SpinQuest: Investigating sea quark and gluon Sivers effects in the nucleon

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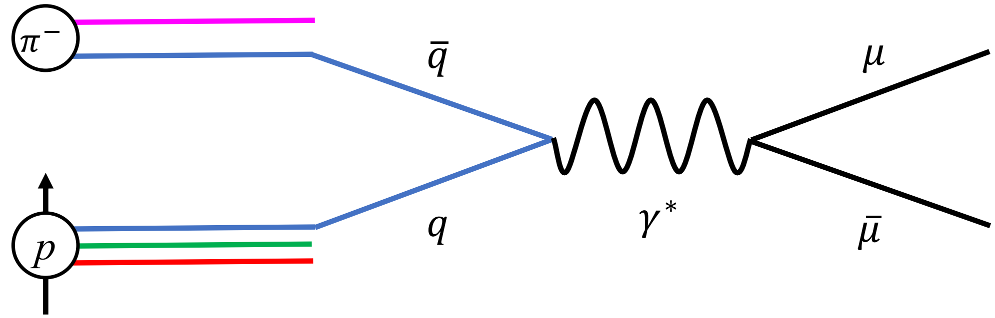
(for the SpinQuest Collaboration)

Pacific Spin 2024 Hefei

What is SpinQuest?

- 120 GeV unpolarized proton beam
- Spin-polarized frozen ammonia (NH_3 or ND_3) target
- Dimuon spectrometer
- Physics Goals
  - Observe the transverse single-spin asymmetry (TSSA) in Drell-Yan production, to extract the Sivers asymmetry for $\bar{u}$ and $\bar{d}$ quarks; **if non-zero, then $\bar{u}$ and $\bar{d}$ quarks have non-zero orbital angular momentum in the nucleon.**
  - Observe the TSSA in J/ψ production, sensitive to the gluon Sivers function in the nucleon.

π^--induced DY

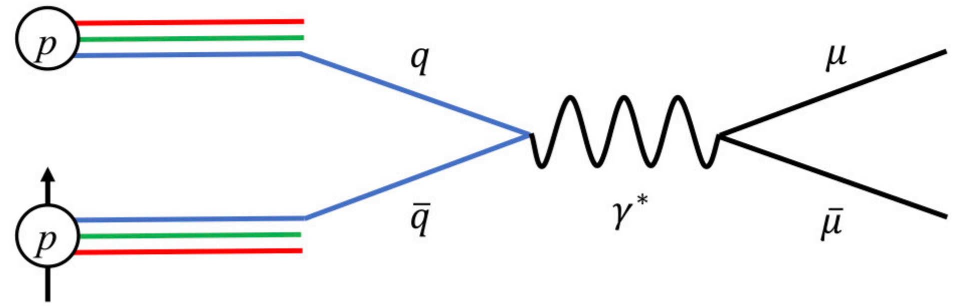


- Beam particle is $\pi^- = \bar{u}d$ + sea
- Target particle is $p = uud$ + sea
- Dominant interaction is $\bar{u}_{\text{beam}} u_{\text{target}}$ annihilation
  - $q_u^2 = 4q_d^2$ electric charges
  - $\bar{u}_{\text{beam}}$ and u_{target} are both valence

=> Transverse polarized target asymmetries will be mostly sensitive to properties of u_{target}

=> Can observe sign-change of u DY Sivers asymmetry compared to DIS Sivers

p-induced DY



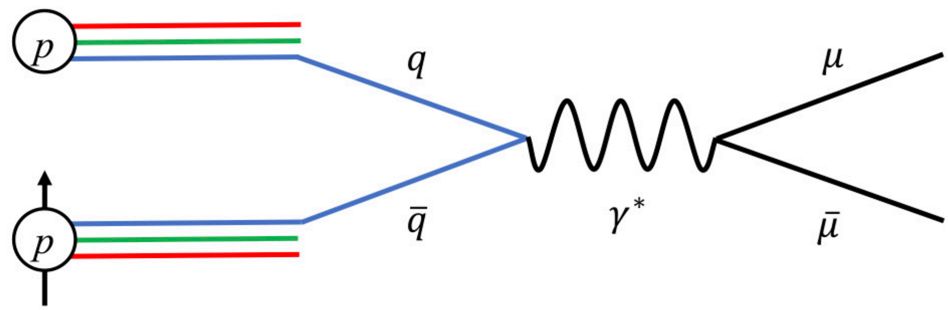
- Beam particle is $p = uud$ + sea
- Target particle is $p = uud$ + sea
- Dominant interaction is $\bar{u}_{\text{target}} u_{\text{beam}}$ annihilation
    - $q_u^2 = 4q_d^2$ electric charges
    - $x(u_{\text{beam}})$ large and $x(\bar{u}_{\text{target}})$ small

=> Transverse polarized target asymmetries will be mostly sensitive to properties of $\bar{u}_{\text{target}}$

=> Can measure $\bar{u}$ DY Sivers asymmetry for the first time (separate $\bar{u}$ and $\bar{d}$ by using NH_3 and ND_3 targets)

=> Eventually, EIC $\bar{u}$ DIS Sivers asymmetry might observe sign change

Sivers Asymmetry in SpinQuest Drell-Yan



- The Sivers asymmetry arises from a correlation between the intrinsic transverse momentum $\vec{k}_T$ of the parton, and the spin $\vec{S}$ and momentum $\vec{p}$ of the parent nucleon.

$$\vec{S} \cdot \left(\vec{k}_T \times \vec{p}\right)$$

- $\vec{k}_T$ cannot be measured directly but the virtual photon transverse momentum $\vec{q}_T = \vec{k}_T^q + \vec{k}_T^{\bar{q}}$ can be.

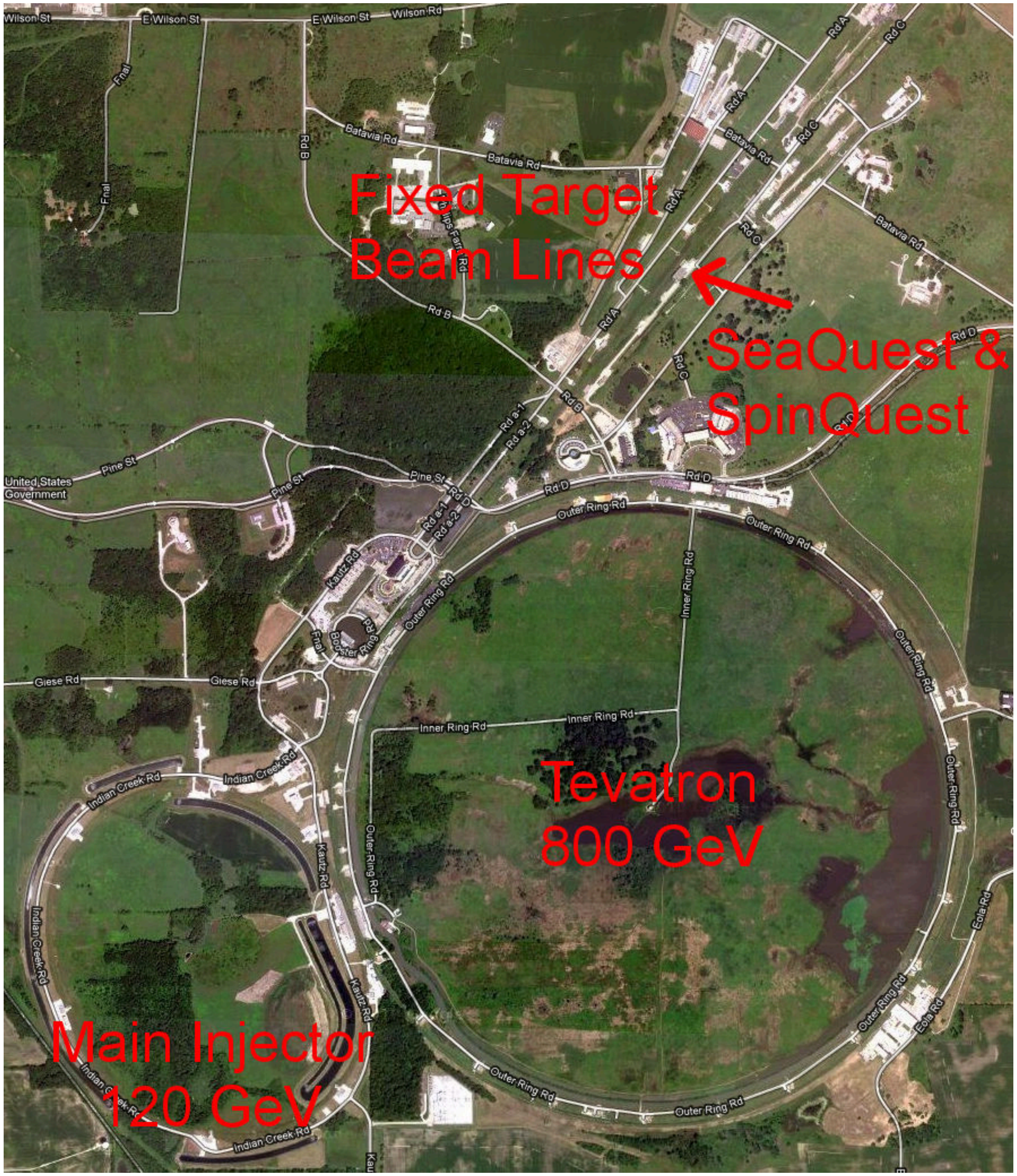
- If the spin is transverse to the beam direction, then:

$$\vec{S}_\perp \cdot (\vec{q}_T \times \vec{p}) = \left(\vec{S}_\perp \times \vec{q}_T\right) \cdot \vec{p} = S_\perp q_T p \sin(\phi_T - \phi_{q_T})$$

ϕ_{q_T} = Azimuthal angle of $\vec{q}_T$ in detector rest frame
ϕ_T = Azimuthal angle of target spin direction

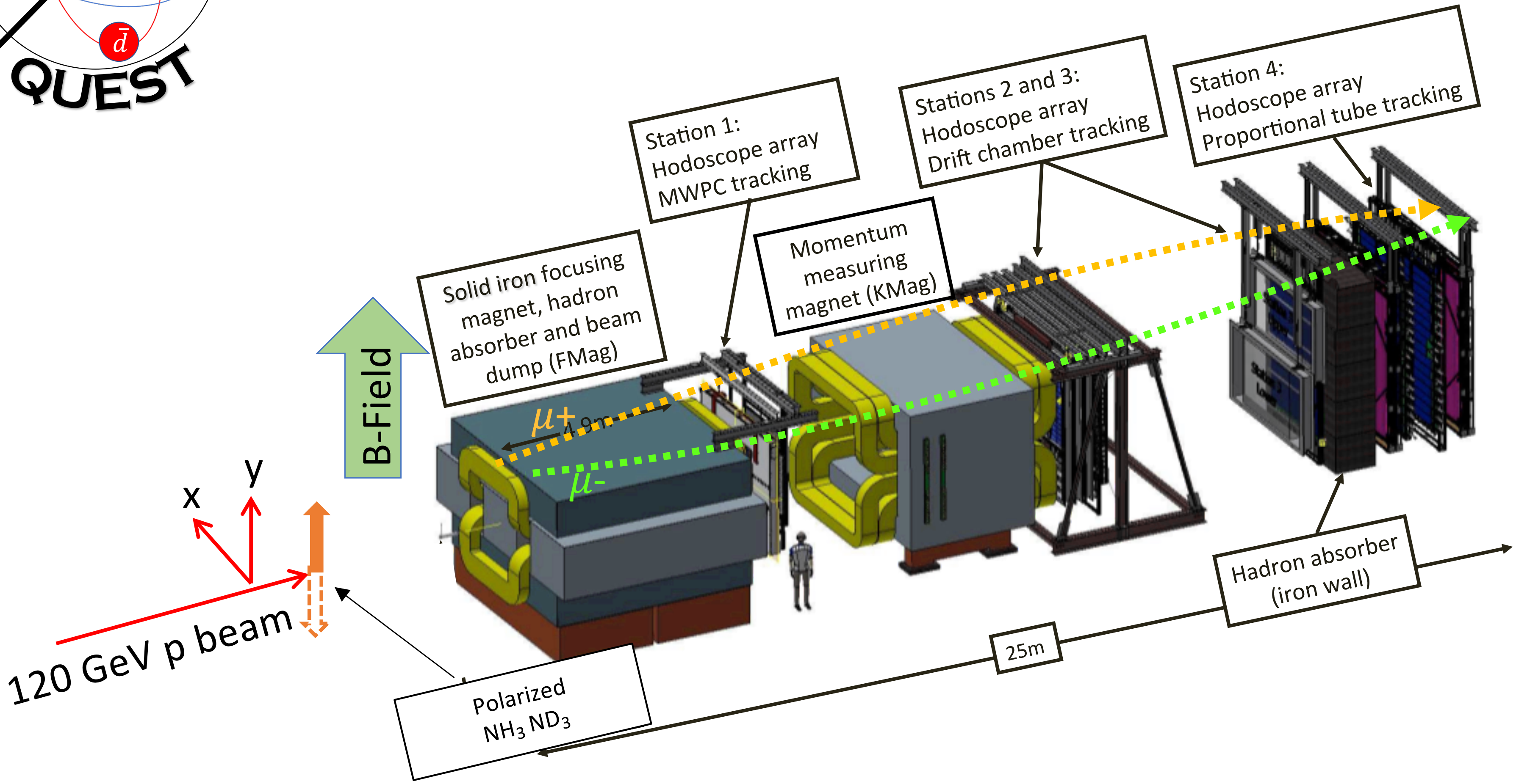
- If the $\vec{k}_T^{\bar{q}}$ of the anti-quark in the polarized target proton is correlated to the spin (i.e. Orbital Angular Momentum), then the azimuthal **Sivers asymmetry will be non-zero**

Proton Beam for SpinQuest @ FNAL



- From Main Injector
- Unpolarized
- Energy E = 120 GeV
  ($\sqrt{s}$ = 15 GeV)
- Bunches
  - Interval: 19 nsec (53 MHz)
  - ~10k protons per bunch
  - ~ 2.5E12 protons
    per spill (in 4 sec)
- Duty cycle
  - 4 sec for SpinQuest
  - 56 sec for neutrinos

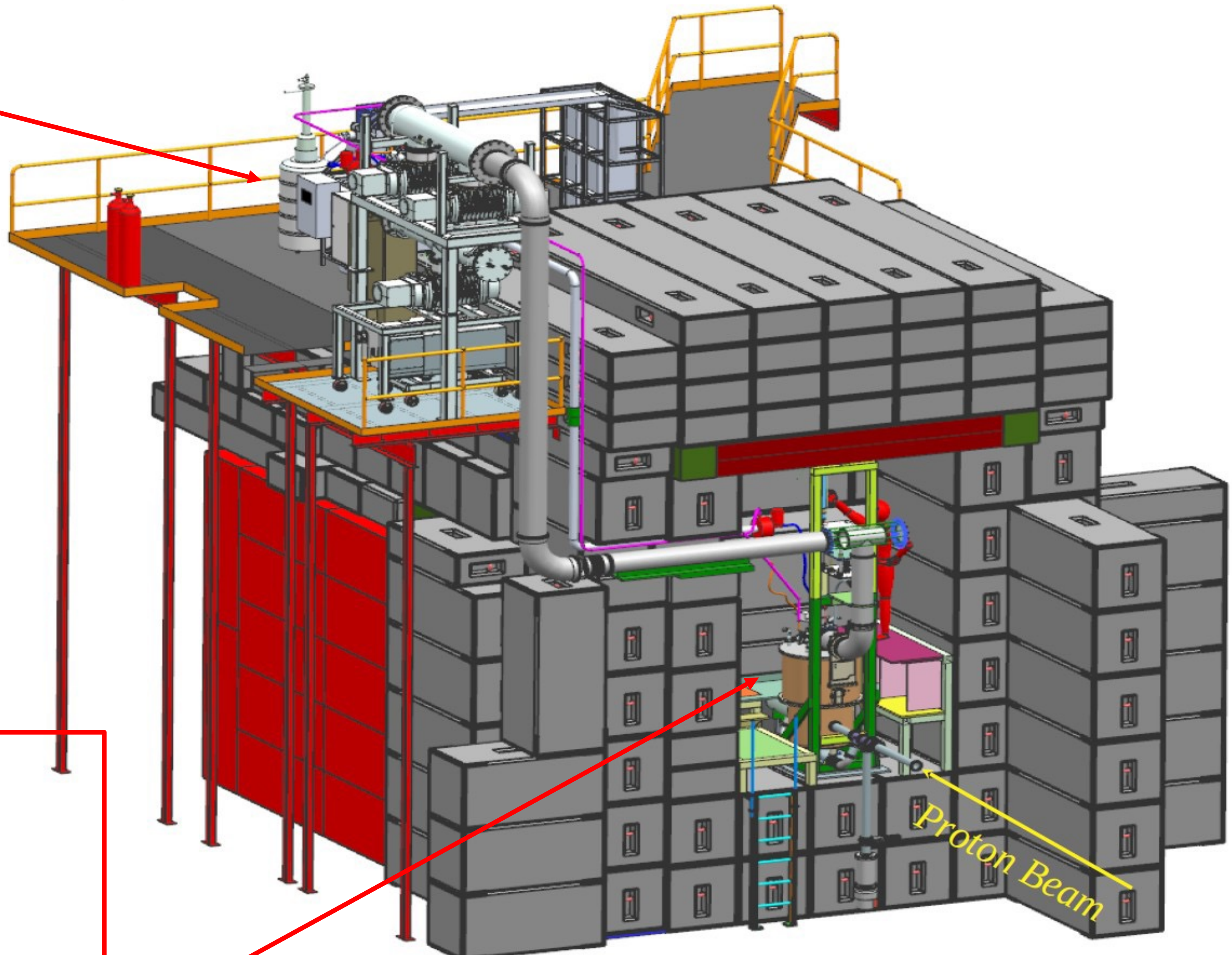
- 120 GeV unpolarized proton beam
- Spin-polarized frozen ammonia (NH_3 or ND_3) target
- Dimuon spectrometer



Spectrometer: C.A. Aidala et al., Nucl. Inst. Meth, volume **930**, 49 (2019)

Polarized Target

Roots pumps (17,000 m^3/h), compressors, control systems, NMR measurement, slow controls



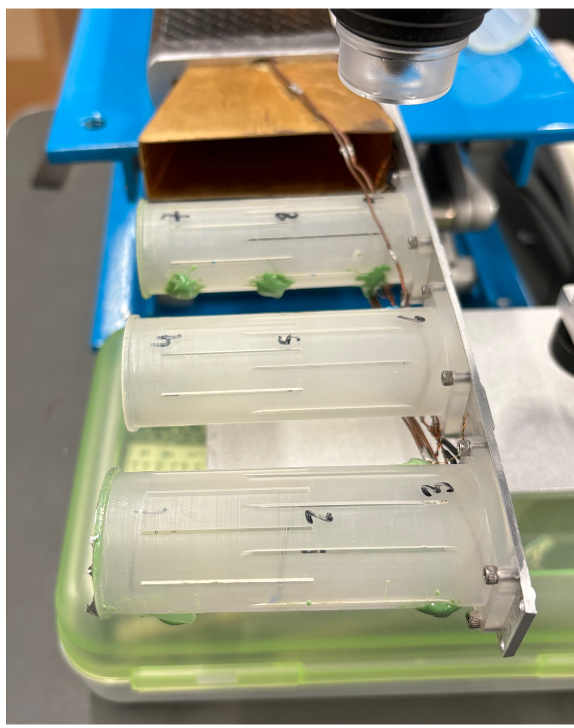
Refrigerator, magnet, target ladder, turbo pumps for insulating vacuum

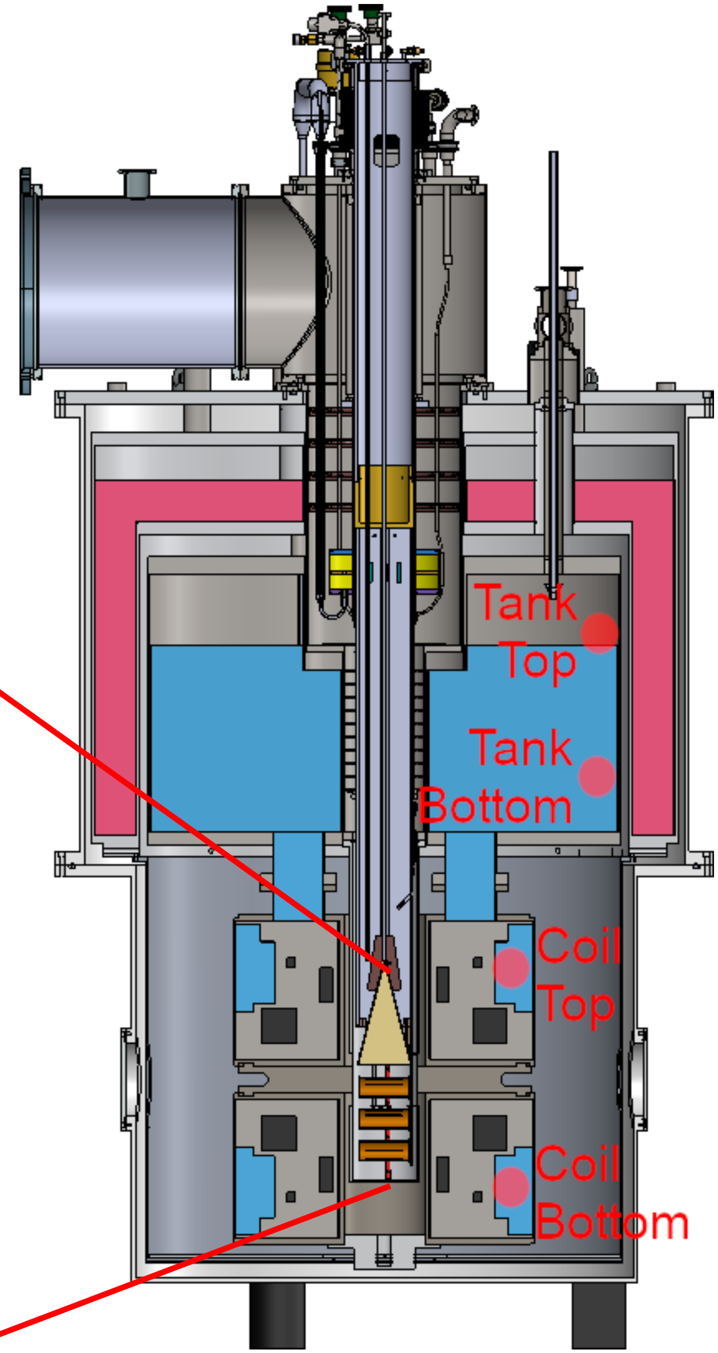
“target cave”

Polarized Target

Evaporation refrigerator -- 5 W cooling, 1 K
Frozen ammonia – NH_3 or ND_3
Field -- 5 T
Cell length -- 8 cm
Packing fraction -- ~0.6

Three Kel-F cells, each with three NMR coils and temperature sensors.



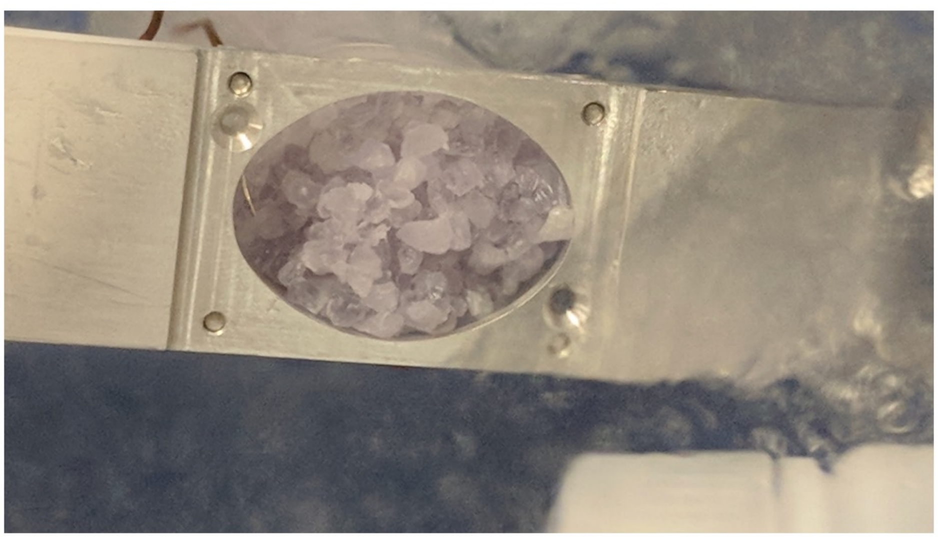


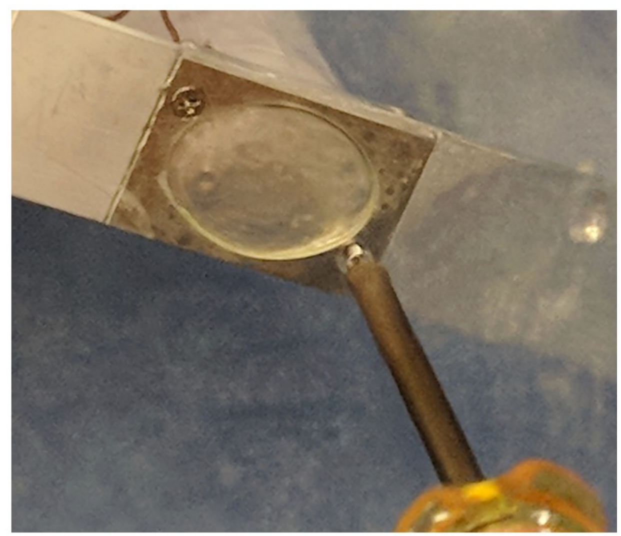
Polarized Target

Frozen ammonia pellets after electron irradiation at NIST. This irradiation produces the color centers necessary for dynamic nuclear polarization. The material is white/translucent before irradiation.

Polarized Target

Filling the target cells is a manual procedure, practiced many times to ensure safety and reproducibility.





TSSA in Drell-Yan: Projected Uncertainties

1 "year" (~200 days) of running on each of NH_3 and ND_3

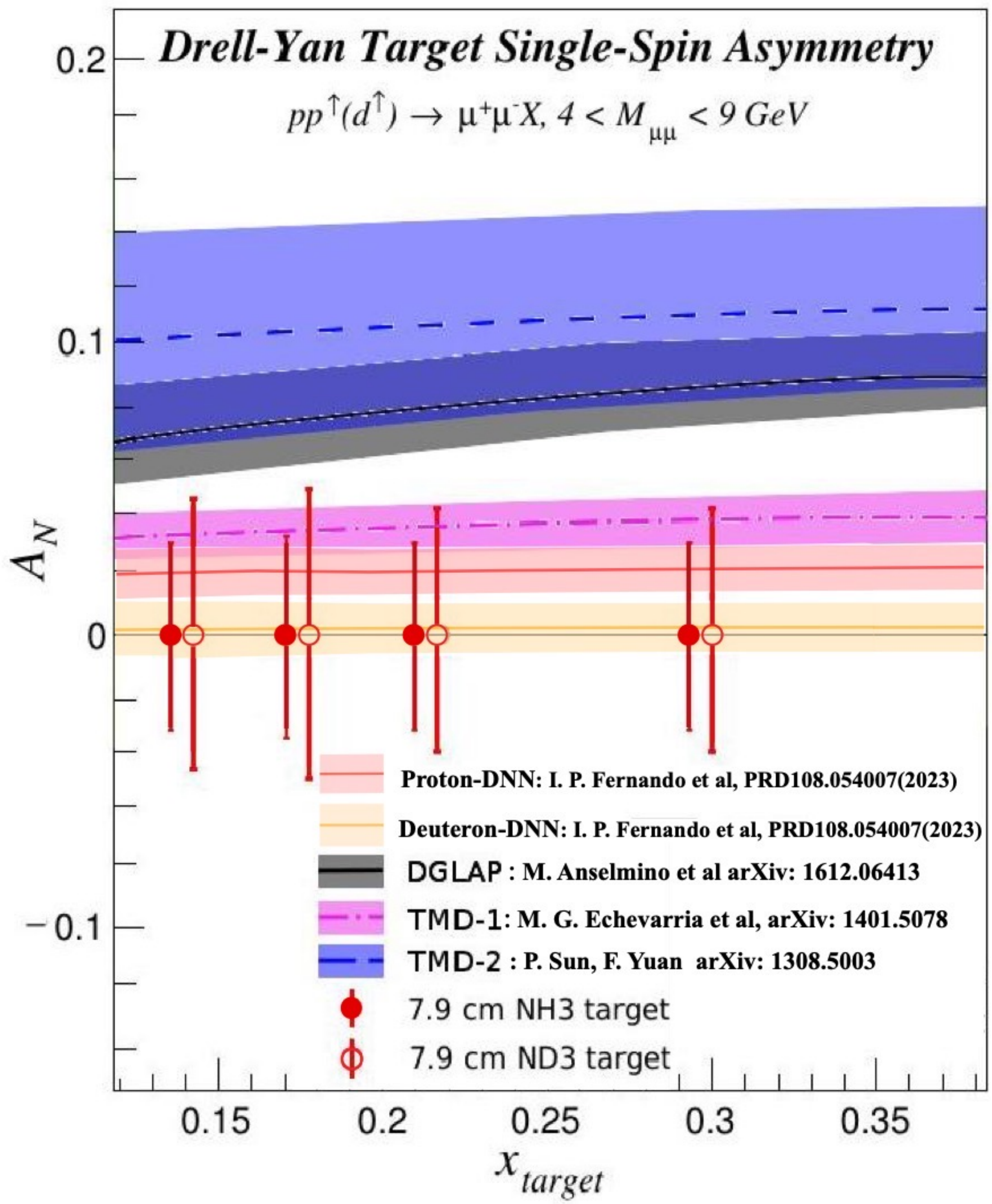
~2.5E12 protons/spill

Polarizations

$$\langle P_H \rangle = 0.80$$
$$\langle P_D \rangle = 0.32$$

Dilutions (dynamic):

$$f_{\mathrm{NH_3}} \approx 3/17$$
$$f_{\mathrm{ND_3}} \approx 3/10$$



J/ψ Transverse Single Spin Asymmetry in $\vec{p}p$ interactions at $\sqrt{s} = 15$ GeV

This is our "Day 1" physics program, as we can measure this asymmetry in just a few weeks due to the much higher production cross section compared to Drell-Yan.

Data exists for this TSSA from PHENIX at $\sqrt{s} = 200$ GeV.

SPD/NICA will measure at $\sqrt{s} = 24$ GeV.
https://nica.jinr.ru/projects/spd.php

Sensitive to both the $q\bar{q}$ and gg production channels.

With a polarized target, we have sensitivity to the Sivers functions for gluons.

PHENIX J/ψ TSSA Measurement; results vs. p_T

Phys. Rev. D 98, 012006

Possible non-zero asymmetry in *pp*: 0.034 +/- 0.016 at <p_T> = 3 GeV and backward x_F

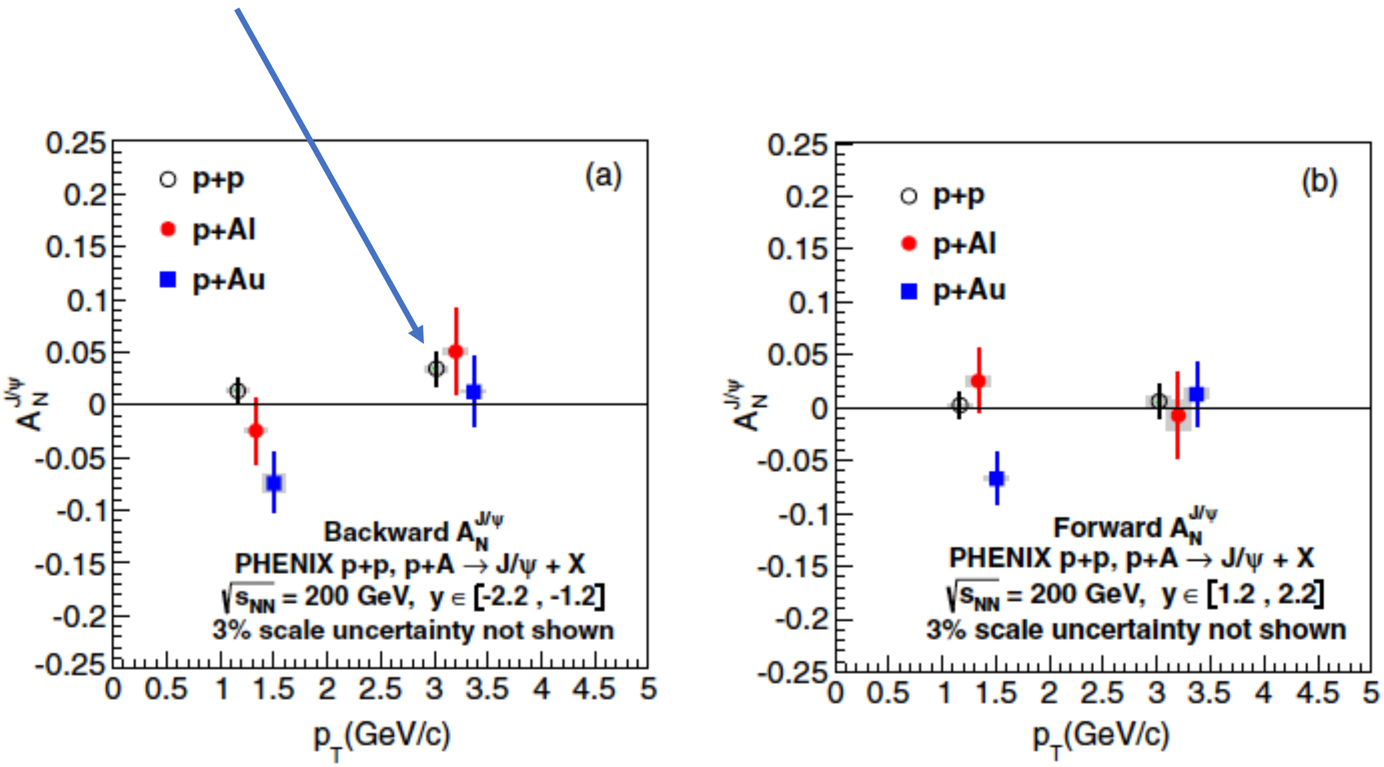


FIG. 4. (a) Backward [$x_F < 0$] and (b) forward [$x_F > 0$] $A_N^{J/\psi}$ vs p_T for open [black] circles $p + p$, closed [red] circles $p +$ Al, and closed [blue] boxes $p +$ Au collisions. The shaded [gray] boxes show the systematic uncertainty. The data points for $p +$ Al and $p +$ Au collisions have been shifted in p_T for clarity.

This result is statistically limited.

PHENIX J/ψ TSSA Measurement; results vs. x_F

Phys. Rev. D 98, 012006

Possible non-zero asymmetry in *pp*: 0.030 +/- 0.015 at $\langle x_F \rangle = -0.1$

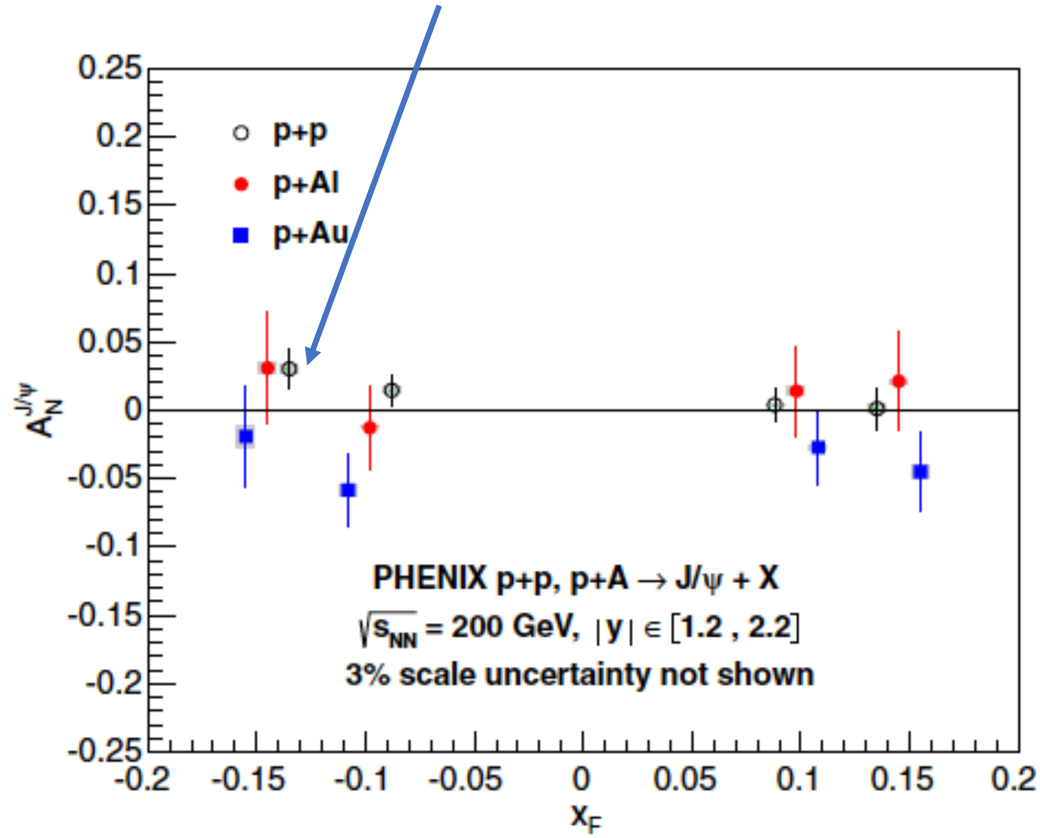


FIG. 5. $A_N^{J/\psi}$ vs x_F for open [black] circles $p+p$, closed [red] circles $p+$Al, and closed [blue] boxes $p+$Au collisions. The shaded [gray] boxes show the systematic uncertainty. The data points for $p+$Al and $p+$Au collisions have been shifted in x_f for clarity.

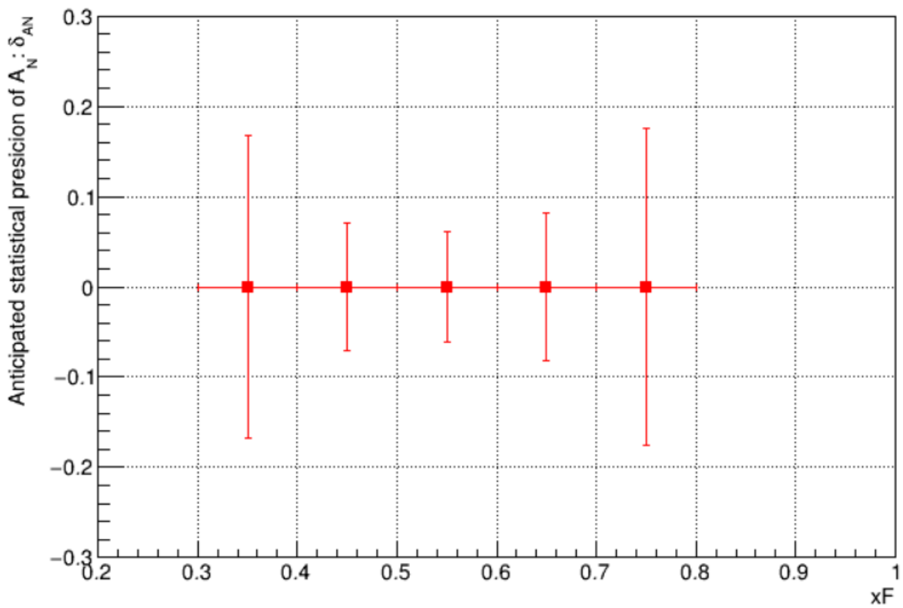
This result is statistically limited.

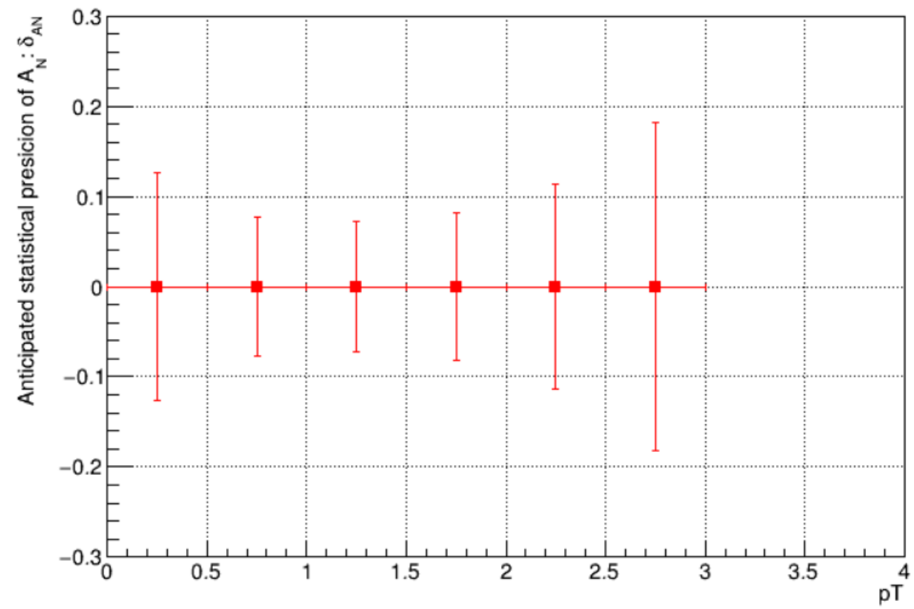
J/ψ TSSA: SpinQuest and PHENIX

- SpinQuest and PHENIX kinematics don't overlap:
  - In PHENIX $\sqrt{s} = 200$ GeV and $|x_F| < 0.3$
  - In SpinQuest $\sqrt{s} = 15$ GeV and $|x_F| > 0.4$
  - The p_T in PHENIX is generally larger than in SpinQuest.
- So, a SpinQuest measurement will be complementary compared to PHENIX. We will explore a new region of kinematics.
- In PHENIX, J/ψ production is dominated by gg fusion, but in SpinQuest there is a strong contribution from $q\bar{q}$ annihilation.
- Desired Goal: Measure A_N with a similar absolute error (±0.015 or better) for a few p_T and/or x_F bins

TSSA in J/ψ Production: Projected Statistical Uncertainties

<u>For one week of production data;</u>
typical error is about $\pm$0.10.



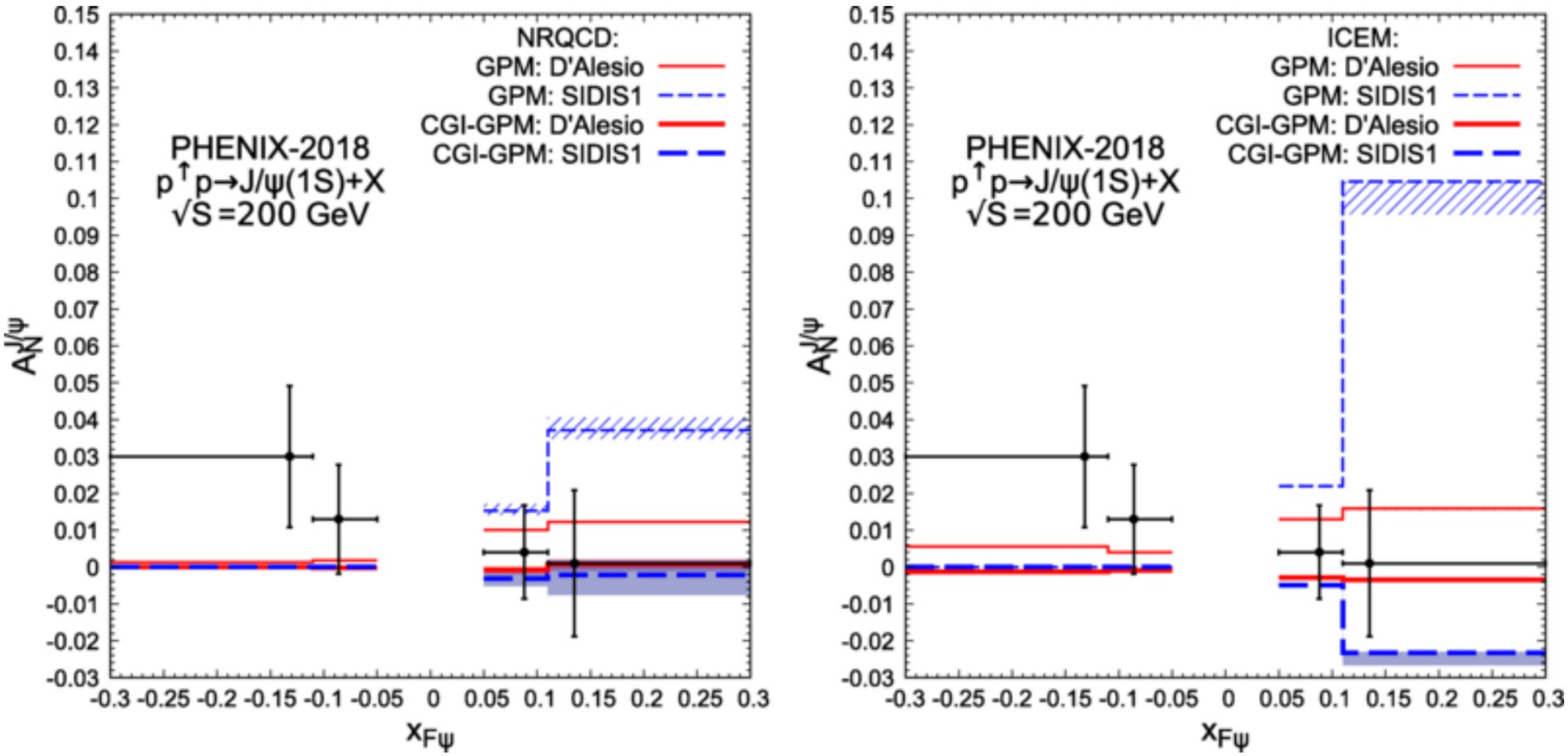


<u>We currently expect 10-12 weeks of production data in 2025.</u>
We should be able to get close to our desired goal of $\pm$0.015 if we use fewer bins.

J/ψ TSSA

A. V. Karpishkov, V. A. Saleev, and M. A. Nefedov
Phys. Rev. D 104, 016008

PHENIX Data $\sqrt{s} = 200$ GeV



TSSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 200$ GeV within the GPM (thin histograms) and CGI-GPM (thick histograms). The theoretical results are obtained with SIDIS1 [6] (dashed histograms) and D'Alesio *et al.* [25] (solid histograms) parametrizations of GSFs. Experimental data are from Ref. [40]. Left panel: NRQCD final-state factorization. Right panel: ICEM final-state factorization.

NRQCD: Non-relativistic QCD

ICEM: Improved Color Evap. Model

GPM: Generalized Parton Model

CGI: Color Gauge Invariant

GSF: Gluon Sivers function

J/ψ TSSA

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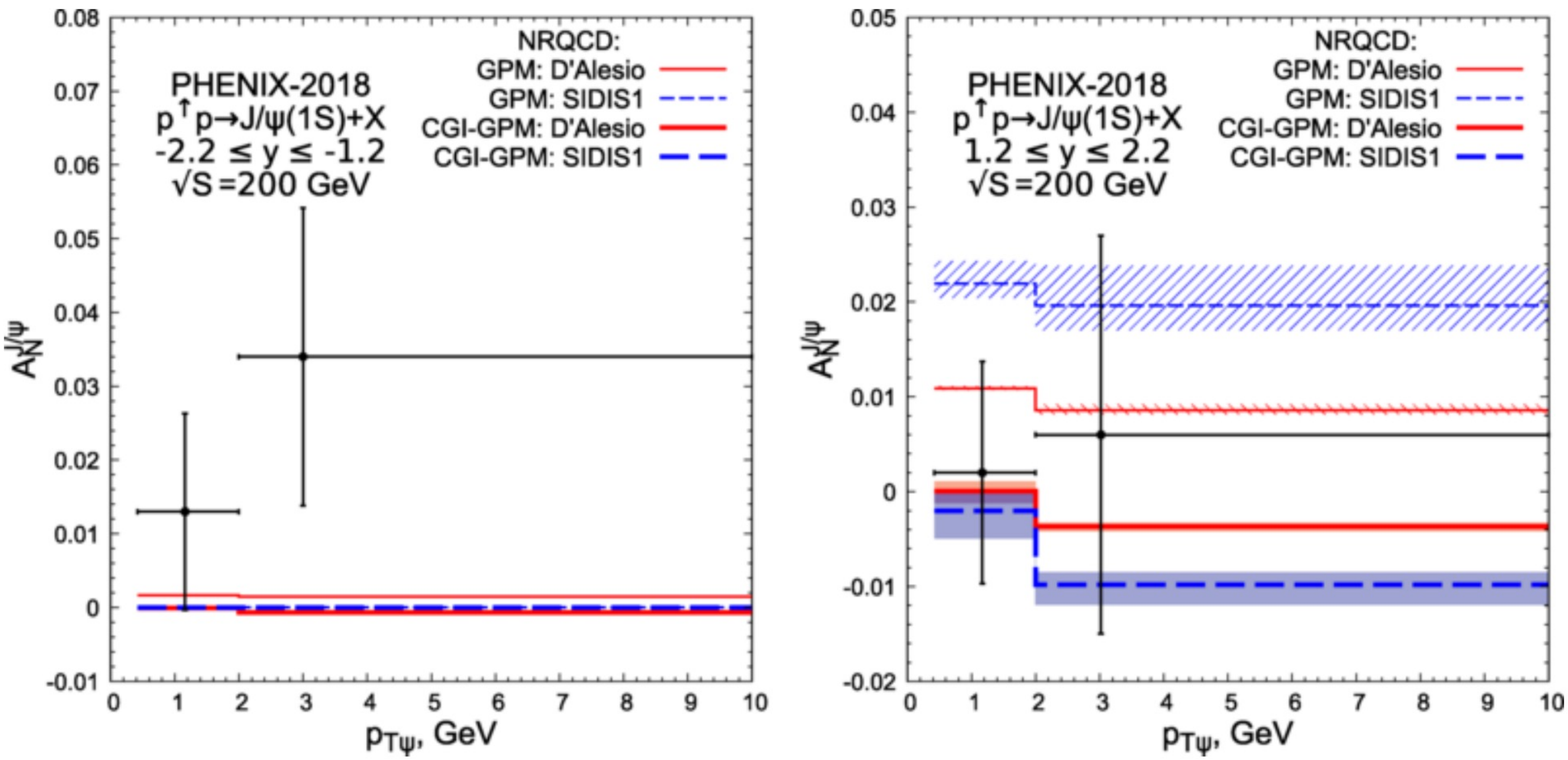
PHENIX Data $\sqrt{s} = 200$ GeV



NRQCD predictions for TSSA $A_N^{J/\psi}$ within the GPM (thin histograms) and CGI-GPM (thick histograms) as a function of J/ψ transverse momentum at $\sqrt{s} = 200$ GeV. The theoretical results are obtained with SIDIS1 [6] (dashed lines) and D'Alesio *et al.* [25] (solid lines) parametrizations of GSFs. Left panel: backward production $(-2.2 < y < -1.2)$. Right panel: forward production $(1.2 < y < 2.2)$. Experimental data are from Ref. [40].

NRQCD: Non-relativistic QCD

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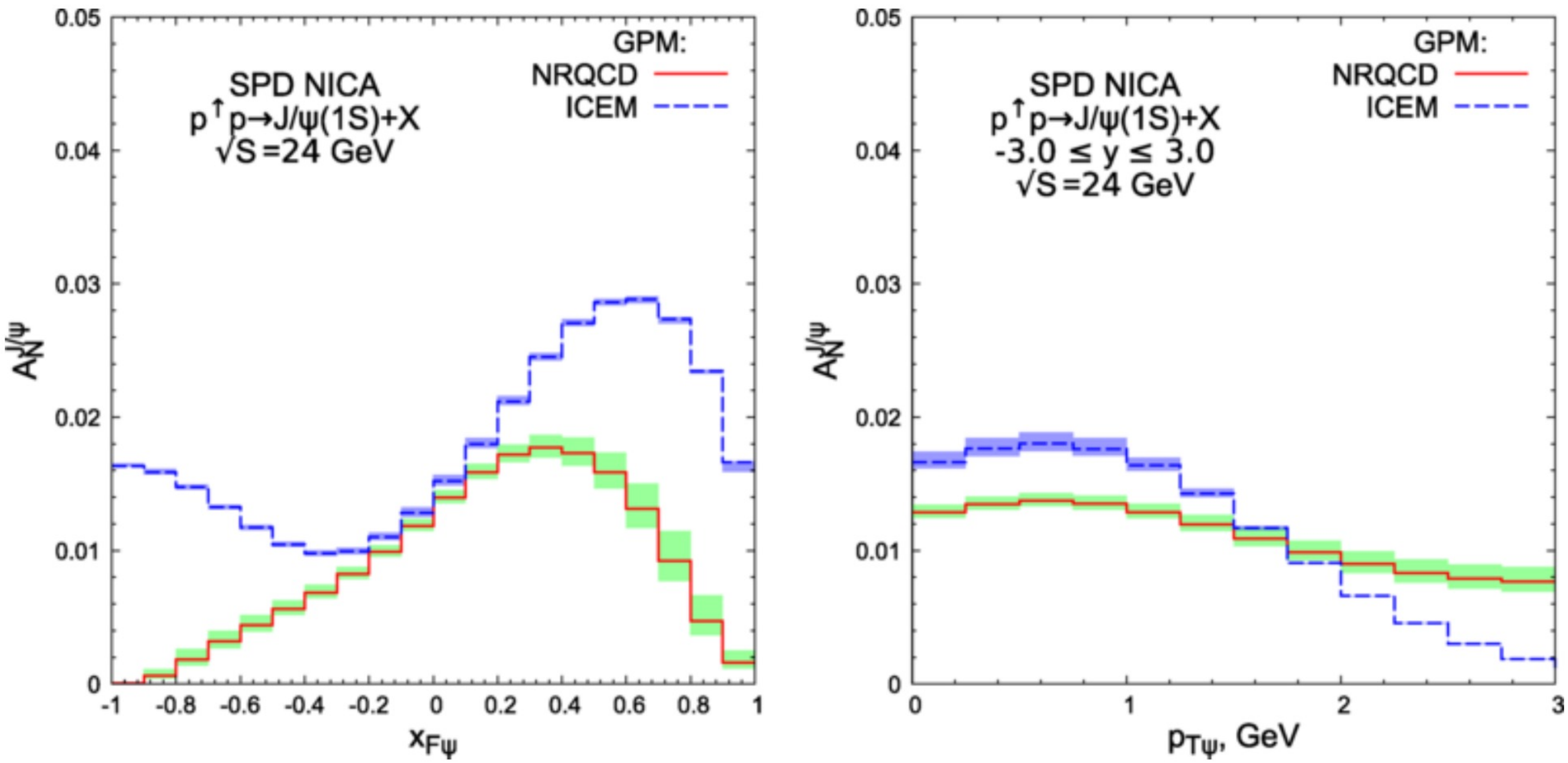
Phys. Rev. D 104, 016008

SPD NICA Kinematics $\sqrt{s} = 24$ GeV



Comparison of predictions in GPM for TSSA $A_N^{J/\psi}$ as a function of x_F (left panel) and transverse momentum (right panel) at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. The D'Alesio *et al.* [25] parametrization of GSFs is used.

N.B. SpinQuest $\sqrt{s} = 15$ GeV

NRQCD: Non-relativistic QCD

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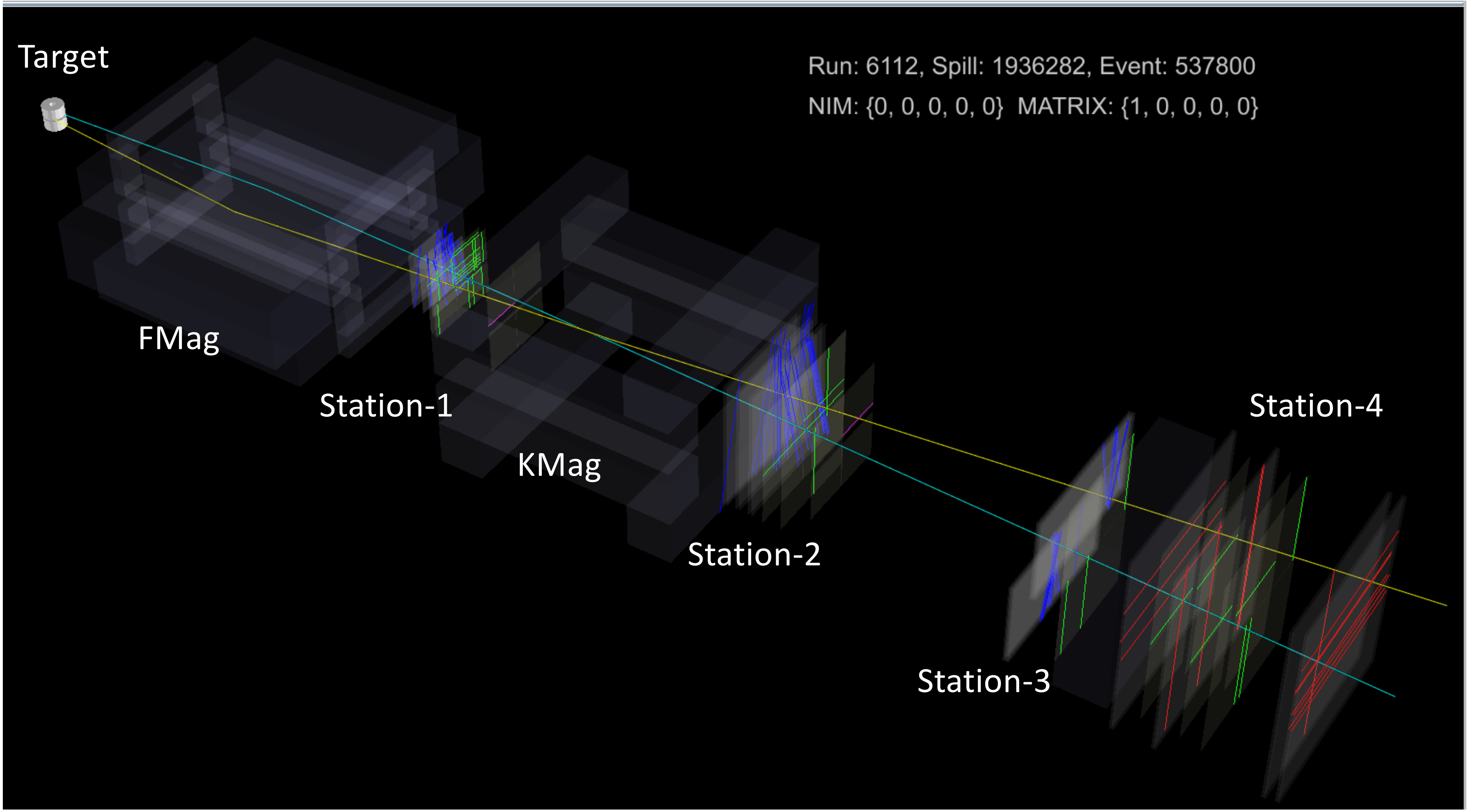
First Beam! May 25 - July 12, 2024

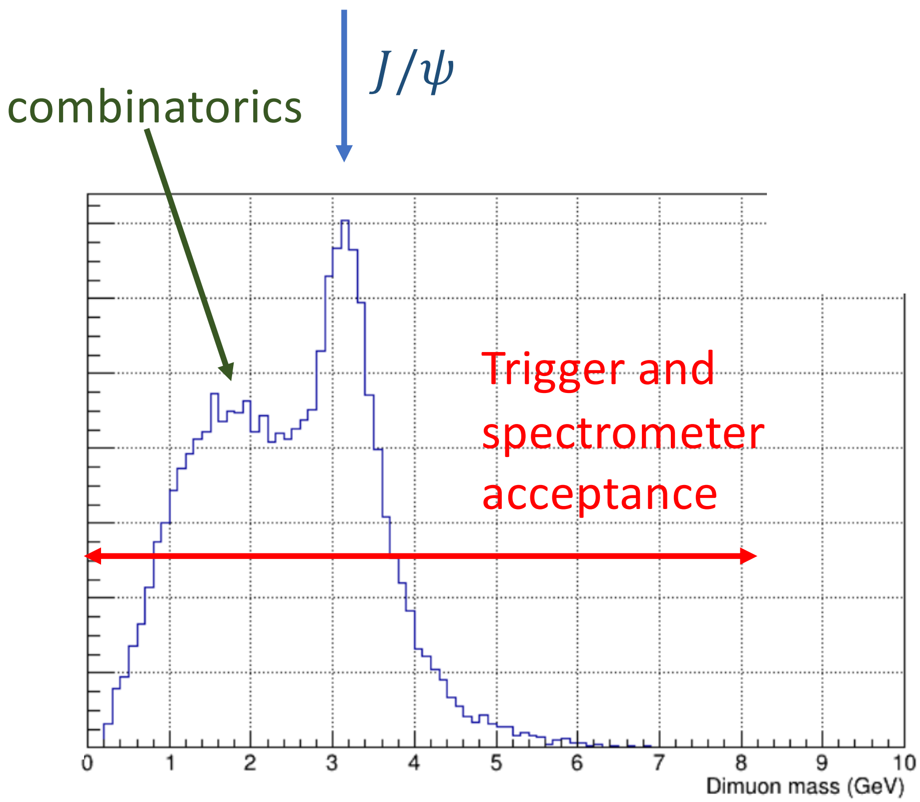
- Extensive commissioning of the target and spectrometer systems
- Careful alignment of the beam onto the target
- Able to run at ~2.5E12 protons/spill without quenching the superconducting target magnet; agrees with expectation given in the proposal
- Target Density: 8 cm of solid NH_3 with packing fraction of ~0.6 is ~3E23 nucleons/cm^2
- Instantaneous luminosity: ~2E35/cm^2/s
- This is the highest luminosity ever for any polarized NH_3 target
- Infrastructure problems were uncovered that we are addressing during the current shutdown

Dimuon event from the commissioning run

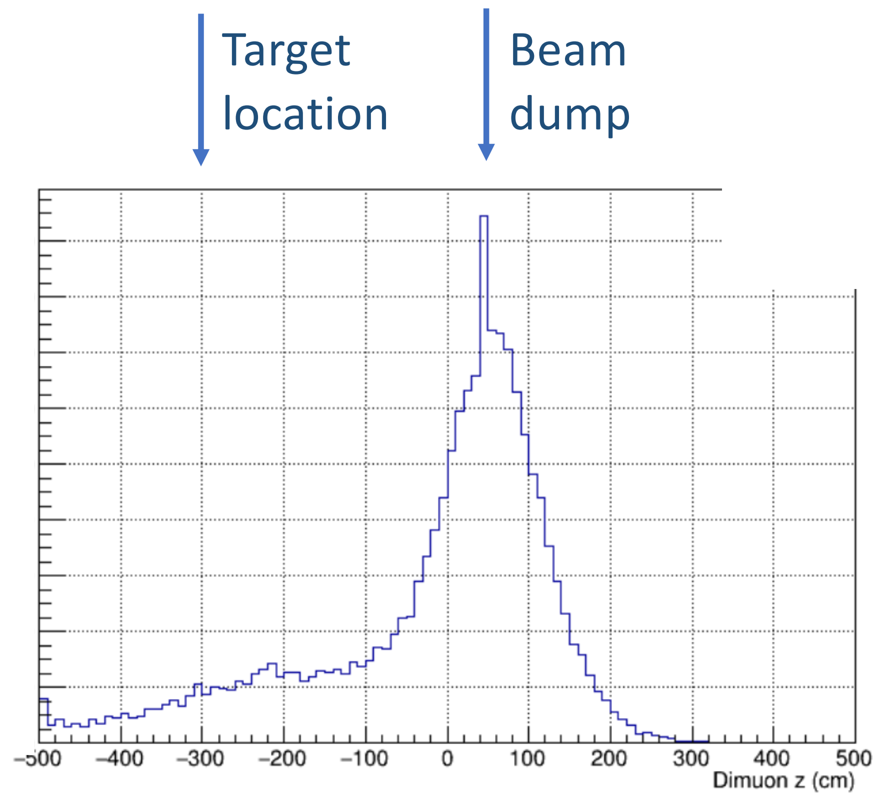


Dimuon Spectra from Commissioning Data

3153 4-sec spills; KMag is on; all triggers, all events, no cuts



Dimuon Invariant mass (GeV)



Dimuon z_{vertex} (cm)

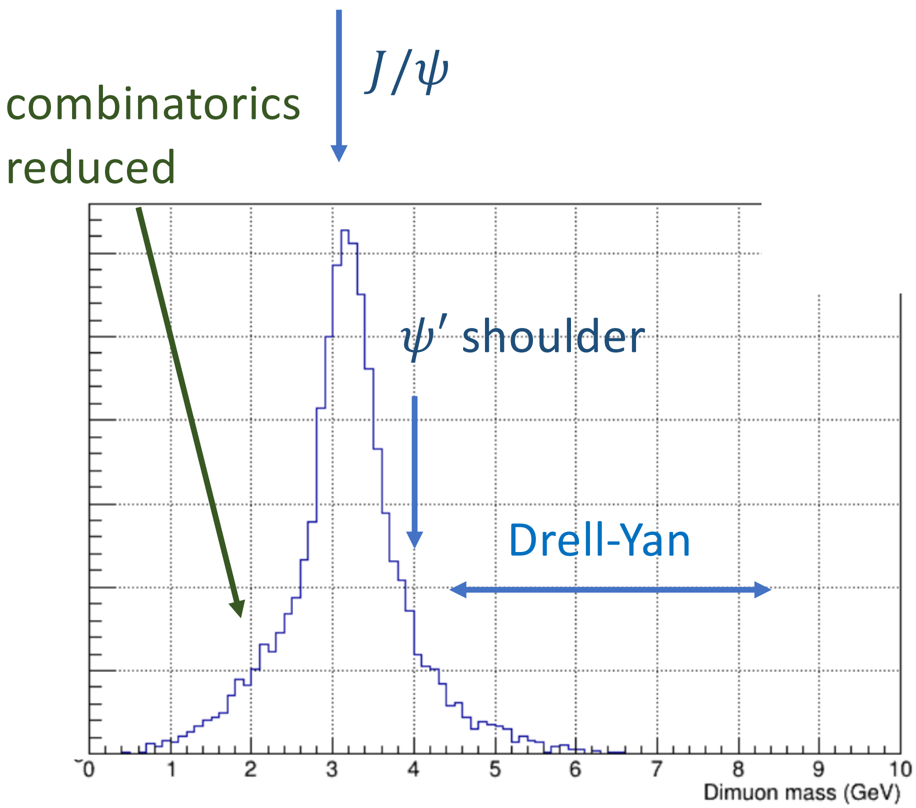
Dimuon Spectra from Commissioning Data

<u>4 simple cuts</u>:

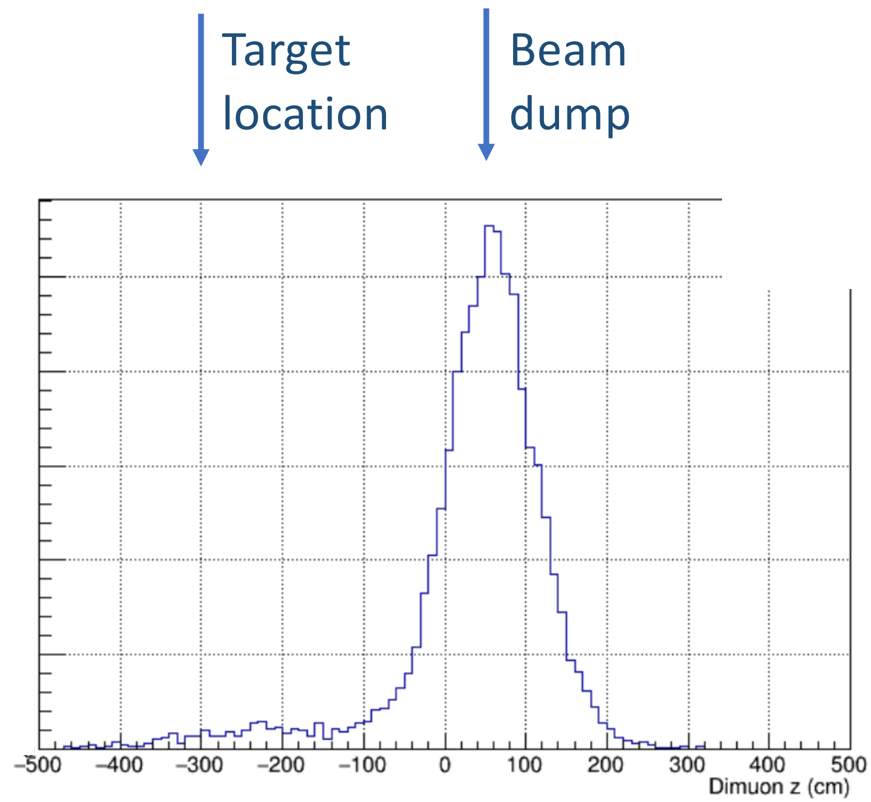
Use only “top/bottom” trigger; Enforce road-set match;

Tracks must originate downstream of the collimator;

$\Delta z^{+-}_{vertex} < 200$ cm



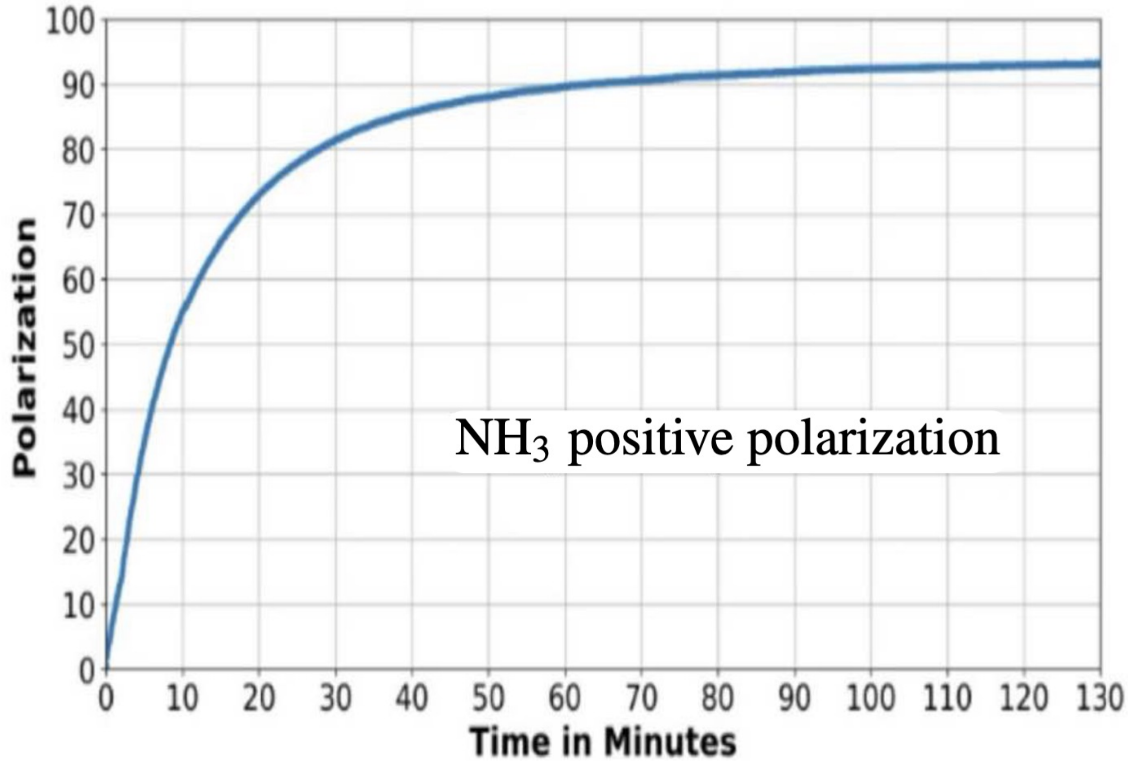
Dimuon Invariant mass (GeV)



Dimuon z_{vertex} (cm)

Polarized Target

We achieved a peak polarization above 90% for NH_3.



The proton beam produces radiation damage to the target material, which reduces the polarization over time.
In-situ annealing can largely repair this damage.
After several annealing cycles, the target material must be replaced.

SpinQuest Talks, post-commissioning

- PSTP 2024 (JLab) 9/22-27
  - "Beam Commissioning Result of Polarized Target at SpinQuest" Kenichi Nakano
  - "SpinQuest Polarized Target System" Vibodha Bandara
- Joint "20th International Workshop on Hadron Structure and Spectroscopy" and 5th workshop on "Correlations in Partonic and Hadronic Interactions" (Yerevan) 9/30-10/4
  - "SpinQuest experiment: overview" Liliet Calero Diaz
- DNP (Boston) 10/7-10
  - "Measurement of transverse single-spin asymmetries for J/ψ production in polarized p + p collisions at √s = 15 GeV" Chatura Kuruppu
  - "Extracting Sivers Asymmetry in Drell-Yan at E1039 experiment using a likelihood method" Harsha Kalu Arachchige
  - "UVA NMR System of the SpinQuest Polarized Target System" Nuwan Chaminda
  - "Deep-Learning Unfolding for Extraction of Drell-Yan Angular Parameters in pp Collisions with 120 GeV Beam Energy" Dinupa Nawarathne
  - "First Look at SpinQuest Studies with Polarized Targets" Vaniya Ansari
  - "Optimizing Dimuon Reconstruction in SpinQuest" Jordan Roberts
  - "Development of an Advanced RF Level Converter for SpinQuest's Trigger and Data Acquisition System" Jessica Brant
- Pacific Spin 2024 (Hefei) 11/9-12
  - "SpinQuest: Investigating sea quark and gluon Sivers effects in the nucleon" SP

Physics Production Run 2025

- We expect to start our 2025 run in January. Main Injector schedule is "under construction" due to infrastructure problems that must be addressed.
- We expect about 16 weeks of Main Injector operation in 2025, due to infrastructure problems and budgetary constraints.
- We will complete a few additional commissioning tasks and then start physics running with the NH_3 target. Expect 10-12 weeks of physics running.
- SpinQuest has started!

Questions?


POST COFFEE
咖啡邮局
咖啡
邮局
POST COFFEE
合肥三河古镇店
营业时间 business hours
9:00-19:00
节假日营业时间另行安排