Insights from the SpinQuest Experiment after the First Commissioning Run

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(ON BEHALF OF THE SPINQUEST COLLABORATION)

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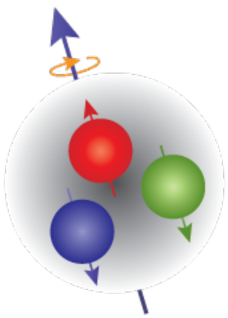
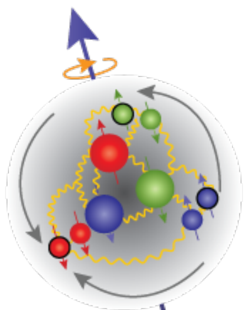
Proton Spin

How the nucleon's spin is built up from its quark and gluon constituents?



1980s

Naive quark model (only valence quarks)



Now

2 major formulations of the decomposition:

Infinite-momentum frame decomposition (Jaffe-Manohar sum rule)

$$J = \frac{1}{2}\Delta\Sigma + L_q^{JM} + \Delta G + L_G,$$

- $\frac{1}{2}\Delta\Sigma$: $q\,,\bar{q}$ spin (valence and sea)
- L_q^{JM}: $q\,,\bar{q}$ OAM
- ΔG: gluons spin
- L_G: gluons OAM

- Measured experimentally
- Challenge for lattice QCD

Frame independent decomposition (Ji's sum rule)

$$J = \frac{1}{2}\Delta\Sigma + L_q^{Ji} + J_G,$$

- J_G: gluons total AM

- EMC experiment $\Rightarrow \int_0^1 dx\Delta\Sigma(x) \approx 0.06$

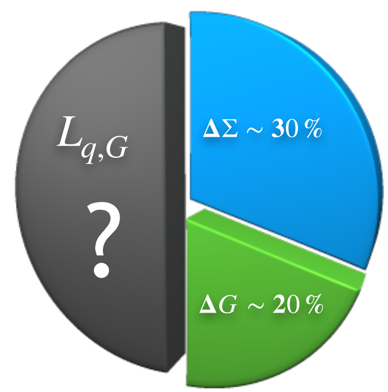
  [E. Leader and M. Anselmino, Z. Phys. C 41 , 239 (1988)]

- COMPASS, HERMES $\Rightarrow \int_0^1 dx\Delta\Sigma(x) \approx 0.3$

  [V. Y. Alexakhin et al. (COMPASS Collaboration), Phys.Lett. B 647, 8 (2007)]
  [A. Airapetian et al. (HERMES Collaboration), Phys.Rev. D 75, 012007 (2007)]

- PHENIX, STAR, COMPASS $\Rightarrow \int_{0.05}^{0.2} dx\Delta G(x) \approx 0.2$

  [D. de Florian et al (DSSV Collaboration). Phys Rev. Lett. 113, 012001 (2014)]
  [E. R. Nocera et al. (NNPDF Collaboration), Nuc. Phys. B 887, 276 (2014)]



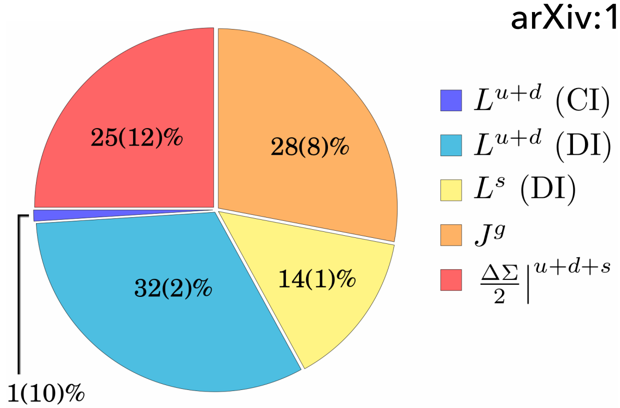
The sum of both quark and gluon spin contributions still cannot account for the total proton spin.

Proton Spin

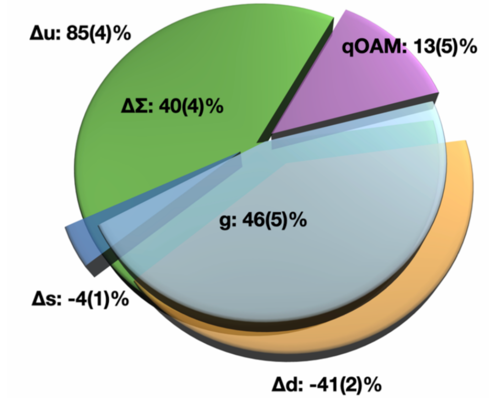
Insight into OAM contribution and transverse momentum

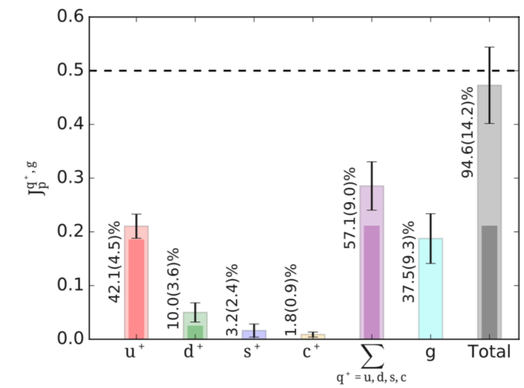
- Proton spin contributions from lattice QCD

arXiv:1504.0



arXiv:2112.08416



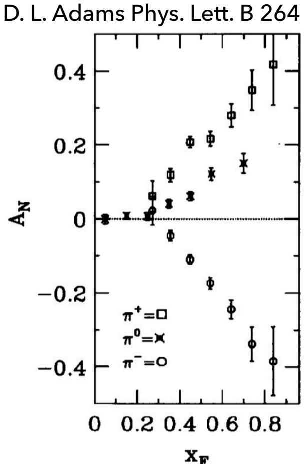


- near **50%** comes from quarks OAM
- **50%** comes from OAM: 38 - 46 (20) % gluons
  13 - 18 (50) % quarks

sea
valence

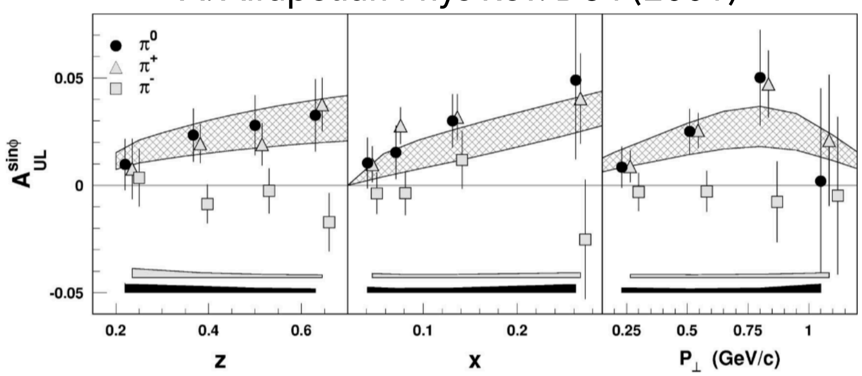
- Experimental hints at OAM

D. L. Adams Phys. Lett. B 264 (1991)



$pp^\uparrow \to \pi X$ at E704

A. Airapetian Phys Rev. D64 (2001)



Unpolarized pion electro production at HERMES

significant azimuthal asymmetries, which are directly related to the transverse momentum of the partons

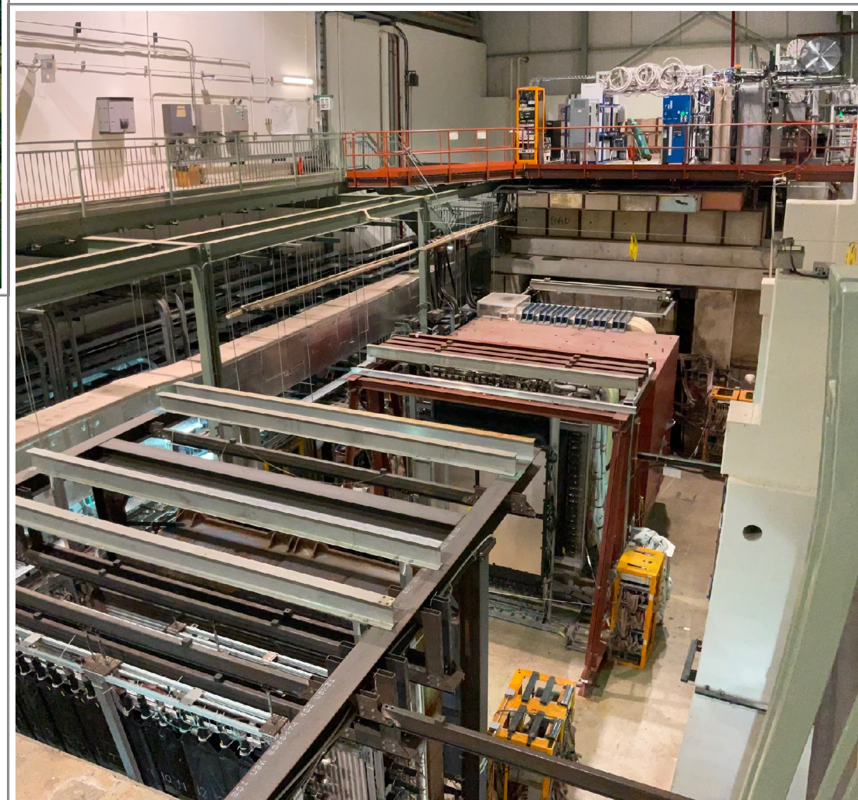
potentially large OAM

SpinQuest (E1039) at a glance

Polarized Drell-Yan Fixed target experiment.

120 GeV Fermilab unpolarized proton beam energy.

Sensitive to $\bar{u}$ and $\bar{d}$ Sivers function.



Physics Goals:

Probe spin/orbit effects (OAM) of sea quarks.

TSSA J/ψ production, additional sensitivity to the gluon Sivers function in the nucleon.

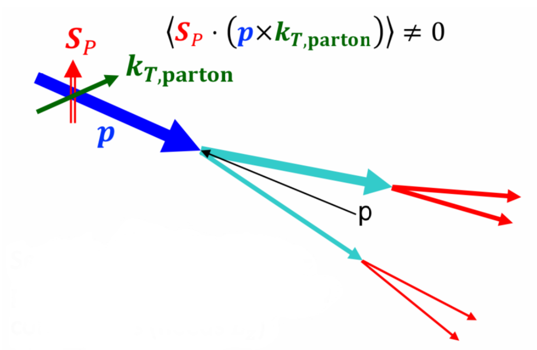
3D Partons Momentun Distributions.

TMDs Sivers function

Sivers function

Sivers function $f_{1T}^{\perp}(x, \mathbf{k_T})$: Describes the correlation between the transverse momentum direction of the struck quark and the spin of its parent nucleon.

$$f_{q/p^{\uparrow}}\left(x, \mathbf{k_T}\right) = f_{q/p}\left(x, \mathbf{k_T}\right) + f_{1T}^{\perp}\left(x, \mathbf{k_T}\right) \mathbf{S_P} \cdot \left(\hat{\mathbf{p}} \times \hat{\mathbf{k}}_{\mathbf{T}}\right)$$

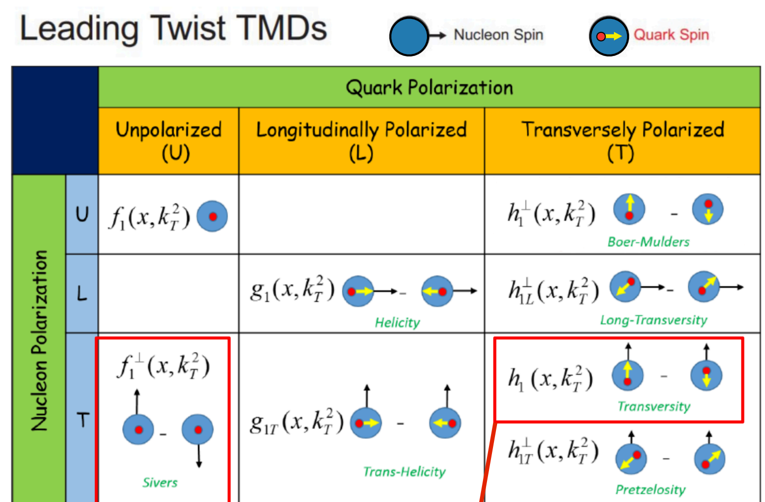


... k_T distribution of the partons could have an azimuthal asymmetry, when the hadron was transversely polarized.

D. Sivers, Phys. Rev. D41 (1990) 83

spin-orbit correlation

XX-th International Workshop on Hadron Structure and Spectroscopy / 5-th Workshop on Correlations in Partonic and Hadronic Interactions
Armenia 09/30/24 - 10/04/24



Extension
https://arxiv.org/abs/2205.01249

- The existence of the Sivers function requires non-zero quark orbital angular momentum (OAM).
- There is no model-independent connection between the Sivers distribution and the size of the quark OAM, additional theoretical work is needed to provide a direct connection.

TMDs Sivers function

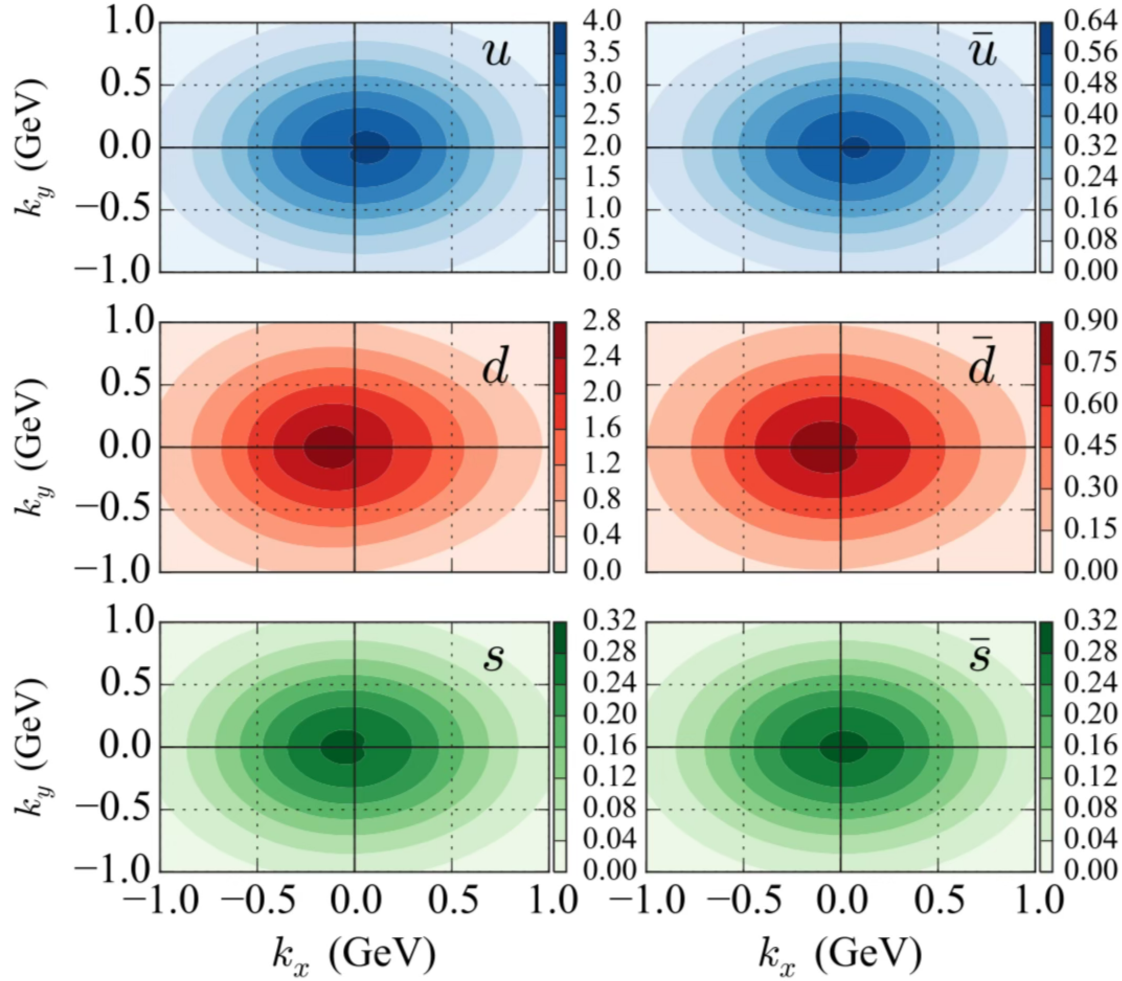
3D momentum imaging

Use Sivers TMD function to map distribution of quarks in 3D momentum space

Quark density distributions from proton-DNN model at x=0.1 and $Q^2 = 2.4\text{GeV}^2$ using global Sivers measurements.

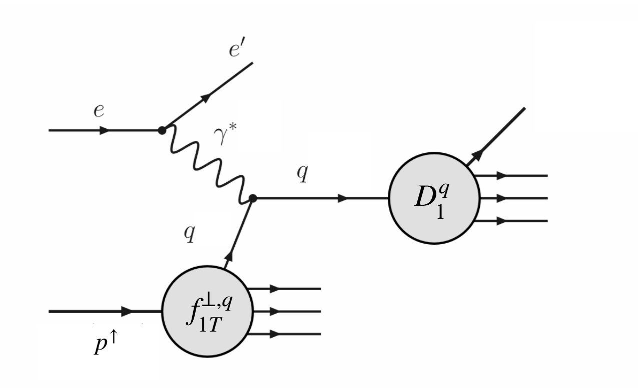
- The observed shifts in each quark flavor are linked to the correlation between the OAM of quarks and the spin of the proton.
- Evidence of nonzero OAM in the wave function of the proton's valence and sea quarks.

I. FERNANDO, D. KELLER PHYS. REV. D **108,** 054007 (2023)



Accessing Sivers function

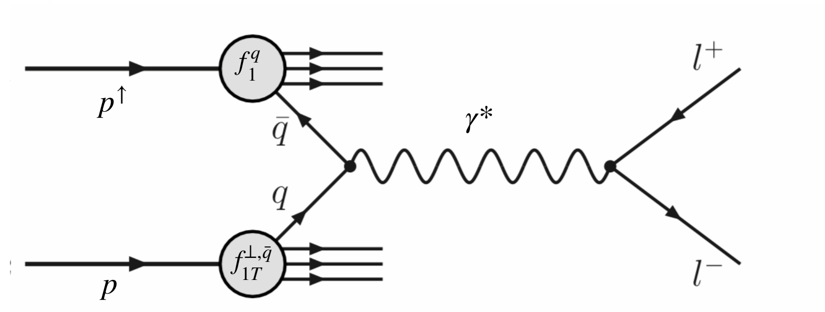
Polarized Semi Inclusive DIS



$$A_{UT}^{\text{SIDIS}} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,k_T) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to Hadron Fragmentation function
- Valence-Sea quark: Mixed

Polarized DY



$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2,k_T) + 1 \leftarrow\rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}$$

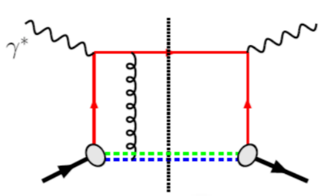
- L-R asymmetry in Drell-Yan production
- No Quark Fragmentation function
- Ability to select valence or sea quark dominated

Cleanest probe to study hadron structure

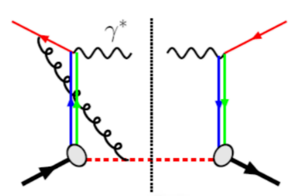
"Modified-universality" of the "Sivers" function

QCD:

DIS	Drell-Yan
Final-state interaction	Initial-state interaction



attractive



repulsive

Courtesy of J. Drachenberg

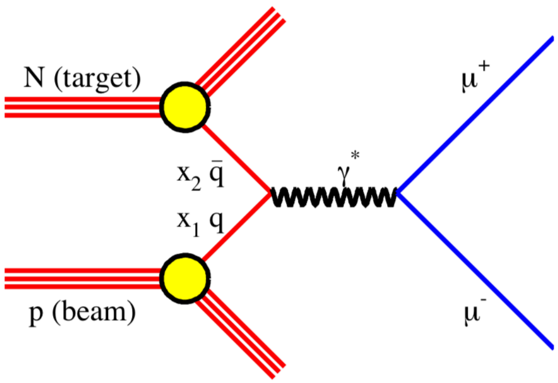
$\text{Sivers}_{\text{DIS}} = -\text{Sivers}_{\text{Drell-Yan}}$

Fundamental prediction of QCD gauge invariance.

One interpretation: ***Repulsive interaction between like color charges!***

Drell-Yan TSSA - SpinQuest Program

Sivers Asymmetry via Proton - induced Drell-Yan Process

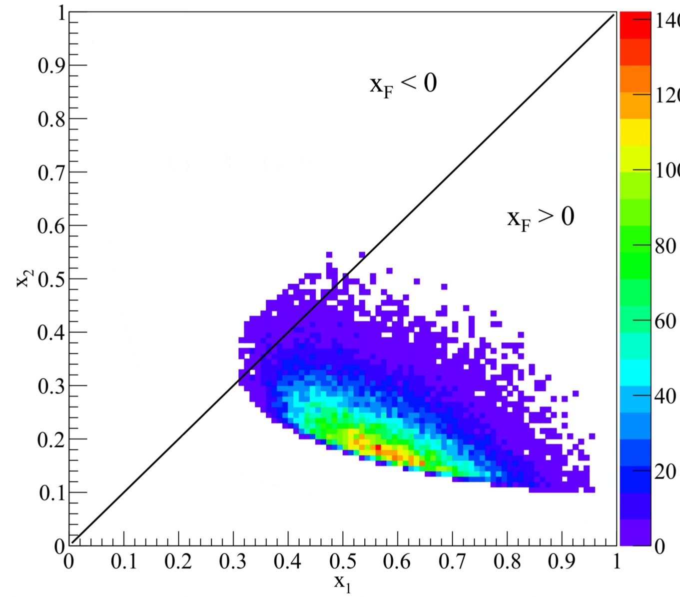


p-p polarized Drell-Yan

Dominated by sea quark
@ forward rapidity

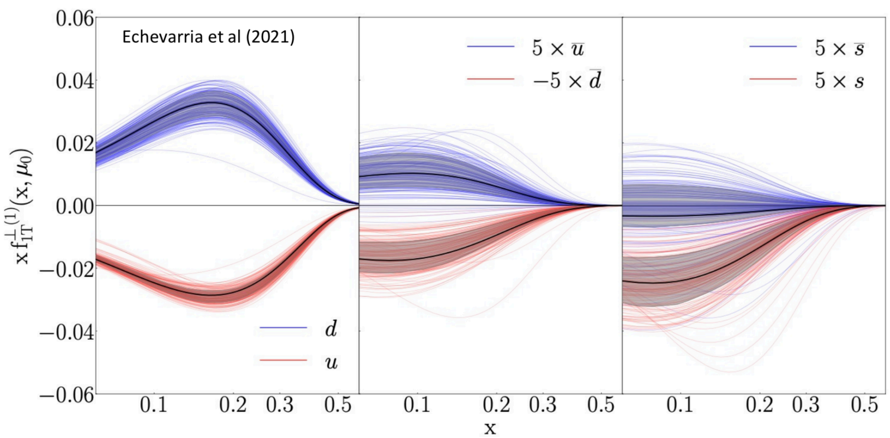
$$A_N^{DY} \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)}$$

$$\propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2, k_T) + 1 \leftarrow \rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow \rightarrow 2 \right]}$$



Acceptance and kinematics optimized for anti-quark component from target → Sea anti-quarks ($\bar{u}$, $\bar{d}$) Sivers functions
Using transversely-polarized targets of NH_3 & ND_3

If non-zero, "smoking gun" for sea quark OAM



Most experimental data are focused on the valence region.

Need for p-p Drell-Yan since you can almost guarantee your are sampling anti-quarks from the target.

Critical to have experiments like SpinQuest that tackle the sea!

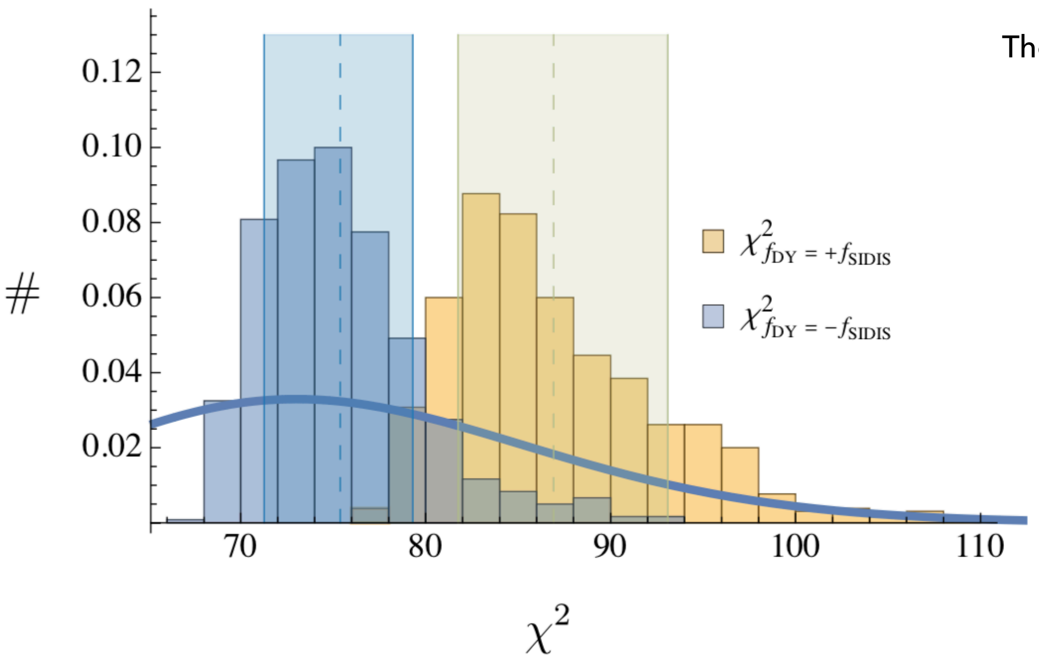
Drell-Yan TSSA - SpinQuest Program

Sivers function sign change

A direct QCD prediction is a Sivers effect in the Drell-Yan process that has the opposite sign compared to the one in semi-inclusive DIS:

$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = - f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

Bury et al, PRL 126, 112002 (2021)



Quote from Bury et al

... to clearly distinguish sign-flip/non-sign-flip scenarios, one needs the data with more substantial restrictions on the sea contribution, such as DY and kaon-production in SIDIS.

These results are in agreement with Anselmino et al, arXiv: 1612.06413

Sign-change is preferred but not nearly confirmed!

Still statistics (and kinematics) limited

Complementary to future EIC sea-quark Sivers function measurements in SIDIS.

Drell-Yan TSSA - SpinQuest Program

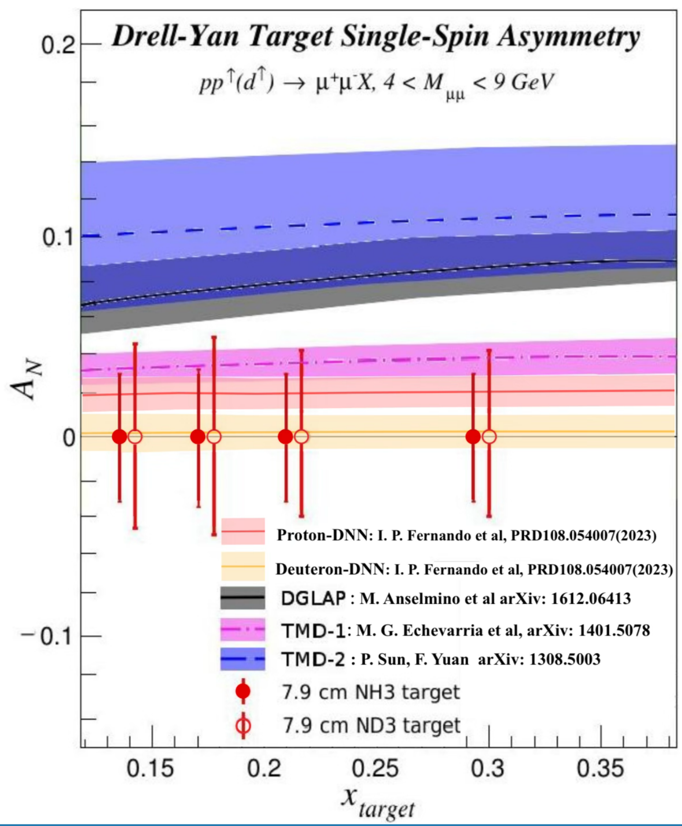
Projected sensitivity and asymmetry

Transverse Single-Spin Asymmetry (TSSA): A_N

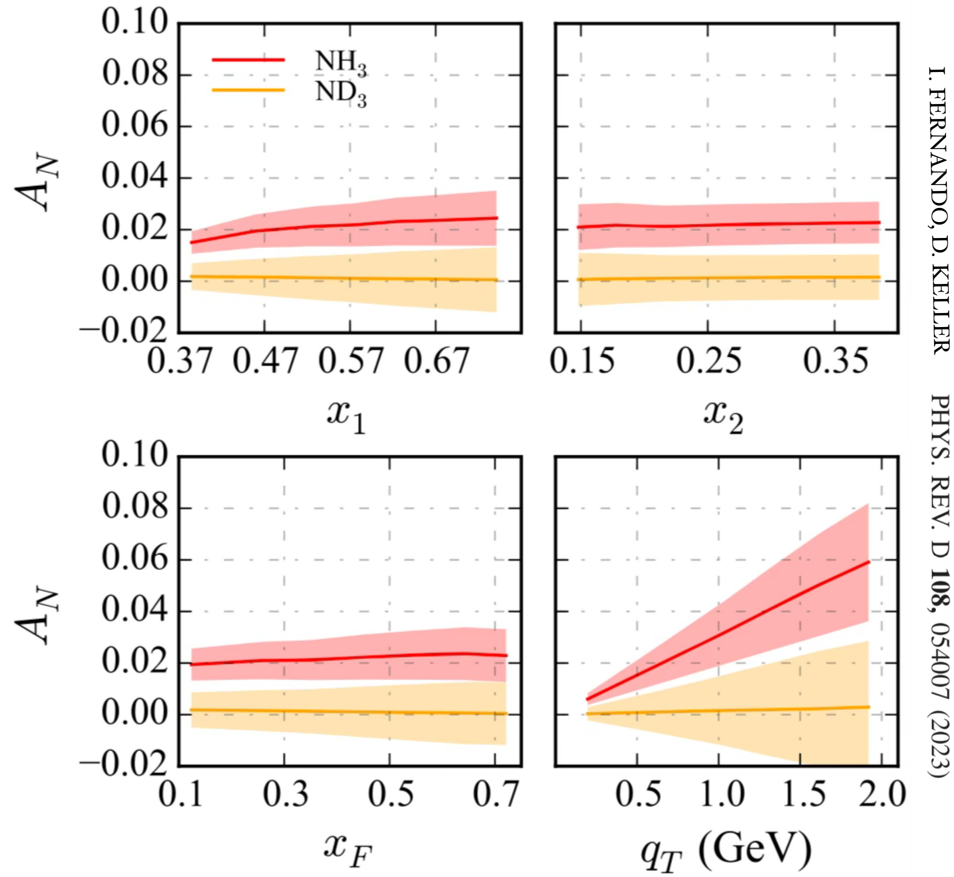
- $0.1 \lesssim x_{Target} \lesssim 0.3$
- Precision $\delta A_N \sim 0.04$

Measurement conditions (Details in the E1039 proposal)

- Two years of data taking.
- NH3:ND3 = 50%:50% in time



Proton and deuteron-DNN model projections for the SpinQuest DY kinematics



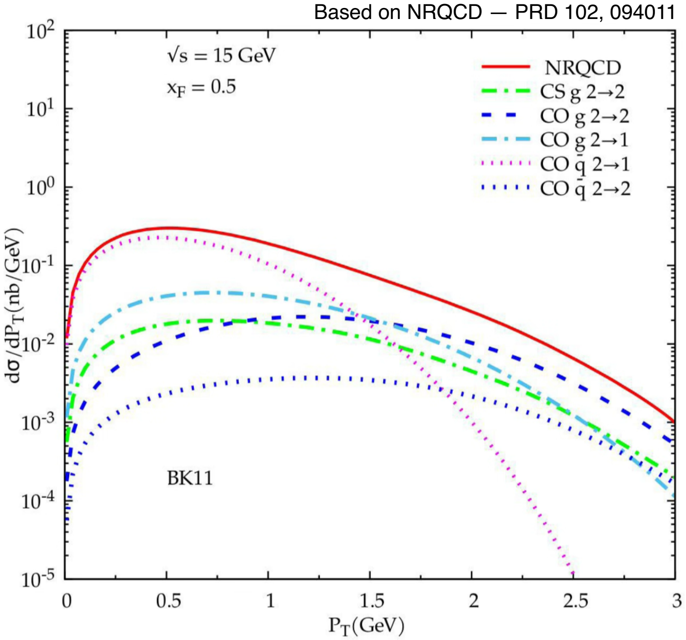
Important constraints on global models

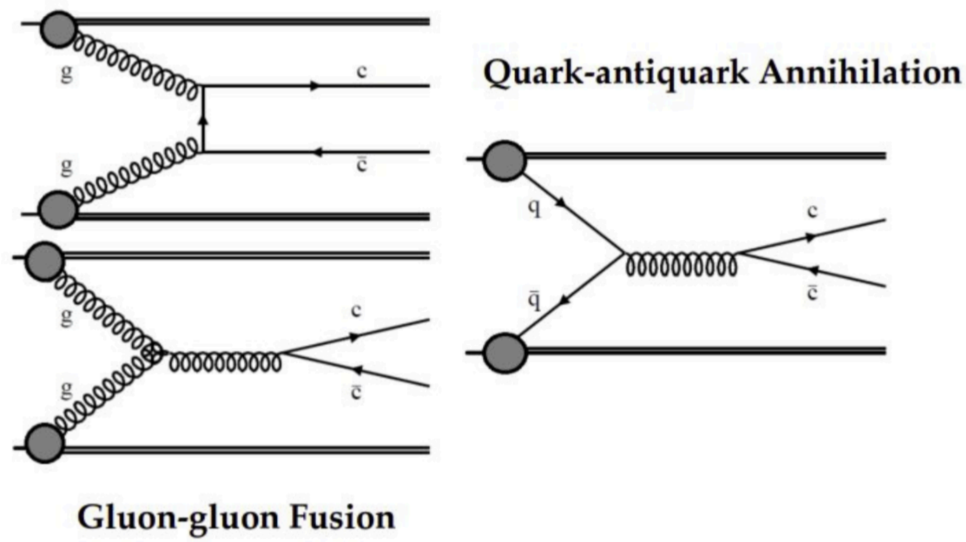
J/ψ TSSA - SpinQuest Program

J/ψ Production

- J/ψ is bound charm-anticharm pair, a "charmonium".

Based on NRQCD — PRD 102, 094011





- Subprocess fractions vary largely with p_T.
- Sensitive to both the $q\bar{q}$ and gg production channels.

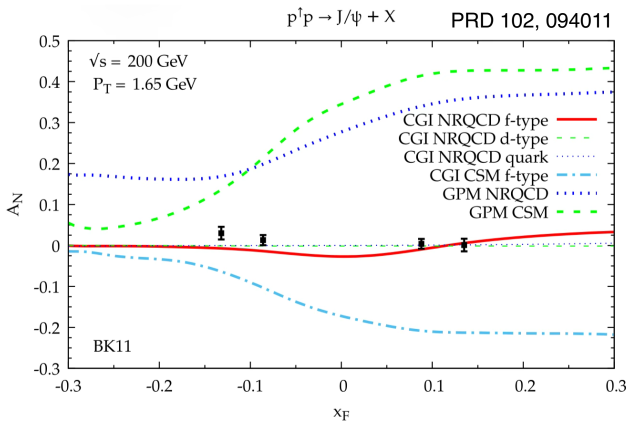
This is our "Day 1" physics program, as we can measure this asymmetry in just a few weeks due to the much higher production cross section compared to Drell-Yan.

J/ψ TSSA - SpinQuest Program

Transverse Single Spin Asymmetry

- Data exists for this TSSA from RHIC-PHENIX –PRD 98 012006–@ $\sqrt{s}$ = 200 GeV, x_F ~ 0.1 .

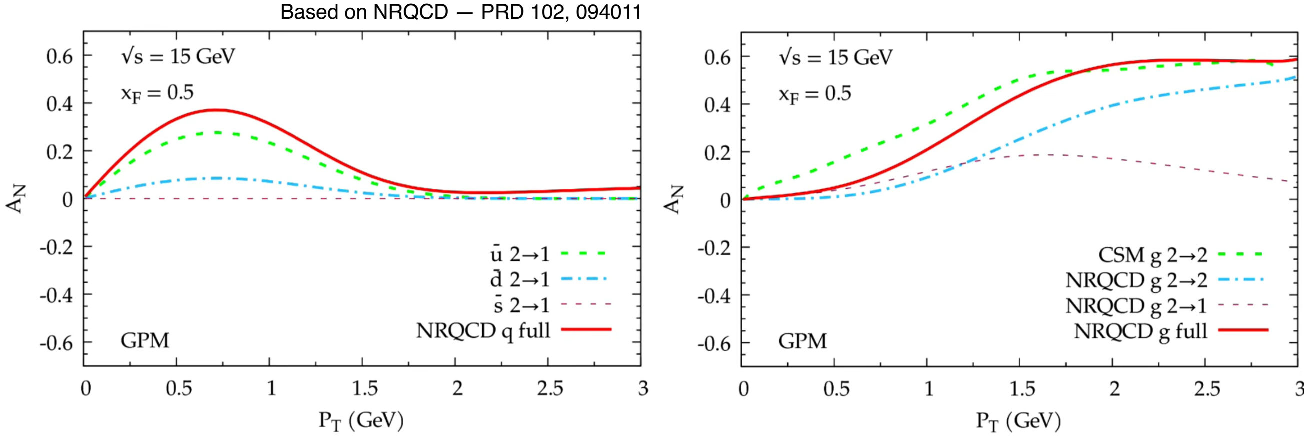
PRD 102, 094011



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

- Theoretical estimate of max Sivers asymmetry @ SpinQuest – $\sqrt{s}$ = 15 GeV, x_F ~ 0.5

Based on NRQCD — PRD 102, 094011

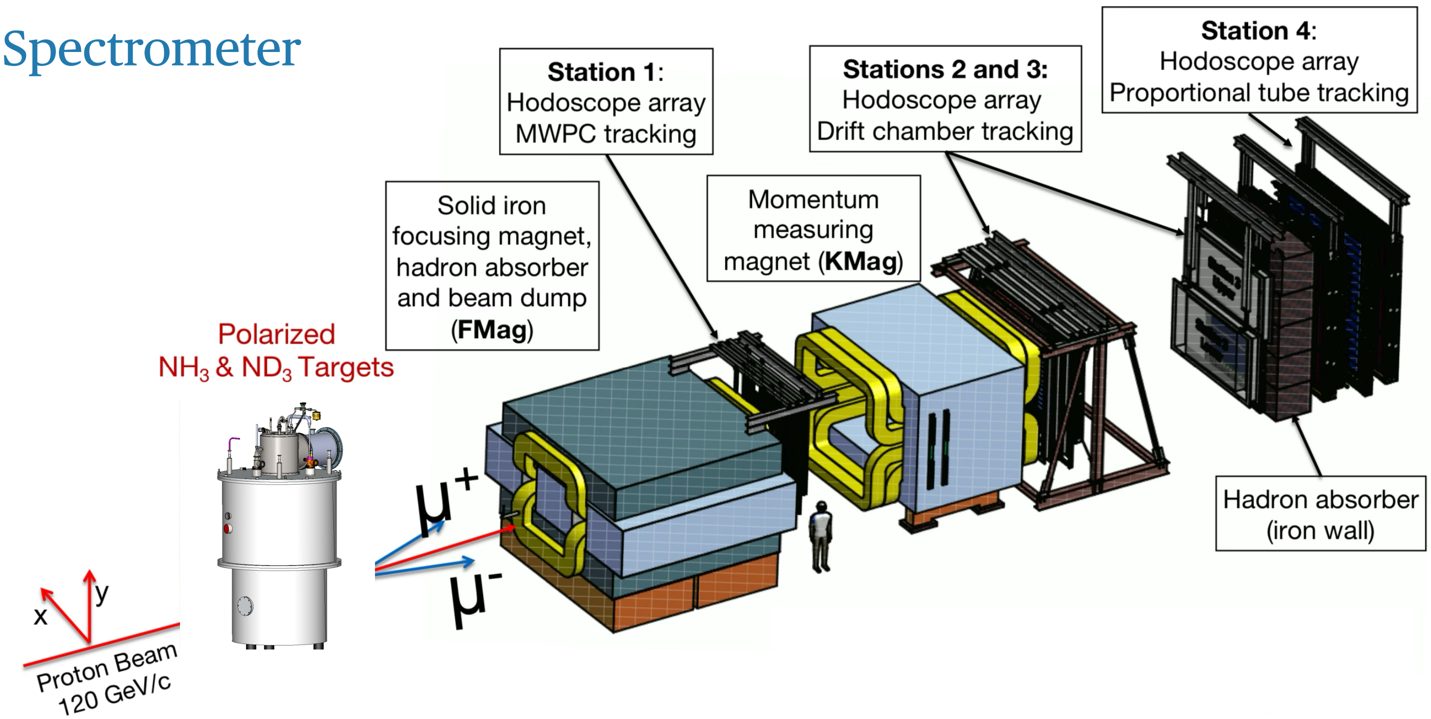


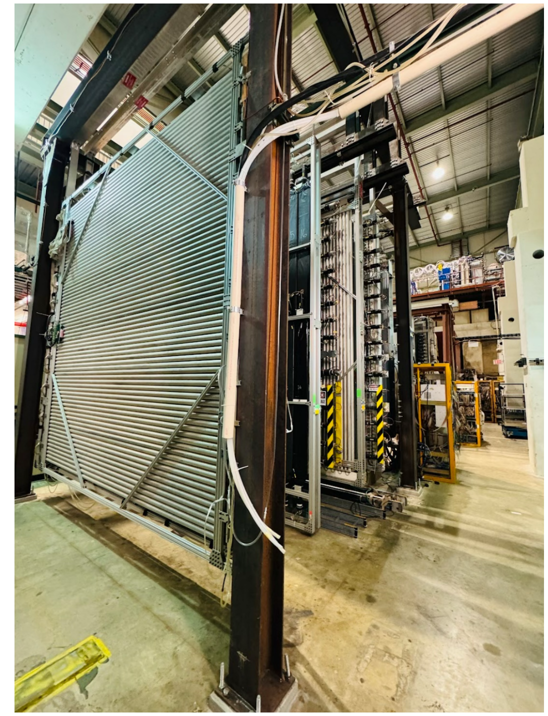
Sensitivity to antiquarks at low p_T & gluons at high p_T

Unique measurement in terms of $\sqrt{s}$ & x_F.

SpinQuest Experiment

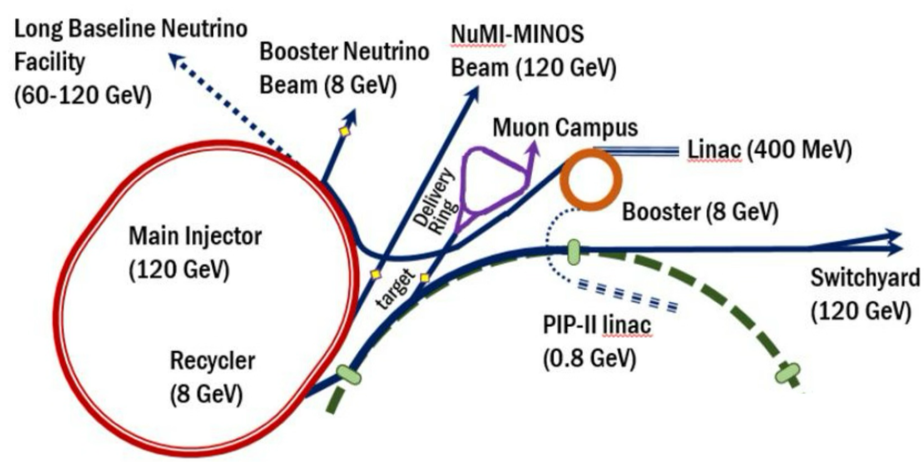
Spectrometer





Beamline @ Fermilab

- Unpolarized protons are sent from the Main Injector.
- Energy 120 GeV ($\sqrt{s}$ =15.5 GeV)
- Duty cycle: ○ **4s spill for SpinQuest** ○ 56s for neutrinos
  - Interval of 19 ns (53MHz)
  - ~10k protons per RF bucket.
  - ~ 2×10^{12} protons/spill.



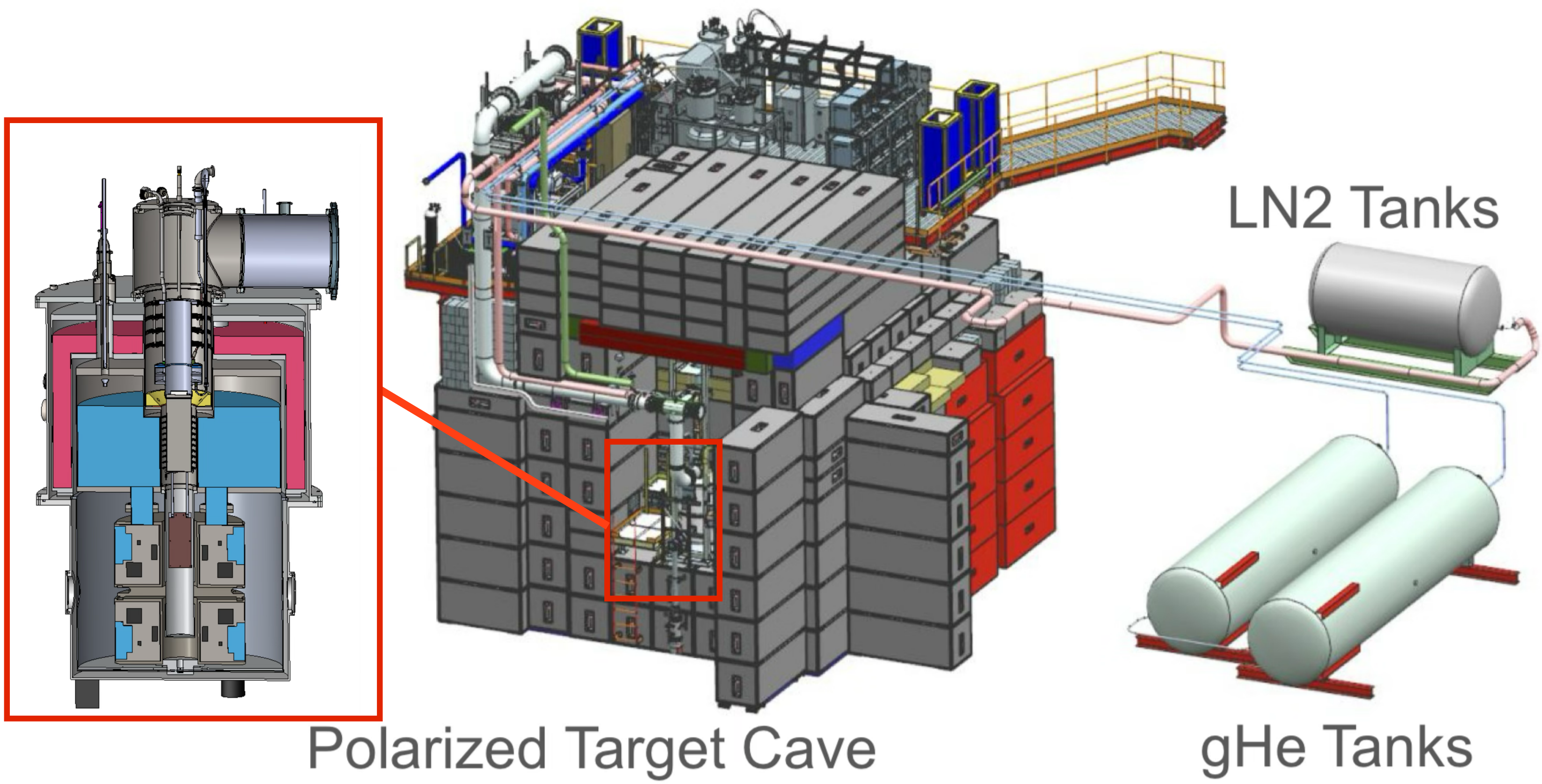
Highest proton intensity ever attempted on a solid polarized target of ~3 x 10^{12} p/spill

(~ $2 \times 10^{35} cm^{-2} s^{-1}$)

SpinQuest Experiment

Target System

- Target cryostat in "Cave"
  - Surrounded by concrete blocks for radiation shielding ○ Evaporation fridge at T≈1K & B=5T
  - Turbo pumps for insulating vacuum
- On "Cryo Platform"
  - Helium liquefaction plant ○ Roots pump for evaporation fridge
- Closed helium system: Capture and recirculate gHe for sustained running during production data taking.

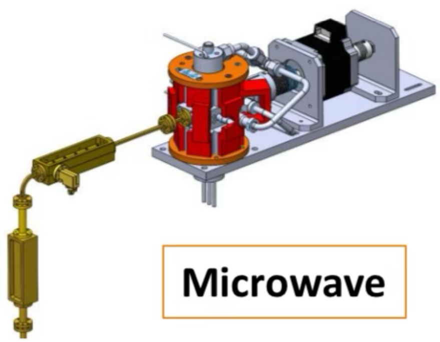


SpinQuest Experiment

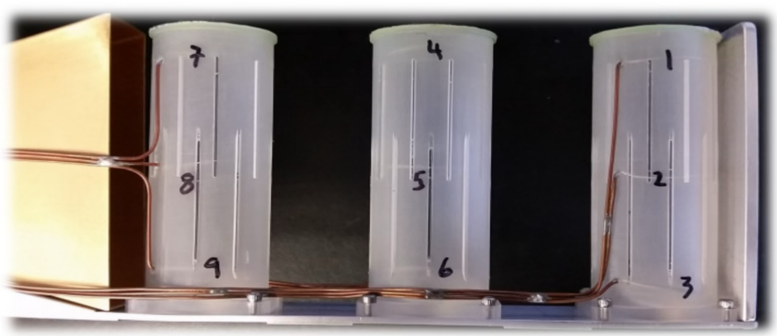
Target System

- 140 GHz microwave source. The signal is generated by extended interaction oscillator coupled to the target cups via a wave guide

Target uses Dynamic Nuclear Polarization.
- Proton max. polarization: 95%
- Deuteron max. polarization: 50%

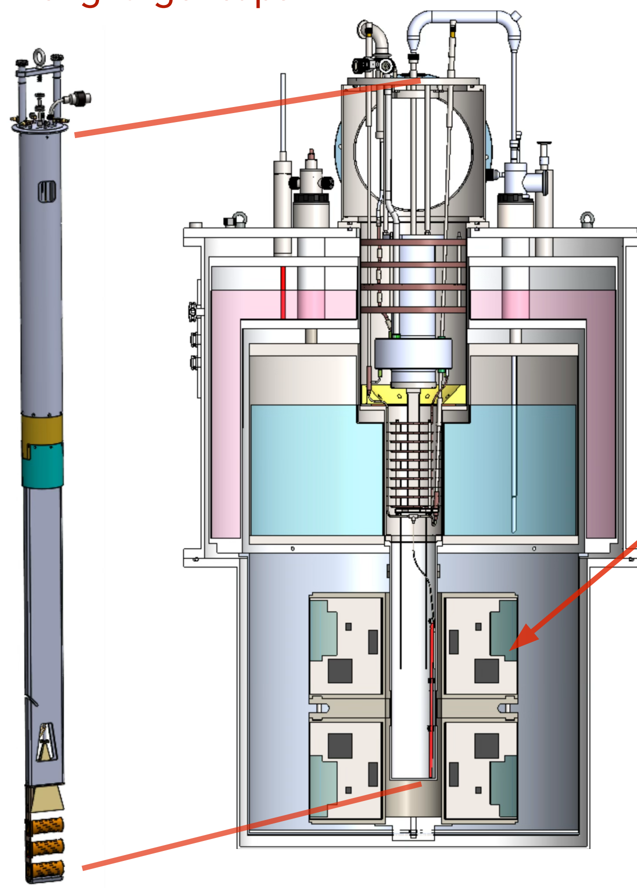


- Three Kel-F cells, each with three NMR coils for polarization measurements and temperature sensors.



- Carbon fiber insert has three 8 cm long target cups

- Evaporation refrigerator consists of 5 W of cooling power to keep the target at about 1 K with 17,000 m3/h capacity root pumps



- The superconducting magnet provides a **5T** uniform transverse magnetic field

- Ammonia beads (NH_3 or ND_3)

Beam Commissioning 05/24 - 07/24

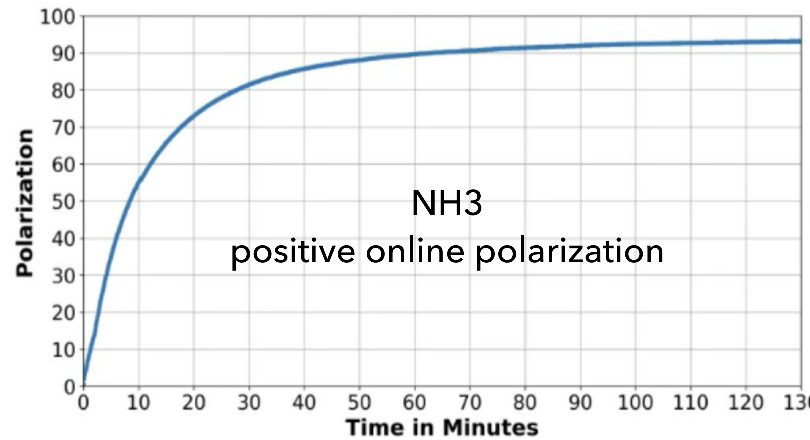
Objectives

FIRST BEAM!!

- **Polarized Target Commissioning**
  - Alignment of beam and the target cells
  - Run with polarized CH2 and NH3 on both target polarities
  - Test material extraction and shipment protocols of irradiated ammonia
  - Test target annealing method
  - Quench commissioning to determine best (and highest) intensity to run
  - Sustainable operation of LHe production and consumption.
- **Spectrometer Commissioning**
  - Demonstrate the spectrometer and data acquisition are in working condition for production
  - Timing of the trigger and tracking detectors
  - Calibrate beam intensity monitors and provide beam quality feedback to the Main Control Room
  - Trigger performance with various beam intensities and magnet settings.

Target Polarization

First solid-state polarized target successful operation under a high intensity beam



- ***Successful operation of polarized target in high-intensity proton beam up to 3 x 10^{12} protons per spill.***
- Instantaneous luminosity: $2 \times 10^{35} cm^{-2} s^{-1}$
- **This is the highest luminosity ever for any polarized NH_3 target.**
- P = 26% with CH2 at 1K and 5T which has never been achieved before.
- Achieved 95% online polarization with NH_3 target at 1 K and 5 T.
- Production data collected for both spin polarizations.

Undergoing offline analysis of the polarization data

Data analysis

Production Data

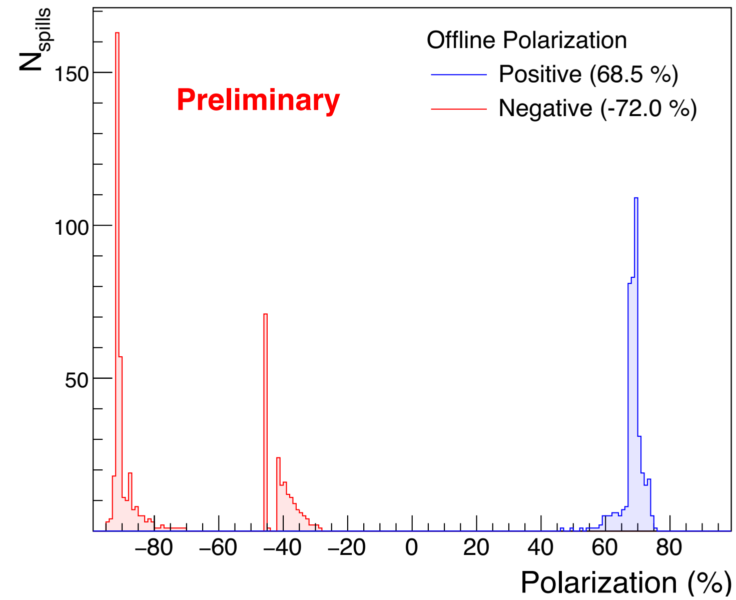
About 900 spills (15 hours) of "production" data were recorded in 3 nights:

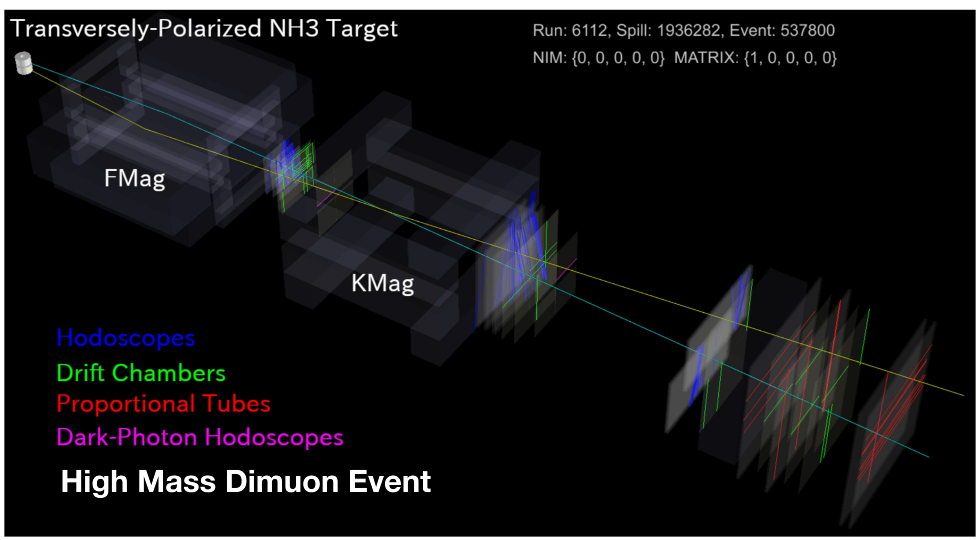
- With the spectrometer fully operational and magnets (FMag & KMag) ON.
- With the target material (NH3) polarized.
- Limited by the capacity of the cooling water system for the magnets & the helium liquefier.

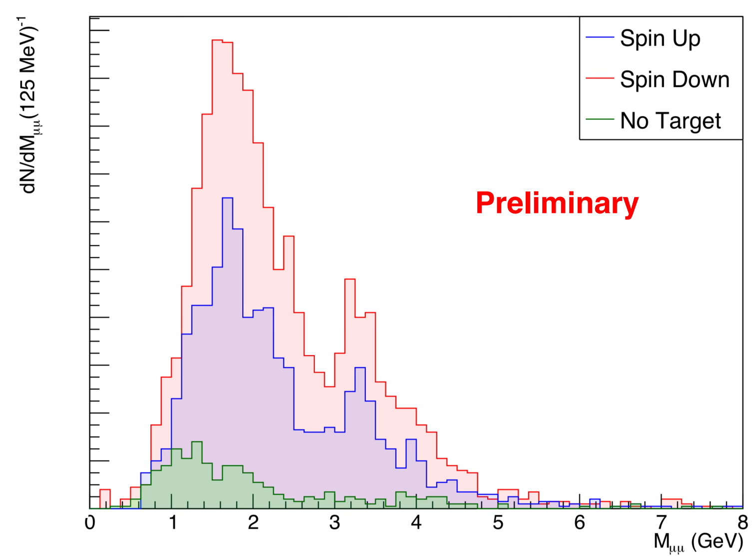
Polarization

- |P| ~ 70%
- Similar amounts of data (spills) for positive & negative directions.

No J/psi peak observed when there was no target in place.





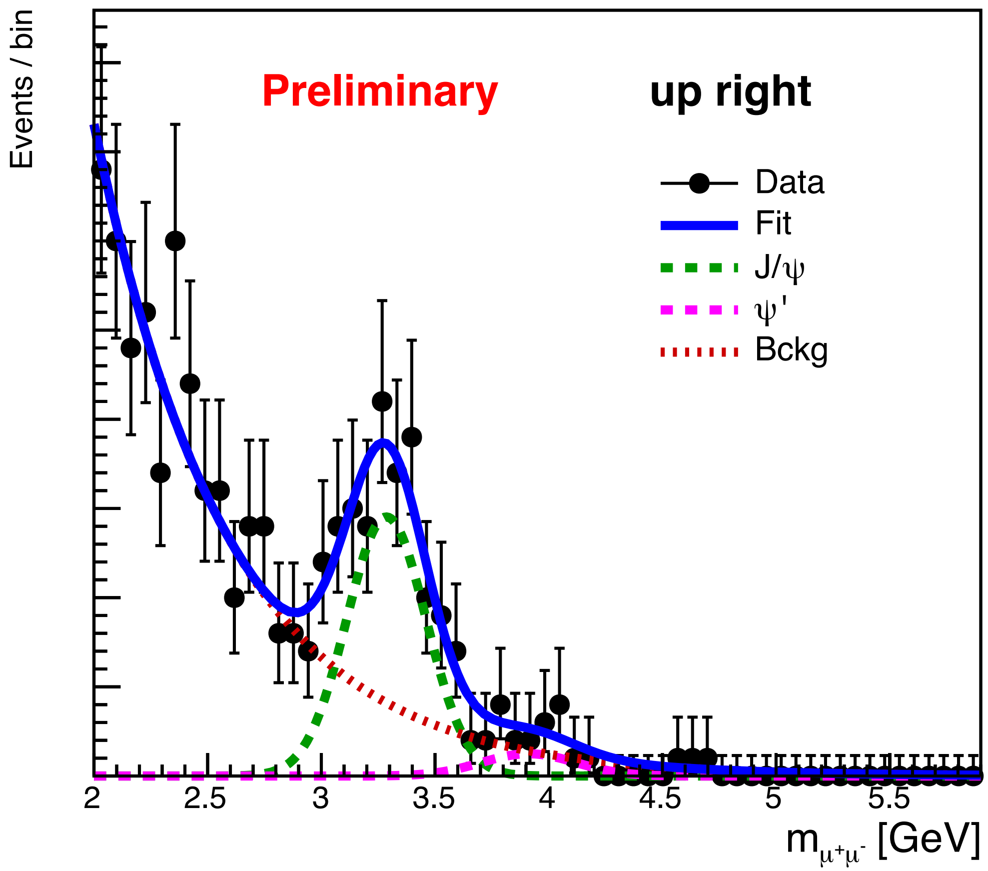


Focus on offline analysis of the production data for J/psi TSSA!

Data analysis

Dimuons mass distribution

Dimuons in the ***right*** half of the detector with the target spin ***up***.



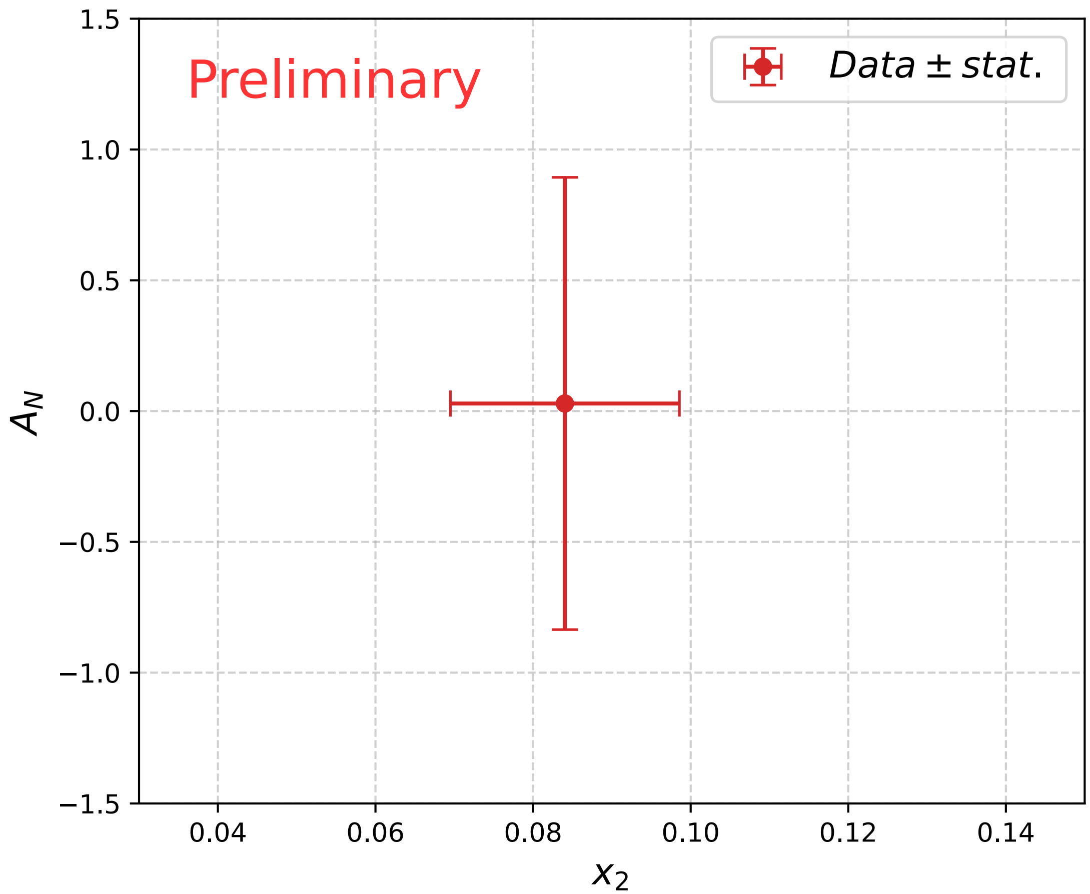
- Clear J/ψ peak.
- Also measured in the 3 other spin-detector half configuration.
- Yield extraction using unbinned maximun likelihood functional-form fitting.
- Derive left-right asymmetry using cross-ratio formula:

$$A_N = \frac{1}{pf} \cdot \frac{1}{\frac{P^{\uparrow} + P^{\downarrow}}{2}} \cdot A_N^{\text{raw}}$$

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

Data analysis

J/ψ TSSA



Large statistical error due to limited data (**15 hours).**

First successful extraction of TSSA from the SpinQuest real data!!

Validate our data analysis framework.

The statistical precision is expected to increase significantly, by about a factor of **ten**, after the planned beam time next year (1st physics data taking)

Summary

SpinQuest Goals and Uniqueness

- Sivers function of sea-quarks in the nucleon.
- TSSA of Drell-Yan process & J/ψ production.
- Transversely polarized NH_3 and ND_3 solid targets.
- Eventually, EIC $\bar{u}$ DIS Sivers asymmetry might observe (or not) the sign change.
- SpinQuest is a polarized target high intensity frontier experiment - 120 GeV proton beam.
- High luminosity experiment (~ 2 x 10^{35} $cm^{-2}s^{-1}$).

Commissioning Run 2024

- Target and spectrometer subsystems worked.
- 15 hours of production data collected.

Production Data Analysis

- Polarization of production data in both spin states |P| ~ 70 %.
- Clear J/ψ mass peak.
- J/ψ TSSA data analysis framework validated.

Improvements in data analysis and preparations for future data taking in 2026 are ongoing.

SpinQuest Experiment

https://spinquest.fnal.gov

INSTITUTIONS 23	FULL MEMBERS 55 Postdocs 8 Grad. Students 12	AFFILIATE MEMBERS
1) Abilene Christian University	Donald Isenhower (PI), Michael Daugherity, Shon Watson Sean McDonald, Bethany Beavers	Roy Salinas, Rusty Towell, Shannon McNease, Yves Ngenzi, Thomas Fitch
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3) Aligarh Muslim University	Huma Haider (PI), Mohit Singh	
4) Boston University	David Sperka (PI), Zijie Wan	
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6) KEK	Shin'ya Sawada (PI)	Shigeru Ishimoto
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19) Yamagata University	Yoshiyuki Miyachi (PI), Norihito Doshita	Takahiro Iwata, Norihiro Doshita
20) Yerevan Physics Institute	Hrachya Marukyan (PI)	
21) National Center for Physics	Waqar Ahmed (PI), Muhammad Farooq	
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Thank You!

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Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity $(cm^{-2}s^{-1})$	$A_T^{sin\varnothing_s}$	P_b or P_t (f)	$rFOM^{\#}$	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	190 $\sqrt{s} = 17.4$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f=0.22	1.1×10^{-3}	2015, 2018
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f=0.22	1.1×10^{-4}	2032
PAX (GSI)	$p^\uparrow + \bar{p}$	Collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	?
NICA (JINR)	$p^\uparrow + p^\uparrow$	Collider $\sqrt{s} = 27$	$x_b = 0.02 - 0.9$	1×10^{32}	0.04	$P_b = 70\%$	6.8×10^{-5}	2028
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	Collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	2000-2016
sPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	2023-2025
SpinQuest (FNAL: E-1039)	$p + p^\uparrow$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.5$	5×10^{35}	0-0.2*	$P_t = 80\%$ f=0.176	0.15 or 0.09	2024-2027
SpinQuest (Transversity + Dark Photon)	$p + p^\uparrow$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.5$	5×10^{35}	0-0.2*	$P_b = 80\%$ f=0.176	0.15 or 0.09	2027-2032