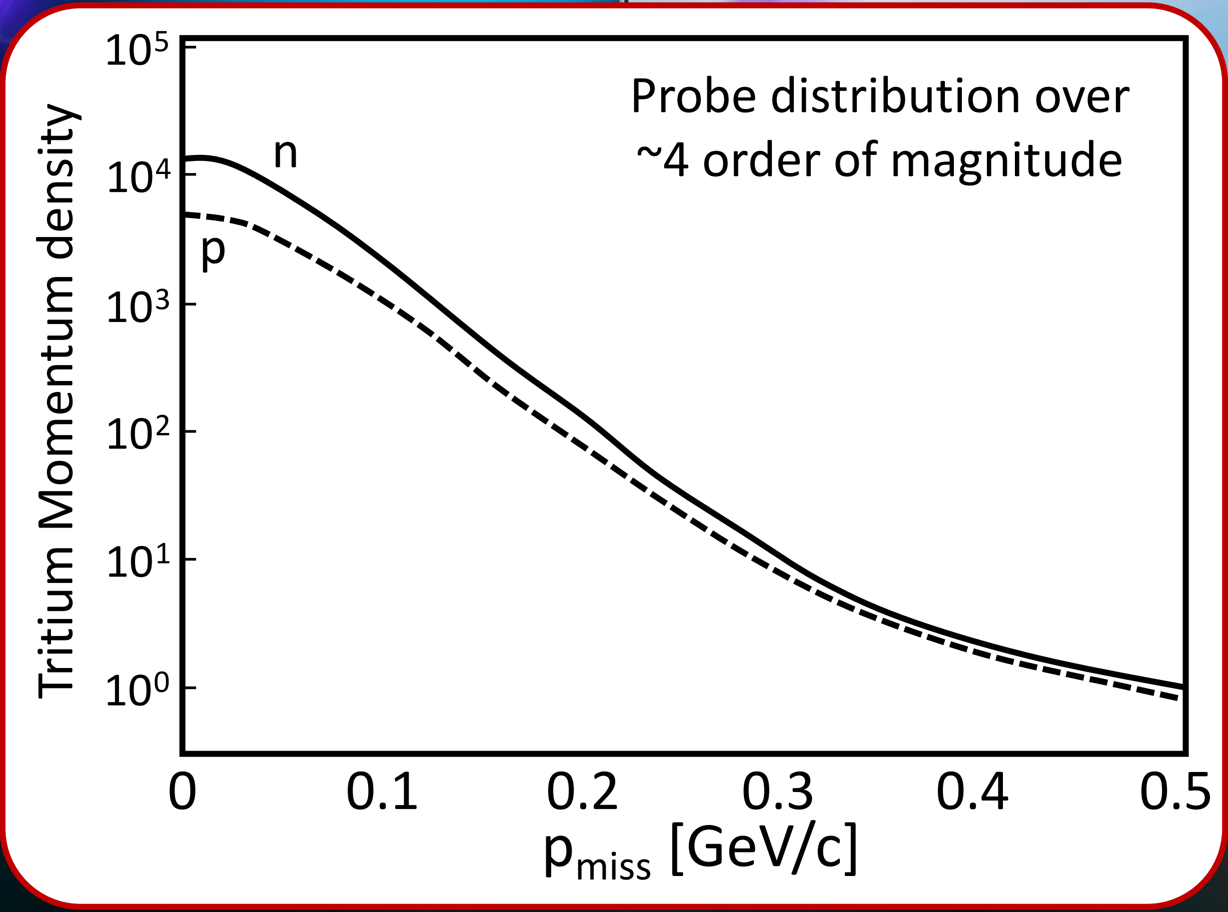
Tritium p = Helium-3 n



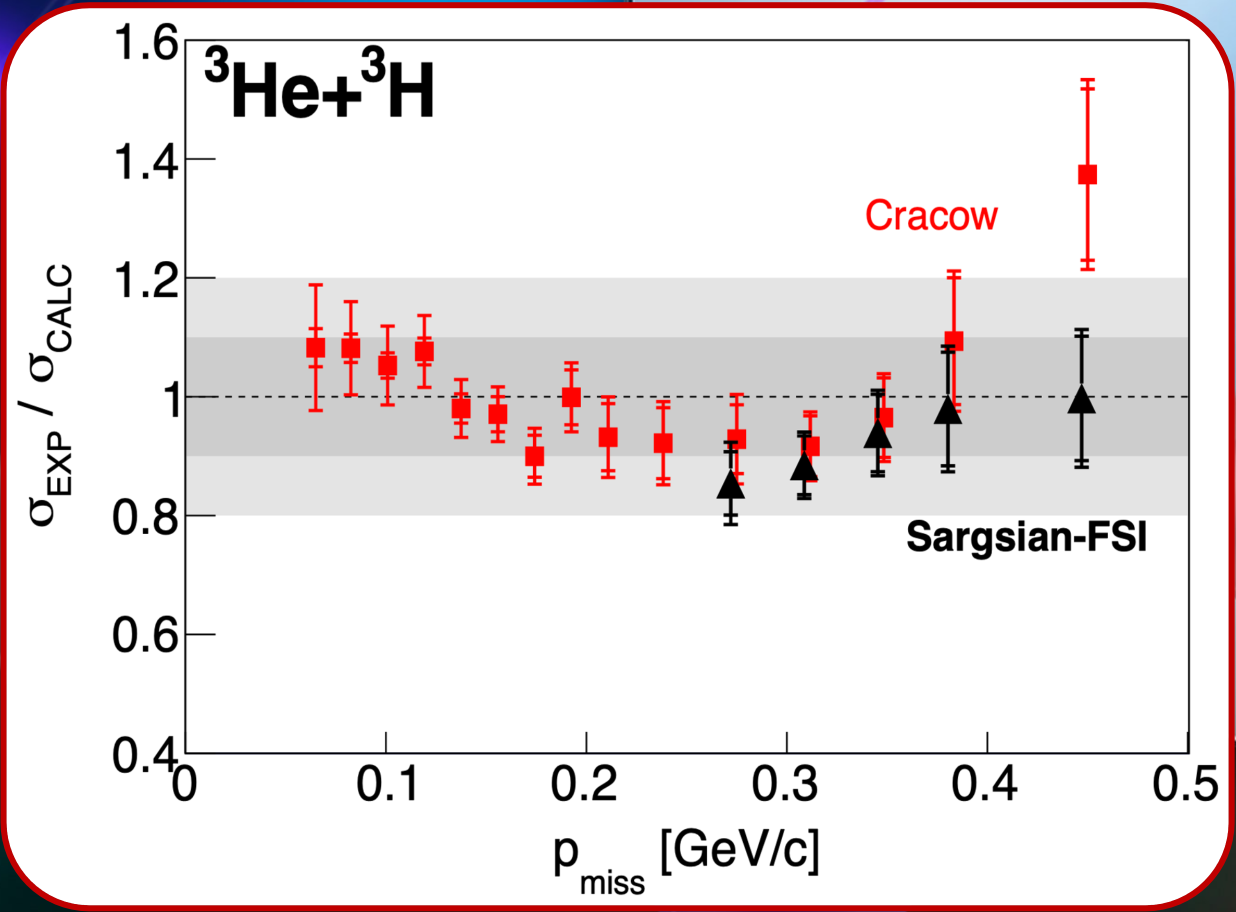
Editors' Suggestion

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

Challenges: Tritium Radioactivity
Low High-p States Density



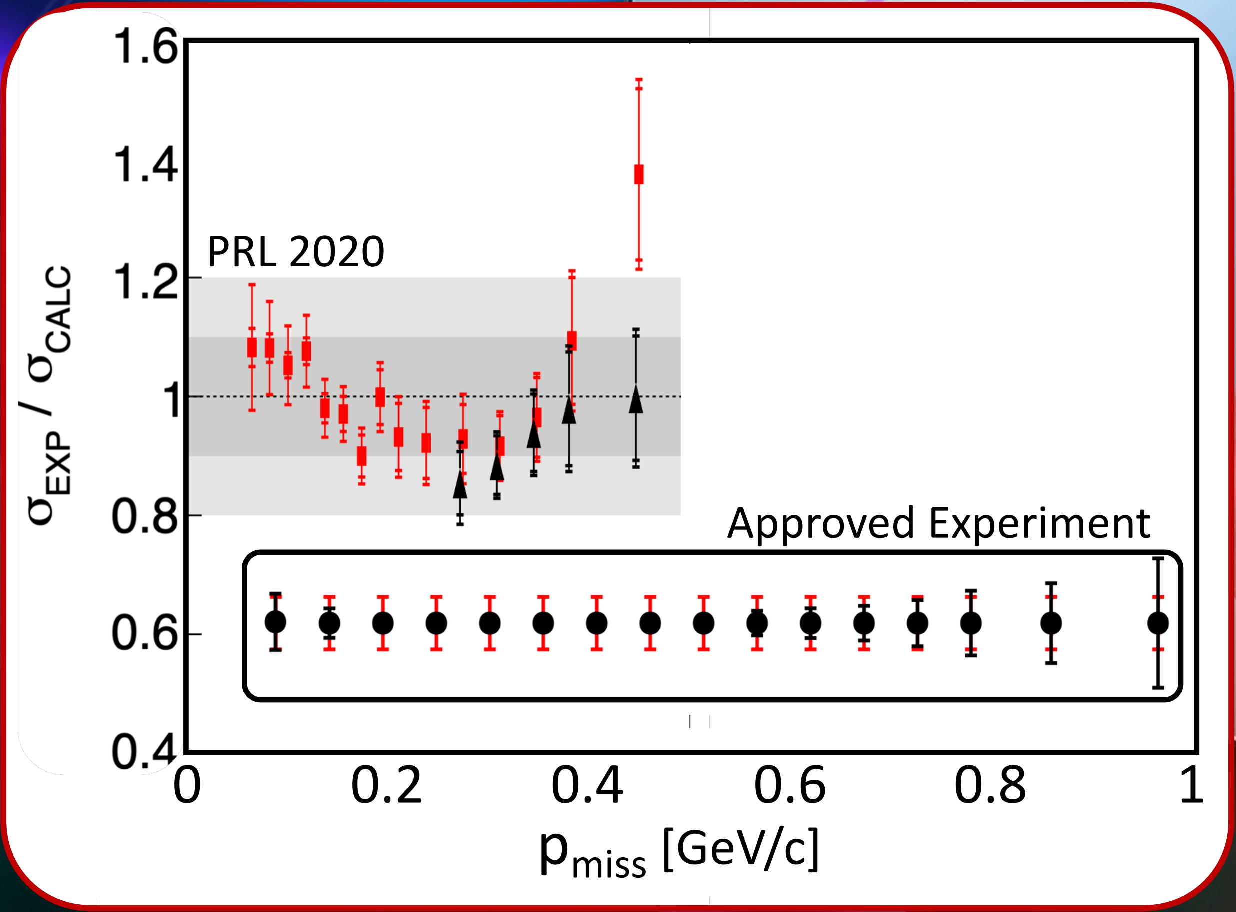
✓ Agreement Over 4 Orders of Magnitude



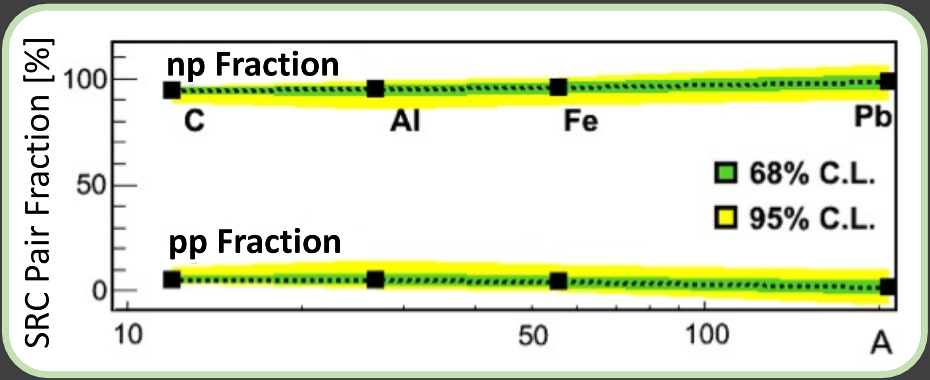
Editors' Suggestion

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

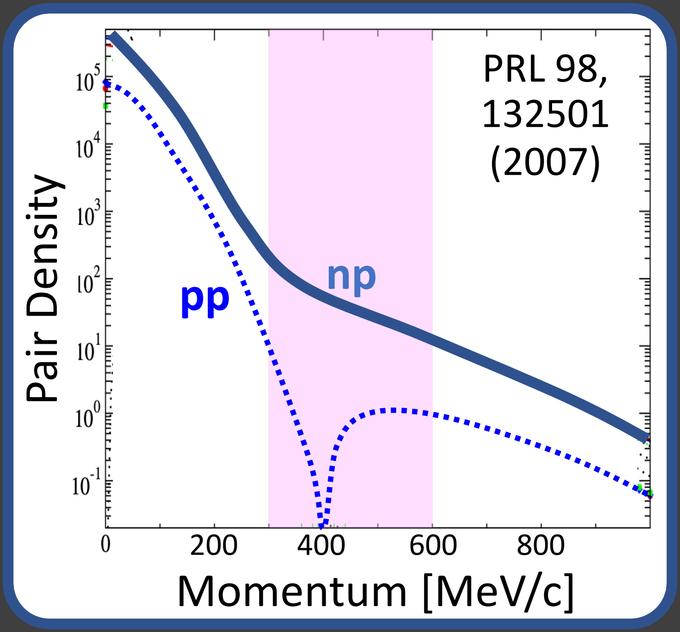
Next Step: Double the Reach



Short-Ranged Interactions in Nuclei



np pairs = Tensor force dominance (spin-dependent)



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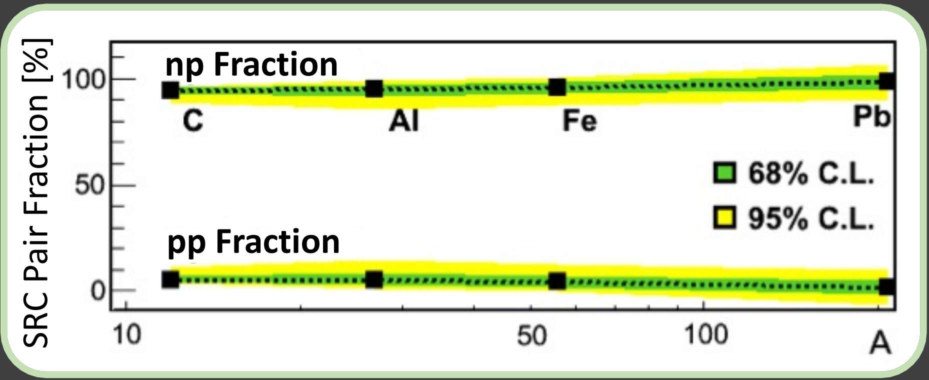

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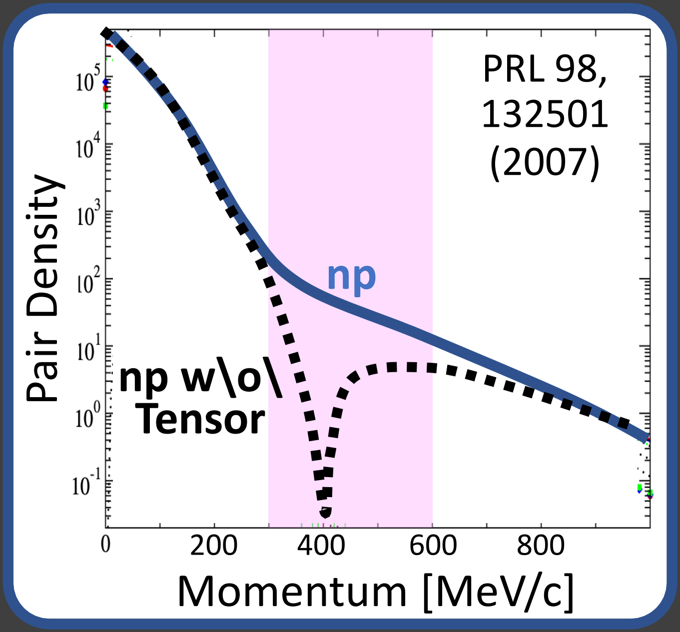

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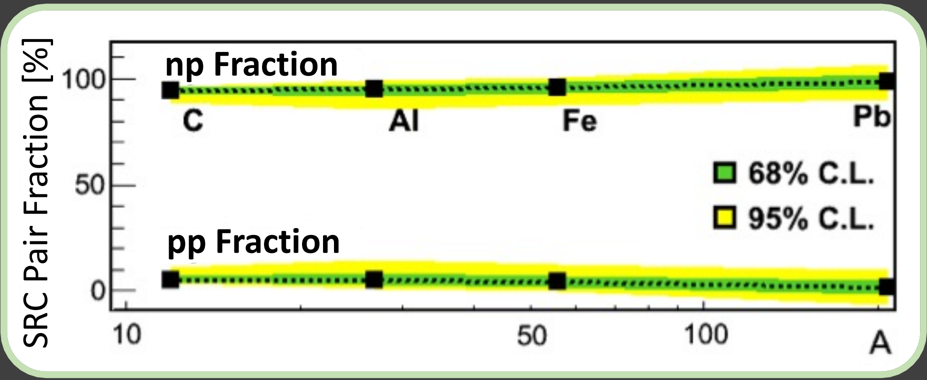

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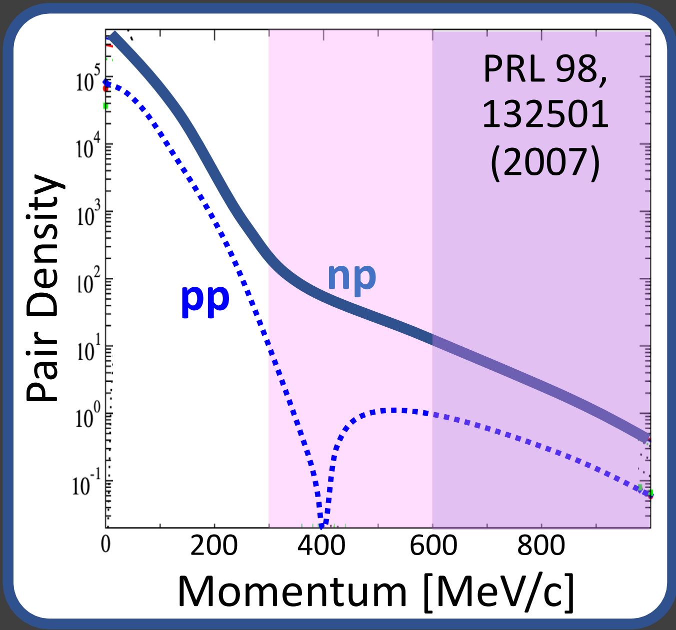
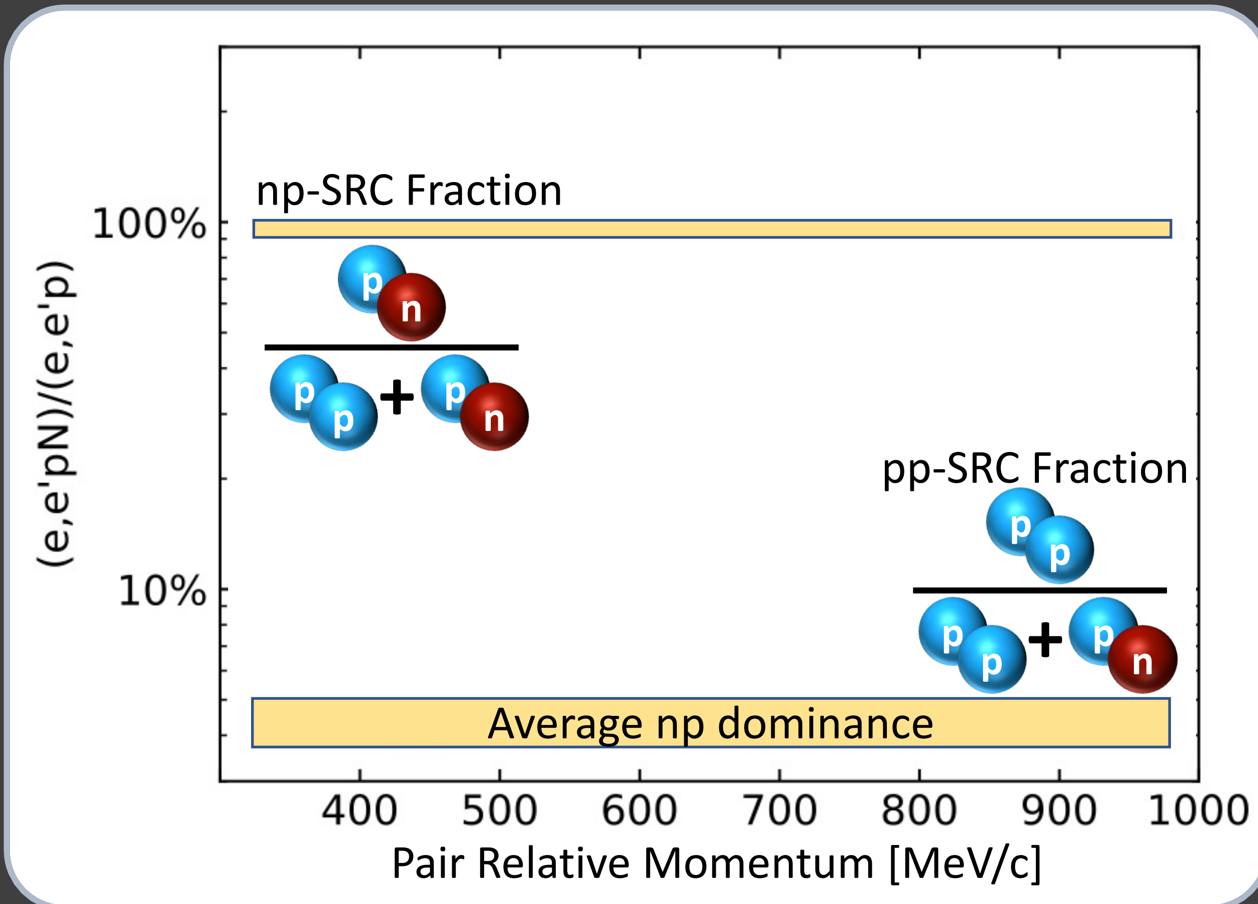


Repulsive core transition:

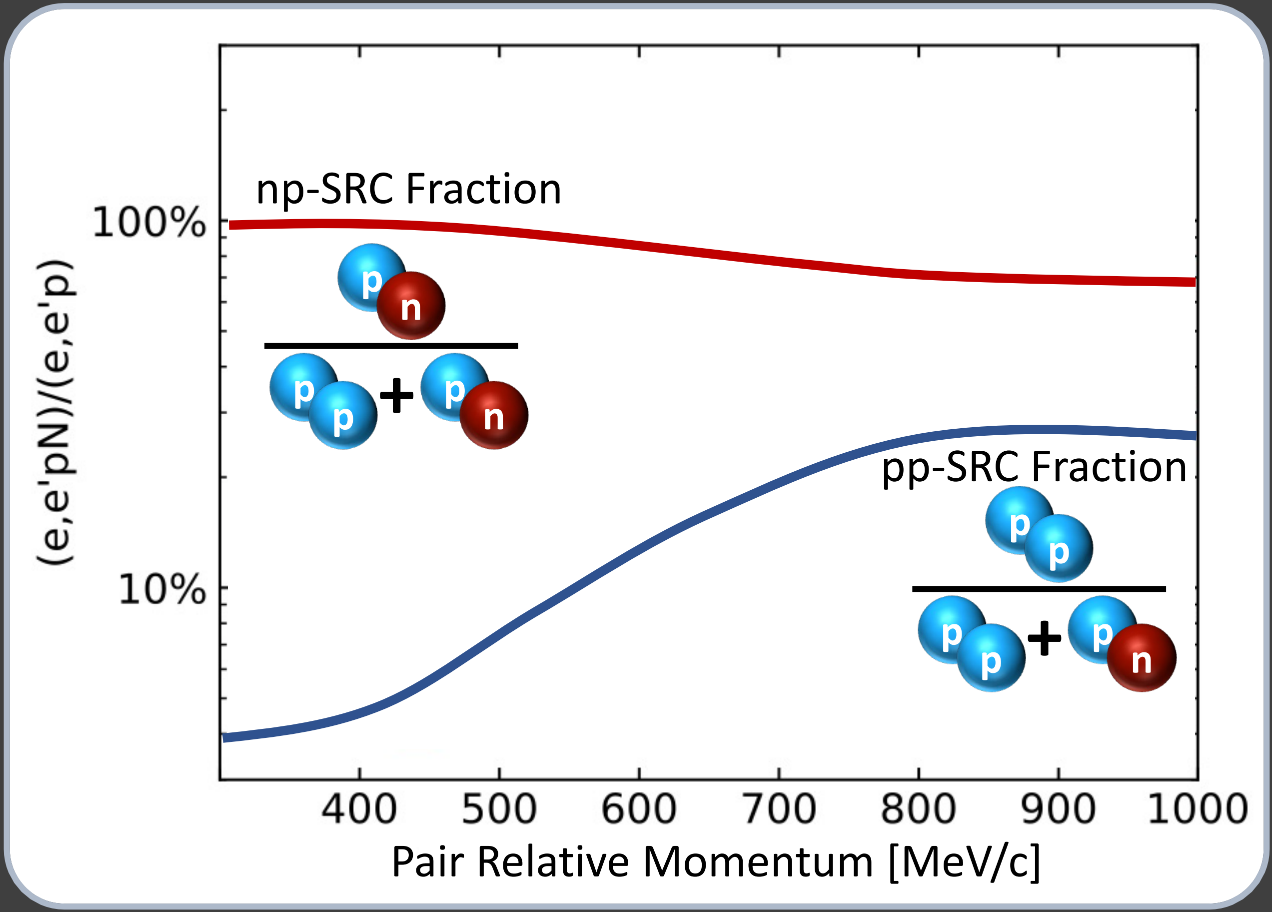
Scalar (spin-independent) core produces more pp pairs

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



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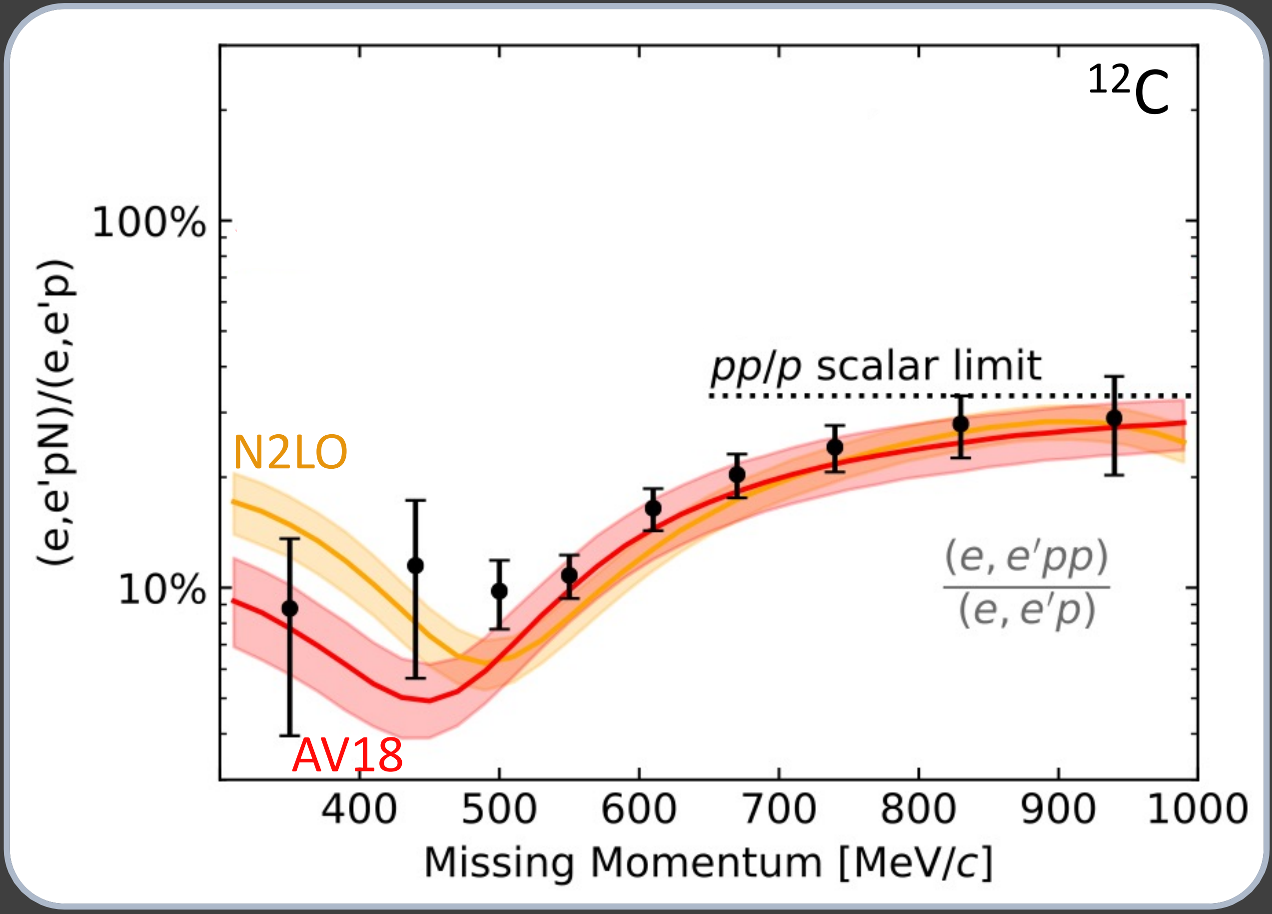

Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

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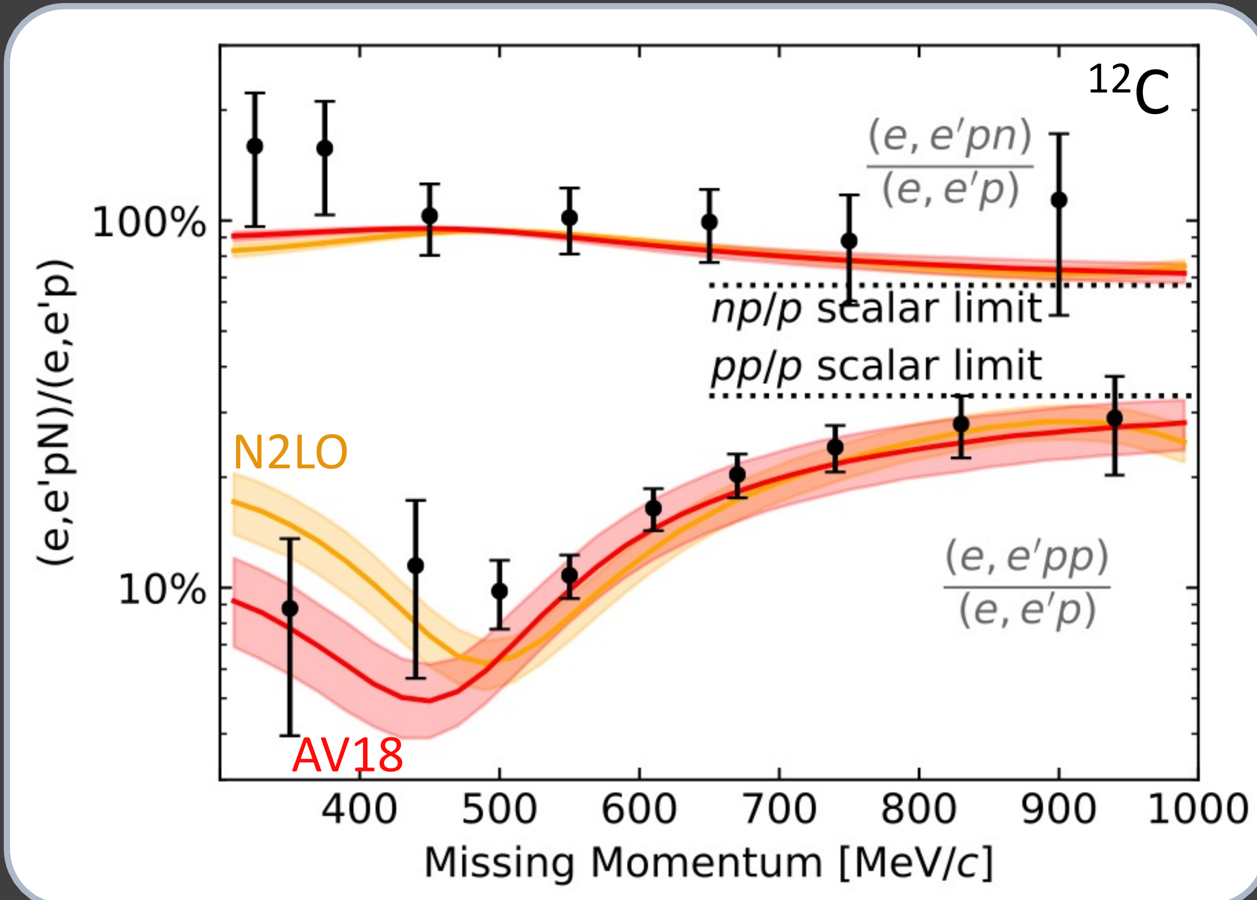
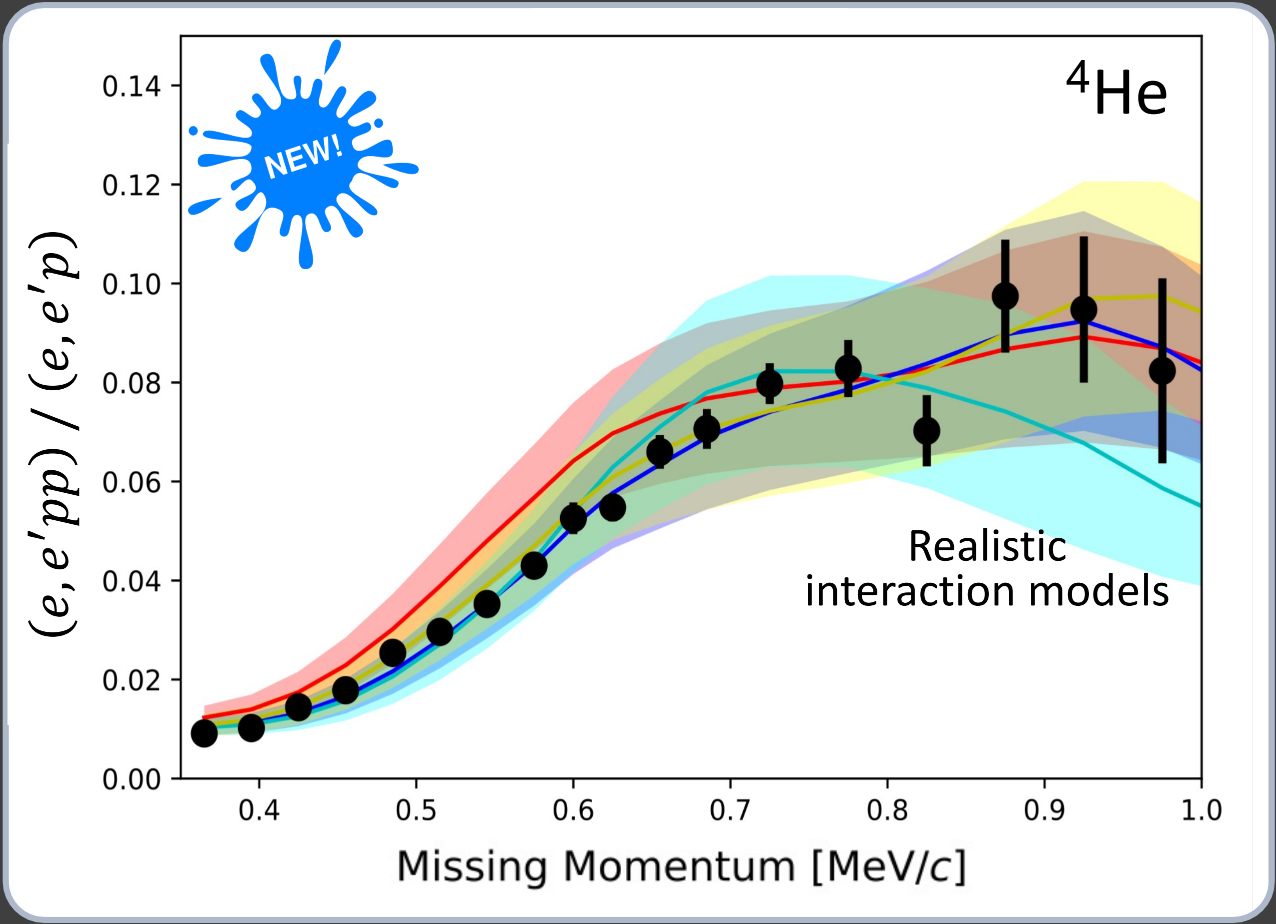




Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

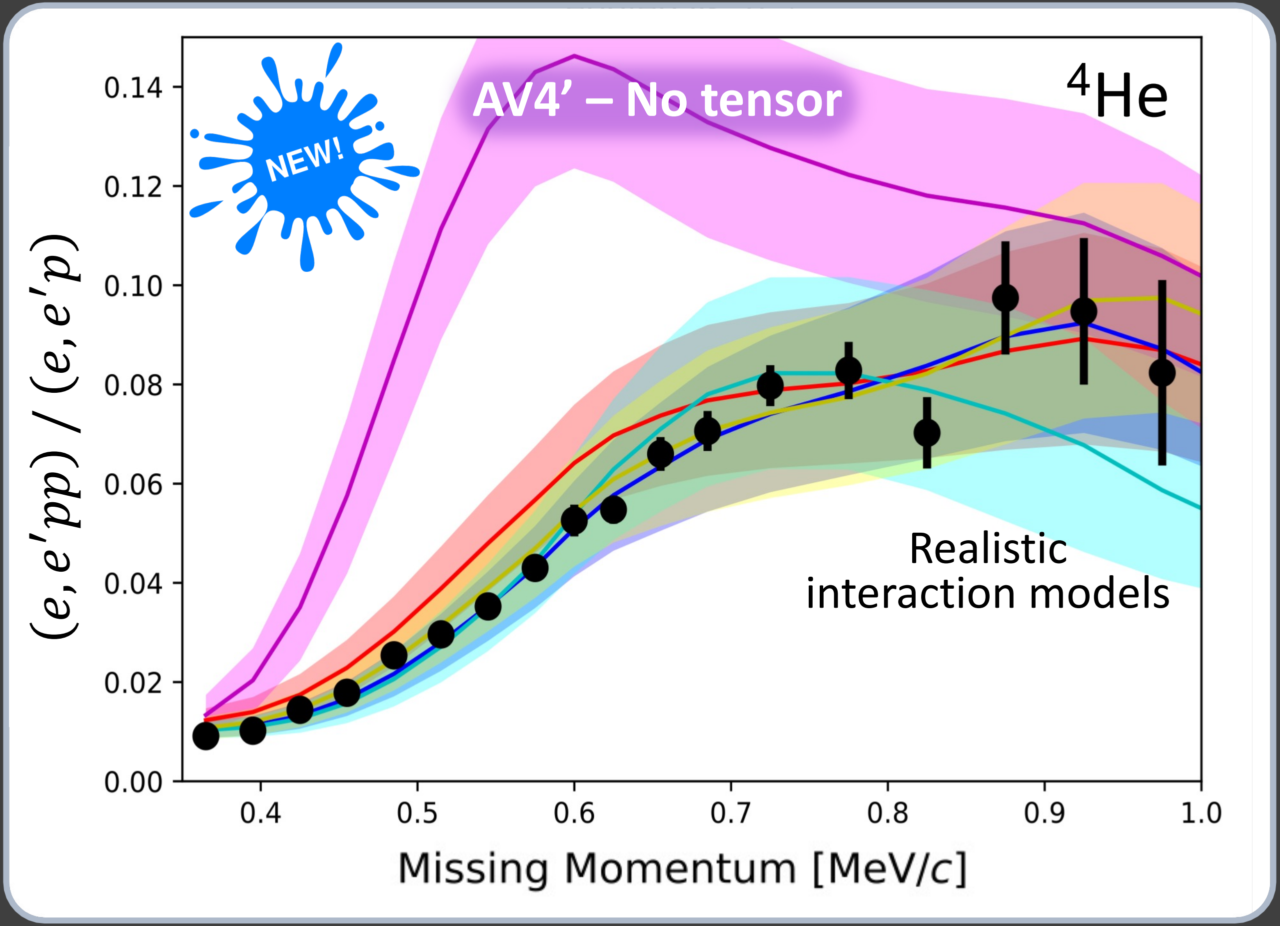
New: High-Precision Data



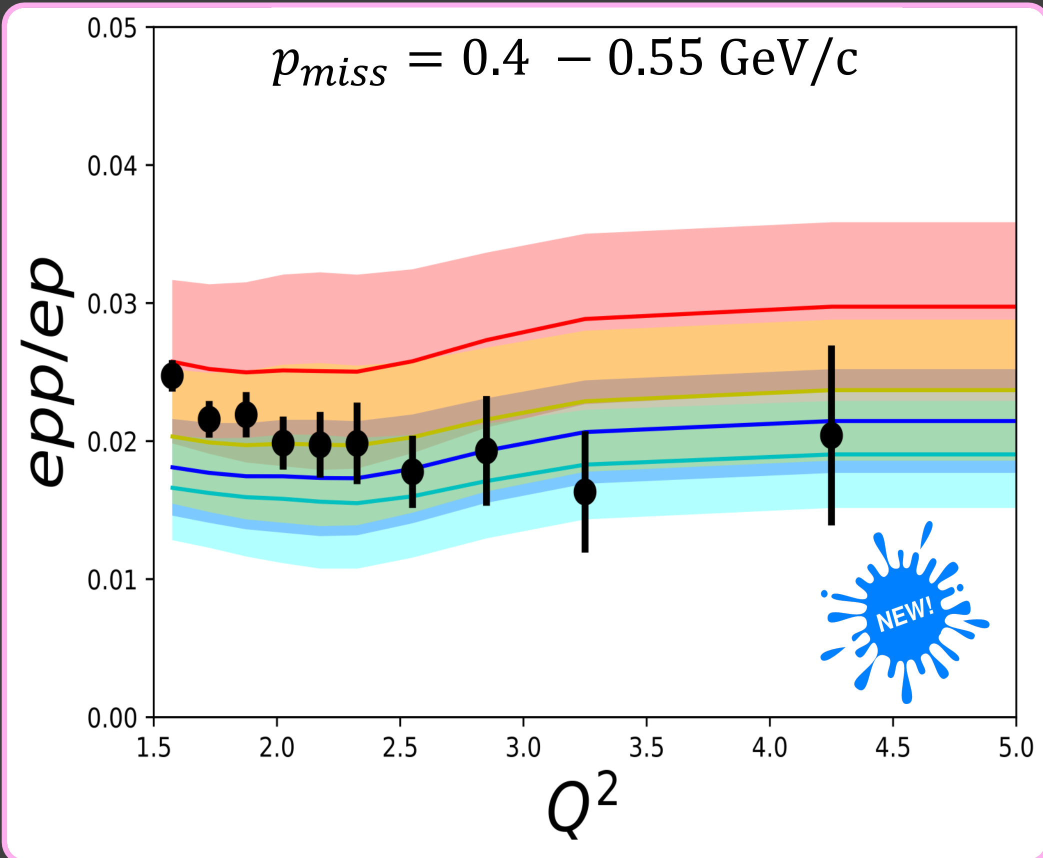
Nature 2020: ~500 pp-SRC events

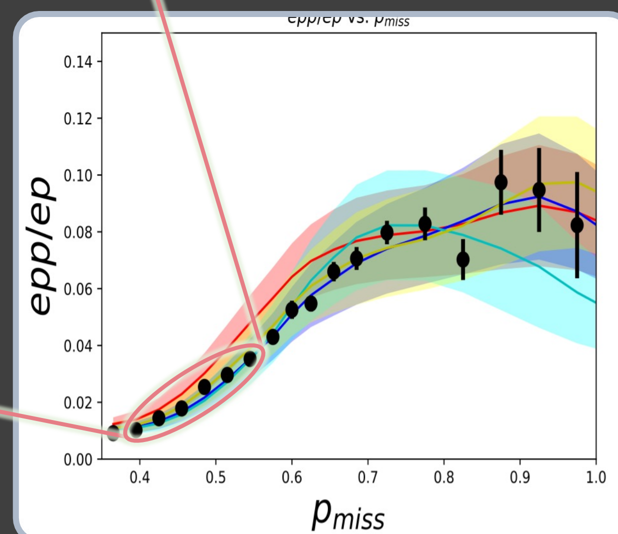
New data: x20 higher stat (4,000 events used above)!

New: High-Precision Data



✓ Scale Independence





Probe Independence?

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

Single-nucleon

Pair distribution

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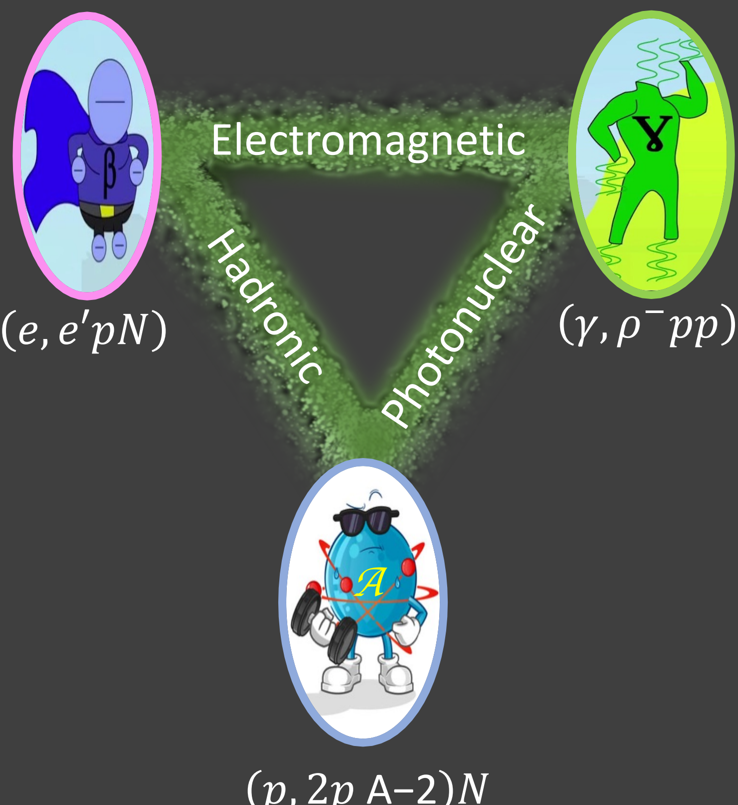

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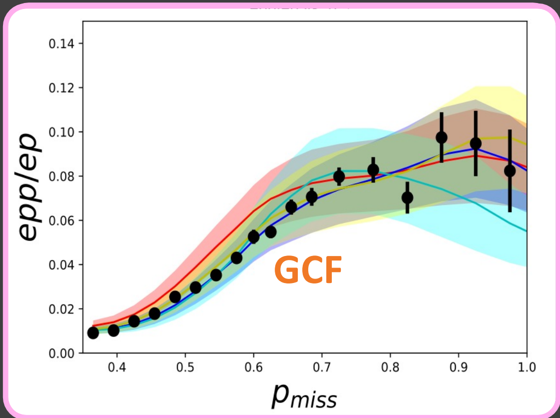
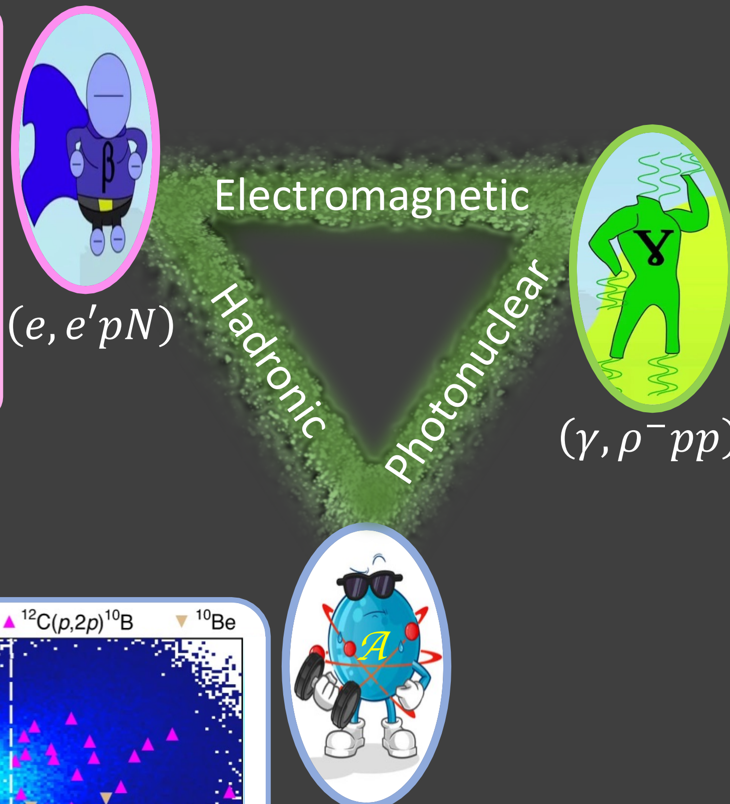
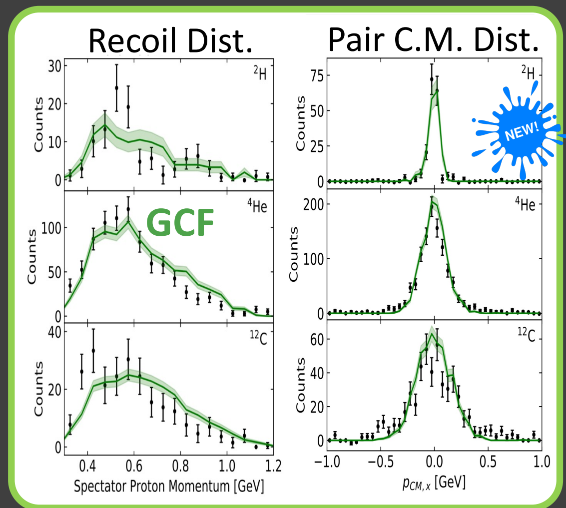
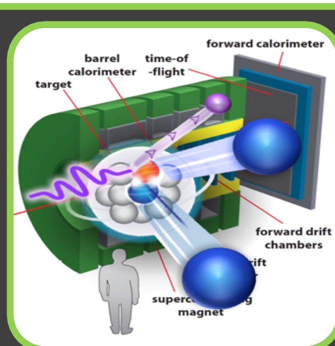
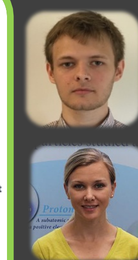
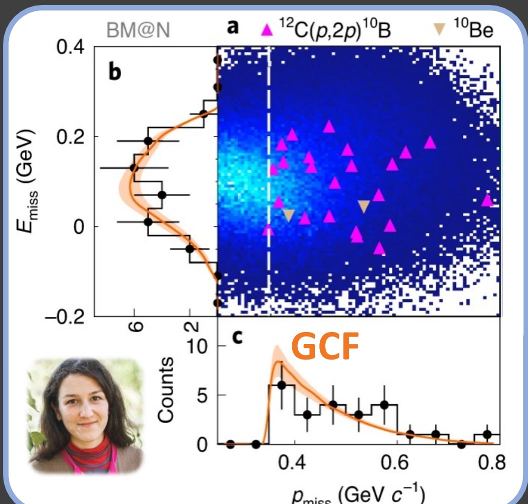


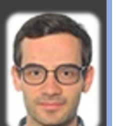


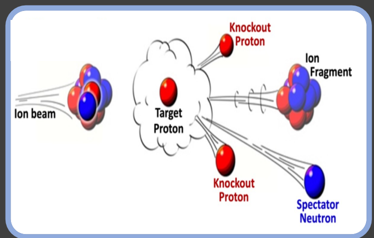






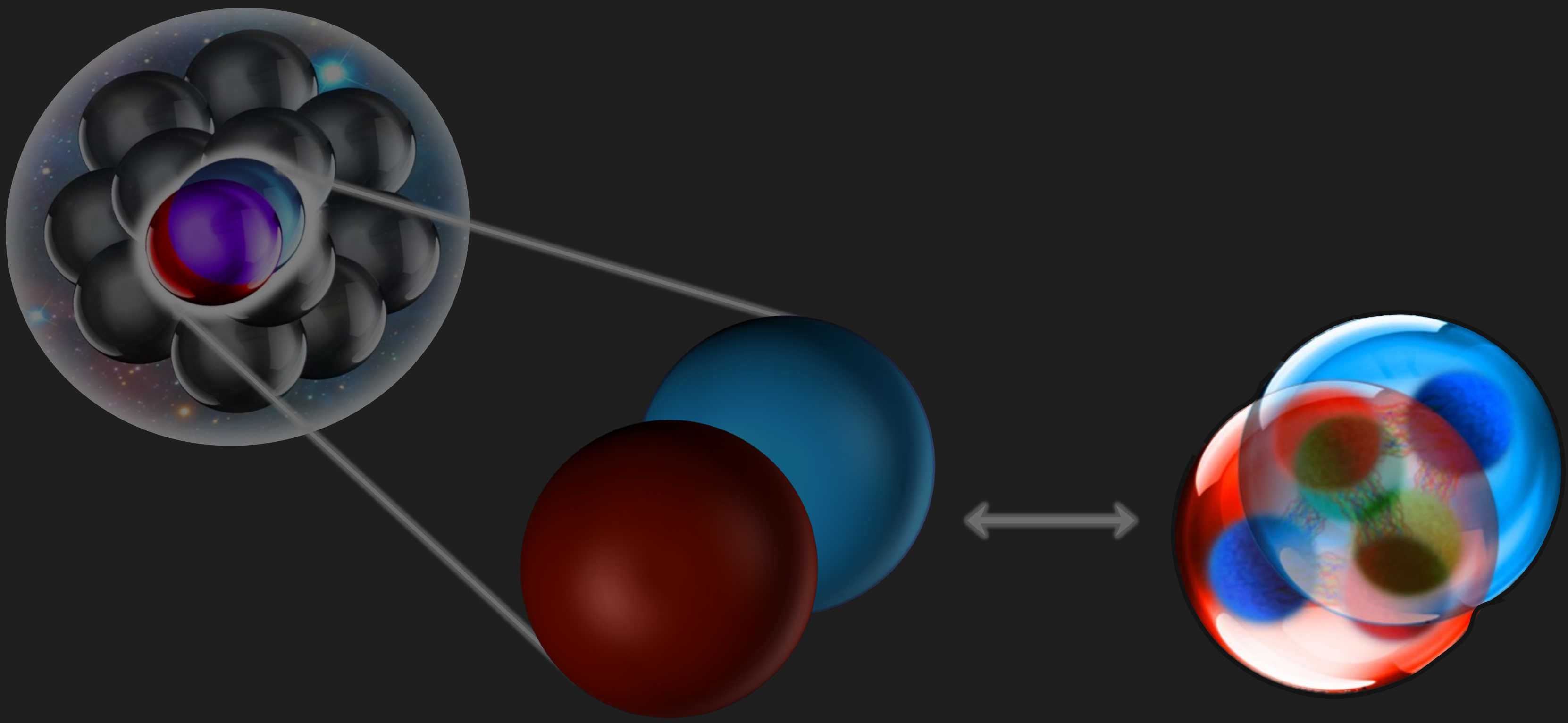




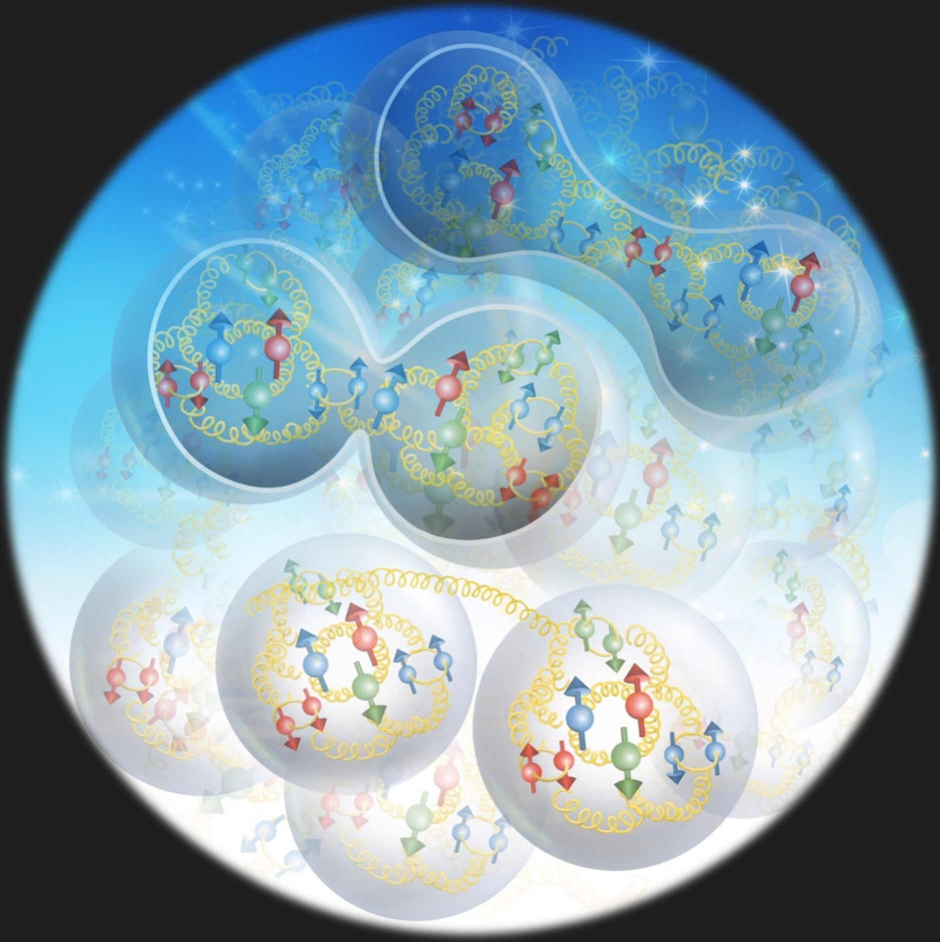


Patsyuk and Kahlbow et al., Nature Physics (2021)

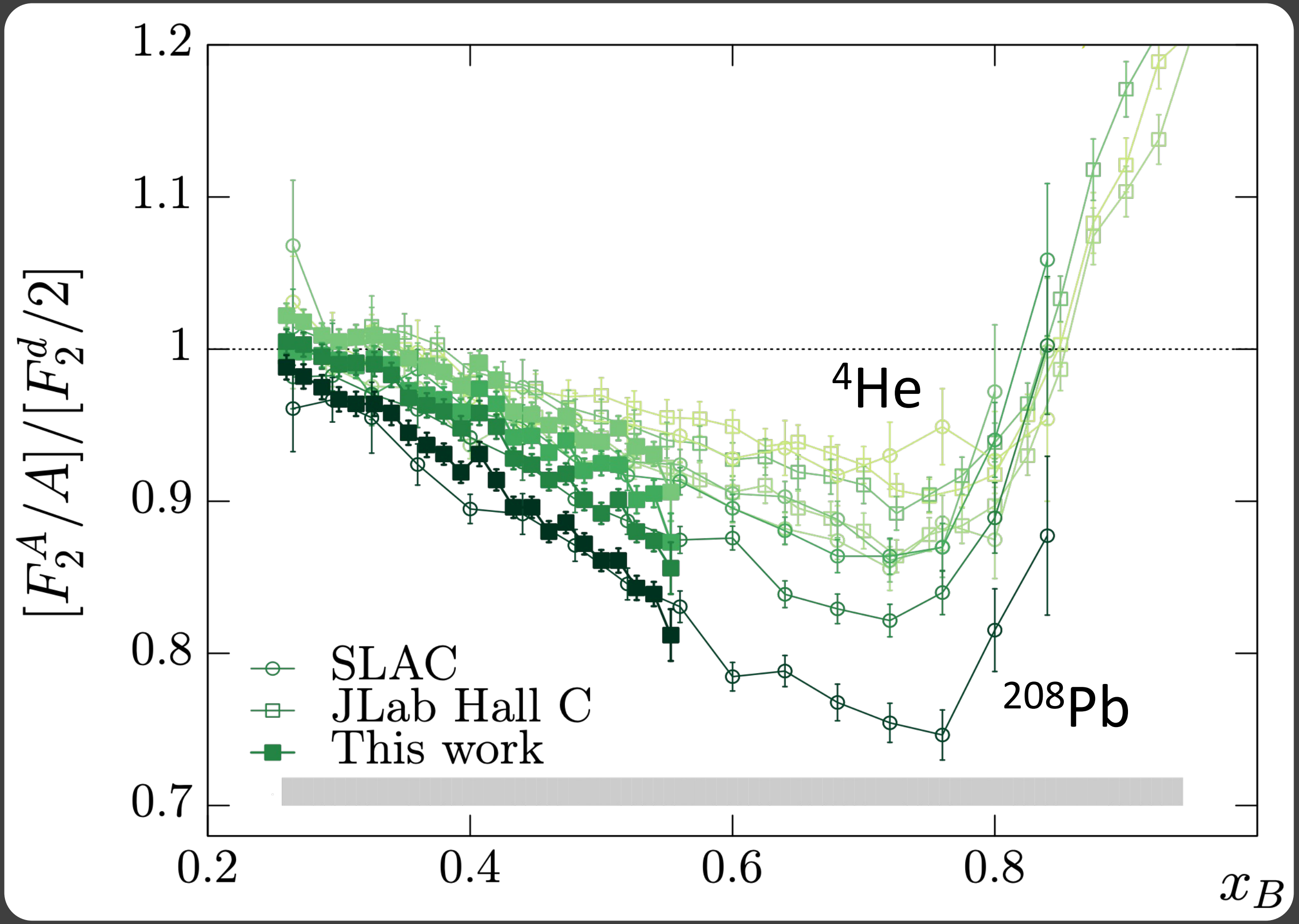
Quarks in Nuclei



Do QCD dynamics affect the identity of nucleons in nuclei?



Quark Momentum Suppression in Nuclei (EMC Effect)



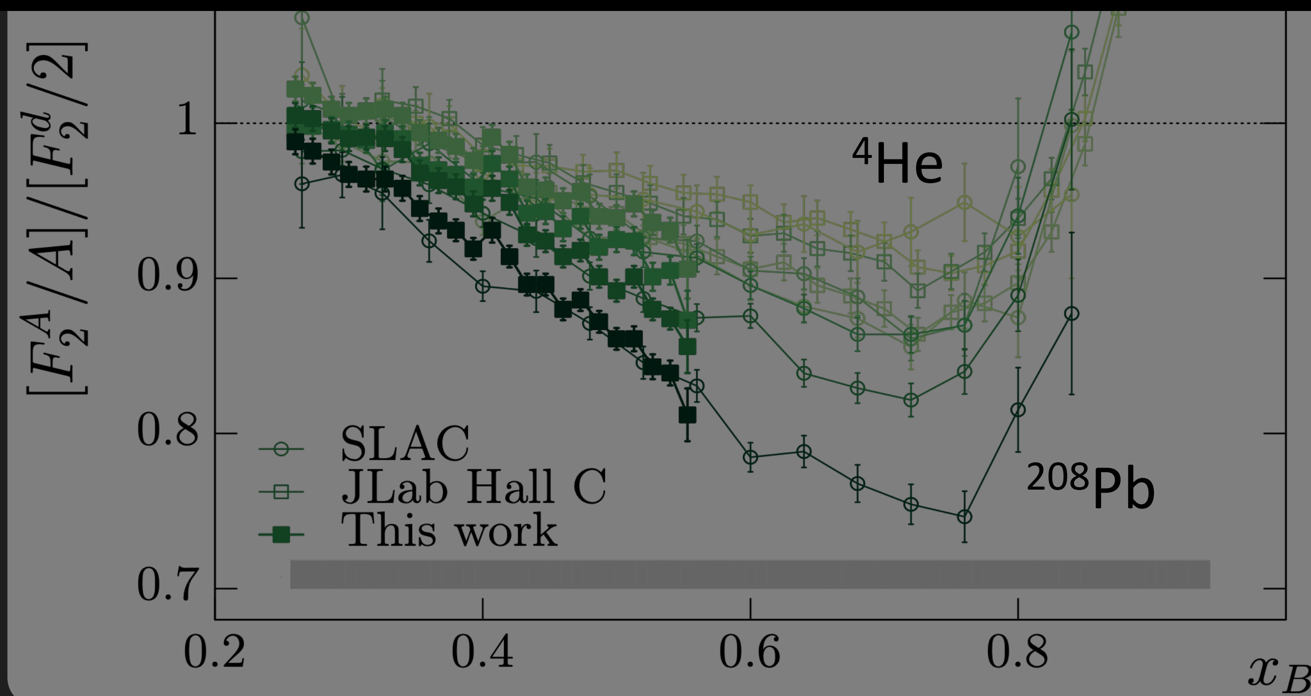
x_B = quark momentum fraction

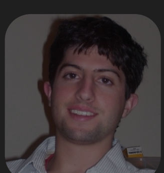
Aubert et al., PLB (**1983**); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Nature (**2019**)

Quark Momentum Suppression

38 years, > 1000 publications, no consensus.

Effect driven by nuclear structure & dynamics





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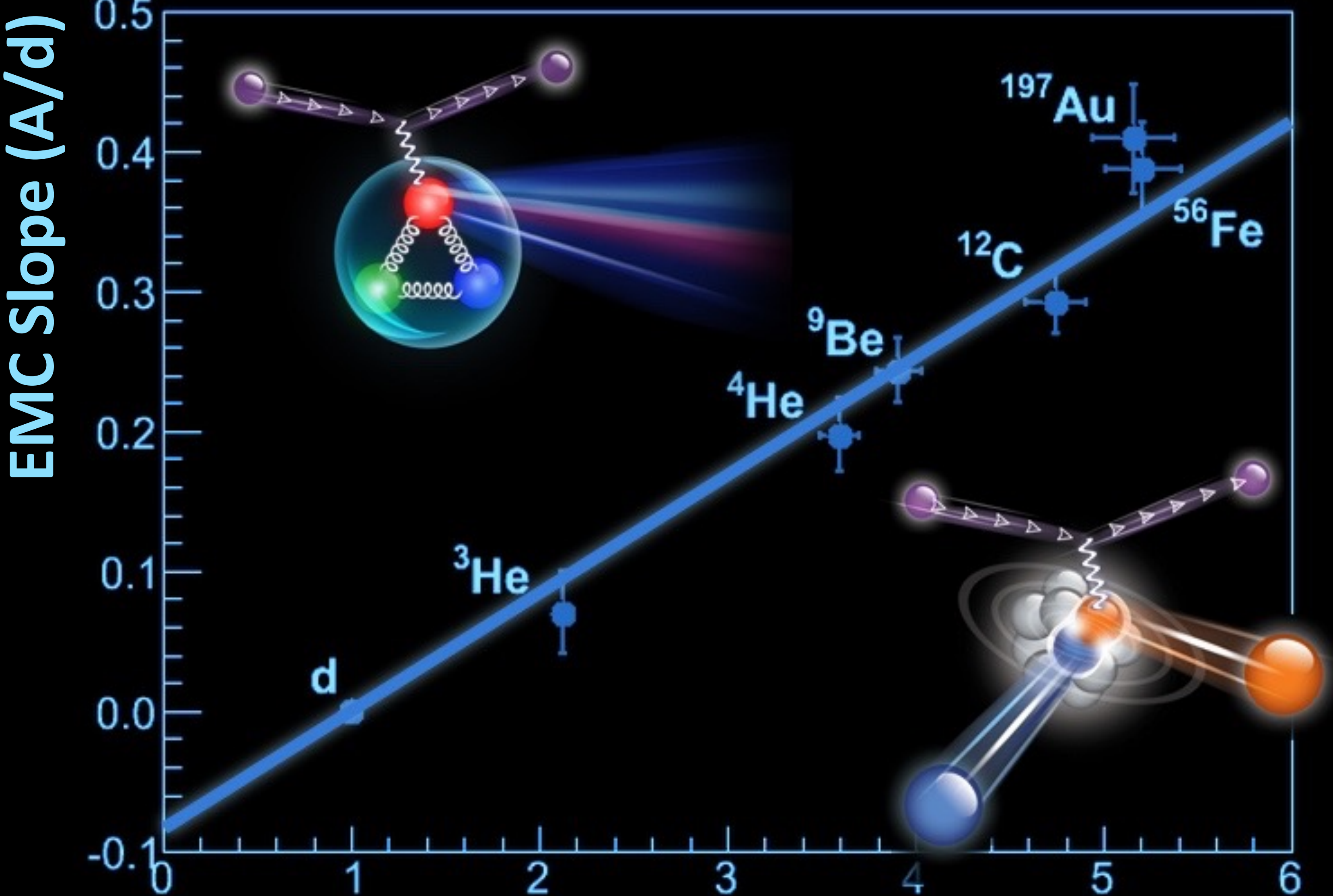
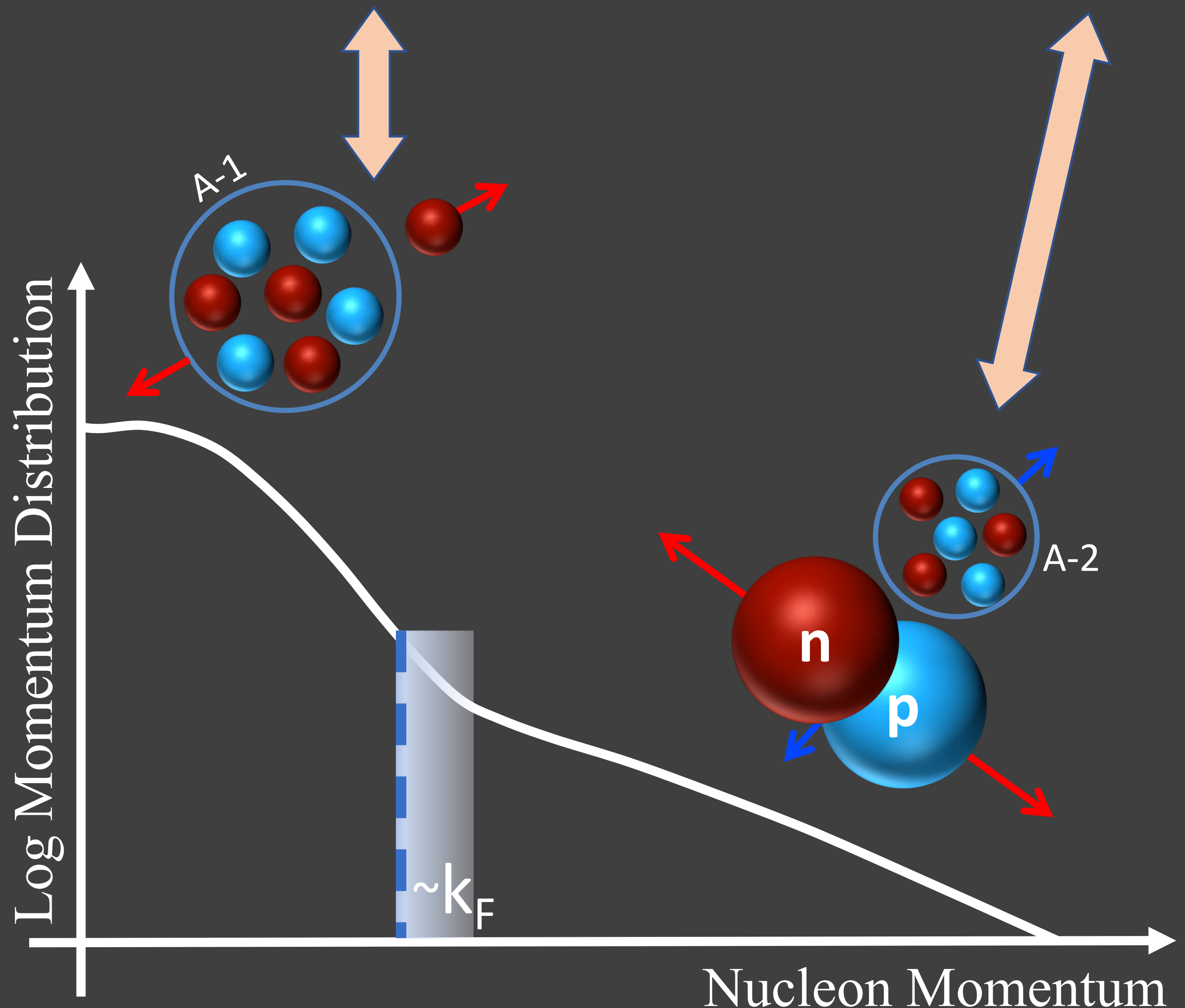
EMC – SRC Correlation



SRC Fraction (A/d)

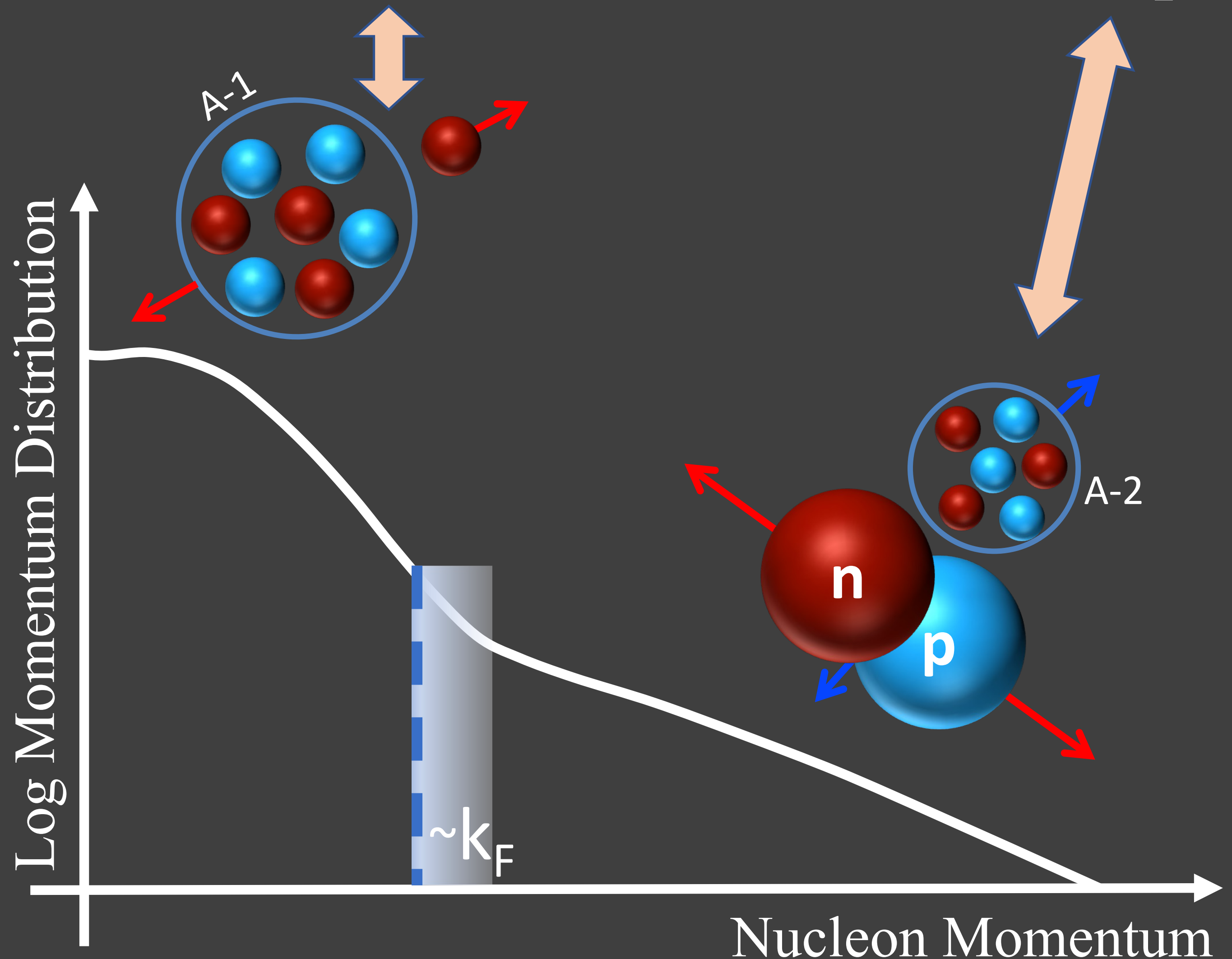
Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011);

Bound = 'Quasi-Free' + Modified SRCs



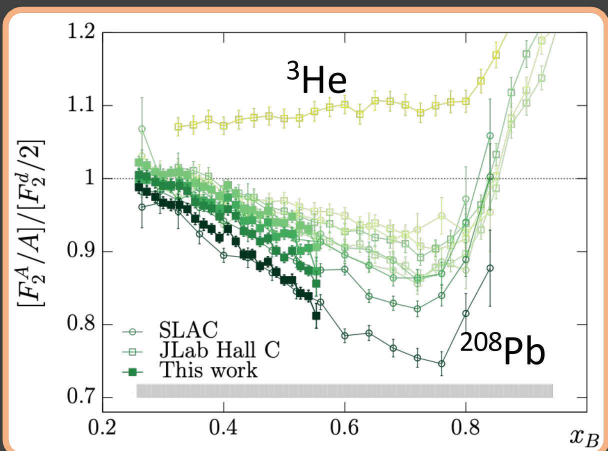
Bound = 'Quasi-Free' + Modified SRCs

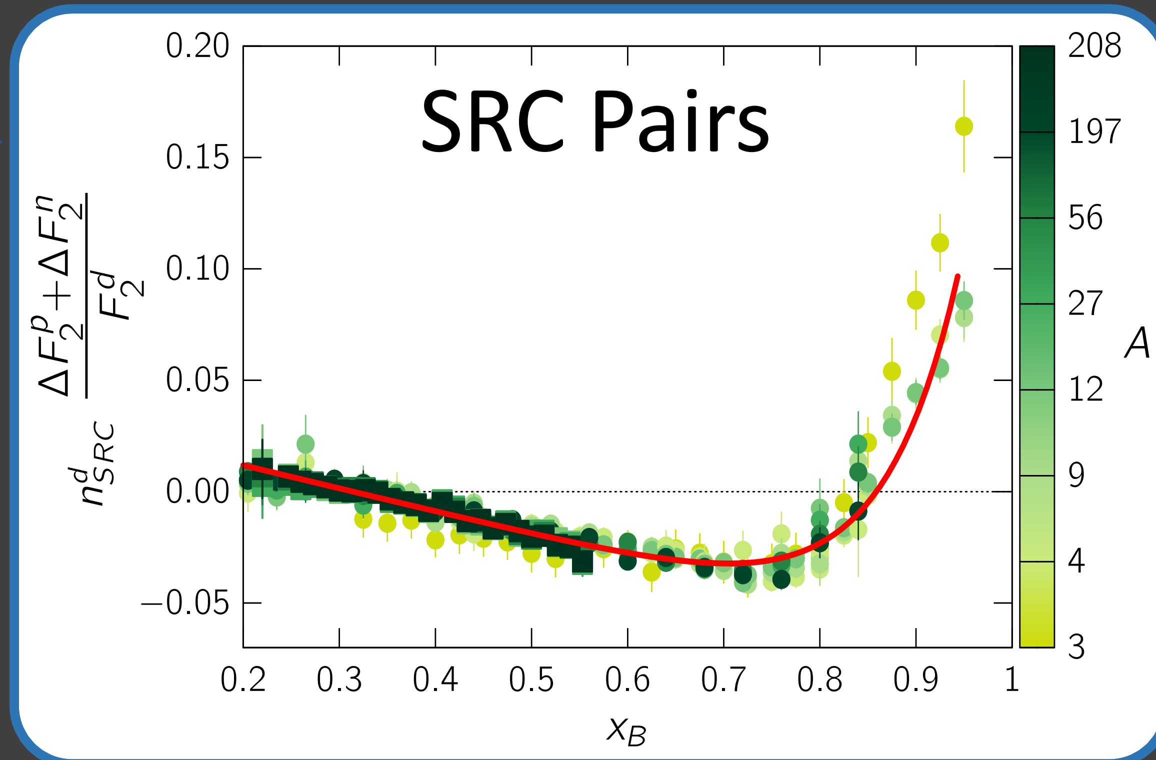
$$F_2^A = (A - \#SRC_A) \cdot F_2^N + \#SRC_A \cdot F_2^{SRC}$$



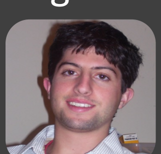
SRC Universality!

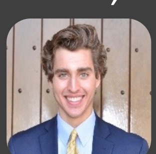
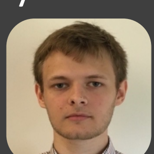
All Nucleons



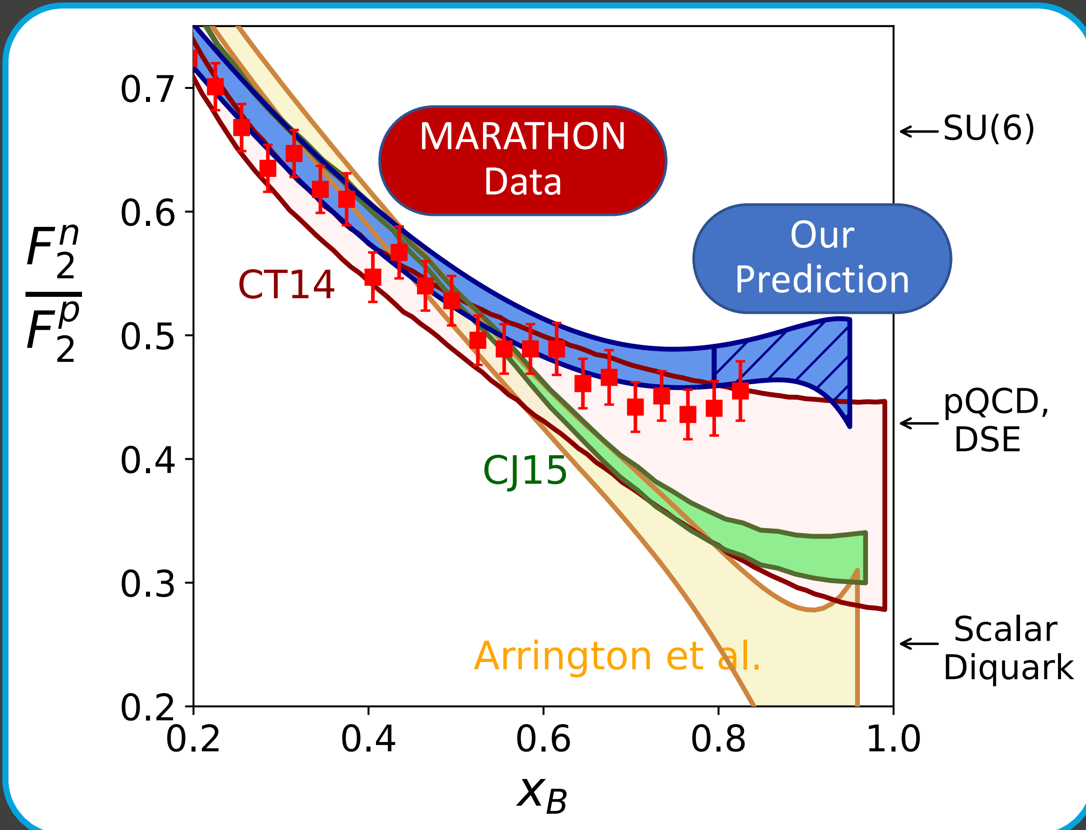


Schmookler et al., Nature (2019);
Segarra et al., Phys. Rev. Lett. (2020);
Segarra and Pybus et al., Phys. Rev. Research (2021)



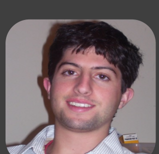



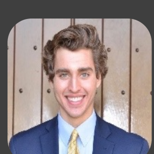
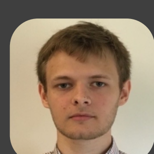
Verified Predictions!



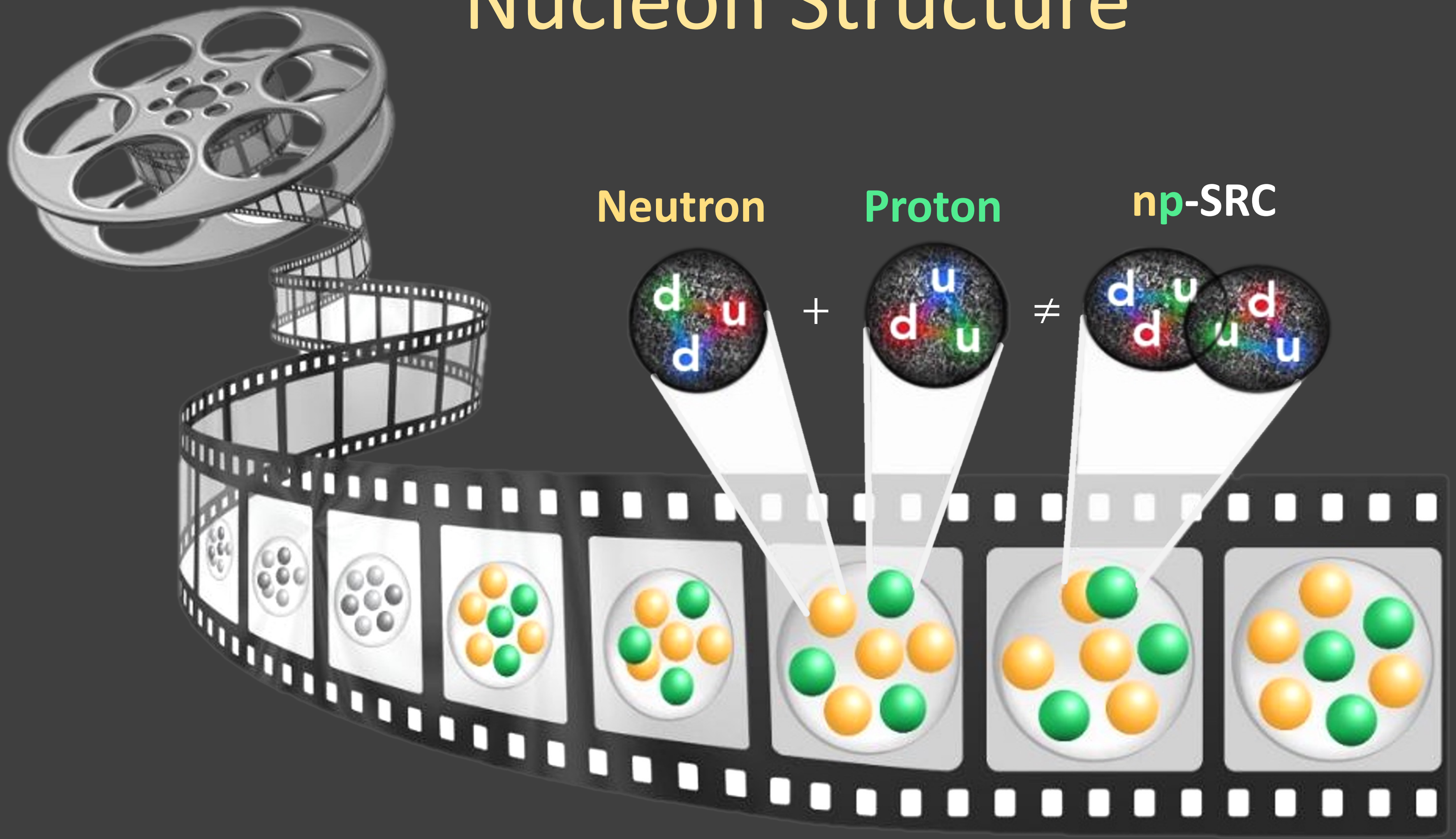
MARATHON Data: Abrams et al., Phys. Rev. Lett. (2022)

Our Prediction: Segarra et al., Phys. Rev. Lett. (2020)



Nuclear Interactions Impact Nucleon Structure

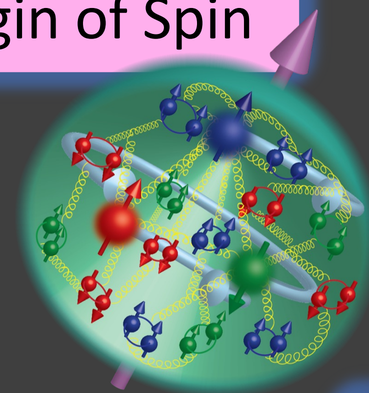


Next Generation QCD Frontier at the Electron-Ion Collider (EIC)

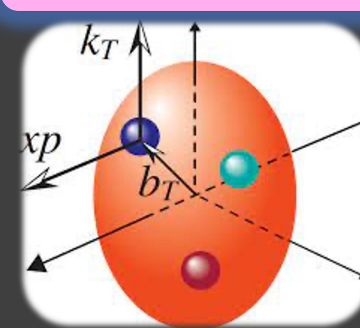
EIC Science

Origin of Mass

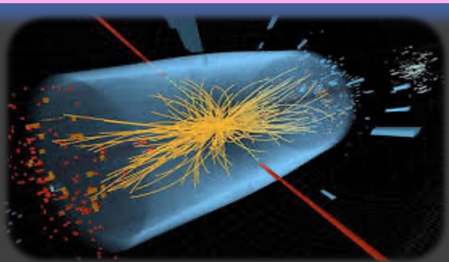
Origin of Spin



Femtography

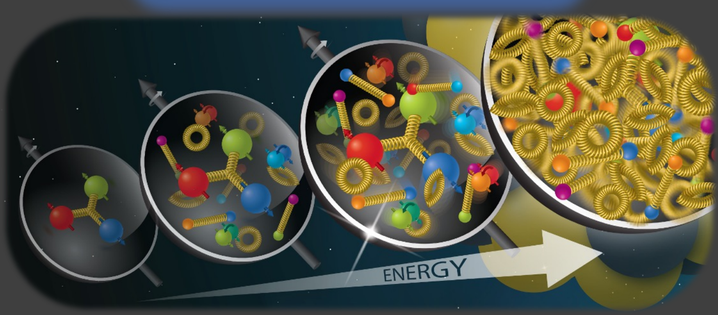


Standard Model



Nuclei

Dense Gluons

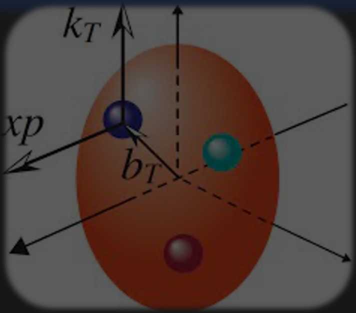


Origin of Mass

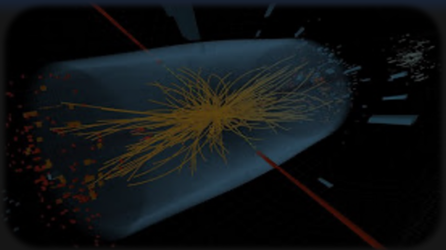
Origin of Spin

EIC Science

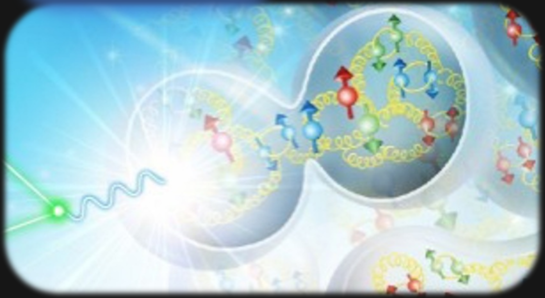
Femtography



Standard Model

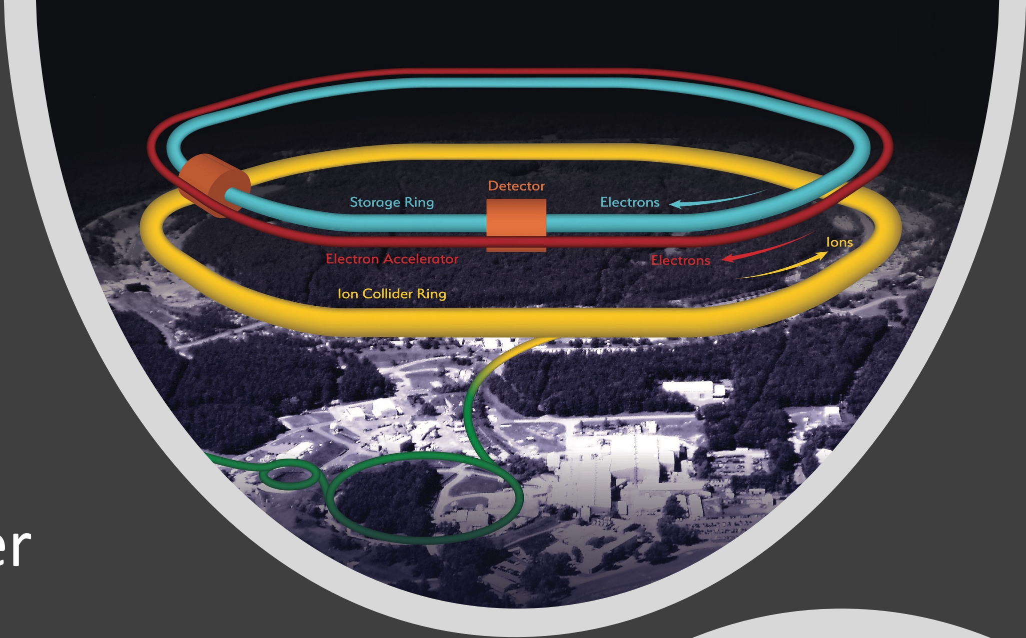


Nuclei



Dense Gluons

Electron-Ion Collider (EIC)

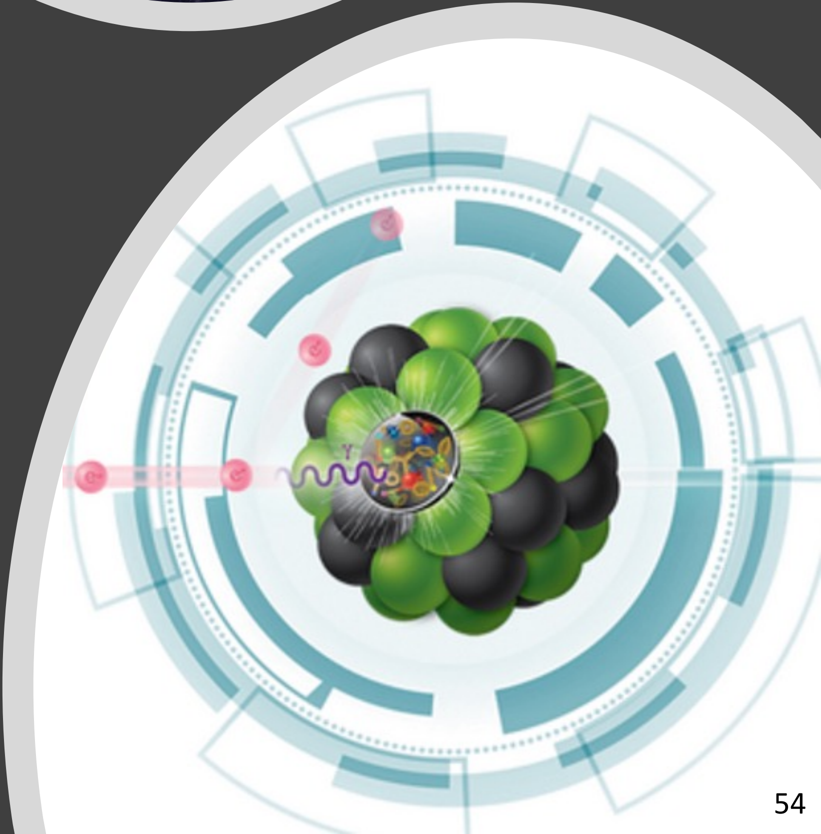


Polarized ep & eA collider

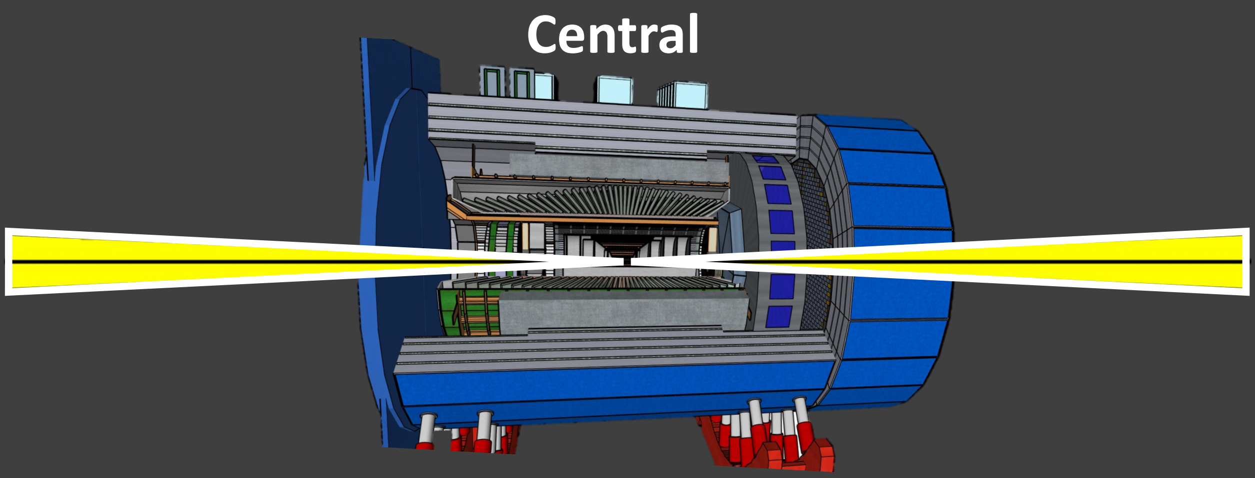
$2.4M DOE project located at Brookhaven National Lab

p: 40 – 275 GeV
e: 2.5 – 18 GeV

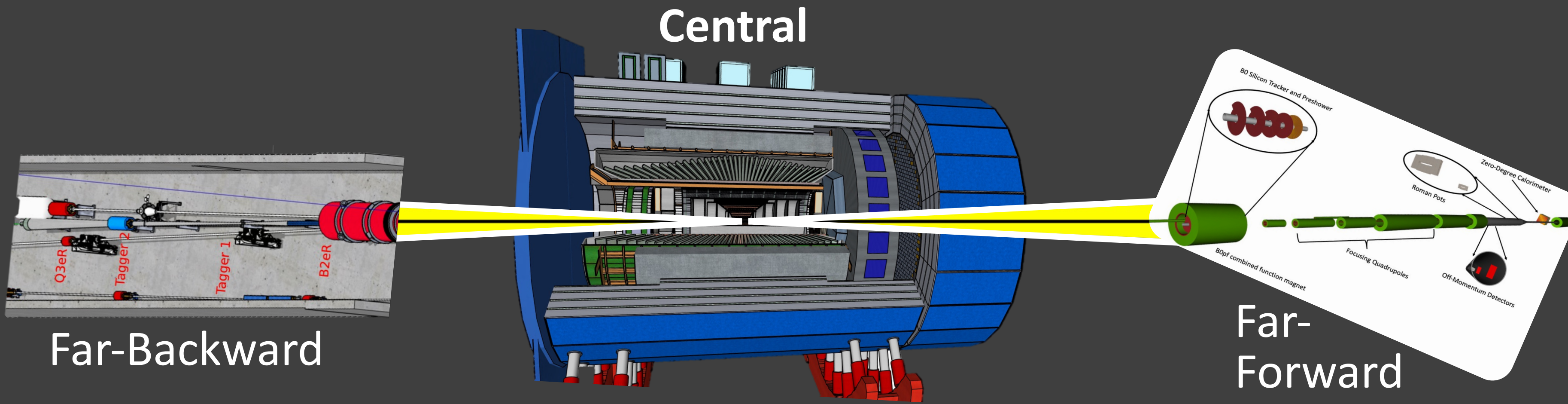
Initial data taking 2031/32



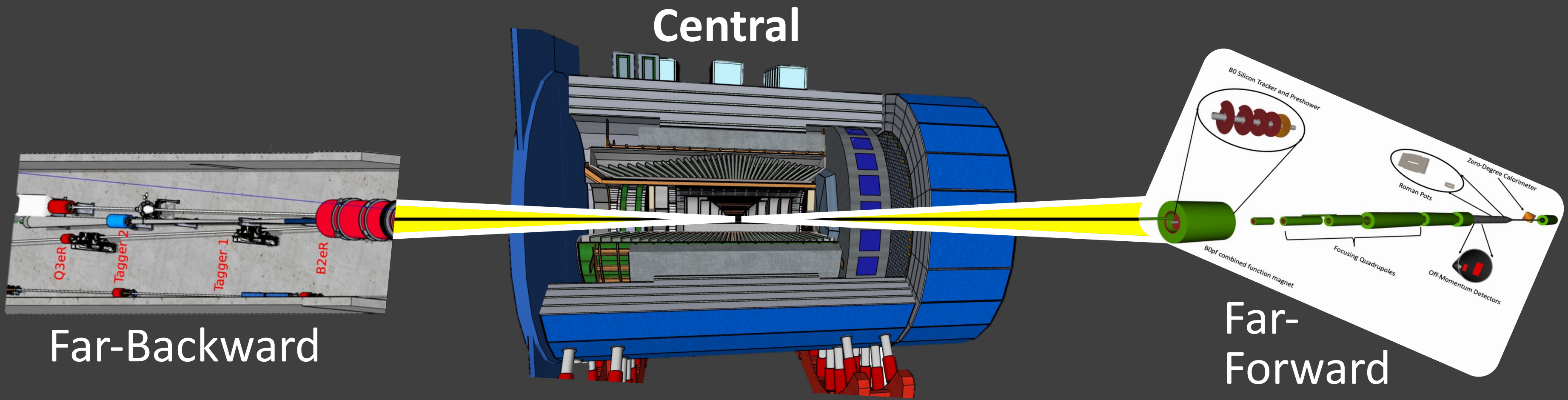
A Tale of Three Detectors…



A Tale of Three Detectors…



Inverse Kinematics eA Machine!

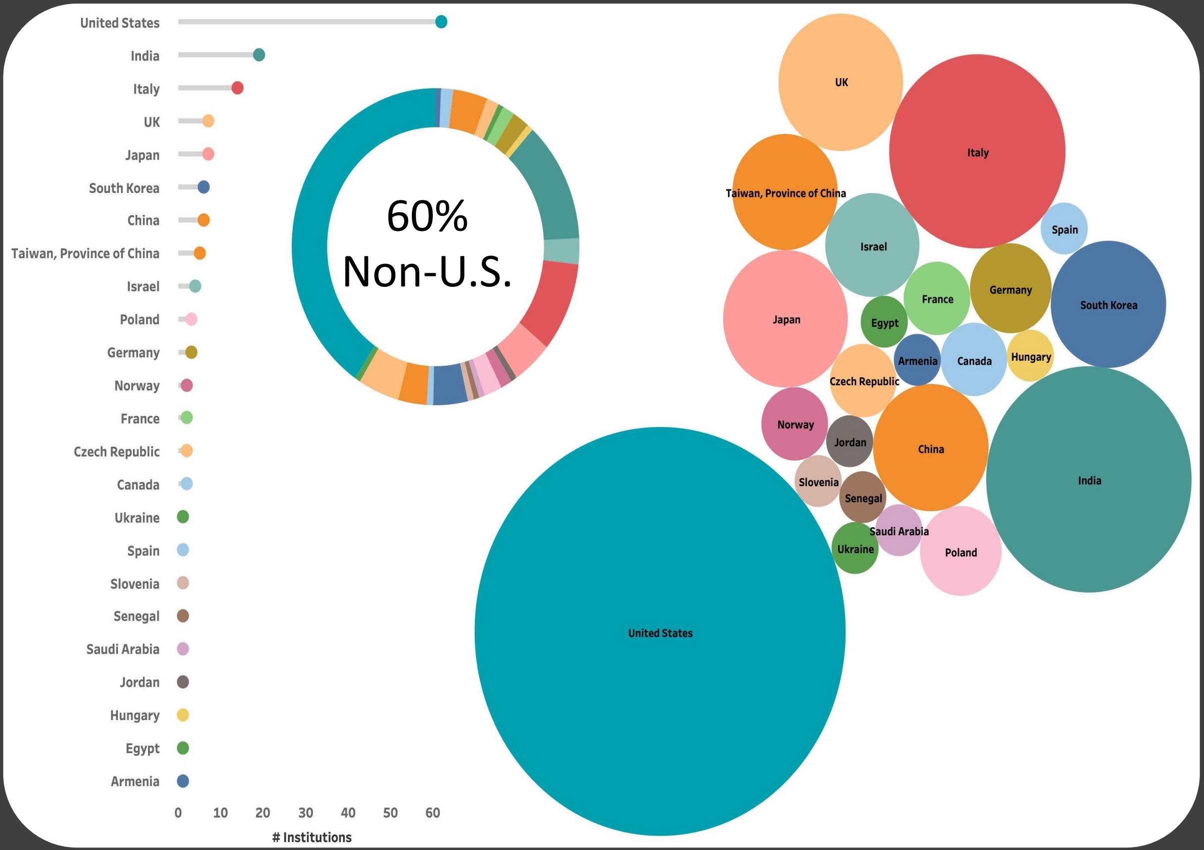


Physics of Nuclei Workhorse

160+ institutions
24 countries

500+ collaborators

A truly global pursuit for a new experiment at the EIC!

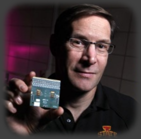


Current leadership:


Dalla Torre


Hen

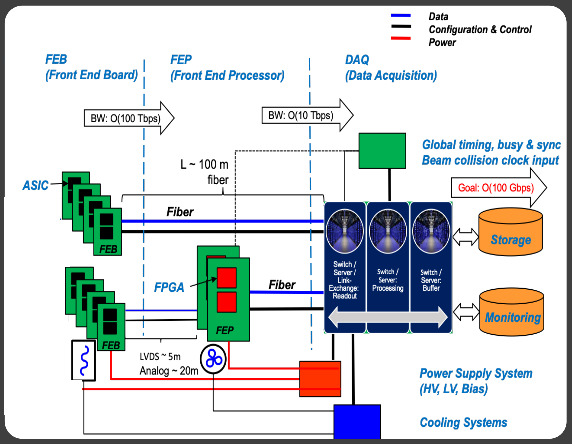

Horn


Lajoie

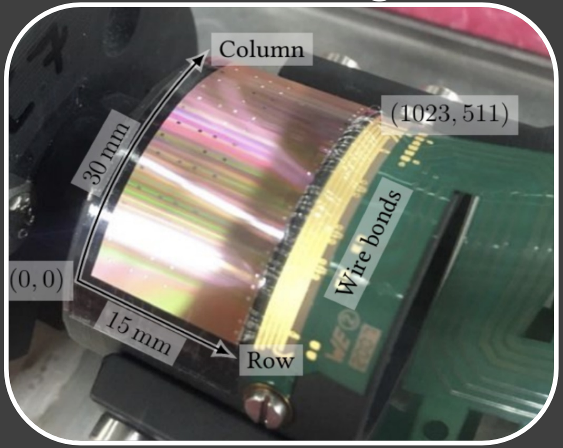

Surrow

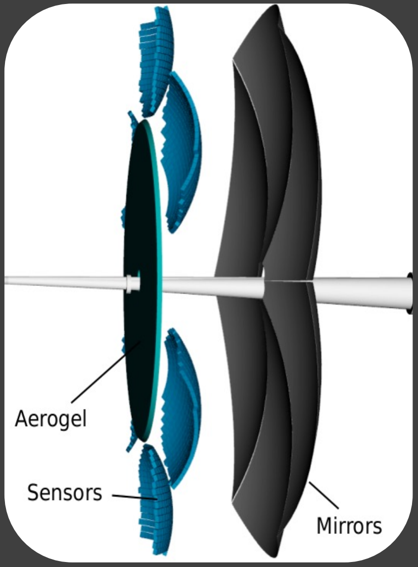
State-of-the-Art Technology R&D

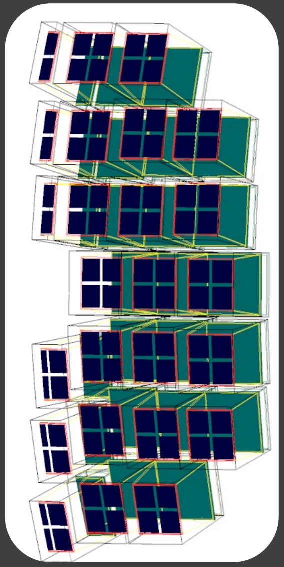
Streaming Readout

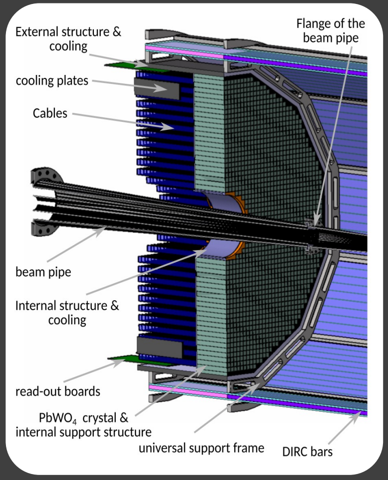


Si tracking

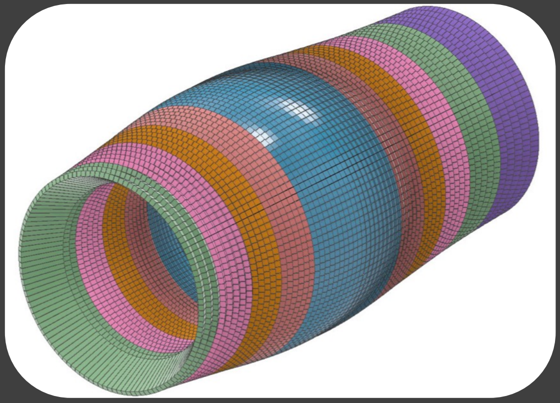




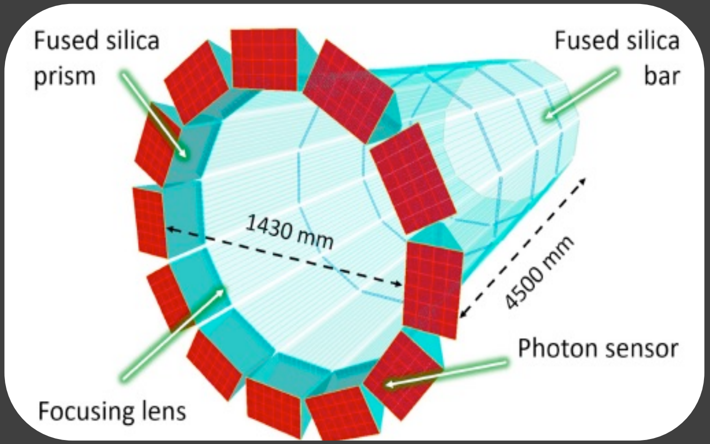




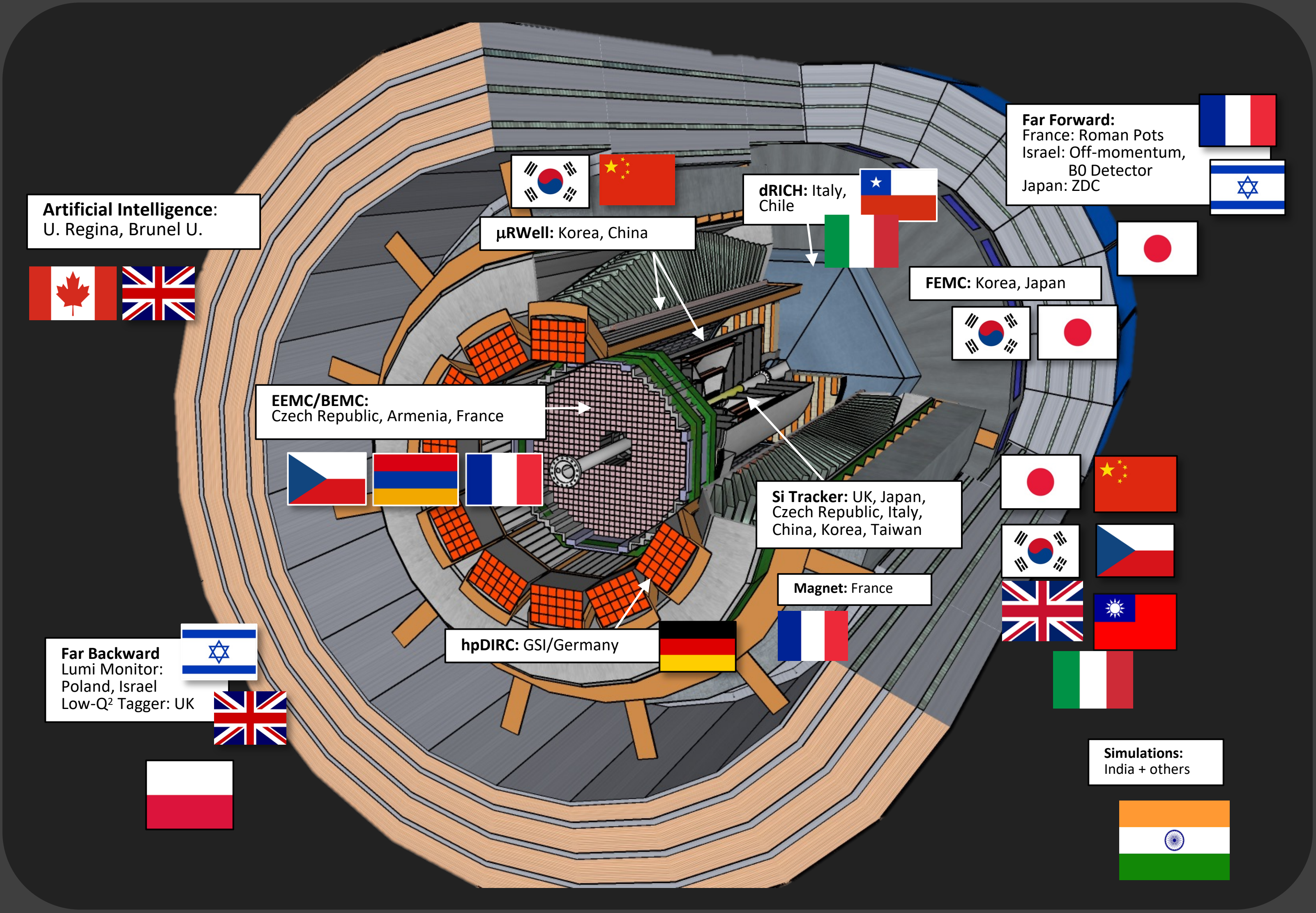
Crystal Calorimetry

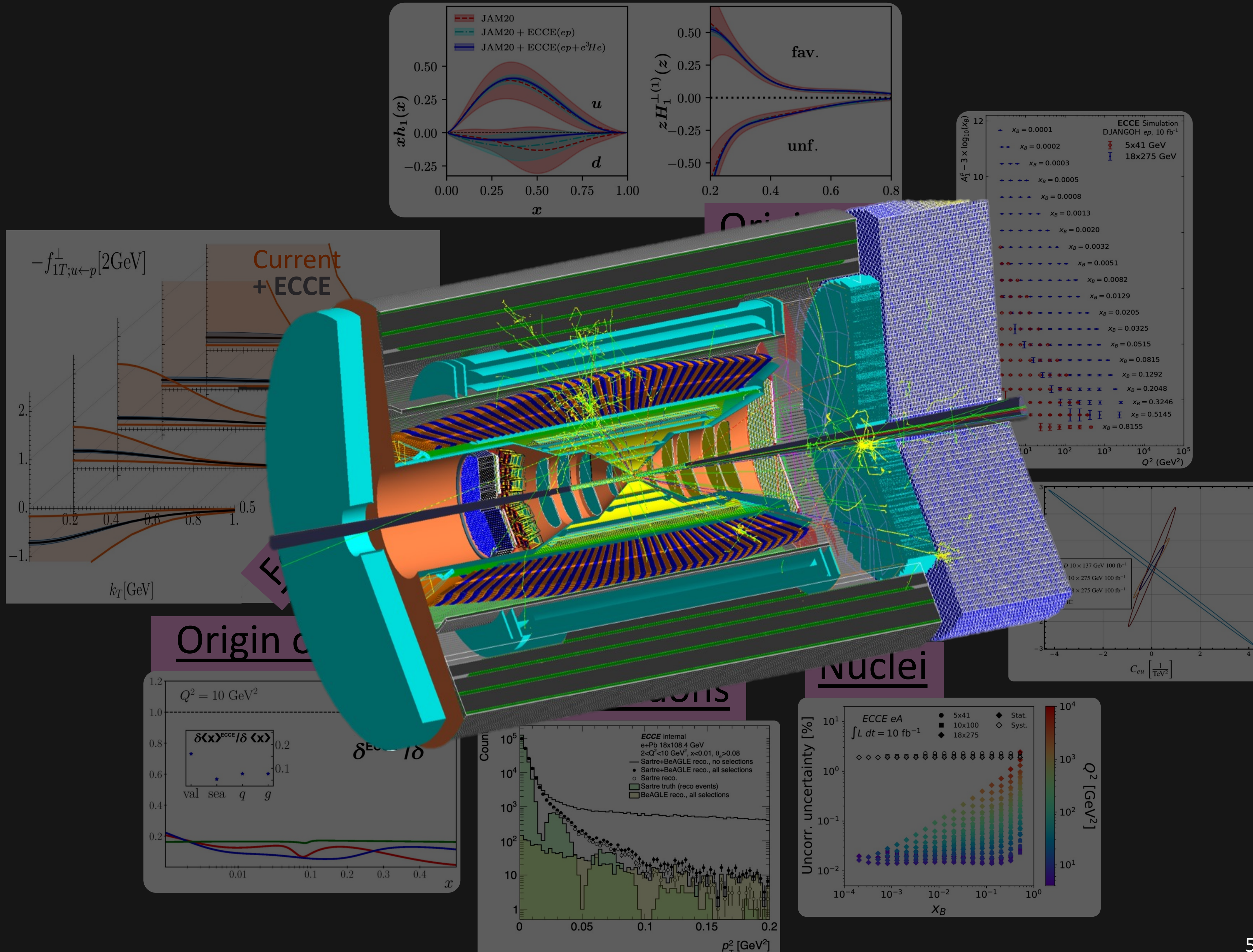


RICH & New Photon Sensor Tech



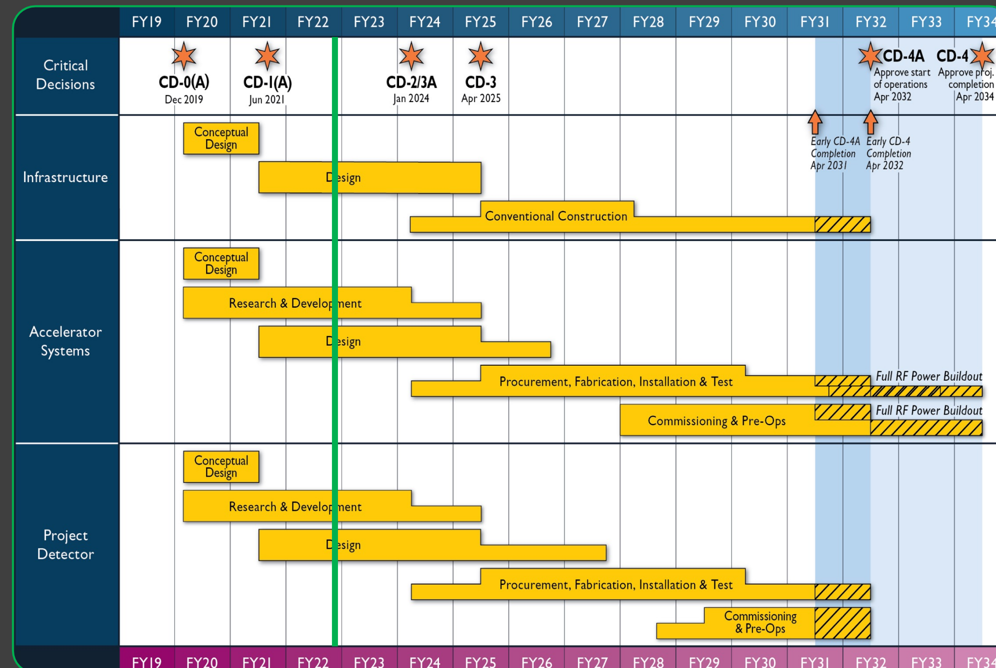
Open International Collaboration

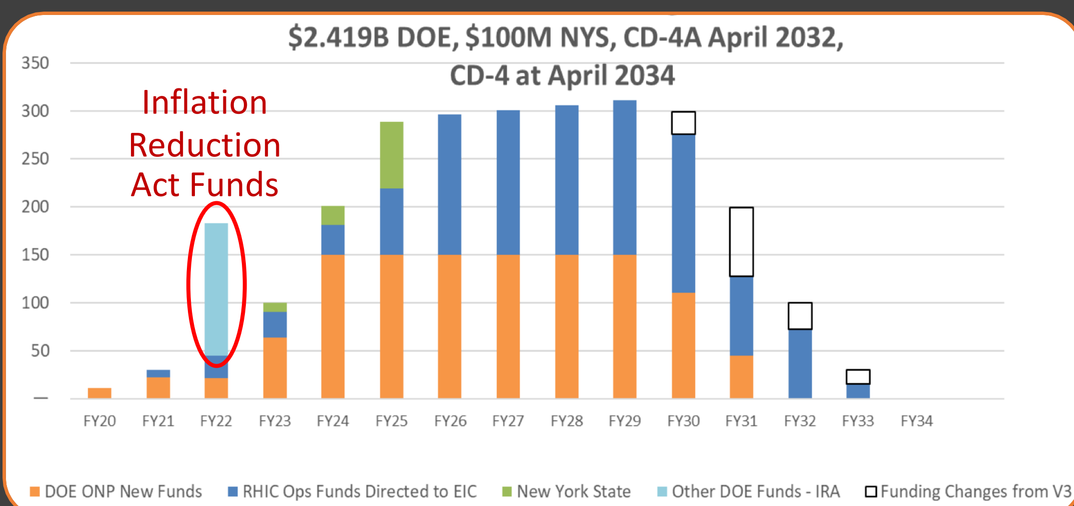



JAM20
JAM20 + ECCE(ep)
JAM20 + ECCE(ep+e³He)
fav.
unf.
Current
+ ECCE
ECCE Simulation
DJANGOH ep, 10 fb⁻¹
5x41 GeV
18x275 GeV
Origin o
Nuclei
ECCE internal
e+Pb 18x108.4 GeV
Sartre+BeAGLE reco., no selections
Sartre+BeAGLE reco., all selections
Sartre reco.
Sartre truth (reco events)
BeAGLE reco., all selections
ECCE eA
Stat.
Syst.
5x41
10x100
18x275
Uncorr. uncertainty [%]
$Q^2 = 10$ GeV^2
val
sea
q
g

Timeframe

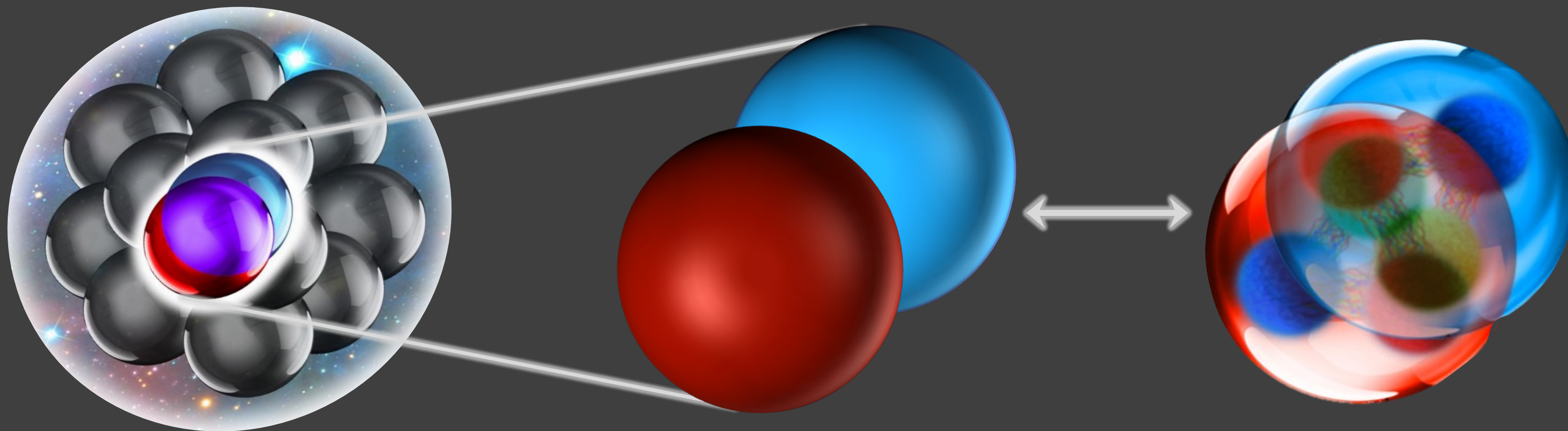
- Funding secured through CD-3 (construction start)
- Initial operations planned for 2031/32

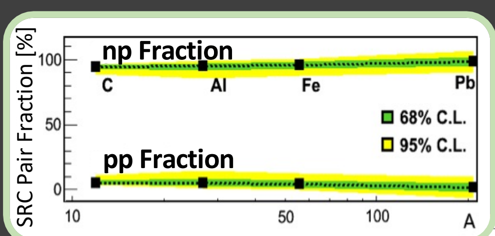


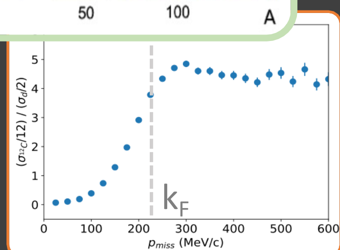


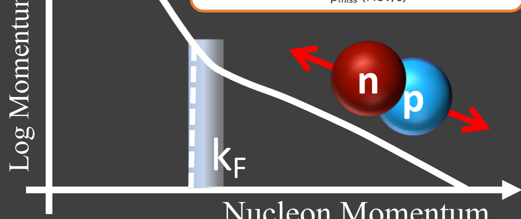
We’re reducing inflation! ☺

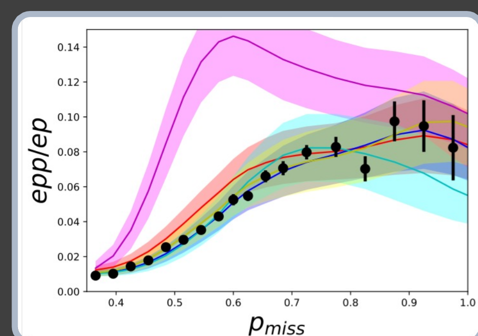
Summary: Correlations Across Scales

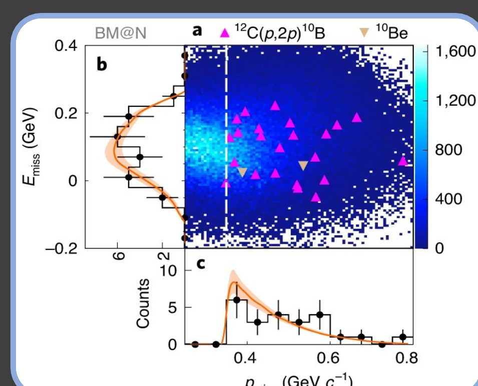


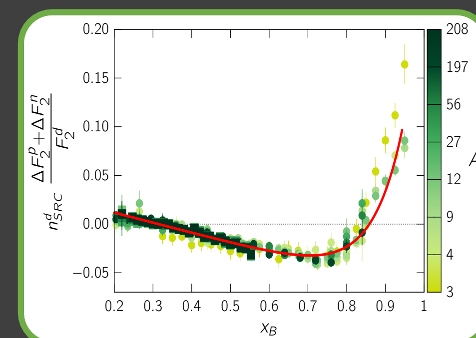


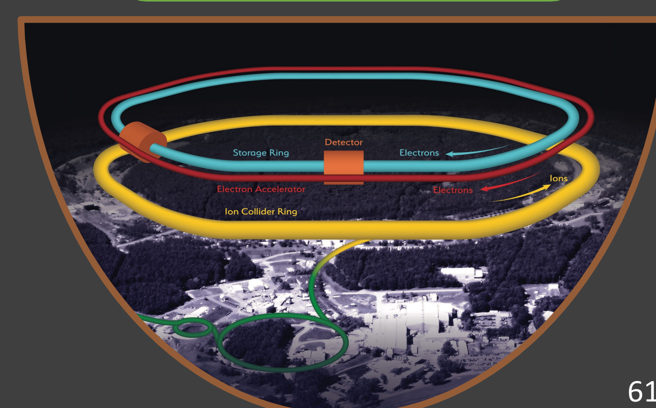




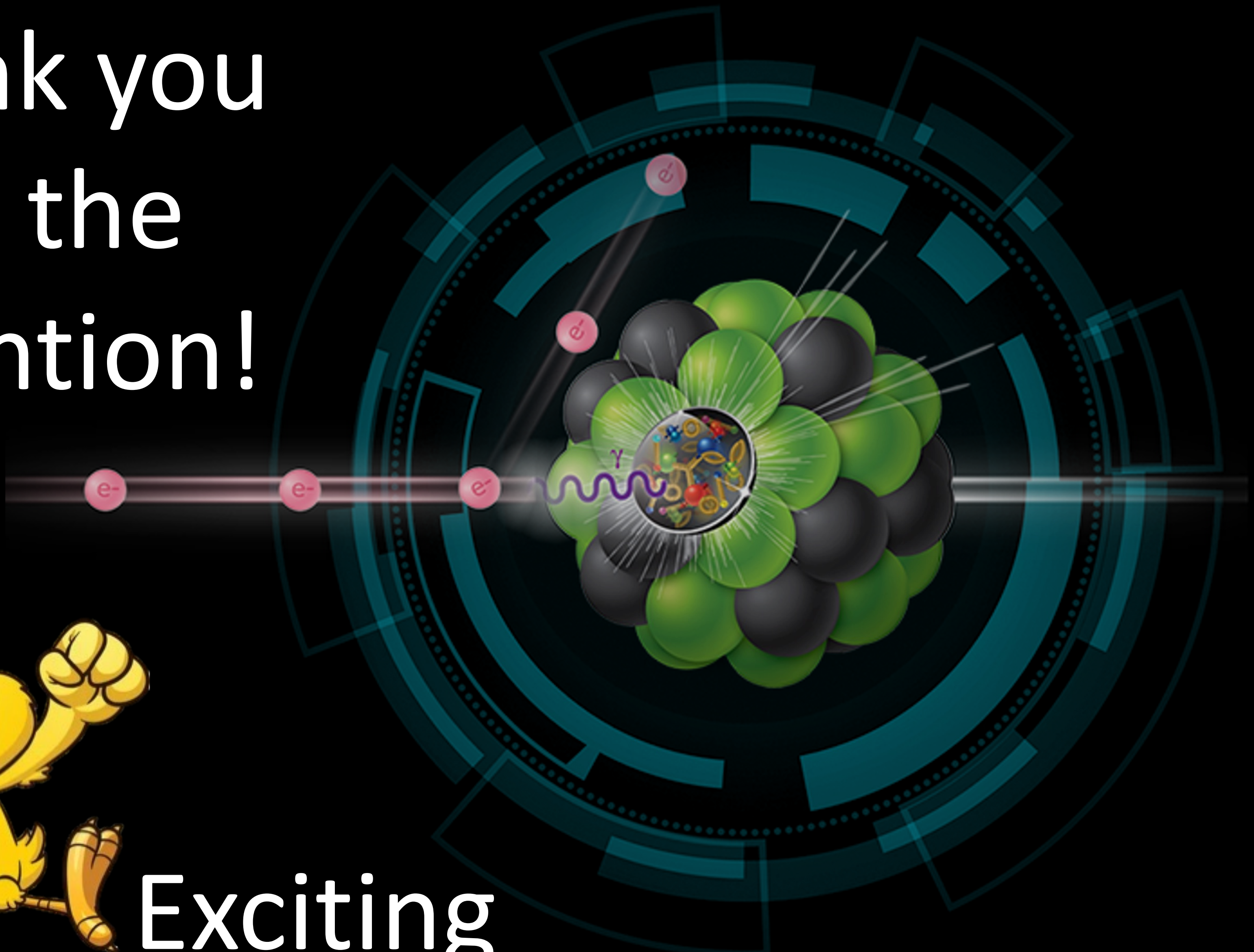








Thank you for the attention!



Exciting Times Ahead!