Knocking a Proton out of Proton Process at Jefferson Lab

Zichen Yin, Mississippi State University
HUGS, 2025, Newport News

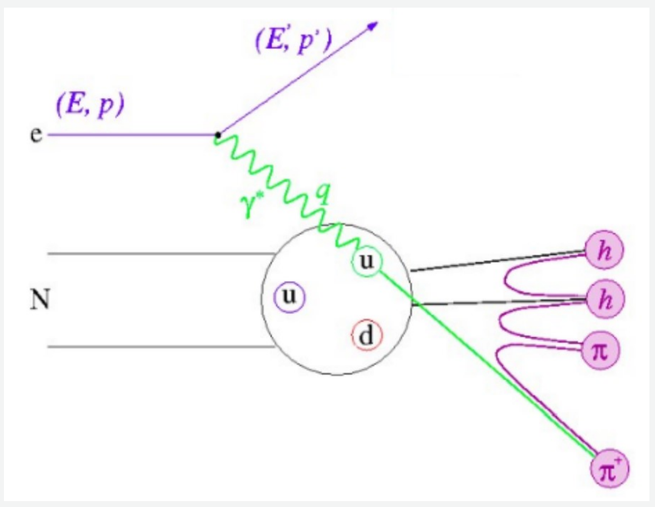
Abstract

Precision measurements of semi-inclusive deep-inelastic scattering (SIDIS) cross sections provide critical insights into quark fragmentation and hadronization from a fixed nucleon target. The upcoming "R-SIDIS" experiment at Jefferson Lab Hall C aims to investigate the probability of quark hadronization into a charged pion. A surprising feature of this process is the significant production of high-momentum protons, leading to an unintuitive scenario where a proton appears to be ejected from a proton target. This phenomenon challenges conventional expectations and suggests the presence of underlying QCD mechanisms that involve multiple parton exchange in this fragmentation process. The objective of this study is to explore and characterize this "Knocking a Proton out of a Proton" process, providing new insights into the hadronization mechanisms governing SIDIS.

R-SIDIS - Motivation

- Over the past decades, inclusive scattering has provided key insights into nucleon structure, particularly through measurements of the longitudinal and transverse polarized virtual photon scattering and their ratio, $R = \sigma_L/\sigma_T$. Early observations of the smallness of R in deep inelastic scattering (DIS) were crucial in establishing the spin-1/2 nature of partons. However, inclusive measurements cannot distinguish quark flavors. SIDIS offers a significant advantage: by tagging the type of produced hadron, it becomes possible to access the flavor structure of the nucleon.
- In the high-energy limit, theory predicts that the ratio R in SIDIS should behave similarly to that in DIS, vanishing as $1/Q^2$. Yet, this assumption has not been thoroughly tested, especially at lower energies or as one approaches the exclusive limit (where the detected hadron carries nearly all the energy, $z \to 1$).
- The R-SIDIS experiment is motivated by the need to directly measure R in SIDIS for the first time, to test these theoretical assumptions and to clarify the connection between inclusive, semi-inclusive, and exclusive processes in pion electroproduction. These measurements are essential for interpreting flavor decomposition in SIDIS at JLab's 12-GeV beam energy and for advancing our understanding of quark fragmentation and confinement dynamics in QCD.

Inclusive Scattering



For (semi-)inclusive electron-nucleon scattering the differential cross section can be written as:

$$\frac{d^2\sigma}{d\Omega_e dE'} = \sigma_{Mott}\left\{W_2(Q^2, W^2) + 2W_1(Q^2, W^2)\tan^2(\theta/2)\right\}$$

with σ_{Mott} the Mott cross section defined as

$$\sigma_{Mott} = \frac{\alpha^2\cos^2(\theta/2)}{4E^2\sin^4(\theta/2)}$$

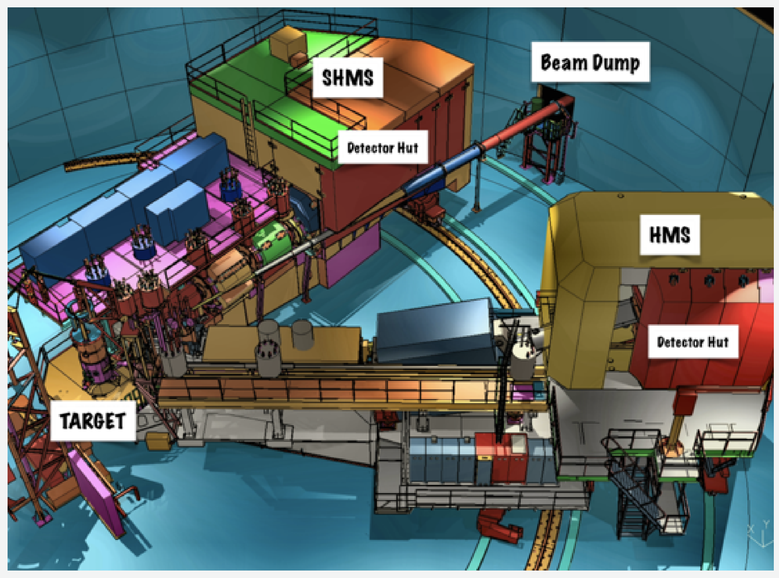
W_1 and W_2 the structure functions that contain information about the electromagnetic structure of the nucleon.
In the Bjorken limit, in which both Q^2 and $\nu \to \infty$, but x is fixed, the structure functions W_1 and W_2 were found to exhibit scaling. Therefore, it was convenient to introduce the dimensionless functions F_1 and F_2, defined by

$$F_1(x, Q^2) = MW_1(\nu, Q^2)$$
$$F_2(x, Q^2) = \nu W_2(\nu, Q^2)$$

The inclusive cross section can be expressed in terms of the cross sections for the absorption of transverse and longitudinal photons, σ_T ad σ_L:

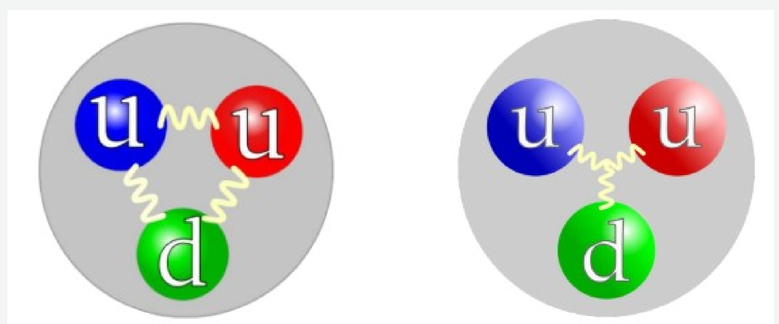
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1 + \frac{4M^2x^2}{Q^2}\right) - 1$$

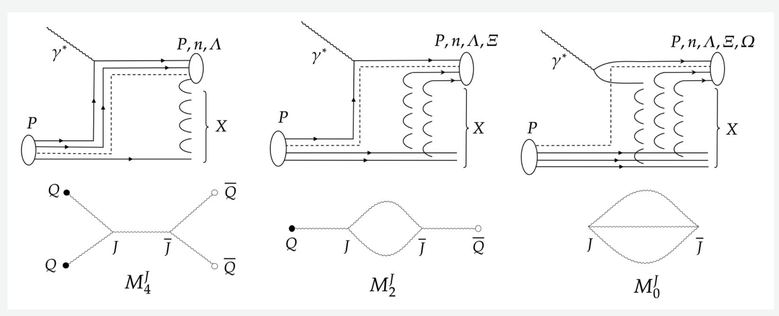
Hall C Detectors



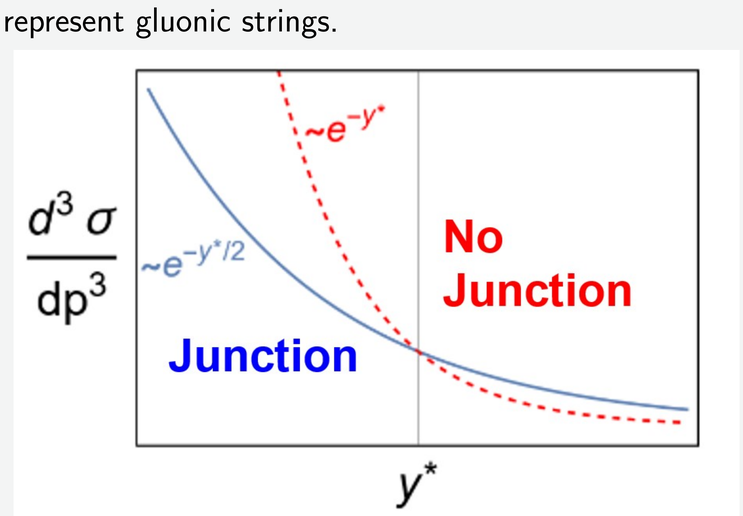
Proton Identity Puzzle(Baryon Junction)

What carries baryon number? Left: quark; Right: Verton(Baryon Junction)





(Top) Semi-inclusive processes in which the baryon junction mediates the forward baryon production. Either 2,1 or 0 valence quarks can accompany the junction. The final-state mesons X are produced as a result of 1, 2 or 3 strings fragmentation, respectively. Solid lines represent quarks, dashed lines represent the junction. (Bottom) Exotic meson states exchanged in the t-channel of the corresponding process shown in the top panel. Wiggly lines represent gluonic strings.



The baryon junction prediction for the c.m.s. rapidity distribution of forward baryons is shown in blue. Dashed red line indicates a cross section expected in conventional model.

Experimental Setup

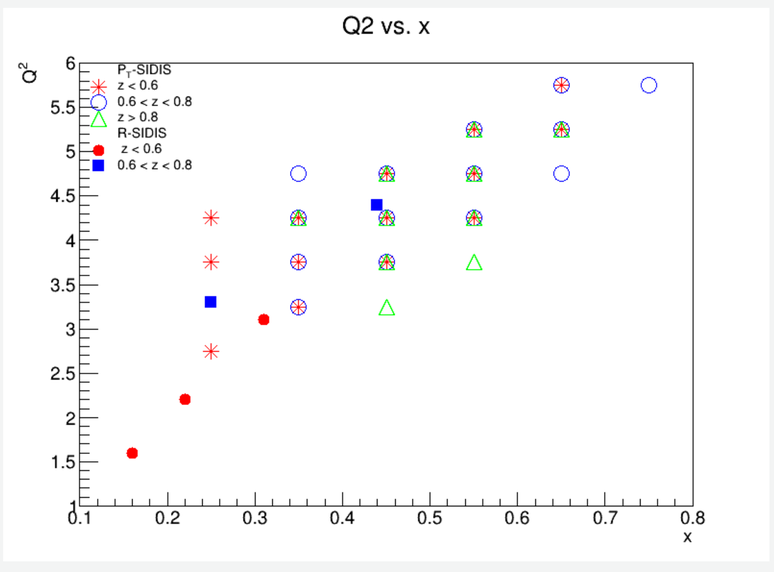
Beam:
- Energies 6.5 GeV (17 PAC days), 8.6 GeV(15 PAC days), and 10.7 GeV (15 PAC days).
- Beam pipe size: Medium.
- Polarized for 3 and 5 pass.

High Momentum Spectrometer(HMS):
- Standard configuration for electrons/positrons.
- Momentum range: 1.5 to 5.3 GeV.
- Angle range: 13.5 to 49 degrees.

Super High Momentum Spectrometer(SHMS):
- Momentum range: 1.6 to 6 GeV.
- Angle range: 7.1 to 20 degrees.
- Detectors:
  - Noble gas Cerenkov detector with standard gas (pion threshold 7 GeV: 40% neon, 60% argon)
  - Heavy gas Cerenkov detector(1 atmosphere C4F10 for pion threshold of 2.6 GeV)
  - Aerogel Cerenkov detector with index 1.015 (kaon threshold 2.85 GeV).
  - standard scintillators, drift chambers, and calorimeter.

Triggers:
- Coincidence of HMS 3/4 and SHMS 3/4
- Coincidence of HMS ELREAL and SHMS 3/4
- HMS 3/4 (SHMS read out even if no trigger)
- HMS ELreal (ditto)
- HMS ELreal only (no SHMS readout)
- HMS 3/4 only (no SHMS readout)
- SHMS 3/4 (for cosmics)

R-SIDIS & P_T-SIDIS Kinematics



Run Plan

The current plan is to start running of R-SIDIS on July 15, 2025. The run will be broken into 2 run periods. Part of the experiment will run in the summer of 2025, and the remainder in FY26 (TBD).

Summary

- R-SIDIS experiment will extend our measurement of R to the semi-inclusive regime.
- Hall C at JLab has very well understood detectors for precision measurement of R.
- The high-momentum proton production measurement with R-SIDIS may shift our understanding of baryon number origin.