Measurement of charmonium production in p + p and p + d interaction in the Fermilab SeaQuest experiment

DIS2022
May 2 – 6, 2022

Ching Him Leung
University of Illinois at Urbana-Champaign
Representing the SeaQuest Collaboration
• Performed at Fermilab
  • With a 120 GeV proton beam from Main Injector
  • A new spectrometer is constructed

• Design to probe the partonic structure of nucleons at larger $x$ compared to E866
Motivation

• SeaQuest experiment has obtained new dimuon production data with 120 GeV proton beam on hydrogen and deuterium targets over mass range of 2-9 GeV, containing both Drell-Yan and charmonium events

• Drell-Yan is an electromagnetic interaction in leading order
  • Sensitive to the quark and antiquark distribution in the nucleon
  • The p+d/p+p cross section ratio can provide information on the $\bar{d}/\bar{u}$ asymmetry

• $J/\psi$ are produced via strong interaction
  • Sensitive to quark and antiquark distribution as well as gluon distribution
  • Provide information complimentary to Drell-Yan data
Timeline

- Commissioning began in 2012 and data collection finished in July 2017
- Current analysis based on run2 and run3 data
- Corresponds to ~50% of the full data set
Mass spectrum for proton on hydrogen

• The $J/\psi$ peak as well as the Drell-Yan continuum at higher mass are clearly observed
• The $\psi'$ shoulder is also visible
Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratio

- The Drell-Yan process has been used to probe the sea quark asymmetry

$$\frac{d^2\sigma_{DY}}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_ts} \sum_i e_i^2 [q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)]$$

- For $x_b \gg x_t$, the cross-section ratio can be approximated as

$$\frac{\sigma_{pd}}{2\sigma_{pp}} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]_{x_b \gg x_t}$$

May 4, 2022
The Drell-Yan process involves the production of the $J/\psi$ meson via strong interaction, which can be described by two subprocesses at LO $q\bar{q}$ annihilation and gluon fusion.
Color Evaporation Model (CEM)

- The $c\bar{c}$ pairs production is calculated perturbatively, and a fixed probability $F$ for hadronizing into a charmonium state.
- The relative importance of each subprocess is a strong function of kinematics.
  - The $q\bar{q}$ is more important at forward $x_F$.

\[
\frac{d\sigma}{dx_F}\bigg|_{J/\psi} = F \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{s \sqrt{x_F^2 + 4M_{c\bar{c}}^2/s}} 
\times f_{i/A}(x_b, \mu_F) f_{j/B}(x_t, \mu_F) \sigma[ij \rightarrow c\bar{c}X](x_b P_A, x_t P_B, \mu_F, \mu_R)
\]

\[x_F \approx x_b - x_t\]
Energy dependency

• The relative importance of each process depends on the energy
  • More contribution from quarks at lower energy
  • 800 GeV (E866) $\rightarrow$ 450 GeV (NA51) $\rightarrow$ 120 GeV (E906)
• SeaQuest is also probing a different kinematic region compared to previous experiment
Non-Relativistic QCD (NRQCD)

- The $c\bar{c}$ pairs production is calculated perturbatively.
- The hadronization is described by the long-distance matrix elements (LDMEs), which depend on the color and spin of the $c\bar{c}$ pairs.
- Relative weighting of the two processes depend on the choice of LDMEs.

$$\frac{d\sigma^H}{dx_F} = \sum_{i,j=q,q,G} \int_0^1 dx_b dx_t \delta(x_F - x_b + x_t)$$

$$\times f_{i/A}(x_b, \mu_F) f_{j/B}(x_t, \mu_F) \hat{\sigma}[i,j \rightarrow H](x_b P_A, x_t P_B, \mu_F, \mu_R, m_c)$$

$$\hat{\sigma}[i,j \rightarrow H] = \sum_n C_{cc|n}^{ij} (x_b P_A, x_t P_B, \mu_F, \mu_R, m_c) \langle O_n^H \mid^{2S+1} L_J \rangle$$

Production of $c\bar{c}$ pairs

LDMEs

CT14NLO

May 4, 2022

LDME from CY Hsieh et al, Chin. J. Phys. 73, 13 (2021)
Obtaining $J/\psi$ yield from mass spectrum

- Performing a component fit to the mass spectrum
- Use Monte Carlo to simulate signal events ($J/\psi, \psi', \text{Drell-Yan}$)
- Use mixed single-track events to simulate accidental background
- The mass spectrum for various $x_F$ bins are also well described using this fitting procedure
Obtaining $J/\psi$ yield from mass spectrum

- The $p + d$ mass distribution is also well described using this fitting procedure
Obtaining the cross section

• The $J/\psi$ yield is obtained from the mass spectrum
• The acceptance and efficiency correction is applied, which are obtained from Monte Carlo simulations

$$B \frac{d\sigma}{dx_F} = \frac{N_{\text{events}}}{\Delta x_F \mathcal{L} \epsilon}$$

Branching ratio \hspace{2cm} Charmonium yield from mass spectrum

$$\mathcal{L} = N_A \rho \lambda \left( 1 - e^{-L/\lambda} \right) N_{\text{incident}}$$

Acceptance and efficiency correction

• The main sources of systematics comes from the background simulation and the beam luminosity
**$J/\psi$ absolute cross sections**

- The measured cross section is compared with CEM prediction
- The normalization for the CEM calculation are adjusted to fit the data
$J/\psi$ absolute cross sections

- The measured cross section is compared with NRQCD prediction.
- The preliminary result is in reasonable agreement with NRQCD, including the overall magnitude.
The measured ratio consistent with 1 within uncertainty

The SeaQuest measurement covers a higher $x_F$ region than previous measurements

$J/\psi$ and Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratios vs $x_t$

- $J/\psi$ ratio is closer to 1 compared to Drell-Yan
  - The Drell-Yan ratio is more sensitive to the flavor asymmetry
  - Contribution from gluon fusion in $J/\psi$ production
  - The $J/\psi$ data is at a region where $\bar{d}/\bar{u}$ asymmetry is small
- The overall trend for both $J/\psi$ and Drell-Yan are in reasonable agreement with calculation
The LDMEs depend on the charmonium state
The relative importance of each subprocess is different between $J/\psi$ and $\psi'$

- $q\bar{q}$ annihilation is the dominant contribution to $\psi'$ at all $x_F$
$\psi'$ production

• The LDMEs depend on the charmonium state
• The relative importance of each subprocess is different between $J/\psi$ and $\psi'$
  • $q\bar{q}$ annihilation is the dominant contribution to $\psi'$ at all $x_F$
Summary

• The preliminary $p + p$ and $p + d$ $J/\psi$ cross section with 120GeV beam is obtained and compared with NRQCD calculation
  • SeaQuest has provided new information at a lower energy and higher $x_F$ compared to previous measurements
  • The measured absolute $J/\psi$ cross section is in good agreement with NRQCD

• The preliminary $(p + d)/2(p + p) J/\psi$ cross section ratio is consistent with 1
  • The difference between the $J/\psi$ ratio and the Drell-Yan ratio is reflecting the different mechanism between the different processes
Summary (cont.)

• NRQCD suggests the relative importance of $q\bar{q}$ annihilation and gluon fusion are different between $J/\psi$ and $\psi'$
  • The extraction of the $\psi'$ cross section is currently underway
• The ongoing analysis of the remaining data will double the statistics for both Drell-Yan and $J/\psi$
SeaQuest Event Distribution

• The SeaQuest data covers the $x_F > 0.4$ region for $J/\psi$ and $\psi'$

• $x_F = \frac{2P_Z}{\sqrt{s}(1-M^2/s)}$

May 4, 2022
• Calculated cross section ratio using CEM with CT14nlo at two different energy

• At lower energy, the deviation from unity is more significant as $q\bar{q}$ annihilation is more important

$E_{\text{beam}}=120\text{GeV}$

$E_{\text{beam}}=800\text{GeV}$

$\bar{d}/\bar{u}$ extracted from SeaQuest
$J/\psi$ and $\psi' \sigma_{pd}/2\sigma_{pp}$