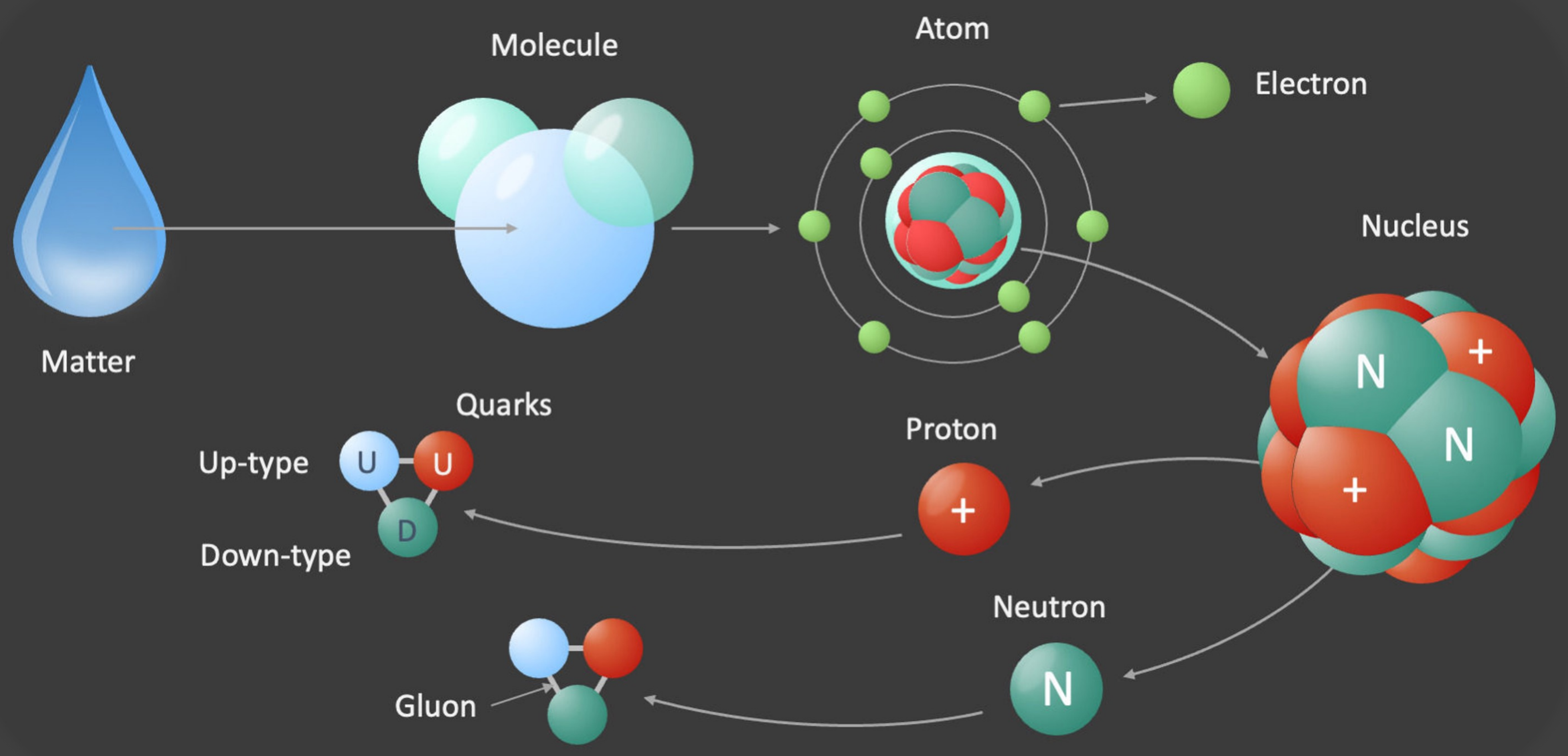
EIC Physics: Experimental Perspective (2)

Or Hen
(MIT)

Fundamental ~~Structure~~ of Matter *constituents*



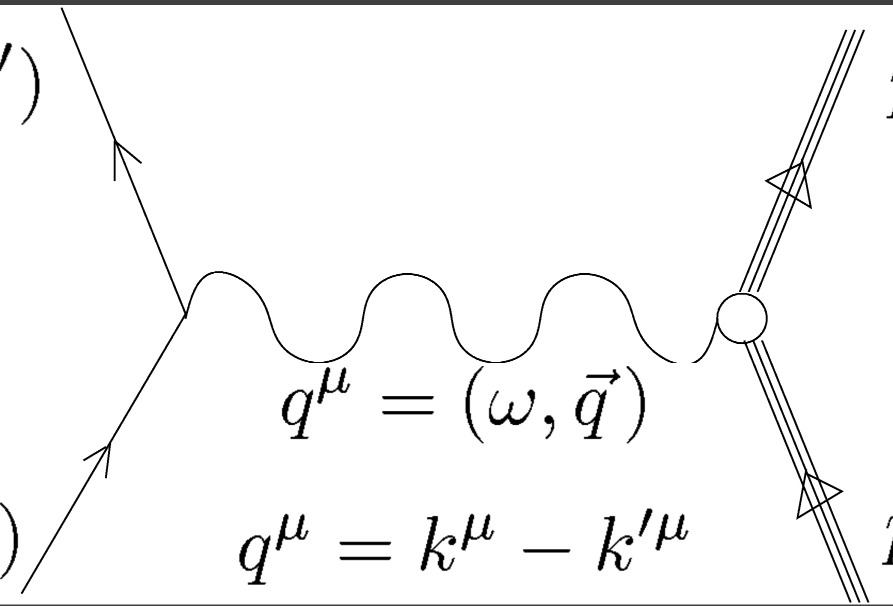
Discovering the constituents of matter is often viewed as telling us about its structure

However, **the emergence of structure is a complex process;**

Its understanding goes beyond knowing its constituents and their interactions

Reminder: Electron Scattering

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:

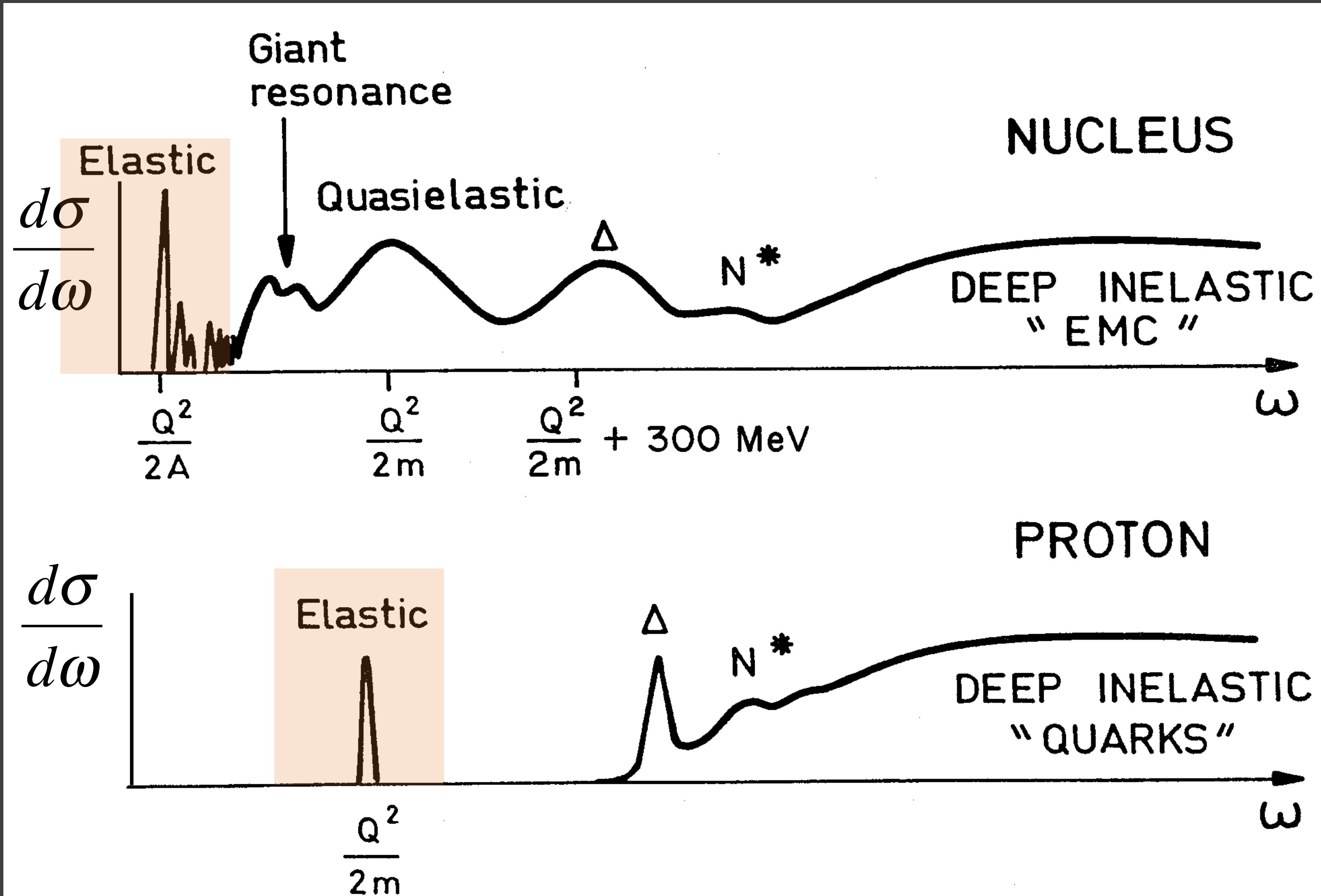
$$p^{\mu} p_{\mu} = M^2$$

$$p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2$$

$$W^2 = (q^{\mu} + p^{\mu})^2 = p'_{\mu} p'^{\mu}$$

(e,e'): Energy conservation defines physics



Nucleon Form Factors

Recoil factor

Form factors

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

$$= \sigma_M \frac{E'}{E}\left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2\frac{\theta}{2} G_M^2(Q^2)\right]$$

$$= \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^4} R_L(Q^2) + \left(\frac{Q^2}{2\vec{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(Q^2)\right]$$

F_1, F_2: Dirac and Pauli form factors

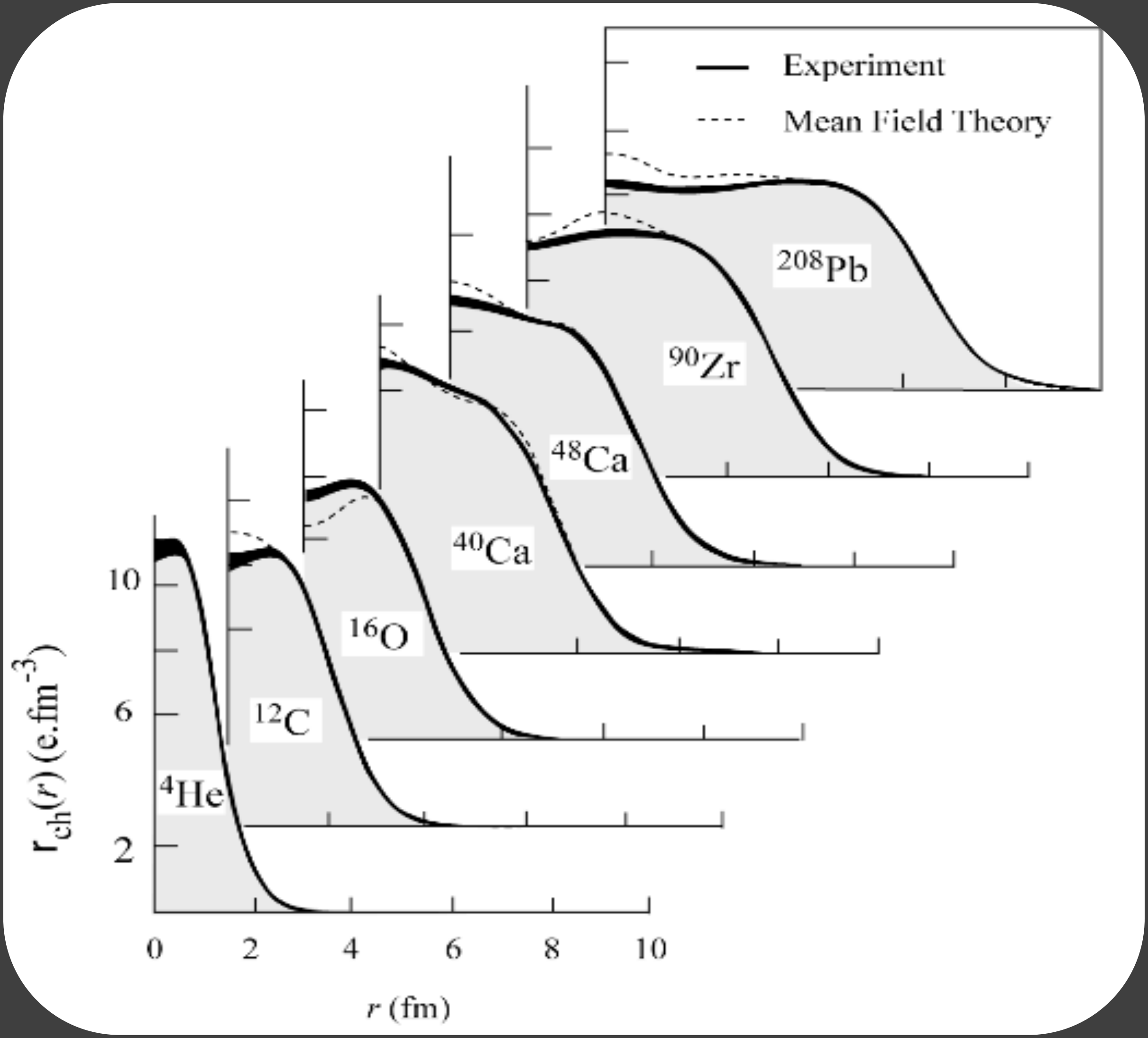
G_E, G_M: Sachs form factors (electric and magnetic)

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

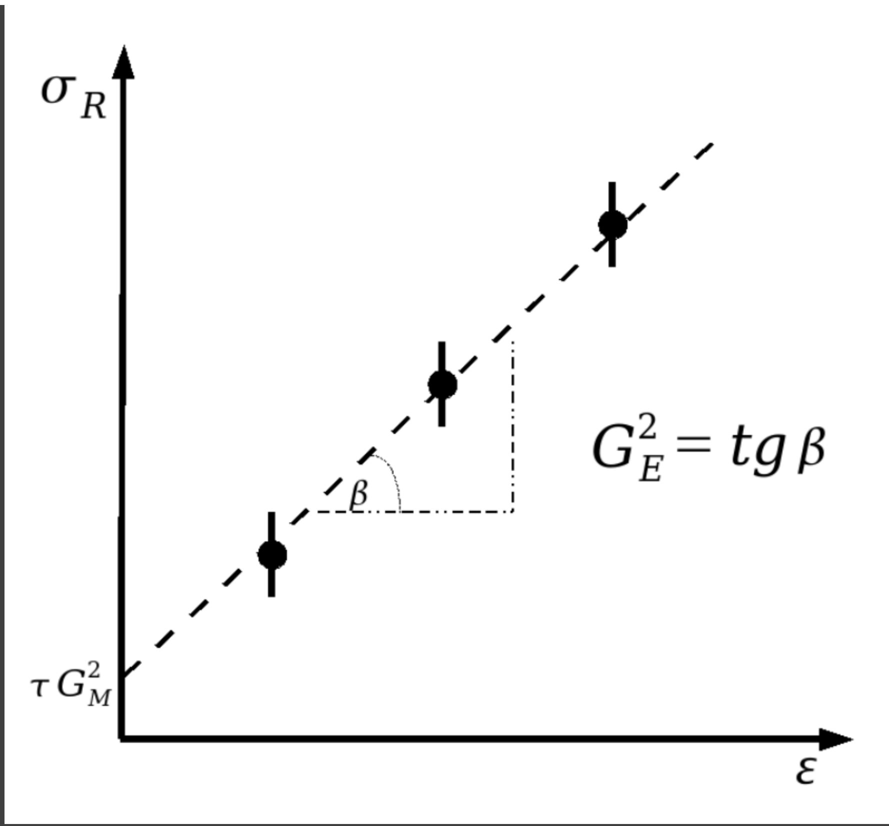
R_L, R_T: Longitudinal and transverse response functions

Nuclear Targets: Charge Distribution

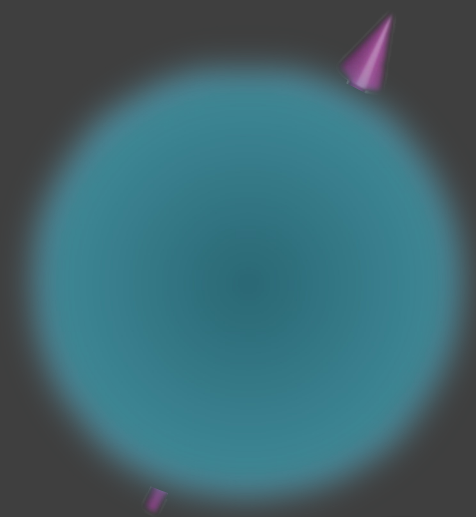


Form Factors: Cross-Sections

$$\frac{\varepsilon}{\tau} G_E^2 + G_M^2 = \frac{\varepsilon(1+\tau)}{\tau} \left[\frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega} \right)_{Mott+recoil} \right]$$

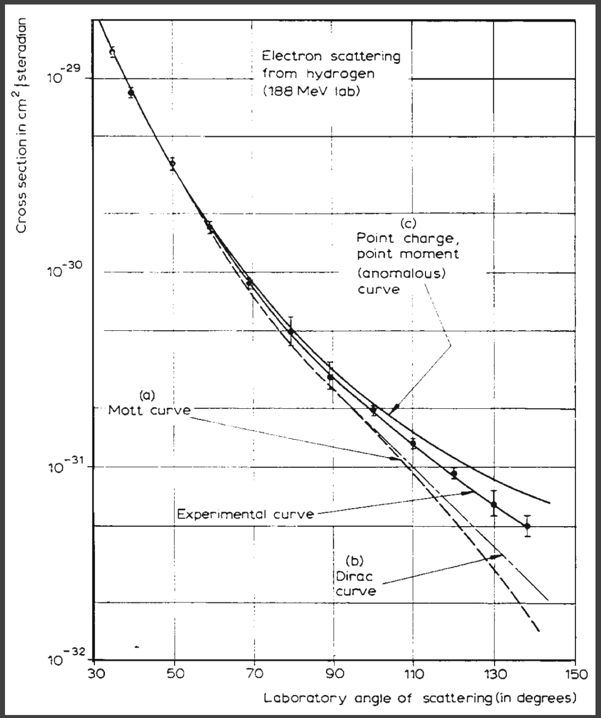


First Elastic scattering show protons are not point particles

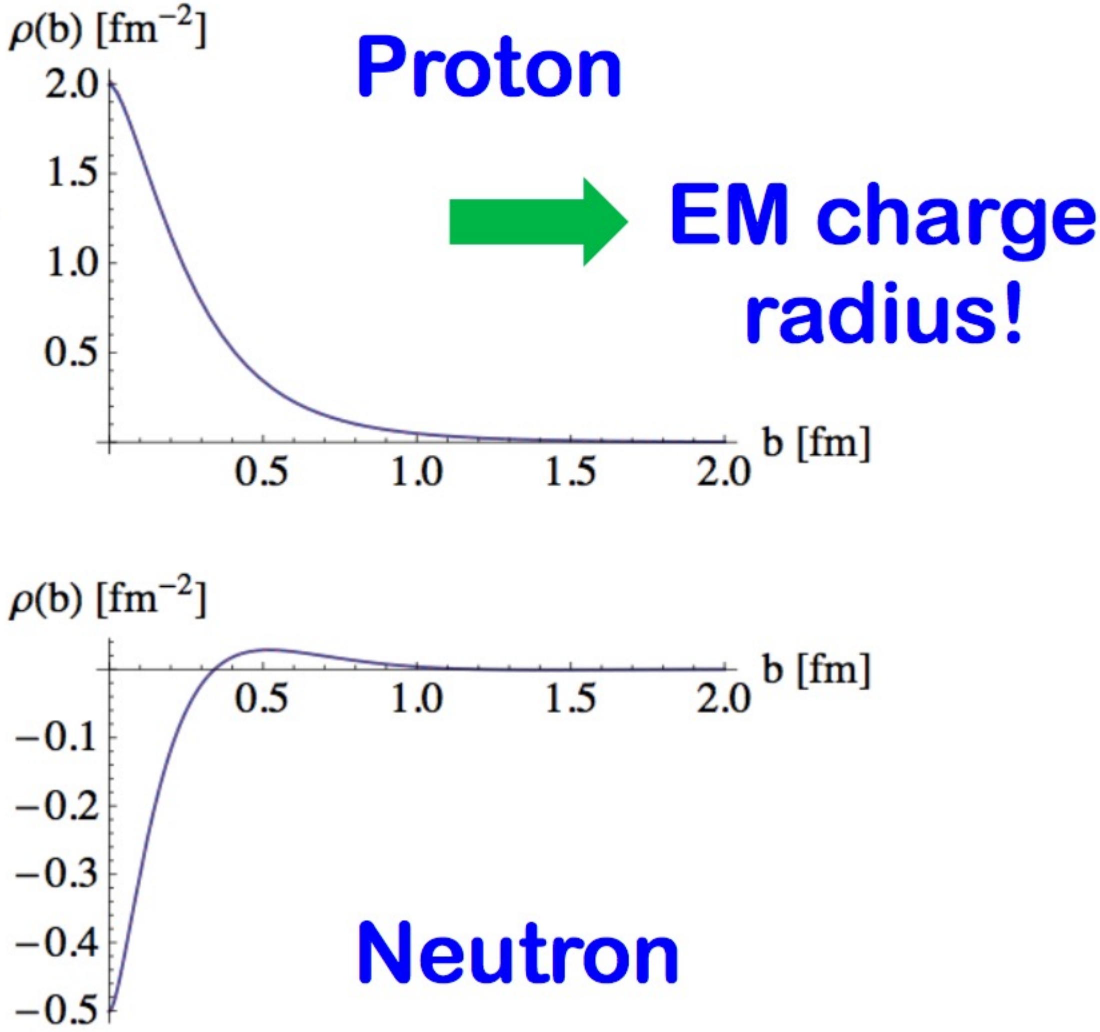


The Proton
(early 1900s)

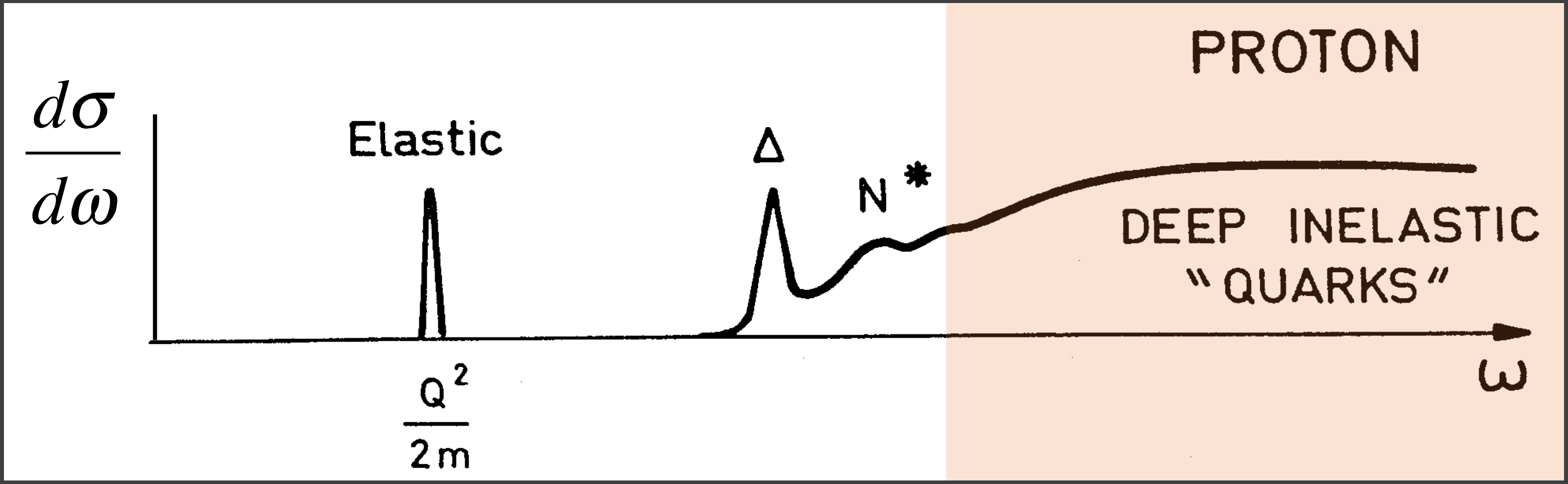
1961



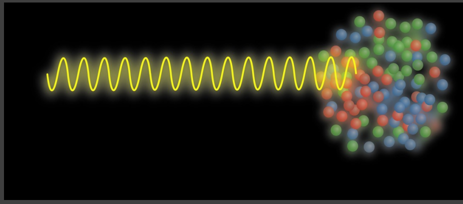
Electric charge distribution

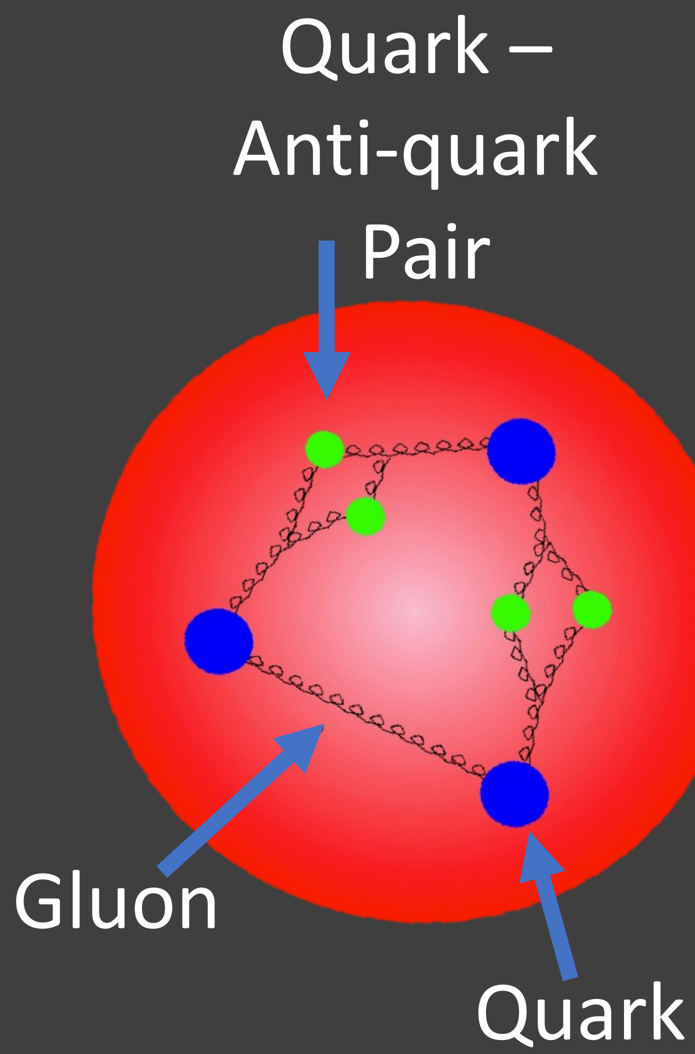


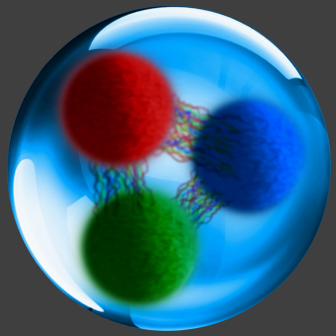
(e,e'): Energy conservation defines physics

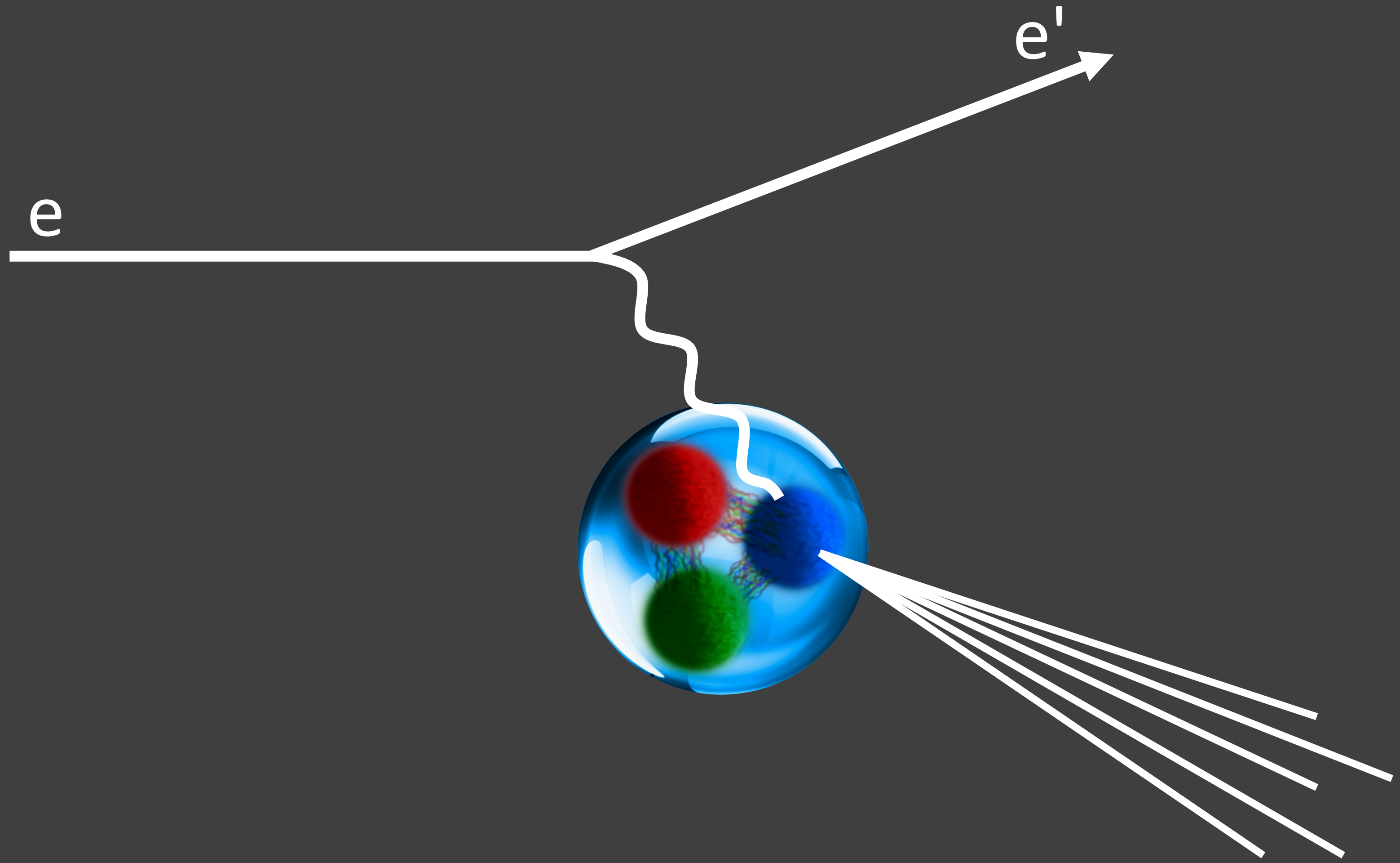


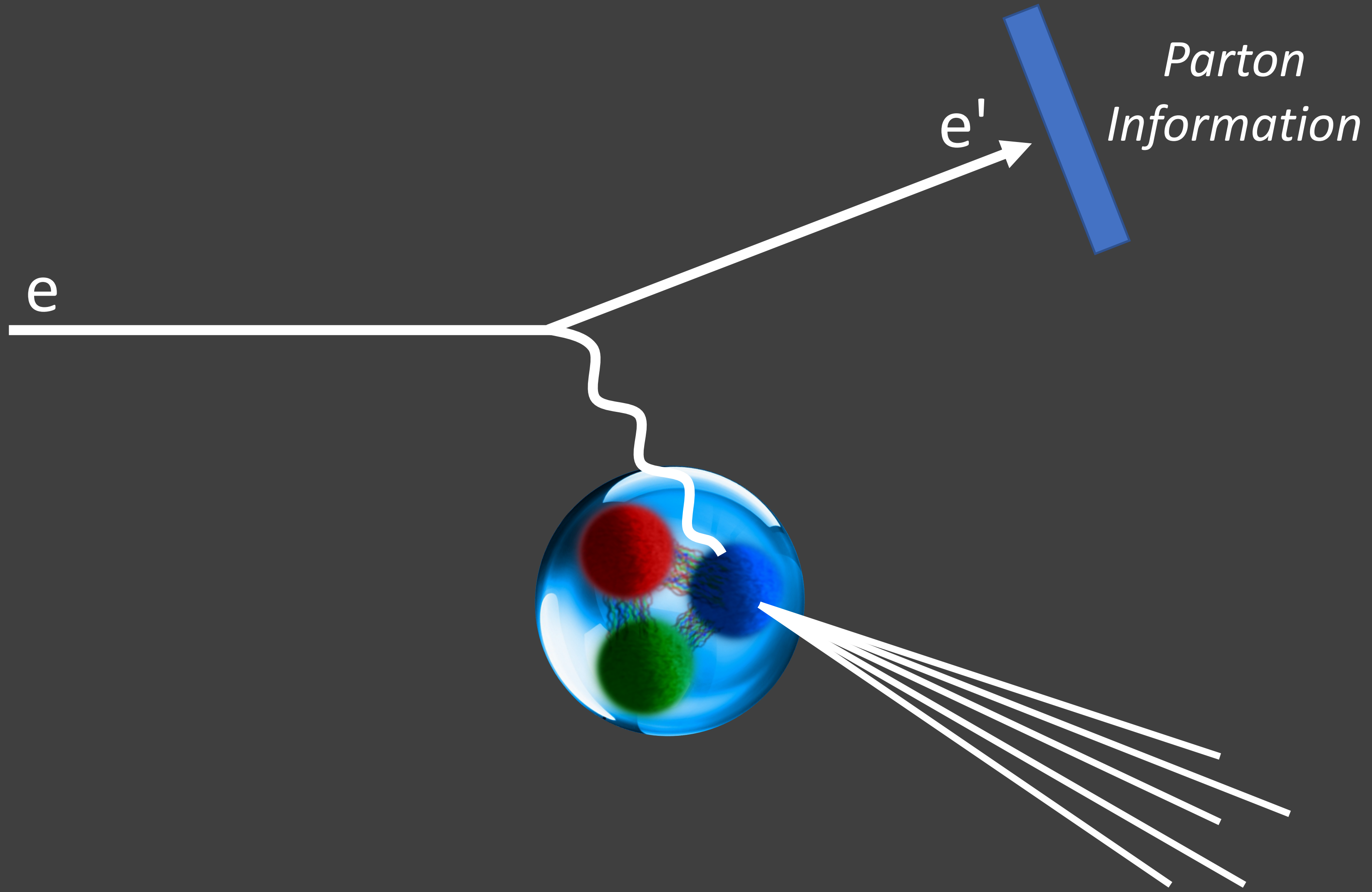
Partonic Structure





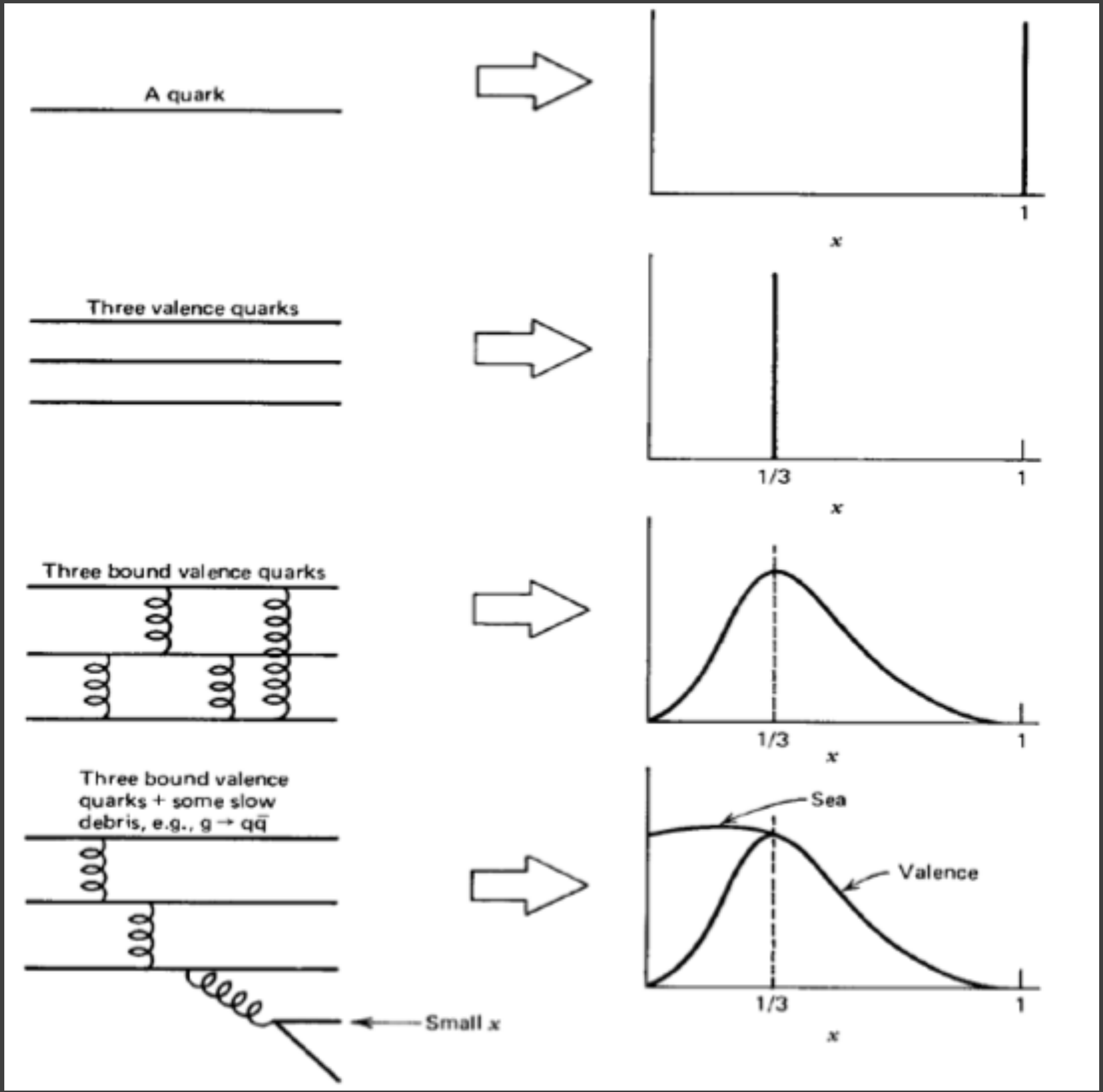



e'
e


Parton
Information
e'
e

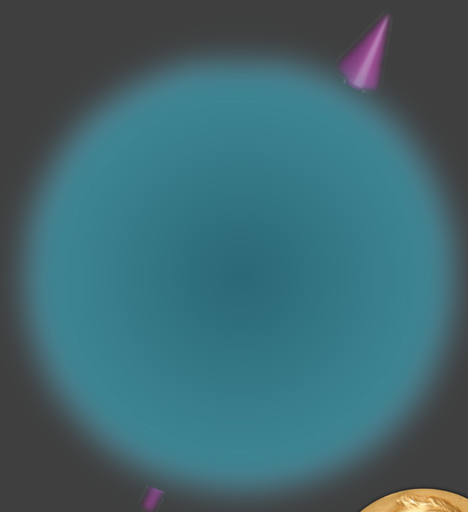
Partonic Structure:

$$F_2\left(x,Q^2\right)=\sum_i e_i^2\cdot x\cdot f_i\left(x\right)$$

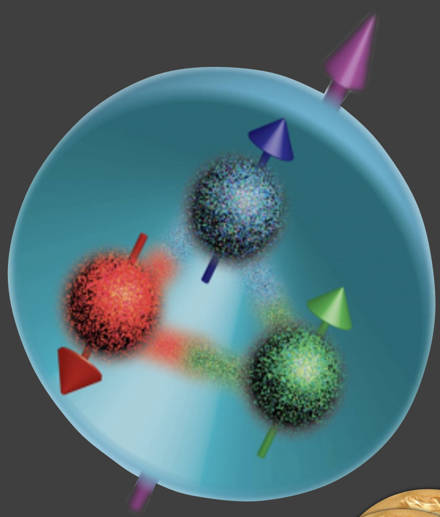


→ Imaging the subatomic world was key for gaining new understanding

The Proton
(early 1900s)



The Proton
(1970s)



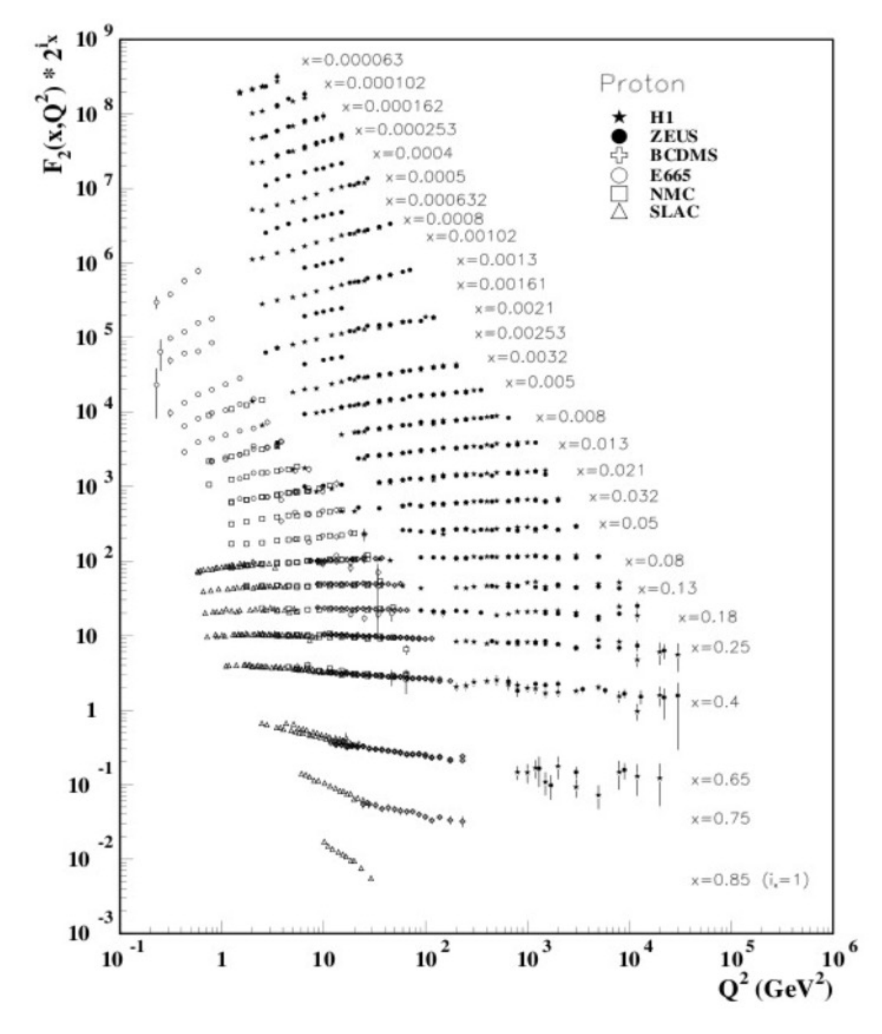
1961

QCD!

1990, 2004

Partonic Structure:

$$F_2\left(x,Q^2\right)=\sum_i e_i^2\cdot x\cdot f_i\left(x\right)$$



$$\frac{d^2\sigma}{d\Omega dE'}=\sigma_A=\frac{4\alpha^2E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right)+\frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right]$$

Partonic Structure:

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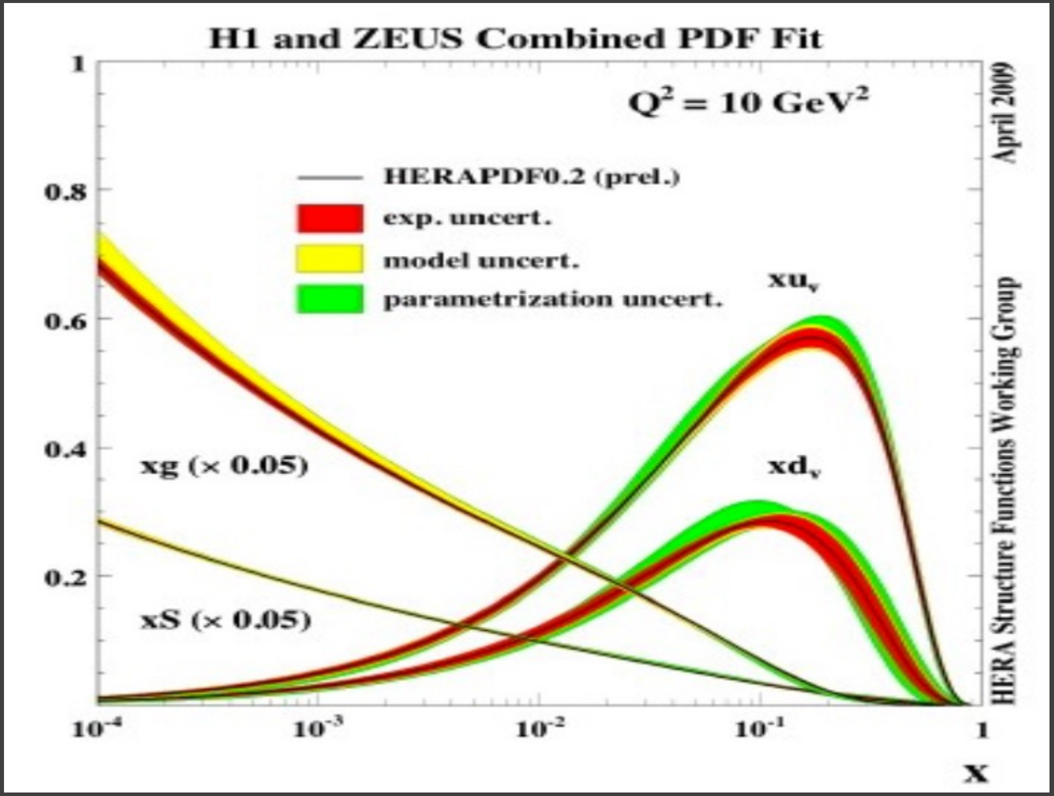

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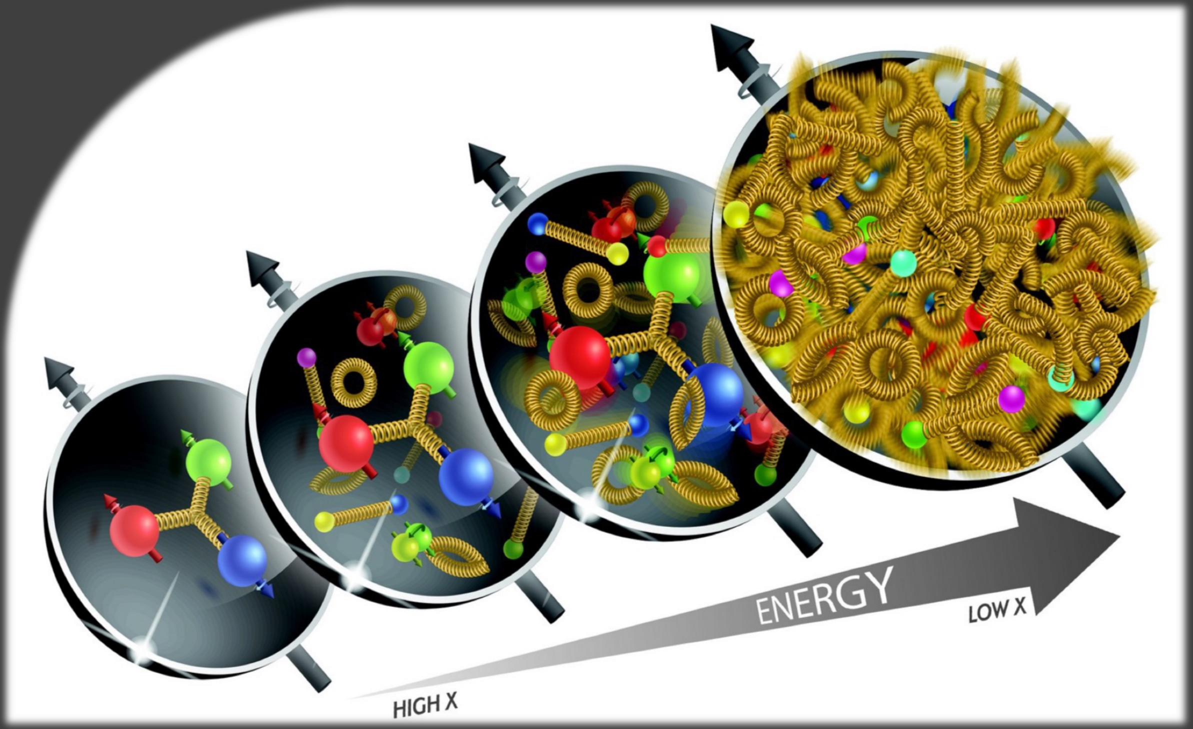
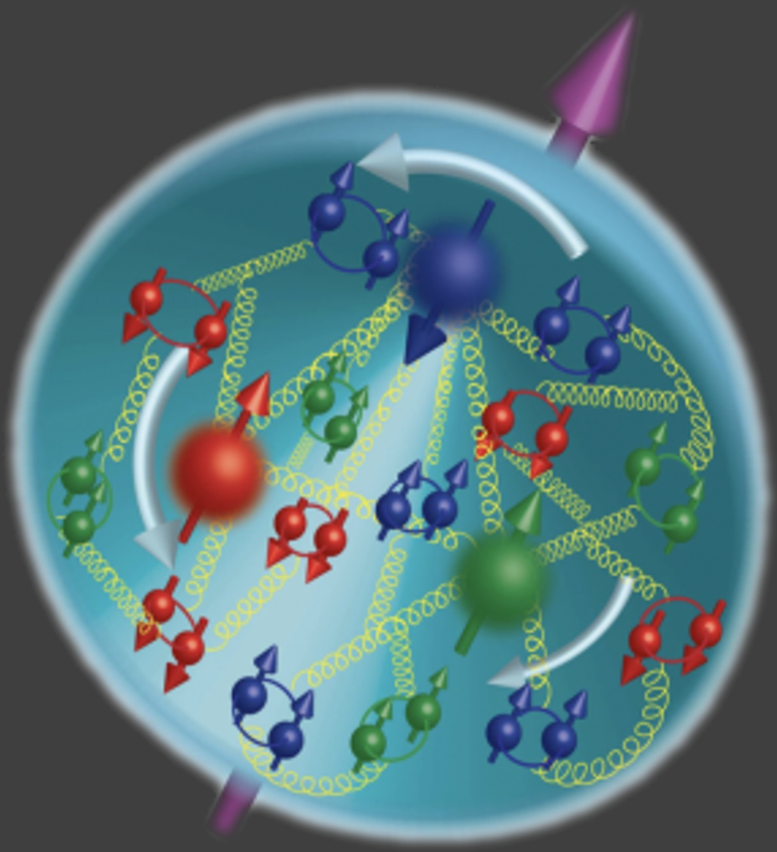
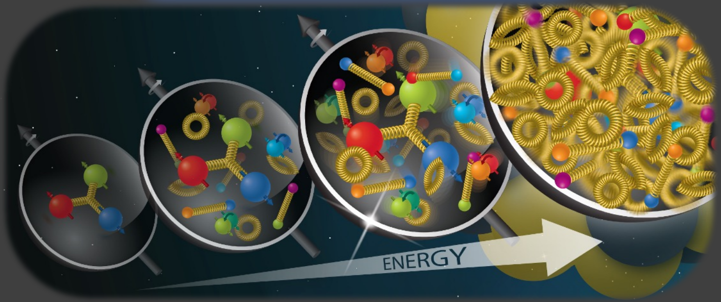
Improved measurements, incl. polarization observables, led to new insights!



“Today’s” proton is one of the most complex QM systems we know



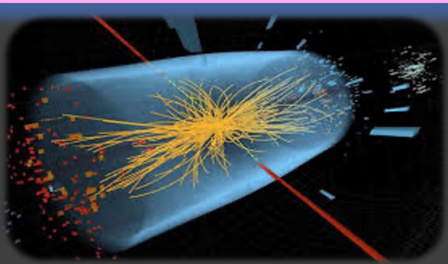
Dense Gluons



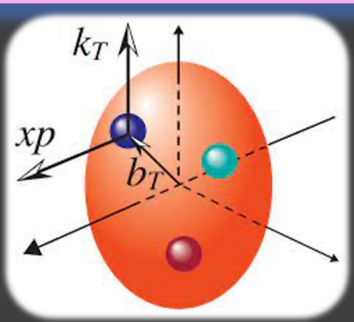
Nuclei

QCD Science

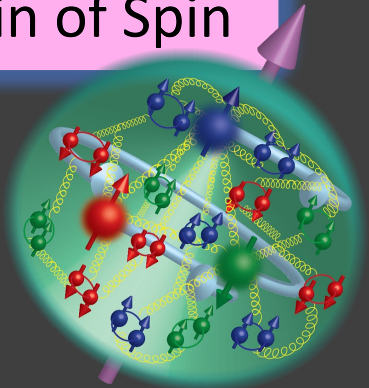
Standard Model



Femtography



Origin of Spin

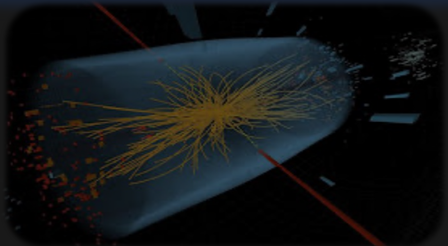


Origin of Mass

Dense Gluons

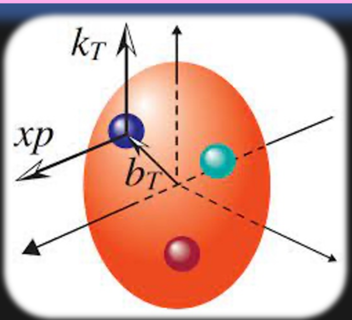
Nuclei

Standard Model



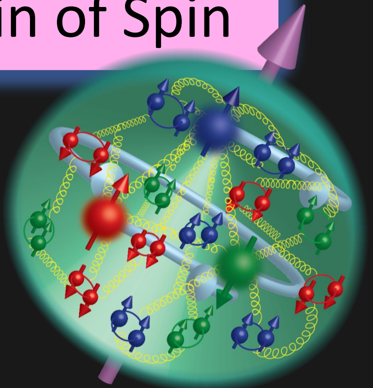
QCD Science

Femtography

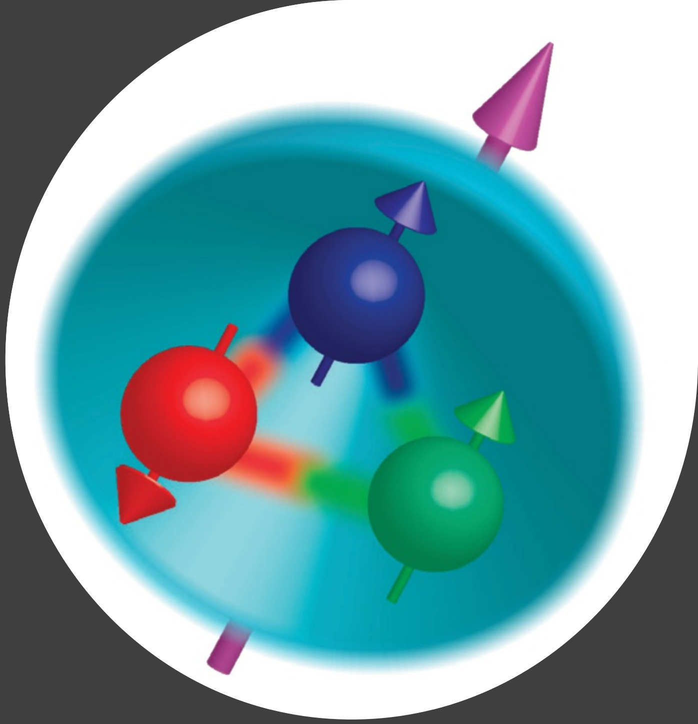


Origin of Mass

Origin of Spin



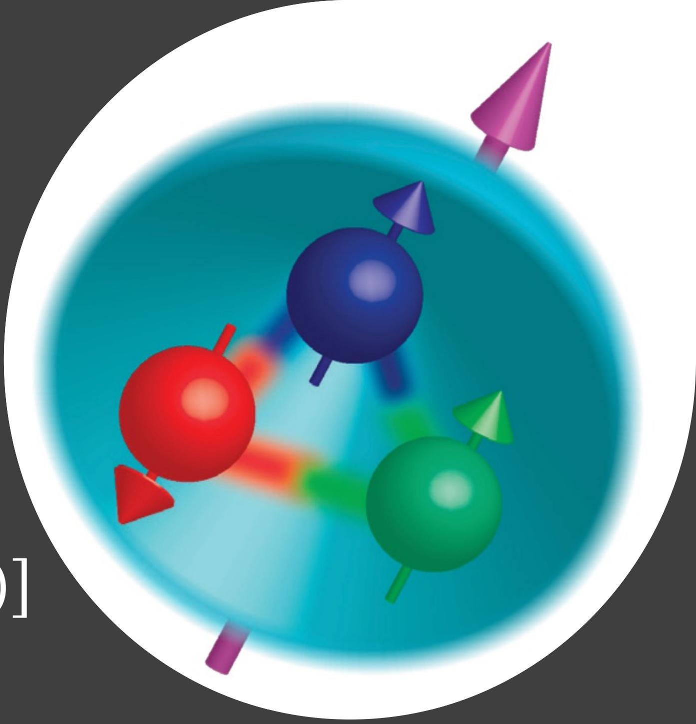
Q1: Protons Spin



Naively:

- 3 spin ½ valance quarks couple to produce a spin ½ nucleon.
- No orbital AM contribution.
- No need for sea / glue contribution.

Spin-Dependent DIS



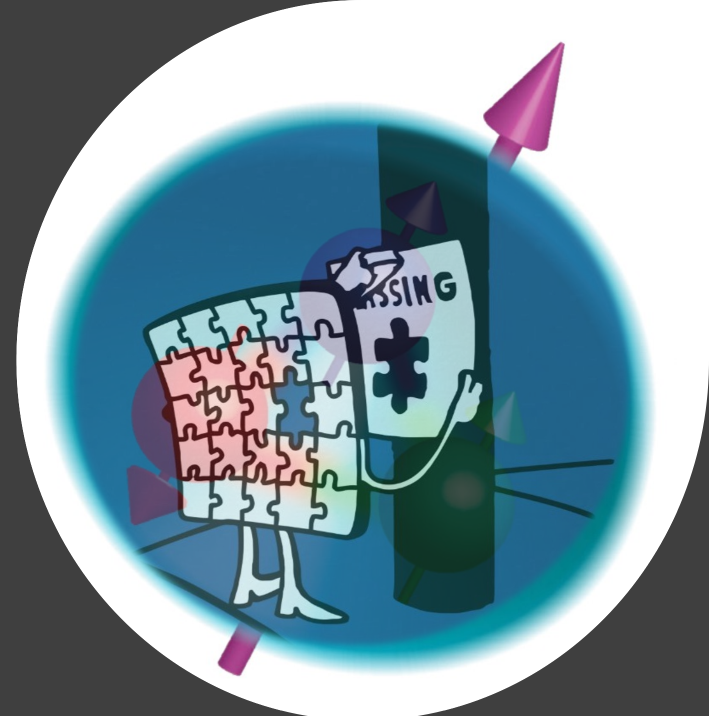
Spin structure embedded in $g_1(x)$:

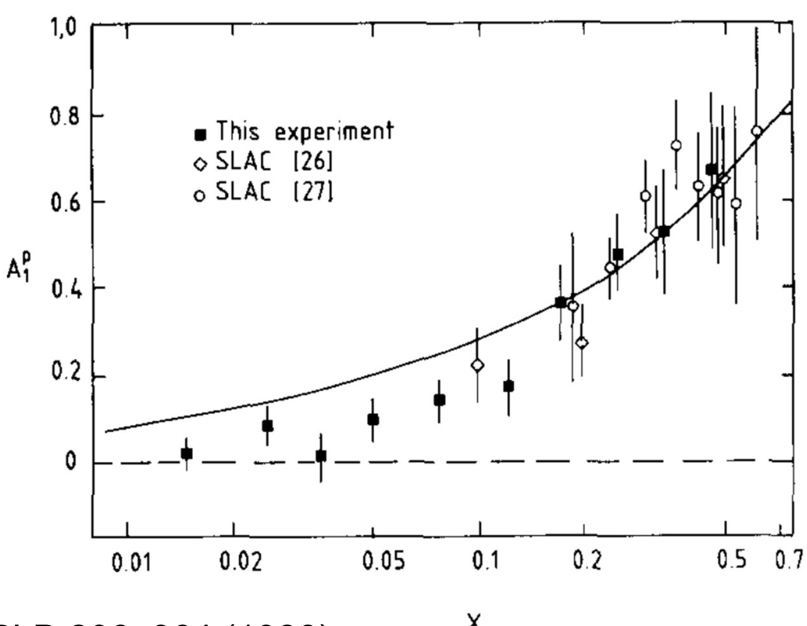
$$g_1(x) = {}^1\!/_2 \sum e_i^2 [q_i^+(x) - q_i^-(x)]$$

Probed in polarized DIS asymmetries:

$$A_{\overrightarrow{DIS}} = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} \approx \frac{2x(1+R)}{F_2(x)} \cdot \boldsymbol{g_1(x)}$$

$\underline{g_1(x)\text{ integral:}}$ quarks spin accounts for ~ 15 - 20% of total proton spin



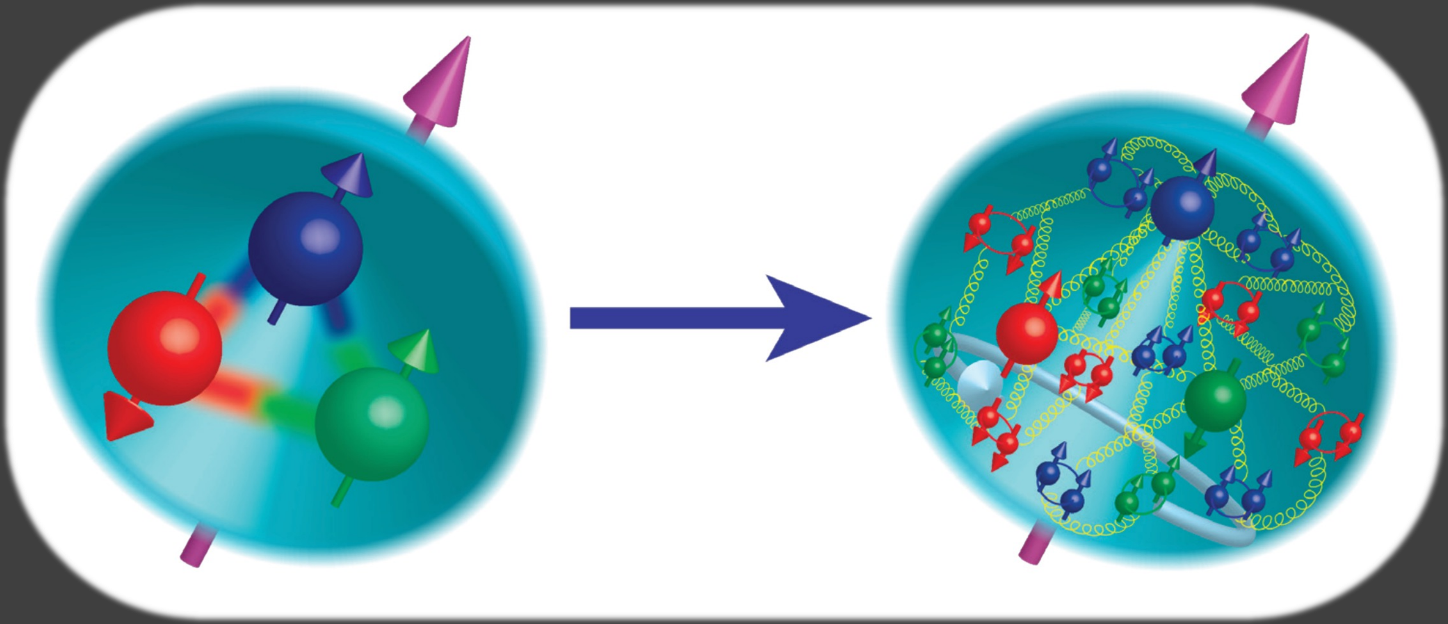


PLB 206, 364 (1988)

Spin Sum rule

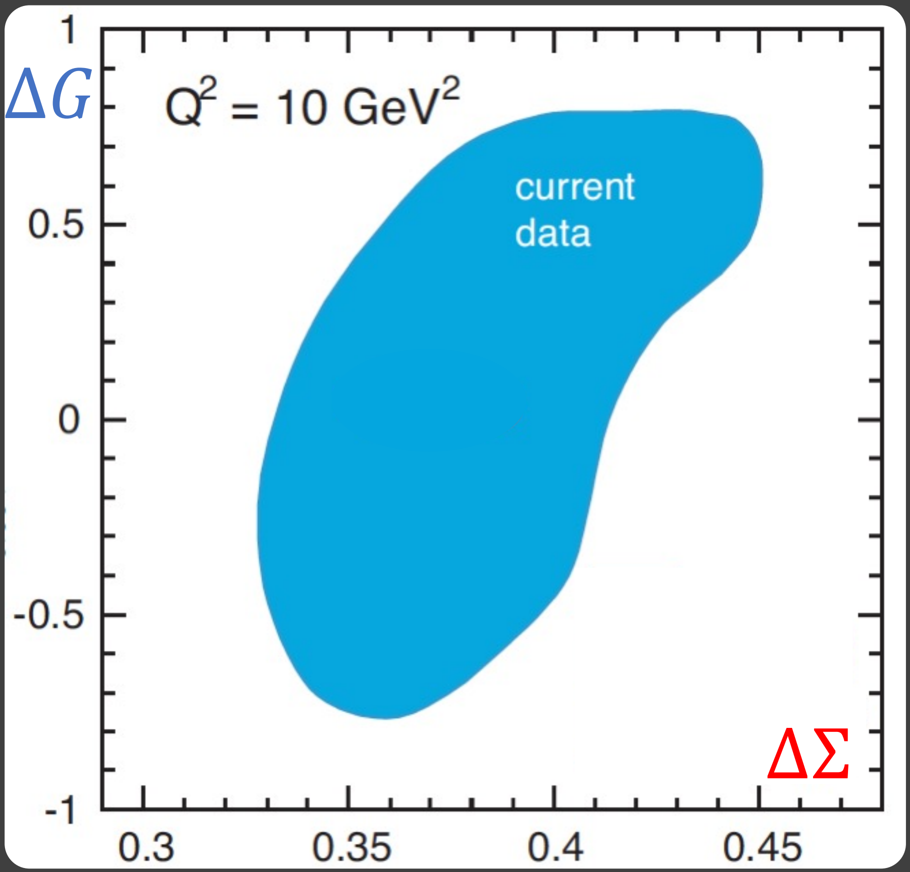
$$\frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g = \frac{1}{2}$$

Quark spin　Gluon spin　Orbital AM

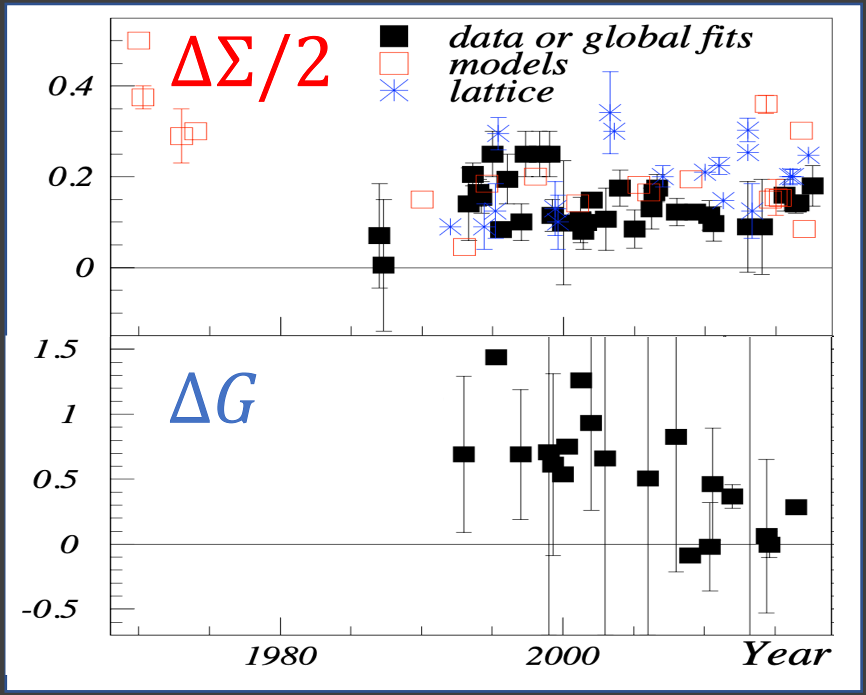


But… Large uncertainties from low-x_B

$$\frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g = \frac{1}{2}$$

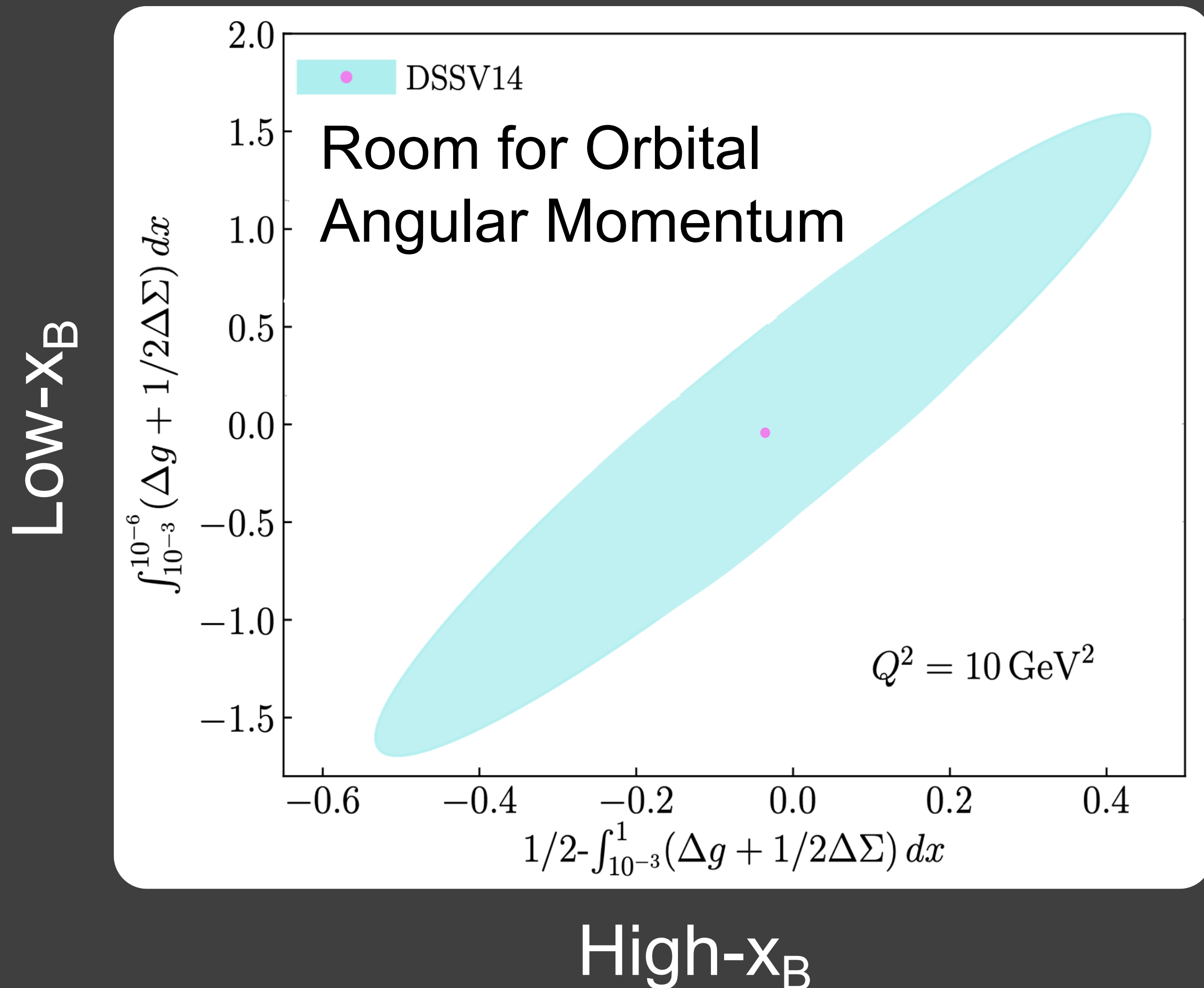


Eur. Phys. J. A 52, 268 (2016)
Phys Rev Lett 113, 012001 (2014)



Rep. Prog. Phys. **82** 076201 (2019)

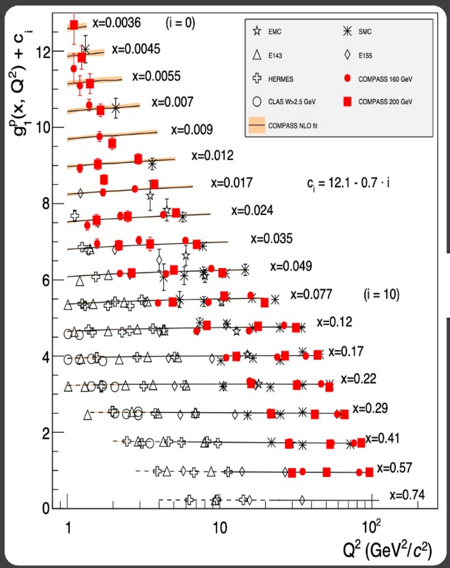
+ Orbital AM Unconstrained

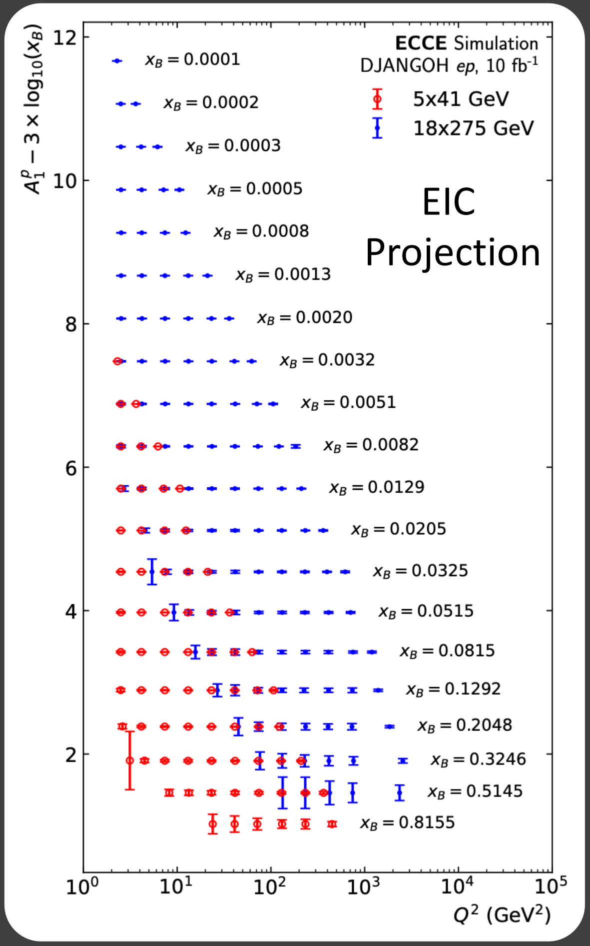


Path Forward @ EIC

1. Low-x_B measurements

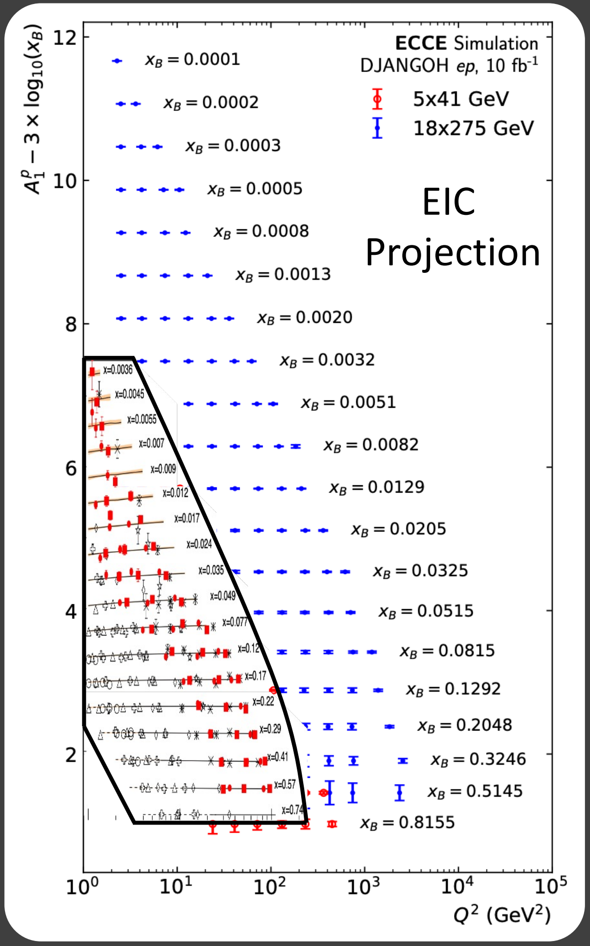
World Data





Path Forward @ EIC

1. Low-x_B measurements



Path Forward @ EIC

1. Low-x_B measurements

2. Orbital Angular Momentum (OAM) measurements

   Angular Momentum → Going Transverse

   Transverse → Form Factors

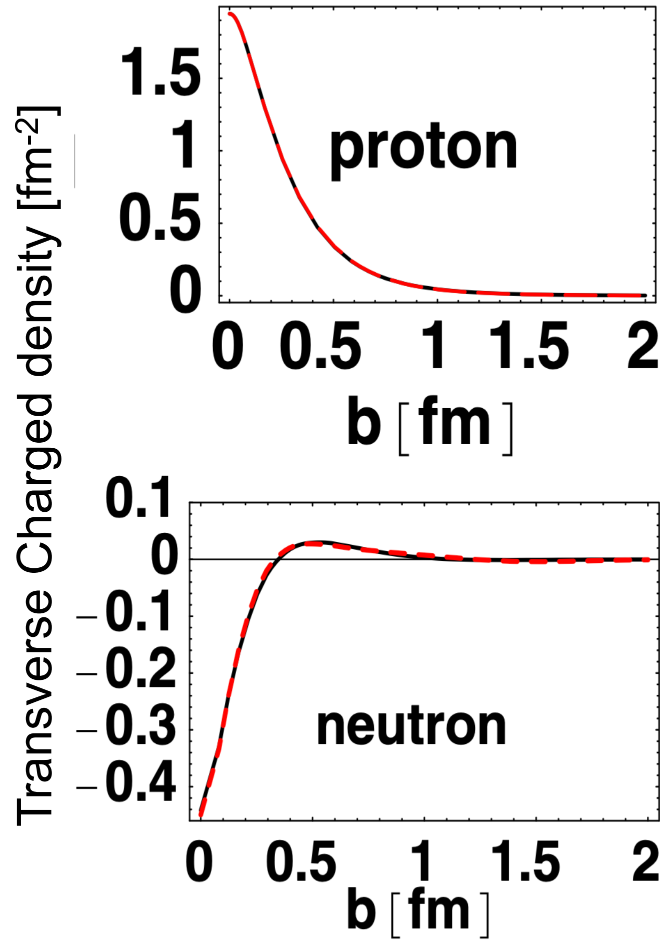
Example: ElectroMagnetic Form-Factors

$$\langle P'|j^{\mu}|P\rangle =$$
$$\overline{U}(P')\left[F_1(q^2)\gamma^{\mu} + F_2(q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M}\right]U(P)$$

Spatial moment of the electromagnetic current

Magnetic moment:

$$\mu = \left(F_1(0) + F_2(0)\right)\cdot\mu_N$$



PRL **99,** 112001 (2007)

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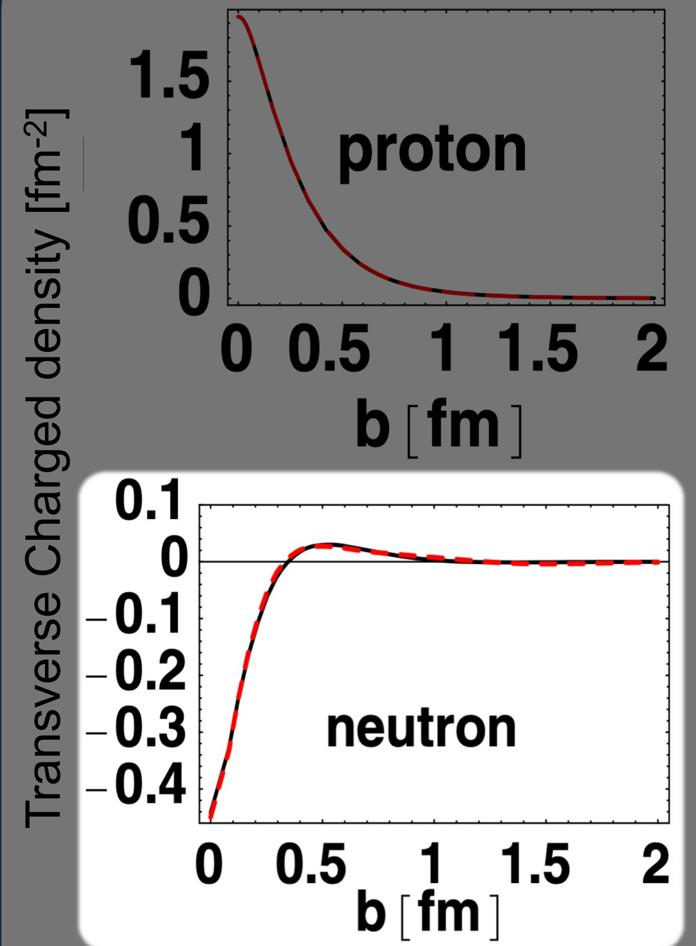
Spati
ele

EM Form Factors Revolutionized our Understanding of the Neutron!



PRL **99**, 112001 (2007)

QCD Energy-Momentum Tensor (EMT)

Matrix elements of the quark and gluon momentum density

$$\langle P'|T^{\mu\upsilon}|P\rangle =$$

$$\bar{U}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\upsilon)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\upsilon)\alpha}\Delta_{\alpha}}{2M} + C(t)\frac{\Delta^{(\mu}\Delta^{\upsilon)}}{M}\right]U(P)$$

Total angular momentum:

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right]$$

QCD Energy-Momentum Tensor (EMT)

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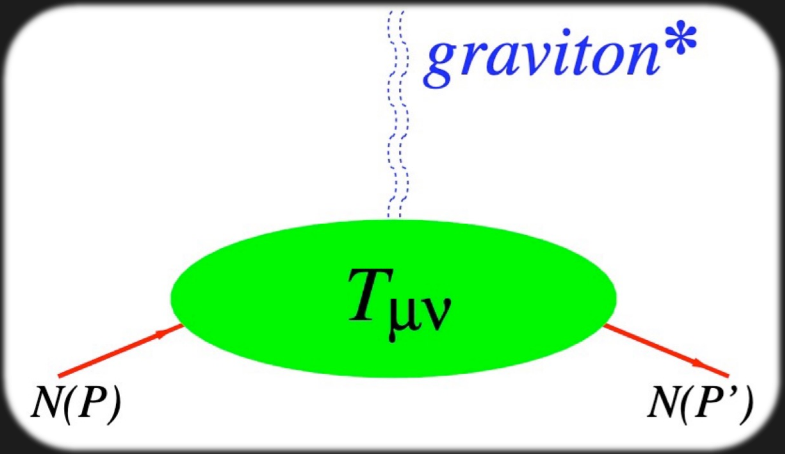
Total angular momentum:

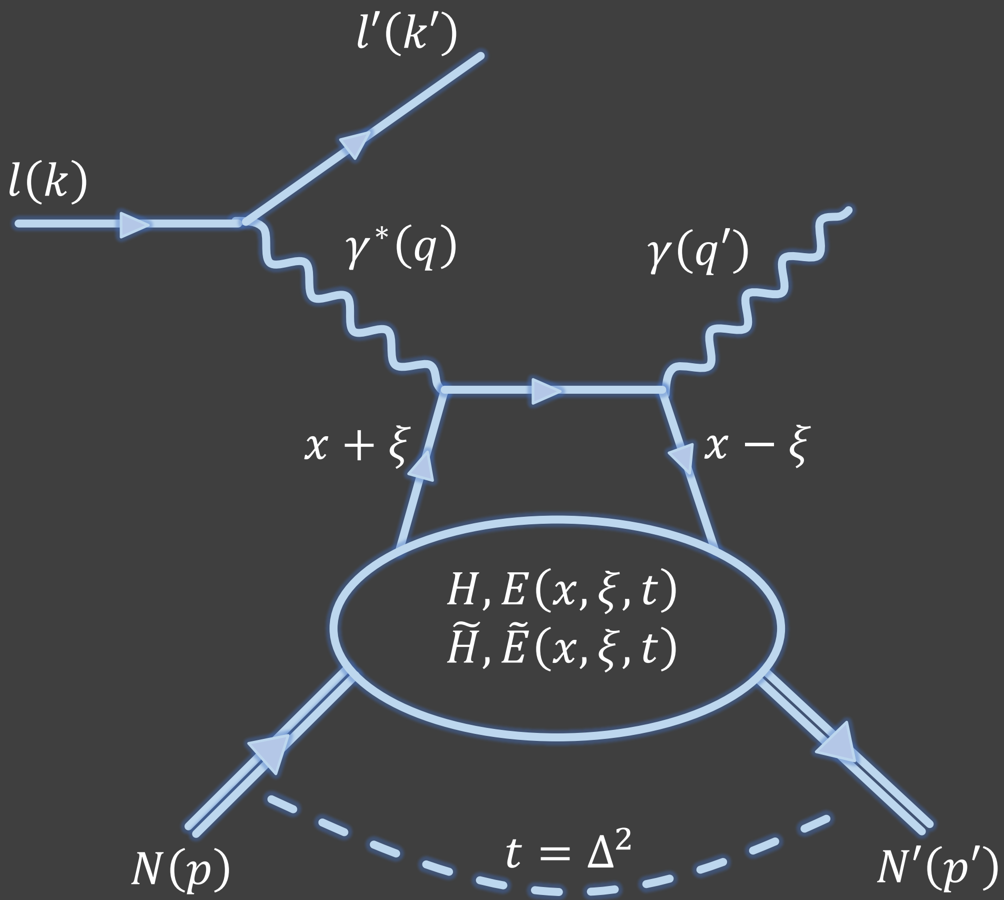
$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right]$$

EMT Form-Factors tells us about the proton's gravitational and spin structure!

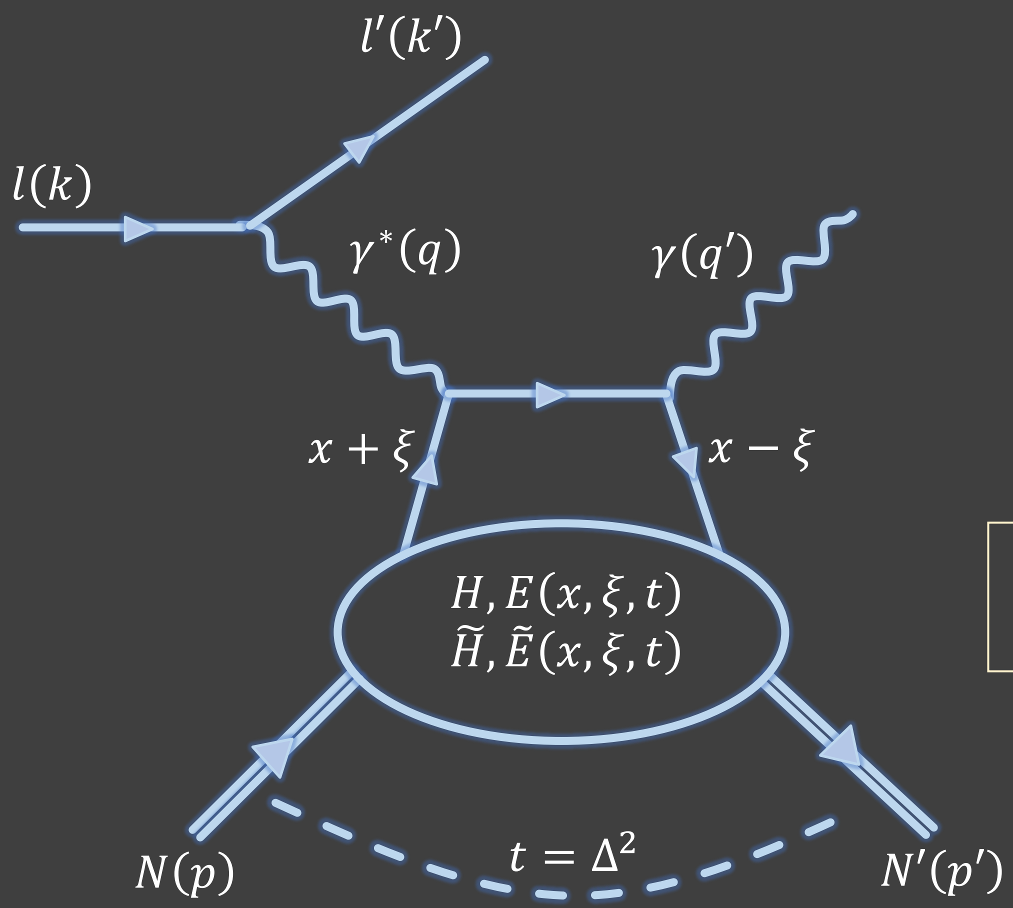
But... need a graviton to directly probe the QCD EMT
(rank-2 tensor)



EMT Form-Factors Probe: Deeply Virtual Exclusive Processes



EMT Form-Factors Probe: Deeply Virtual Exclusive Processes

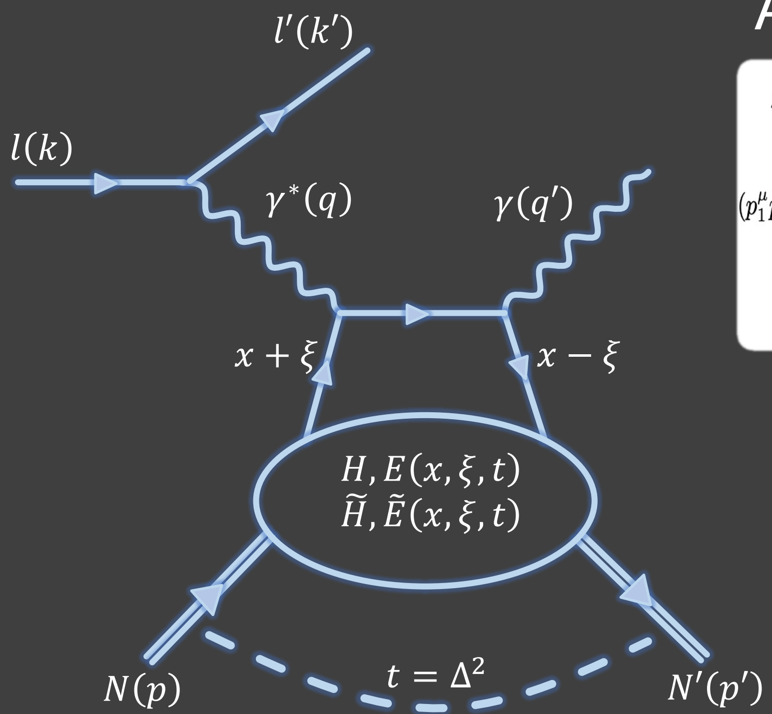


x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – Fourier conjugate to transverse impact parameter

EMT Form-Factors Probe: Deeply Virtual Exclusive Processes



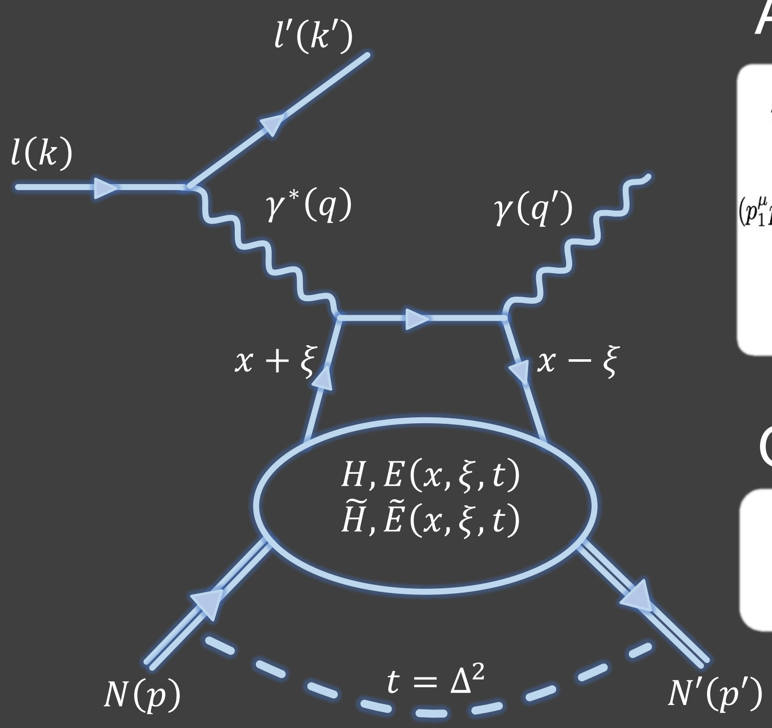
Amplitude given by four GPDs:

$$i\mathcal{M} = -i\sum_q (|e|Q_q)^2 \epsilon^*_\mu \epsilon_\nu \Bigg\{$$

$$(p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - g_\perp^{\mu\nu}) \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] \times \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p') i\sigma^{+\alpha}\frac{\Delta_\alpha}{2m_N} u(p)\right]$$

$$+ i\epsilon^{\mu\nu+-}\int_{-1}^{1} dx \left[\frac{1}{x+\xi-i\epsilon} - \frac{1}{x-\xi+i\epsilon}\right] \times \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta^+}{2m_N}u(p)\right]\Bigg\}$$

EMT Form-Factors Probe: Deeply Virtual Exclusive Processes



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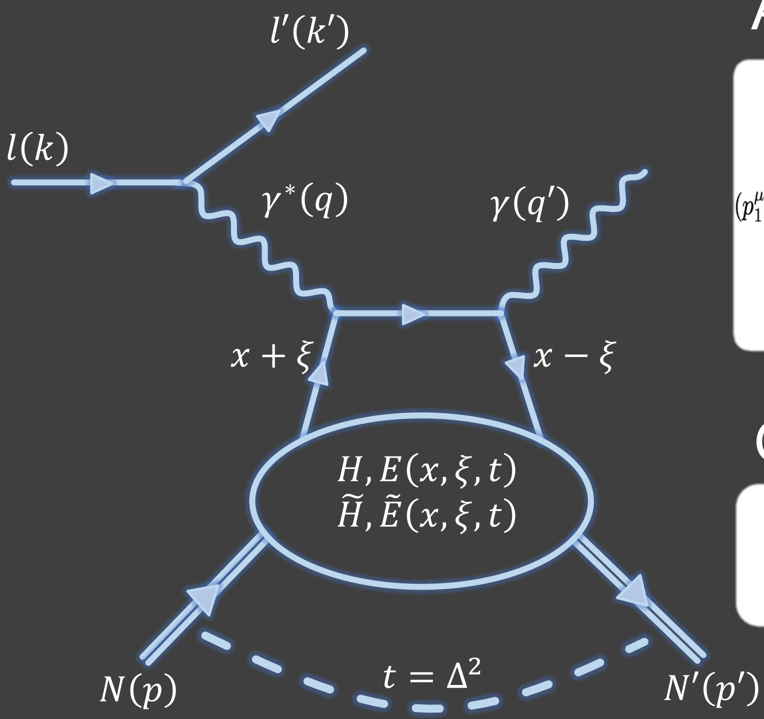
$$+ i\epsilon^{\mu\nu+-}\int_{-1}^{1} dx \left[\frac{1}{x+\xi-i\epsilon} - \frac{1}{x-\xi+i\epsilon}\right] \times \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta^+}{2m_N}u(p)\right]\Bigg\}$$

GPDs access EMT Form-Factors:

$$\int_{-1}^{1} dx\, x[H(x,\xi,\Delta^2) + E(x,\xi,\Delta^2)] = A(\Delta^2) + B(\Delta^2)$$

EMT Form-Factors Probe: Deeply Virtual Exclusive Processes



Amplitude given by four GPDs:

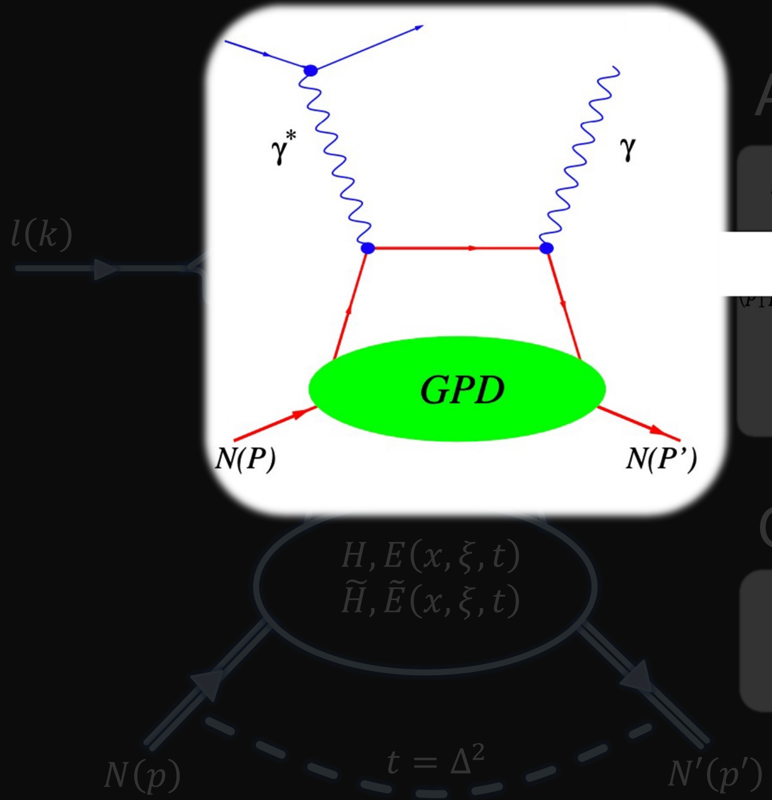
$$i\mathcal{M} = -i\sum_q (|e|Q_q)^2 \epsilon^*_\mu \epsilon_\nu \Bigg\{ (p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - g_\perp^{\mu\nu}) \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] \times \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p') i\sigma^{+\alpha}\frac{\Delta_\alpha}{2m_N}u(p)\right]$$
$$+ i\epsilon^{\mu\nu+-}\int_{-1}^{1} dx \left[\frac{1}{x+\xi-i\epsilon} - \frac{1}{x-\xi+i\epsilon}\right] \times \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta^+}{2m_N}u(p)\right]\Bigg\}$$

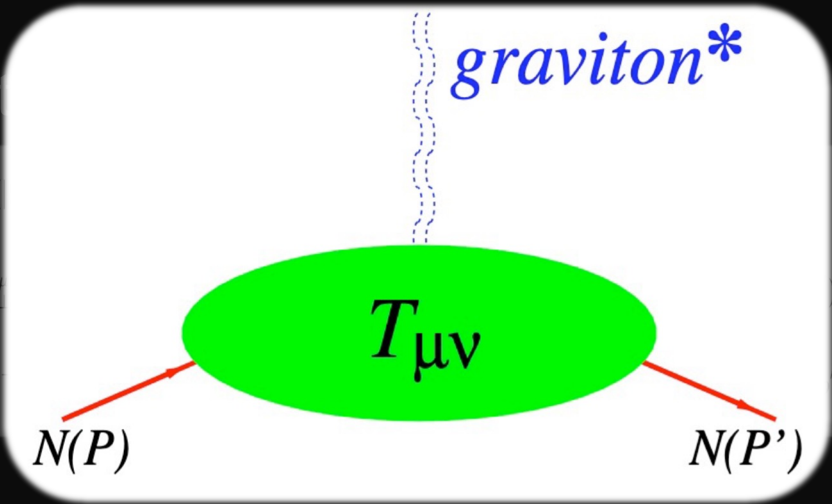
GPDs access EMT Form-Factors:

$$\int_{-1}^{1} dx\, x[H(x,\xi,\Delta^2)+E(x,\xi,\Delta^2)] = A(\Delta^2)+B(\Delta^2)$$

+ angular momentum: $J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$

Deeply Virtual Exclusive Processes: EMT Form-Factors Probe





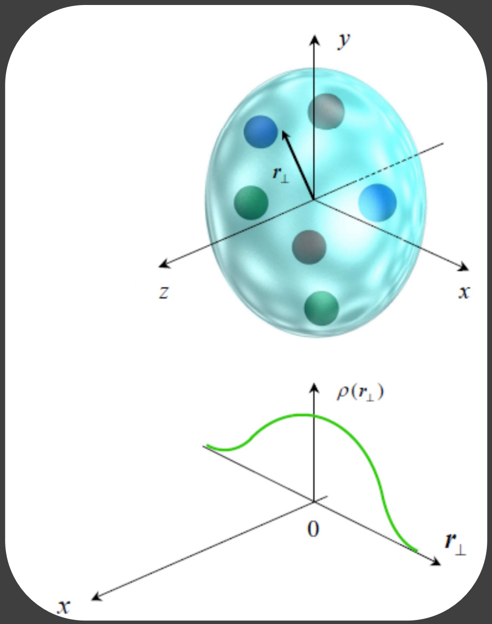
Amplit

GPDs access EMT Form-Factors:

$$\int_{-1}^{1} dx\, x[H(x,\xi,\Delta^2)+E(x,\xi,\Delta^2)] = A(\Delta^2)+B(\Delta^2)$$

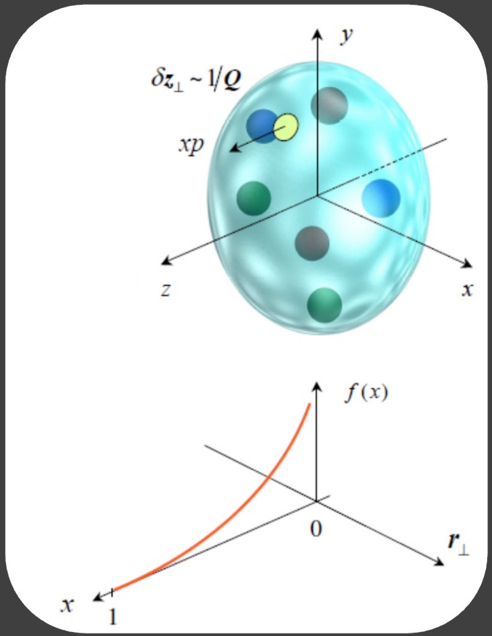
+ angular momentum: $J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$

“old” view of nuclei considered
Electromagnetic or QCD structure *separately*



EM structure
Form factors, **transverse**
charge & current distributions

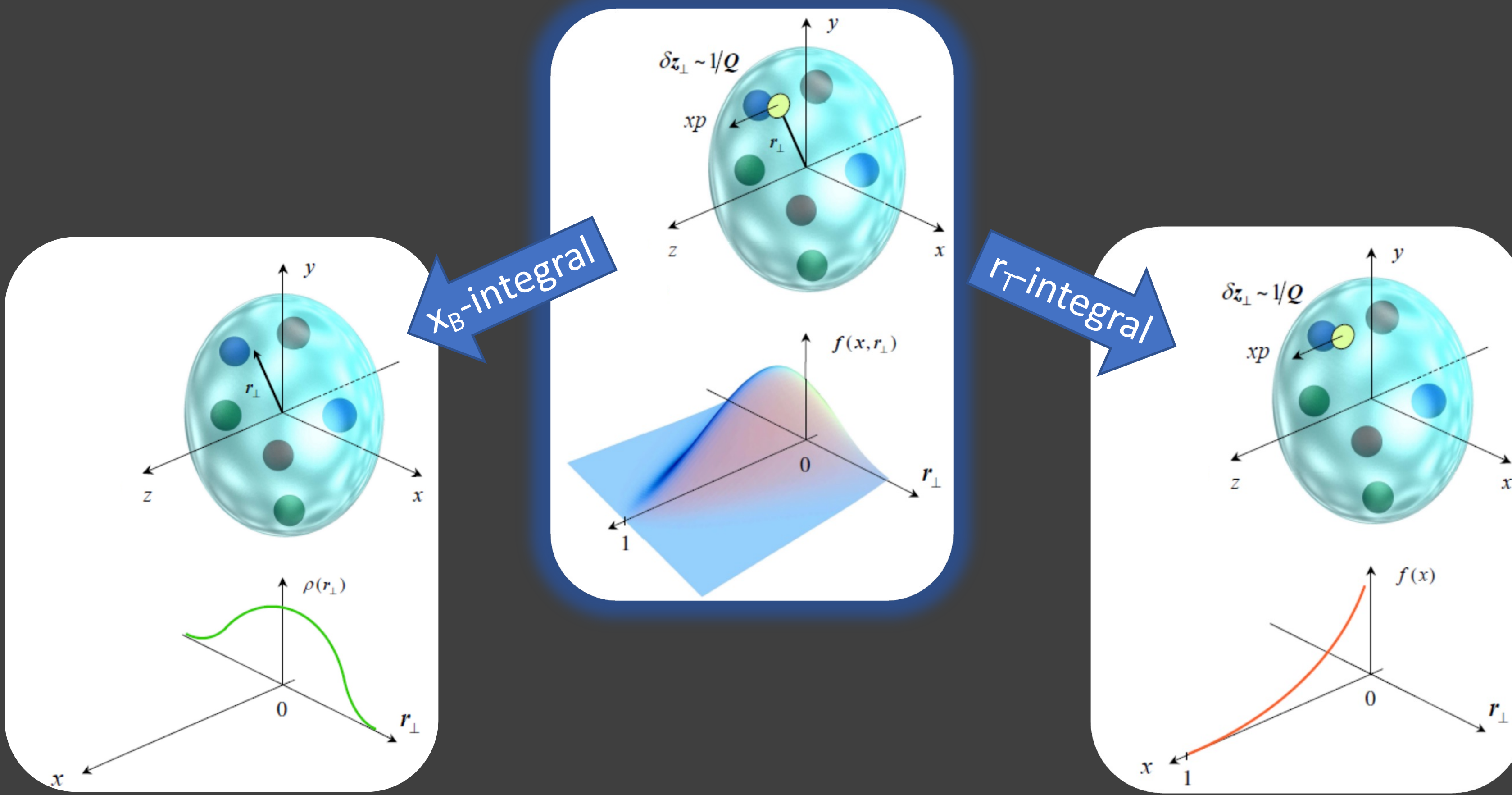
Nobel prize 1961-
Hofstadter



Quark-gluon structure
longitudinal momentum
& helicity distributions

Nobel prize 1990 -
Friedman, Kendall, Taylor

We now have *New* exp and theory tools that *connect* parton distribution in transverse space & longitudinal momentum



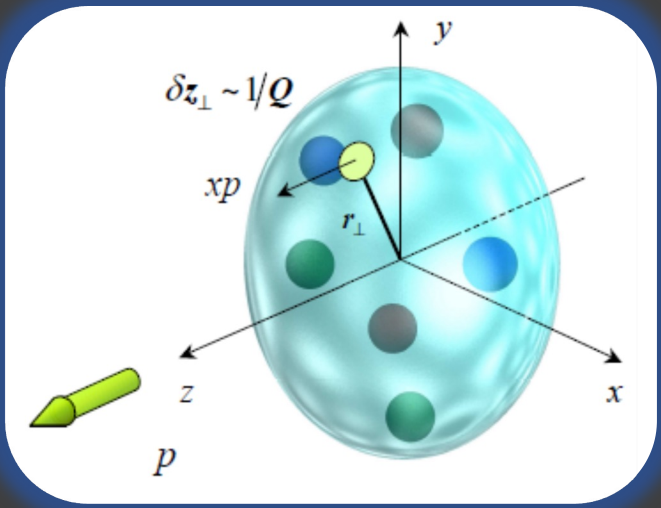
EM structure
Form factors, **transverse** charge & current distributions

Nobel prize 1961- Hofstadter

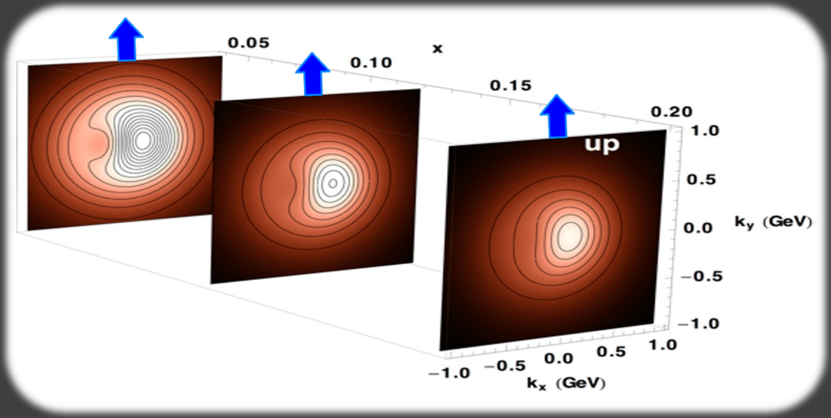
Quark-gluon structure
longitudinal momentum & helicity distributions

Nobel prize 1990 - Friedman, Kendall, Taylor

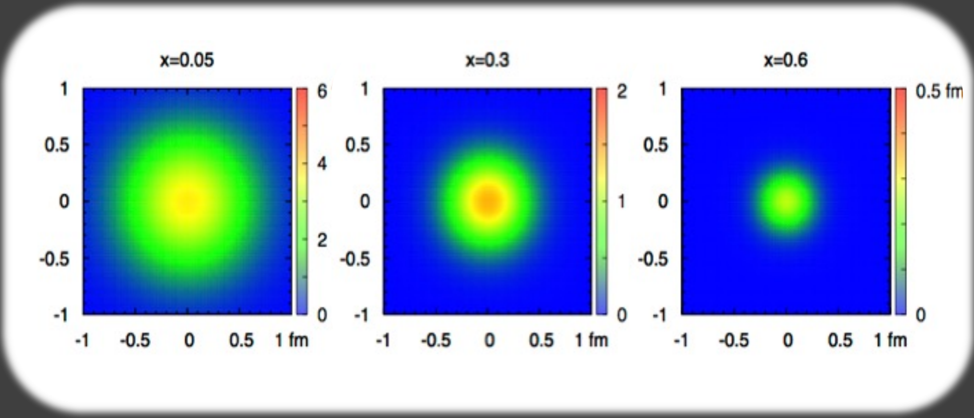
Ushering the Era of 3D Parton Femtography!



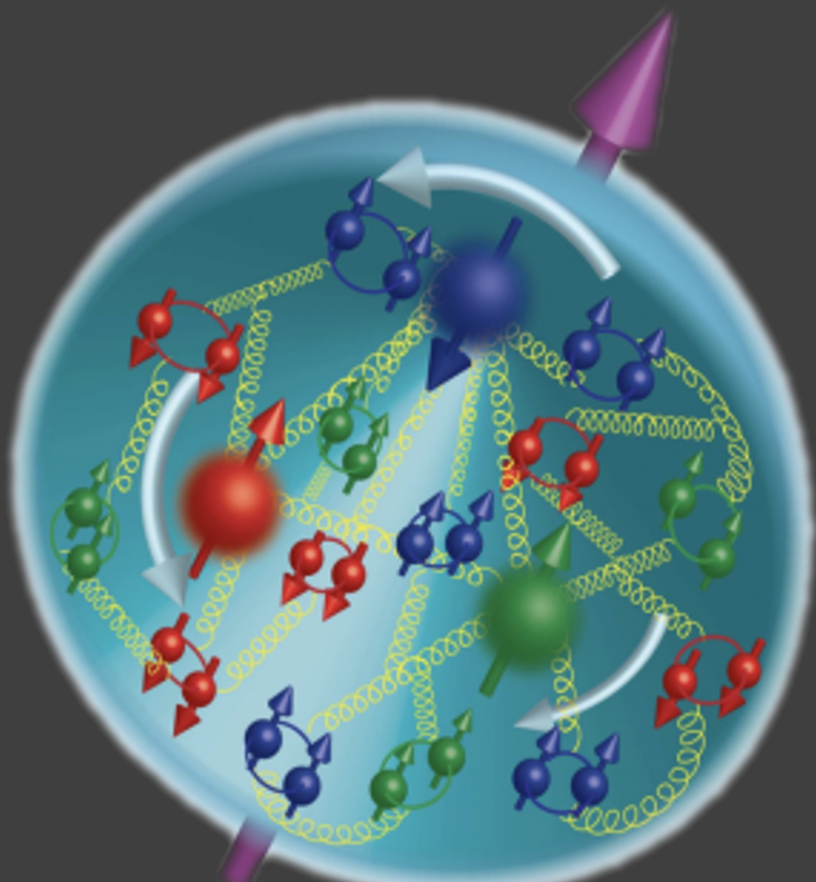
Transverse momentum: f(**x**,**k**$_T$)



Transverse position: f(**x**,**b**$_T$)



The ‘3-dimentional’ Proton (2030s)

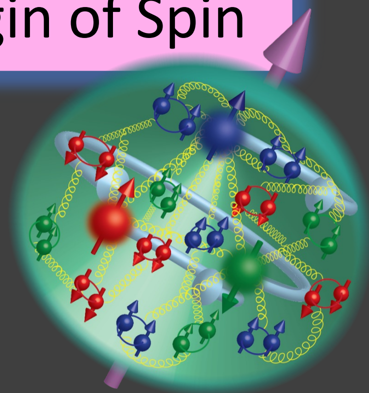


Like King Saul…

Went looking for a solution to the spin puzzle and ended up with a formalism to probe the QCD EMT and 3D Nucleon Structure in a whole new way! ☺

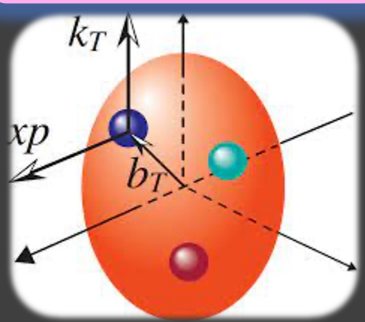
The Bible, Book of Samuel 1, 9 – 10 (long ago)

Origin of Spin



Origin of Mass

Femtography



Hadron Structure @ EIC

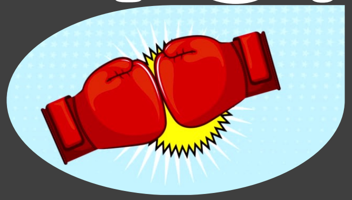
$$\langle P'|T^{\mu\upsilon}|P\rangle = \bar{U}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\upsilon)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\upsilon)\alpha}\Delta_\alpha}{2M} + C(t)\frac{\Delta^{(\mu}\Delta^{\upsilon)}}{M}\right]U(P)$$

Wait…!

Isn't Lattice QCD already doing it?

Wait…!
Isn't Lattice QCD already doing it?

Vs.



From the TMD Handbook:

PDFs and TMDs and related objects are defined precisely in QCD by operators that involve correlations of quark and gluon fields with lightlike separations in spacetime. It is therefore very natural to ask whether given sufficient computing power we could calculate the PDFs and TMDs, and in general, the leading quark-gluon correlations inside a bound nucleon *directly* in LQCD. If it were possible, the quantum correlations between a hadron's mass and spin and the motion of quarks and gluons inside it could be determined, shedding light on how quarks and gluons are confined inside the hadrons. However for these partonic quantities, an impediment to LQCD calculations is raised by the light-cone nature of their definition. Since LQCD is most practically formulated in Euclidean space, direct determinations of such lightlike separated correlations are not possible. For that reason, most QCD studies of partonic physics have concentrated on the x^n weighted Mellin moments of PDFs. However for technical reasons, these calculations have been restricted to the lowest few moments, $n \in \{1, 2, 3\}$.

https://arxiv.org/abs/2304.03302

Lattice Struggles Calculating Full PDFs

From the TMD Handbook:

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https://arxiv.org/abs/2304.03302

Still, Lattice QCD is capable of A LOT!

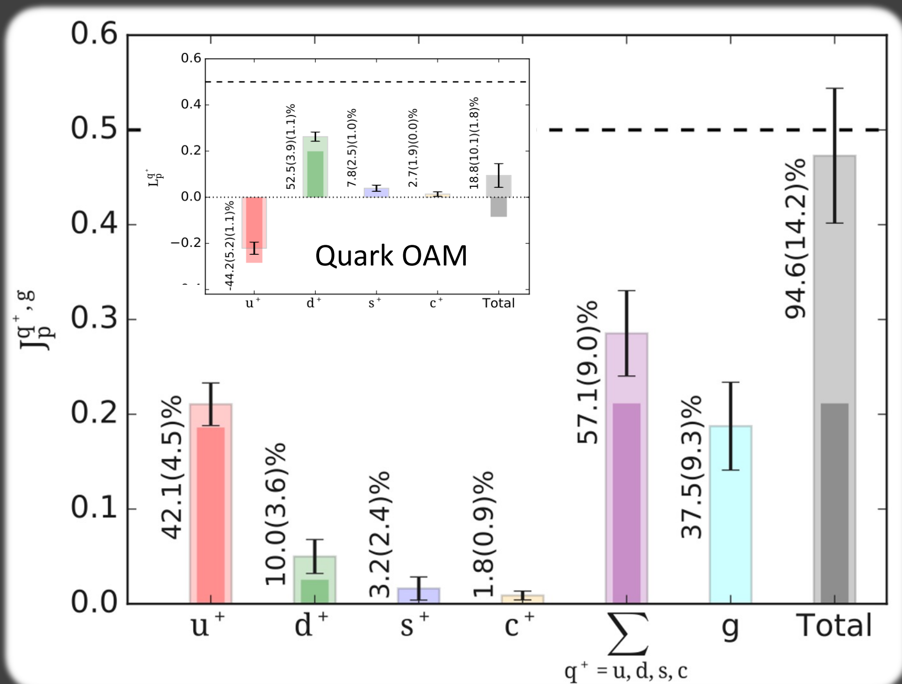
From the TMD Handbook:

extract from experiment. For example, calculations can cover parameter values and kinematics that are difficult for experiments to reach. Moreover in LQCD, we have the freedom to choose the combinations of operators that are calculated in order to determine aspects of hadron structure that might not be readily accessible in experiments. Despite the so-far insurmountable challenges for *direct* LQCD calculations of PDFs, TMDs and other leading quark-gluon correlation functions, the various LQCD approaches that will be discussed below definitively enhance our ability to explore the rich, nonperturbative structure of hadrons and the dynamics of quarks and gluons at the QCD scale.

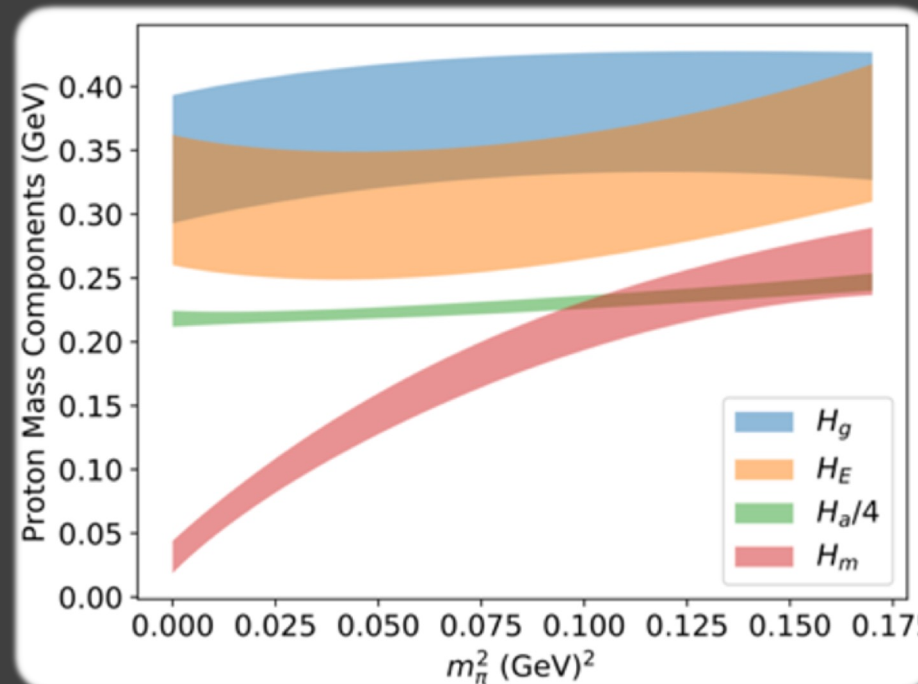
https://arxiv.org/abs/2304.03302

Lattice QCD is capable of <u>A LOT</u>!

Spin Decomposition



Mass Decomposition

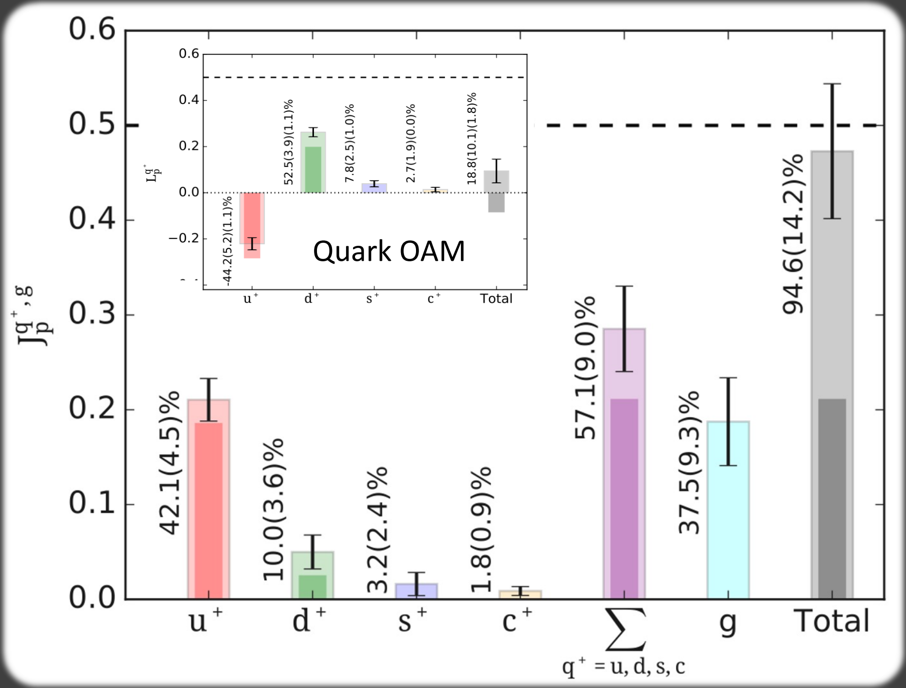


Phys. Rev. D 101, 094513 (2020)
Phys. Rev. Lett. 121, 212001 (2018)

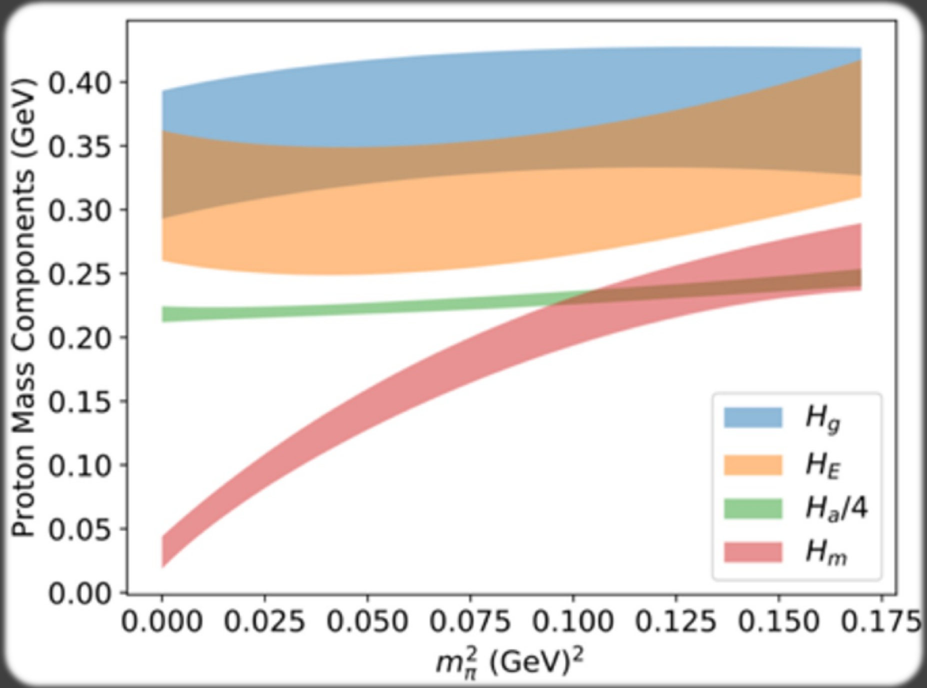
Lattice QCD is capable of A LOT!

But not everything…

Spin Decomposition



Mass Decomposition



Phys. Rev. D 101, 094513 (2020)
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My personal take: *understanding* hadrons requires it all – Experiment, QCD models, and Lattice QCD calculations.

Synergy yields groundbreaking understanding!

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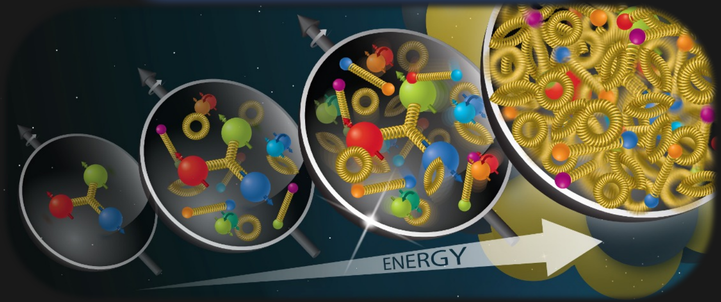
Synergy yields groundbreaking understanding!

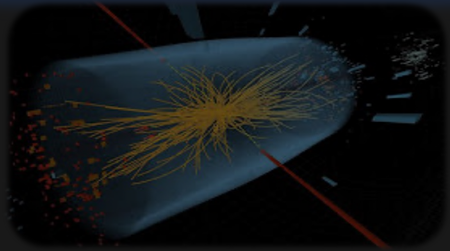
QCD Science

Dense Gluons

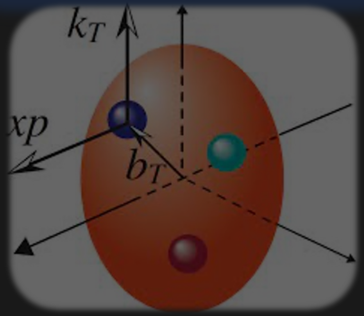


Nuclei

Standard Model

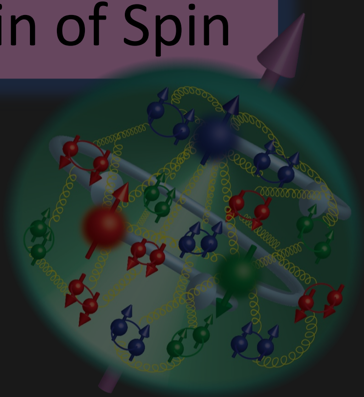


Femtography

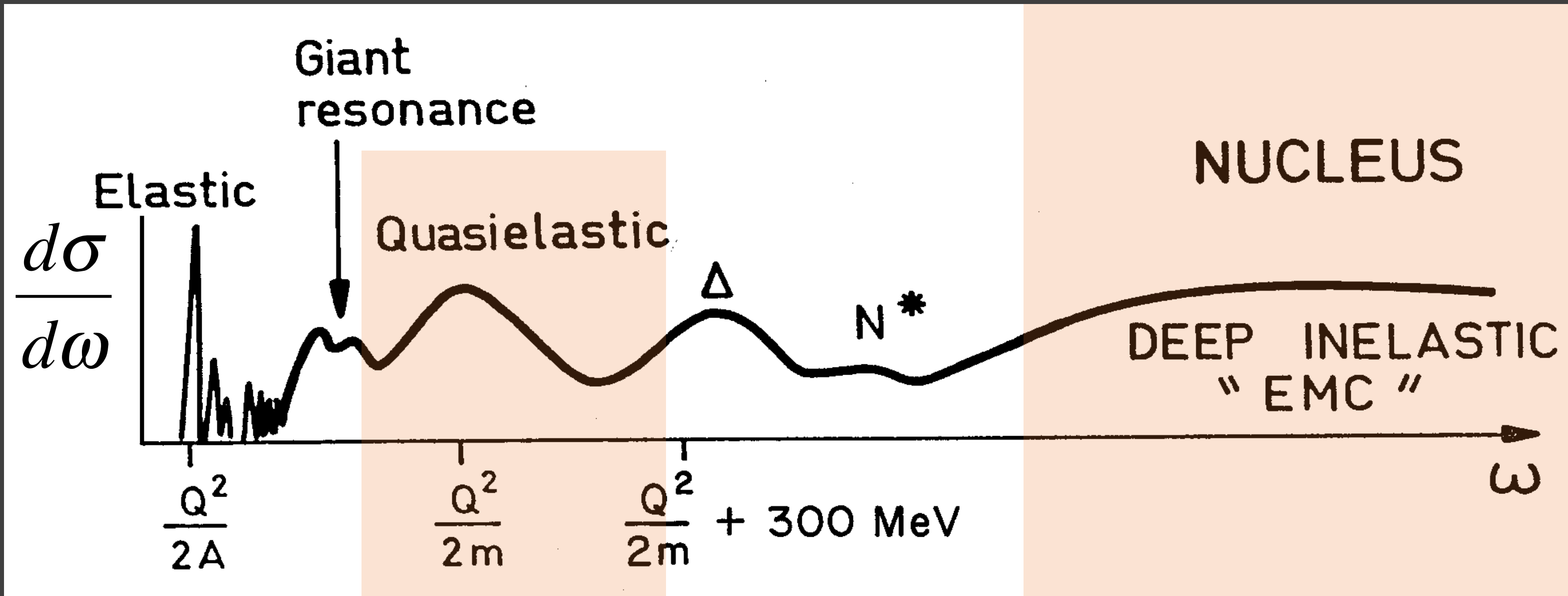


Origin of Mass

Origin of Spin

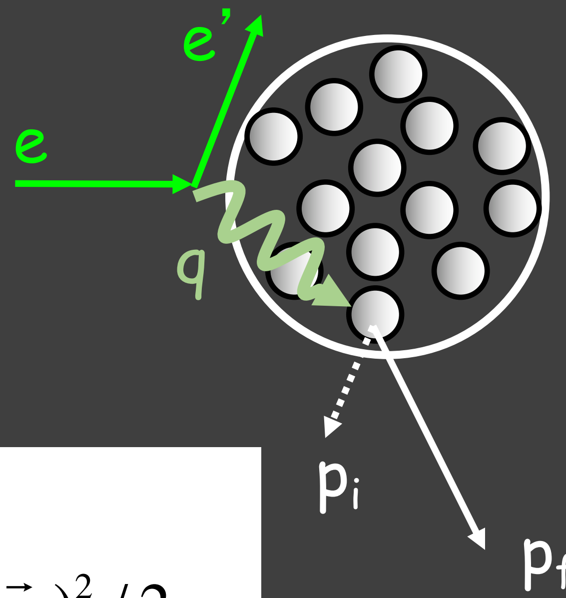


(e,e’): Energy conservation defines physics



Fermi gas model:

[Energy conservation informs distribution]



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

Expect:

- Peak centroid at $\nu = q^2/2m_p + \varepsilon$
- Peak width $2qp_{fermi}/m_p$
- Total peak cross section = $Z\sigma_{ep} + N\sigma_{en}$

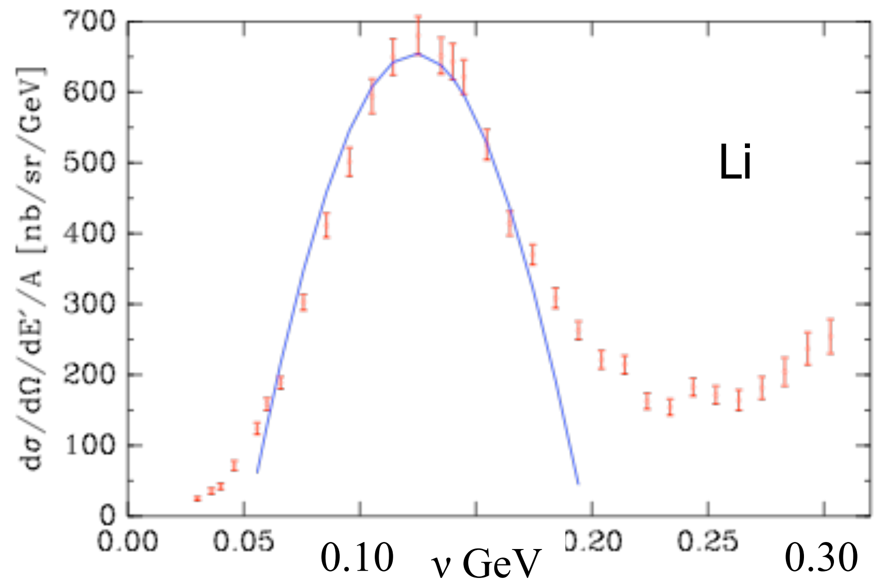
Early 1970's Quasielastic Data

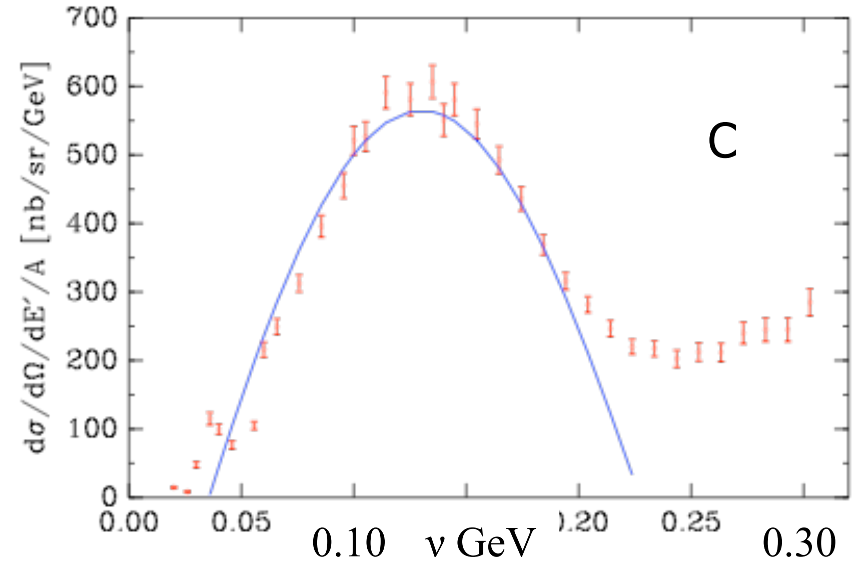
-> getting the bulk features

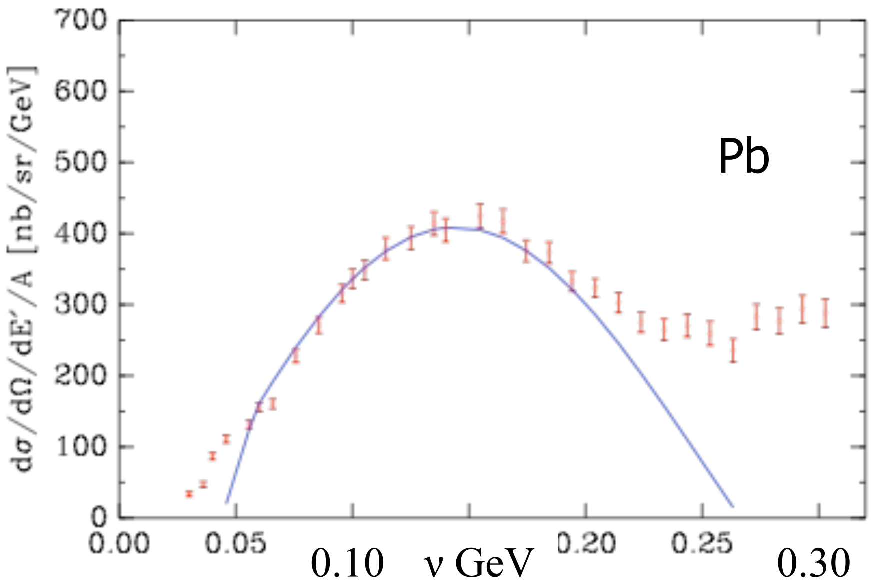
500 MeV, 60 degrees

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

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







Nucleus	k_F MeV/c	$\bar{\epsilon}$ MeV
^{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

compared to Fermi model: fit parameter k_F and ε

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

y = momentum of the struck nucleon parallel to momentum transfer: $y \approx -q/2 + m\nu/q$

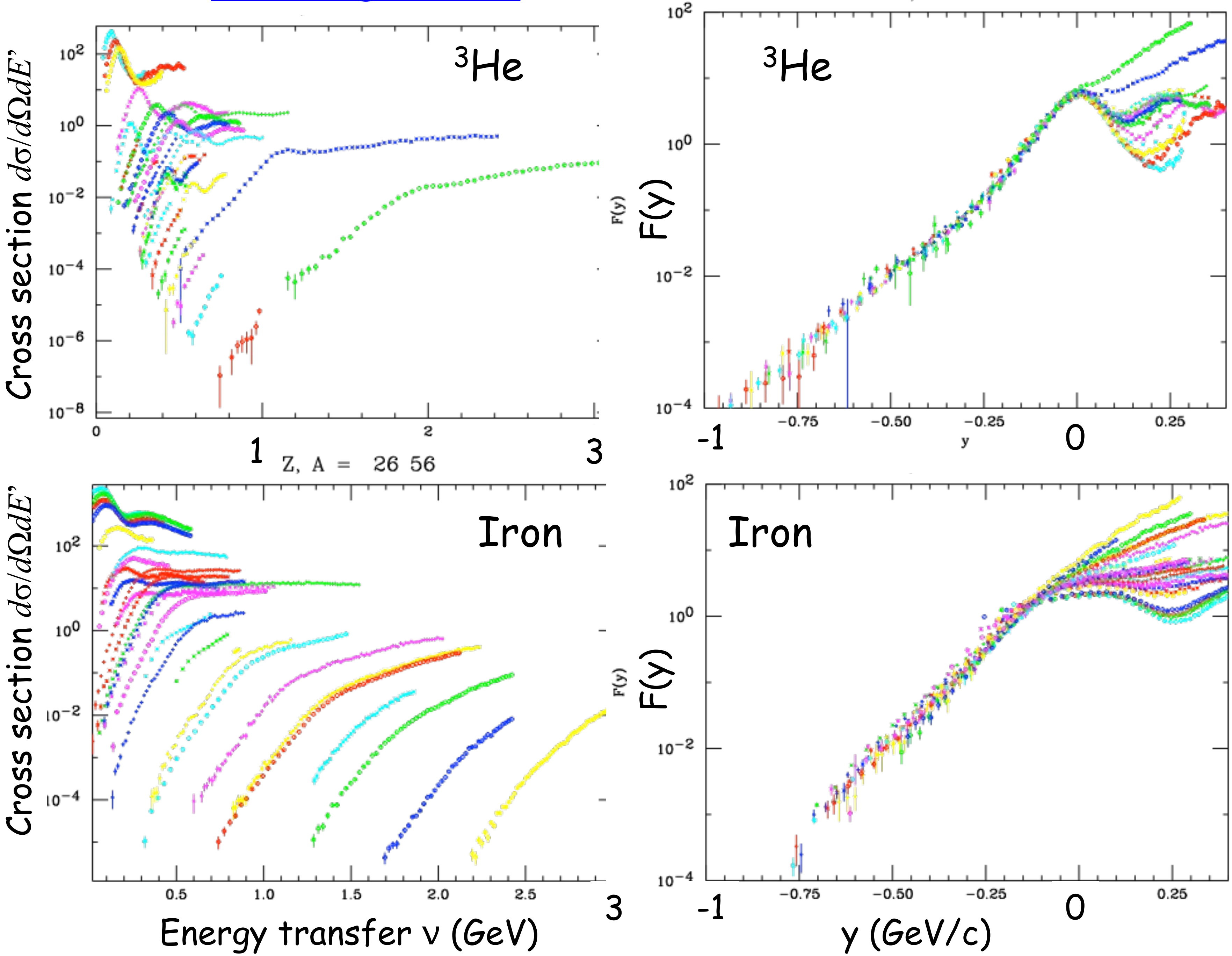
IF the scattering is quasifree, then $F(y)$ is the integral over all perpendicular nucleon momenta.

Goal: extract the momentum distribution $n(k)$ from $F(y)$.

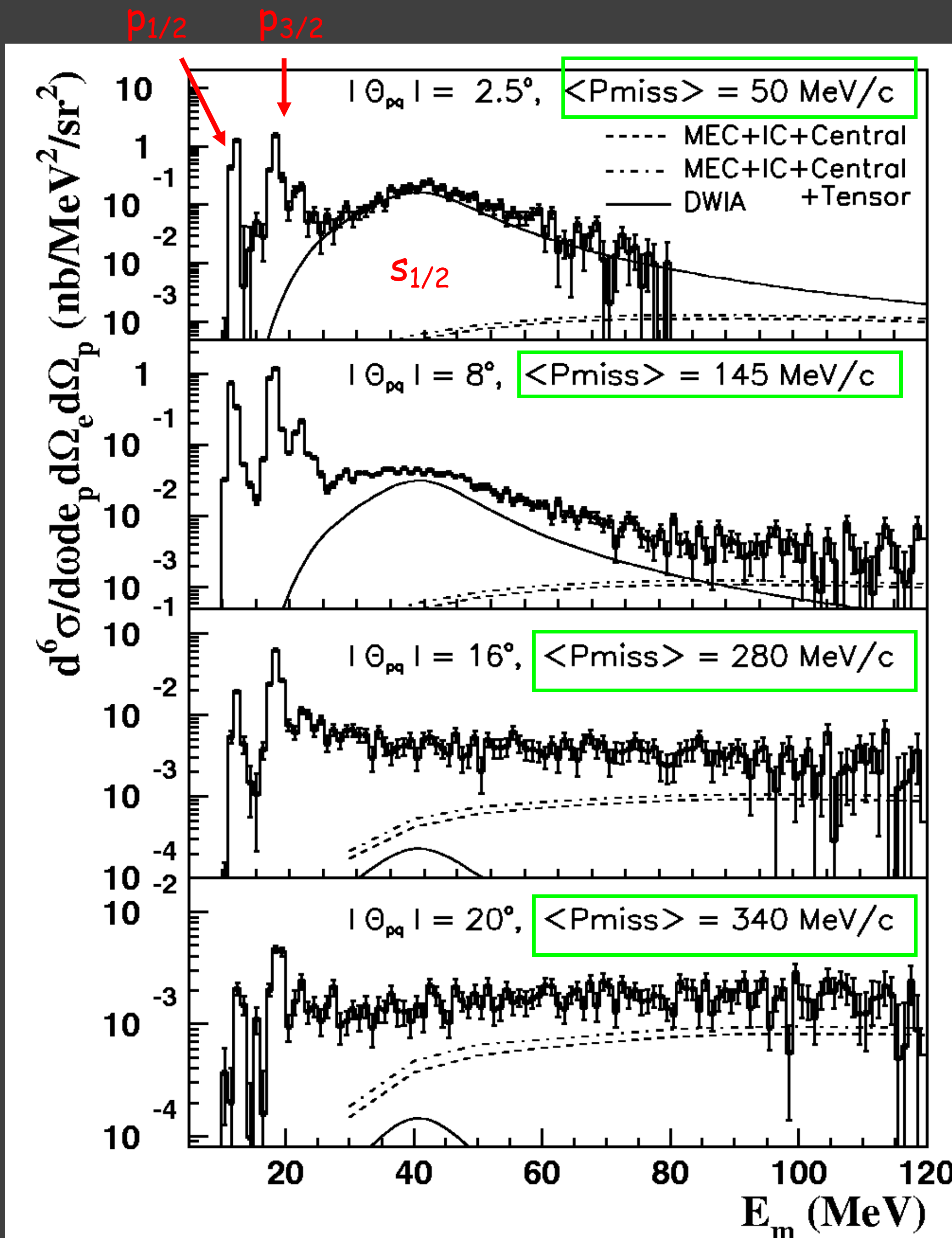
$$F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

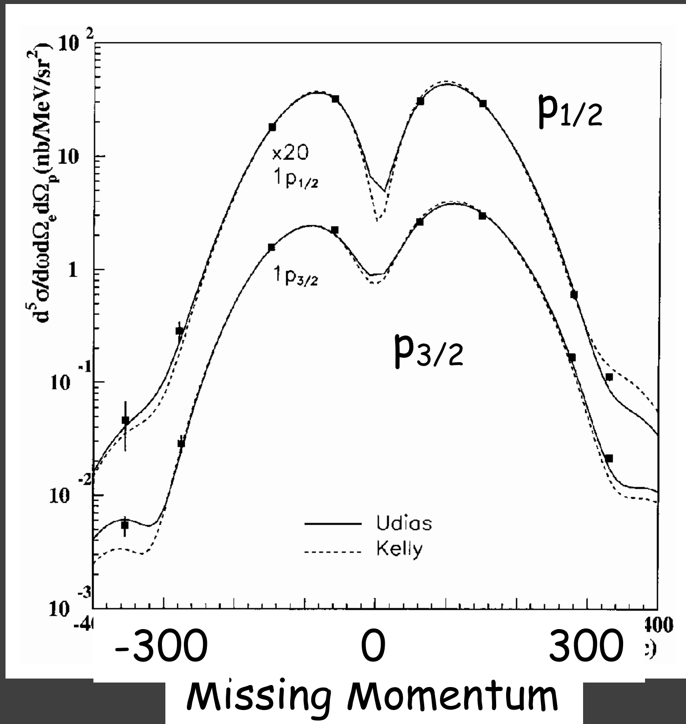
$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

Y-scaling works!



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



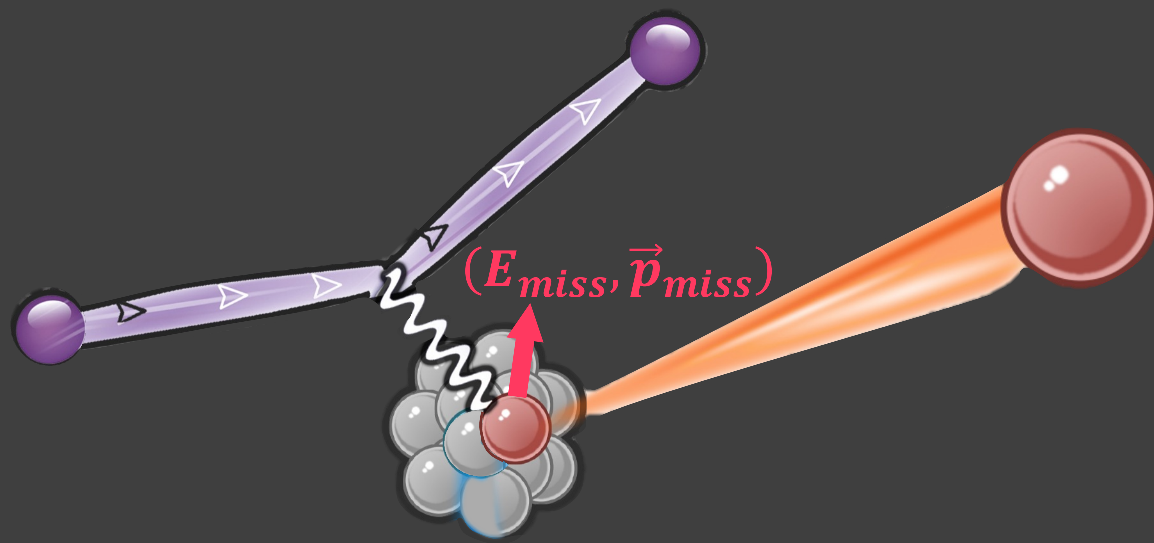


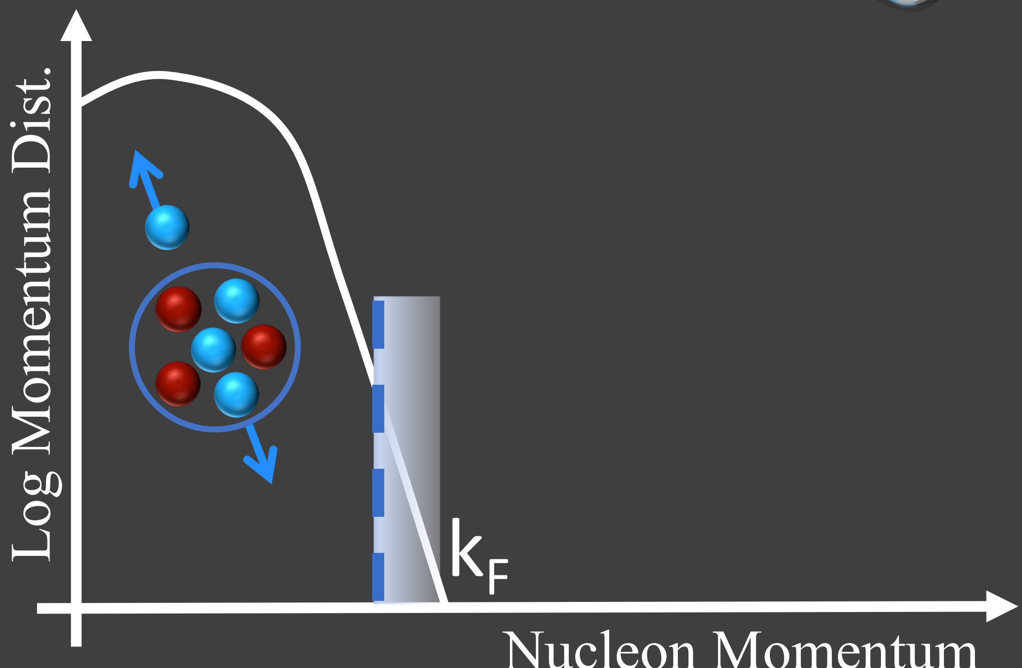
$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

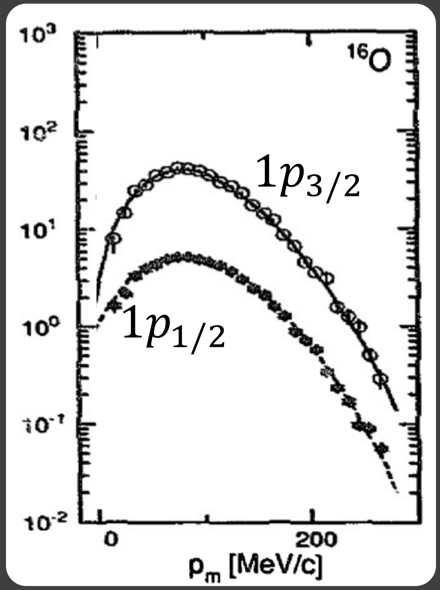
Momentum distribution as expected for $l = 0, 1$

Fissum et al, PRC 70, 034606 (2003)

Probing Nuclei With Electrons



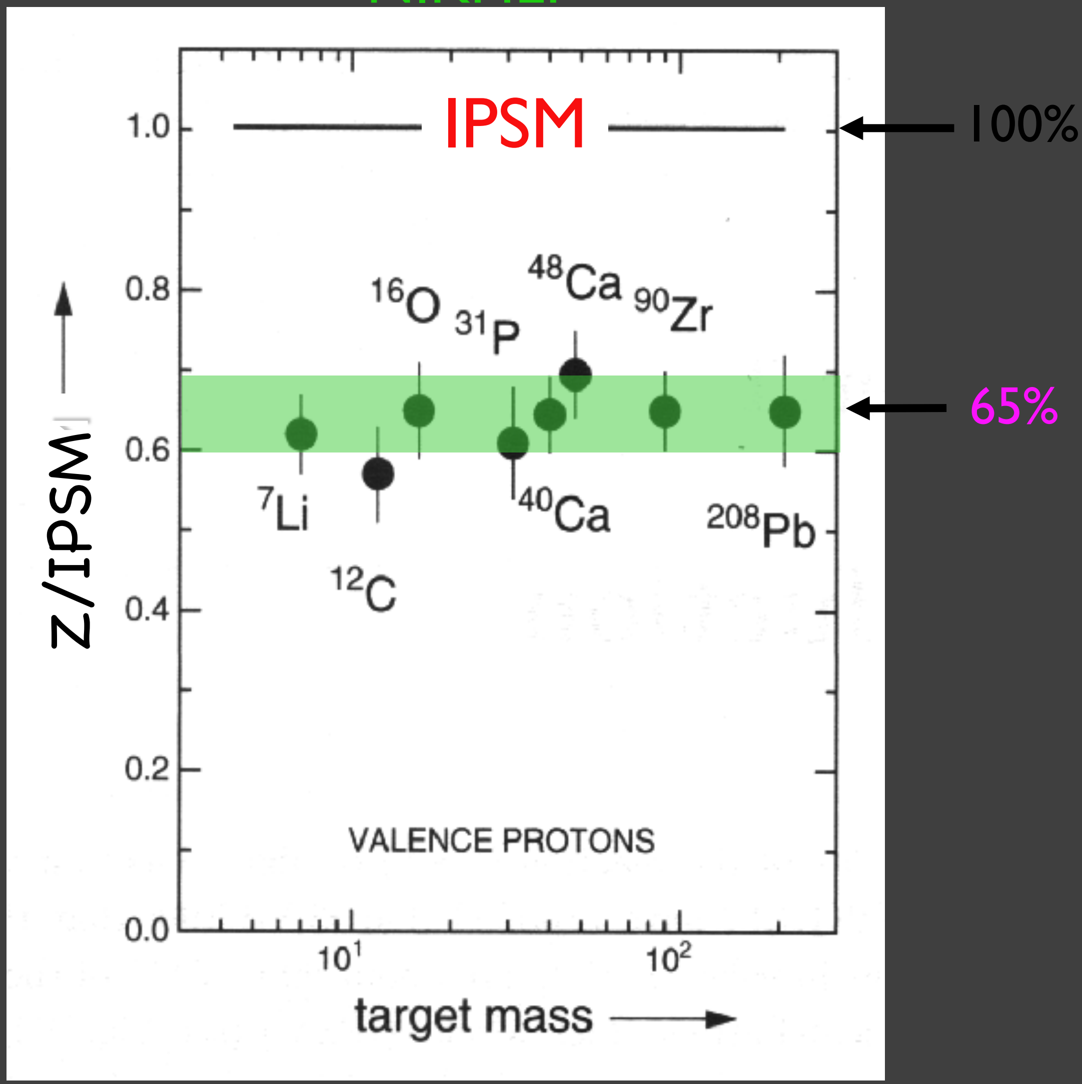




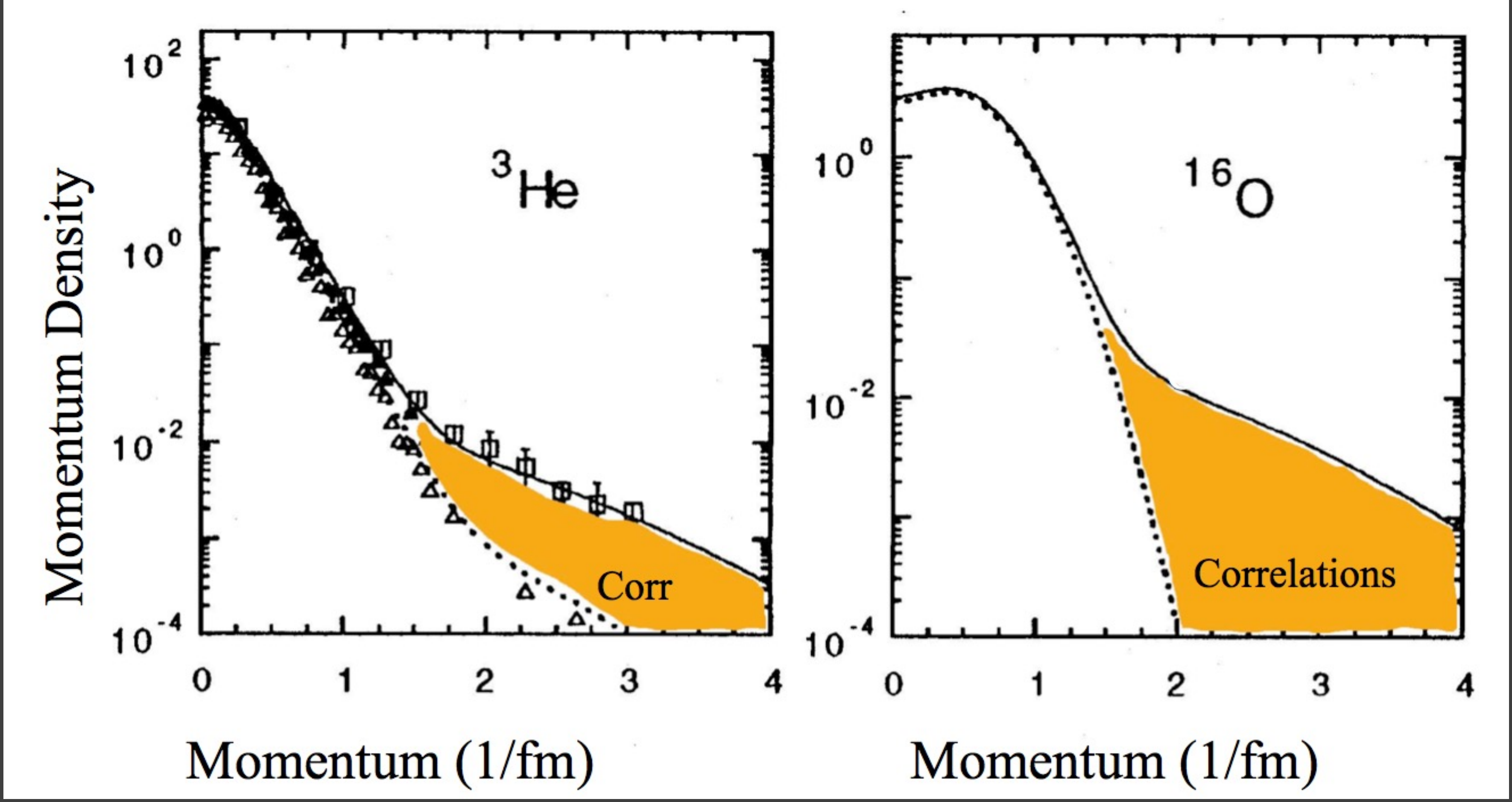
Lapikas Nuc. Phys. A '93

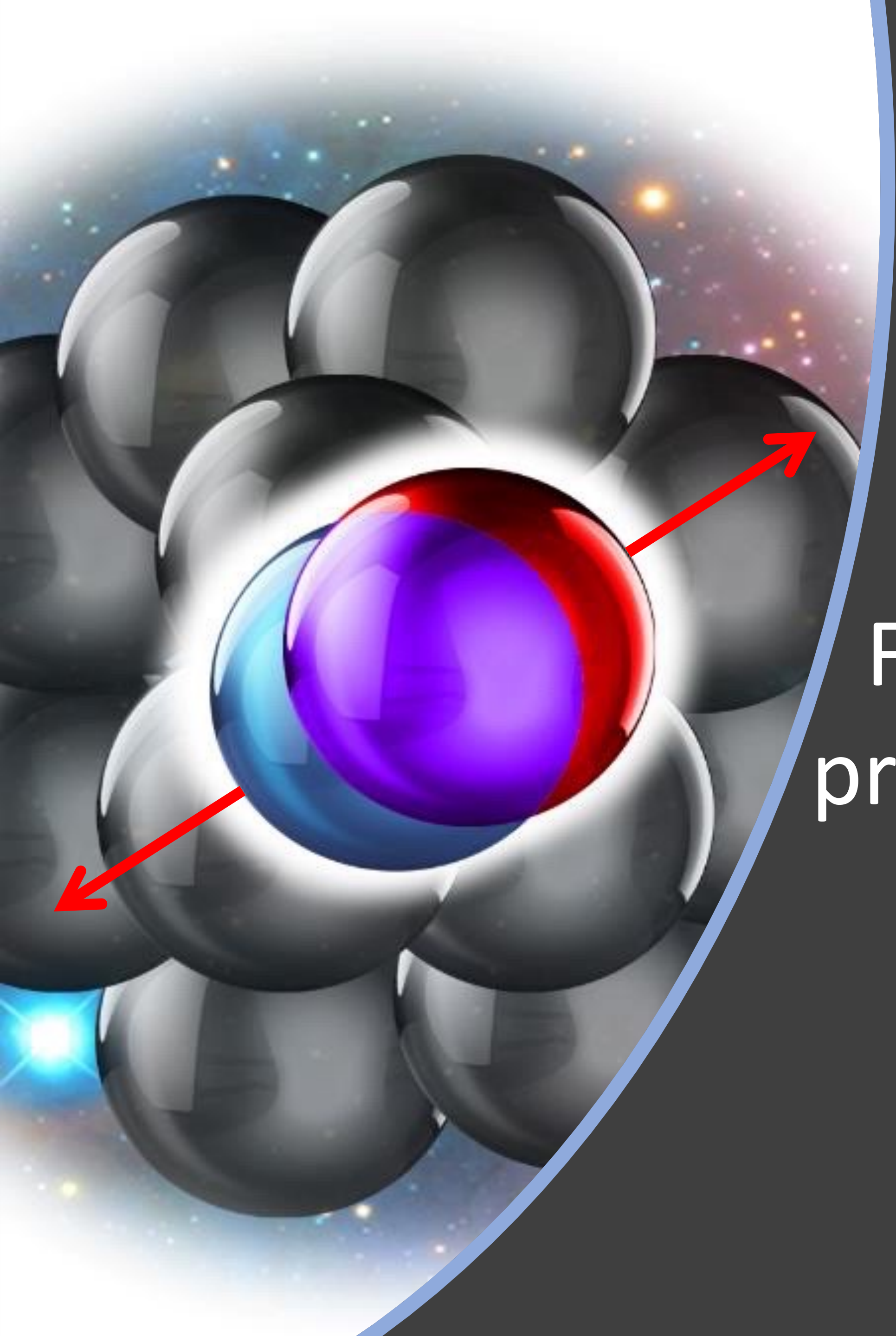
But we do not see enough protons!

NIKHEF



But we do not see enough protons!

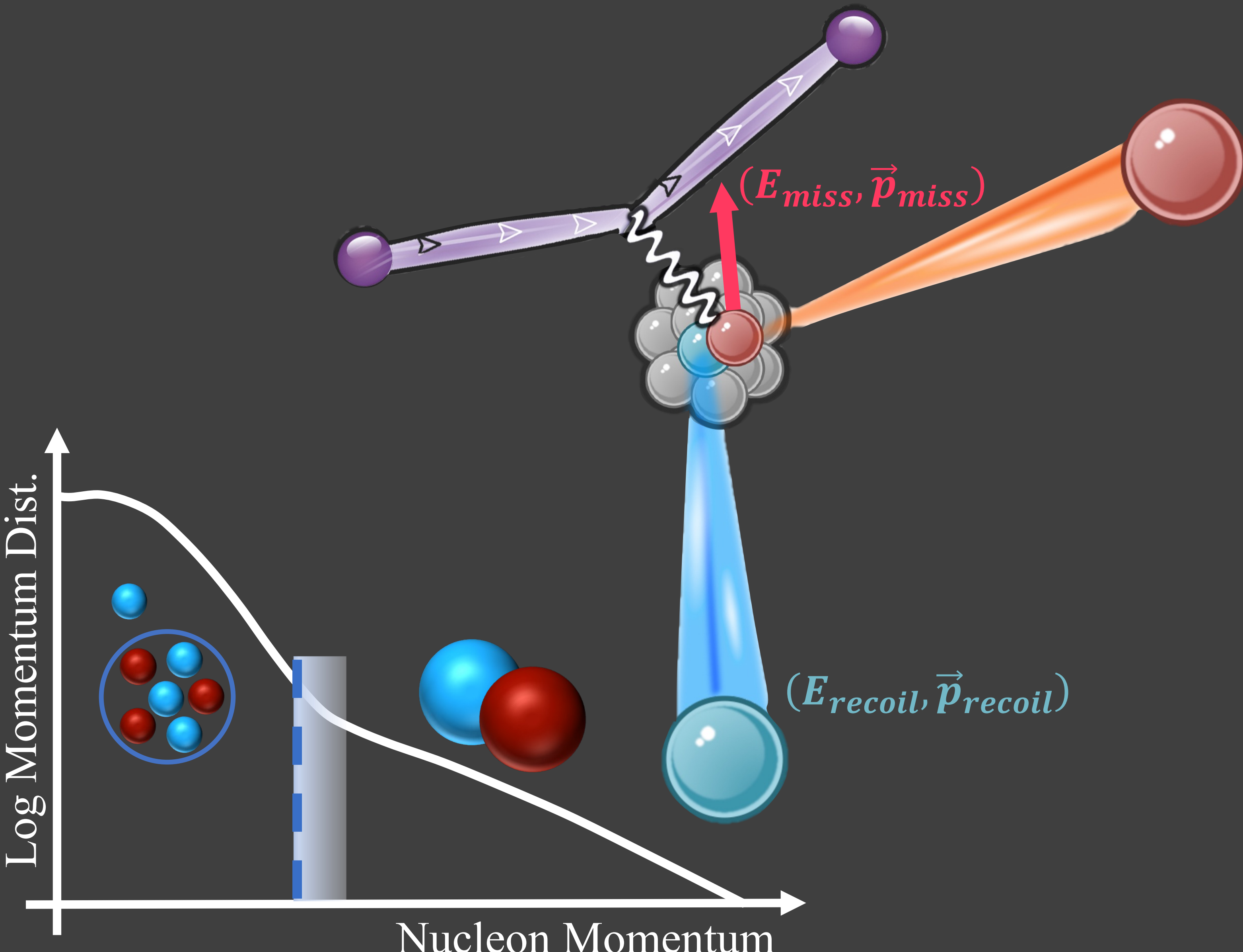




Short-Range Correlations (SRC)

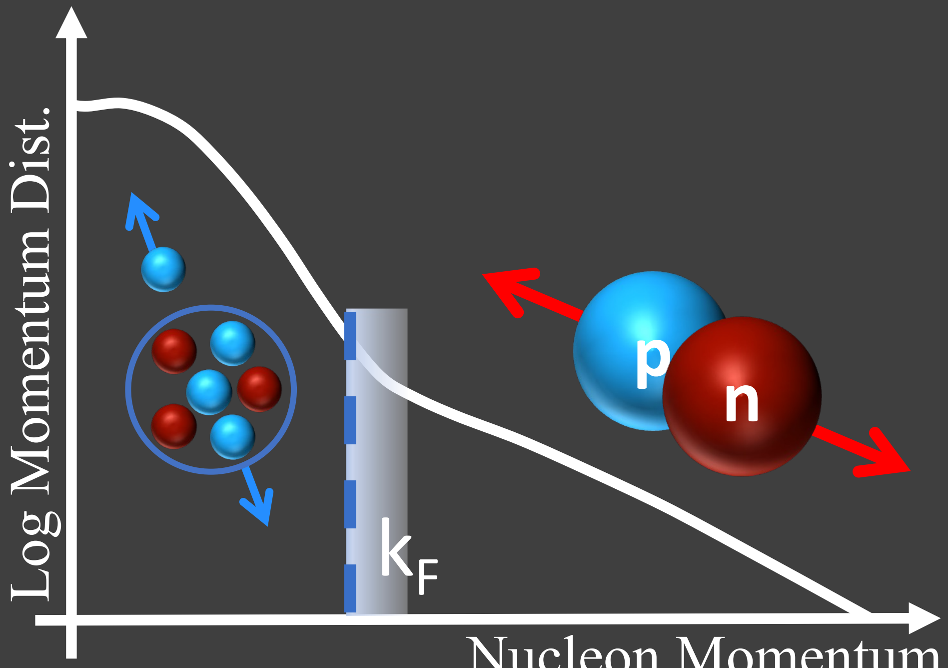
Fluctuations of close-proximity nucleon pairs

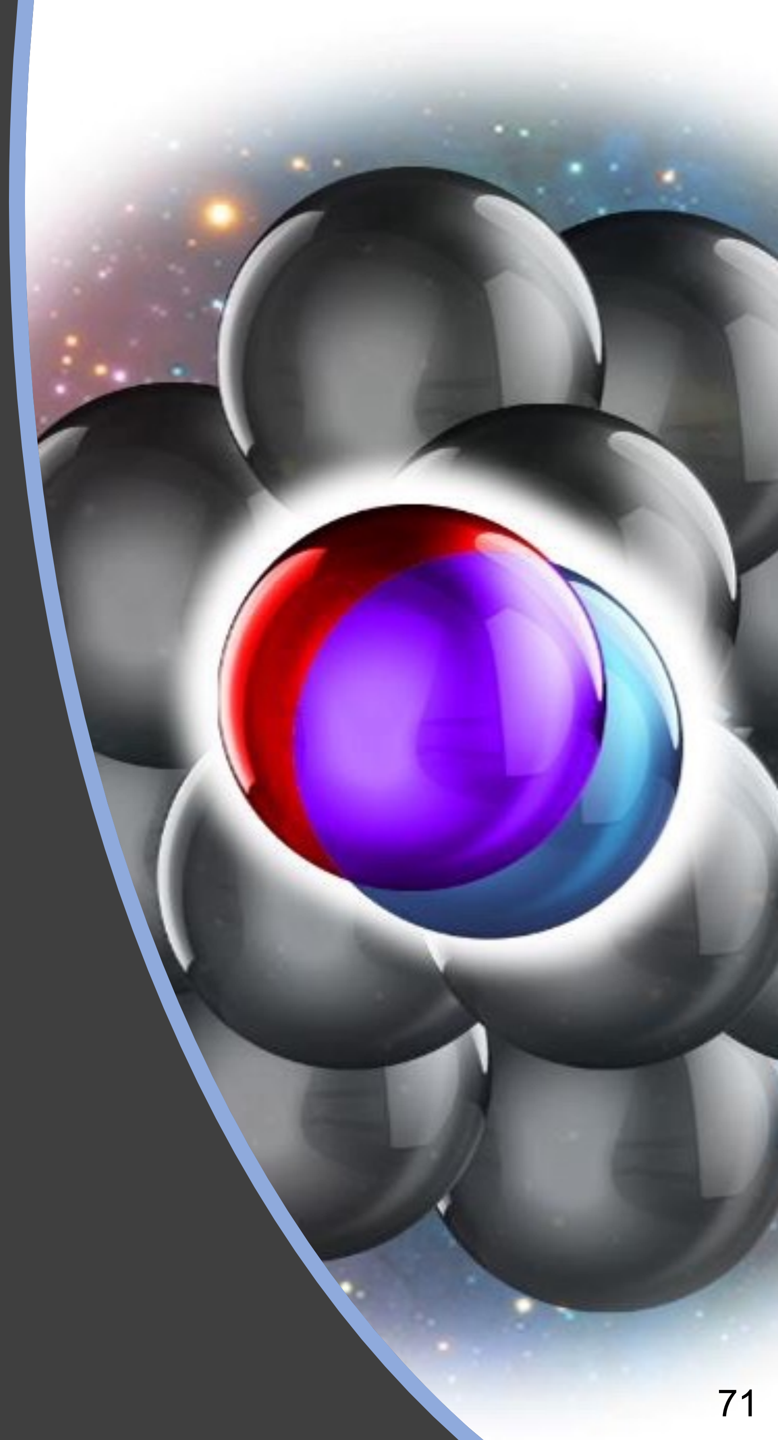
Probing SRCs



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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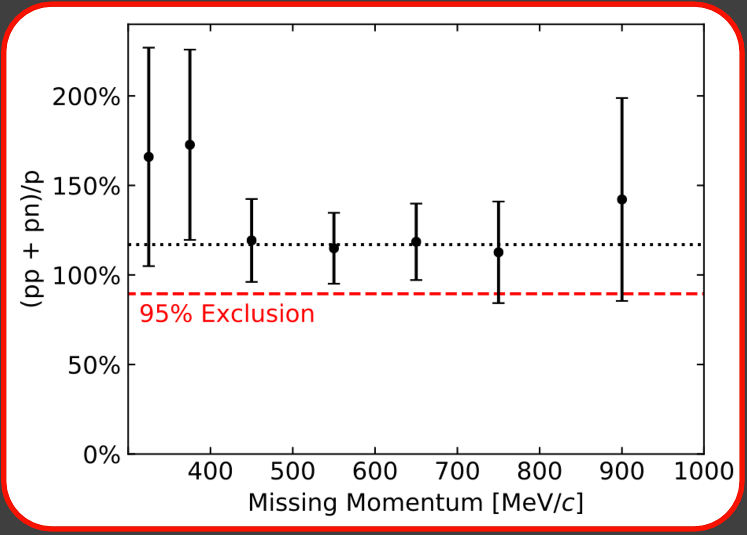

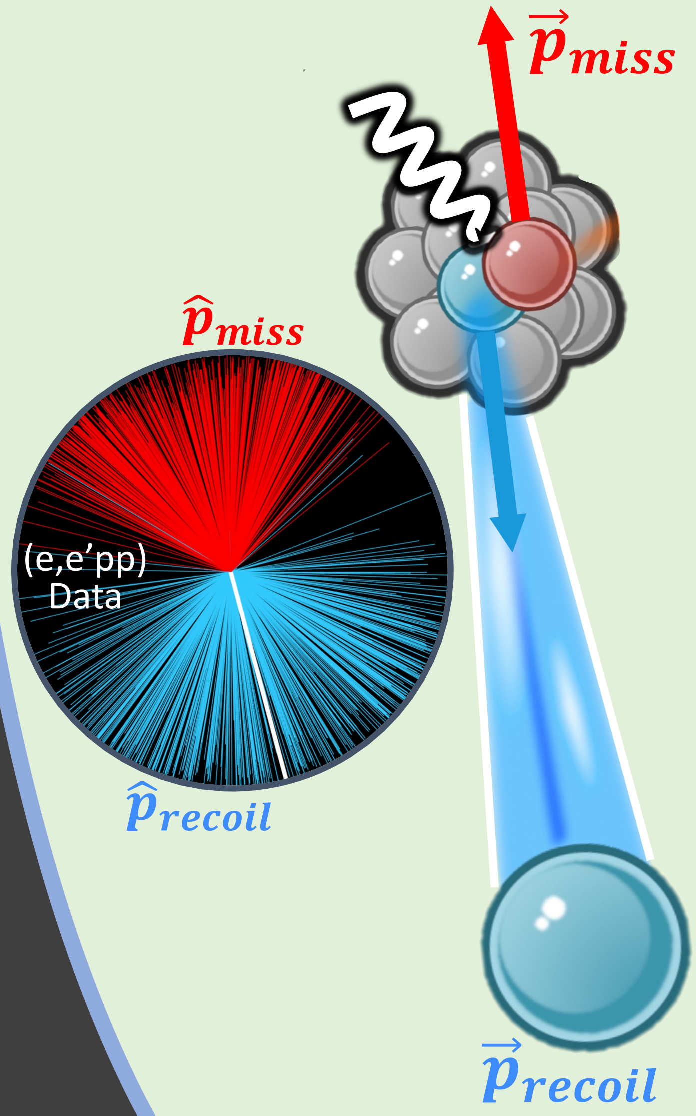

Hen et al., Science (2014)

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

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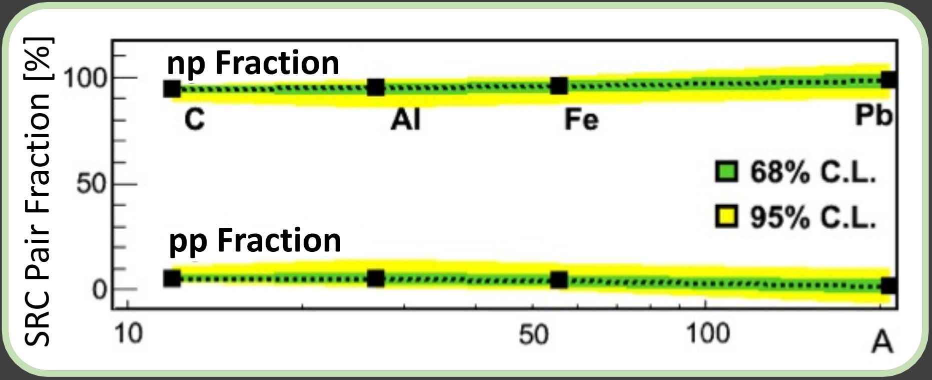

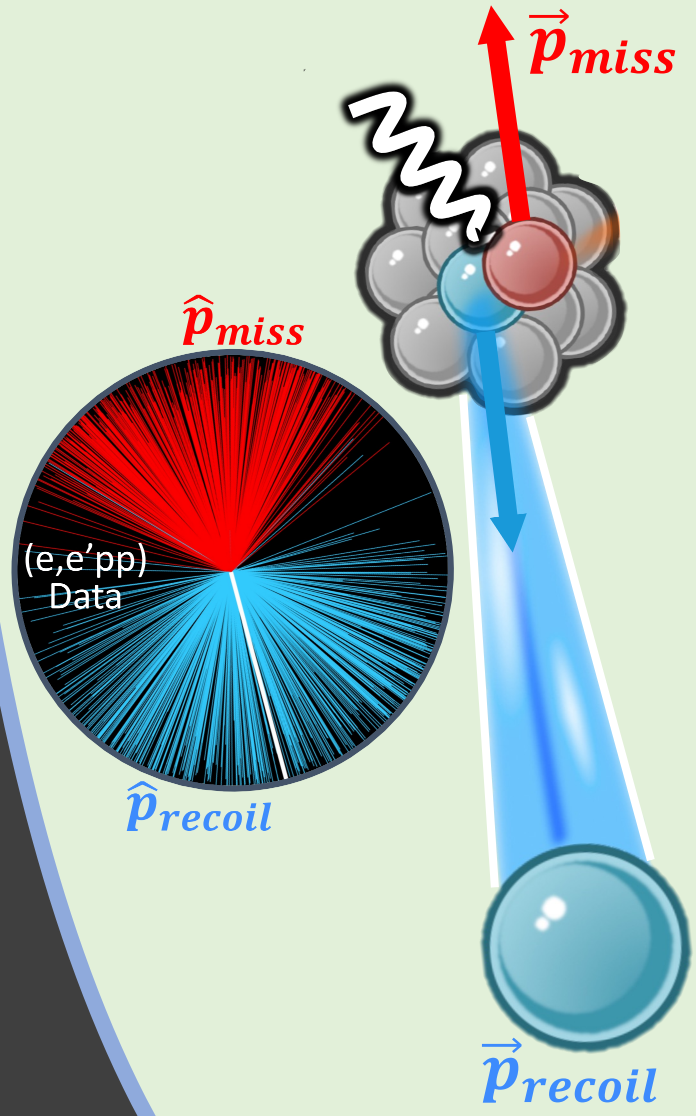

Korover PLB '21; Duer PRL '19; Duer Nature '18; Hen Science '14; Korover PRL '14; Subedi Science '08; Shneor PRL '07; Piasetzky PRL '06; Tang PRL '03; Review: Hen RMP '17

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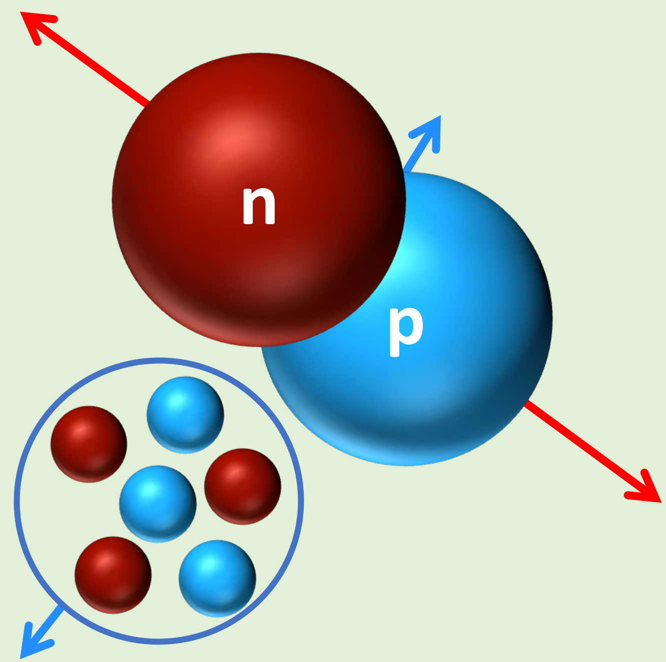

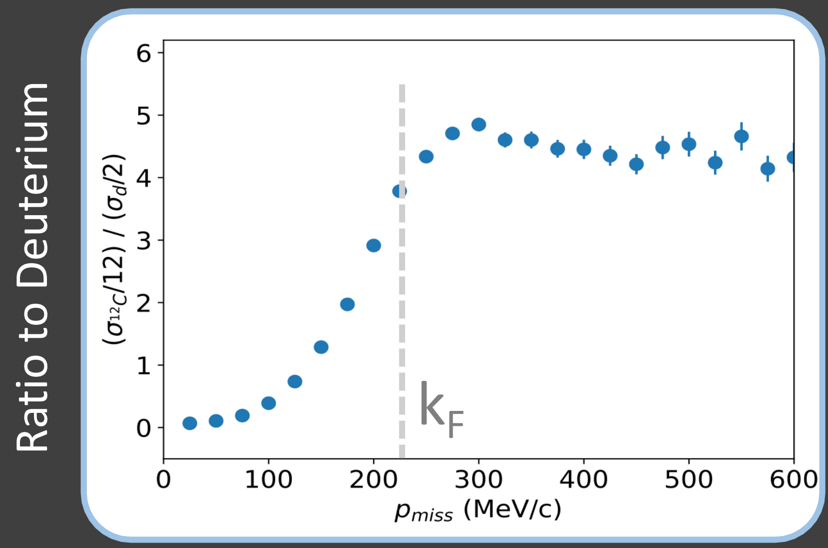

Korover and Denniston et al., Submitted (2022)

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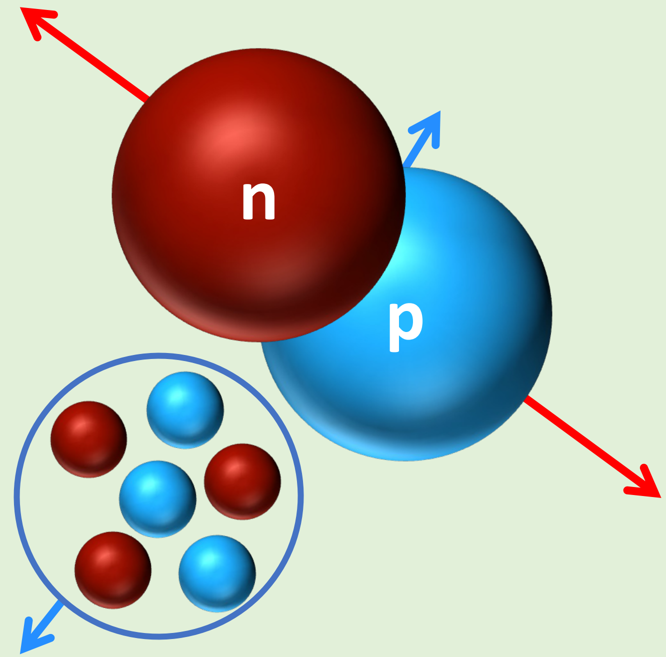

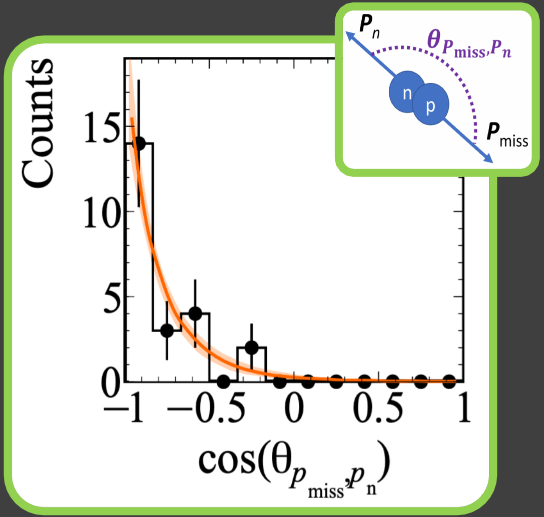

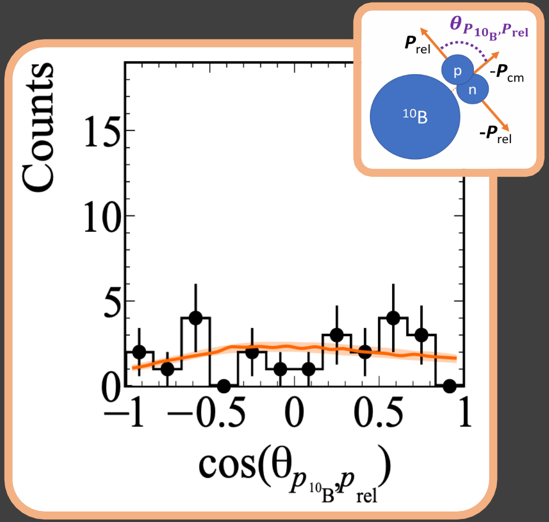

Theory:

Cruz-Torres+, Nature Physics (2020)

Weiss+, Phys. Rev. C (2015)

Weiss+, Phys. Lett. B (2018)

Lynn+, J. Phys. G (2020)

Chen+, Phys. Rev. Lett. (2017)

…

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

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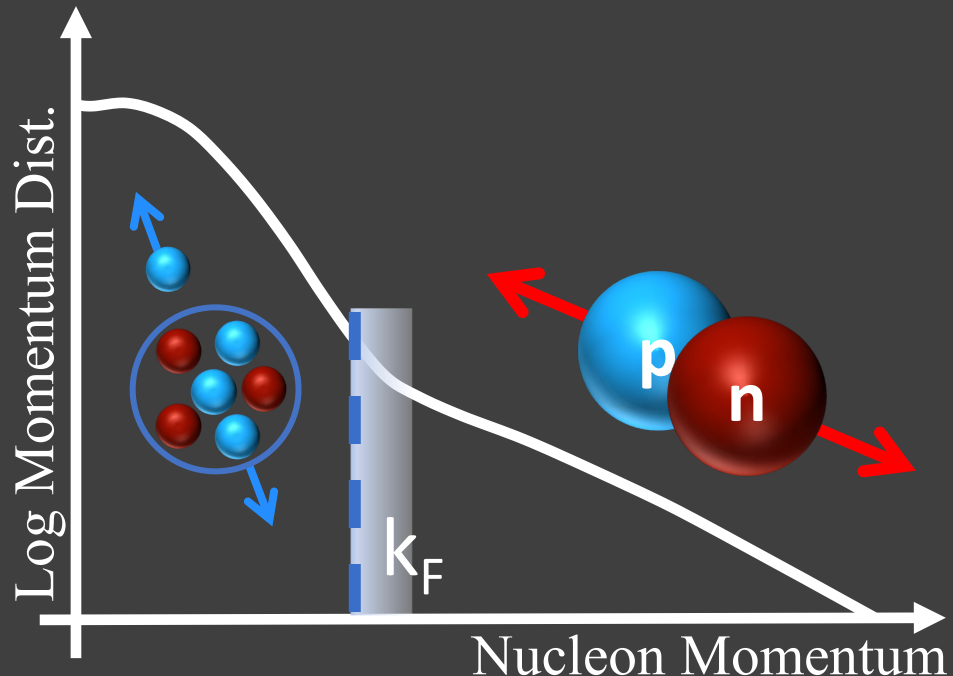


Isospin Structure:

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)

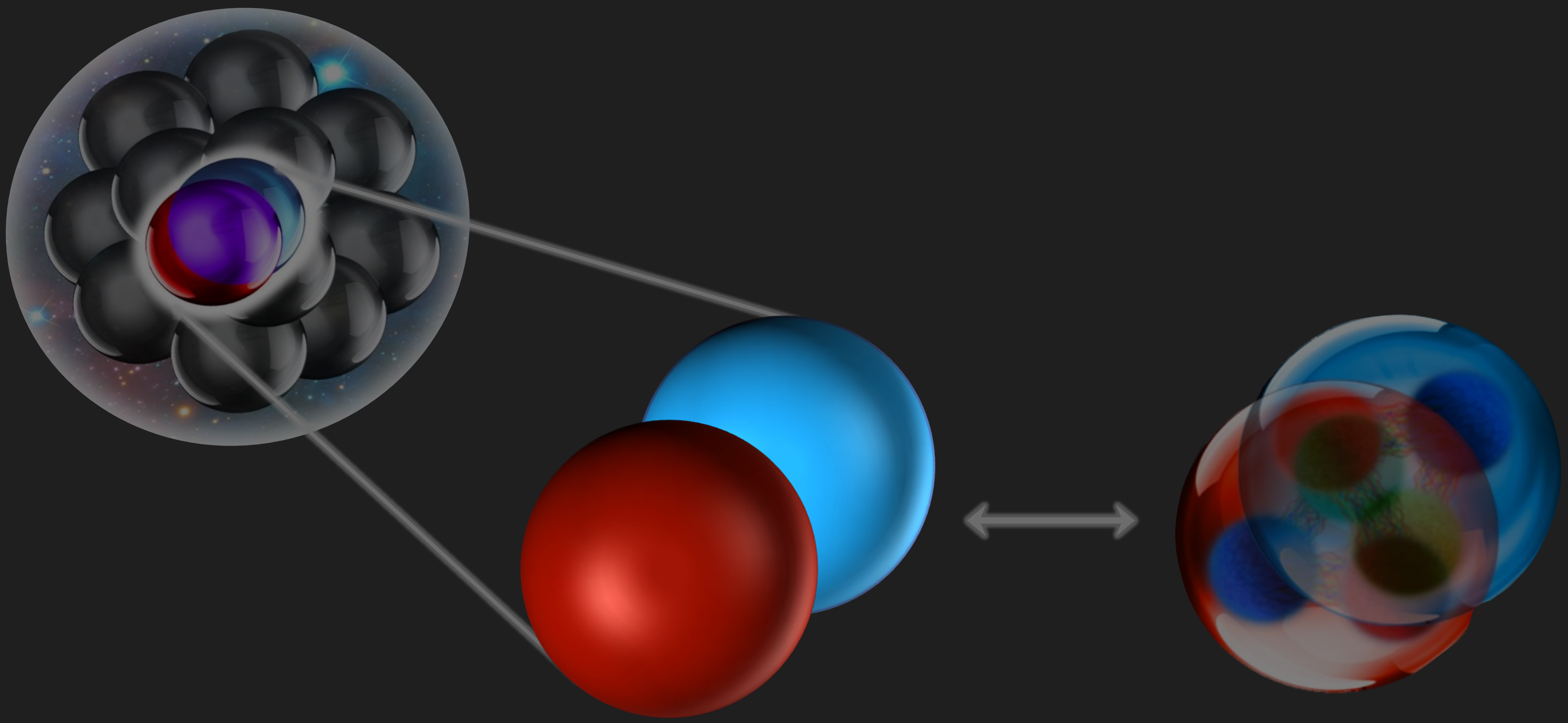
Effective Theory:

Nature Physics 17, 306 (2021)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 791, 242 (2019)

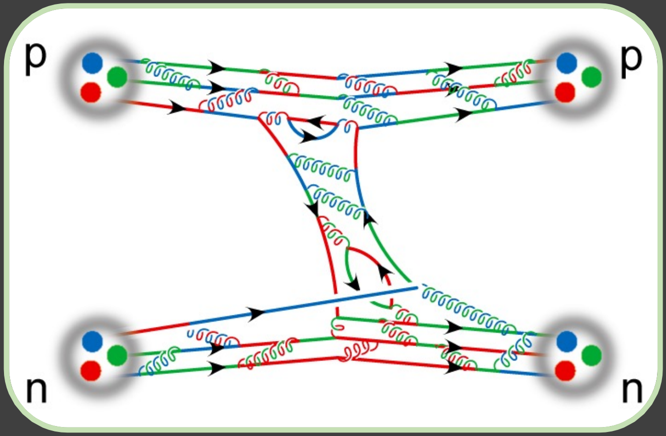
Quantum Numbers, Mass, Asymmetry Dependence:

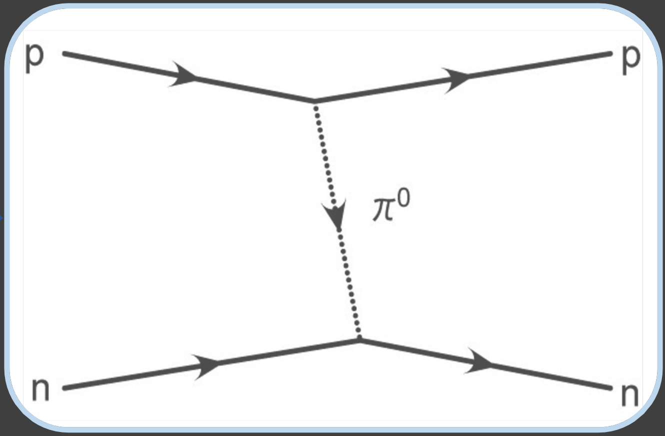
Phys. Rev. C 103, L031301 (2021)
Phys. Lett. B 780, 211 (2018)
PRC 92, 024604 (2015)
PRC 92, 045205 (2015)

Probing the NN interaction



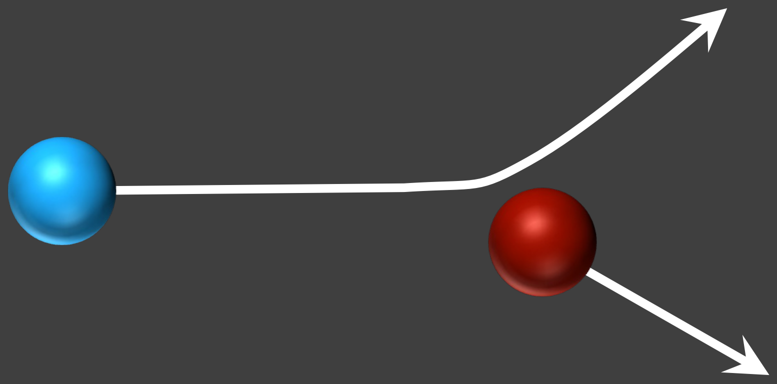
Effective Nucleon-Nucleon Interactions





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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- Model parameters constrained by data*
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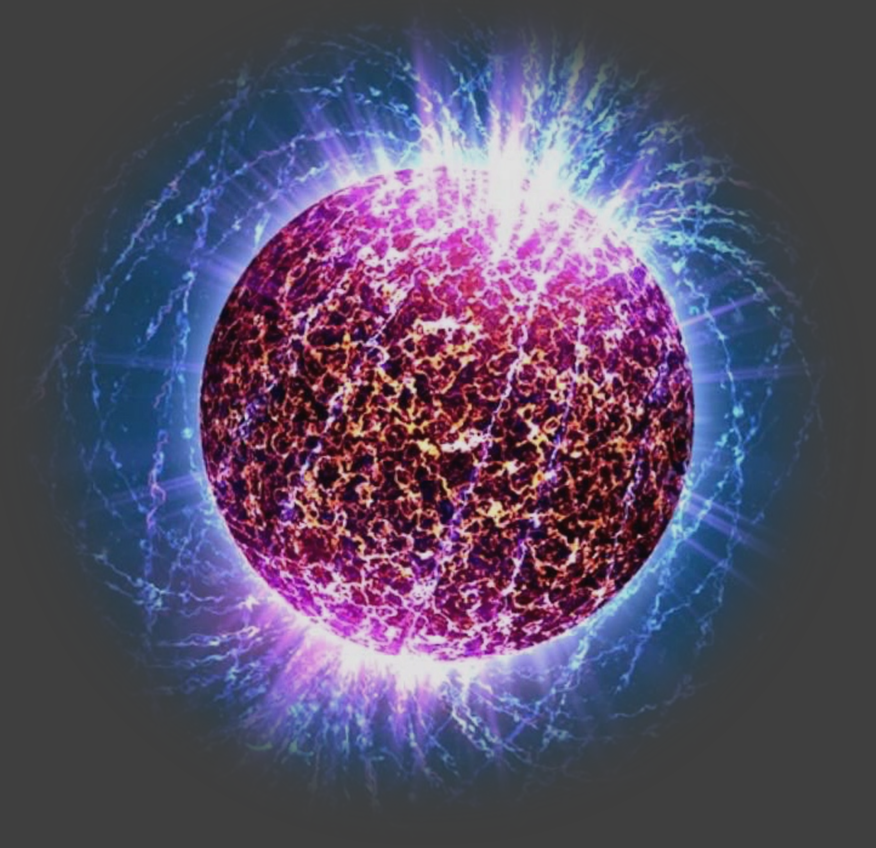
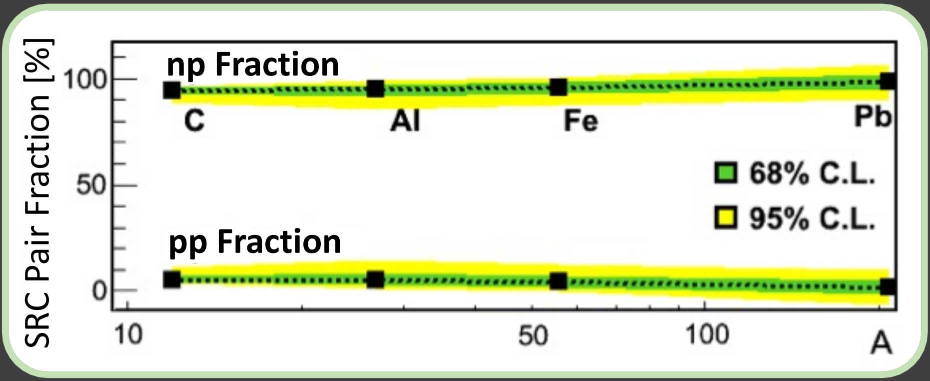


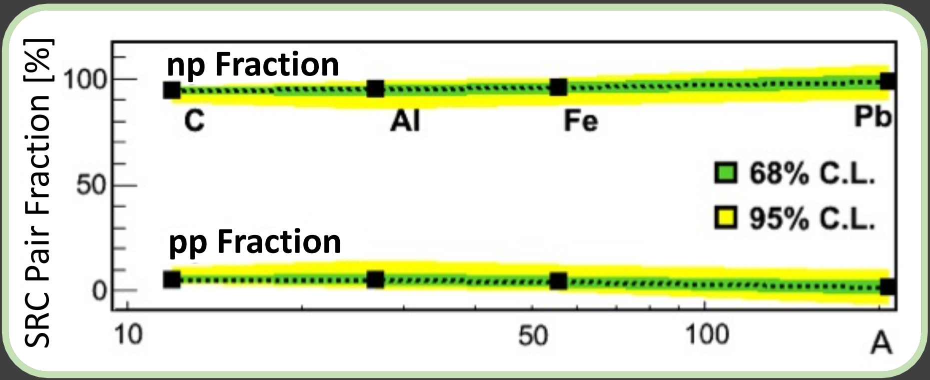
*Recently also lattice QCD

Short-Ranged Interactions

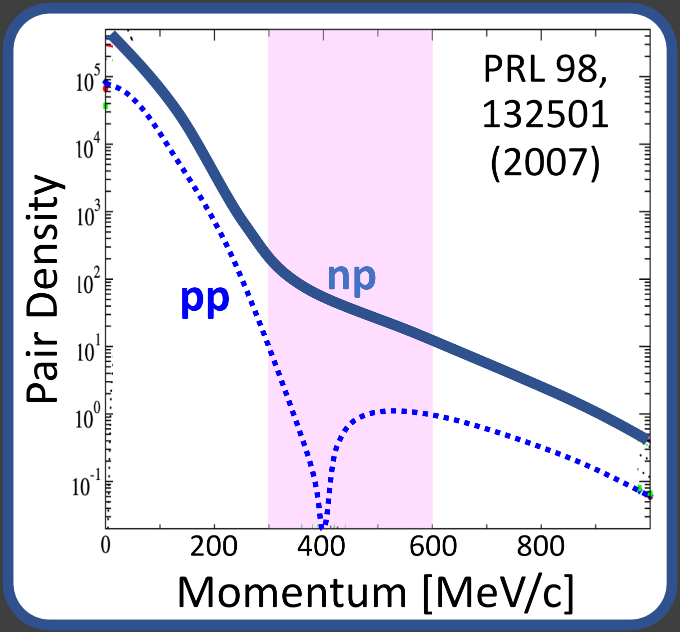


np pairs = Tensor force
dominance
(spin-dependent)

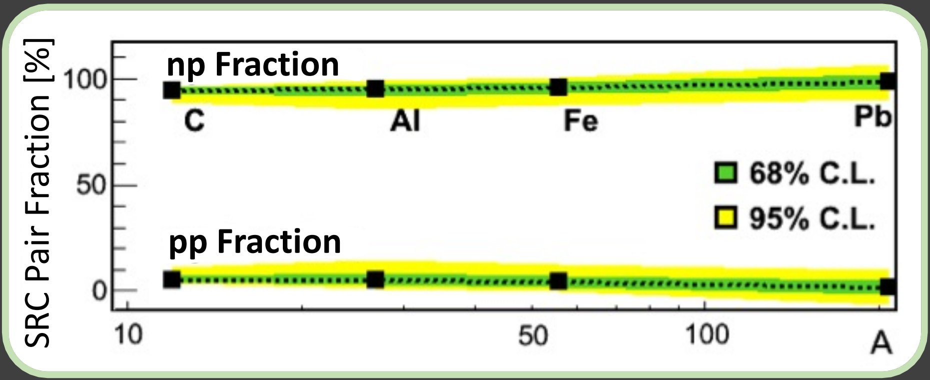
Short-Ranged Interactions



np pairs = Tensor force
dominance
(spin-dependent)



Short-Ranged Interactions



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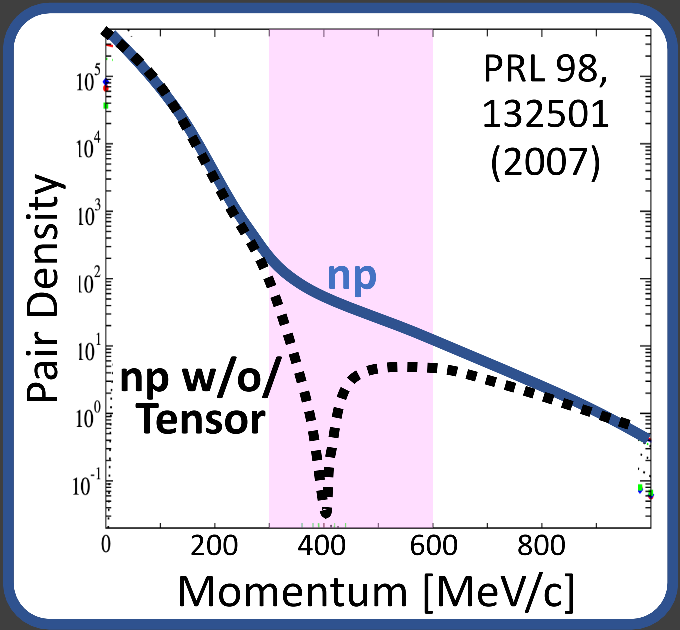
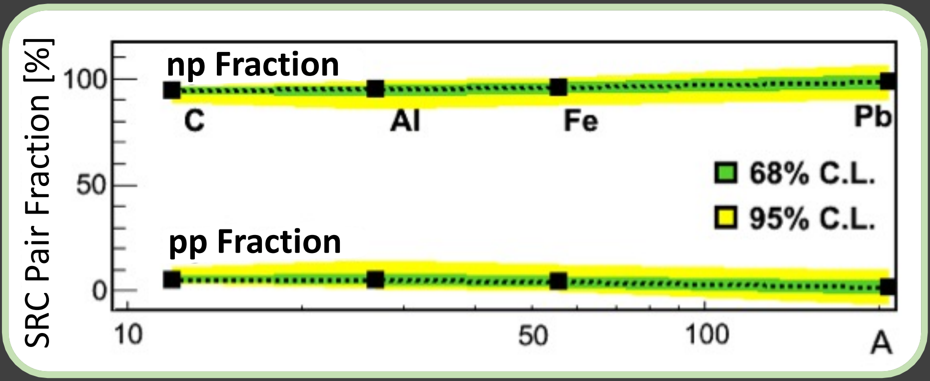
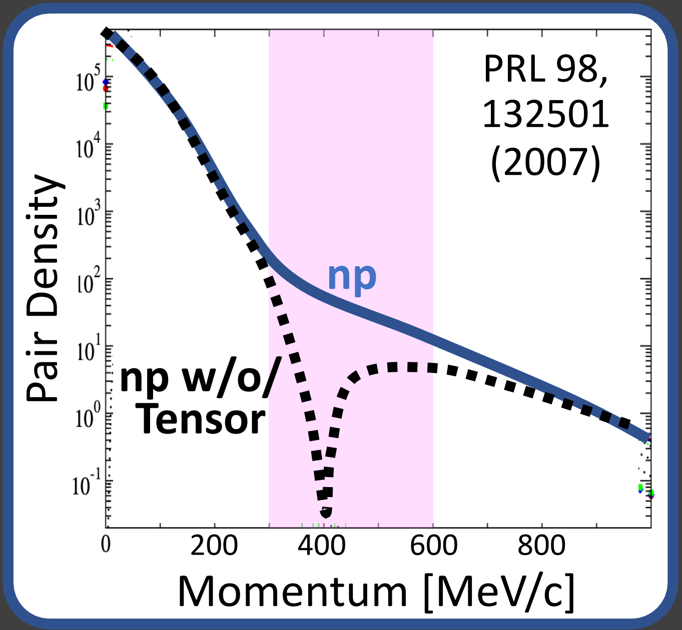
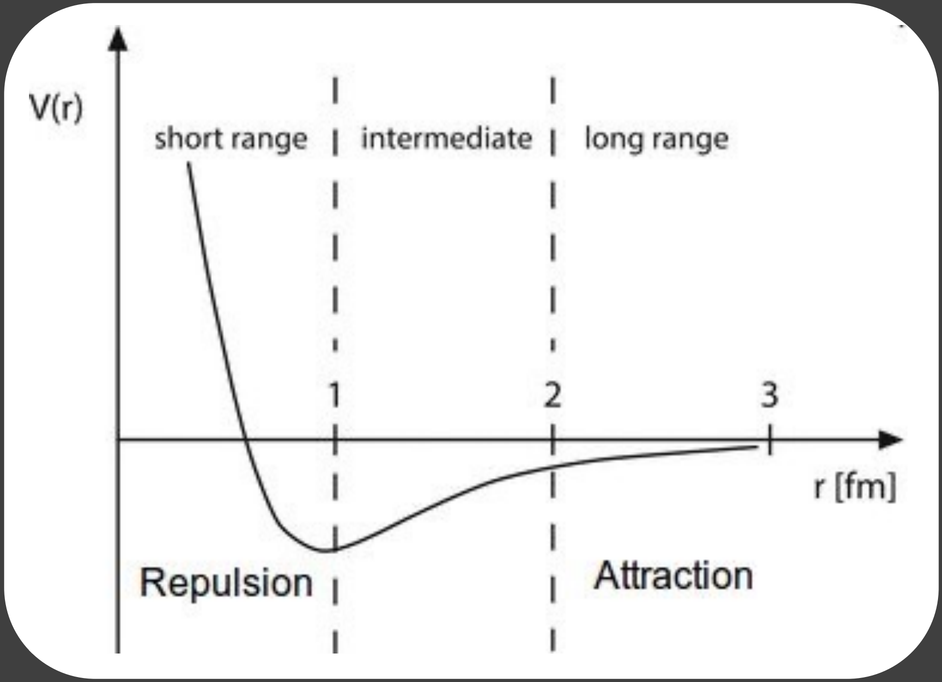


Short-Ranged Interactions

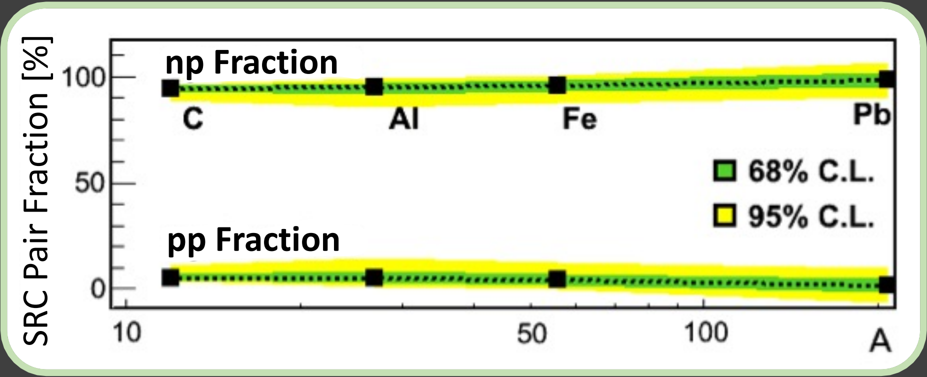


np pairs = Tensor force dominance (spin-dependent)

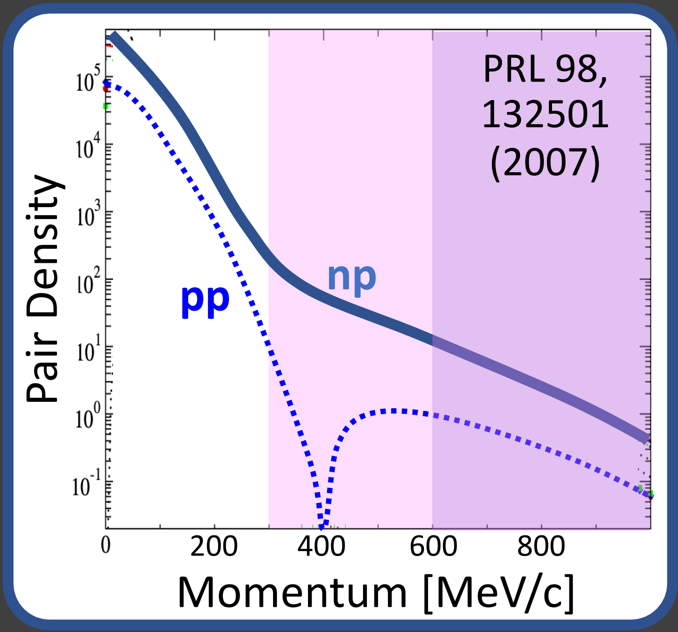




Short-Ranged Interactions



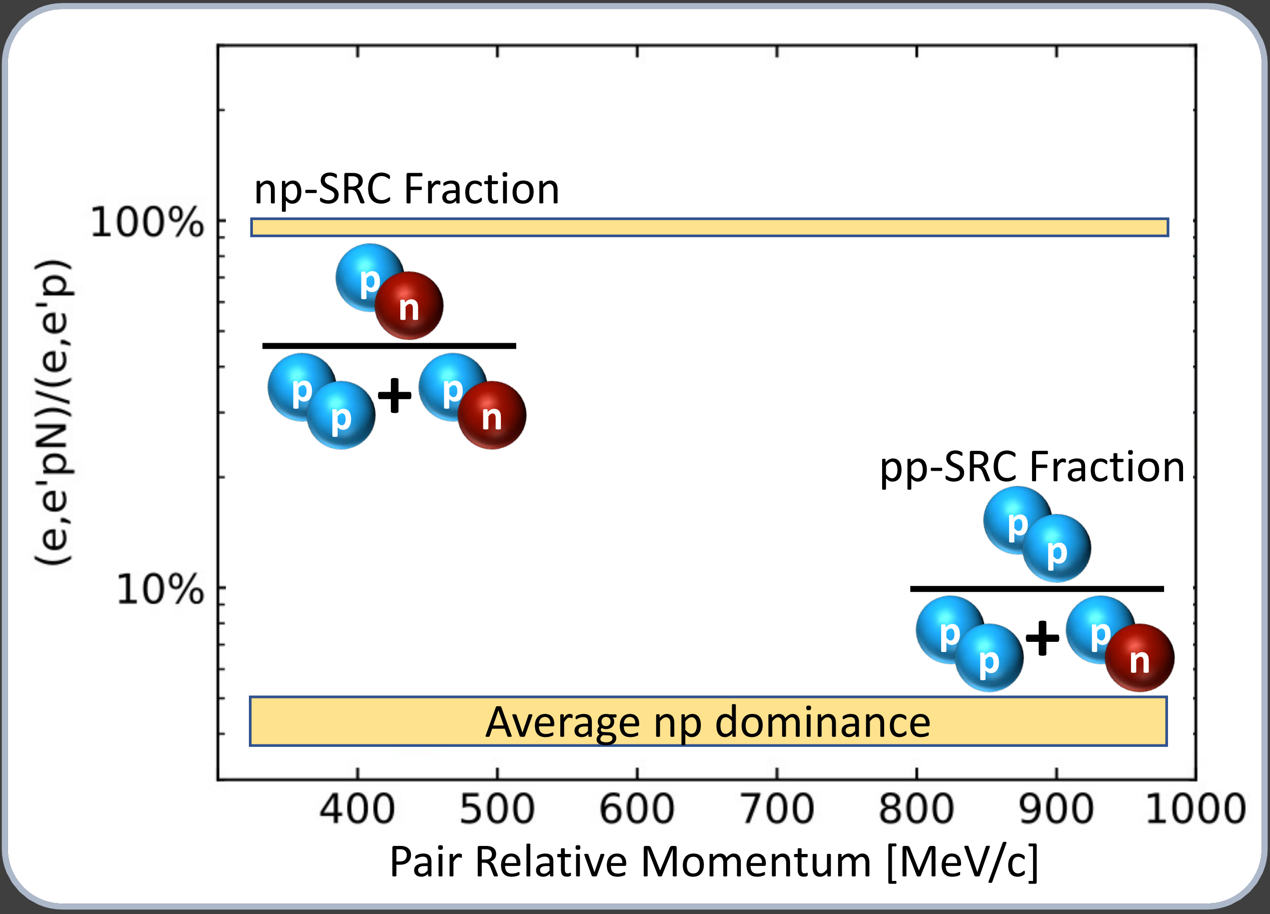
np pairs = Tensor force dominance (spin-dependent)



<u>Repulsive core transition:</u>

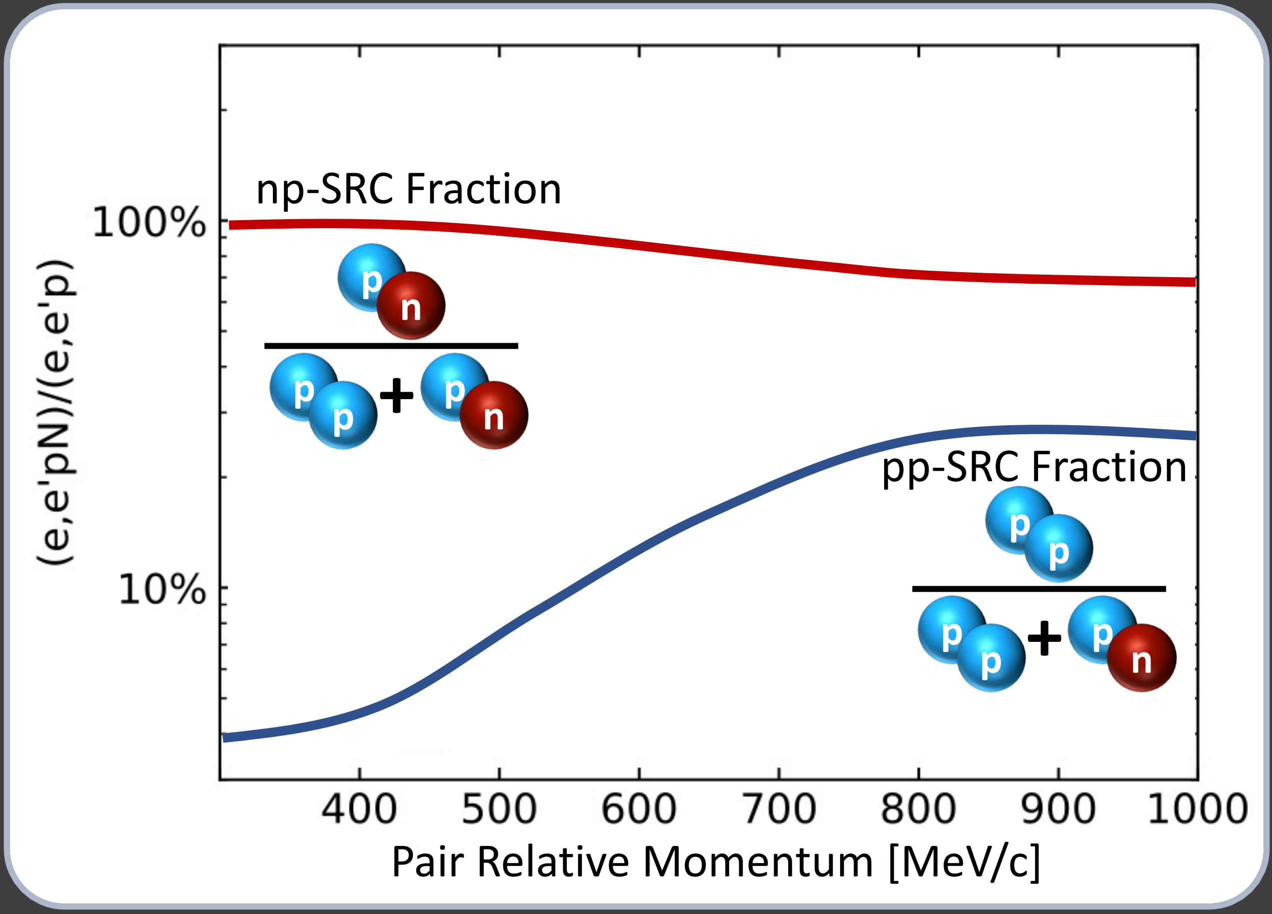
Scalar (spin-independent) core produces more pp pairs

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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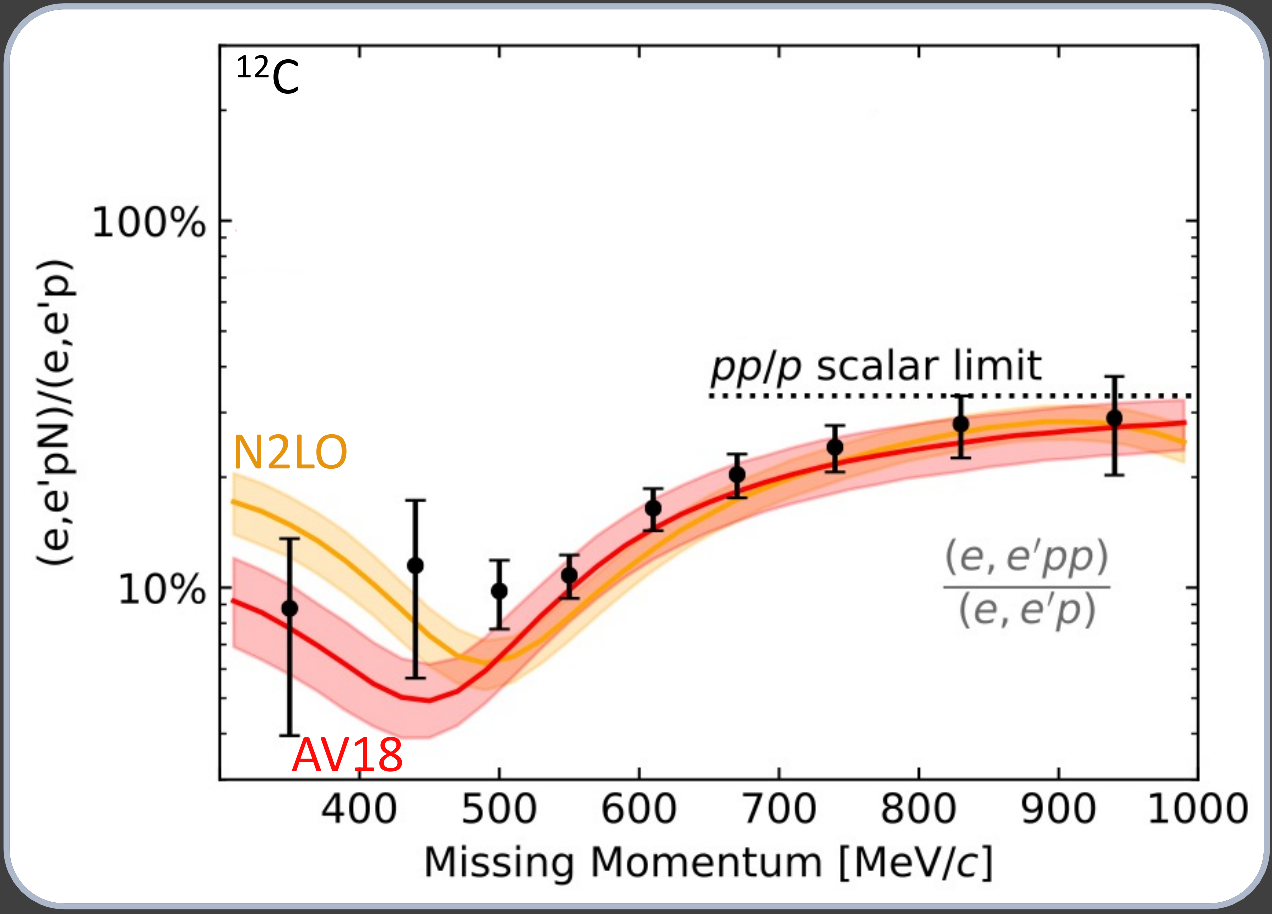

Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

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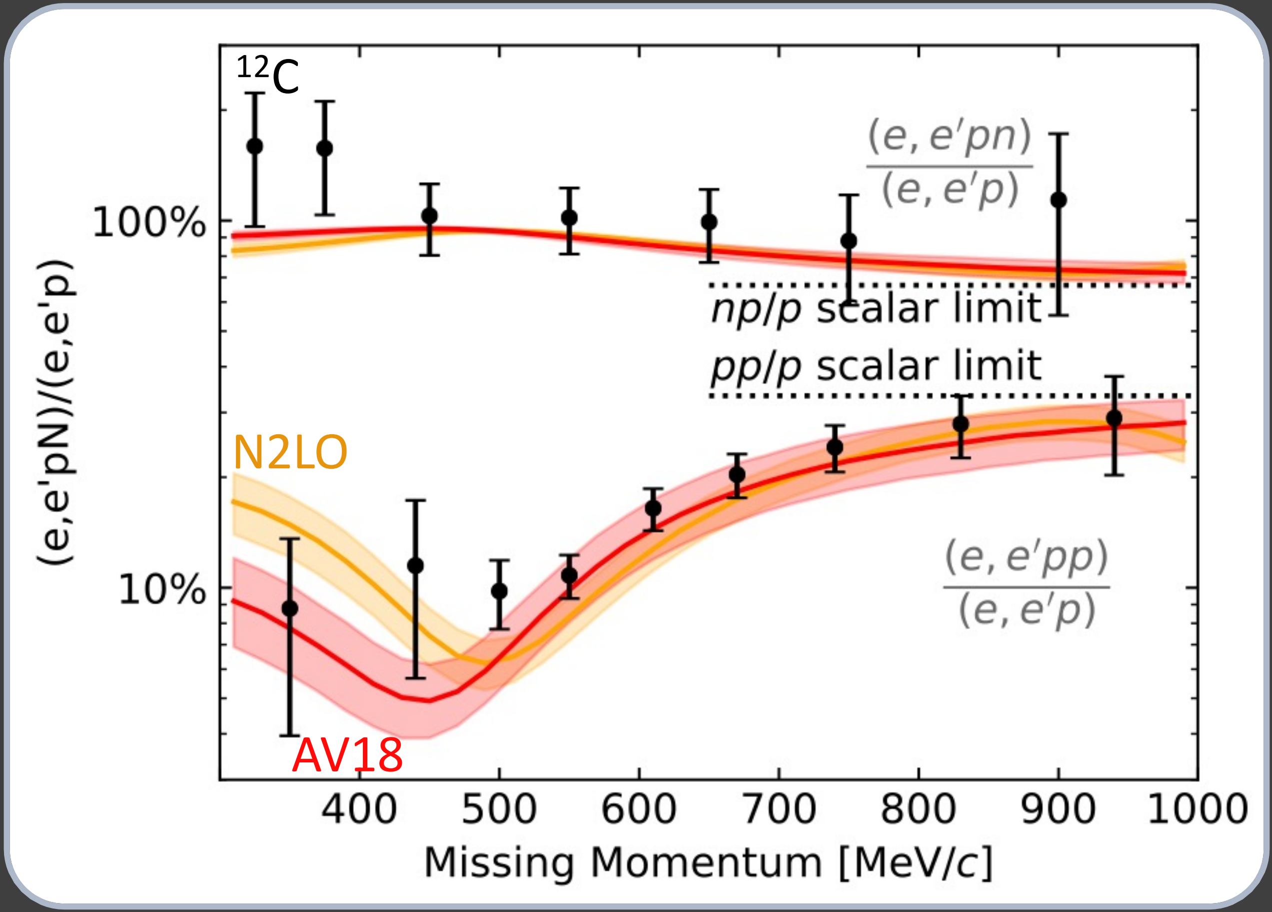
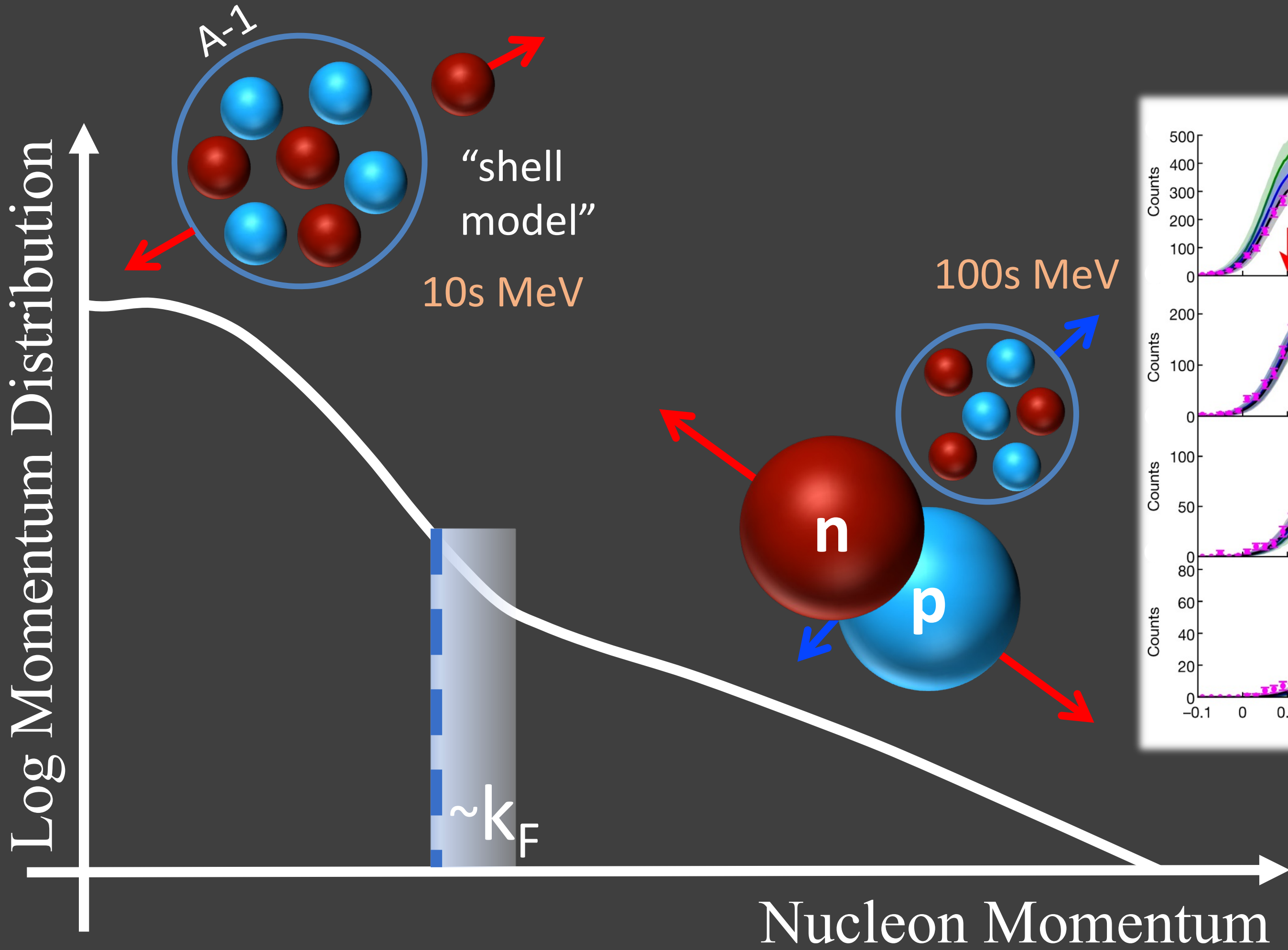
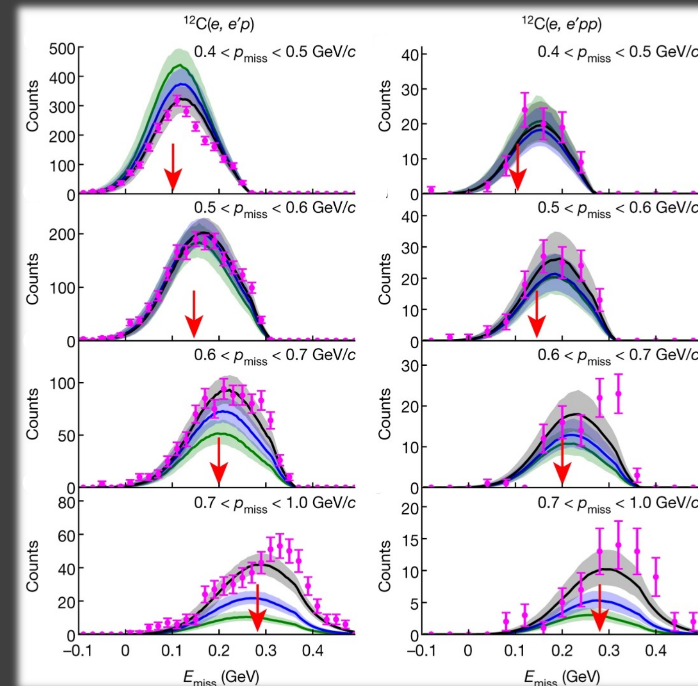




Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)

The Two-Phased Nucleus



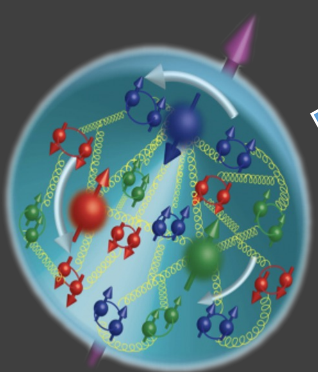


Nature 578, 540 (2020)

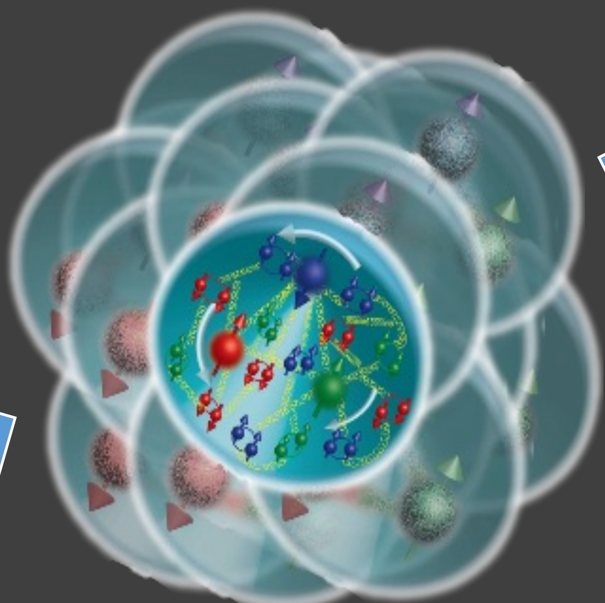
Korover PLB '21; Duer PRL '19; Duer Nature '18; Hen Science '14; Korover PRL '14; Subedi Science '08; Shneor PRL '07; Piasetzky PRL '06; Tang PRL '03; Review: Hen RMP '17

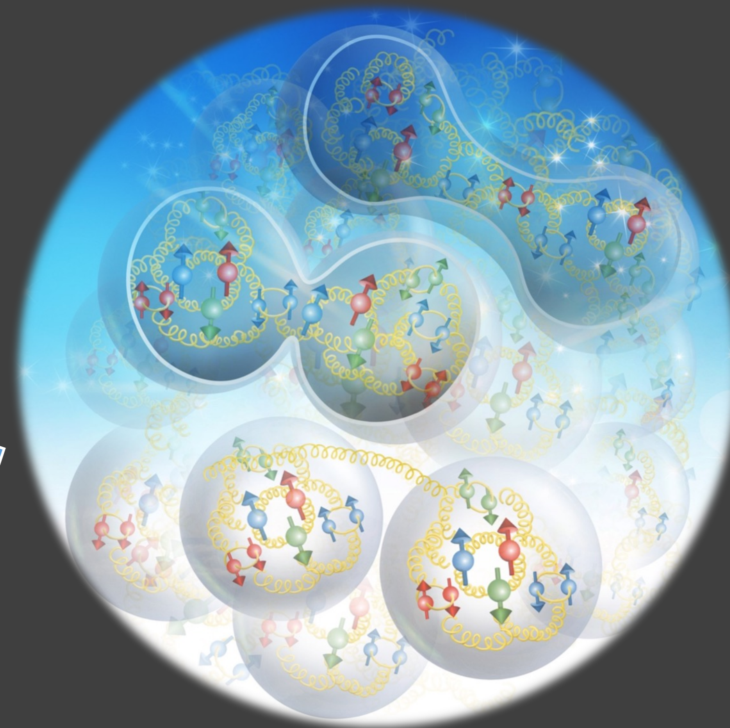
Do QCD dynamics affect the identity of protons and neutrons in nuclei?

The Proton

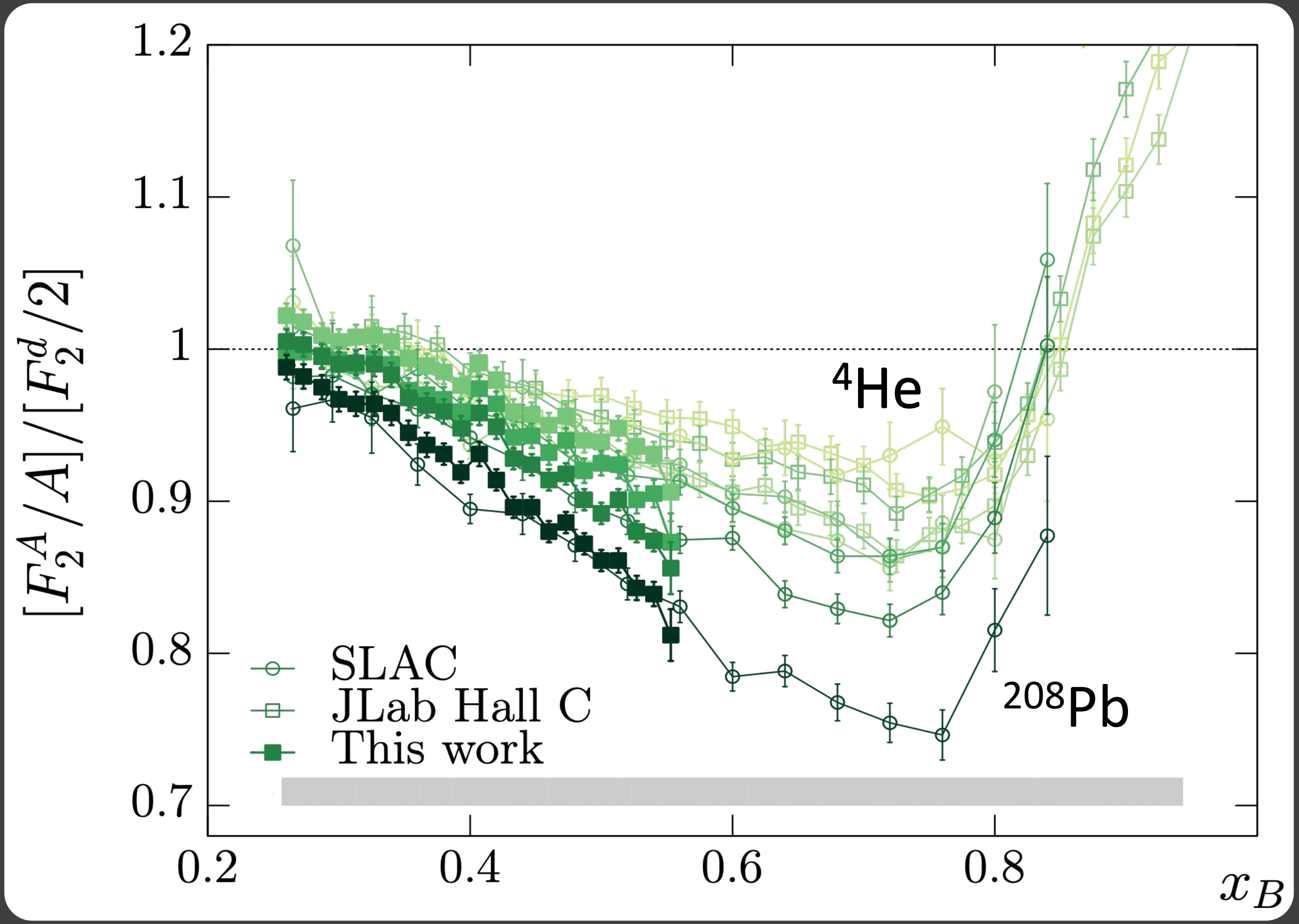


The Proton in a nucleus





Quark Momentum Suppression in Nuclei (EMC Effect)

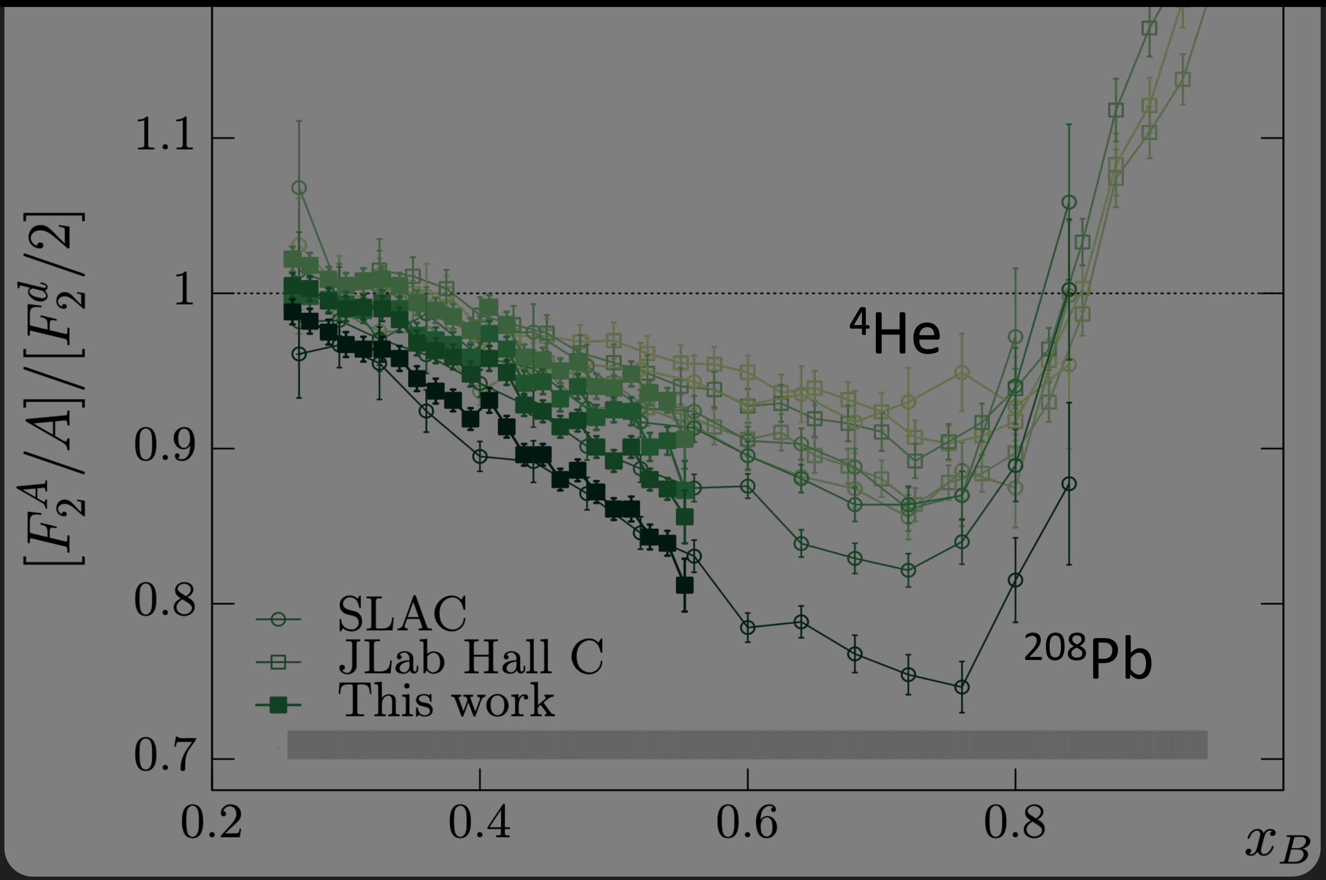


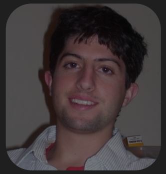
x_B = quark momentum fraction

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

40 years, > 1000 publications, no consensus.





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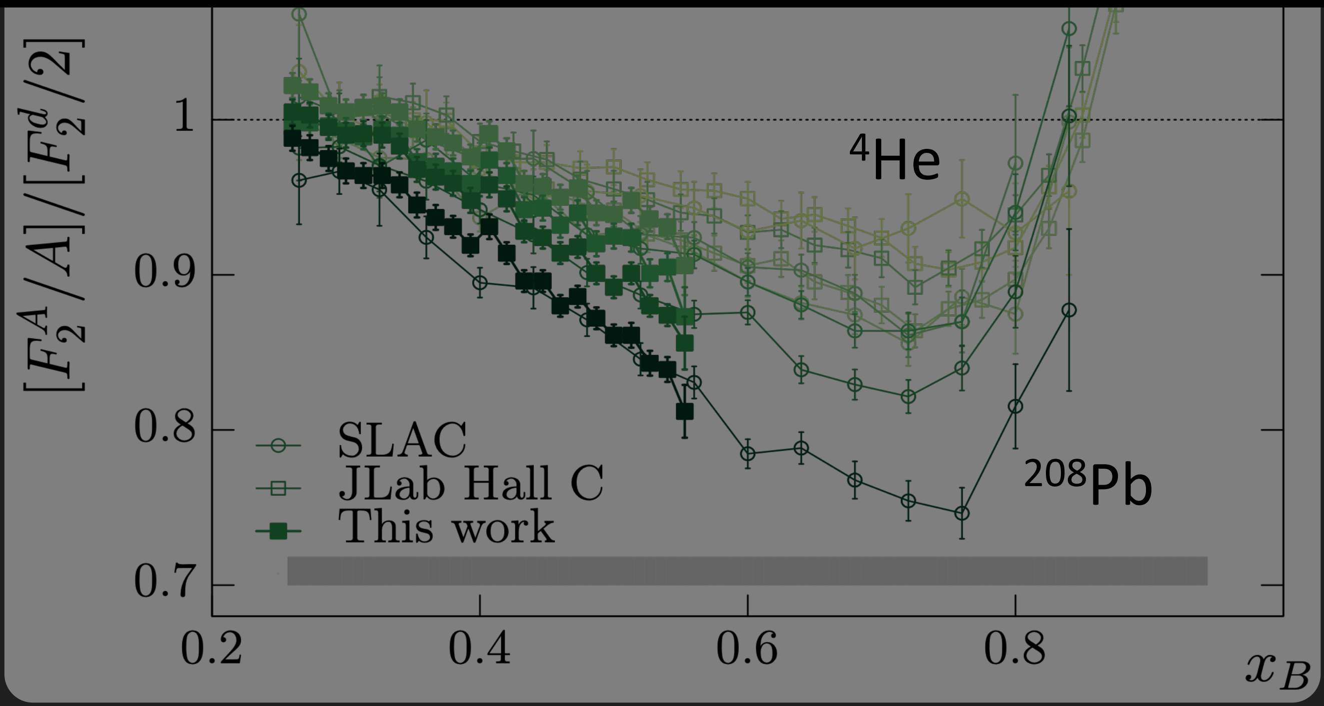
But, effect clearly driven by nuclear dynamics



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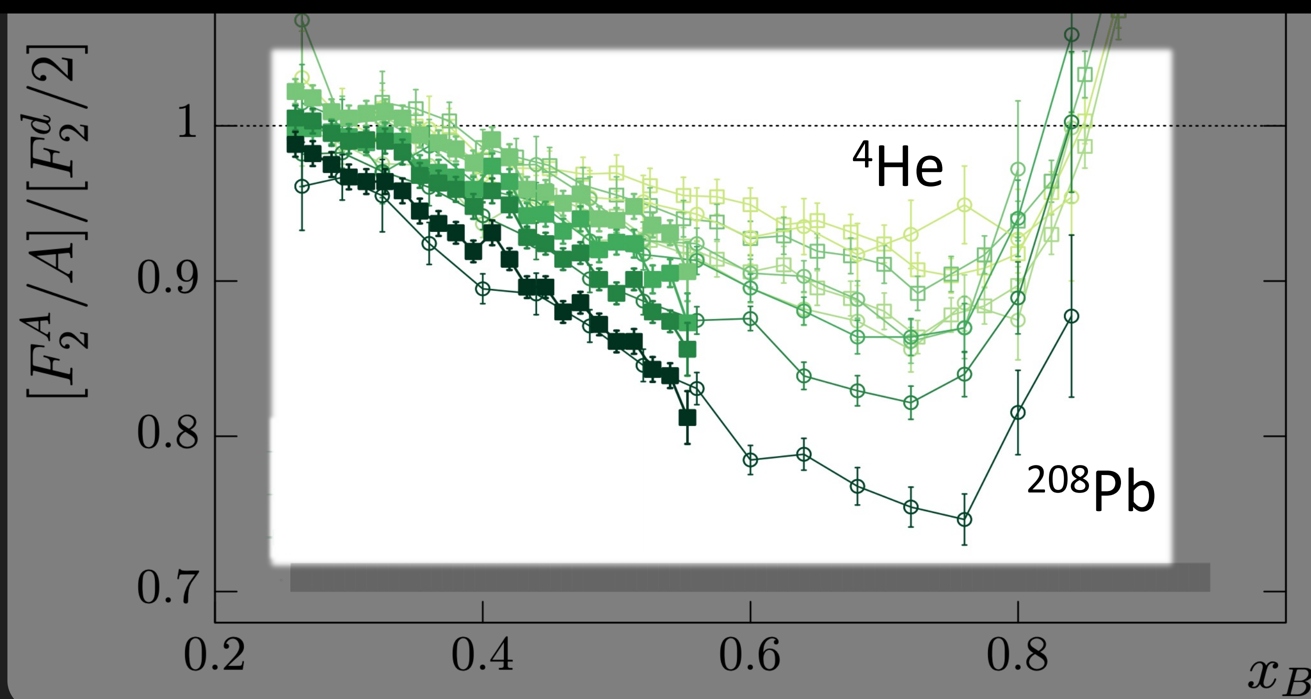

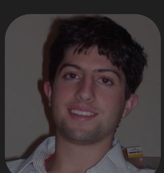

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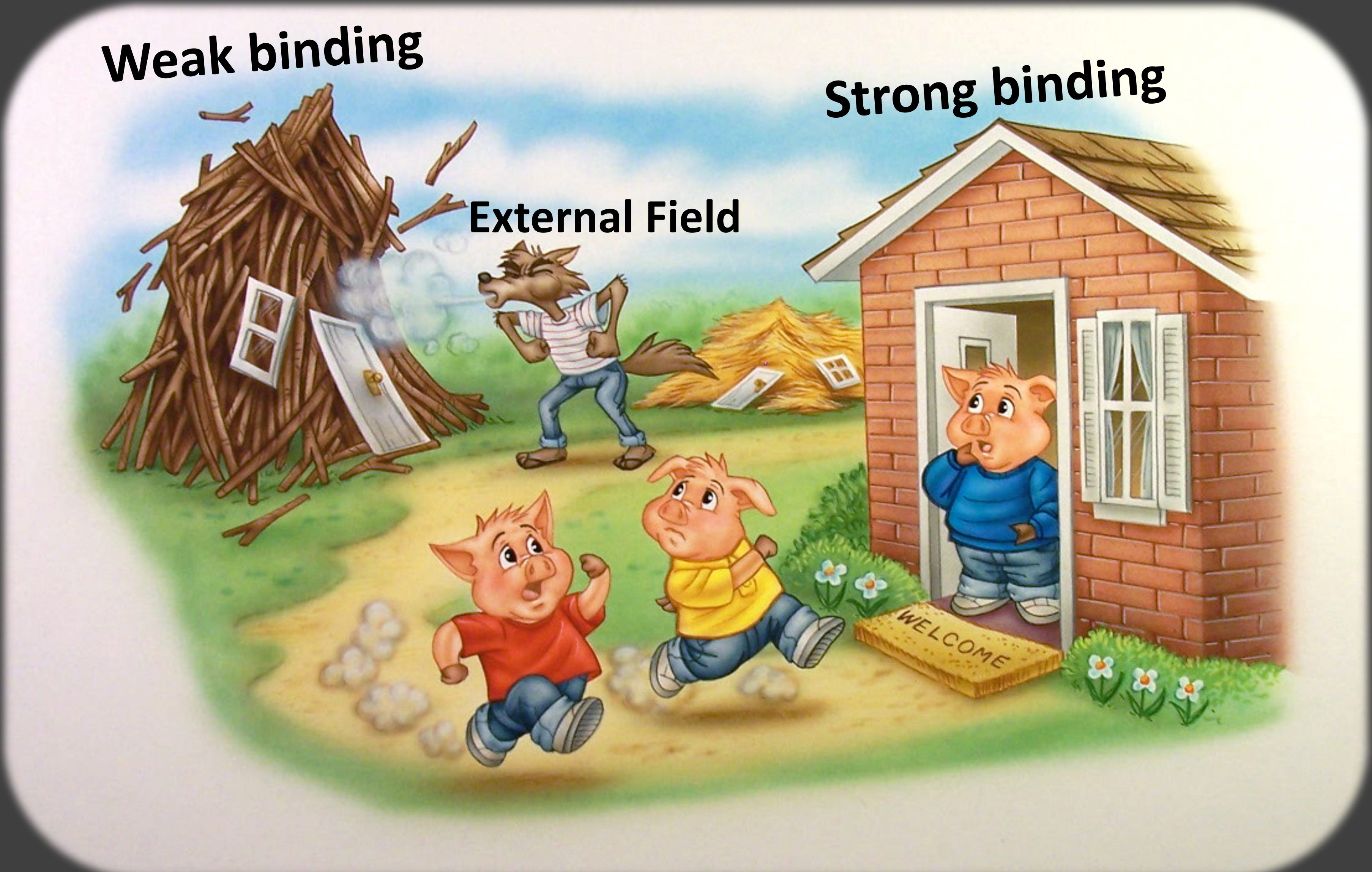
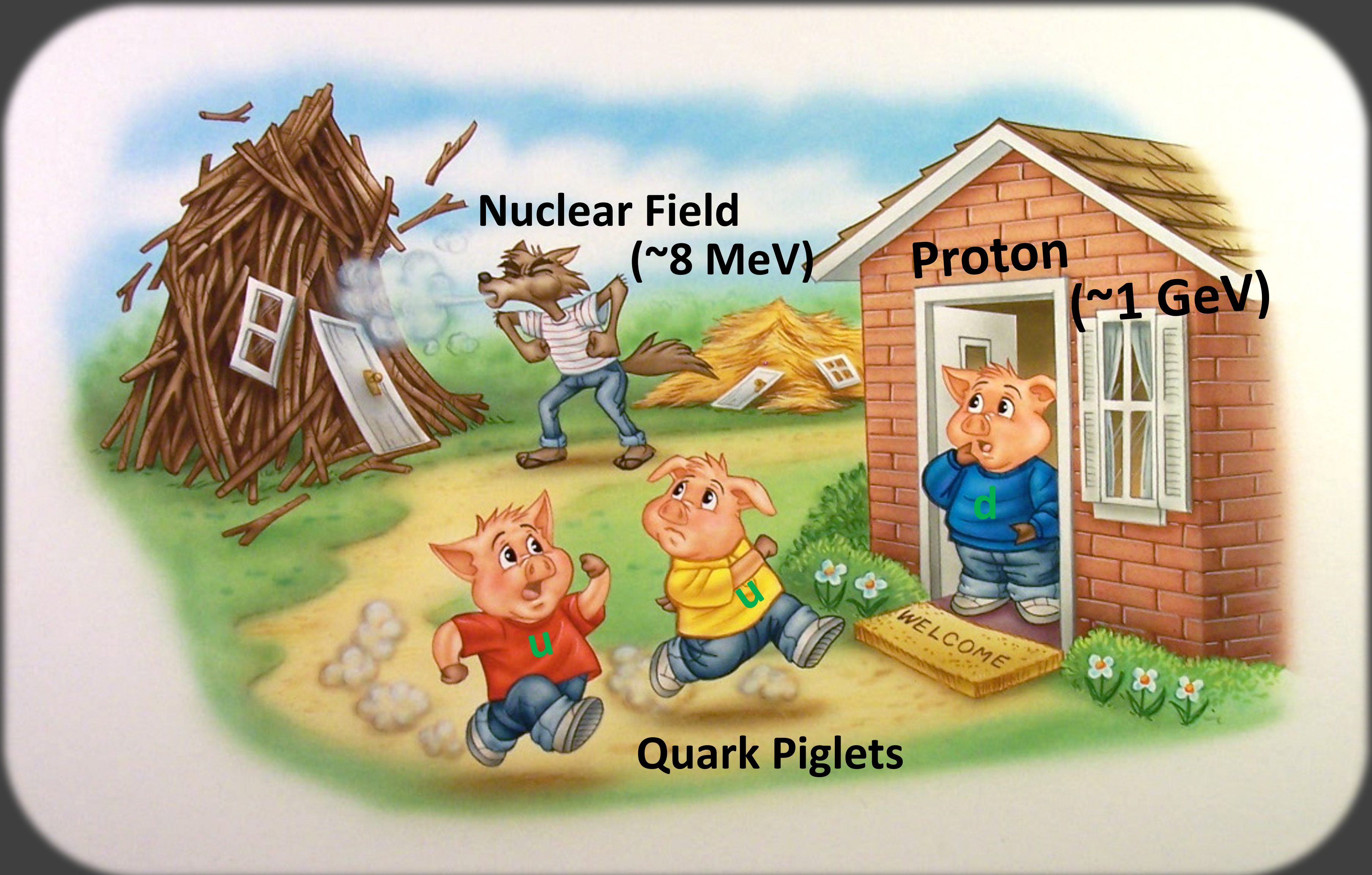
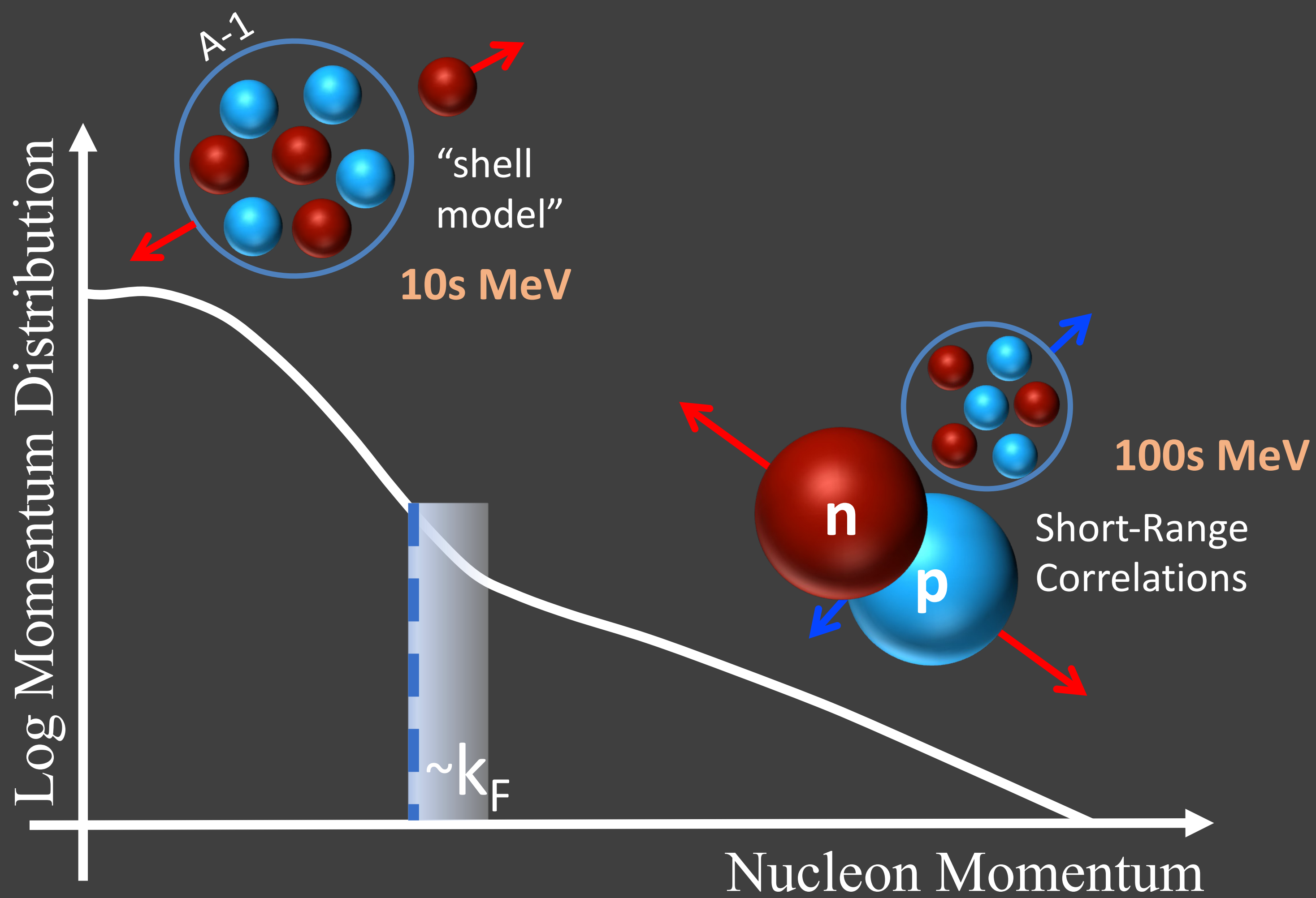
Quarks and Nuclear Structure: A Tale of Scale Separation and Confinement


WELCOME


Weak binding
Strong binding
External Field
WELCOME


Nuclear Field
(~8 MeV)
Proton
(~1 GeV)
d
u
u
WELCOME
Quark Piglets

The Two-Phased Nucleus



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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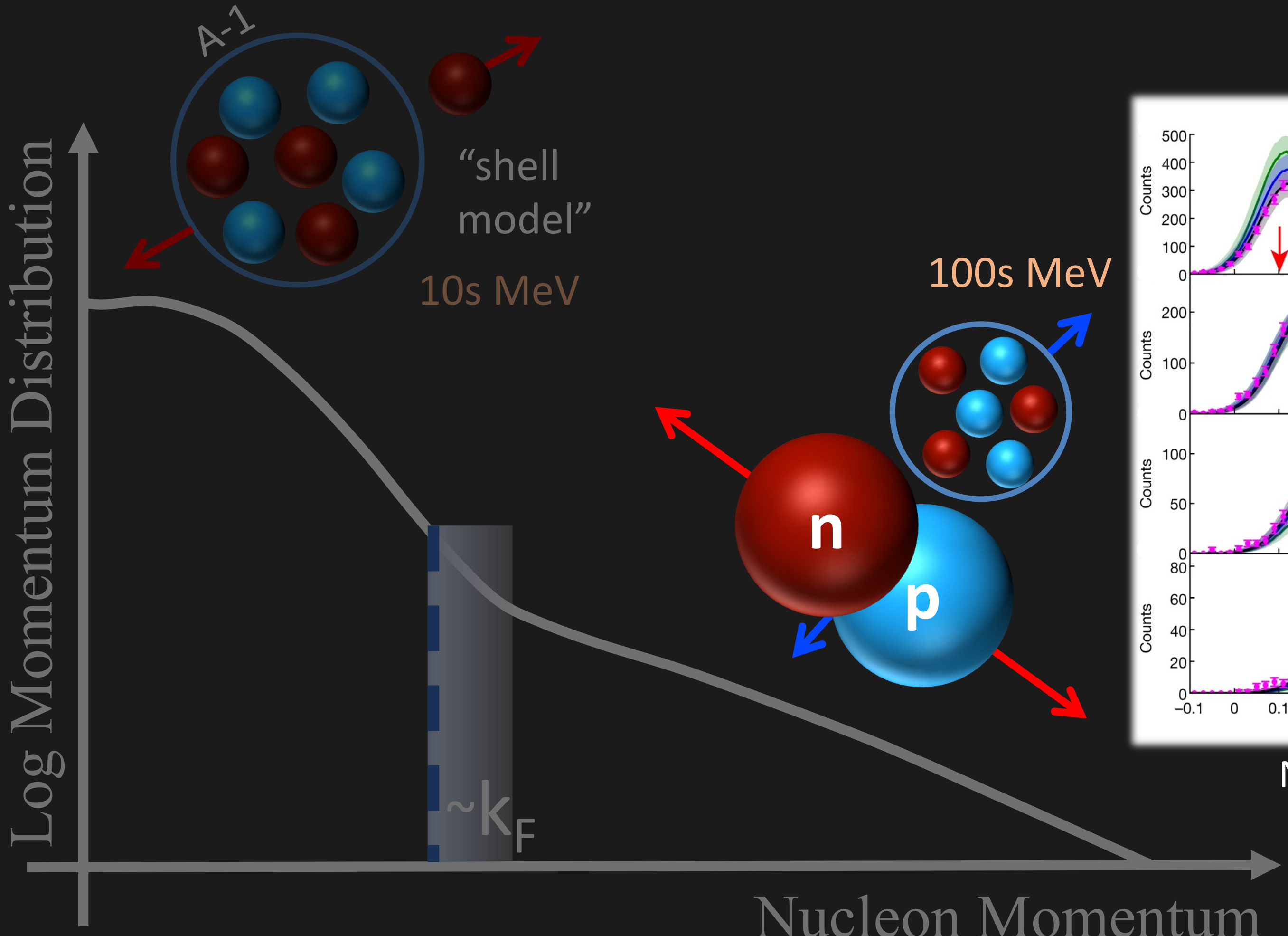

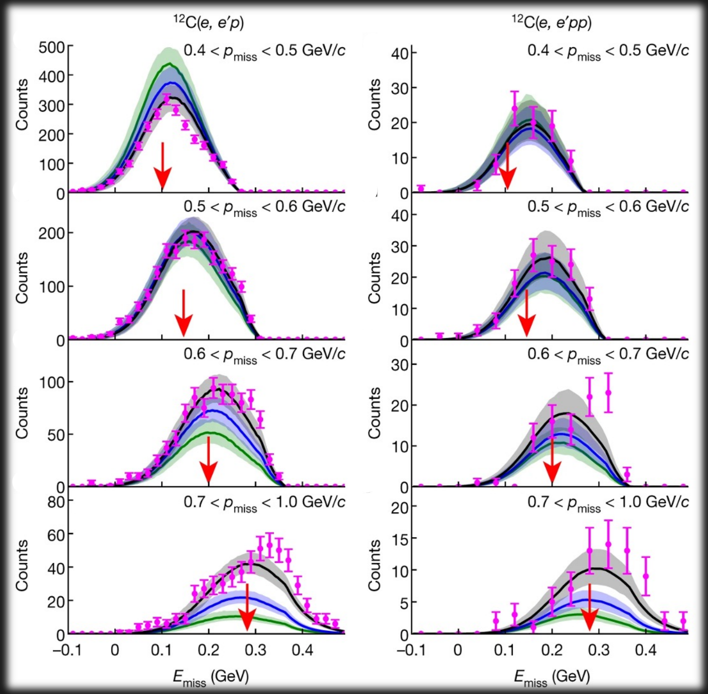

Nature 578, 540 (2020)

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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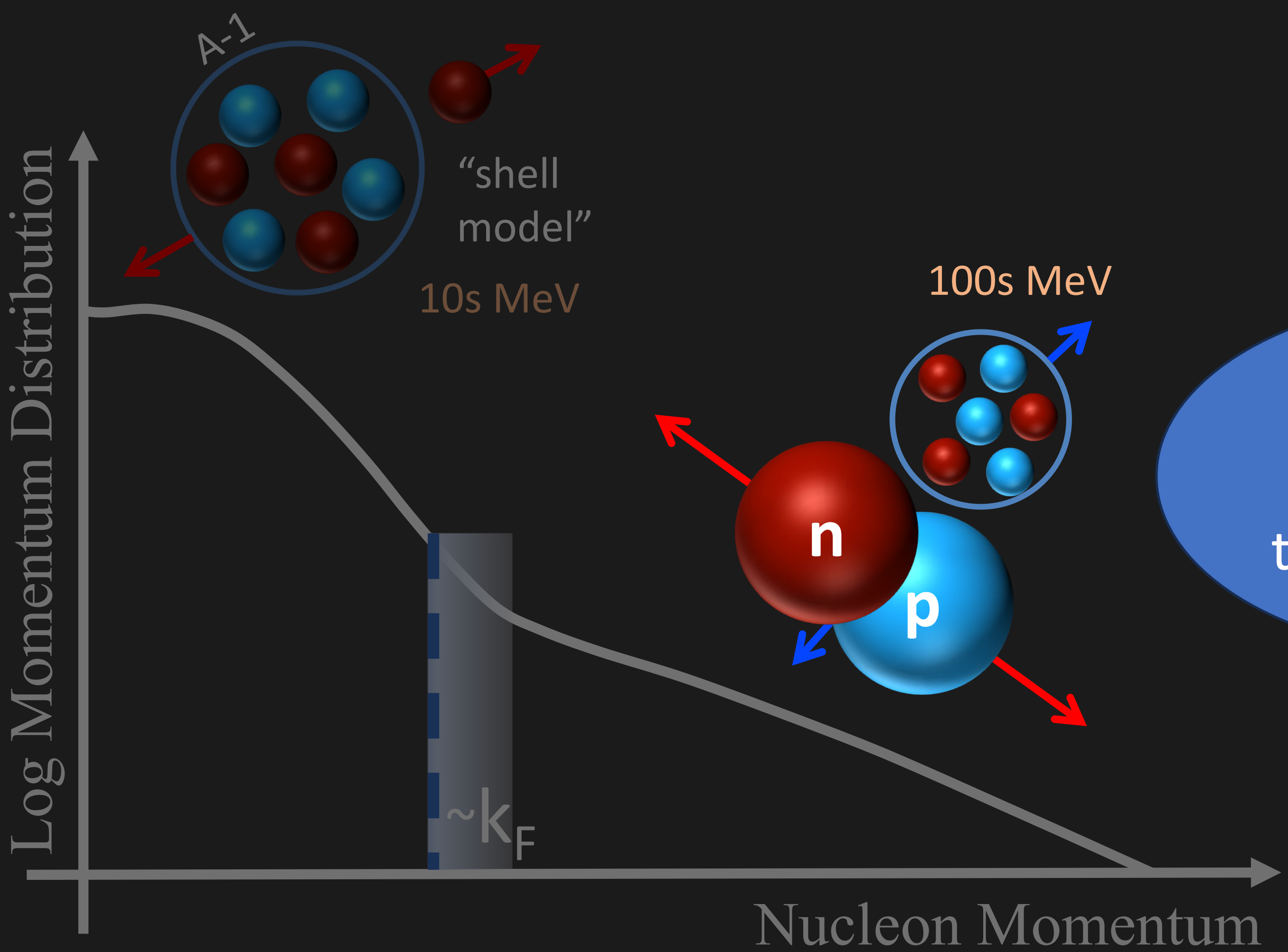
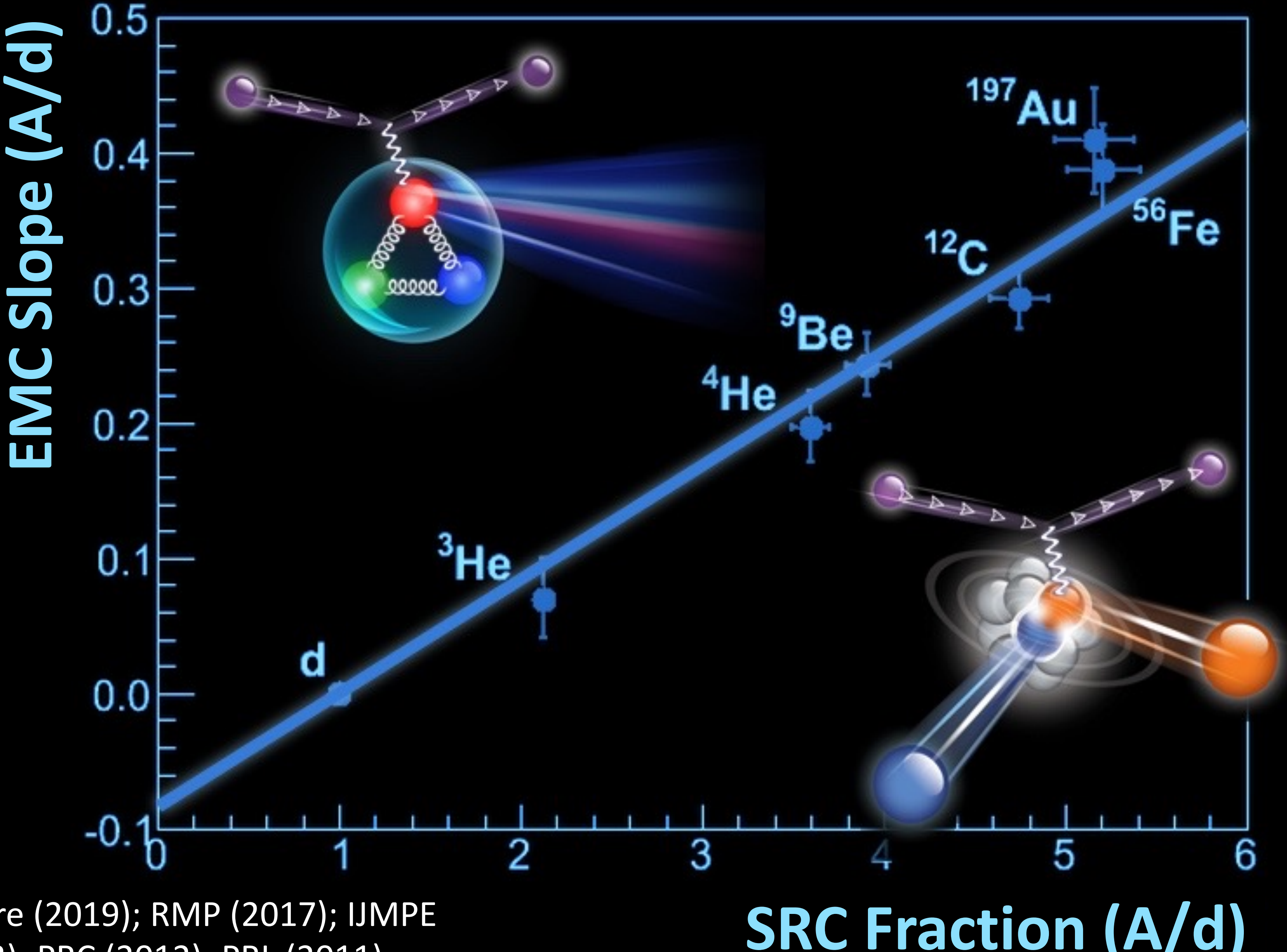


Can SRCs be a main driver for the EMC effect?

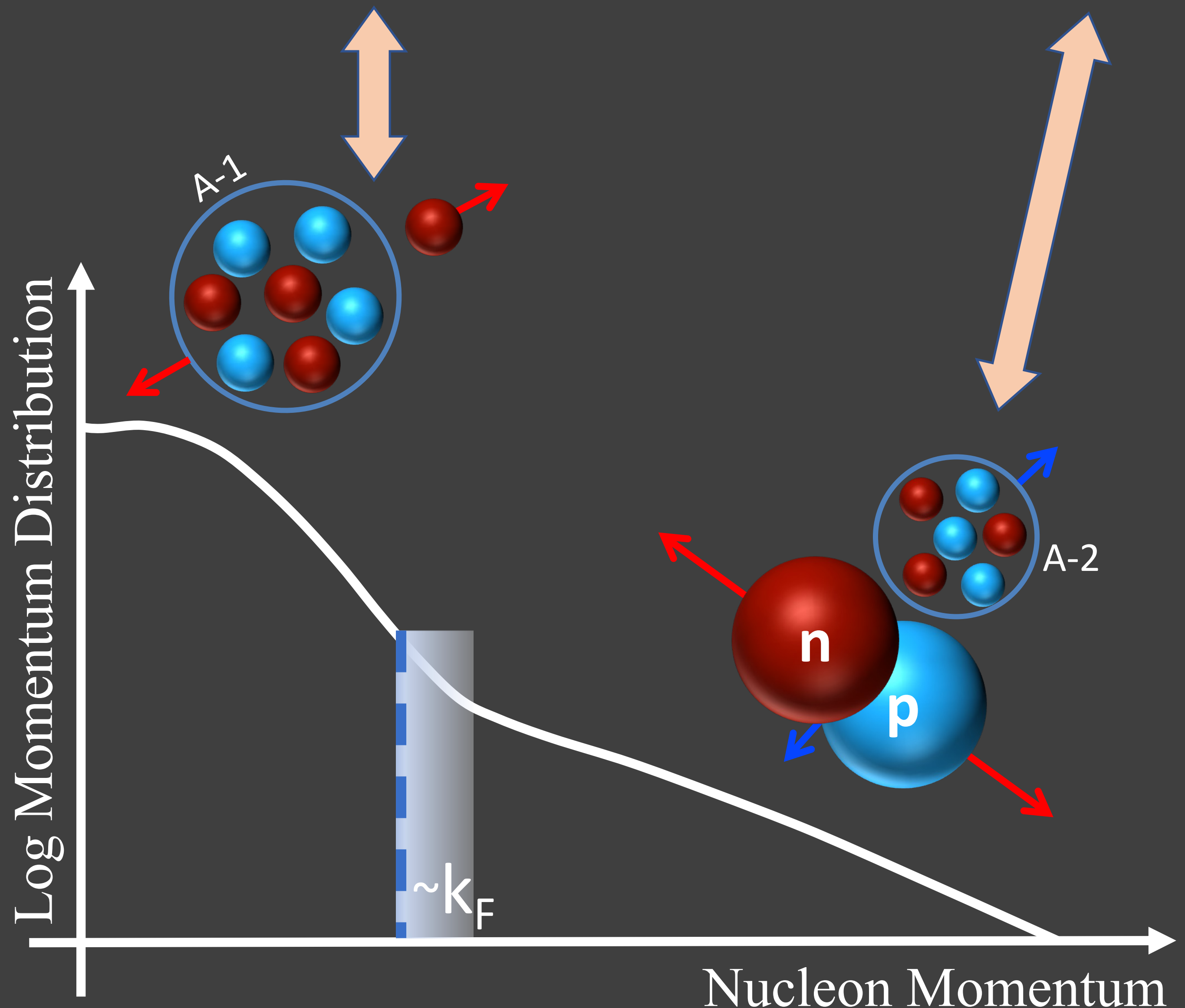
Korover PLB '21; Duer PRL '19; Duer Nature '18; Hen Science '14; Korover PRL '14;
Subedi Science '08; Shneor PRL '07; Piasetzky PRL '06; Tang PRL '03; Review: Hen RMP '17

EMC – SRC Correlation

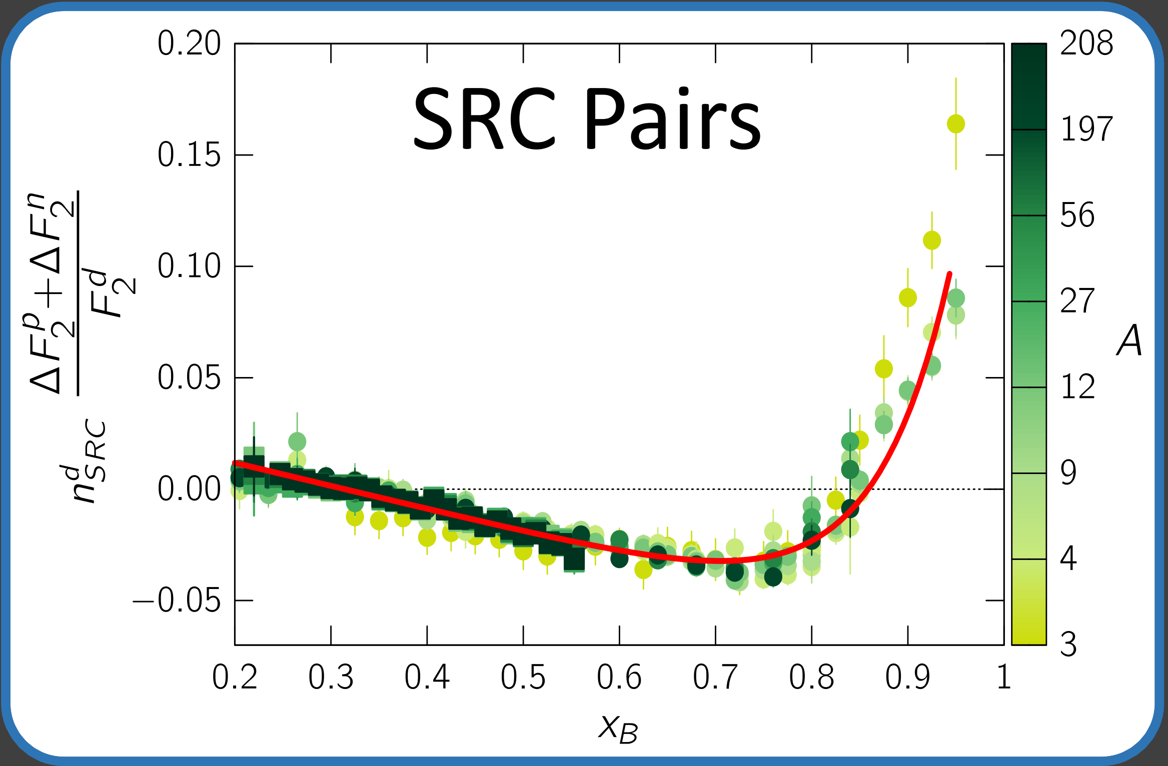


Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011);

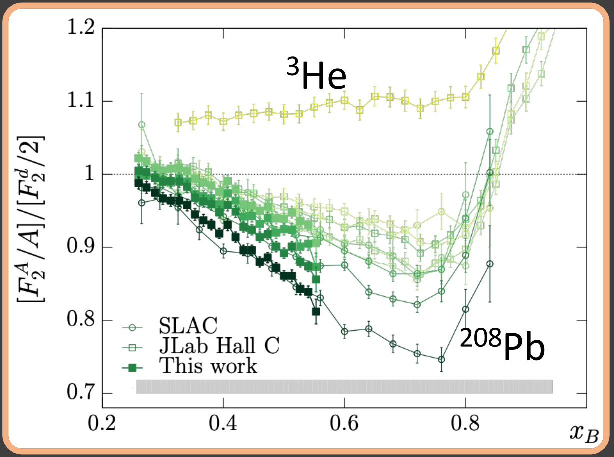
Bound = ‘Quasi-Free’ + Modified SRCs



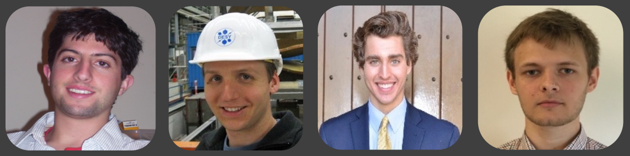
SRC Universality!



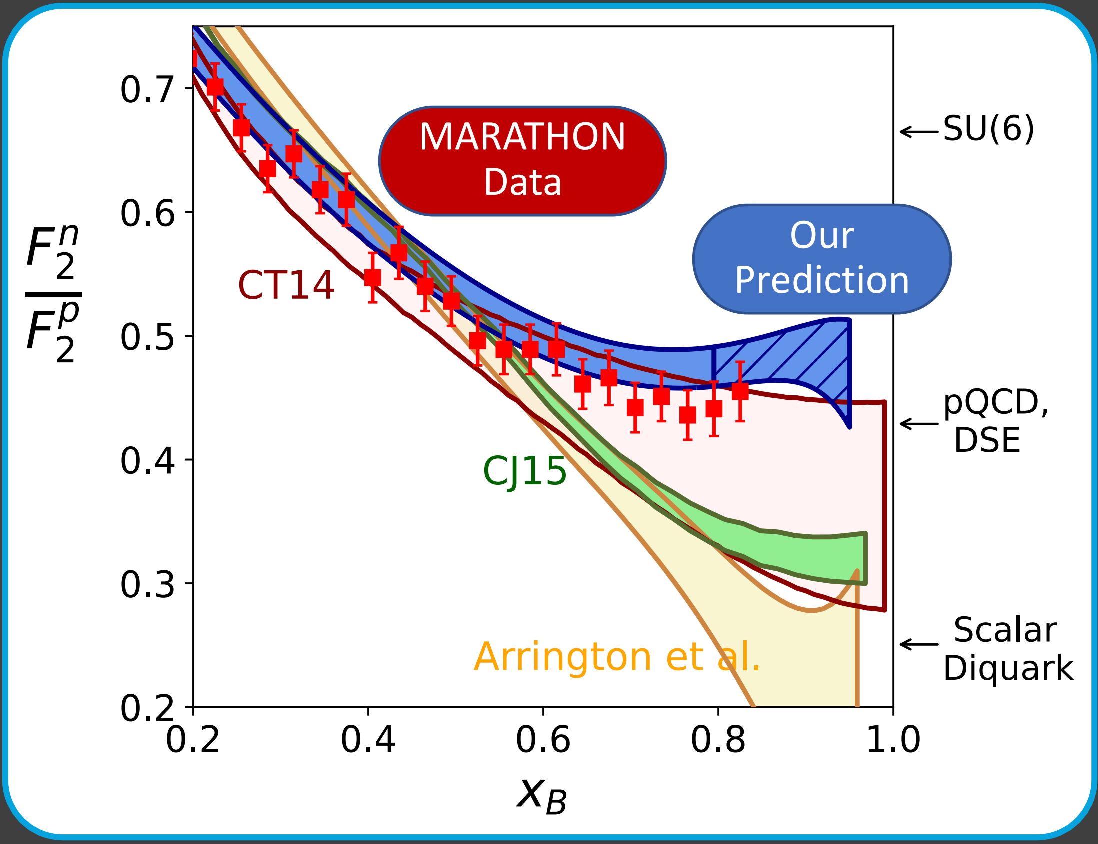
All Nucleons



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



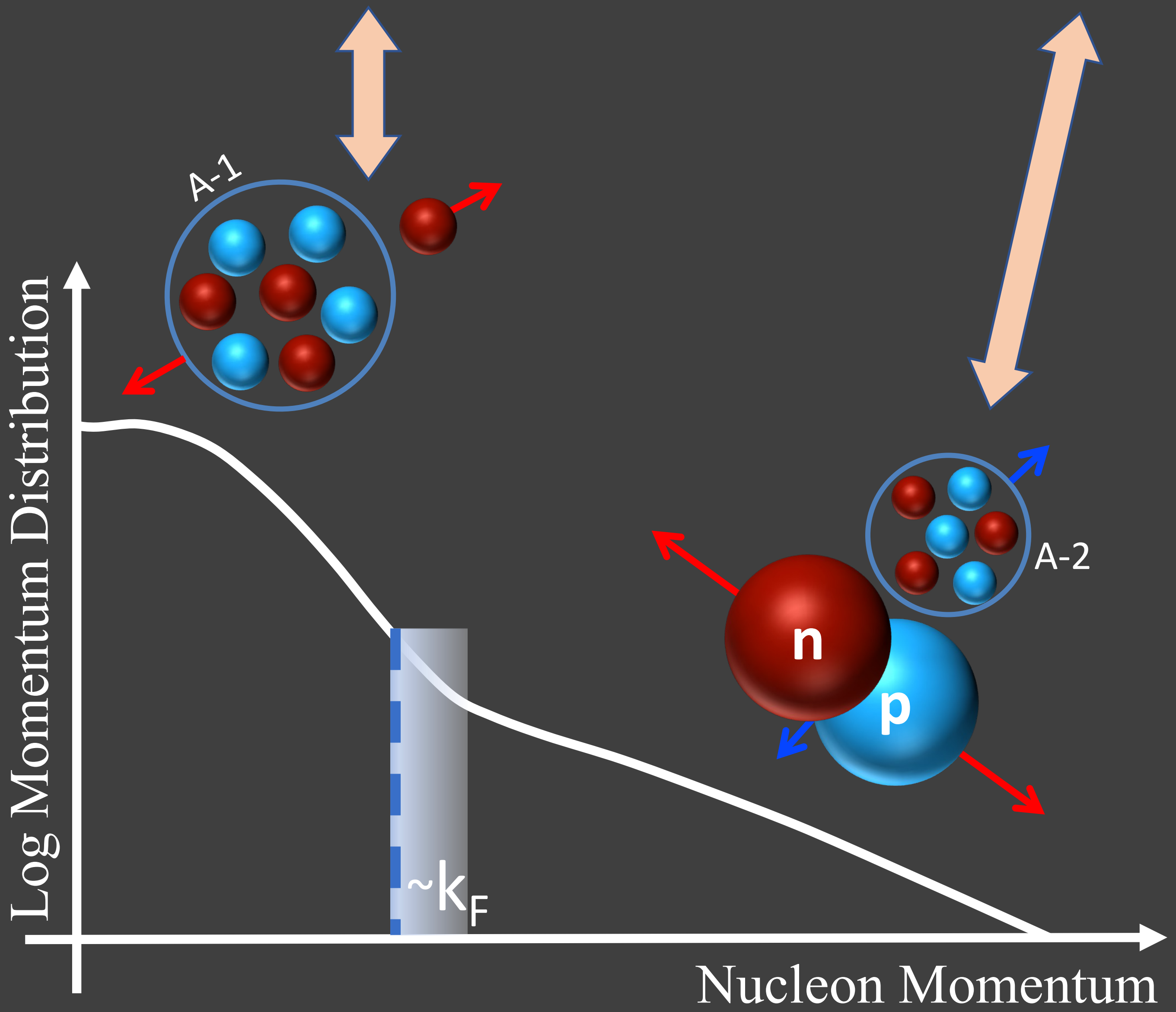
Verified Predictions!



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

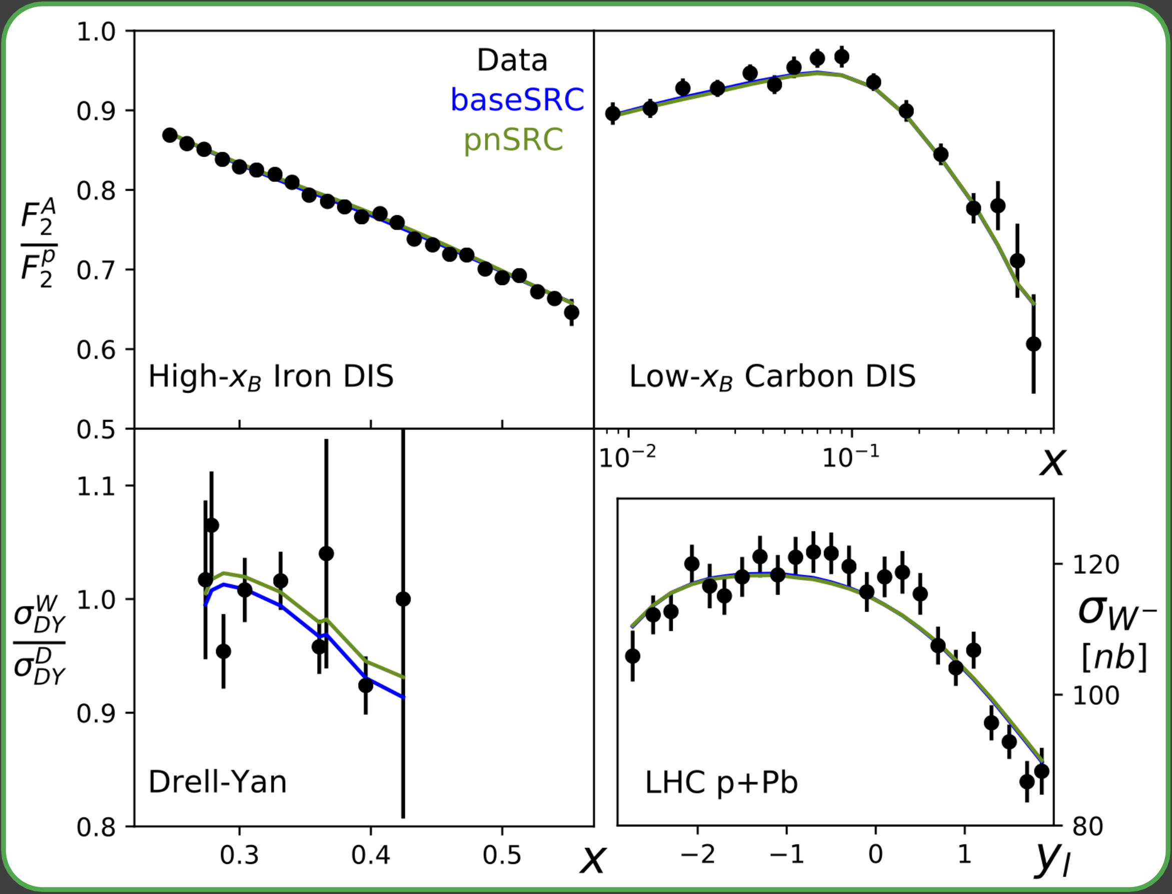
Our Prediction: Segarra et al., Phys. Rev. Lett. (2020)

Bound = 'Quasi-Free' + Modified SRCs



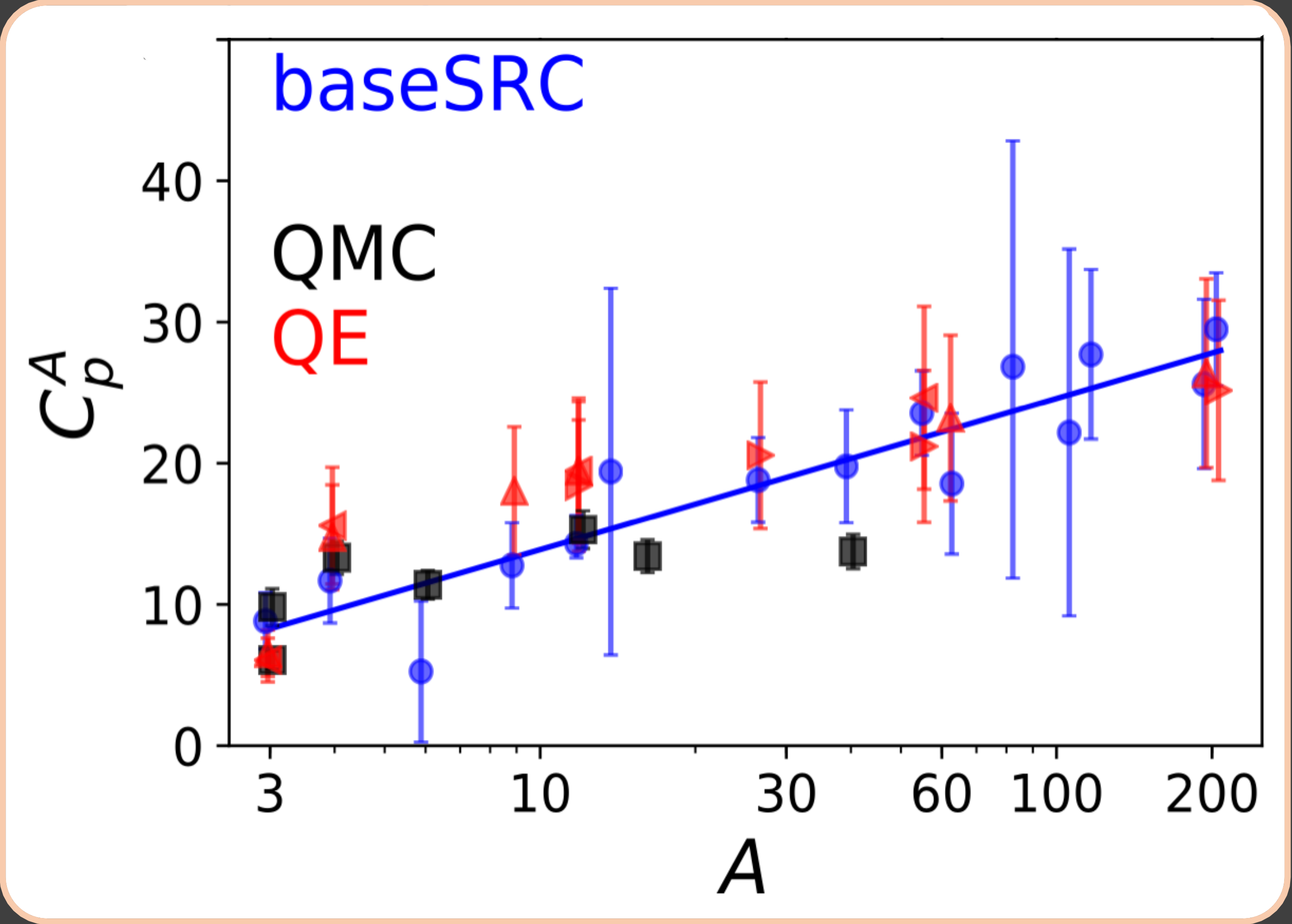
Nuclear Quark-Gluon Distributions From Global Analysis

$$q_i^A(x,Q) = \left(1 - \%_{SRC}^A\right) \times f_i^{free}(x,Q) + \%_{SRC}^A \times f_i^{SRC}(x,Q)$$

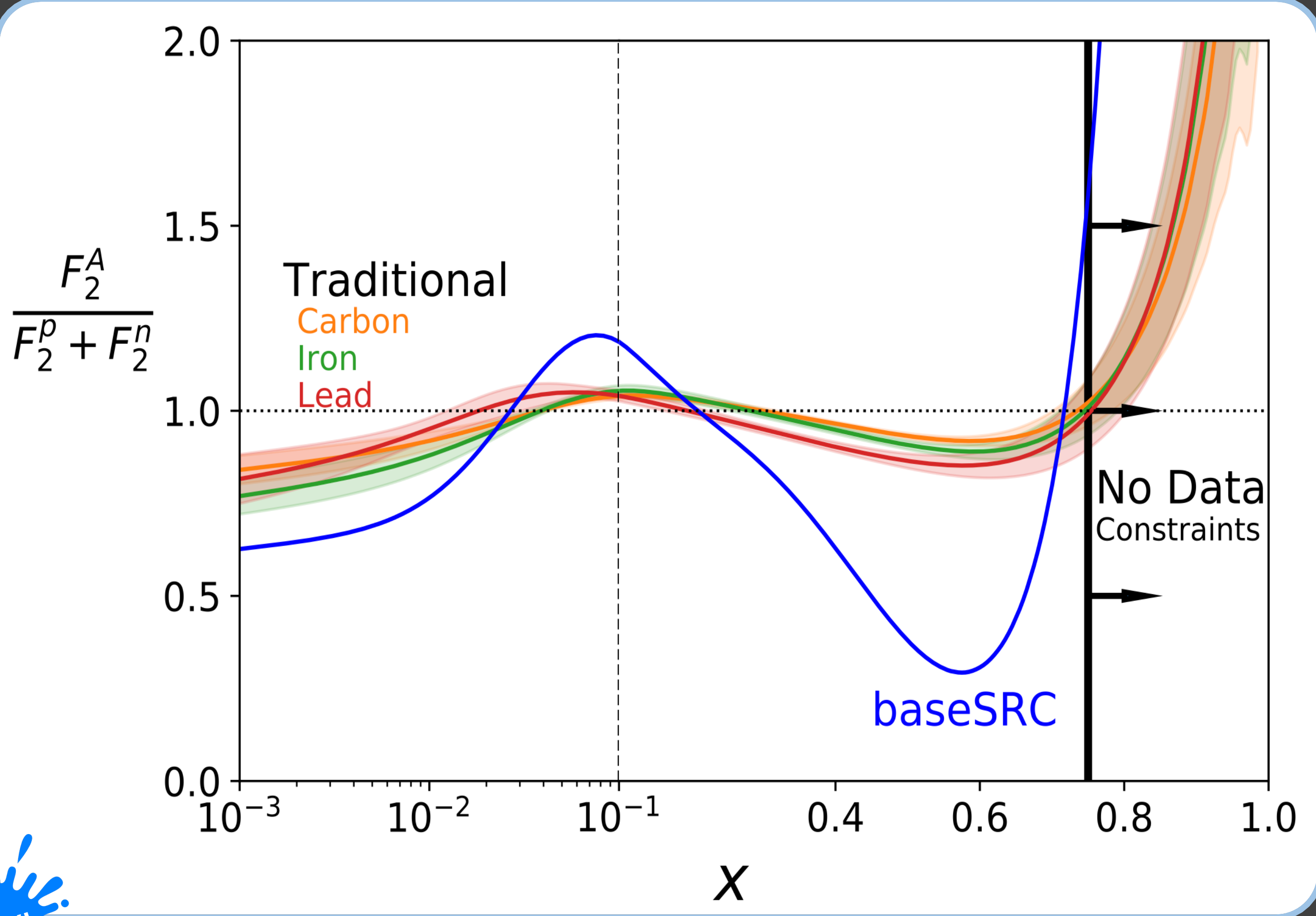


Utilizing PRD 103, 114015 (2021)

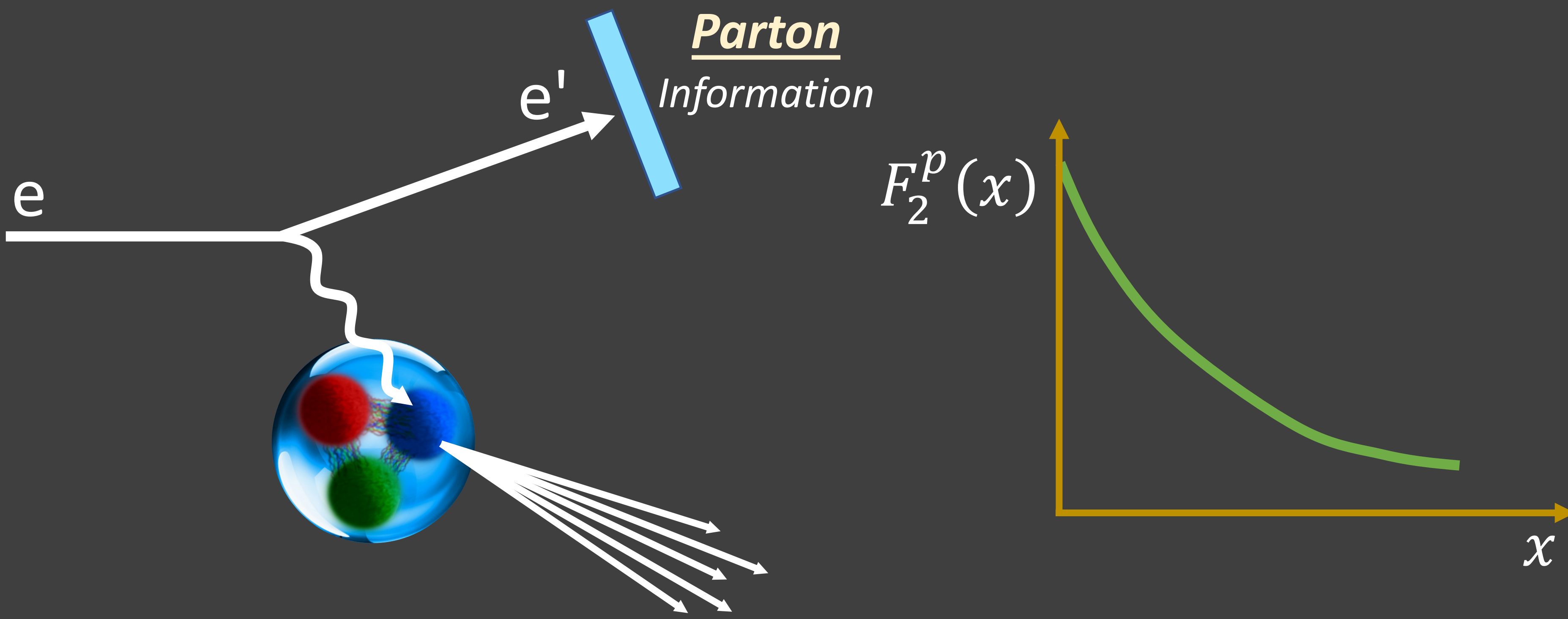
✓ Correctly *Predicts* SRC Abundances



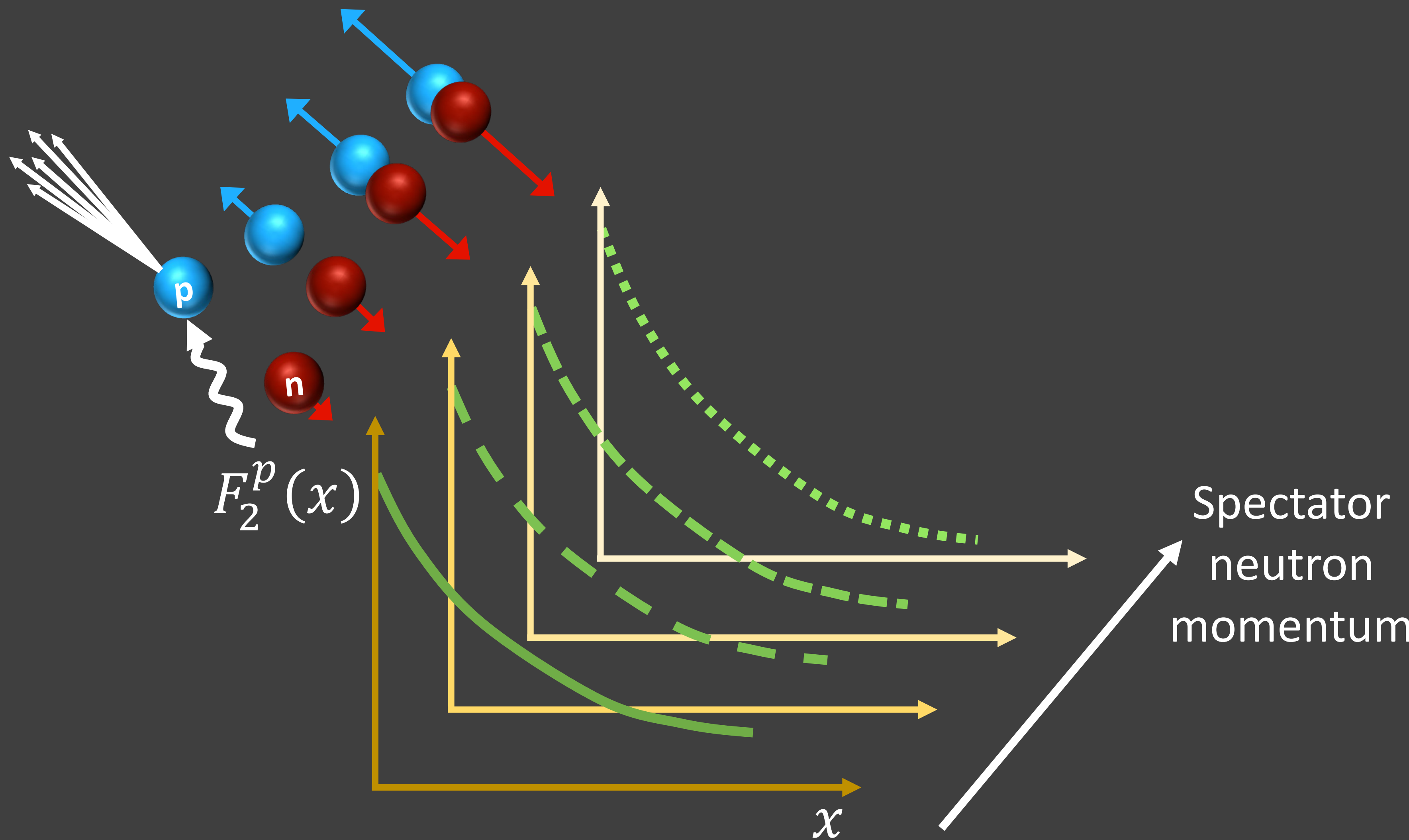
+ Predict Large SRC Modification



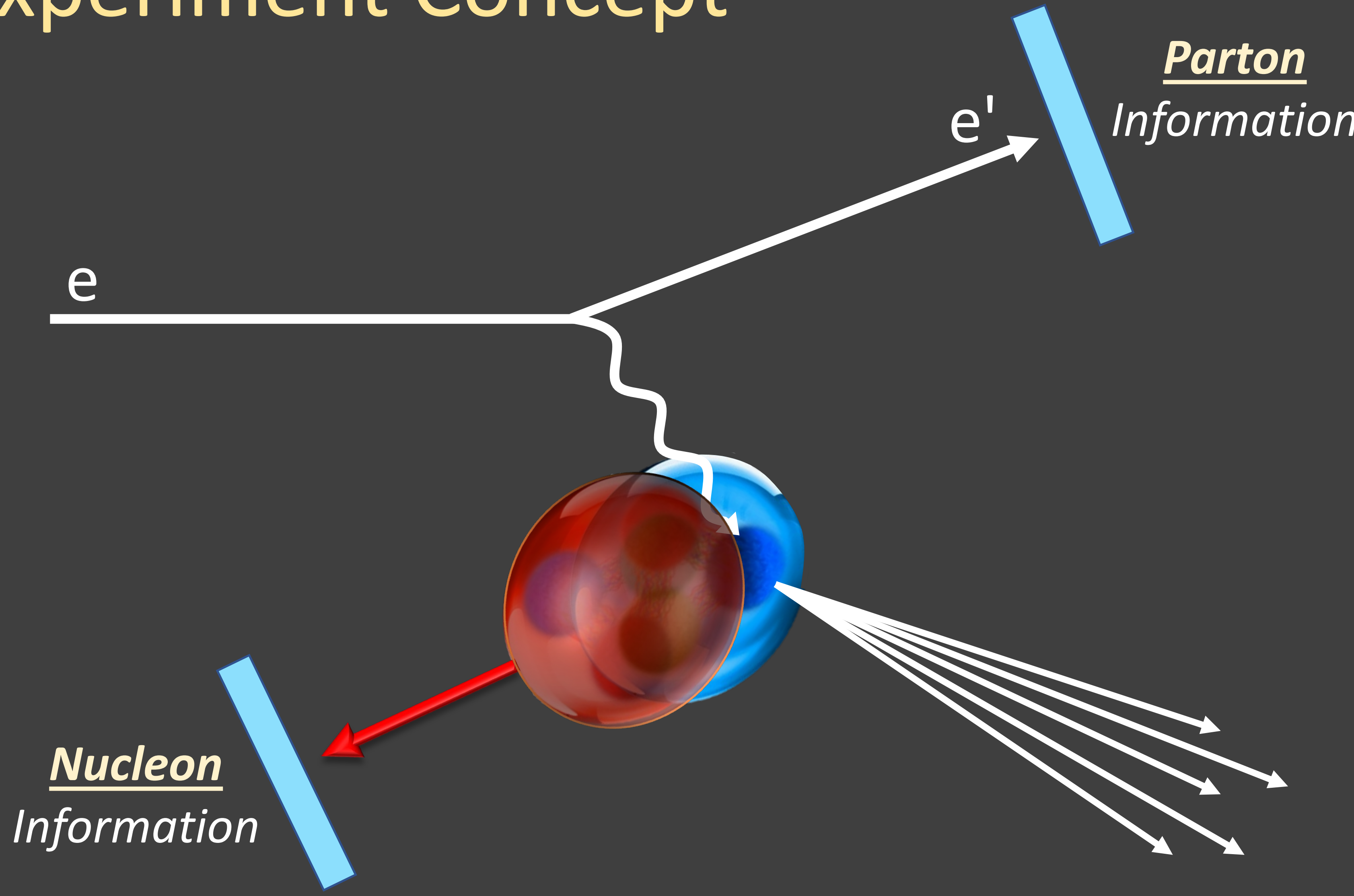
Can we measure it Directly? YES!



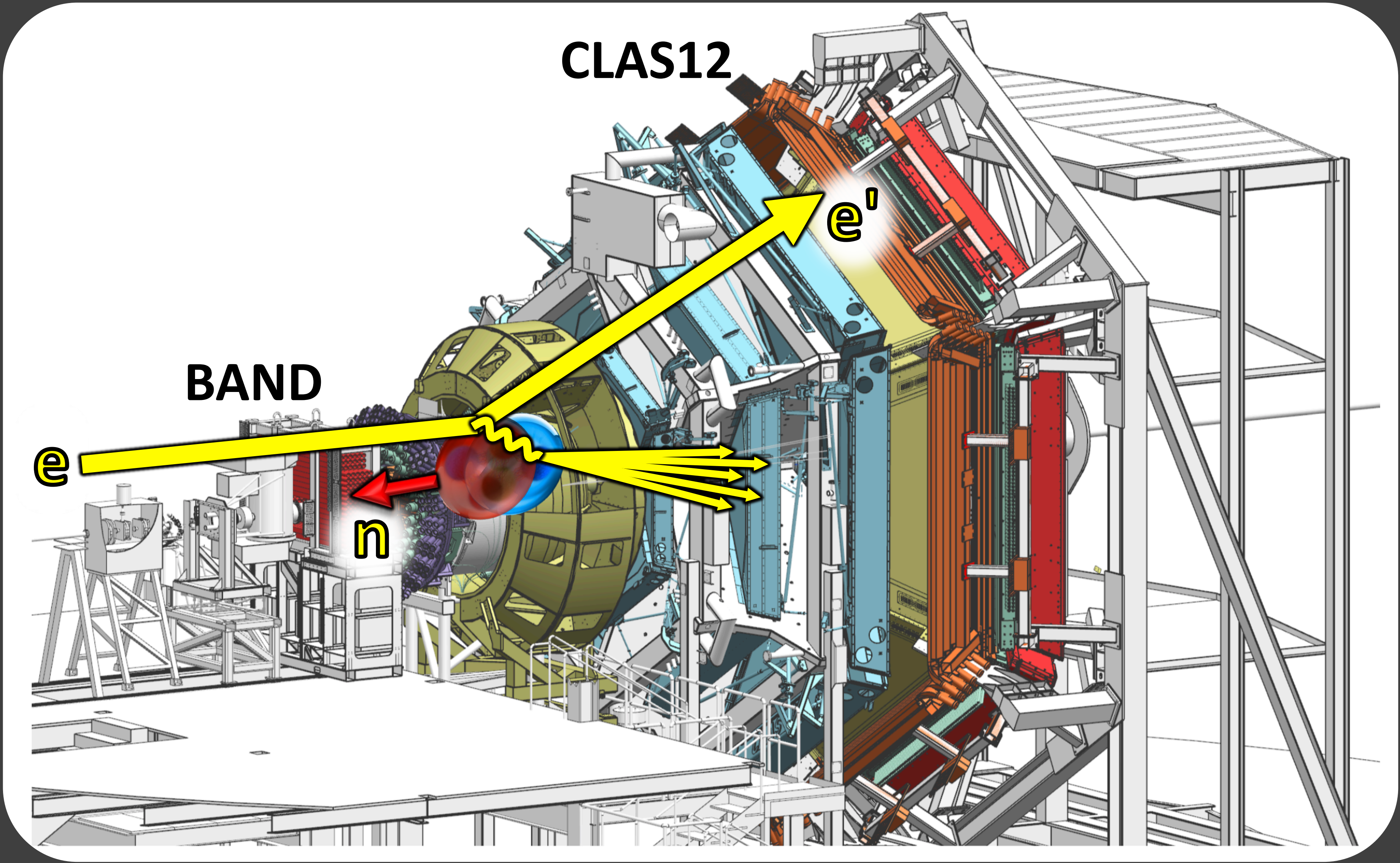
Deuteron: Nucleon structure lab

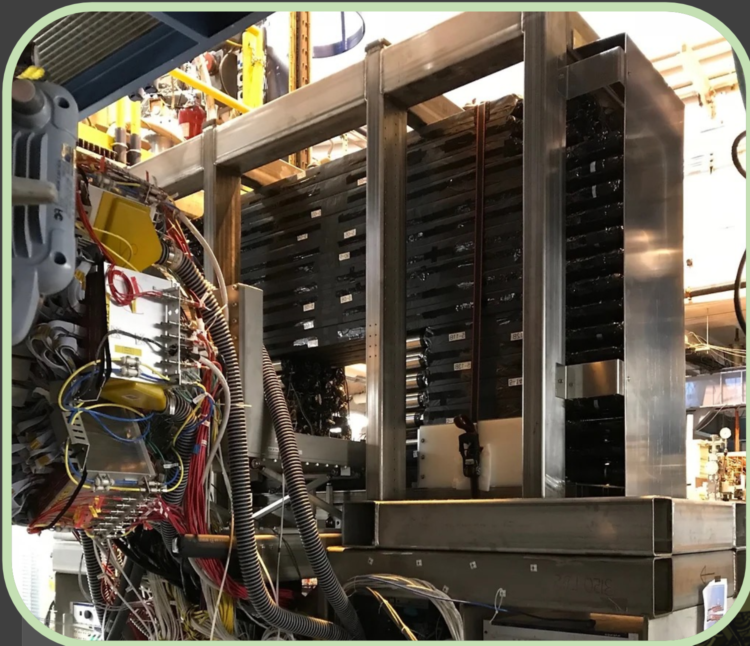


Experiment Concept

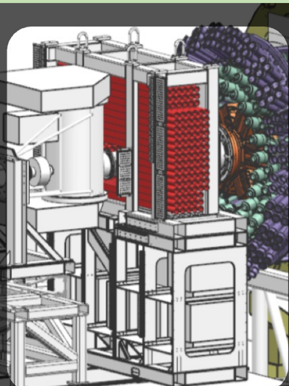


Experiment Layout





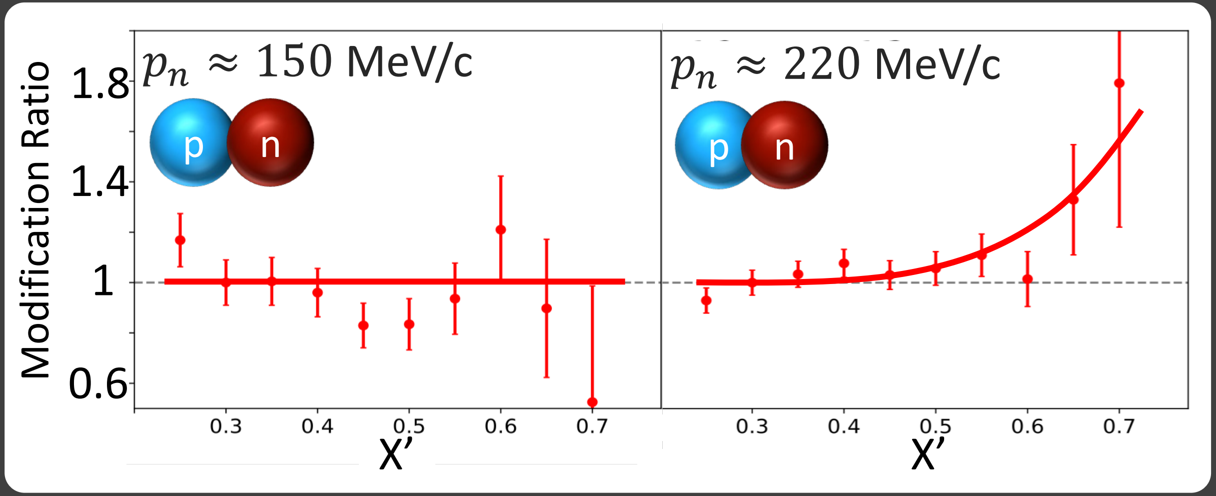
NIM-A 978, 164356 (2020)
NIM-A 973, 164177 (2020)

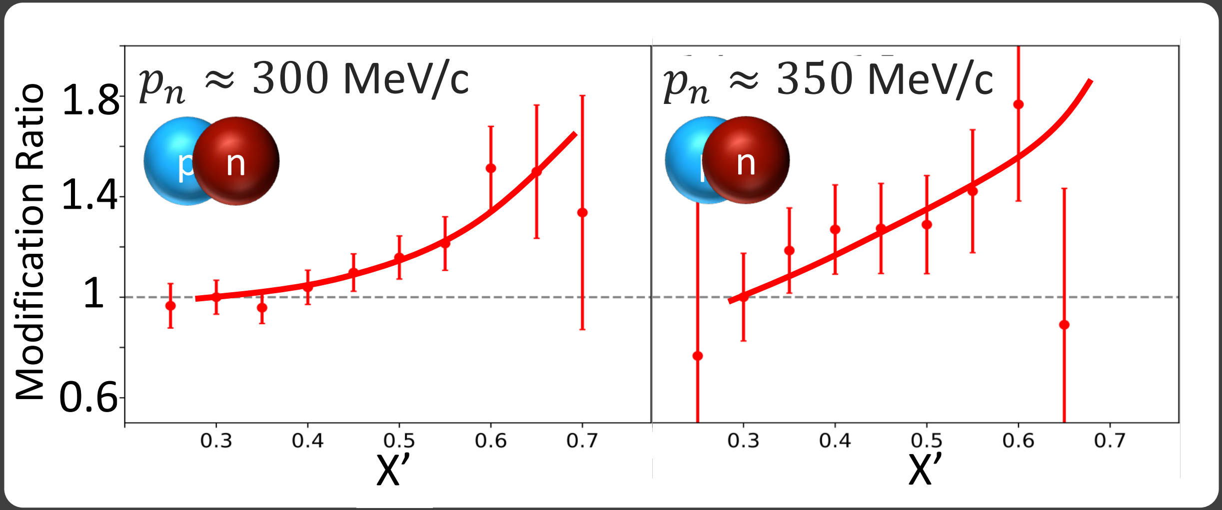


Initial Modification Observation!

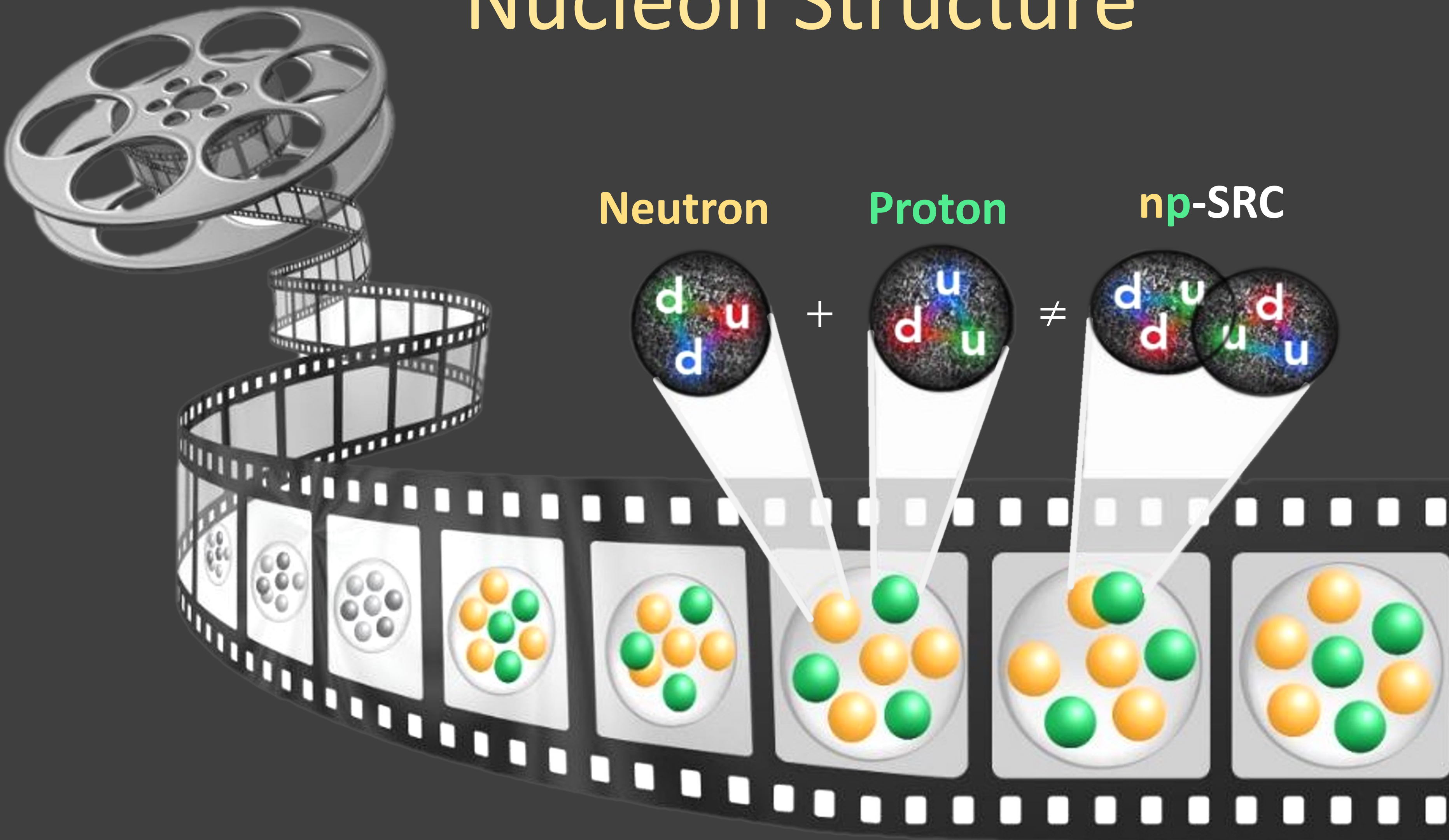
Bound / Free

$$\sigma\left(\frac{x'}{0.3}, p_n\right)$$

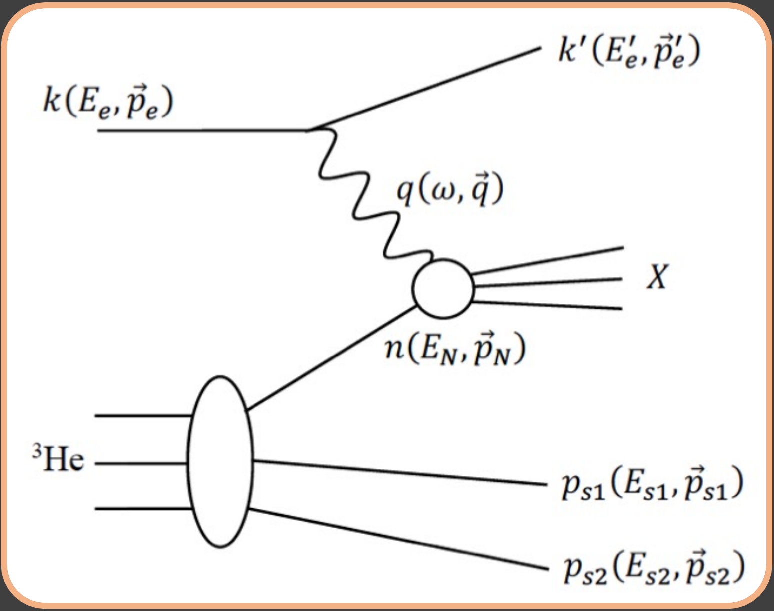


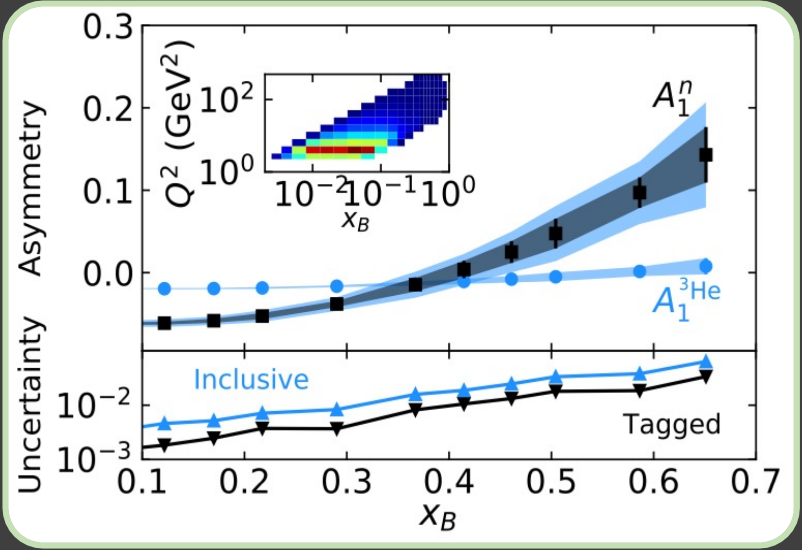


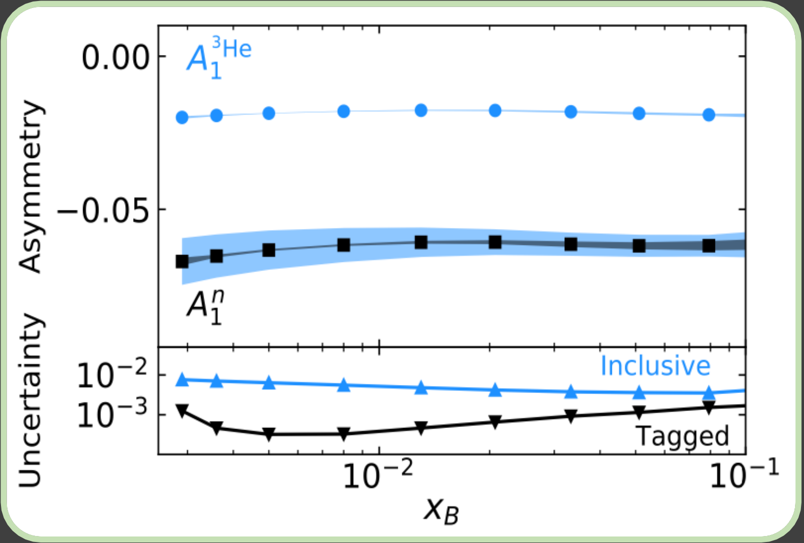
Nuclear Interactions Impact Nucleon Structure

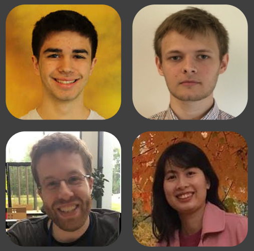


EIC: Tagging the Neutron Spin Structure



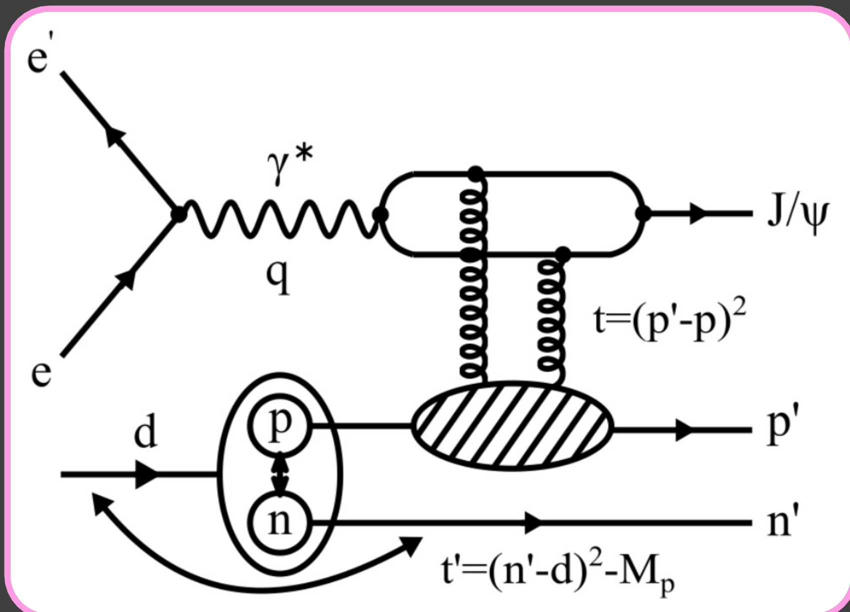


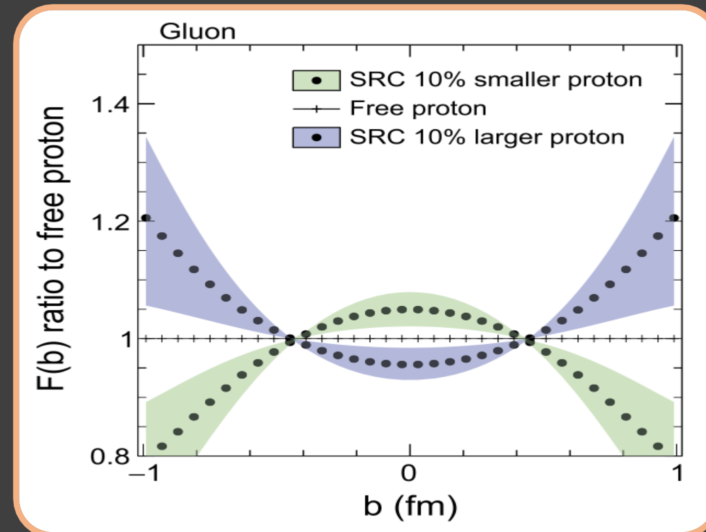


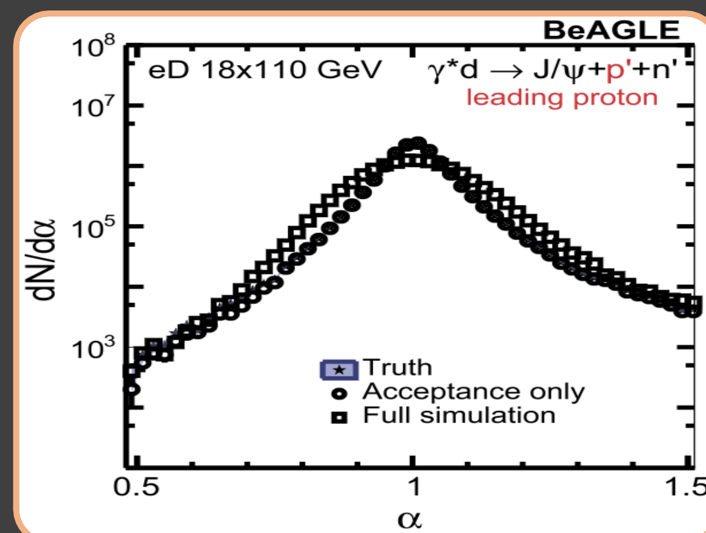


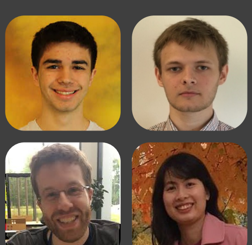
Tu et al., Phys. Lett. B (2020)
Friscic et al., Phys. Lett. B (2021)
Hauenstein et al., Phys. Rev. C (2022)

EIC: SRC Gluon Structure and Light-cone Density









Tu et al., Phys. Lett. B (2020)

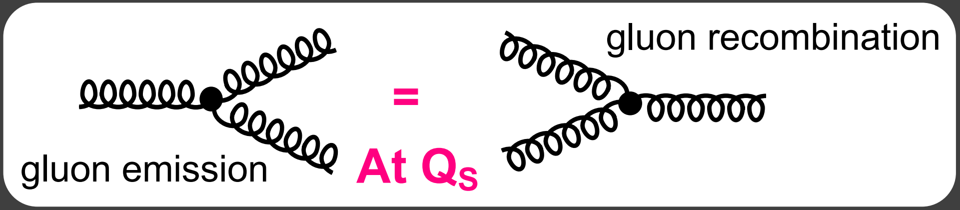
Friscic et al., Phys. Lett. B (2021)

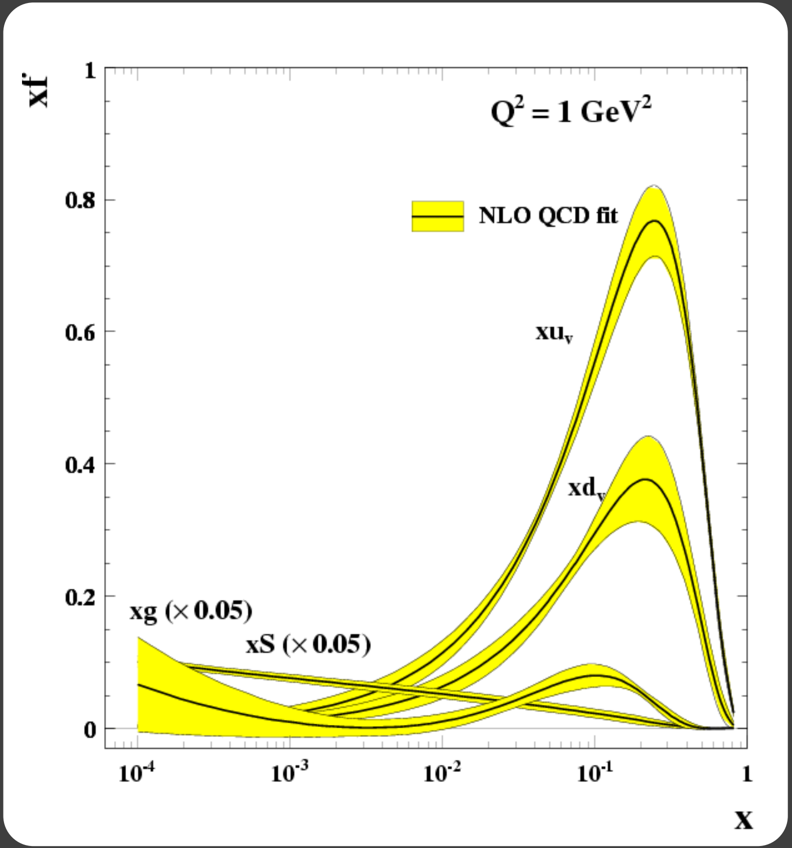
Hauenstein et al., Phys. Rev. C (2022)

Understanding dense gluonic systems

What happens to the gluon density in nuclei?

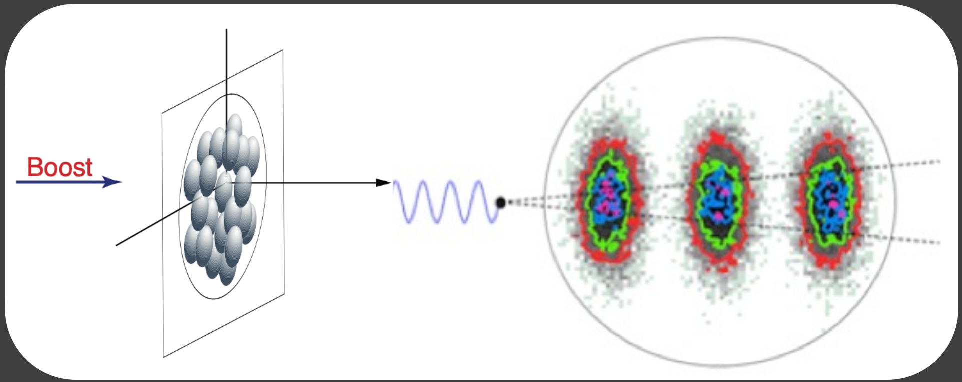
Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclear matter?





Nuclear Glue Lab in Nuclei

Low-x gluons longitudinal wave-length spans the nucleus

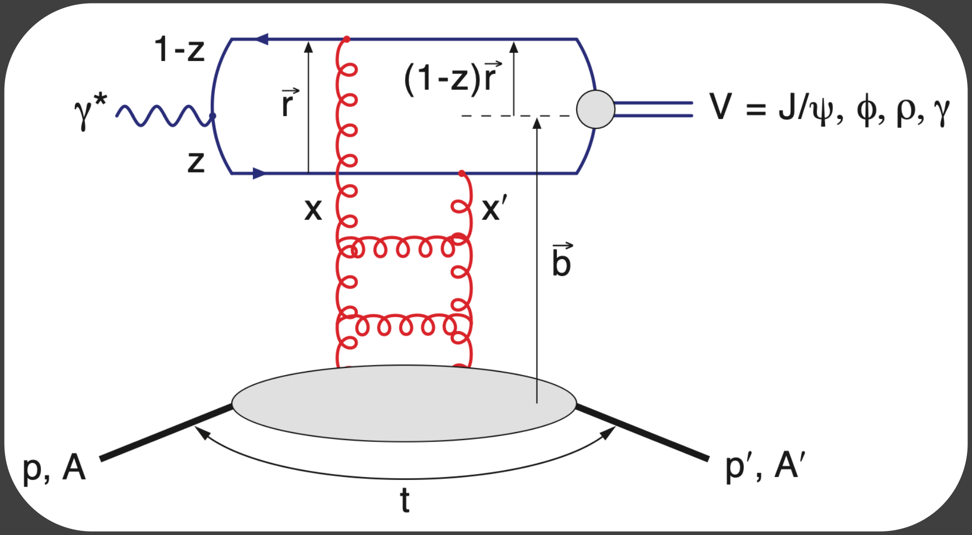


➔ Gluon density scale as $A^{1/3}$

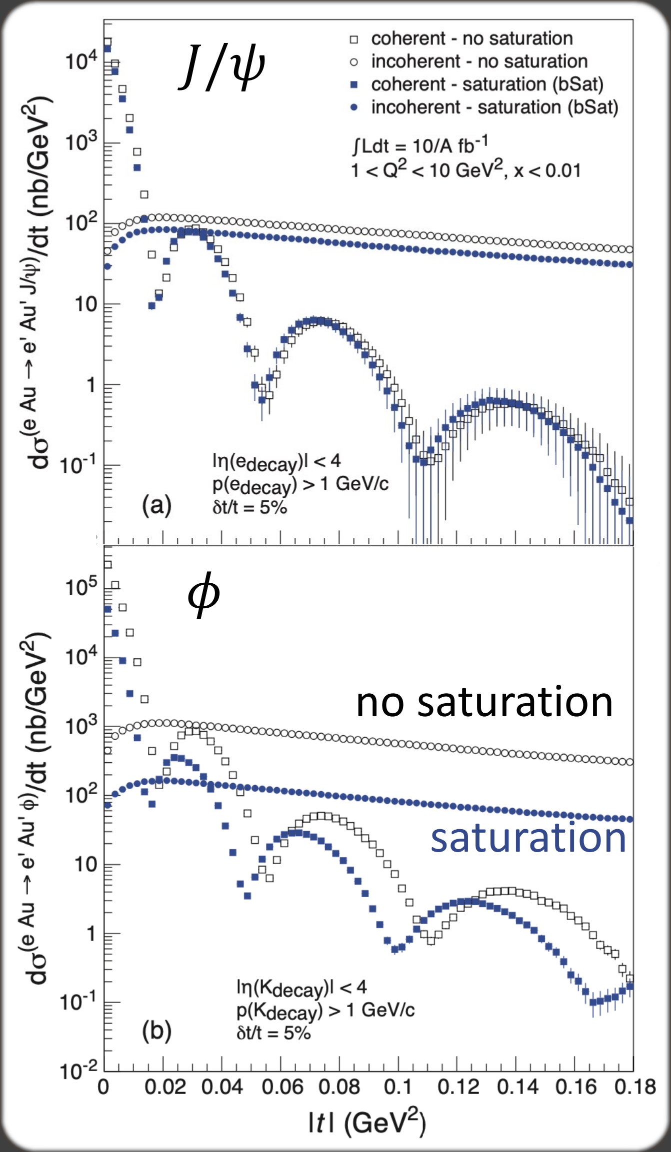
➔ Gluon distributions are sensitive to saturation

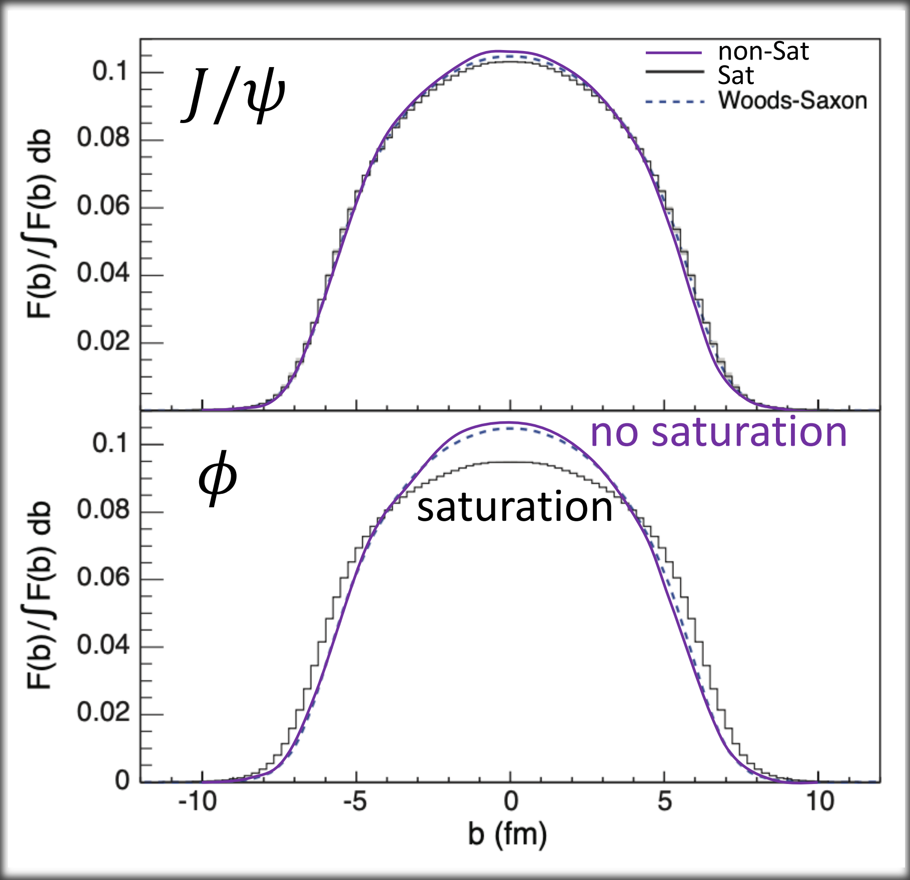
Nuclear Glue Lab in Nuclei

Coherent vector-meson production is mitigated by gluons and therefore sensitive to gluon density and saturation!



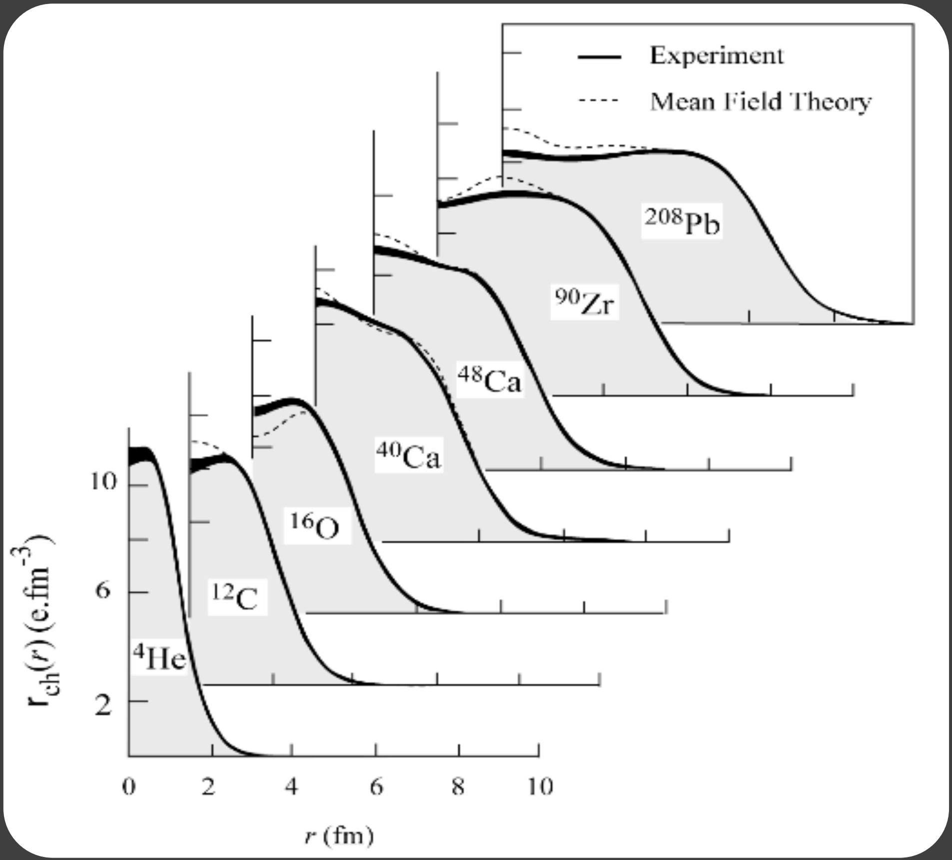
EIC Will Measure the Glue Density



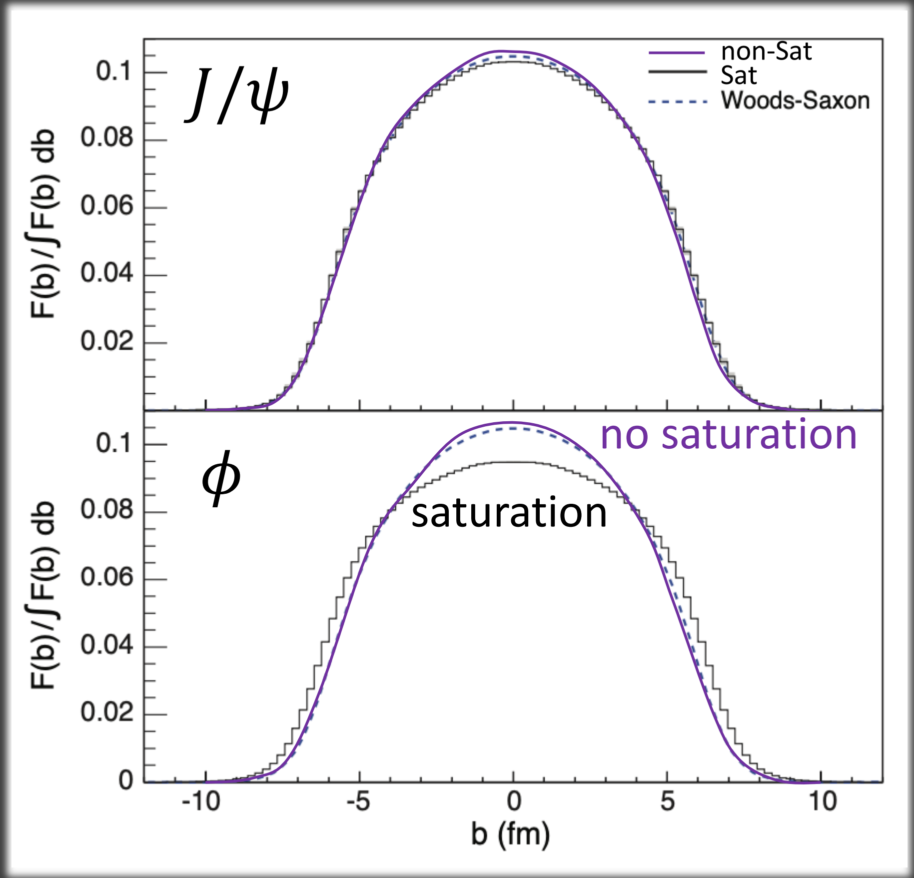


EIC Will Measure the Glue Density

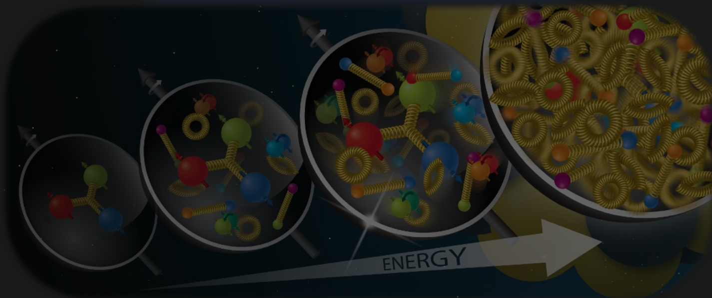
Charge



Glue

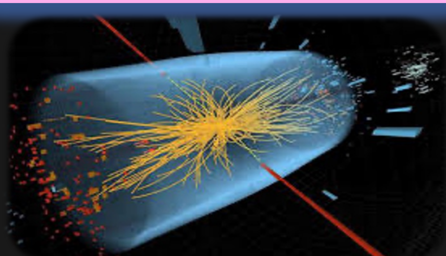


Dense Gluons



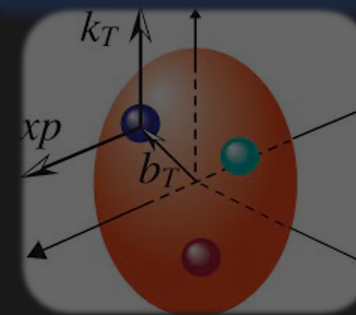
Nuclei

Standard Model

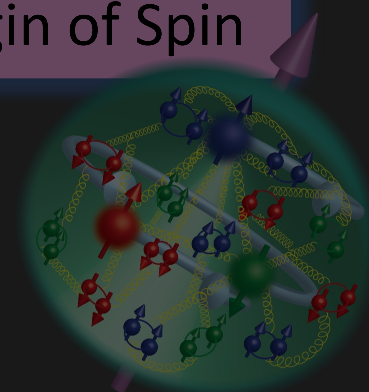


QCD Science

Femtography



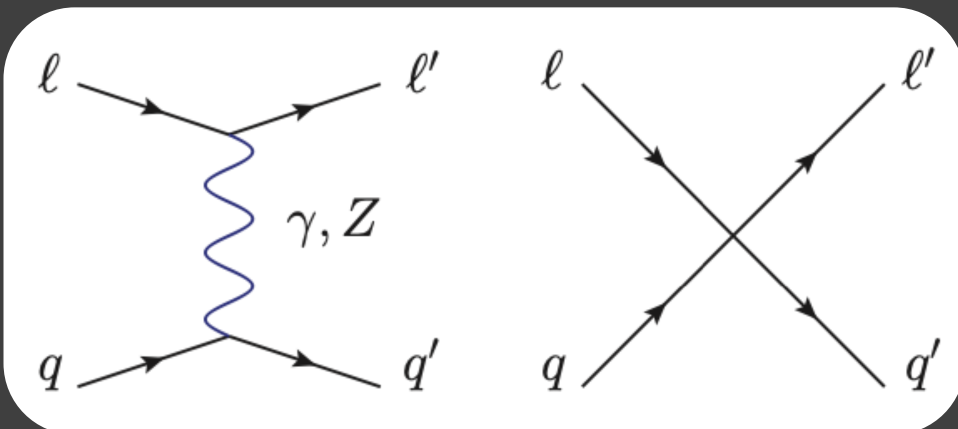
Origin of Spin

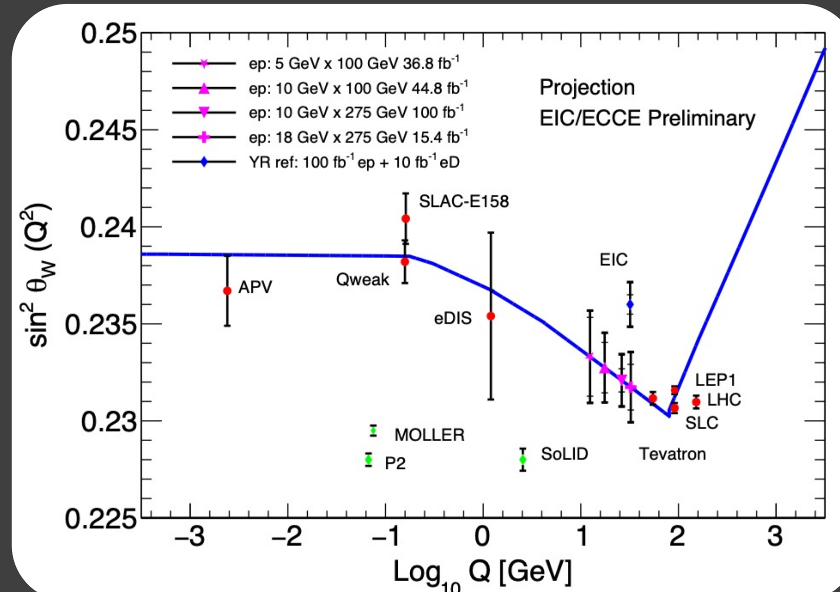


Origin of Mass

Neutral-Current Electroweak Physics and SMEFT Studies at the EIC

Radja Boughezal[1], Alexander Emmert[2], Tyler Kutz[3], Sonny Mantry[4], Michael Nycz[2], Frank Petriello[1,5], Kağan Şimşek[5], Daniel Wiegand[5], Xiaochao Zheng[2]

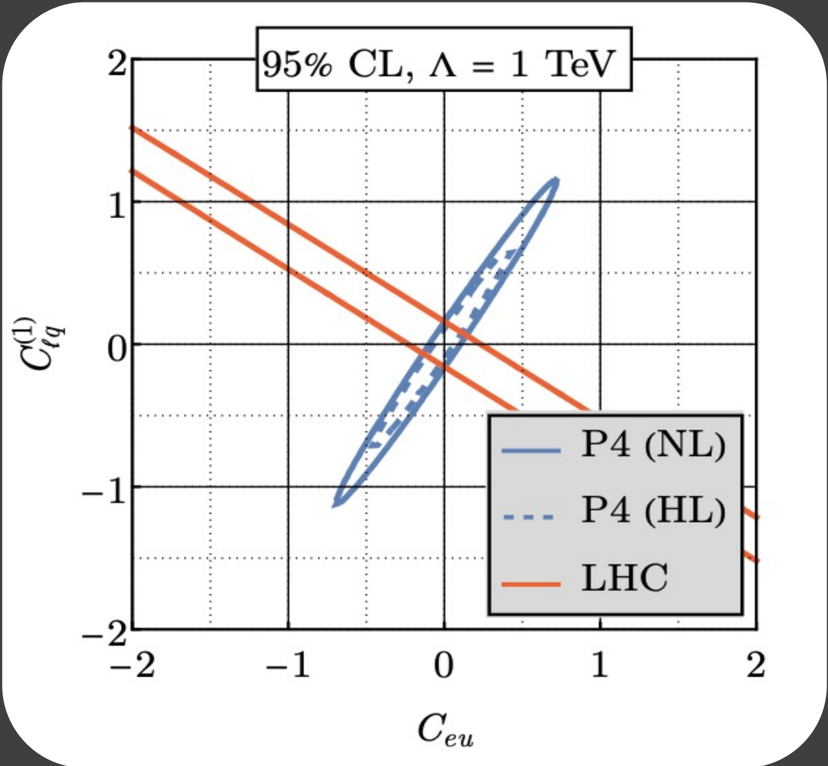




Phys. Rev. D 106, 016006 (2022)

Neutral-Current Electroweak Physics and SMEFT Studies at the EIC

Radja Boughezal[1], Alexander Emmert[2], Tyler Kutz[3], Sonny Mantry[4], Michael Nycz[2], Frank Petriello[1,5], Kağan Şimşek[5], Daniel Wiegand[5], Xiaochao Zheng[2]



10 GeV × 275 GeV ep, 100 fb^{-1}

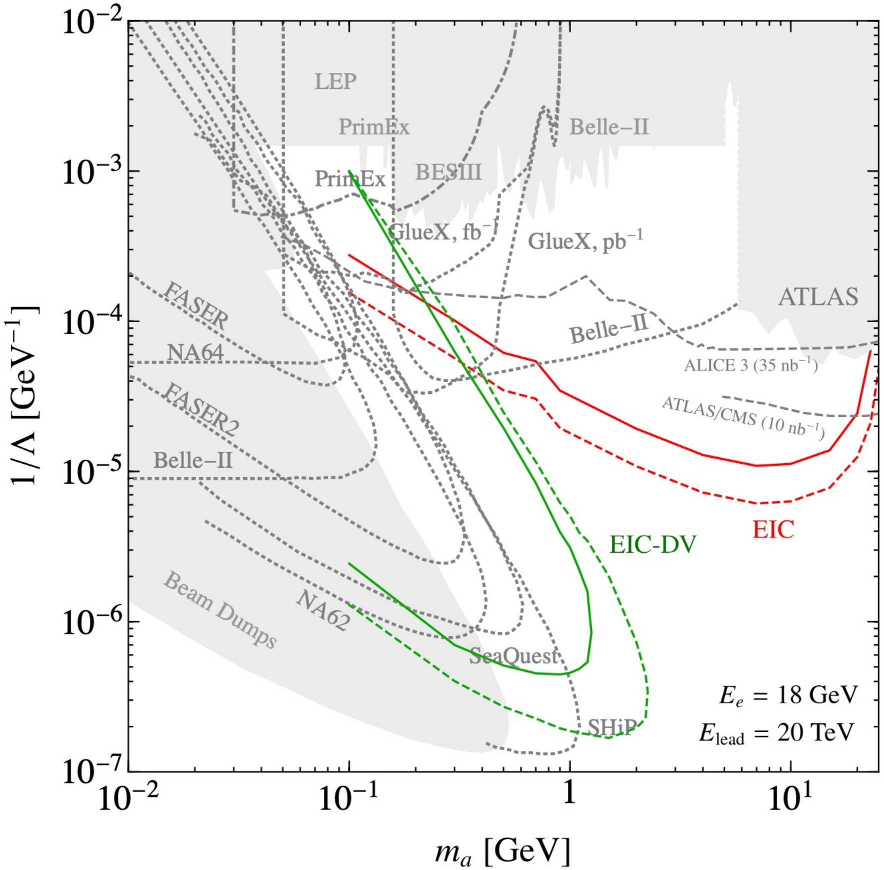
High precision + Polarization = LHC Complementarity!

C_r	$\mathcal{O}_r$	$\tilde{C}_r$	$c^e_{V_r}$	$c^e_{A_r}$	$c^u_{V_r}$	$c^u_{A_r}$	$c^{d,s}_{V_r}$	$c^{d,s}_{A_r}$
$C_{\ell q}^{(1)}$	$\mathcal{O}_{\ell q}^{(1)} = (\bar{L}_L\gamma^\mu L_L)(\bar{Q}_L\gamma_\mu Q_L)$	$C_{\ell q}^{(1)}/4$	1	1	1	1	1	1
$C_{\ell q}^{(3)}$	$\mathcal{O}_{\ell q}^{(3)} = (\bar{L}_L\gamma^\mu \tau^I L_L)(\bar{Q}_L\gamma_\mu \tau^I Q_L)$	$C_{\ell q}^{(3)}/4$	1	1	-1	-1	1	1
C_{eu}	$\mathcal{O}_{eu} = (\bar{e}_R\gamma^\mu e_R)(\bar{u}_R\gamma_\mu u_R)$	$C_{eu}/4$	1	-1	1	-1	0	0
C_{ed}	$\mathcal{O}_{ed} = (\bar{e}_R\gamma^\mu e_R)(\bar{d}_R\gamma_\mu d_R)$	$C_{ed}/4$	1	-1	0	0	1	-1
$C_{\ell u}$	$\mathcal{O}_{\ell u} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma_\mu u_R)$	$C_{\ell u}/4$	1	1	1	-1	0	0
$C_{\ell d}$	$\mathcal{O}_{\ell d} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma_\mu d_R)$	$C_{\ell d}/4$	1	1	0	0	1	-1
C_{qe}	$\mathcal{O}_{qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma_\mu e_R)$	$C_{qe}/4$	1	-1	1	1	1	1

Phys. Rev. D 106, 016006 (2022)

Probing axion-like particles at the electron-ion collider

Reuven Balkin,[a] Or Hen,[b] Wenliang Li,[c,d] Hongkai Liu,[a] Teng Ma,[a,e,f] Christoph Paus,[b] Yotam Soreq,[a] Mike Williams[b]



$$\mathcal{L}_a = -\frac{1}{2}m_a^2 a^2 - \frac{a}{4\Lambda}F^{\mu\nu}\tilde{F}_{\mu\nu},$$