

Drell-Yan program at SeaQuest

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Arun S. Tadepalli, and Ronald A. Gilman



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Drell-Yan Program at SeaQuest

Arun S. Tadeballi^{a)} and Ronald A. Gilman^{b)}

Rutgers, The State University of New Jersey, Piscataway, NJ 08855, USA
for the SeaQuest Collaboration

^{a)}Corresponding author: tadeballi@physics.rutgers.edu

^{b)}rgilman@physics.rutgers.edu

Abstract. Fermilab E906/SeaQuest is an experiment aimed at studying the anti-quark distributions of nucleons and nuclei. The experiment uses a 120 GeV/c proton beam extracted from the Main Injector at Fermilab to collide with various solid and cryogenic targets to study a variety of physics topics ranging from light anti-quark flavor asymmetry in the nucleon sea to dark photons. The experiment takes advantage of the Drell-Yan process in order to probe specifically the high- x anti-quark distributions of the target nucleus. The acceptance of the spectrometer is tuned to explore the unprecedentedly high Bjorken- x region, thereby extending our knowledge of the anti-quark sea structure of nucleons and nuclei. Some of the physics goals from the Drell-Yan program at SeaQuest and the current status of some analyses are reported in this paper.

ACCESSING THE ANTI-QUARKS: THE DRELL-YAN PROCESS

In 1970, Christenson *et al.* measured the production of massive lepton pairs in 29 GeV/c proton-Uranium collisions at high energies [1]. Two prominent features can be noted in their cross section versus invariant mass of dimuons as shown in Figure 1.

- A shoulder near an invariant mass around 3.1 GeV (which we now know is because of the J/ψ particle and its resonance states).
- An underlying continuum that fell rapidly as a function of the invariant mass.

Sidney Drell and Tung-Mow Yan interpreted this in the framework of the parton model as a parton from one hadron annihilating with an anti-parton from another hadron forming a virtual photon that decays into a lepton anti-lepton (l^+l^-) such as [2].

$$q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-.$$

The leading order [3] Drell-Yan scattering cross section is given by

$$\frac{d^2\sigma}{dx_{beam}dx_{targ}} = \frac{4\pi\alpha^2}{9x_{beam}x_{targ}s} \sum_{i \in \{u,d,s,\dots\}}^n e_i^2 [f_i(x_{beam})\bar{f}_i(x_{targ}) + \bar{f}_i(x_{beam})f_i(x_{targ})] \quad (1)$$

where $f_i(x_{beam})$ and $\bar{f}_i(x_{targ})$ are the quark distributions, x_{beam} and x_{targ} are the fractions of longitudinal momentum carried by the participating beam and target quarks, respectively, s is the square of the center of mass energy, α is the fine structure constant revealing the electromagnetic nature of the process, e_i is the quark flavor's charge and the sum is over all the quark flavors (u, d, s, c, t, b). The leading order formula gives reasonable results for the mass and x_T dependence but yields only $\approx 50\%$ of the observed cross section. Higher order corrections to the leading order Drell-Yan process that include additional gluon emission and absorption lines (as shown in Figure 2) account for the remainder of the cross section. At large values of x , the quark distributions are dominated by the valence regions, and at small x the quark distributions are dominated by the sea. The acceptance of the SeaQuest spectrometer is tuned to probe specifically the anti-quark sea structure.

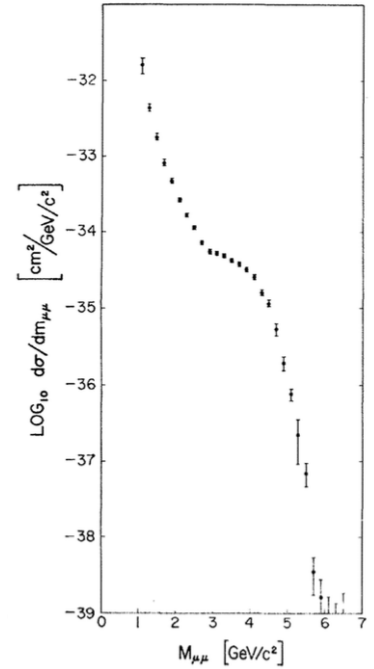


FIGURE 1. Cross section as a function of the invariant mass taken from [1]

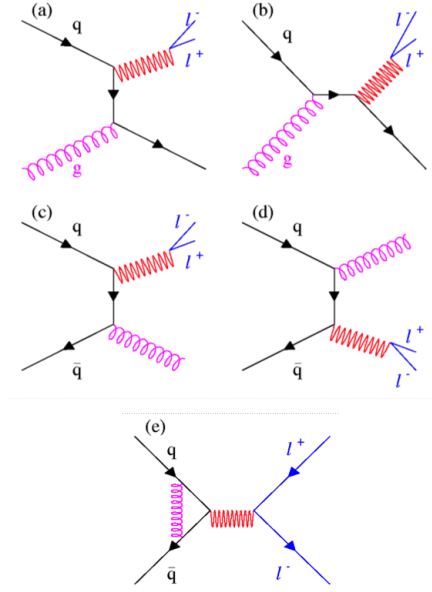


FIGURE 2. Higher order corrections to the leading order Drell-Yan process that include additional gluon diagrams.

1. LIGHT ANTI-QUARK FLAVOR ASYMMETRY IN THE NUCLEON SEA

Although no known symmetry constraint requires them to be the same, until the early 1990's it was assumed that the nucleon sea is light quark flavor symmetric: $\bar{u}(x) = \bar{d}(x)$. As gluons do not couple to flavor and the masses of u and d quarks are similar and small compared to the Λ_{QCD} scale, a flavor symmetric nucleon sea was thought to be generated from gluon splitting (shown in Figure 3). Subsequent experiments showed that the nucleon sea is not just flavor asymmetric but must have a non-perturbative origin.

The Gottfried Sum Rule is a generalized sum rule in QCD which offers insight into the structure of the nucleon [4]. This sum rule assumes that the proton and the neutron's quark distributions are related by charge symmetry i.e. the up quark distributions in the proton are almost identical to the down quark distributions in the neutron and vice versa.

It also assumes that the nucleon is made up of only the light quarks (u, d and s) and the strange quark distributions are the same in the proton and the neutron. In such a case, one can take the difference in the proton and neutron leading order structure functions (assuming strange quark distributions are the same) and perform the Gottfried integral S_G to obtain:

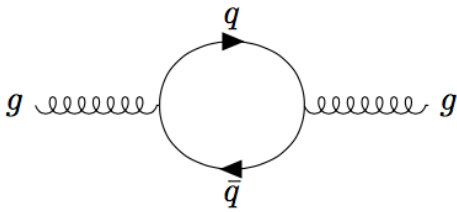


FIGURE 3. Feynman diagram of gluon splitting

$$S_G = \frac{1}{3} + \int_0^1 \frac{2}{3} (\bar{u}^p(x) - \bar{d}^p(x)) dx. \quad (2)$$

A purely perturbative origin of the nucleon sea would imply that $\int_0^1 \bar{u}(x) dx$ and $\int_0^1 \bar{d}(x) dx$ distributions in the proton are identical, thus reducing the Gottfried integral S_G to 1/3. Any significant deviation from this value reflects a non-perturbative contribution.

In 1991, the NMC (New Muon Collaboration) experiment at CERN published an evaluation of the Gottfried sum rule [5, 6]. The experiment used a 90 GeV and 280 GeV muon beam incident on liquid hydrogen and liquid deuterium targets [7]. They reported a value of $S_G = \int_{0.004}^{0.8} (F_2^p - F_2^n) dx/x = 0.221 \pm 0.008(\text{stat}) \pm 0.019(\text{syst})$ at a value of $Q^2 = 4 \text{ GeV}^2$. The values for $F_2^p - F_2^n$ were extrapolated on either ends of x and a total integral of $S_G = \int_0^1 \frac{1}{x} (F_2^p - F_2^n) dx = 0.235 \pm 0.026$ was reported. This was the first clear evidence of a violation of the Gottfried sum rule. It was also suggested that perhaps the assumed charge symmetry could be broken [8, 9] or that there is a non negligible contribution from the small- x region. It was suggested by Ellis and Stirling that one could take advantage of the Drell-Yan process to disentangle the two possible scenarios

(non-symmetric sea parton distributions and isospin symmetry breaking) reported by the NMC experiment [10]. The NA51 experiment performed at CERN measured the Drell-Yan reaction cross sections with a 450 GeV/c proton beam on liquid hydrogen and liquid deuterium targets and obtained [11]:

$$\left. \frac{\bar{d}}{\bar{u}} \right|_{x=0.18} = 1.96 \pm 0.15(\text{stat}) + 0.19(\text{syst}) \quad (3)$$

The E866/NuSea experiment was the first to measure an x -dependence of the ratio $\bar{d}(x)/\bar{u}(x)$ over a range $0.015 < x < 0.35$ [12, 13]. The experiment used the 800 GeV proton beam extracted from the Tevatron at Fermilab and liquid hydrogen and liquid deuterium targets. Approximately 360,000 Drell-Yan dimuon pairs remained after analysis cuts on the data. The data from this experiment put several tight constraints on non-perturbative models that attempt to explain the origin of the nucleon sea. Plots of the ratio of cross sections $\sigma_{pd}/2\sigma_{pp}$ (left) and $\bar{d}(x)/\bar{u}(x)$ (right) show

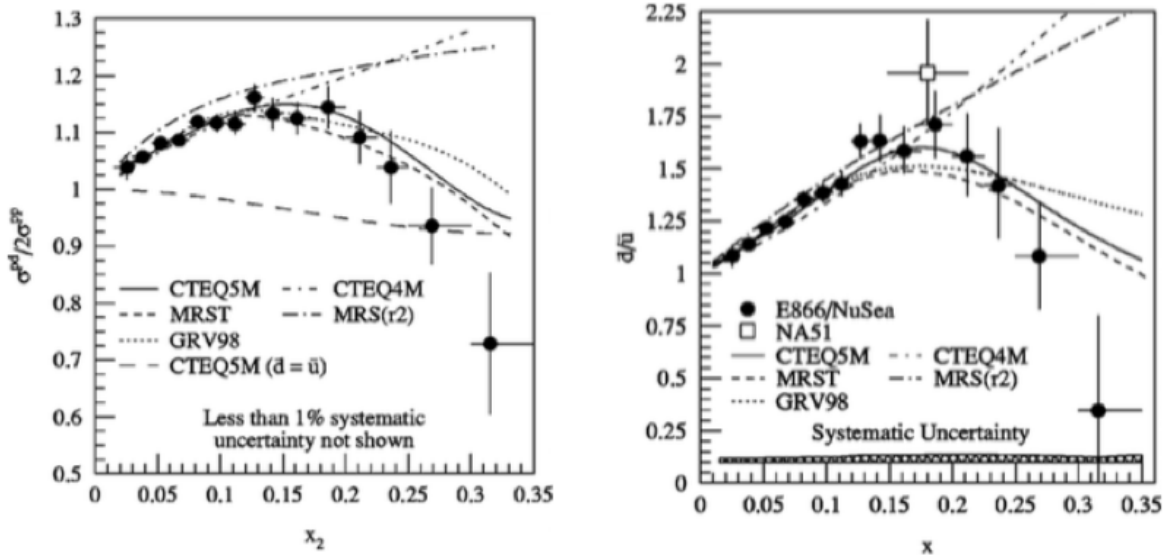


FIGURE 4. Results from E866 experiment. Left plot shows the ratio of cross sections $\sigma_{pd}(x)/2\sigma_{pp}(x)$ and the right plot shows the extracted ratio $\bar{d}(x)/\bar{u}(x)$ [13].

two prominent features. The ratio seems to rise up until $x \approx 0.18$ and surprisingly starts falling down to a value below 1 (with limited statistical precision) near $x \approx 0.25$. After the quantity $\bar{d}(x)/\bar{u}(x)$ is extracted, the value of $\bar{d}(x) + \bar{u}(x)$ is taken from parameterizations and the quantity $\bar{d}(x) - \bar{u}(x)$ is calculated. $\bar{d}(x) - \bar{u}(x)$ is a unique quantity, which is essentially the non-perturbative asymmetric sea contribution [14].

The results from NuSea experiment for $\bar{d}(x)/\bar{u}(x)$ and $\bar{d}(x) - \bar{u}(x)$ (later confirmed by HERMES with limited statistical precision [15]) put constraints on models that attempt to explain the nucleon sea and the observed flavor asymmetry. Initially, the sea was assumed to be generated perturbatively by gluon splitting. Field and Feynman suggested that the presence of an “additional” valence u quark in a proton could lead to the suppression of the gluon splitting to $u\bar{u}$ relative to $d\bar{d}$ due to Pauli blocking [16]. Ross and Sachradja reported that the perturbative contribution to the $\bar{d}(x) - \bar{u}(x)$ is very small [17] and argued that by taking the parameterizations suggested by Field and Feynman in [16] Pauli blocking is not important. A purely perturbative mechanism is unable to account for the flavor asymmetry observed by NuSea. Therefore, this asymmetry must be of a non-perturbative origin. Several theoretical models were proposed to explain the origin of the nucleon sea as well as the flavor asymmetry. For example, the pion cloud model rewrites the proton (under the one meson approximation) as a linear combination of several different fluctuations of baryon virtual meson Fock states. If p_0 is the bare proton with a symmetric sea, the proton can be written as

$$|p\rangle = \alpha|p_0\rangle + \beta|p_0\pi^0\rangle + \gamma|n\pi^+\rangle + \delta|\Delta^{++}\pi^-\rangle + \dots \quad (4)$$

If one were to consider the Clebsch-Gordan coefficients of different baryon virtual meson Fock states, the lower energy state $|n\pi^+\rangle$ has a larger Clebsch-Gordan coefficient than the higher energy state $|\Delta^{++}\pi^-\rangle$. One would expect

a $\bar{d} > \bar{u}$ for SeaQuest's x range but cannot intuitively imagine an overturn of the ratio at $x \approx 0.25$. The meson cloud model predicts an overturn at a later value due to a shift in the mechanism where $|\Delta^{++}\pi^- \rangle$ dominates $|n\pi^+ \rangle$ although not at $x \approx 0.25$ [18]. The meson cloud model (π, ω, ρ etc.) which incorporates other baryon virtual meson Fock states is able to somewhat reproduce the $\bar{d}(x) - \bar{u}(x)$ difference but predicts that the ratio will cross 1 at a larger value of x compared to NuSea [19, 20]. Also, another challenge in this model is to find the exact place to truncate the hadronic expression in Equation 4. Furthermore, some analyses report results that suggest a delicate balance between several competing mechanisms that include a $\pi\Delta$, πN and a parameterized Pauli blocking component [21]. Chiral perturbation theory suggests that the constituent quarks couple to goldstone bosons ($u \rightarrow d\pi^+$ and $d \rightarrow u\pi^-$) and that the excess of $\bar{d}$ is simply due to the presence of an 'extra' u constituent quark [22]. The prediction for this model falls short in explaining all the asymmetry. The statistical parton distributions model, which considers the nucleon as a gas of massless partons (quarks, anti-quarks and gluons) in equilibrium at a given temperature in a finite volume, predict a monotonic increase in the $\bar{d}(x)/\bar{u}(x)$ ratio [23]. The ratio $\bar{d}(x)/\bar{u}(x)$ is shown for several other non-perturbative models such as Chiral Quark model [24], Chiral Quark Soliton model [25] and Instanton induced models [26]. While some models are able to reproduce $\bar{d}(x) - \bar{u}(x)$, they are unable to predict the surprising overturn and drop below unity in the ratio (with limited statistical precision) observed at $x \approx 0.25$ by NuSea. It is evident that higher precision data is needed in the range $0.15 < x < 0.45$ region to map out the overturn at $x \approx 0.18$ and confirm the seeming drop below unity at $x \approx 0.25$.

Role of SeaQuest

SeaQuest is a fixed target experiment that takes advantage of the Drell-Yan process to access the nucleon anti-quark structure [27]. The experiment uses a 120 GeV proton beam extracted from the Main Injector at Fermilab to collide with liquid hydrogen and deuterium targets. SeaQuest is able to probe the region $0.1 < x < 0.45$ with higher statistical precision compared to the previous Drell-Yan experiment, NuSea.

- Since the Drell-Yan signal scales as $1/s$, at the same x_{Beam} and x_{Target} with 7 times lower beam energy than NuSea (800 GeV), SeaQuest has higher statistics in the high- x region compared to NuSea (given the same number of protons on target).
- An important background for the experiment consists of the muons originating from the decay of J/Ψ particle. Since the production of J/Ψ scales as s [28], due to a lower beam energy, the background from J/Ψ is relatively lowered by a factor of 7 compared to NuSea.

With higher statistical precision compared to NuSea, the experiment explored the high- x region constraining models that attempt to explain the generation of the nucleon sea, thereby shedding light on the anti-quark structure of the nucleon sea.

The experimental capability of SeaQuest has been discussed in [29]. A new Intensity-Extrapolation method was developed to counter the rate dependence challenge at SeaQuest. Using this method, the ratio of cross sections of liquid deuterium and liquid hydrogen, $\sigma_{pd}(x)/2\sigma_{pp}(x)$, was measured in the range $0.1 \leq x_T \leq 0.45$. Figure 5 shows

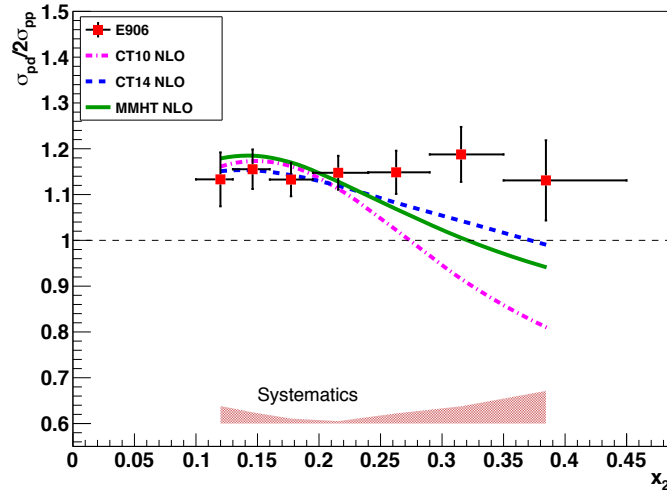


FIGURE 5. $\sigma_{pd}(x)/2\sigma_{pp}(x)$ vs x_T plot along with PDF predictions. The red points are SeaQuest data points which are plotted along with the systematics band shown at the bottom. The data points are consistently above 1 for all x_T and agree quite well with the PDF predictions in the low- x region up to $x_T \approx 0.25$. Since there are no data in the high- x region to constrain the PDFs, it is natural to expect differences between the E906 and PDF predictions which are data driven.

the $\sigma_{pd}(x)/2\sigma_{pp}(x)$ cross section ratio as a function of the x_T (or x_2). The red points are SeaQuest data points which are plotted along with the systematics band shown at the bottom. Some observations regarding the data points:

- SeaQuest data points are consistently above unity for all x_T .
- Also plotted together with SeaQuest data are three other PDF predictions; CT10 NLO (CTEQ-TEA collaboration) [30], CT14 NLO [31] and MMHT NLO [32]. The data seem to agree quite well with the PDF predictions in the low- x region up to $x_T \approx 0.2$. Since there are no data in the high- x region to constrain the PDFs, it is natural to expect differences between SeaQuest and the PDF predictions which are data driven.
- The systematic uncertainty for the fourth x_T bin is small compared to the other bins. It is “natural” to some extent because of the nature of simultaneous fitting used in the Intensity-Extrapolation method. This bin has the most statistics and also, it is constrained by the other outer bins when a simultaneous fit is applied.

The collaboration is in the process of optimizing the process of extracting $\bar{d}(x)/\bar{u}(x)$ from the ratio of cross sections results which will put constraints on the various mechanisms that attempt to explain the origin of the nucleon sea.

2. NUCLEAR DEPENDENCE OF ANTI-QUARKS IN NUCLEI

Much of the data for the anti-shadowing and the valence regions is provided by DIS data which does not differentiate between quarks and anti-quarks and in regions which are dominated by valence quarks. Recent review articles cover the current status of nuclear dependence [33, 34, 35, 36]. However, one can ask the question “Do we see the same nuclear dependence for the sea quark distributions or is this just a valence effect?” It is possible that nuclear effects on sea quarks are completely different from those in the valence sector [37]. Higher precision data in the anti-shadowing region as well as larger x than E772 [38] could access would provide crucial information in differentiating the predictions for sea quarks, especially in the high- x region. As shown in Fig 6, calculations by Berger and Coester [39, 40] and Jung and Miller [41] expect an enhancement in the ratio of Drell-Yan reaction cross sections whereas those by Dieperink and Korpa [42] and Brown et. al. [43] expect a decrease. Smith and Miller [44] (not shown) predict no enhancement in the ratios whereas Kulagin and Petti [37, 45] (not shown) a slight enhancement ($\sim 5\%$) that drops with increasing x . Drell-Yan data in the high- x region is crucial in differentiating these models.

By taking advantage of the Drell-Yan process, SeaQuest is able to investigate the modification of sea distributions in the range $0.1 < x < 0.45$ with higher statistical precision compared to E772 [38] and E866 [46]. SeaQuest has taken data on C, Fe and W targets during the duration of the experiment. The ratio of Drell-Yan dimuons yields of these three targets to liquid deuterium up to a region of 0.45 in Bjorken- x is sensitive to the modifications of the anti-quark distributions in nuclei in the anti-shadowing and EMC region. Analysis of the solid target data (in progress) will put tight constraints on various models that attempt to explain the nuclear dependence on anti-quarks in nuclei.

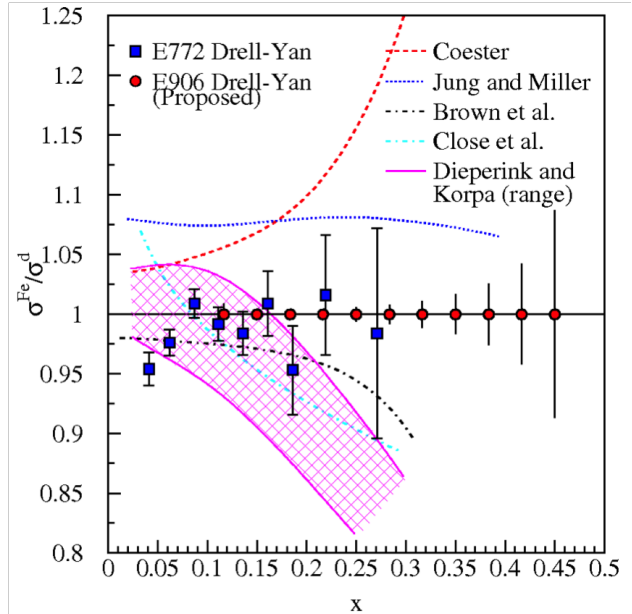


FIGURE 6. SeaQuest projections for nuclear dependence in sea quarks for Fe. The various models predictions were made for E772 kinematics (800 GeV/c proton beam).

3. PARTON ENERGY LOSS IN COLD NUCLEAR MATTER

Parton energy loss in p-A collisions serves as an important tool in exploring the properties of the Quark Gluon Plasma (QGP). With minimal final state interactions, the dimuon pair arising from the Drell-Yan process in p-A collisions will help set a baseline relative to energy loss in QGP. Feynman- x or x_F , is a variable of interest that sheds light on the longitudinal structure of the initial state of the interacting quark. If there is no energy loss of the incoming parton (which could be very small in deuterium), then the x_{Beam} distributions are centered around a particular x_{Beam} value. However, if the beam parton is subject to initial-state energy loss in a heavier nucleus, the x_{Beam} distributions in this nucleus (relative to deuterium) are shifted, making the ratio of the per-nucleon cross section R_{pA} have an overall slope as a function of x_{Beam} . A decrease in the R_{pA} value with increasing x_F is typically attributed to the energy loss of the incoming parton due to its interaction with the cold nuclear medium according to some theoretical models [47]. Previous experiments found a slight depletion in the high x_F region which could also be attributed to shadowing effects coming from the low- x region [46, 48]. Therefore, data outside of the shadowing region is essential to decouple the effects of shadowing and parton energy loss in cold nuclear matter. SeaQuest is sensitive to this region outside of the shadowing region and analysis of data taken on solid targets (C, Fe and W) are in progress.

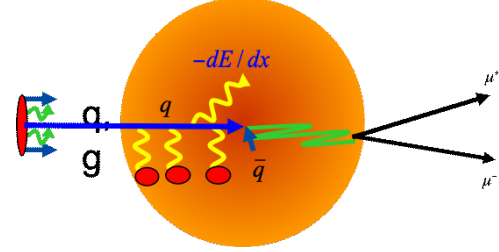


FIGURE 7. Depiction of energy loss of a parton while traversing a cold nucleus.

CONCLUSION

Understanding the structure and behavior of the constituents of matter is one of the central goals of modern physics. SeaQuest is one such experiment that explored the unexplored by making Drell-Yan measurements in an unprecedentedly high- x region. The physics goals and the status of the analysis of many interesting physics topics have been presented in this paper. Other physics topics such as angular distributions, Boer-Mulders function, J/ψ and ψ' (p_T and x_F) suppression in p-A collisions, and the search for dark photons [49] have not been discussed in this paper but major analysis efforts are underway.

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