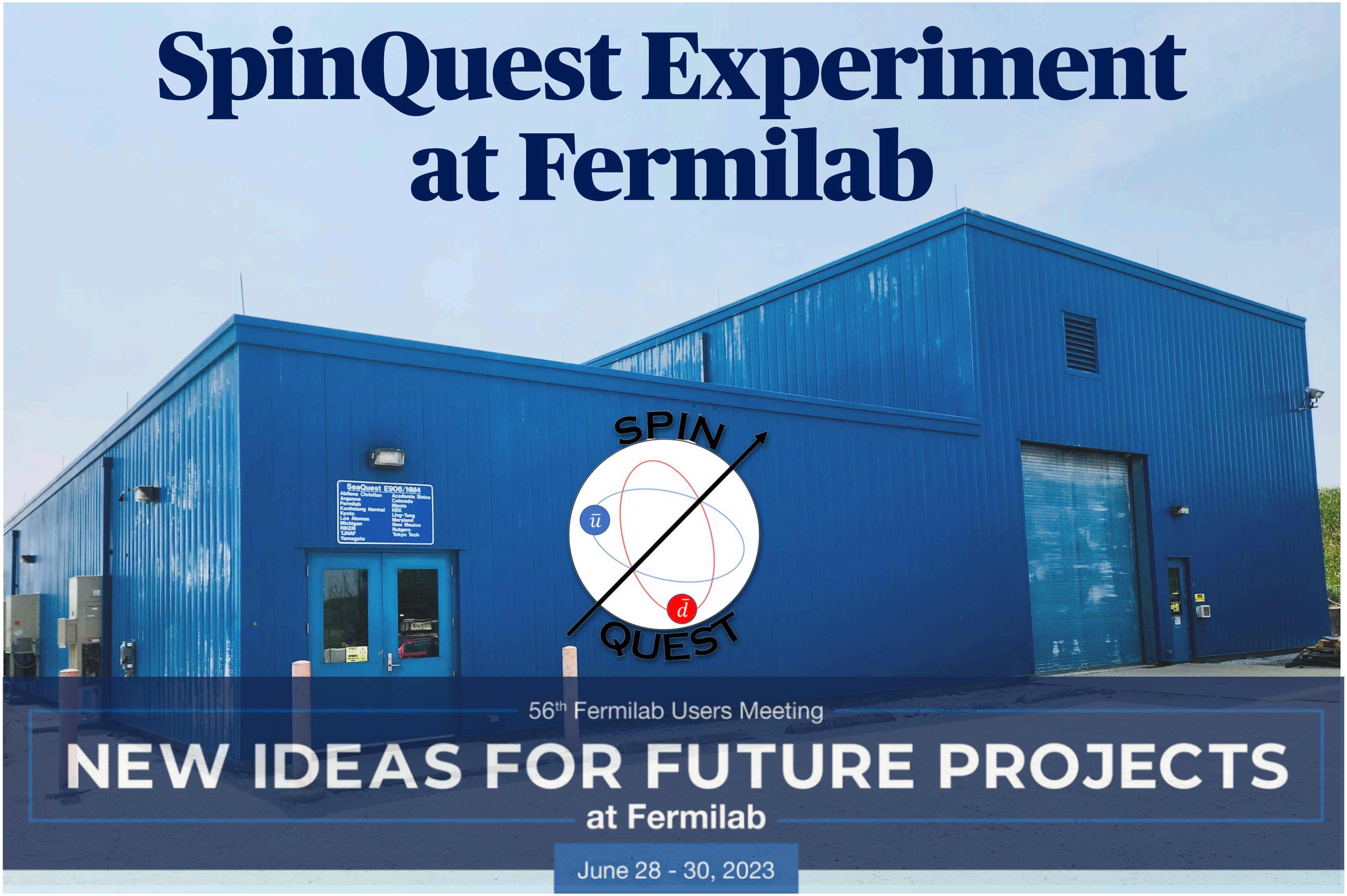
LILIET CALERO DIAZ

SpinQuest Experiment at Fermilab



56th Fermilab Users Meeting

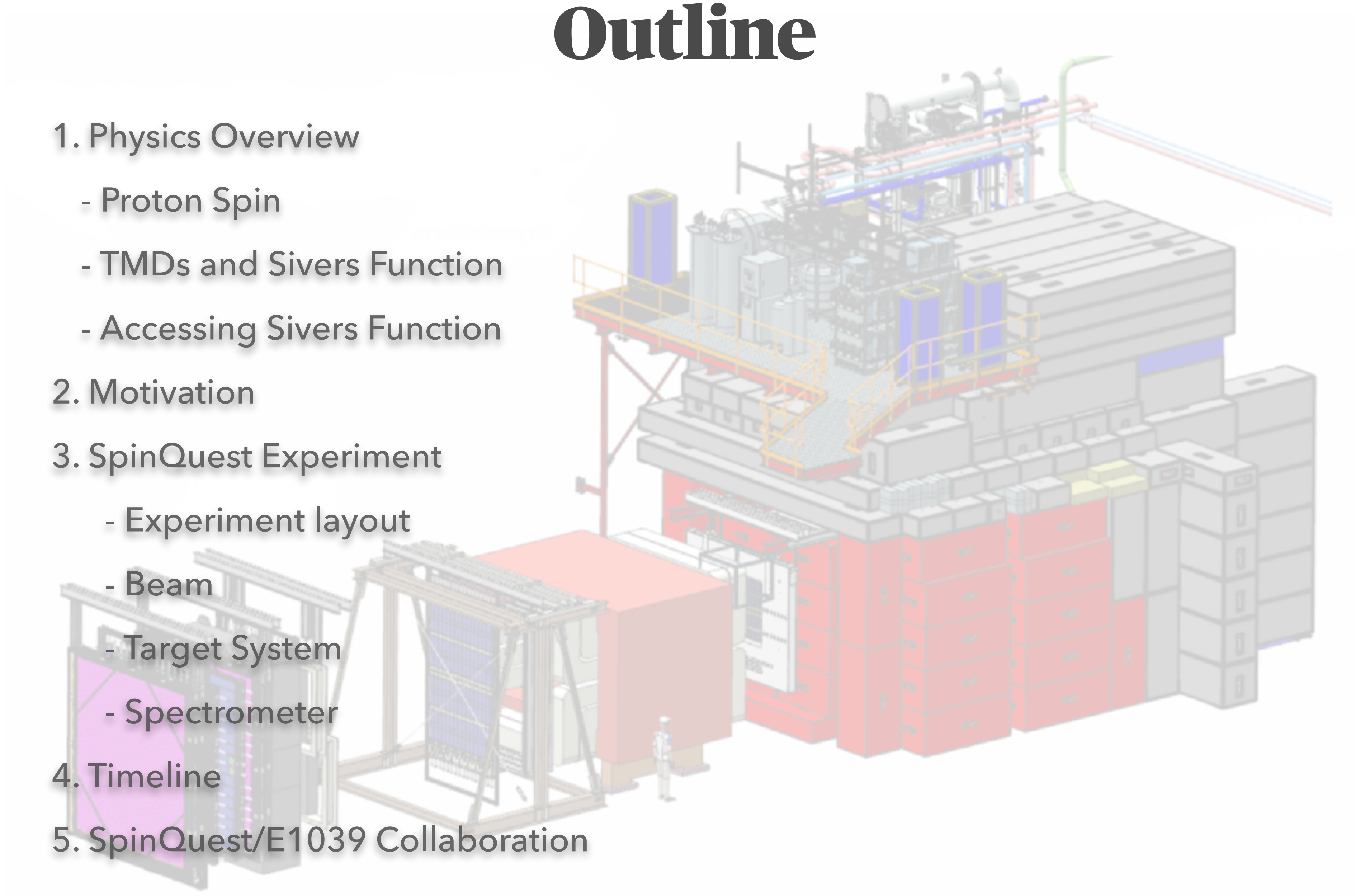
NEW IDEAS FOR FUTURE PROJECTS

at Fermilab

June 28 - 30, 2023

This work is supported by DOE contract DE-FG02-96ER40950

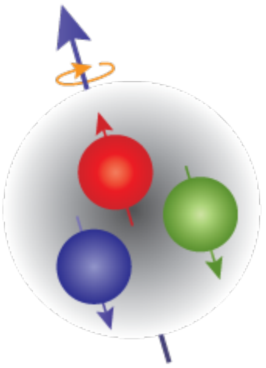
Outline



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

Proton Spin

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

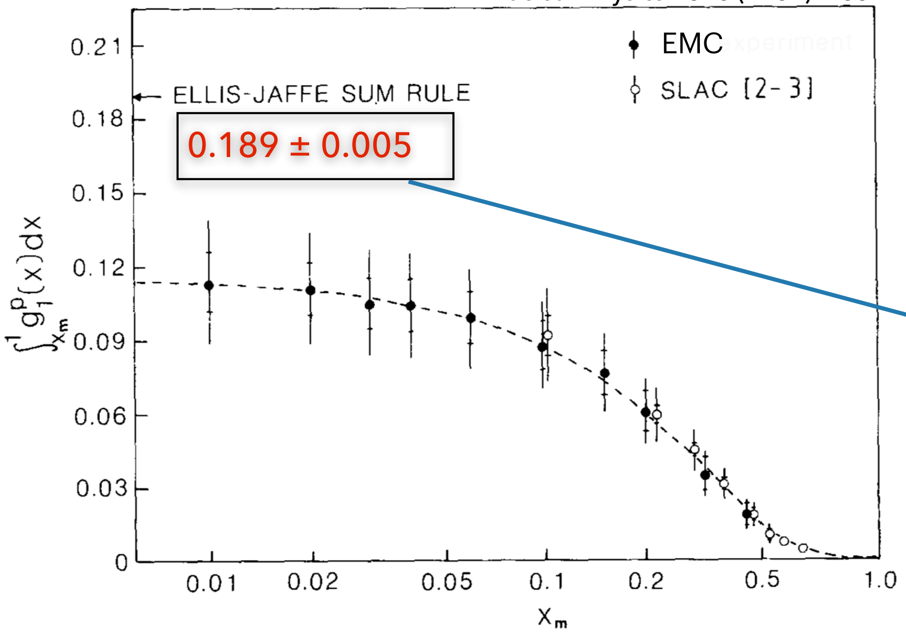


1980s

Naive quark model (only valence quarks)

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

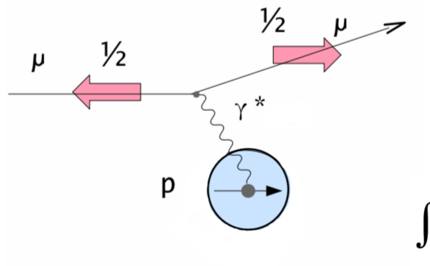
Nuclear Physics B328 (1989) 1-35



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:

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

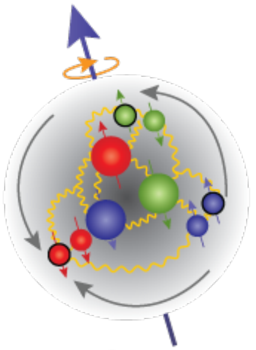
consistent with zero!

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

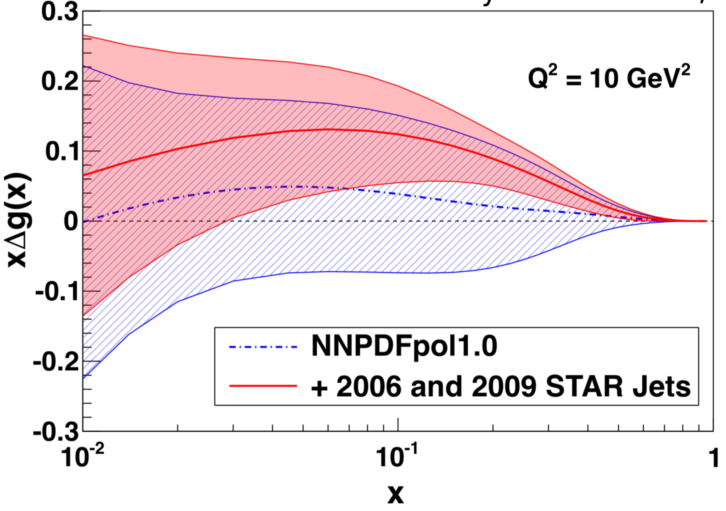
PHYS. REV. D 98, 074505 (2018)

	Δu	Δd	Δs	$\Delta\Sigma$
de Florian *et al.* ($Q^2 = 10$ GeV^2)	$0.793^{+0.028}_{-0.034}$	$-0.416^{+0.035}_{-0.025}$	$-0.012^{+0.056}_{-0.062}$	$0.366^{+0.042}_{-0.062}$
NNPDFpol1.1 ($Q^2 = 10$ GeV^2)	0.76(4)	−0.41(4)	−0.10(8)	0.25(10)
COMPASS ($Q^2 = 3$ GeV^2)	[0.82, 0.85]	[−0.45, −0.42]	[−0.11, −0.08]	[0.26, 0.36]

$\Delta\Sigma \approx 30\,\%$

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

Phys. Rev. Lett. 115,



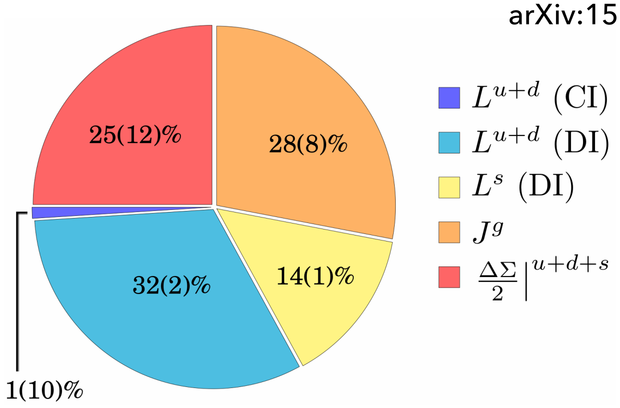
Gluon intrinsic AM is still under active investigation at the Relativistic Heavy Ion Collider.

Proton Spin

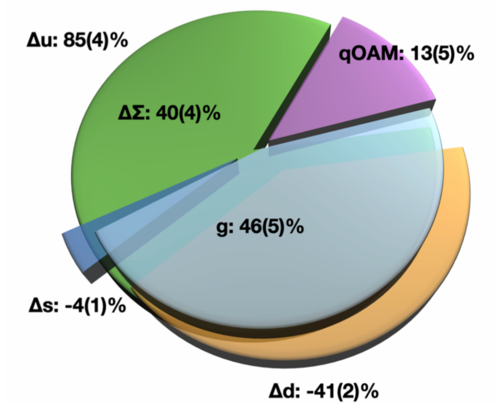
Insight into OAM contribution and transverse momentum

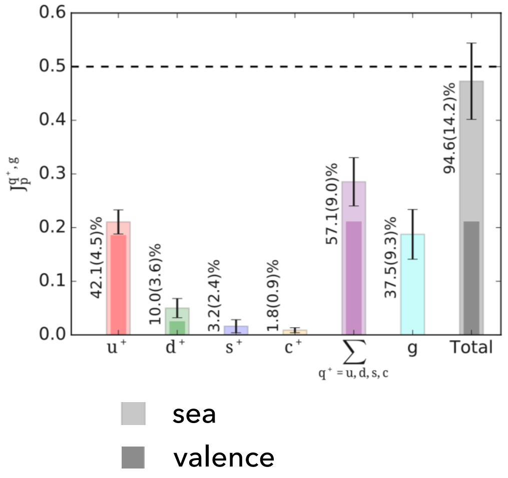
- Proton spin contributions from lattice QCD

arXiv:1504.066



arXiv:2112.08416

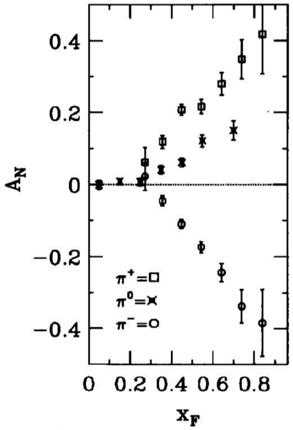




- ∘ near **50%** comes from quarks OAM
- ∘ **50%** comes from OAM: 38 - 46 (20) % gluons
  13 - 18 (50) % quarks

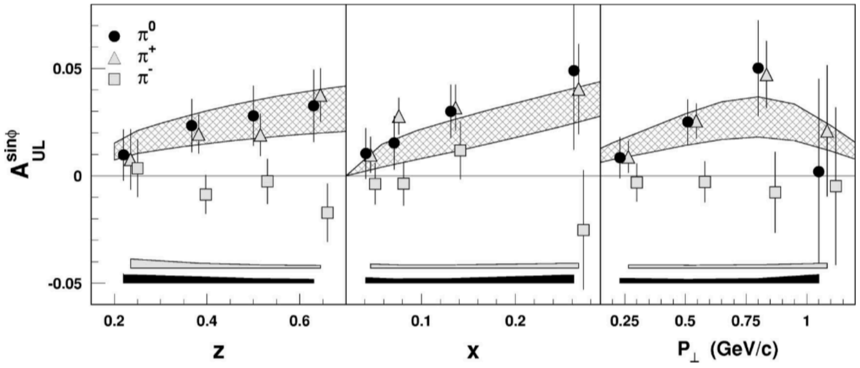
- Experimental hints at OAM

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



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

A. Airapetian Phys Rev. D64 (2001) 097101



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

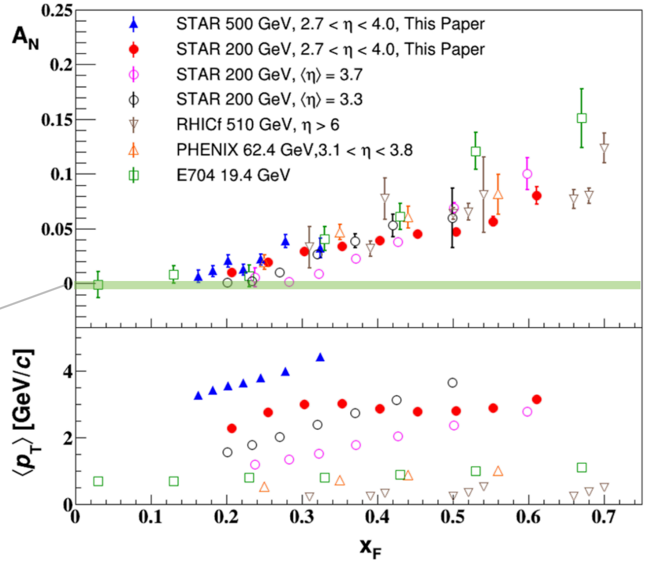
Transverse Momentum Dependent Parton Distribution Functions (TMD - PDFs)

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

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

Transverse single spin asymmetries should be small

Phys. Rev. D 103, 092009



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

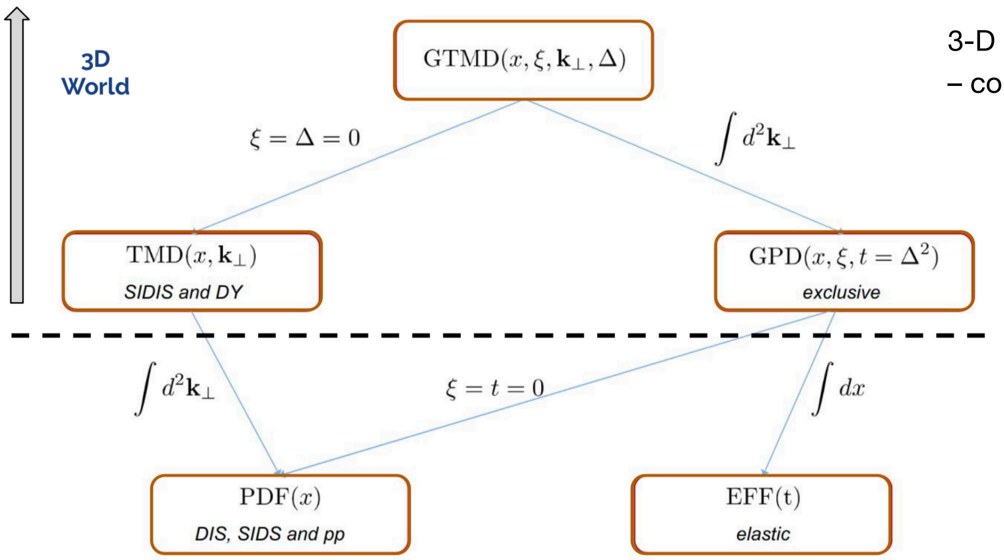
Partonic nucleon structure *beyond* collinear approximation

$$\Phi(x,\boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1\not{n}_+ + f_{1T}^\perp\frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \Big(S_L\, g_{1L} + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M}\, g_{1T}^\perp\Big)\gamma^5\not{n}_+ \; h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \\ + \Big(S_L\, h_{1L}^\perp + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M}\, h_{1T}^\perp\Big)\frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M} + h_1^\perp\frac{\sigma_{\mu\nu}k_\perp^\mu n_+^\nu}{M}\Big]$$

TMD-PDFs: the leading-twist correlator, with intrinsic $\mathbf{k}_\perp$, contains 8 independent functions.

TMDs and Sivers function

Transverse Momentum Dependent Parton Distribution Functions (TMD - PDFs)



3-D structure in (x, $\mathbf{k}_\perp$) - space
– complementary to 3-D structure in (x, $\mathbf{k}_\perp$)-space (→ GPDs)

TMDs , GPDs

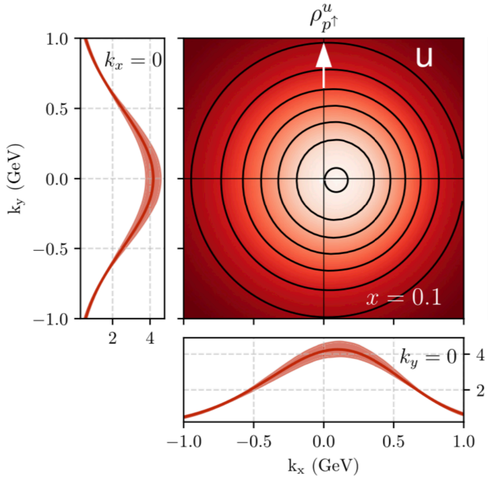
↓

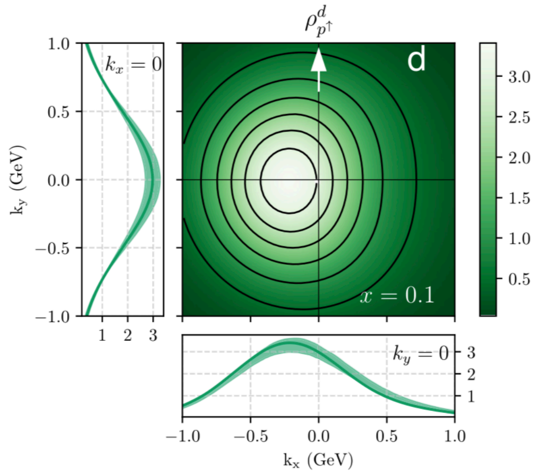
Transverse structure

↓

OAM

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





Pavia, PLB 827, 136961 (2022)

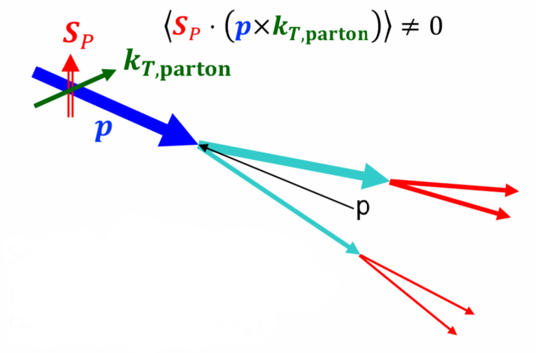
- Distortions require wavefunctions to have component w/ non-zero angular momentum.
- Important constraints on nucleon models.

TMDs and Sivers function

Sivers functions

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.

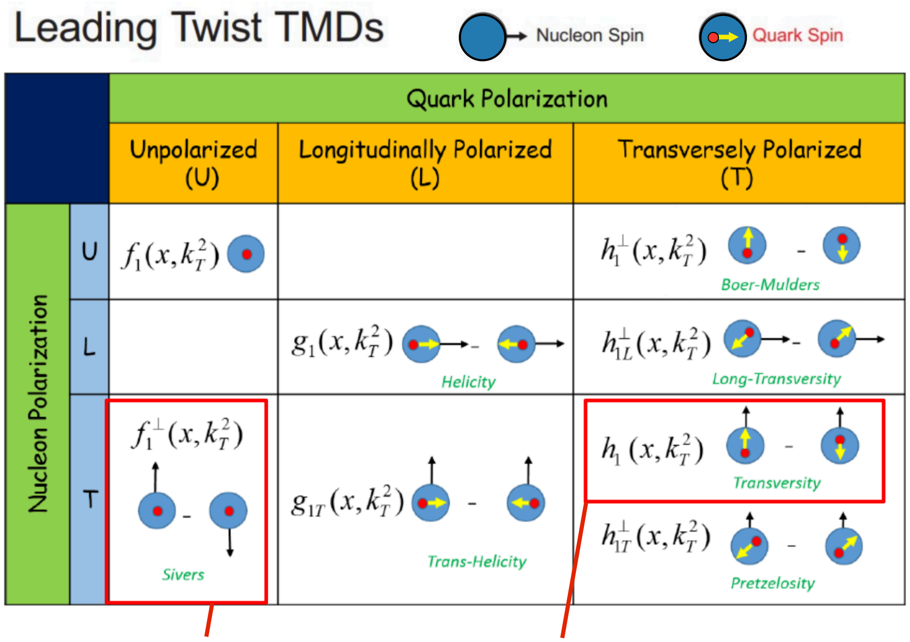
$$f_{q/p^{\uparrow}}(x, \mathbf{k_T}) = f_{q/p}(x, \mathbf{k_T}) + f_{1T}^{\perp}(x, \mathbf{k_T})\, \mathbf{S_P} \cdot \left(\hat{\mathbf{p}} \times \hat{\mathbf{k}}_\mathbf{T}\right)$$



... 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


Leading Twist TMDs

● Nucleon Spin   ● Quark Spin

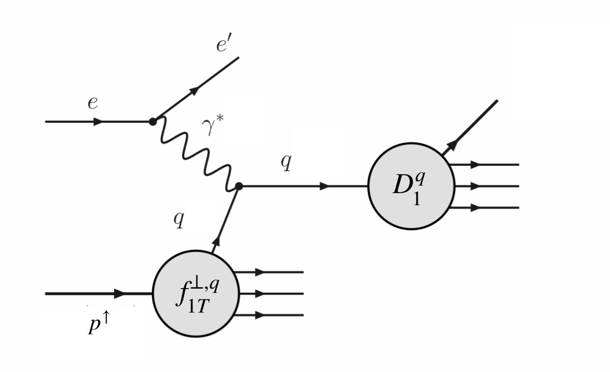
		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x, k_T^2)$		$h_1^{\perp}(x, k_T^2)$ - Boer-Mulders
	L		$g_1(x, k_T^2)$ - Helicity	$h_{1L}^{\perp}(x, k_T^2)$ - Long-Transversity
	T	$f_{1T}^{\perp}(x, k_T^2)$ - Sivers	$g_{1T}(x,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

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

- 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

Accessing Sivers function

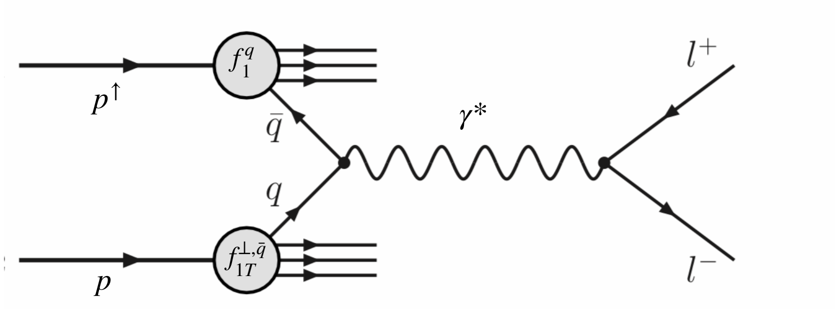
Polarized Semi Inclusive DIS



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

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

Polarized DY



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

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

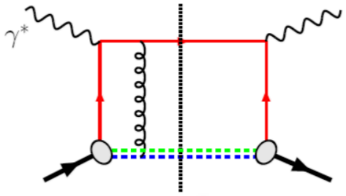
Cleanest probe to study hadron structure

“Modified-universality” of the “Sivers” function

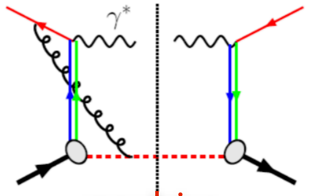
QCD:

DIS
Final-state interaction

Drell-Yan
Initial-state interaction



attractive



repulsive

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

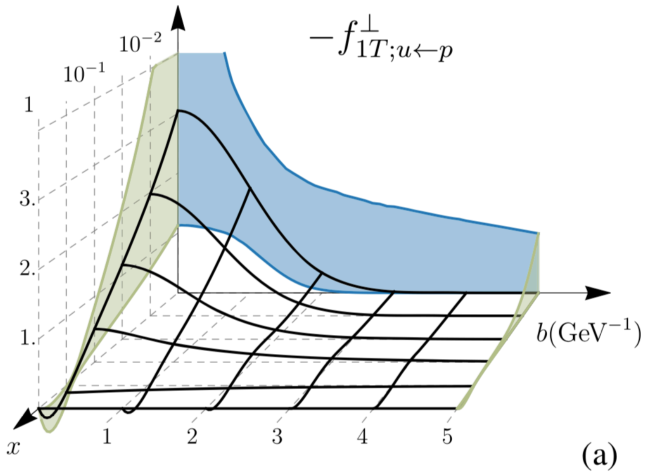
Fundamental prediction of QCD gauge invariance.

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

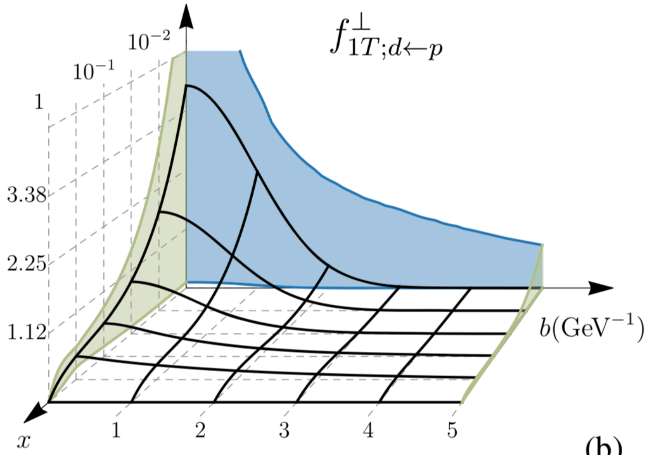
Courtesy of J. Drachenberg

Accessing Sivers function

Global Sivers Measurements



(a)

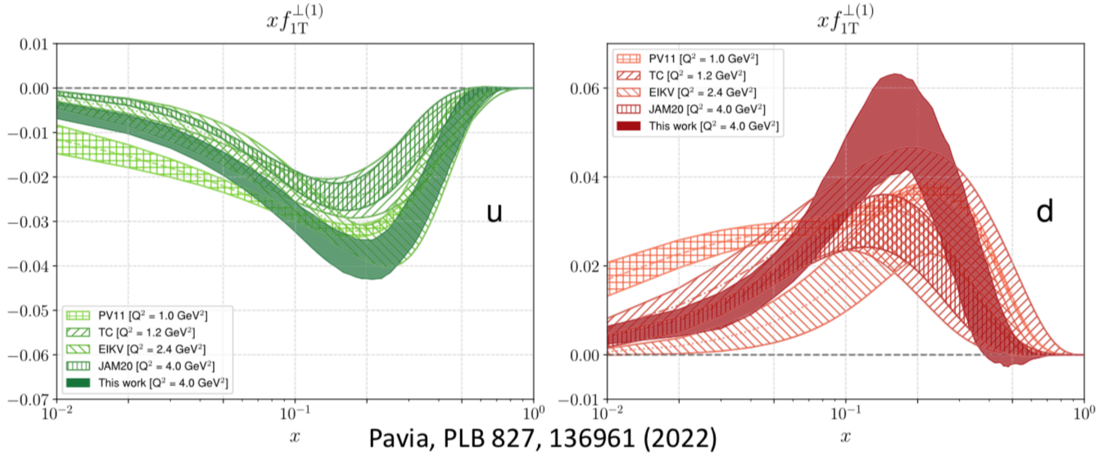


(b)

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)

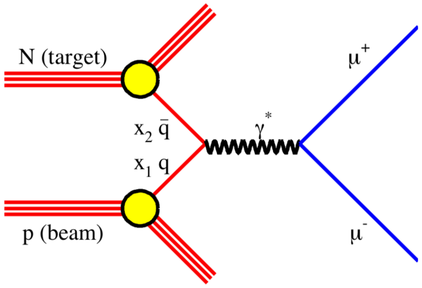
HERMES (2020), COMPASS (2009),COMPASS (2015)
JLab (2011)

Motivation

Sensitivity to sea quarks Sivers functions

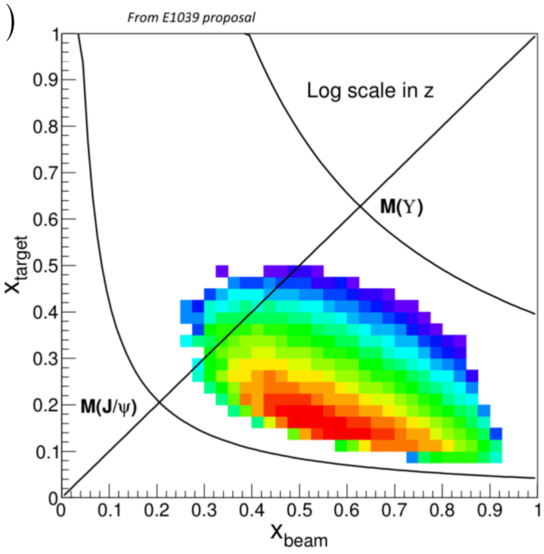
Drell-Yan cross section

$$\frac{d\sigma}{dx_1dx_2}=\frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2\left(\underbrace{q_i^B\left(x_1,Q^2\right)\bar{q}_i^T\left(x_2,Q^2\right)}_{\text{dominant}}+\bar{q}_i^B\left(x_1,Q^2\right)q_i^T\left(x_2,Q^2\right)\right)$$



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

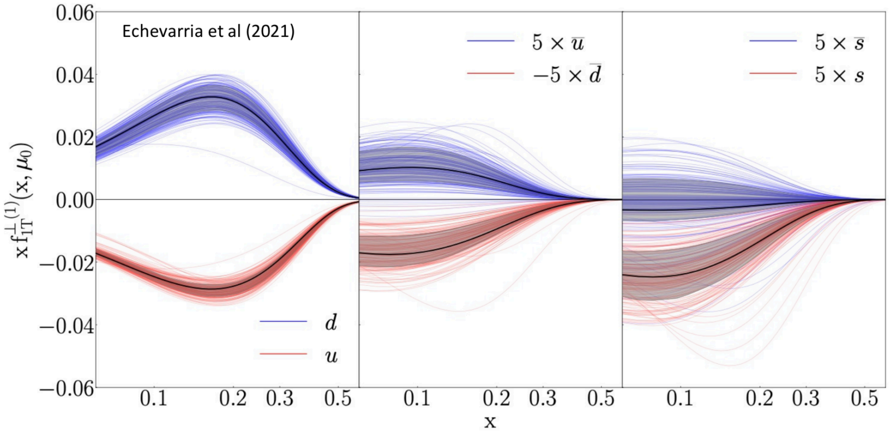
Acceptance and kinematics optimized for anti-quark component from target → Sea anti-quarks ($\bar{u}$, $\bar{d}$) Sivers functions



Sea-quarks dominance

Valence-quarks dominance

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



Most experimental data are focused on the valence region.

Uncertainties of the 'sea' quarks through global fitting became large relative to the 'valence' quarks.

Critical to have experiments like SpinQuest that tackle the sea!

Motivation

Independent $\bar{u}$ and $\bar{d}$ Sivers functions: spin sensitive flavor asymmetry?

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.

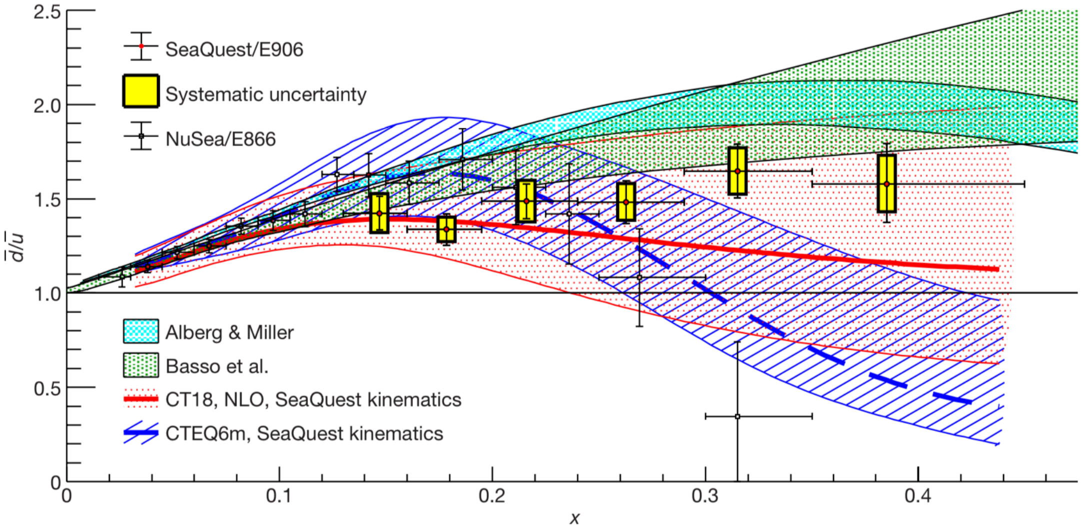
Combined analysis of TSSAs in $p + p^{\uparrow}$ & $p + d^{\uparrow}$ → Separation of $\bar{u}$ & $\bar{d}$

- Polarized $\bar{d}/\bar{u}$ ratio

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

Check sensitivity of flavor asymmetry to spin.

Nature 590, 561–565 (2021)



Motivation

Sivers function sign change

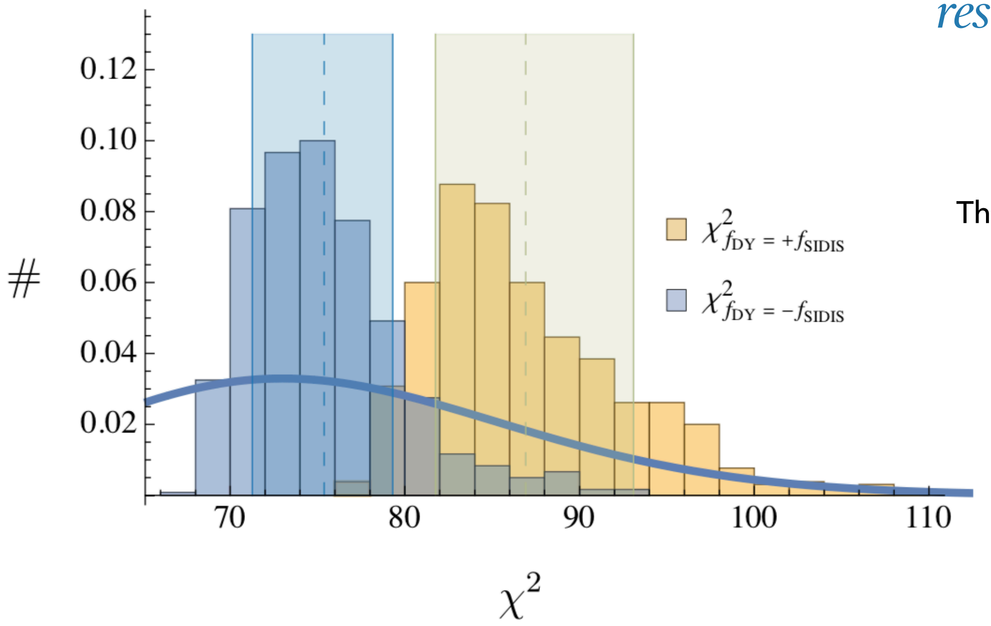
A direct QCD prediction is a Sivers effect in the Drell-Yan process that has the opposite sign compared to the one in semi-inclusive DIS:

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

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

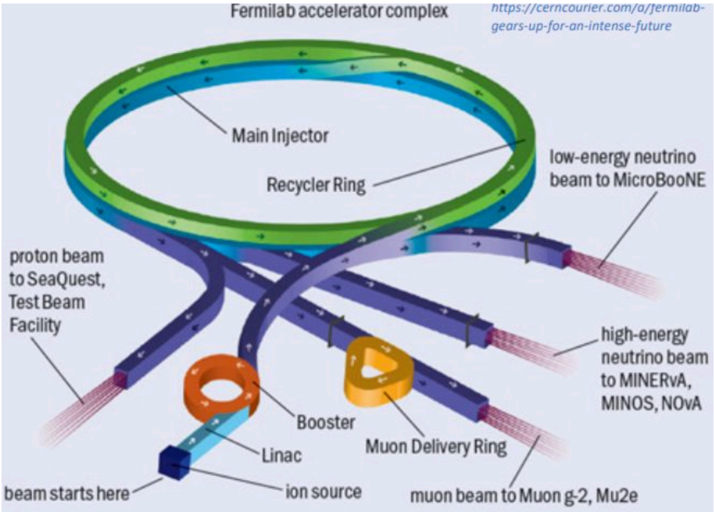
Sign-change is preferred but not nearly confirmed!

Still statistics (and kinematics) limited

SpinQuest Experiment

Beamline

- The Main Injector Beam will deliver 120 GeV protons (unpolarized).
- $\sqrt{s}$ =15.5 GeV
- 4.4 second spill ~10^{12} protons
    - ○ Buckets of 1 ns length with interval 19 ns (54 MHz)
        - ▪ Each bucket contains ~5,000 protons.
- ~10^{17} protons delivered per year
- Highest proton intensity ever attempted on a solid polarized target.


Fermilab accelerator complex

https://cerncourier.com/a/fermilab-gears-up-for-an-intense-future

SpinQuest Experiment

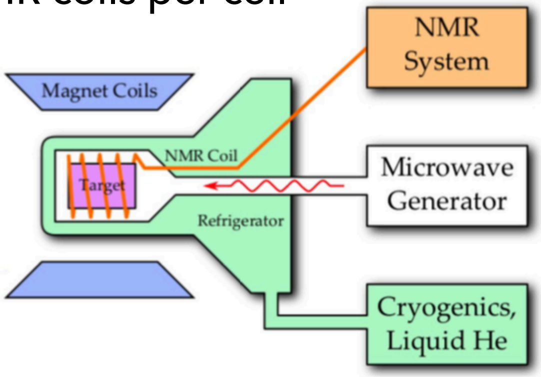
Target System

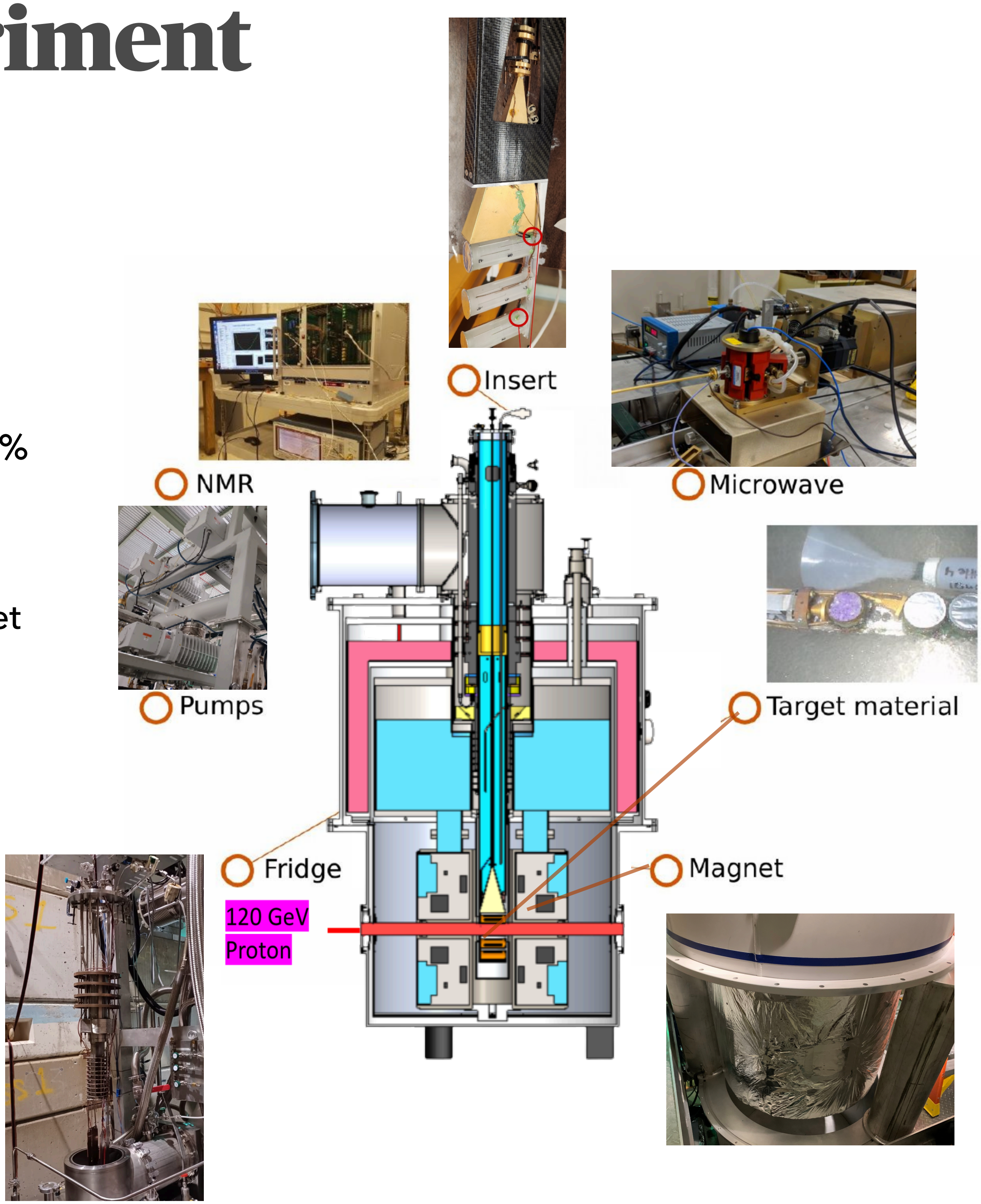
- Carbon fiber insert with 3 cells
- 140 GHz microwave source

Target uses Dynamic Nuclear Polarization.

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

- Ammonia beads (NH_3 or ND_3)
- 5T Magnet
- 4He evaporation refrigerator: keeps target material polarized and Helium liquid.
  - ○ 3 W of maximum cooling power keeping the target at 1.1 K
- 17,000 m3/h pumps
- 3 NMR coils per cell





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.

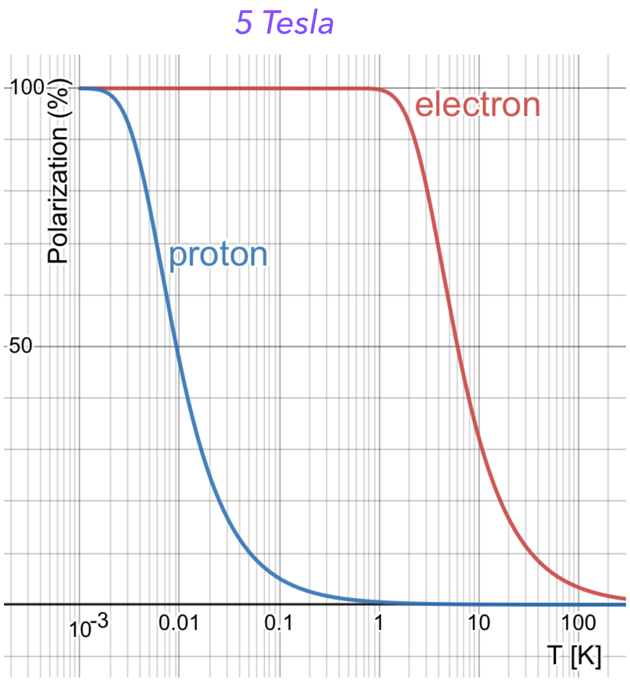
$$P = tanh\left(\frac{\mu B}{kT}\right)$$

- Proton has small magnetic moment

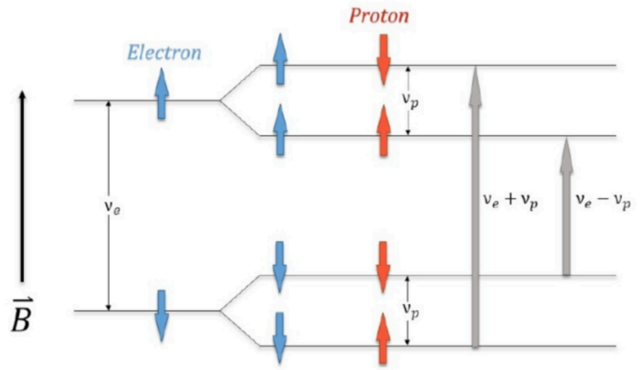
$$\mu_e \approx 660\mu_p$$

- 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



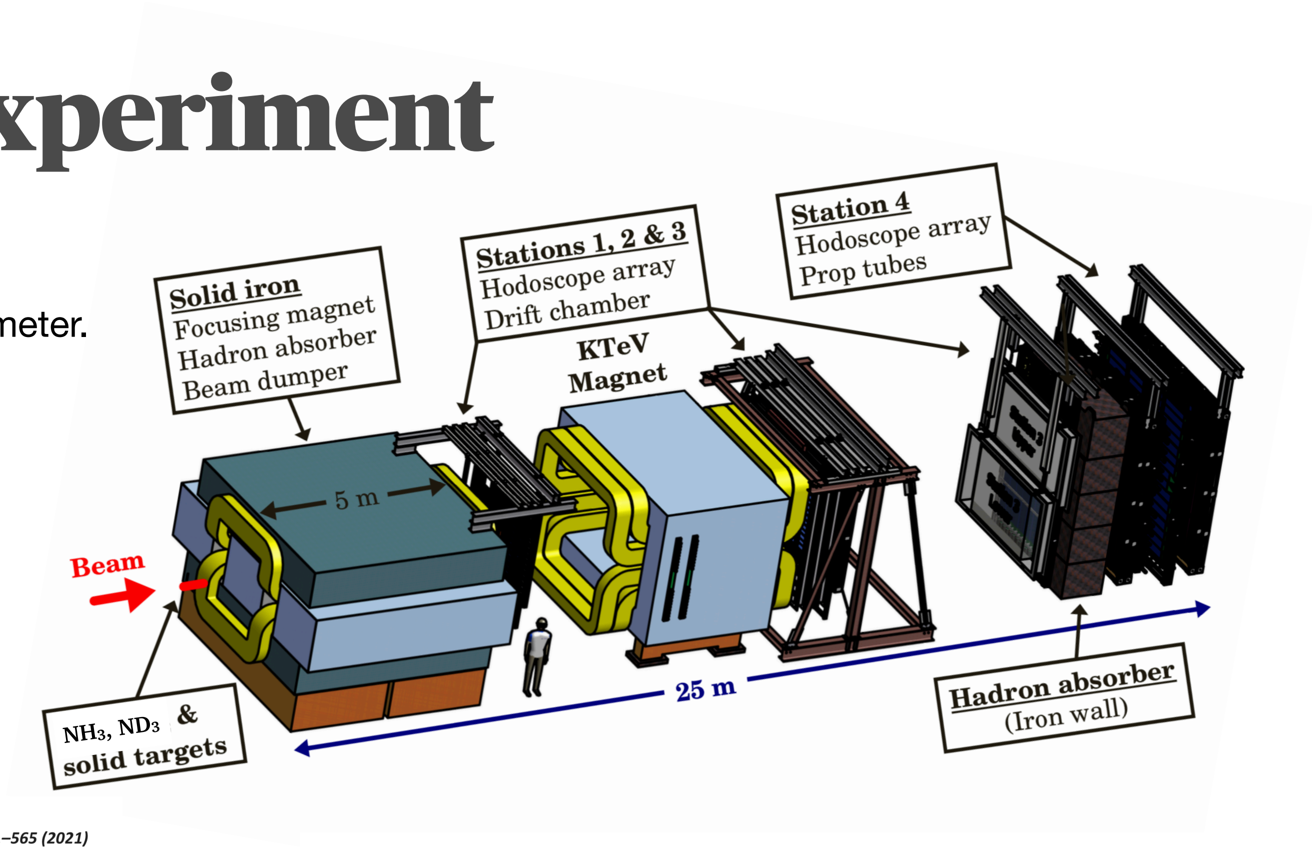
The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization.

Allows to achieve proton polarization of > 90%

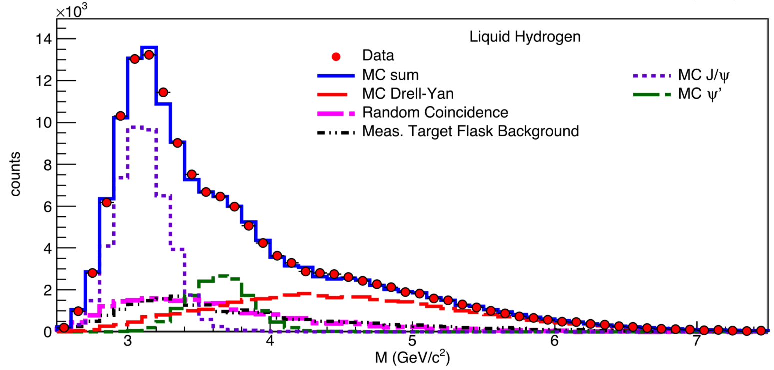
SpinQuest Experiment

Spectrometer

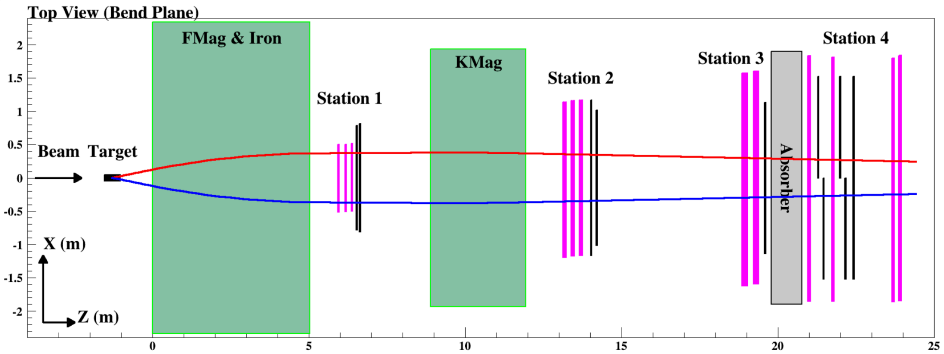
- Existing E906 (SeaQuest) Spectrometer.
- 2 Magnets
  - Focusing magnet (FMag)
  - Tracking magnet (KMag)
- 4 Tracking Stations
  - Drift Chambers
  - Hodoscopes
  - Proportional Tubes



Nature 590, 561–565 (2021)



- Accurate Monte-Carlo description of data.
  - Origins of measured dimuons well understood.
- Dominated by Drell-Yan at M > 4.5 GeV.



typical Drell-Yan event

Momenta of detected muons are 40 GeV/c on average

The projected event selection/reconstruction is expected to be the same for SpinQuest.

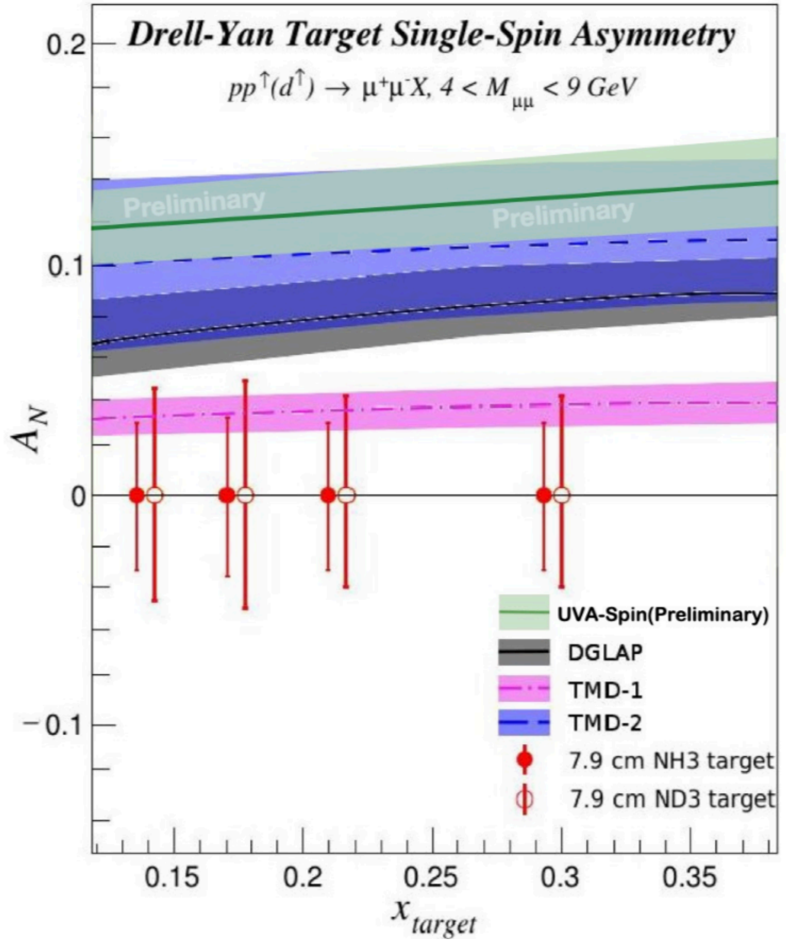
SpinQuest Experiment

Predicted sensitivity

- ➢ Beam (∽ 2.5%)
  - Relative luminosity (∽ 1%)
  - Drifts (< 2%)
  - Scraping (∽ 1%)

- ➢ Analysis sources (∽ 3.5%)
  - Tracking efficiency (∽ 1.5%)
  - Trigger & geometrical acceptance (<2%)
  - Mixed background (∽ 3%)
  - Shape of DY (∽ 1%)

- ➢ Target (∽ 6-7 %)
  - TE calibration (proton ∽ 2.5%; deuteron ∽ 4.5%)
  - Polarization inhomogeneity (∽ 2%)
  - Density of target ($NH_{3(s)}$) (∽ 1%)
  - Uneven radiation damage (∽ 3%)
  - Beam-Target misalignment (∽ 0.5%)
  - Packing fraction (∽ 2%)
  - Dilution factor (∽ 3%)

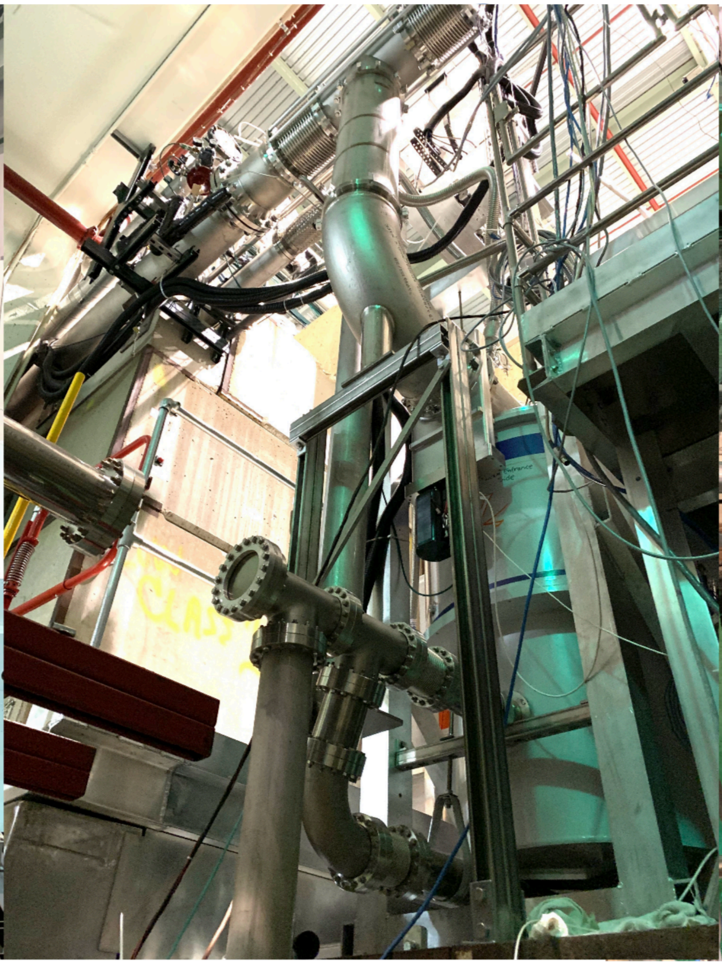


- Conditions
  - ○ Two years of data taking
  - ○ NH3:ND3 = 50%:50% in time ○ Details in the E1039 proposal
- Transverse Single-Spin Asymmetry (TSSA)
  - ○ Measurement precision δ_{AN} ~ 0.04

SpinQuest Experiment

Setup

From beam down-stream

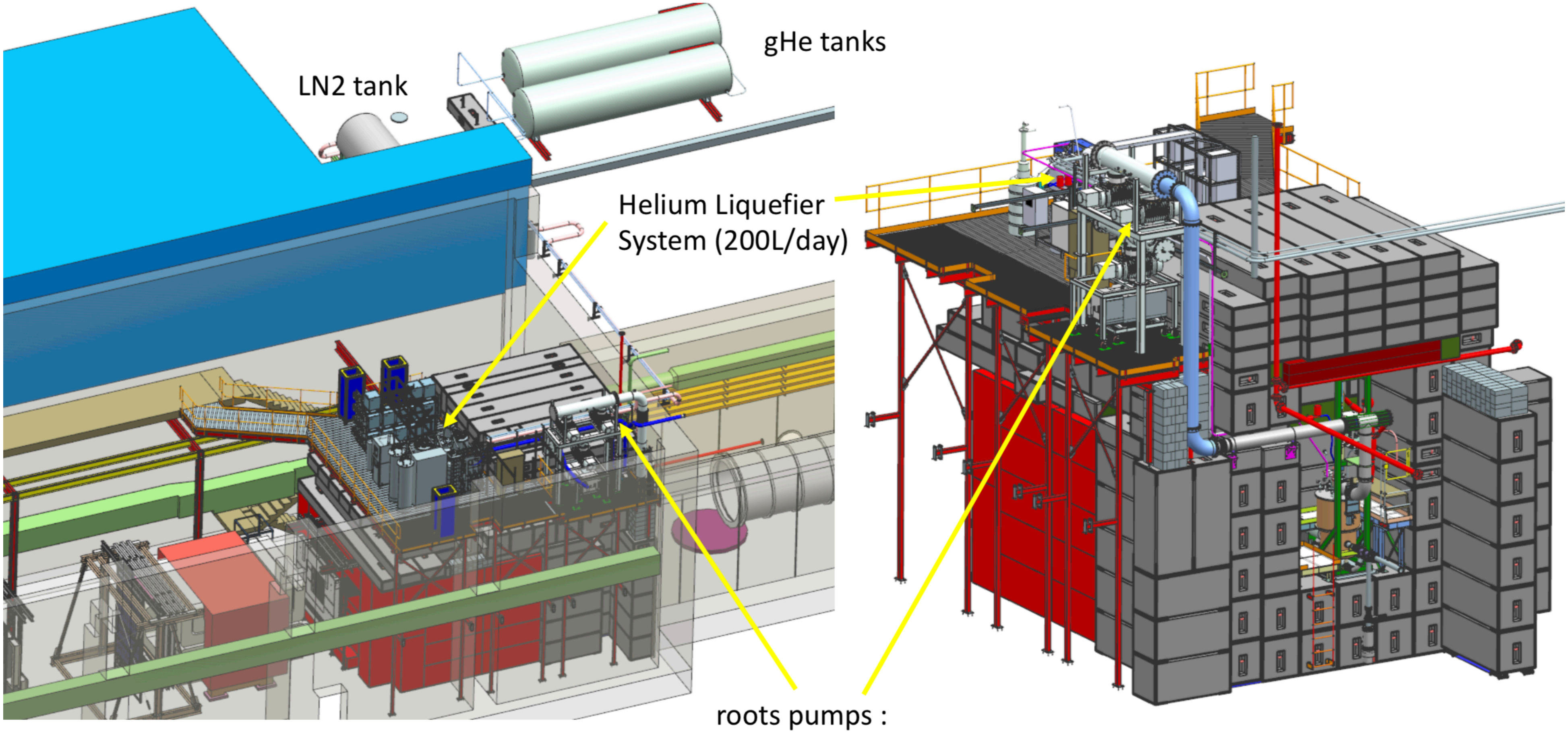


Beam-window and superconducting magnet

From target cave to beam-upstream

SpinQuest Experiment

Setup



LN2 tank

gHe tanks

Helium Liquefier
System (200L/day)

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

SpinQuest Experiment

Timeline

- 2018, March: DOE approval
- 2018, May: Fermilab stage-2 approval
- 2018, June: E906 decommissioned
- 2019, May: Transferred the polarized target from UVA to Fermilab
- Now: commission all components using cosmic rays
- Phase 1 of cryosystem commissioning completed
- Phase 2 (with polarized ammonia) September 2023
- E1039 commissioning starts in this Fall 2023
- [Run for 2+ years, 2023-2025+]

SpinQuest Experiment

Collaboration Members

https://confluence.its.virginia.edu/display/General/Collaboration+List

22 Institutions

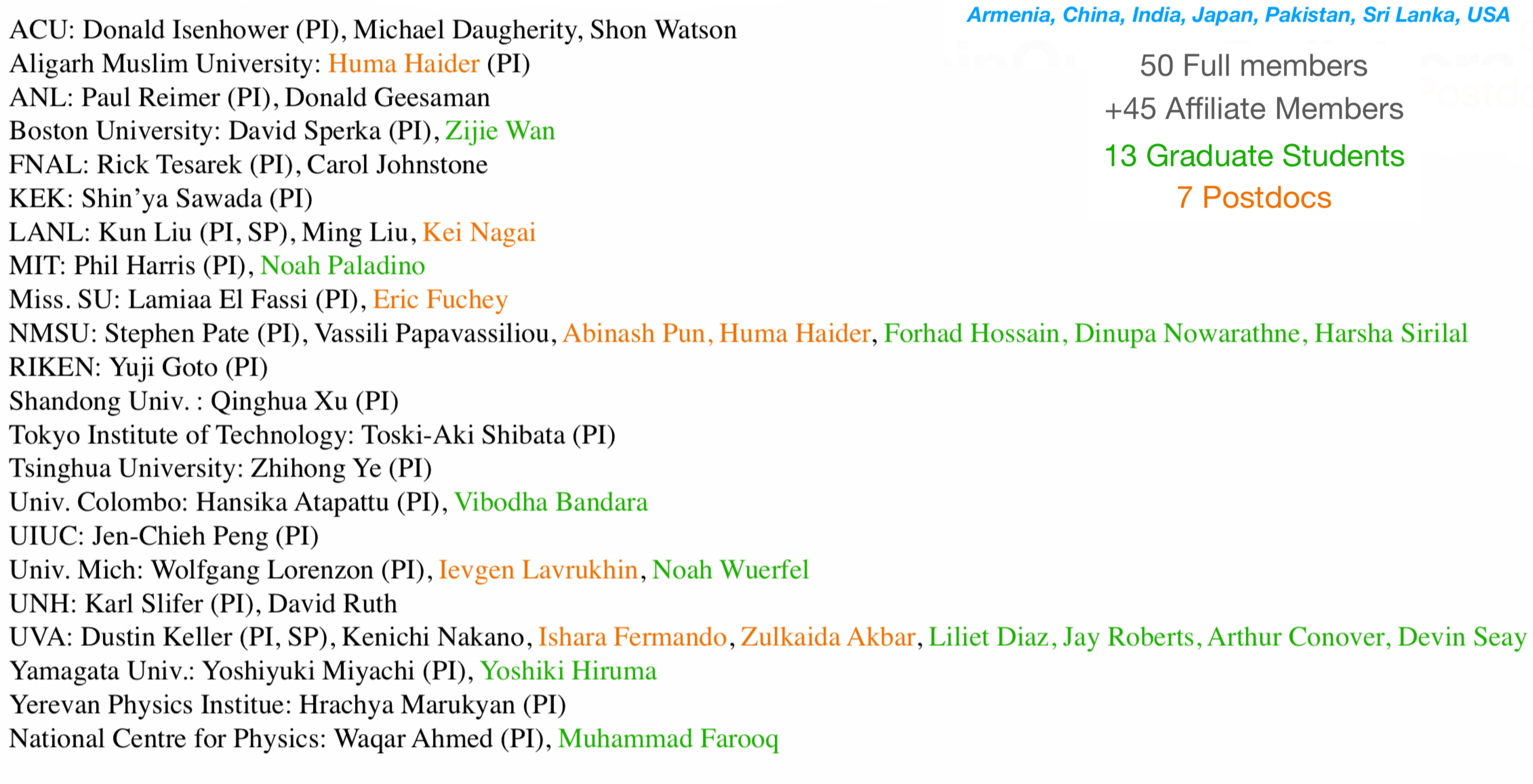
Armenia, China, India, Japan, Pakistan, Sri Lanka, USA

50 Full members

+45 Affiliate Members

13 Graduate Students

7 Postdocs



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Boston University: David Sperka (PI), Zijie Wan
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Summary

SpinQuest Goals and Uniqueness

- SpinQuest is poised to provide critical insight:
  - For DY sign change compared to SIDIS process.
  - For the sea-quark Sivers function and sea-quark OAM.
  - For $\bar{u}, \bar{d}$ flavor asymmetry sensitivity to spin.
  - For the comprehensive mapping of the Sivers function to come.
- Measurement of Sivers function for gluons (J/ψ TSSA)
- Perform the first measurement of the sea-quarks Sivers asymmetry in Drell-Yan p-p scattering.
- Separately measure the Sivers function for $\bar{u}$ and $\bar{d}$ quarks.
- Longest (along the beam-line) target cell to date for an evaporation fridge.
- Pushes the 120 GeV-proton-beam intensity frontier on a solid polarized target

Thank You!

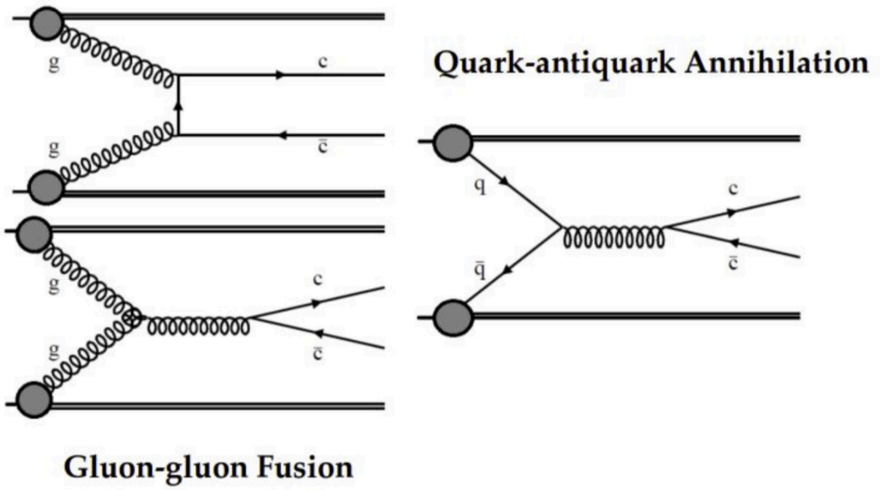
This work is supported by DOE contract DE-FG02-96ER40950

Motivation

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.



RHIC-PHENIX ○ $\sqrt{s}$ = 200 GeV, xF~0.1

SpinQuest ○ $\sqrt{s}$ = 15 GeV, xF~0.5

Access gluon Sivers functions