# *SpinQuest/E1039 Report*

(On behalf of the SpinQuest Collaboration)

Fermilab 57th Annual Users Meeting
July 10-12, 2024

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# What is Proton


Subatomic particle ($t_{1/2} > 1.67\times10^{34}$ yrs)

=> not elementary:

- valence quarks (uud)
- gluons
- sea quarks

=> Size (R ~1fm)

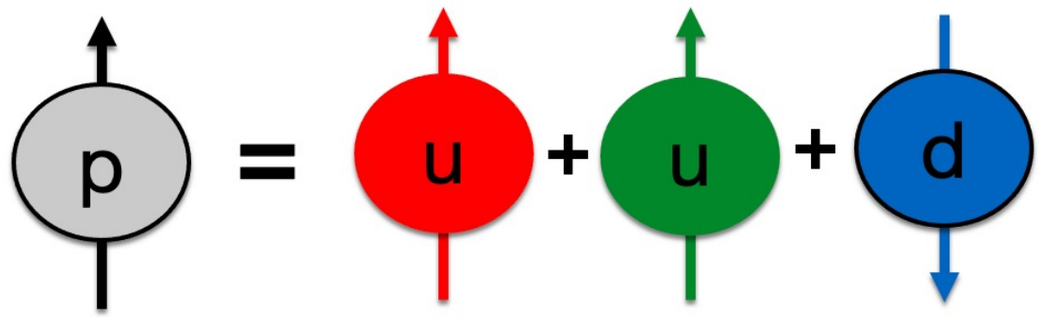
=> Mass (~ 1 a.m.u)

=> Charge (+1)

=> Spin (1/2)

- Proton Spin = ½
- quark Spin = ½
- 3 x valence quarks

Naïve approach:



# Proton Spin Puzzle

- Helicity distribution function:

$$\Delta f = f^{+} - f^{-}$$

=> quarks (s=1/2) contribution to the spin:

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

=> gluons (s=1) contrition to the spin:

$$\Delta G$$

- Quarks and Gluons contribution to the spin of proton :

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

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**Proton Spin Crisis** (EMC, SLAC, CMS …):

$$\frac{1}{2}\Delta\Sigma \approx 25\%, \ \Delta G \approx 20\%$$

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- Quarks and Gluons contribution to the spin of proton :

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

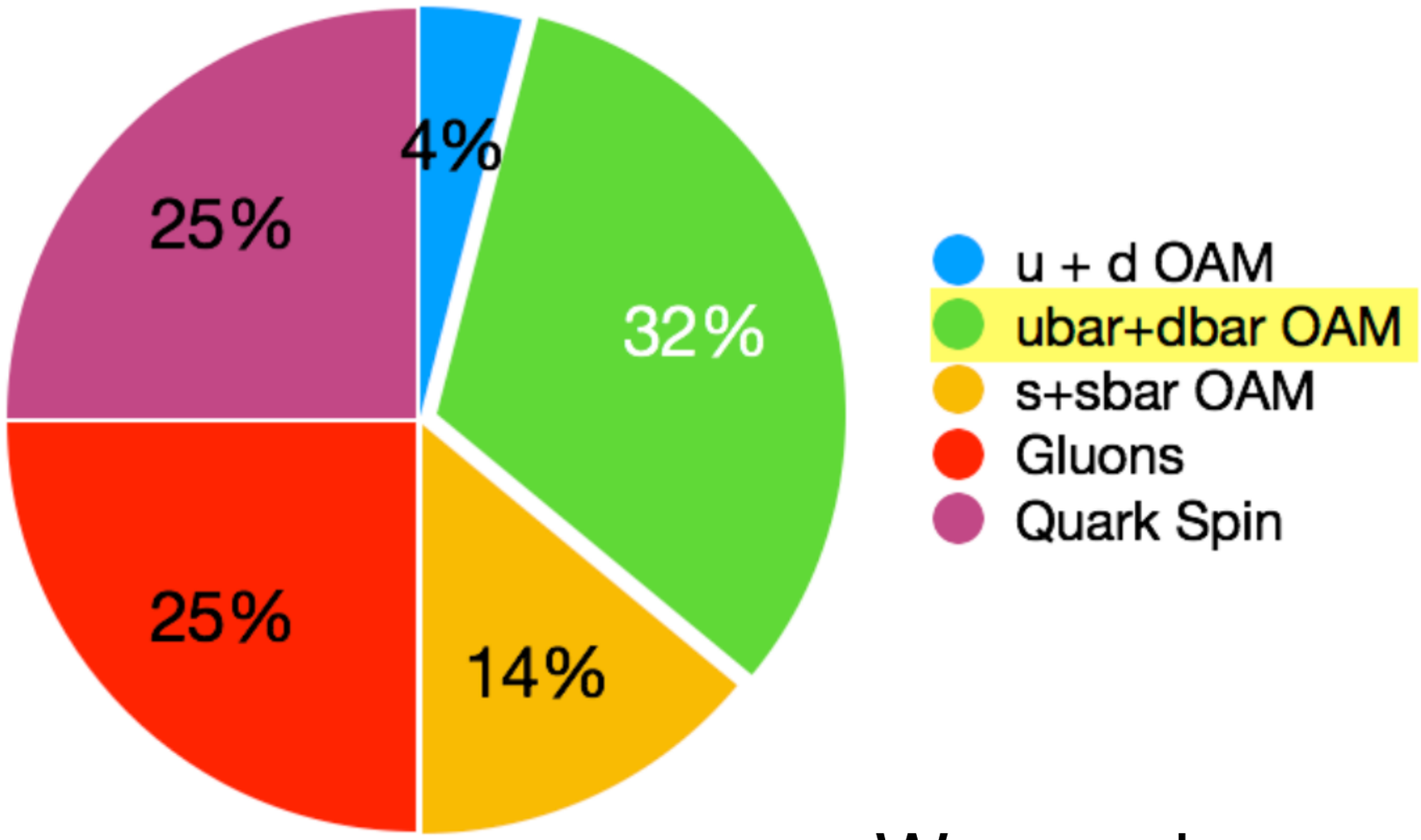
Orbital angular momentum

**Proton Spin Crisis** (EMC, SLAC, CMS …):

$$\frac{1}{2}\Delta\Sigma \approx 25\%, \ \Delta G \approx 20\%$$

# Proton Spin Puzzle

- Lattice QCD suggests a link between quark OAM and nucleon spin:




We need prove the presents of quark OAM?

=> In particular sea quarks!

[K.-F. Liu et al arXiv:1203.6388]

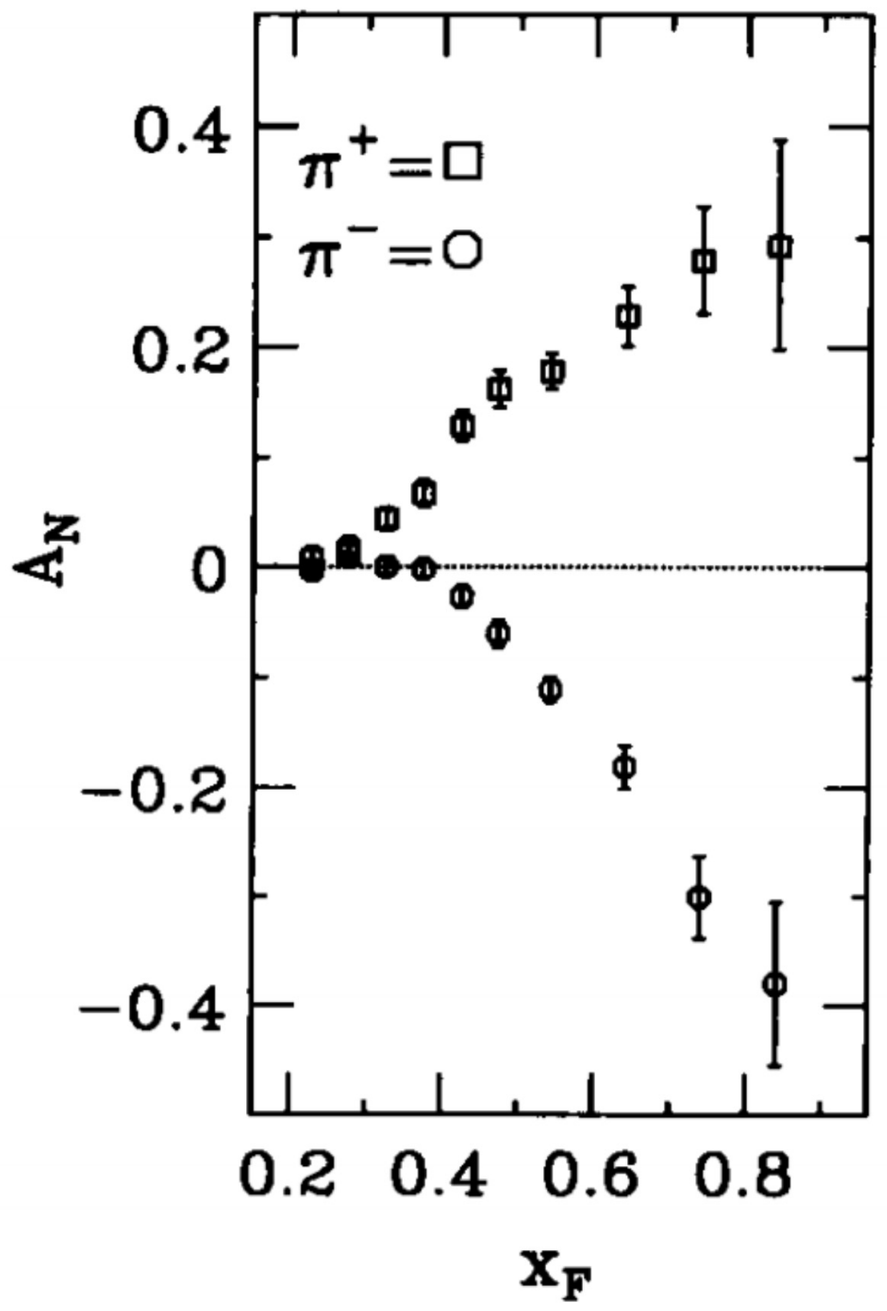
# Sivers Function

[https://drdennissivers.com]

Dennis Sivers proposed quark OAM as possible source of large **asymmetry** observed in E704!

$$d\sigma(pp_{\uparrow} \to \pi X) \quad , \quad A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$$

[Phys. Lett. B 264, 462 (1991)]

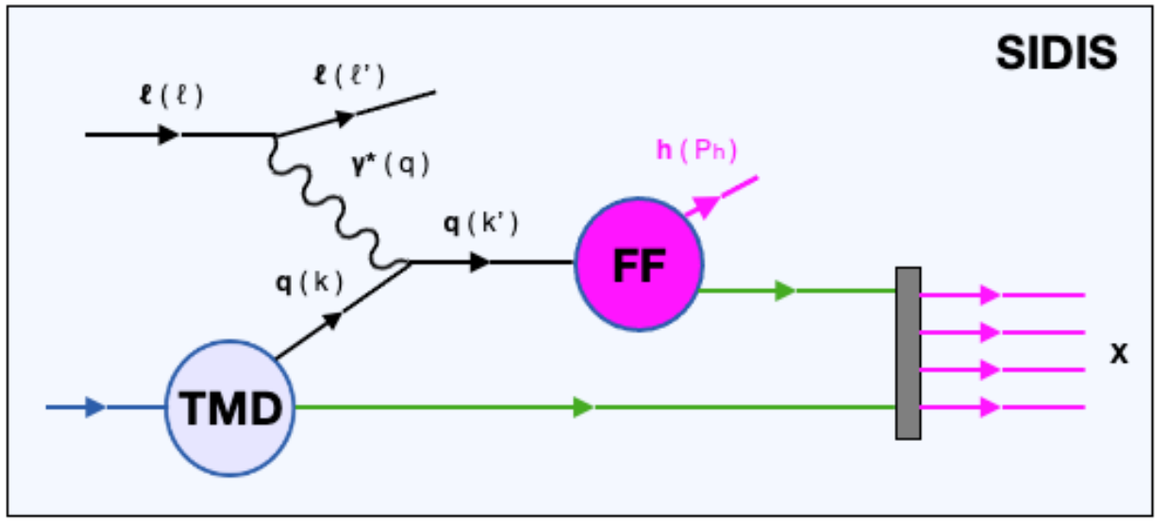



## Two Major Predictions:

- Sivers function requires quark OAM.
- QCD predicts sign flip between SIDIS and DY measurements from gauge link:

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS}$$

# Sivers Function from SIDIS




$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

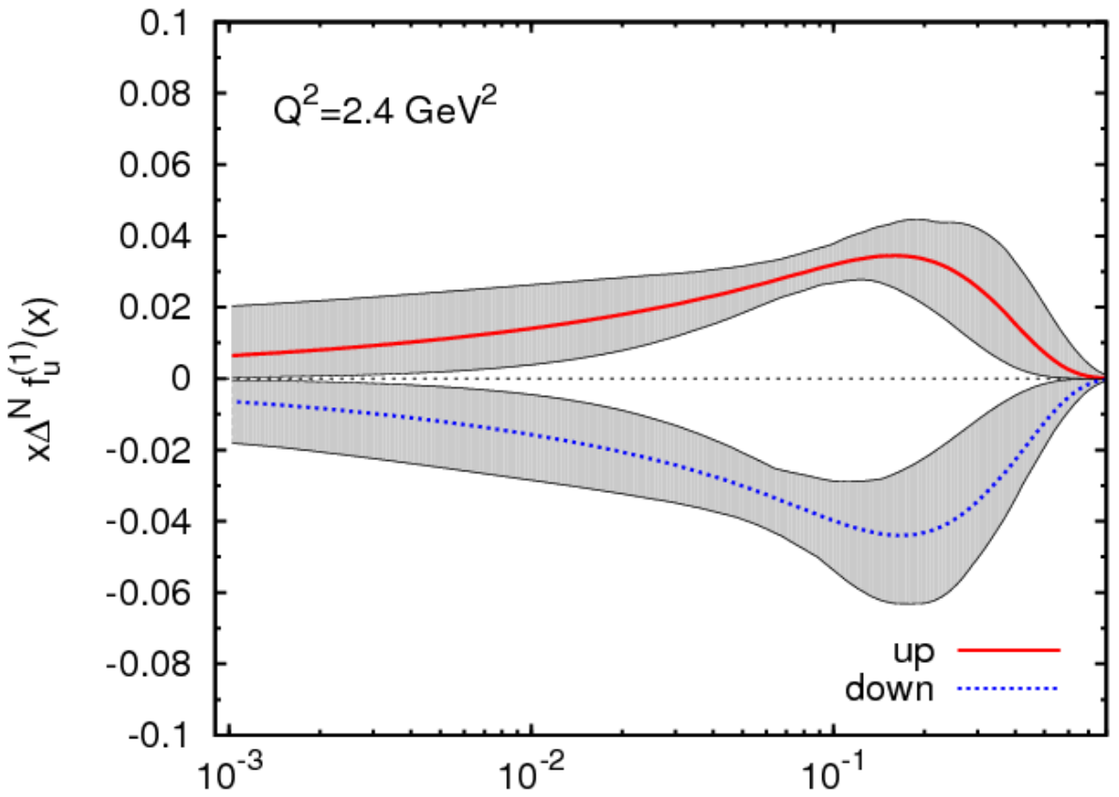
$$\times\left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right.$$

$$\left. + \; S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \; \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \; \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{array}\right]\right.$$

| | | |
|---|---|---|
| $A_{UU}^{\cos 2\phi_h}$ | $\propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$ | **BM ⊗ CF** |
| $A_{UT}^{\sin(\phi_h-\phi_S)}$ | $\propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$ | **Sivers ⊗ FF** |
| $A_{UT}^{\sin(3\phi_h-\phi_S)}$ | $\propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$ | **Transv ⊗ CF** |
| $A_{UT}^{\sin(\phi_h+\phi_S)}$ | $\propto h_1^{q} \otimes H_{1q}^{\perp h}$ | **Pretz ⊗ CF** |

Simultaneous fit of HERMES and COMPASS data:

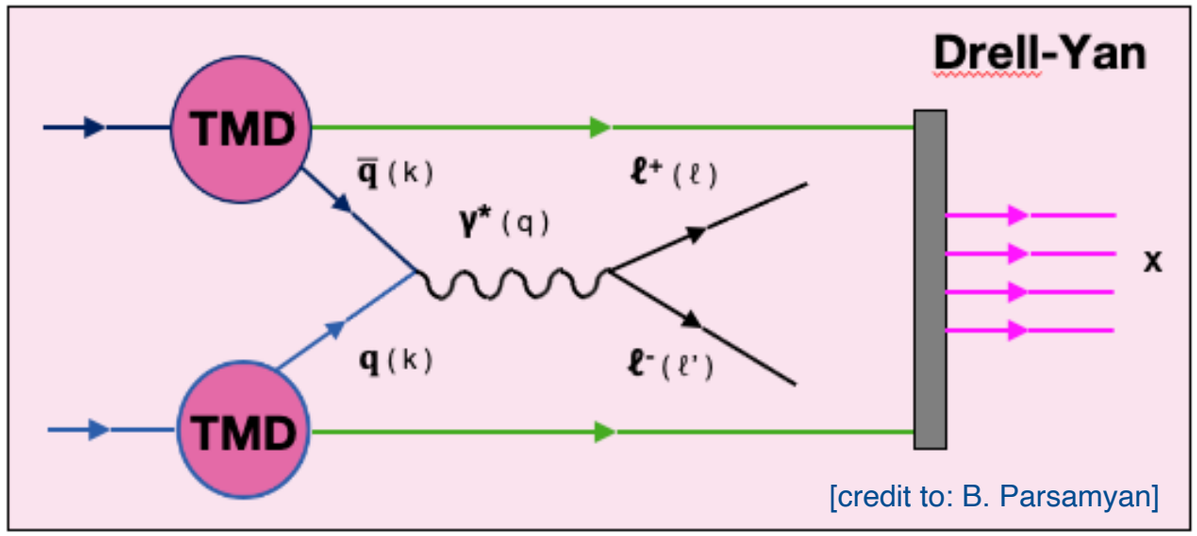
[Eur.Phys.J.A39(2009)89,arXiv:0805.2677]




- u- and d-Sivers have opposite signs, of roughly equal magnitude
- u-Sivers slightly smaller than d-Sivers

=> Sea-quarks Sivers are poorly constrained

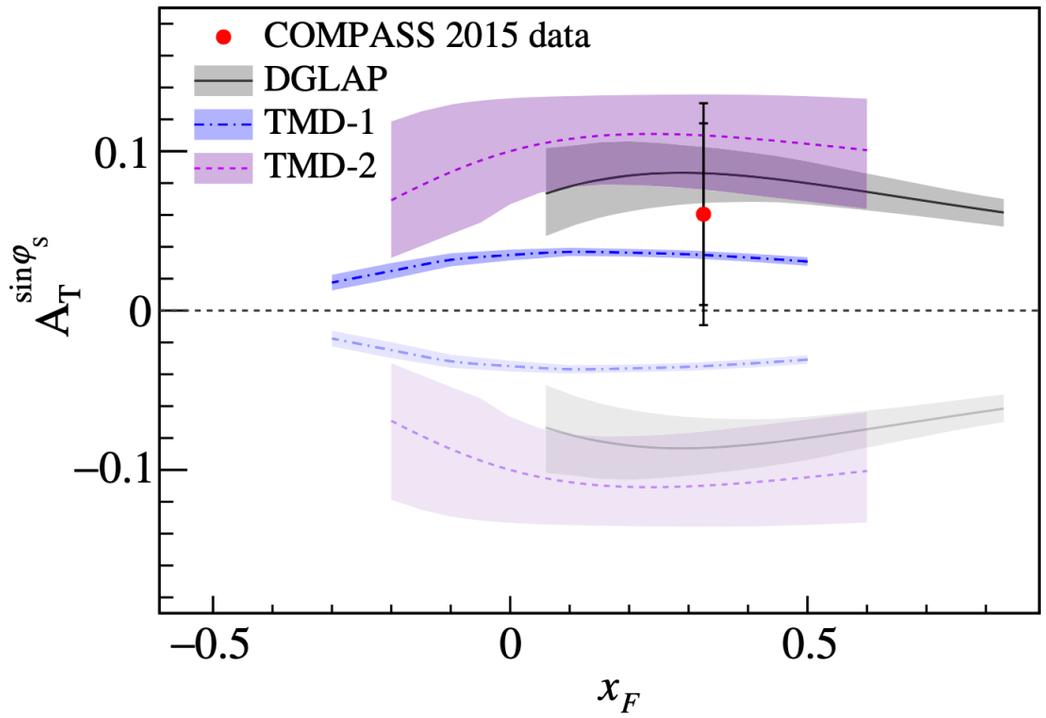
# Sivers Function from Drell-Yan




$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2\theta + \sin^2\theta A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$
$$+ S_T \left[ \left(1 + \cos^2\theta\right) A_T^{\sin\varphi_S} \sin\varphi_S \right.$$
$$+ \sin^2\theta A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS} + \varphi_S)$$
$$\left. \left. + \sin^2\theta A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right] \right\}$$

| | | | |
|---|---|---|---|
| $A_U^{\cos 2\varphi_{CS}}$ | $\propto h_1^{\perp q} \otimes h_1^{\perp q}$ | BM | ⊗ BM |
| $A_T^{\sin\varphi_S}$ | $\propto f_1^q \otimes f_{1T}^{\perp q}$ | $f_1$ | ⊗ Sivers |
| $A_T^{\sin(2\varphi_{CS}+\varphi_S)}$ | $\propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$ | BM | ⊗ Transv |
| $A_T^{\sin(2\varphi_{CS}-\varphi_S)}$ | $\propto h_1^{\perp q} \otimes h_1^q$ | BM | ⊗ Pretz |

COMPASS DY (2017): [PRL 119, 112002 (2017)]



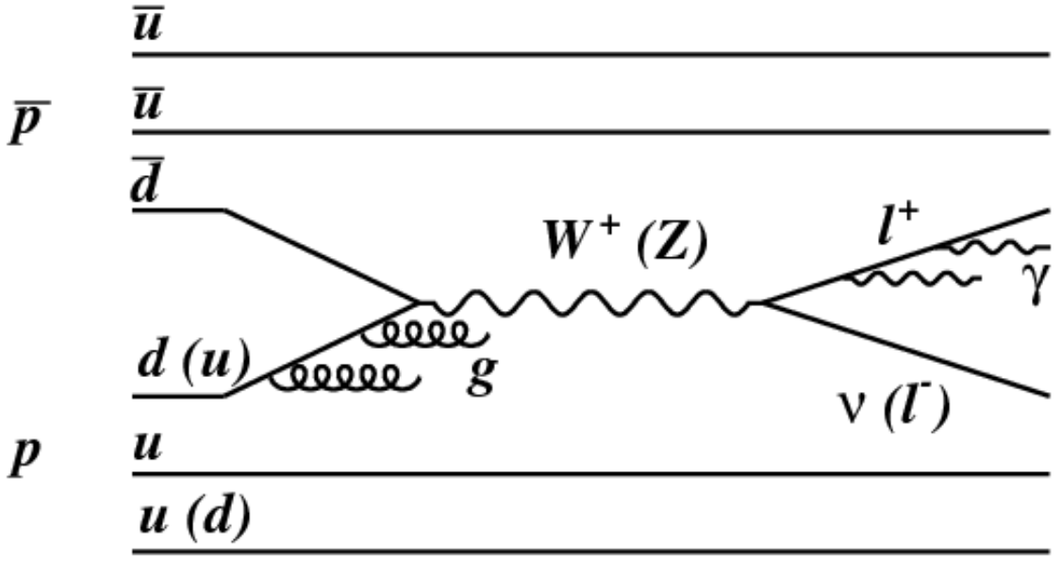

- 190 GeV/c $\pi^-$ secondary beam;
- Transverse polarized $NH_3$ target;
- Consistent with sign change but also consistent with zero!

$\frac{\sigma(DY)}{\sigma(nuc)}$ ≈ $10^{-7}$ for hadron beam

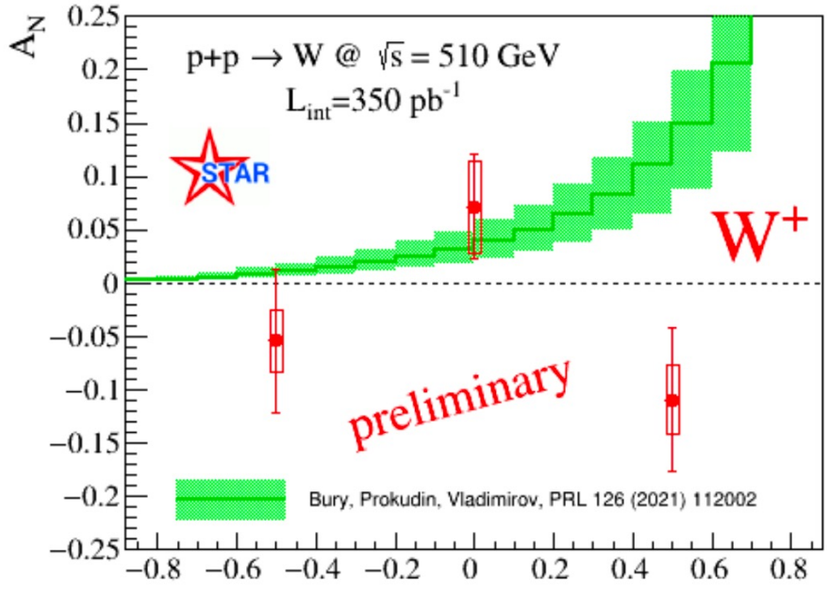
**=> We need primary beam!**

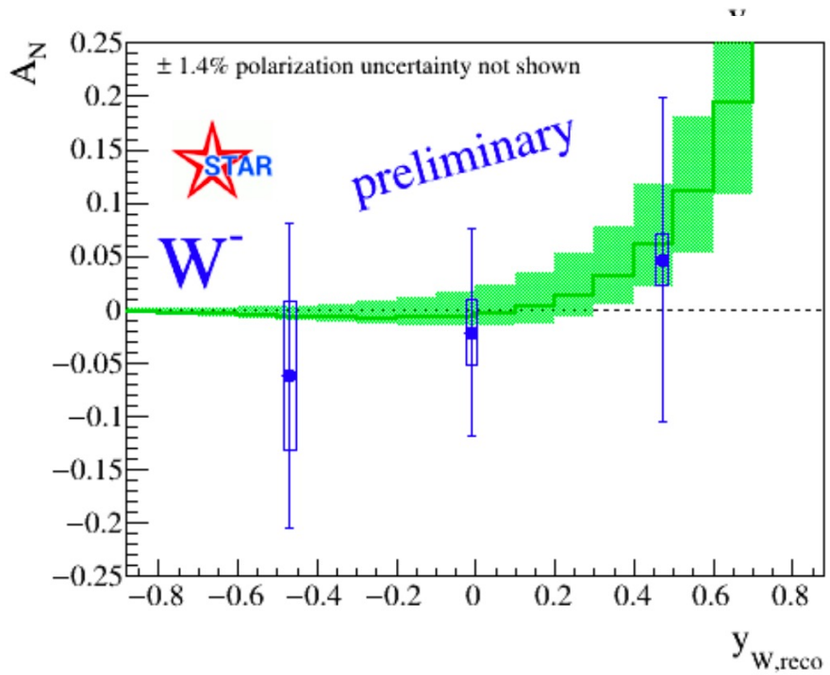
# Sivers Functions from Collider Experiments

[plot from: arXiv:1311.0894]




[O. Eyser (BNL)/STAR 2021]



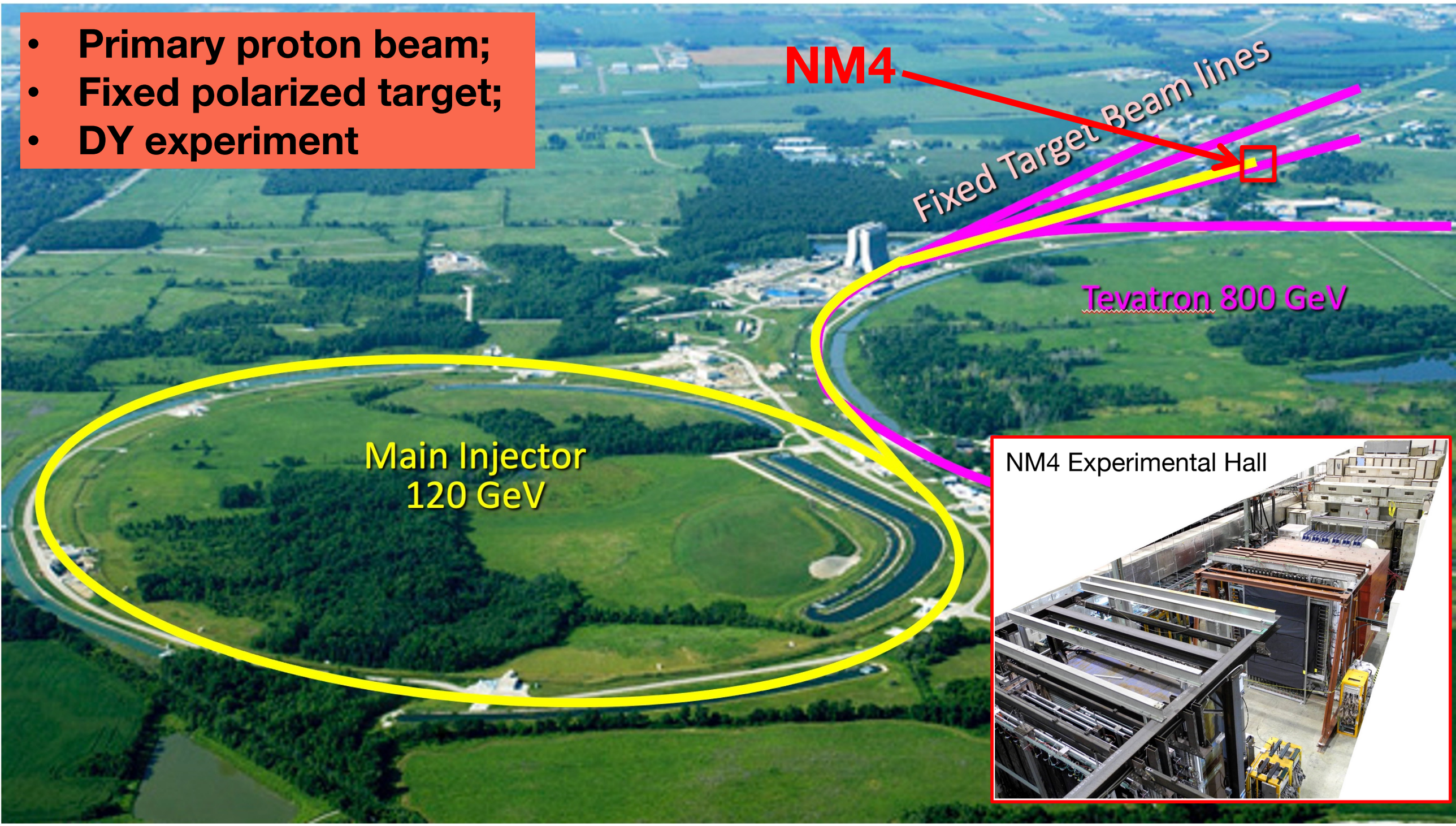

## STAR $W^{+/-}$ TSSA Experiments:

- RHIC p+p (500 GeV);
- Statistically limited!
- Consistent with sign change but also consistent with zero!

=> We need fixed target experiment!

# SpinQuest Experiment @ Fermilab

- **Primary proton beam;**
- **Fixed polarized target;**
- **DY experiment**



# *SpinQuest Experiment @ Fermilab*

- SpinQuest's p**rimary goal** is to measure correlations between OAM of the sea-quark and the spin state of the parent nucleon to address Proton Spin Puzzle:

  => **cannot be done at any other facility**

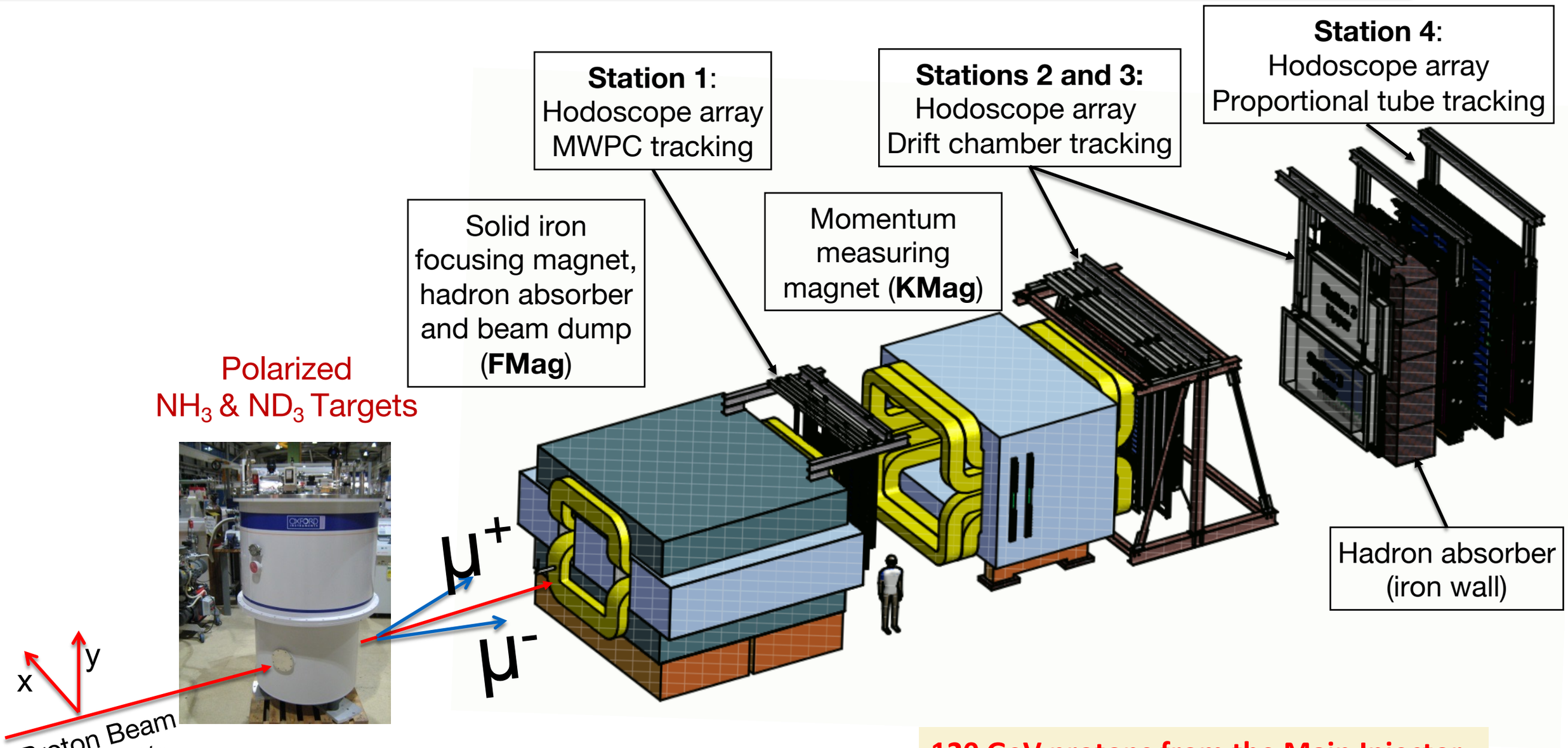
- SpinQuest is a **polarized target *intensity frontier*** experiment:

  => Never before has there been a polarized target system specialized to push the proton beam intensity at this level (up to 4 x $10^{12}$ protons over 5 sec).

  => Highest power evaporation refrigerator ever made for a polarized target experiment.

- With Fermilab's help we intend to break new ground…

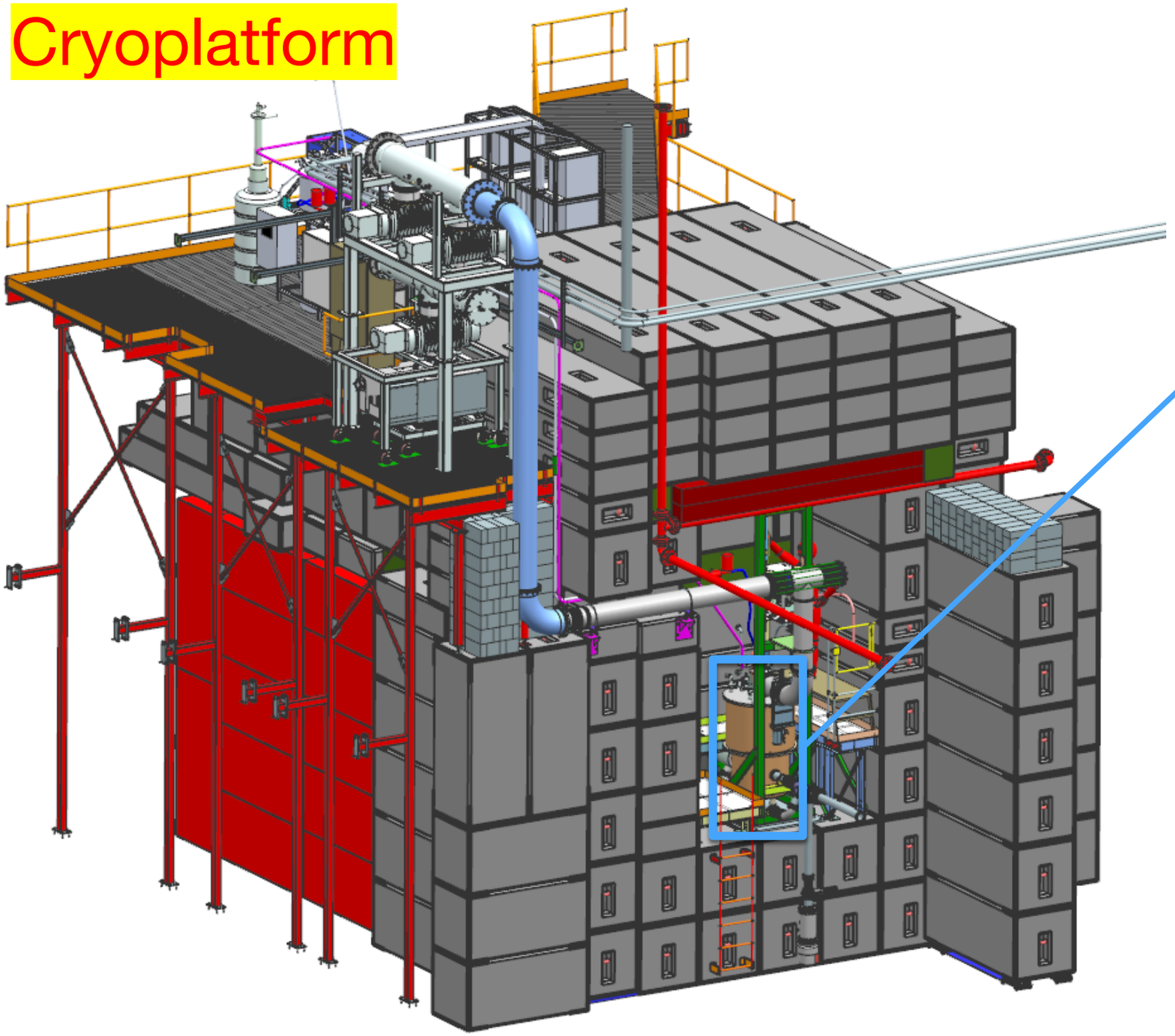
# Spectrometer Overview

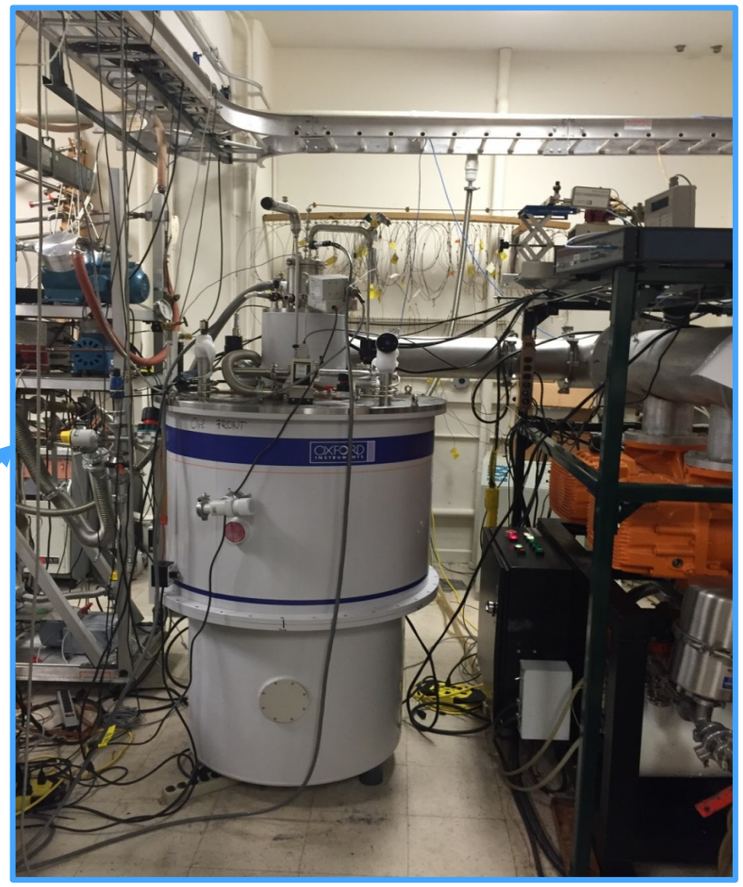



**120 GeV protons from the Main Injector**

- 4.3s beam spill every 60 sec
- 19ns RF, ~10Ks p/RF bucket
- $5 \times 10^{12}$ p/spill
- E1039 (2-year)

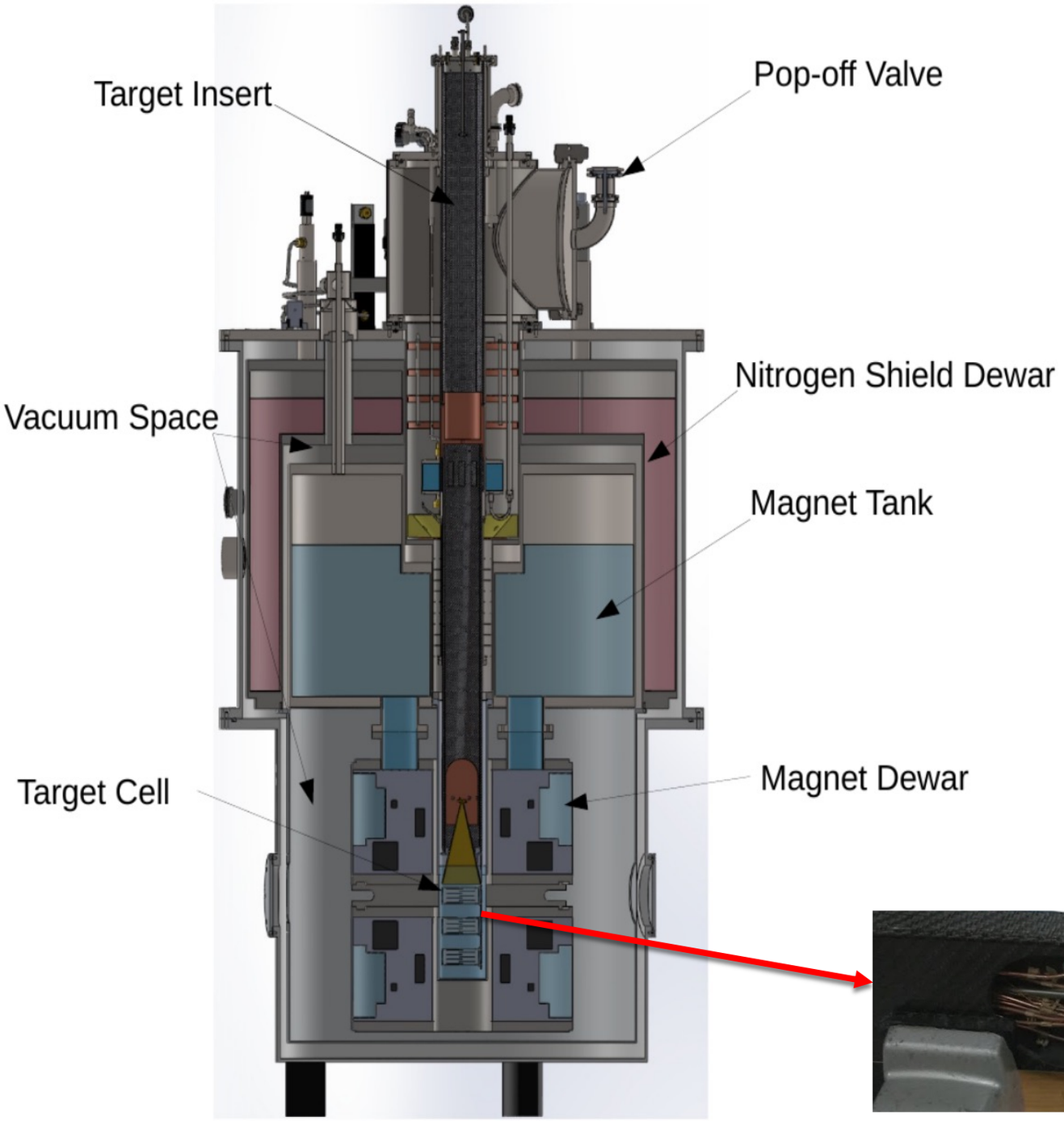
# SpinQuest Polarized Target



- QT LHe liquifier
- SC Magnet feeds fridge
- Capture and recirculate gHe
- Designed for sustained continuous running under production data taking

# SpinQuest Polarized Target



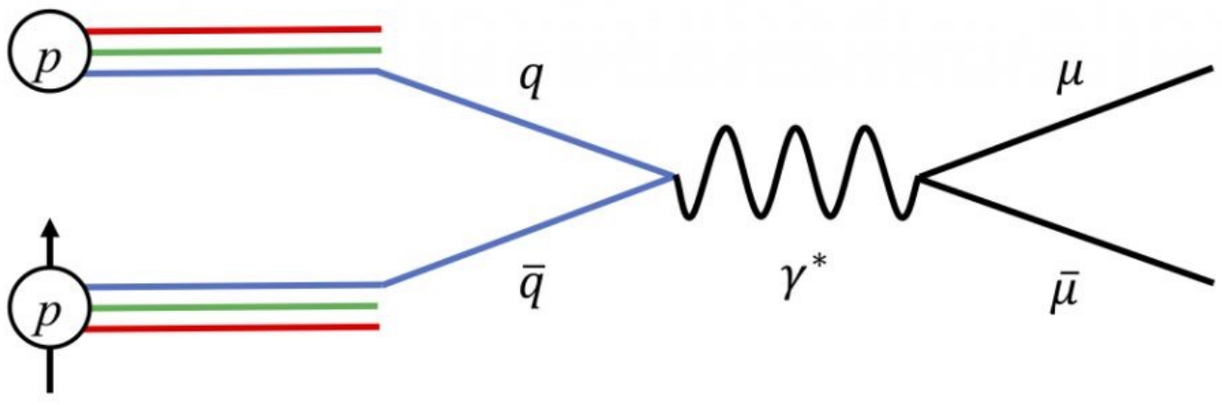

- Dynamic nuclear polarization yields **~80%** average proton target polarization at ~4% uncertainty.
- Target maintained at 1K in 5 T field, polarization flip every 8 hours.
- Designed for largest luminosity of any previous evaporation refrigeration system:

  up to 4 x $10^{12}$ protons over 5 sec

- $NH_3$, $ND_3$, and Background target.

# Measuring Sivers TMD in SpinQuest

Polarized DY:



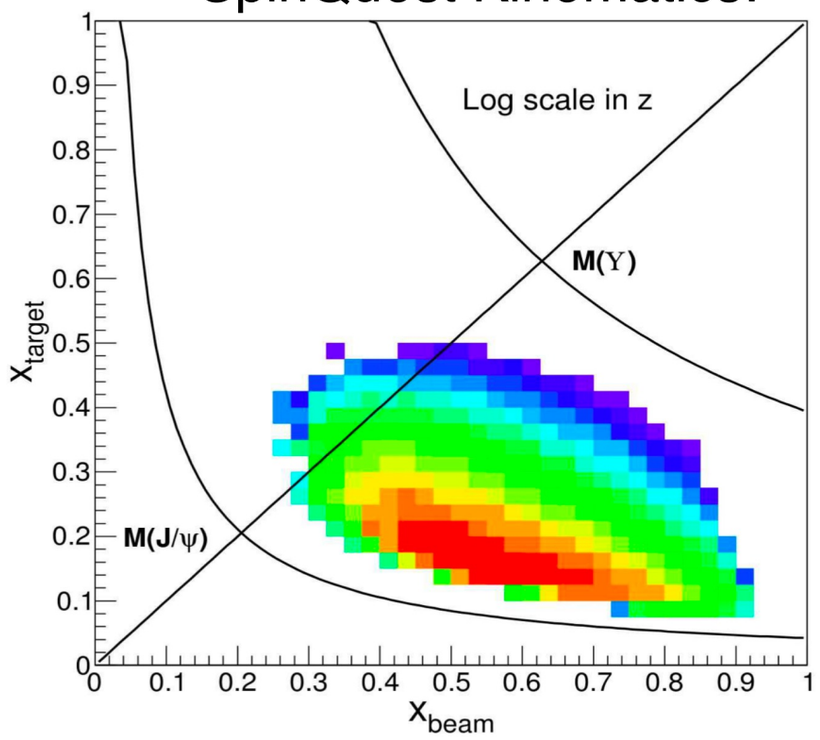

Accessing Sea Quark Sivers function from Cross Section Asymmetry:

$$A_N = \frac{\sigma_{\uparrow}^{DY} - \sigma_{\downarrow}^{DY}}{\sigma_{\uparrow}^{DY} + \sigma_{\downarrow}^{DY}}$$

Kinematically Suppressed!

$$A_N \propto \frac{\sum_q e_q^2 \left[ f_1^q(x_b) \cdot f_{1T}^{\perp,\bar{q}}(x_t) + f_1^q(x_t) \cdot f_{1T}^{\perp,\bar{q}}(x_b) \right]}{\sum_q e_q^2 \left[ f_1^q(x_b) \cdot f_1^{\bar{q}}(x_t) + f_1^q(x_t) \cdot f_1^{\bar{q}}(x_b) \right]}$$

SpinQuest Kinematics:




**SpinQuest goals:**

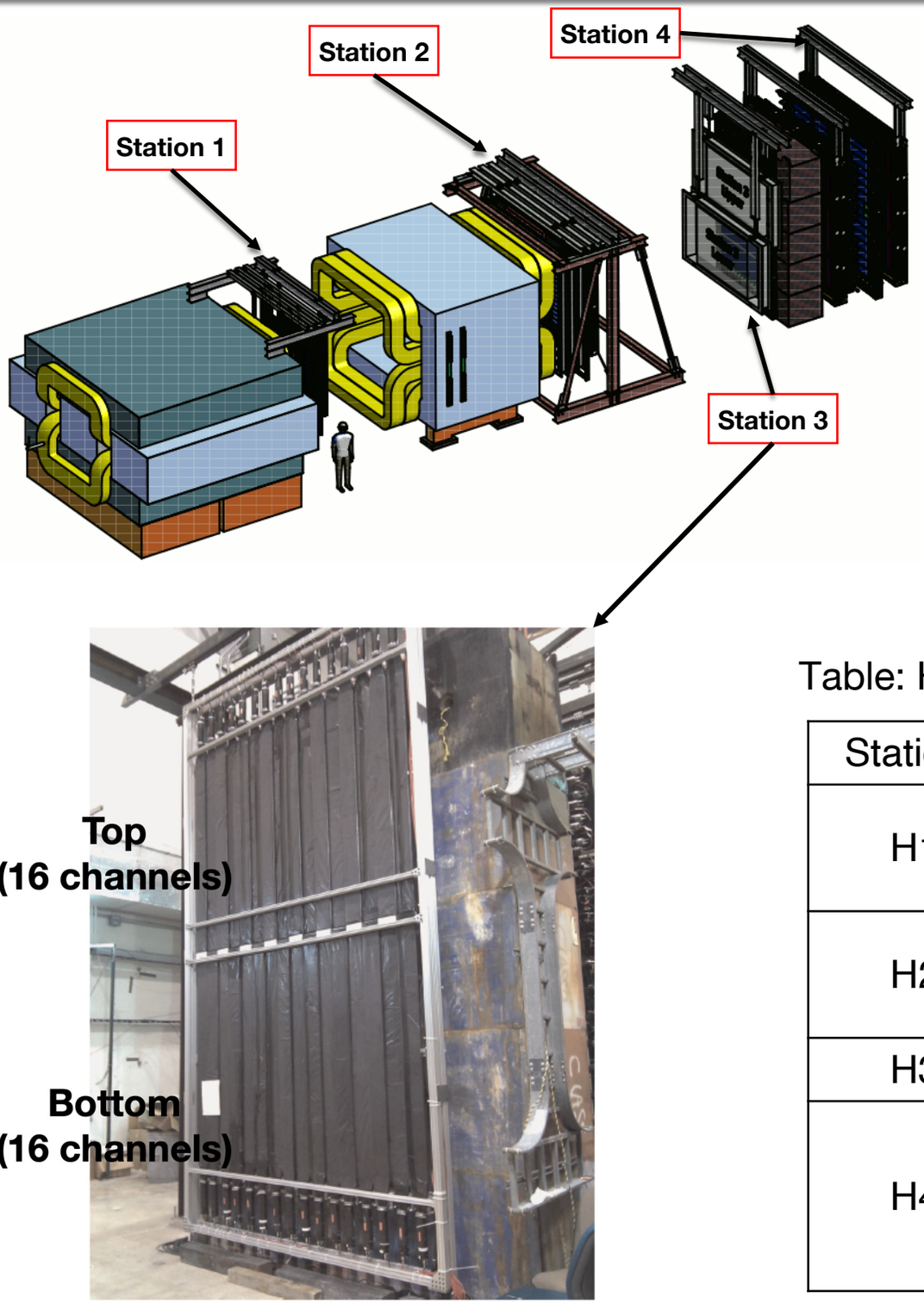
Measuring sign and magnitude of $\bar{u}$ and $\bar{d}$ Sivers Function$[f_{1T}^{\perp,\bar{q}}(x_t)]$:

=> Proton Spin Puzzle

=> QCD TMD framework test

If $A_N \neq 0$, **major discovery**: "Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$

# SpinQuest Event Selection




Hodoscope Readout Diagram:

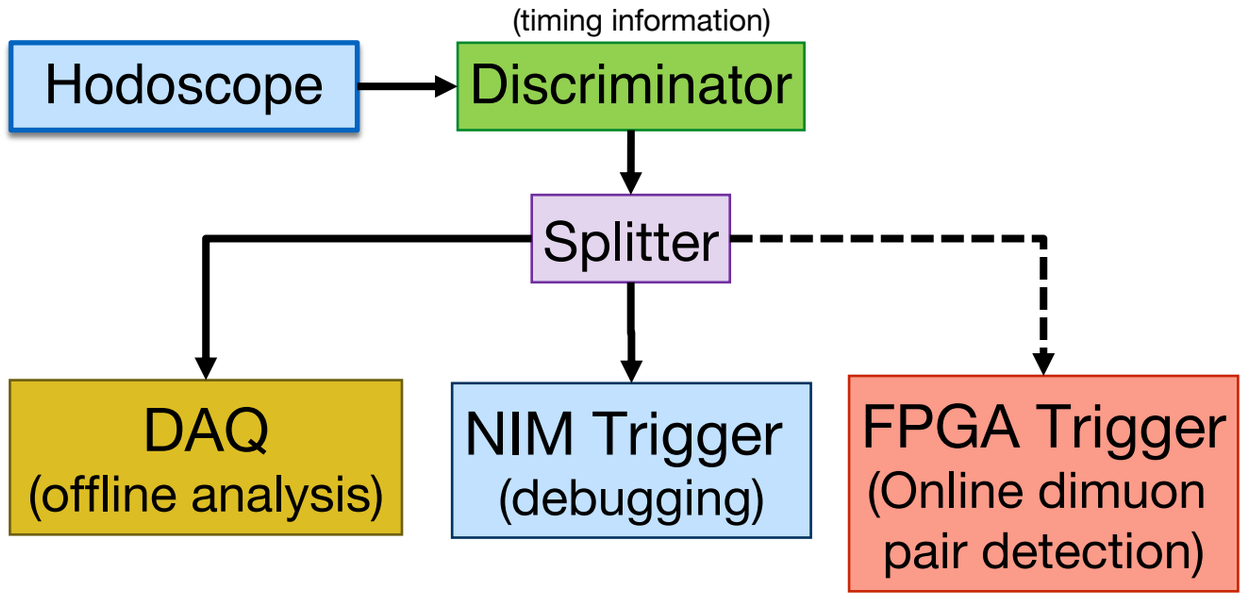
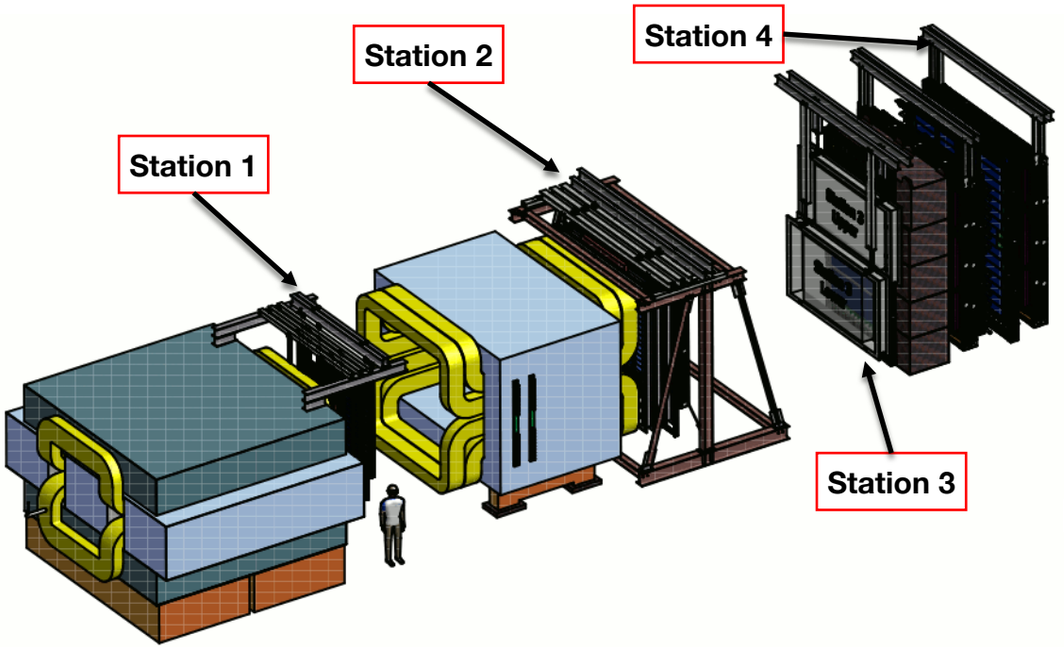


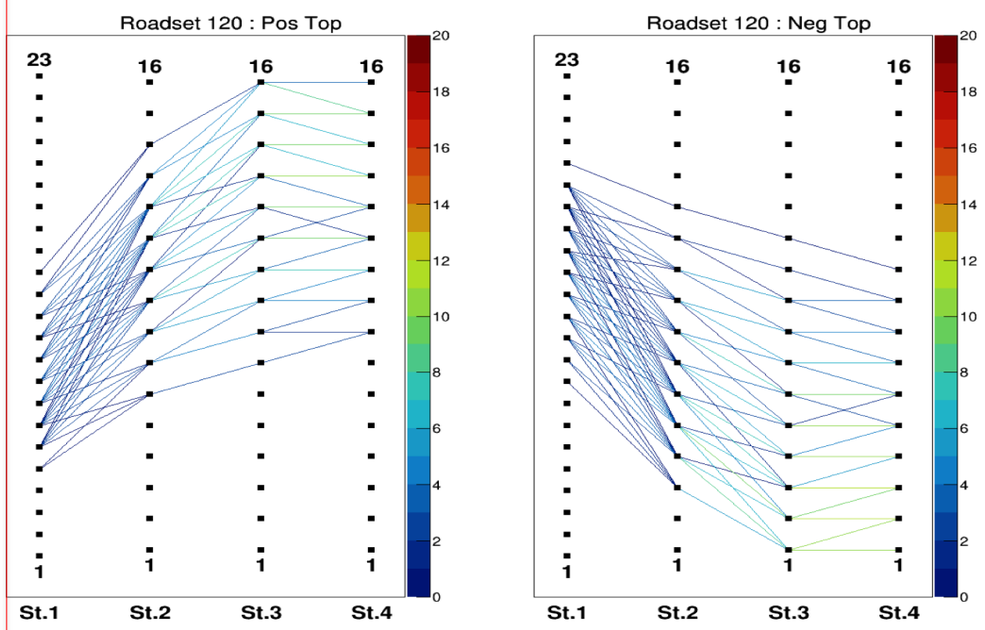

Table: Hodoscope Channels Summary.

| Stations | Plane | Number | In FPGA Trigger? |
|---|---|---|---|
| H1 | H1X (T & B) | 23 x 2 | **Yes** |
| | H1Y (L & R) | 20 x 2 | |
| H2 | H2X (T & B) | 16 x 2 | **Yes** |
| | H2Y (L & R) | 19 x 2 | |
| H3 | H3X (T & B) | 16 x 2 | **Yes** |
| H4 | H4X (T & B) | 16 x 2 | **Yes** |
| | H4Y1 (L & R) | 16 x 2 | |
| | H4Y2 (L & R) | 16 x 2 | |

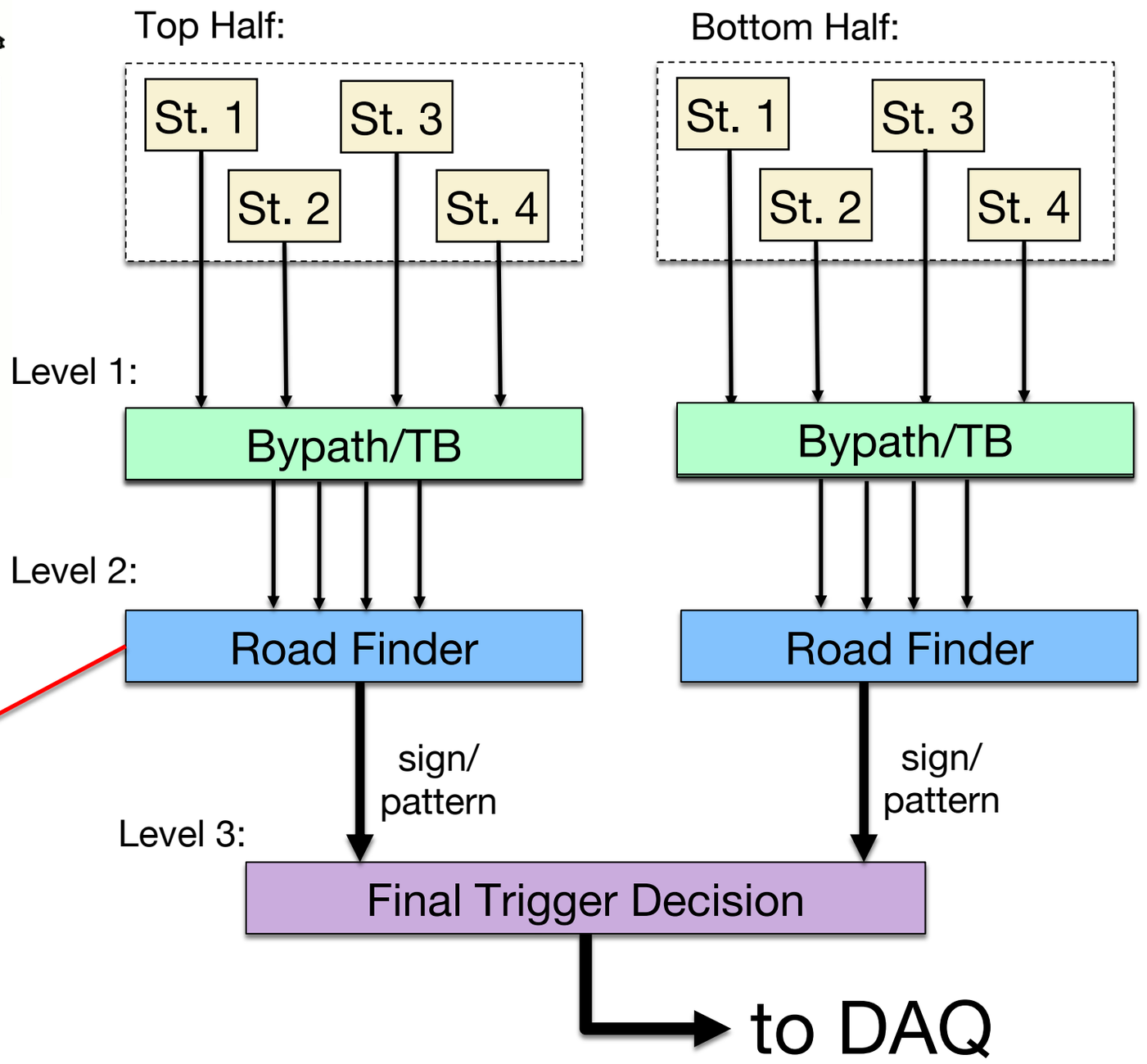
# SpinQuest Event Selection




J/ψ & D-Y (mass = 2-9 GeV):




## Three Level FPGA Trigger:



# 2024 Beam Commissioning

**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.

**Polarized Target Commissioning:**

- ✓ Beam alignment on 27x20x80 mm target cell
- ✓ Test all the operation procedures and $NH_3$ handling protocols
- ✓ Test heat-load on target and polarization requirements
- ✓ Quench commissioning (determine best (and highest) intensity to run)

# *First Production Data were Taken*

**Day One Physics:**

- Combined $J/\psi$ and Drell-Yan data taking.
- Running with both positive and negative polarization

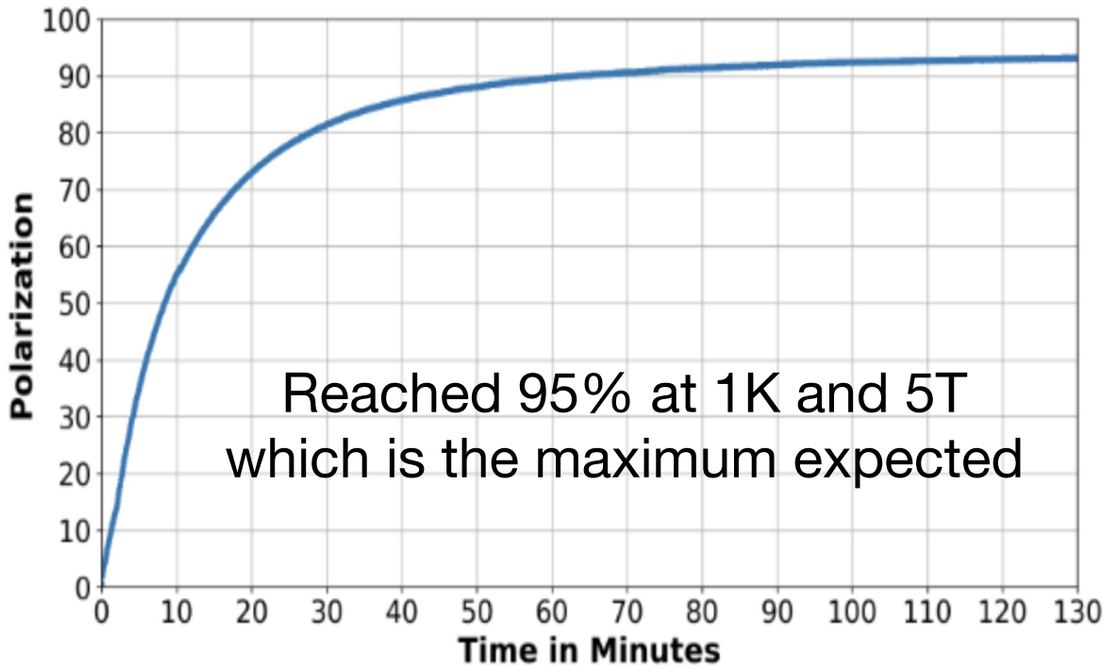
  => 35 Quality runs of production data

  => 900 spills with Kmag and Polarized Target ON

Total Events Collected:

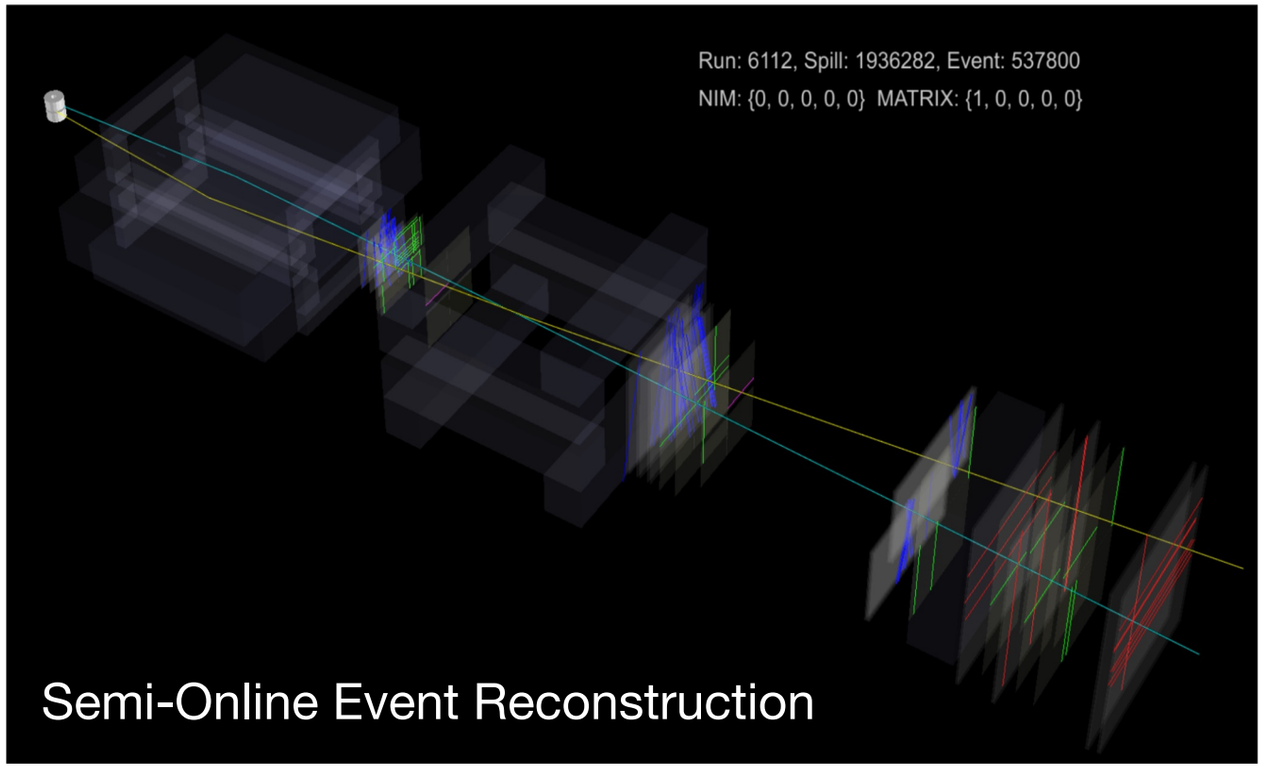
| | Average target polarization, % | POT |
|---|---|---|
| Positive polarization | ~85 | $10^{15}$ |
| Negative polarization | ~71 | $10^{15}$ |

$NH_3$ Target Polarization:

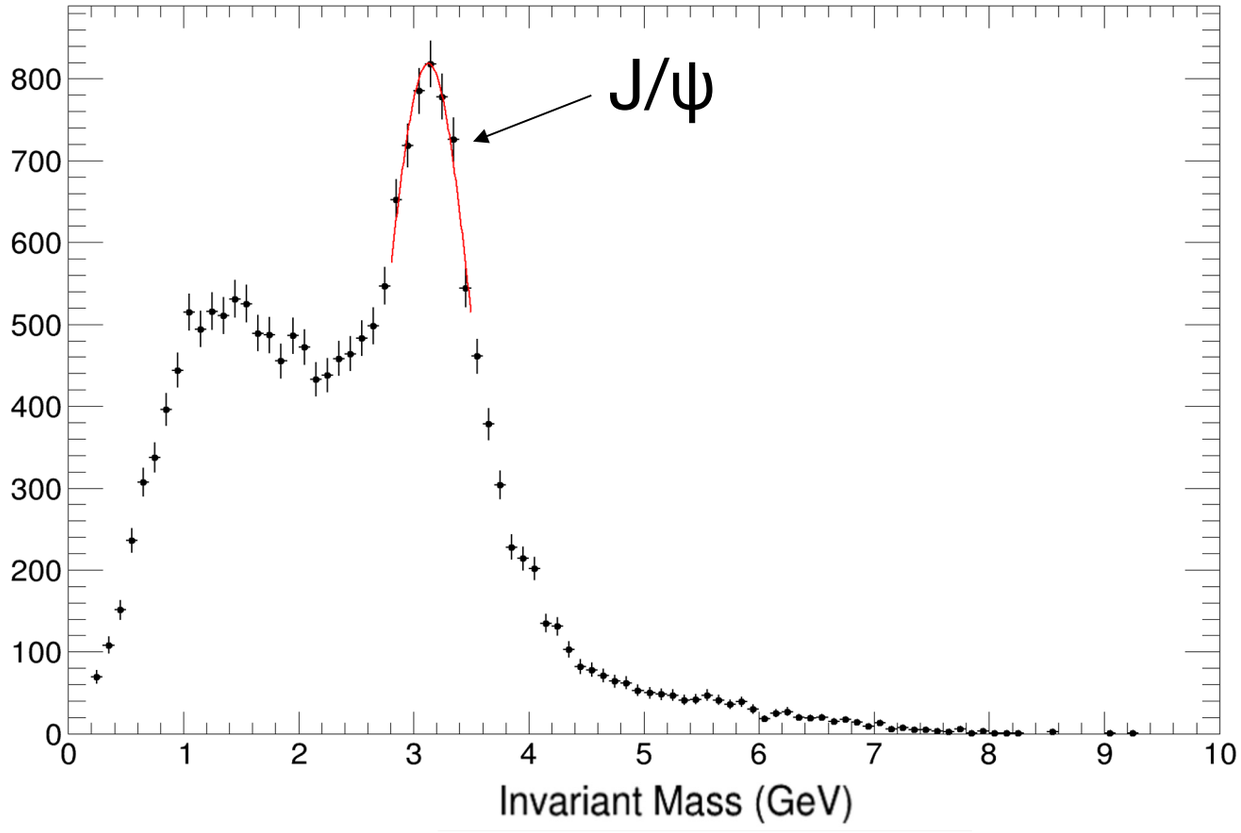


# First Production Data were Taken

Typical high-mass dimuon from target:




Clear J/ψ and high-mass dimuon events were observed:



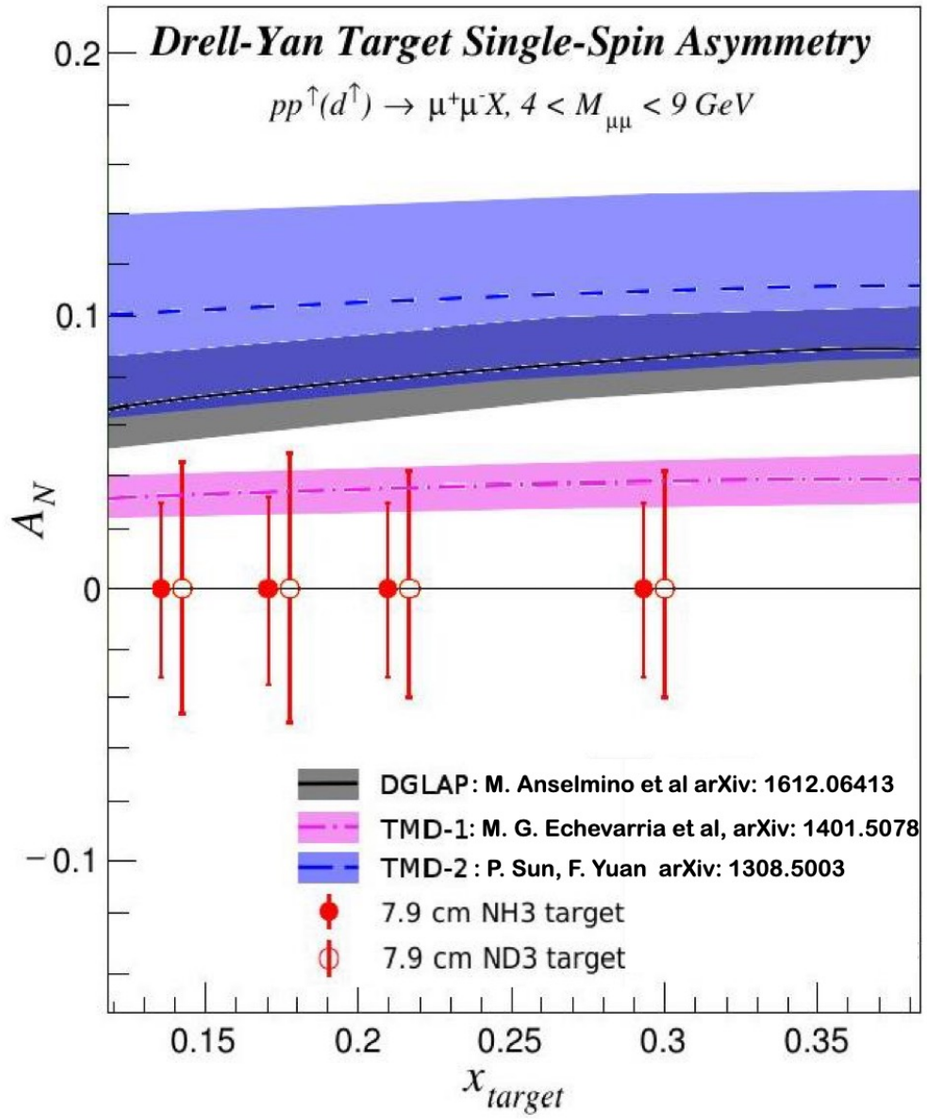

**During Shutdown:**

- Analyze the commissioning data
  => study systematics
- Repair broken/noisy detectors
- Prepare target for long term running

Offline analysis of the commissioning and production data is ongoing!

# SpinQuest Sivers Program

- SpinQuest will run for 2 years, beginning in Spring 2024, alternating $NH_3$, $ND_3$ and background subtraction targets.
- Projected Statistical uncertainty ~ 3-5%.
- Systematic uncertainties:
  - Beam (∽ 2.5%)
  - Analysis sources (< 3.5% )
    - Tracking efficiency
    - Trigger & geometrical acceptance
    - others
  - Target (< 6 %)
    - Polarization inhomogeneity
    - Density of target ($NH_{3(s)}$)
    - Uneven radiation damage
    - Beam-Target misalignment
    - Packing fraction
    - Dilution factor




- If $A_N \neq 0$, **major discovery**: "Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$ !

# *Thank you for your attention!*

**Learn more about SpinQuest/E1039: https://spinquest.fnal.gov/**