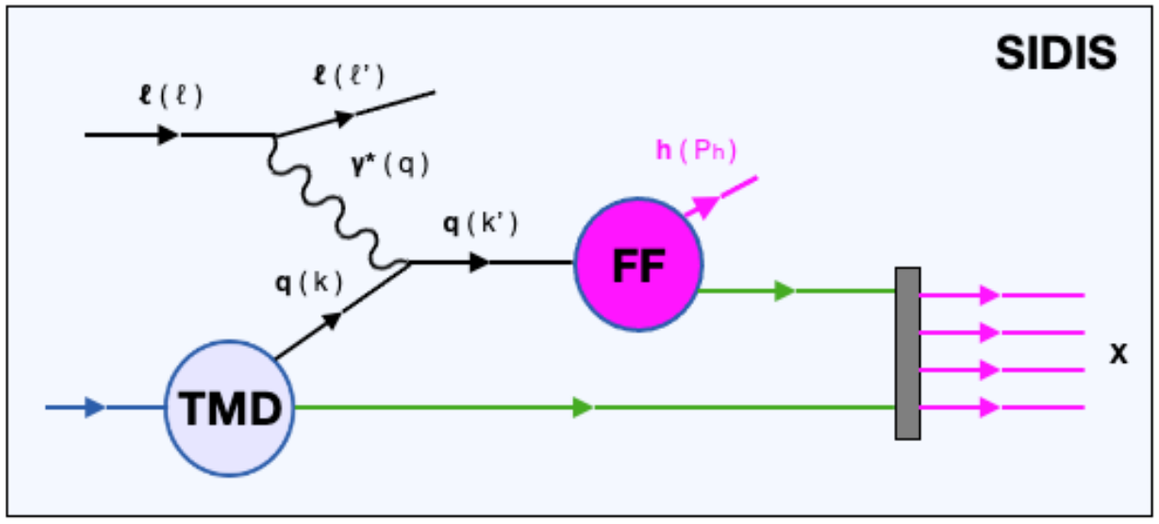
SpinQuest Project: status and perspectives

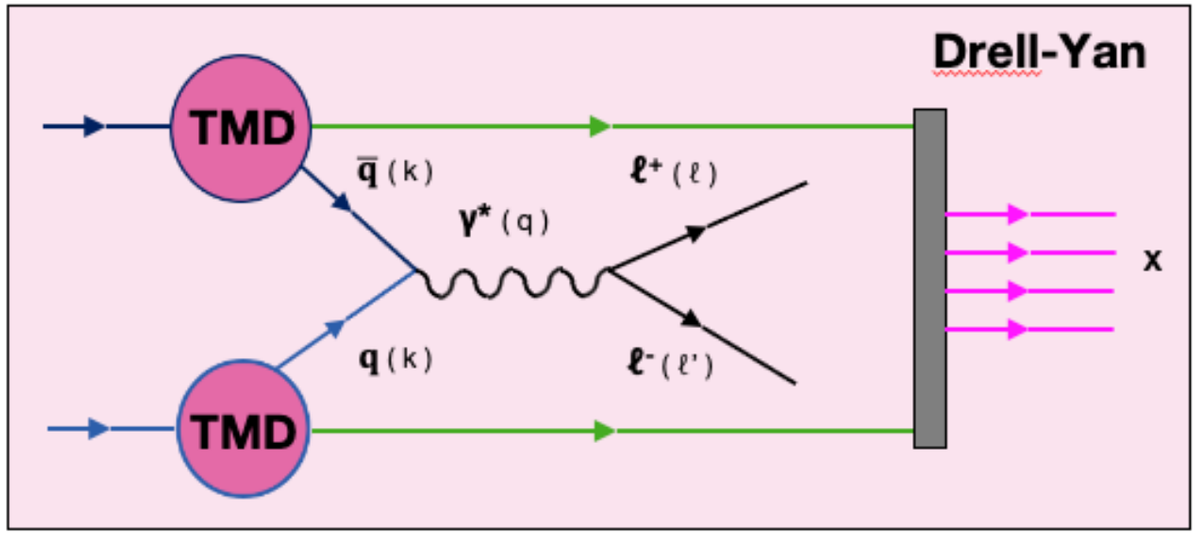
(On behalf of the SpinQuest Collaboration)

"*International Workshop on Hadron Structure and Spectroscopy - 2022*"
(IWHSS-2022)
CERN, Geneva, Switzerland
August 29-31, 2022.

Ievgen Lavrukhin

Probing Hadrons





- First method used to study hadron structure.
- Nuclear structure and fragmentation.
- QCD final state effects.
- **Fragmentation complicates selection between valence/sea quarks.**

- Cleanest method to study hadron structure.
- No fragmentation process.
- Two (TMD) parton distributions.
- **Directly access sea quark distributions.**

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

Leading Order Cross Section

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right.$$

$$\left. + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{bmatrix}\right\}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\ \gamma = \frac{2Mx}{Q}$$

SIDIS

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

Drell-Yan

$\pi N^{\uparrow}$

credit: B. Parsamyan

		TMD		FF
$A_{UU}^{\cos 2\phi_h}$	$\propto h_1^{\perp q}\otimes H_{1q}^{\perp h}$	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

		TMD		TMD
$A_U^{\cos 2\varphi_{CS}}$	$\propto h_1^{\perp q}\otimes h_1^{\perp q}$	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

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS},\ h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

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$A_{UT}^{\sin(3\phi_h-\phi_S)}$	$\propto h_{1T}^{\perp q}$	⊗	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_h+\phi_S)}$	$\propto h_1^{q}$	⊗	$H_{1q}^{\perp h}$

	TMD	⊗	FF
BM		⊗	CF
Sivers		⊗	FF
Transv		⊗	CF
Pretz		⊗	CF

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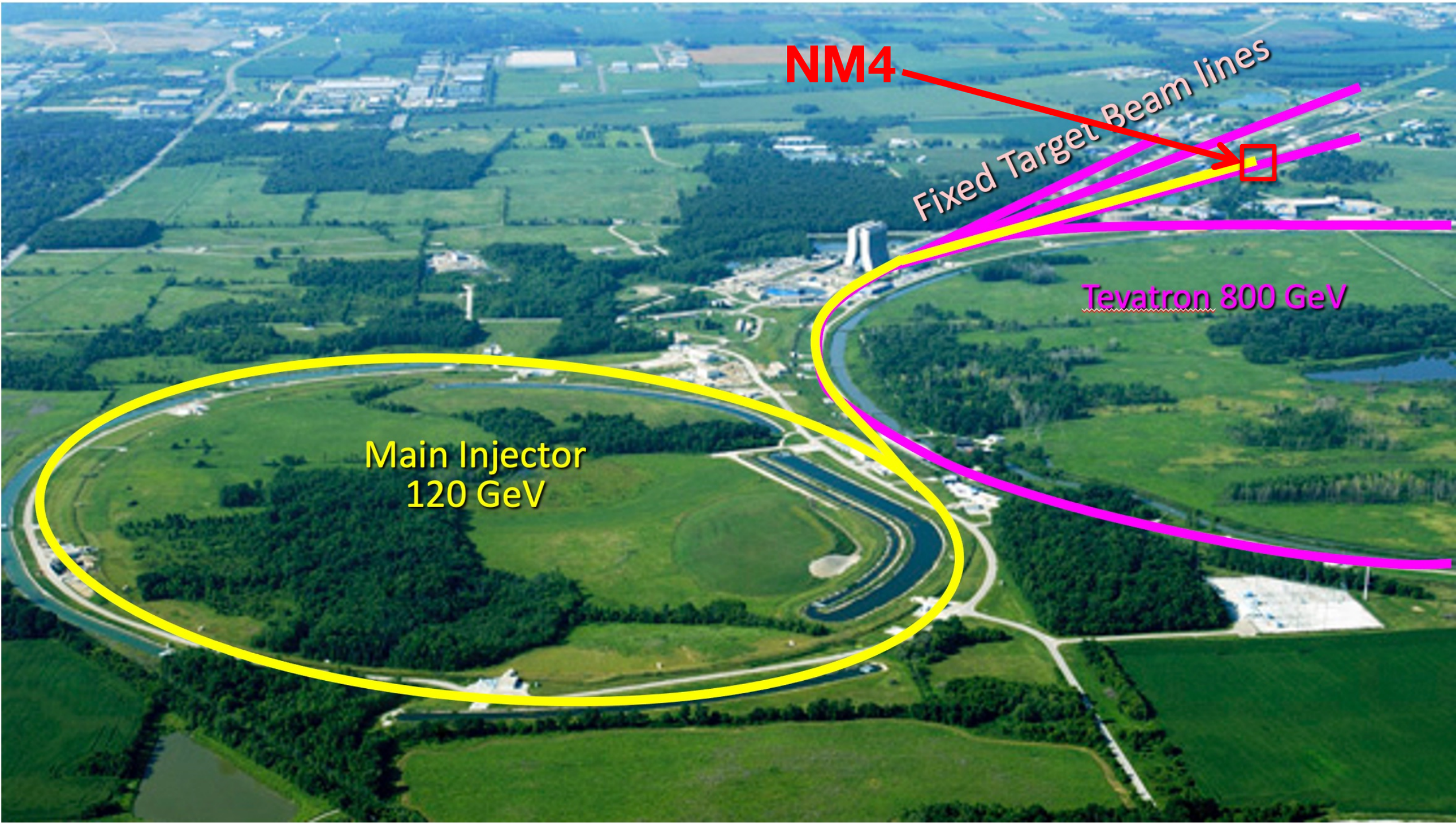
	TMD	⊗	TMD
BM		⊗	BM
f_1		⊗	Sivers
BM		⊗	Transv
BM		⊗	Pretz

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS},\ h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

E-906
E-1039

Fixed Target DY Program at Fermilab



Fixed Target DY Program at Fermilab

Unpolarized beam and target

- **E906 / SeaQuest:** 120 GeV p on LH_2, LD_2, C, Fe, and W targets.
- Data from March 2014 – July 2017 : dbar/ubar ratio, energy loss in cold nuclear matter.

Unpolarized beam and polarized target

- **E1039 / SpinQuest:** 120 GeV p on solid, polarized H and D targets.
- Data taking starting this Fall, running for two years total: Sea Quark Sivers.

Extended Spin Program

- **"LongQuest":** dedicated spin-1 target + dark sector search.
- Deuteron vector and tensor polarization for Transversity extraction.

Unpolarized Drell-Yan @ SeaQuest

Measure antimatter asymmetry in proton with cross section ratio:

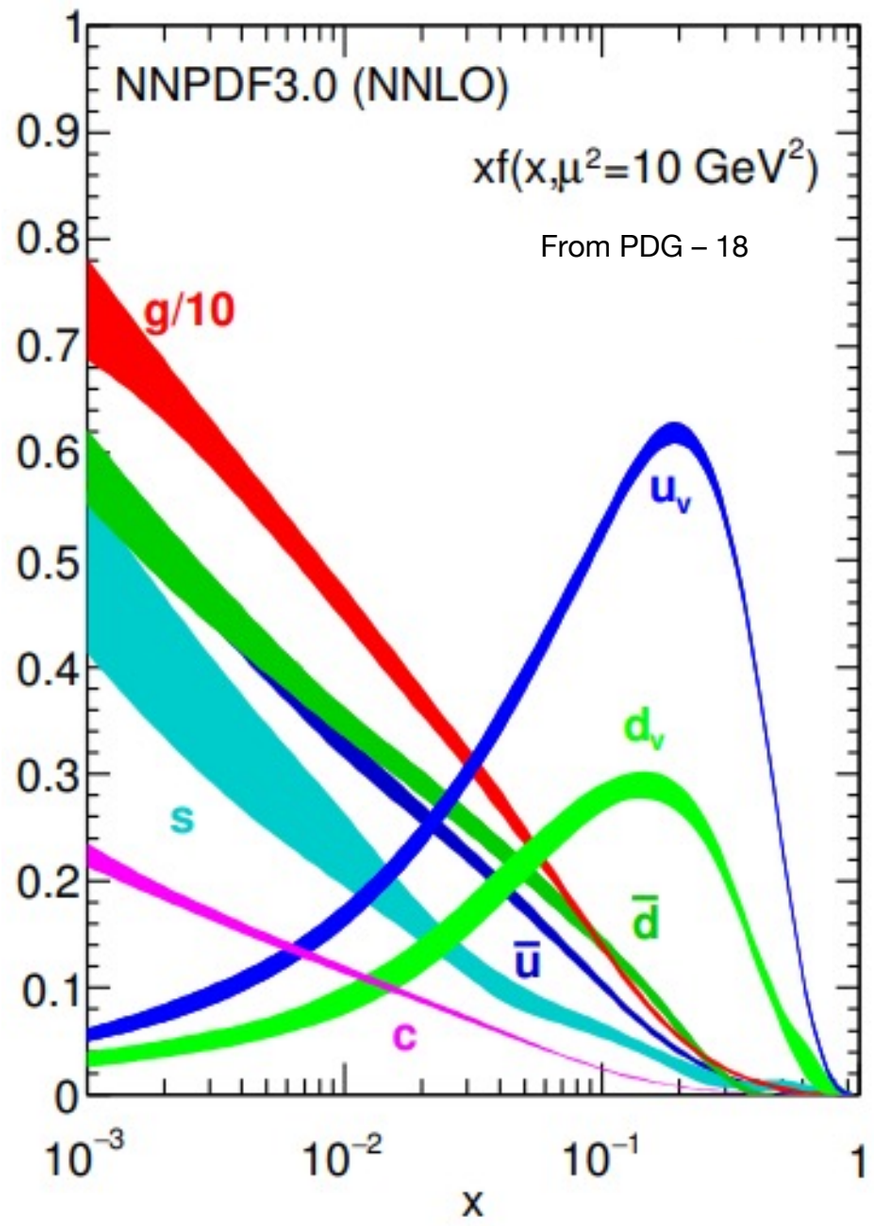
$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\,\pi\,\alpha^2}{9\,s\,x_b\,x_t}\sum_q e_q^2[q(x_b)\bar{q}(x_t) + \bar{q}(x_b)q(x_t)]$$

"Choose" antiquark in target

Small for SeaQuest acceptance

Unpolarized PDF



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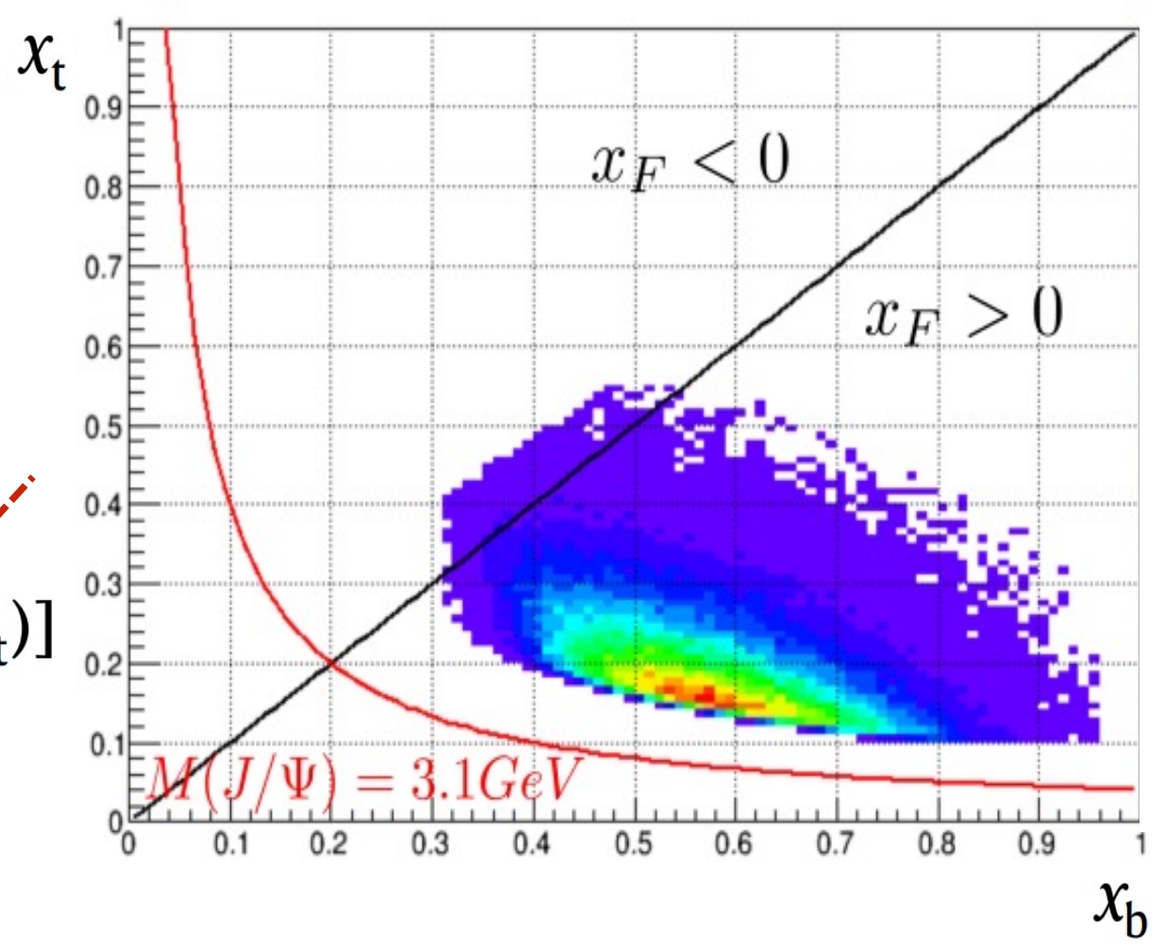
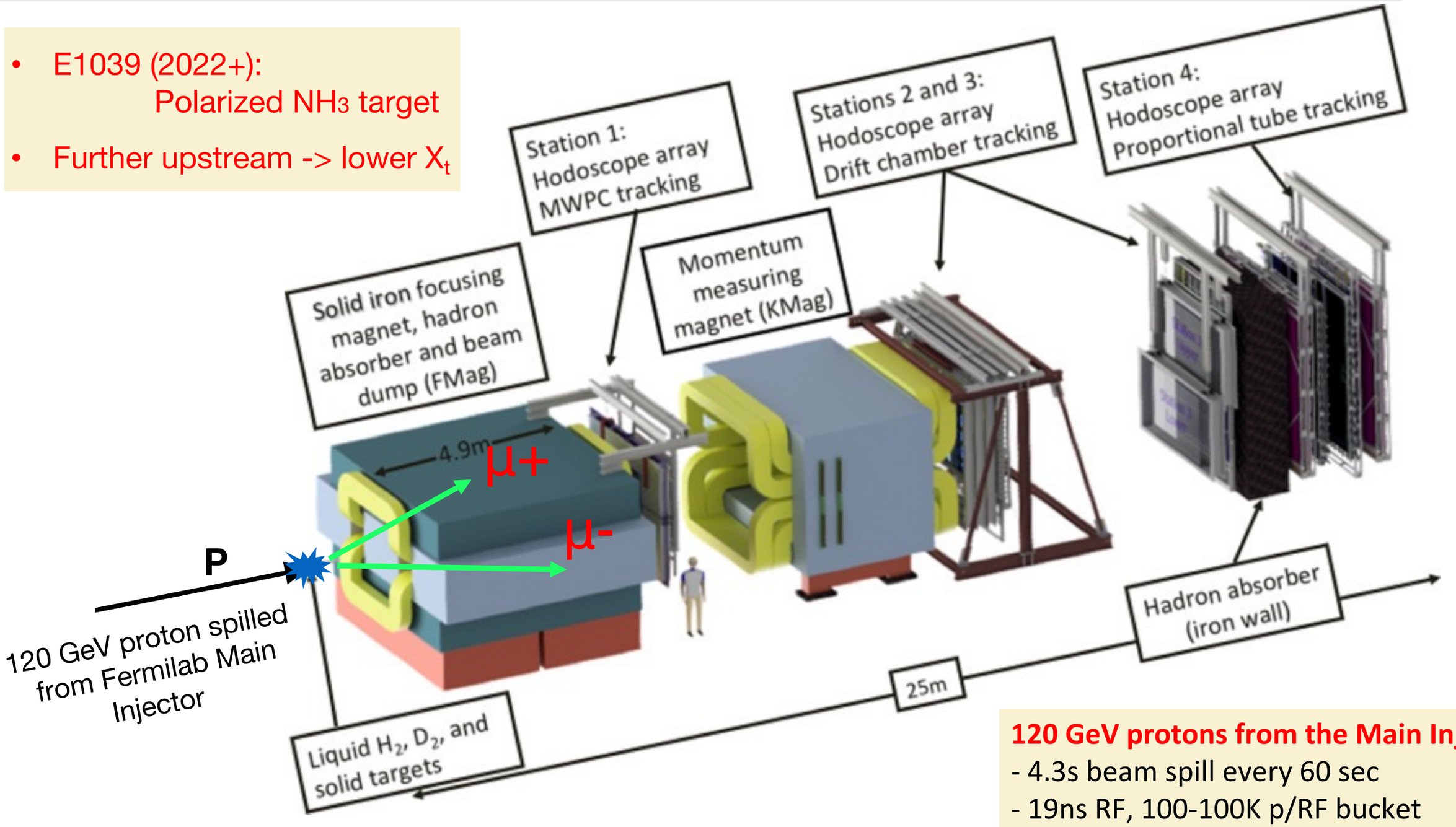
MC Acceptance of SeaQuest Spectrometer



SeaQuest Spectrometer

- E1039 (2022+):
  Polarized NH_3 target
- Further upstream -> lower X_t



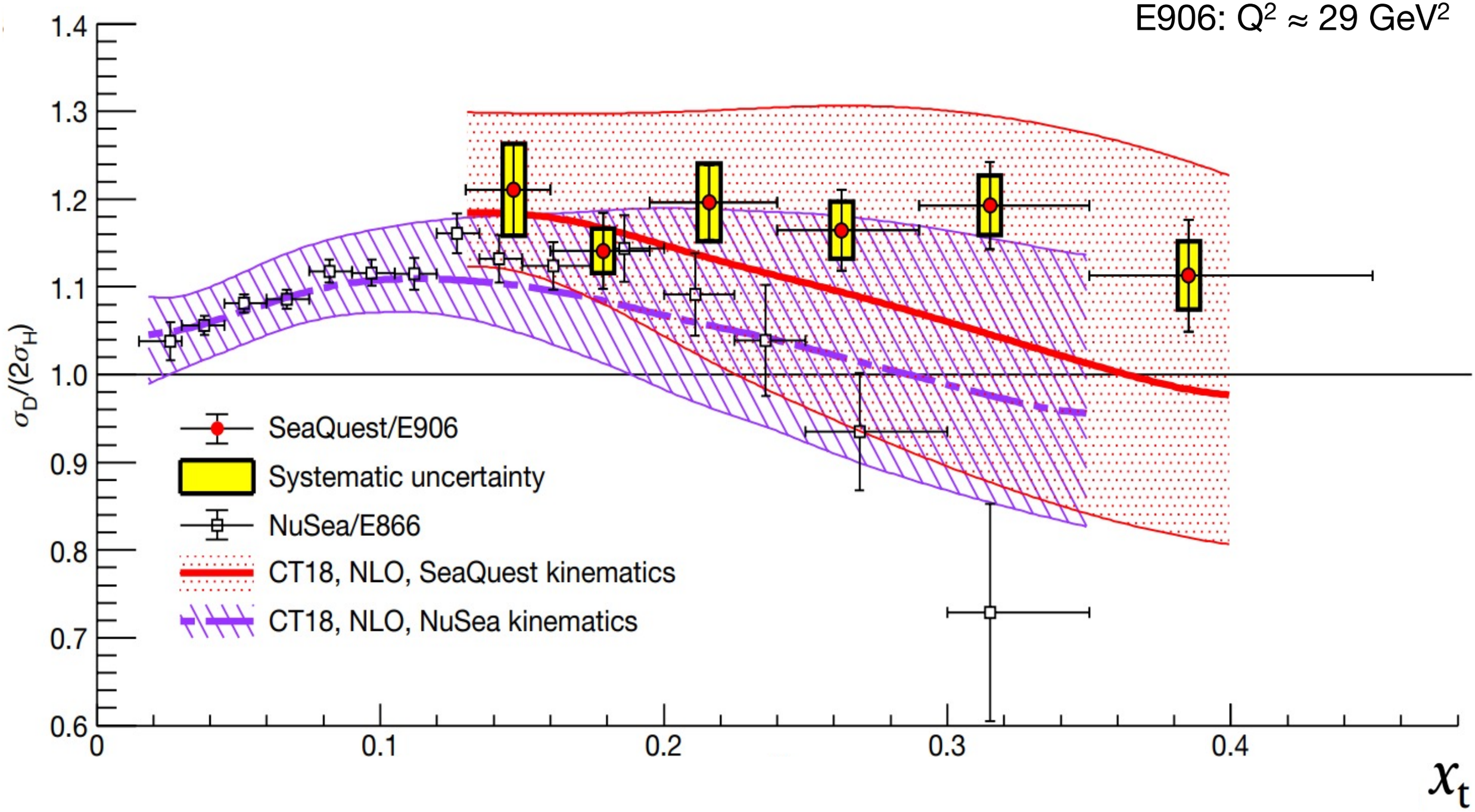
120 GeV protons from the Main Injector
- 4.3s beam spill every 60 sec
- 19ns RF, 100-100K p/RF bucket
- $5x10^{12}$ p/spill
-Integrated POT for 2 years: $1.4x10^{18}$ POT

SeaQuest Results

Nature **volume 590**, pages 561–565 (2021)

E866: $Q^2 = 54$ GeV^2

E906: $Q^2 \approx 29$ GeV^2



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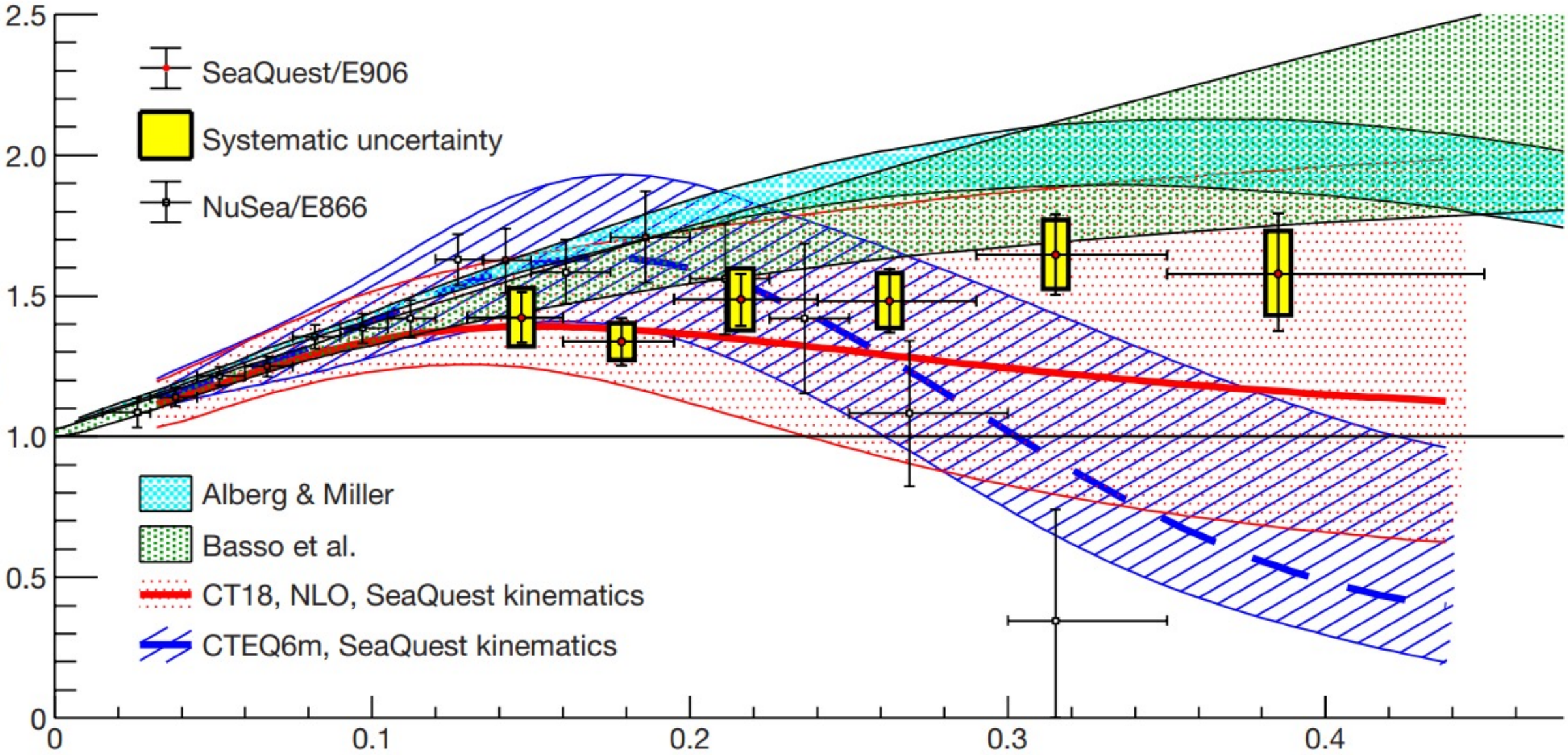


Proton Spin Puzzle

- Spin Crisis (deviations from the Ellis-Jaffe sum rule):

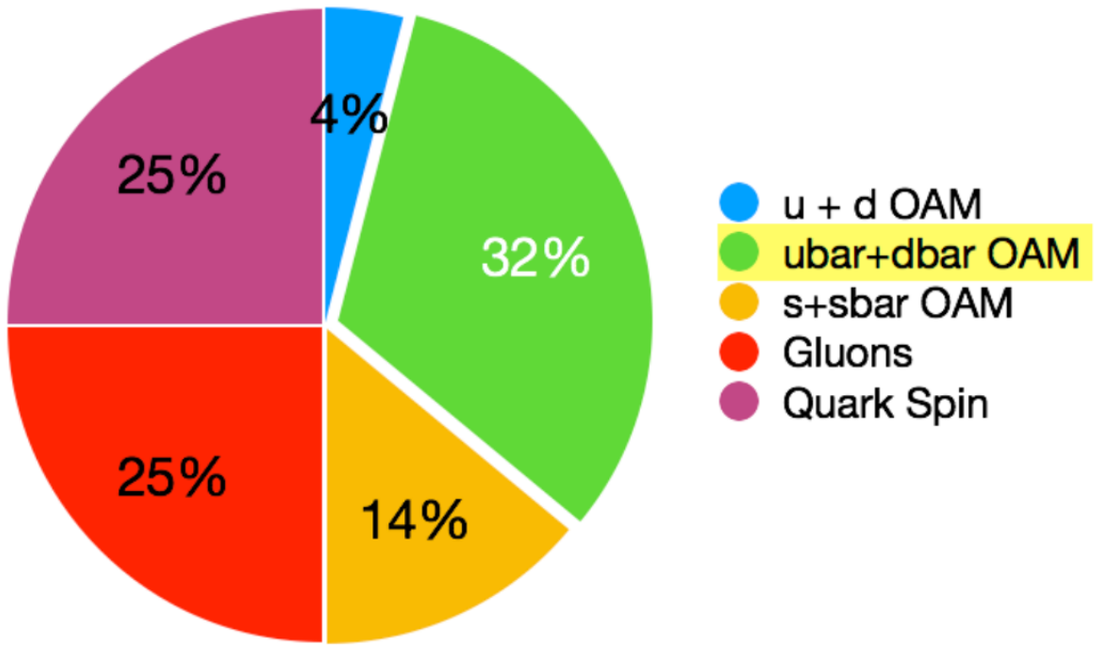
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$\tfrac{1}{2}\Delta\Sigma \approx 25\%; \quad \Delta G \approx 20\%$$

$$\mathrm{L} \approx \text{ unmeasured}$$

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



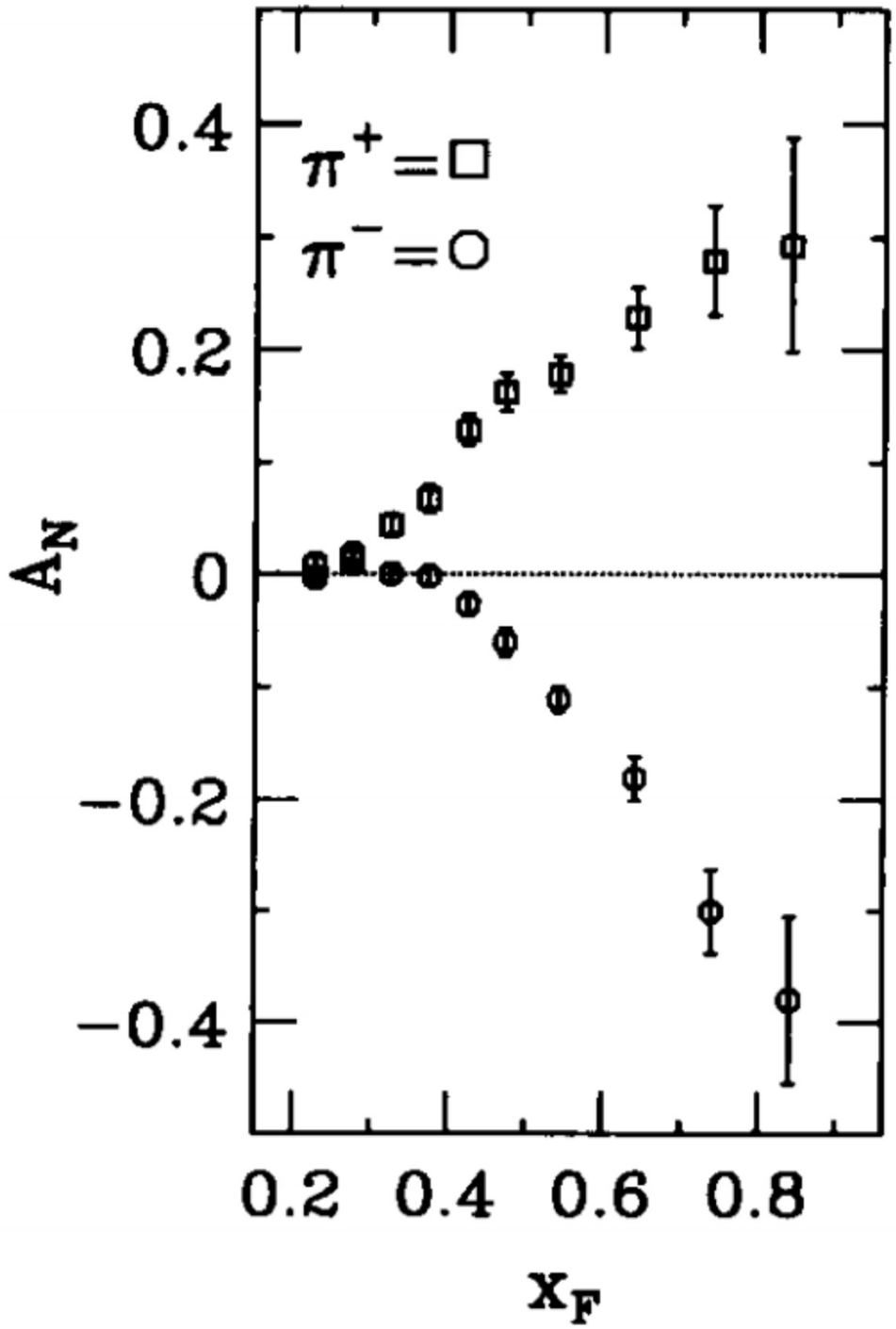
[K.-F. Liu et al arXiv:1203.6388]

Proton Spin Puzzle

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

Dennis Sivers proposed quark OAM as possible explanation of "**E-704 effect**":

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



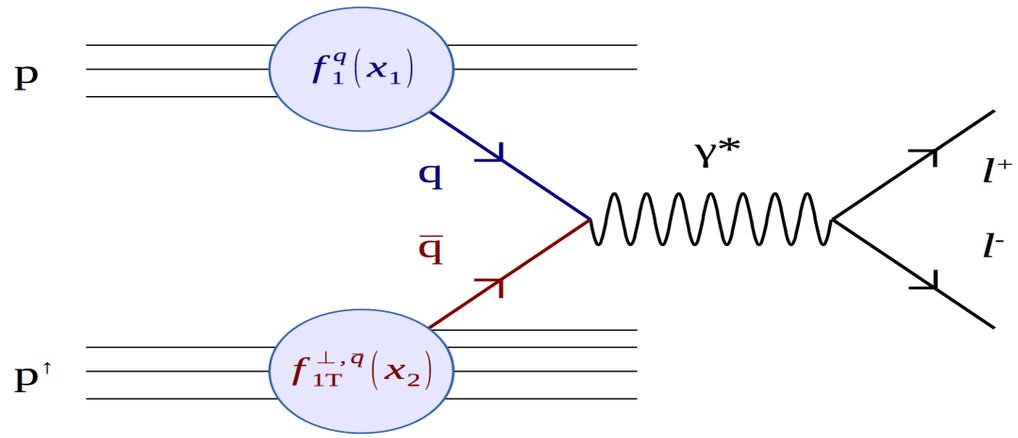
Two major predictions:

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

Polarized Drell-Yan @ SpinQuest

Measure Drell-Yan azimuthal asymmetry to extract sea quark Sivers:

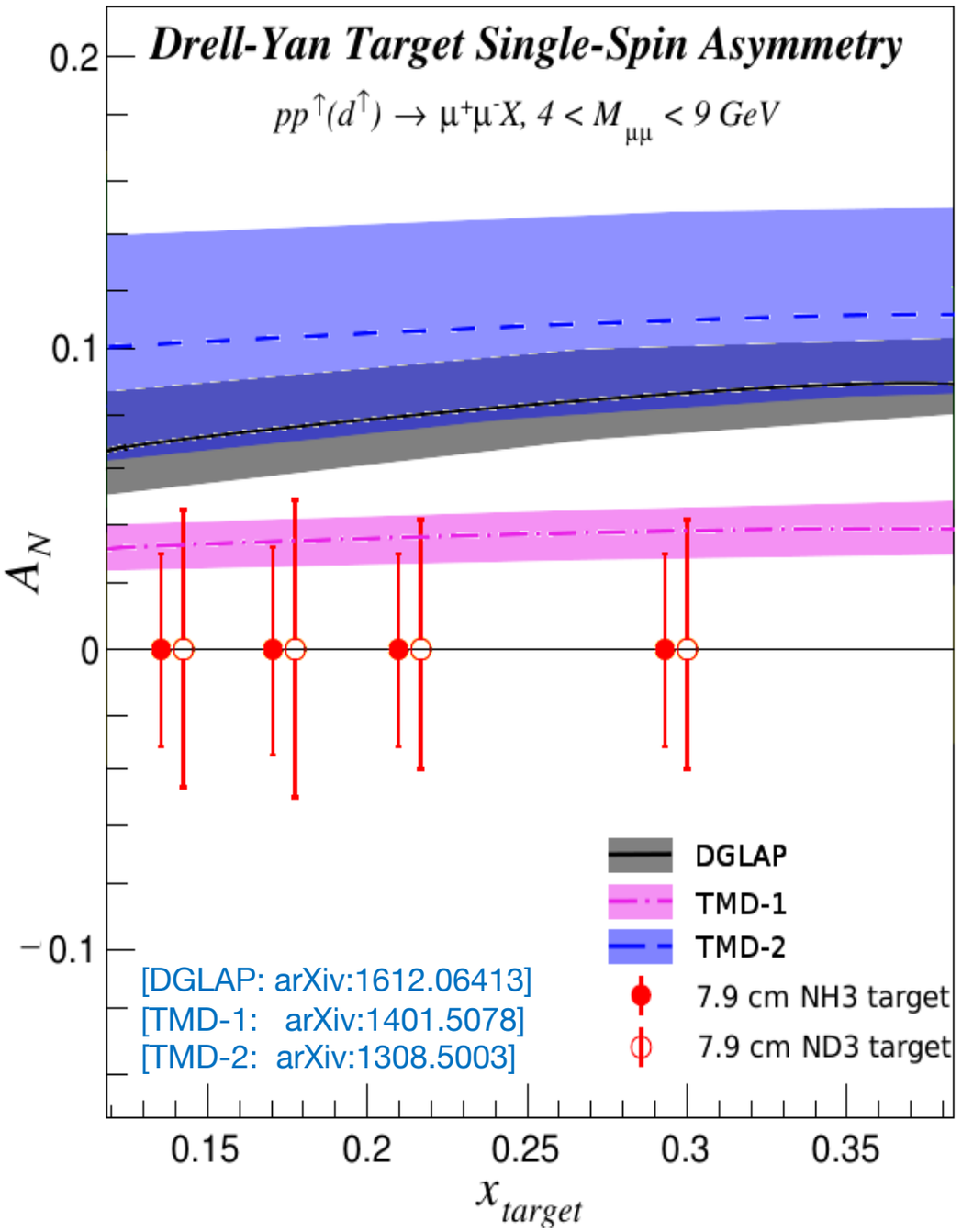
$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$



Two-year runtime:

- Add solid NH3 target, upstream for lower X_t
- Proton on target: 1.4 x 10^{18}

Anticipated Sensitivity



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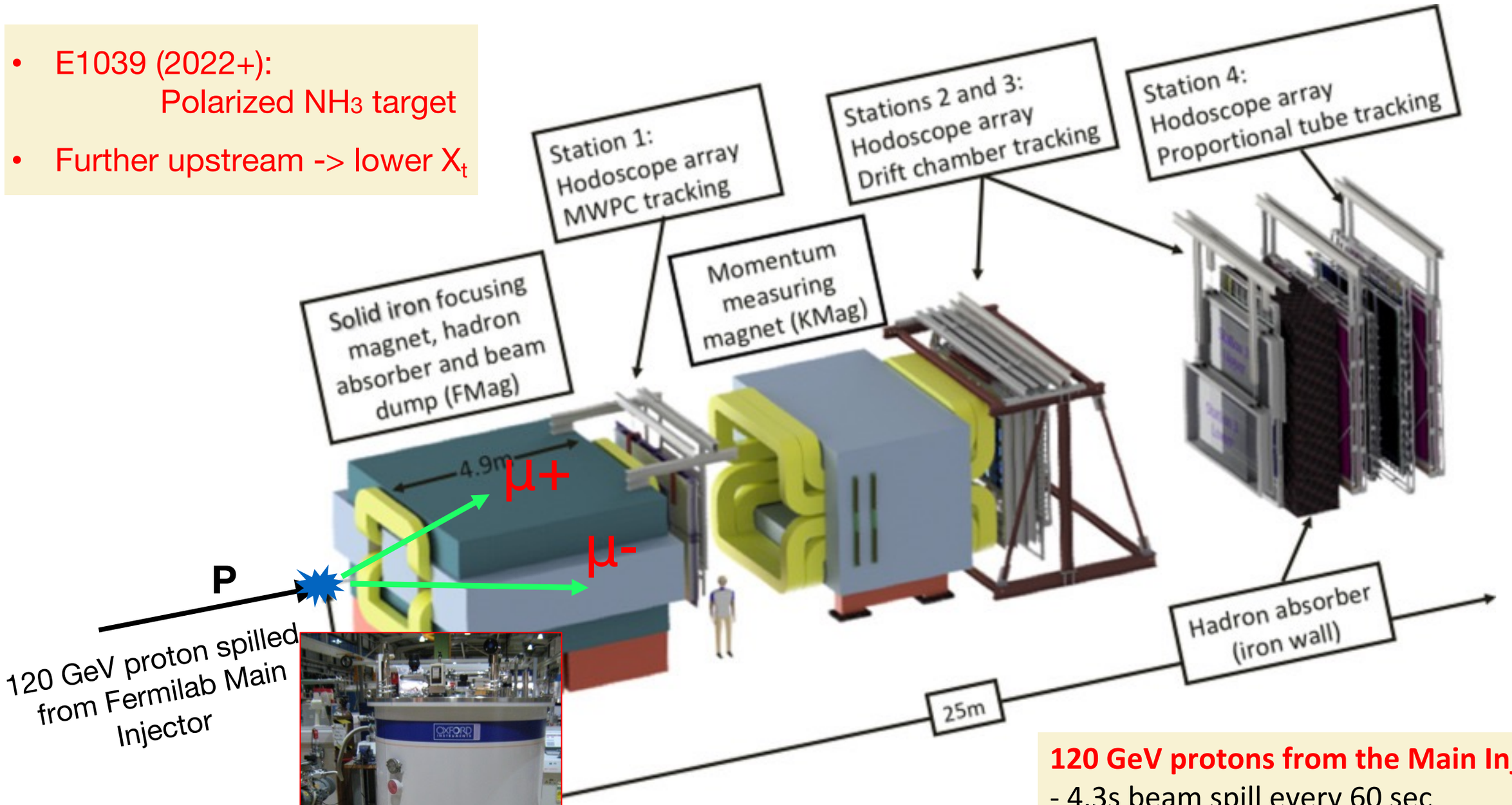

Polarized
NH_3 & ND_3 Targets

120 GeV protons from the Main Injector
- 4.3s beam spill every 60 sec
- 19ns RF, 100-100K p/RF bucket
- $5x10^{12}$ p/spill
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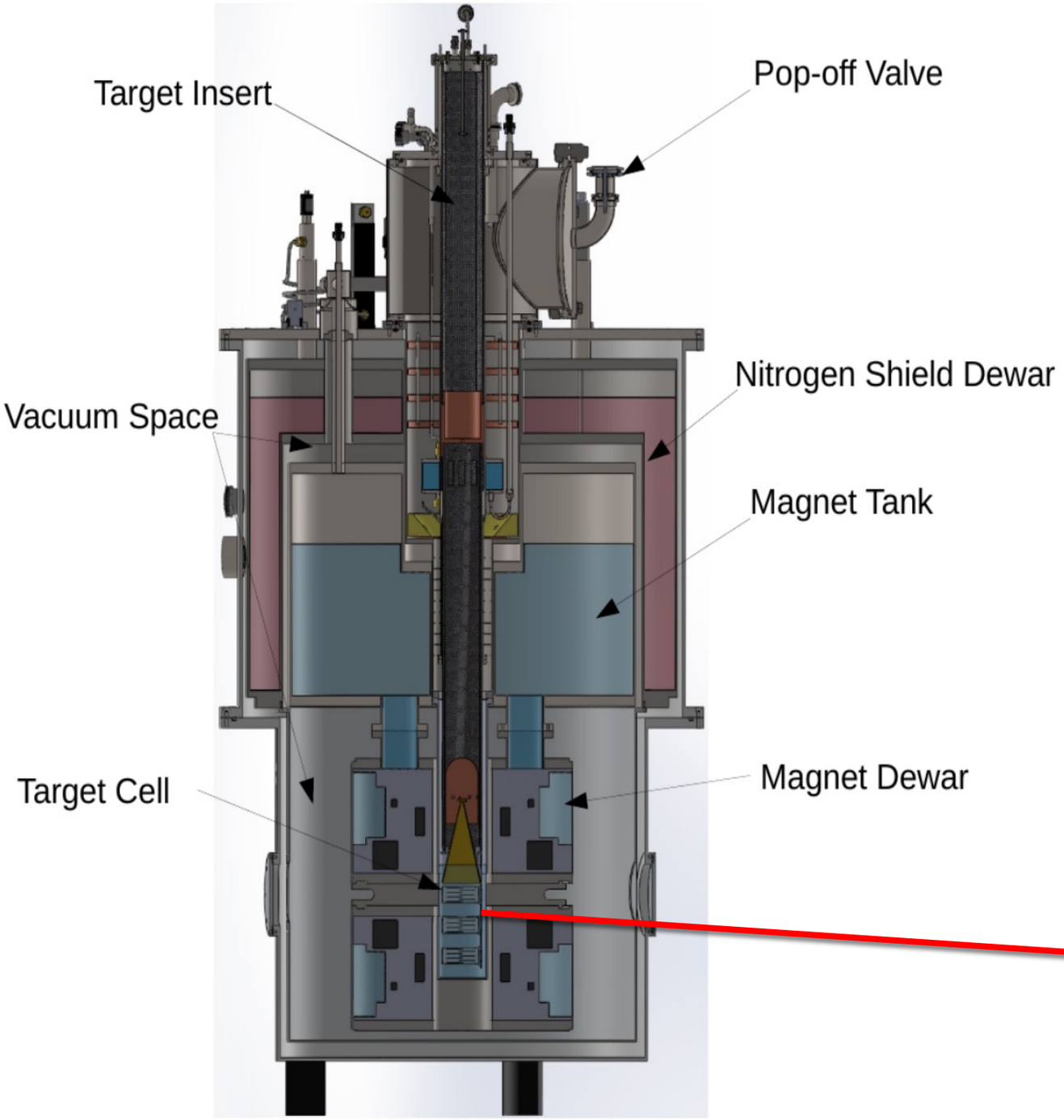
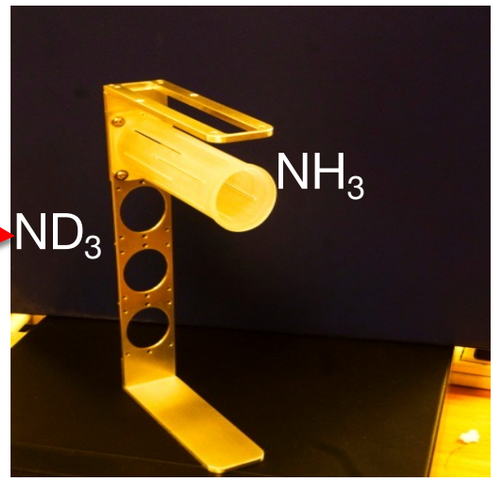
SpinQuest Target



- 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

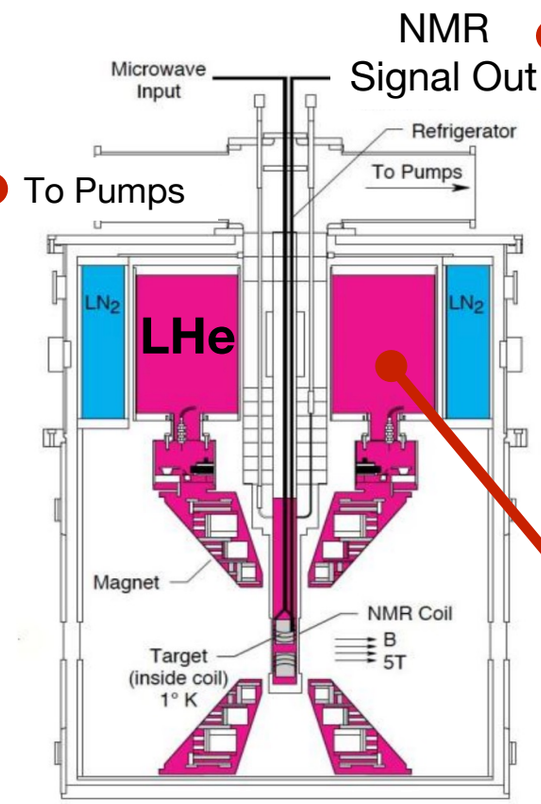
- NH_3, ND_3, and Background target.



SpinQuest Target Status

Target installation and full safety review will be completed within ~ 1 month

Target installed in cave with nearly complete connections to cryo-platform above



2018 UVA cooldown polarization data

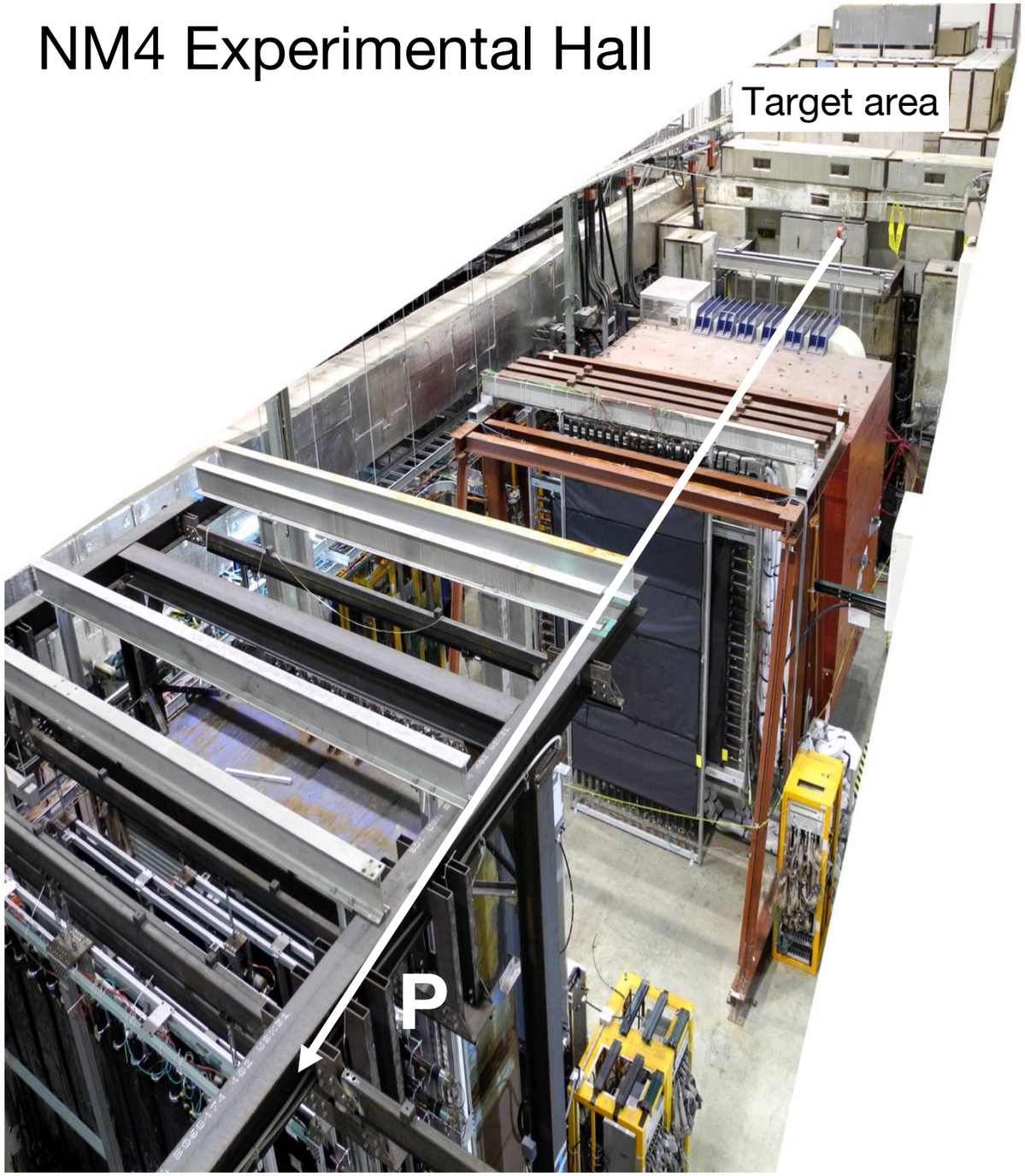
Cooldown at Fermilab next month

Quantum Technology Helium Recovery
200 L / day capacity – self sustaining

Target commissioning during summer shutdown, start data taking in late October / early November with protons

SpinQuest Experiment Status

NM4 Experimental Hall



- DOE approval and Fermilab stage 2 approval in 2018
- E1039 installation began in Fall 2019, commissioning and data taking starts Fall 2022
- Detector has been taking cosmic data for last several months
- Tracking detectors in (nearly) final configuration
- Trigger and DAQ system read out successfully stress tested
- Online reconstruction running on cosmics

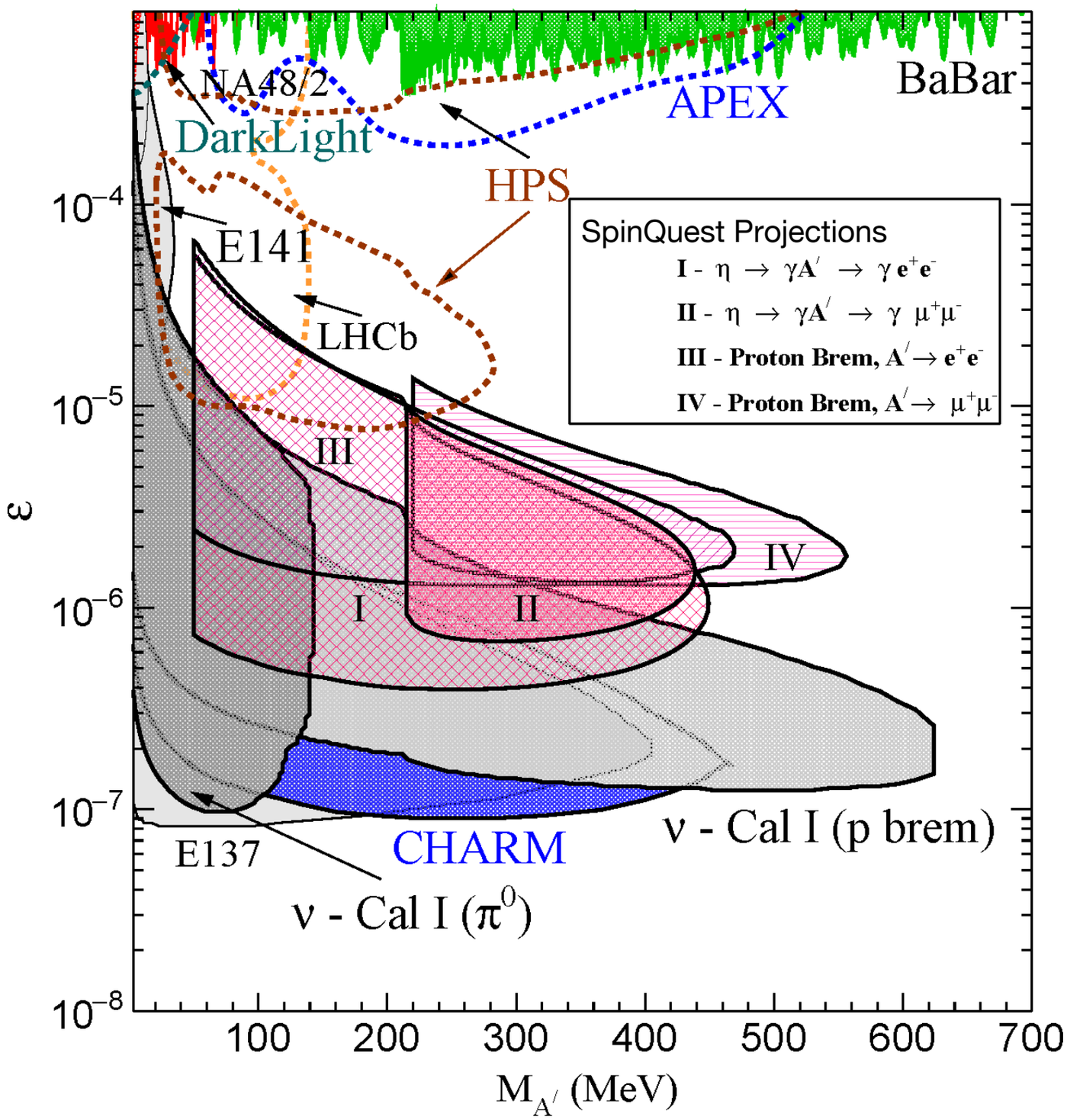
SpinQuest Plans

- SpinQuest will run for 2 years, beginning this fall, alternating NH_3, ND_3 and background subtraction targets.
- Projected Statistical uncertainty ~ 3-5%.

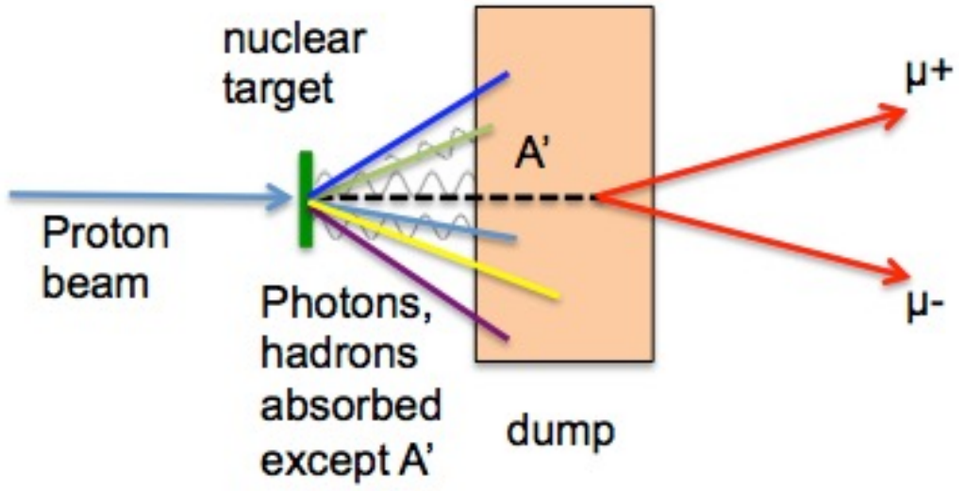
Range x_2	Mean x_2	N events p	ΔA % p	N events n	ΔA % n
0.1-0.16	.139	5.0×10^4	3.2	5.8×10^4	5.4
0.16-0.19	0.175	4.5×10^4	3.3	5.2×10^4	5.7
0.19-0.24	0.213	5.7×10^4	2.0	6.6×10^4	5.0
0.24-0.6	0.295	5.5×10^4	3.0	6.4×10^4	5.1

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

SpinQuest & Dark Photons



Classic Beam Dump Experiment:



$$l_o \approx \frac{0.8\,cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$

[J. D. Bjorken et al, PRD **80** (2009) 075018]

SeaQuest experimental parameters:

- E_0 = 5 - 110 GeV for Proton Bremsstrahlung
- N_{eff} = 2
- l_0 = 0.17m – 5.95m

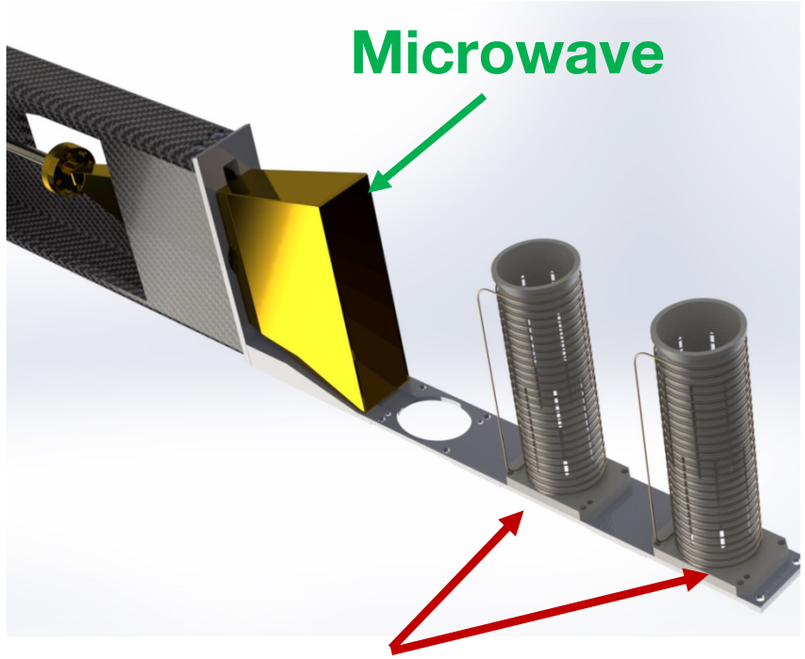
SpinQuest & Future Transversity Studies

First ever Spin-1 TMD measurements with Vector/ Tensor Polarized Deuteron target

$$A_{UT}^{\sin(\varphi_{cs}+\varphi_s)\frac{q_T}{M_N}}\Big|_{pD^\uparrow\to l^+l^-X} \simeq$$

Vector Polarized

$$-\frac{\left[4h_{1u}^{\perp(1)}(x_p)+h_{1d}^{\perp(1)}(x_p)\right]\left[\bar{h}_{1u}(x_{D^\uparrow})+\bar{h}_{1d}(x_{D^\uparrow})\right]}{\left[4f_{1u}(x_p)+f_{1d}(x_p)\right]\left[\bar{f}_{1u}(x_{D^\uparrow})+\bar{f}_{1d}(x_{D^\uparrow})\right]}$$



- Directly access sea quark transversity by vector polarization in transverse direction.
- Utilize vector + tensor polarization to isolate linearly polarized gluons in deuteron.

[arXiv:2008.09515v1]

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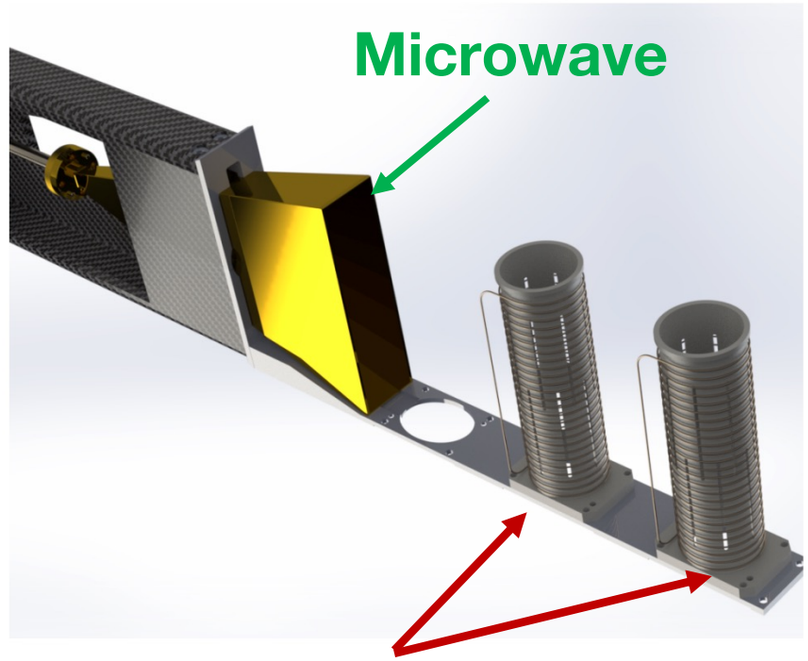
BM constrained by unpolarized DY- E906

Vector Polarized

$$-\frac{\left[4h_{1u}^{\perp(1)}(x_p)+h_{1d}^{\perp(1)}(x_p)\right]\left[\bar{h}_{1u}(x_{D^\uparrow})+\bar{h}_{1d}(x_{D^\uparrow})\right]}{\left[4f_{1u}(x_p)+f_{1d}(x_p)\right]\left[\bar{f}_{1u}(x_{D^\uparrow})+\bar{f}_{1d}(x_{D^\uparrow})\right]}$$



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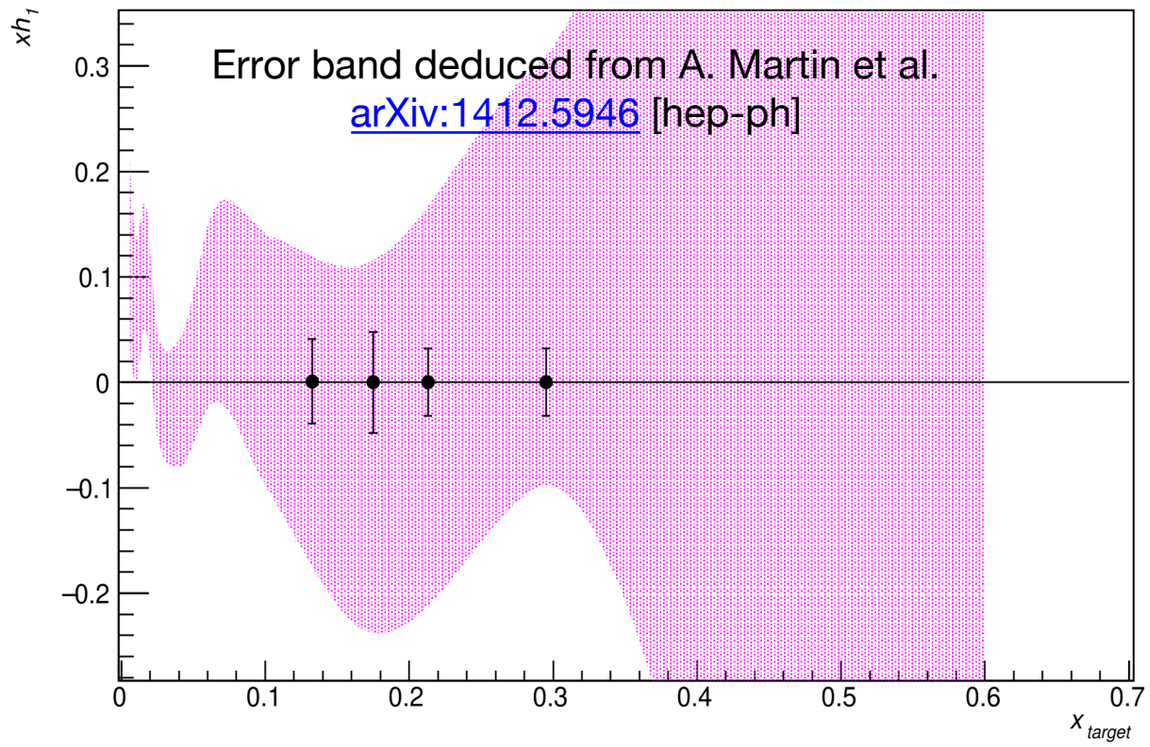
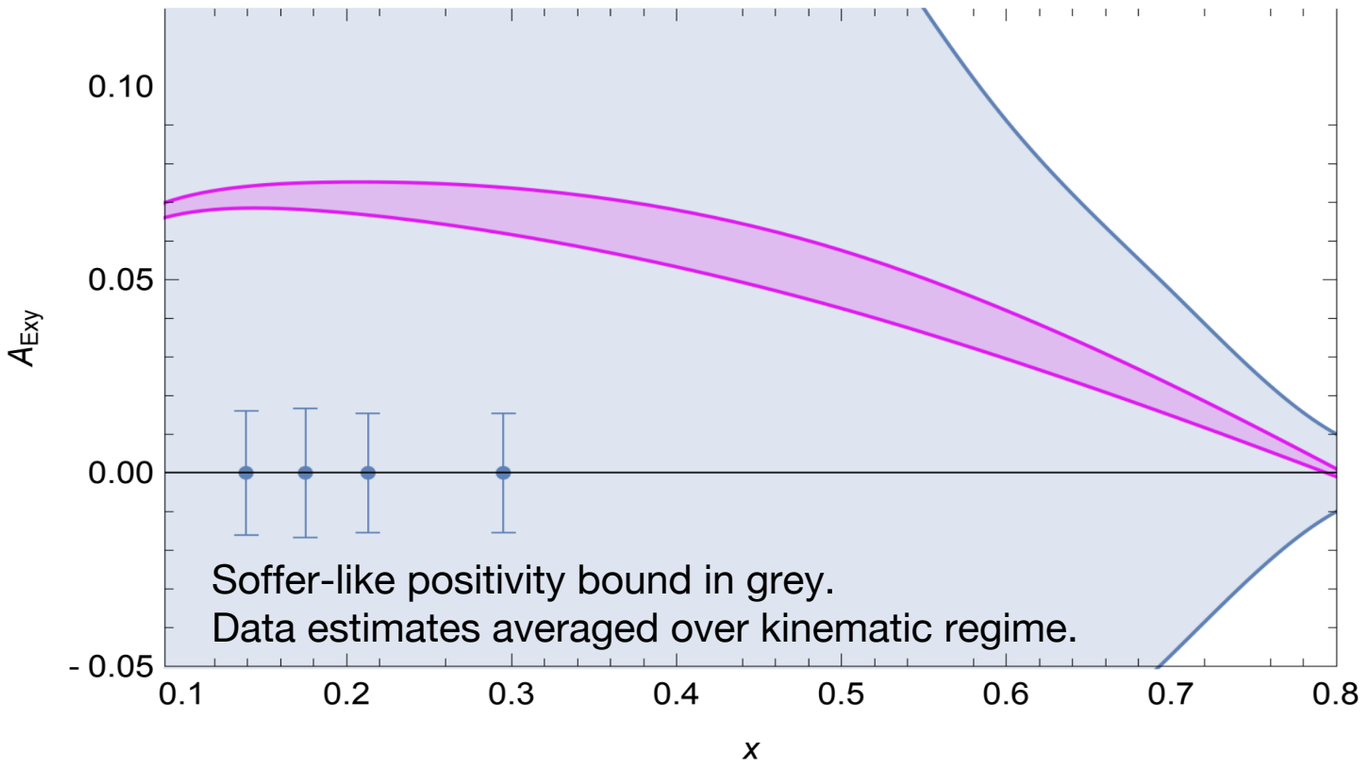
SpinQuest & Future Transversity Studies

Anticipated seaquark transversity sensitivity



Anticipated Spin-1 linearly polarized gluon asymmetry sensitivity



Fermilab advantages:

- High luminosity from main injector
- Large x-coverage
- High intensity beam with time (55s) between spills to change target polarization

Contact:

Dustin Keller (UVA) – dustin@virigina.edu

More Info:

D. Keller arXiv:2205.01249 [nucl-ex]

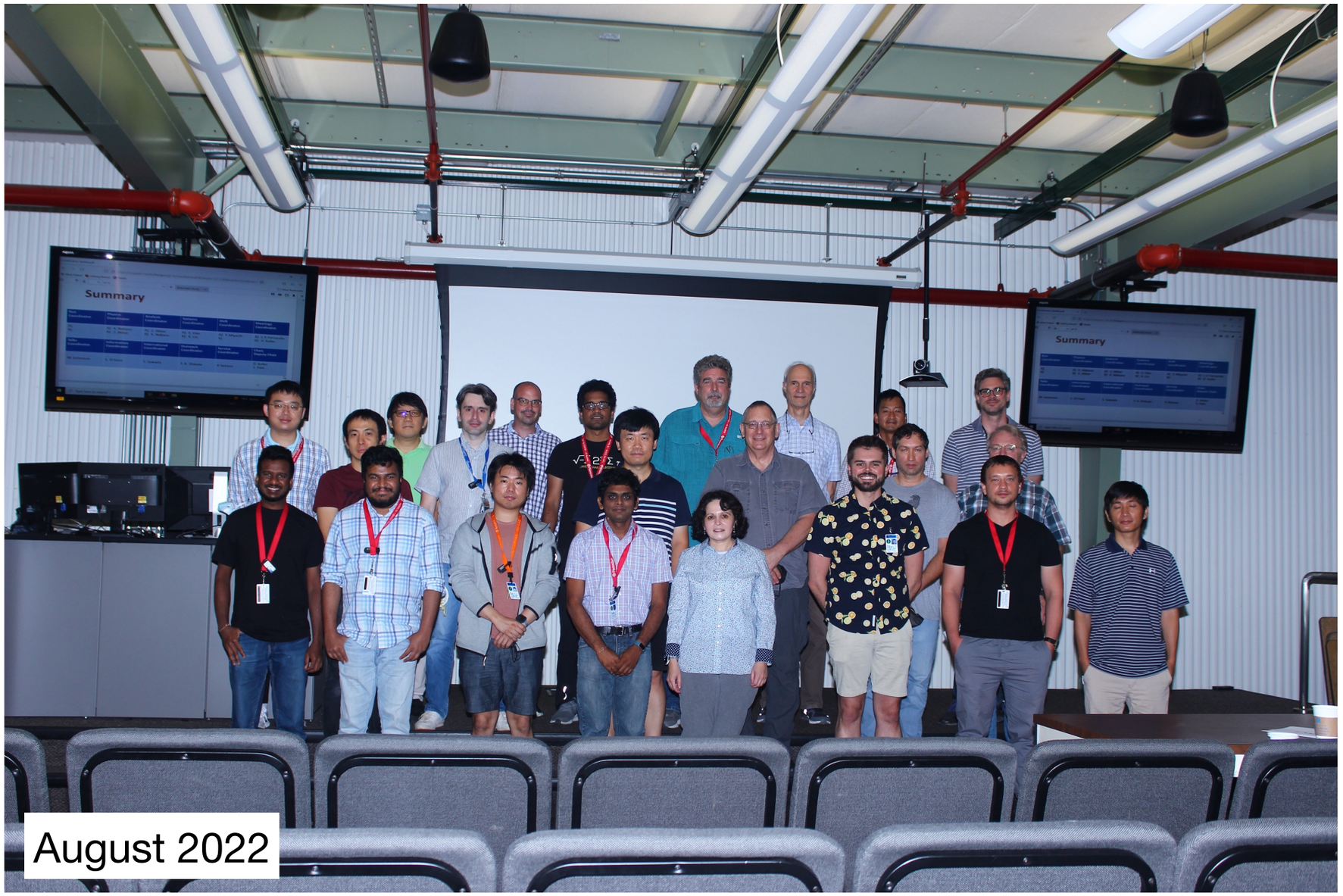
SpinQuest/E1039 Collaboration

- Relatively small collaboration
  - → 36 full members, 76 affiliate members
  - → 14 institutions and Fermilab

Abilene Christian University
Argonne National Laboratory
KEK
Los Alamos National Laboratory
Mississippi State University
New Mexico State University
RIKEN
Tokyo Institute of Technology
University of Colorado, Boulder
University of Illinois, Urbana-Champaign
University of Michigan
University of New Hampshire
University of Virginia
Yamagata University

- US collaborators supported by NSF and DOE Medium Energy

SpinQuest/E1039 Collaboration



Contact Spokespersons:

Kun Liu (liuk@fnal.gov) - LANL
Dustin Keller (dustin@jlab.org) - UVA

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

Thank you!