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

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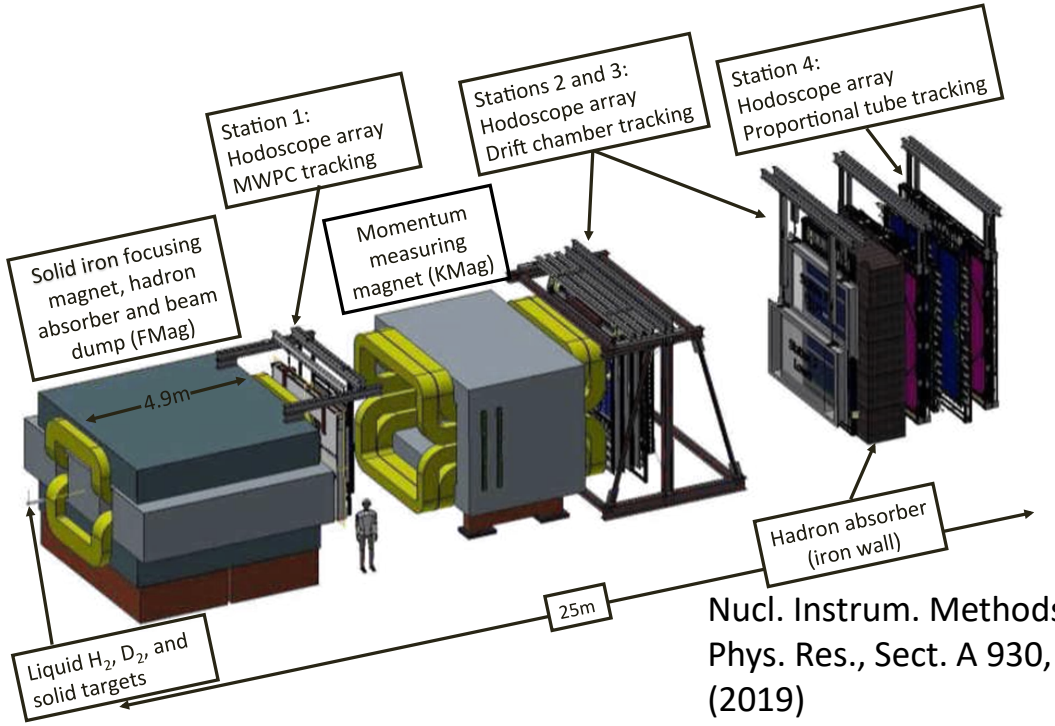
Ching Him Leung

University of Illinois at Urbana-Champaign

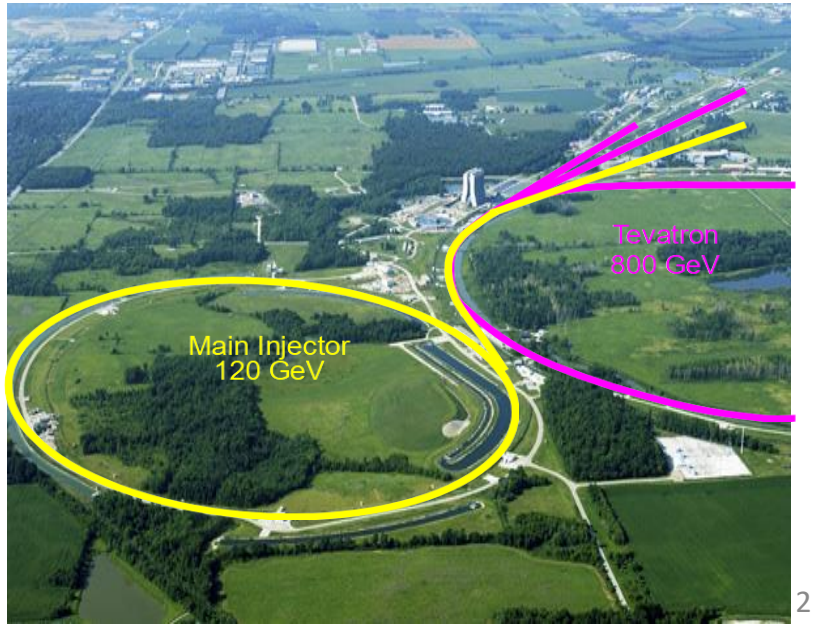
Representing the SeaQuest Collaboration

SeaQuest
E906

- 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



Nucl. Instrum. Methods Phys. Res., Sect. A 930, 49 (2019)

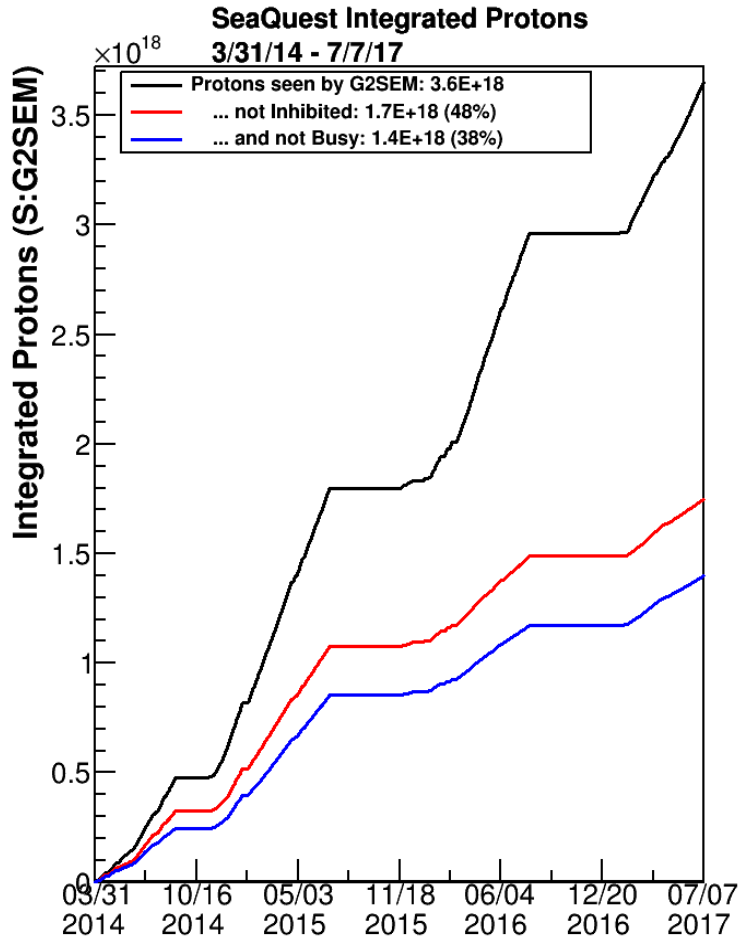


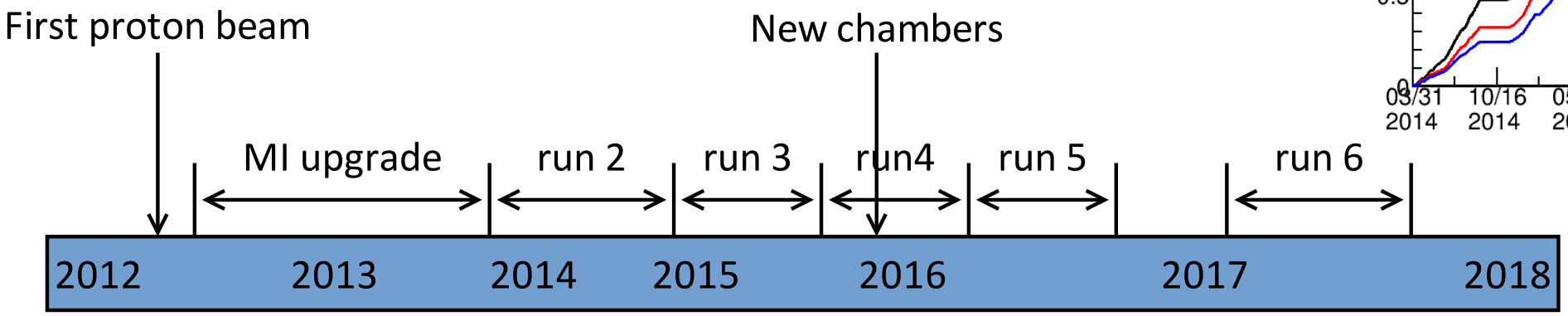
Motivation

- 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/ψ are produced via strong interaction
  - Sensitive to quark and antiquark distribution as well as gluon distribution
  - Provide information complimentary to Drell-Yan data

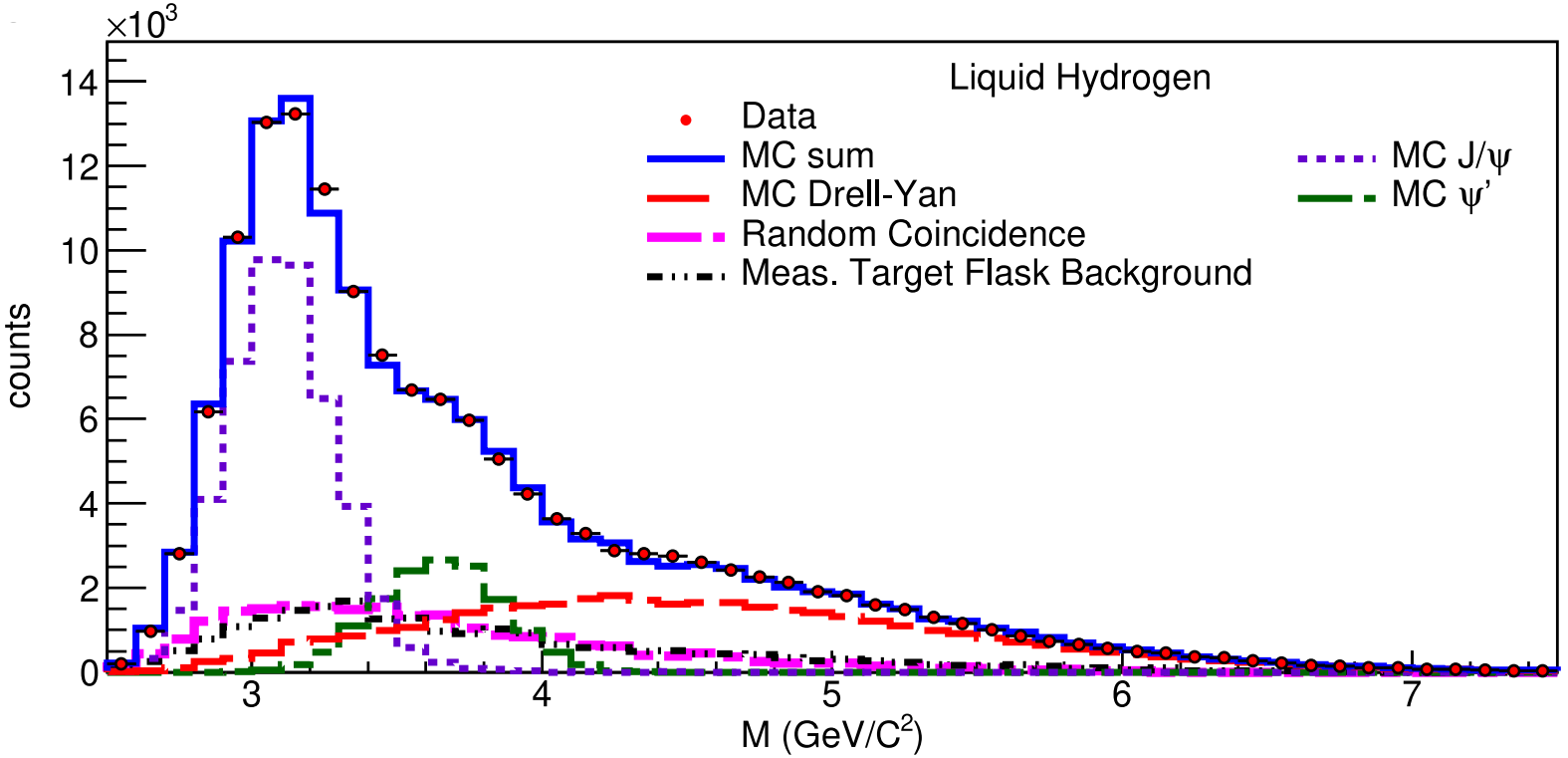
Timeline

- 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





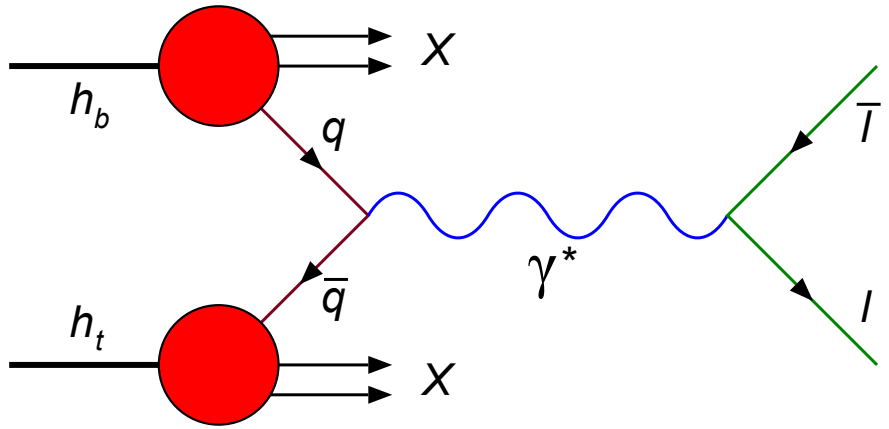
Mass spectrum for proton on hydrogen



J. Dove et al, Nature volume 590, pages 561–565 (2021)

- The J/ψ peak as well as the Drell-Yan continuum at higher mass are clearly observed
- The ψ' shoulder is also visible

Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratio

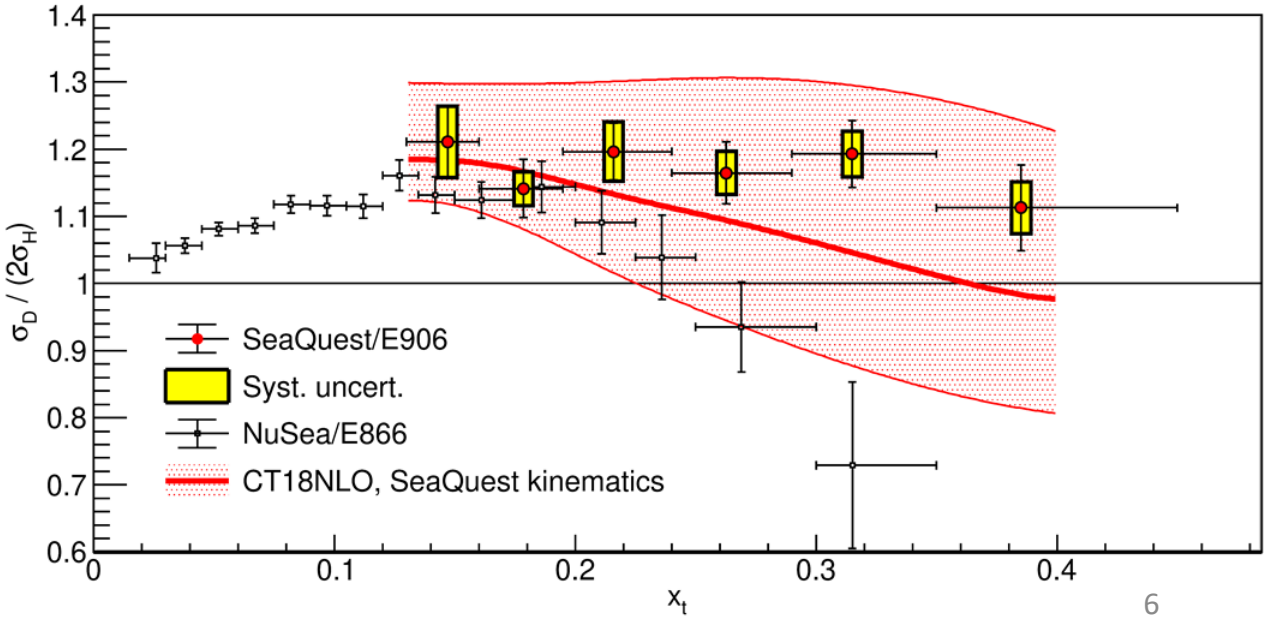


- The Drell-Yan process has been used to probe the sea quark asymmetry

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

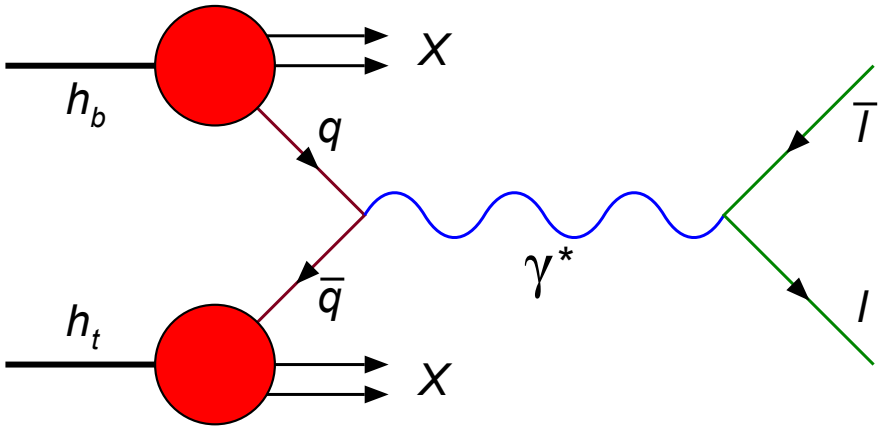
- For $x_b \gg x_t$, the cross-section ratio can be approximated as

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

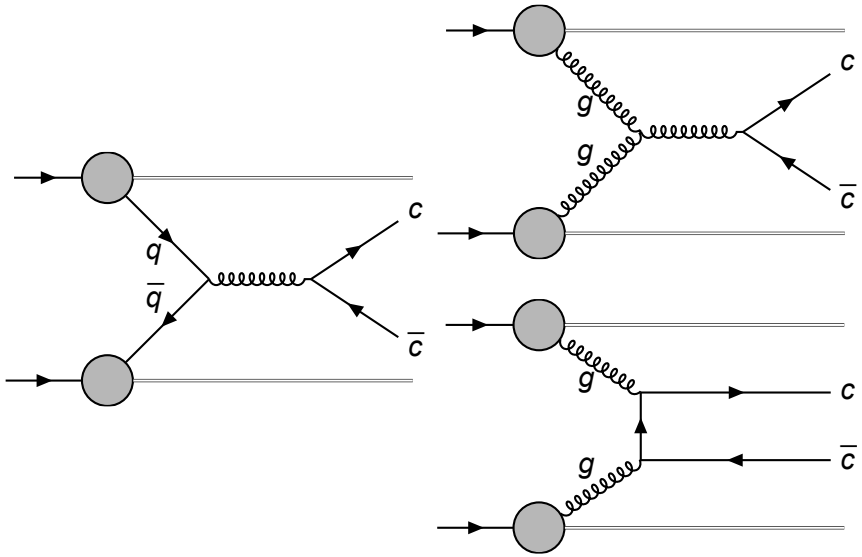


J/ψ production and Drell-Yan process

- The Drell-Yan is an electromagnetic process



- The J/ψ meson is produced via strong interaction:
  - Involve two subprocesses at LO $q\bar{q}$ annihilation and gluon fusion

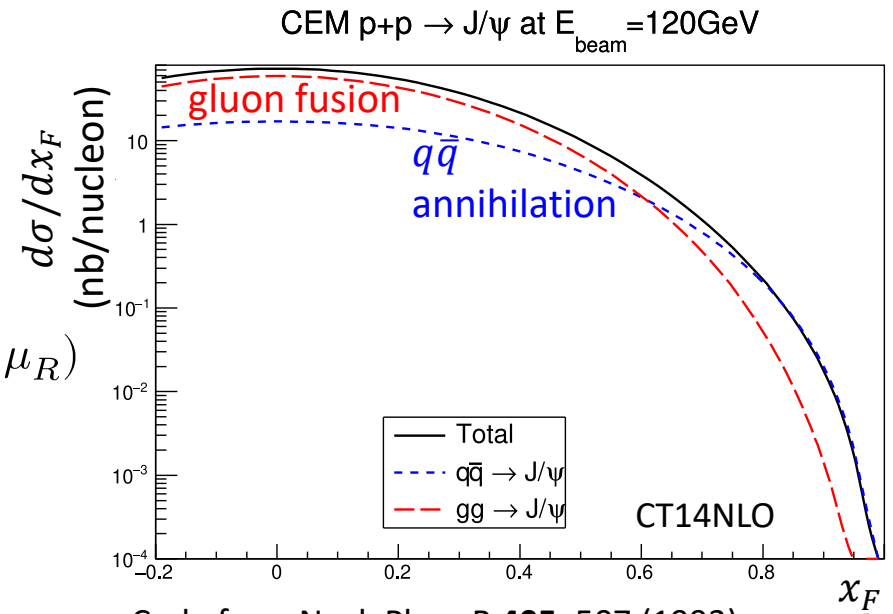


Color Evaporation Model (CEM)

- 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

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

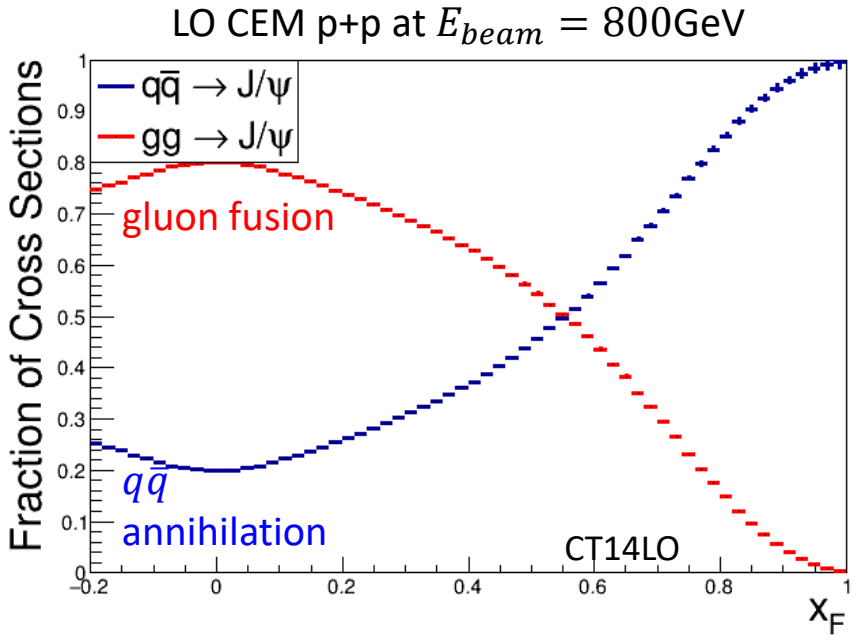
$$x_F \approx x_b - x_t$$

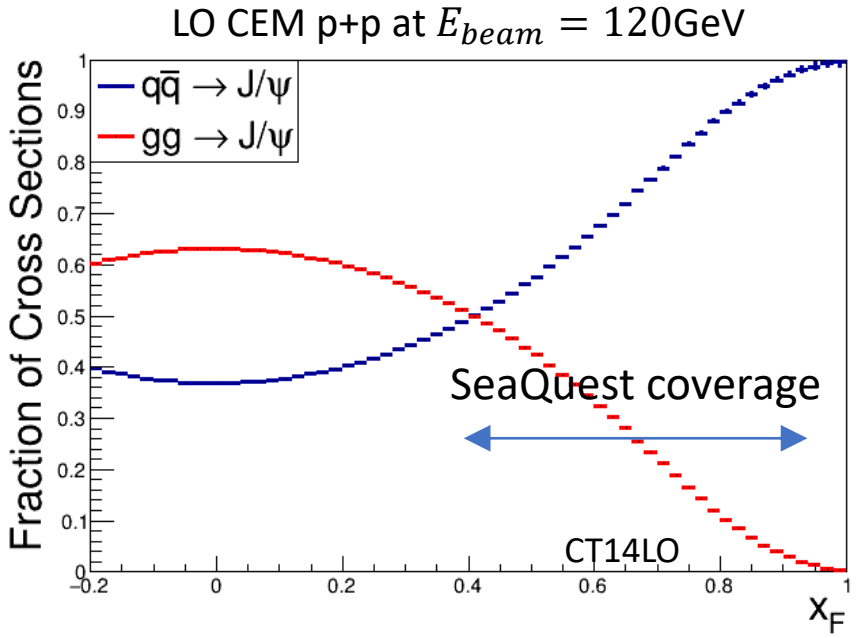


Code from Nucl. Phys. B **405**, 507 (1993).

Energy dependency

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

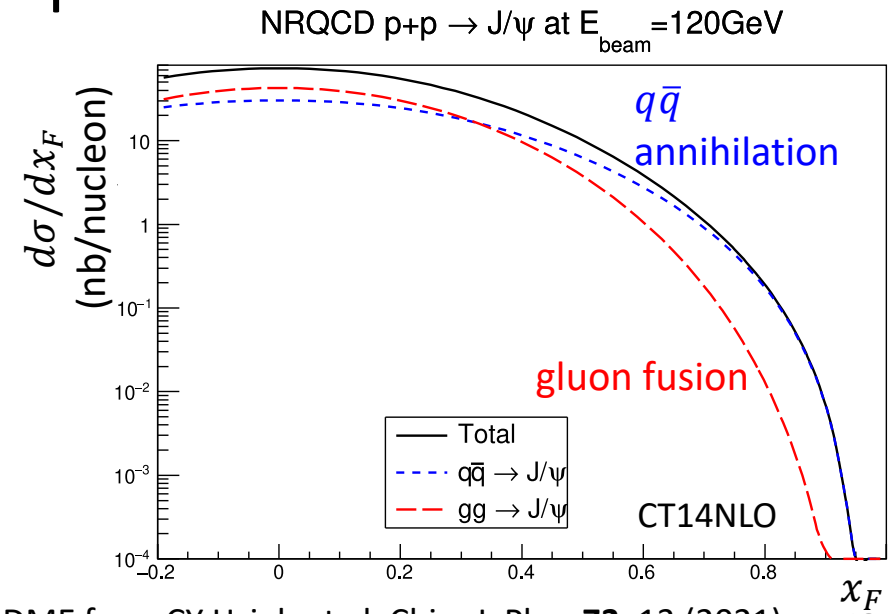




Non-Relativistic QCD (NRQCD)

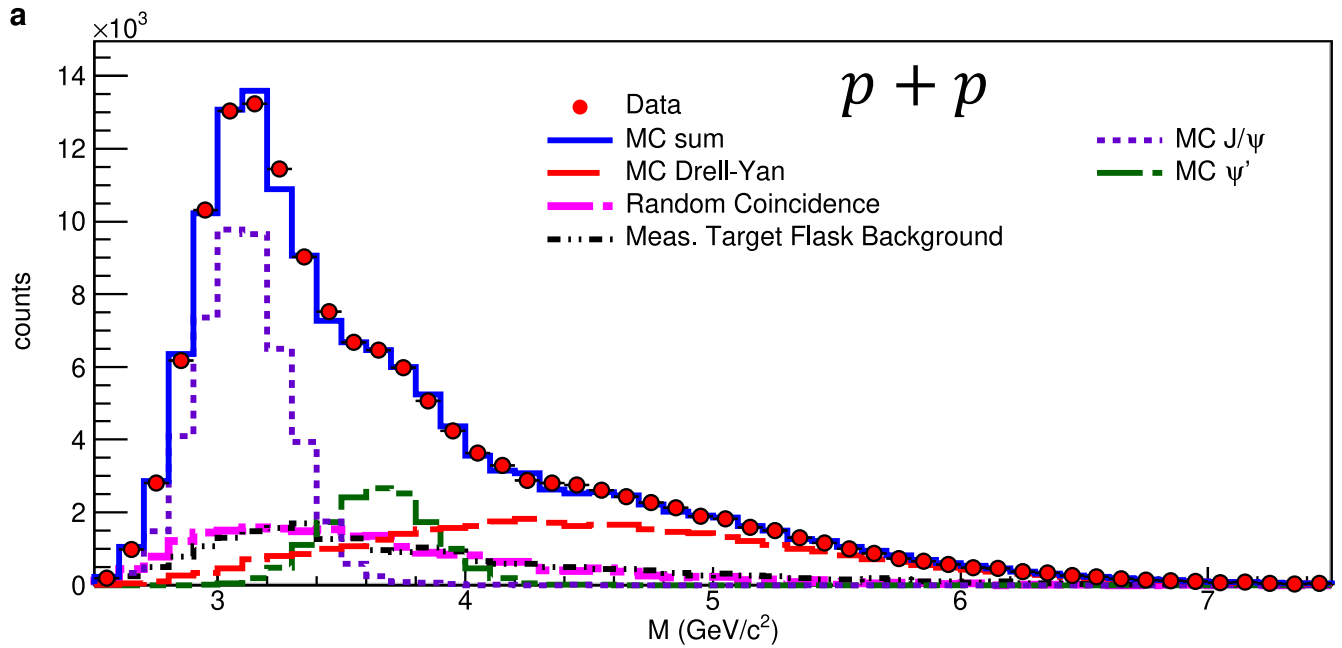
- The $c\bar{c}$ pairs production is calculated perturbatively
- The hadronization is described by the long-distance matrix elements (LDMEs), which depend on the color and spin of the $c\bar{c}$ pairs
- Relative weighting of the two processes depend on the choice of LDMEs

$$\frac{d\sigma^H}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_b dx_t \delta(x_F - x_b + x_t)$$
$$\times f_{i/A}(x_b, \mu_F) f_{j/B}(x_t, \mu_F) \hat{\sigma}[ij \to H](x_b P_A, x_t P_B, \mu_F, \mu_R, m_c)$$
$$\hat{\sigma}[ij \to H] = \sum_n \underbrace{C^{ij}_{c\bar{c}[n]}(x_b P_A, x_t P_B, \mu_F, \mu_R, m_c)}_{\text{Production of } c\bar{c} \text{ pairs}} \underbrace{\langle O^H_n [^{2S+1}L_J] \rangle}_{\text{LDMEs}}$$



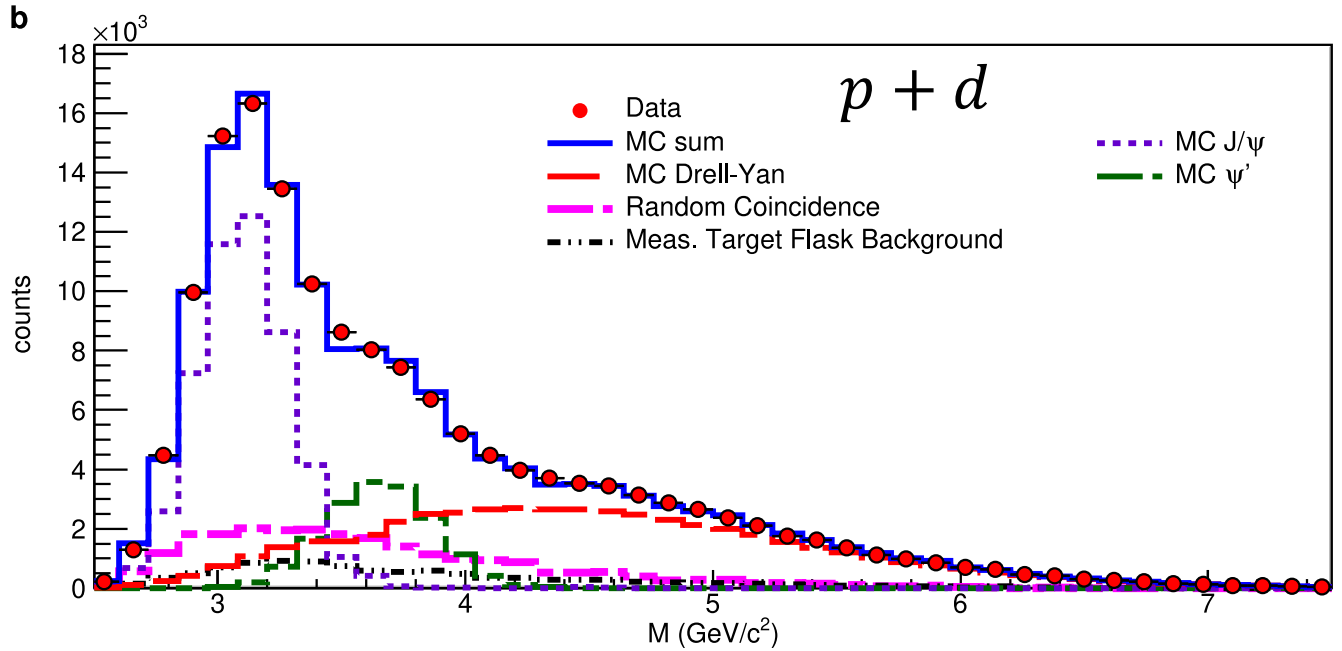
LDME from CY Hsieh et al, Chin. J. Phys **73**, 13 (2021)

Obtaining J/ψ yield from mass spectrum



- Performing a component fit to the mass spectrum
- Use Monte Carlo to simulate signal events ($J/\psi, \psi'$, 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/ψ yield from mass spectrum



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

Obtaining the cross section

- The J/ψ yield is obtained from the mass spectrum
- The acceptance and efficiency correction is applied, which are obtained from Monte Carlo simulations

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

Charmonium yield from mass spectrum

Branching ratio

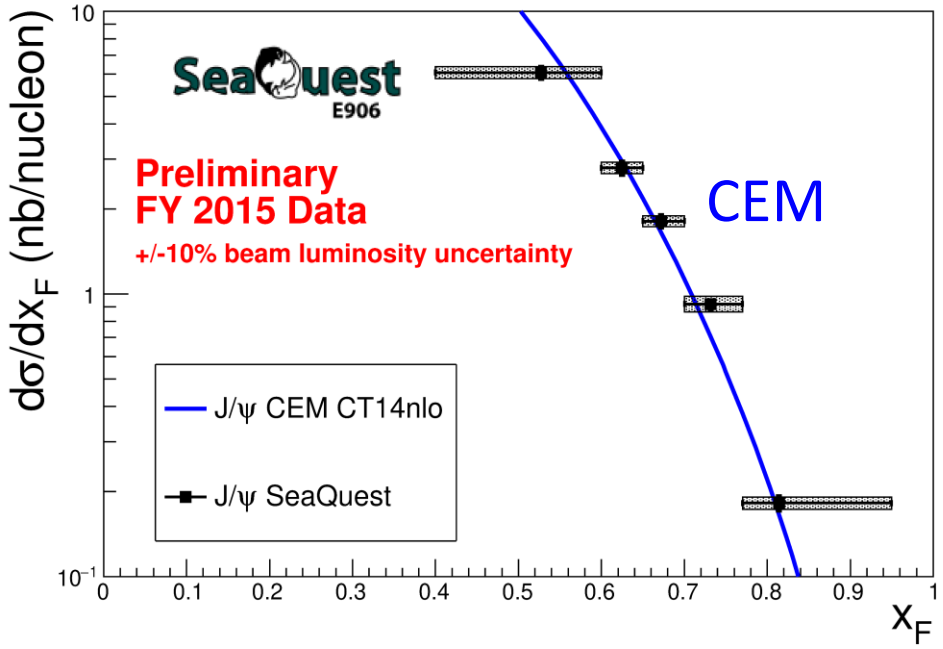
Acceptance and efficiency correction

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

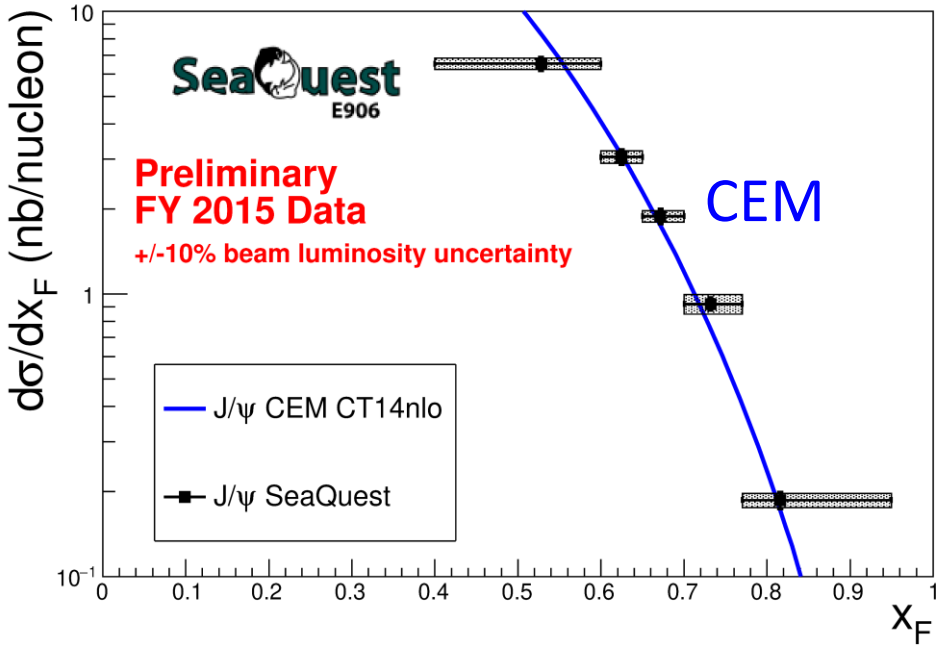
- The main sources of systematics comes from the background simulation and the beam luminosity

J/ψ absolute cross sections

$p + p$



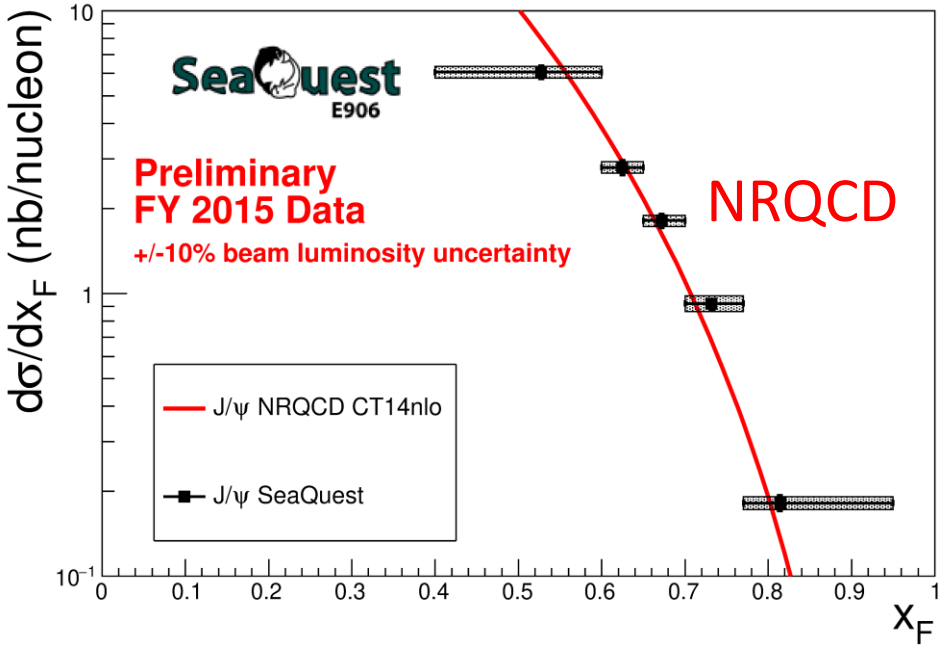
$p + d$



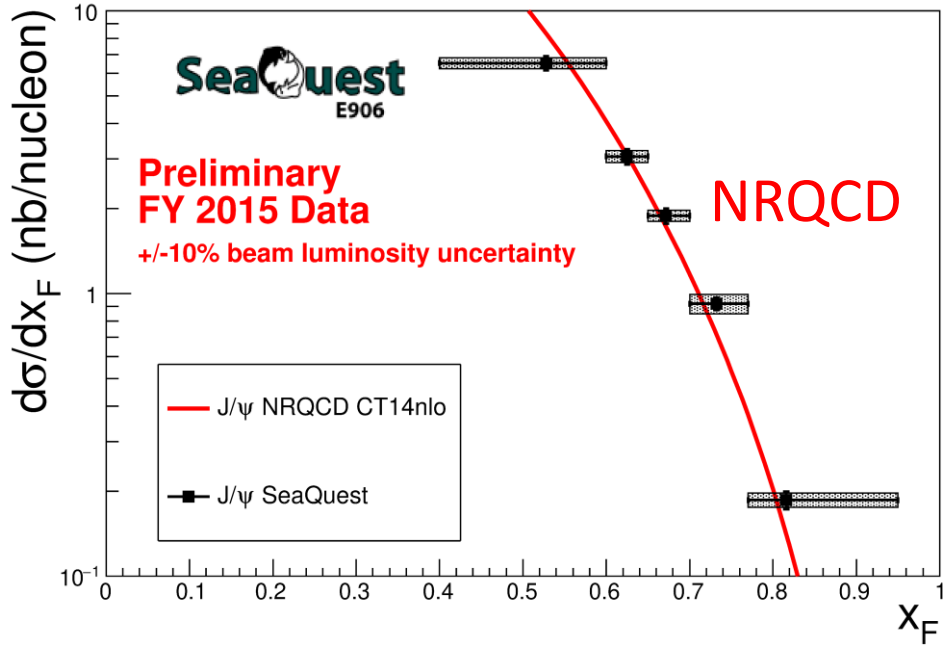
- The measured cross section is compared with CEM prediction
- The normalization for the CEM calculation are adjusted to fit the data

J/ψ absolute cross sections

$p + p$

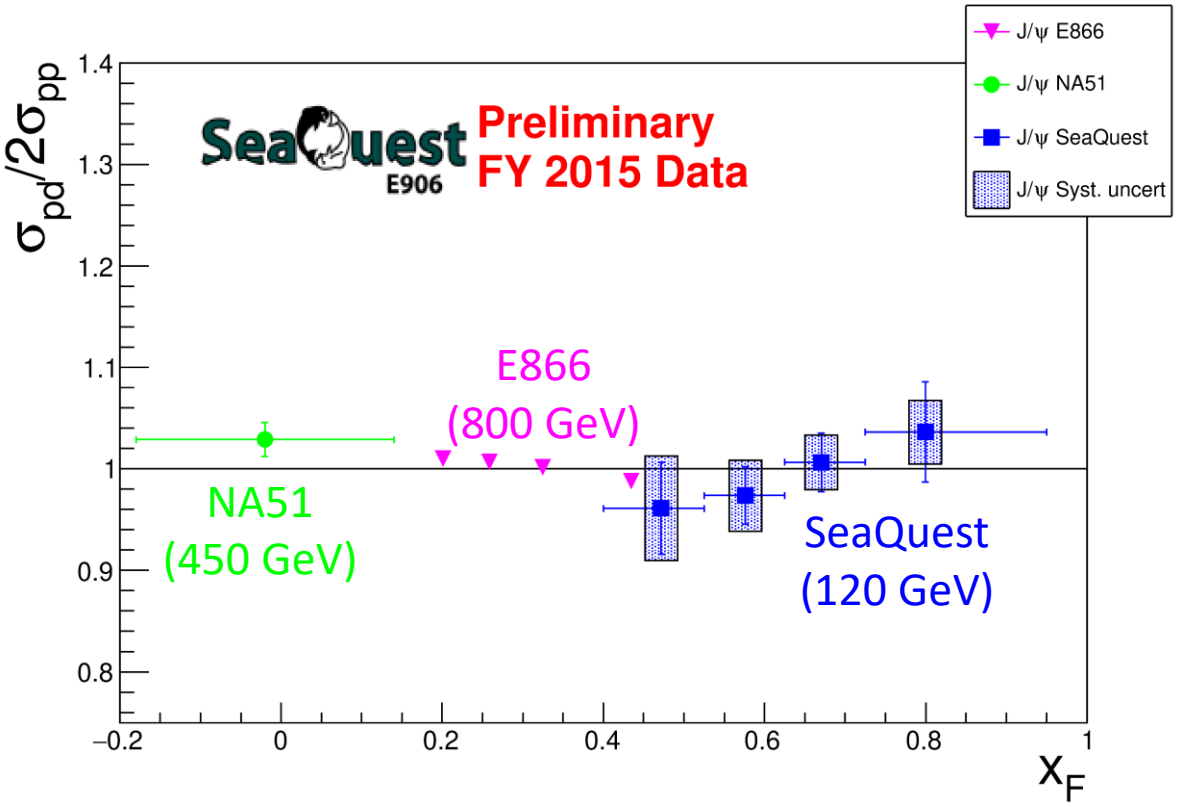


$p + d$



- The measured cross section is compared with NRQCD prediction
- The preliminary result is in reasonable agreement with NRQCD, including the overall magnitude

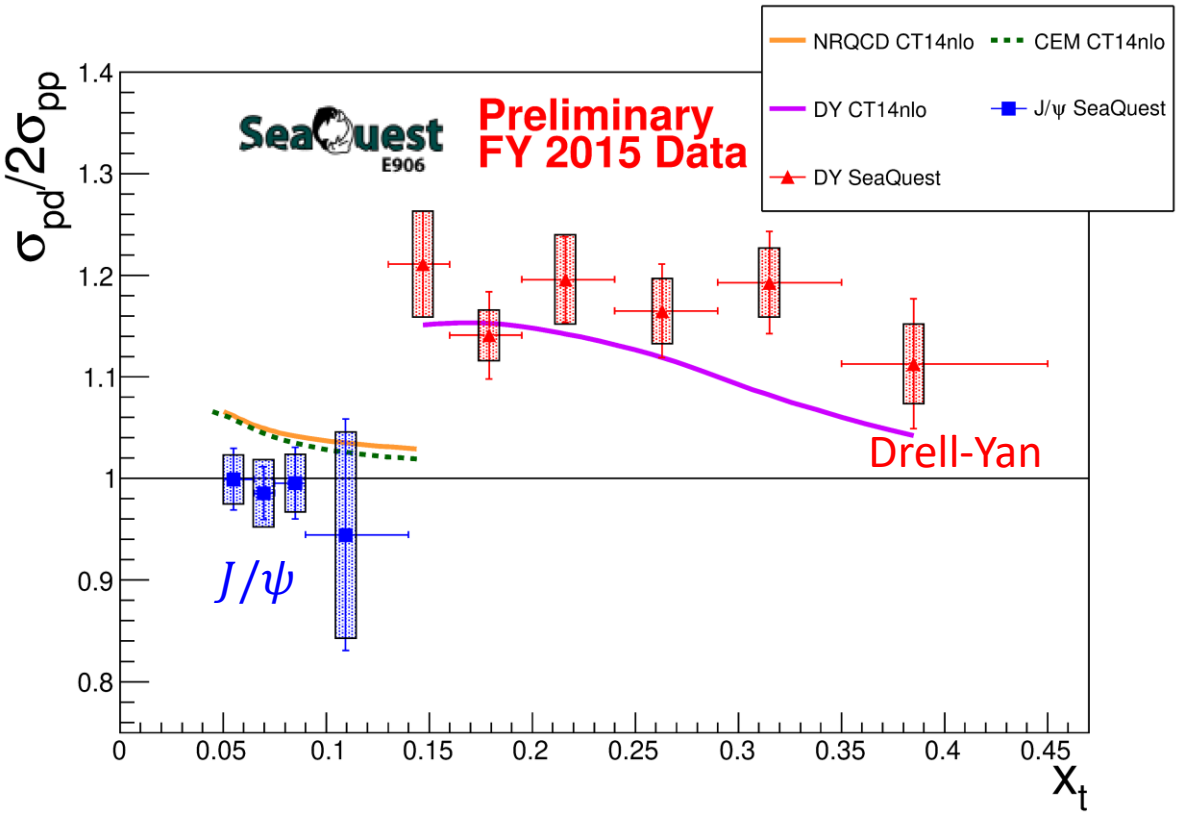
$J/\psi\ \sigma^{pd}/2\sigma^{pp}$ ratio vs x_F



- The measured ratio consistent with 1 within uncertainty
- The SeaQuest measurement covers a higher x_F region than previous measurements

M. C. Abreu et al, Physics Letters B **438**, 35 (1998).
J.-C. Peng, Eur. Phys. J. A **18**, 395 (2003).

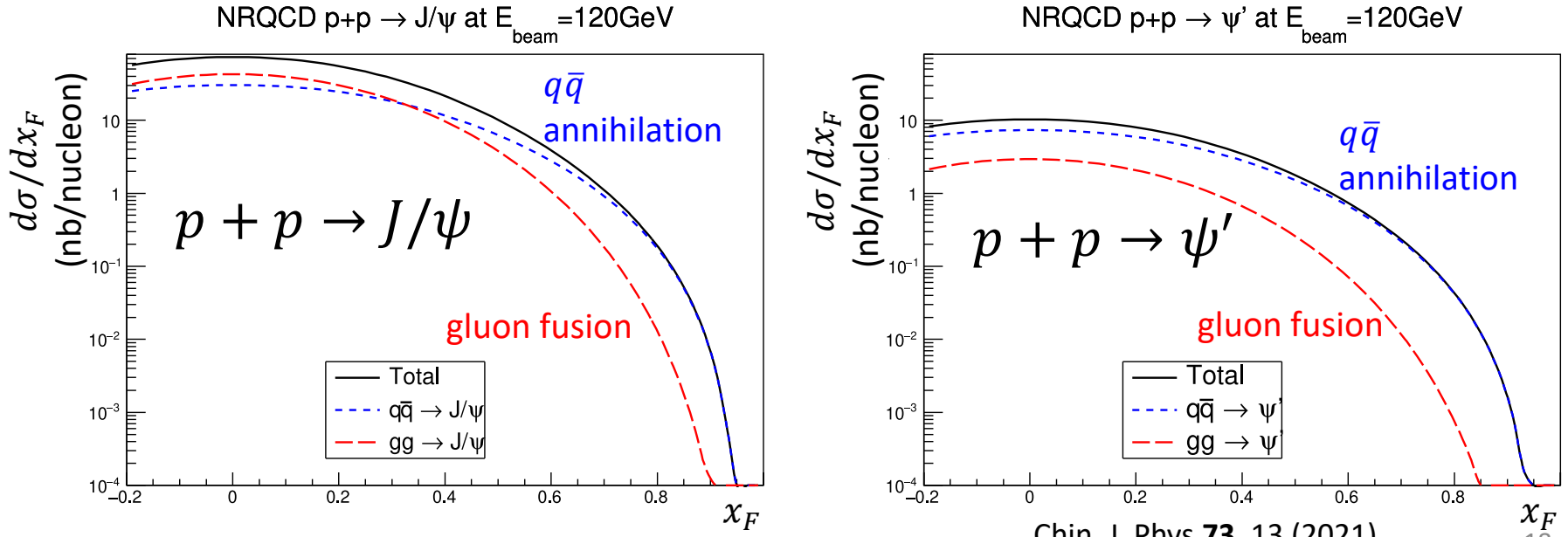
J/ψ and Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratios vs x_t



- J/ψ 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/ψ production
  - The J/ψ data is at a region where $\bar{d}/\bar{u}$ asymmetry is small
- The overall trend for both J/ψ and Drell-Yan are in reasonable agreement with calculation

ψ' production

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



Chin. J. Phys **73**, 13 (2021)

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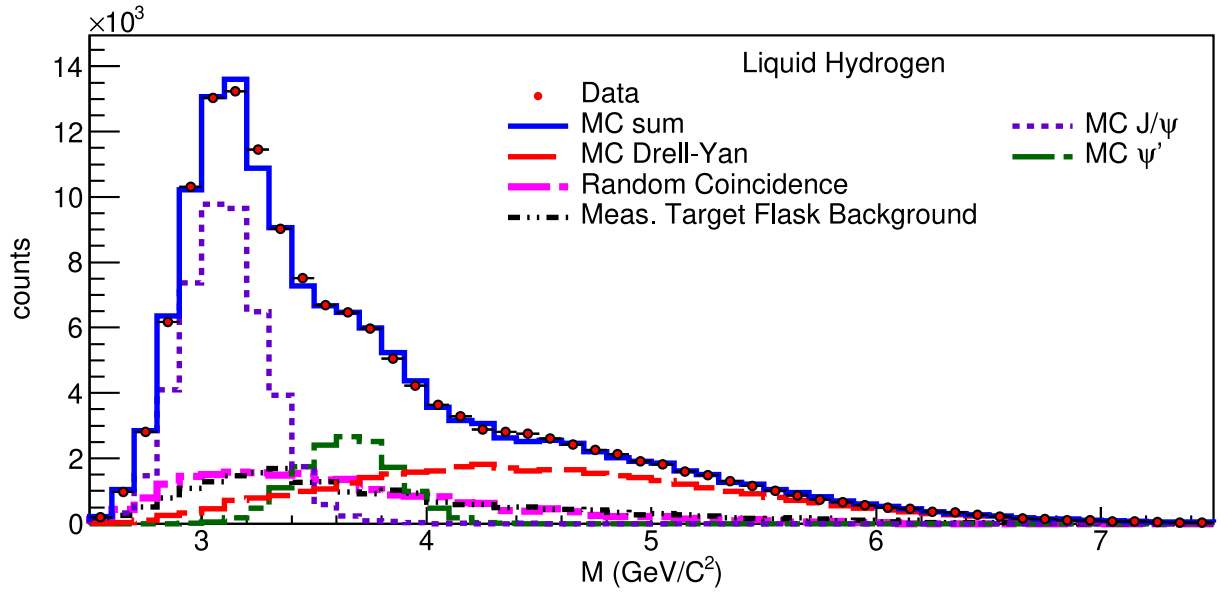
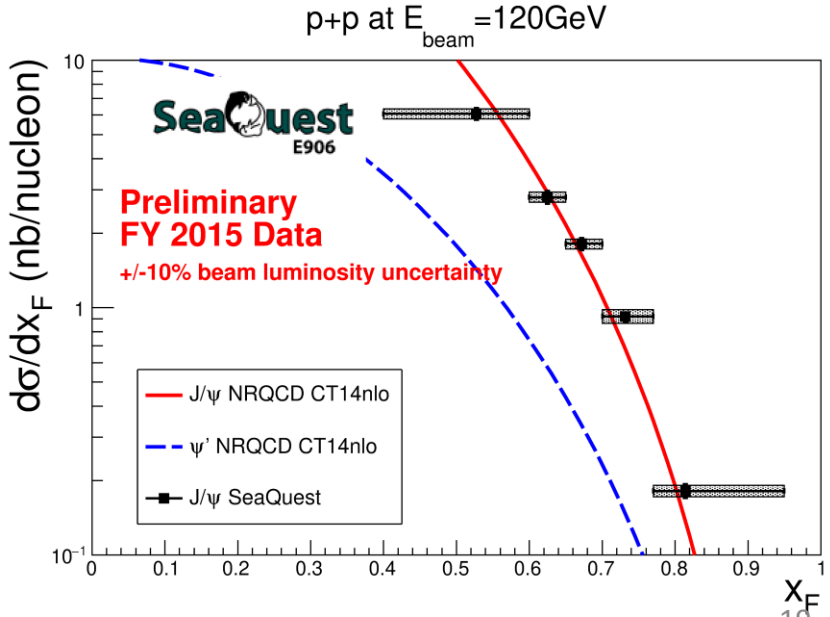




Summary

- The preliminary $p + p$ and $p + d$ J/ψ cross section with $120\mathrm{GeV}$ 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/ψ cross section is in good agreement with NRQCD
- The preliminary $(p + d)/2(p + p)$ J/ψ cross section ratio is consistent with 1
  - The difference between the J/ψ ratio and the Drell-Yan ratio is reflecting the different mechanism between the different processes

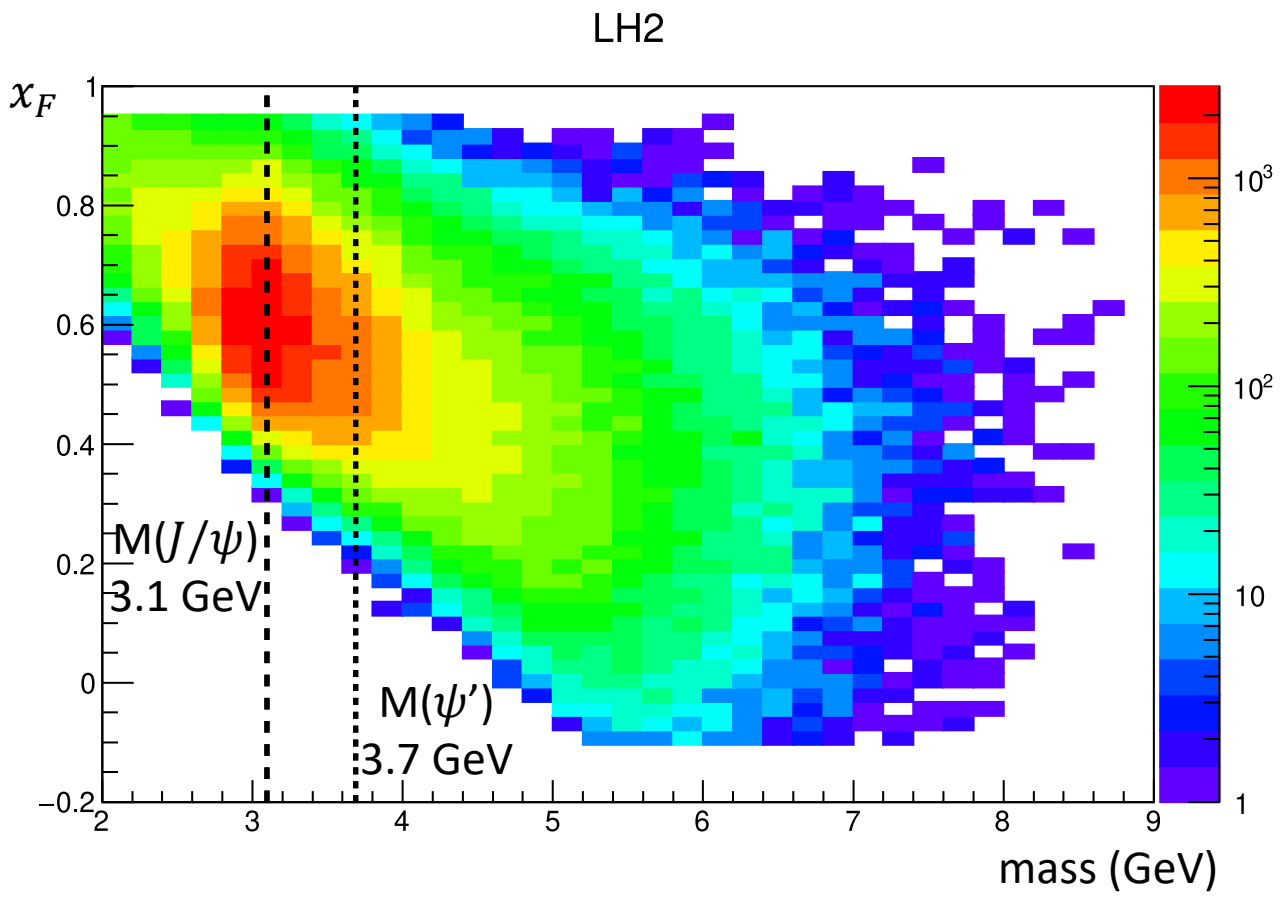
Summary (cont.)

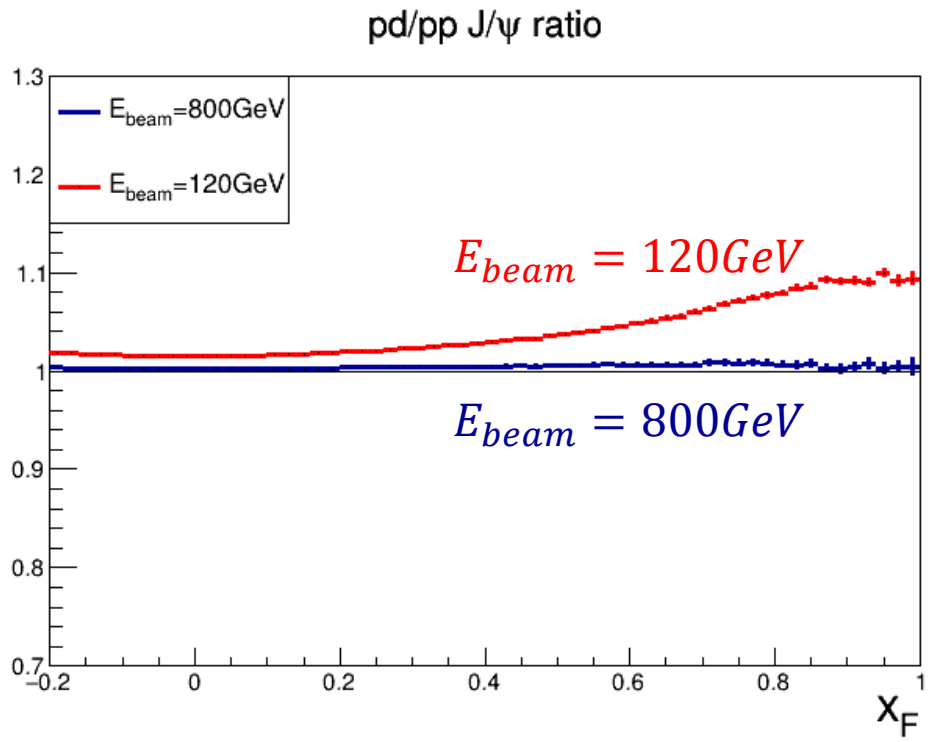
- NRQCD suggests the relative importance of $q\bar{q}$ annihilation and gluon fusion are different between J/ψ and ψ'
  - The extraction the of the ψ' cross section is currently underway
- The ongoing analysis of the remaining data will double the statistics for both Drell-Yan and J/ψ

SeaQuest Event Distribution

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

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

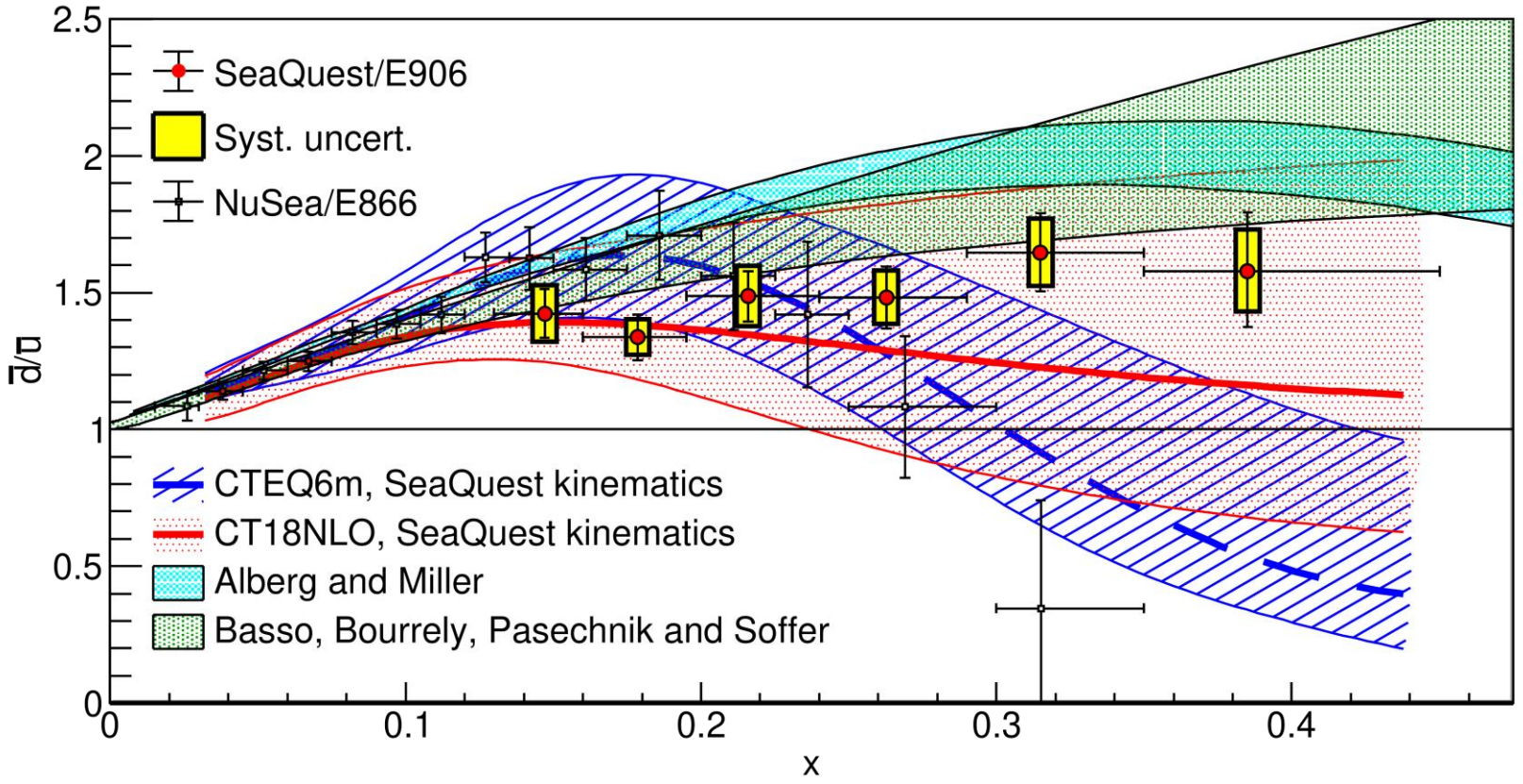




M. L. Mangano et al, Nuclear Physics B 405, 507 (1993).
S. Dulat, et al, Phys. Rev. D 93, 033006 (2016).

- 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

$\bar{d}/\bar{u}$ extracted from SeaQuest



J/ψ and ψ' $\sigma^{pd}/2\sigma^{pp}$