Probing the proton structure with Drell-Yan process and charmonium production at the SeaQuest experiment

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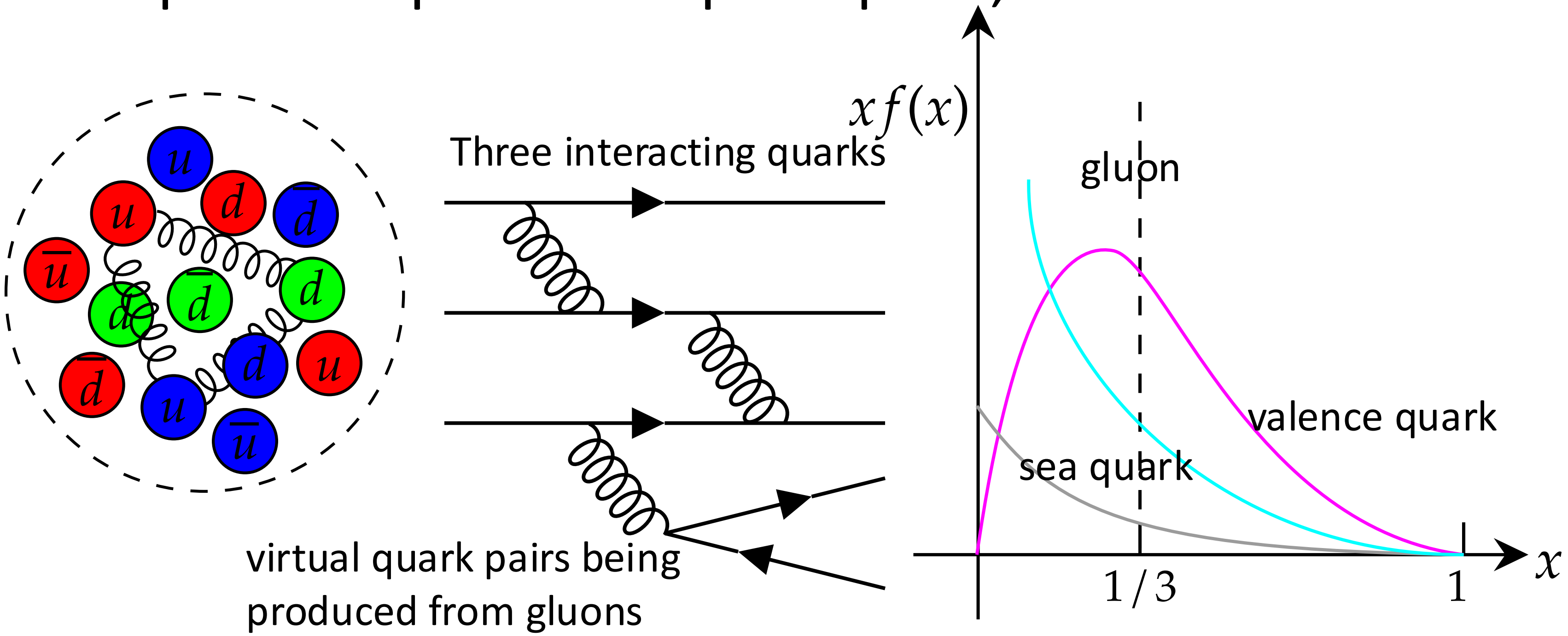
Parton structure

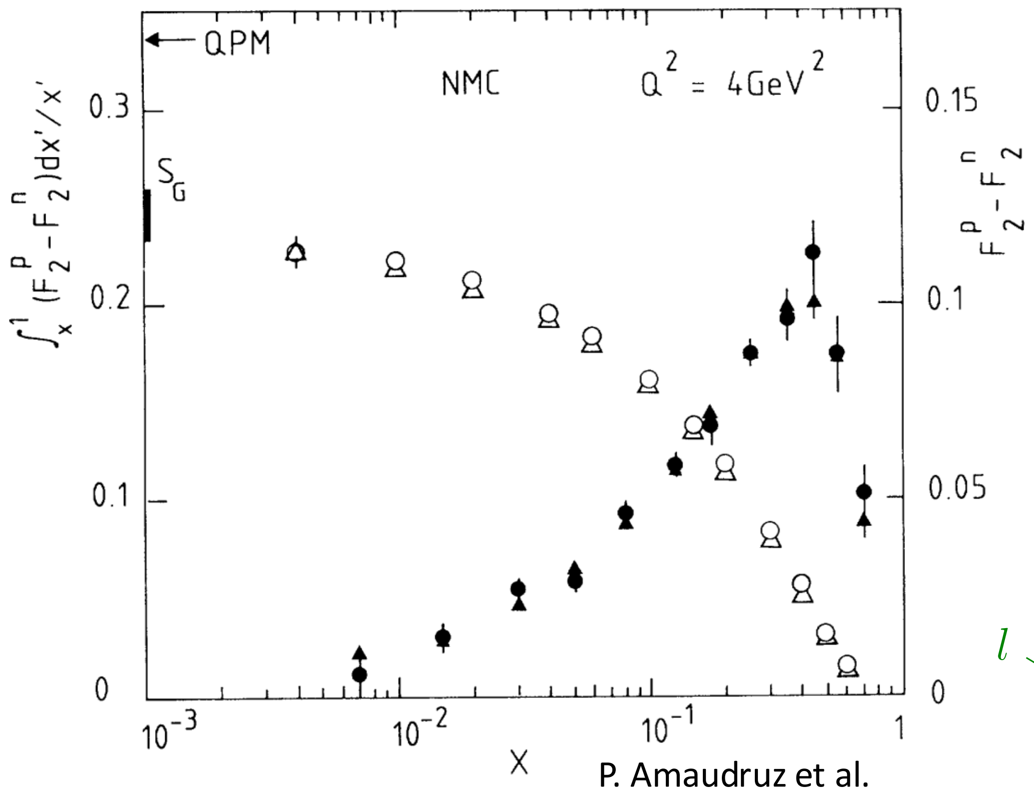
- The proton consists of 2 up quarks and 1 down quark (valence)
- The exchange of gluons redistribute the momenta among the quarks
- The gluons can also split into quark-antiquark pairs, known as sea quarks



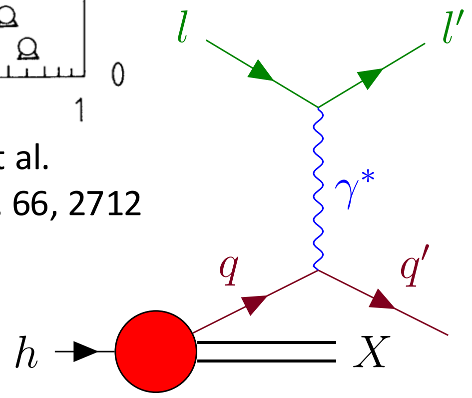
Early evidence of flavor asymmetry

$$S_G = \int_0^1 \frac{\mathrm{d}x}{x} \left(F_2^p - F_2^n\right)$$
$$= \frac{1}{3} + \frac{2}{3} \int_0^1 \mathrm{d}x \left[\bar{u}(x) - \bar{d}(x)\right]$$

- The measured value of the Gottfried sum by NMC is 0.240 ± 0.016 less than the expected 1/3
- Indicating $\bar{u}(x) \neq \bar{d}(x)$



P. Amaudruz et al.
Phys. Rev. Lett. 66, 2712



"...the pairs $u\bar{u}$ expected to occur in the small x region (the "sea") are suppressed more than $d\bar{d}$ pairs by the exclusion principle." (Field and Feynman 1977)

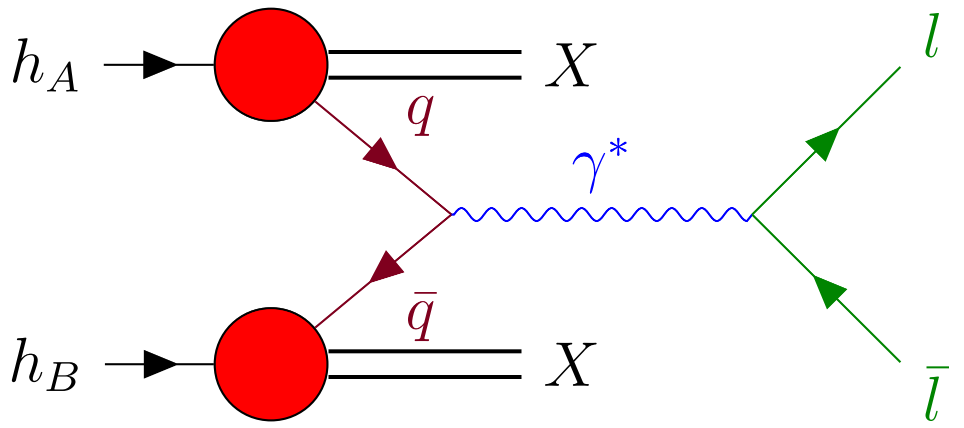
Drell-Yan process

- Drell-Yan process is another tool to probe the partonic structure
  - Related to DIS via crossing symmetry
- Two partons from the two colliding hadrons annihilate into a dilepton pair
- Particularly useful in probing the antiquark structure of the nucleon

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

$$x_F = \frac{2P_L}{\sqrt{s}} = x_1 - x_2$$

$$Q^2 = M^2 = s x_1 x_2$$



First high mass dimuon production experiment

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

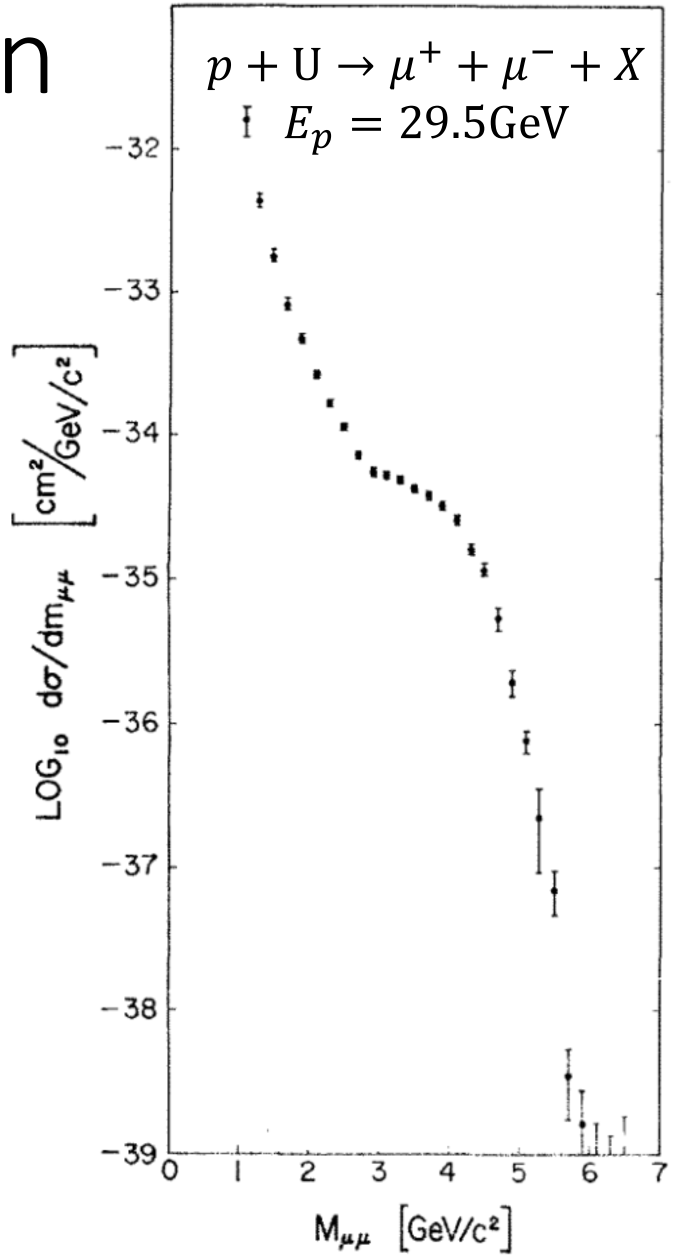
Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7\ \mathrm{GeV}/c^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-31}/m_{\mu\mu}\mathrm{cm}^2(\mathrm{GeV}/c)^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.



Exploring the sea-quark asymmetry

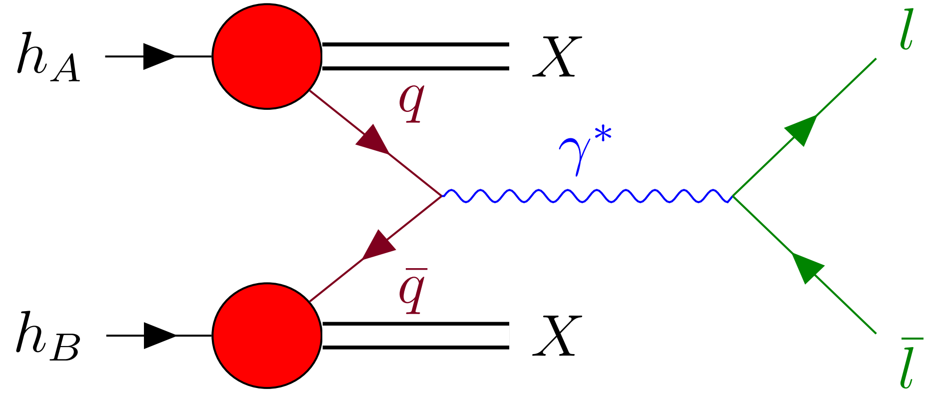
- In fixed target experiments

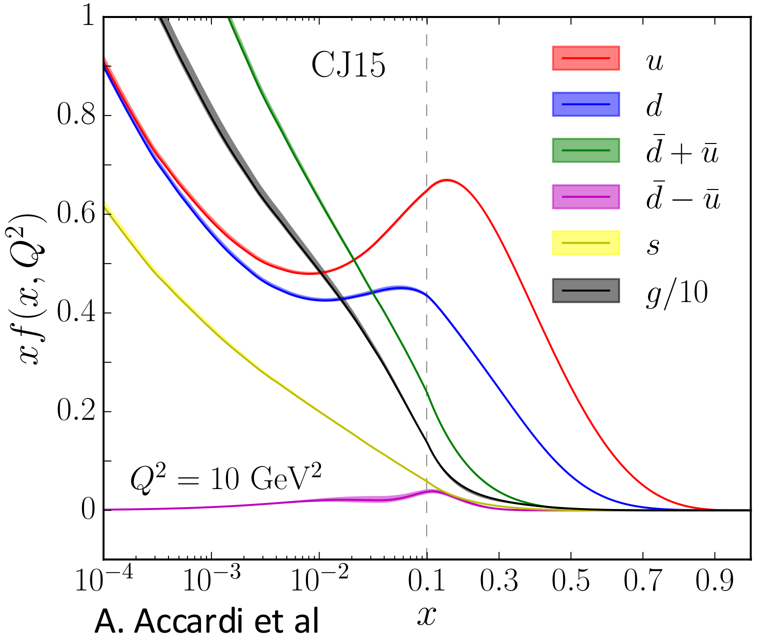
u-quark dominance

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

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

Acceptance limited
(Forward spectrometer, $x_1 \gg x_2$)





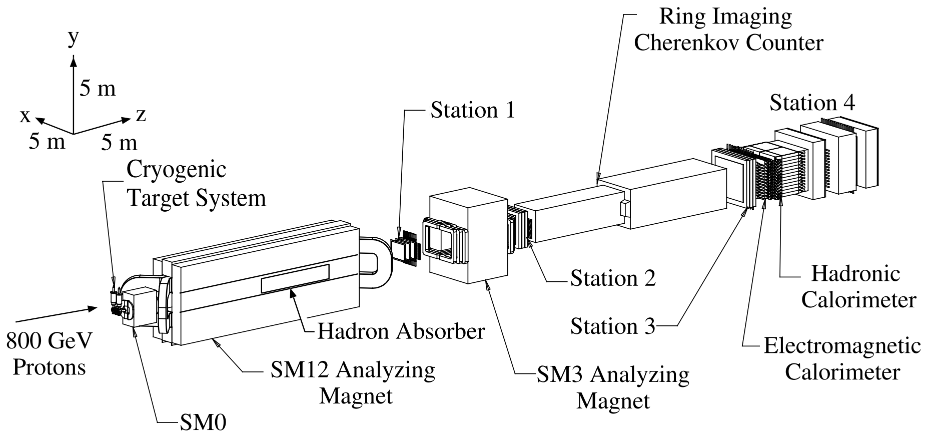
A. Accardi et al
Phys. Rev. D 93, 114017

E866 NuSea

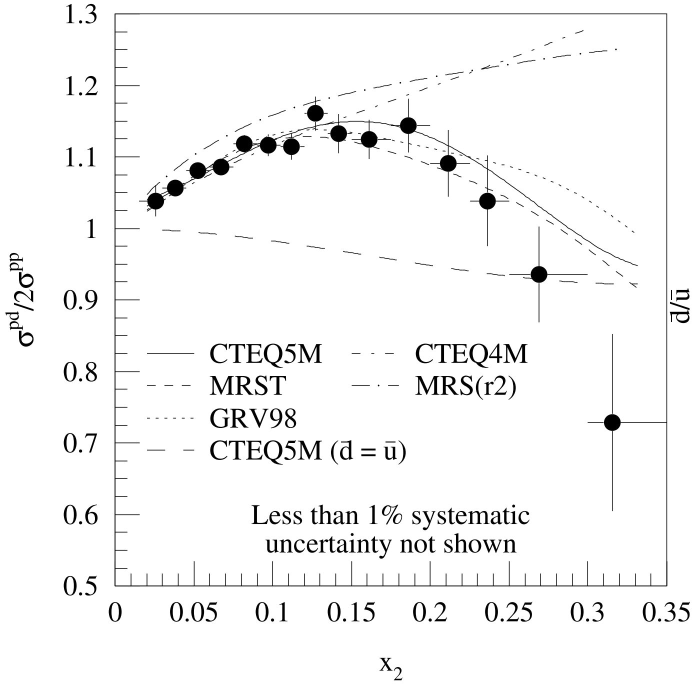
- 800 GeV proton beam on hydrogen and deuterium

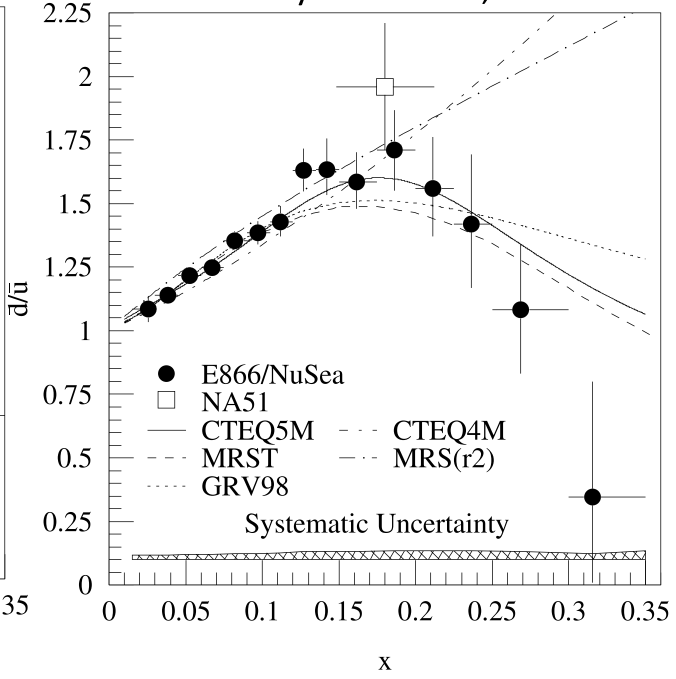
$$\frac{\sigma^{p+d}}{2\sigma^{p+p}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

- It was observed the cross-section ratio (hence the $\bar{d}(x)/\bar{u}(x)$) drops below 1 at $x > 0.3$



R. S. Towell et al
Phys. Rev. D 64, 052002



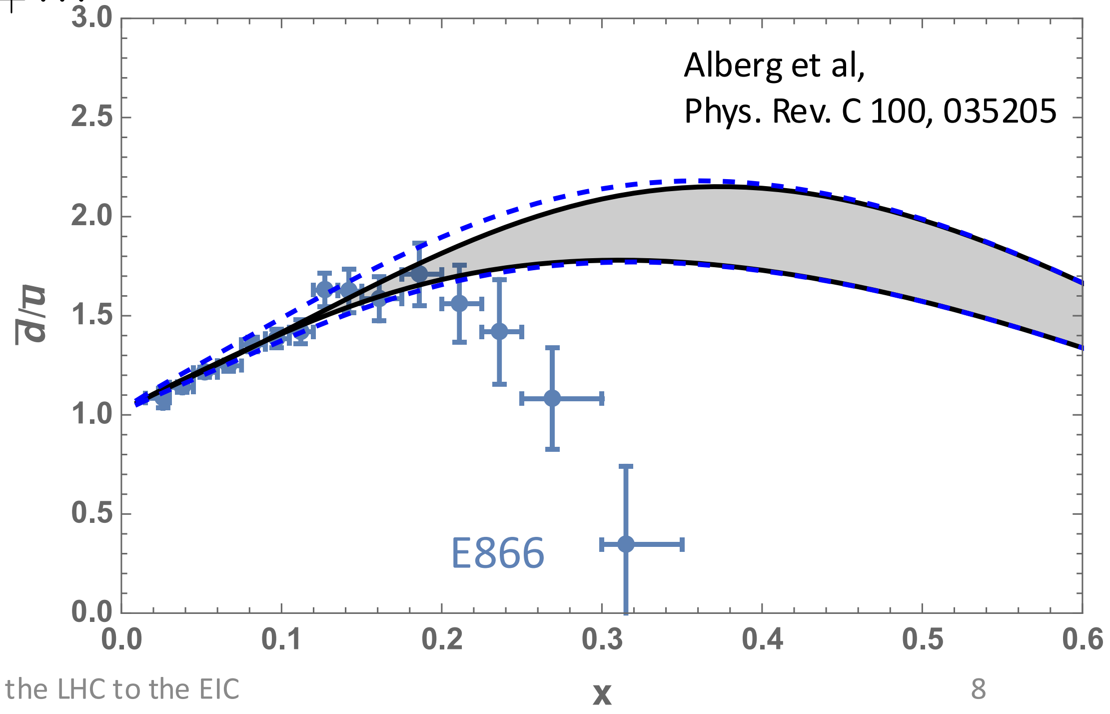


Origin of the asymmetric sea

- Meson Cloud model

$$|p\rangle = \sqrt{Z}\,|p_0\rangle + a_{N\pi/p}\left[-\sqrt{\frac{1}{3}}\,|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}\,|n_0\pi^+\rangle\right] + a_{\Delta\pi/p}\left[\sqrt{\frac{1}{2}}\,|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}\,|\Delta_0^{+}\pi^0\rangle + \sqrt{\frac{1}{6}}\,|\Delta_0^{0}\pi^+\rangle\right]$$
$$+ a_{\Lambda K/p}\,|\Lambda_0 K^+\rangle + a_{\Sigma K/p}\left[-\sqrt{\frac{1}{2}}\,|\Sigma_0^{+}K^0\rangle + \sqrt{\frac{1}{2}}\,|\Sigma_0^{0}K^+\rangle\right] + \cdots$$

- The asymmetry arises from the dominance of the $|n_0\pi^+\rangle$ state



Origin of the asymmetric sea

- Statistical model
- The nucleon is viewed as a gas of massless partons in equilibrium in a finite volume

$$xq^h\left(x, Q_0^2\right) = \frac{A_q X_{0q}^h x^{b_q}}{\exp\left[\left(x - X_{0q}^h\right)/\bar{x}\right] + 1} + \frac{\tilde{A}_q x^{\tilde{b}_q}}{\exp\left(x/\bar{x}\right) + 1}$$

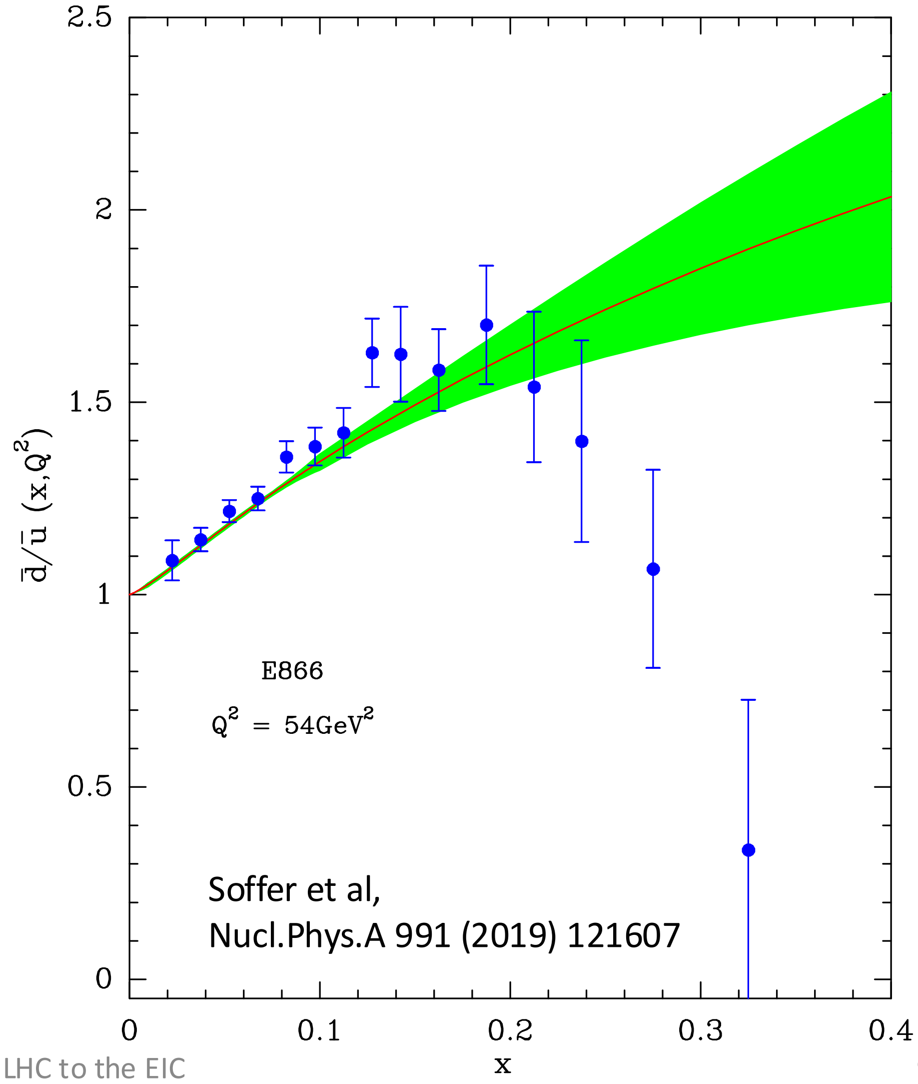
$$x\bar{q}^h\left(x, Q_0^2\right) = \frac{\bar{A}_q \left(X_{0q}^{-h}\right)^{-1} x^{\bar{b}_q}}{\exp\left[\left(x + X_{0q}^{-h}\right)/\bar{x}\right] + 1} + \frac{\tilde{A}_q x^{\tilde{b}_q}}{\exp\left(x/\bar{x}\right) + 1}$$

- The thermodynamic potential for the quarks and antiquarks are related as follows

$$X_{0q}^h = -X_{0\bar{q}}^{-h}$$

- Since there are more u valence quarks

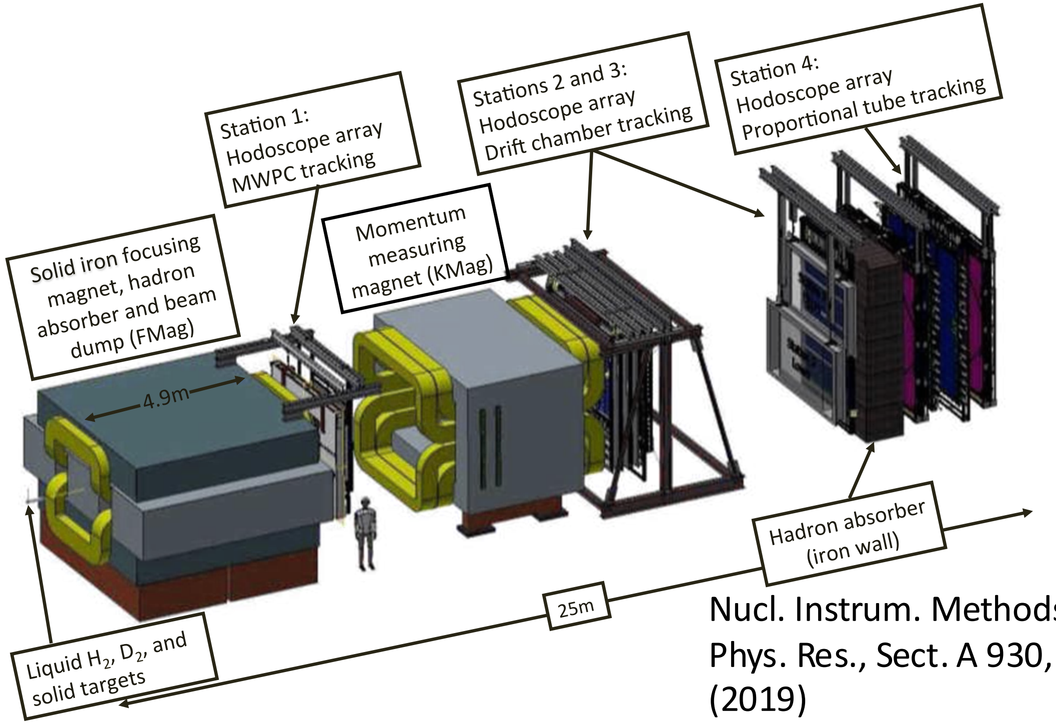
$$X_{0u}^+ + X_{0u}^- > X_{0d}^+ + X_{0d}^-$$



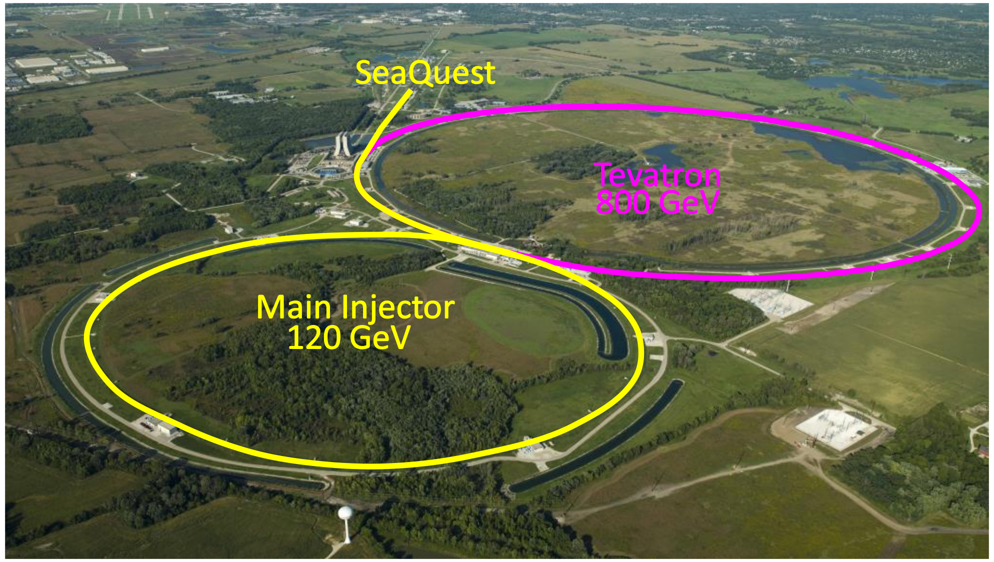
SeaQuest
E906

- 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

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

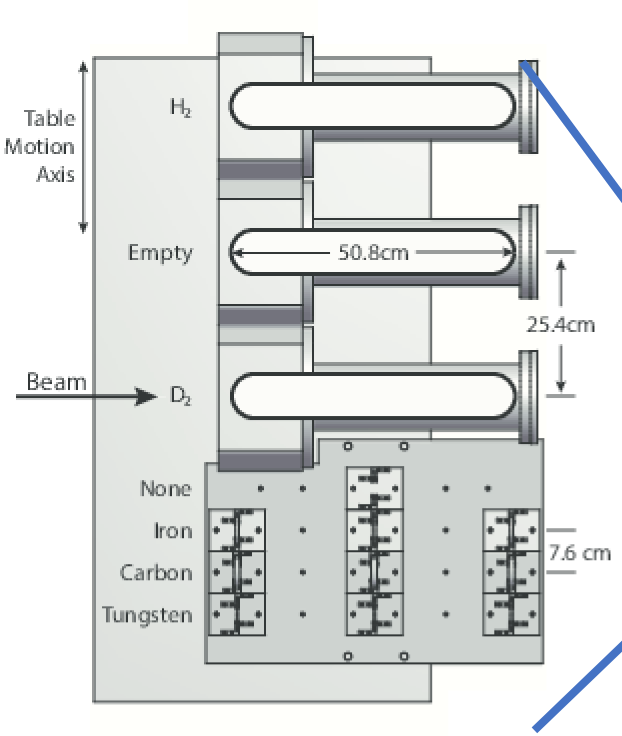


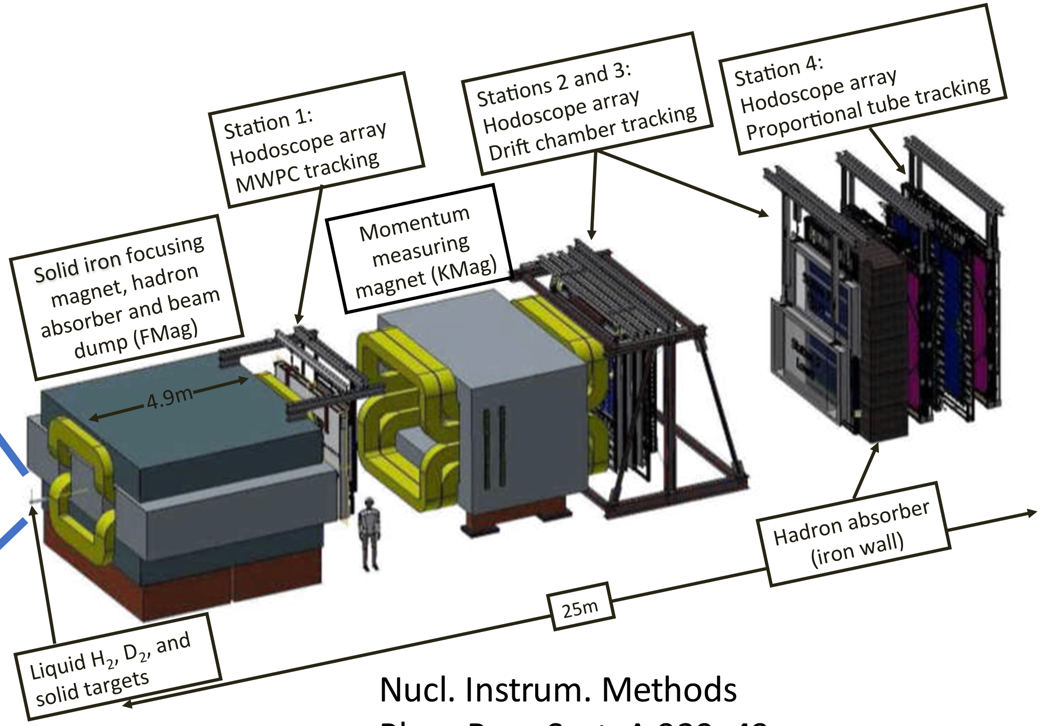
Nucl. Instrum. Methods Phys. Res., Sect. A 930, 49 (2019)



Target System

- We have both hydrogen and deuterium targets
- An empty flask target for background subtraction

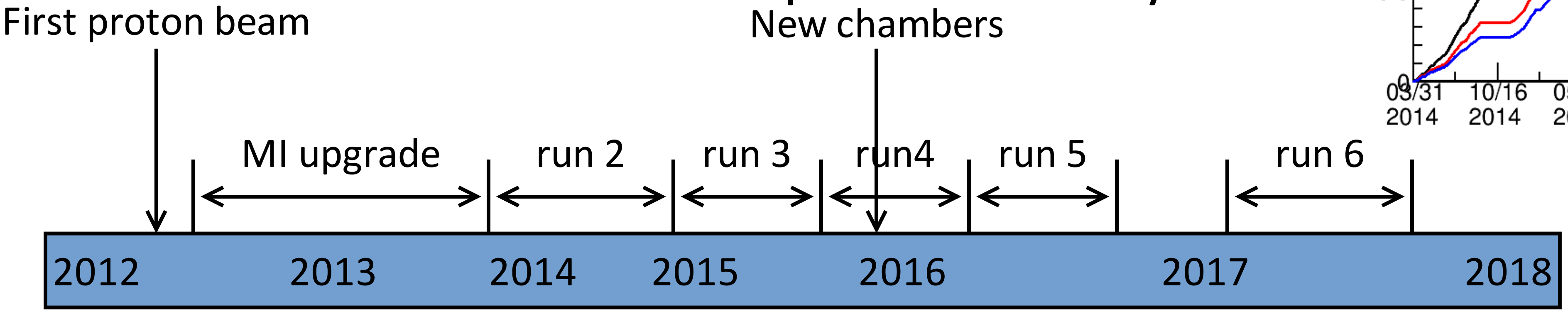


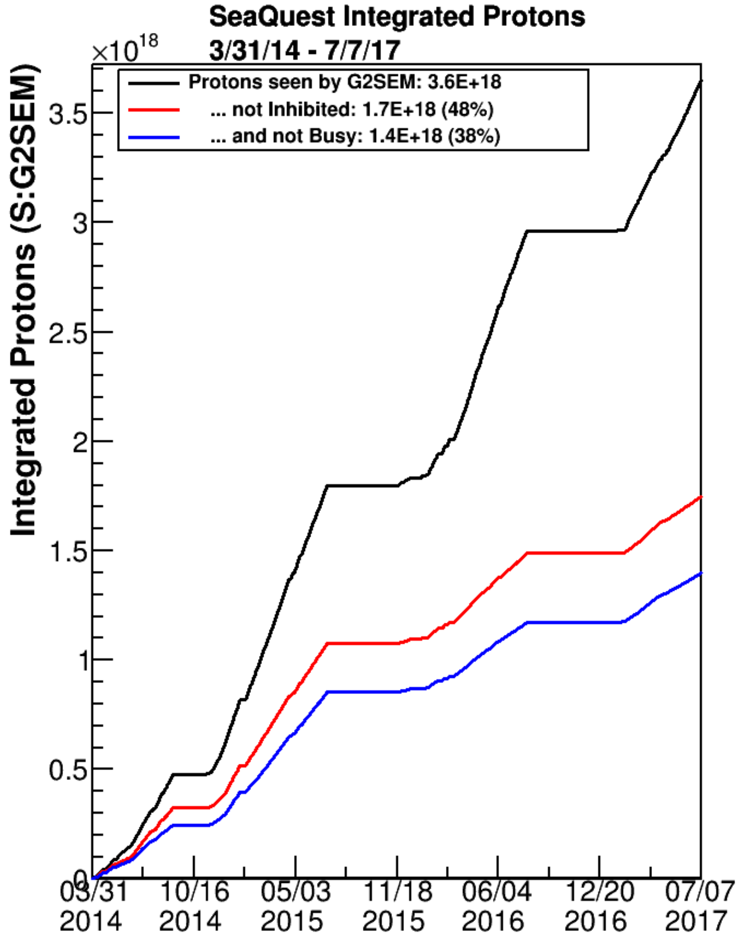


Nucl. Instrum. Methods Phys. Res., Sect. A 930, 49 (2019)

Timeline

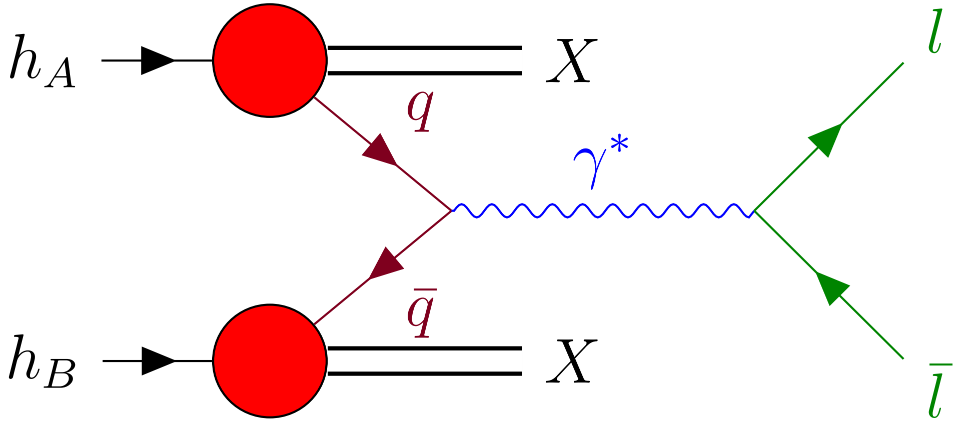
- Commissioning began in 2012 and data collection finished in July 2017
- Drell-Yan cross section ratio extracted from run2 and run3 data has been reported
- Results on the charmonium production from the full data set were also reported recently

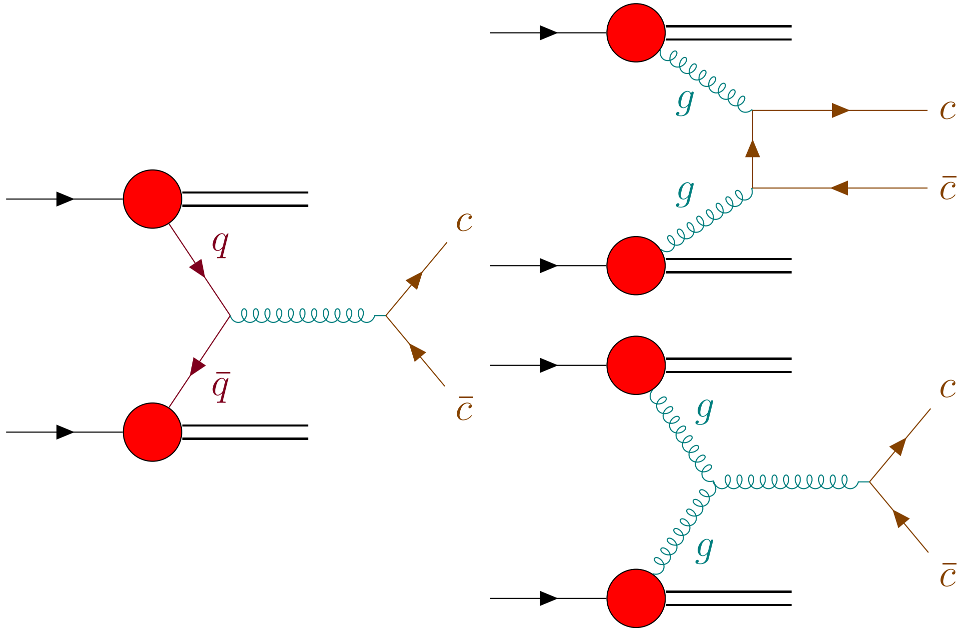




Results

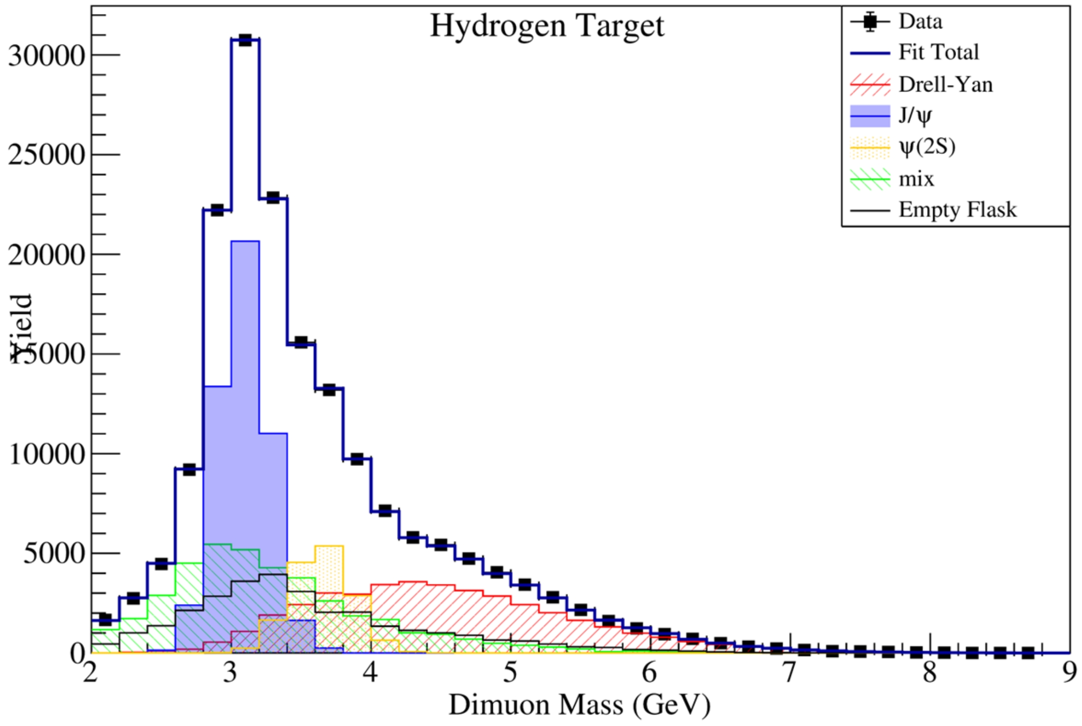
- Drell-Yan cross section ratio
  - A new mass decomposition procedure for extracting the Drell-Yan yield
- Charmonium cross section
  - The x_F and P_T dependence of J/ψ and $\psi(2S)$
  - The $\sigma_{pd}/2\sigma_{pp}$ ratio for J/ψ





Understanding the data

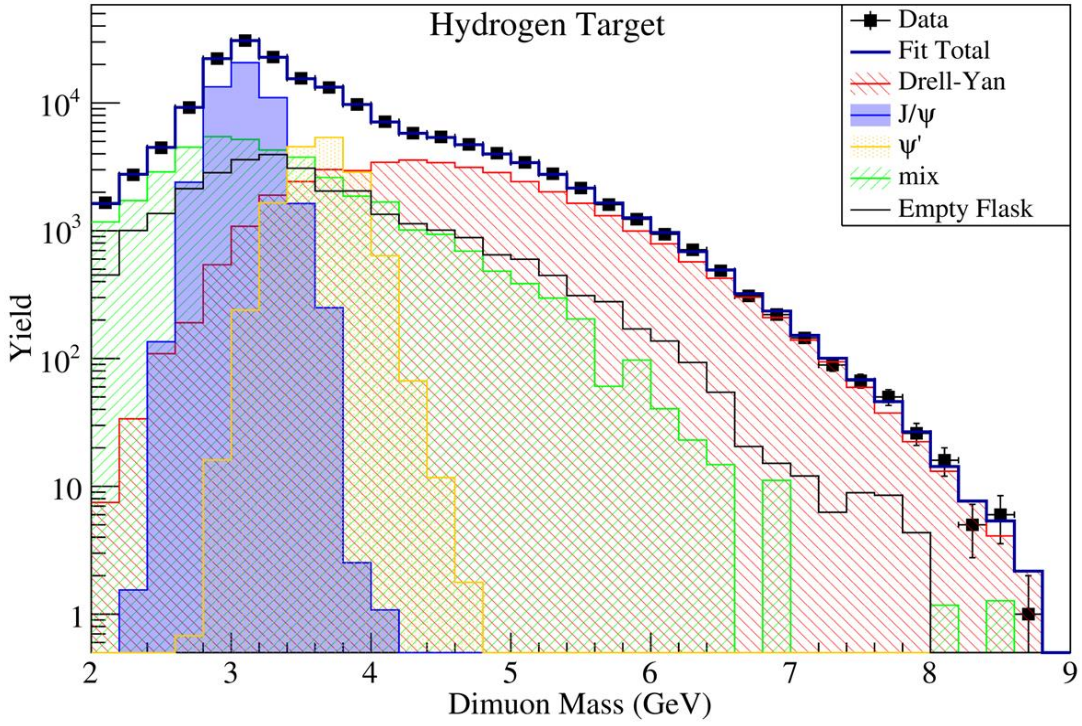
- The J/ψ peak as well as the Drell-Yan continuum at higher mass are clearly observed
- The $\psi(2S)$ shoulder is also visible
- By applying a mass cut at 4.5 GeV, the J/ψ and $\psi(2S)$ are effectively removed
- The challenge is to remove the accidental background



Phys. Rev. C 108, 035202 (2023)

Mass fit method

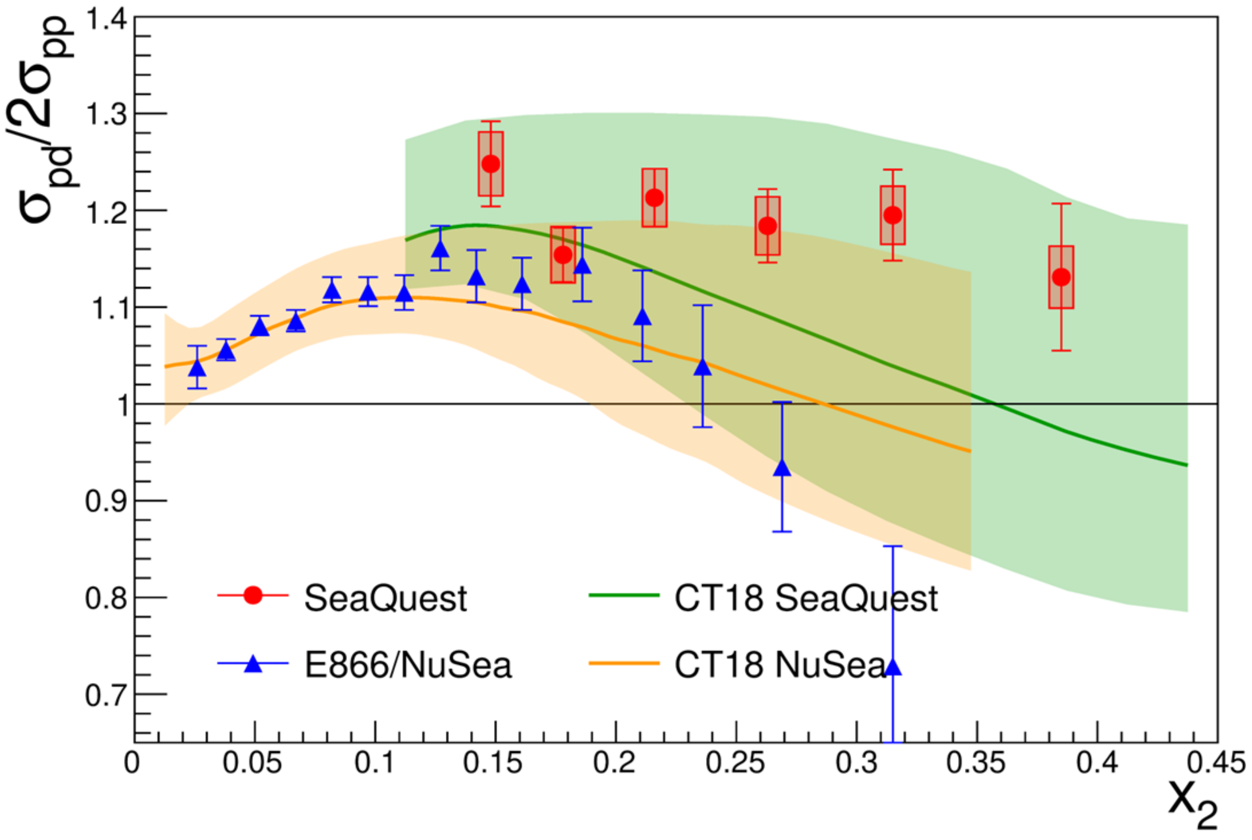
- Extract the Drell-Yan yield is to study the mass distribution
- Use Monte Carlo to simulate signal events ($J/\psi, \psi(2S)$, Drell-Yan)
- Use mixed single-track events to simulate accidental background
- Performing a component fit to the mass spectrum to obtain the relative importance of each component



Phys. Rev. C 108, 035202 (2023)

$\sigma_{pd}/2\sigma_{pp}$ from the mass fit method

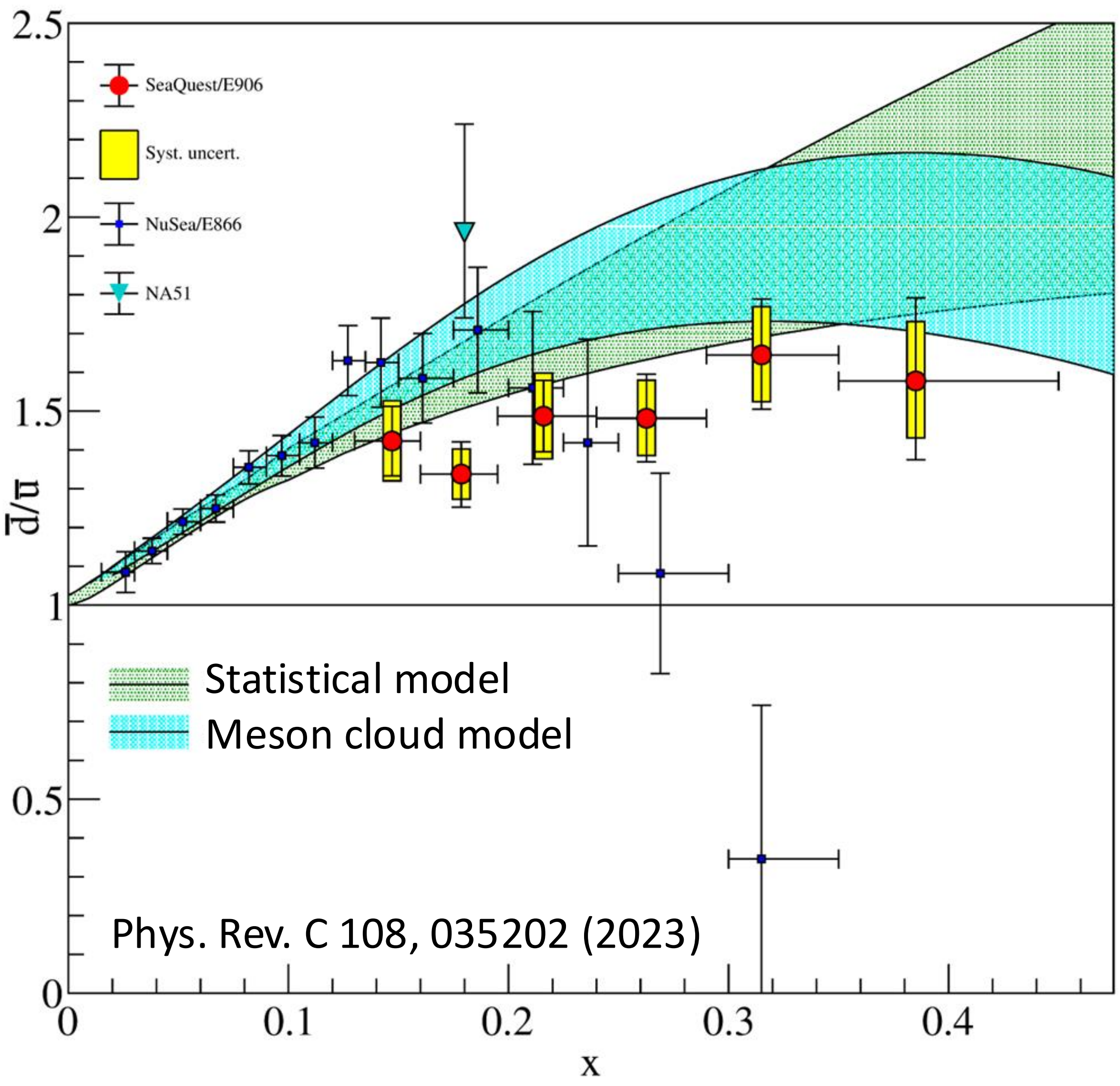
- The $\sigma_{pd}/2\sigma_{pp}$ ratio remains above 1 up to $x_2 \approx 0.4$
- Suggesting that $\bar{d}$ should be larger than $\bar{u}$ across the measured region
- The CT18 PDF is published before the SeaQuest results
- This method can also be used to study the J/ψ



Phys. Rev. C 108, 035202 (2023)

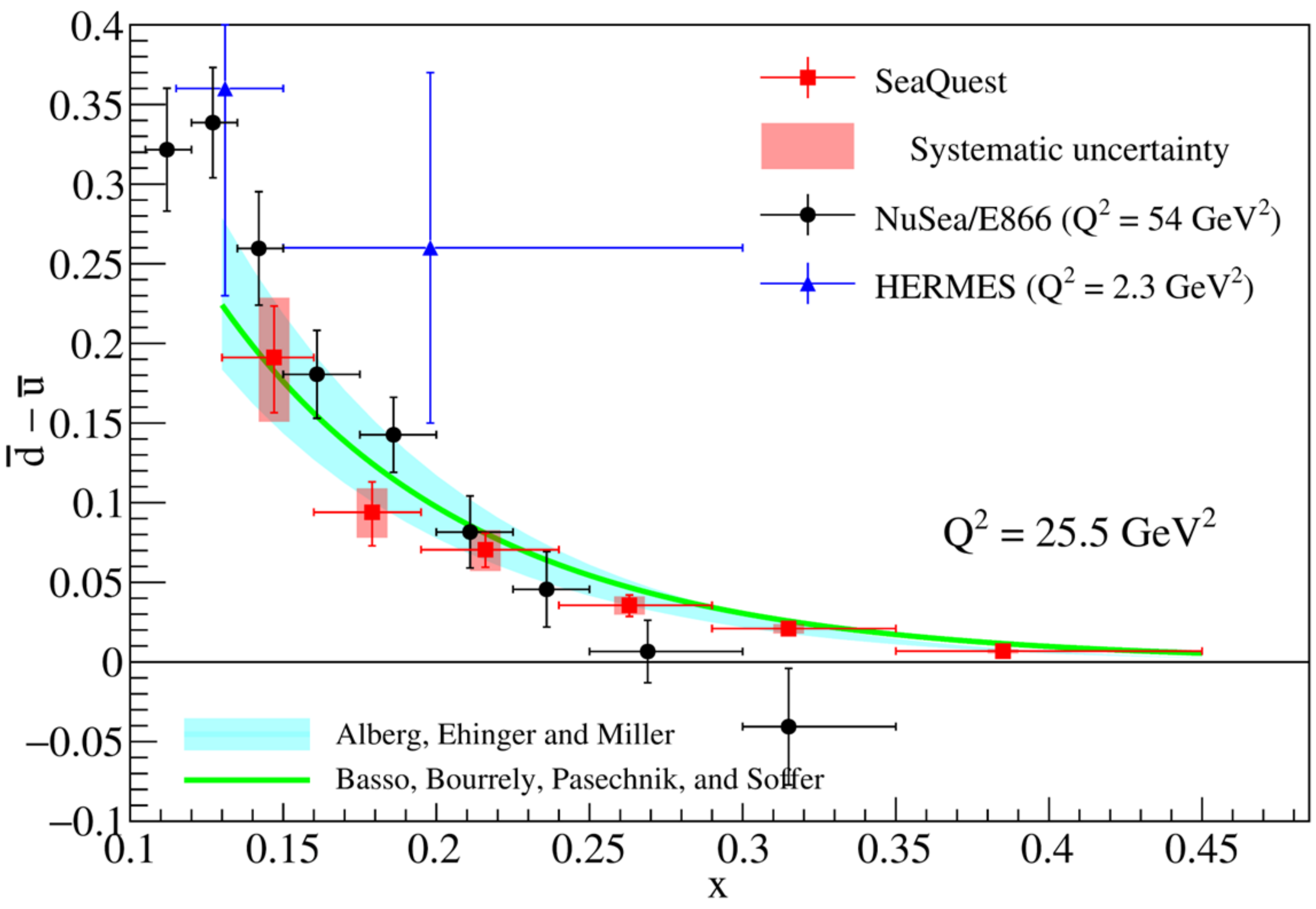
$\bar{d}/\bar{u}$ extraction

- The measured cross section ratio is compared to NLO calculation
- The $\bar{d}/\bar{u}$ ratio is varied, while keeping other PDF fixed, until the calculated cross section ratio converged with measured results
- The SeaQuest results are in better agreement to model predictions



Impact on $\bar{d} - \bar{u}$

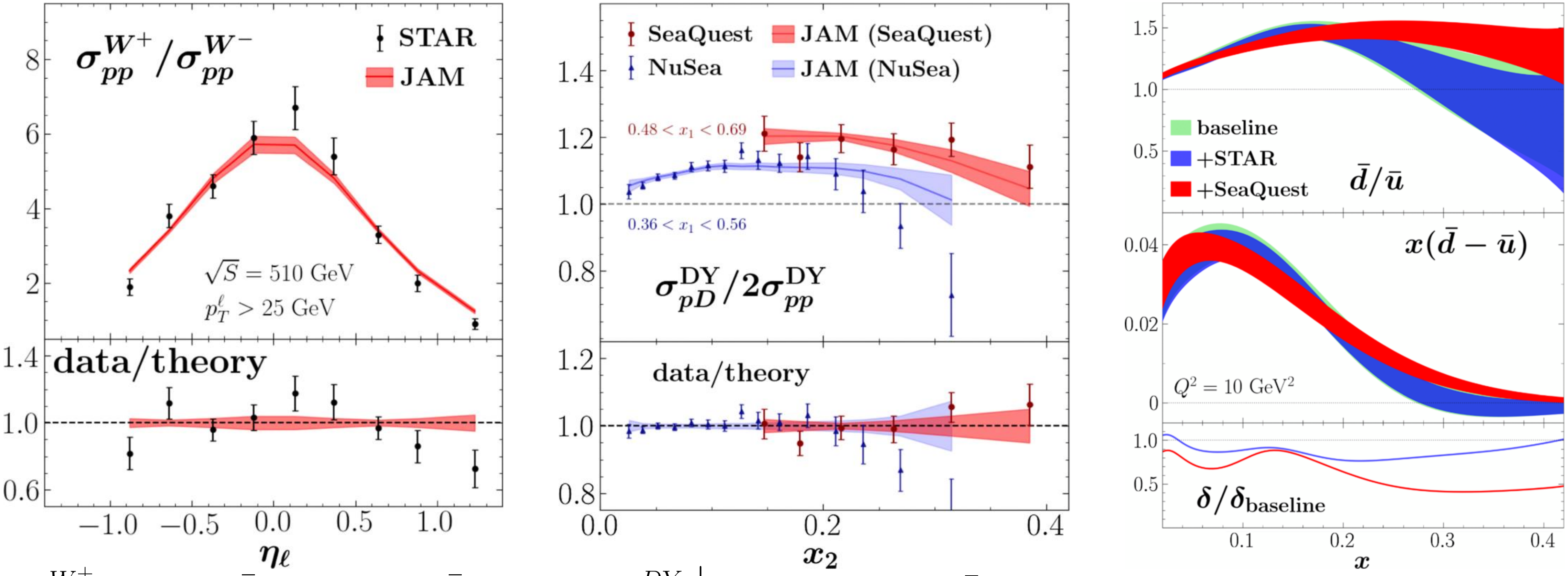
- $\bar{d} - \bar{u}$ is that the this is a flavor non-singlet quantity
- And can be calculated with Lattice QCD



Phys. Rev. C 108, 035202 (2023)

Impact of SeaQuest measurement

JAM,
Phys. Rev. D 104, 074031

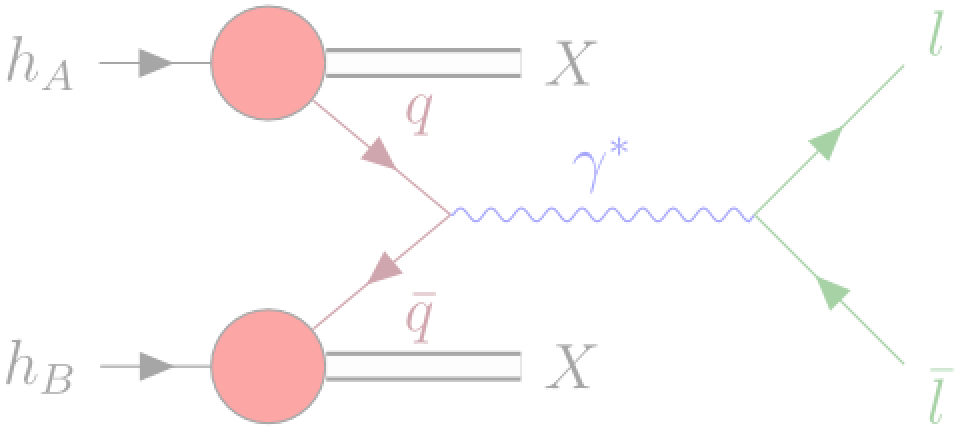


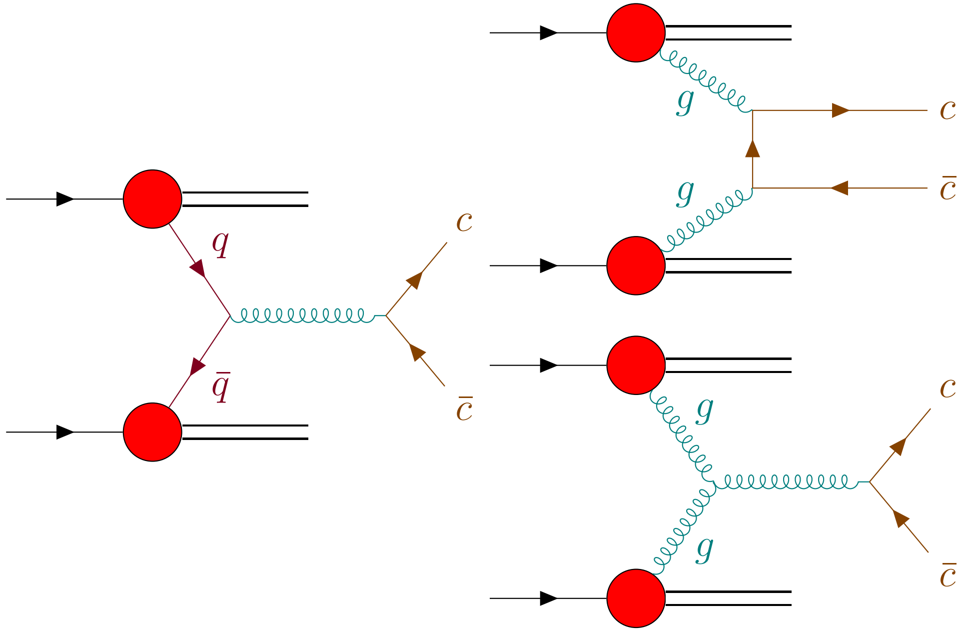
$$\frac{\sigma_{pp}^{W^+}}{\sigma_{pp}^{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)}$$

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

Results

- Drell-Yan cross section ratio
  - A new mass decomposition procedure for extracting the Drell-Yan yield
- Charmonium cross section
  - The x_F and P_T dependence of J/ψ and $\psi(2S)$
  - The $\sigma_{pd}/2\sigma_{pp}$ ratio for J/ψ





Non-Relativistic QCD (NRQCD)

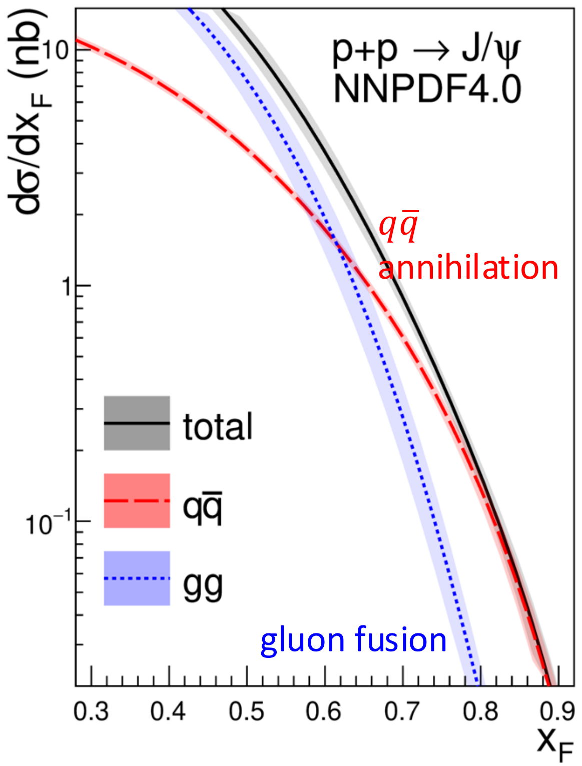
- The $c\bar{c}$ pairs production is calculated perturbatively
- The hadronization is described by the long-distance matrix elements (LDMEs), which depend on the color and spin of the $c\bar{c}$ pairs
- Relative weighting of the two processes depend on the choice of LDMEs

$$\frac{d\sigma^H}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_1 dx_2 \delta(x_F - x_1 + x_2)$$

$$\times\, f_{i/A}(x_1,\mu_F)\, f_{j/B}(x_2,\mu_F)\, \hat{\sigma}\left[ij \to H\right](x_1P_A, x_2P_B, \mu_F, \mu_R, m_c)$$

$$\hat{\sigma}\left[ij \to H\right] = \sum_n \underbrace{C^{ij}_{c\bar{c}[n]}(x_1P_A, x_2P_B, \mu_F, \mu_R, m_c)}_{\text{Production of } c\bar{c} \text{ pairs}} \langle O^H_n \rangle \leftarrow \text{LDMEs}$$

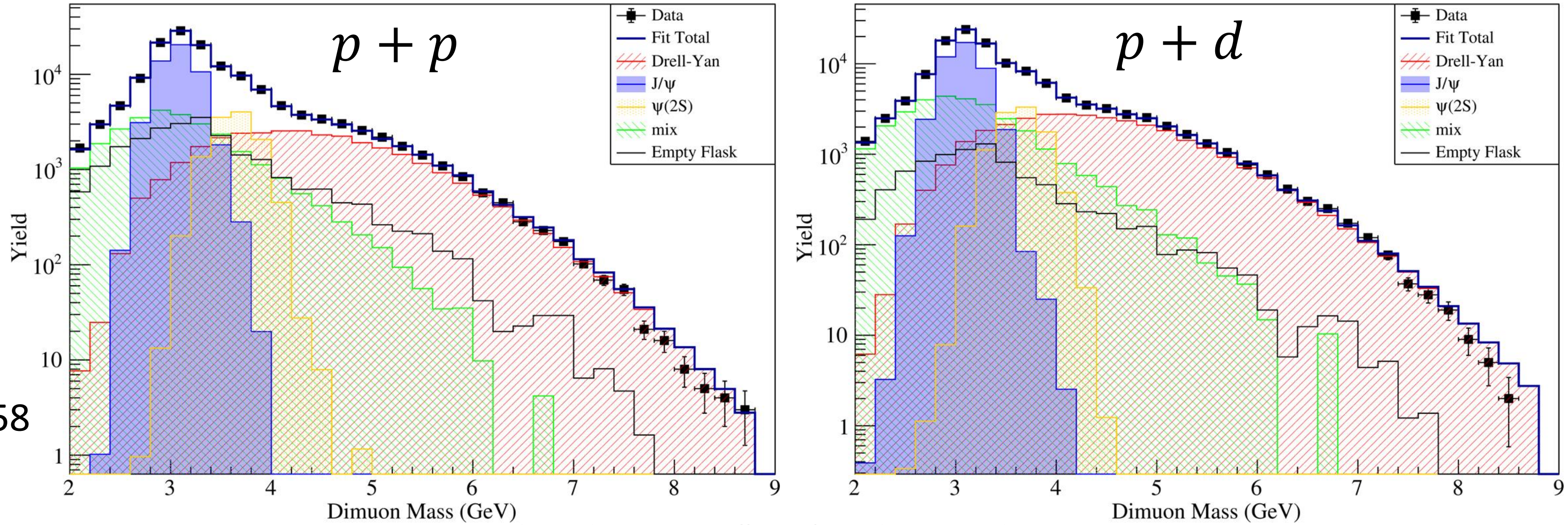
$$n = {}^{2S+1}L_j^{[1,8]}$$



LDME from W.-C Chang et al, PRD 107 056008 (2023)

Obtaining J/ψ yield from mass spectrum

- Performing a component fit to the mass spectrum
- Use Monte Carlo to simulate signal events (J/ψ, $\psi(2S)$, Drell-Yan)
- Use mixed single-track events to simulate accidental background
- A fit is done for each x_F bin to obtain the yield



Phys. Lett. B 858 (2024) 139032

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

Charmonium yield
from mass spectrum

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

Branching ratio

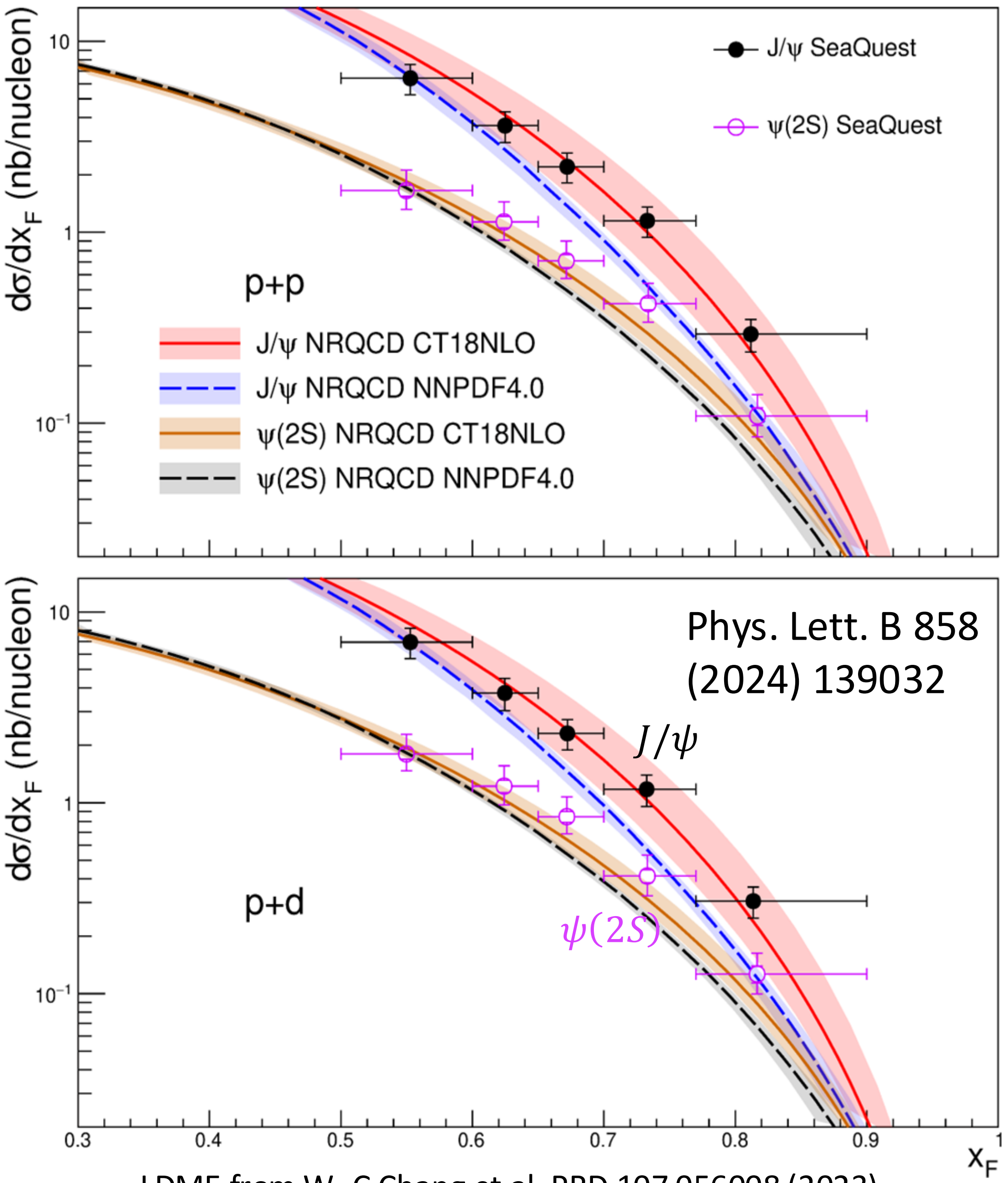
Acceptance and
efficiency correction

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

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

Charmonium production

- The two data sets are analyzed separately and are then combined together, with the uncertainty taken into account
- The measured J/ψ cross sections are in reasonable agreement with NRQCD with CT18, including the overall magnitude
- The x_F distributions are different between J/ψ and $\psi(2S)$

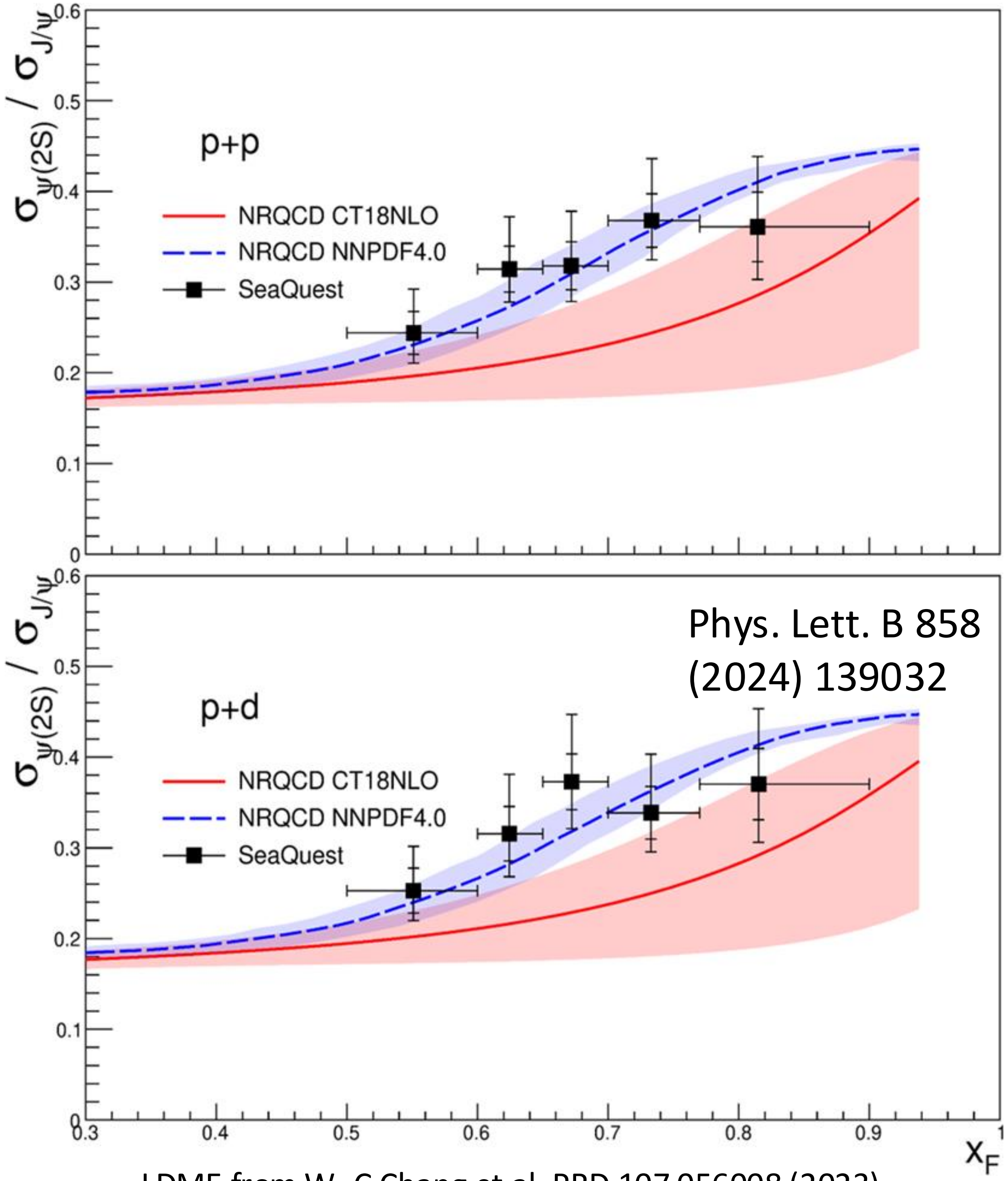


CT18: Hou et al, Phys. Rev. D 103, 014013 (2021)
NNPDF4.0: Ball et al, Eur. Phys. J. C 82, 428 (2022)

LDME from W-.C Chang et al, PRD 107 056008 (2023)

Charmonium production

- The $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ ratios are found to increase as x_F increases.
- The x_F distribution is broader in $\psi(2S)$ production than J/ψ.
- This is due to the increasing importance of $q\bar{q}$ annihilation in $\psi(2S)$ production



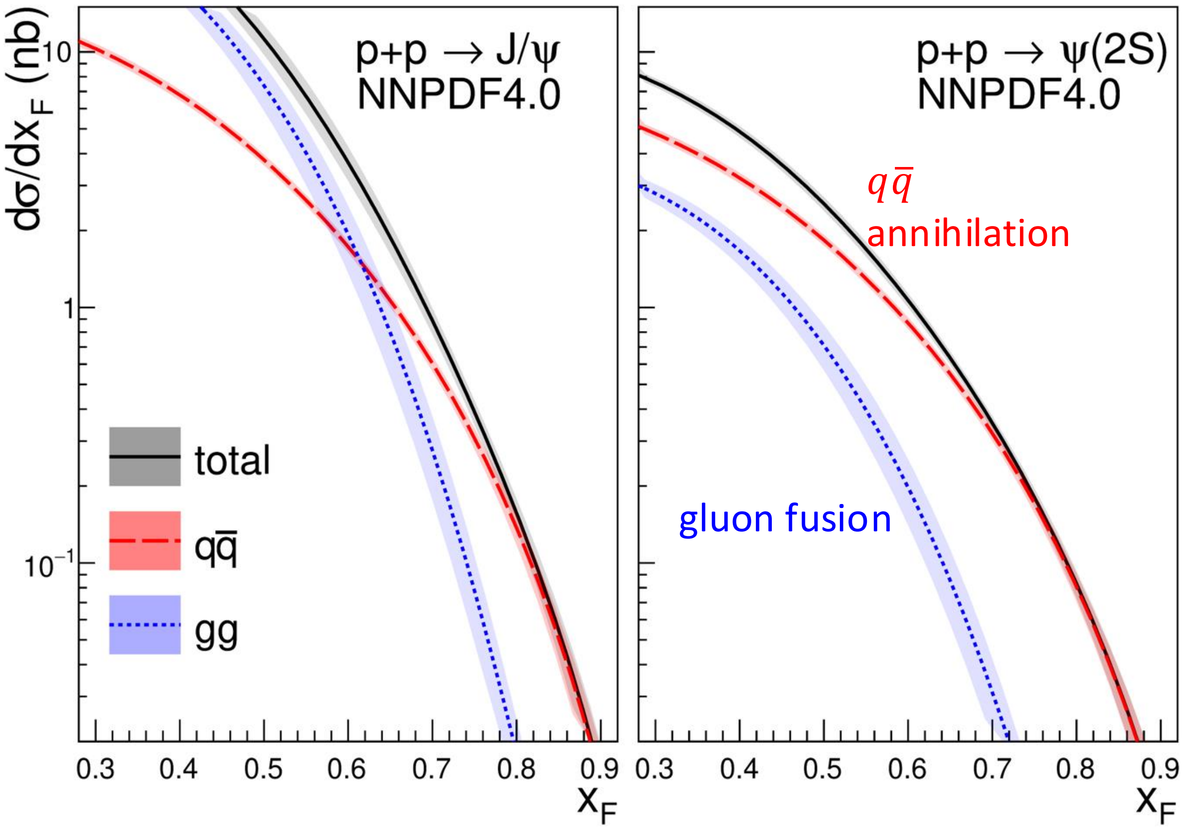
Phys. Lett. B 858 (2024) 139032

CT18: Hou et al, Phys. Rev. D 103, 014013 (2021)
NNPDF4.0: Ball et al, Eur. Phys. J. C 82, 428 (2022)

LDME from W-.C Chang et al, PRD 107 056008 (2023)

$\psi(2S)$ production

- The LDMEs depend on the charmonium state
- The relative importance of each subprocess is different between J/ψ and $\psi(2S)$
  - $q\bar{q}$ annihilation is the dominant contribution to $\psi(2S)$ at all x_F



LDME from W-.C Chang et al, PRD 107 056008 (2023)

P_T distribution

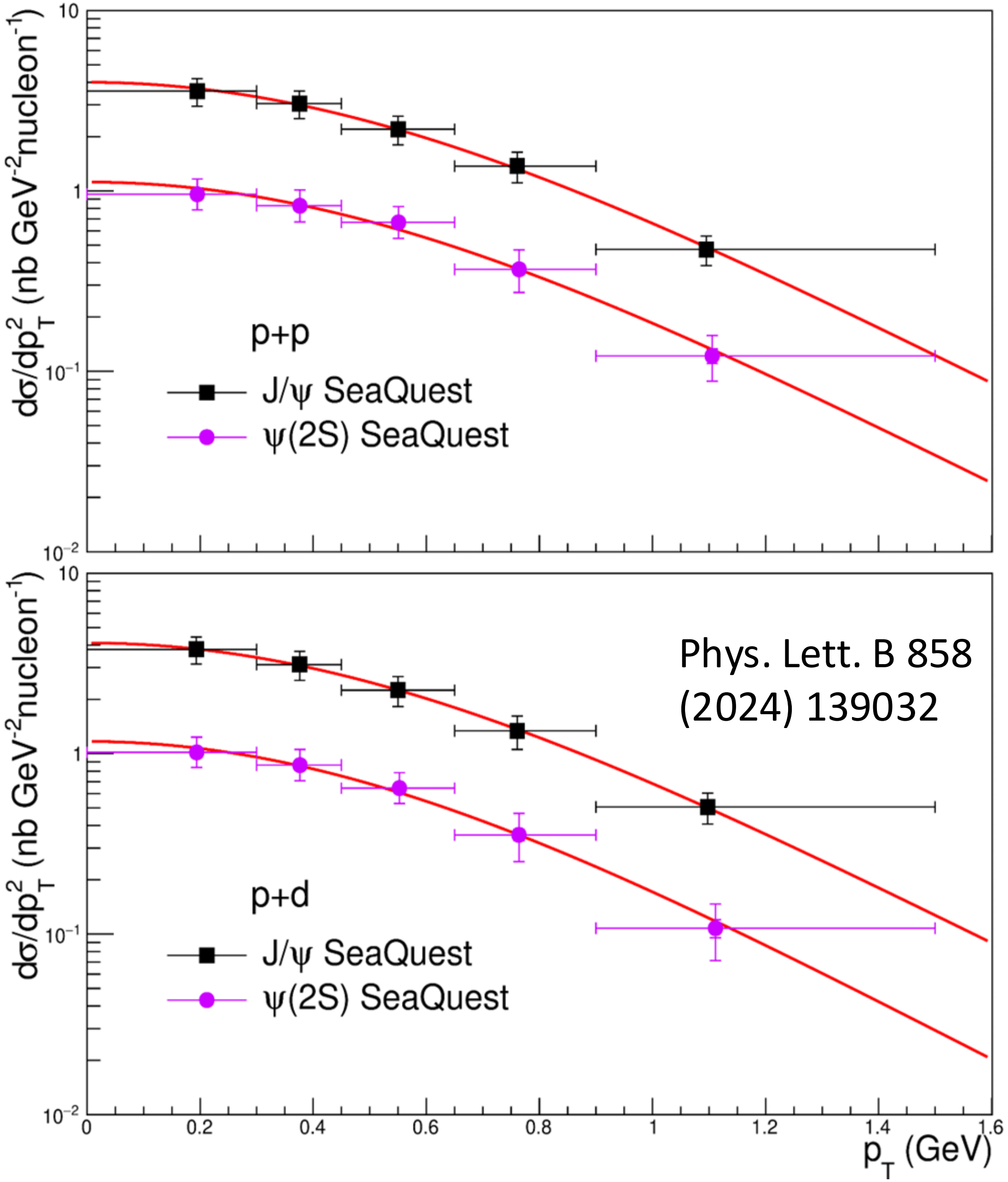
- The P_T distributions are fitted to

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2} = p_0 \left(1 + p_T^2/p_1^2\right)^{-6}$$

$$\langle P_T \rangle = \frac{35\pi p_1}{256}, \quad \langle P_T^2 \rangle = \frac{p_1^2}{4}$$

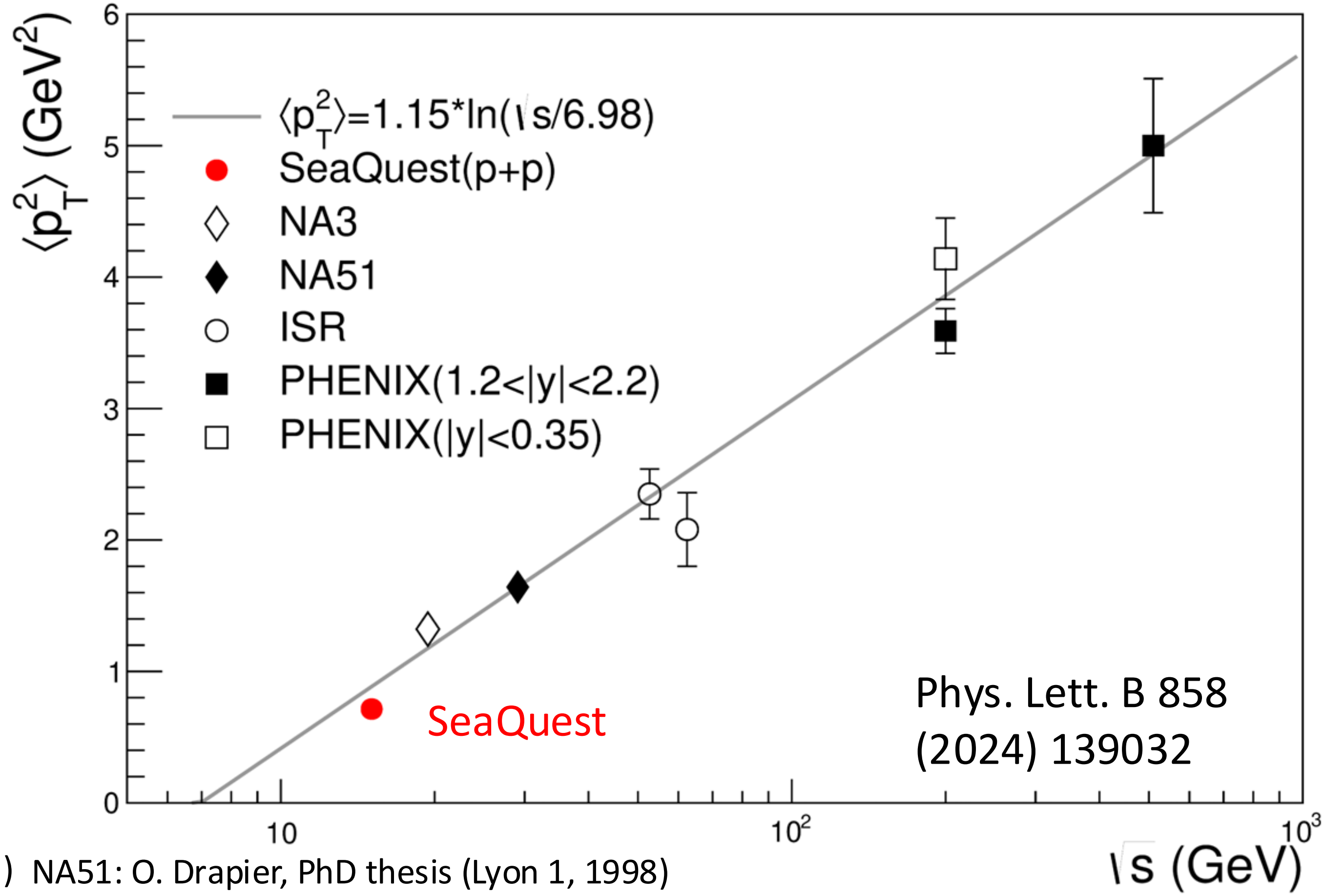
- The extracted $\langle P_T^2 \rangle$ are very similar

	J/ψ	$\psi(2S)$
$p+p$	$0.714 \pm 0.021 \pm 0.040$	$0.714 \pm 0.036 \pm 0.068$
$p+d$	$0.717 \pm 0.022 \pm 0.046$	$0.663 \pm 0.035 \pm 0.067$



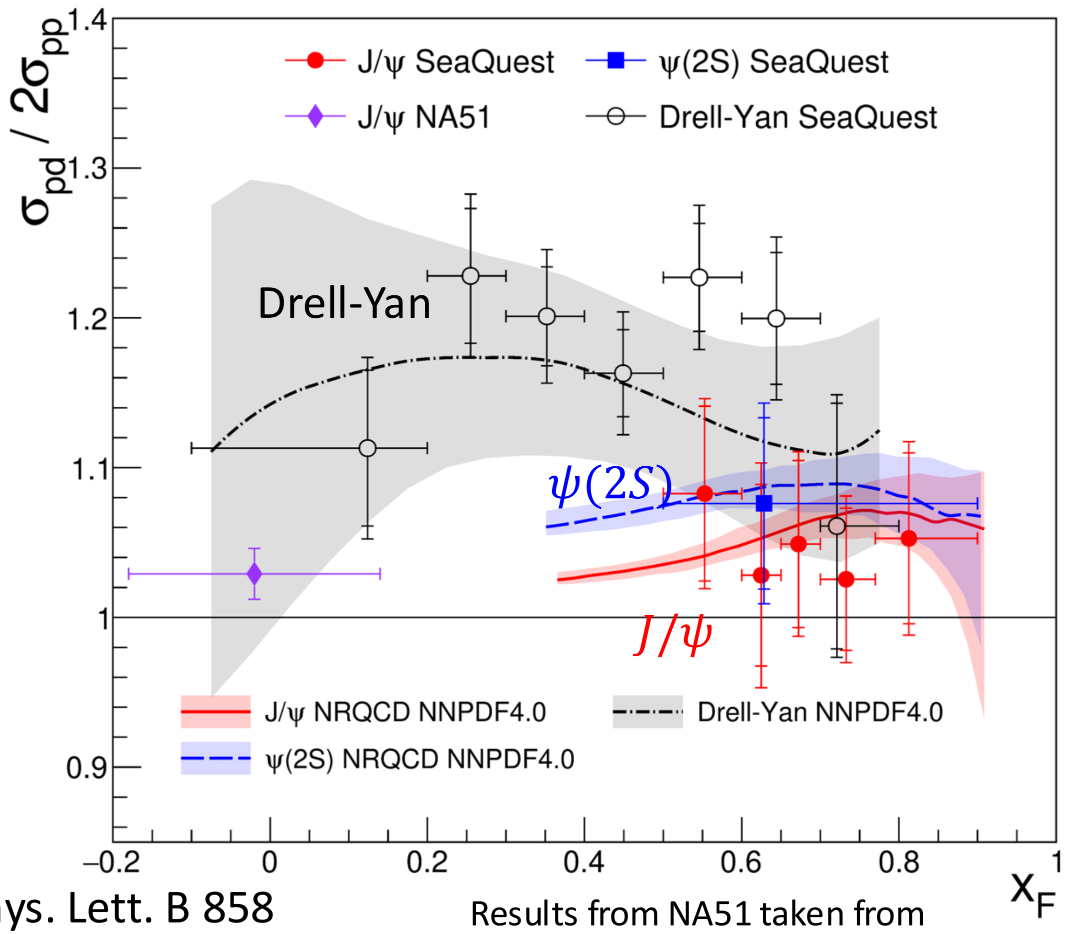
$\langle P_T^2 \rangle$ for $p + p \rightarrow J/\psi$ at different $\sqrt{s}$

- The $\langle P_T^2 \rangle$ increases as a function of $\sqrt{s}$
- The behavior is very well described by linear fit to $\ln(\sqrt{s})$
- Some small deviation is expected as the rapidity measured by different experiments are different



NA3: Z. Phys. C: Part. Fields 20, 101 (1983)
ISR: Nucl. Phys. B 142, 29 (1978)
NA51: O. Drapier, PhD thesis (Lyon 1, 1998)
PHENIX: Phys. Rev. D 101, 052006 (2020)

Charmonium and Drell-Yan $\sigma^{pd}/2\sigma^{pp}$ ratios vs x_F



Phys. Lett. B 858 (2024) 139032

Results from NA51 taken from Abreu et al, Phys Let B **438**, 35 (1998).

- 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 ratio can provide alternative constraints on the flavor asymmetry

What we have learnt from SeaQuest

- $\sigma^{pd}/2\sigma^{pp}$ Drell-Yan cross section ratio using the mass fit method
  - $\bar{d}/\bar{u} > 1$ for the entire measured region
  - This new result can provide better constraints on the antiquark distribution
- New result on J/ψ cross section from the full data set
  - The extracted J/ψ and $\psi(2S)$ cross sections are in good agreement with NRQCD
  - $q\bar{q}$ annihilation is found to be more important in $\psi(2S)$ production than in J/ψ
  - The difference between the J/ψ and Drell-Yan $\sigma_{pd}/2\sigma_{pp}$ ratios are reflecting the different mechanisms

Future prospects

- The Drell-Yan process requires $Q^2 > 20\ \mathrm{GeV}^2$, the low Q^2 behavior would need to be probed using SIDIS
- The $\bar{d} - \bar{u}$ at small x remain poorly constrain, SIDIS data can provide better constrain at these kinematics
- Extending the study of sea quarks to other flavor, such as the strange quarks through kaon SIDIS
- Charmonium production with electron beam can provide constraints on the LDMEs