Unity Parton Dynamics Imaging Project

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This document provides an over all description of the superficial aspects of the physics that should be represented in the interactive three dimensional environment for the parton dynamics imaging project. Also provided is some details about the various layers necessary for visualization of the dynamics at different scales.

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I. INTRODUCTION TO QCD

Upon its discovery, the quark seemed to contradict many of the established principles of quantum mechanics. Quarks combine in groups of three to form hadrons, but have never been observed to exist as independent particles. In addition, scientists have observed the ++ particle which consists of three up quarks whose spins point in the same direction. This violates the Pauli exclusion principle which excludes that two or more particles with spin in the same direction can occupy the same quantum system. The peculiar properties of quarks led to the introduction of the quantum chromodynamics theory (QCD) which explains the strong force acting between quarks.

The strong force acts between color charges of quarks and does not affect particles without color charges, called colorless particles. Color charges can be broken into three basic groups: red minus green (R - G), green minus blue (G - B), and blue minus red (B - R). Each quark can have a value of -1/2, 0, or +1/2 for each of the three charges. For example, the charge configurations for red, green, and blue quarks are shown below.

(R - G) (G - B) (B - R)

Red + 1 / 2 0 - 1 / 2

Green - 1 / 2 + 1 / 2 0

Blue 0 - 1 / 2 + 1 / 2

The antiquarks are formed by reversing the signs of the three charges. These are the only three types of quarks that have been observed in nature. These three quarks and three antiquarks have the property that they have the only combinations of non-zero charges for which the total charge equals zero. Furthermore, since the color charges of a quark add up to zero, the values of any two of the charges uniquely determines the value of the third. This allows mathematicians / theoretical physicists to consider only two charges and exclude the third when analyzing the properties of quarks.

The quarks combine to form color neutral particles, whose color charges are all zero in two ways: one red, one white, one blue, or quark and an antiquark. The first combination forms a baryon, and the second combination forms a meson. The mechanism that has been proposed to explain these interactions is the gluon. The gluon is a massless particle that transmits the strong force between quarks. The gluons are charged particles, unlike the photon, and come in nine different types according to their color-carrying properties: R to G, R to B, G to R, G to B, B to R, B to G, R to R, G to G, B to B. The superposition of the last three gluons, (R to R) + (G to G) + (B to B) does not change the color configuration of a quantum system. So, mathematicians / theoretical physicists can disregard this superposition, and only two independent gluons of the last three are needed in the quark model, making a total of eight gluons.

Since the gluons are charged, quark and gluon interactions can cause the quark to change color. For example, a Red quark could emit a (R to G) gluon and thus be transformed into a Green quark. The three color charges of a gluon can be determined by applying the law of conservation of color charges e.g. the color charges of the Red quark plus the color charges of the (R to G) gluon must equal the charges of the Green quark.

The fact that gluons are charged limits the quark - gluon interactions. For example, a red quark can only emit (R to G), (R to B), and (R to R) gluons, and it can only absorb (G to R), (B to R), and (R to R) gluons.

When a quark is placed alone in a vacuum, it becomes immediately surrounded by a cloud of virtual quarks and antiquarks and gluons. The antiquarks become polarized such that the antiquarks cluster nearer to the true quark than the virtual quarks. Hence, the actual color charge of the quark is shielded by the antiquark cloud. However, gluons act oppositely such that opposite charges repel and like charges attract, and the quark becomes surrounded by a cloud of virtual gluons of the same charge. Since there are far more virtual gluons than virtual antiquarks, the net result is that the apparent charge of the quark is spread out over the area around it. As a result, the true quark plus the cloud of virtual gluons exerts a greater force on the surrounding area than the true quark alone. Thus, more and more virtual gluons are attracted to the cloud, making it stronger and stronger. Eventually, the whole universe would be filled with a cloud of virtual gluons. The simplest solution to prevent the destruction of the order of the universe is to assume that there are no isolated quarks. They exist only in configurations that form baryons and mesons.

Observations show that the strong force between two quarks does not decrease as distance increases, but actually remains the same. This means that it would take huge amounts of energy to separate quarks and afterwards to keep them separated. Asymptotic freedom refers to the fact that strong forces become weak at very short distances, and quarks are free to move independently as long as they stay very close to each other. This provides evidence supporting that quarks do not exist independently in nature, since an isolated quark would be very unstable.

The QCD theory is new and has not had the chance to be tested out very much. Scientists are, however, fairly certain that the color force model of strong forces correctly describes quark-quark interactions. This theory is beautiful in its simplicity and mathematical symmetry and will lead to advancements in the understanding of the secret of matter.

II. INSIDE OF THE NUCLEON

The atomic nucleus is made of protons and neutrons (nucleons), which are themselves composed of quarks and gluons. Understanding how the quark–gluon structure and dynamics manifestly from the nucleons and providing a framework to model and visualize these intricacies is the focus of the Unity Parton Dynamics Imaging Project. We will attempt to use the Unity game engine to represent what is currently understood about the broad aspects of the quark and gluon dynamics and produce an interactive real-time simulation for different quantum states of the parent nucleon. We should incorporate what is presently known about charge density, spin, mass, sheer, pressure, as well as the longitudinal and transverse structure.

Though these partons can be many inside a single nucleon the amount of any physical quantity reflected on the outside must be conserved. Things like spin, energy, momentum, charge and so on – must equal sum to what is observed on the outside of the nucleon. The conservation rules help to keep track of whats happening inside with the quarks whizzing around at near the speed of light. Quarks are confined inside the nucleon by the strong force and set the stage of the dynamics we are interested in.

The nucleons have three valence quarks. Quarks have their own various intrinsic properties, including electric charge, mass, color charge, and spin. They are the only elementary particles in the Standard Model of particle physics to experience all four fundamental forces (electromagnetism, gravitation, strong interaction, and weak interaction). The nucleon have valance quarks of either *up* or *down* flavor with electric charge of $+2/3$ and $-1/3$ respectively. In total there are six types, known as flavors, of quarks: *up*, *down*, *strange*, *charm*, *bottom*, and *top*. The up and down quarks have the lowest masses of all quarks. The heavier quarks rapidly change into up and down quarks through a process of particle decay: the transformation from a higher mass state to a lower mass state. For every quark flavor there is a corresponding type of antiparticle, known as an antiquark, that differs from the quark only in that some of its properties (such as the electric charge) have equal magnitude but opposite sign. Quarks are bound by 1 GeV as compared to nucleons which are bound by 8 MeV in the nucleus.

The nucleons have their quantum number. Of particular importance is the intrinsic angular momentum, or *spin*. Spin is a quantum-mechanical property, akin to the angular momentum of a classical sphere rotating on its axis, except it comes in discrete units of integer or half-integer multiples of $\hbar$. The proton, like the electron and neutron, has a spin of $\hbar/2$, or $spin - 1/2$. So do each of its three quarks. How these spin add up to create to spin-1/2 of the proton we see is not clear but we do know its non-trivial.

In 1988 the European Muon Collaboration (EMC) at CERN shocked the physics community by announcing that the sum of the spins of the three quarks that make up the proton is much less than the spin of the proton itself. This was unexpected because the summing-up approach had worked for several of the proton's other properties. For example, the proton's electric charge of +1 can be accounted for by adding the charge of its two "up" flavoured quarks (+2/3) to that of its one "down" quark (–1/3). The density of the charge inside the nucleon is another matter and is largely dependent on where the quarks are distributed. The EMC experiment discovered that the net spin of the three quarks actually accounted for no more than 24% of the protons spin.

It was also discovered by the same collaboration that the cross section from a nucleon that is bound in a nucleus is different than if it was free. This EMC effect seems to be caused by the slowing down of quark motion in overlapping nucleons. Essentially causing energy depletion in the dynamics of quarks that are shared by the strong force [1]. This effect requires bound nucleons so we will ignore this for now and just focus on a single proton to start with focusing on spin and charge density.

Determining the alternative sources of the proton spin is the primary focus of spin physics. But understand this has been a multi-decade long endeavor for spin physicists. It could have come from the momentum acquired by quarks and gluons as they rotate about the proton's spin axis. But, this orbital angular momentum is hard to measure. It also could come for the spin of the gluons.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven Laboratory continues to provide information on gluon spin contributes [2]. These results seem to indicate that gluons contribute significantly and maybe as much as the quarks. But the RHIC results still have large error bars but more data is on the way.

The limits of theory:

Physicists would like to be able to calculate the proton's spin from first principle QCD. In practice this ends up being far too complex to permit analytical calculations due to the strength of the strong nuclear force. Electromagnetism or the weak nuclear force can be represented well mathematically and small higher-order corrections can be added as needed. But with the strong force, those corrections are themselves large making computation prohibitively difficult even in simple processes.

These higher-order corrections are necessary to say anything about the observables and to account for the fact that gluons themselves possess color and can interact with each other. Gluons can also decay into pairs of quarks and antiquarks, as a consequence of Heisenberg's uncertainty principle. This can happen continuously and very quickly. These pairs are virtual quarks or sea-quarks and can have an uncertainty in mass-energy that is very large, which implies that these pairs can pop in and out of existence very easily being transient vacuum fluctuations. Sea-quarks do not necessarily carry the same mass as real quarks, although they always conserve energy and momentum. The longer the sea-quark exists, the closer its characteristics have to be to real quarks.

The real quarks that are stable in bound states in the nucleon on the valance quarks and behave under normal energy-momentum conservation. Other results from RHIC indicate that different flavors of virtual antiquarks contribute differently to the proton's overall spin and in a way that's opposite to those flavors' relative abundance. [3].

The extraordinary complexity of QCD means that physicists must derive many key parameters of the parton dynamics and nucleon structure from phenomenology, without first being able to predict them from a model independent theoretical framework. The scattering process used to study the internal structure of the proton are called deep processes and produce a virtual photon at a short wavelength to probe deep inside the nucleon. An example that has been extraordinarily fruitful is deep-inelastic scattering (DIS). To measure quark spin using DIS, both the incoming leptons and the target protons must be polarized, so that the spins of the two particle are parallel or anti-parallel. Conservation of spin means that leptons can only interact (via the exchange of a spin-1 photon) with quarks of opposing spin. So by firing leptons first polarized in one direction and then the other, and recording the number of angular distribution in each case, physicists can work out the distribution of spin oriented quarks.

Early measurements showed that quarks contribute about 60% of the proton's spin, which was not surprising, since relativistic effects had already been predicted to transform some of the quark spin into orbital angular momentum. This transformation happens because quarks are confined in a small space inside the proton, and according to the uncertainty principle, this implies that those quarks have significant momentum perpendicular to, as well as along, their direction of motion. This means the quarks gyrate, and they do so at relativistic speeds because of their small mass.

Energy is a crucial parameter in scattering experiments because higher energies correspond to shorter wavelengths and therefore higher resolutions. And the higher the resolution, the more dense is the sea of virtual quarks and gluons visible inside the proton – given that quarks radiate gluons that split into quark–antiquark pairs, which then emit further gluons, and so on. That ever higher density in turn means an ever greater parcelling up of the proton's energy, which means that each particle carries an ever smaller momentum. Since quark spin has to be integrated across quarks of all momenta, higher-energy probes provide a better estimate of the total contribution of all quarks to the spin of the proton. The modern estimate of all experimental data indicate that valance quark spin contributes about 30(+/–5)% of the proton's spin.

Gluons vs orbital motion:

With the quark-spin contribution thus pinned down, attention turned to the remaining 65–75% of unaccounted-for proton spin. These contributions come from the quarks' orbital angular momenta, the gluons' spin and the gluons' orbital angular momenta.

It has been asserted that all of the remaining fraction of missing spin can be accounted for via the conversion of quark spin into quark and antiquark orbital angular momenta [4, 5]. This comes from the use of a model that treats the proton as a "bag" of three quarks surrounded by a cloud of pions, which are very short-lived particles with a quark–antiquark core. This is known as a "cloudy-bag" model, the effects of three phenomena add up to generate the required spin-to-orbital angular momentum conversion: one, the relativistic movement of quarks; two, the exchange of gluons when quarks interact; and three, a proton's brief "fluctuation" into a proton or neutron plus a pion so any flipping of the proton spin results in the pion carrying away orbital angular momentum. These results are consistent with lattice QCD calculations when analyzed as a similar energy scale. But with more gluon data coming from RHIC gluons are showing themselves more clearly. RHIC collides two beams of polarized protons, and (as in the earlier, lepton-based deep-inelastic scattering experiments) it makes measurements with the spins of the beams aligned and then anti-aligned. However, whereas leptons cannot scatter off gluons directly because they do not feel the strong force, the colliding RHIC beams produce plenty of interactions involving quarks and/or gluons, thus providing direct information about gluon spin.

Gluon spin can screen the total quark spin contribution through a quantum effect called the axial anomaly. Another issue is that the topological effect can delocalize the quark spin inside the proton so that it is, in part, invisible to scattering on individual and localized quarks.

Energy boost:

As is the case with quark spin, gluons' spin contributions must be summed across all momenta – and RHIC's collision energies of 500 GeV are not quite energetic enough to probe gluons at the lowest end of the momentum scale [6].

The gluon spin contribution has still to be settled. The gluons true contribution to proton spin remains unclear because primarily at higher energies, where their spin contribution increases, their angular momentum contribution actually goes down. It is still possible that slow-moving gluons have their spins aligned against that of the proton, thereby reducing gluons' contribution or even cancelling it altogether. Models tend to predict that gluon spin is aligned at low momenta.

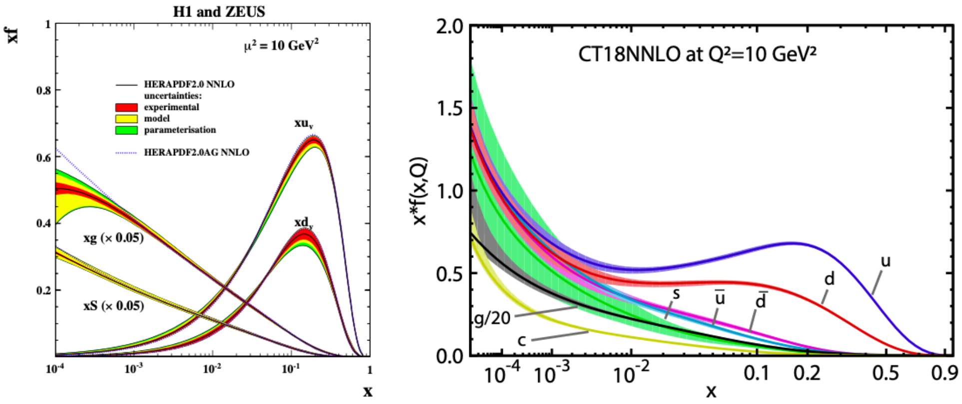

FIG. 1. The parton distribution functions show the increase in gluons and sea-quarks with increased energy of the probe.

III. INSIDE THE PROTON

In this project we aim to create a computer generated dynamical model to represent these quark gluon dynamics. The construction of the various proton spin states that we build can be represented by the Wigner function quantum mechanically but we should also try to represent this same information in a mechanical model that represents the phenomenology as technically accurate as possible. The first step for this project is just to demonstrate that its possible to visualize multiple variables dynamically using the Unity engine.

Energy is a crucial parameter in scattering experiments because the higher the energy of the probe the shorter the wavelengths and therefore the higher the resolution of the image of the inner working. The shorter the wavelength of the probe providing better resolution of the higher density sea of virtual quarks and gluons visible inside the proton. Quarks radiate gluons that split into quark antiquark pairs, which then emit further gluons, and so on. This higher density of partons in turn means an ever greater parcelling up of the protons energy, which means that each parton carries an ever smaller fraction of the total momentum. Since quark spin has to be integrated across quarks of all momenta. The lower x or higher-energy probes provide (see Fig. 1) a better estimate of the total contribution of all quarks to the spin of the proton from the most energetic valence quarks to the lowliest sea quarks.

Measurements at CERN and DOE's Fermi National Accelerator Laboratory have consistently found more down antiquarks than up antiquarks in the proton. The momentum space distribution of flavor is understood in terms of orbital angular momentum.

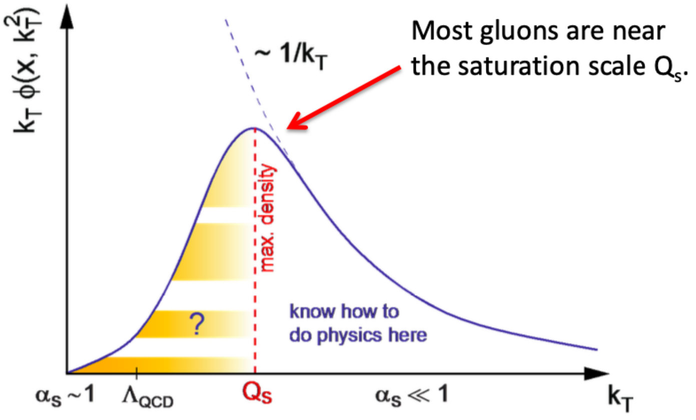

FIG. 2. Change in gluon density as a function of transverse momentum as determined by Transverse Momentum Distribution functions (TMDs)

From Zeus data we know that quarks are about 2000 times smaller than a proton at $(0.43x10^{-16}$ cm) [7] where the quantum foam exists at $(10^{-33}$ cm). As energy increases partons are produced overlapping each other and all of them are about the same size. When a critical density is reached no more of that size can fit in the wave function.

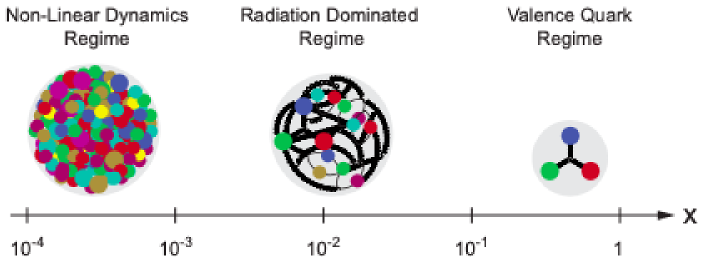

FIG. 3. The change in internal quark and gluon structure of the proton going from high to low x or increasing energy.

The proton starts producing smaller partons to fit. The density of partons of smaller and smaller size increase with small-x. With increase resolution (Q^2) you can see more partons. With increase energy (decreasing x) there are more partons and they are more tightly packed. The gluon size is about $1/k_T$ or 1 over the transverse momentum.

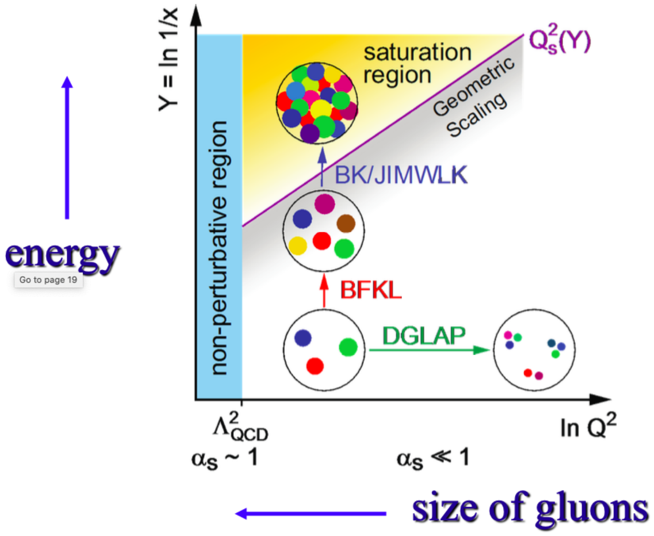

FIG. 4. Change in density of the gluons as a function of energy and Q^2.

Gluons can be represented as getting larger with small x and ultimately run into some sort of gluon saturation that fills the space of the proton with infinitely dense gluons distributions. There is a larger number of small-x gluons and quarks as shown by the PDFs. At very small-x high number of gluons populates the transverse extend of the proton or nucleus, leading to a very dense saturated wave function known as the Color Glass Condensate. The proton starts producing smaller partons to fit them in. The gluon size decreases with $\ln(Q2)$. The number of gluons and sea-quarks increases with $\ln(1/x)$. Networks of highly dense gluons that are interconnected swarm in all spatial regions until the regions are completely filled.

FIG. 5. Graphic of flux tubes

From Lattice qualitatively we can represent some generalized dynamics. Bound quarks are constantly exchanging virtual gluons, which we can think of as forming a flux tube between the three. This spatial region between the valence quarks suppresses the gluon field. The gluons can bind to them selves and other virtual gluons and sea quarks. Any odd number of quarks can make up the proton at any time. There are always three valance quarks and arbitrary number of quark antiquark pairs n resulting in $3+2n$ total quarks. The quarks will most probably be at the peaks in the gluon field fluctuations with none manifesting between the valance quark flux tubes. The motion of the valence quarks pushes the sea quarks around creating phase dynamic to the energy and charge density to the sea that are also spin orientation dependent. When the proton is polarized transversely with the spin pointing vertically with respect to the probe the up quark have a greater momentum density to the right while the down quark has a greater momentum density to the left.

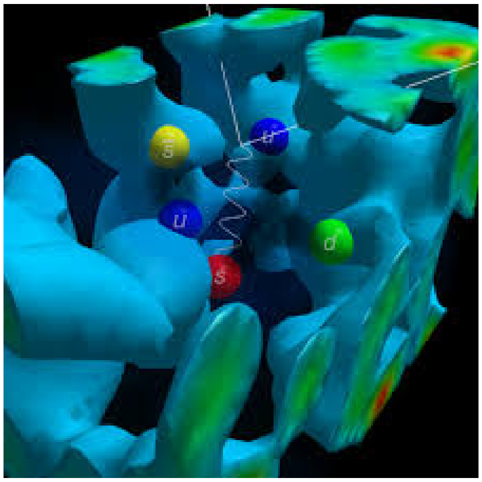

FIG. 6. Representation from Lattice QCD showing how quarks sit at the peaks in the gluon field fluctuations

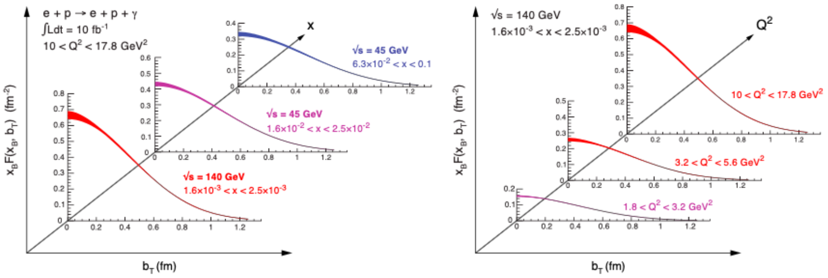

FIG. 7. The projected precision of the transverse spatial distribution of partons obtained from the Fourier transform of the measurement of the unpolarized DVCS cross-sections as a function of $|t|$. b_T is the distance from the center of the proton, also called the impact parameter. Left plots show the evolution in x at a fixed Q^2 ($10 < Q^2 < 17.8$ GeV^2). Right plot shows the evolution in Q^2 at a fixed x ($1.6 \times 10^{-3} < x < 2.5 \times 10^3$).

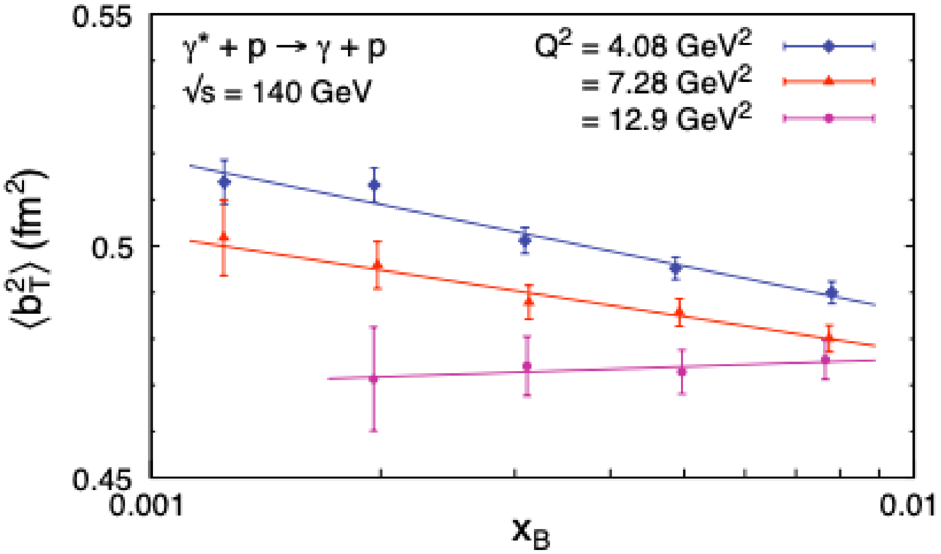

FIG. 8. The average value of the mean squared parton radius of the prton, extracted from the DVCS cross-section, plotted as a function of x. Results are shown for three different values of Q^2.

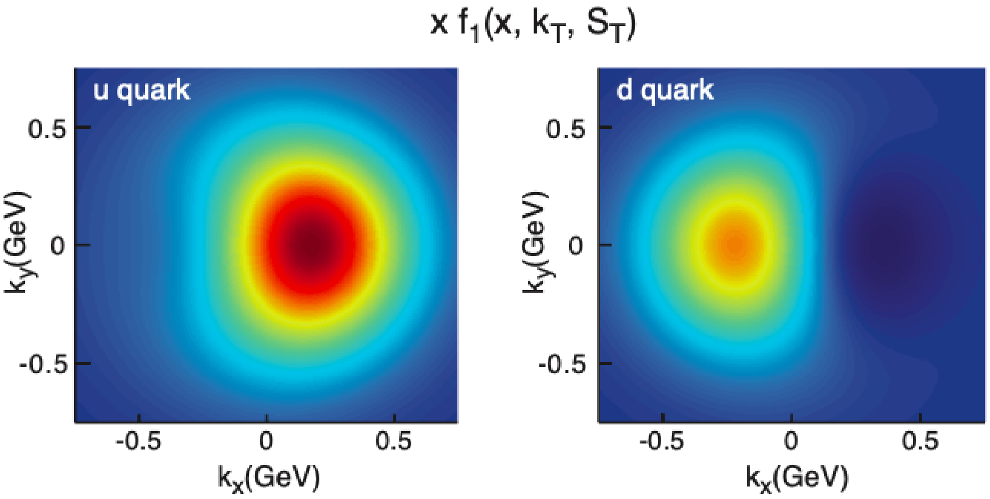

FIG. 9. The density in the transverse-momentum plane for unpolarized quarks with $x = 0.1$ in a nucleon polarized along the $\hat{y}$ direction. The anisotropy due to the proton polarization is described by the Sivers function with model of [8]. The deep red (blue) indicates large negative (positive) values for the Sivers function.

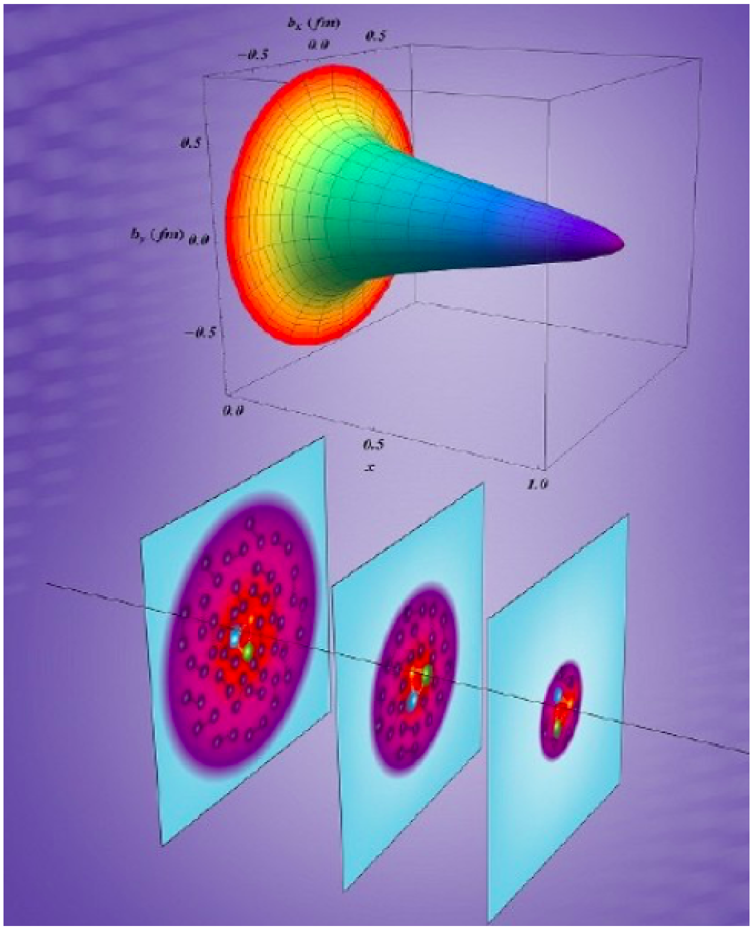

FIG. 10. The density as a function of the impact parameter shown for various x. For smaller x the is much more partonic interaction over a larger region of space. This picture is constructed using DVCS information.

IV. REPRESENTATION IN MULTIPLE UNITY LAYERS

In the first round of this project we will start with five layers of magnification.
Lets start with a transversely polarized proton.

- Outside of the proton
- High x with valance quarks visible (Q^2 slider)
- Lower x with flux tubes and sea visible (Q^2 slider)
- small x with focus on sea and gluon fluctuations with sliders in Q^2 and k_T
- gluon network

For this initial test mock-up we will start with polarized hydrogen atom with a single polarized proton as the nucleus. The distance from the proton to the electron orbiting in its ground state is one Bohr radius or 5.29×10^{-11} m where the charge radius of the proton is about 0.84×10^{-15} m. The speed of the electron in hydrogen is about 2.2×10^{6} m/s.

It would be good to be able to scale in at ones choice of magnification with the capacity to navigate around spatially and change the time scale as desired.

A. Outside the Proton

This layer starts from the outside of the hydrogen atom showing the electron whizzing around to make a cloud with its fast moving electron. Its not necessary to have the velocity correct but we need the ratio of things to be correct and we need to keep track of these ratios. The quarks should be represented as sphere or point like particle jiggling around and orbiting the central access of the proton.

Zooming into the proton we must see also a sphere formed by fast moving particles. A polarized proton is made up of three quarks orbiting the center with d quark following a right hand orbit and the two u following a left hand orbit. The density of the quarks at a particular instant in time should follow what is presented in Fig. 9. It should be able to zoom in and see that shape of the proton produced by the three quarks motion. So this should be zooming into a frame that is about 5×10^{-15} m. The quarks are about 2000 times smaller than a proton so one can not see them at this level just the proton structure formed by the fast moving quarks.

Quarks are confined in a small space inside the proton, and according to the uncertainty principle, this implies that the quarks have significant momentum perpendicular to, as well as along, their direction of motion. This means the quarks gyrate, and they do so at relativistic speeds because of their small mass. The quarks move back and forth at a speed close to the speed of light, and in random directions. This back and forth movement, or zigzag motion, has been quantified [9]. For our purposes we should use about 2.5×10^{8} m/s for the orbiting speed with up and down and side to side motion about 1% of that.

The path should be mapped out using the information in the plots of the Sivers function. This indicates where the quarks spend most of their time as they orbit. We should be able to match the slices provided and made our own based on our orbiting quarks. We should also have a slider here that can change as a function of x from about 1 to 0.6. This doesn't produce very high resolution but does change these density plots by broadening them a bit and sharpening the quark visibility.

B. High x Quarks and Gluons

From the above perspective we must zoom in by a factor of 500 showing the orbital dynamics of the three valance quarks orbiting the center with d quark following a right hand orbit and the two u following a left hand orbit with superficial views of the quarks flux tubes.

Since gluons themselves carry color charge, they participate in strong interactions. These gluon-gluon interactions constrain color fields to string-like flux tubes, which exert constant force when stretched. Due to this force, quarks are confined within the proton. This effectively limits the range of the strong interaction to about a femtometer. Beyond a certain distance, the energy of the flux tube binding two quarks increases linearly. At a large enough distance, it becomes energetically more favorable to pull a quark-antiquark pair out of the vacuum rather than increase the length of the flux tube. This would result in two new particles from the orignial one.

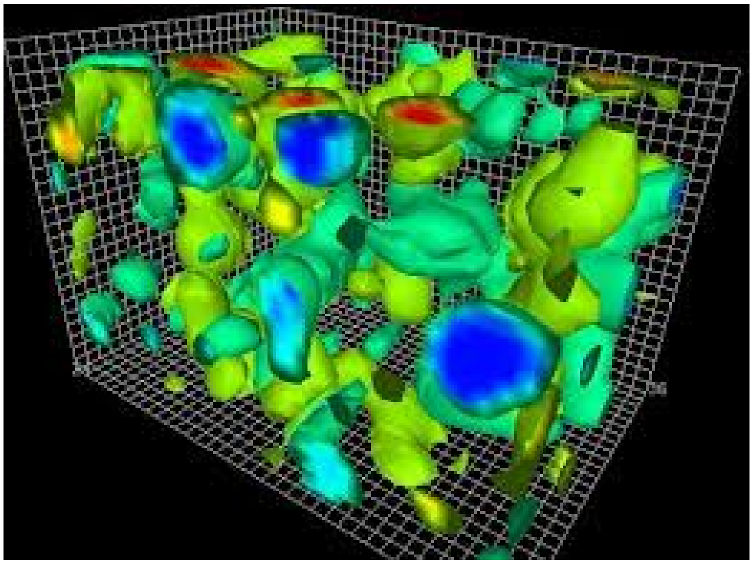

FIG. 11. The quantum fluctuation represented from LQCD

In the space taken up by the proton that the valance quarks do not occupy the sea-quarks pop in and out of existence randomly at a rate that is just a little slower than the rotation rate of the valance quarks. The sea-quarks interact with the valance quarks and their orbit. Some sea-quarks follow the valance quarks dragging then in temporary flux tubes. These flux tubes also exist between the sea-quark pairs. As the high speed quarks move through this space they pull sea-quarks pairs into existence. Each quark flavor must be represented. And each two or three quark combinations must be color neutral. The color of quark could be represented by the real color image. Red, blue and green are common with antigreen (magenta), antiblue (yellow), and antired (cyan) for the antiquarks. Gluons are mixtures of two colors, such as red and antigreen, which constitutes their color charge. The gluons can be represented as spheres about 10% of the quarks when passing between them with the color charge in the center and the anti-color charge on the outside. There are eight possible combinations of color and anticolor for the gluons. Each exchanged gluon hold the color it came from and the anticolor that its going to.

The spin of all the quarks and antiquarks should also be represented. This can be indicated as having a slightly pointed top in the direction of spin rather than having each quark be perfectly spherical. For unpolarized quarks the spin oriented randomly. It may also be better to be able to switch the spin indicator off and on by having a 3D arrow point in the parton spin direction when the switch is on.

C. Lower x Quarks and Gluons

At low x we should have the capacity to zoom in by another 1000 times. At the highest magnification of this layer the quarks and gluon fluctuations are quite visible and the density of the vacuum fluctuations becomes overwhelming. More and more partons are visible as x gets smaller. For high Q^2 the partons are smaller in size so there should be a slider for Q^2. So the greatest number of quarks fit in the proton space with very low x and very high Q^2 as shown in Fig. 2, Fig. 3 and Fig. 4. k_T also become important for gluon as the saturation scale of Fig. 2 is defined by it so this should also have a slider.

In the flux tube model, the gluons become tubes connecting two or three quarks. In a system of many quarks, the selection of which pairs or triplets to connect is done in a way to minimize the total distance involved. The longer the flux tube, the further that the gluon particles are must travel. Since they travel at a finite velocity, a longer distance requires a longer time. By the uncertainty equation, $\Delta t \Delta E \geq \hbar/2$, the longer the virtual particle exists, the lower the energy available to be borrowed to make the virtual particle.

The flux tube at this level can be see as structures that exist between both valance and sea-quarks leading to suppression of the gluon field between them. quarks always exist in sets of two or three and the space between them caries the binding force that hold them together and suppressing all gluon fluctuations between them. This empty space between the quarks (flux tube) is truly empty with no fluctuations of any kind within that space. As the quarks become more separated the flux tube remains the same diameter and same sort of depth of suppression of the gluon field. So this force does not increase. These quarks are always confined until enough energy is put in that is become

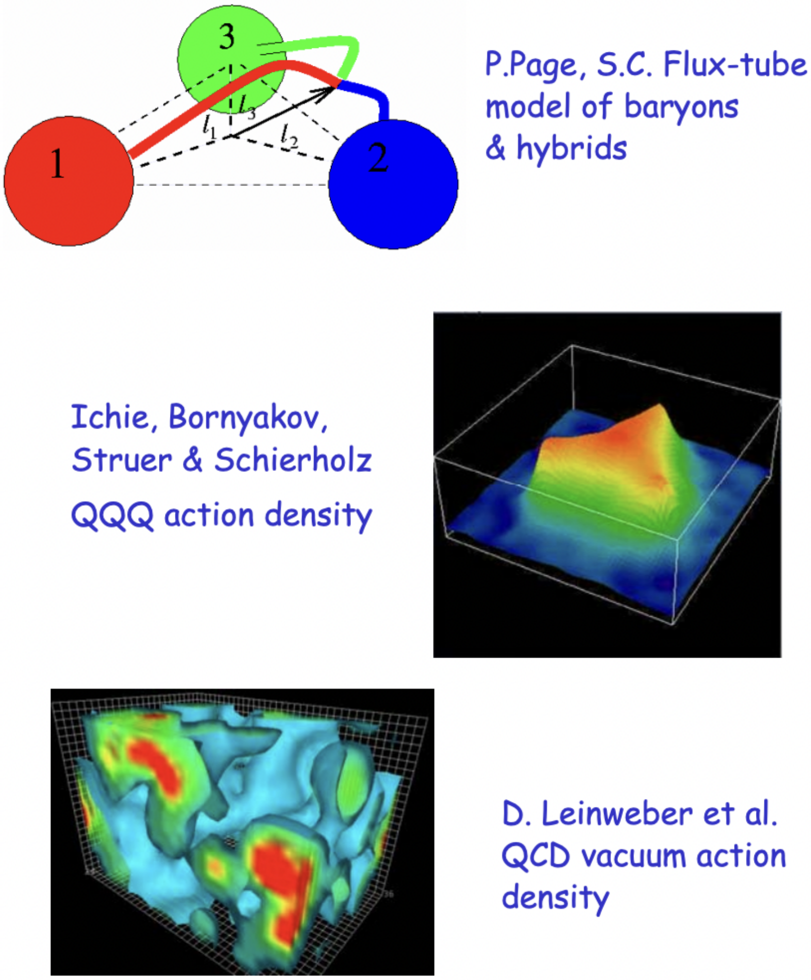

FIG. 12. flux tubes and vacuum fluctuations.

more efficient to pull new quark out of the sea. In the proton you get Y-shaped flux tubes which create suppression of the gluon fluctuation in a Y shape as its orbits around the center of the proton with one leg moving in the opposite direction as the other two.

At this level all of the fluctuations are very visible at high resolution and even gluon-gluon states can be seen. See figure above.

In truth the flux tube are not solid but instead exists as a hollowing out of the space between the quarks. Gluons do not move inside of the tubes but instead exchange along the outside of the tube in the space of the gluon vacuum fluctuations. The color of the valance and sea-quarks continuously change. This leads to continuous fluctuations in the flavor dependence of the dynamics of the quarks being that u quarks have a motion orbiting in the opposite direction of the d quark.

D. Small x Quarks and Gluons

On the final magnification scale we go down by another scale of 1000 where the gluons form networks of gluons and sea-quarks. All the above dynamics are still happening making these networks form and reform continuously. Gluon fluctuations play a large role at this level. We know that, on average, a proton is about one femtometer in size. But data indicates that protons are very different at high energies, with a width of half a femtometer for the distribution of the position of the individual quarks and an extra variation of 15% on the proton size for the gluon clouds around the quarks [10, 11].

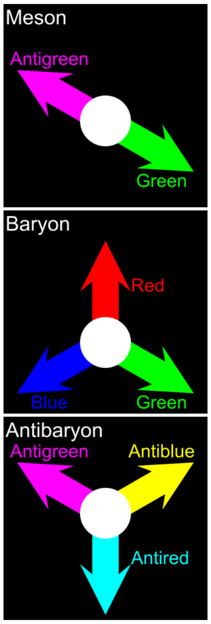

FIG. 13. The color of the quarks each of these combinations shoe the thee colors and anticolors. For Baryons there must always be three colors to make a color neutral particle. For mesons only a color and anticolor or required.

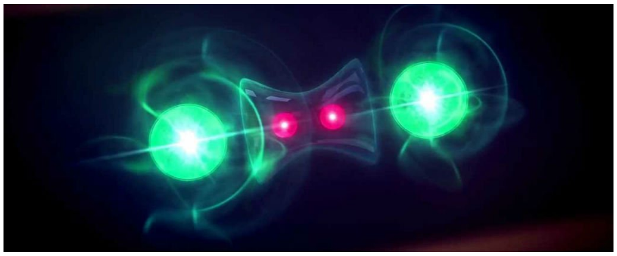

FIG. 14. A cartoon of what a flux tube between two quarks might look like. In truth the flux tube are not solid but instead exists as a hollowing out of the space between the quarks. Gluons to not move inside of the tubes.

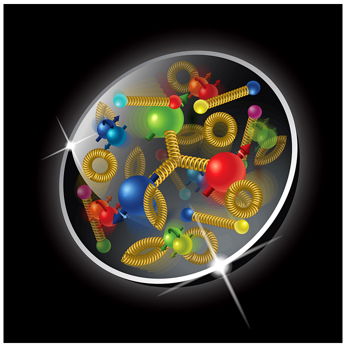

FIG. 15. A cartoon of the inside of the proton. The gluons are represented by springs. This is just an artistic notion of how everything inside of the proton has to come together.

Gluon fluctuations like the sea-quarks are very fast and very random and interconnect creating a vast network of instantaneous connections that change as fast as they form which is about 99% of the speed of light. So at 10^{24} frames per second we would see them popping in and out of existence a few times per second. In the region of space inside the proton without dynamics from the quarks the volume containing gluon fluctuations is about 40%. But what 40% changes continuously. The density of gluon fluctuations is strangest around the quarks and the flux tubes. These fluctuations outline where the flux tubes form but do not penetrate the tubes. The tubes are completely empty of

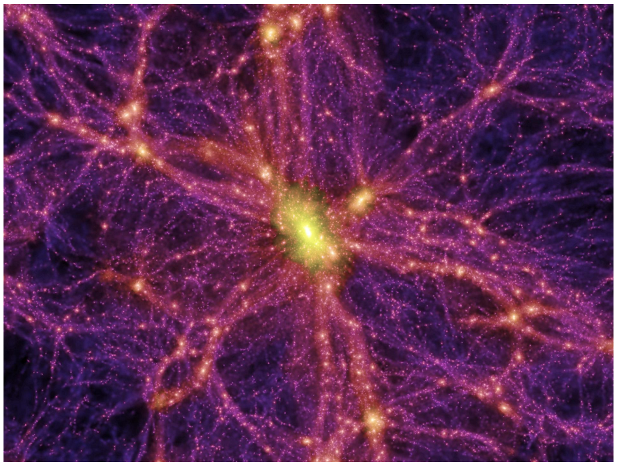

FIG. 16. This is a computer generated map of the dark energy in the universe but it is also a close representation of what a gluon network might look like.

the gluon fluctuations.

The both the valance and sea-quarks sit on these fluctuations mounts in the gluon field. These gluon fluctuations mounts have to then follow the valence quarks in their orbiting dynamics as these fluctuations create potential wells for quarks to form. The space between the quarks (flux tubes) exists by suppressing the gluon fields creating the binding force.

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