

Perspectives on the 2023 NSAC Long Range Plan for U.S. Nuclear Physics

October 2023

https://nuclearsciencefuture.org/

- Most recent field-wide national planning exercise by nuclear physics
- Hot and Cold QCD Town Meeting, MIT, on September 23-25, 2022

https://indico.mit.edu/event/538/

- Resolution meeting at Virginia Beach on July 10-14, 2023

2023 LRP Working Group (60): QCD Subcommittee (22)

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The Fundamental Structure of Visible Matter

CEBAF QCD Program

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Highlights since 2015 LRP

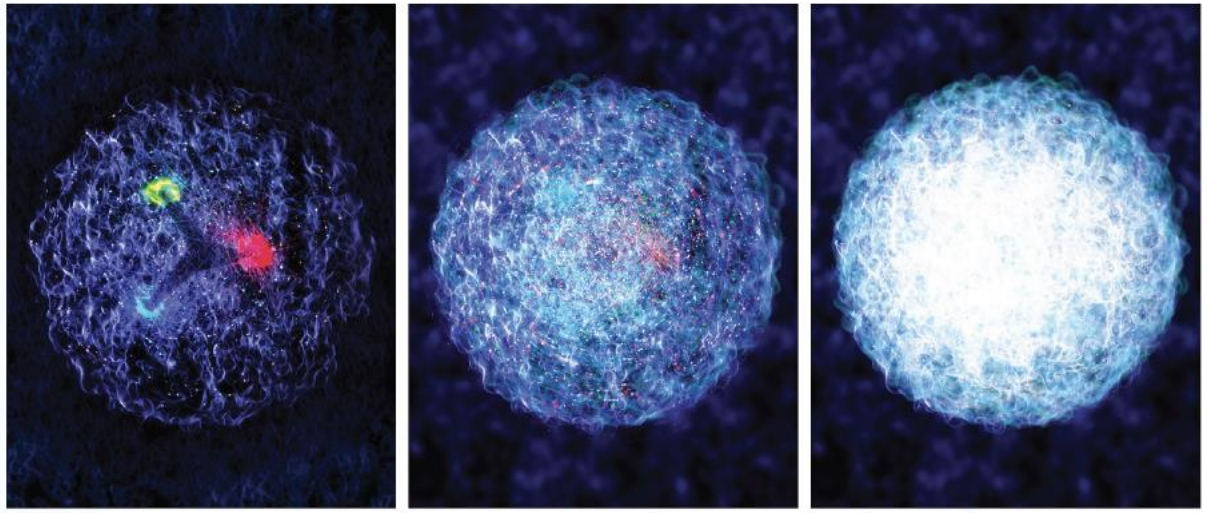

Figure 3.1. An artistic rendering of the nucleon with three different values of the momentum fraction of the quarks inside the nucleon. *The x value goes from (left) the largest to (right) the smallest, matching the focus of Jefferson Lab at high x and the future EIC from medium to low x [1].*

- A new and innovative measurement of the proton's charge radius,
- Extraction of pressure distribution inside the proton,
- Measurements of intriguing quark momentum distributions, both in the nucleon and when bound in a nucleus,
- First measurements of the gluon spin contribution to the spin of the proton,
- Measurements of the correlation between the direction of the proton's spin and the motion and spin of the quarks inside it.
- Observation and discovery of new and exotic hadronic states, including new XYZP states.
- Evidence for having very tightly correlated nucleon pairs inside a nucleus.

Stimulated deeper questions

- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

How big is the proton?

Daniel C. Hackett, Dimitra A. Pefkou and Phiala E. Shanahan,
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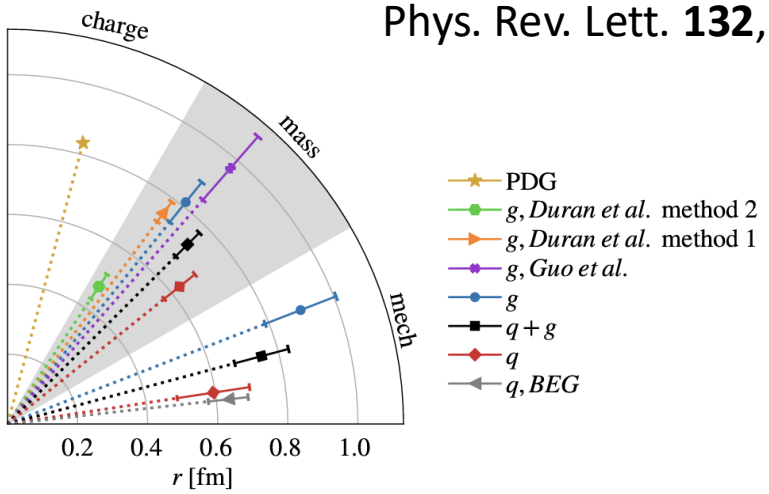
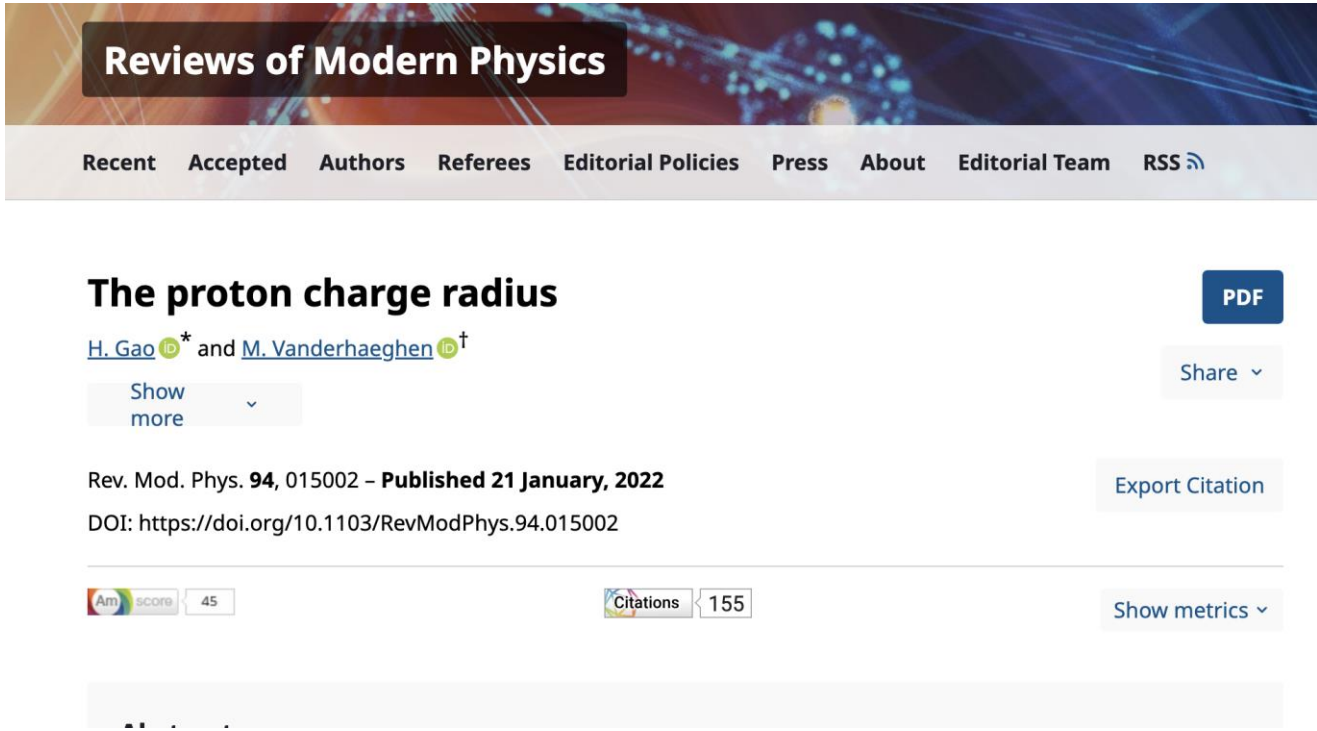


FIG. 4. Comparison of different proton radii. In addition to the results obtained on the lattice QCD ensemble of this work, the charge radius from Ref. [89] (PDG), the gluonic mass radii from Ref. [42] (Duran et al.) and Ref. [46] (Guo et al.), and the quark mechanical radii from Ref. [88] (BEG) are shown. While the latter only includes the light quark contributions, they are compared directly as the strange quark contribution is found to be negligible for this quantity. The uncertainty of the charge radius is too small to be visible.



How are quarks distributed in the nucleon?

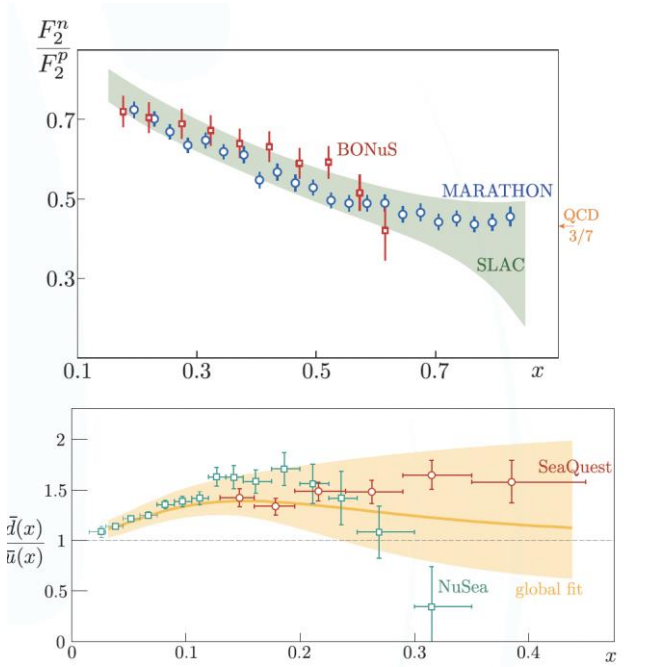


Figure 3.2. Measurements of quark and antiquark PDFs. *Top: The ratio of the neutron and proton structure functions plotted as a function of x from MARATHON, the 6 GeV BONuS experiment, and a global fit (green band) of previous SLAC data. Bottom: A plot of the ratio of antiquark distributions extracted from the SeaQuest experiment, compared with data from the E866/NuSea experiment at Fermilab and from a global fit (orange band) [2].*

Sidebar 3.1 Transformative Progress in Lattice QCD

Lattice QCD offers the only way to make rigorous predictions of the properties of hadrons from QCD. In the past 10 years, a combination of novel theoretical ideas and use of world-leading computation facilities has led to transformative progress that enables new areas of study for the spectrum, structure, and interactions of hadrons, as well as the behavior of QCD at nonzero temperature.

New techniques allow access within lattice QCD to the distribution of momentum of the quarks and gluons in a nucleon. Pioneering calculations have provided the first results (Figure 1), and the next stage is to obtain full control of systematic effects to allow comparison with distributions extracted from experimental data.

The spectrum of excited hadrons can be studied by computing hadron–hadron scattering amplitudes, in which the hadrons appear as short-lived resonances (Figure 2). Recent calculations have moved from the simplest case of elastic scattering, where the resonance has only one possible decay mode, to coupled-channel scattering, where multiple final states are populated. Predictions for the preferred decay modes of exotic mesons are being used to guide current experiments.

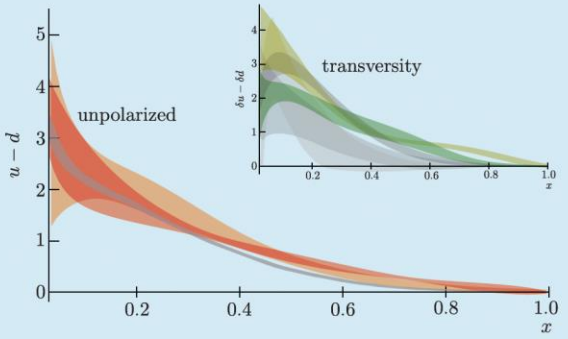


Figure 1. Unpolarized and transversity proton PDFs computed with lattice QCD (colored curves showing different pioneering approaches) compared to global fits to experimental data (grey curves) [S6].

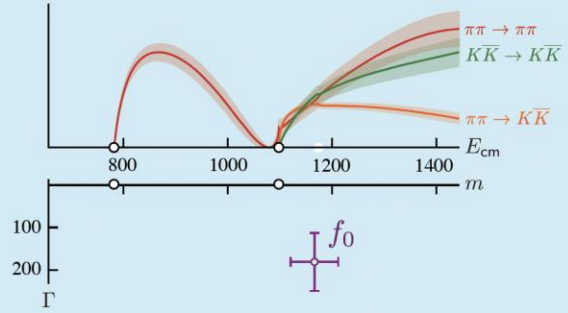


Figure 2. Coupled-channel scattering as a function of energy computed in lattice QCD showing how pion pairs can transform into kaon-antikaon pairs, enhanced by the presence of a resonant f_0 state whose mass and decay width are determined [S7].

Lattice QCD can precisely determine the hadronic or nuclear matrix elements that might otherwise obscure observables sensitive to breaking of fundamental symmetries or new physics. A relevant example is the axial charge of the nucleon, which has recently been computed with controlled uncertainty at the level of 1% (Figure 3), illustrating techniques that are used to explore matrix elements of few-nucleon systems.

The ability to compute QCD at finite temperature has been used to obtain the heavy quark diffusion coefficient that describes the action of the quark–gluon plasma on a heavy quark. The results agree with expectations for the behavior of a perfect fluid (Figure 4) and provide a vital ingredient in the interpretation of experiments measuring the flow of heavy-flavor hadrons in heavy ion collisions.

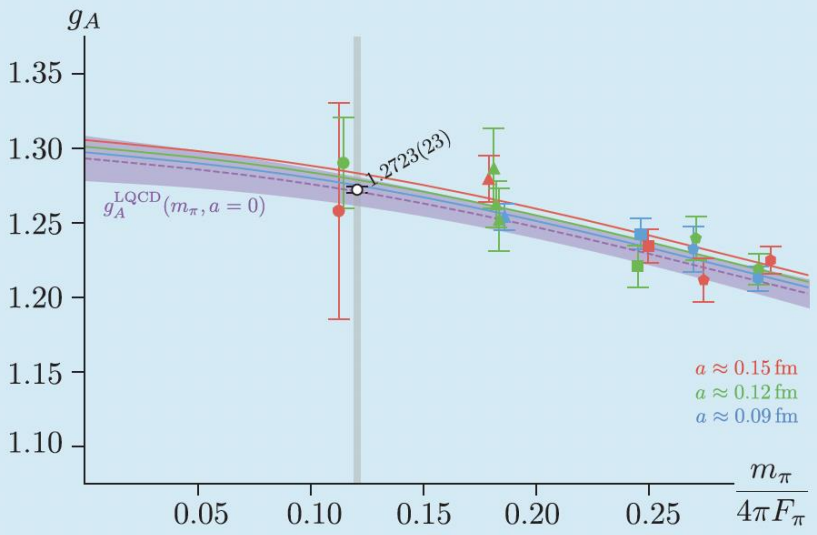


Figure 3. Precise physical-point determination of the nucleon axial coupling from lattice QCD extrapolated from non-zero lattice spacings, a, and unphysical pion masses [S8].

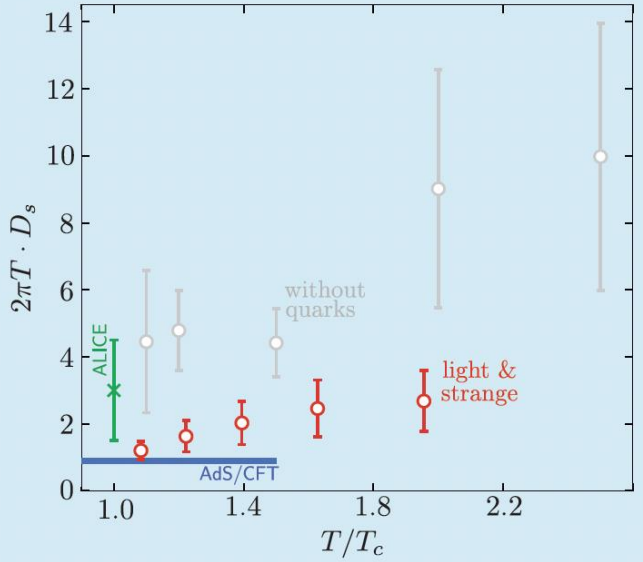


Figure 4. Heavy-quark diffusion as a function of temperature computed in lattice QCD (open circles) showing the effect of the presence of lighter quarks, and agreement with experimental data at the critical point [S9].

Where does the proton spin come from?

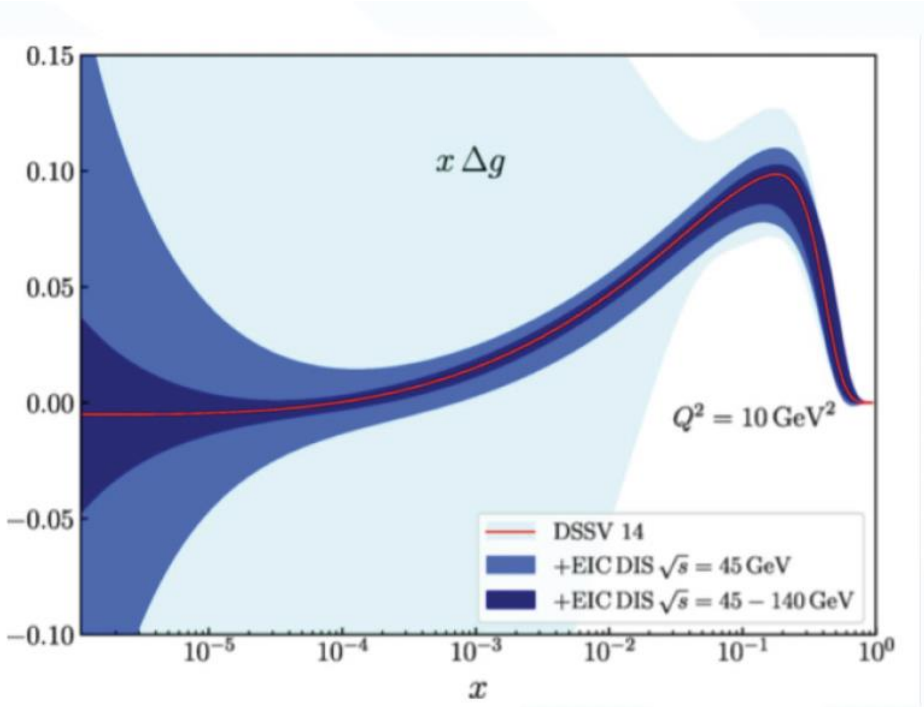


Figure 3.11. The best fit value of the gluon spin distribution from a global analysis.*The light blue band captures the uncertainty from the fit to existing data and the darker blue band shows the significant reduction that will be achieved with the EIC data [11].*

Three-dimensional imaging of the proton

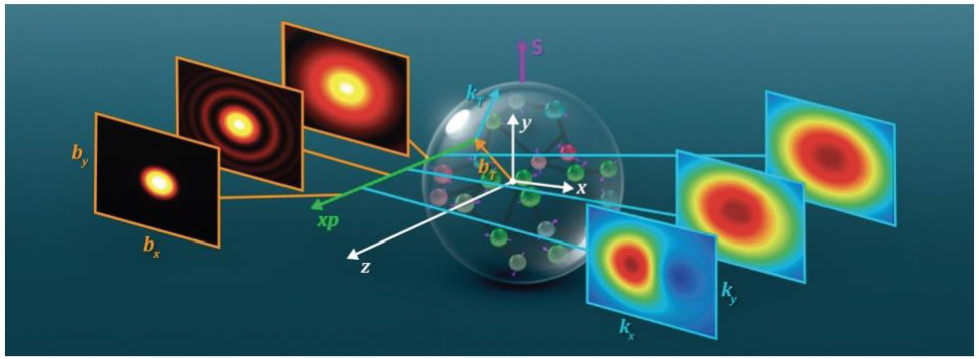


Figure 3.3. Parton images for a spin-up proton (magenta arrow) in slices of parton fractional momentum, x, for the quarks and gluons in a colliding hadron. *The images on the left give a spatial distribution in transverse location, while the images on the right picture the transverse momentum distribution [3].*

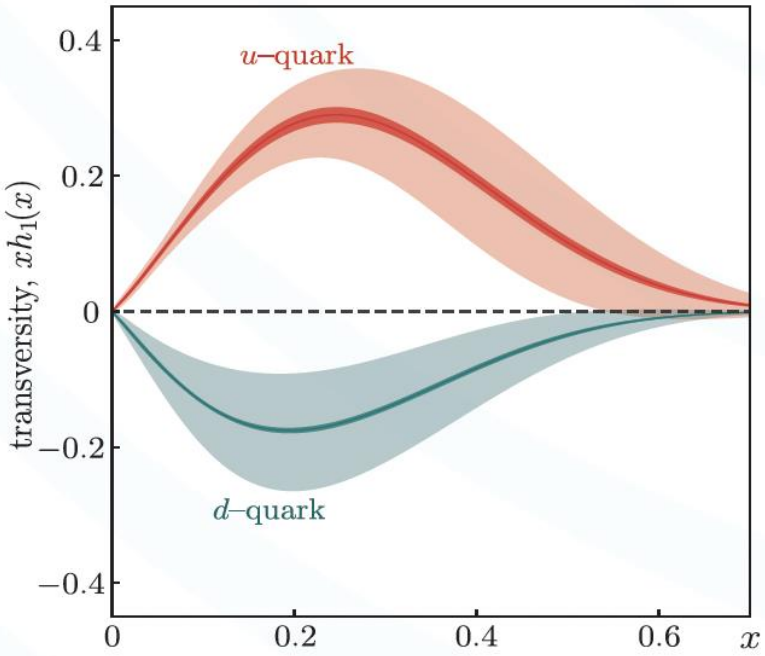


Figure 3.4. The up (red) and down (blue) quark transversity spin-spin correlation in the proton. *The wide uncertainty bands show the latest results based on a global fit to world data while the narrower, darker bands show the expected improvement by the SoLID detector [4].*

Sidebar 3.2 The Pressure Inside the Proton

In the history of the universe, protons were formed microseconds after the Big Bang, when the universe expanded and cooled sufficiently for the binding forces to become strong enough to freeze quarks and gluons together into protons and neutrons, the building blocks of the atom's nucleus.

The internal structure of the proton has been studied in great detail using the electromagnetic interaction as a probe. The elastic form factors, its internal distribution of charge and magnetism, have been studied for the past 70 years. Its quark structure has been studied for over 55 years, and its helicity, or spin structure, for over 40 years. In contrast, we know very little about the proton's mechanical properties: its internal mass distribution, angular momentum, pressure and shear stress. These properties are encoded in gravitational form factors, which can be probed directly only in the proton's interaction with gravity- a practical impossibility due to the extreme weakness of the gravitational force. Thus, the mechanical properties were completely unknown until recently.

A theoretical breakthrough enabled the first experimental extraction of one of the gravitational form factors, D(t), and the determination of the pressure distribution inside the proton shown in Figure 1 obtained in 2018 by scientists

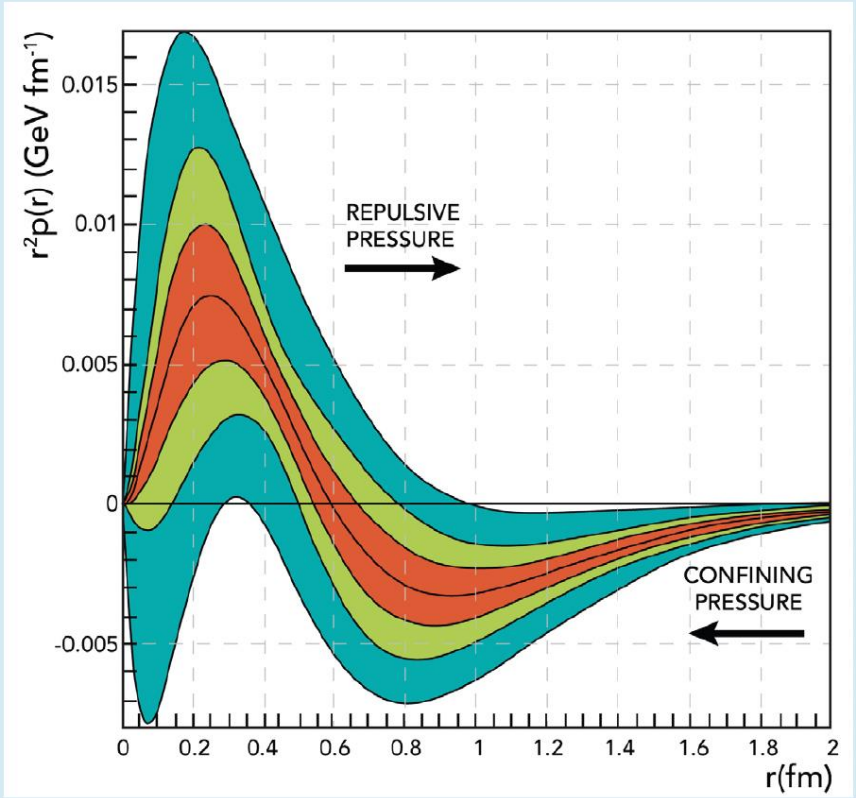


Figure 1. Pressure distribution in the proton weighted as $r^2p(r)$. The peak pressure at r = 0 corresponds to 10^{35} Pascal. The green shaded bands represent uncertainties if only initial world data (dark) or more recent high statistics data (light) are included. The red band represent projections of future experiments [S10].

from Jefferson Lab. These results were based on the analysis of deeply virtual Compton scattering (DVCS) data, measured with the CEBAF Large Acceptance Spectrometer CLAS, and combined with information provided by generalized parton distributions (GPDs), a theoretical framework for mapping out the internal structure of protons.

The comparison of peak pressure measured in various regions and objects on Earth, in the solar system, and in the universe are displayed in Figure 2. The tiny proton with a peak pressure of 10^{35} Pascal beats them all, including the most densely packed known macroscopic objects in the universe -the cores of neutron stars.

With current and planned state-of-the-art experimental facilities, further development and breakthroughs in theory and in lattice QCD, we will be able to reveal more of the mystery of the strong force, the most powerful force in nature, that binds quarks together to form the fundamental building blocks of the atomic nuclei.

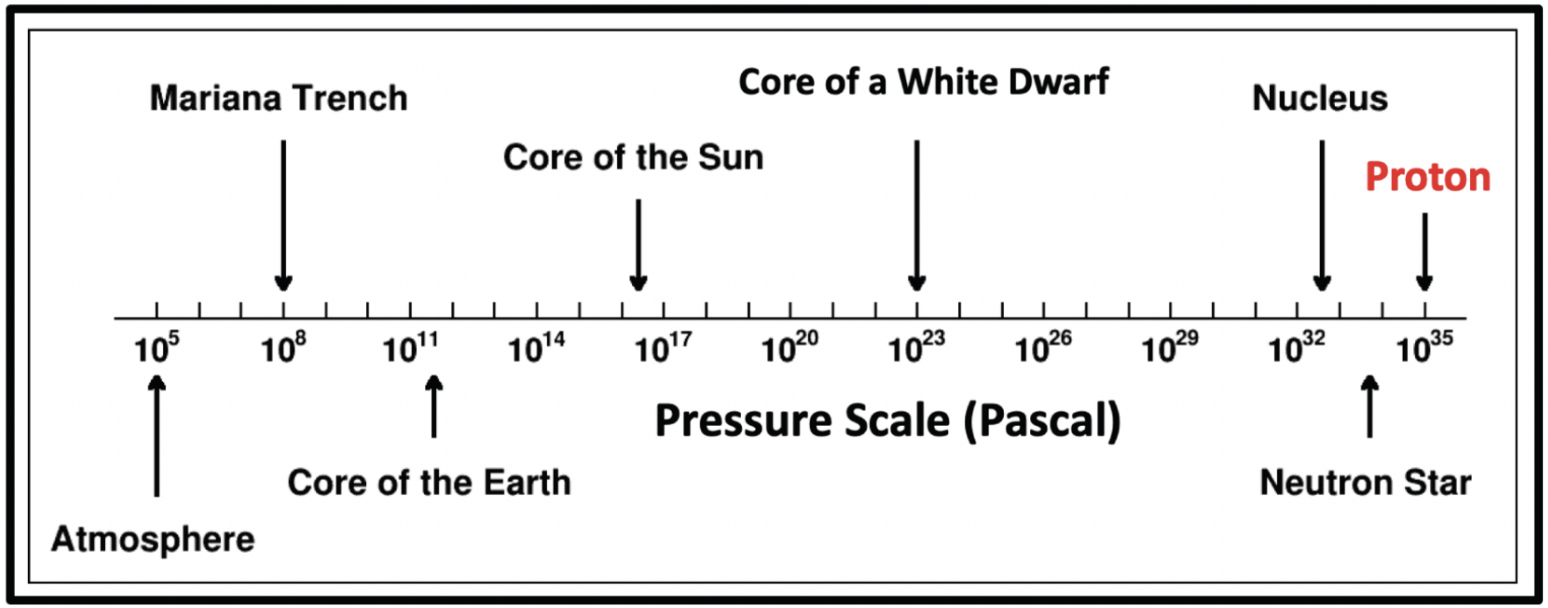


Figure 2. Peak pressure of objects in the universe, including the peak pressure inside the proton [S11].

Spectrum of excited hadrons

Sidebar 3.3 Connecting the World of QCD to the Visible World.

Because of confinement, we never observe the color-charged particles of QCD—quarks and gluons—in isolation; they are confined to color-neutral hadrons. Thus, every time a high-energy collision breaks up a proton, the energy of the collision allows the creation of more quark–antiquark pairs by converting energy into mass ($E = mc^2$), and the new quarks and antiquarks rapidly bind to the various constituents of the broken-up proton, "snapping" into mesons and baryons, the QCD bound states, which can be detected.

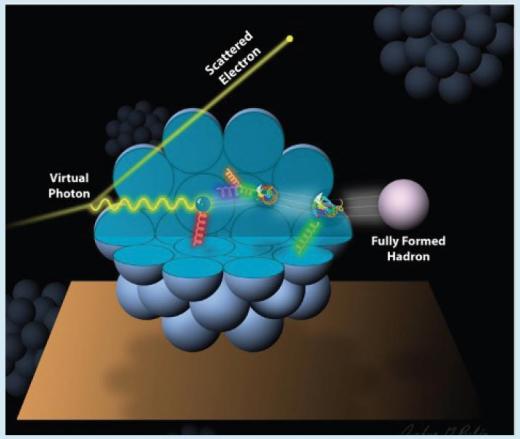


Figure 1. Representation of a high energy collision [S12].

Like blowing soap bubbles from the film with a bubble wand, when every free-streaming bubble must have closed off to become a whole bubble, every free-streaming product of a high-energy collision must have somehow become a "whole" color-neutral particle (Figure 1). Each time you blow on the soap film, a different number of bubbles of varying sizes may be produced. Likewise, each time a high-energy collision involving a proton occurs, a different number of hadrons of varying masses and quantum numbers may be produced.

To date, most efforts have focused on studying the production of a single hadron at a time along the same direction as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticated ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation measurements in hadronization by the STAR experiment at RHIC, multivariable measurements of identified hadron production in jets by the LHCb experiment at CERN, an investigation by the CLAS experiment at Jefferson Lab of how hadron-pair production is modified in cold nuclear matter, and the modifications to hadrons in jets induced by interactions with the quark–gluon plasma, observed at both RHIC and the LHC.

These exciting results naturally point to more questions.

- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization change in a dense partonic environment?

The upcoming decade holds great promise for advancements, both in how we think about hadronization theoretically and in our ability to experimentally untangle the various mechanisms that contribute to this phenomenon. Theoretically, recent developments in quantum computing provide unique opportunities to explore the inherent dynamic nature of hadronization as a process unfolding in time. Experimentally, hadron identification capabilities at the STAR experiment at RHIC, CLAS12 experiment at Jefferson Lab, LHCb and ALICE experiments at CERN, Belle II experiment in Japan, and the ePIC experiment at the future EIC will allow us to measure and compare a wide range of traditional and novel observables related to hadronization.

QCD and nuclei

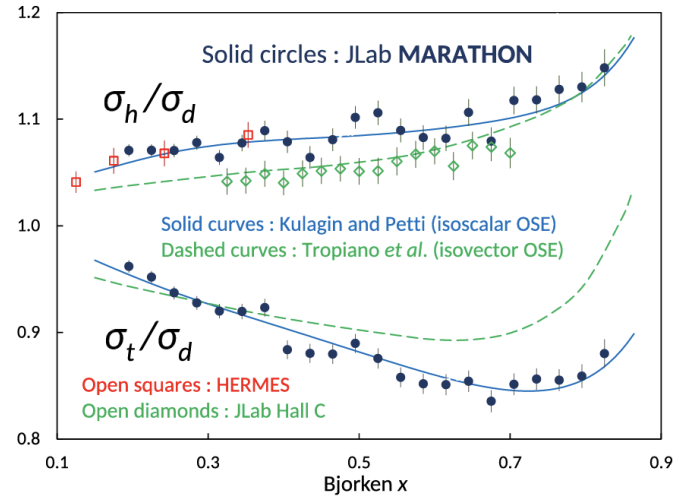


FIG. 1. The MARATHON results on the ^{3}He/^{2}H and ^{3}H/^{2}H DIS cross section ratios as a function of Bjorken x. The solid curves are the prediction of the K-P model (with isoscalar OSE) [19,45], and the dashed curves are the result of Tropiano *et al.* (with isovector OSE) [22]. Also shown are overlapping results from the HERMES experiment [5], as binned in Ref. [50], and final results from JLab Experiment E03-103 [6] (see text). The error bars include statistical and point-to-point systematics uncertainties, added in quadrature.

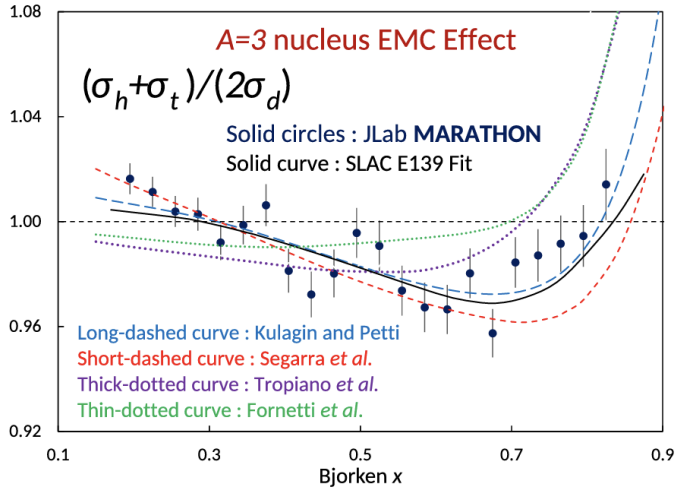


FIG. 2. The $A = 3$ EMC effect in a isoscalar combination of the ^{3}He and ^{3}H cross sections as a function of Bjorken x. The error bars include statistical and point-to-point systematics uncertainties. The long-dashed curve is the prediction of the K-P model [19,45] (with isoscalar OSE), the thick-dotted, dashed, and thin-dotted curves are results from Refs. [22] (TEMS, with isovector OSE), [25], and [53], respectively. The solid curve shows the A-dependent SLAC-E139 parametrization [3].

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Nuclear shell structure governs short-range nucleon pairing

D. Nguyen, C. Yero, H. Szumila-Vance, F. Hauenstein, N. Swan, L. B. Weinstein, J. Kahlbow, G. A. Miller, A. Schmidt, E. Piasetzky, O. Hen, C. Ayerbe Gayoso, E. Cohen, P. Datta, A. Denniston, B. R. Devkota, M. Diefenthaler, C. Fogler, B. R. Gamage, D. Higinbotham, I. Korover, C. Morean, M. Nycz, M. Satnik, ... E. W. Wertz + Show authors

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Summary

- It is possible to frame the powerful science case for studying the QCD structure of hadrons in the form of a handful of simple questions or statements.
- CEBAF can probe the valence quark region at low Q^2 with its world class beams.
- CLAS12 is a unique twenty-first century large acceptance detector specifically designed to study the final states in electron and photon scattering.
- Relatively modest investment in CLAS12 and CEBAF can open up unique and powerful new opportunities for world class research that will be complementary to EIC and extend for more than a decade.