Quarkonium at SeaQuest

Noah Wuerfel

On behalf of the SeaQuest Collaboration

Quarkonia as Tools 2025

Jan 5 - 11, 2025

Aussois, France

Fermilab

SeaQuest E906

Fixed Target DY program at Fermilab

NAL PROPOSAL # 288

Scientific Spokesman:

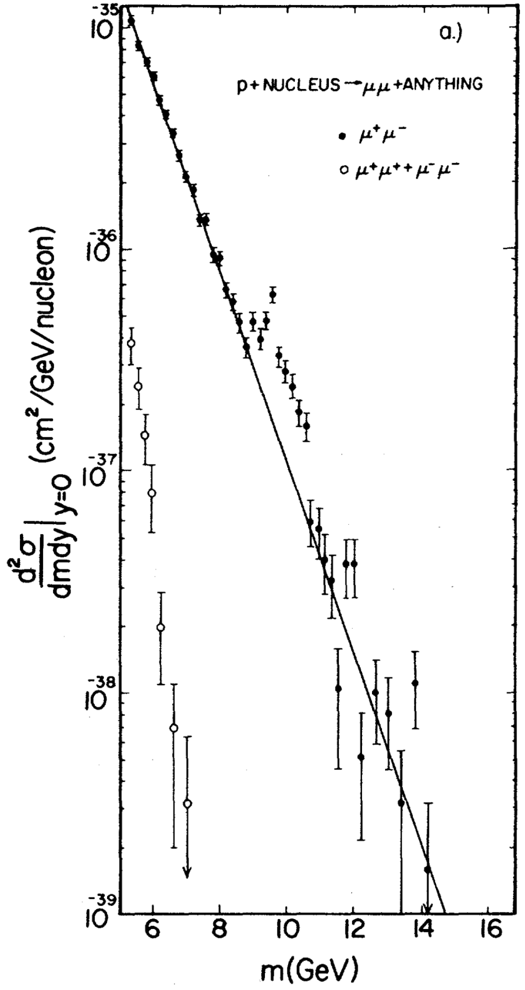
L. M. Lederman
Physics Department
Columbia University
New York, New York 10027

FTS/Off-net: 212 - 460-0100
280-1754

A Study of Di-Lepton Production in Proton Collisions at NAL

J. A. Appel, M. H. Bourquin, D. C. Hom, L. M. Lederman, J. P. Repellin, H. D. Snyder, J. K. Yoh (Columbia University); B. C. Brown, P. Limon, T. Yamanouchi (NAL).

(Formerly #70 Phase III)



Herb et al., PRL 39 (1977)

The Last Decade

- Unpolarized beam and target
  - **E906 / SeaQuest:** 120 GeV p on LH_2, LD_2, C, Fe, and W targets.
    - Data from March 2014 – July 2017 : **dbar/ubar ratio, energy loss in cold nuclear matter.**
- Unpolarized beam and polarized target
  - **E1039 / SpinQuest:** 120 GeV p on solid, polarized H and D targets.
    - Detector commissioned with beam summer 2024, planning on running for two years total: **Sea Quark Sivers.**
- Extended Dark and Spin Program
  - Beam Dump search for **Dark Matter** + **deuteron vector and tensor polarization** to measure Transversity and spin-1 linear gluon polarization.

Highlights from SeaQuest

- Nature 2021

The Asymmetry of Antimatter in the Proton

arXiv:2103.04024

- Phys Rev C 2023

Measurement of flavor asymmetry of the light-quark sea in the proton with Drell-Yan dimuon production in $p + p$ and $p + d$ collisions at 120 GeV

arXiv:2212.12160

- Phys Lett B 2024

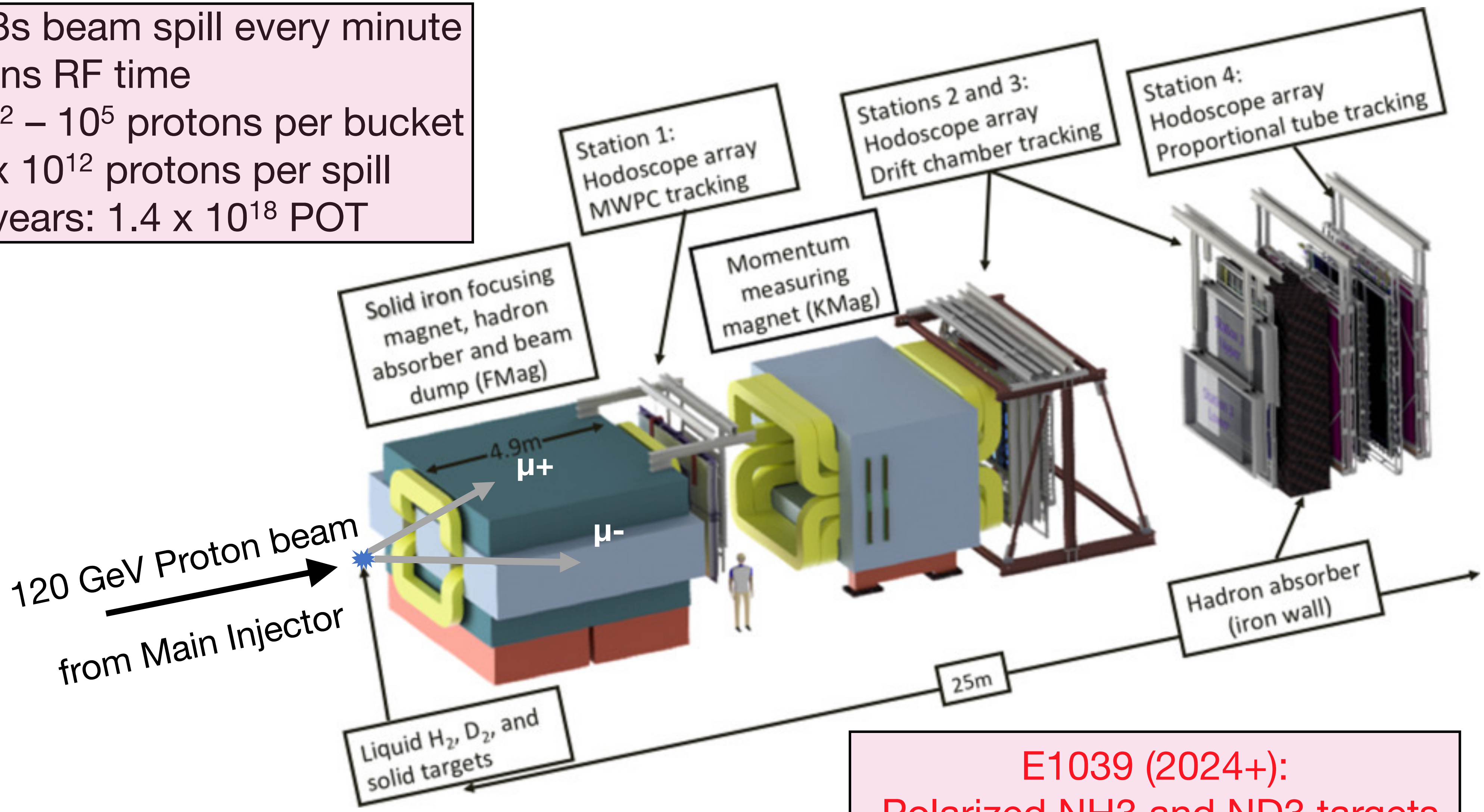
Measurement of J/ψ and $\psi(2S)$ production in $p + p$ and $p + d$ interactions at 120 GeV

C. H. Leung

arXiv:2406.11459

SeaQuest Spectrometer

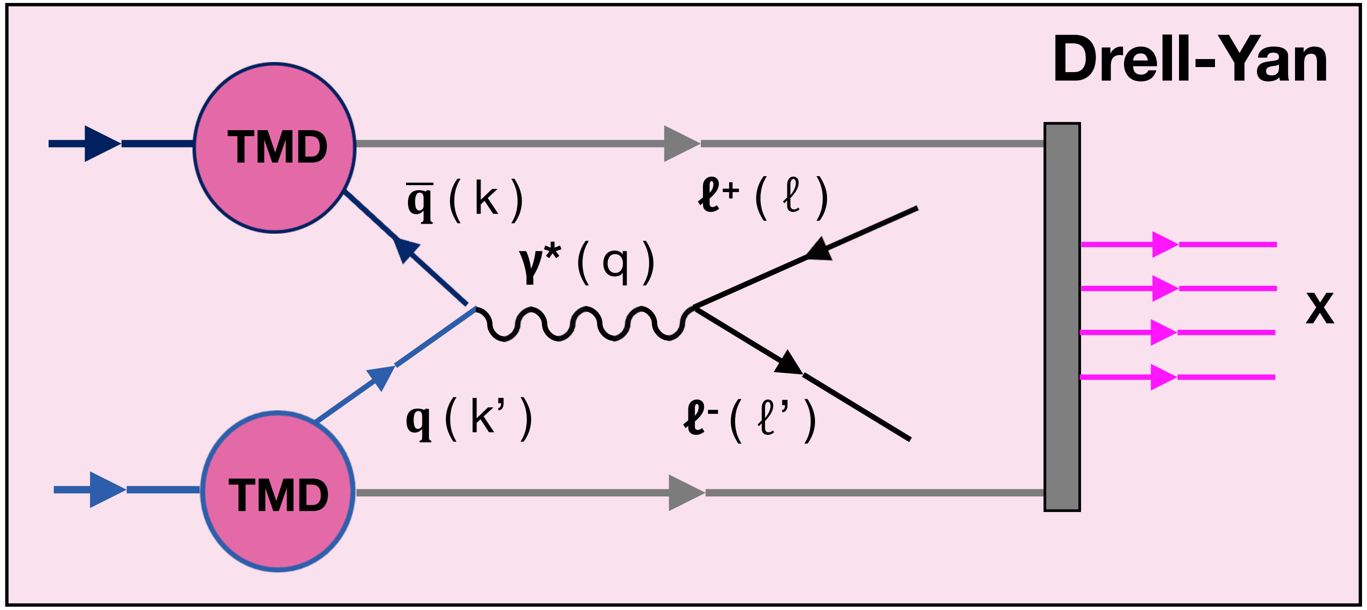
- 4.3s beam spill every minute
- 19ns RF time
- $10^2 – 10^5$ protons per bucket
- 5×10^{12} protons per spill
- 2 years: 1.4×10^{18} POT



E1039 (2024+):
Polarized NH3 and ND3 targets

Drell-Yan

1. Want to understand parton interactions / properties.
2. Connect parton dynamics with hadron properties.



- Clean method to study hadron structure.
- Two (TMD) parton distributions.
- Directly access sea quark distributions.
- Needs intense beam and thick target.

$\frac{\sigma(DY)}{\sigma(nuc)} \approx 10^{-7}$ For Hadron Beam

Unpolarized Drell-Yan at SeaQuest

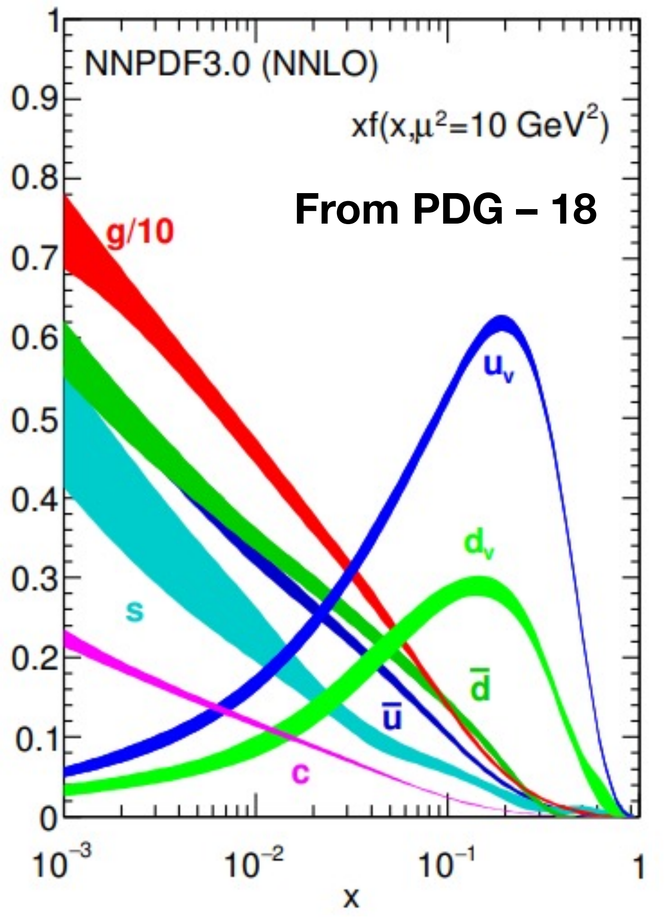
Measure antimatter asymmetry in proton with cross section ratio:

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

"Choose" antiquark in target

$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9\, s\, x_b\, x_t}\sum_q e_q^2[q(x_b)\bar{q}(x_t) + \bar{q}(x_b)q(x_t)]$$

Small for SeaQuest acceptance



Unpolarized PDF

Unpolarized Drell-Yan at SeaQuest

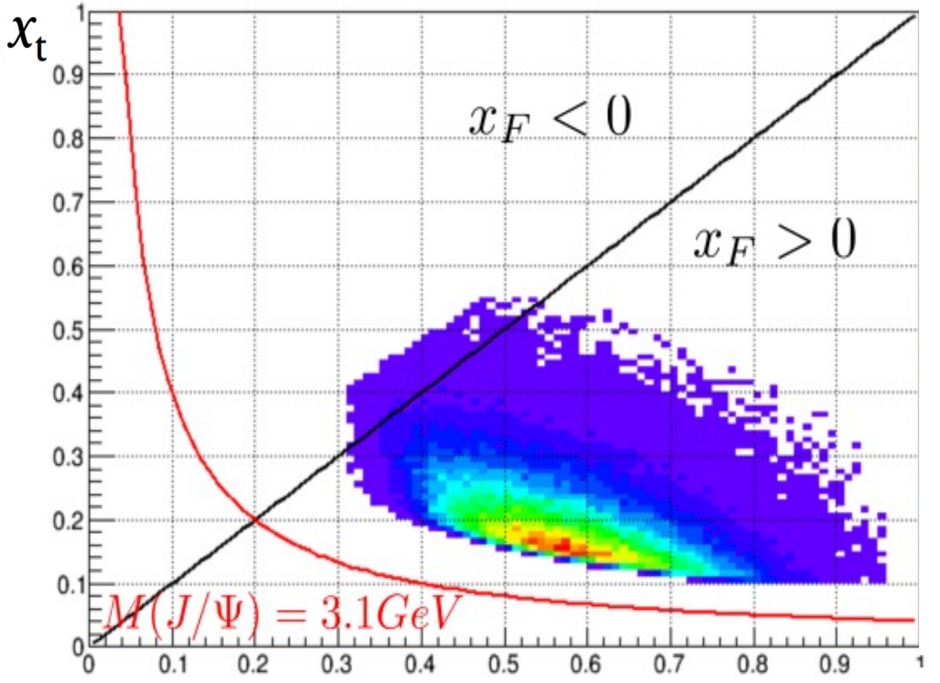
Measure antimatter asymmetry in proton with cross section ratio:

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

"Choose" antiquark in target

$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9\, s\, x_b\, x_t} \sum_q e_q^2 [q(x_b)\underline{\bar{q}(x_t)} + \bar{q}(x_b)q(x_t)]$$

Small for SeaQuest acceptance

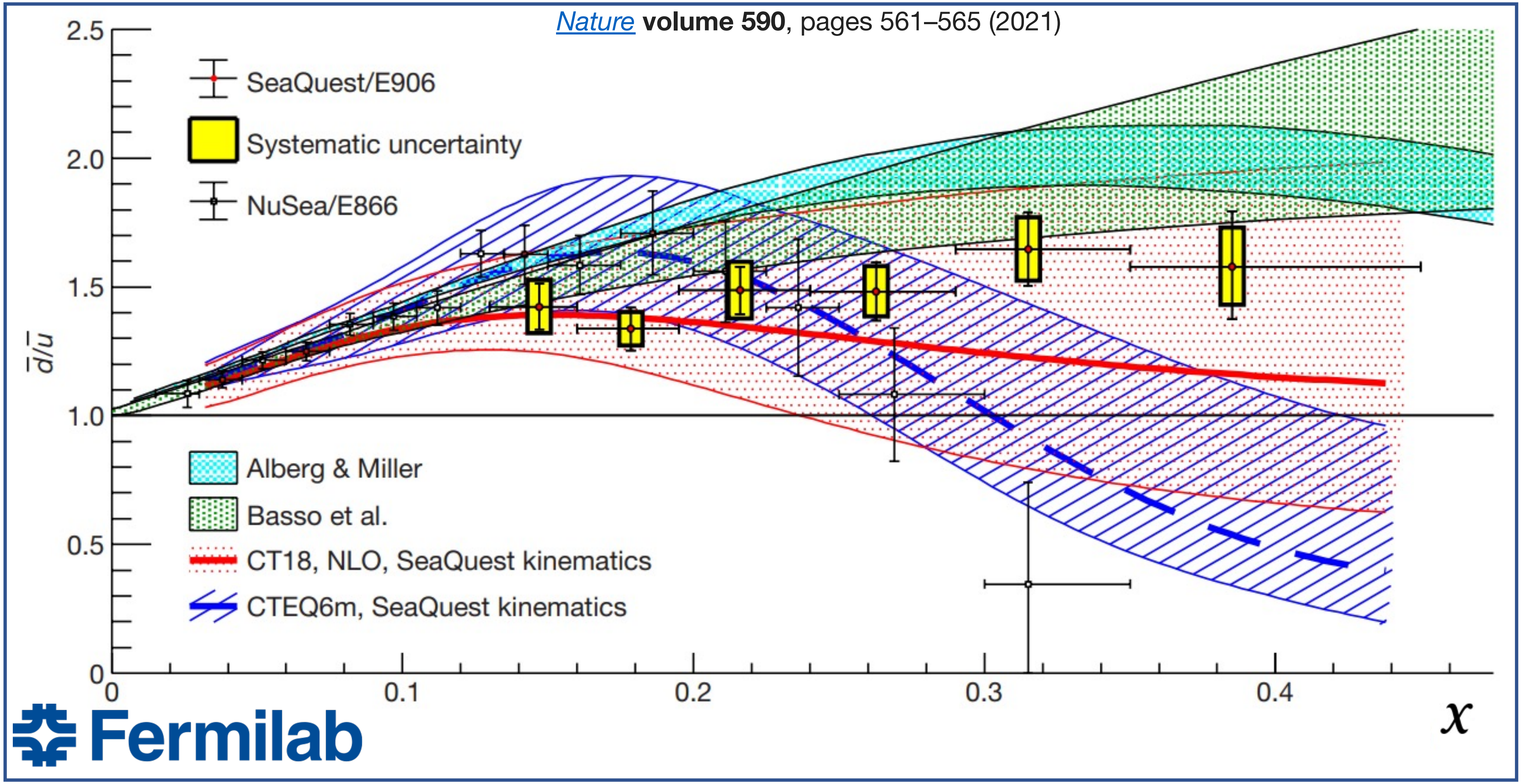


SeaQuest Acceptance

SeaQuest Results

E866: $Q^2 = 54\ GeV^2$

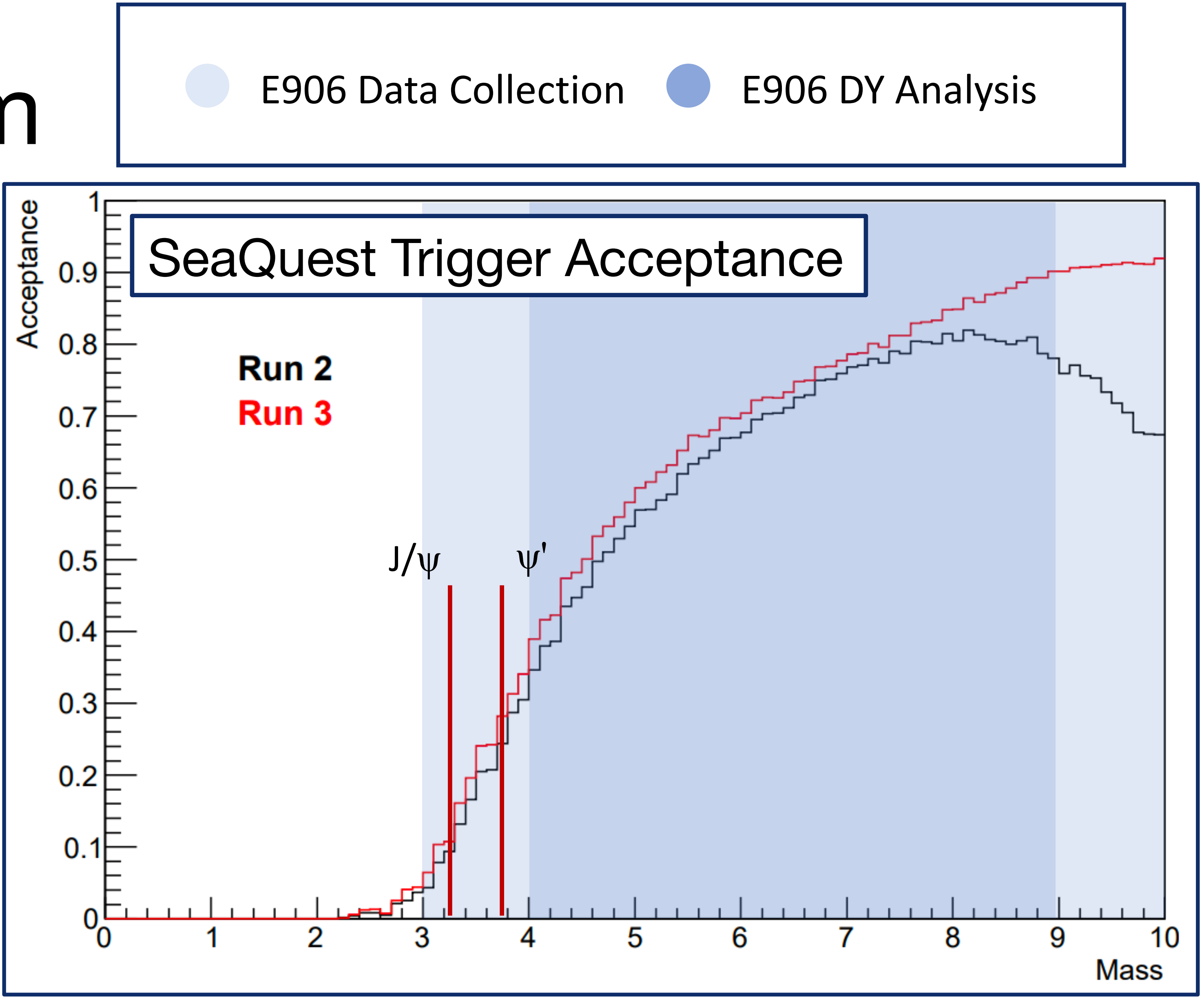
E906: $Q^2 \approx 29\ GeV^2$



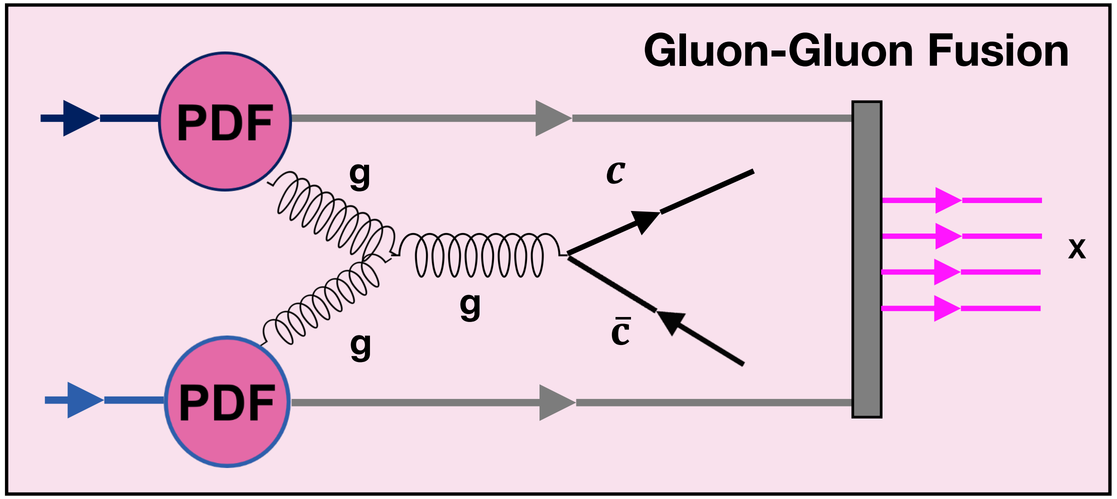
Fermilab

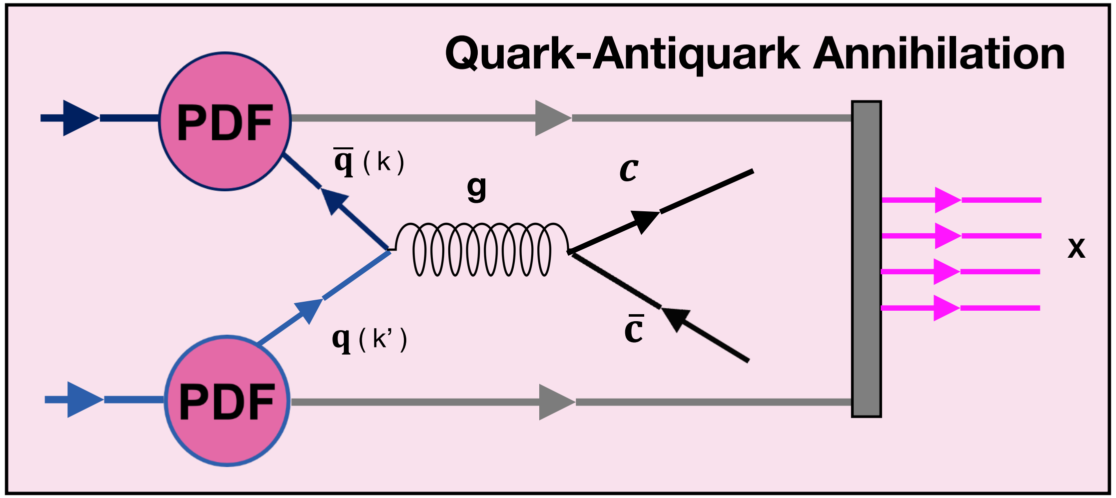
Light Charmonium

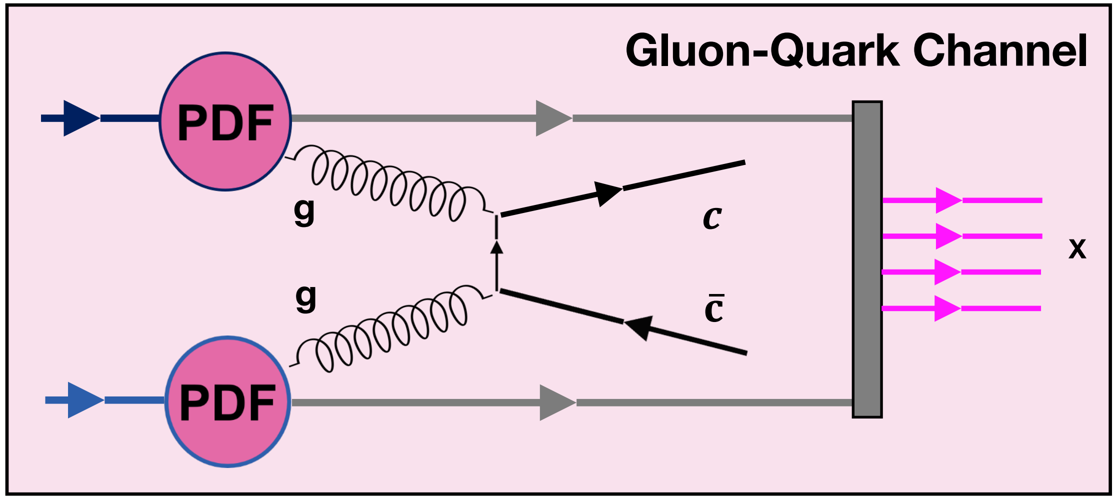
- lightest $c\bar{c}$ bound state and first excited state.
- Resonances near 3.1 GeV and 3.7 GeV.
- Richter and Ting's teams announced discovery in November 1974.
  - 50th anniversary.
- OZI rule limits hadronic decay modes -> 5% go to muons.



Charmonium production at SeaQuest







Why Study Charm at SeaQuest?

New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

Tie-Jiun Hou,[1,†] Jun Gao,[2] T. J. Hobbs,[3,4] Keping Xie,[3,5] Sayipjamal Dulat,[6,‡] Marco Guzzi,[7] Joey Huston,[8] Pavel Nadolsky,[3,§] Jon Pumplin,[8,*] Carl Schmidt,[8] Ibrahim Sitiwaldi,[6] Daniel Stump,[8] and C.-P. Yuan[8,‖]

If quark antiquark annihilation is big subprocess, Charmonium cross section ratio pd/pp sensitive to dbar / ubar in the proton -> Cross check of the DY results.

J/ψ production as a probe of charge symmetry violations and nuclear corrections in parton distributions

G. Piller[1], A. W. Thomas[2]

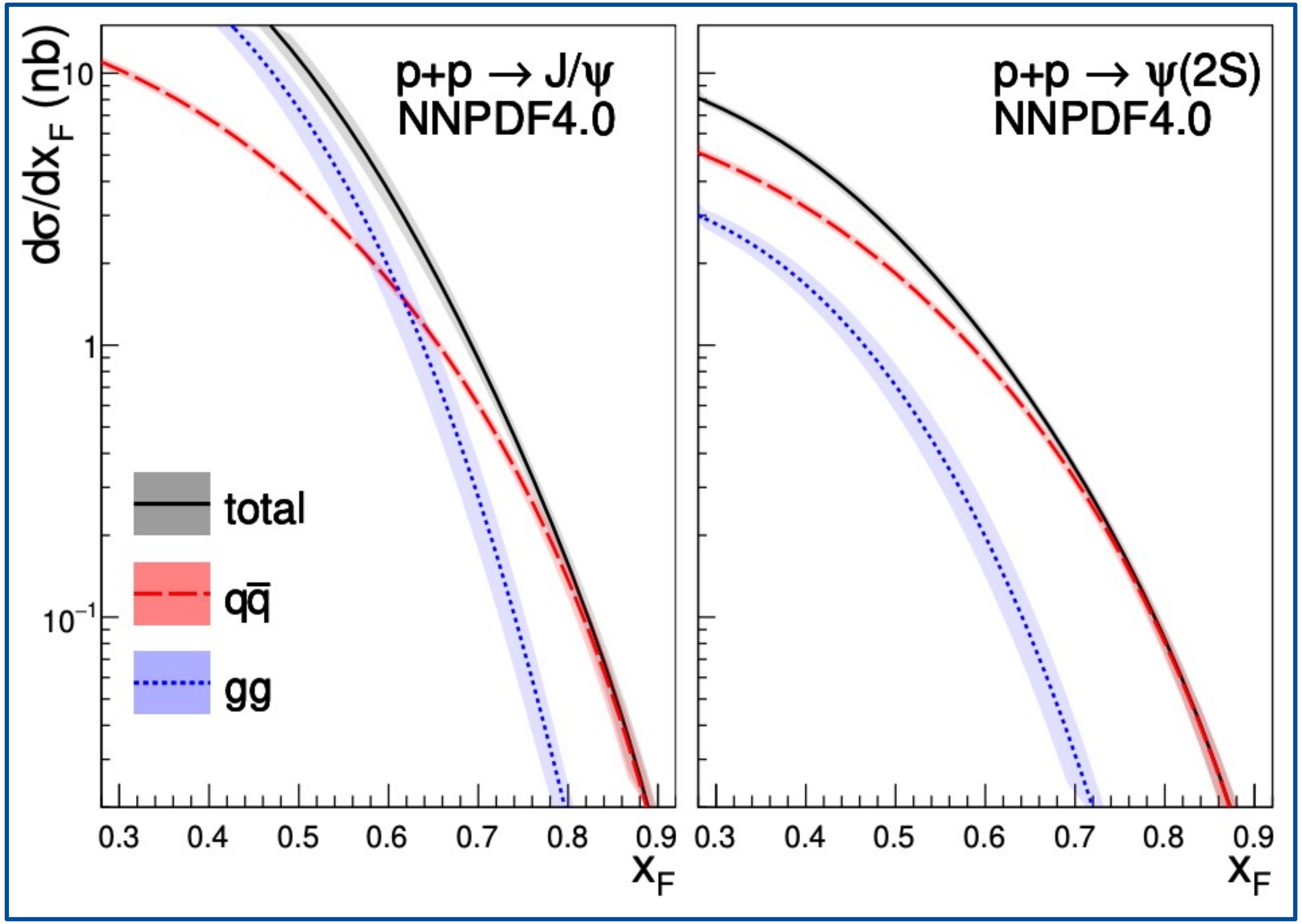
If gluon gluon is big subprocess, Charmonium cross section ratio pd/pp could probe ratio of gluons in deuteron / proton -> partonic level test of charge symmetry.

Charmonium subprocesses at SeaQuest

- Expected subprocess contributions calculated in NRQCD as a function of xF.

  Phys. Rev. D **107**, 056008
  Chang et al.

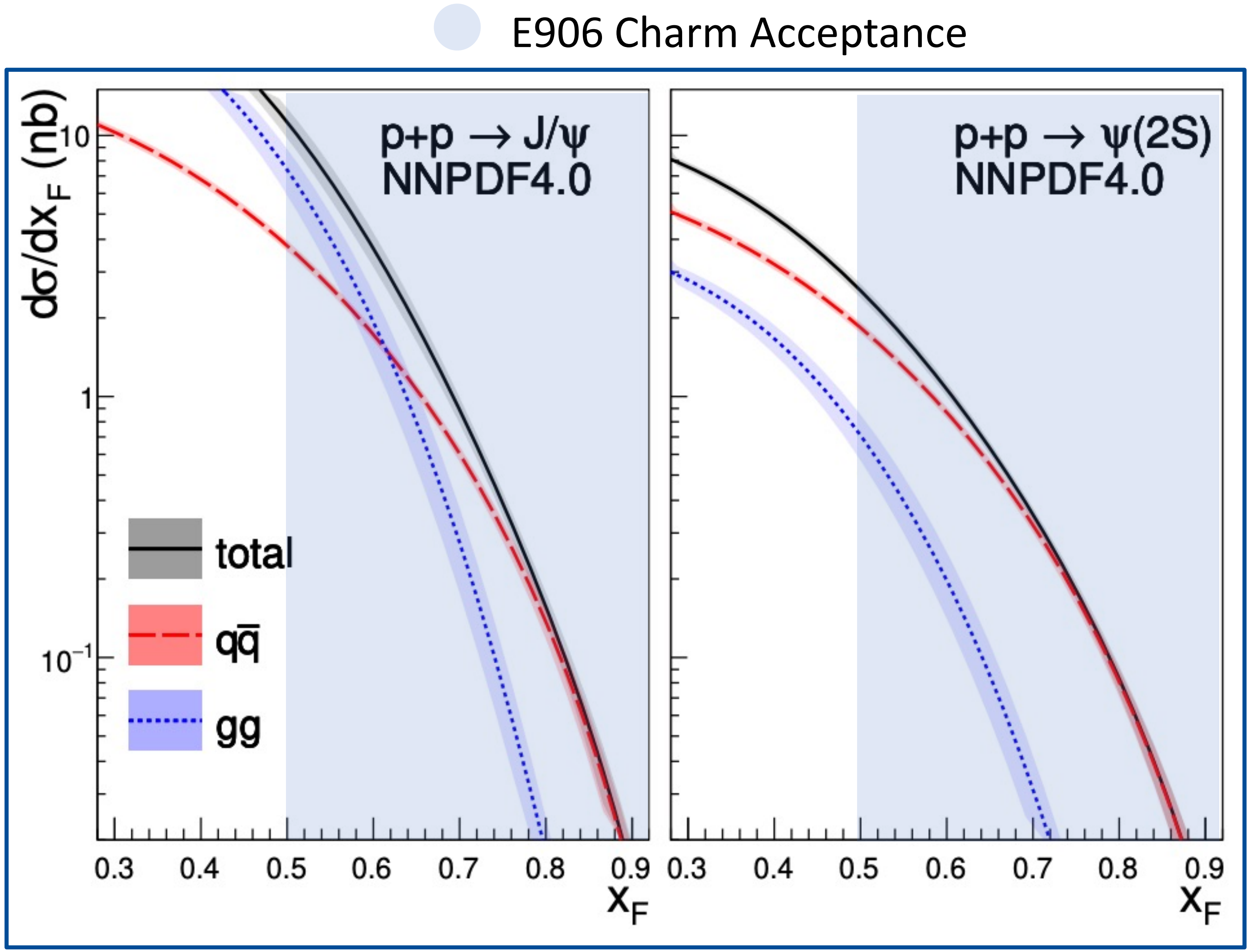
- SeaQuest covers a broad range of 0.5 < xF < 0.9.



Charmonium subprocesses at SeaQuest

- Gluon fusion becomes subdominant to quark annihilation for J/Psi near 0.7 xF.
- Quark annihilation dominates Psi(2S) particularly at high xF.
- Similar results have been seen in pion-induced charm production at Fermilab in 90’s.

Phys. Rev. D **44**, 1909



Most recent publication

Measurement of J/Ψ and $\Psi(2S)$ production in p + p and p + d interactions at 120GeV

- Differential cross sections for J/Psi and Psi(2S) production for p + p and p + d at 120 GeV in xF and pT.
- Cross section ratios for production on p / production on d.
- Comparison with NRQCD predictions.

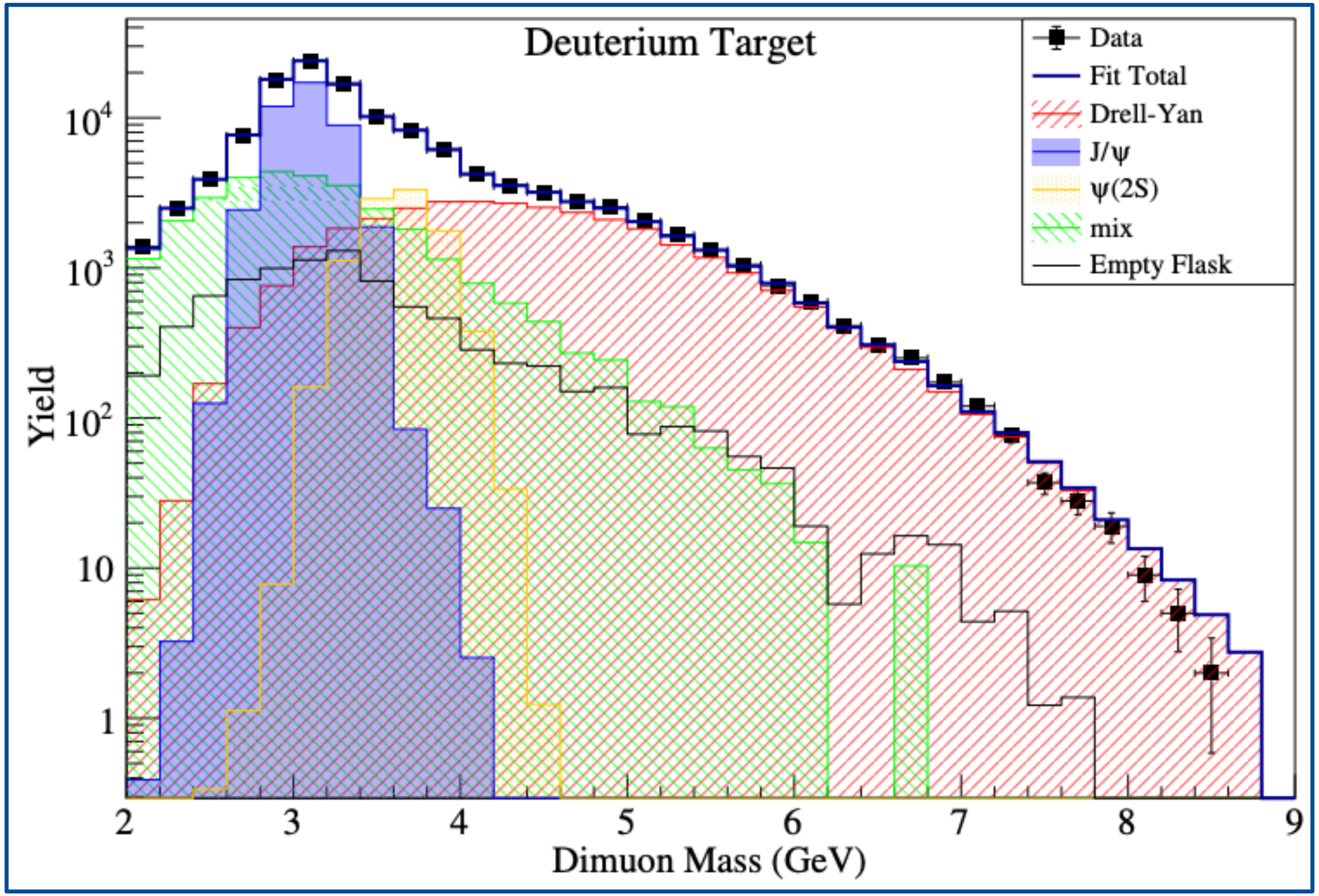
Need to extract charm yields!

$$d\sigma = \frac{dY}{B \cdot \mathrm{Acc} \cdot \mathrm{Eff} \cdot \mathrm{Lum}}$$

Experimental / Detector dependent variables.

Extracting Charm Yields

- Use ROOT TFractionFitter to fit MC components to data.
- Accounts for finite MC uncertainty.
- Fix normalization by “empty flask” or “no data” target position.
- Use yields to compute the differential cross sections and cross section ratios.



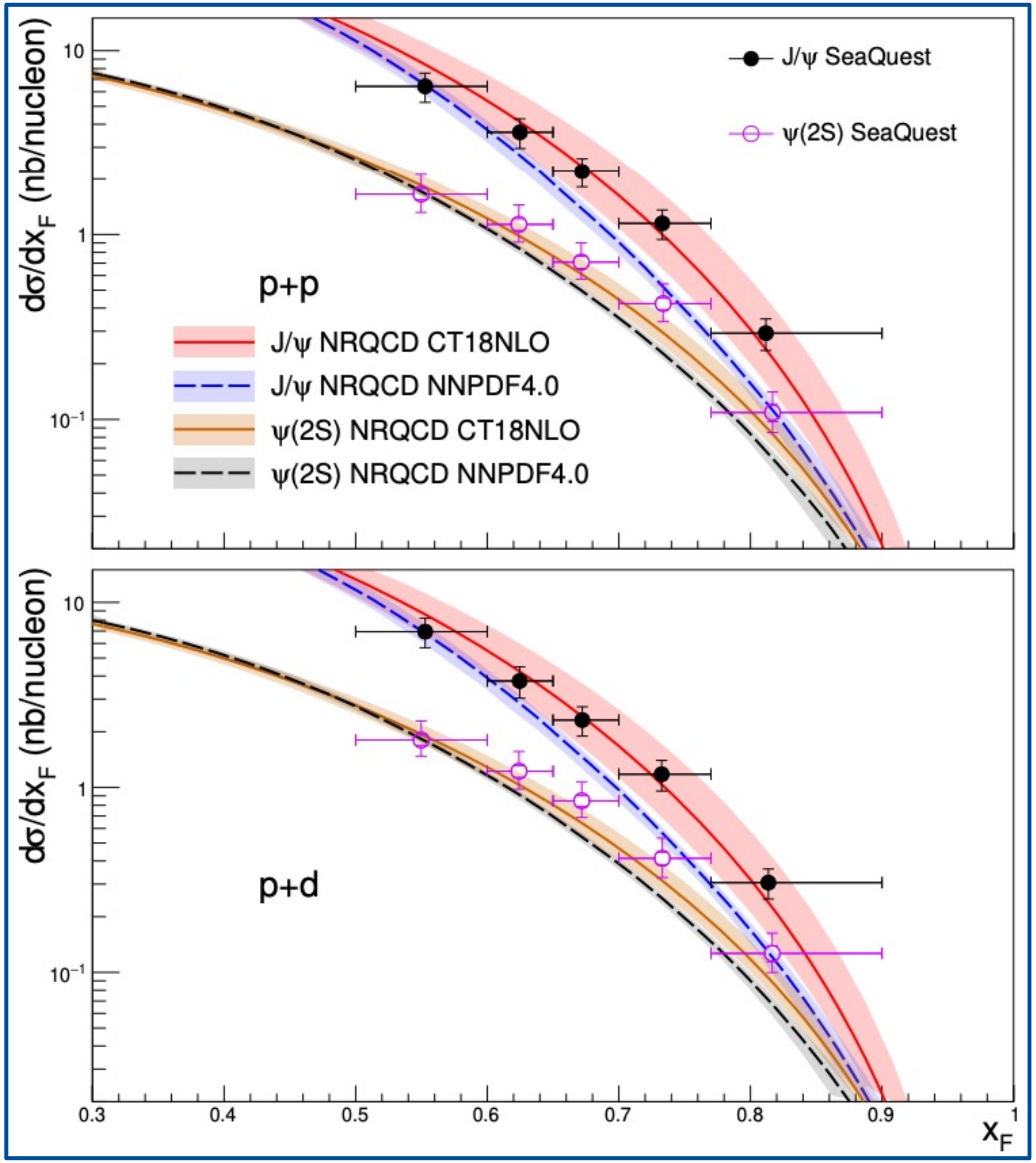
dσ in xF

- Theory curves from NRQCD calculation using long-distance matrix elements from global DY fits.

Phys. Rev. D **107**, 056008

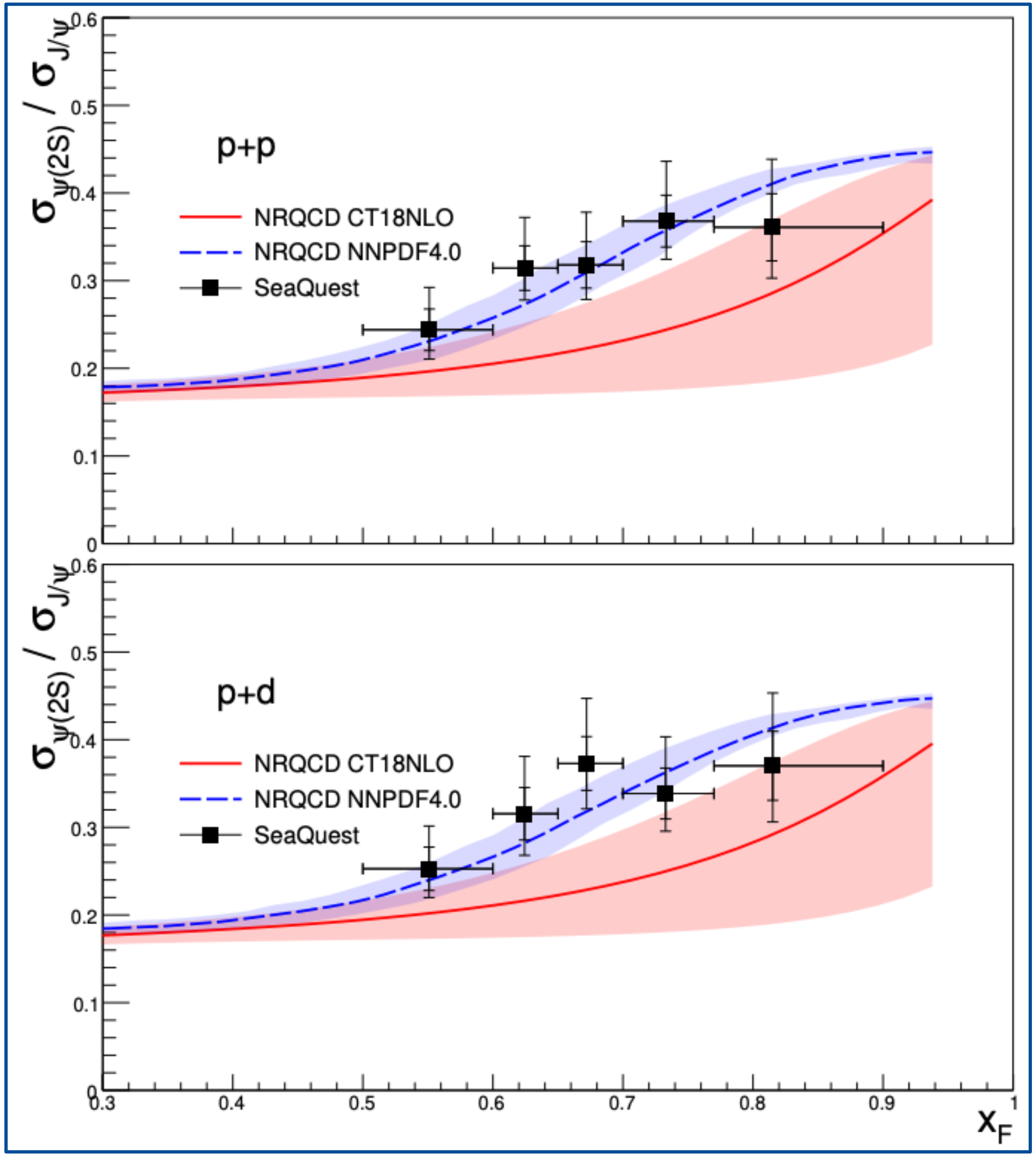
Chin. J. Phys. **73**

- Predictions show both CT18 and NNPDF4.0 PDFs, while error band is 68% confidence interval.
- Horizontal errors show bin widths while the markers are at bin averages.
- Good agreement with NRQCD predictions.
- Also good agreement with color evaporation model calculations except at high xF.



Psi(2S) / Psi in xF

- Cross section ratio increases with xF
- Suggests a broader xF distribution for the Psi(2S) than the Psi.
- NRQCD calculations describe this behavior well.
- Valence quarks in proton have much broader x distribution than gluons.
- Hence a broader xF distribution for Psi(2S) comes from the increasing importance of the qqbar subprocess.
- Color evaporation model suggests xF distribution should be the same for both, which does not qualitatively agree.



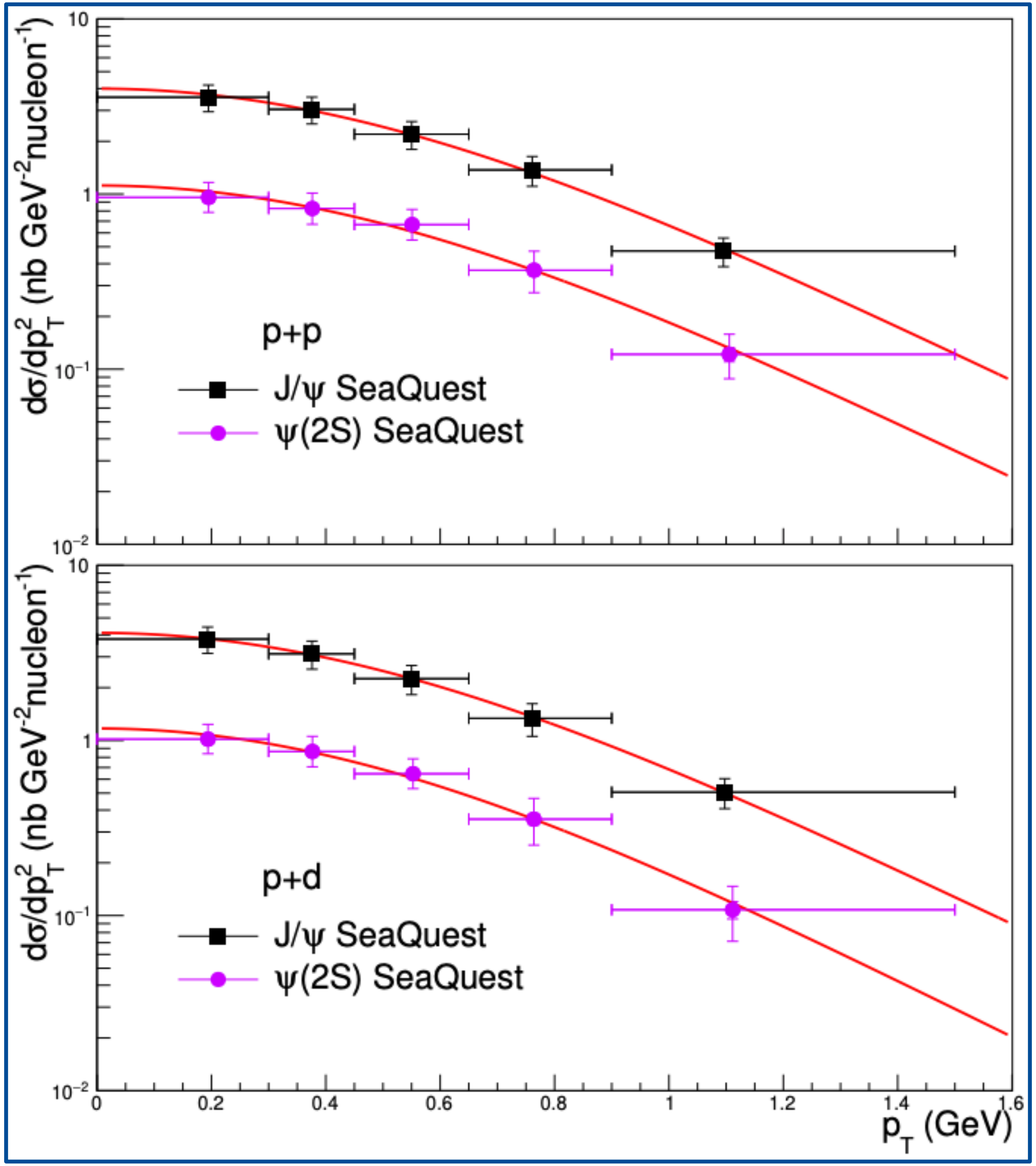
dσ in pT²

- Cross sections in pT^2 are integrated over $0.5 < xF < 0.9$.
- Curves are given by phenomenological Kaplan form.

$$d\sigma/dp_T^2 = c(1 + p_T^2/p_0^2)^{-6}$$

- P. Sun, C.P. Yuan, and F. Yuan have suggested a method to compute the pT distribution in NRQCD with soft gluon resummation and it would be interesting to compare the results.

Phys. Rev. D **88**, 054008.



Average pT^2

- Extracted <P_T^2> compared with results from other experiments across a range of √S
- Increasing logarithmically against √S

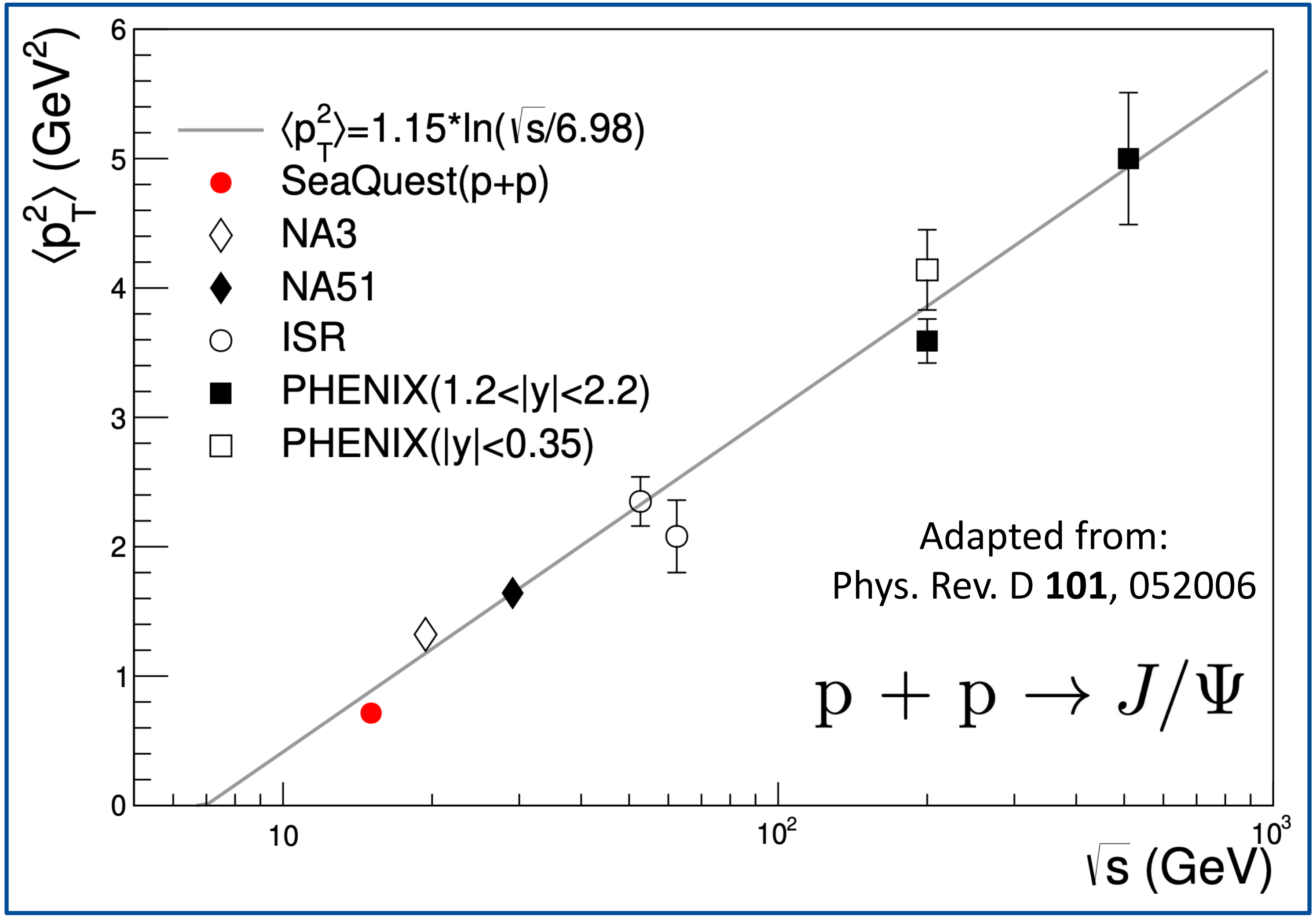
$$\left\langle p_T^2 \right\rangle = a \ln\left(\sqrt{s}/b \right)$$

$$a = (1.150 \pm 0.043)\,\mathrm{GeV}^2$$

$$b = (6.98 \pm 0.37)\,\mathrm{GeV}$$

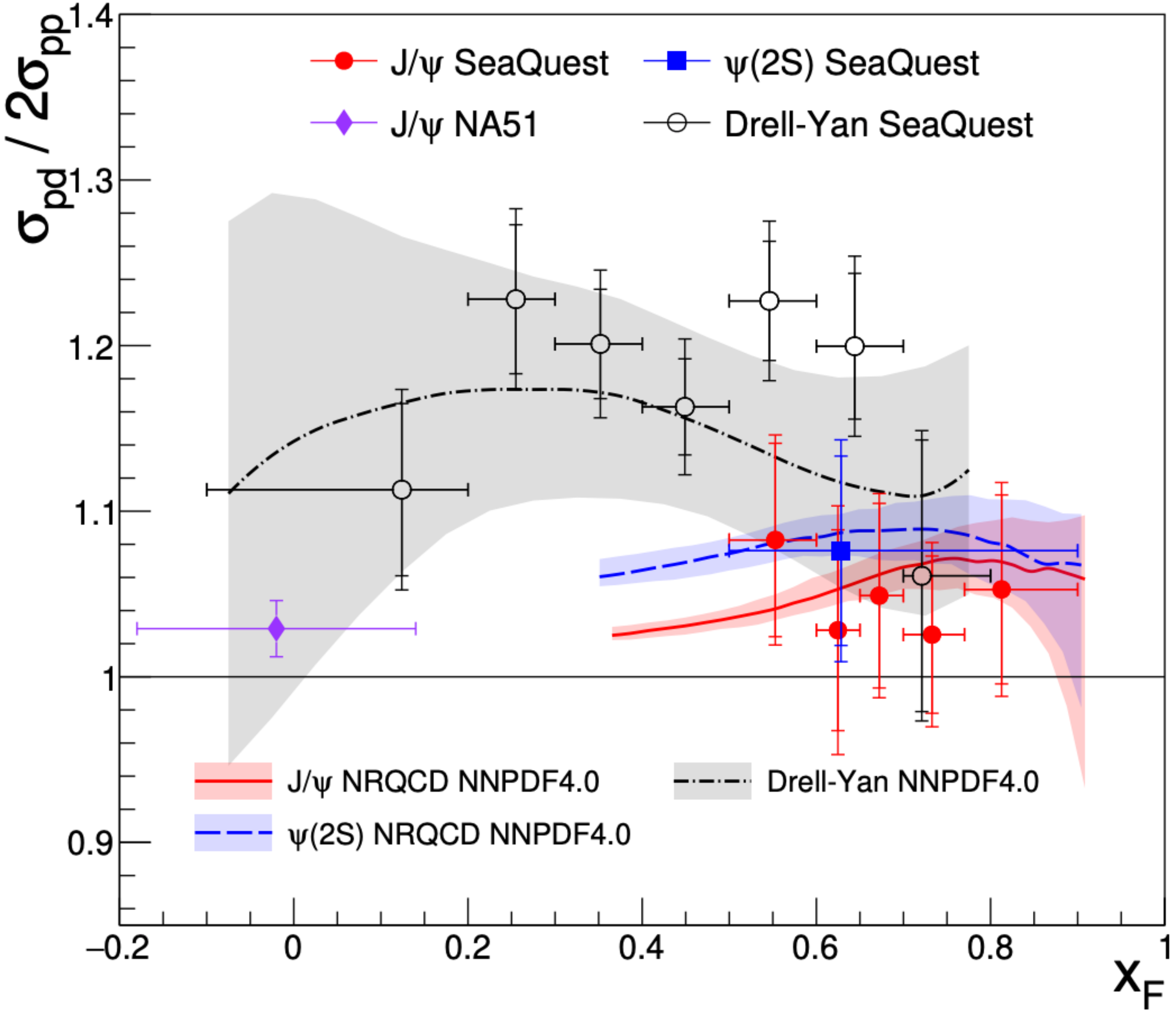
- Variation from rapidity range is expected and previously observed in fixed target experiments at Fermilab in 1980’s

Phys. Rev. Lett. **58**, 2523



Cross Section Ratios

- Inner error bars are statistical, outer error bars are total.
- Also included are the ratios from SeaQuest DY and NA51.
- NA51 and SeaQuest charmonium data show dbar/ubar > 1 at 2sigma significance.
- Difference from DY results reflects the different production mechanisms.
- Strong interaction isn't sensitive to charge, so the uubar and ddbar weighting is different for Charm.



Summary of recent published results

- The differential cross section ratios for light charmonia production in xF and pT have been reported.
- The cross section ratios for light charmonia production on deuterium and hydrogen targets have been presented.
- These results are compared to predictions from NRQCD with CT18 and NNPDF4.0 PDFs.
- Quark-Antiquark annihilation is a dominant process for Psi(2S) production at SeaQuest Kinematics.
- Data from charm production in this kinematic regime provides information on both the light antiquark and gluon content of p and n.

Why (else) Study Charm at SeaQuest?

THE INTRINSIC CHARM OF THE PROTON

S.J. BRODSKY [1] and P. HOYER, C. PETERSON and N. SAKAI [2]

Stanford Linear Accelerator Center, Stanford, California 94305, USA

NORDITA, Copenhagen, Denmark

Received 22 April 1980

High Feynman-x Data needed – part of SeaQuest's design

Limits on Intrinsic Charm Production from the SeaQuest Experiment

R. Vogt

Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA and Department of Physics and Astronomy, University of California, Davis, CA 95616, USA

Lower incident energy than previous experiments

Ideal kinematics to test Improved Color Evaporation Model

Nuclear Suppresion at SeaQuest

- Report the J/ ψ production cross section ratio on nuclear targets vs. liquid deuterium target in pT and xF to compare with the 2021 Vogt predictions for nuclear suppression factor:

$$R_{pA}^{D} = \frac{2}{A}\frac{\sigma_{pA}}{\sigma_{pd}}$$

- Reweighting our Monte Carlo (not discussed in this talk).
- Start by determining the J/ ψ yields from each target in each kinematic bin.
- Correct the yields for experimental counting inefficiencies.
    - Geometric acceptance
    - Tracking efficiency

Cross Section Ratios

$$R^D_{pA} = \frac{2}{A}\frac{\sigma_{pA}}{\sigma_{pd}}$$

Due to contamination in the Deuterium target, a term proportional to the hydrogen cross section is needed.

$$\sigma_{pd} = \frac{Y_D M_D}{T^D_D P_D A_D N_D \varepsilon_D} - \sigma_{pp}\frac{T^D_H P_D A_D N_D \varepsilon_D}{M_H}\frac{M_D}{T^D_D P_D A_D N_D \varepsilon_D}$$

Yield **Acceptance x Tracking**

$$R^D_{pA} = \frac{2}{M_D}\frac{\langle T^D_D\rangle}{T^A_A}\left[\frac{Y_A/(P_A A_A \varepsilon_A)}{Y_D/(P_D A_D \varepsilon_D) - \frac{\langle T^D_H\rangle}{T^H_H} Y_H/(P_H A_H \varepsilon_H)}\right]$$

Areal Density of hydrogen in deuterium target

Correcting Charm Yields

Need to correct the massfit yields because there are known inefficiencies in dimuon counting.

1. Correct for Geometric Acceptance.
   - Differences in target acceptances show up in CSR.
   - Clean / 4pi MC

2. Correct for kTracker "Efficiency"
   - kTracker's ability to identify dimuons has a strong dependence on the chamber occupancy.
   - Messy / Clean MC

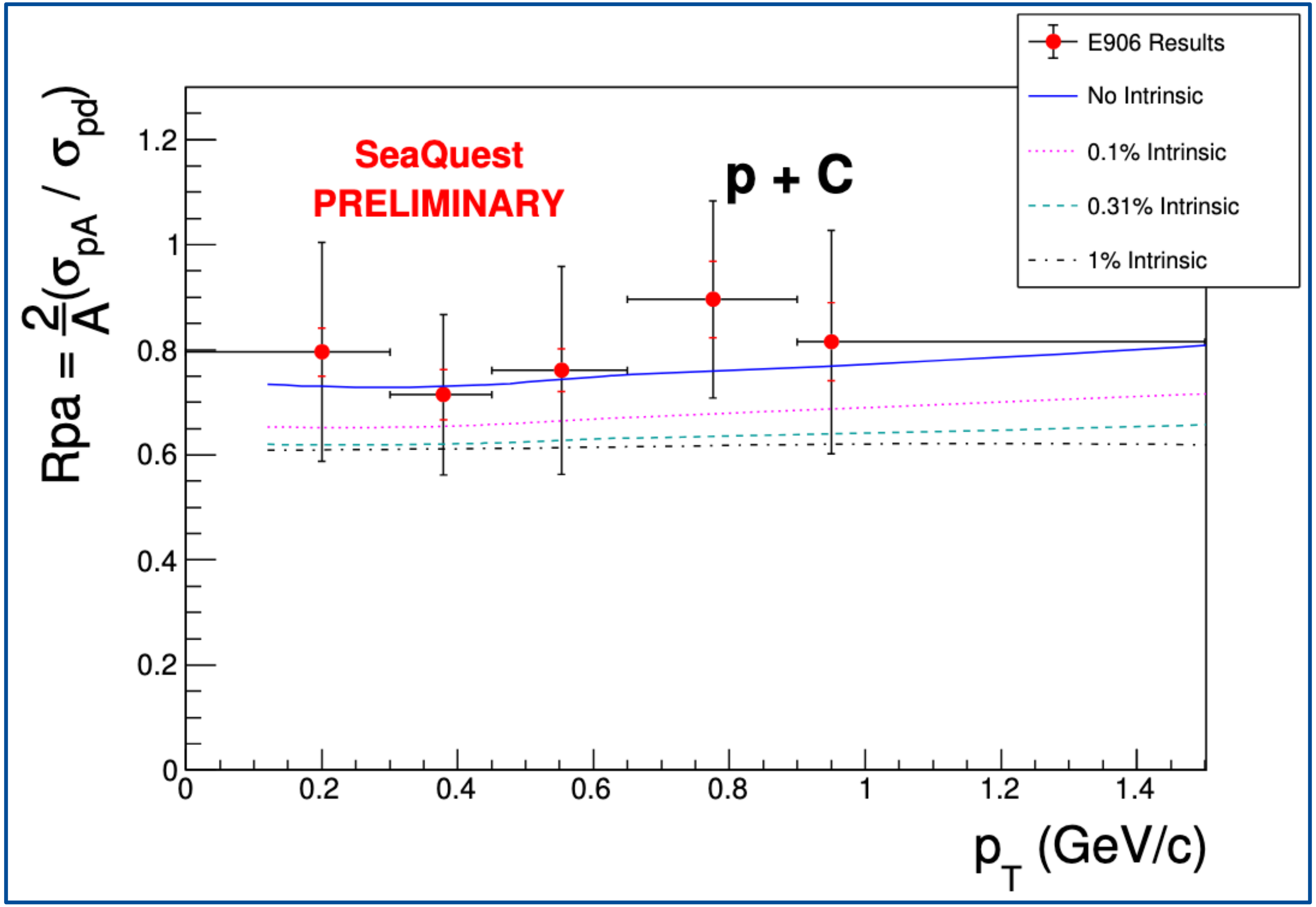
Systematic Uncertainty

- Consider 4 primary sources of systematic uncertainty in the analysis:
  1. pT Reweighting for messy MC
  2. Tracking efficiency parameters
  3. Uncertainty in Acceptance from limited nuclear MC samples.
  4. Choice of mixed background
- Central values reported utilize the reweighted DY and Charm MC, the central fit value for the tracking efficiency fit, and the mixed background produced by Jason Dove used in the 2023 SeaQuest paper.
- NMSU mixed background used to estimate the uncertainty introduced by the background mixing method.
- Dominant uncertainty from acceptance, particularly in pT, which had been neglected in previous studies of the nuclear targets.
  - Expect the systematics to be comparable to statistics for final results.

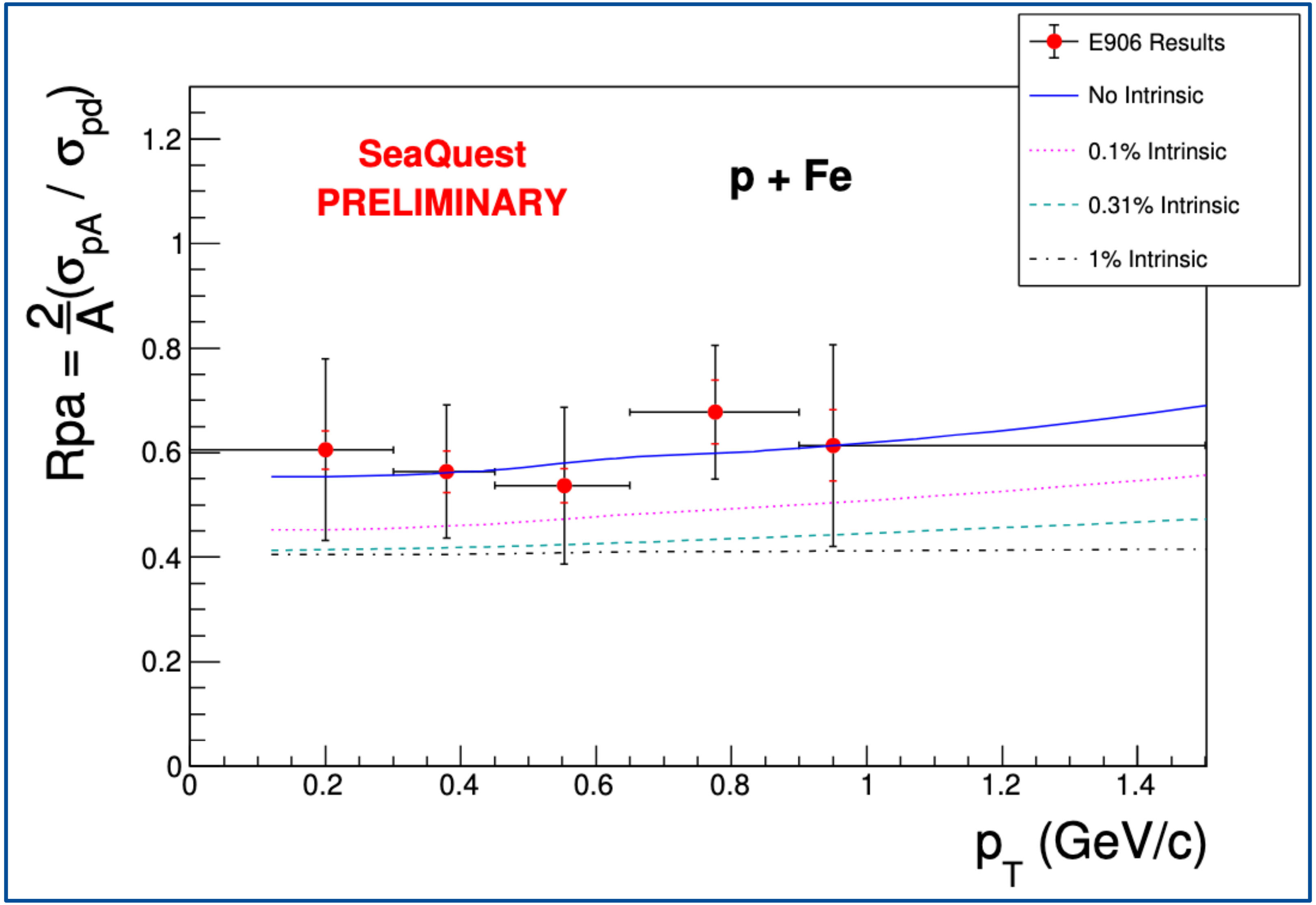
Nuclear effects considered by Vogt

- Considered three effects from cold nuclear media
  1. Nuclear modification of the parton distributions, provided by the EPPS16 nPDF sets.
  2. Absorption by cold nuclear matter.
  3. Enhanced kT broadening in nuclear matter compared to free nucleons.
- Then, added the possibility of hitting “intrinsic charm” in the proton in $|uudc\overline{c}>$ Fock state.
- In shown predictions, all nuclear effects are included and only the intrinsic charm probability changes.

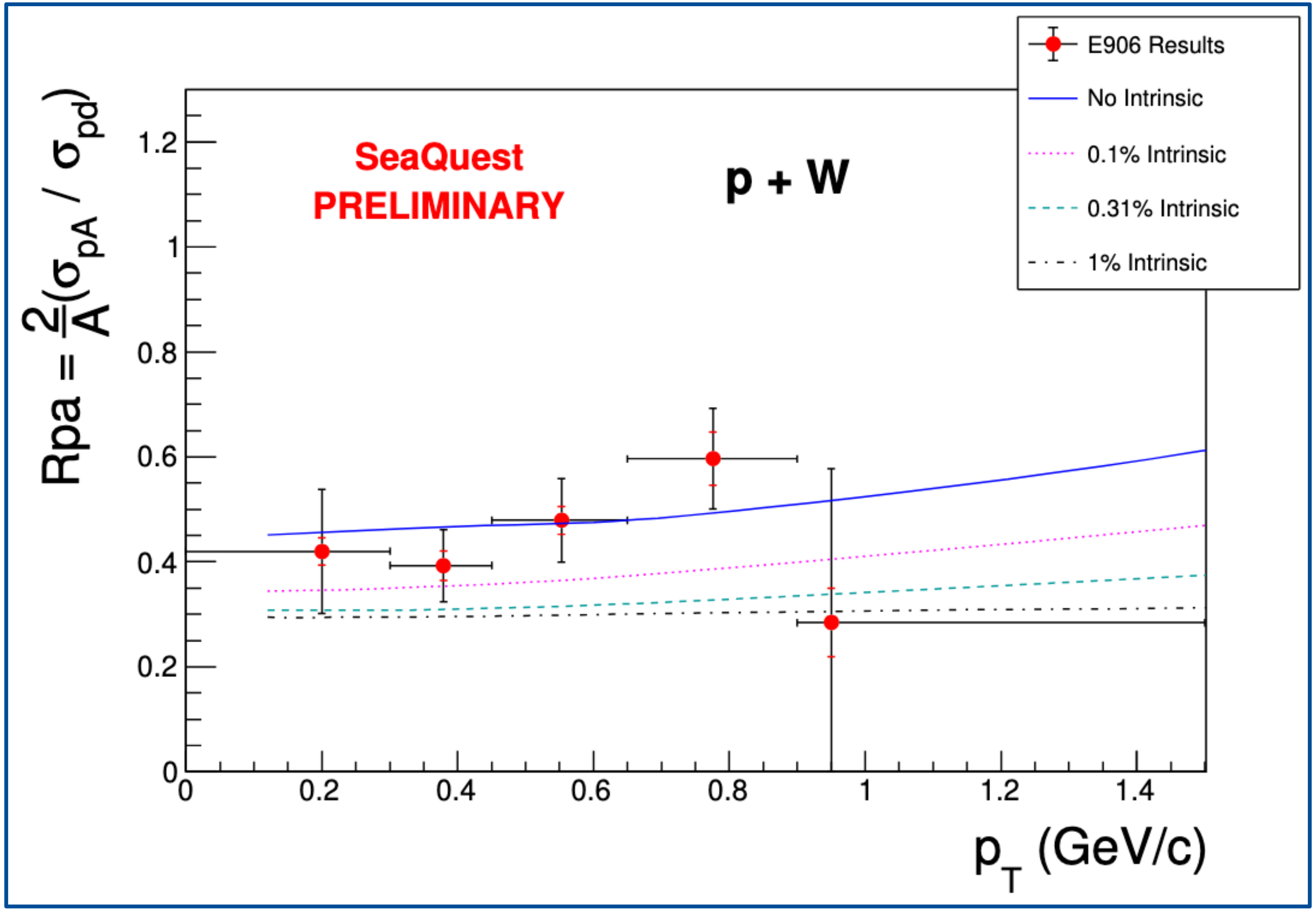
J/ψ Results compared with theory



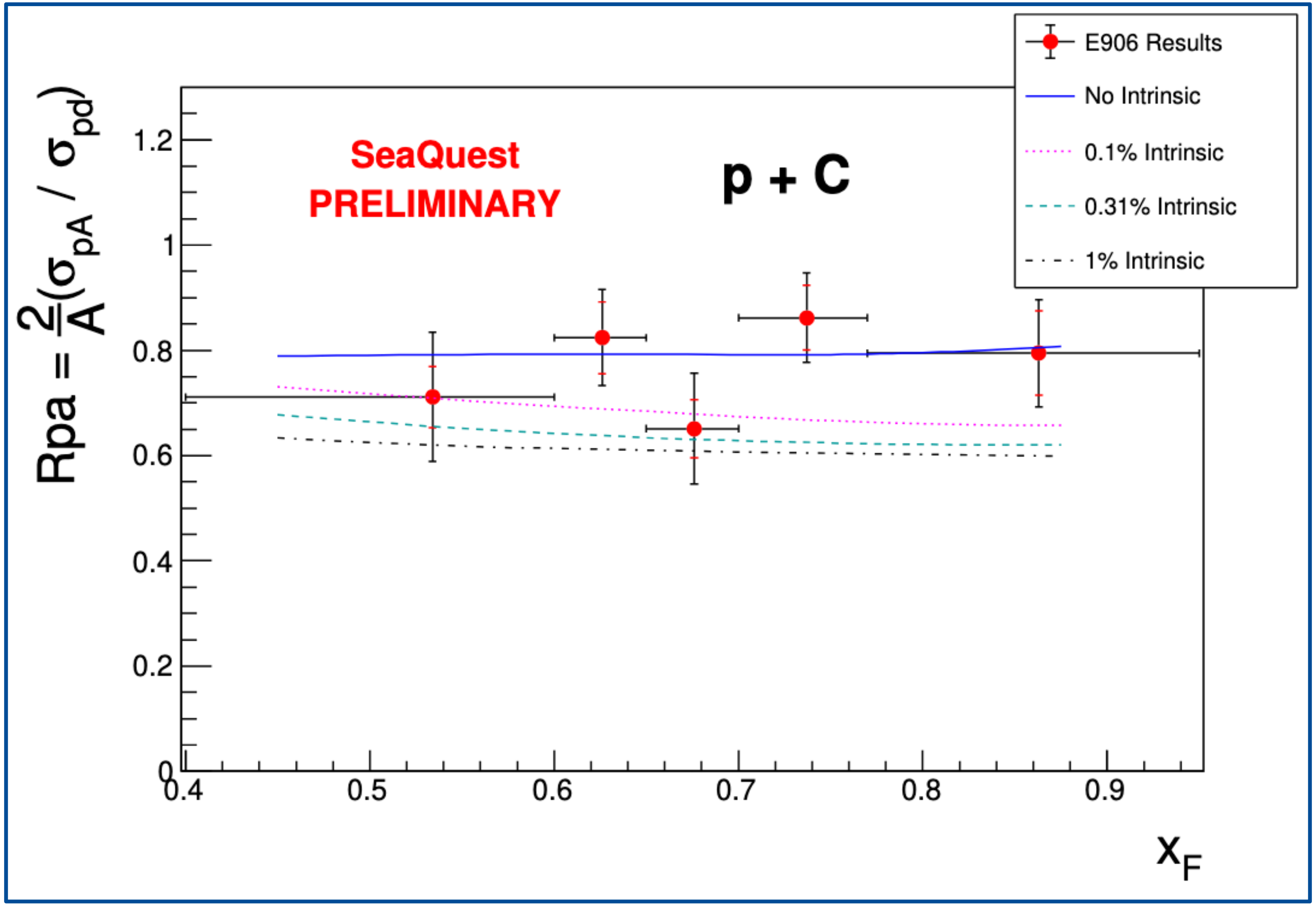
J/ψ Results compared with theory



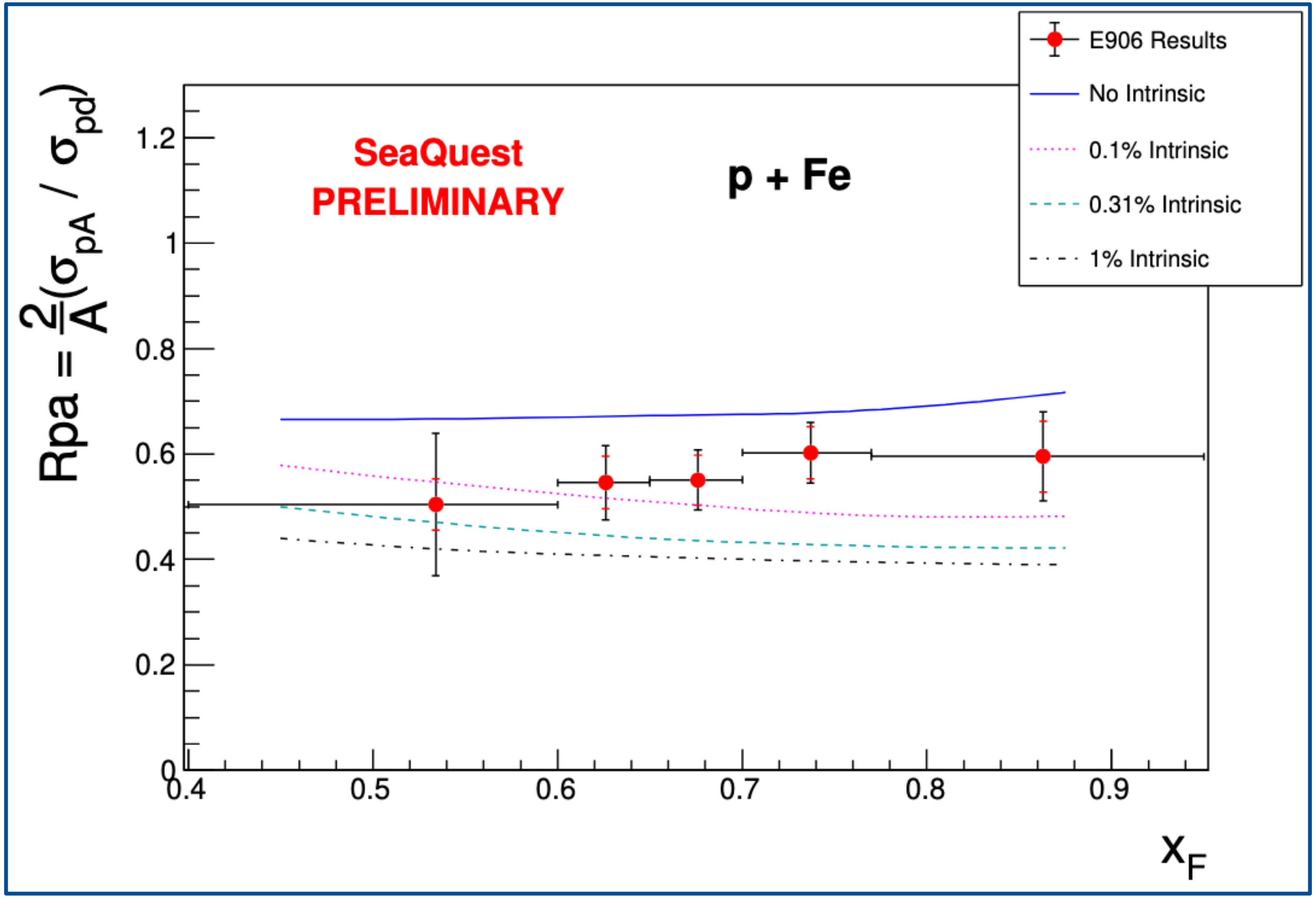
J/ψ Results compared with theory



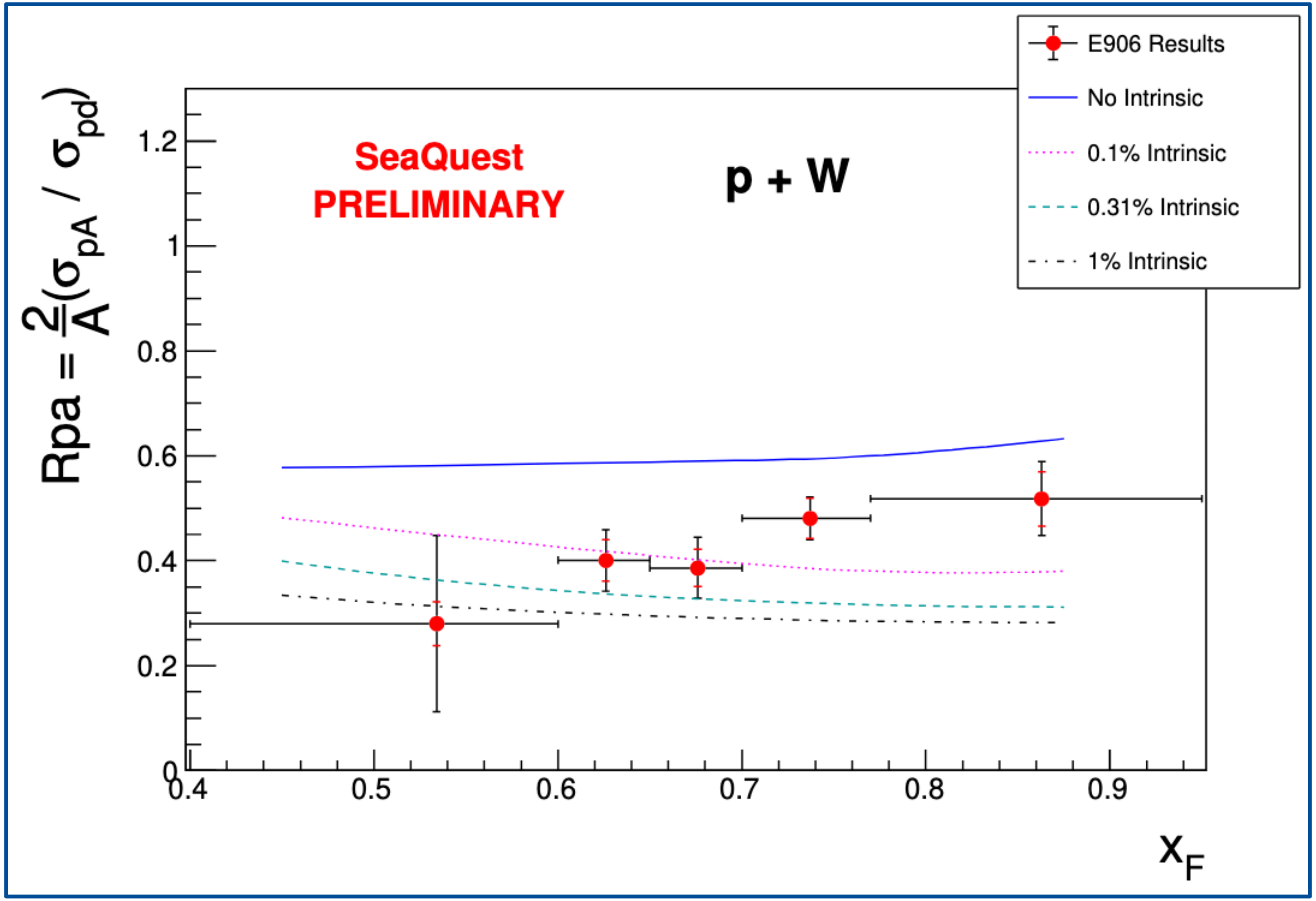
J/ψ Results compared with theory



J/ψ Results compared with theory



J/ψ Results compared with theory



Rpa Conclusions

- As expected, the magnitude of the suppression grows with A.
- In pT, data is consistent with enhancement to the CSR at higher pT.
- The central values are more consistent with either a smaller probability of intrinsic charm or smaller nuclear absorption cross section.
- In the xF analysis, the carbon data is consistent with being flat.
- For the iron and tungsten targets, there is an apparent enhancement in the CSR at higher xF, which does not agree with the predictions.
- The magnitude of suppression is also larger than expected for these targets.
- Qualitatively, the slope is positive in both the pT and xF analysis which is consistent with the shape of the “no intrinsic” predictions.

J/ψ TSSA at SpinQuest

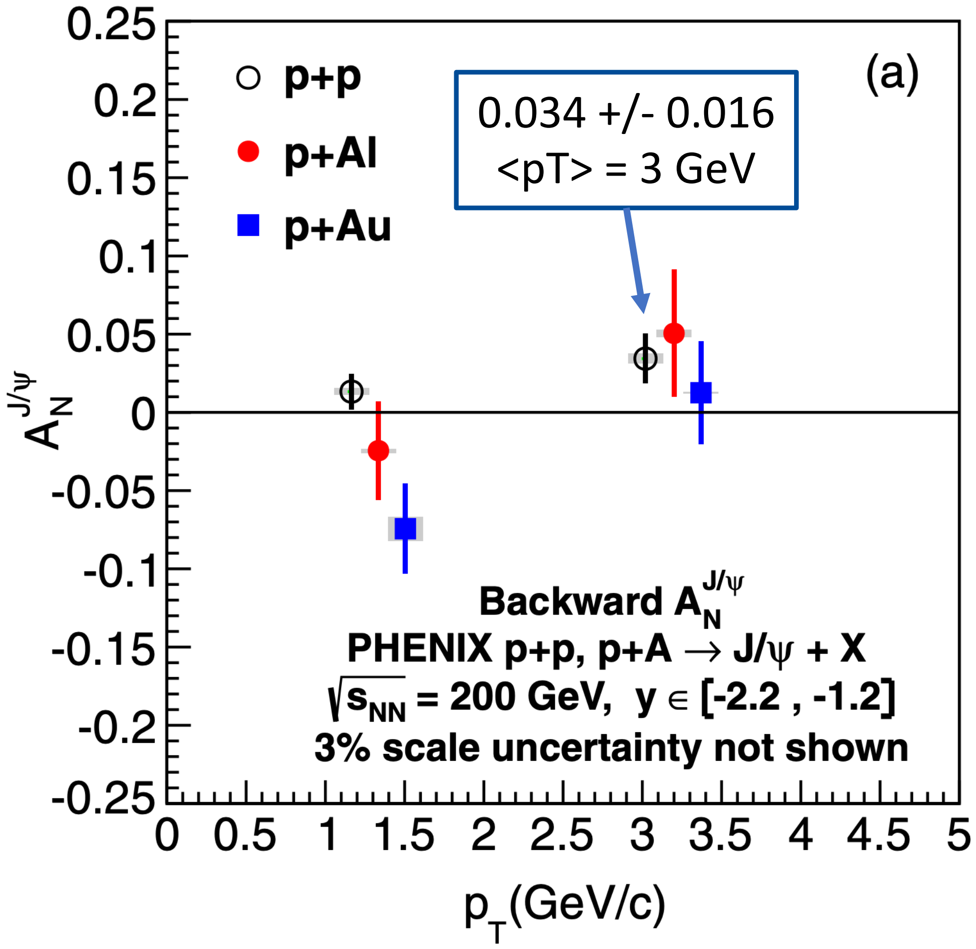
- Day 1 physics program at SpinQuest will focus on charm TSSA as we can gather data much faster than DY.
- Similar data has been measured at $\sqrt{S}$ = 200 GeV at PHENIX.
- Current plan for SPD at NICA to measure at $\sqrt{S}$ = 24 GeV.

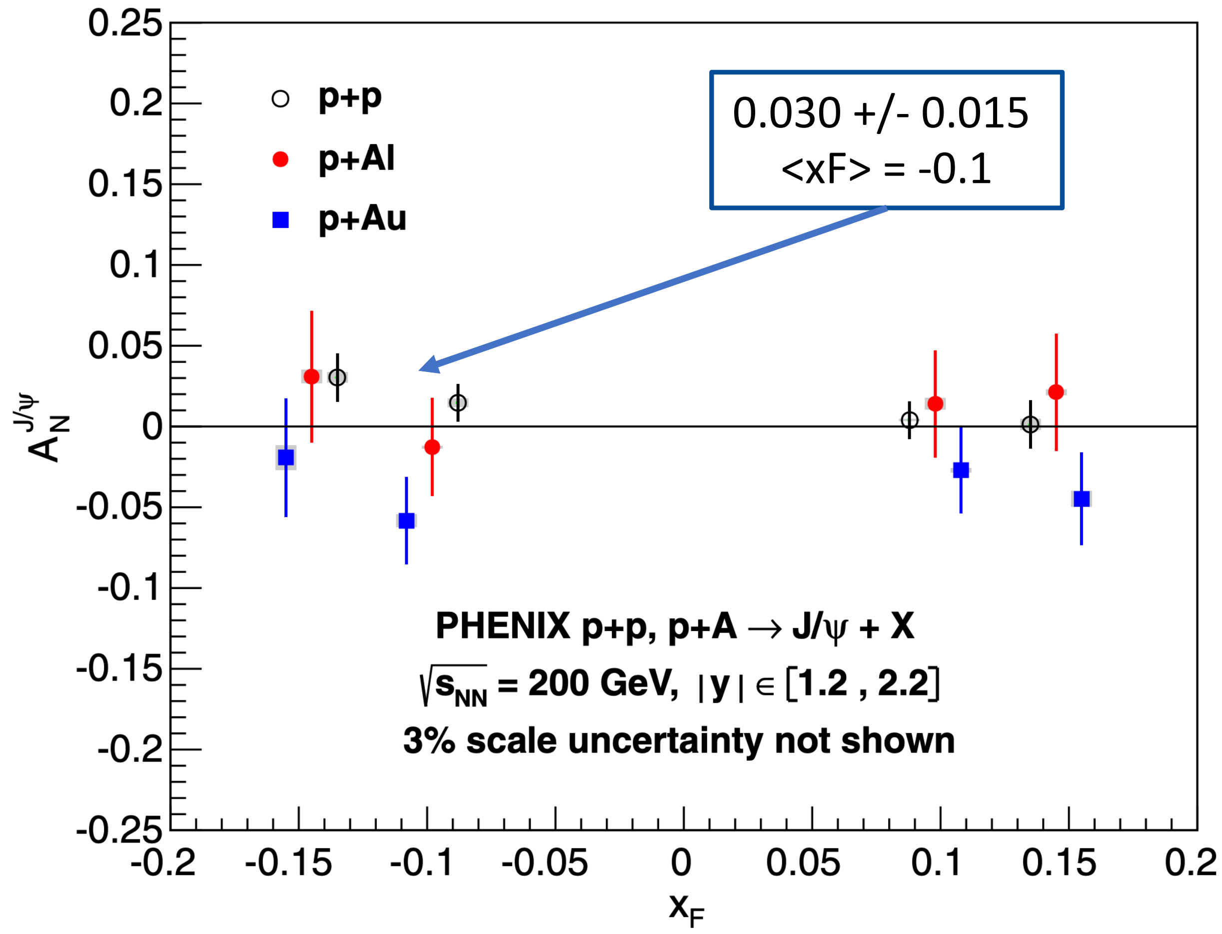
https://nica.jinr.ru/projects/spd.php

- At $\sqrt{S}$ = 15 GeV we can access both the qqbar and gg production channels.
- With a polarized target, potential sensitivity to the gluon sivers.

J/ψ TSSA at PHENIX

2018 PHENIX data from
Phys. Rev. D **98**, 012006



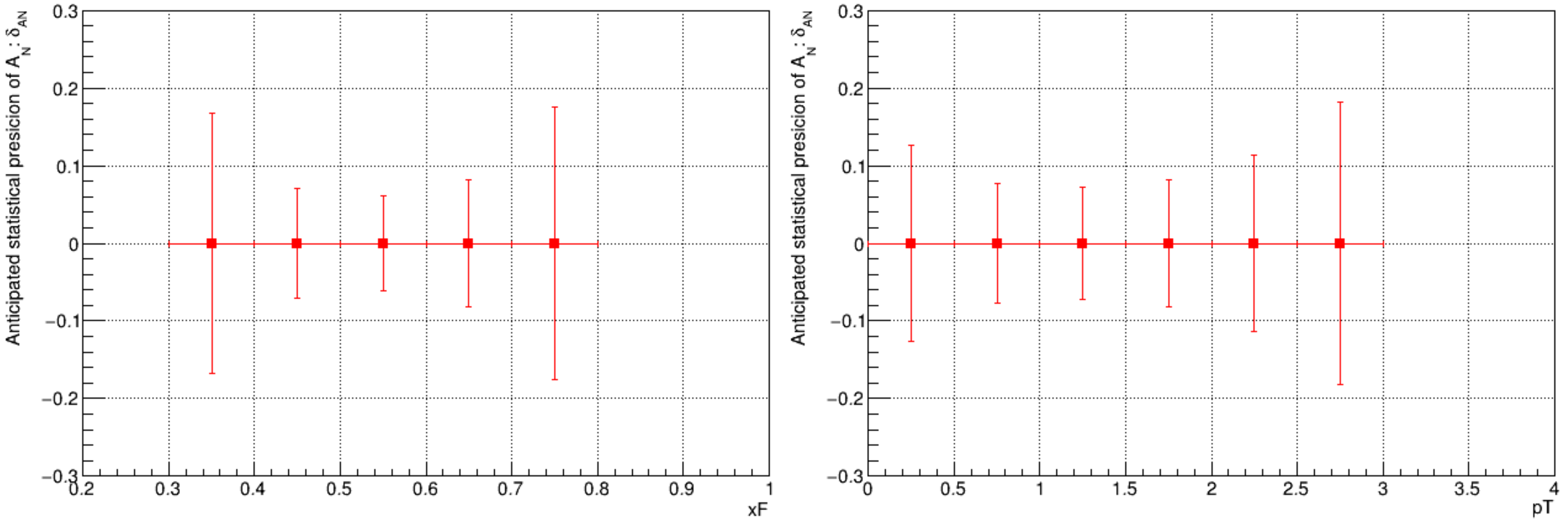


Possible p+p asymmetries observed in pT and xF.

SpinQuest is Complementary

- Distinct Kinematics between SpinQuest and PHENIX:
  - PHENIX: √S = 200 GeV and |xF| < 0.3
  - SpinQuest: √S = 15 GeV and |xF| > 0.4
  - PHENIX <pT> larger than SpinQuest.
- Probing a complimentary region of kinematics to compare with PHENIX data and upcoming NICA data.
- In PHENIX the J/ψ is produced almost entirely from gg fusion, but at SpinQuest there is a significant contribution from qqbar annhiliation.
- Objective with 10 - 12 weeks of production data: measure J/ψ TSSA with an uncertainty of 0.015.

SpinQuest Charm



Projected statistical uncertainties for J/Ψ TSSA for **one week** of Main Injector Beam Data
With 10-12 weeks of production data we hope to achieve uncertainty ≈±0.015

FIN