Measurement of Anti-Quark Sivers Asymmetry at FNAL-SpinQuest

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Outline

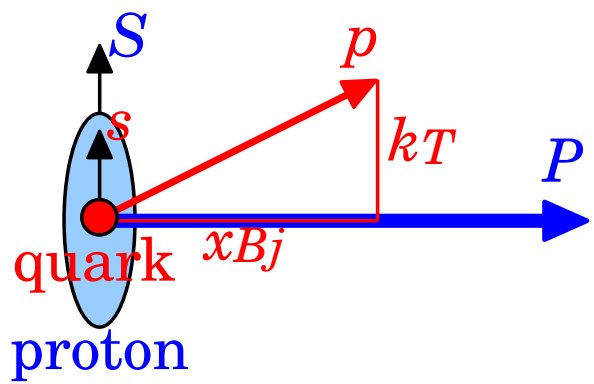
- Introduction
  - Present knowledge of Sivers function
  - Aim of SpinQuest experiment
- Measurements of Transverse Single Spin Asymmetry (TSSA)
  - Drell-Yan process
  - J/ψ production
- Experimental setup
  - Schedule
  - Target & spectrometer
- Outcomes of beam commissioning in 2024
- Conclusions

Sivers Function: $f_{1T}^{\perp}(x, k_T)$

- One of the eight Transverse-Momentum-Dependent (TMD) PDFs

		Parton spin		
		U	L	T
Nucleon spin	U	Density f_1		Boer-Mulders $h_1^{\perp}$
	L		Helicity g_1	Worm gear #2 $h_{1L}^{\perp}$
	T	Sivers $f_{1T}^{\perp}$	Worm gear #1 g_{1T}	Transversity h_1 & Pretzelosity $h_{1T}^{\perp}$

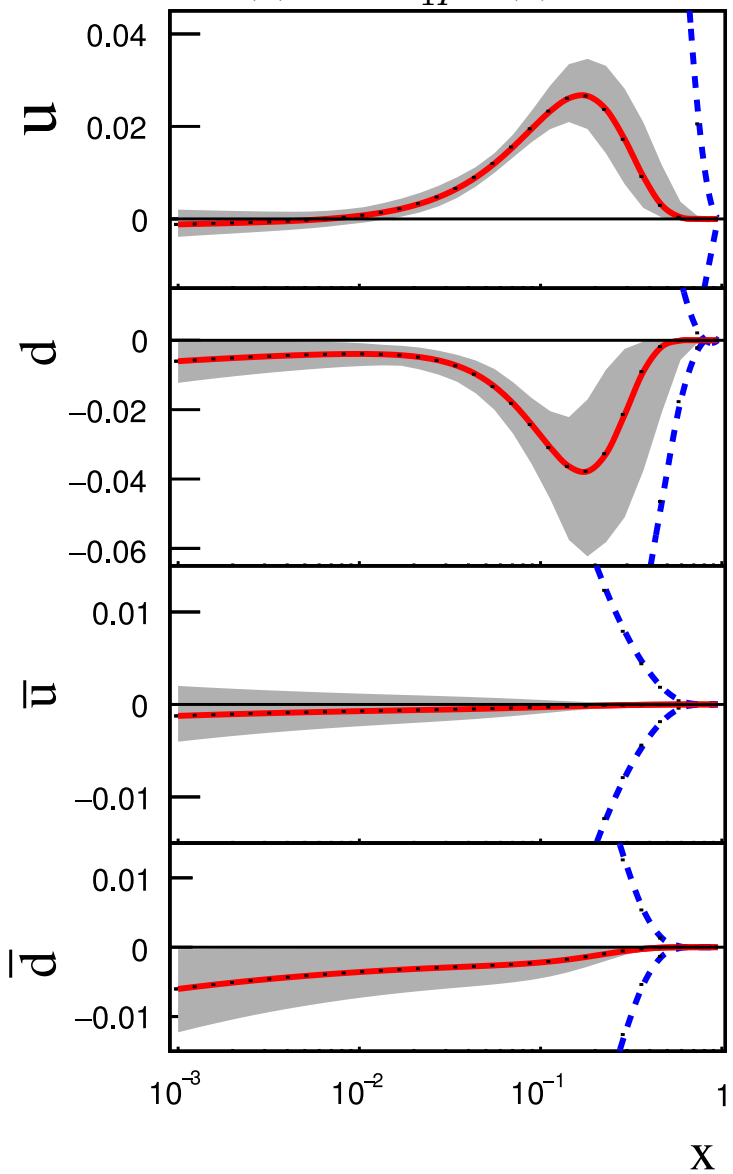
- Correlation between nucleon spin (S) & parton transverse momentum (k_T)



Sivers Function of Anti-Quarks

- Extraction by global analyses:
  Use of HERMES, COMPASS & JLab data
  - PRD 88 (2013) 114012, P. Sun & F. Yuan
  - PRD 89 (2014) 074013, M. G. Echevarria et al.
  - JHEP 04 (2017) 046, M. Anselmino et al.
  - PRD 108 (2023) 054007, I. P. Fernando et al.
- $f_{1T}^{\perp}(x)$ of anti-quarks is not well known
  - Since $\bar{q}$ & q are mixed up in SIDIS
- SpinQuest will
  - Measure Sivers asymmetry of $\bar{u}$ & $\bar{d}$
  - Mainly via proton-induced Drell-Yan process
  - Using transversely-polarized targets of NH_3 & ND_3

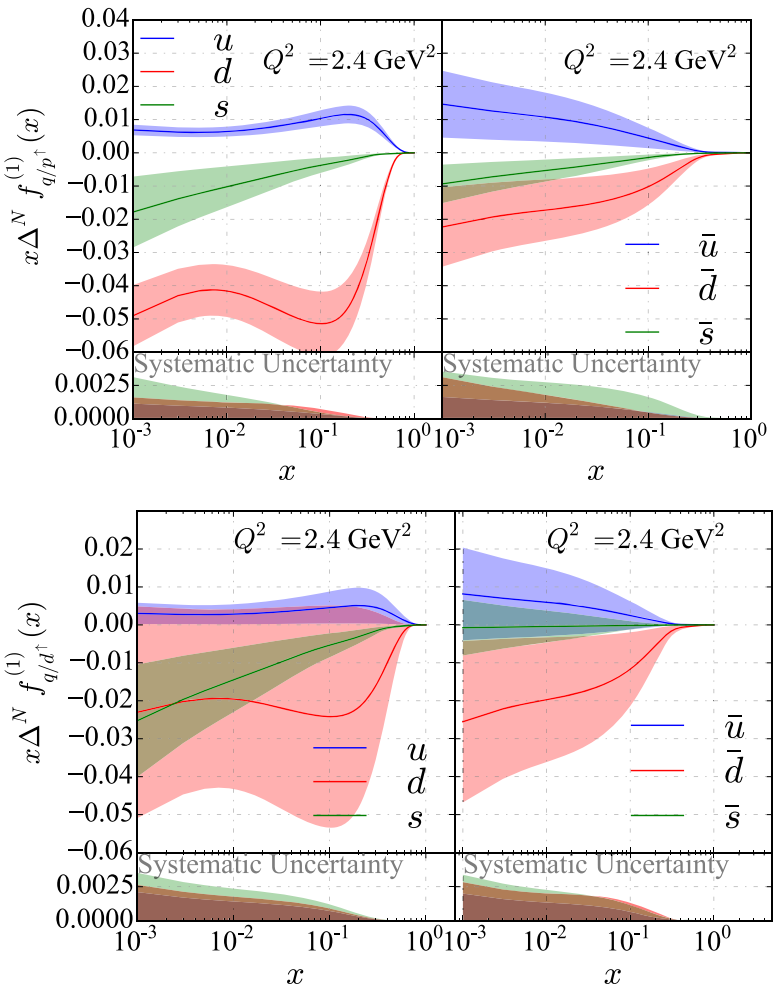
First moment of Sivers function:
$x\Delta^N f^{(1)}(x) \equiv -x f_{1T}^{\perp(1)}(x)$



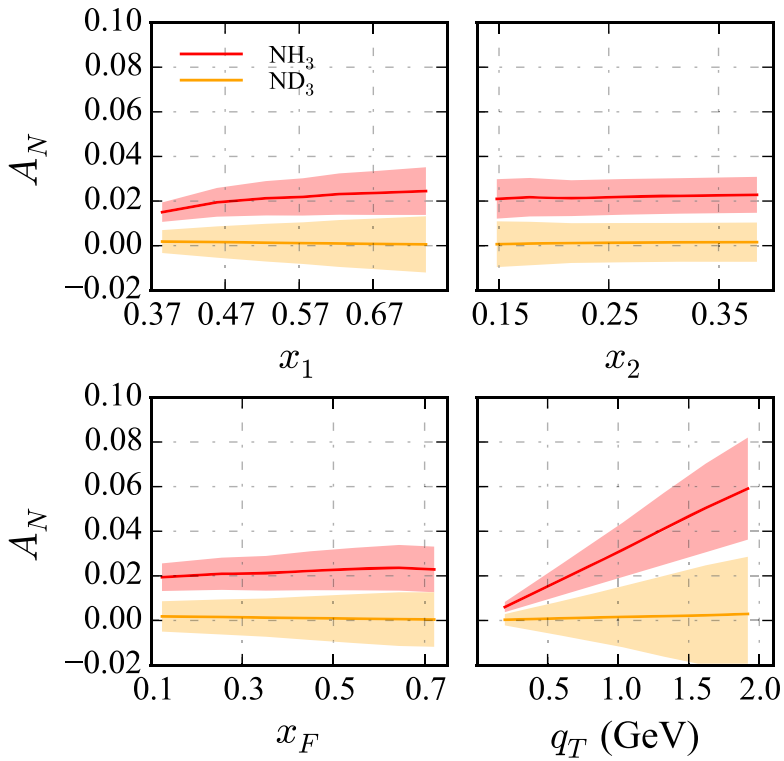
DNN-Based Extraction of Sivers Function

- First-ever DNN-based extraction with all quark flavors in SU(3) — PRD 108 (2023) 054007, I. P. Fernando et al.

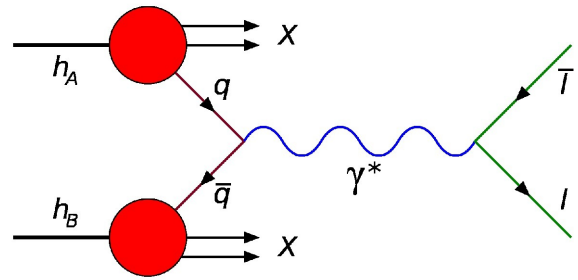
- Extraction from SIDIS data



- Prediction for D-Y @ SpinQuest



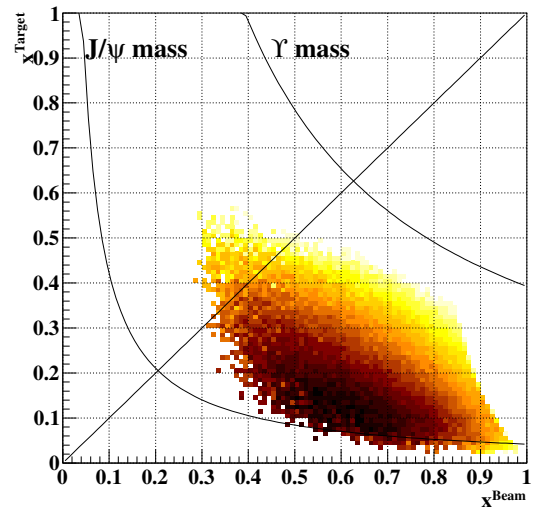
Drell-Yan Process @ SpinQuest



- Production of high-mass lepton pair in hadron+hadron reaction: $p + p \rightarrow \mu^+ + \mu^- + X$
- (Unpolarized) cross section @ LO

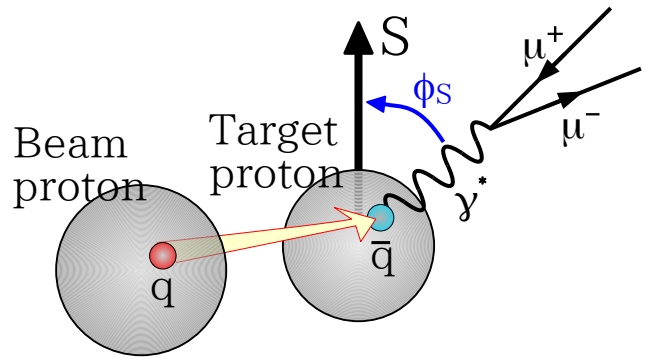
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i {e_i}^2 \cdot \{q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)\}$$

  - Only "$q_i(x_1)\ \bar{q}_i(x_2)$" survives @ forward rapidity — Always anti-quark @ target
  - Distinction of $\bar{q}$ and reconstruction of x event-by-event



Measurement of Drell-Yan TSSA @ SpinQuest

- Proton beam + Transversely-polarized NH_3 & ND_3 targets



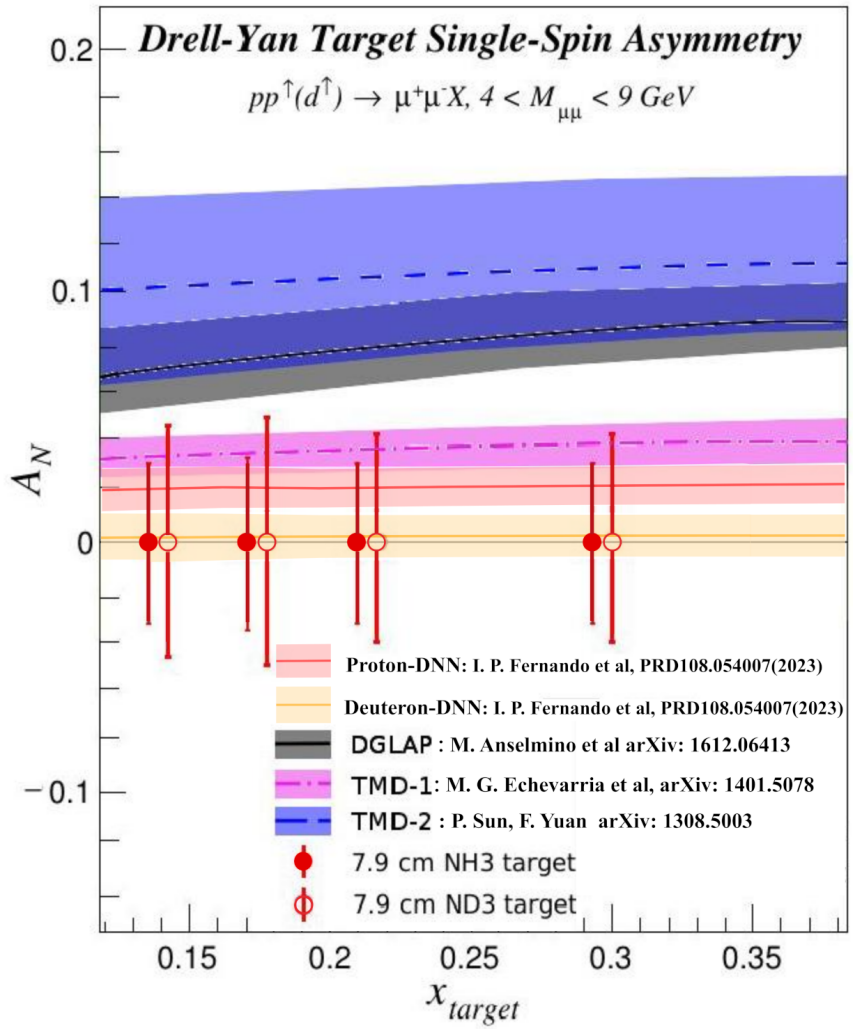
  - $\phi_S \sim$ Azimuth of proton spin to muon pair (=virtual photon)
  - Polarized cross section: $\sigma^{\uparrow}(\phi_S) \sim F^1_{UU} + S_T \ \sin\phi_S \ F^1_{UT}$
  - Structure function: $F^1_{UT} \sim \frac{\boldsymbol{q}_T \cdot \boldsymbol{k}_{T,1}}{q_T M_p} f_1(x_1, k_{T,1}) \, \bar{f}^{\perp}_{1T}(x_2, k_{T,2})$
- Observable: Transverse Single Spin Asymmetry (TSSA): A_N

$$A_N(\phi_S) \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)} \sim \frac{f(x_1) \cdot \bar{f}^{\perp}_{1T}(x_2)}{f(x_1) \cdot \bar{f}(x_2)}$$

  - $\sin\phi_S$ modulation $\Longrightarrow$ Non-zero $f^{\perp}_{1T}(x_2)$
- Sivers function of anti-quarks
  - Combined analysis of TSSAs in $p + \vec{p}$ & $p + \vec{d}$ $\Longrightarrow$ Separation of $\bar{u}$ & $\bar{d}$

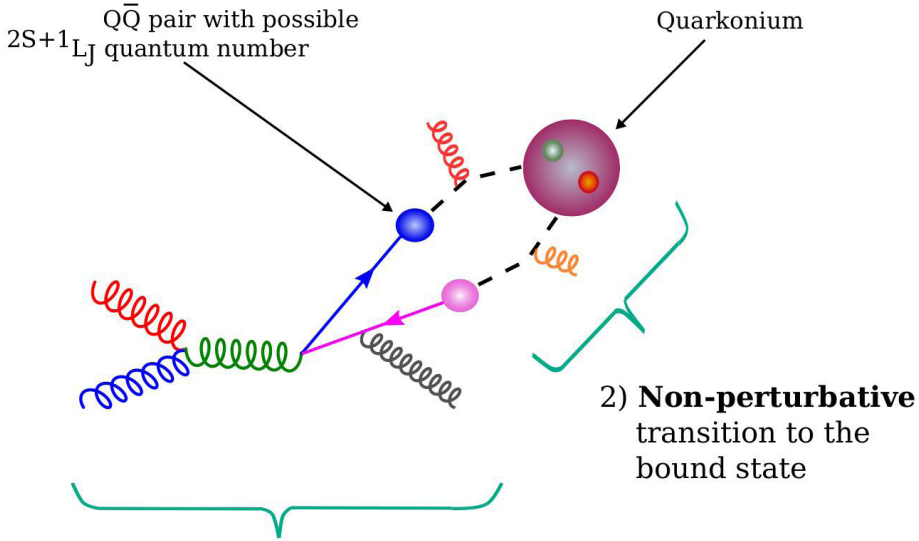
Anticipated Sensitivity

- Measurement condition
  - Two years of data taking
  - NH_3:ND_3 = 50%:50% in time
  - Details in the E1039 proposal
- Transverse Single-Spin Asymmetry (TSSA): A_N
  - $0.1 \lesssim x_{Target} \lesssim 0.3$
  - Precision $\delta_{A_N} \sim 0.04$
- Aim to observe non-zero anti-quark Sivers asymmetry!!
- Key requirement:
  High & stable polarization under high beam intensity
  - Since the cross section of Drell-Yan process is small



J/ψ Productions in $p+p$

- $p+p \to J/\psi + X$

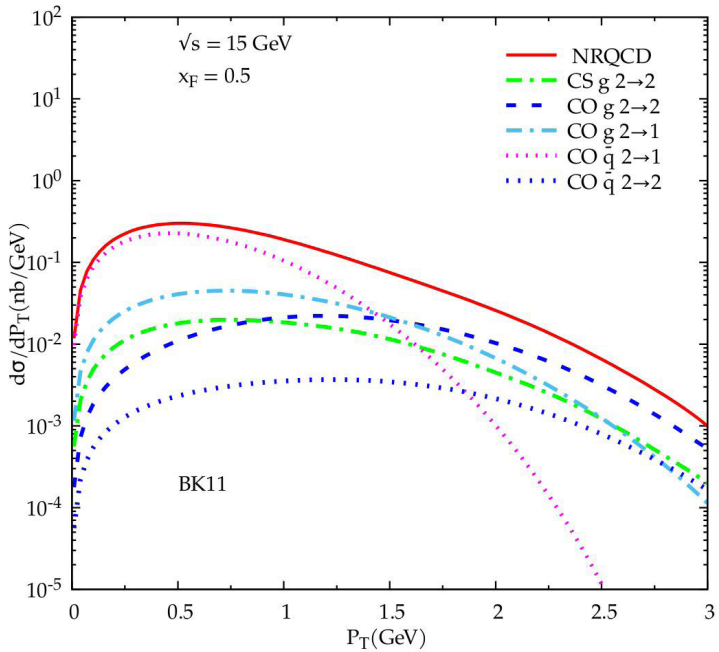


  - $g+g \to c+\bar{c}+X$
  - $q+\bar{q} \to c+\bar{c}+X$

  - Color Evaporation Model (CEM) ... NPB 405, 507 (1993)
    - $$\frac{d\sigma_{J/\psi}}{dx_F} = F_{J/\psi} \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM \frac{2M}{s\sqrt{x_F^2 + 4M^2/s}} f_i(x_1) f_j(x_2) \sum_n \hat{\sigma}_{ij\to c\bar{c}[n]}(x_1, x_2)$$
  - Non-Relativistic QCD (NRQCD) ... arXiv:2103.11660
    - $$\frac{d\sigma_{J/\psi}}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_1 dx_2 \delta(x_F - x_1 + x_2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij\to J/\psi}(x_1, x_2)$$
    - $\hat{\sigma}_{ij\to J/\psi} = \sum_n C^{ij}_{c\bar{c}[n]} \left\langle \mathcal{O}_n^{J/\psi} \right\rangle$

J/ψ @ SpinQuest

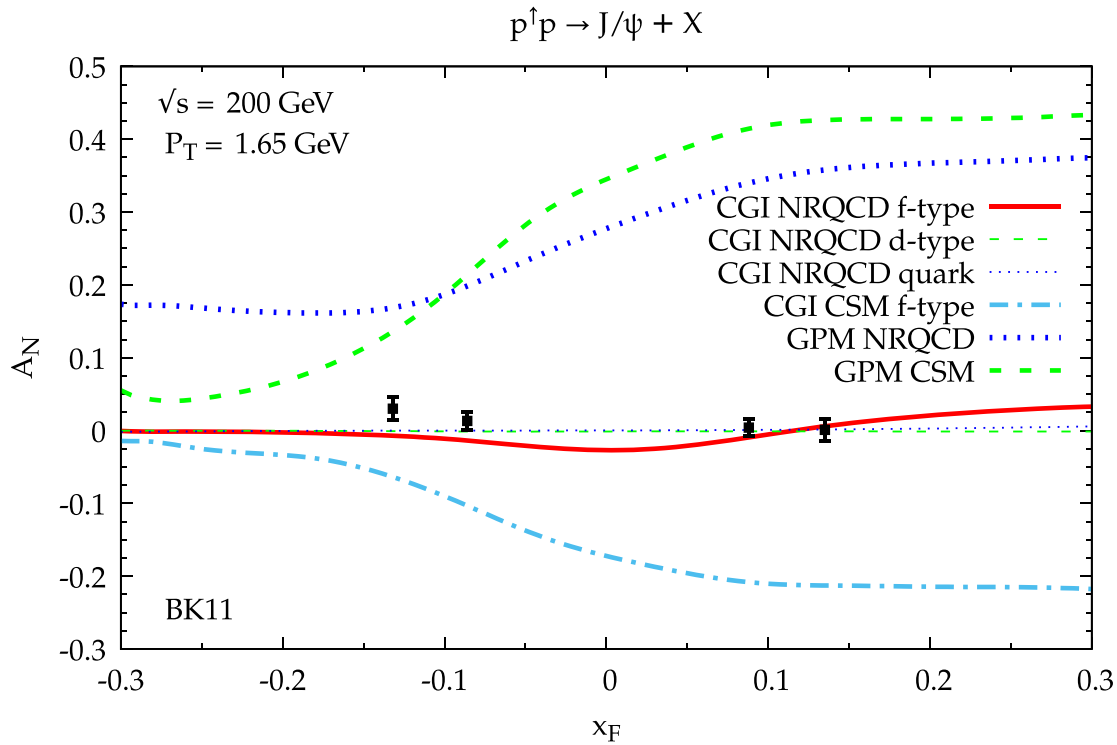
- Cross section
  - Based on NRQCD — D'Alesio *et al.*, PRD 102, 094011; https://spin.physics.virginia.edu/wiki/spinquest/seminars



  - Subprocess fractions vary with p_T largely
  - Sensitive to distributions of anti-quarks and gluons (at target side)

Transverse Single Spin Asymmetry of J/ψ

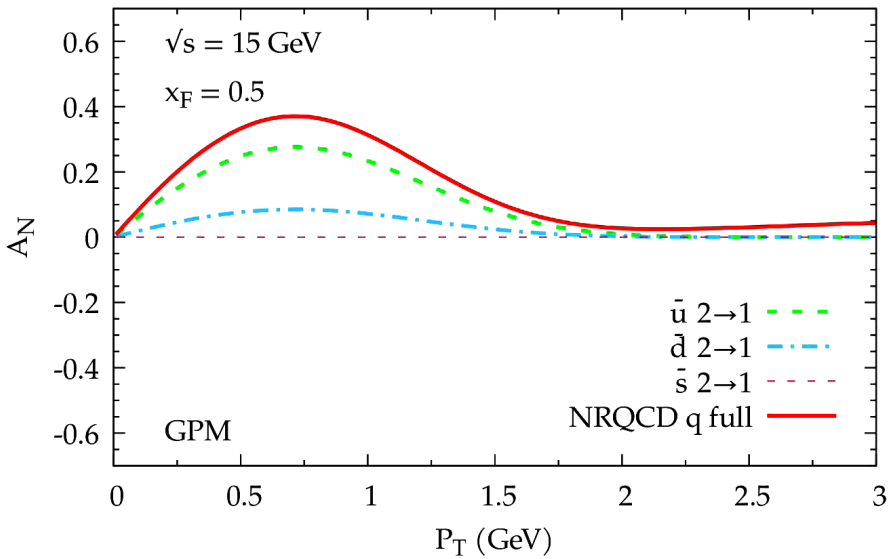
- Sensitive to the Sivers functions of antiquark & gluon
- Measurement at RHIC-PHENIX — PRD 98, 012006 (2018)
  - $\sqrt{s} = 200$ GeV, $x_F \sim 0.1$
  - Theoretical estimate of maximum TSSA — D'Alesio *et al.*, PRD 102, 094011

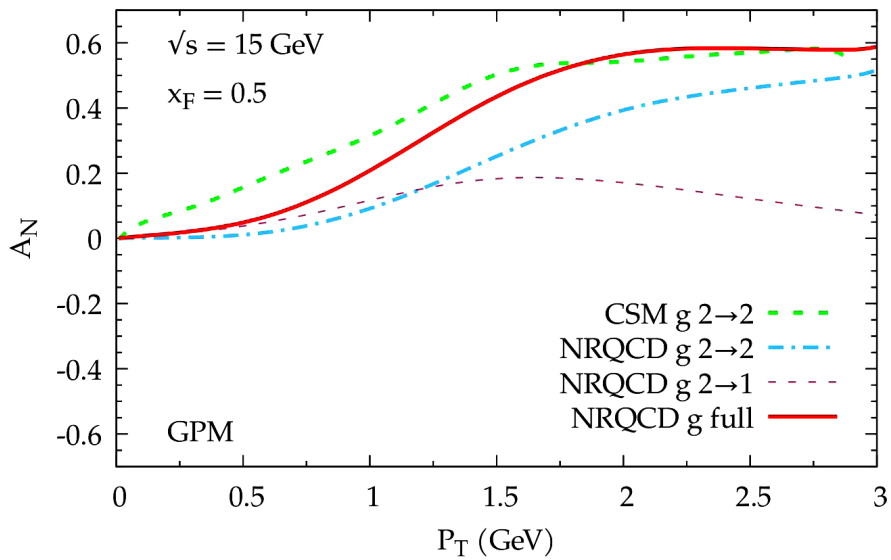


Measurement of J/ψ TSSA @ SpinQuest

- Theoretical estimate of max Sivers asymmetry
  - $\sqrt{s} = 15$ GeV, $x_F \sim 0.5$

D'Alesio *et al.*, PRD 102, 094011





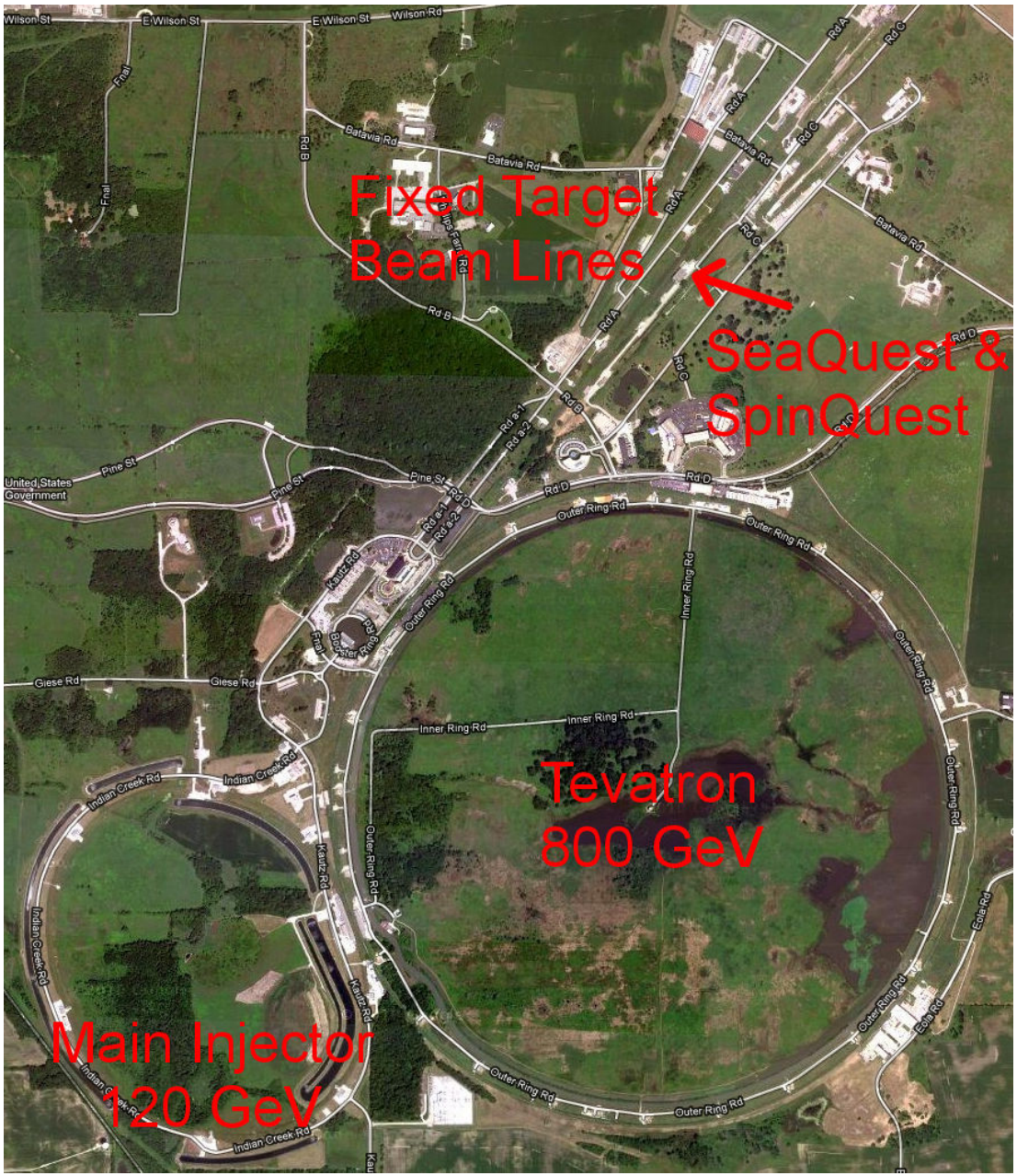
  - As large as $\mathcal{O}(0.1)$
  - Sensitivity to antiquarks at low p_T & gluons at high p_T
- Unique measurement in terms of $\sqrt{s}$ & x_F

SpinQuest Schedule

Year	Month	Event
2023		Commissioning of spectrometer using cosmic rays
2024	03	Lab safety approval for switchyard beam operation
	05	Delivery of first proton beam to SpinQuest
	05-07	Commissioning of target & spectrometer using beam
2026	09-12	First dedicated physics data taking
2027	01	Long accelerator shutdown
		$\Downarrow$ 2 years
2029-		Second physics data taking & More programs

- Carried out the beam commissioning in May-July 2024
  - Improvements about stability & efficiency of system operation
  - Acquisition of "asymmetry" data
    - With NH_3 target polarized
    - With spectrometer fully operational
  - Data analysis & system upgrades are ongoing

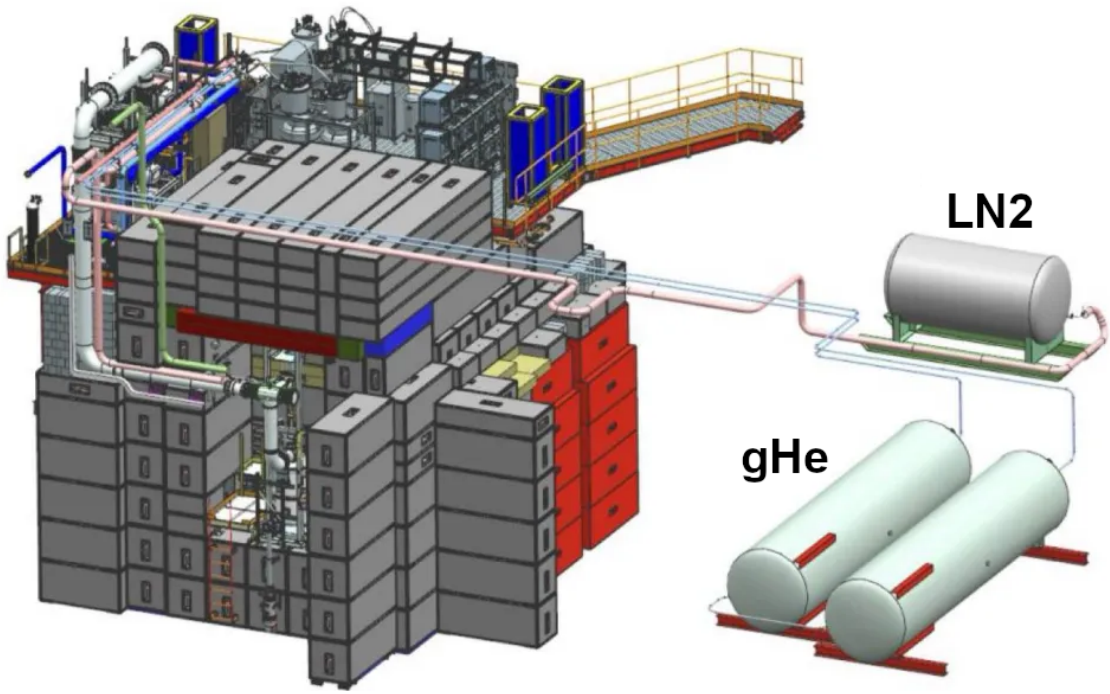
Proton Beam for SpinQuest @ FNAL



- From Main Injector
- Unpolarized
- Energy $E = 120$ GeV
  ($\sqrt{s} = 15$ GeV)
- Bunch
  - Interval: 19 nsec (53 MHz)
  - $\sim$10k protons per RF bucket
  - $\sim 2 \times 10^{12}$ protons
    per spill (in 4 sec)
- Duty cycle
  - 4 sec for SpinQuest
  - 56 sec for ν exp.

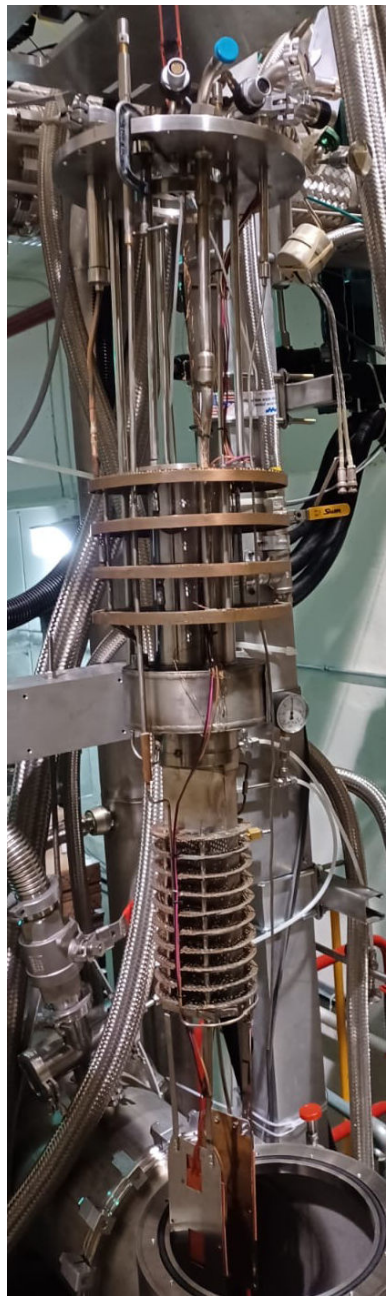
SpinQuest Target System

- Target cryostat in “Cave”
  - Surrounded by concrete blocks for radiation shielding
  - Evaporation fridge at $T \approx 1$ K & $B = 5$ T
- On “Cryo Platform”
  - Helium liquefaction plant
  - Roots pump for evaporation fridge
- Gaseous helium tank at outside
  - Closed helium system



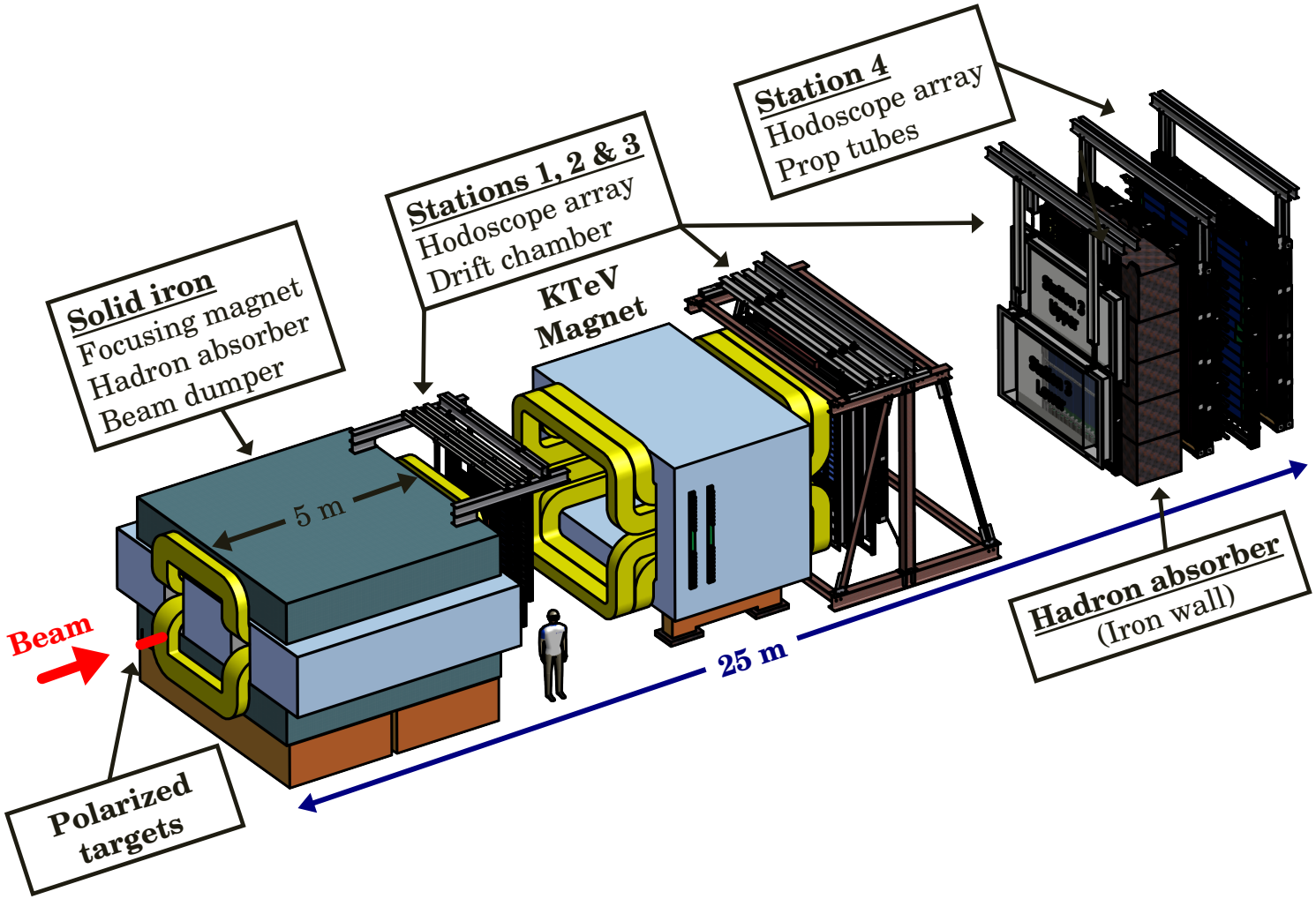
Vacuum Chamber Top

Fridge



Insert

SpinQuest Spectrometer

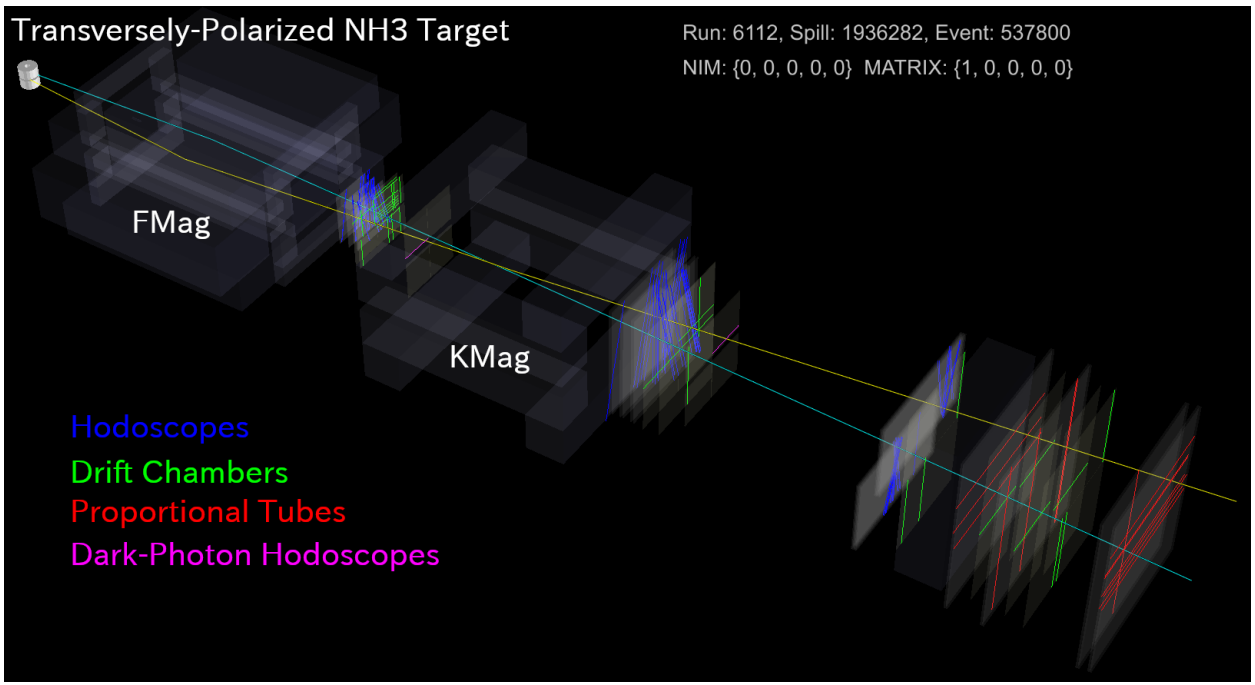


- Target: Transversely-polarized NH_3, ND_3
- Focusing magnet (FMag) & Tracking Magnet (KMag)
- Iron core of FMag = Hadron absorber & Beam dump


BAD

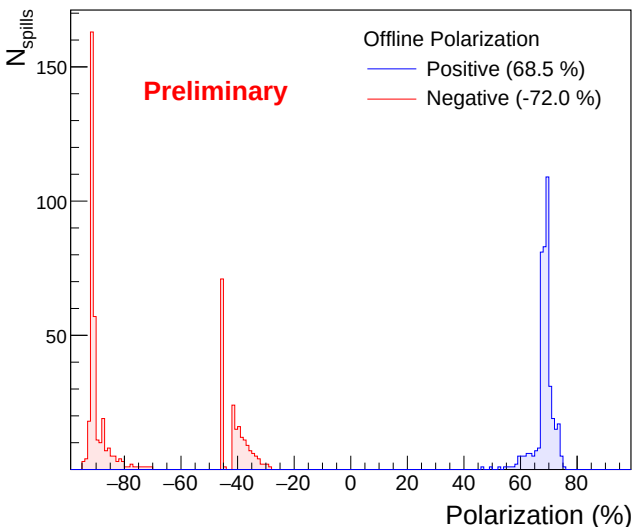
Dimuon Detection & Reconstruction

- Trigger for high-mass unlike-sign dimuons
  - Based on hodoscope hit pattern
  - For both J/ψ & Drell-Yan
- Event reconstruction
  - Tracking from downstream using the Kalman filter
  - A typical high-mass dimuon event



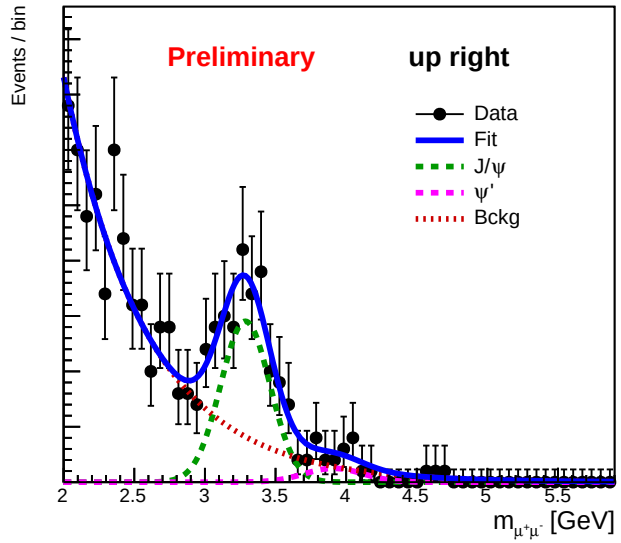
Data Taking

- About 900 spills (15 hours) of "asymmetry" data were recorded in 3 nights
  - With the spectrometer magnets (FMag & KMag) on
  - With the target material (NH_3) polarized
  - Limited by the capacity of the cooling water system for the magnets & the helium liquefier
- Polarization
  - $|P| \sim 70\%$
  - Similar amounts of data (spills) for positive & negative directions



Measured Mass Distribution

- Dimuons in the right detector half with the target spin up



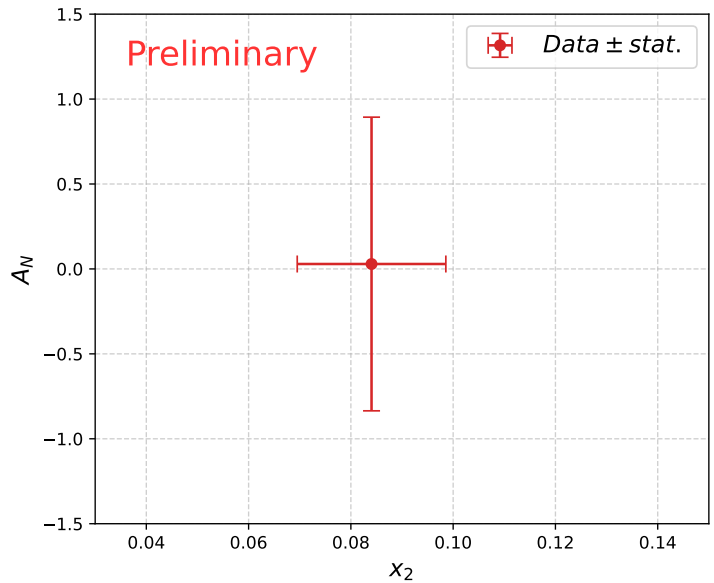
  - Clear J/ψ peak
  - Also measured in the other combinations of detector half & target spin
- J/ψ yields
  - Extraction using functional-form fitting
  - Use of the "cross-ratio" formula to derive left-right asymmetry

$$A_N^{raw} \equiv \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$$

Measured TSSA

- Left-right asymmetry: $A_N = \dfrac{A_N^{raw}}{\langle P \rangle \cdot f \cdot \eta}$

$$A_N^{raw} \equiv \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$$



  - Large statistical error, due to the limited data taking (15 hours)
  - First successful extraction of TSSA from the SpinQuest real data!!
- Improvements in data analysis and future data taking are ongoing
  - Expect to achieve at least 10× smaller error in the 1st physics data taking

Prospects

- Improvements for data taking in 2026
  - New cooling water supply for the target system
  - Fast target spin manipulation (AFP)
  - Extraction of $\sin\phi_S$ modulation
  - Modeling of background muons
- Future data taking

2029	Second physics data taking for polarized proton
2030	Start physics data taking for polarized deuteron
2031	Start transversity program runs
	in parallel with the dark sector physics program

  - Transversity Program
    - Using both vector and tensor polarized deuteron target
    - FNAL stage-1 approval in March 2025
  - "DarkQuest": Dark-photon search

Conclusions

- SpinQuest
  - Sivers function of anti-quarks in proton
  - High-intensity 120-GeV proton beam @ FNAL
  - Transversely-polarized NH_3 & ND_3 targets
  - TSSA of Drell-Yan process & J/ψ production
- Commissioning run in 2024
  - All target & spectrometer subsystems worked
  - 900 spills (15 hours) of "asymmetry" data
  - Polarization $|P| \sim 70\%$
- Analysis of commissioning data
  - Clear J/ψ mass peak
  - Successful extraction of J/ψ TSSA
- Preparation for the physics data taking in 2026

- If you are interested in SpinQuest, please contact me or spokespersons;
  - Dustin Keller (UVA, dustin@virginia.edu) & Kun Liu (LANL, liuk@lanl.gov)
- This work is supported by DOE contract DE-FG02-96ER40950