Los Alamos NATIONAL LABORATORY
Fermilab
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SpinQuest (E1039) Experiment: After the First Commissioning Run

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(ON BEHALF OF THE SPINQUEST COLLABORATION)

Physics Opportunities at an Electron-Ion Collider XI (P O E T I C X I)
Feb 24 - 28, 2025
Miami, FIU

LA-UR-25-21904
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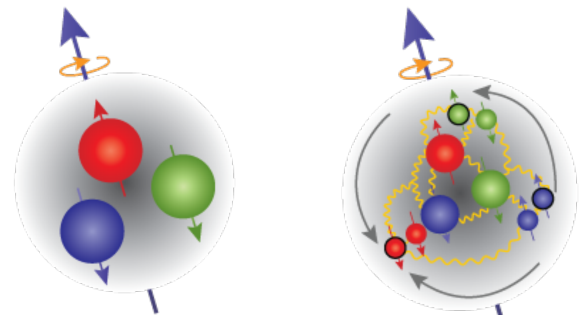
Proton Spin

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

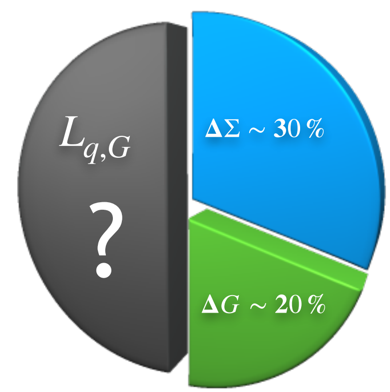
  [E. Leader and M. Anselmino, Z. Phys. C 41 , 239 (1988)]

- 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)]



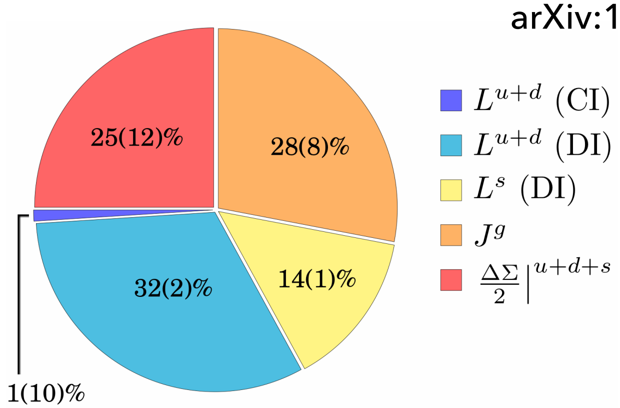
The sum of both quark and gluon spin contributions still cannot account for the total proton spin.

Proton Spin

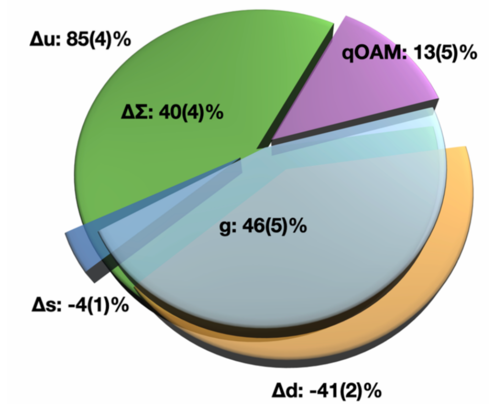
Insight into OAM contribution and transverse momentum

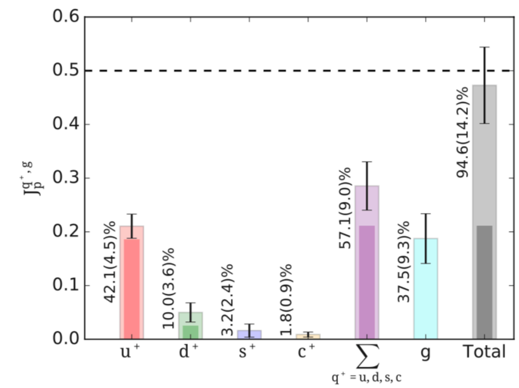
- Proton spin contributions from lattice QCD

arXiv:1504.0



arXiv:2112.08416



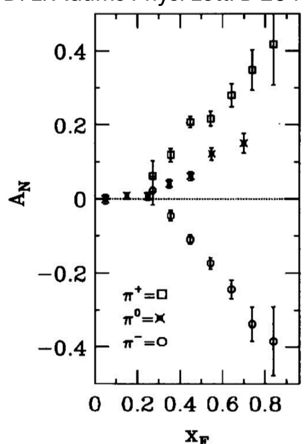


- near **50%** comes from quarks OAM
- **50%** comes from OAM: 38 - 46 (20) % gluons; 13 - 18 (50) % quarks

sea
valence

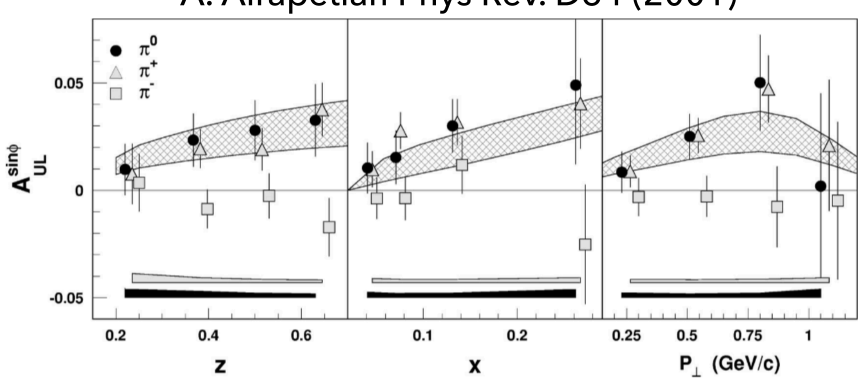
- Experimental hints at OAM

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



$pp^{\uparrow} \rightarrow \pi X$ at E704

A. Airapetian Phys Rev. D64 (2001)

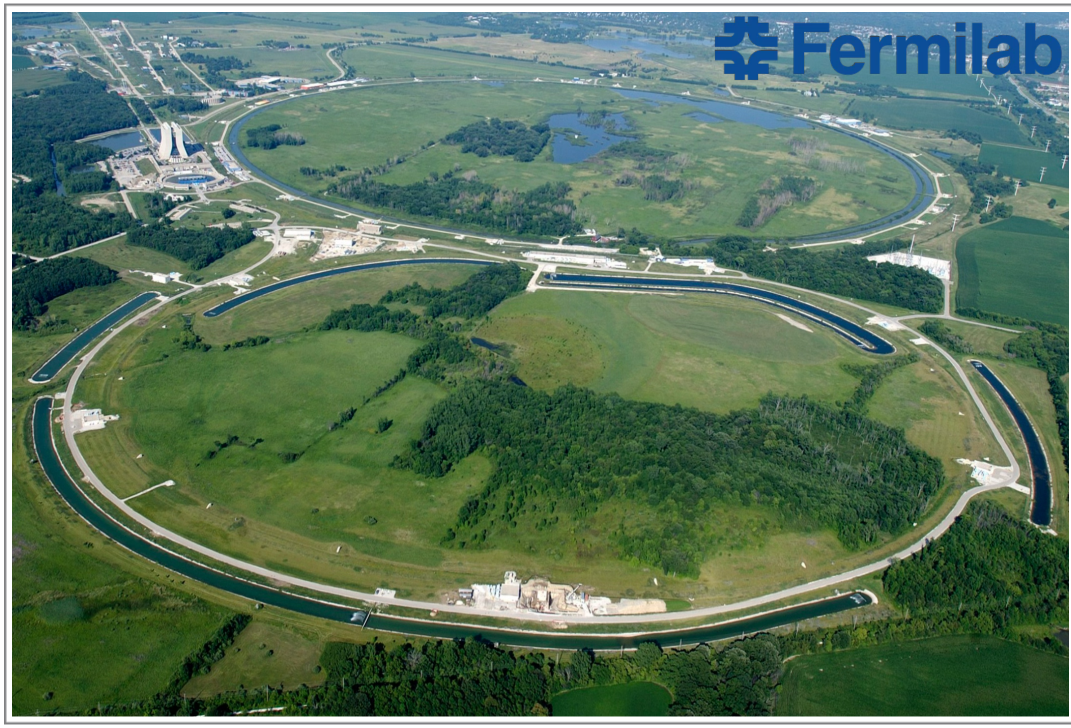


Unpolarized pion electro production at HERMES

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

potentially large OAM

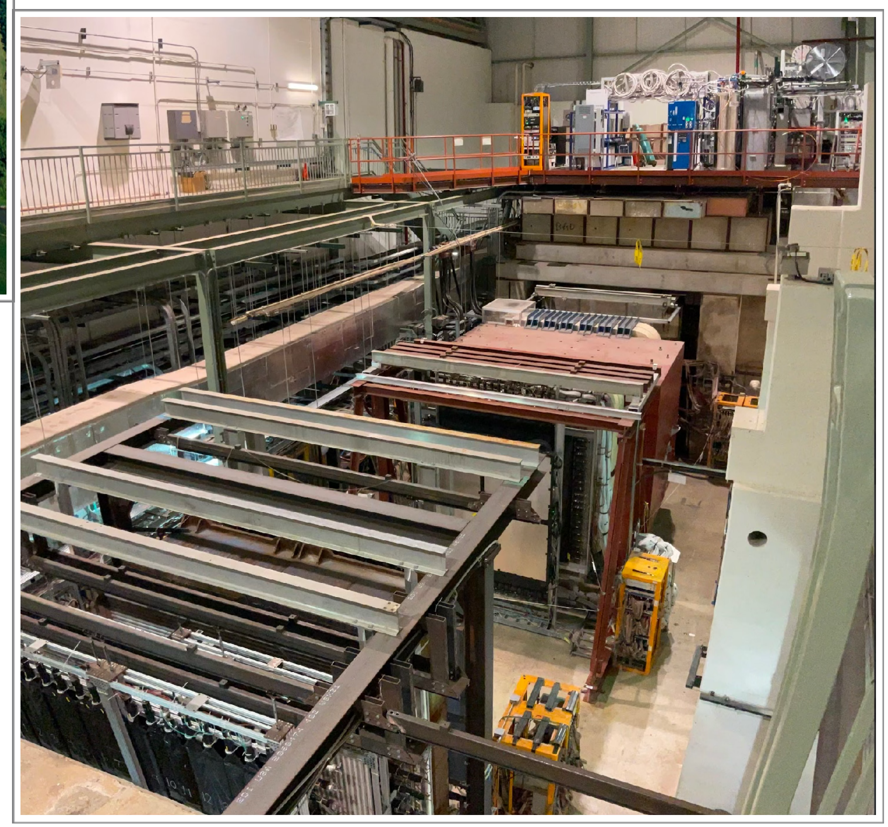
SpinQuest (E1039) at a glance



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.

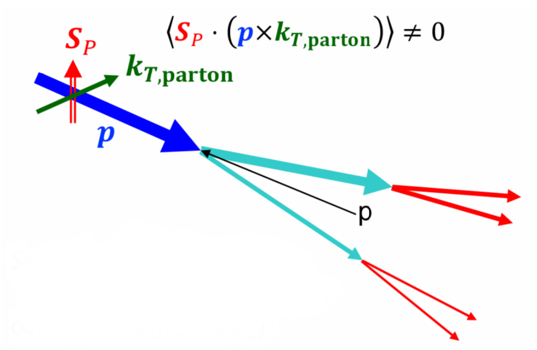
3D Partons Momentun Distributions.

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.

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

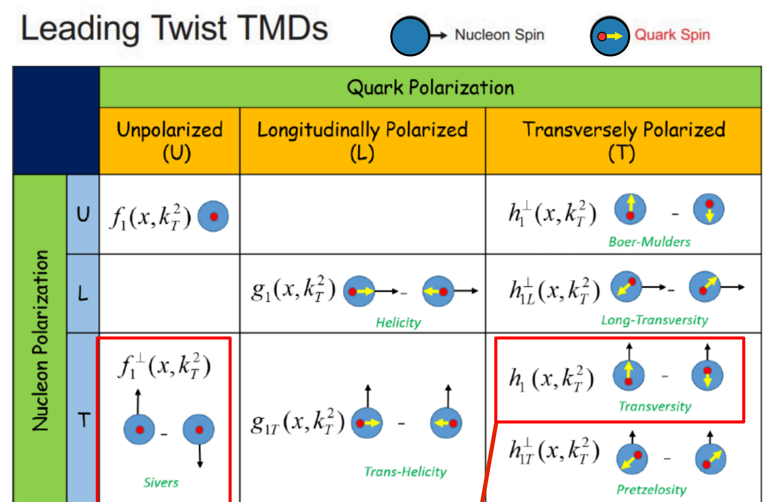


... k_T distribution of the partons could have an azimuthal asymmetry, when the hadron was transversely polarized.

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

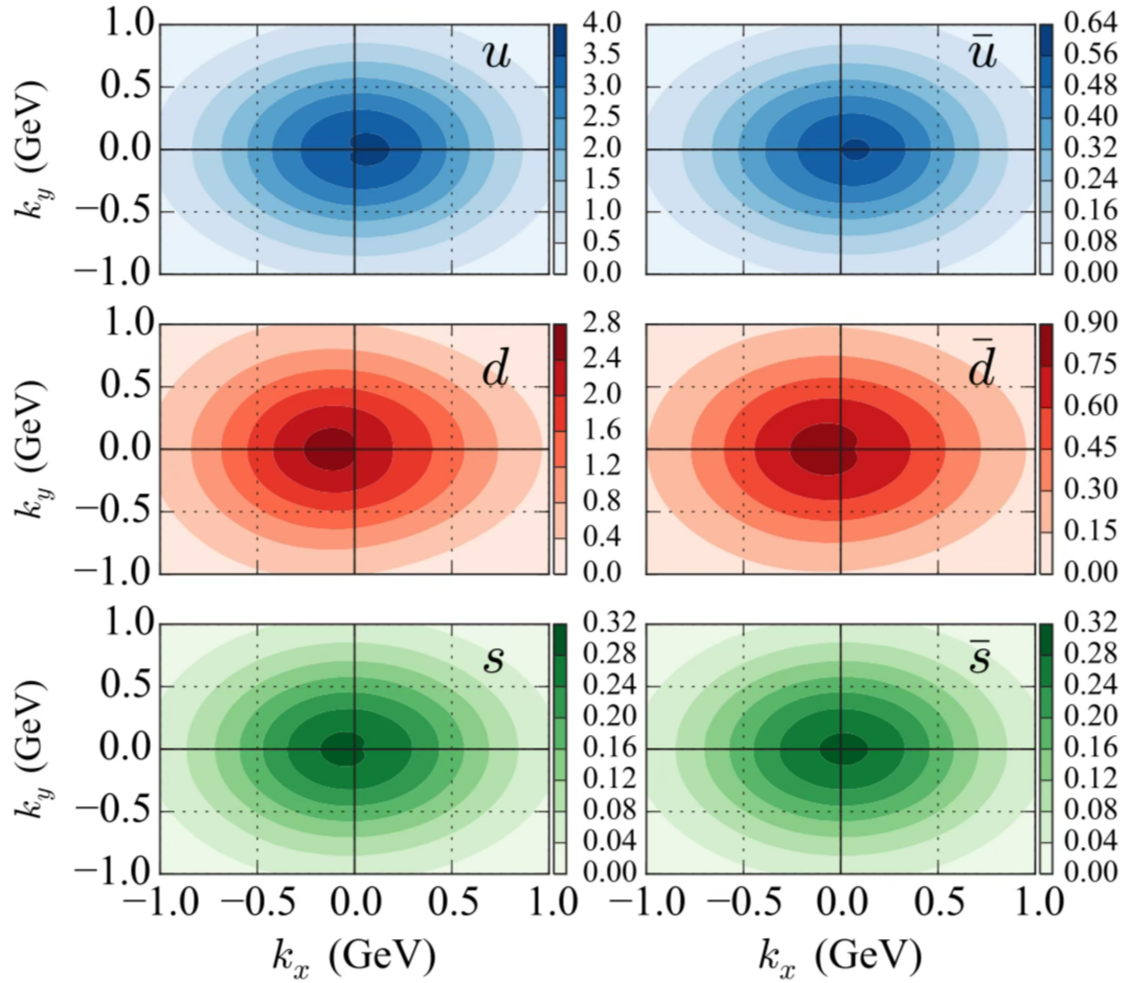
3D momentum imaging

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.

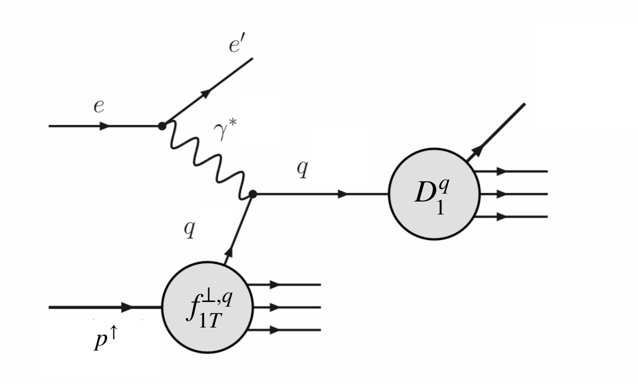
- The observed shifts in each quark flavor are linked to the correlation between the OAM of quarks and the spin of the proton.
- Evidence of nonzero OAM in the wave function of the proton's valence and sea quarks.

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



Accessing Sivers function

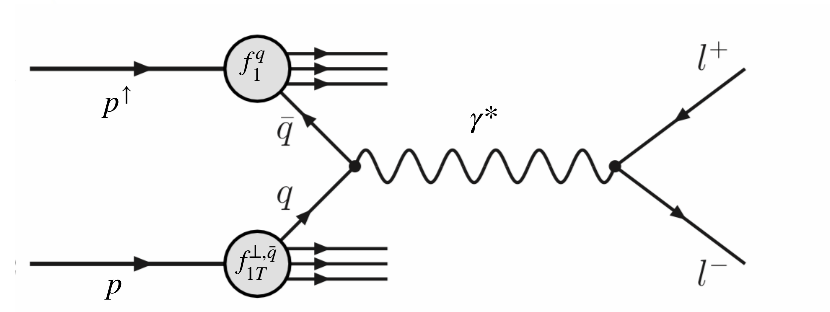
Polarized Semi Inclusive DIS



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

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

Polarized DY



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

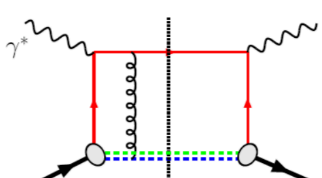
- L-R asymmetry in Drell-Yan production
- No Quark Fragmentation function
- Ability to select valence or sea quark dominated

Cleanest probe to study hadron structure

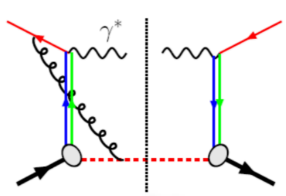
"Modified-universality" of the "Sivers" function

QCD:

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



attractive



repulsive

Courtesy of J. Drachenberg

Fundamental prediction of QCD gauge invariance.

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

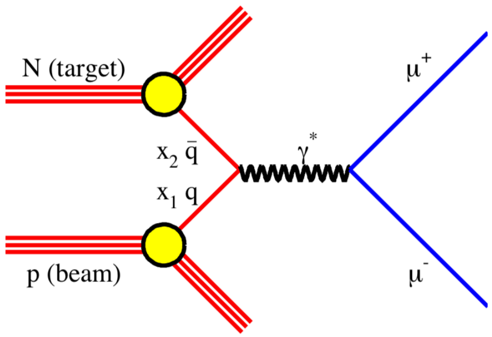
One interpretation: ***Repulsive interaction between like color charges!***

SpinQuest Program

Drell-Yan Transverse Single Spin Asymmetry

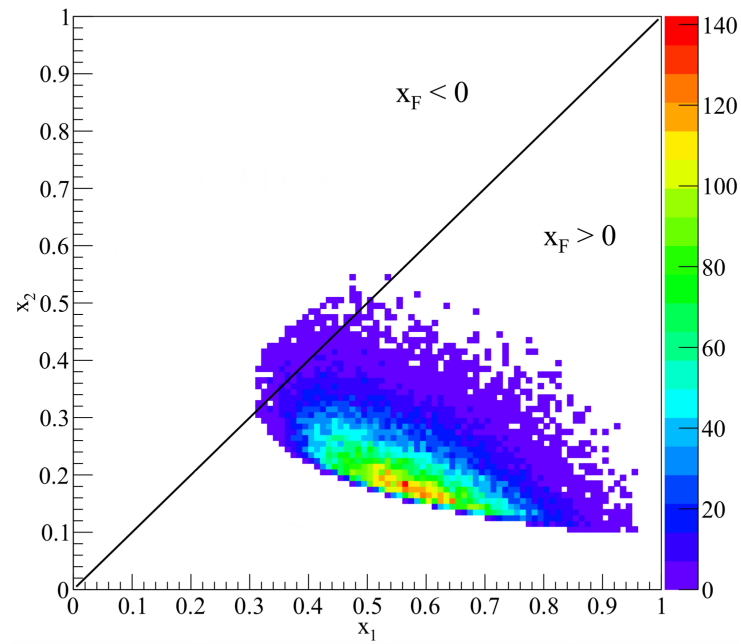
p-p polarized Drell-Yan

Dominated by sea quarks



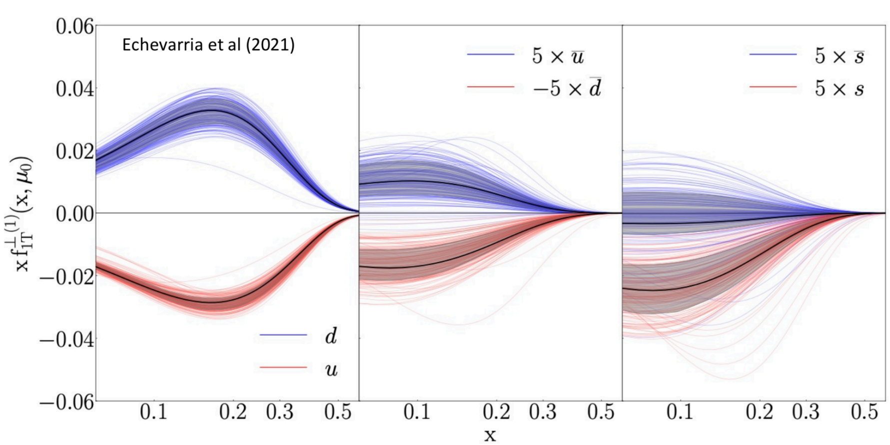
$$A_N^{DY} \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)}$$

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



Acceptance and kinematics optimized for anti-quark component from target → Sea anti-quarks ($\bar{u}, \bar{d}$) Sivers functions

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!

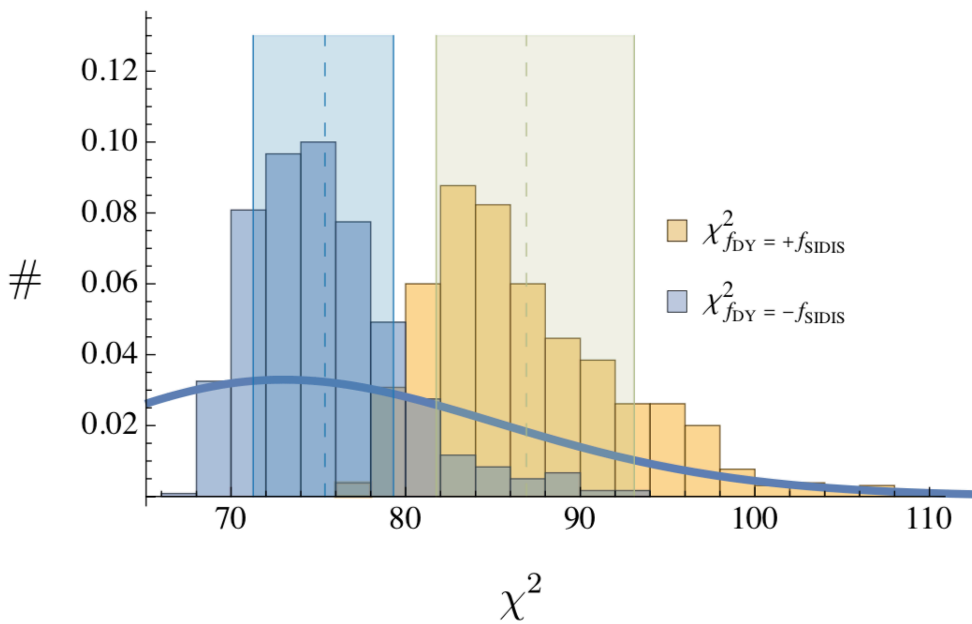
SpinQuest Program

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.

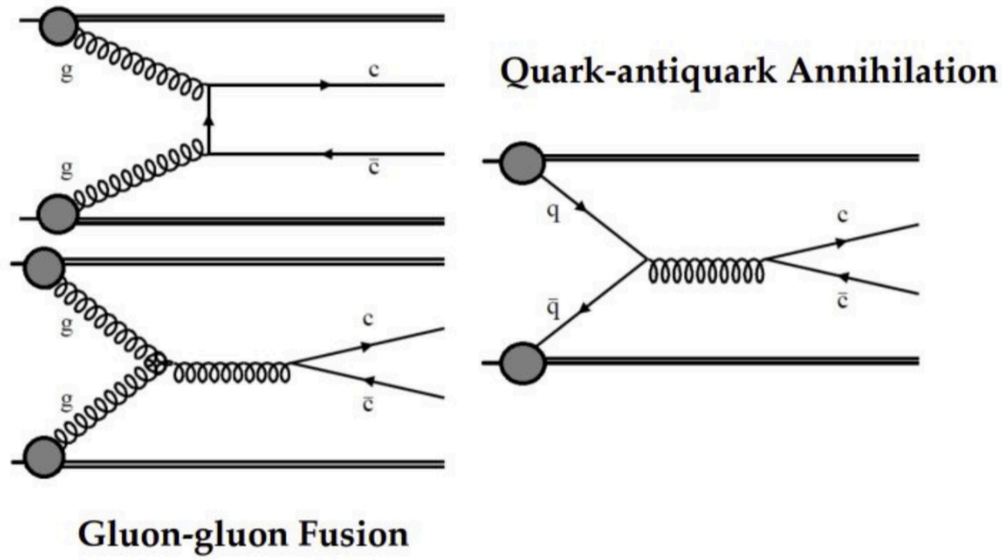
SpinQuest Program

J/ψ Transverse Single Spin Asymmetry

J/ψ Production

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

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.

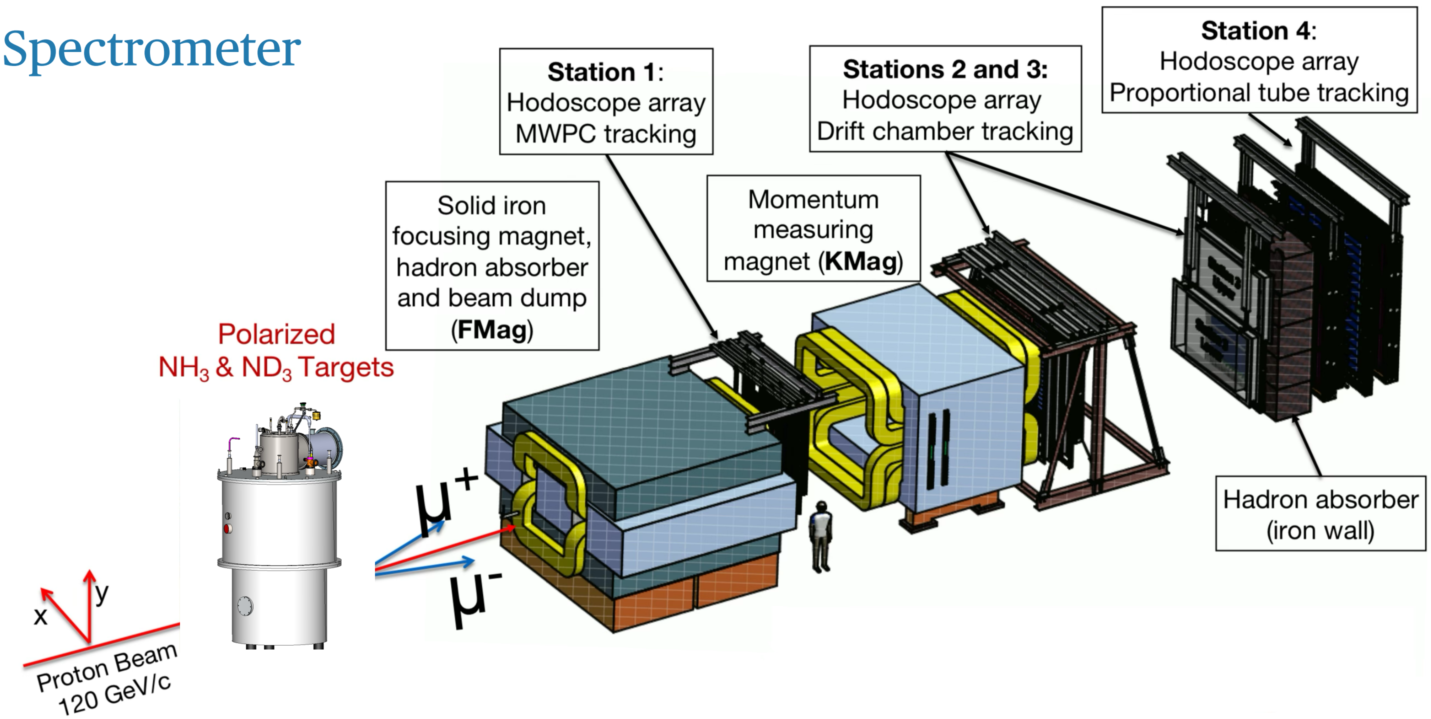
RHIC-PHENIX ○ √s = 200 GeV, xF~0.1

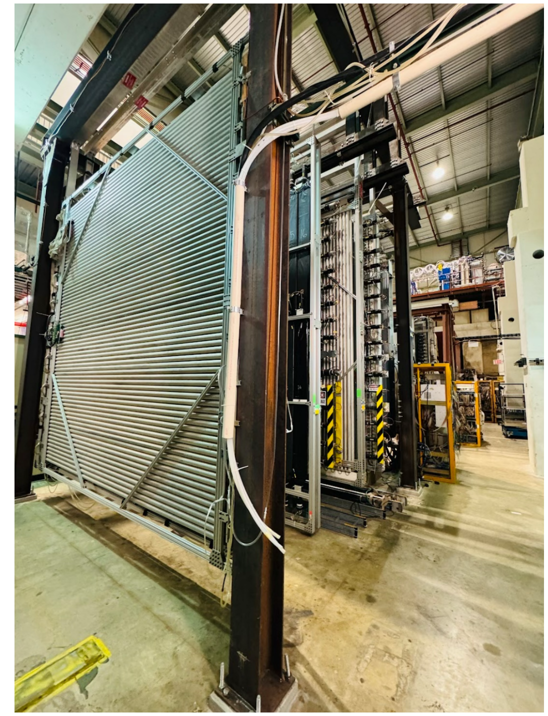
SpinQuest ○ √s = 15 GeV, xF~0.5

We have additional sensitivity to the Sivers functions for gluons.

SpinQuest Experiment

Spectrometer



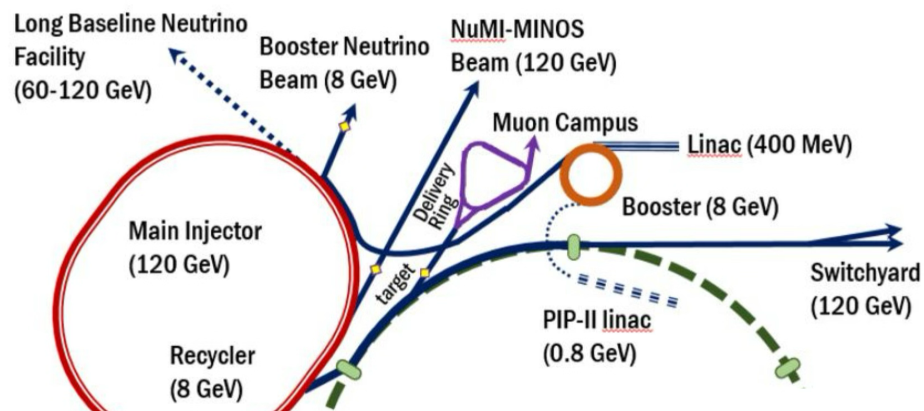


Beamline @ Fermilab

- 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.

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

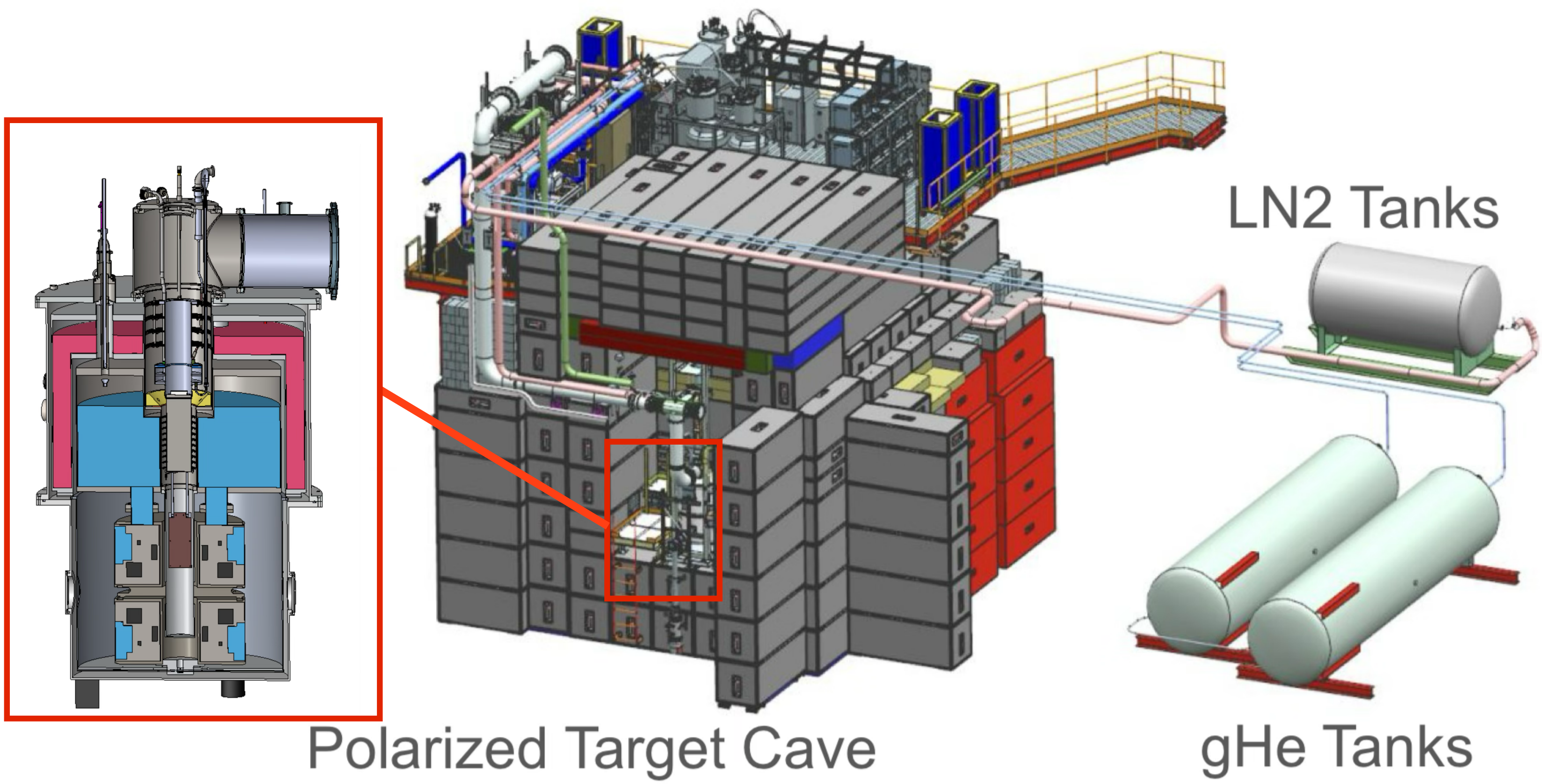
(~ $2 \times 10^{35} cm^{-2} s^{-1}$)



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.

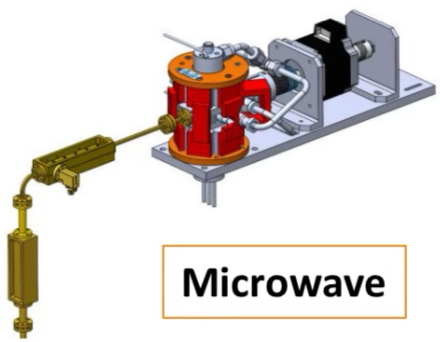


SpinQuest Experiment

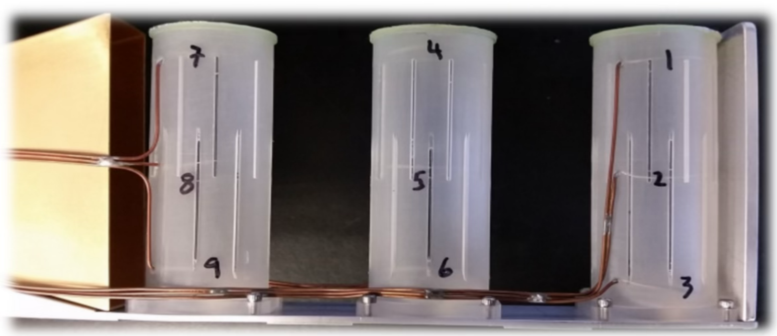
Target System

- 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%

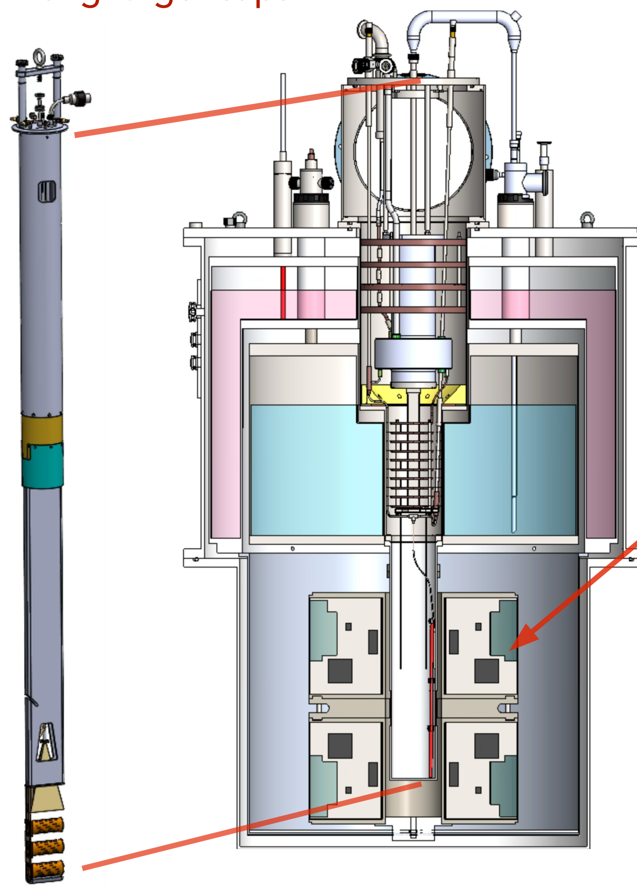


• Three Kel-F cells, each with three NMR coils for polarization measurements and temperature sensors.



• 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)

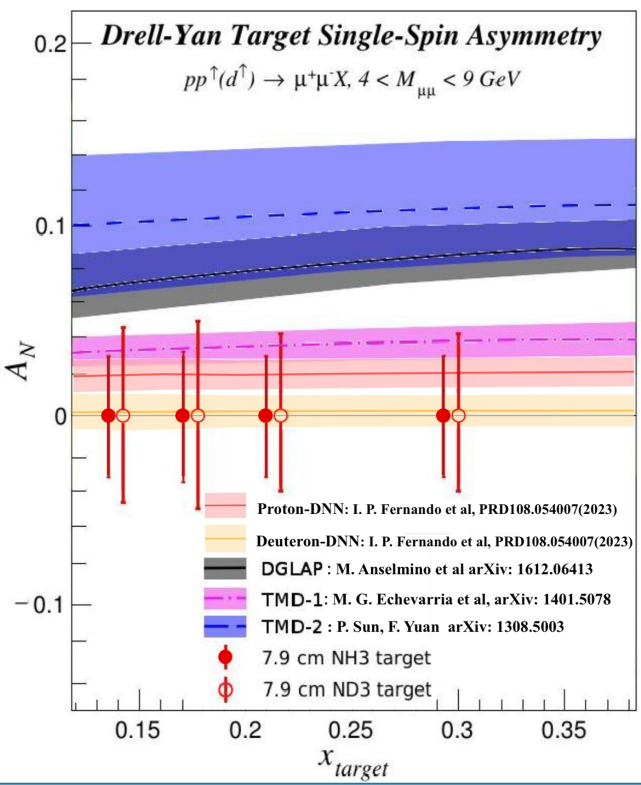
SpinQuest Experiment

Projected sensitivity and asymmetry

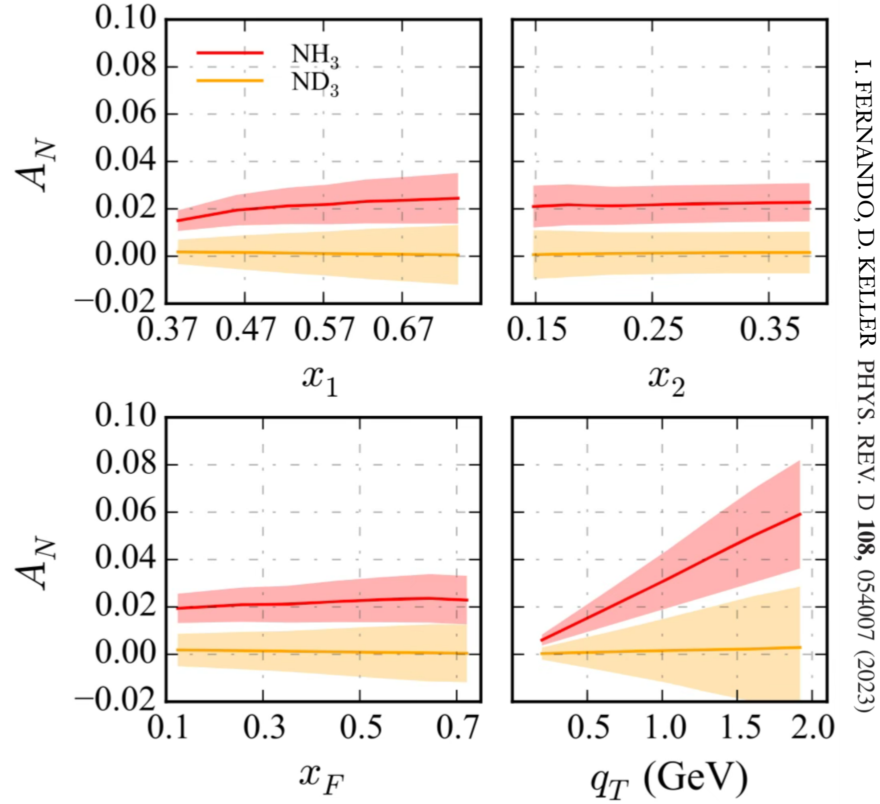
Projected Statistical uncertainty ~ 3-5%.

Systematic uncertainties:

- Beam (~ 2.5%)
- Analysis sources (< 3.5%)
- Target (< 6 %)



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



- Conditions
  - 1 year of data taking
  - NH3:ND3
- Transverse Single-Spin Asymmetry (TSSA)
  - Measurement precision δ_{AN} ~ 0.04
- Important constraints on global models

Beam Commissioning 05/24 - 07/24

Objectives

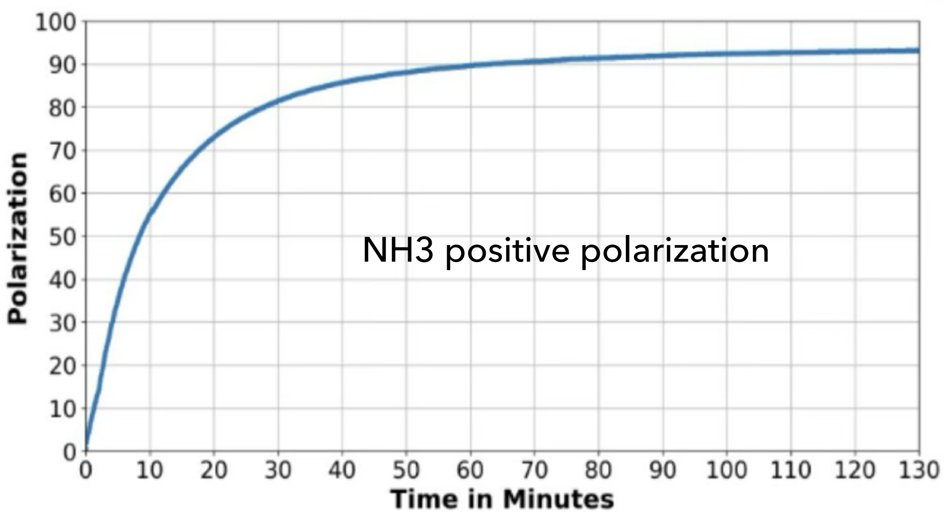
FIRST BEAM!!
We took last week for production data

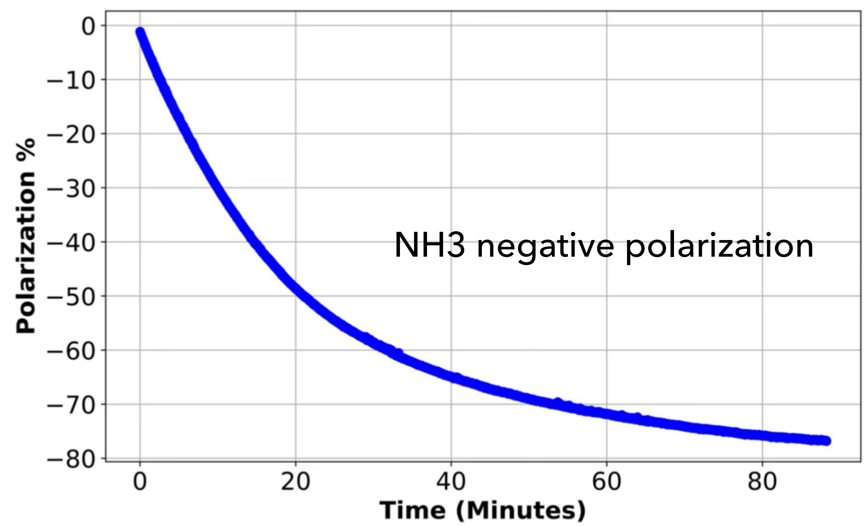
- **Polarized Target Commissioning**
  - Alignment of beam and the target cells
  - Run with polarized CH2 and NH3 on both target polarities
  - Test material extraction and shipment protocols of irradiated ammonia
  - Test target annealing method
  - Quench commissioning to determine best (and highest) 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
  - Timing of the beam intensity monitors and provide beam quality feedback to MCR
  - Trigger performance with various beam intensities and magnet settings.

Proton Polarization

First solid target polarization achieved 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 NH3 target.**
- P = 26% with CH2 at 1K and 5T which has never been achieved before.
- P = +95%, -85% with NH3 at 1K and 5T.





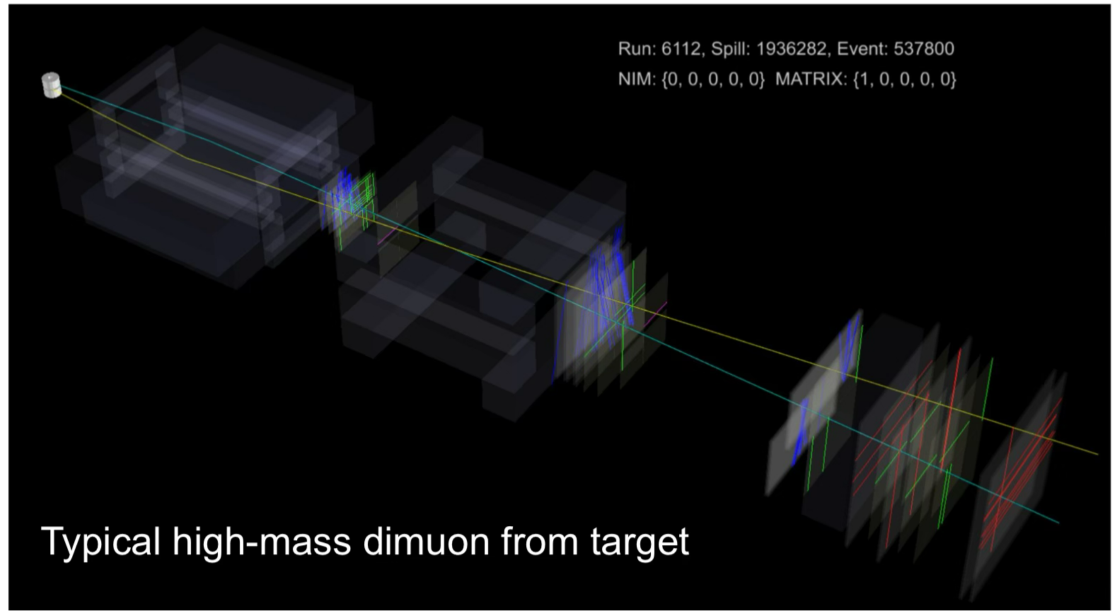
Undergoing offline analysis of the polarization data

Data analysis

Dimuon events reconstruction

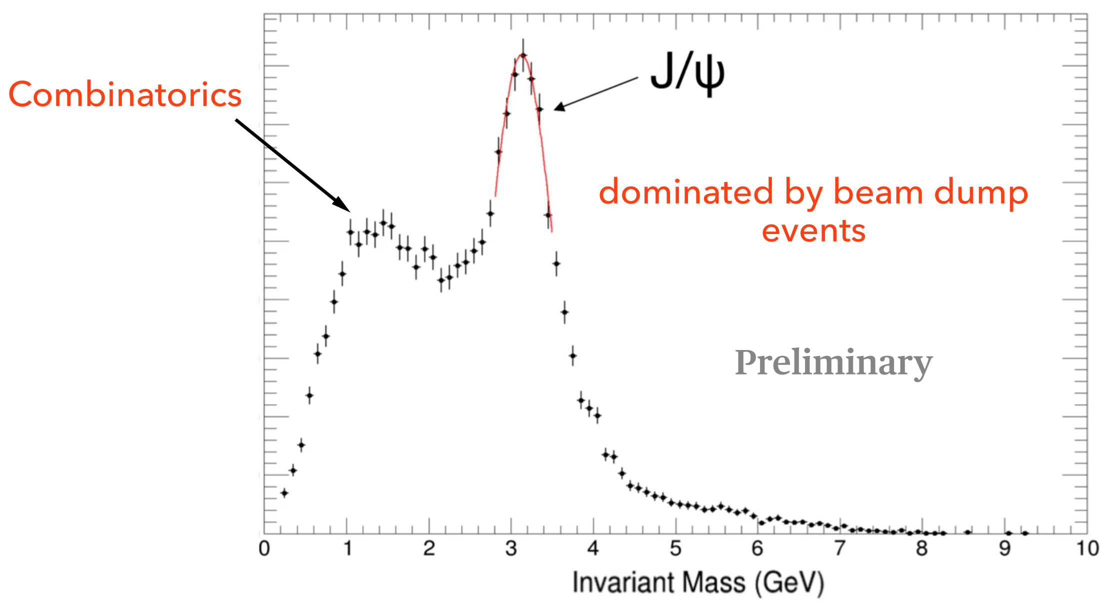
Clear J/ψ and high-mass dimuon events observed in the online plots.

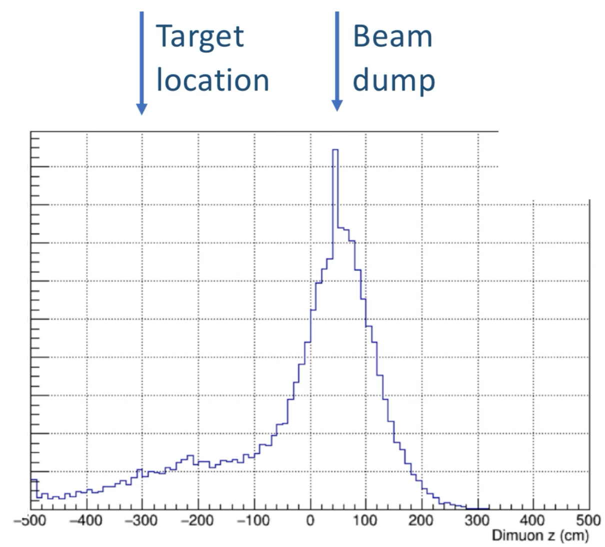
Focus on offline analysis of the commissioning and production data for J/psi TSSA!



Typical high-mass dimuon from target

3153 spills (4s); KMag is on; no cuts





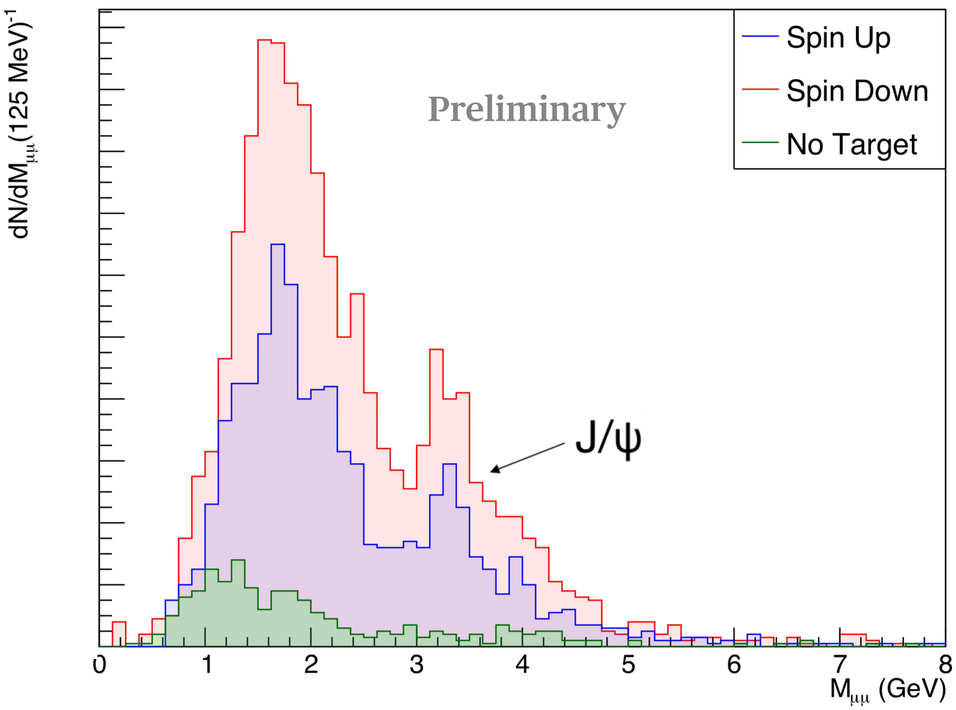
Dimuon z_{vertex} (cm)

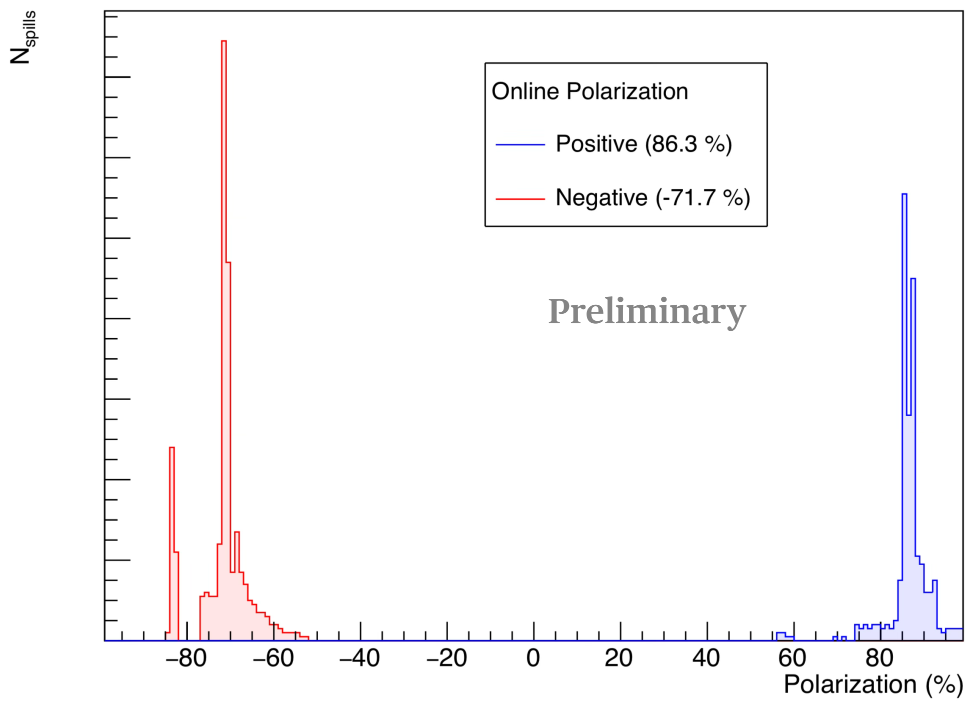
Data analysis

Dimuon events from polarized target

Selections:

Target-like cuts, “top/bottom” trigger; $|Z_{\mu^+} - Z_{\mu^-}| < 200\text{cm}$

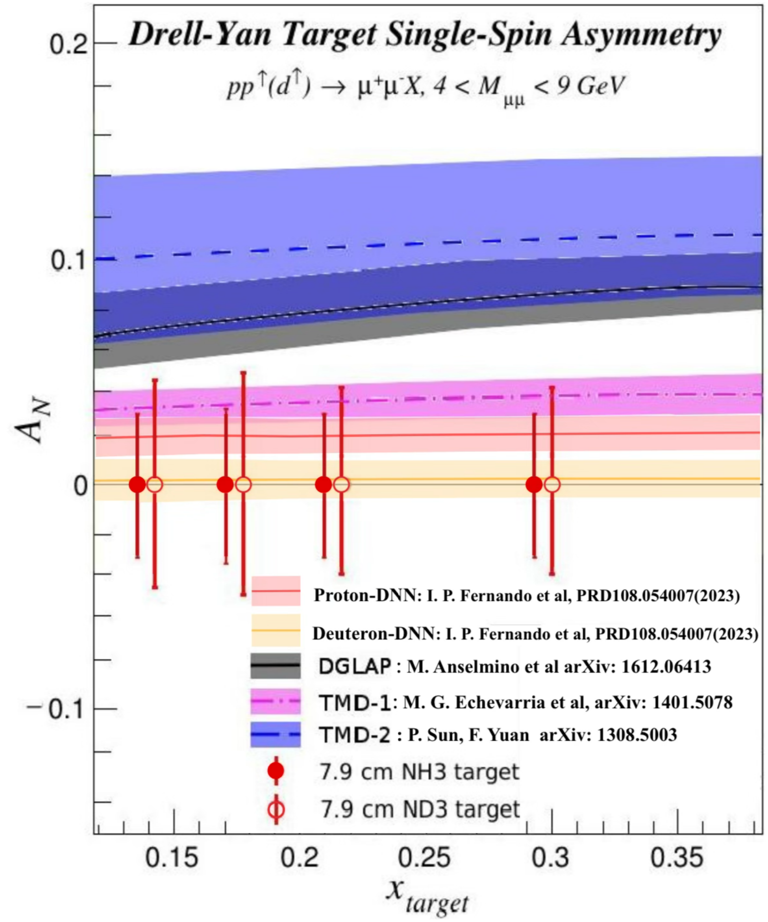




Summary

SpinQuest Goals and Uniqueness

- SpinQuest's primary goal is to measure correlations between momentum direction of the struck sea-quark and the spin state of the parent nucleon.
- Can measure $\bar{u}$ pp-DY Sivers asymmetry for the first time.
- Eventually, EIC $\bar{u}$ DIS Sivers asymmetry might observe (or not) the sign change.
- SpinQuest is a polarized target high intensity frontier experiment. Never before has there been a polarized target system specialized to push the proton beam intensity at this level.
- High luminosity experiment (~ 2×10^{35} $cm^{-2}s^{-1}$).
- SpinQuest has the highest power evaporation refrigerator ever made for a polarized target experiment.



SpinQuest Experiment

https://spinquest.fnal.gov

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3) Aligarh Muslim University	Huma Haider (PI), Mohit Singh	
4) Boston University	David Sperka (PI), Zijie Wan	
5) FNALNational Accelerator Laboratory	Nhan Tran (PI), Evan Niner, Erik Voirin	Carol Johnstone, Charles Brown
6) KEK	Shin'ya Sawada (PI)	Shigeru Ishimoto
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10) RIKEN	Yuji Goto (PI)	
11) Shandong University	Qinghua Xu (PI)	
12) Tokyo Institute of Technology	Toshi-Aki Shibata (PI)	
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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

SpinQuest Experiment

Polarized Target

Given the small magnetic moment of the proton we can not reach a significant polarization just by using a large B field and a low T.

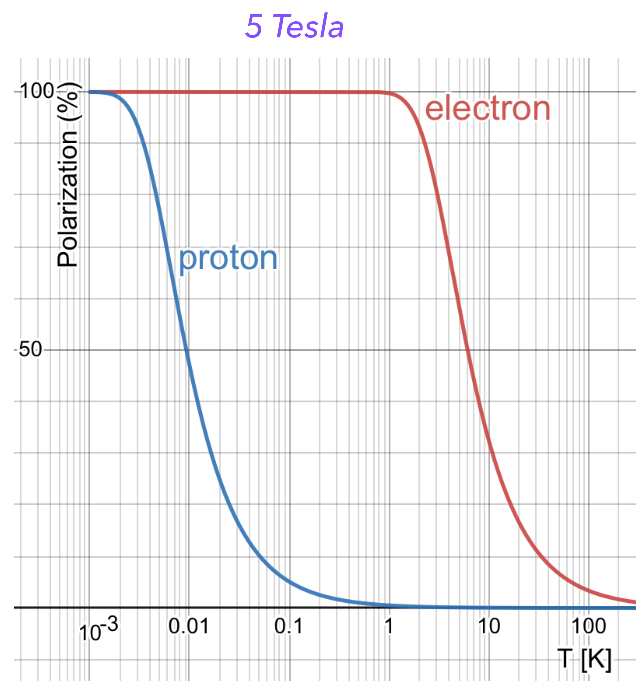
$$P = tanh\left(\frac{\mu B}{kT}\right)$$

- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- At B = 5 Tesla & T = 1 K

$$P_e = {\sim}98\%,\ P_p = 0.51\%$$



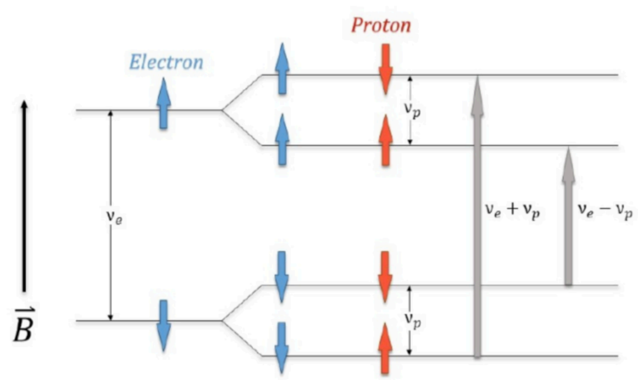
- Dynamic Nuclear Polarization

  - Dope target material with paramagnetic centers:

  chemical or irradiation doping to just the right density (10^{19} spins/cm^3)

  - Polarize the centers: Just stick it in a magnetic field

  - Use microwaves to transfer this polarization to nuclei:
  mutual electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other



The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization.

Allows to achieve proton polarization of > 90%