Measurement of p+d/p+p charmonium cross section ratio with 120 GeV proton beam in the SeaQuest experiment

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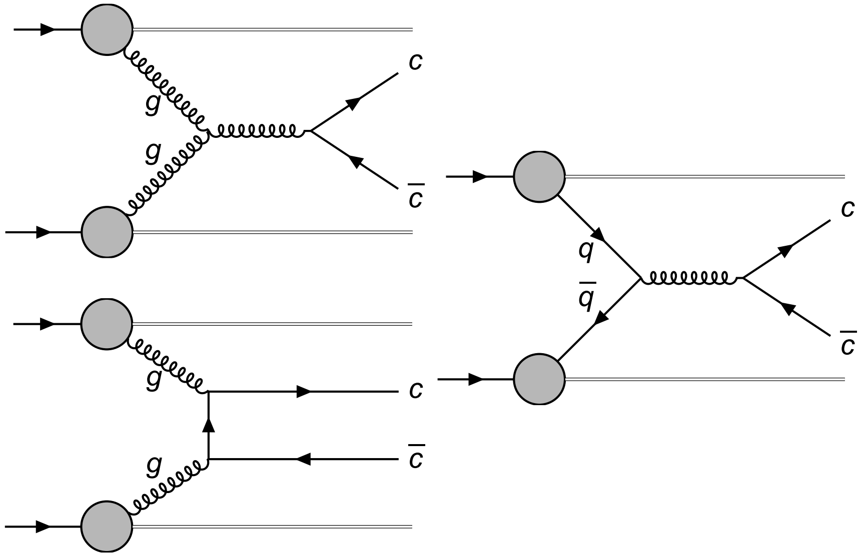
Motivation

- 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 J/ψ event
- Drell-Yan is an electromagnetic interaction
  - 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 is produced via strong interaction
  - Sensitive to both quark and antiquark distribution as well as gluon distribution
  - Provide information complimentary to Drell-Yan data

J/ψ production mechanism

- In NRQCD[1], the production of $c\bar{c}$ pairs is calculated with perturbative QCD and the hadronization into charmonium state is described by the associated long-distance matrix elements (LDMEs)



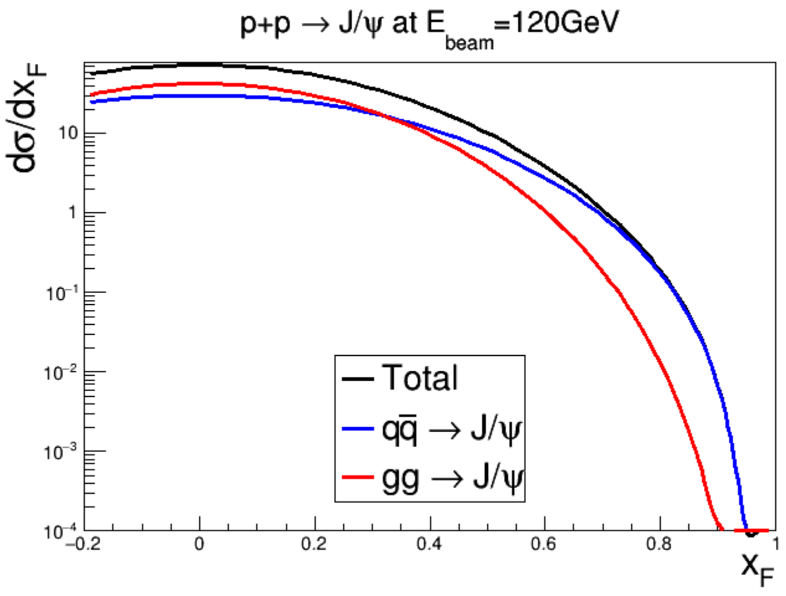
$$\frac{d\sigma^H}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_1 dx_2 \delta(x_F - x_1 + x_2)$$
$$\times f_i^h(x_1, \mu_F) f_j^N(x_2, \mu_F) \hat{\sigma}[ij \to H](x_1 P_h, x_2 P_N, \mu_F, \mu_R, m_c),$$
$$\hat{\sigma}[ij \to H] = \sum_n C^{ij}_{c\bar{c}[n]}(x_1 P_h, x_2 P_N, \mu_F, \mu_R, m_c) \times \langle \mathcal{O}_n^H[^{2S+1}L_J] \rangle$$

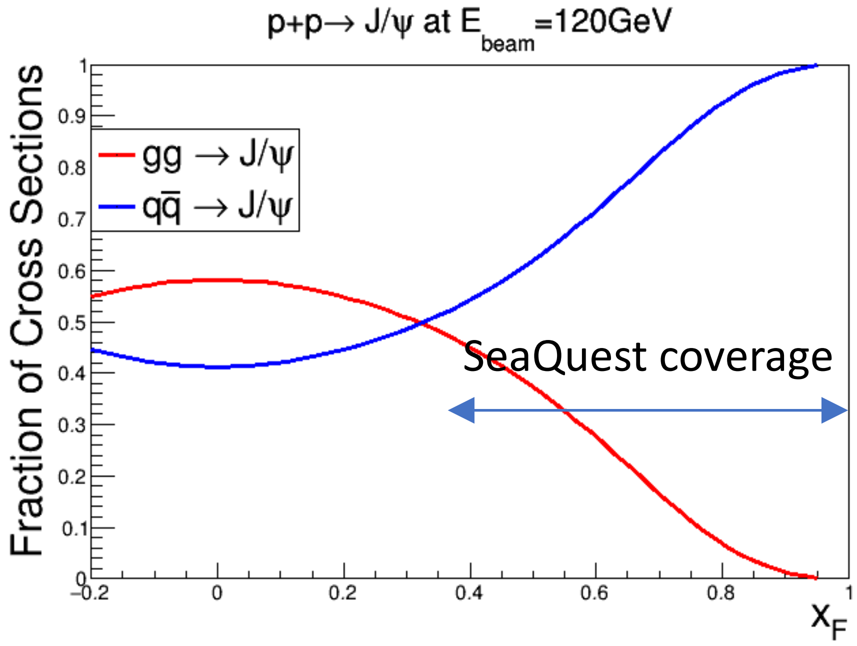
$$x_F = 2p_L/\sqrt{s},\ x_{1,2} = \frac{\sqrt{x_F^2 + 4M_{c\bar{c}}{}^2/s} \pm x_F}{2}$$

[1] CY Hsieh et al, arXiv:2103.11660v1 [hep-ph]

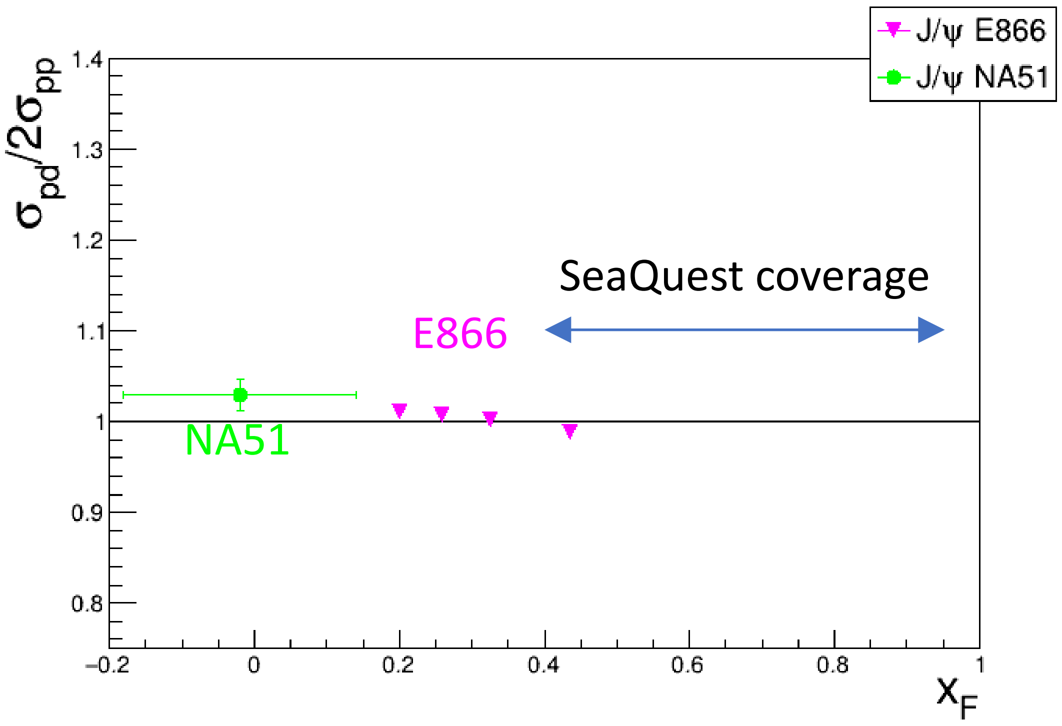
Contribution from different components

- The relative importance of each component is a strong function of x_F
- At high x_F $q\bar{q}$ annihilation dominate over gluon fusion





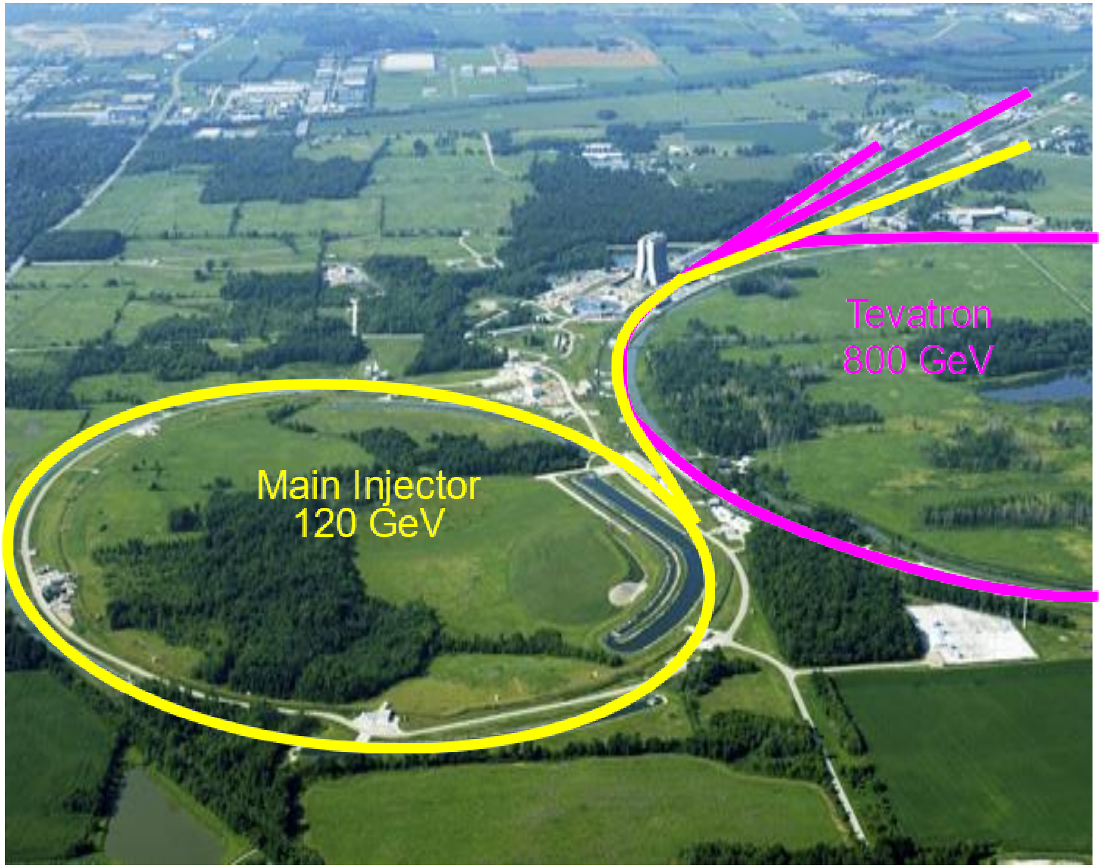
Previous J/ψ measurements



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

- Both NA51[2] and E866/NuSea[3] have measured the J/ψ cross section ratio
- The previous results are at lower x_F, and are dominated by gluon fusion
- SeaQuest measurement is at higher x_F

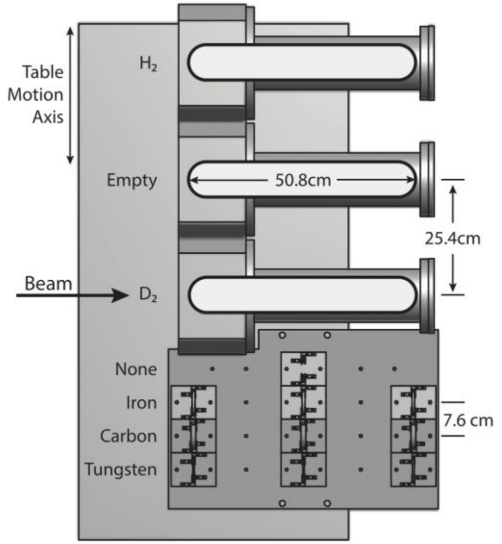
SeaQuest
E906

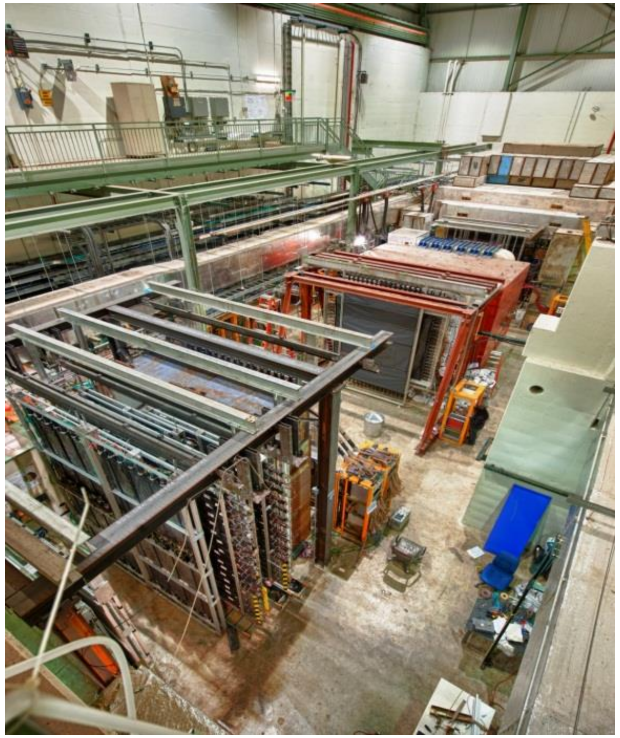


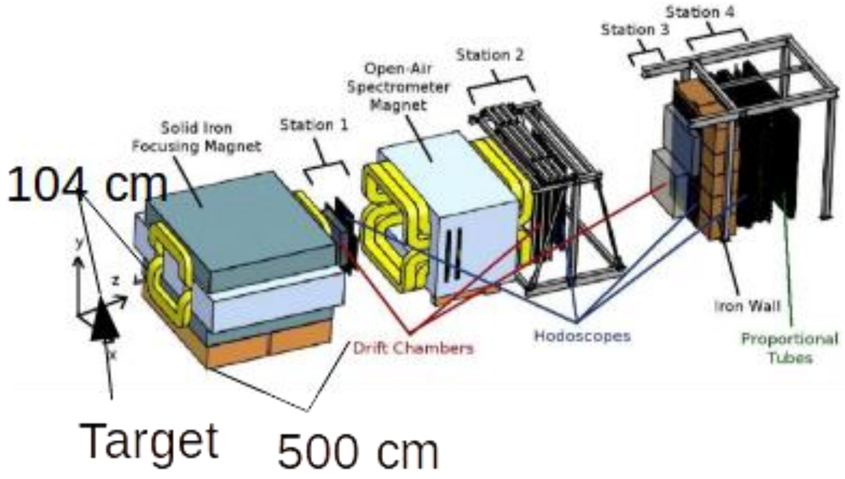
- 120 GeV proton beam
- ~10x instantaneous intensity as compared to E866/NuSea (800GeV proton beam)

E906 Apparatus

- 120 GeV proton beam on LH_2, LD_2 targets
- New beamline
- New apparatus
- Forward spectrometer ($x_F > 0$)
- Focusing magnet to bend tracks into spectrometer
- Spectrometer magnet to measure momentum of tracks



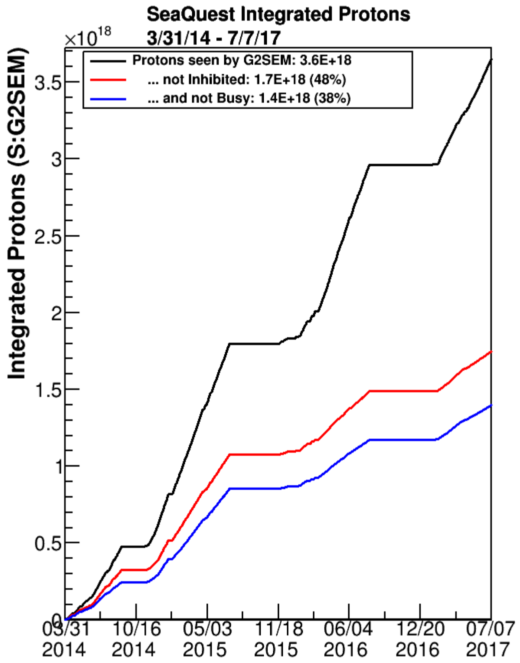


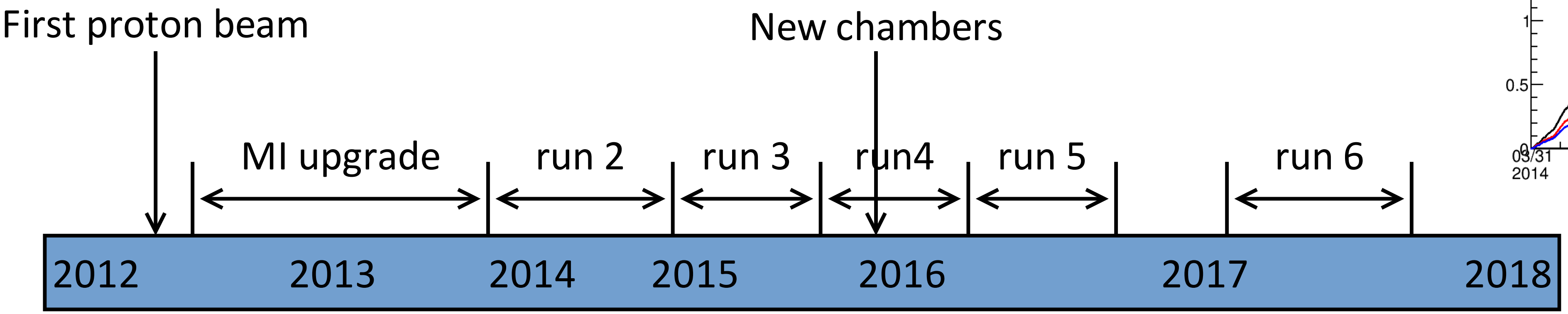


[4] C. A. Aidala et al, *Nucl.Instrum.Meth.A* 930 (2019) 49-63

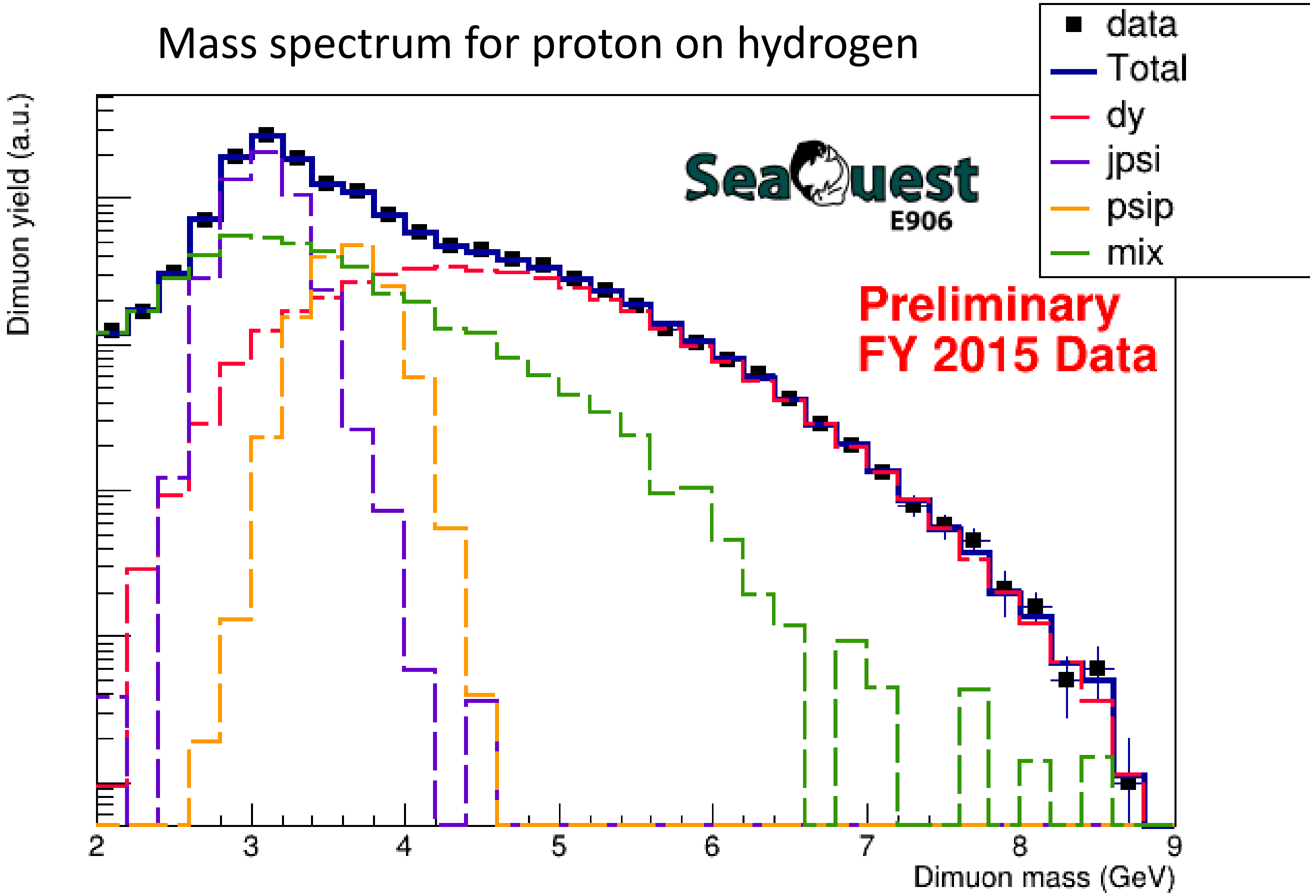
Timeline

- Commissioning began in 2012 and data collection finished in July 2017
- First Drell-Yan result has been published recently
- J/ψ analysis based on run2 and run3 data
- Corresponds to 40% of the full data set



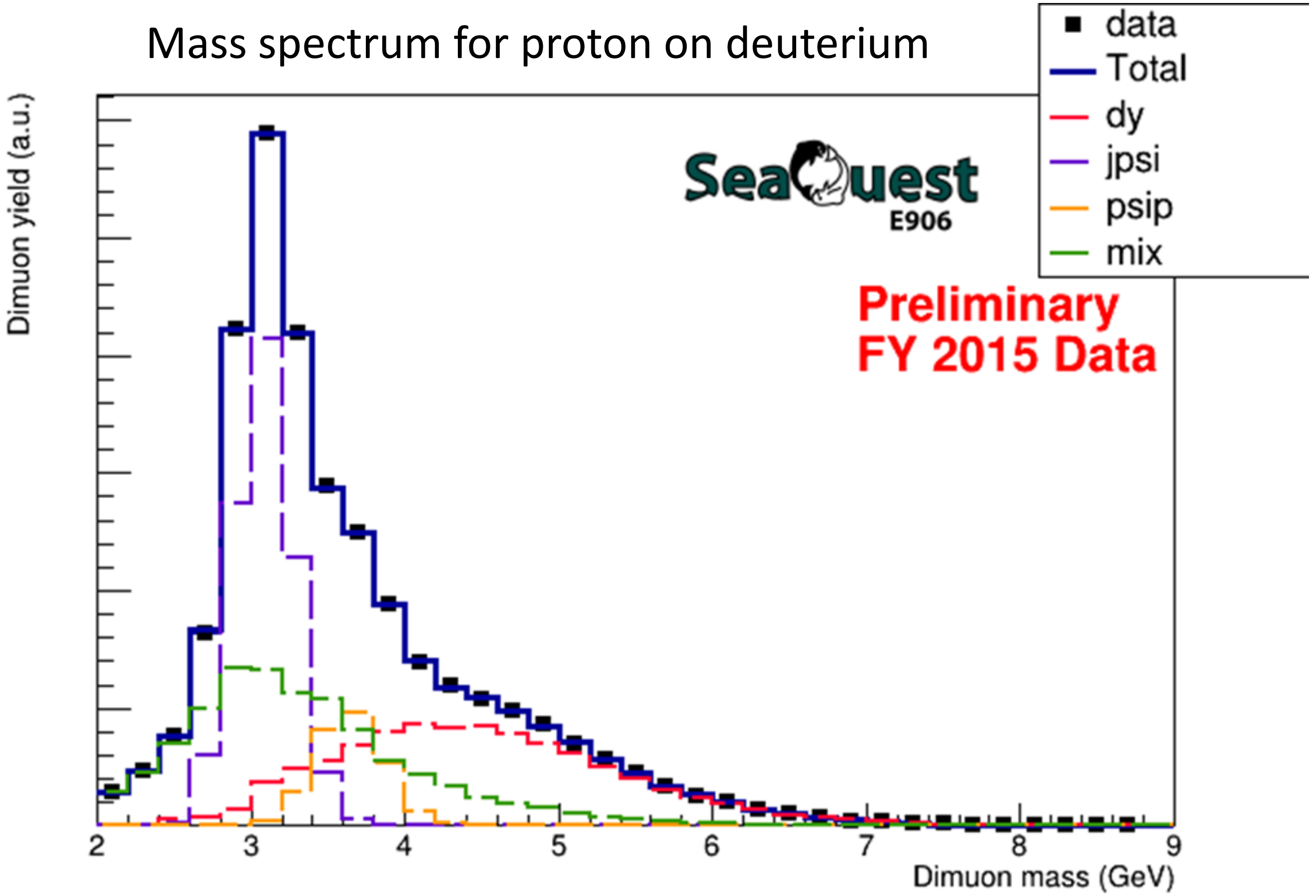


Mass spectrum for proton on hydrogen



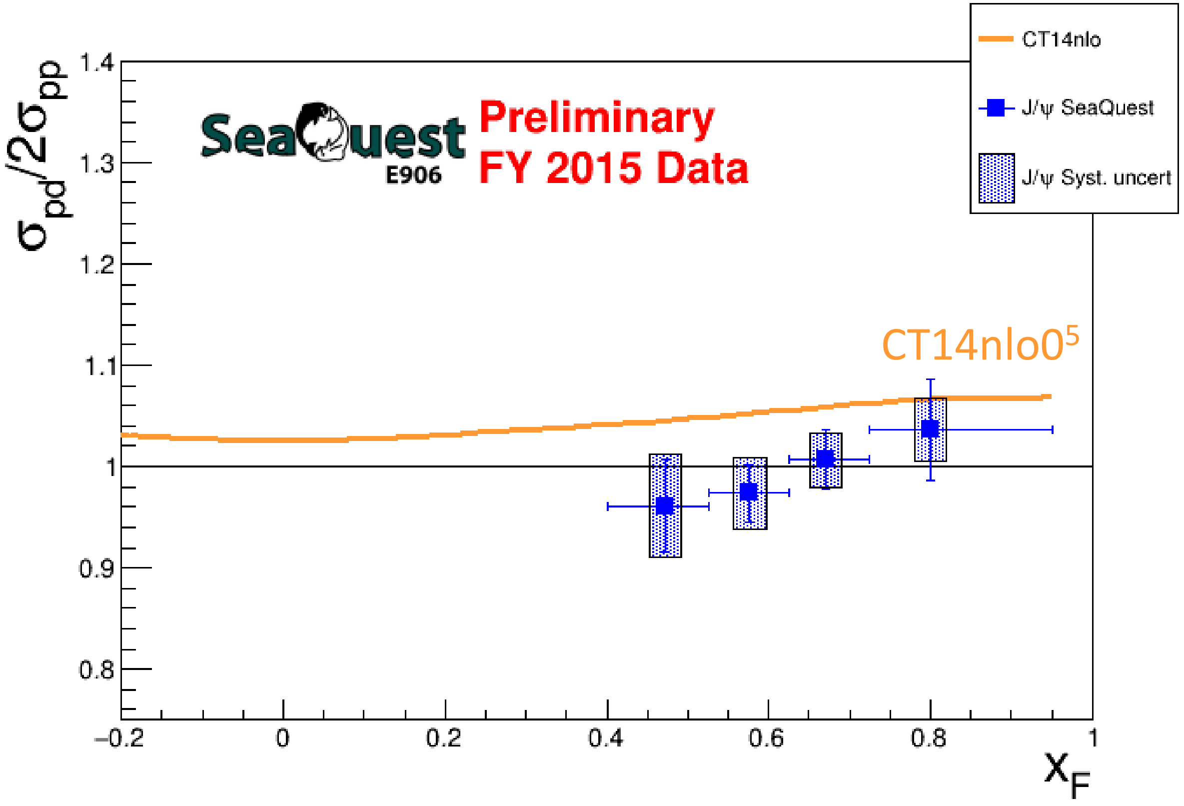
- Use Monte Carlo to simulate signal events $(J/\psi, \psi', DY)$
- Use mixed single-track events to simulate accidental background
- By fitting the mass spectrum, we obtain the J/ψ yield for individual targets

Mass spectrum for proton on deuterium



- Major sources Systematics
  - Modeling of the accidental background
  - Relative normalization between targets
- other sources
  - Event selection
  - Empty flask subtraction

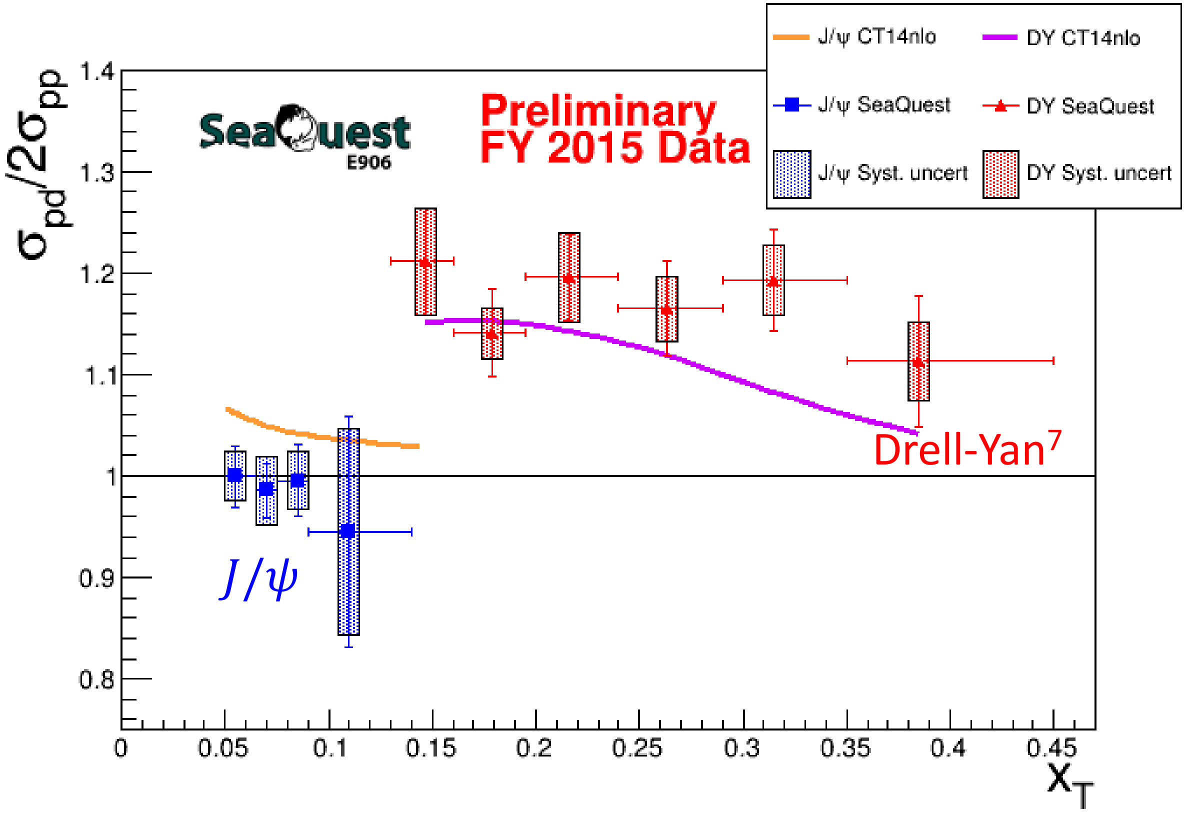
J/ψ Cross section ratio vs x_F



- The measured ratio consistent with 1 within uncertainty
- The preliminary result is compared with prediction from NLO NRQCD[1]

[1] CY Hsieh et al, arXiv:2103.11660v1 [hep-ph]
[5] S. Dulat, et al, Phys. Rev. D 93, 033006 (2016).

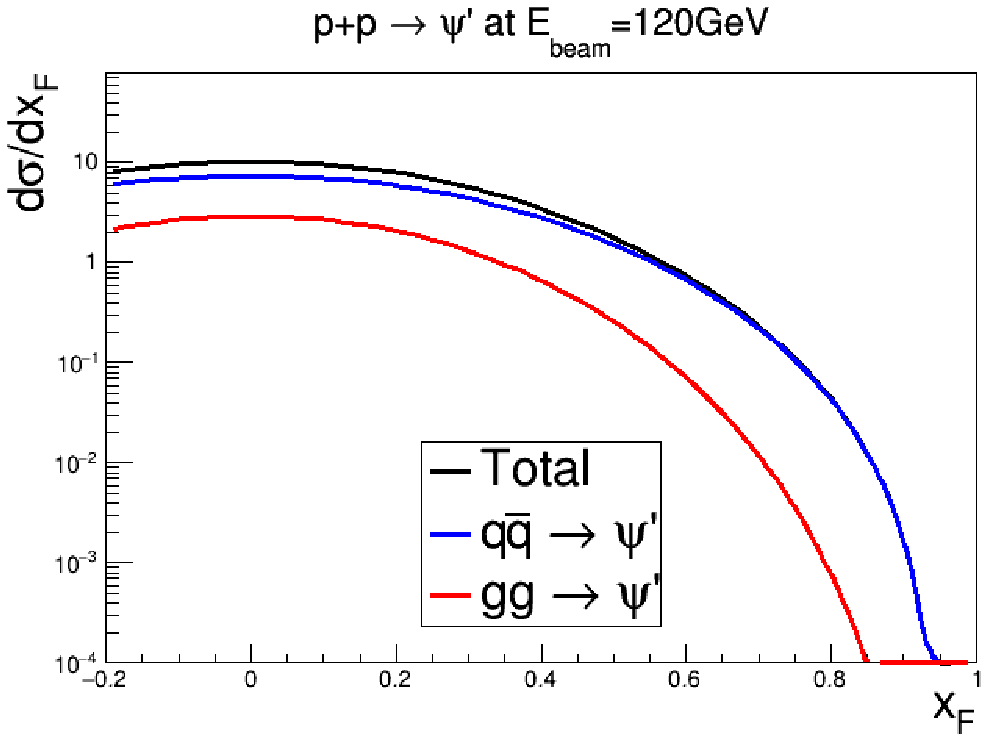
J/ψ and Drell-Yan cross section ratios vs x_T



- J/ψ ratio is closer to 1 compared to Drell-Yan
  - 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

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

Ψ' production



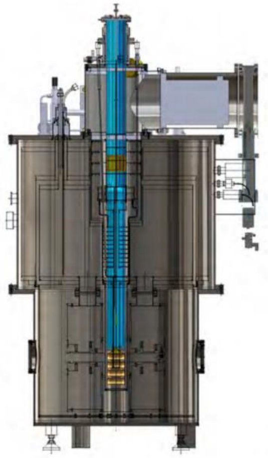
- $q\bar{q}$ annihilation is more important in Ψ' production
- The SeaQuest spectrometer has better acceptance at high mass region

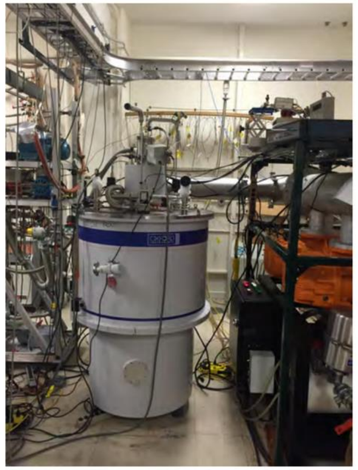
Summary and outlook

- The preliminary p+d/p+p J/ψ cross section ratio with $120 GeV$ beam is reported
- The measured J/ψ cross section ratio is consistent with 1
- This new result could provide additional constraints on nucleon PDF
- Analysis including data taken after 2016 is underway and would double the statistics
- The ψ' production can also be studied at SeaQuest

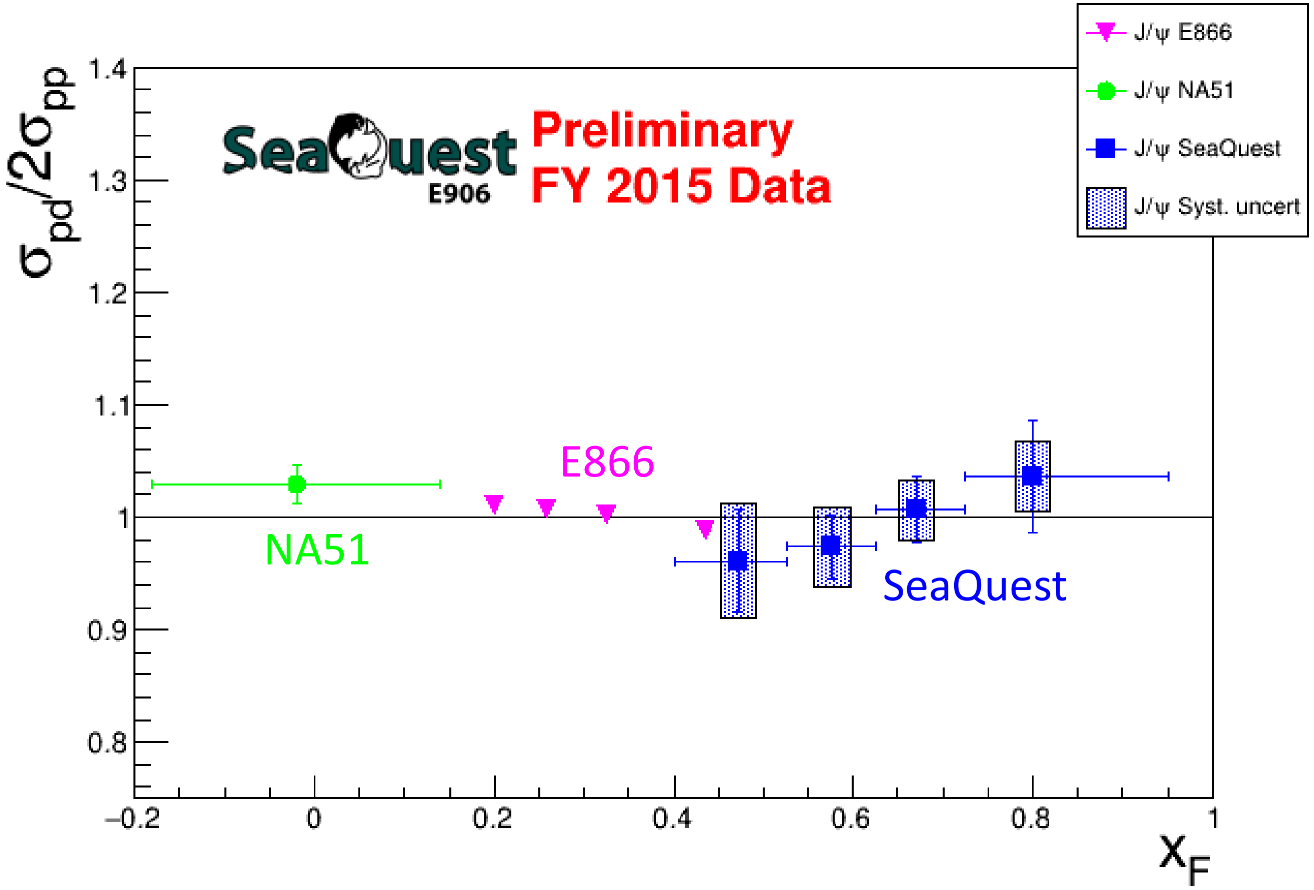
E1039/SpinQuest

- E1039/SpinQuest is a follow up experiment of E906/SeaQuest
  - Same spectrometer but with a transversely polarized NH_3 and ND_4 target
- Measure the single-spin asymmetry in both Drell-Yan process and J/ψ production
  - Provide information on Sivers function of both light sea quarks and gluon
- Expect to begin beam commissioning in December 2021





J/ψ Cross section ratio



[2] M. C. Abreu et al, Physics Letters B **438**, 35 (1998). [3] J.-C. Peng, Eur. Phys. J. A **18**, 395 (2003).

NRQCD

- In J/ψ, a $c\bar{c}$ pair is first produced via QCD processes
- The hadronization probability is a function of spin, color and angular momentum

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

$$\times f_i^h(x_1, \mu_F) f_j^N(x_2, \mu_F) \hat{\sigma}[ij \to H](x_1 P_h, x_2 P_N, \mu_F, \mu_R, m_c), \quad (2.1)$$

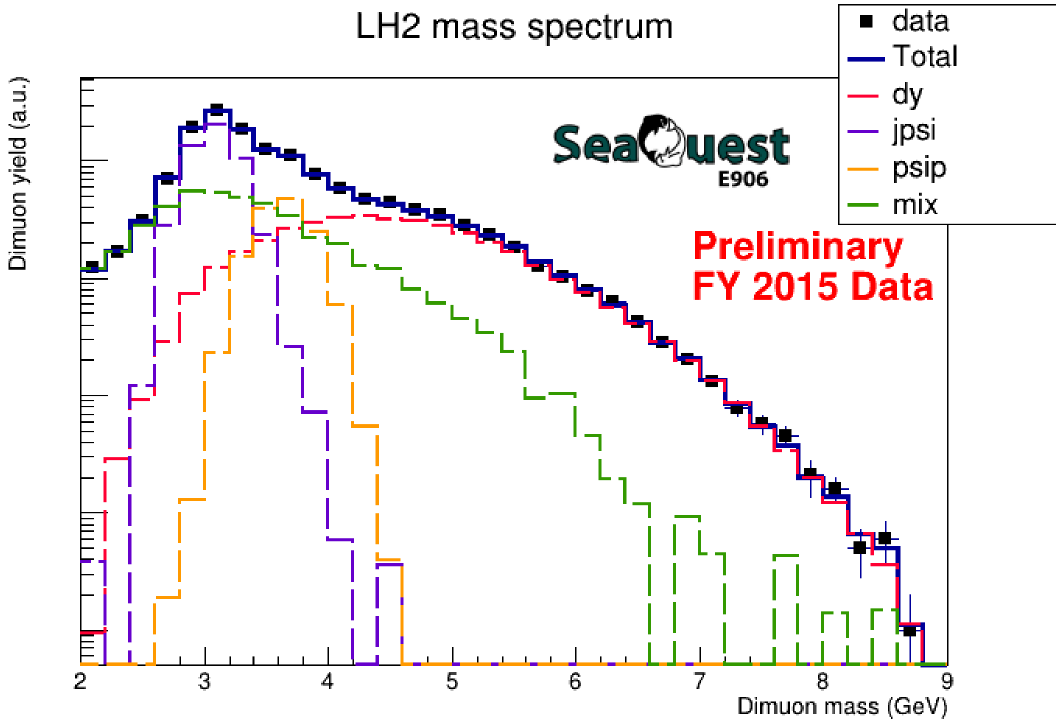
$$\hat{\sigma}[ij \to H] = \sum_n \underbrace{C^{ij}_{c\bar{c}[n]}(x_1 P_h, x_2 P_N, \mu_F, \mu_R, m_c)}_{c\bar{c}\text{ production pQCD}} \times \underbrace{\langle \mathcal{O}_n^H [^{2S+1}L_J] \rangle}_{\text{Hadronization LDME}} \quad (2.2)$$

$$x_F = 2p_L/\sqrt{s},\ x_{1,2} = \frac{\sqrt{x_F^2 + 4M_{c\bar{c}}{}^2/s} \pm x_F}{2} \quad (2.3)$$

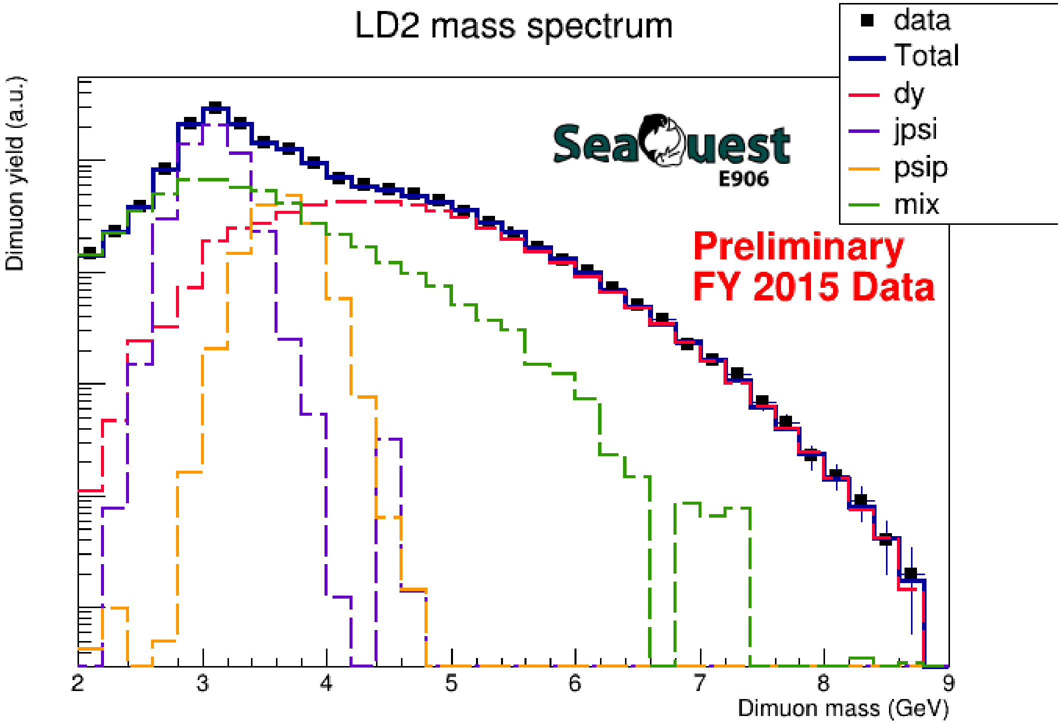
[1] CY Hsieh et al, arXiv:2103.11660v1 [hep-ph]

Mass spectrum

LH2 mass spectrum



LD2 mass spectrum



Color evaporation model

- the color evaporation model (CEM) assumes a constant probability for $Q\bar{Q}$ pairs to hadronize into a quarkonium state
- In J/ψ, a $c\bar{c}$ pair is first produced via QCD processes
- a constant probability F, specific for each quarkonium, accounts for the hadronization of $c\bar{c}$ pairs into the colorless J/ψ state

$$\left.\frac{d\sigma}{dx_F}\right|_{J/\psi} = F \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{s\sqrt{x_F^2 + 4M_{c\bar{c}}^2/s}}$$

$$\times f_i^B(x_1, \mu_F) f_j^T(x_2, \mu_F) \sigma[ij \to c\bar{c}X](x_1 p_B, x_2 p_T, \mu_F, \mu_R)$$

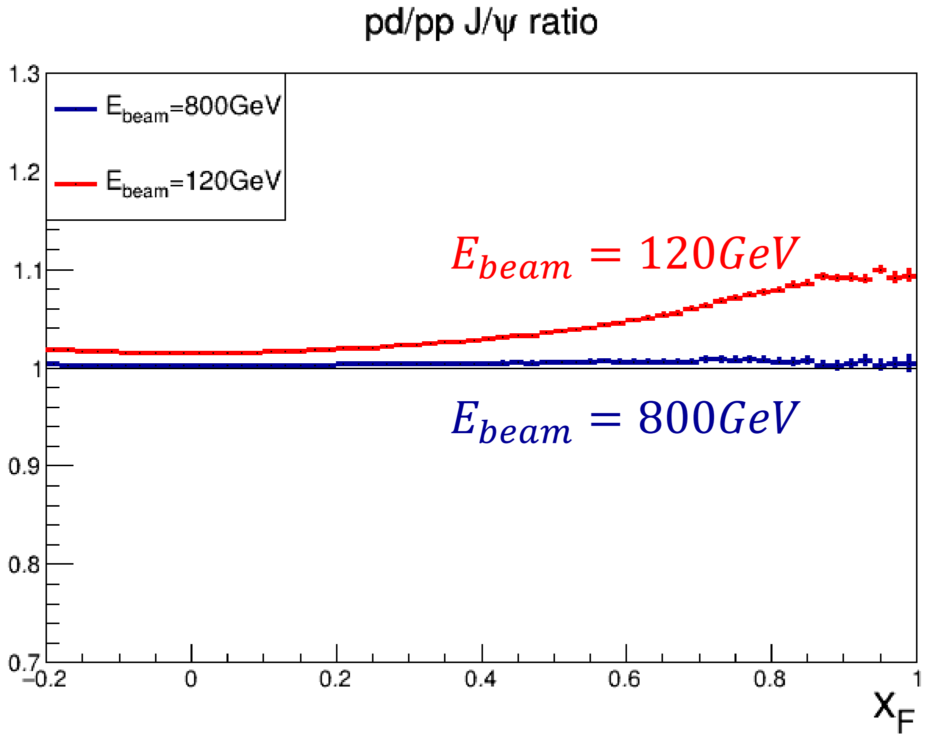
- In Leading-Order
- The contribution to the cross section from gluon fusion is given by

$$\sigma(GG \to c\bar{c}) = \frac{\pi\alpha_s^2}{3M_{c\bar{c}}^6}\left\{\left(M_{c\bar{c}}^4 + 4M_{c\bar{c}}^2 m_c^2 + m_c^4\right)\ln\left(\frac{M_{c\bar{c}}^2 + \lambda}{M_{c\bar{c}}^2 - \lambda}\right) - \frac{1}{4}\left(7M_{c\bar{c}}^2 + 31m_c^2\right)\lambda\right\}$$

- The contribution from $q\bar{q}$ annihilation is given by

$$\sigma(q\bar{q} \to c\bar{c}) = \frac{8\pi\alpha_s^2}{27M_{c\bar{c}}^6}\left(M_{c\bar{c}}^2 + 2m_c^2\right)\lambda$$

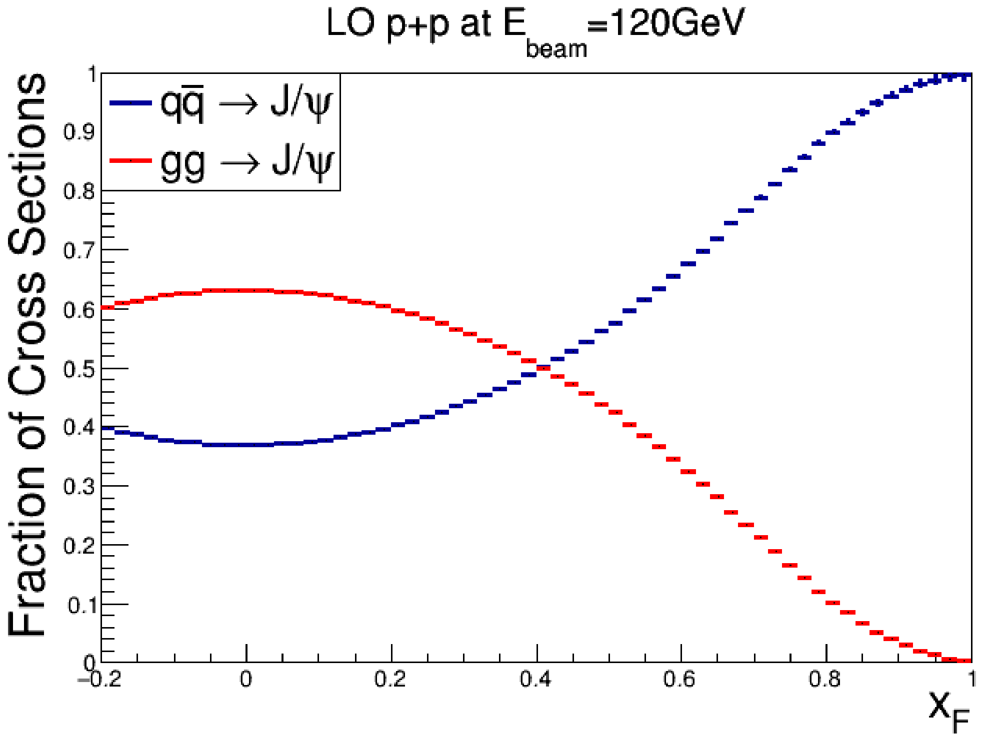
- Where $\lambda = \left(M_{c\bar{c}}^4 - 4M_{c\bar{c}}^2 m_c^2\right)^{1/2}$

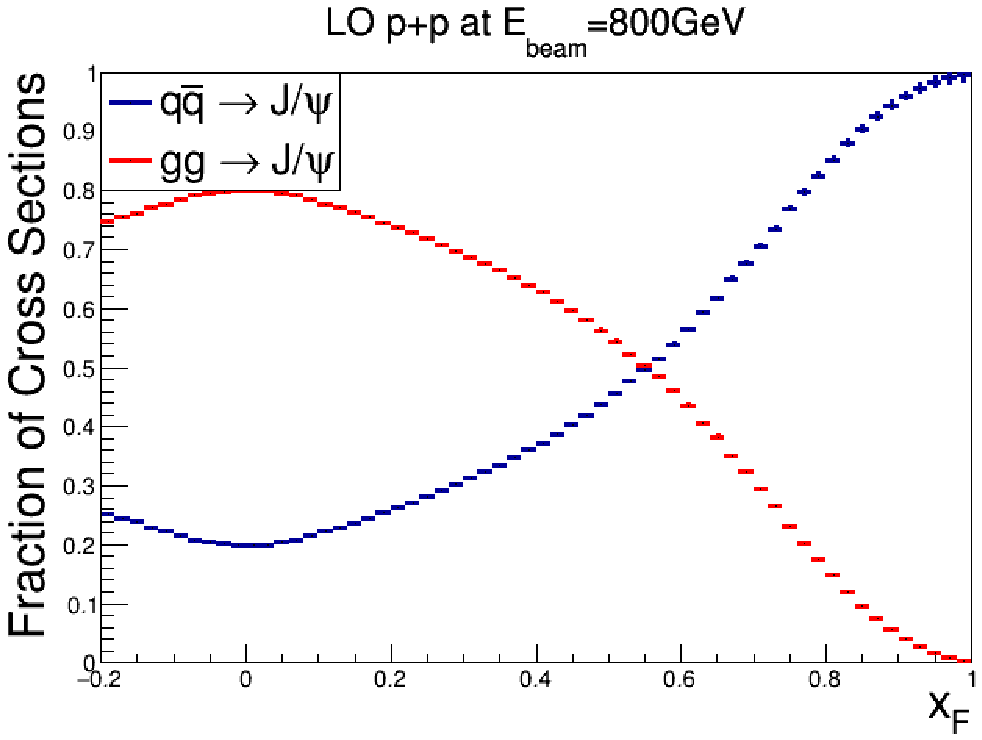


- Calculated cross section ratio using CEM[1] with CT14nlo[5] at two different energy
- At lower energy, the deviation from unity is more significant as $q\bar{q}$ annihilation is more important

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

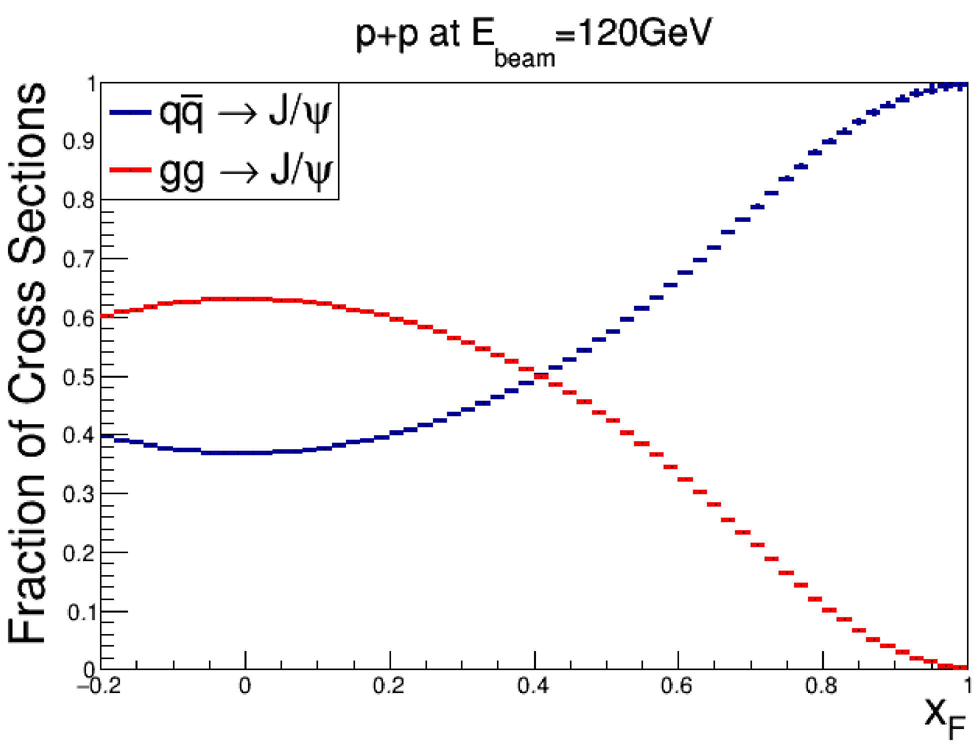
Relative importance of different components



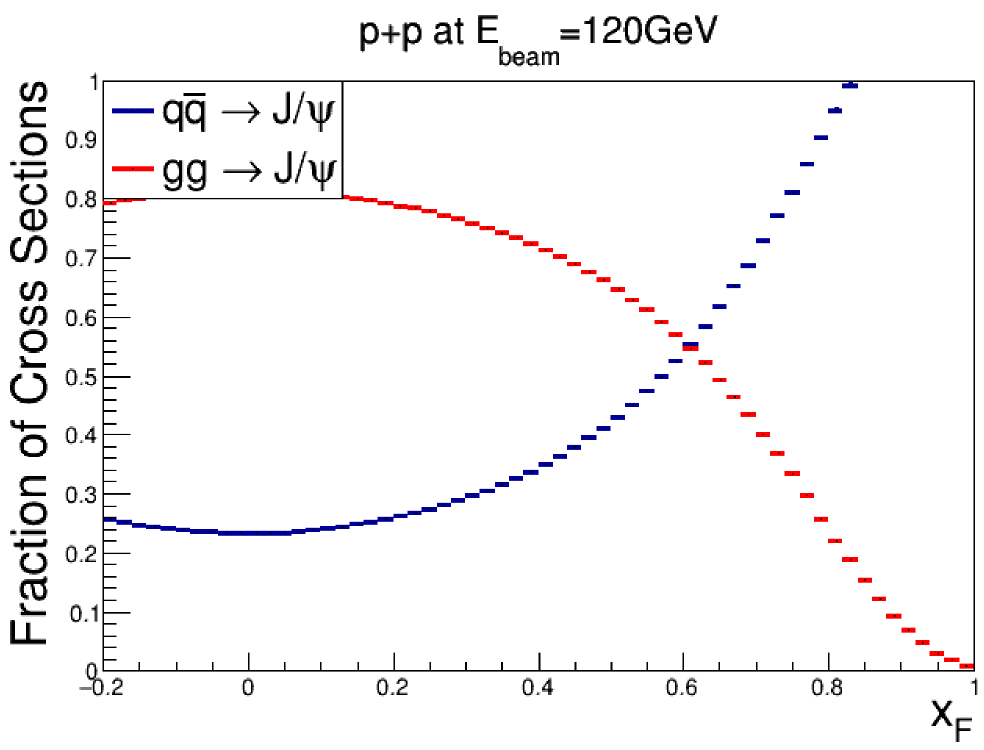


Comparison between LO and NLO

Leading Order



Next to Leading Order



- In the limit that $x_1 \gg x_2$, we can assume the quark comes from the beam and the antiquark comes from the target

Coming from the charge squared in QED

$$\left.\frac{\sigma_{DY}^{pd}}{2\sigma_{DY}^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\frac{\left[1+\frac{1}{4}\frac{d(x_1)}{u(x_1)}\right]}{\left[1+\frac{1}{4}\frac{d(x_1)}{u(x_1)}\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

- At the same limit, we can assume the gluon contribution to J/ψ cross section is small

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