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Measurement of Charmonium Production in $p + p$ and $p + d$ Interactions in the Fermilab SeaQuest Experiment

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Abstract

The Fermilab SeaQuest experiment has measured dimuon events from the interactions of 120 GeV proton beam on liquid hydrogen and deuterium targets with dimuon mass between 2 and 9 GeV. These dimuon events contain both the Drell-Yan process and the charmonium (J/ψ and ψ') production. Unlike the Drell-Yan process which probes the antiquark distributions in the nucleons, the charmonium production is sensitive to both quark and gluon distributions. SeaQuest has extracted the $\sigma^{pd}/2\sigma^{pp}$ ratio as well as the differential cross sections for charmonium production in the kinematic region of $0.4 < x_F < 0.9$. The $\sigma^{pd}/2\sigma^{pp}$ ratio for charmonium production are found to be significantly different from that of the Drell-Yan process. The measured differential cross sections for charmonium production are compared with theoretical calculations using Color Evaporation Model and Non-Relativistic QCD model.

1 Introduction

The SeaQuest experiment at Fermilab was designed to measure high-mass dimuons produced in the interactions of 120 GeV proton beam with various targets. Dimuons originating from the Drell-Yan process [1] as well as the decay of quarkonium states were collected simultaneously. Result from SeaQuest on the $\sigma^{pd}/2\sigma^{pp}$ Drell-Yan cross section ratio, which is sensitive to the flavor asymmetry of $\bar{d}/\bar{u}$ in the proton, was reported recently [2].

Unlike the Drell-Yan process which primarily involves the annihilation of quark and antiquark via electromagnetic interaction, charmonium production proceeds via strong interaction containing contributions from both the quark-antiquark annihilation and the gluon-gluon fusion processes [3].

While proton-induced charmonium production is expected to be dominated by gluon-gluon fusion process [3], some contributions from the quark-antiquark annihilation process is also expected. The relative importance of these two processes is expected to depend on the energy of the colliding hadron as well as the Feynman-x (x_F) of the charmonium [4]. The quark-antiquark annihilation process is sensitive to the light sea-quark asymmetry in the proton, as in the case of Drell-Yan process, while the gluon-gluon fusion process is expected to be identical for the reaction on hydrogen and deuterium targets.

The NA51 Collaboration reported the simultaneous measurement of the charmonium production and Drell-Yan for $p + p$ and $p + d$ at 450 GeV at a single value of x_F [5]. The SeaQuest measurement covers a broader kinematic range of $0.3 < x_F < 0.8$. The 120 GeV beam energy in the SeaQuest experiment is expected to probe the parton distributions at a values of x different from the NA51 experiment at 450 GeV.

2 E906/SeaQuest Experiment

SeaQuest is a fixed-target experiment using the 120 GeV proton beam from the Fermilab Main Injector. Details of the SeaQuest spectrometer can be found in Ref. [6]. The target system consists of seven interchangeable targets, including a flask with liquid hydrogen, a flask with liquid deuterium, an empty flask (vacuum), solid carbon, iron, and tungsten targets as well as an empty space with no target (air). The targets are interchanged periodically to reduce systematic uncertainties in the measured cross section ratios for the different targets.

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The spectrometer consists of two magnets and four tracking stations. FMag, is a solid iron magnet that acts as a focusing magnet as well as the beam dump. It is then followed by the first tracking station. An open air dipole magnet (KMag) is placed between station 1 and station 2. The vertical magnetic field from both magnets bends the muons horizontally, allowing the measurement of the momentum of the muons. Downstream of station 3, there is a 1 m iron wall acting as a hadron absorber. Station 4 is located behind the hadron absorber and acts as a muon identifier. Tracks that pass through the hadron absorber and produce hits on station 4 are identified as muons.

3 Extraction of J/ψ cross section

SeaQuest experiment took data from April 2014 to July 2017. The analysis presented here is performed on data collected until August 2015, about half of the entire data set. After applying various analysis cuts to select candidate dimuon events from the liquid hydrogen target, the dimuon invariant mass distribution is shown in Fig. 1. The J/ψ peak and ψ' shoulder are clear visible and are the predominant sources of signal at the lower mass region. The mass distribution is fitted with several different components. First, the mass spectrum from the data collected with the empty target flask, properly normalized by the integrated beam intensity, is included. Second, the expected mass distributions for J/ψ and ψ', based on the analysis of the GEANT4 based Monte-Carlo simulation are obtained. The third component is from the analysis of the Drell-Yan Monte-Carlo, generated using a next-to-leading order calculation and CT14 parton distributions. Finally, the random dimuon background is simulated using the data collected with a "single-muon" trigger. Two "single-muon" events are combined to create a simulated "dimuon" events, which are sent through the same analysis chain. The data is then fitted to a sum of these different components. The data are well described by this fitting procedure. This fitting procedure can also describe the mass distribution in each kinematic bin.

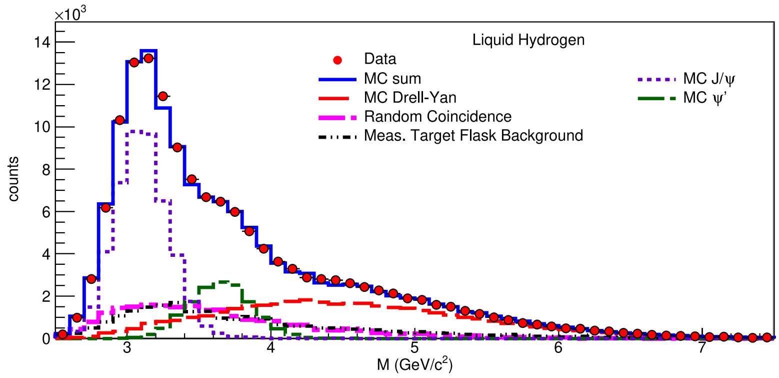

Figure 1: The reconstructed dimuon invariant mass distribution for data collected on liquid hydrogen target after all analysis cuts [2]. In the lower mass region, the predominant signal is from the decay of J/ψ and ψ'.

After the number of J/ψ events is extracted from the mass distributions, the quarkonium production cross section is obtained as follows

$$B\frac{\mathrm{d}\sigma}{\mathrm{d}x_F} = \frac{N_{\text{events}}}{\Delta x_F \mathcal{L}\epsilon}, \tag{1}$$

where B is the branching ratio for J/ψ to decay into a muon pair, ϵ is the spectrometer acceptance and efficiency correction, and $\mathcal{L}$ is the effective luminosity. The spectrometer acceptance and efficiency correction are obtained by studying the Monte-Carlo simulation. We define the following kinematic variables for the J/ψ:

$$x_F = \frac{2P^L_{CM}}{\sqrt{s}}, \tag{2}$$

$$x_b = \frac{P_{\text{target}} \cdot P_{\text{sum}}}{P_{\text{target}} \cdot (P_{\text{beam}} + P_{\text{target}})}, \tag{3}$$

$$x_t = \frac{P_{\text{beam}} \cdot P_{\text{sum}}}{P_{\text{beam}} \cdot (P_{\text{beam}} + P_{\text{target}})}, \tag{4}$$

where P_{CM}^{L} is the dimuon longitudinal momentum in the nucleon-nucleon center-of-mass (CM) frame, s is the CM energy squared. x_b and x_t are the fraction of the hadron momentum carried by the parton in the beam and target nucleon, respectively. They are defined using the four momentum of the beam hadron ($P_{\rm beam}$), target hadron ($P_{\rm target}$) and the dimuon ($P_{\rm sum}$).

To compare the measured J/ψ production cross section with theoretical expectations, we have performed calculation using the Next-to-Leading order (NLO) Color Evaporation Model (CEM)[7] and Non-Relativistic QCD (NRQCD) model [8], with CT14NLO [9] as the input PDF. In both models, the heavy quark-antiquark ($\bar{Q}Q$) pair production via various QCD hard processes is calculated using perturbative QCD. The main difference between the two models is in the hadronization into specific quarkonium state. In the CEM framework, a constant probability F, specific for each charmonium state, accounts for the hadronization into colorless charmonium state. In contrast, in NRQCD, the hadronization is described by a set of long-distance matrix elements (LDMEs) which depend on the spin, color and angular momentum of the $\bar{Q}Q$ pairs and the charmonium state.

The model predictions from both models for the J/ψ production in $p+p$ with a 120 GeV proton beam are shown in Fig. 2. At forward x_F, both models suggest that quark-antiquark annihilation is more important than gluon-gluon fusion, but NRQCD gives somewhat greater importance for the quark-antiquark annihilation.

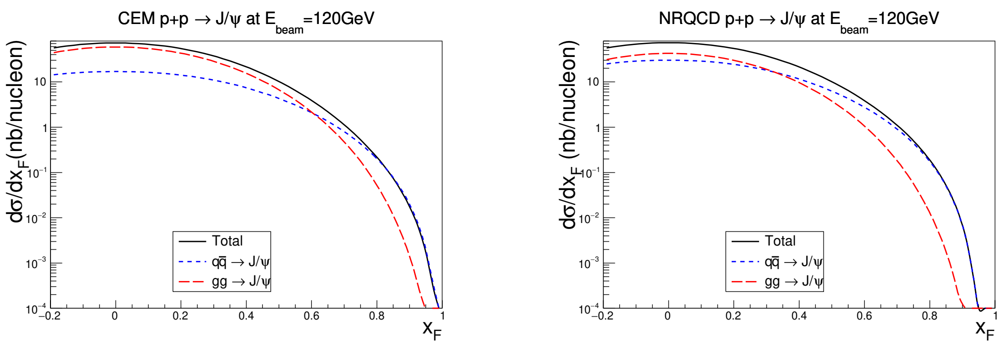

Figure 2: The model prediction for J/ψ production in $p+p$ with a 120 GeV proton beam using CEM (left) and NRQCD (right). Contribution from the quark-antiquark annihilation and gluon-gluon fusion are shown as blue dotted line and red dashed line.

The preliminary result of $\frac{d\sigma}{dx_F}$ from SeaQuest are shown in Fig. 3, and compared with both the CEM and NRQCD calculation. The main sources of systematic uncertainties come from the modeling of the random background and the beam luminosity normalization. The normalization of the CEM calculation, which accounts for the hadronization probability, is adjusted to fit the data. The shape of the extracted cross section is in good agreement with CEM. For the NRQCD calculation, the LDMEs are taken from [10], which are extracted from a global analysis of pion and proton induced charmonium production in fixed-target experiments. The magnitude and the shape of the extracted cross sections are also in good agreement with the NRQCD calculation.

The $\sigma^{pd}/2\sigma^{pp}$ cross section ratios for the J/ψ production can also be obtained. As most of the systematic uncertainties are correlated between the hydrogen and deuterium targets, they would cancel out in the ratio. The preliminary J/ψ $\sigma^{pd}/2\sigma^{pp}$ ratio is shown in Fig. 4. The SeaQuest measurement is at a lower energy and higher x_F compared to previous measurements. The preliminary result is consistent with unity within uncertainty, in qualitative agreement with earlier measurement at 450 GeV by the NA51 Collaboration [5] and 800 GeV by the E866 Collaboration [11].

Fig. 5 shows the comparison of the J/ψ $\sigma^{pd}/2\sigma^{pp}$ ratio as a function of x_t compared with the measured Drell-Yan ratio [2]. The difference of the $\sigma^{pd}/2\sigma^{pp}$ ratios between Drell-Yan process and J/ψ production mainly originate from the fact that the Drell-Yan process is an electromagnetic interaction, while the J/ψ production is a strong interaction. The deviation of the cross section ratio from unity is indicative of the light sea quark asymmetry. In the Drell-Yan process, the sensitivity is amplified by the fact that Drell-Yan process is sensitive to the charge of the quarks. On the contrary, the J/ψ production is insensitive to the charge of the quarks, and the sensitivity to the flavor asymmetry is further diluted by the gluon fusion process, which is expected to be identical in both $p+d$ and $p+p$. These different characteristics between the two processes are reflected in the $\sigma^{pd}/2\sigma^{pp}$ ratios. While the measured Drell-Yan ratio is significantly different from unity as a result of the $\bar{d}/\bar{u}$ flavor asymmetry of the light-quark sea, the J/ψ production cross section ratio is close to unity. The CEM and NRQCD calculation are shown as green

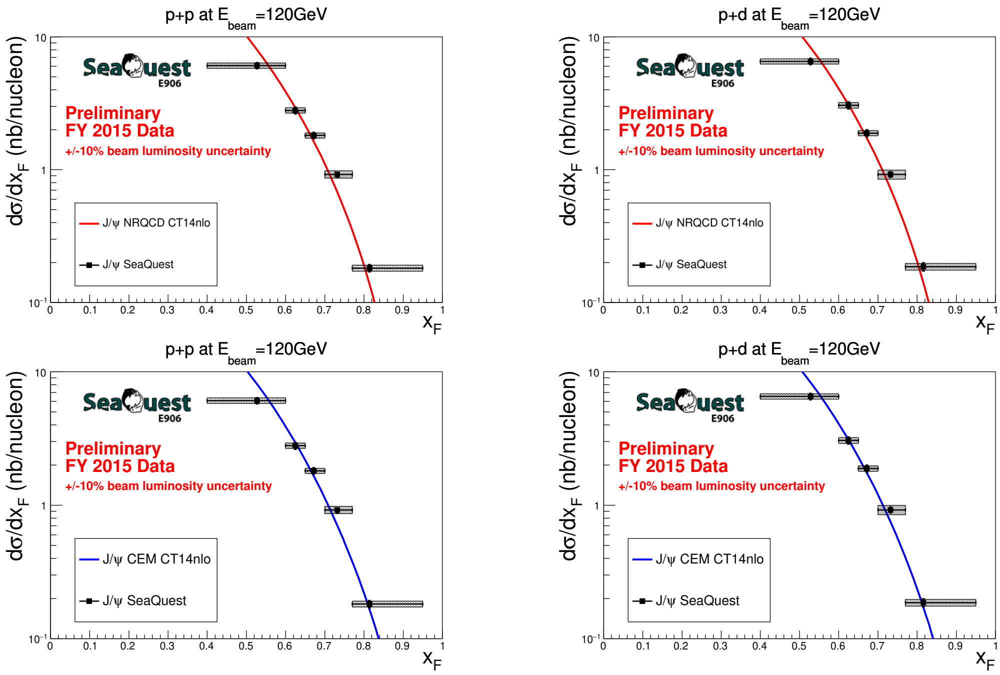

Figure 3: The preliminary result on the extracted J/ψ cross section for proton on hydrogen (left) and proton on deuterium (right). The result is also compared with NRQCD predictions (top) and CEM prediction (bottom).

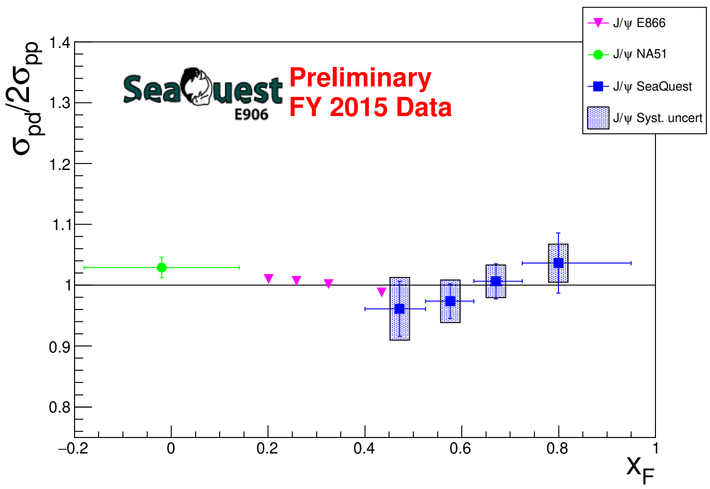

Figure 4: The preliminary result on the extracted J/ψ $\sigma^{pd}/2\sigma^{pp}$ cross section ratio as a function of x_F and compared with with previous measurements by NA51 and E866.

dotted line and orange solid line respectively. The small difference between the two calculations reflects the greater importance of the quark-antiquark annihilation in the NRQCD calculation as shown in Fig. 2.

4 Concluding Remarks

The simultaneous measurement of the charmonium production and the Drell-Yan dimuons in the SeaQuest experiment facilitates a comparison of the two distinct processes. The extracted J/ψ production cross sections are in good agreement with both the CEM and the NRQCD calculation. The $\sigma^{pd}/2\sigma^{pp}$ J/ψ production cross section ratio is close to unity, and the difference between the J/ψ and Drell-Yan ratio is reflecting the different mechanism between the two process.

The NRQCD calculation suggest that the quark-antiquark annihilation would be more important in the ψ' production, and hence ψ' is expected to have a different x_F distribution than J/ψ. The

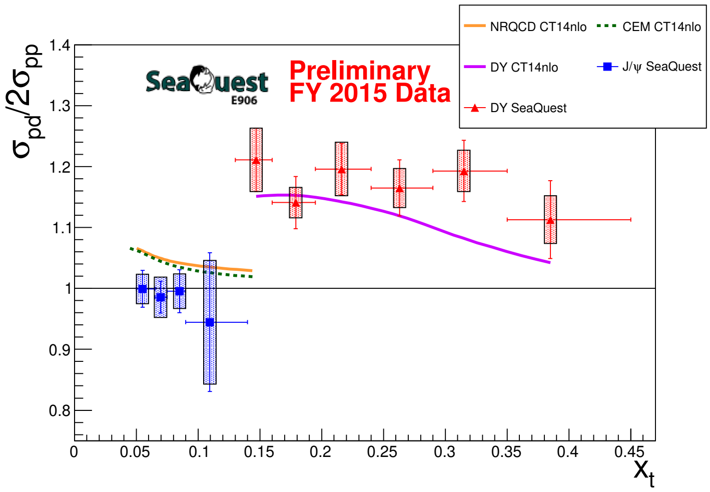

Figure 5: The preliminary result on the extracted J/ψ $\sigma^{pd}/2\sigma^{pp}$ cross section ratio as a function of x_t and compared with the Drell-Yan cross section ratio reported by SeaQuest.

extraction of the ψ' cross section is currently underway and would be able to provide further input to the understanding of charmonium production. Moreover, the data from the remaining data sets would roughly double the statistics for both the charmonium production as well as the Drell-Yan. The SpinQuest experiment [12], the follow-up experiment of SeaQuest, will measure the dimuon production with proton on transversely polarized ammonia target, which can provide information on the transverse spin asymmetry of charmonium production.

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