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U.S. DEPARTMENT OF
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Science

Insights from the SpinQuest (E1039) Experiment at Fermilab

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(ON BEHALF OF THE SPINQUEST COLLABORATION)

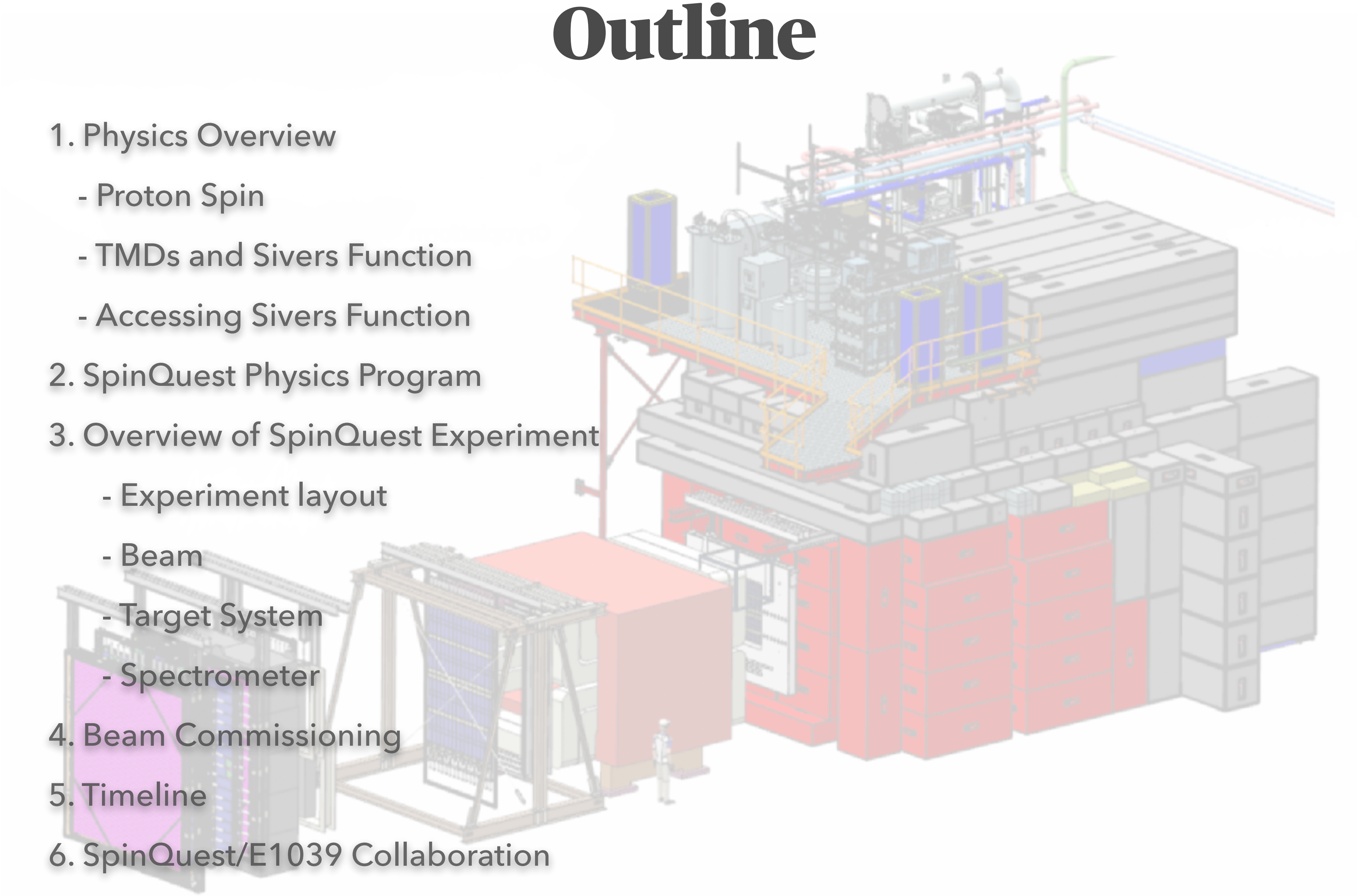
Joint XX-th International Workshop on Hadron Structure and Spectroscopy and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

2024
30/09 - 04/10
CPHI
IWHSS
Yerevan
Armenia

LA-UR-24-30367

This work is supported by US-DOE

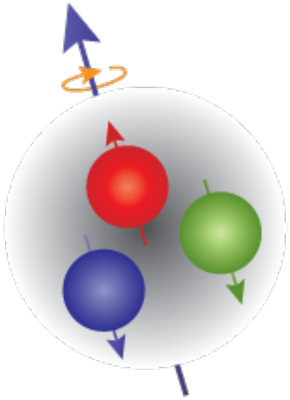
Outline



1. Physics Overview
   - Proton Spin
   - TMDs and Sivers Function
   - Accessing Sivers Function
2. SpinQuest Physics Program
3. Overview of SpinQuest Experiment
   - Experiment layout
   - Beam
   - Target System
   - Spectrometer
4. Beam Commissioning
5. Timeline
6. SpinQuest/E1039 Collaboration

Proton Spin

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

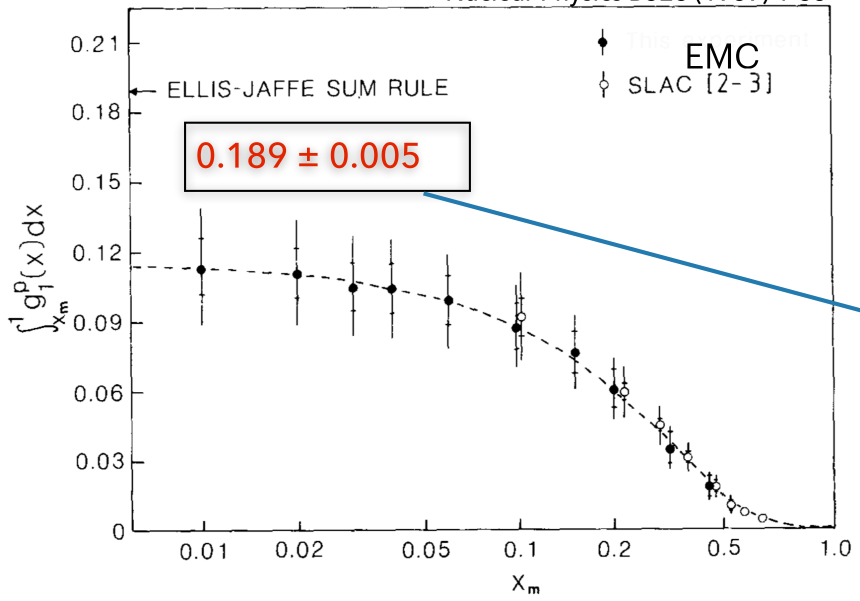


1980s

Naive quark model (only valence quarks)

$1/2 = 1/2 + 1/2 - 1/2$

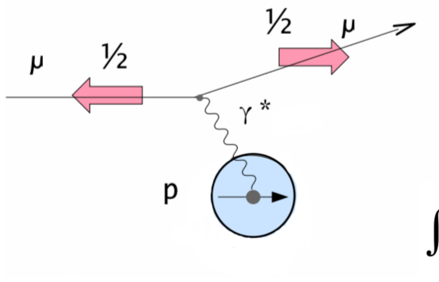
Nuclear Physics B328 (1989) 1-35



0.189 ± 0.005

1987 - European Muon Collaboration

DIS of polarized muon on polarized proton



$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$$

Spin dependent structure function

$$\int_0^1 g_1^p\,dx = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)$$

$$\Delta u = \int_0^1 (u^{\uparrow}(x) - u^{\downarrow}(x))\,dx$$

$u^{\uparrow(\downarrow)}$: distribution of u quarks with spin parallel (antiparallel) to the proton spin

Fraction of the proton spin carried by (valence and sea) quarks:

$\Delta\Sigma(Q^2 = 10\text{GeV}^2) = 0.060 \pm 0.047 \pm 0.069$

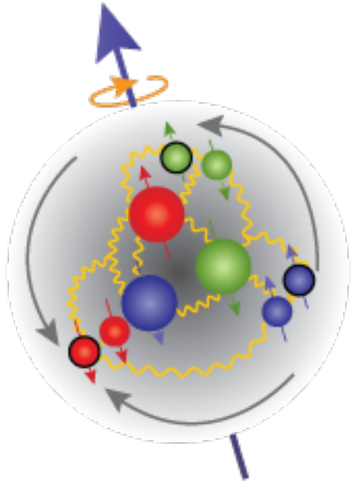
consistent with zero!

based on the constituent quark model picture ($\Delta s = 0$).

proton spin "crisis"

Proton Spin

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



Now

2 major formulations of the decomposition:

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

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

$q\,,\bar{q}$ spin (valence and sea)

$q\,,\bar{q}$ OAM

gluons spin

gluons OAM

- Measured experimentally
- Challenge for lattice QCD

Frame independent decomposition
(Ji's sum rule)

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

gluons total AM

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

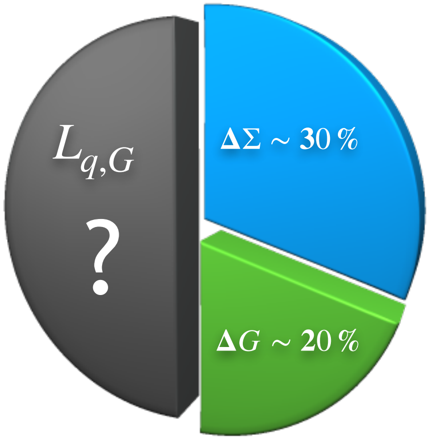
[E. Leader and M. Anselmino, Z. Phys. C 41 , 239 (1988)]

- 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)]



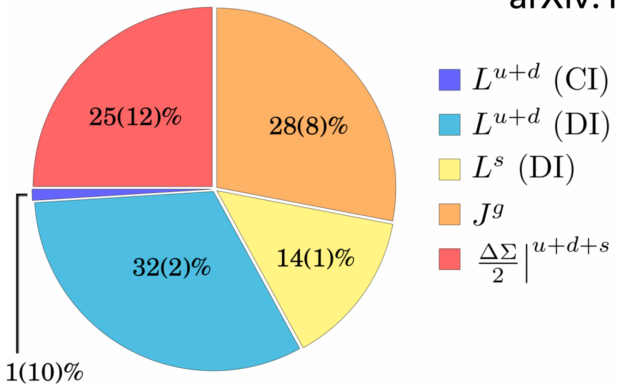
The sum of both quark and gluon spin contributions still cannot account for the total proton spin.

Proton Spin

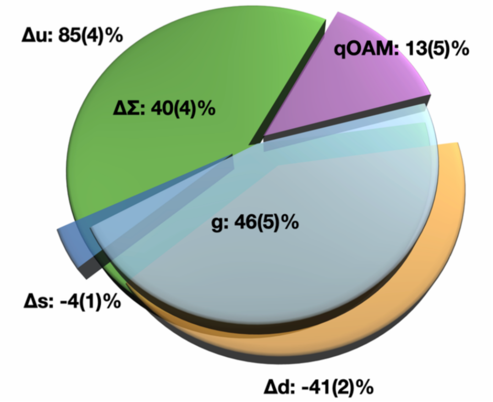
Insight into OAM contribution and transverse momentum

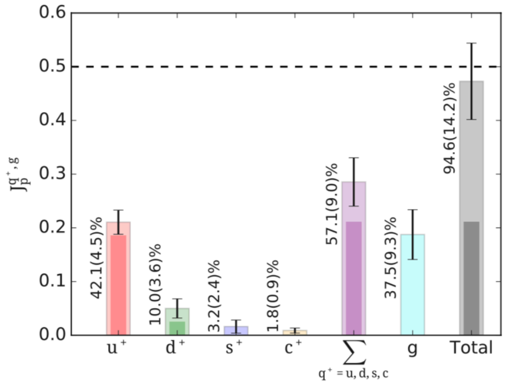
- Proton spin contributions from lattice QCD

arXiv:1504.0



arXiv:2112.08416



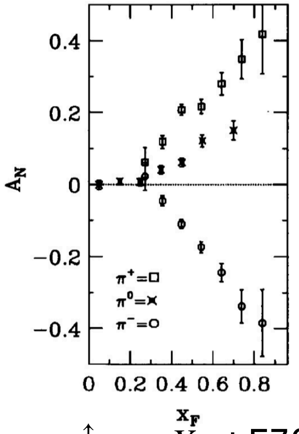


- near **50%** comes from quarks OAM
- **50%** comes from OAM: 38 - 46 (20) % gluons
  13 - 18 (50) % quarks

▨ sea
■ valence

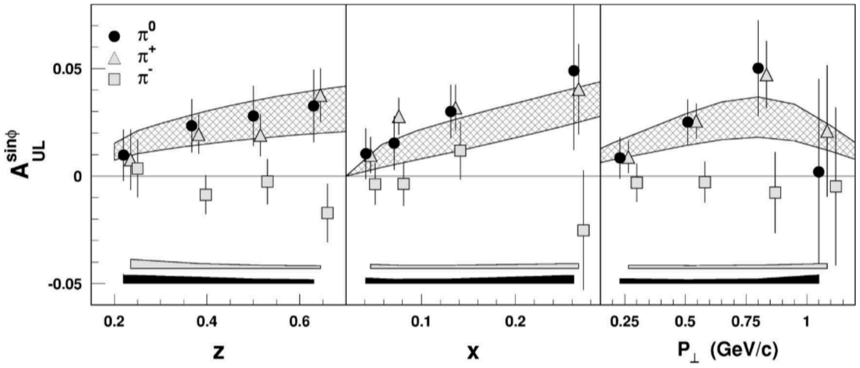
- Experimental hints at OAM

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

TMDs and Sivers function

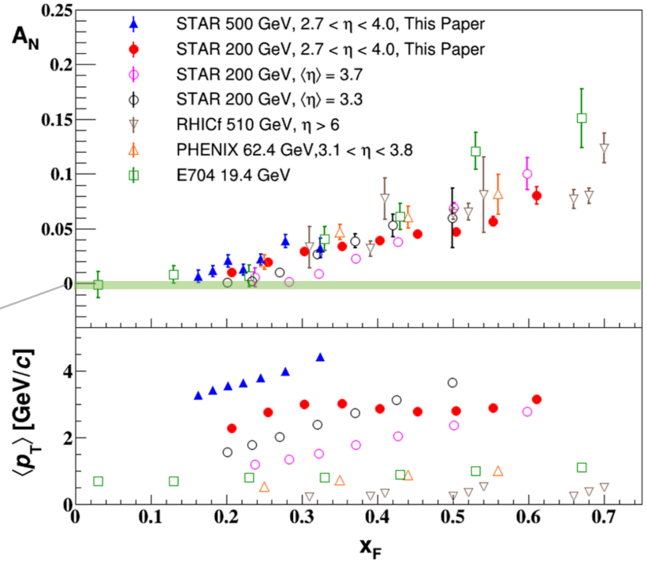
Transverse Momentum Dependent Parton Distribution Functions (TMD - PDFs)

The quark-quark correlator, in collinear configuration:
3 distribution functions

$$\Phi(x,S)=\frac{1}{2}\left[{\color{blue}\boxed{f_1(x)}}\not{n}_+ + S_L{\color{blue}\boxed{g_{1L}(x)}}\gamma^5\not{n}_+ + {\color{blue}\boxed{h_{1T}}}\,i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

Transverse single spin asymmetries should be small

Phys. Rev. D 103, 092009



TSSA for forward scattering MUCH LARGER than **naïve expectation**

Partonic nucleon structure *beyond* collinear approximation

$$\Phi(x,\boldsymbol{k}_\perp)=\frac{1}{2}\left[{\color{blue}\boxed{f_1}}\not{n}_+ + {\color{orange}\boxed{f_{1T}^\perp}}\frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \left(S_L{\color{blue}\boxed{g_{1L}}} + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M}{\color{orange}\boxed{g_{1T}^\perp}}\right)\gamma^5\not{n}_+ \;{\color{blue}\boxed{h_{1T}}}\,i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu +\right.$$

$$\left. + \left(S_L{\color{orange}\boxed{h_{1L}^\perp}} + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M}{\color{orange}\boxed{h_{1T}^\perp}}\right)\frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M} + {\color{orange}\boxed{h_1^\perp}}\frac{\sigma_{\mu\nu}k_\perp^\mu n_+^\nu}{M}\right]$$

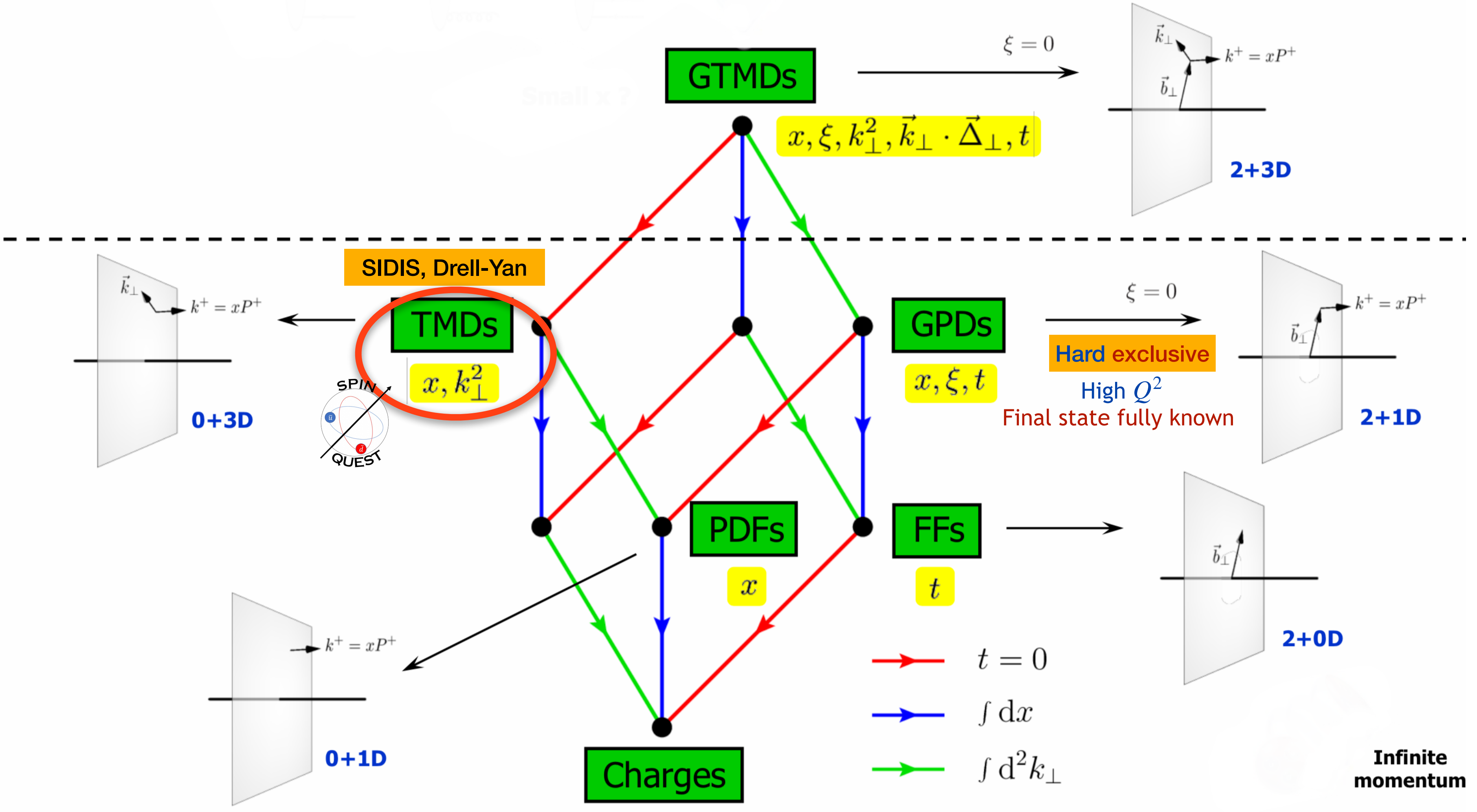
TMD-PDFs: the leading-twist correlator, with intrinsic $k_\perp$, contains 8 independent functions.

TMDs and Sivers function

Transverse Momentum Dependent Parton Distribution Functions (TMD - PDFs)

Theoretical tools

« Physical » objects



GTMDs

$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\xi = 0$

2+3D

SIDIS, Drell-Yan

TMDs

$x, k_\perp^2$

0+3D

GPDs

x, ξ, t

$\xi = 0$

Hard exclusive

High Q^2

Final state fully known

2+1D

PDFs

x

FFs

t

2+0D

0+1D

Charges

$t = 0$

$\int dx$

$\int d^2 k_\perp$

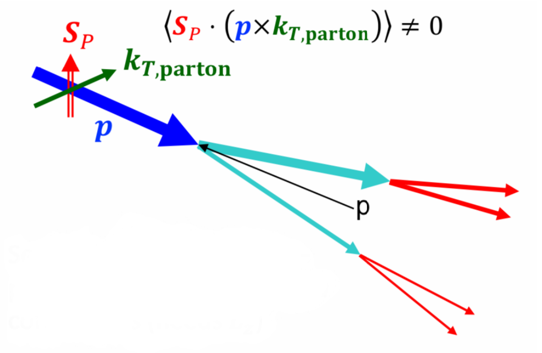
Infinite momentum

TMDs and Sivers function

Sivers function

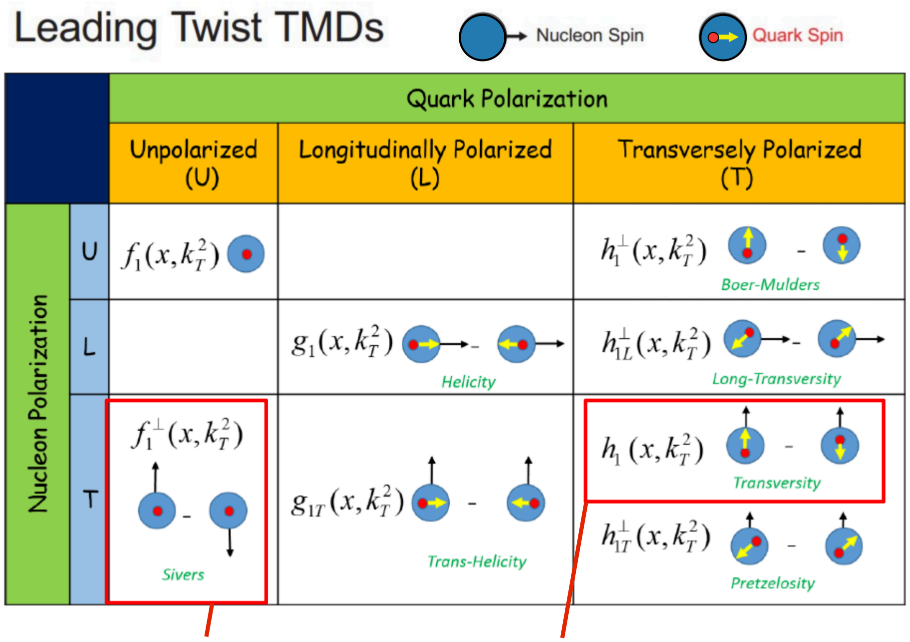
Sivers function $f_{1T}^{\perp}(x,\mathbf{k_T})$: Describes the correlation between the transverse momentum direction of the struck quark and the spin of its parent nucleon.

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



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

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



Leading Twist TMDs

● → Nucleon Spin   ● → Quark Spin

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^{\perp}(x,k_T^2)$ Long-Transversity
	T	$f_1^{\perp}(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity $h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity

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

spin-orbit correlation

- 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 and Sivers function

Sivers function

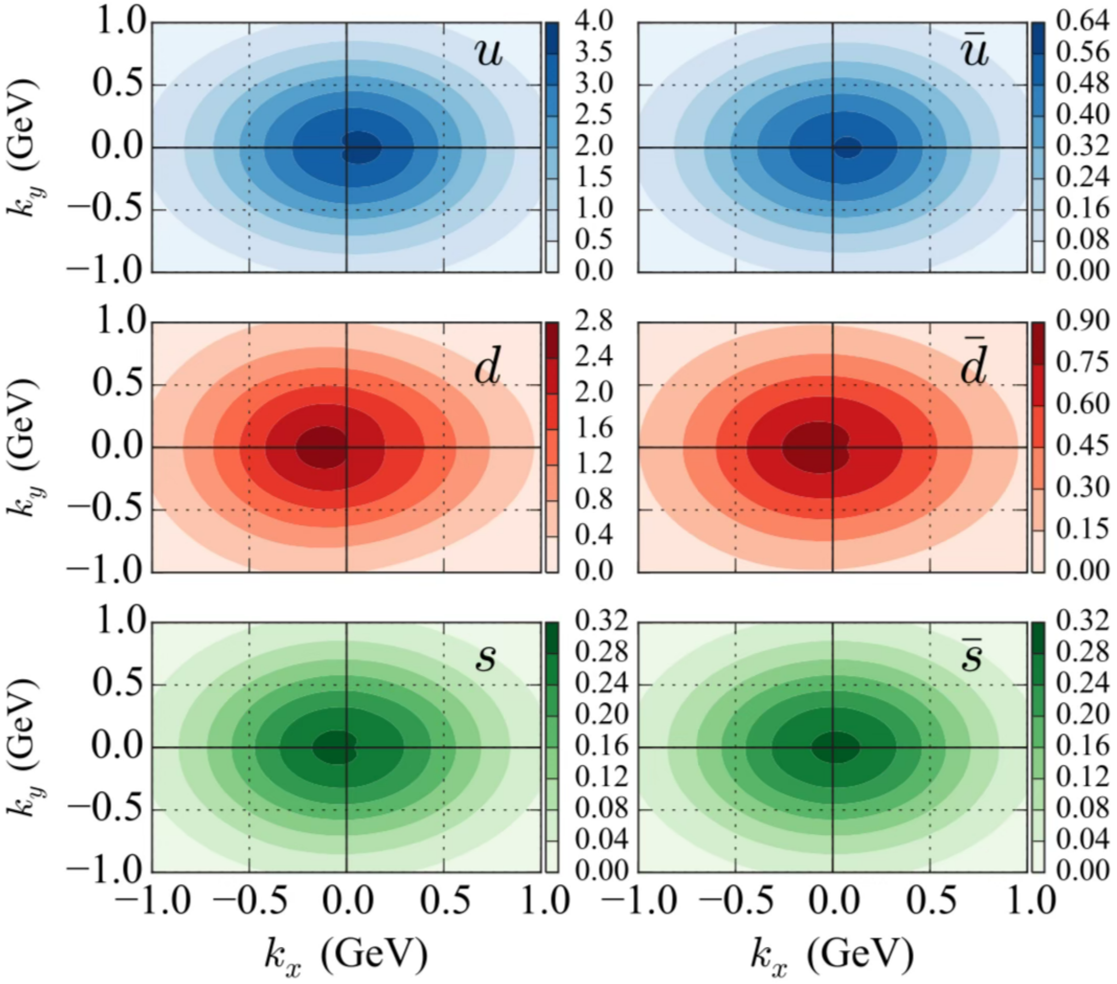
Use Sivers TMD function to map distribution of quarks in 3D momentum space

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.

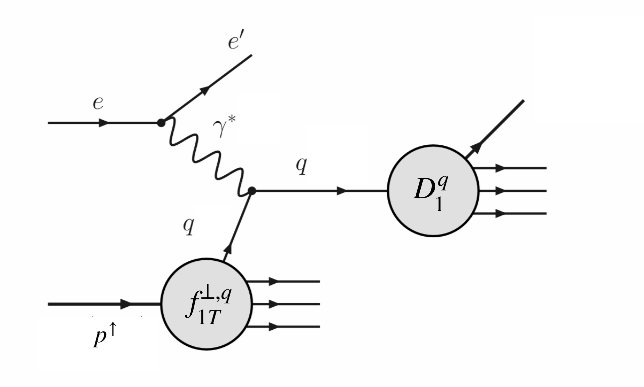
More details in Ishara's Fernando talk

PHYS. REV. D **108**, 054007 (2023)



Accessing Sivers function

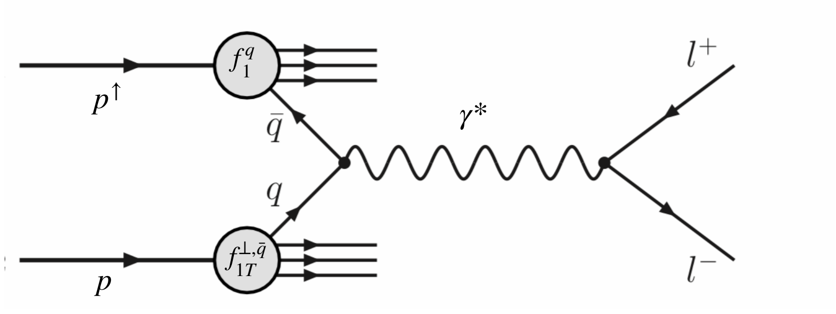
Polarized Semi Inclusive DIS



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

- 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

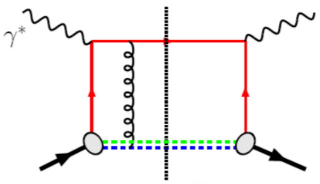
"Modified-universality" of the "Sivers" function

Cleanest probe to study hadron structure

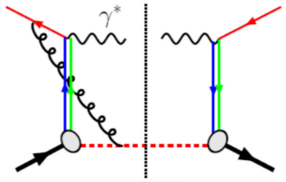
QCD:

DIS
Final-state interaction

Drell-Yan
Initial-state interaction



attractive



repulsive

Courtesy of J. Drachenberg

Fundamental prediction of QCD gauge invariance.

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

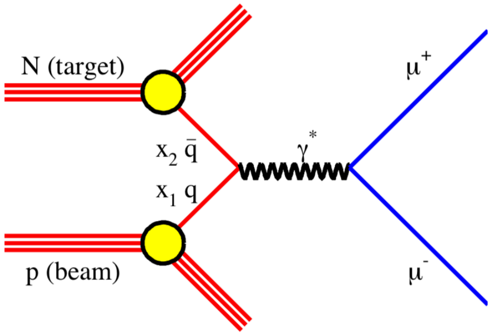
One interpretation: ***Repulsive interaction between like color charges!***

SpinQuest Program

Sensitivity to sea quarks Sivers functions

p-p polarized Drell-Yan

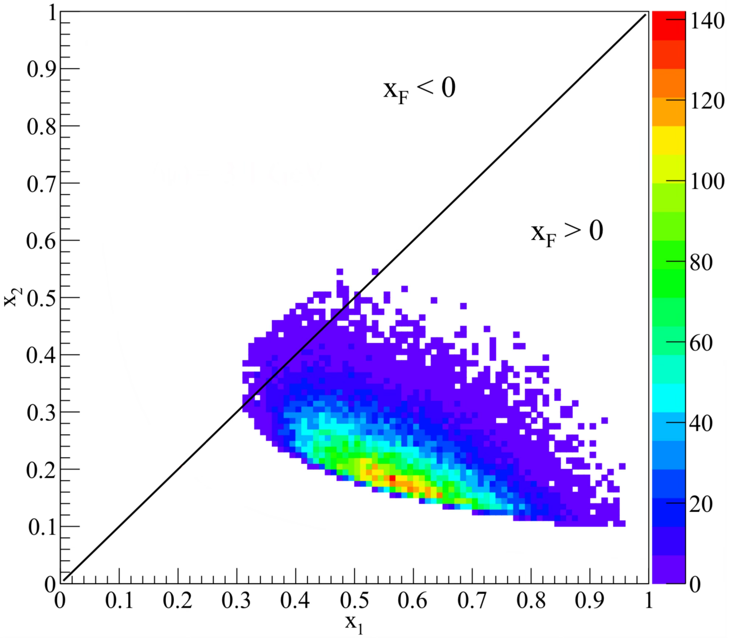
Dominated by sea quarks



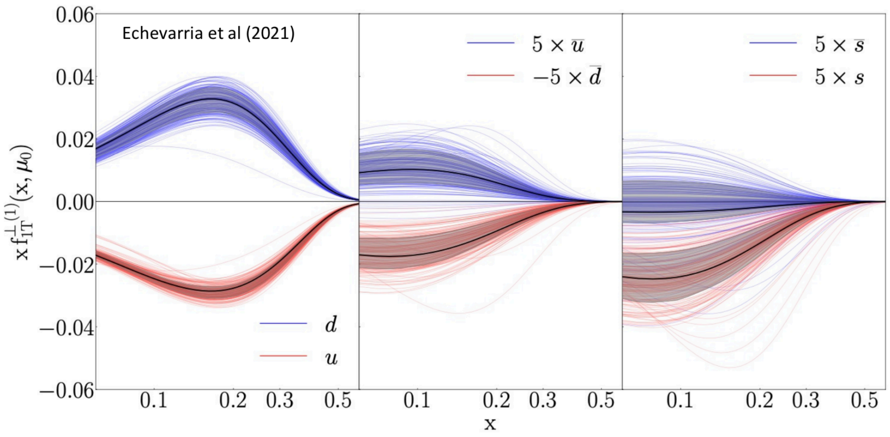
$$A_N^{DY} \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)}$$

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

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

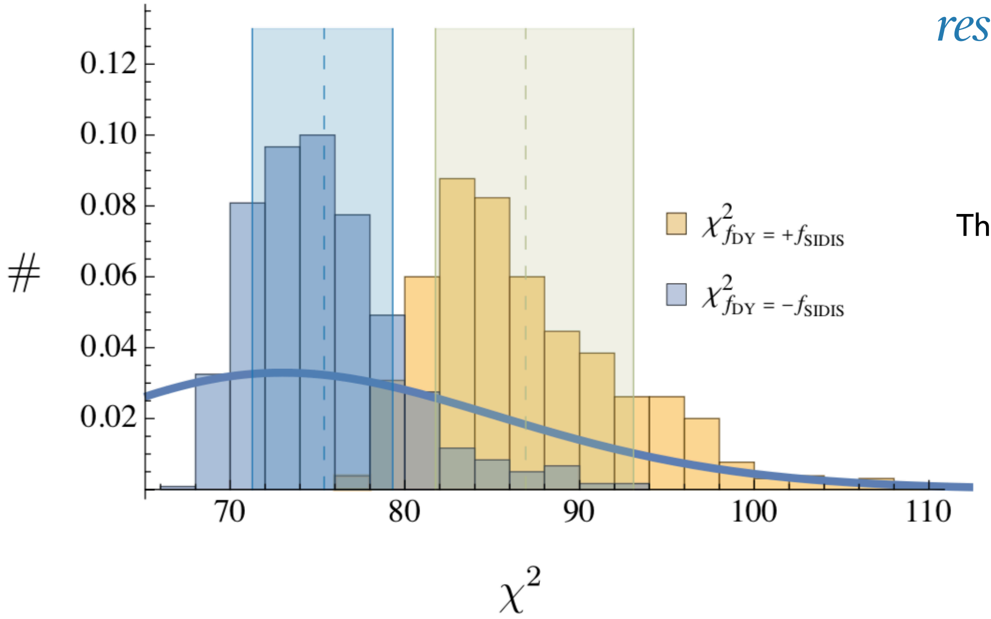
A direct QCD prediction is a Sivers effect in the Drell-Yan process that has the opposite sign compared to the one in semi-inclusive DIS:

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

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.*

Bury et al, PRL 126, 112002 (2021)



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

Sign-change is preferred but not nearly confirmed!

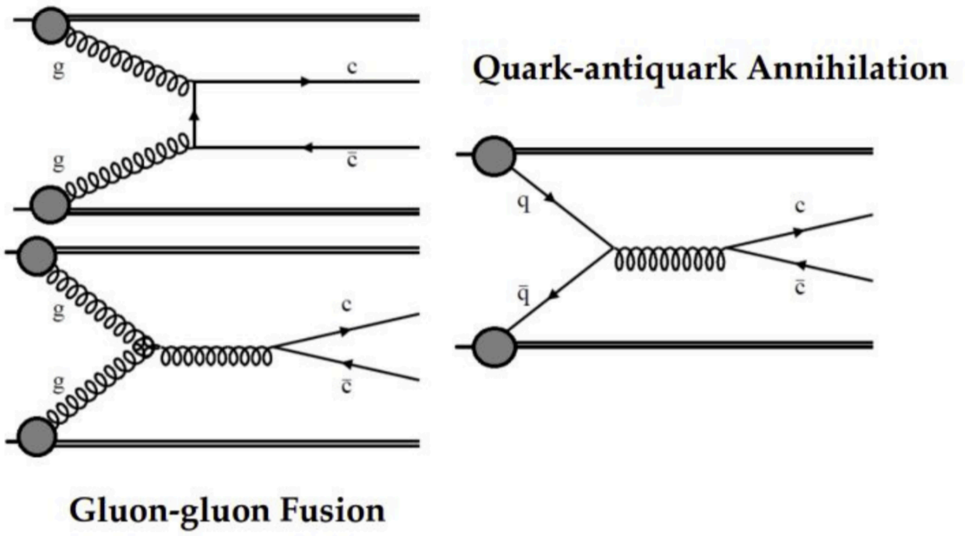
Still statistics (and kinematics) limited

SpinQuest Program

Gluons Sivers function

J/ψ Production

- J/ψ is bound charm-anticharm pair, a “charmonium”.
- Charmonia come from the quark-antiquark annihilation and gluon-gluon fusion partonic-level processes.
- The J/ψ meson can decay into bosons or dileptons, which we can detect in experiments.



Access gluon Sivers functions

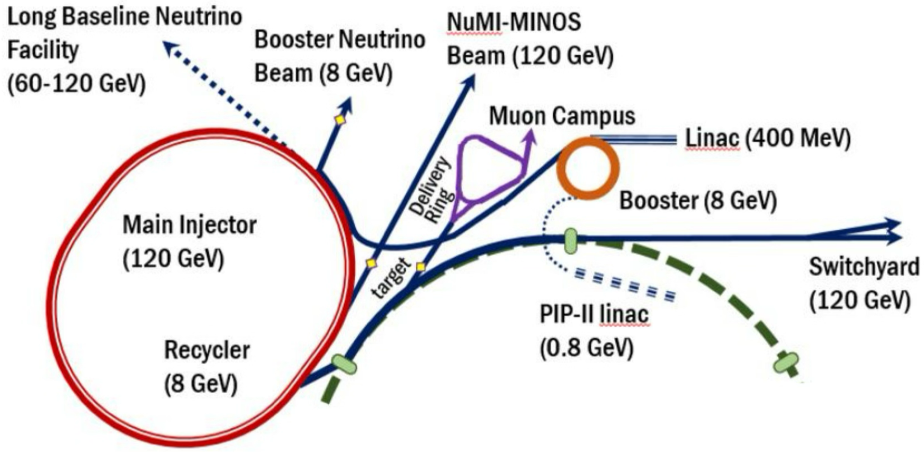
RHIC-PHENIX ○ √s = 200 GeV, xF~0.1

SpinQuest ○ √s = 15 GeV, xF~0.5

SpinQuest Experiment

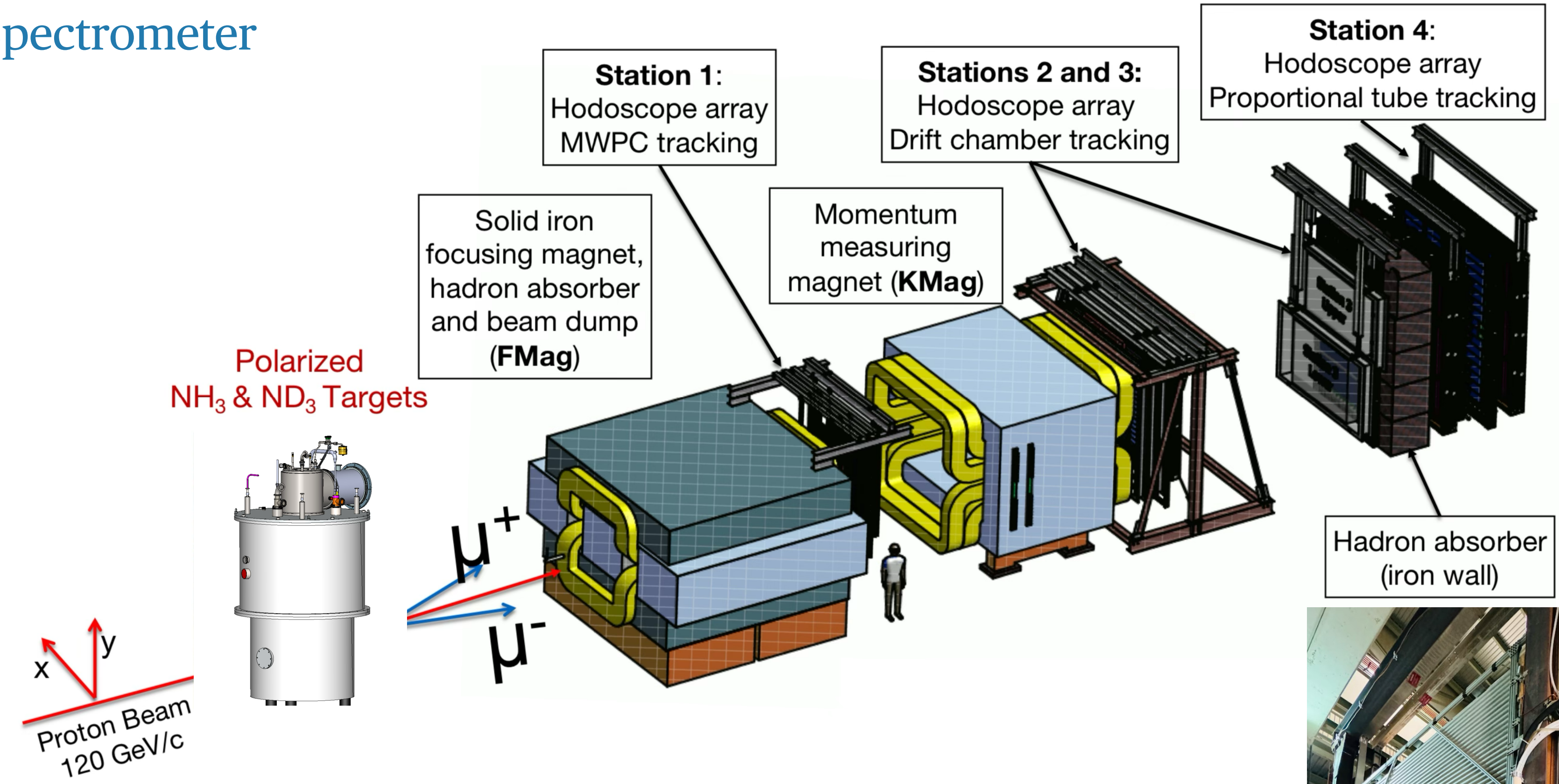
Beamline @ Fermilab

- Unpolarized protons are sent to SpinQuest from Main Injector.
- Energy 120 GeV ($\sqrt{s}$ =15.5 GeV)
- ~4s spill ~2 x10^{12} protons
  - Interval of 19 ns (53MHz)
  - ~10k protons per RF bucket.
- Highest proton intensity ever attempted on a solid polarized target. (3 x 10^{12} p/spill)



SpinQuest Experiment

Spectrometer



Inherited from SeaQuest

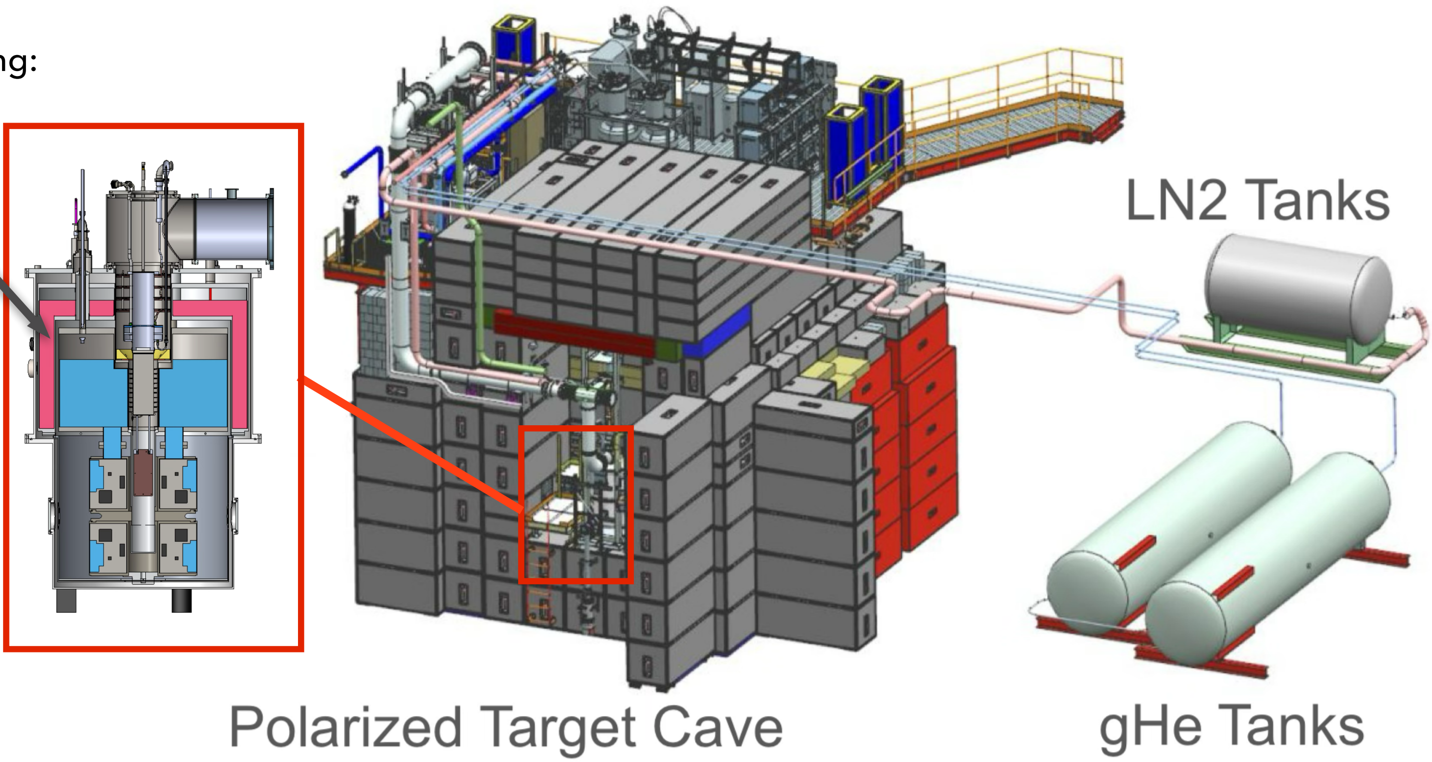
- A beam/spectrometer combination with well-understood capabilities and limitations.
- Necessary instrumentation to cope with high instantaneous intensity environment.
- Well-established analysis procedure.

SpinQuest Experiment

Target System

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

Thermal Shielding:
- LN2
- Outer Vacuum



- **Target maintained at 1K in 5 T field**
- **Capture and recirculate gHe for sustained continuous running under production data taking**

SpinQuest Experiment

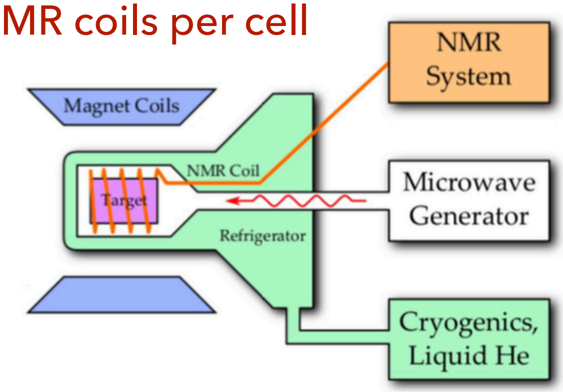
Target System

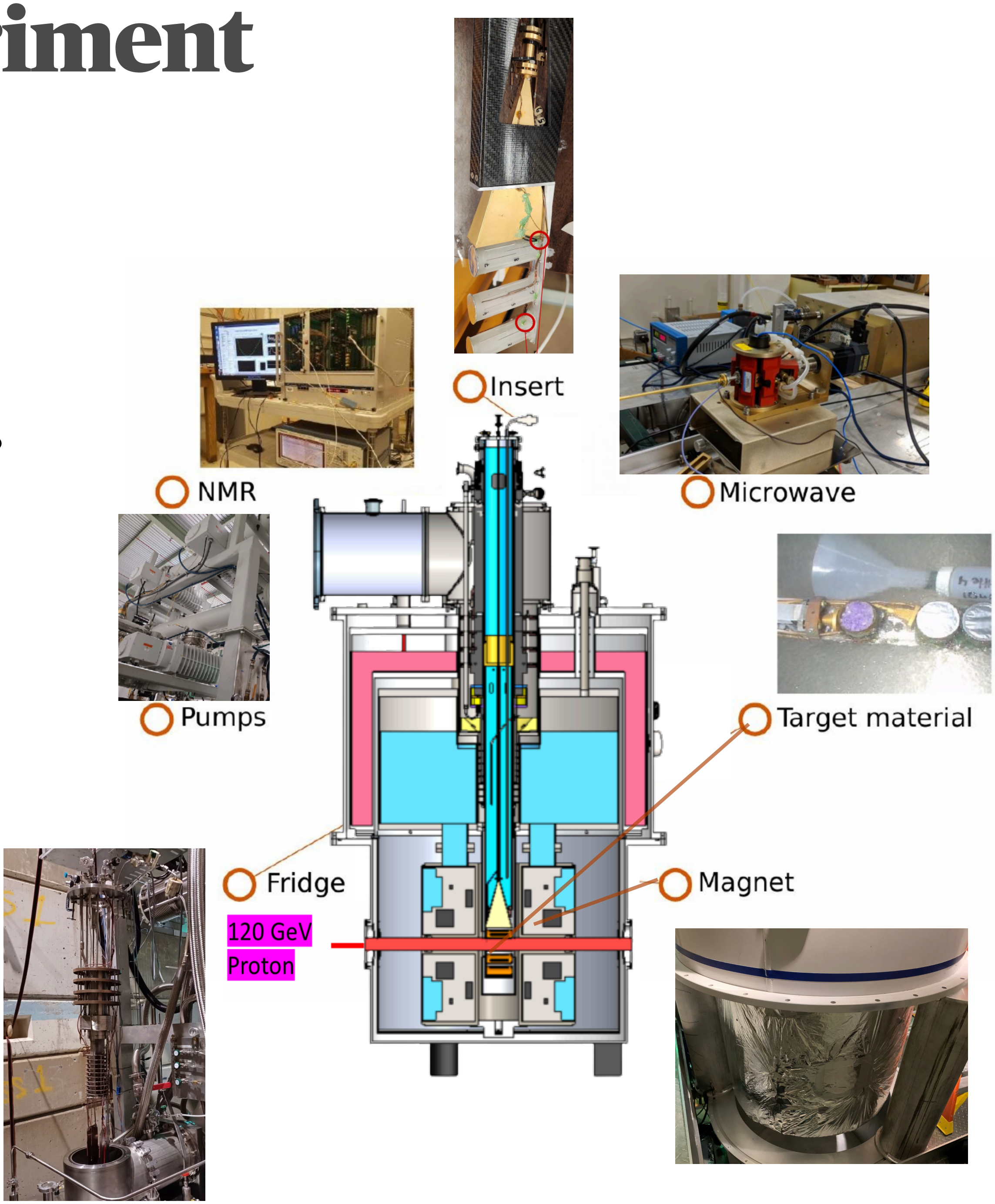
- Carbon fiber insert with 3 cells
- 140 GHz microwave source

Target uses Dynamic Nuclear Polarization.

- Proton maximum polarization: 95%
- Deuteron maximum polarization: 50%

- Ammonia beads (NH_3 or ND_3)
- 5T Magnet
- Evaporation refrigerator: keeps target material polarized and Helium liquid.
  - 16 W of maximum cooling power keeping the target at 1.1 K
- 17,000 m3/h pumps
- 3 NMR coils per cell





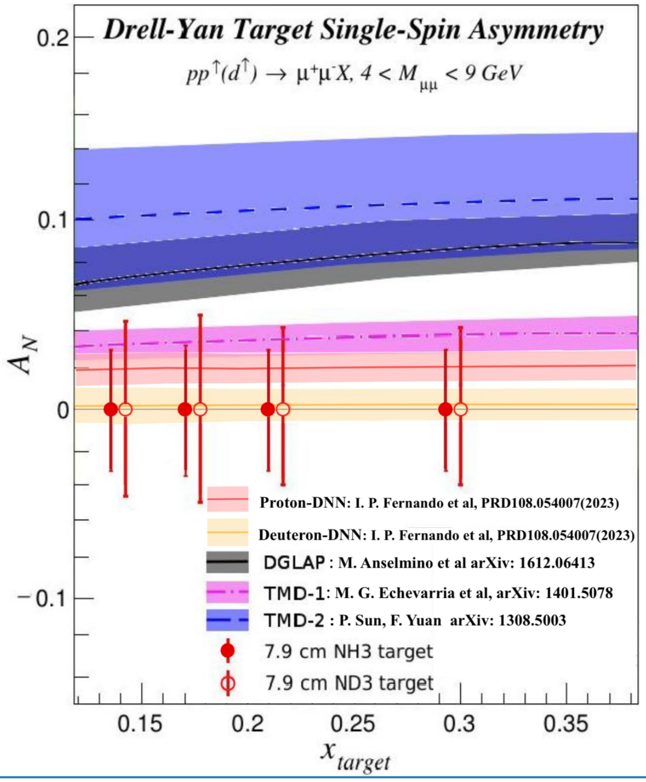
SpinQuest Experiment

Projected sensitivity and asymmetry

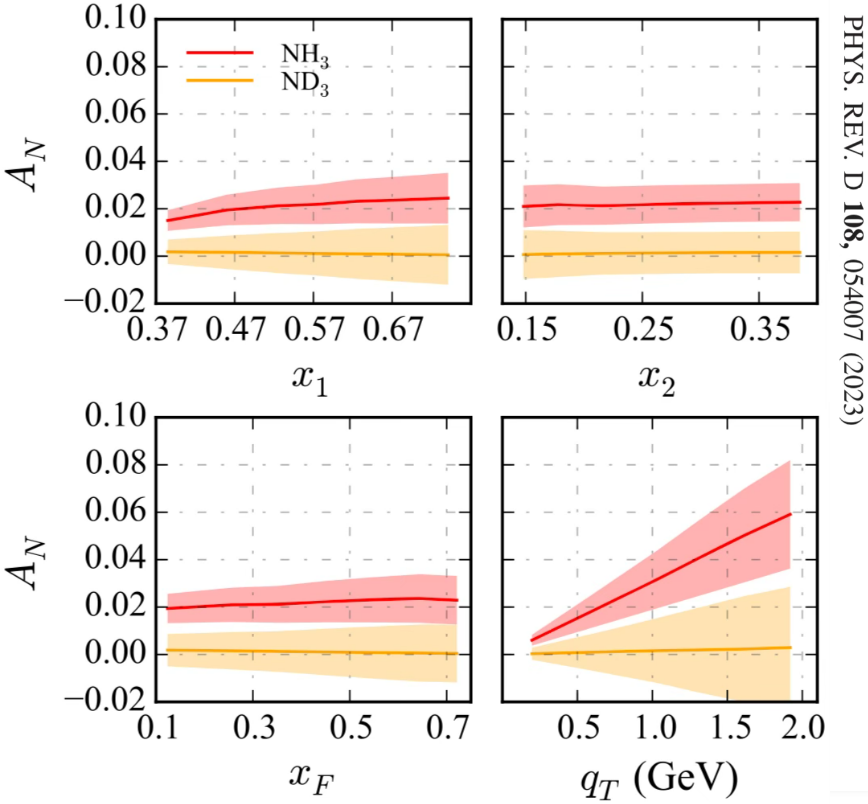
Projected Statistical uncertainty ~ 3-5%.

Systematic uncertainties:

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



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



- Conditions
  - 2.5 years of data taking
  - NH3:ND3 = 50%:50% in time
- Transverse Single-Spin Asymmetry (TSSA)
  - Measurement precision $\delta_{AN} \sim 0.04$
- Important constraints on global models

Beam Commissioning 05/24 - 07/24

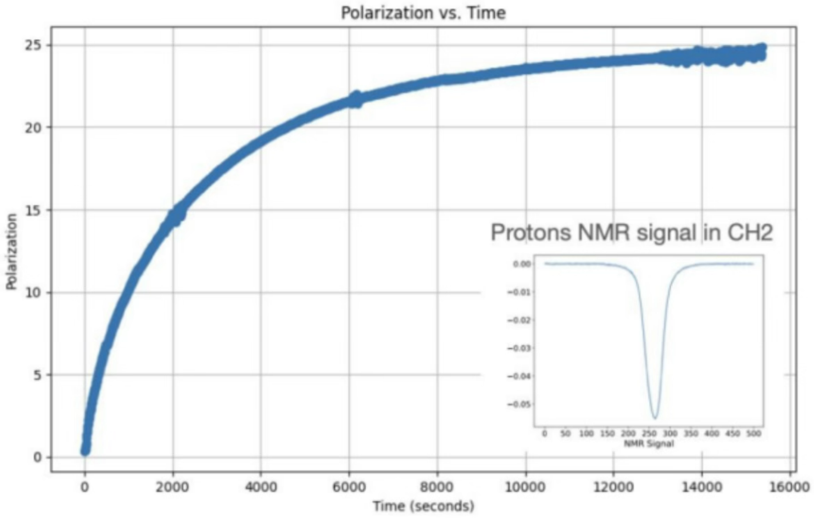
Objectives

- **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.

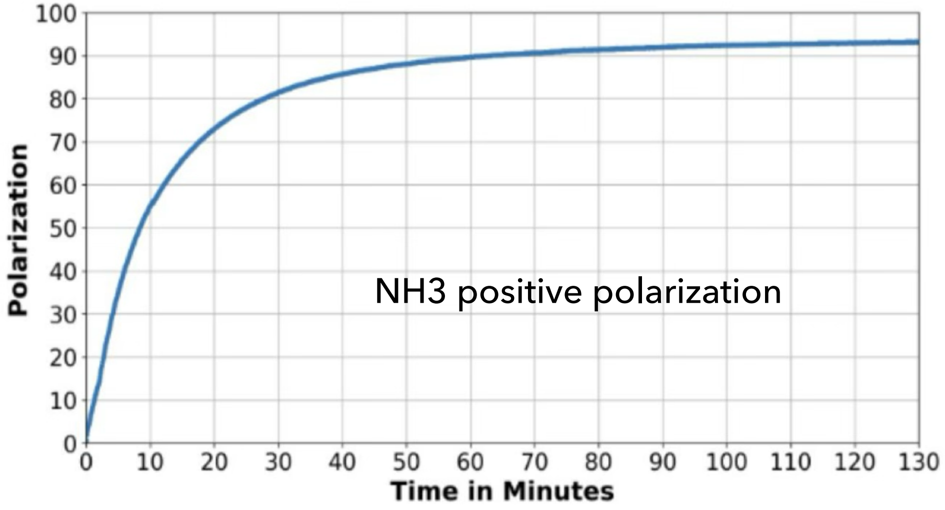
Beam Commissioning 05/24 - 07/24

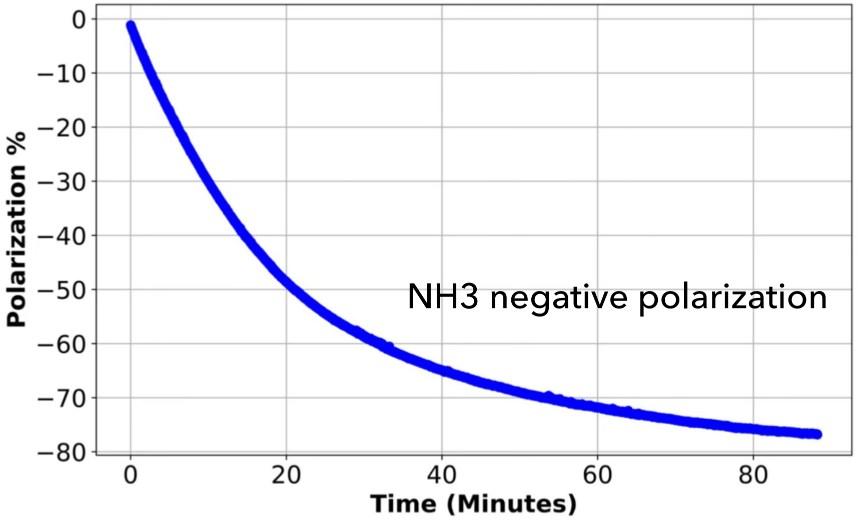
Polarization

- Successful operation of polarized target in high-intensity proton beam up to 3 x 10^{12} protons per spill.
- P = 26% with CH2 at 1K and 5T which has never been achieved before.
- P = +95%, -85% with NH3 at 1K and 5T.



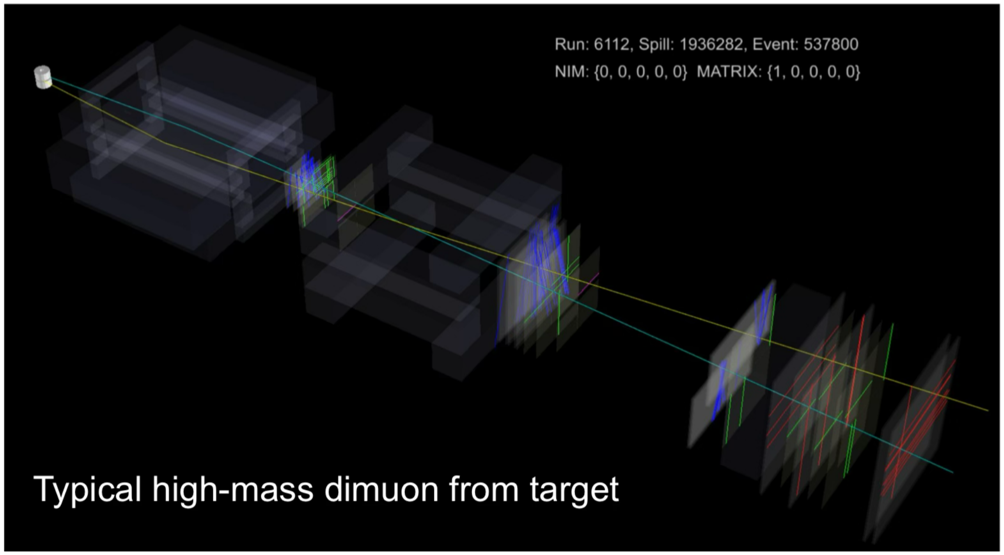
Proton Polarization

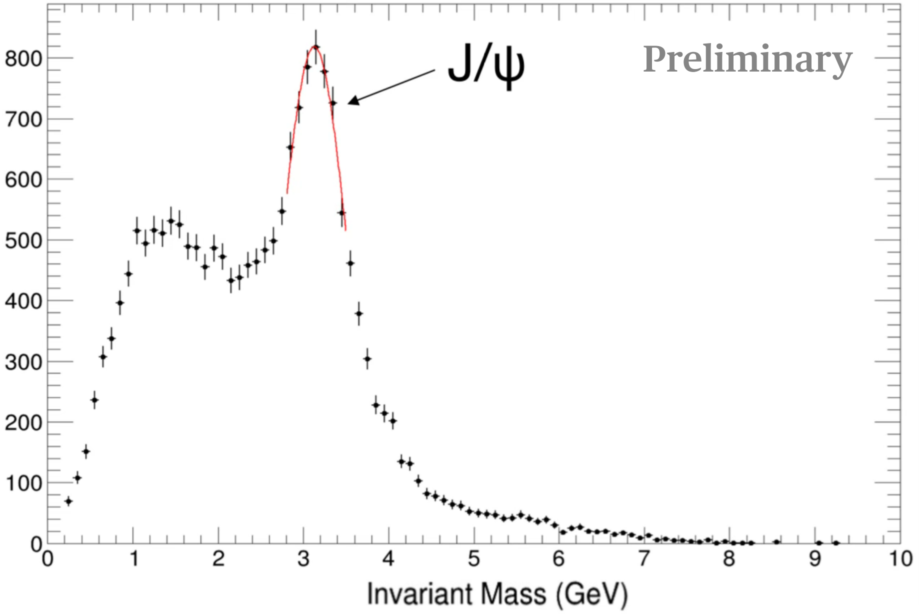




Beam Commissioning 05/24 - 07/24

Event reconstruction



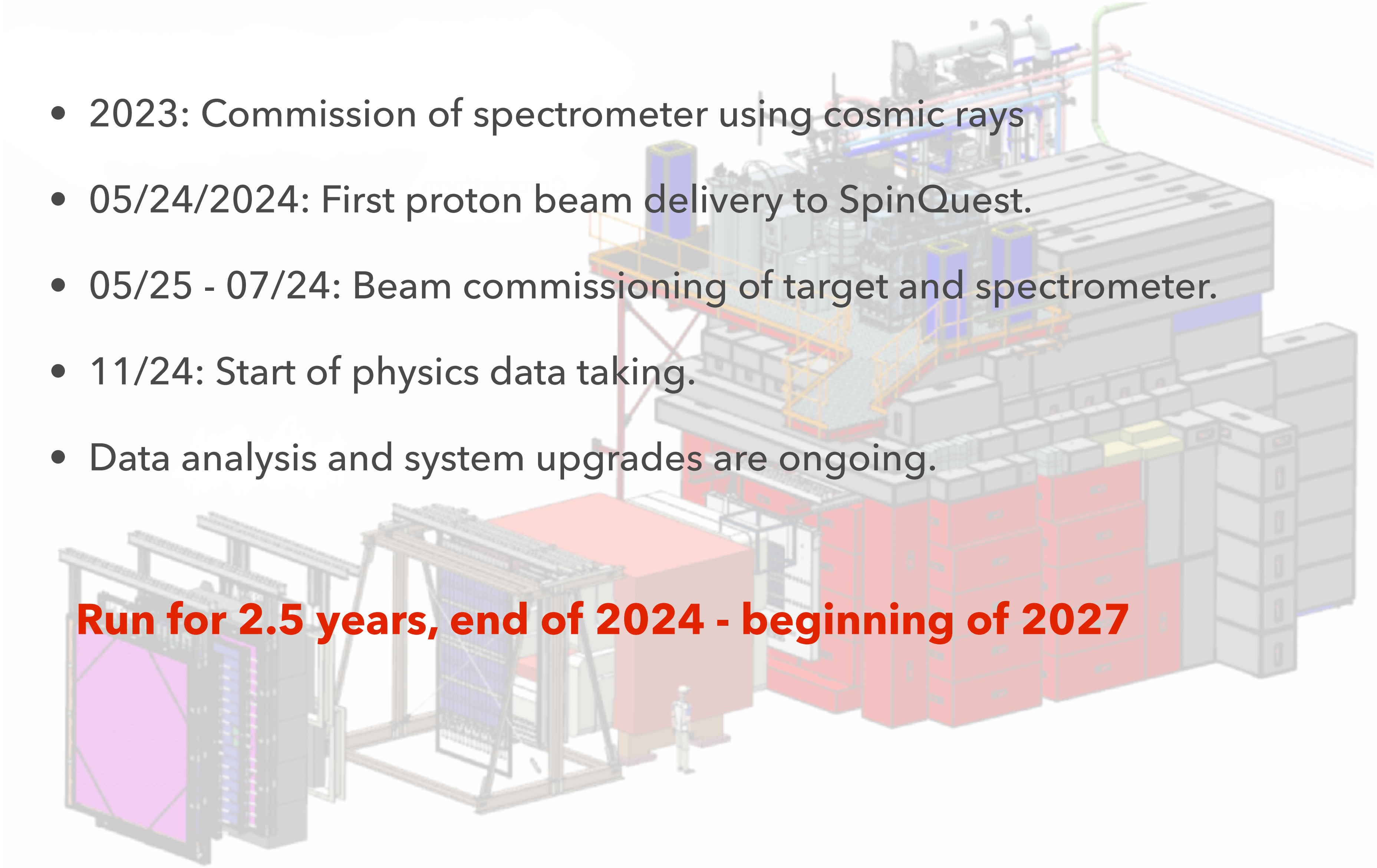


Clear J/ψ and high-mass dimuon events (dominated by beam dump events) observed in the online plots.

Offline analysis of the commissioning and production data is ongoing!

SpinQuest Experiment

Timeline



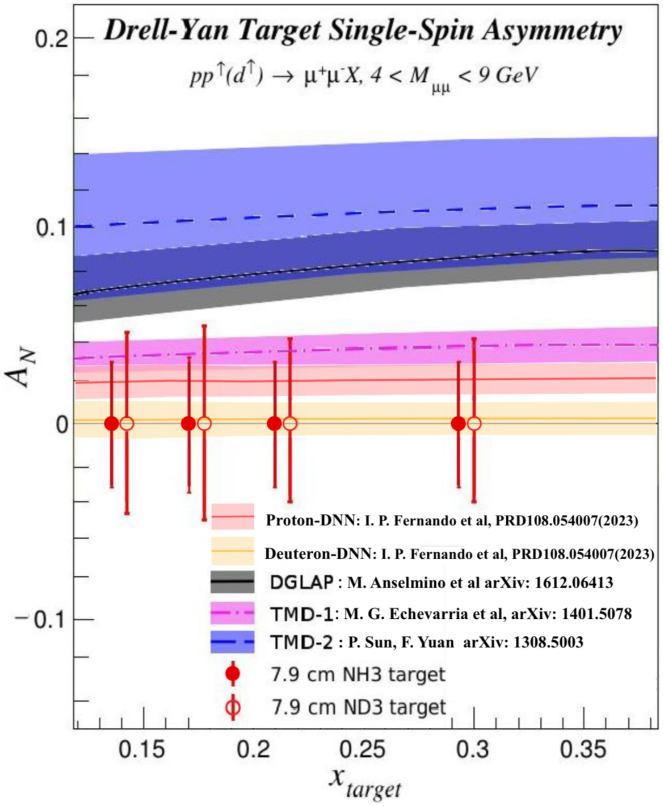
- 2023: Commission of spectrometer using cosmic rays
- 05/24/2024: First proton beam delivery to SpinQuest.
- 05/25 - 07/24: Beam commissioning of target and spectrometer.
- 11/24: Start of physics data taking.
- Data analysis and system upgrades are ongoing.

Run for 2.5 years, end of 2024 - beginning of 2027

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.
- 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 (5 x 10^{35} cm^{-2}s^{-1}).
- Longest (along the beam-line) target cell to date for an 1K evaporation fridge.
- SpinQuest has the highest power evaporation refrigerator ever made for a polarized target experiment.



SpinQuest Experiment

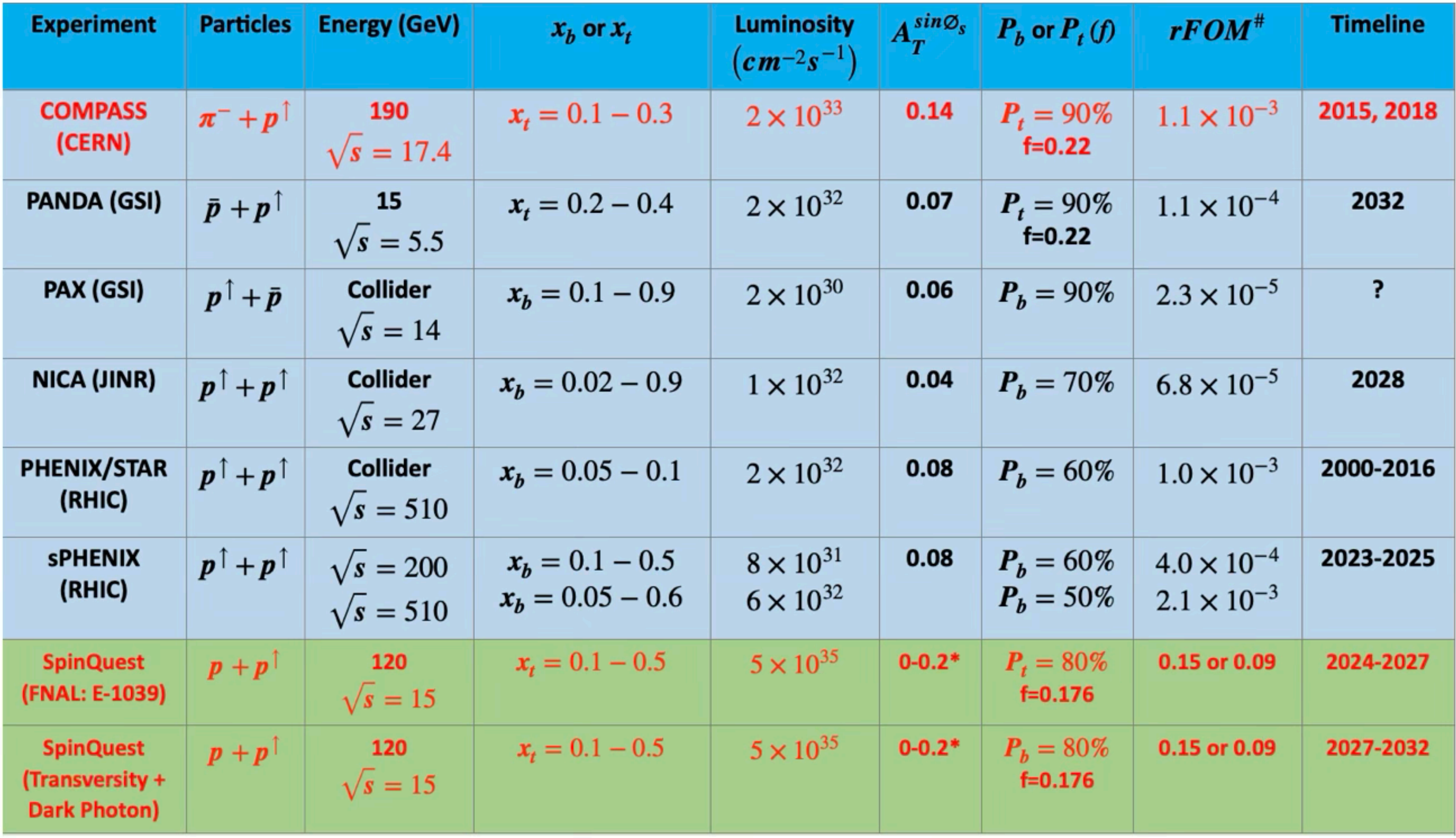
https://spinquest.fnal.gov

INSTITUTIONS 23	FULL MEMBERS 55 Postdocs 8 Grad. Students 12	AFFILIATE MEMBERS
1) Abilene Christian University	Donald Isenhower (PI), Michael Daugherty, Shon Watson Sean McDonald, Bethany Beavers	Roy Salinas, Rusty Towell, Shannon McNease, Yves Ngenzi, Thomas Fitch
2) Argonne National Laboratory	Paul Reimer (PI), Donald Geesaman	Kevin Bailey, Thomas O'Connor
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
7) Los Alamos National Laboratory	Kun Liu (SP), Liliet Diaz	Jan Boissevain, Patrick McGaughey, Andi Klein
8) Mississippi State University	Lamiaa El Fassi (PI), Vaniya Ansari, Utsav Shrestha	Dipangkar Dutta
9) New Mexico State University	Stephen Pate (PI), Vassili Papavassiliou, Chatura Kuruppu, Huma Haider, Dinupa Nawarathne, Harsha Sirilal	
10) RIKEN	Yuji Goto (PI)	
11) Shandong University	Qinghua Xu (PI)	
12) Tokyo Institute of Technology	Toshi-Aki Shibata (PI)	
13) University of Colombo	Hansika Atapattu (PI), Vibodha Bandara	
14) University of Illinois, Urbana-Champaign	Jen-Chieh Peng (PI)	Naomi Makins, Daniel Jumper, Jason Dove, Mingyan Tian, Bryan Dannowitz, Randall McClellan, Shivangi Prasad
15) University of Michigan	Wolfgang Lorenzon (PI), Levgen Lavrukhin	Daniel Morton, Richard Raymond, Marshall Scott
16) University of New Hampshire	Karl Slifer (PI)	Maurik Holtrop
17) Tsinghua University	Zhihong Ye (PI)	
18) University of Virginia	Dustin Keller (SP), Kenichi Nakano, Ishara Fernando, Forhad Hossain, Ernesto Diaz, Jay Roberts, Devin Seay, Amal Pattividana, Dima Watkins, Nuwan Chaminda , Sujan Subedi	Donal Day, Donald Crabb, Oscar Rondon, Zulkaida Akbar
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	
22) University of Memphis	Kei Nagai (PI)	
23) Massachusetts Institute of Technology	P. Harris (PI), Noah Paladino	

Please contact spokespersons if interested:
Dustin Keller (UVA, dustin@virginia.edu) & Kun Liu (LANL, liuk@lanl.gov)

Thank You!

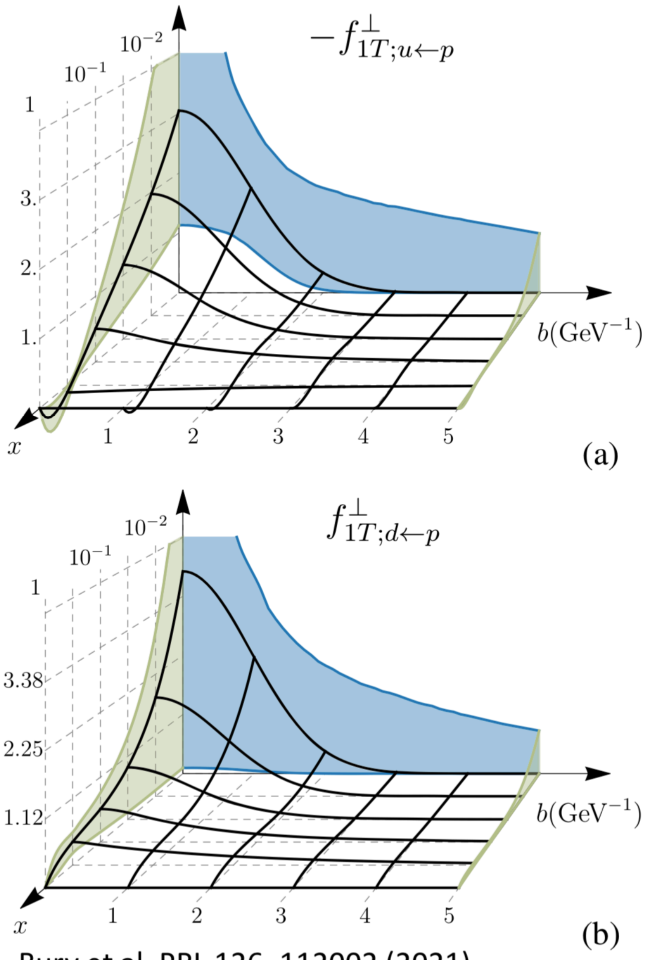
This work is supported by US-DOE



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

Accessing Sivers function

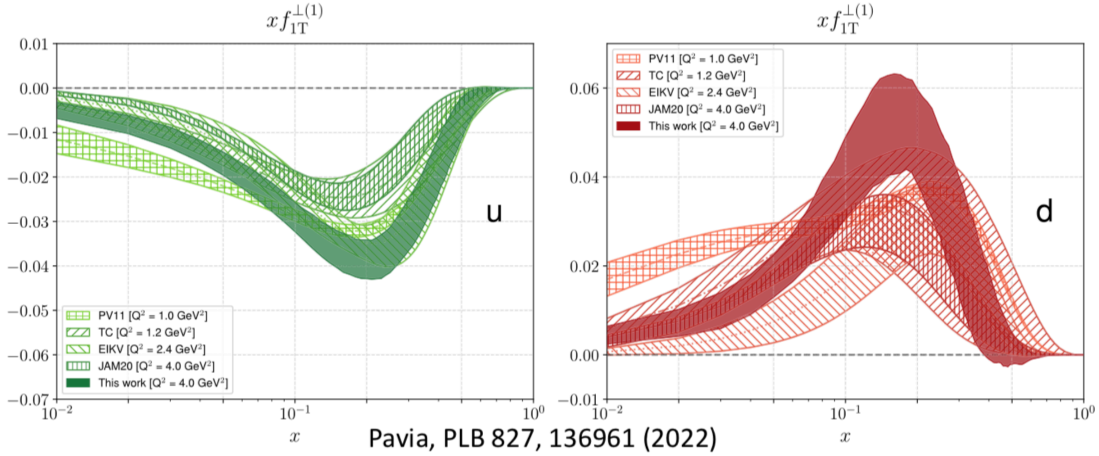
Global Sivers Measurements



Bury et al, PRL 126, 112002 (2021)

HERMES (2020), COMPASS (2009),COMPASS (2015)
JLab (2011), STAR (2016),COMPASS DY (2017)

- Recent global analyses utilize SIDIS+pp/πp data.
- Still statistics (and kinematics) limited.
- BIG questions about the sea!



Pavia, PLB 827, 136961 (2022)

HERMES (2020), COMPASS (2009),COMPASS (2015)
JLab (2011)

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.

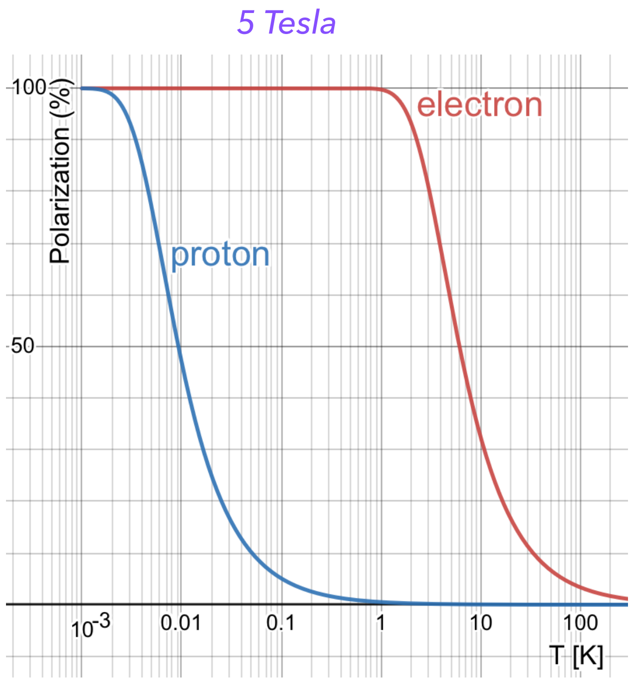
$$P = tanh\left(\frac{\mu B}{kT}\right)$$

- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- At B = 5 Tesla & T = 1 K

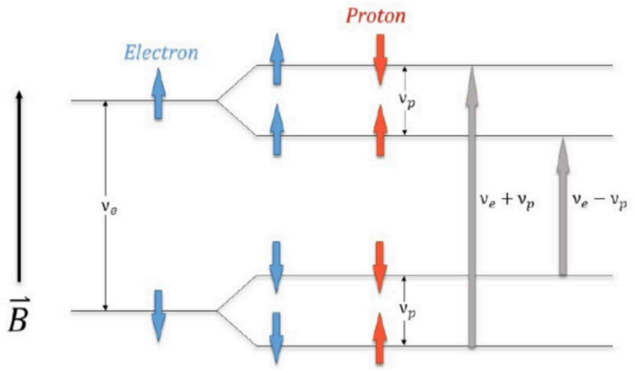
$$P_e = \sim 98\%,\ P_p = 0.51\%$$



- 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%

SpinQuest Program

Independent $\bar{u}$ and $\bar{d}$ Sivers functions

proton beam + transversely-polarized NH_3 (proton target) & ND_3 (neutron target): Drell-Yan processes in $p + p^\uparrow$ & $p + d^\uparrow$

- Determine independently both the $\bar{u}$ and $\bar{d}$ Sivers functions contributions; something no other proposed experiment is able to do.

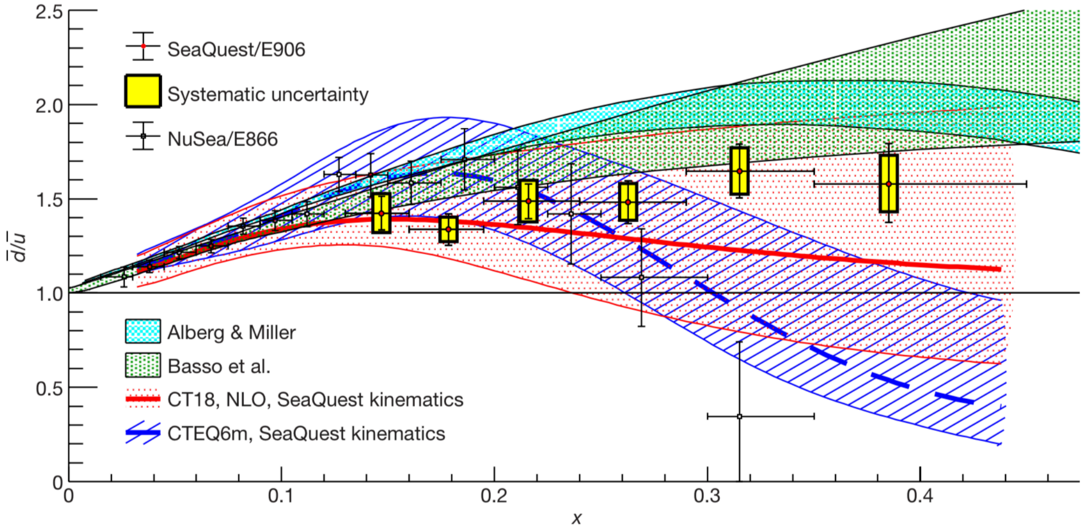
Combined analysis of TSSAs in $p + p^\uparrow$ & $p + d^\uparrow$ → Separation of $\bar{u}$ & $\bar{d}$

- Polarized $\bar{d}/\bar{u}$ ratio: spin sensitive flavor asymmetry?

$$\frac{\sigma_D(x_t)}{2\sigma_H(x_t)} \approx \frac{1}{2}\left(1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

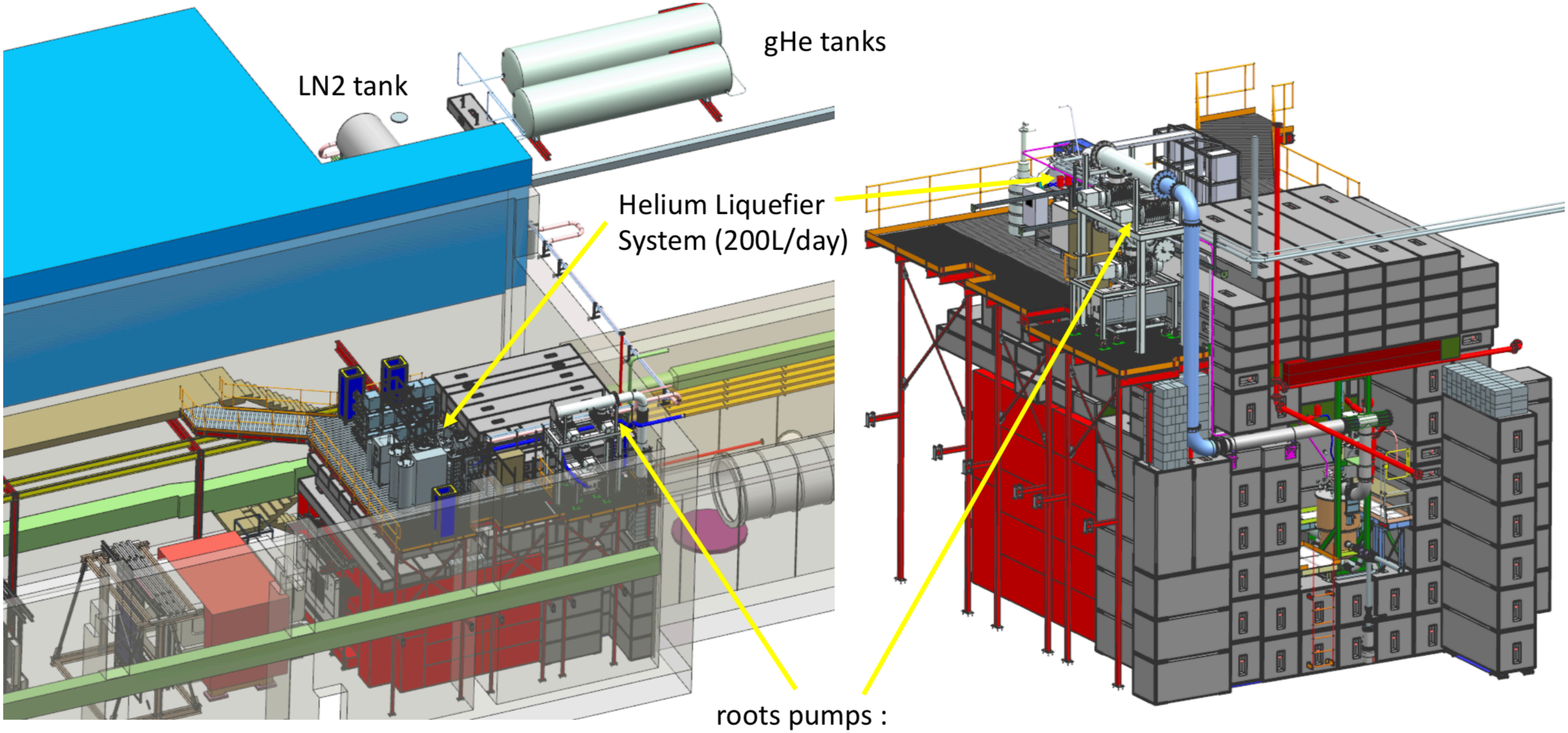
Check sensitivity of flavor asymmetry to spin.

Nature 590, 561–565



SpinQuest Experiment

Setup



LN2 tank

gHe tanks

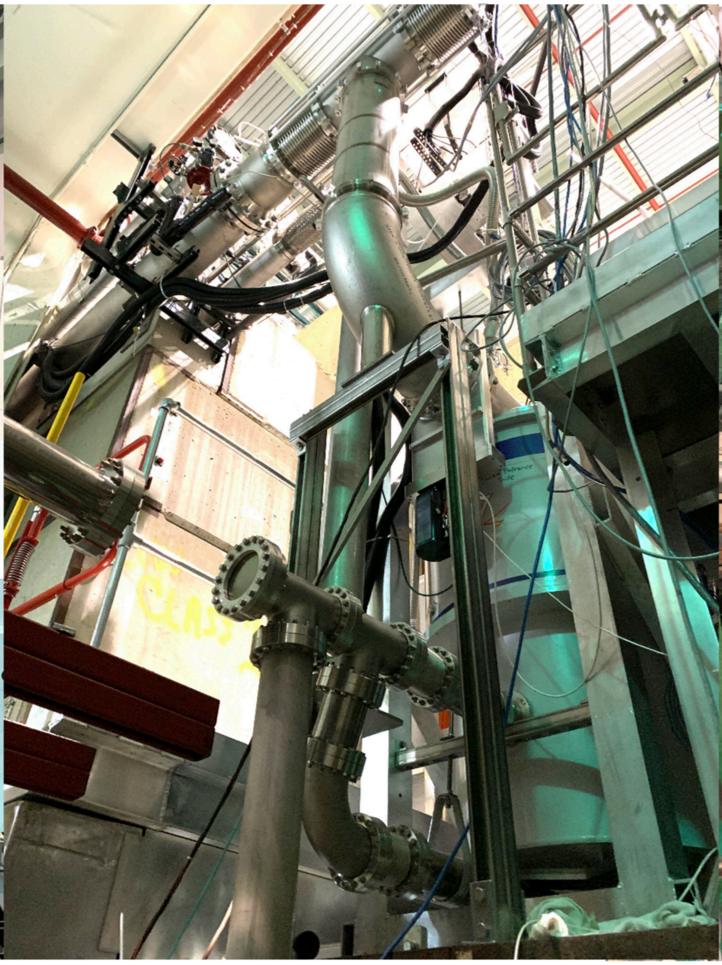
Helium Liquefier
System (200L/day)

roots pumps :
pumping power 17K m^3 per hour

SpinQuest Experiment

Setup

From beam down-stream



Beam-window and superconducting magnet

From target cave to beam-upstream