3D Proton in Unity

This project uses virtual reality (VR) and other visualization tools to model the mechanical and quantum mechanical properties of the partons inside the proton. The quark and gluon dynamics are responsible for more than 98% of all mass around us. Still, it is not clear how this motion manifests and how the energy density and composition of the proton changes under various states. For example, the proton can be polarized so the spin is oriented along some particular axis. This will naturally change the dynamics and the partons state as well. Quarks and gluons can spin, and can have linear and circular motion, and can appear and disappear continuously and sporadically. This project has two overarching goals. One is to visualize the complex internal structure of the proton. We intend to do this with Unity-based VR with help from other tools like Blender, and Niagara from unreal engine 5, and other ways to test and explore visualizing this information. The second goal is to develop a detailed and accurate simulation of these dynamics and the proton's internal structure using data from experiments, lattice QCD, and phenomenology. These simulations should be able to evolve in time and should be able to contain much of what we presently understand about the proton's insides, like charge variations, flux tube geometry, the density of sea-quarks, and gluons at various Q2 and momentum fractions. In the end, these two goals should be merged and the visualization studio should be combined with the simulation and modeling package.

For the VR visualization studio, we are still testing and exploring but the basic approach is to develop assets using 3D modeling of quantum mechanical objects in a somewhat classical and intuitive representation while also utilizing standard and costume physics engine capabilities. The development of a specialized physics engine to manage the electricity and magnetism, the energy and momentum, and the color charge will be required. There are also many quantum mechanical dynamics that require a costume physics engine. Right now the platform is Oculus Quest 2, but we are likely going to need more computational power to achieve the long-term goals.

You can learn about some aspects of the experimental effort and the piecing of these results together here:

Some details on how information is extracted experimentally for the future:

https://www.bnl.gov/eic/rhic-eic-comparison.php

https://indico.cern.ch/event/797767/contributions/3682425/attachments/1965703/3268608/BNL-EIC_Mumbai_2020.pdf

A write-up by Jinge Zhou discusses some hypothetical ways to address some of the goals of the Unity Project:

3D Proton Desig...cumentation.pdf

A high-level write-up to introduce some of the basic goals of the Unity Project:

Unity_Project.pdf

The repository of the project is here:

https://github.com/uva-spin/VR-Unity/

The group Discord page is here:

https://discord.gg/pwExfsum

Other reading about models:

https://physicstoday.scitation.org/doi/10.1063/PT.3.4743

https://physicstoday.scitation.org/doi/10.1063/PT.3.4871

On Projects:

Layer 1: Three valance quarks orbiting inside the proton. Their dynamics are largely random following a turbulent path driven by quantum fluctuations and

momentum as well as the tension that binds them together. These are called flux tubes. When polarized the dynamics are much more orderly and follow a

path around the center of the proton. A swarm of gluons exists in the space around the valance quarks along with sea-quarks with are virtual quarks that pop

in and out of existence continuously.

Physics Implementation:

Flux tube (String) tension on quarks

Flux tube pushing away gluon swarm

forces between gluons and quarks

forces between gluons and gluons

Electricity and magnetism between all quarks

Layer 2: Here we want to zoom in on a region, either a valance quark, a flux tube region, the edge of the proton, or an open region where sea-quarks and gluons

are swarming.

Layer 3: In this layer, we are zoomed in even further than any other one. Things are so zoomed in on the quantum fluctuations that the gluons start to look like

an ever-evolving network connected into space that continuously fluctuates varying in gluon density creating a massive network of interacting gluons in some regions and low-density pockets in other regions.

gluons.mp4

gluons2.mp4

Status video:

https://drive.google.com/file/d/11u1zmO5MYS-LrW_mVfVrKlADVq_nACMT/view?usp=sharing

Description of Parton Dynamics

This tool is intended for the visualization of different models of dynamics so we ultimately want to be able to switch between the various models using the UI.

The following is true for all models:

Forces: There is a centrifugal force on the quarks as they orbit with some momentum. This force should manifest naturally due to the fact that the quarks have some intrinsic energy which means they must be given an initial momentum. There is the color charge force (strong force) which is the flux tube that binds the quarks together. There is electricity and magnetism that are applied to all of the charged quarks. The force between valance quarks should go as $\mathbf{F(r)=Ar+Br^{Cr}}$. In other words, at small **r** where the quarks are close together, there is a spring constant **A**. As **r** gets bigger (beyond the diameter of the proton) then the attractive force gets stronger and stronger very fast (try **A=0.3, B=0.1 C=2.9**). The sea quarks should go as $\mathbf{F(r)=a/r^2+b}$ where **r** is again the distance between them. Both **a** and **b** are constants that play a role in the spatial region that each term kicks in. The sea quarks actually undergo a gluon-mediated scattering interaction governed by an inverse square law just like Coulomb's law. The difference is that there's a second term in the equation, and it's a *constant*. Regardless of the distance between them, two "unpaired" quarks will be attracted to each other with a constant force on top of the inverse square law which is 137 times stronger than the electromagnetic force. So **a** is 137 times the scale of the force between two charges (Coulomb's Law) and **b** should be on the same scale as **a**. Here I've provided some starting parameters but we should have these parameters be something that we can change in our menu by at least 10%.

FluxTubes: Quarks are connected via the flux tubes. The flux tube can be modeled as just a string holding the valence quarks together. The three valence quarks should be orbiting around the center of the proton with a momentum that wants to send them flying off but the string tension of the flux tube keeps them bound to each other. The string tension and the valence quark momentum should be control parameters that can be changed in the UI. The flux tube should get smaller (narrower) as its stretches and the tension tighten. The flux tube is a three-dimensional geometry that has an empty volume inside. Gluons can pass through the volume changing the color of the quarks as they make an exchange. This happens exactly the same in both valence and sea quarks. The valence will always have three flux tube arms while the sea can have two or three or more but normally only two.

Gluons: Each Gluon has two colors as indicated on the Wikipedia page under Color Charge. All combinations of gluon colors should be represented. There are three colors and three anti-colors red, gluon, blue, and anti-red, anti-green, and anti-blue. You can use the same color representation as what you see on Wikipedia. Each gluon can float around and interact with other gluons and quarks. Gluons can attract one another and annihilate turning into two photons. They can only annihilate if the total color charge of the two gluons is color-neutral. Only gluons that can form white will interact. For example, a red and anti-red can interact with another red and anti-red gluon. Three gluons all of different colors can form two color-neutral states. In this way, gluons can interact with each other to make pure gluon states. Other than that all they do is swarm around and interact with the quarks. When they make contact, they can bounce off each other changing from attracting to repelling, or they can pass right through each other. When the gluon density is large more sea quarks pop in and out of the vacuum. Space is full of fluctuating waves/swarms of gluons increasing and decreasing the likelihood of QCD making something happen. The gluons continuously pop in and out of existence but the swarm is always present. As the flux tubes move in space they clear out the fluctuating gluons in the vacuum. The probability of gluon sea-quark interaction is inversely proportional to the sea-quark virtuality.

Quarks: The quarks are charged so besides the color force there is an electromagnetic force as well. This is true for the sea quarks and valence quarks. The Up quark has a charge of +2/3, and the Down quark is -1/3. This is important in the physics of their dynamics because when charges move, they make magnetic fields. The force from the electromagnetic charge scales as 1/r^2, where r is the distance between the quarks (charges). The color force on the other hand does not diminish as fast over distance, it is the same between quarks but will normally only act between two (sea-quarks) or three (valence quarks). The strength of the color force is roughly 137 times that of the electromagnetic force. When the proton is polarized the orbital motion is correlated to the proton's spin when the proton is not polarized the spin direction is chaotic. The up quark and the down quark rotate in opposite directions. The up quark has a mass of about 2 MeV while the down quark has a mass of about 4.8 MeV so the up quark is about 2.4 times faster than the down quark. The momentum of the quarks is faster when the quarks are closer together in the center of the proton and slow when they are farther apart. The valence quarks orbit the center of the proton with Up and Down going in different directions but also following chaotic and wild paths when unpolarized. Polarized protons have much more order with the valence quarks always orbiting the central axis. The sea quarks can also orbit the central axis and follow and interact with the valence quarks. There are sum-rules that govern the exchange between orbital angular momentum, and partonic spin, and how all of this is shared between all the pieces.

Models of Dynamics:

Spin Sum Rule: All of the components of parton spin and dynamics must lead to a total proton spin of 1/2. Its not possible to make this work without imposing some model dependence so its very important that all the above aspects are addressed first. Since the famous EMC experiments revealed that only a small fraction of the nucleon spin is due to quark spins, there has been a great interest in ‘solving the spin puzzle’, i.e. in decomposing the nucleon spin into contributions from quark/gluon spin and orbital degrees of freedom. In this effort, the Ji decomposition:

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q L_q^z + J_g^z$$

not only the quark spin contributions ?q but also the quark total angular momenta. Charged particles in a magnetic field are governed by a velocity **E**X**B** an orbital angular momentum L=**r**X**E**X**B** where **r** is the position vector [ref]. This means that the charges will orbit the center of the proton in opposite directions. This however is a very classical picture. The terms in the above equation are defined as quantum mechanical expectation values of the corresponding terms in the angular momentum tensor. A representation of this decomposition should start with the valence quarks and include the intrinsic spin of the quarks that hold the know spin percentage (randomly oriented otherwise). Then the OAM is represented classically as rotating charges in a B-field.

Meson Cloud Model: At any given instant, the proton might really be a neutron (ddu) plus a positively charged pion (ud$^-$ ud$^-$)—or another proton (uud) plus a neutral pion. This violates energy conservation but it is allowed, for a fleeting moment, by the Heisenberg uncertainty principle. By adding up the contributions from all the possible channels, the theorists can model the composition of the sea.

Constituent Quark: Most basic isospin configuration.

Pauli-blocking: Pauli exclusion principle suppressed the formation of quarks of a certain color and flavor since two like quanta can not be in the same state.

Effective 4-quark Langrangian: ’t Hooft effective four-quark Lagrangian is “flavor nondiagonal,” leading to processes uu(dd$^-$). In a way, the effect is also due to the Pauli exclusion principle, but at a different level. Topological tunneling events, known as instantons, create fields so strong that they fix the color and spin states of participating quarks uniquely. Instead of six possibilities, there remains only one, thus a complete blocking. Since the proton has two valence u quarks and only one valence d quark, that mechanism would suggest that the ratio of anti d to anti u is 2 rather than 1.

Sivers Effect: Map the distribution of unpolarized quarks in 3-dimensional momentum space. A simple first test sea quark model might be to make a single 0^{++} state with both sea-quark spins pointing down and the OAM pointing up. These should orbit the central axis just like the valence in the pattern extracted from the data. We should make the sum rule worked by forcing spin, OAM and momentum be conserved.

UI and Controls:

We also want a nice User Interface that is transparent so you can still see what's going on behind it and provides the option of controlling all of the dynamics and

quantum mechanical parameters. This should be able to help the user navigate but also provide analysis tools and plots of the system given various parameter adjustments.

One example is plotting the Sivers function of the various partons (quarks and gluons). The Sivers function correlates the transverse momentum of the partons with the

polarization of the proton.

Task List and Assignments:

Member	Year	Unity	Major	Project	Team	Notes
Duncan Beauch	3rd year	Novice	Physics/CS	Views and UI and Expanding 3D representation (+ physics team work)	Physics	
Wyndham White	3rd year	Novice	Physics/CS	Unity Fluid simulation tests (+ physics team work)	Physics	
Bryant Lisk	2nd year	Novice	CS	gluon-quark/gluon-gluon/fluxtube force	Modeling	
Jared Conway	2nd year	2 years	CS	Electricity and Magnetism of quarks (Unity EM engine)	Modeling	
Sam Colvin	2nd year	Novice	CS	Optimization for high particle density	Modeling	
Ethan Hanover	4th year	3 years	CS	Sea-quark, gluon, fluxtube interactions	Dynamics/Modeling	
Ishan Mathur	MS student		CS	CS Integration and communication	Systems Organization	
Ishara Fernando	Postdoc		Physics	Physics Integration and communication	Systems Organization	
Liliet Diaz	Phd student		Physics	Physics team lead	Physics	

Misc. documents

1. GitHub_Steps.pdf
2. https://www.uni-muenster.de/Physik.TP/archive/fileadmin/lehre/Quantenmechanik_Friedrich_/book1_01.pdf
3. https://arxiv.org/abs/1907.11903