Drell-Yan and charmonium production in p+p and p+d interaction at 120 GeV from the SeaQuest experiment

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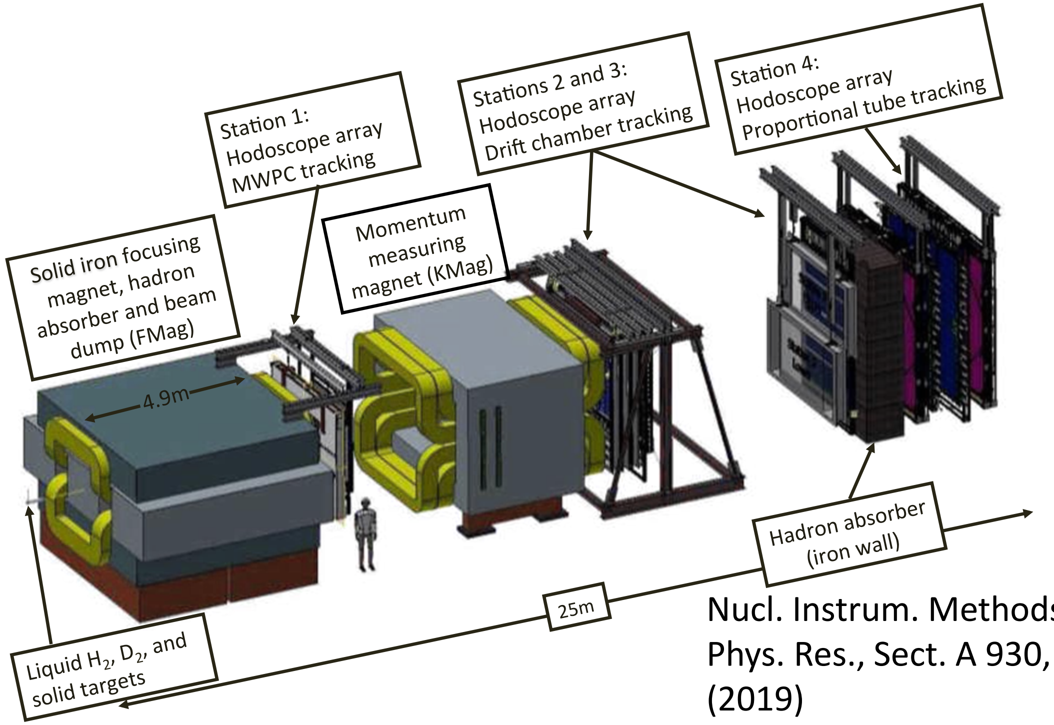
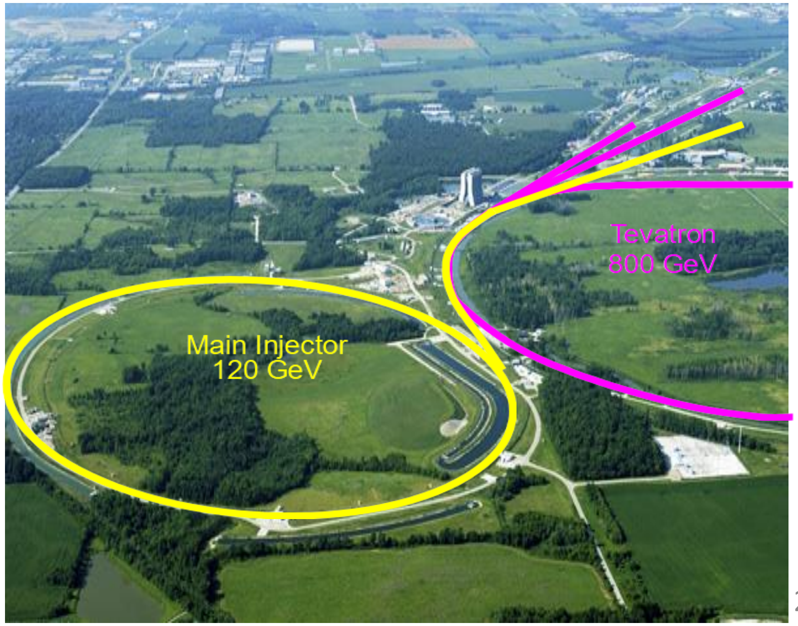
Representing the SeaQuest Collaboration

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



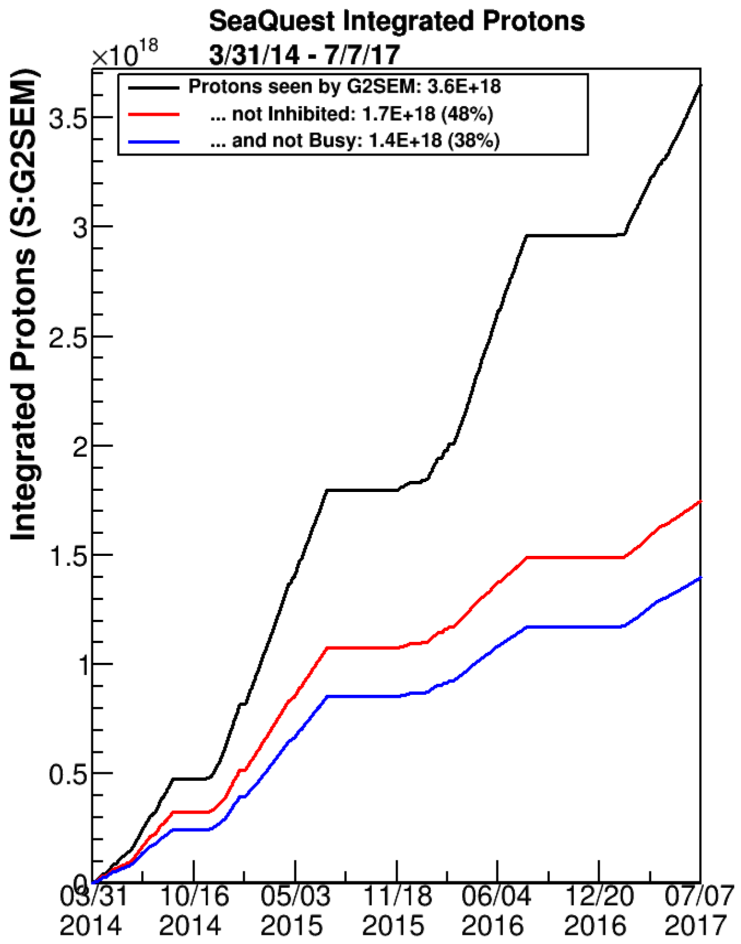
Nucl. Instrum. Methods Phys. Res., Sect. A 930, 49 (2019)

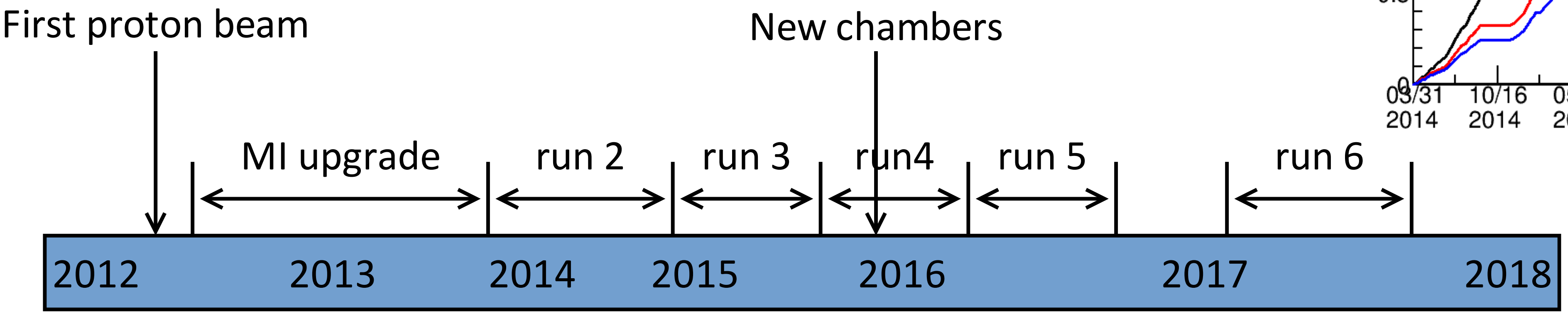


$$\frac{d^2\sigma^{p+p}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9\,s\,x_1 x_2}\sum_i e_q^2\left[f_{q/p}(x_1)\,f_{\bar{q}/p}(x_2) + f_{\bar{q}/p}(x_1)\,f_{q/p}(x_2)\right]$$

Timeline

- Commissioning began in 2012 and data collection finished in July 2017
- Drell-Yan cross section ratio extracted from run2 and run3 data has been reported
- The new analysis includes run 5 and 6 data





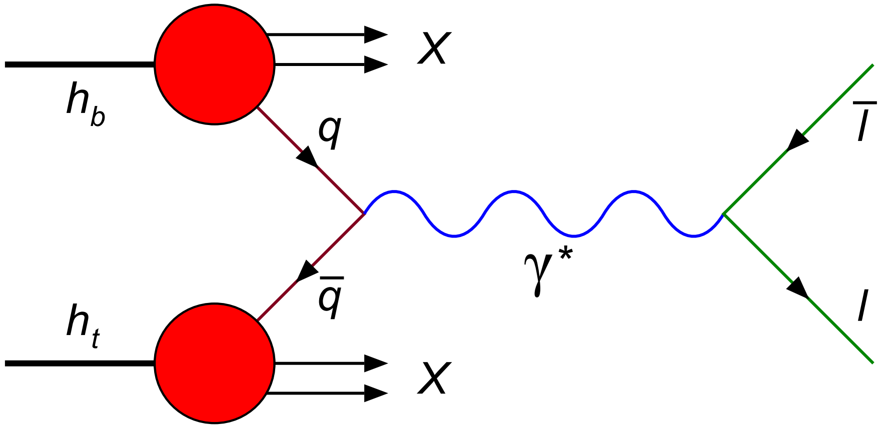
Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratio

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

$$\frac{d^2\sigma^{p+p}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_q^2\left[f_{q/p}(x_1)\,f_{\bar{q}/p}(x_2) + f_{\bar{q}/p}(x_1)\,f_{q/p}(x_2)\right]$$

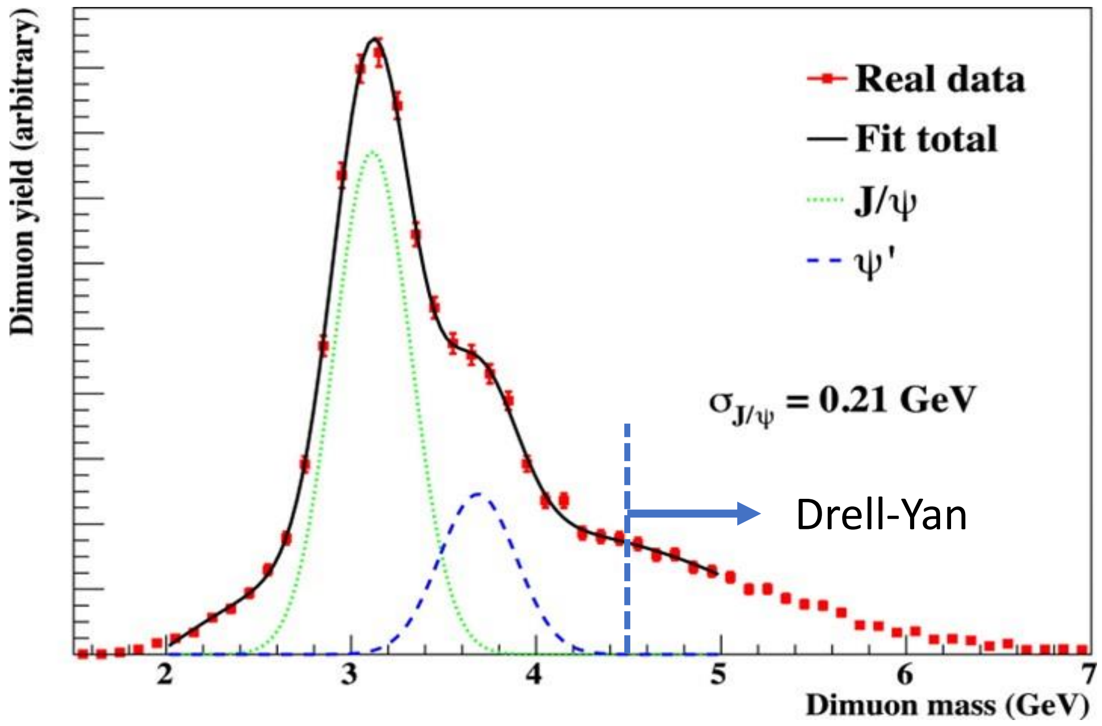
- For $x_1 \gg x_2$, the cross-section ratio can be approximated as

$$\frac{\sigma^{p+d}}{2\sigma^{p+p}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$



Understanding the data

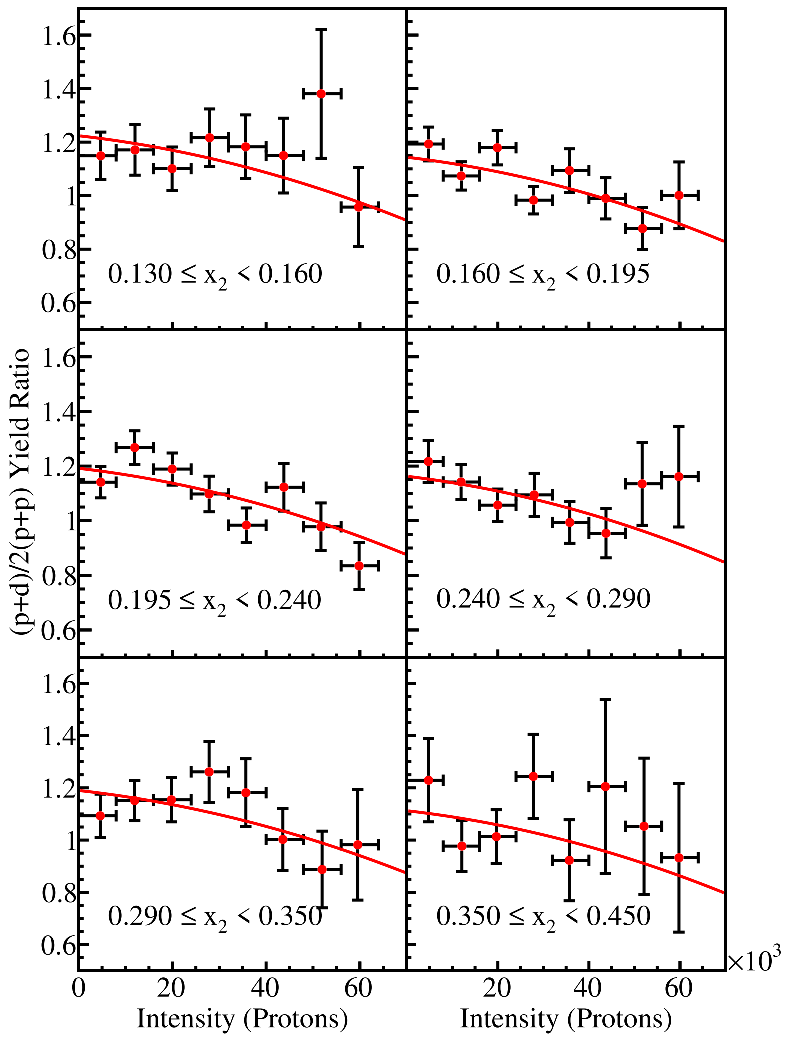
- The J/ψ peak as well as the Drell-Yan continuum at higher mass are clearly observed
- The ψ' shoulder is also visible
- By applying a mass cut at 4.5 GeV, the J/ψ and ψ' are effectively removed
- The challenge is to remove the accidental background



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

Intensity extrapolation method

Nature 590, 561–565 (2021)

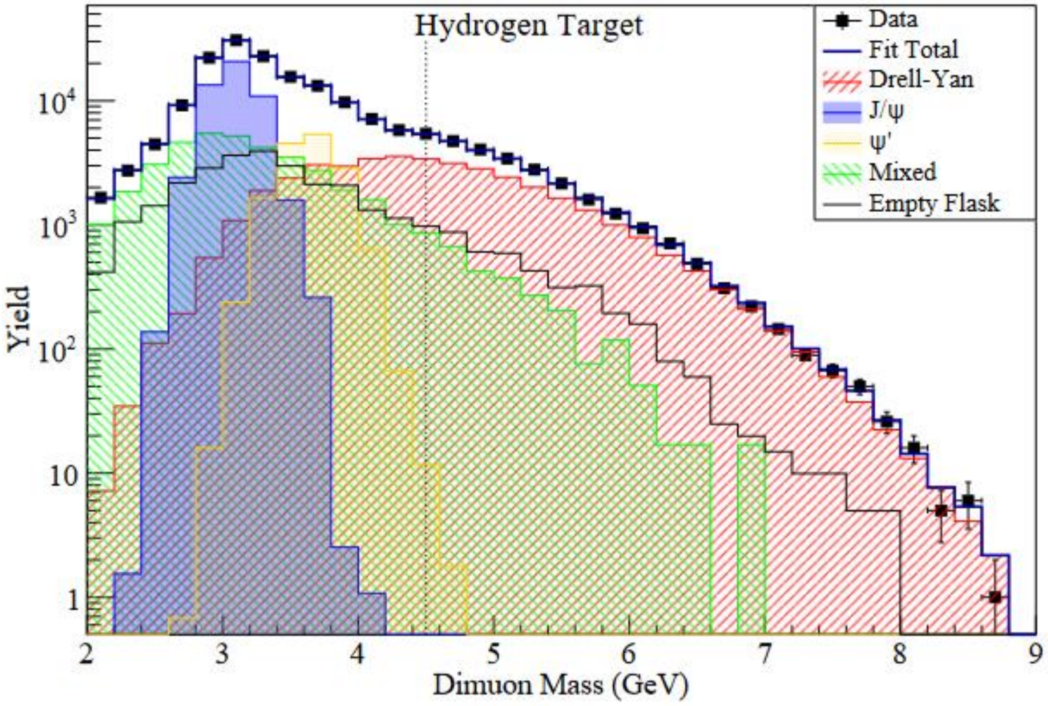


- Using our ability to record the beam intensity for each RF bucket
- And the difference in intensity dependence between accidental background and physics signal
- We fit the yield ratio to

$$\frac{Y_D(x_2, I)}{2Y_H(x_2, I)} = R_{x_2} + aI + bI^2$$

Mass fit method

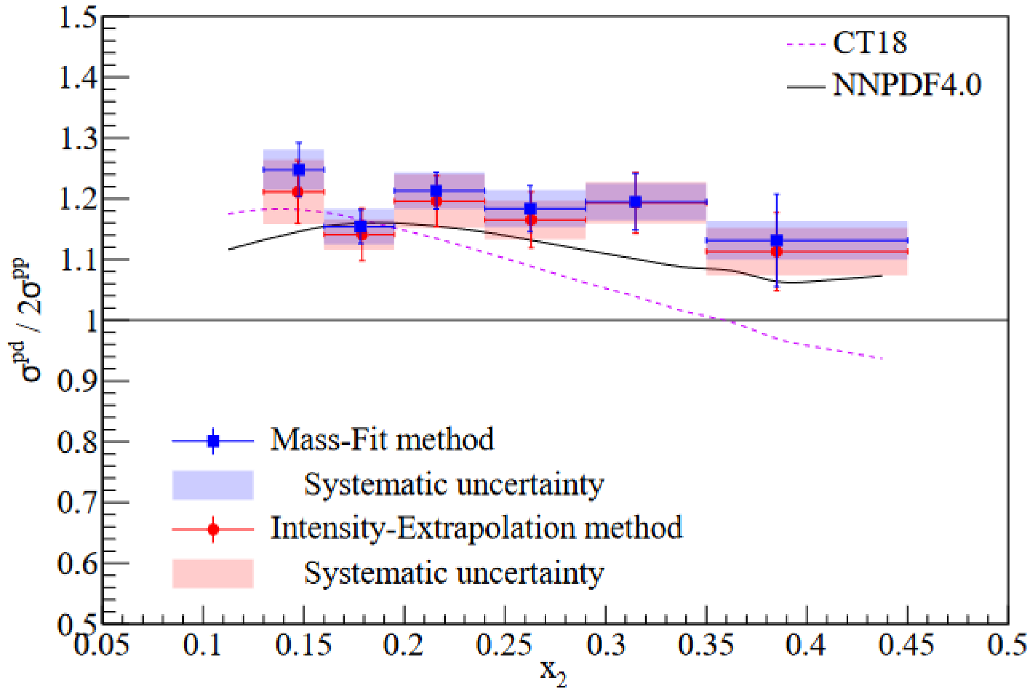
- Another method to extract the Drell-Yan yield is to study the mass distribution
- Use Monte Carlo to simulate signal events ($J/\psi, \psi'$, Drell-Yan)
- Use mixed single-track events to simulate accidental background
- Performing a component fit to the mass spectrum to obtain the relative importance of each component



arXiv:2212.12160

Comparison of the two methods

- The two methods are in very good agreement with each other
- The advantage of the mass fit method is that the absolute yield can be obtained as opposed to the yield ratio
- This method can also be used to study the J/ψ



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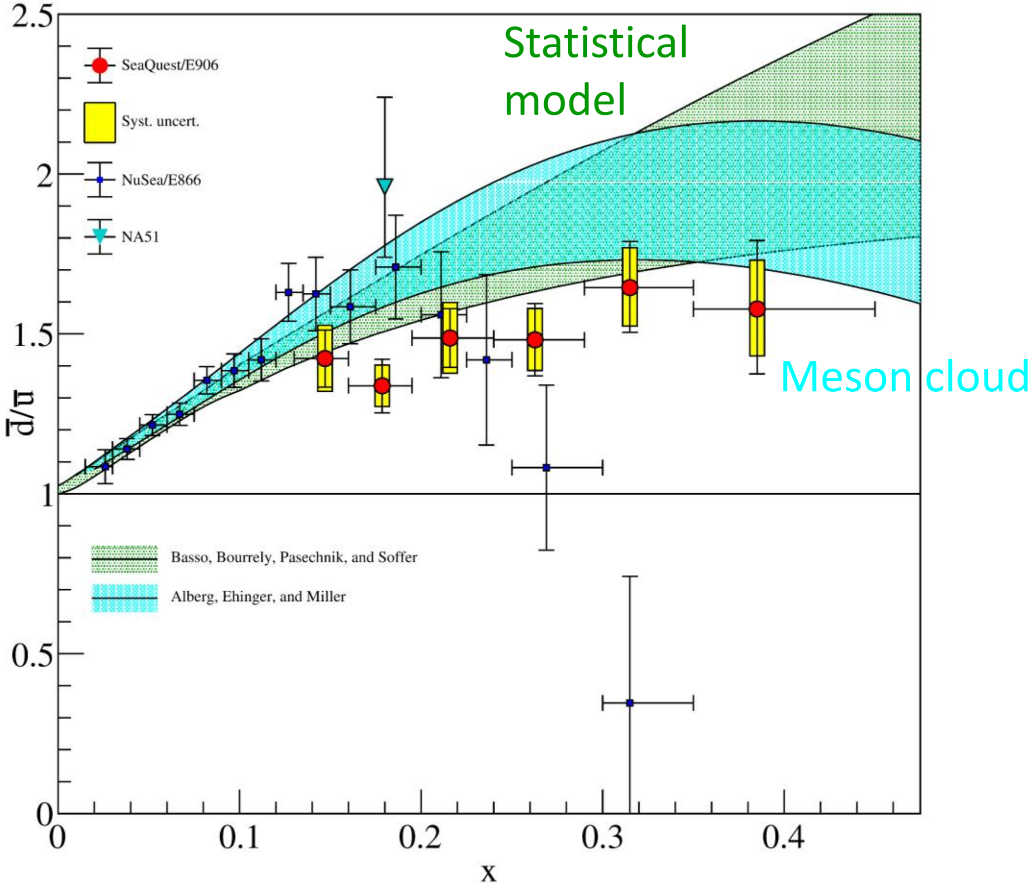
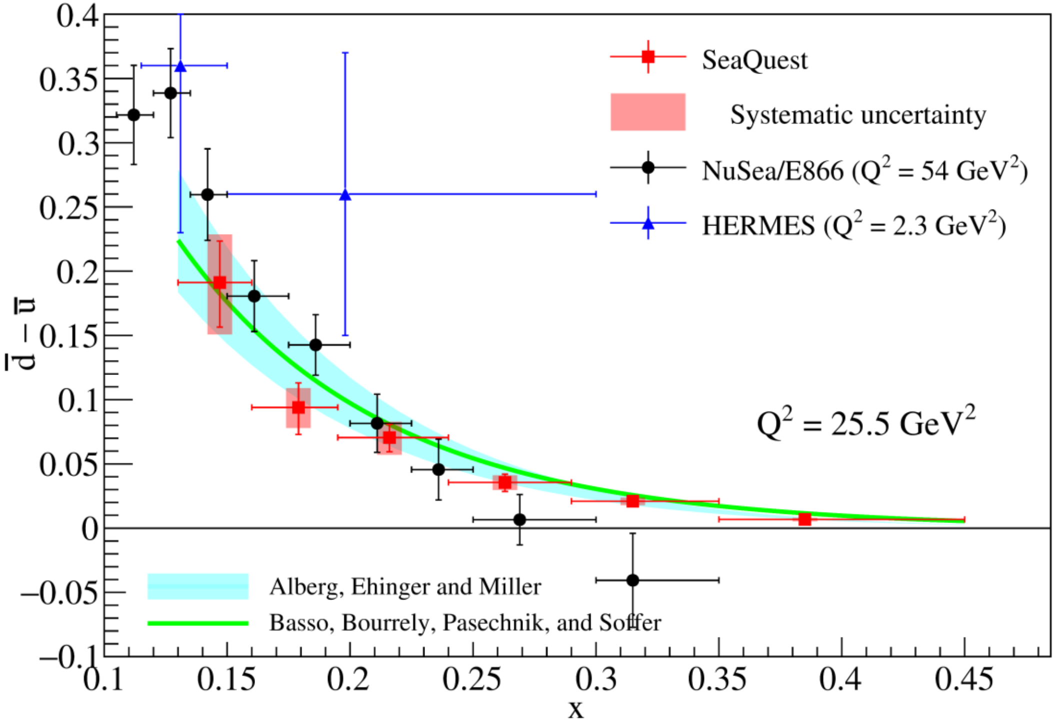
$\bar{d}/\bar{u}$ extraction

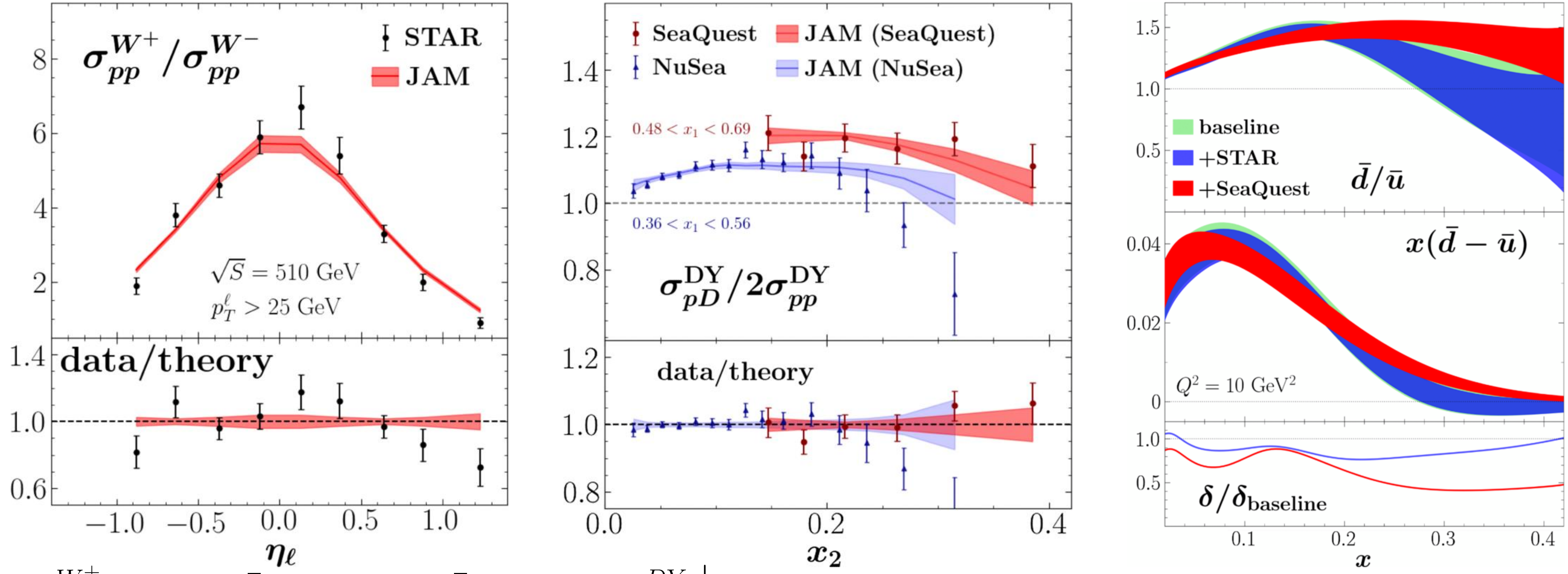




arXiv:2212.12160

Impact of SeaQuest measurement

JAM,
Phys. Rev. D 104, 074031



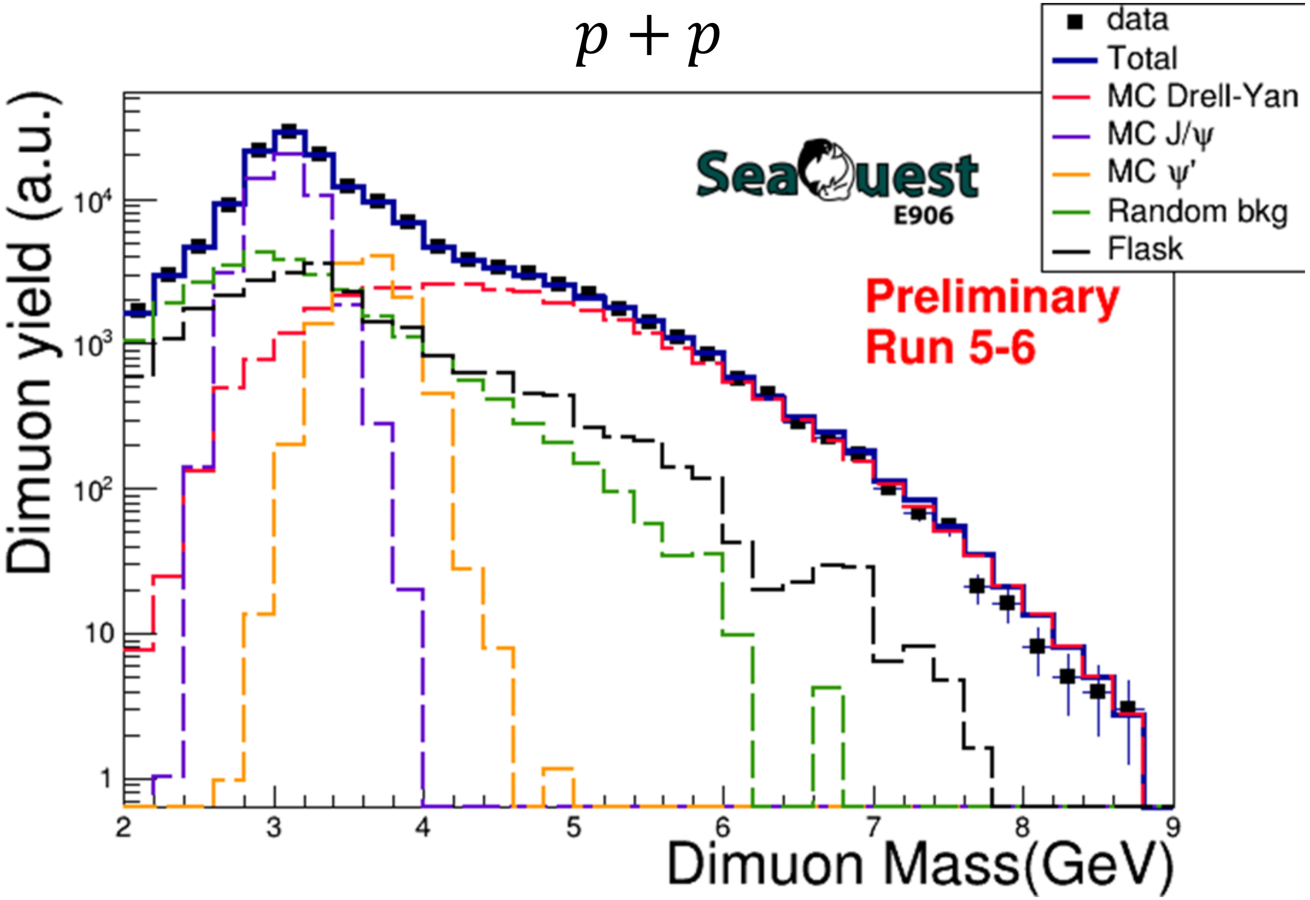
$$\frac{\sigma_{pp}^{W^+}}{\sigma_{pp}^{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)}$$

$$\left.\frac{\sigma_{pd}^{DY}}{2\sigma_{pp}^{DY}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

Analyzing the run 5-6 data

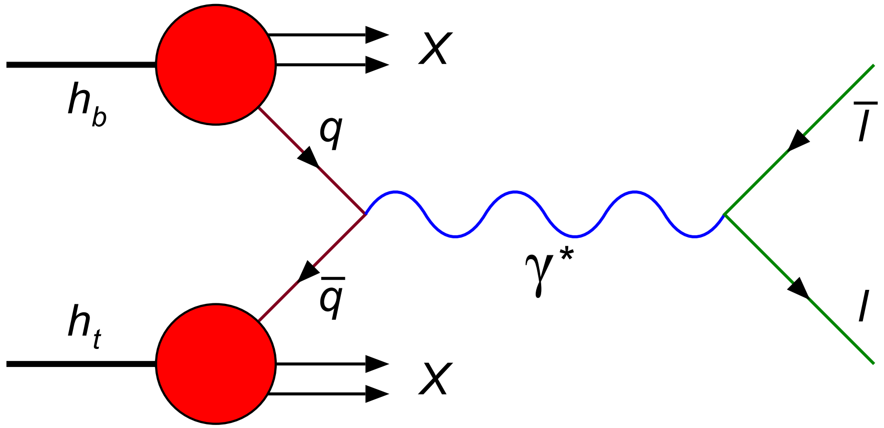
- The reported results are based on run 2-3 data, corresponds to ~50% of the full data
- The remaining data is also being analyzed

$p + p$

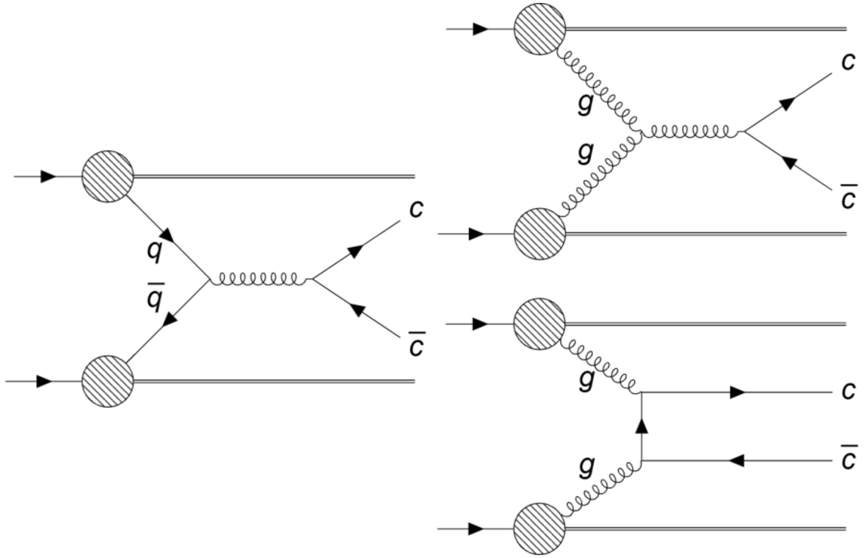


J/ψ production and Drell-Yan process

- The Drell-Yan is an electromagnetic process



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

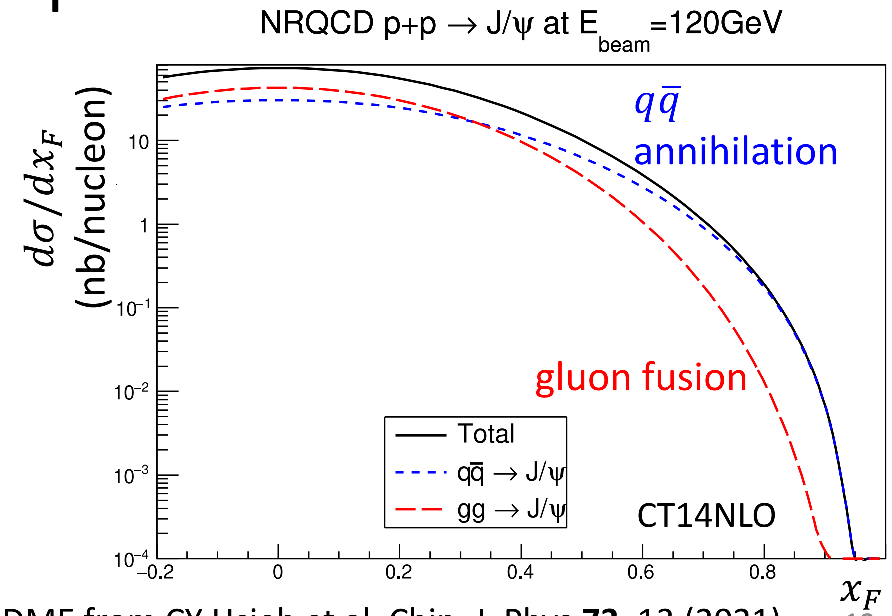


Non-Relativistic QCD (NRQCD)

- 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

$$\frac{d\sigma^H}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_b dx_t \delta(x_F - x_b + x_t) \times f_{i/A}(x_b, \mu_F) f_{j/B}(x_t, \mu_F) \hat{\sigma}[ij \to H](x_b P_A, x_t P_B, \mu_F, \mu_R, m_c)$$

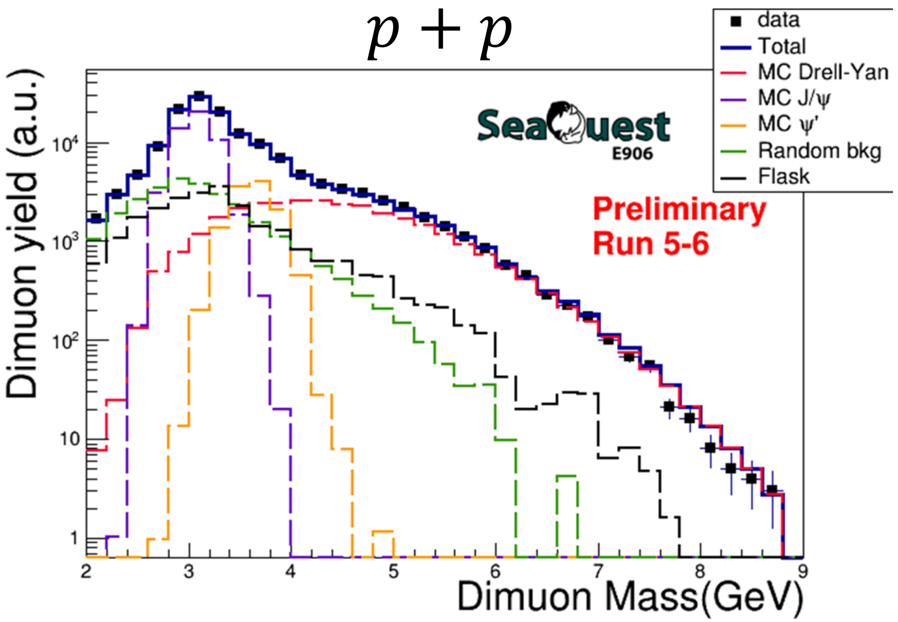
$$\hat{\sigma}[ij \to H] = \sum_n \underbrace{C^{ij}_{c\bar{c}[n]}(x_b P_A, x_t P_B, \mu_F, \mu_R, m_c)}_{\text{Production of } c\bar{c} \text{ pairs}} \underbrace{\langle O^H_n [^{2S+1}L_J] \rangle}_{\text{LDMEs}}$$

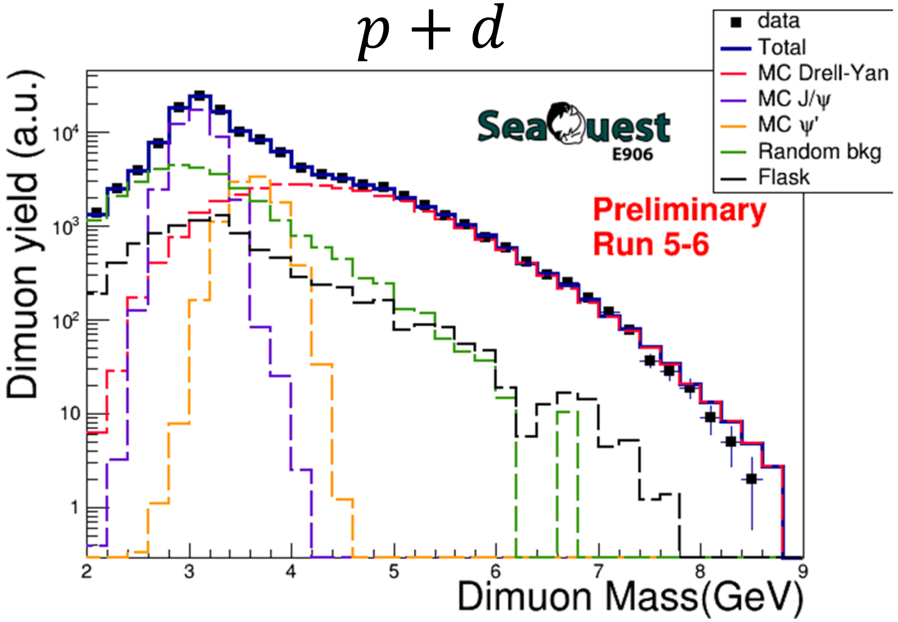


LDME from CY Hsieh et al, Chin. J. Phys **73**, 13 (2021)

Obtaining J/ψ yield from mass spectrum

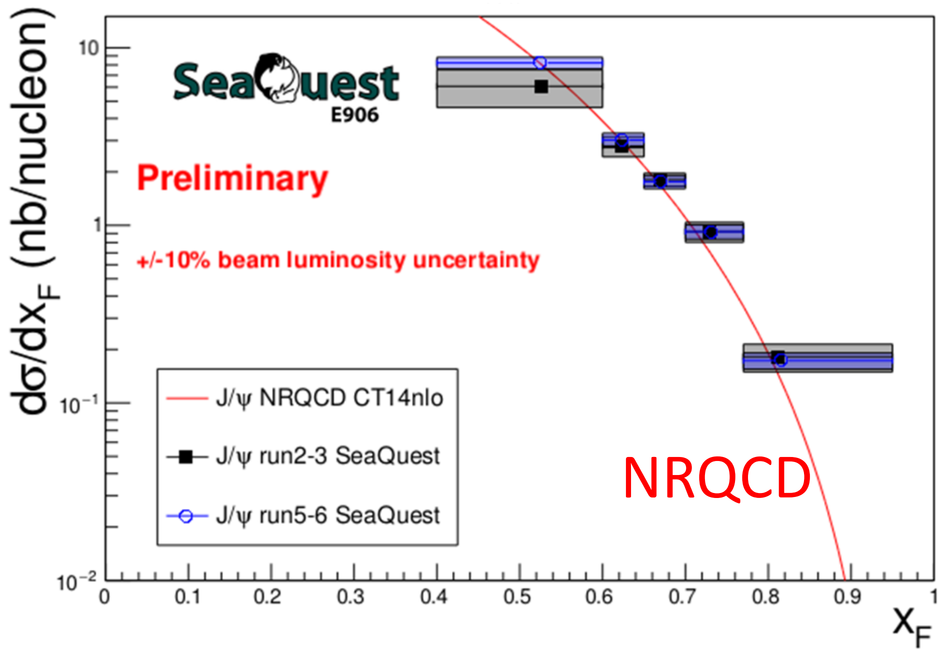
- Performing a component fit to the mass spectrum
- Use Monte Carlo to simulate signal events ($J/\psi, \psi'$, Drell-Yan)
- Use mixed single-track events to simulate accidental background
- A fit is done for each x_F bin to obtain the yield



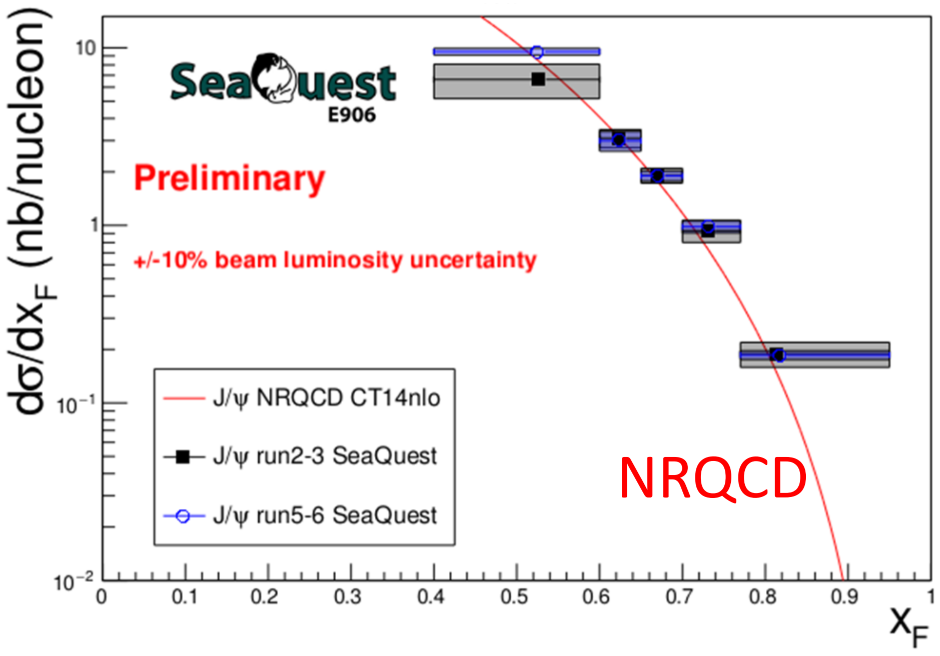


J/ψ absolute cross sections

$p + p$

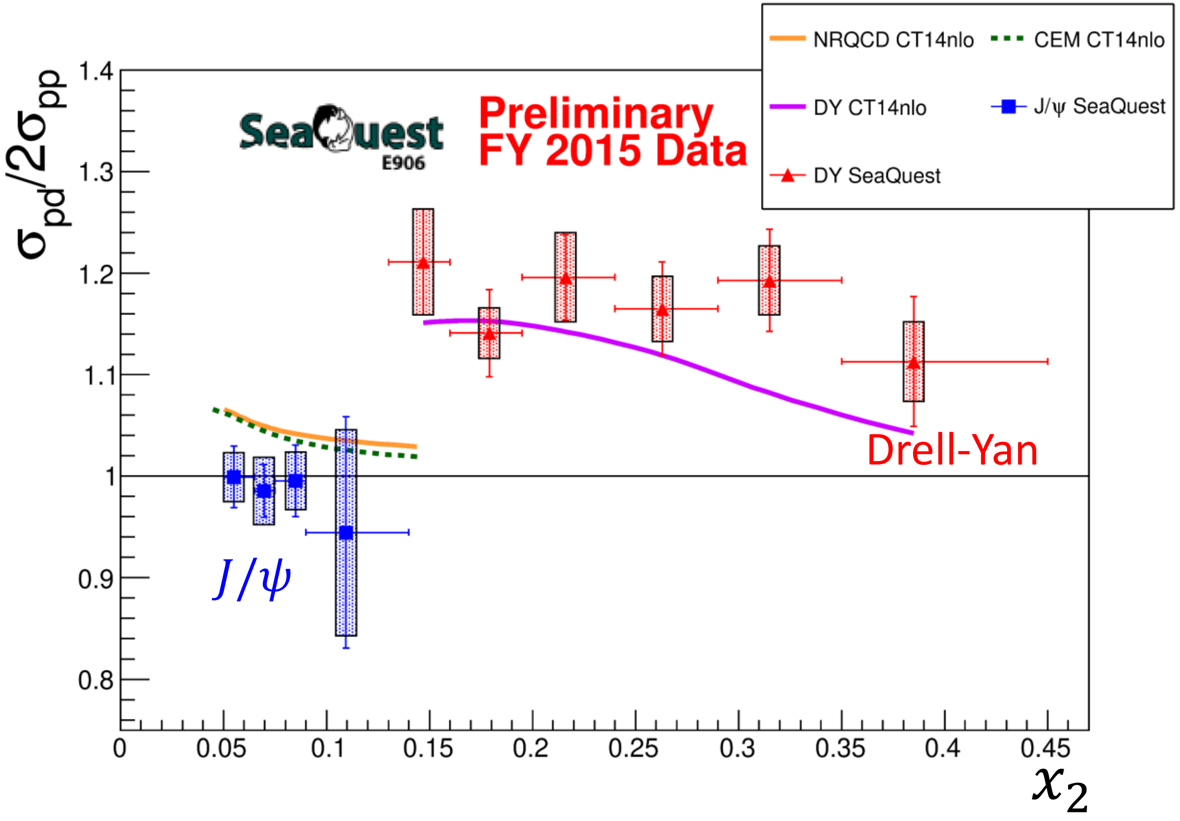


$p + d$



- The extracted cross section from both datasets are in good agreement with each other
- The preliminary J/ψ cross sections result are in reasonable agreement with NRQCD, including the overall magnitude

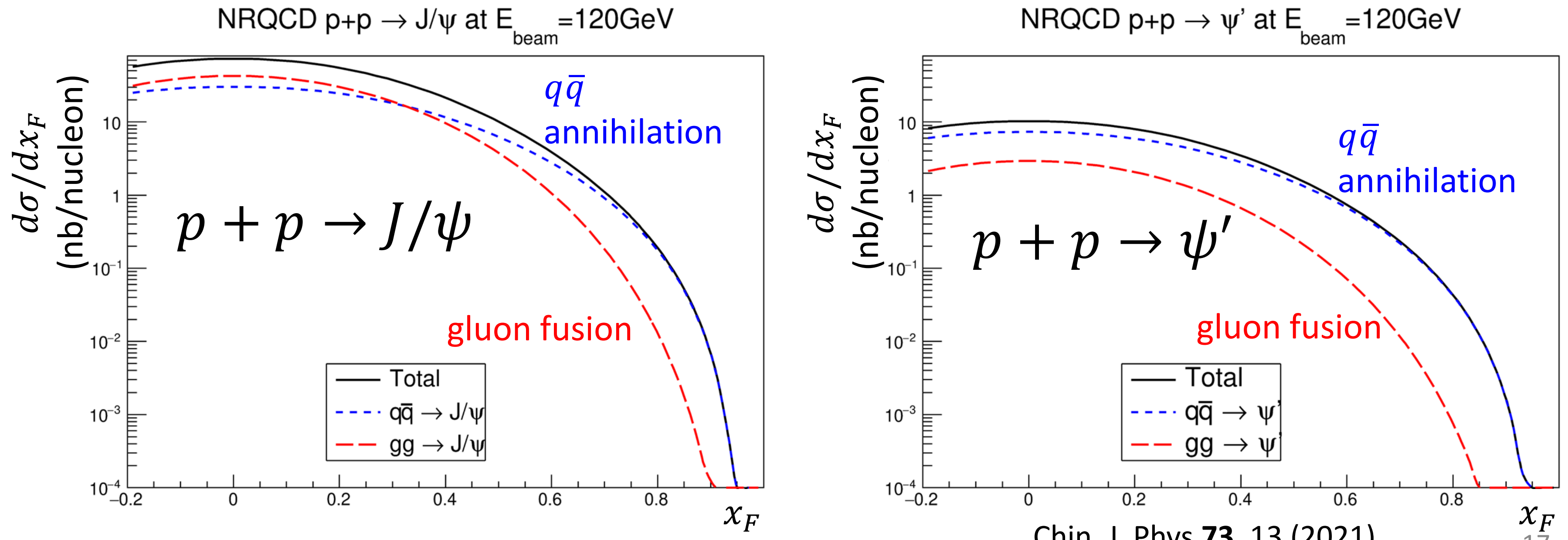
J/ψ and Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratios vs x_2



- 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
- This plot will be updated to include the additional data

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)

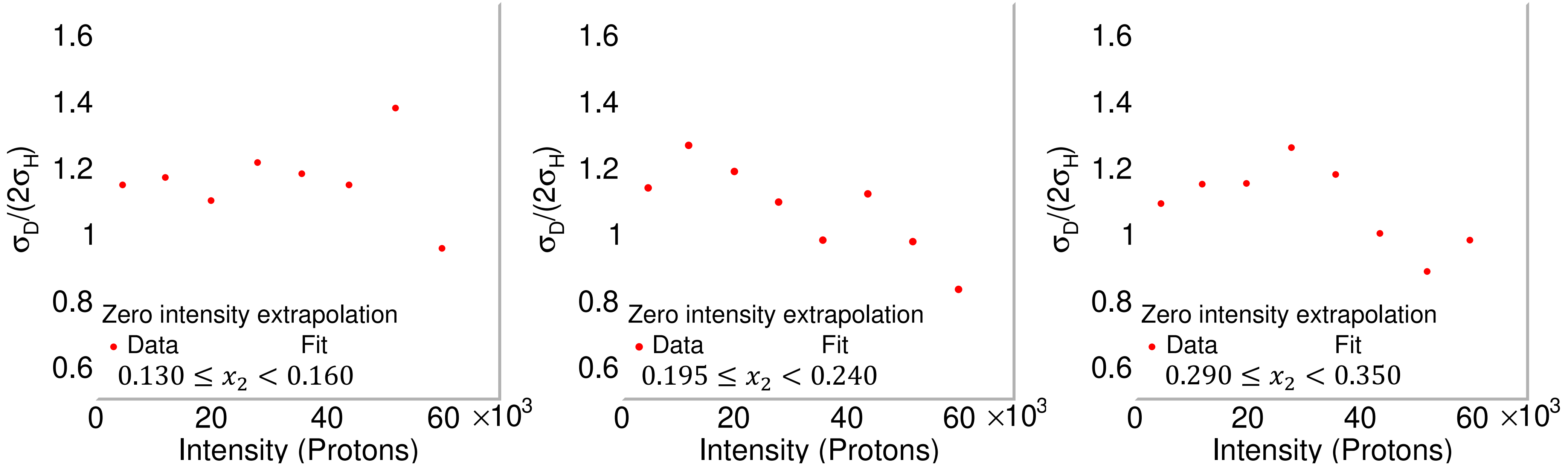
What we have learnt from SeaQuest

- $(p+d)/2(p+p)$ Drell-Yan cross section ratio from run2-3 data using two different methods
  - $\bar{d}/\bar{u} > 1$ for the entire measured region
  - This new result can provide better constraints on the antiquark distribution
- Preliminary J/ψ cross section from the full data set
  - Good agreement between datasets
  - The extracted J/ψ cross section is in good agreement with NRQCD
  - The difference between the J/ψ and Drell-Yan cross section ratio are reflecting the different mechanisms
  - The ψ' data could also used to better understand the charmonium production

Intensity extrapolation method

- Fit the yield ratio to

$$\frac{Y_D(x_2, I)}{2Y_H(x_2, I)} = R_{x_2} + aI + bI^2$$

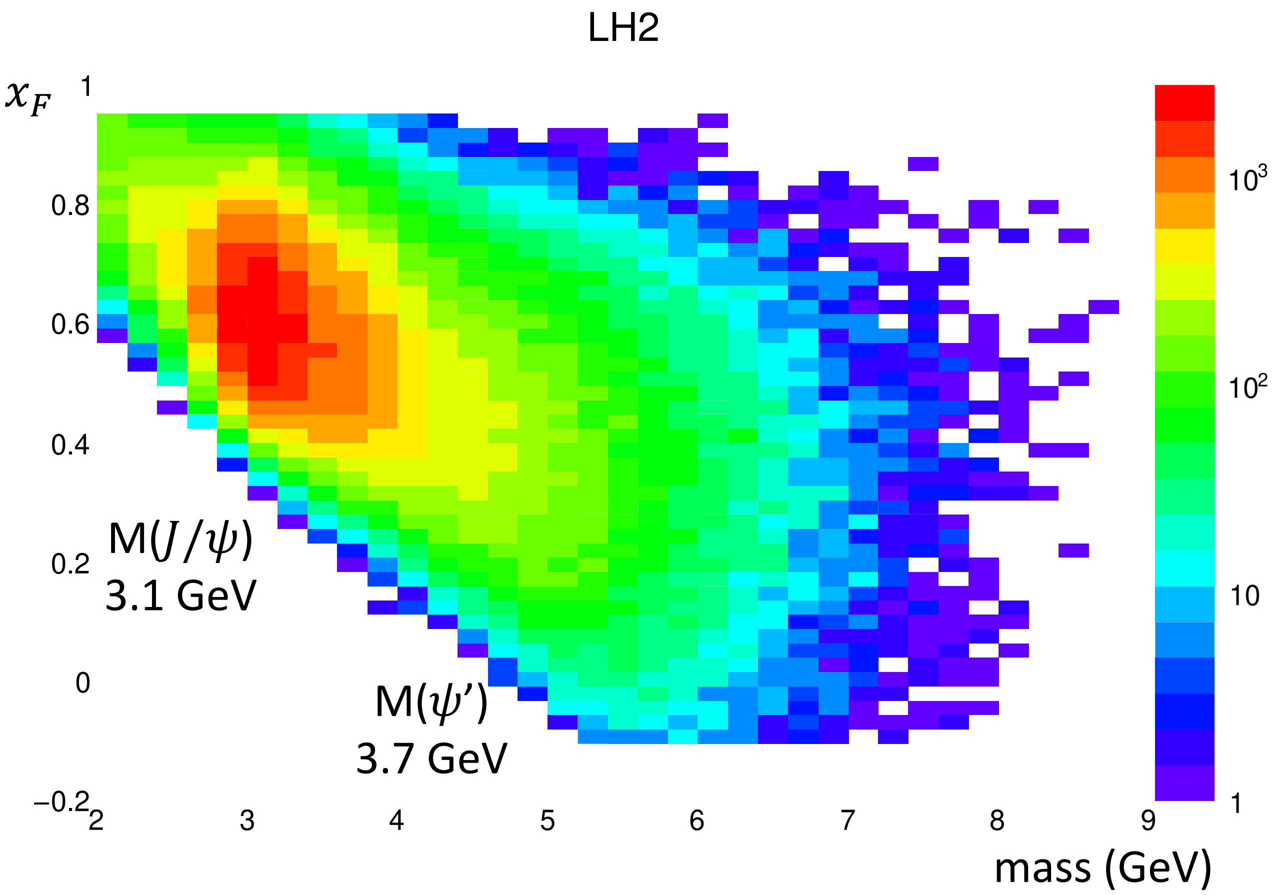


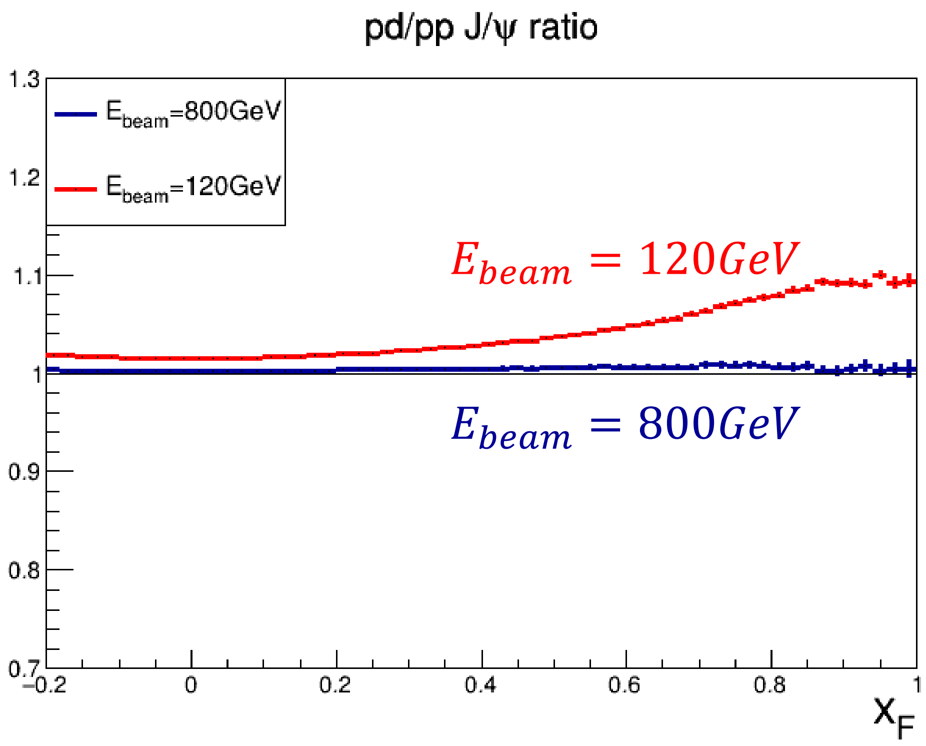
Nature 590, 561–565 (2021)

SeaQuest Event Distribution

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

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

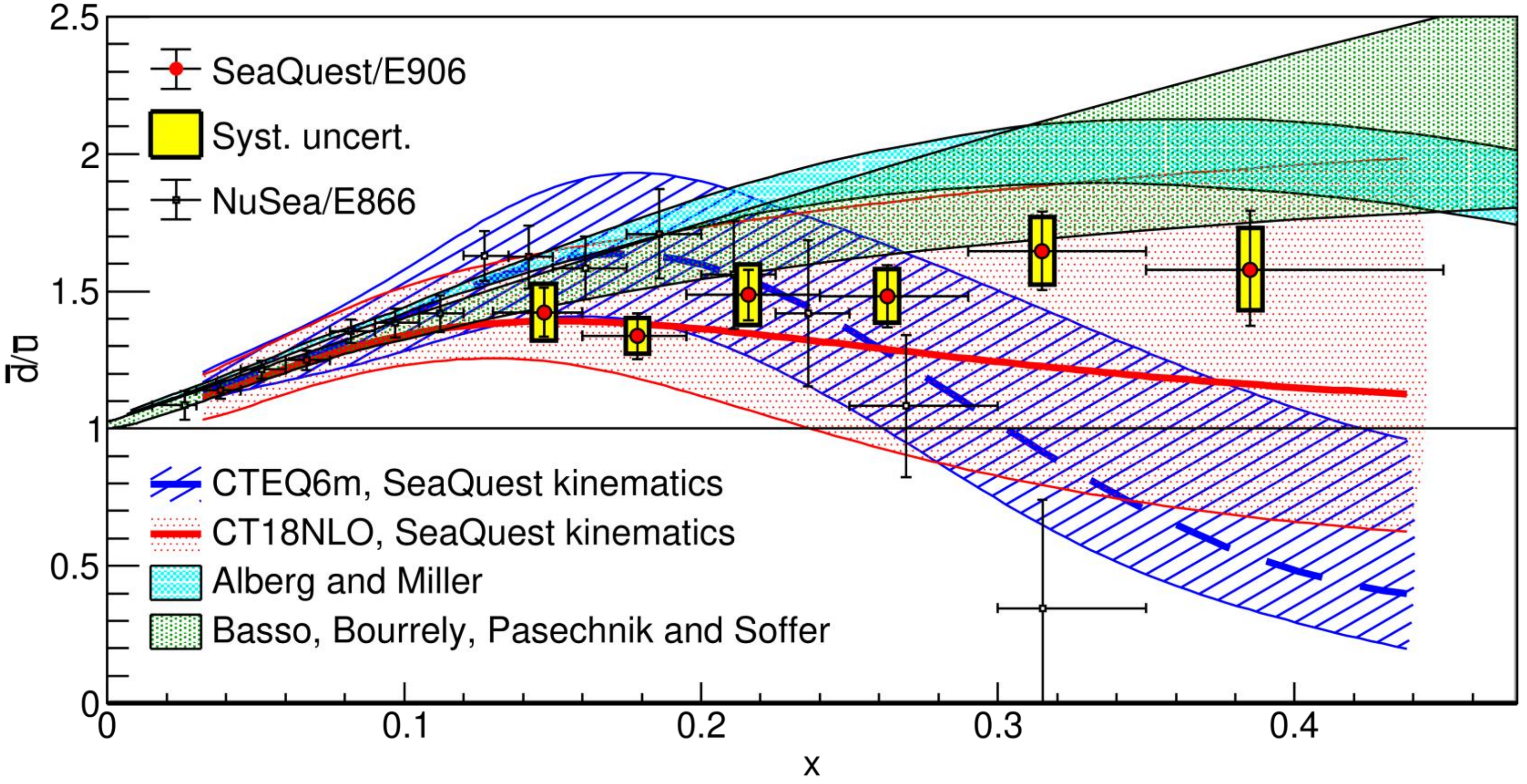




M. L. Mangano et al, Nuclear Physics B 405, 507 (1993).
S. Dulat, et al, Phys. Rev. D 93, 033006 (2016).

- 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' $\sigma^{pd}/2\sigma^{pp}$