Nucleon Spin Measurements from SpinQuest and AMBER

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13th Circum-Pan-Pacific Symposium on High Energy Spin Physics

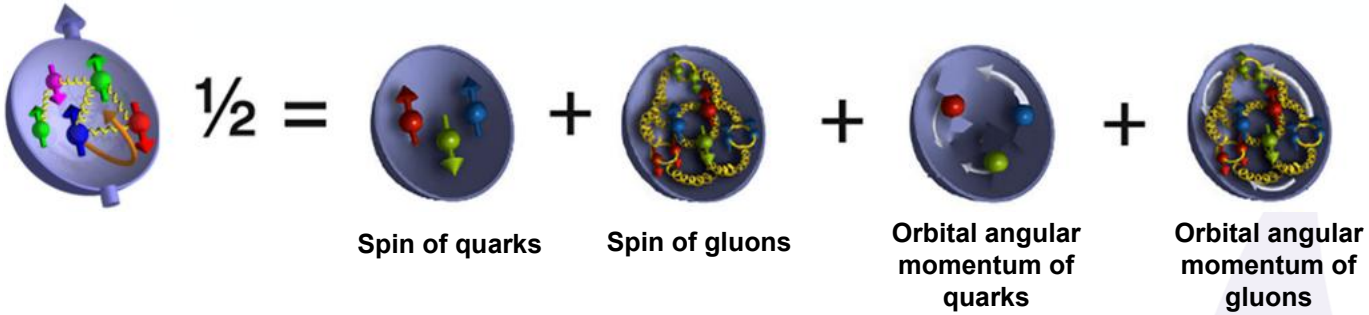
October 30, 2026

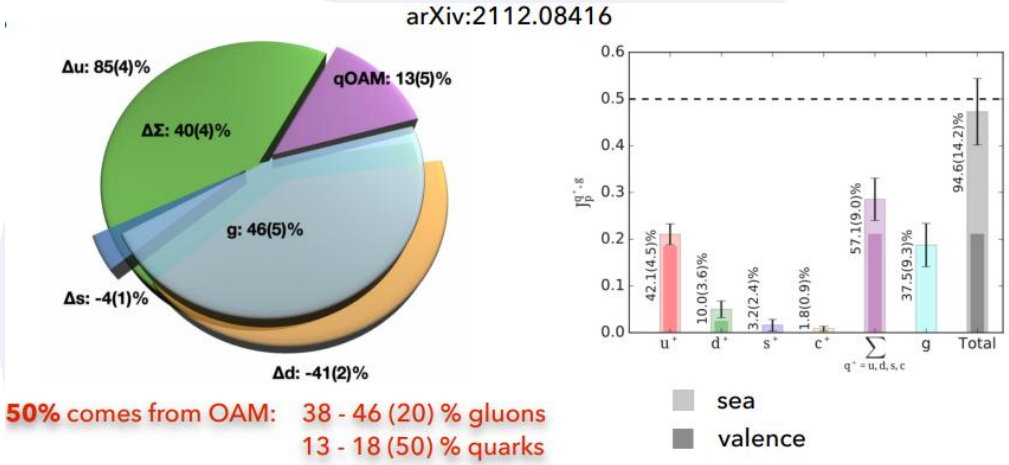
Managed by Triad National Security, LLC, for the U.S. Department of Energy's NNSA.

Outline

- Why polarized Drell-Yan and J/ψ
- SpinQuest at Fermilab
- Boer-Mulders from SeaQuest data
- AMBER at CERN

Why polarized Drell-Yan and J/ψ





leading twist		quark operator		
		unpolarized [U]	longitudinal [L]	transverse [T]
target polarization	U	f_1 = unpolarized		$h_1^\perp$ = Boer-Mulders
	L		g_1 = helicity	$h_{1L}^\perp$ = worm gear 1
	T	$f_{1T}^\perp$ = Sivers	g_{1T} = worm gear 2	h_1 = transversity; $h_{1T}^\perp$ = pretzelosity
	TENSOR	$f_{1LL}(x, \boldsymbol{k}_T^2)$ $f_{1LT}(x, \boldsymbol{k}_T^2)$ $f_{1TT}(x, \boldsymbol{k}_T^2)$	 $g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ h_{1TT}, $h_{1TT}^\perp$ h_{1LT}, $h_{1LT}^\perp$

What we want to learn:

- Sea-quark and gluon Sivers functions: does the sea-quark orbital angular momentum contribute to the nucleon spin?
- Sign change of T-odd TMDs between SIDIS and Drell-Yan
- Gluon transversity, unique to spin-1 targets

Single-polarized Drell-Yan: modulations and access to TMDs

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + \mathrm{D}_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + \ \mathrm{S}_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + \ \mathrm{S}_\mathrm{T} \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + \mathrm{D}_{\left[\sin^2\theta_{CS}\right]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) \\ + \ A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \end{array} \right) \end{array} \right] \end{array} \right.$$

where $\mathrm{D}_{\left[\sin^2\theta_{CS}\right]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$		Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$		Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$		Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$		Pretzelosity

SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

p + p↑ (SpinQuest)
Beam quark meets a target antiquark: sea-quark TMDs of the polarized nucleon

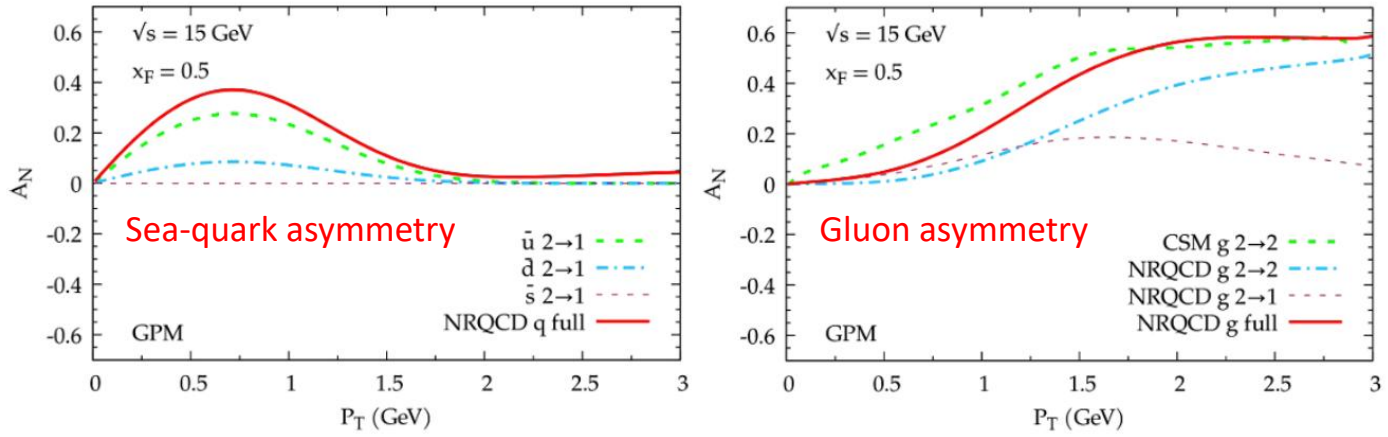
π^- + p↑ (COMPASS)
Pion ubar meets a target valence u: u-quark dominated

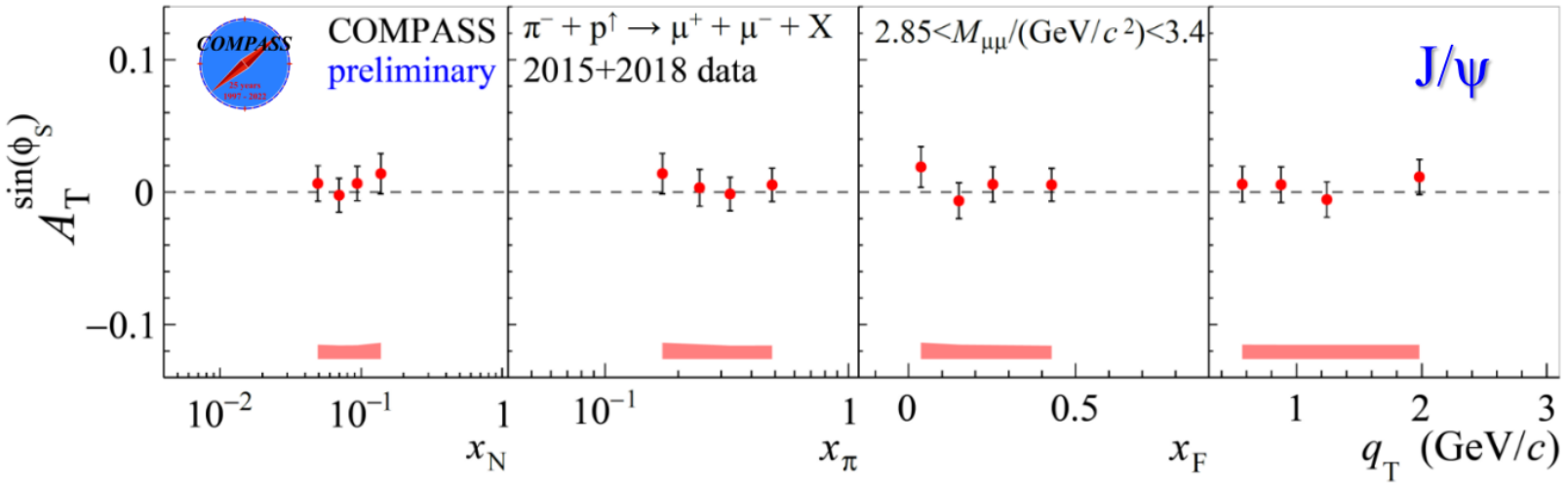
π^+ + p↑ (future)
Pion dbar meets a target valence d: d-quark sensitivity

J/ψ in the same data: access to gluons

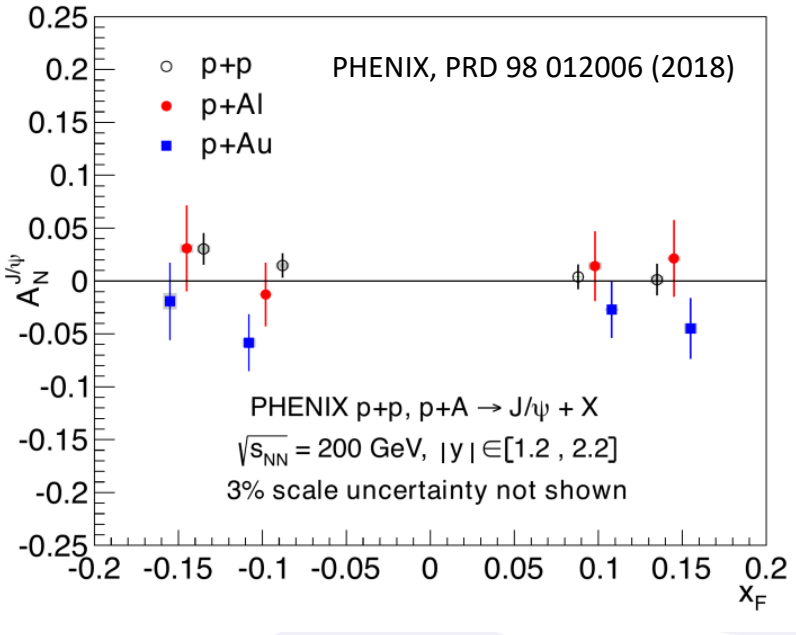
Estimate of max Sivers asymmetry at √s = 15 GeV

Private comm. based on D'Alesio *et al.*, PRD 102, 094011



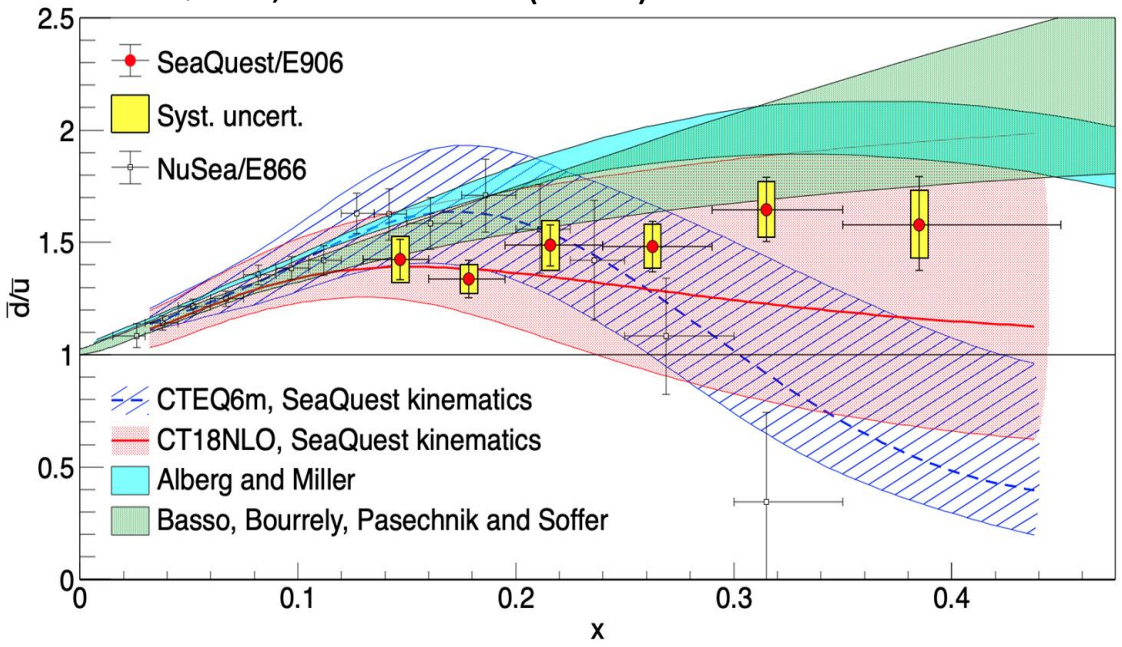


- Much larger yield than Drell-Yan
- Theoretical estimate of the maximum Sivers asymmetry could be as large as O(0.1)
- Sensitive to sea-quarks at low p_T and gluons at high p_T
- Unique measurement in terms of √s and x_F

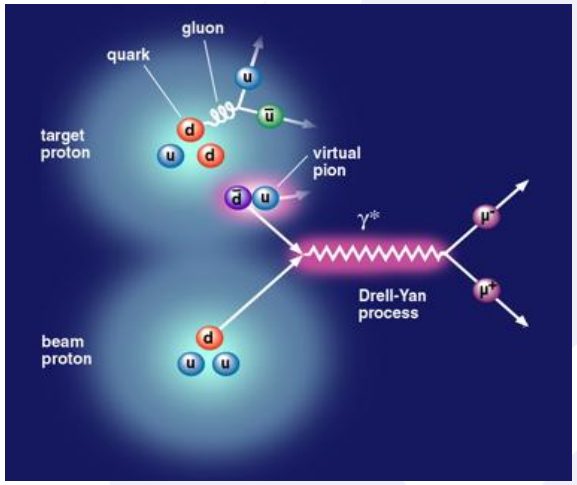


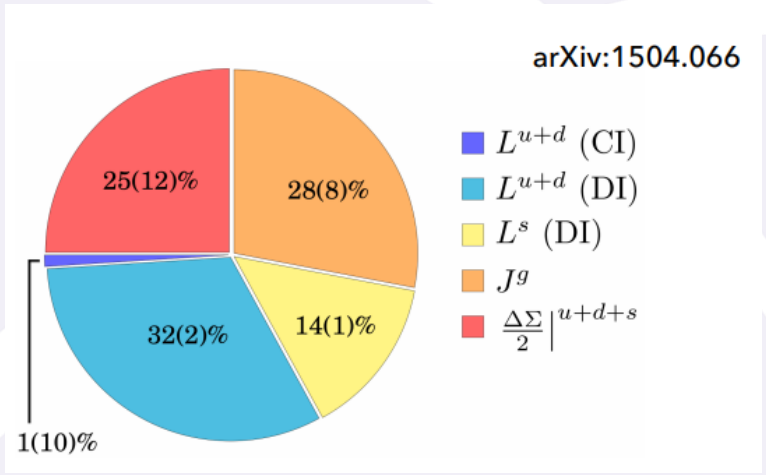
Why the sea: flavor asymmetry and orbital motion

SeaQuest, Nature 590 (2021) 561



Meson cloud in Drell-Yan

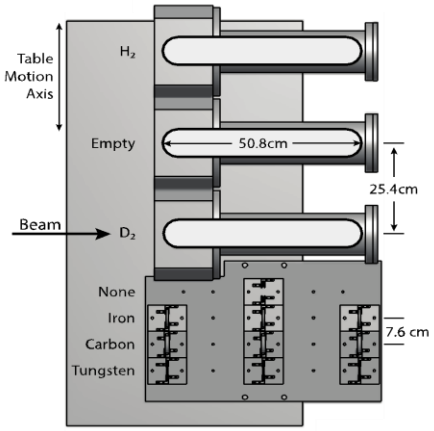


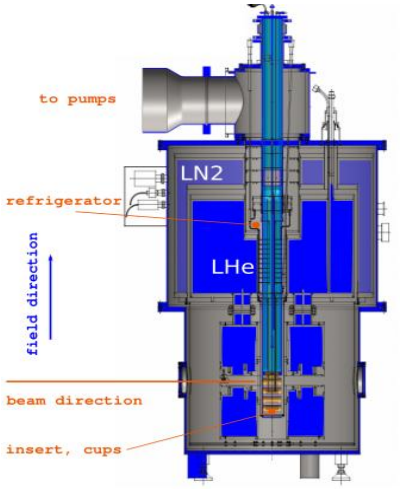


- SeaQuest data indicates dbar/ubar > 1 up to x ~ 0.4, naturally explained by the pion cloud in the nucleon → sizable orbital angular momentum carried by the sea quarks
- Lattice QCD shows OAM makes large contribution (~32%) to the nucleon spin
- In polarized pp DY, $A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$ puts a direct handle on the sea quark Sivers function

SeaQuest/SpinQuest at Fermilab Main Injector





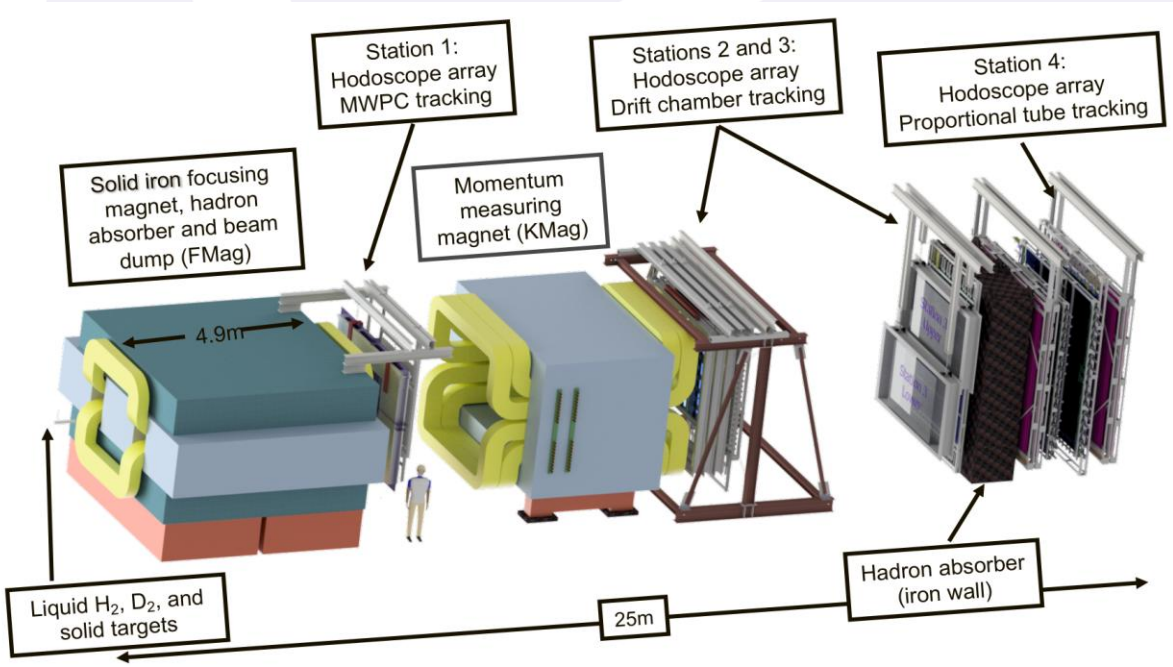


E906/SeaQuest: 2012 – 2017

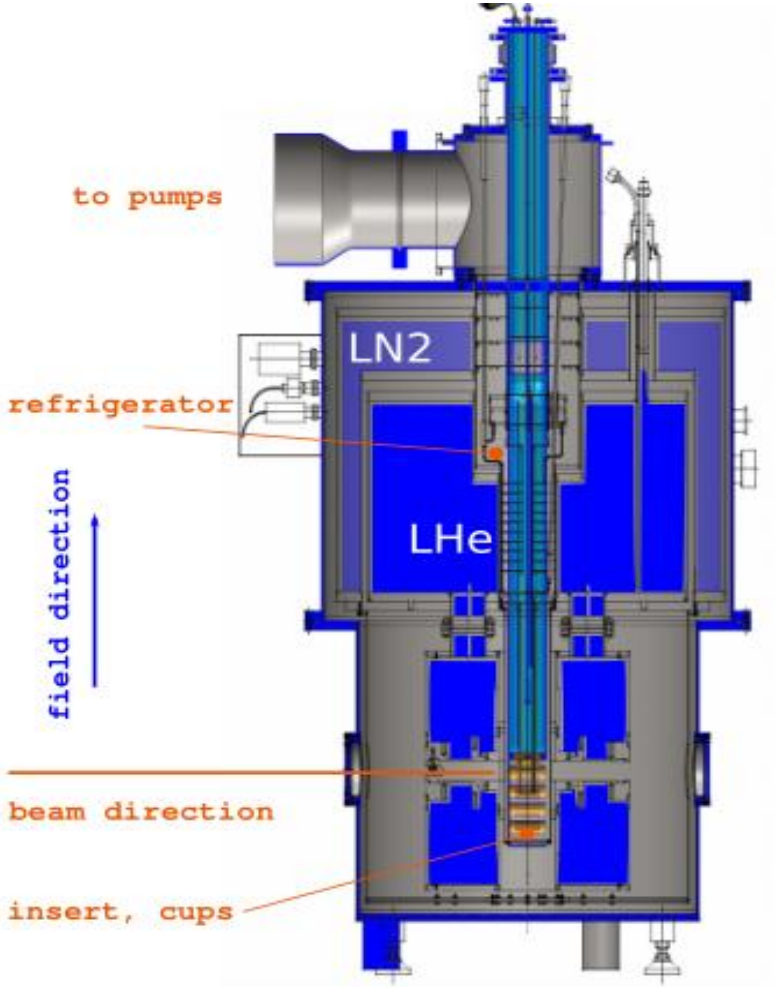
- 120 GeV proton beam with unpolarized proton/deuteron, and nuclear targets

E1039/SpinQuest: 2018 – ?

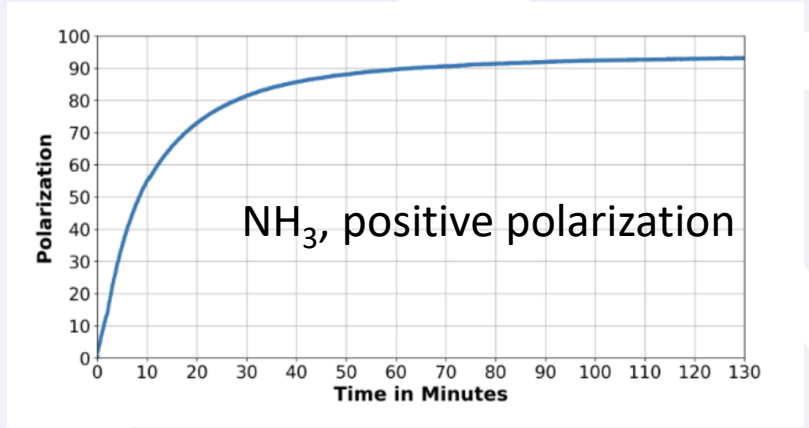
- 120 GeV proton beam with polarized proton/deuteron target

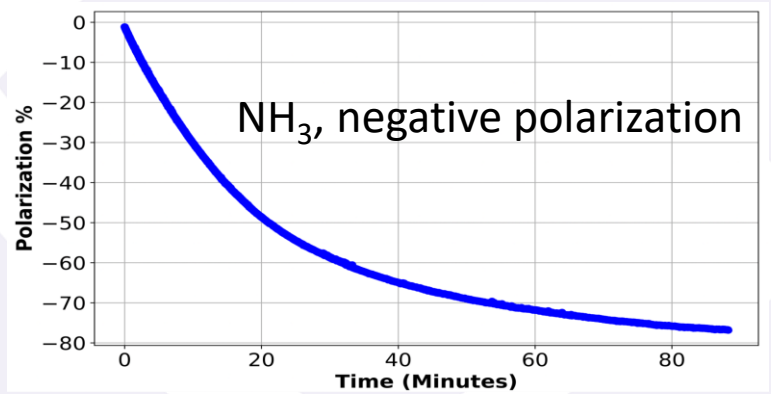


Polarized target: proven with full-intensity beam

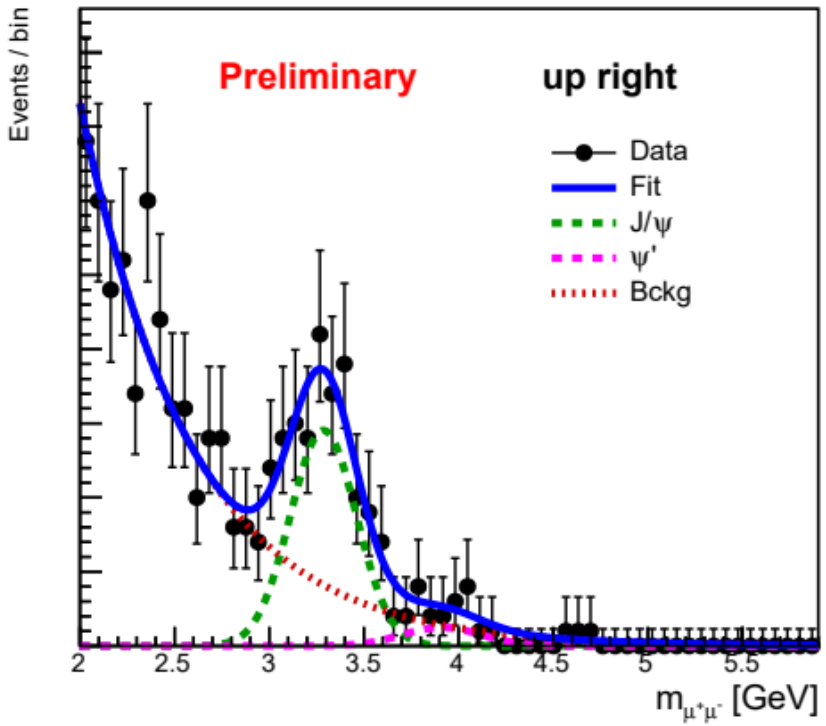


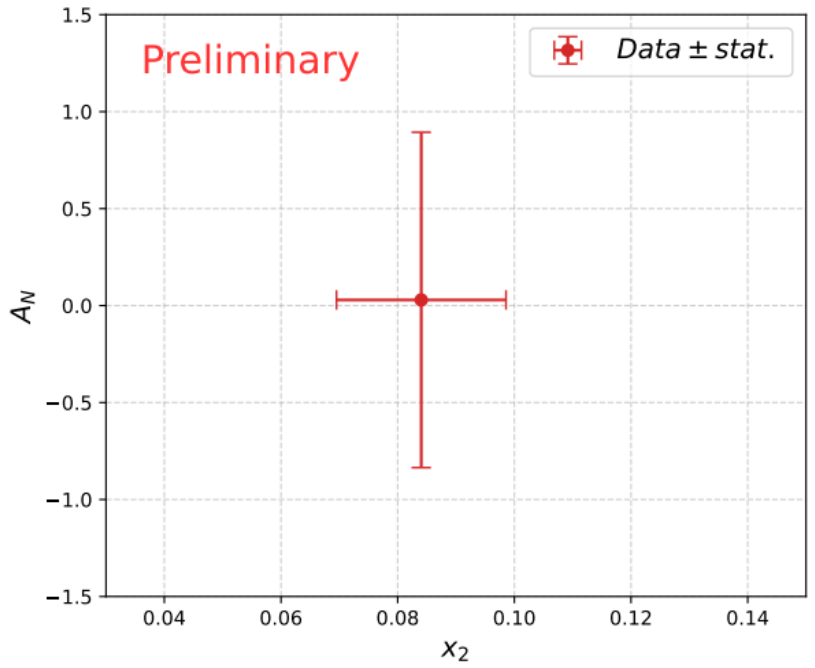
- 5T superconducting magnet, transverse field
- 1K ^{4}He evaporation refrigerator, high cooling power for high beam intensity
- Dynamic nuclear polarization of NH_3 and ND_3 beads in 8cm cells
- Goal: >90% proton and >40% deuteron polarization
- **Commissioned in 2024**: >90% NH_3 polarization held at up to $3x10^{12}$ protons/spill intensity
- **Upgrades since 2024**: rad-hard insulation vacuum, more LHe storage, new insert for higher luminosity





2024 commissioning and first J/ψ TSSA

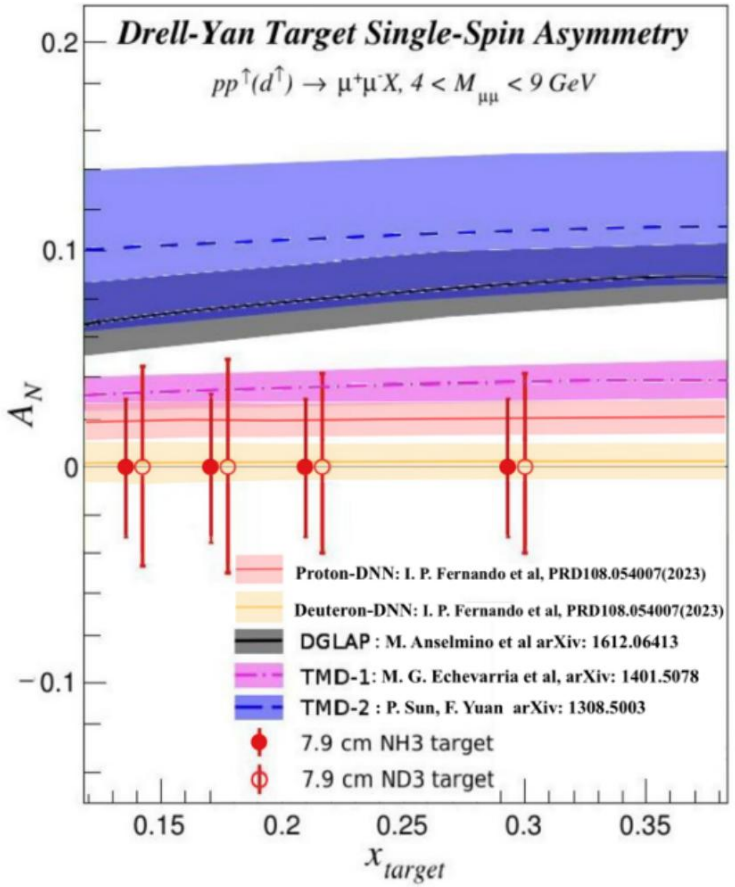




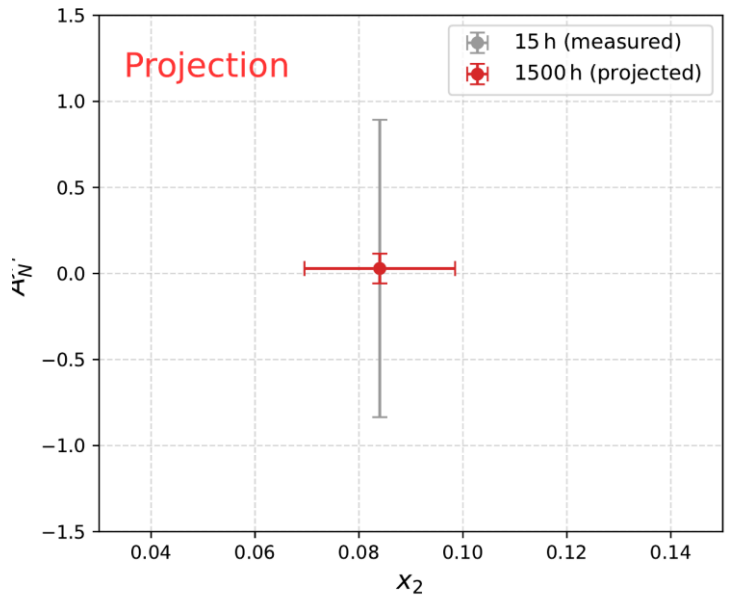
- Beam on the polarized target between May and July 2024
- ~ 900 spills (~15h of data) with magnets on and NH_3 polarized, |P| ~ 70%
- Limited by magnet and helium liquefication plant cooling water
- Full analysis chain to A_N demonstrated and statistics limited.

Expected sea-quark Sivers measurement

SpinQuest projected precision vs model predictions



J/ψ: SpinQuest preliminary and projection



- 2x200 days, NH_3 and ND_3 target, 3.8×10^{17} POT per target
- Drell-Yan: $\delta A_N \approx \pm 3\%$ (NH_3), $\pm 4\%$ (ND_3) per x_2 bin
- $p^{\uparrow}$ and $d^{\uparrow}$ together separate ubar and dbar Sivers
- J/ψ adds antiquark and gluon Sivers

If $A_N \neq 0$, major discovery:

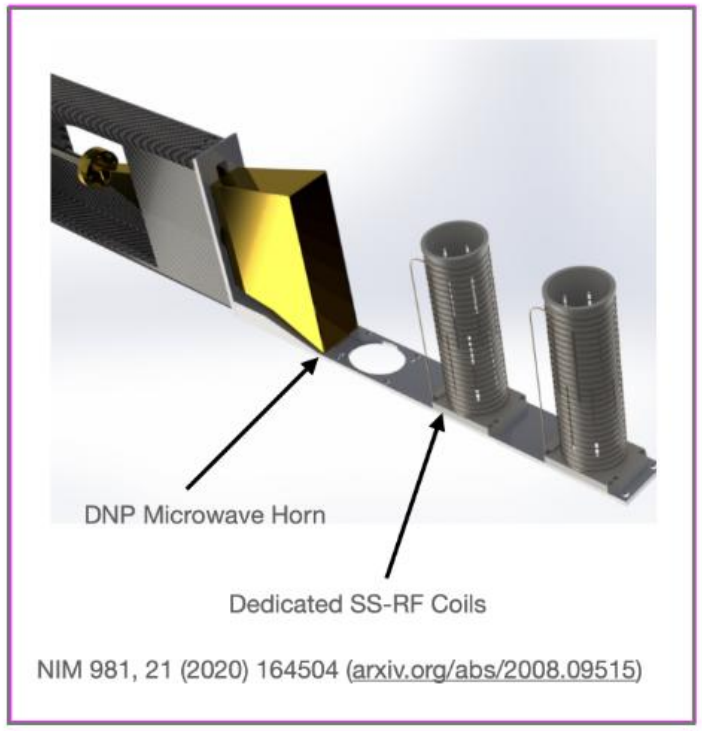
- "Smoking gun" evidence for $L_{sea} \neq 0$
- Determine sign and value for sea quark Sivers function
- Confirm global analysis expectations

If $A_N = 0$:

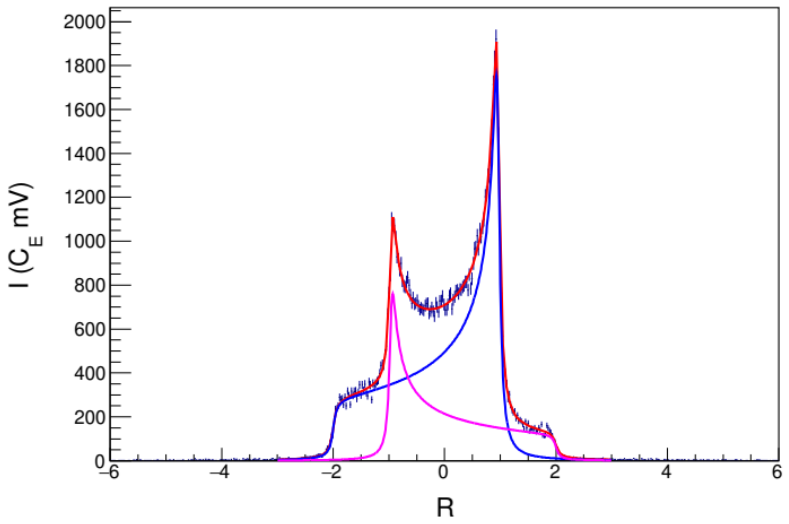
- $L_{sea} = 0$, spin puzzle more dramatic?
- Sea quark flavor asymmetry hard to explain

Next: a vector and tensor polarized deuteron target

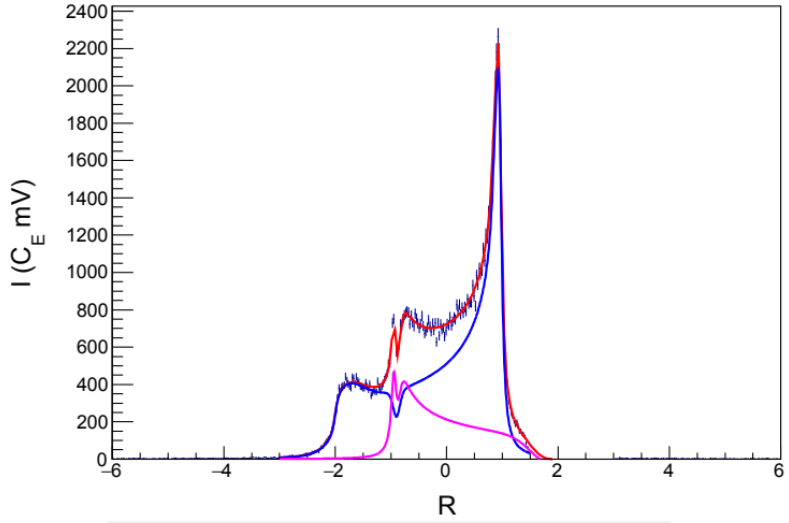
Means: RF coils on target cups
arXiv:2205.01249



DNP only: vector P = 49.8%
D. Keller et al, arXiv:2008.09515



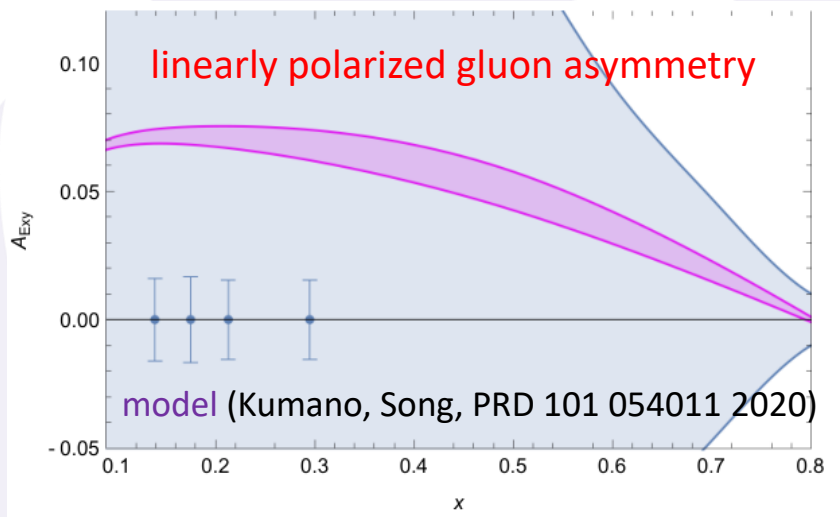
After ss-RF: tensor Pzz = 28.8%
D. Keller et al, arXiv:2008.09515

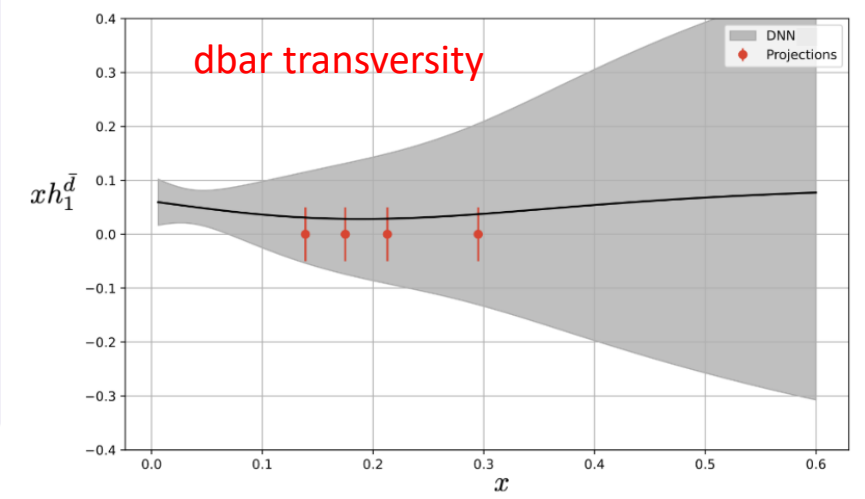


- Vector polarized neutron – dbar Sivers and transversity
- Tensor enhances spin-1 alignment - gluon transversity
- SpinQuest's 4s spill follow by 55s gap allow us ample time to manipulate target between spills

Deuteron physics: sea-quark and gluon transversity

- **dbar Sivers function**
  - ❑ Polarized neutron in ND_3, combined with NH_3
- **Sea-quark transversity**
  - ❑ Vector-polarized neutron, δA ~ 7% per x_2 bin – first dbar transveristy
- **Gluon transversity**
  - ❑ Exists only for spin ≥ 1 and does not mix with quarks – tensor asymmetry A_{Exy}





arXiv: 2205.01249

Reality check: ready to run, waiting for beam

2024	2026	2027	~2030	After
First beam on the polarized target, commissioning May to July	Fall physics run **canceled**	3.5-year accelerator shutdown starts (January)	Beam returns (to be determined)	Proposed 4-year program: NH_3, ND_3, transversity, dark sector in parallel

"The PAC commends the Collaboration for its progress and for the outcome of the commissioning run."
"SpinQuest and DarkQuest provide unique measurements and new particle discovery opportunities, respectively, and are therefore an attractive program to be carried out by FNAL should the switchyard be reactivated"

------ Fermilab PAC report, April 2026

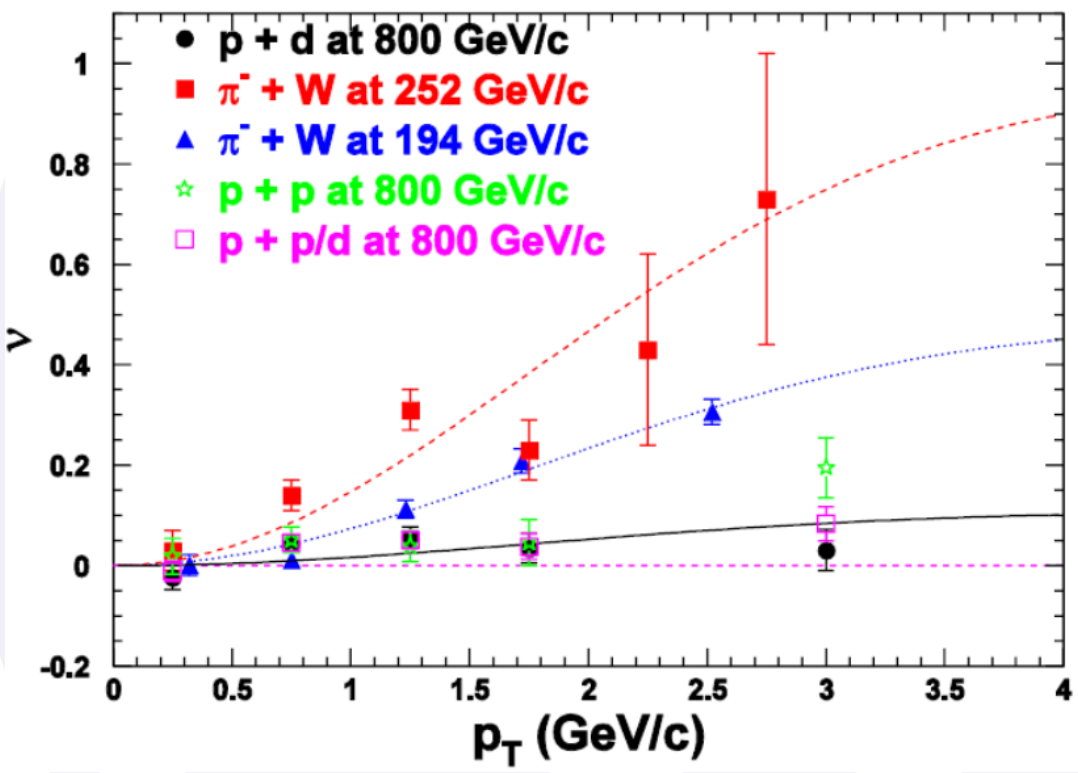
- Switchyard beam was not operated before the shutdown due to budget constraints in 2026.
- The future of switchyard beam is unclear at this time, and depends on future DOE budget

Meanwhile, the unpolarized SeaQuest data already carries spin information

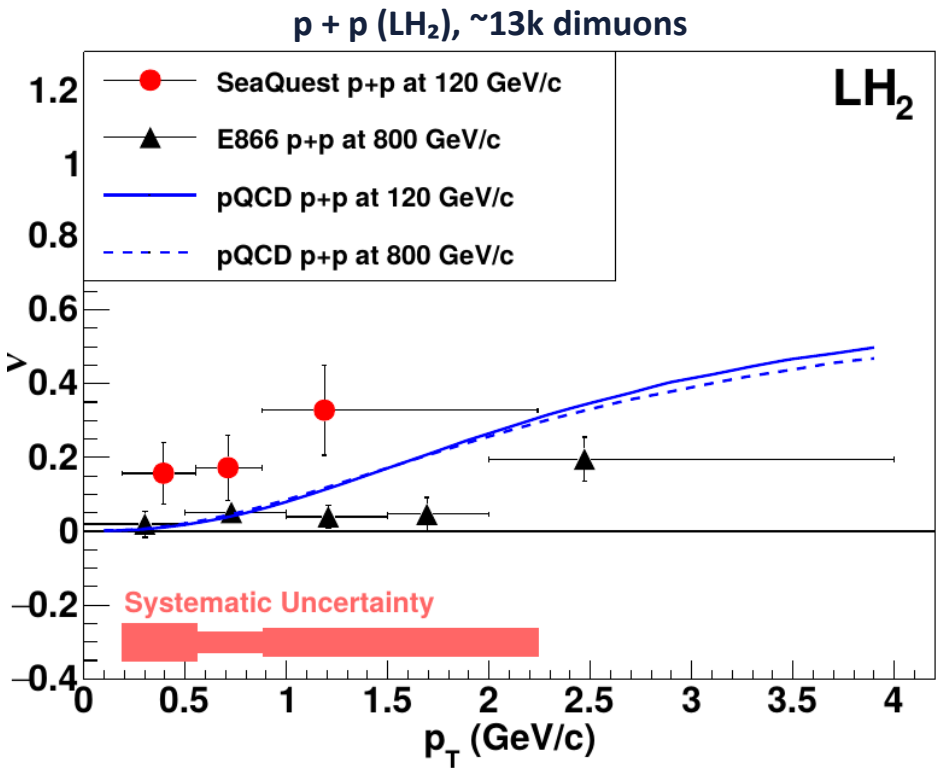
Drell-Yan angular distribution and Boer-Mulders

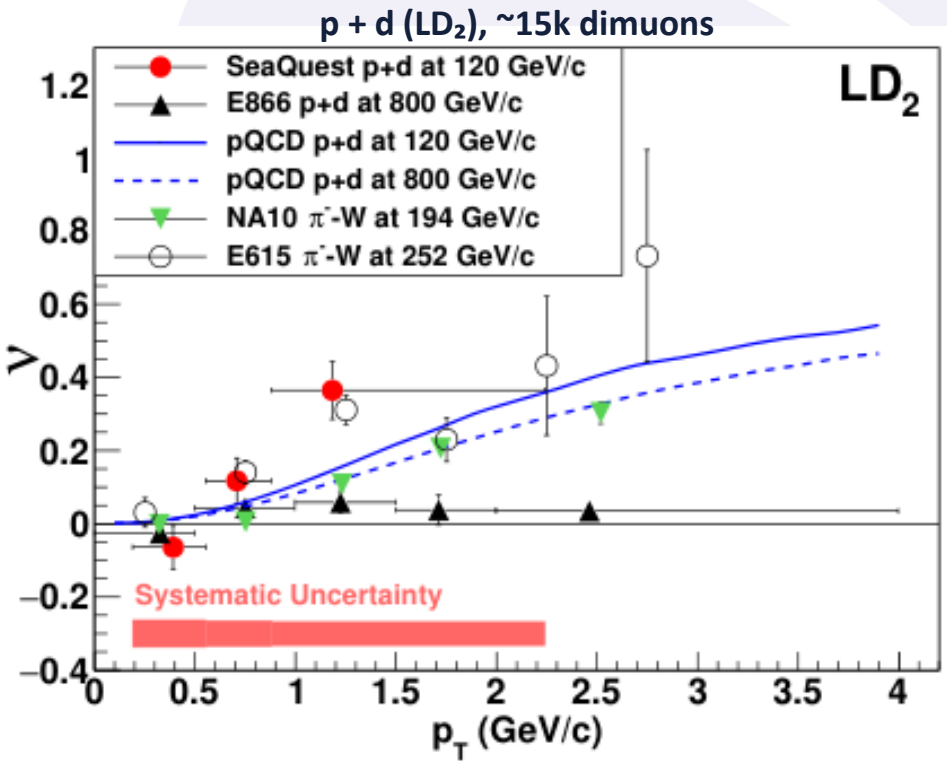
$$d\sigma/d\Omega \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + (\nu/2) \sin^2\theta \cos 2\phi$$

- Collins-Soper frame. Naïve parton model predicts $\lambda = 1, \mu = \nu = 0$
- Perturbative QCD keeps the Lam-Tung relation $1 - \lambda = 2\nu$ up to NLO
- Boer: $\nu \sim h_1^{\perp}(\text{beam}) \otimes h_1^{\perp}(\text{target})$
- π^- + W (NA10, E615) showed large ν and Lam-Tung violated for valence x valence
- p+p/d (E866) showed small ν for valence x **sea**
- Unpolarized DY sees only the product, so the sign stays ambiguous.



SeaQuest: a pronounced cos2φ modulation at 120 GeV





arXiv:2601.16410, submitted to PRL

SeaQuest result in global picture

	$\langle\lambda\rangle$	$\langle\mu\rangle$	$\langle\nu\rangle$
E906 (SeaQuest) $p+p$ 120 GeV/c	N/A	0.03 ± 0.09	0.20 ± 0.05
E906 (SeaQuest) $p+d$ 120 GeV/c	N/A	-0.07 ± 0.06	0.14 ± 0.04
E866 $p+p$ 800 GeV/c [19] $\langle x_1\rangle = 0.435$ [29] $\langle x_2\rangle = 0.074$	0.85 ± 0.10	-0.026 ± 0.019	0.040 ± 0.015
E866 $p+d$ 800 GeV/c [20] $\langle x_1\rangle = 0.433$ [29] $\langle x_2\rangle = 0.075$	1.07 ± 0.07	0.003 ± 0.013	0.027 ± 0.010
NA10 $\pi^- + W$ 194 GeV/c [28]	0.83 ± 0.04	0.008 ± 0.010	0.091 ± 0.009
E615 $\pi^- + W$ 252 GeV/c [17]	1.17 ± 0.04	0.09 ± 0.02	0.169 ± 0.019

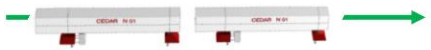
- Highest p_T bin: <pT> ~ 1.2 GeV, ν = 0.33 ± 0.12 (p+p), 0.36 ± 0.08 (p+d), pQCD ≈ 0.1 (PRD 99 014012)
- E866: x_2 ~ 0.07, ν below pQCD, indicating a negative BM contribution
- SeaQuest: x_2 ~ 0.23, ν above pQCD, indicating a positive BM contribution
- Re-analysis of the full SeaQuest dataset is under way.

SeaQuest and E866 results combined suggest sea-quark BM function may have strong x_2 dependence, and possibly change sign between x_2 ~ 0.07 and 0.23

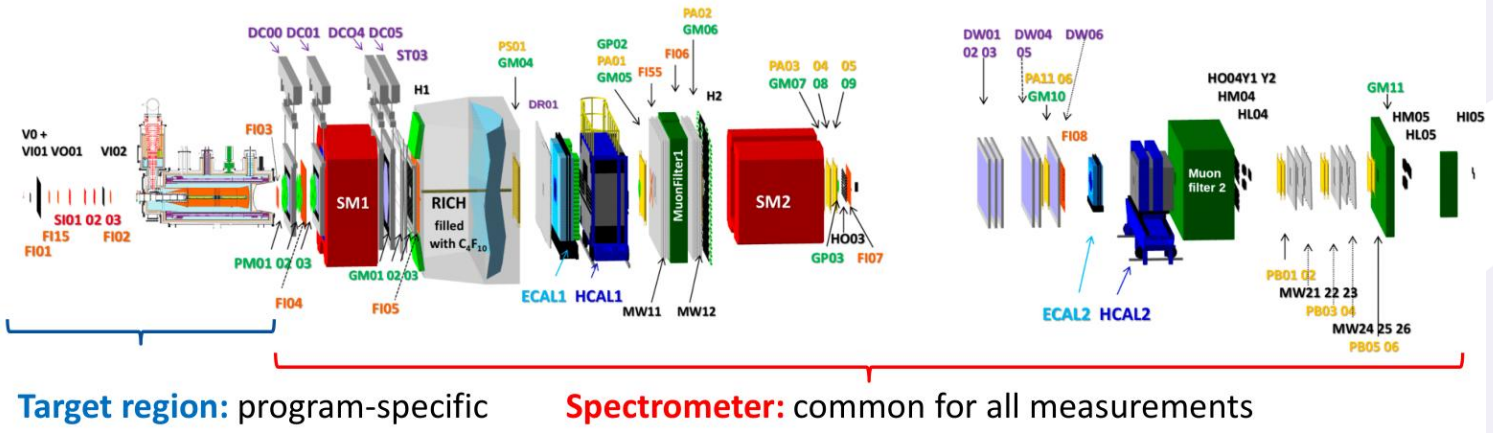
AMBER at the CERN M2 beamline

- Successor of COMPASS, approved in December 2020, ~200 physicists from 34 institutes
- Operating on CERN M2 beamline: $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p beams from 60 – 250 GeV up to 10^9 per spill
- **Approved Phase-I Drell-Yan program**: precision measurement of meson structure. 190 GeV $\pi^{\pm}$ beam on carbon and tungsten target, with kaons (~2%) in parallel, expected to start in 2030 and last for two years
- **Phase-II physics program is currently under discussion**: same 190 GeV $\pi^{\pm}$ beam with a polarized target is one of the possibilities.





CEDAR detector for beam PID



Beam: p, μ, π, K, (e) **Target region:** program-specific **Spectrometer:** common for all measurements

Versatile target area for different physics program

Redundant high-precision tracking with muon identification

Approved unpolarized DY and charmonia program

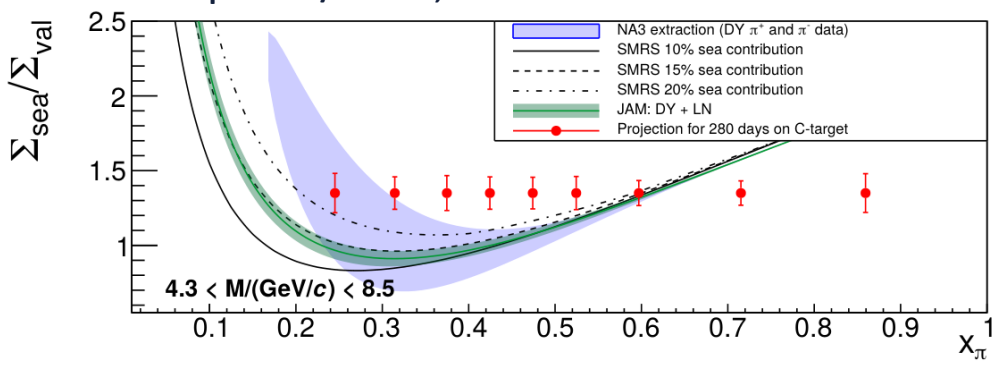
Target	Beam	DY	J/ψ
3x25cm C	π^+ / π^-	31,000/91,100	1.2/1.8 x 10^6
2cm W	π^+ / π^-	11,700/32,100	0.5/0.7 x 10^6

Expected statistics after 280 days of data-taking

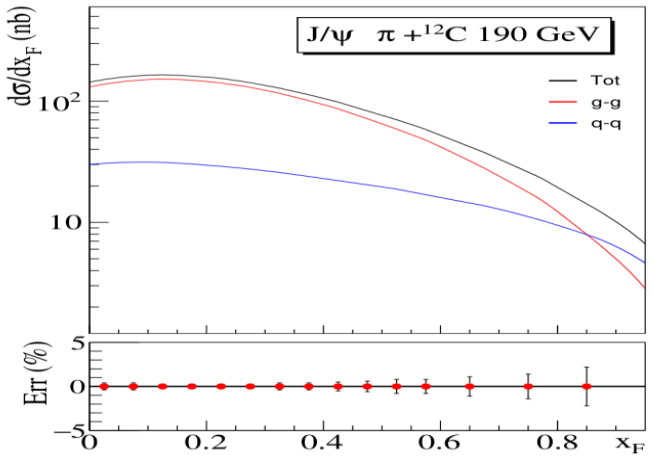
Multiple parallel physics programs:

- Precision measurement of pion/kaon internal structure
- Angular distribution for pion ⊗ nucleon BM, π^+ vs. π^-, C vs W
- J/ψ production and polarization

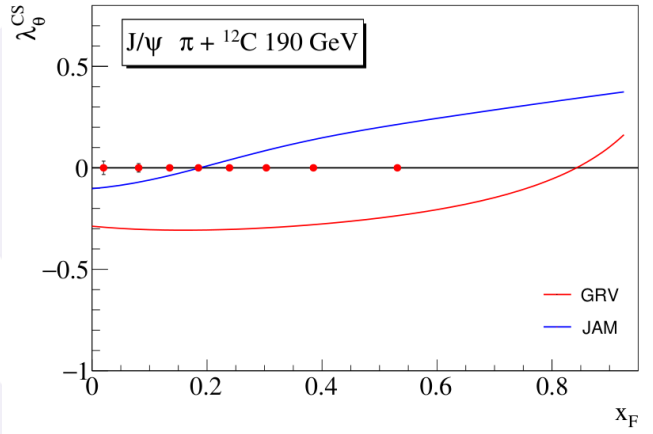
DY: pion sea/valence, $\pi^\pm$ + C



J/ψ $d\sigma/dx_F$, π^+ + C



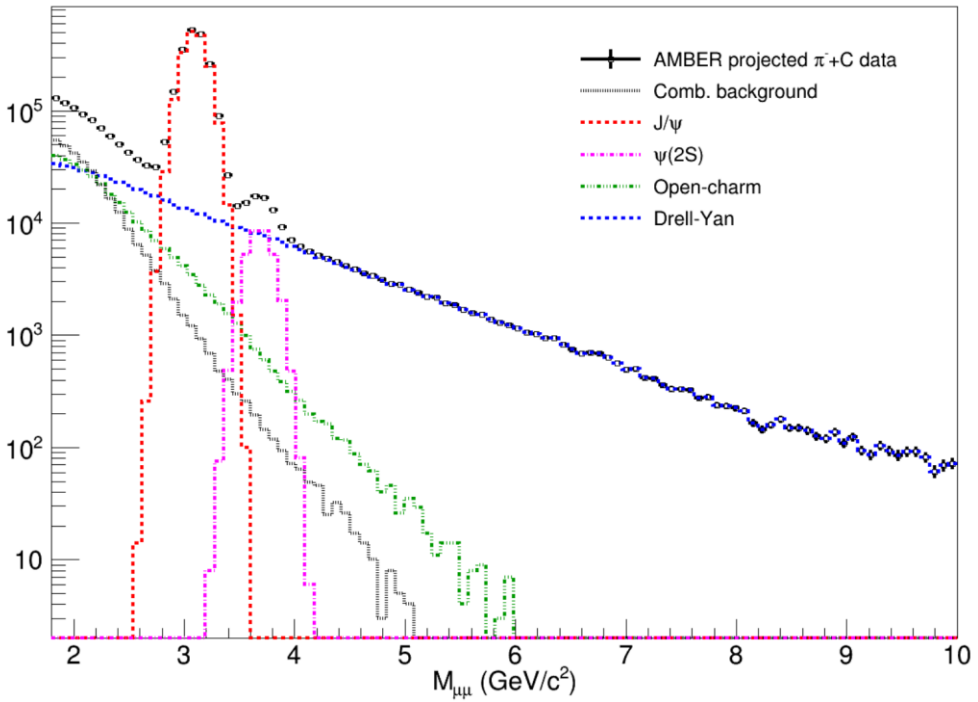
J/ψ polarization, π^+ + C



A stronger dimuon spectrometer than COMPASS had

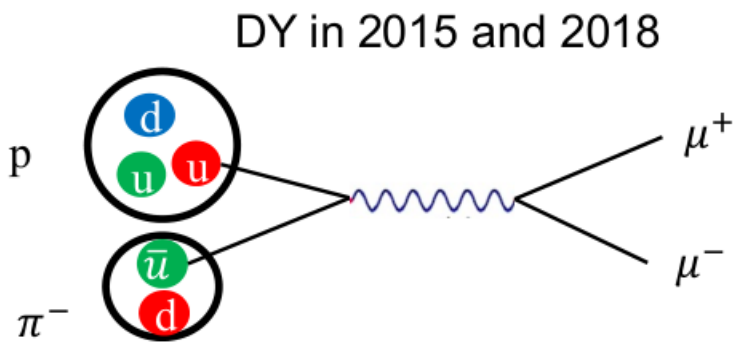
Underway for the unpolarized DY program

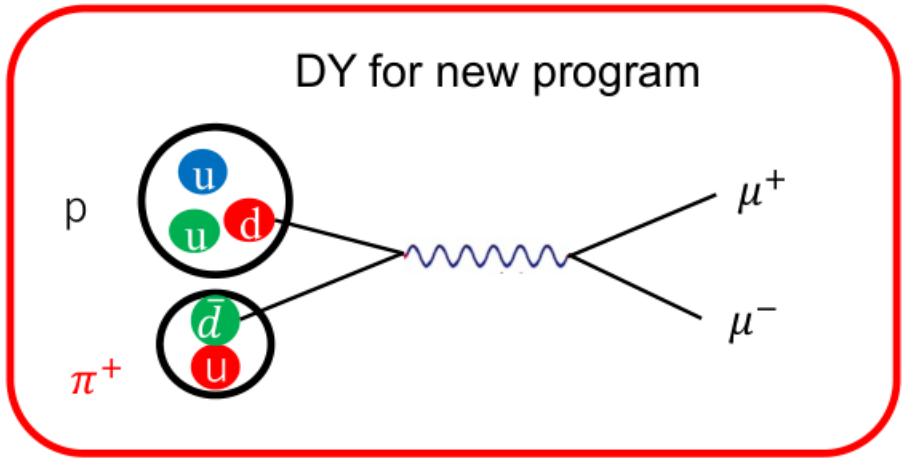
- Silicon strip vertex detector: mass resolution ~200 → 100 to 150 MeV, vertex ~12 → < 3cm, prototype beam-tested.
- Lower DY mass cut (4.3 → 4.0 GeV), clean ψ' access, reduced combinatorial background
- Triggerless readout with new dimuon high-level trigger
- Upgraded beam particle ID detector
- Shielding and rate-tolerant detectors for higher beam intensity



Projected π+C dimuon spectrum with the new vertex detector

Opportunity for polarized DY and charmonia production





Starting point: COMPASS π^- + $p^\uparrow$ (2015, 2018). Sivers asymmetry is positive (~1.5σ), consistent with Sivers sign change. Transversity asymmetry is negative (~2σ), also consistent with BM sign change.

- Unique access to valence TMDs with pion beams, complementary to the SpinQuest's access to sea-quark TMDs
- A definitive answer to the sign-change predictions through both asymmetries is needed
- π^+ beam: sensitivity to d-quark TMDs. Larger expected Sivers effect
- Pion and proton BM functions from ν in the same data
- Sivers and transversity asymmetries in both Drell-Yan and J/ψ, with additional access to ψ' from the better mass resolution
- Still in early brainstorming stage

Expected reach in Drell-Yan and J/ψ

x 2

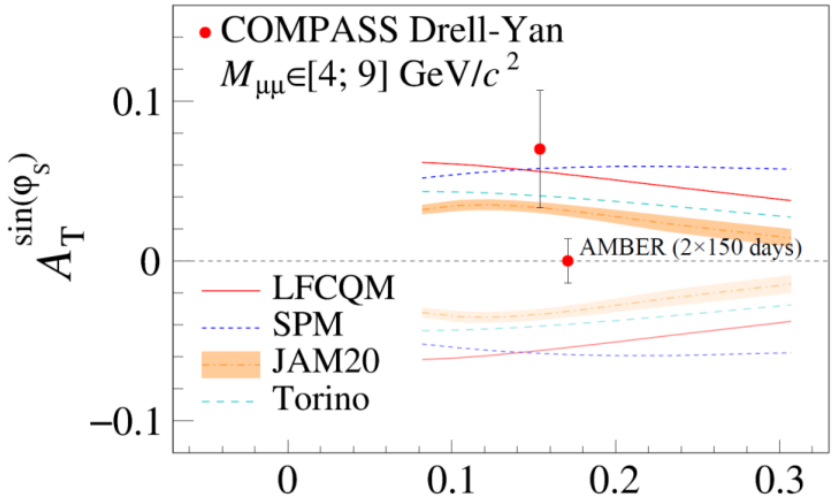
DY events per year vs COMPASS 2015 + 2018

x 2.6

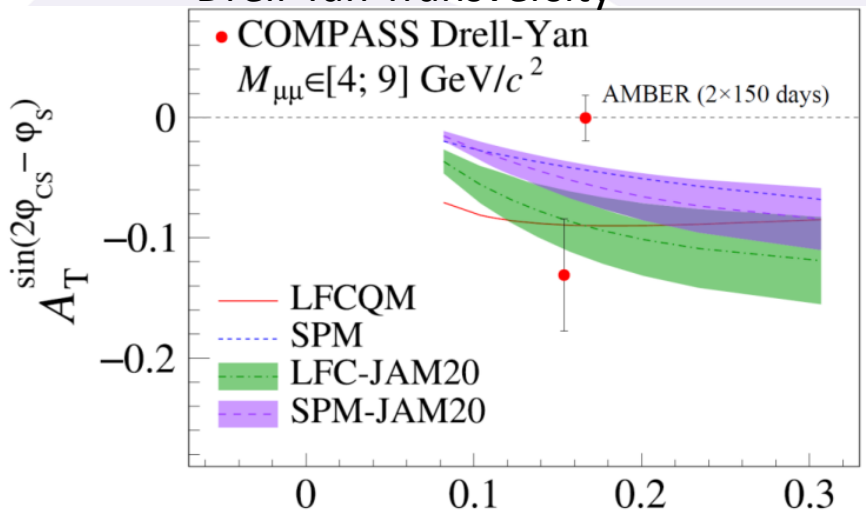
Figure of merit for TSSA measurements, per year

×2 events: intensity ×1.5, spill ×2, live time ×1.2, mass range ×1.4, fewer spills/day.
×1.3 more from target pol. 0.70 → 0.80. π^+ costs ×2.8 in δA.

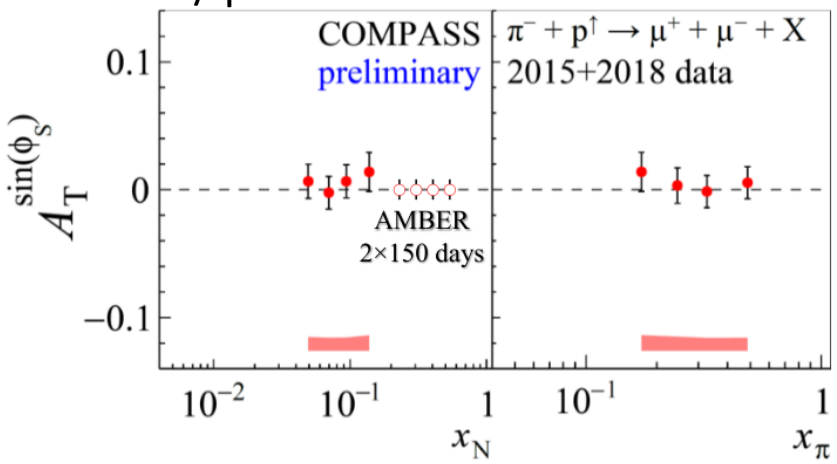
Drell-Yan Sivers



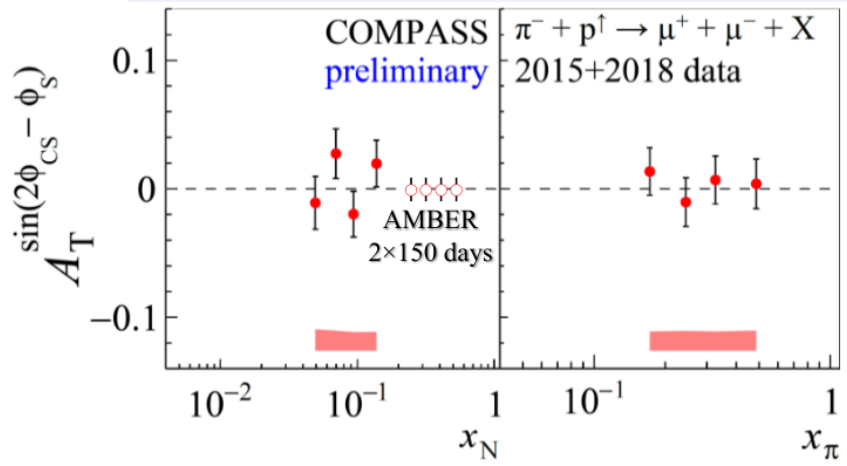
Drell-Yan Transversity



J/ψ Sivers



J/ψ Transversity



Projections courtesy of B. Parsamyan

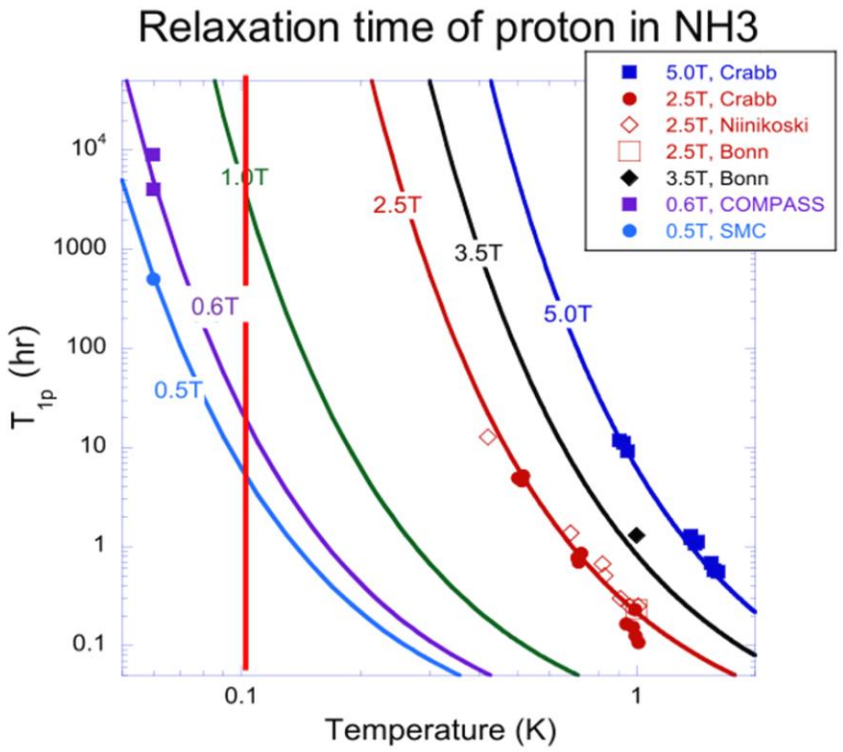
Possible scenarios of the polarized target

Slide courtesy of Norihiro Doshita

- **2.5 T dipole** magnet with 100 ppm homogeneity for 130 cm (60 cm) long
  - 100 mK 3He/4He dilution refrigerator
  - 5 cm in diameter for 60 cm long

- **5 T dipole** magnet with 100 ppm homogeneity for 130 cm long
  - 1 K 4He refrigerator (easier operation)
  - The beam is kicked out.

- **2.5 T solenoid** magnet with 100 ppm homogeneity for 130 cm long + **1.0 T or more dipole**
  - 100 mK 3He/4He dilution refrigerator
  - longer relaxation time in frozen spin mode with the dipole magnet



Complementary reach of SpinQuest and AMBER

SpinQuest

p + p↑, p + d↑ at 120 GeV (√s = 15 GeV)
Drell-Yan: target **sea-quarks** – ubar and dbar Sivers
J/ψ: **gluon** Sivers
Deuteron: dbar and gluon transversity
Technically ready, beam time not secured

AMBER

Approved, $\pi^{\pm}$ + C, W at 190 GeV: ν for the pion and nucleon Boer-Mulders functions
Opportunity, $\pi^{\pm}$ + p↑ at 190 GeV: DY - **valence** u and d Sivers and transversity, sign-change test.
J/ψ - **gluon** Sivers
Upgraded spectrometer, target options under study
Unpolarized program approved. Polarized program is still in early stage

AMBER and SpinQuest together provide a complete picture of Sivers functions of sea quarks, valence quarks and gluons, and the pion and nucleon Boer-Mulders functions for both u and d, at similar center-of-mass energies

The combined picture

Observable	COMPASS π^- p$^\uparrow$	SeaQuest pp, pd	SpinQuest pp$^\uparrow$, pd$^\uparrow$	AMBER $\pi^\pm$ C/W	AMBER $\pi^\pm$ p$^\uparrow$
sea-quark Sivers			first direct measurement of ubar and dbar Sivers		
valence Sivers, sign change	~1.5σ hint				decisive test, both u and d quark
Transversity ⊗ pion BM	~2σ, favors sign change				decisive BM sign test
Boer-Mulders via v	W data	large v @ x_2 ~ 0.23		$\pi^\pm$ on C and W	pion and proton
sea and gluon transversity			ND_3 vector and tensor polarization		
J/ψ	asymmetry consistent with 0	cross sections and production mechanism	gluon Sivers	λ, pion gluons	Sivers, transversity
Status	Published	First result on arXiv, full dataset analysis ongoing	Technically ready, beam time not secured	Approved, expect to start in 2030	Early stage, target R&D needed

Summary

SpinQuest

- Polarized target proven at full intensity, first J/ψ asymmetry from 2024
- Sea-quark Sivers from Drell-Yan (±3% NH_3, ±4% ND_3), gluon Sivers from J/ψ
- Polarized deuteron for sea-quark and gluon transversity
- Technically ready, physics running awaits beam and support

SeaQuest

- Pronounced cos2ϕ in p+p and p+d at 120 GeV, above pQCD
- E866 result is below pQCD at lower x_2: the sea-quark BM function might change sign between x_2 ~ 0.07 and 0.23
- First result on arXiv and submitted to PRL, full-dataset re-analysis is ongoing

AMBER

- Approved unpolarized program: ν with both π^+ and π^- beam updates the pion BM functions
- $\pi^\pm$ beam on a polarized target could decisively test the Sivers and BM sign change for valence u and d, with ~2.6x the COMPASS figure of merit per year
- It needs a new polarized target system and much development first

Neither spin program is scheduled or funded today. Community interest, theory input and new collaborators will decide whether these measurements happen.