Fixed Target Drell-Yan at SpinQuest

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(On behalf of the SpinQuest Collaboration)
University of Michigan
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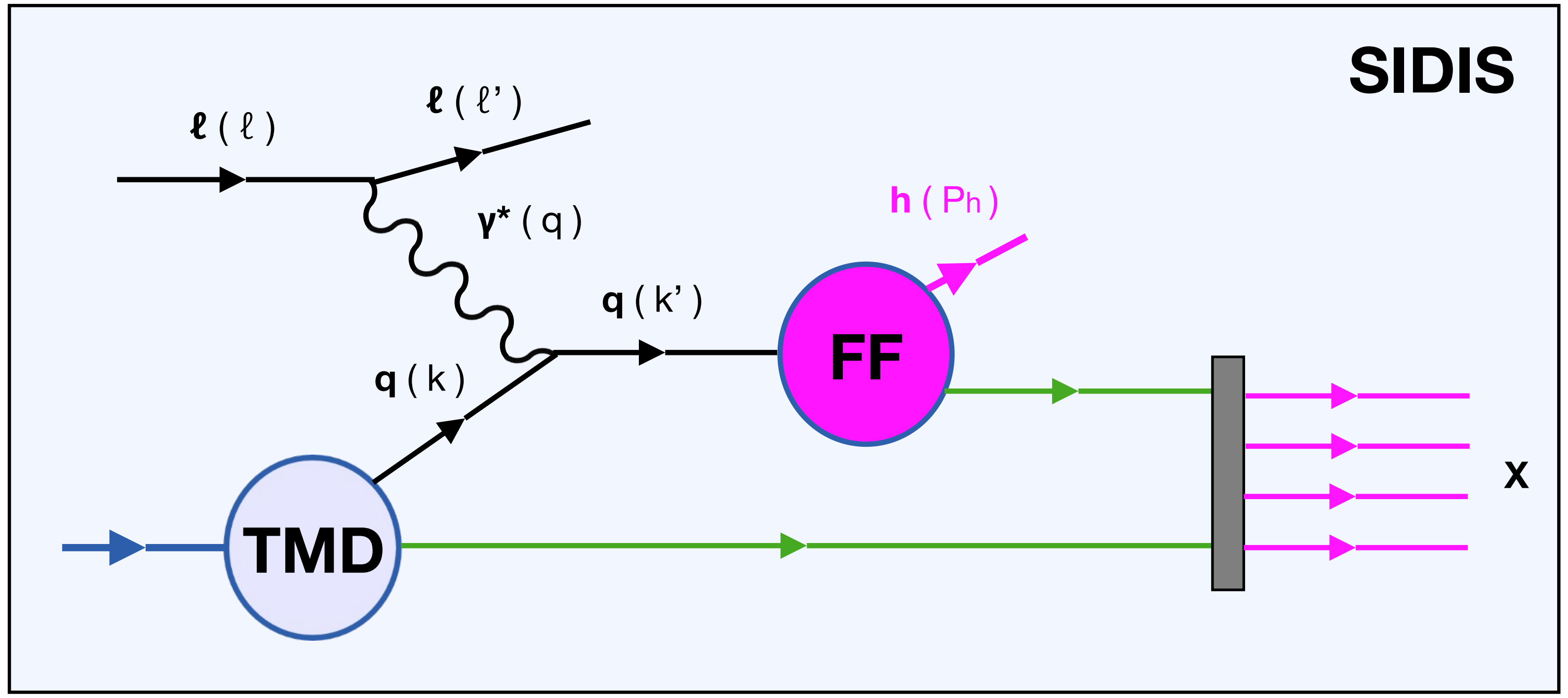
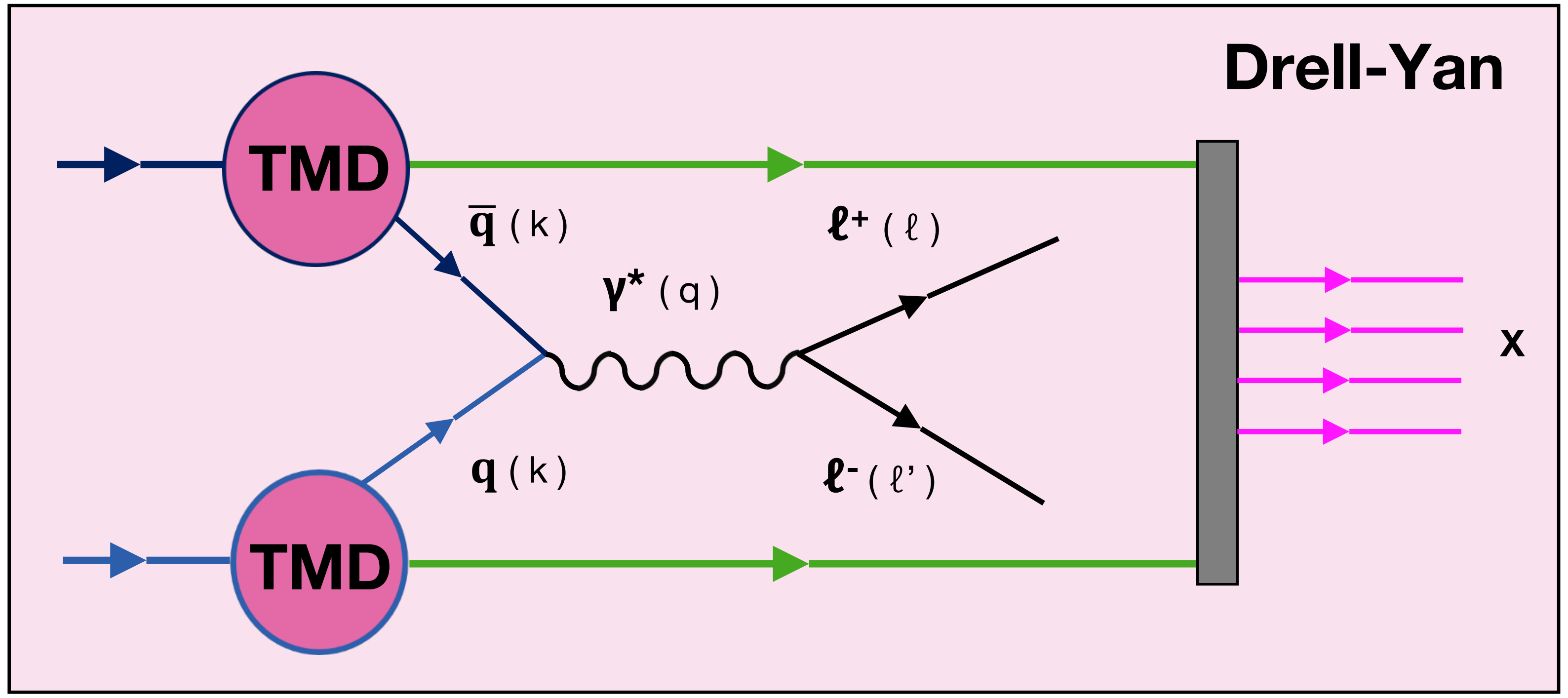
UNIVERSITY OF MICHIGAN
NSF

Probing Hadrons

1. Want to understand parton interactions/ properties.
2. Connect their dynamics with hadron properties.





- 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 Sections

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + S_T\left[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\right]\right\}$$

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

SIDIS

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

Drell-Yan $\pi N^{\uparrow}$

credit: B. Parsamyan

TMD $\otimes$ **FF**

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

TMD $\otimes$ **TMD**

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

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

Leading Order Cross Sections

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + S_T\left[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\right]\right\}$$

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$A_{UT}^{\sin(\phi_h+\phi_S)}$	$\propto h_1^{q}\otimes H_{1q}^{\perp h}$	Pretz	⊗	CF

TMD ⊗ **TMD**

E-906
E-1039

$A_U^{\cos 2\varphi_{CS}}$	$\propto h_1^{\perp q}\otimes h_1^{\perp q}$	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
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$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS}\,,\quad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

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 at SeaQuest

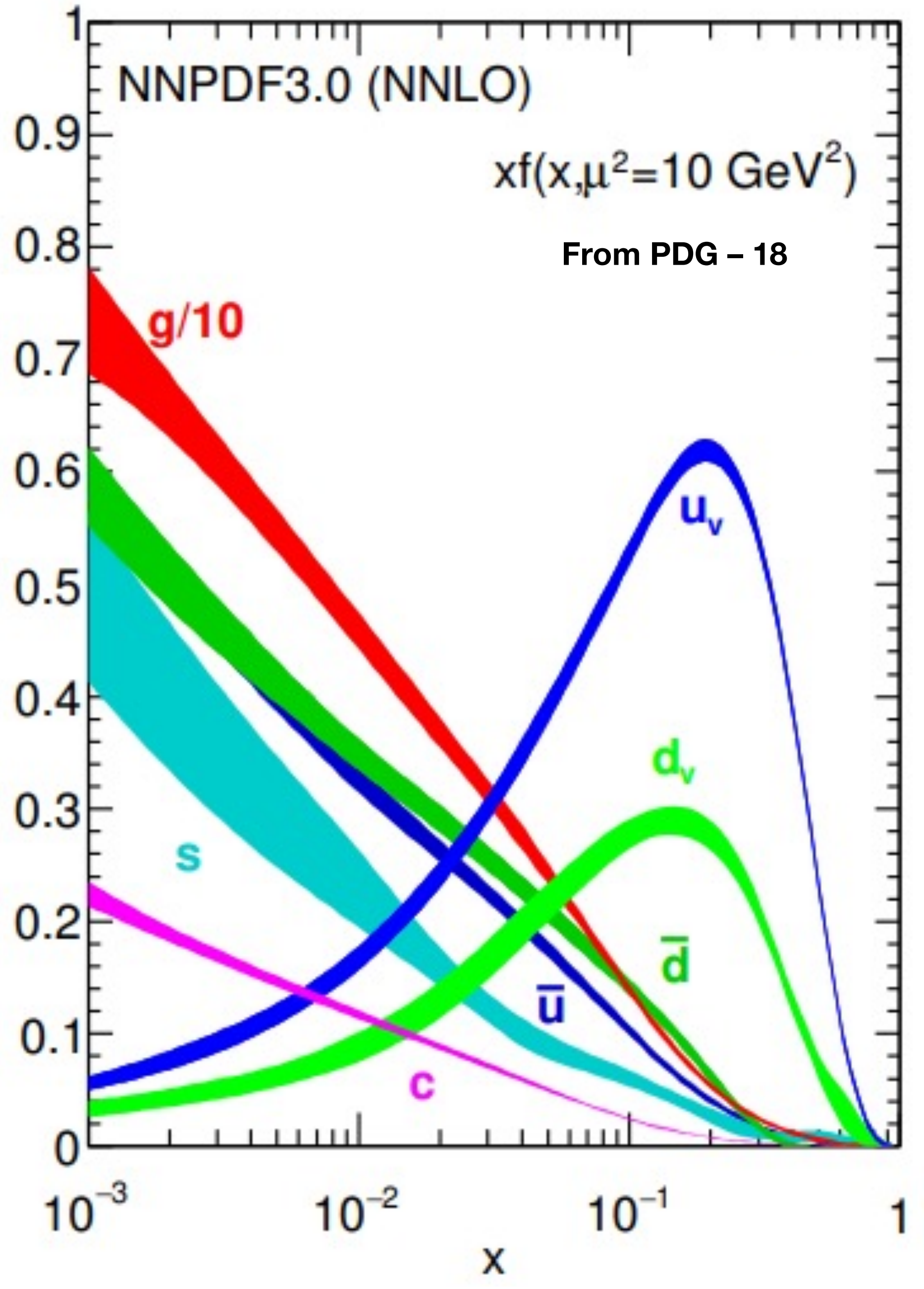
Measure antimatter asymmetry in proton with cross section ratio:

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

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

"Choose" antiquark in target

Small for SeaQuest acceptance



Unpolarized PDF

Unpolarized Drell-Yan at SeaQuest

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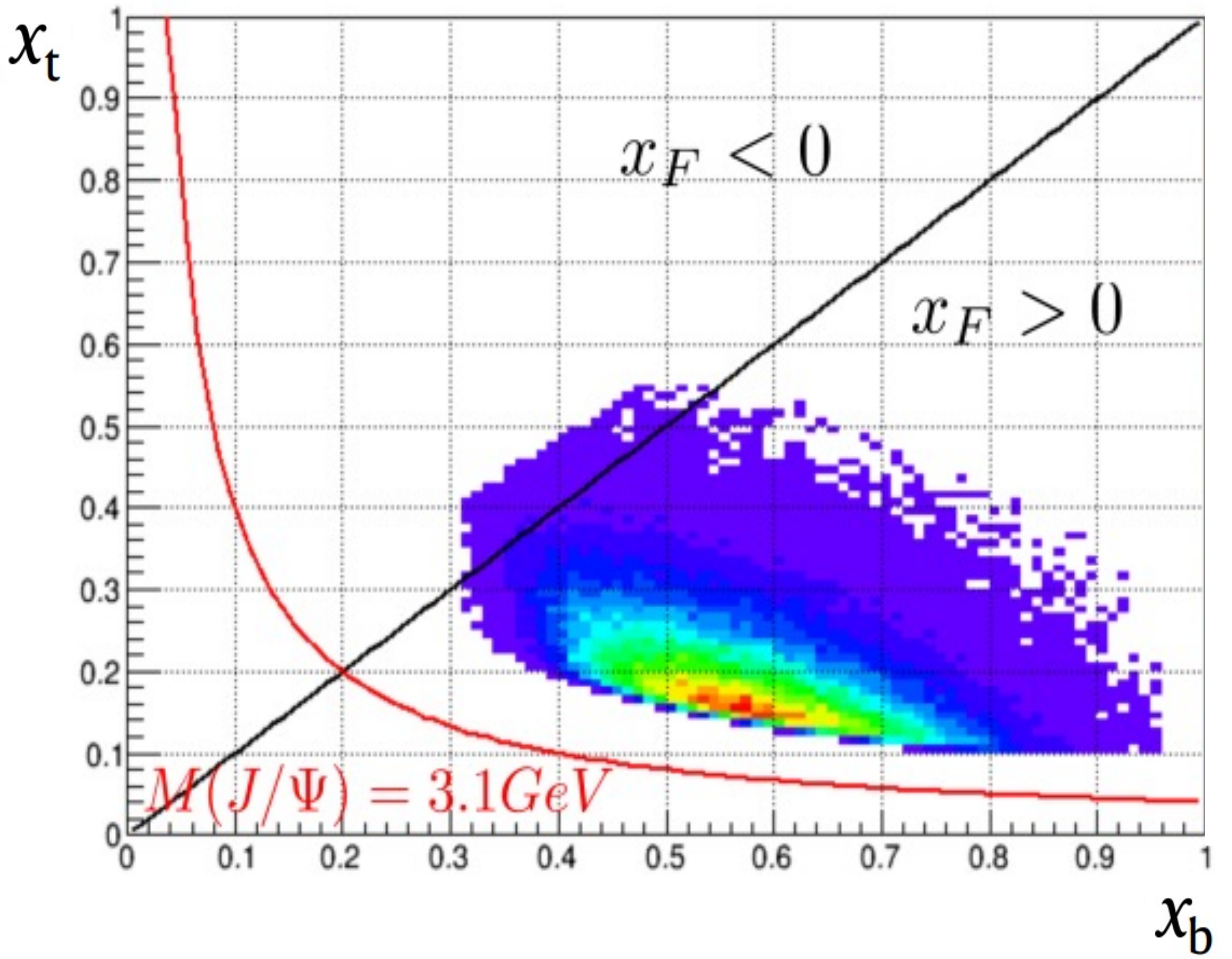


MC Acceptance of SeaQuest Spectrometer

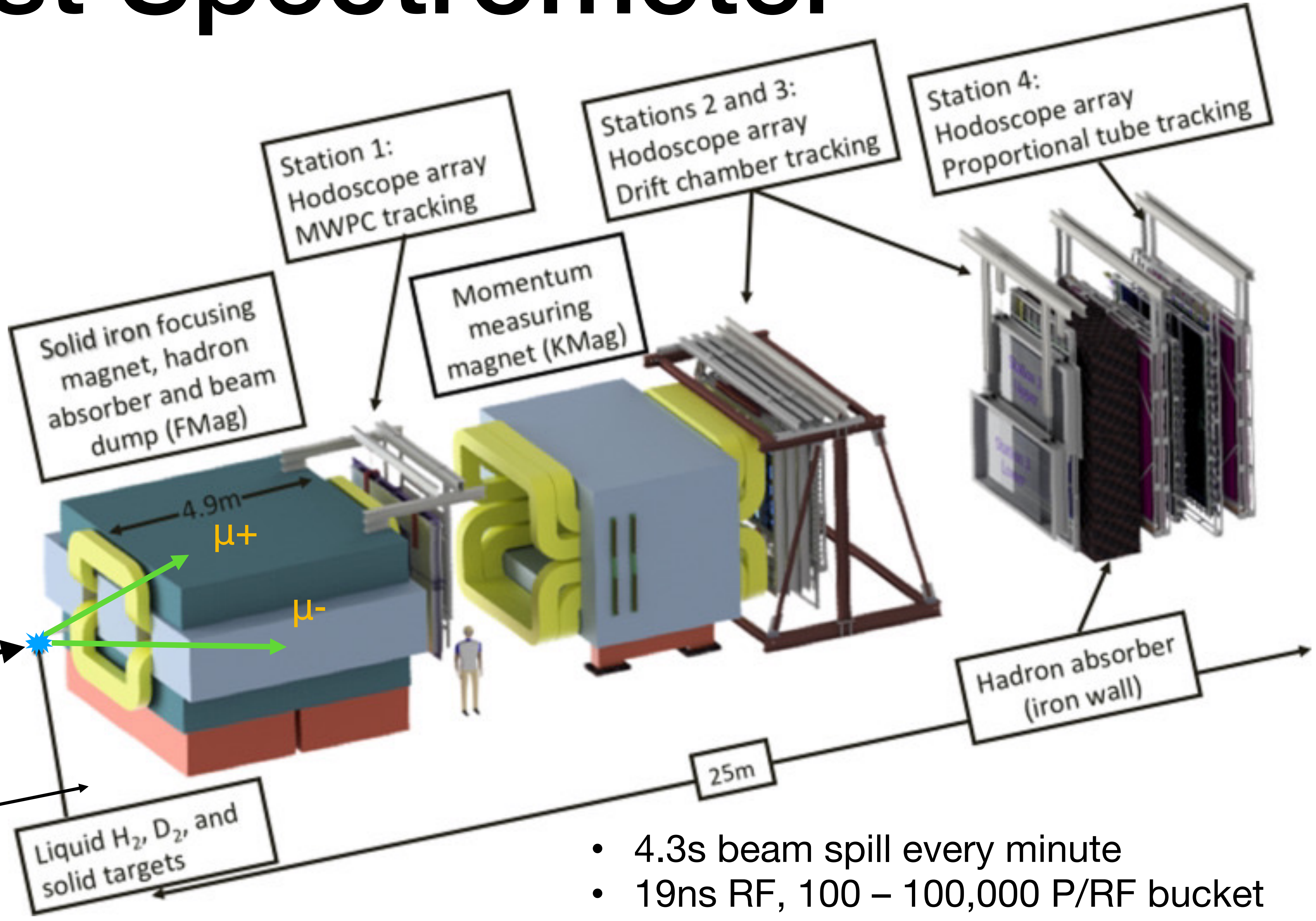
SeaQuest Spectrometer

120 GeV proton spilled
from Fermilab Main Injector

P

E1039 (2022+):
Polarized NH_3 target

Further upstream -> lower X_t



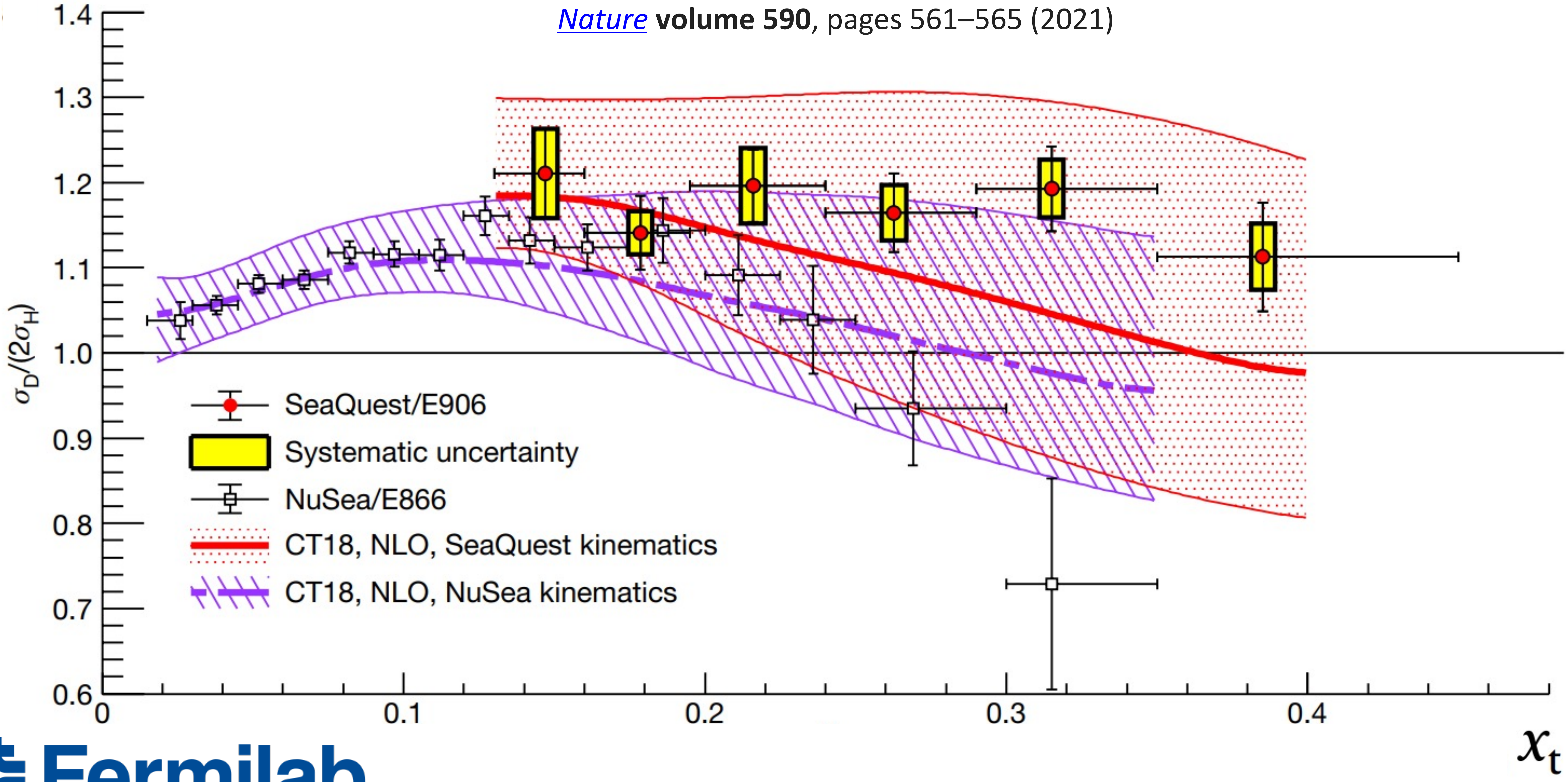
- 4.3s beam spill every minute
- 19ns RF, 100 – 100,000 P/RF bucket
- 5 x 10^{12} P/spill
- Integrated POT for 2 years: 1.4 x 10^{18} POT

SeaQuest Results

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

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

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



Fermilab

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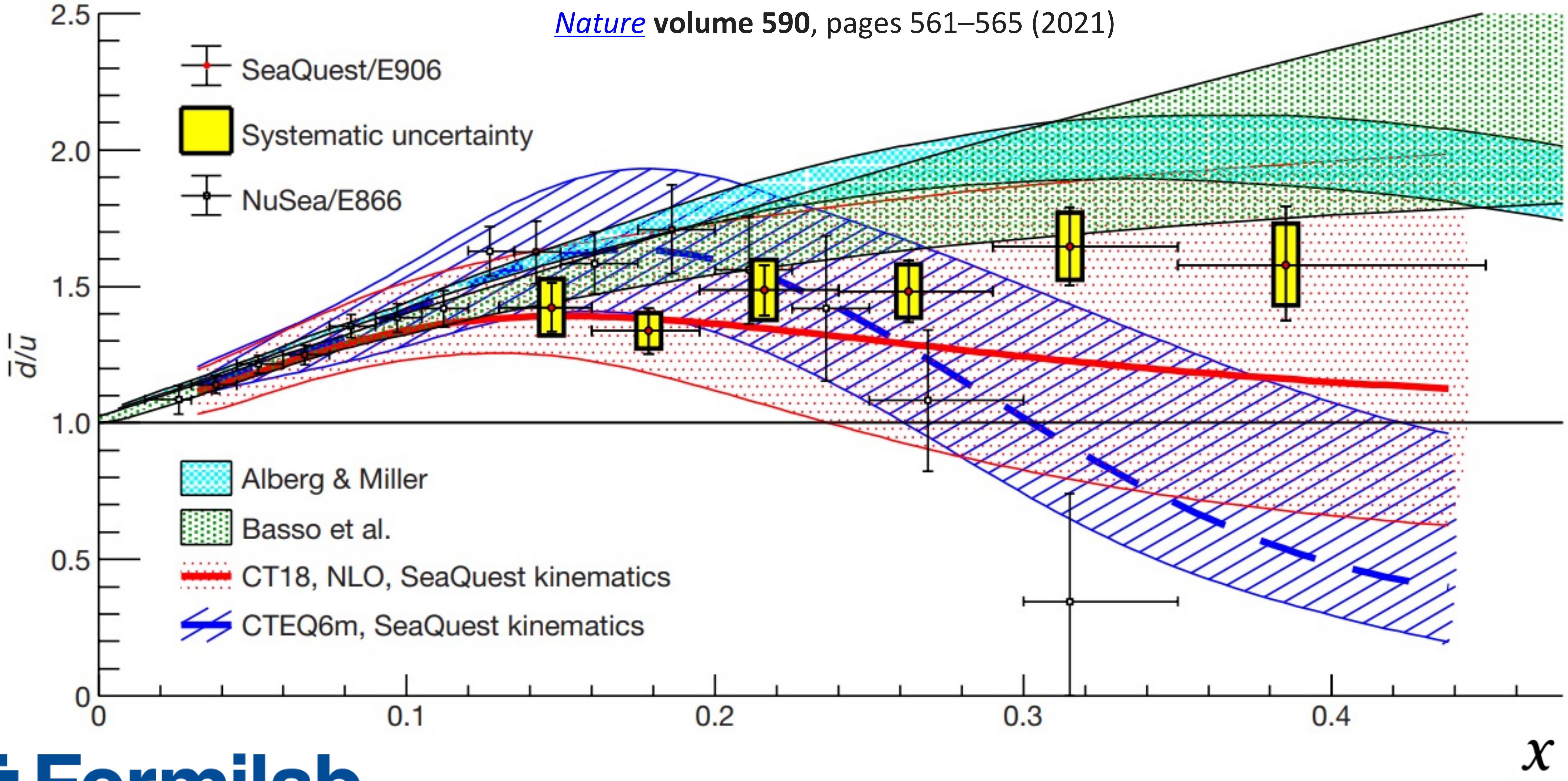


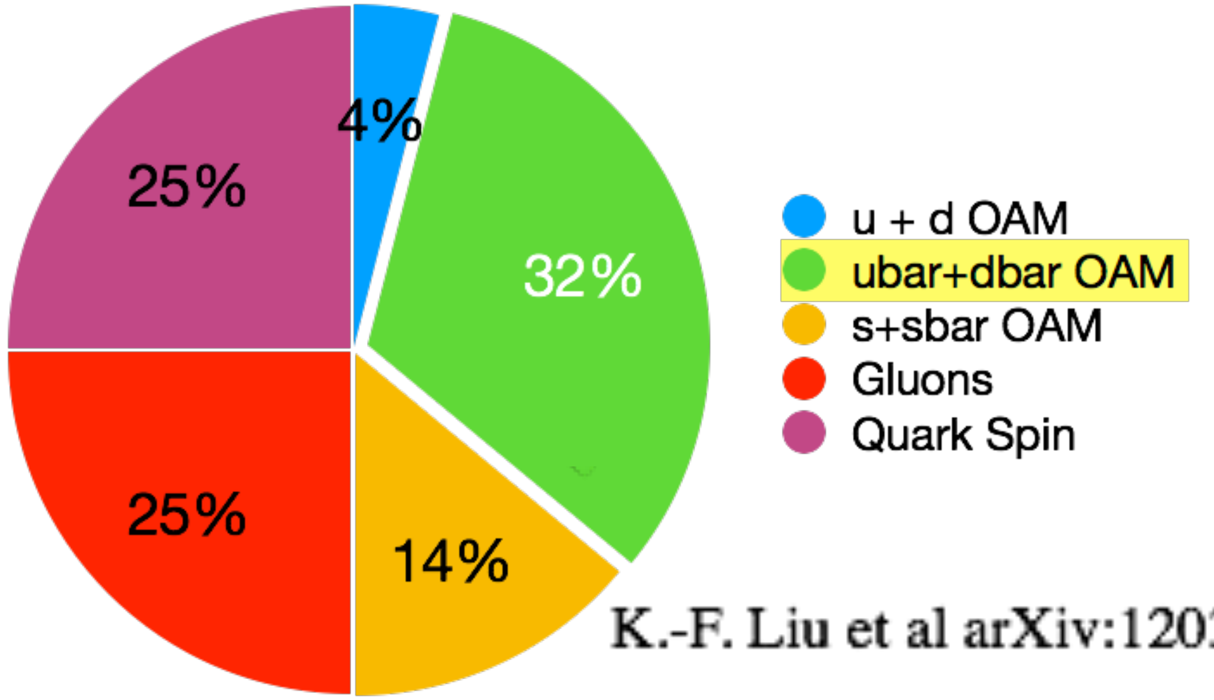
Fermilab

Proton Spin Puzzle

EMC longitudinally polarized DIS concludes:

> Hence $(14 \pm 9 \pm 21)\%$ of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum

Lattice QCD suggests link between antiquark OAM and nucleon spin:

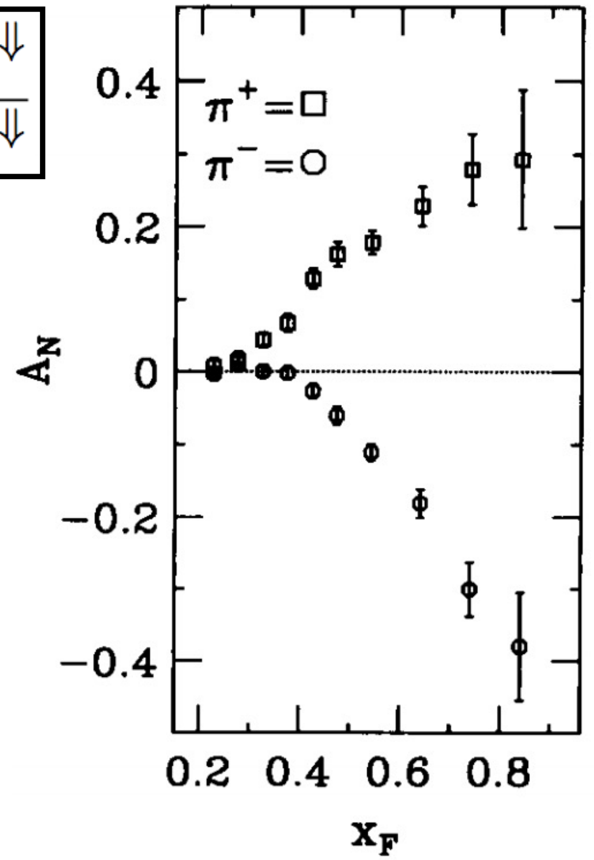


K.-F. Liu et al arXiv:1203.6388

Sivers proposed quark OAM as possible source of large Analyzing Power observed in E704 :

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

Link between quark OAM and proton spin



Phys. Lett. B 264, 462 (1991)

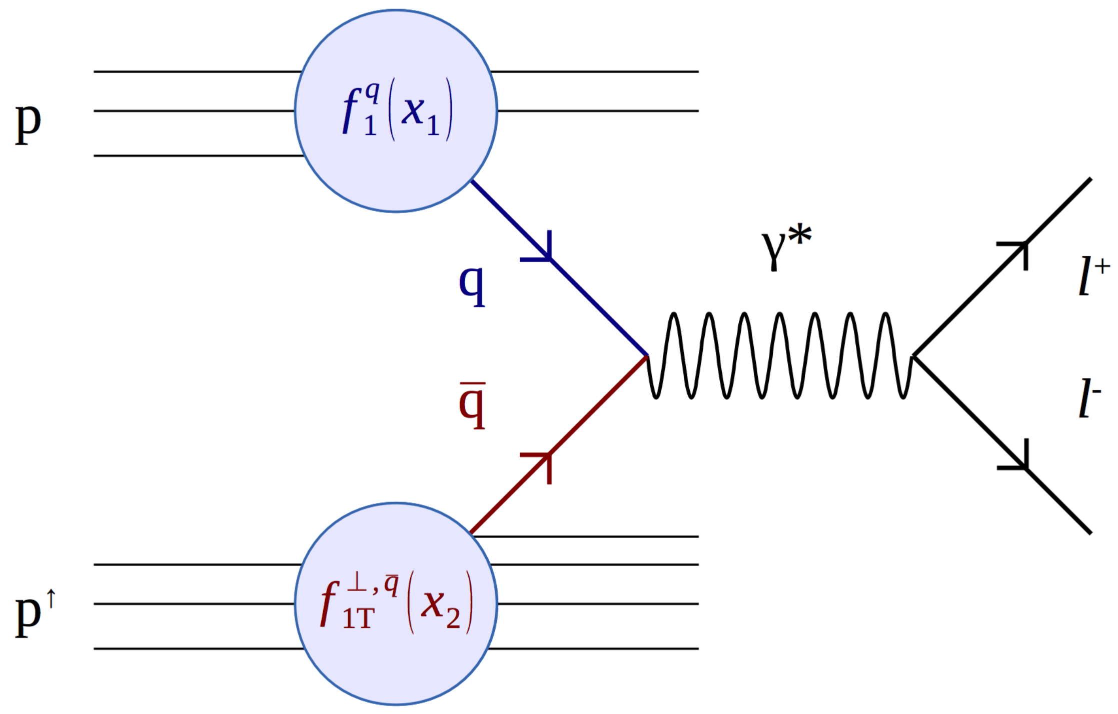
Two major predictions:

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

Polarized Drell-Yan at SpinQuest

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

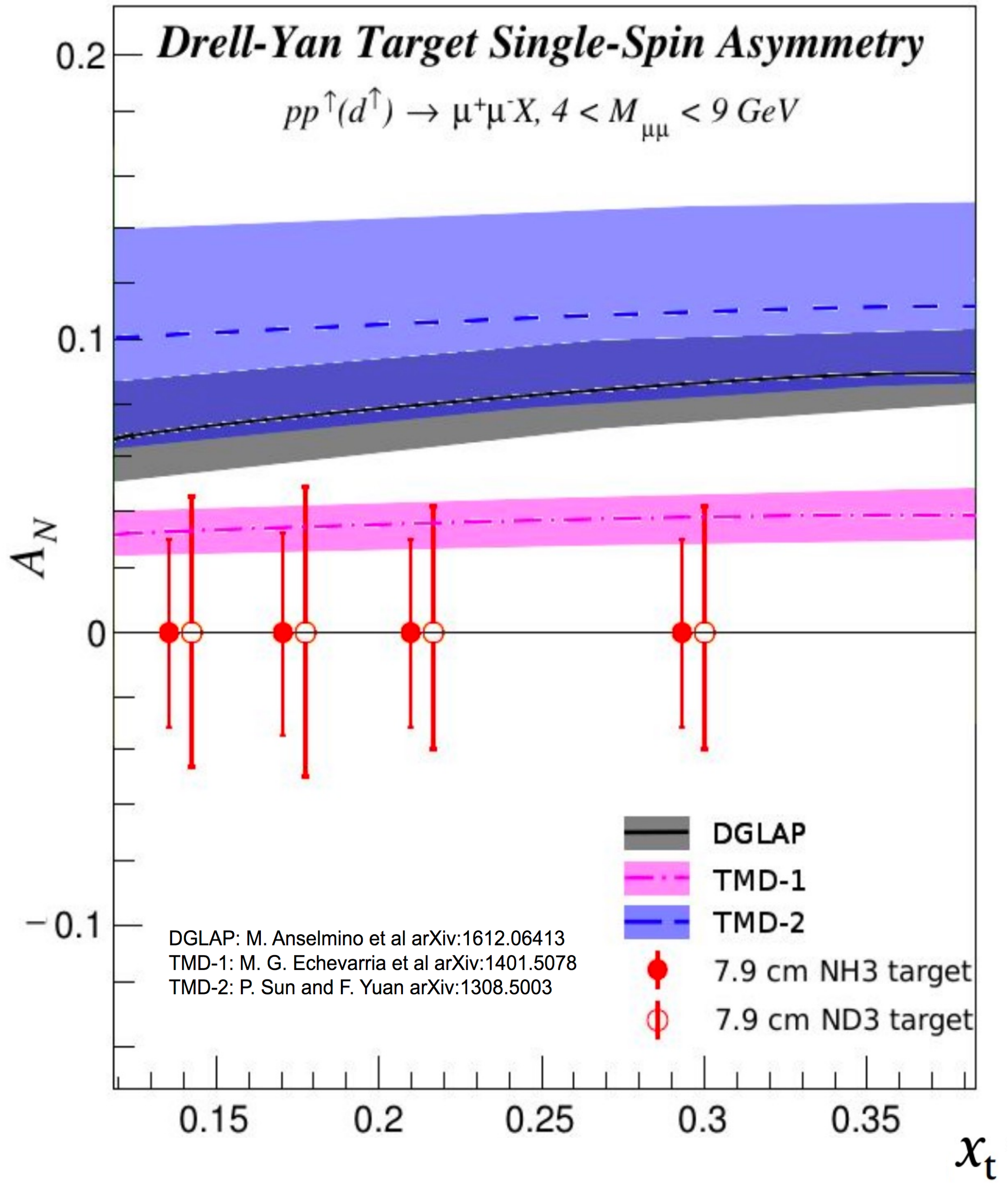
$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}$$



Two-year runtime-

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

Anticipated Sensitivity

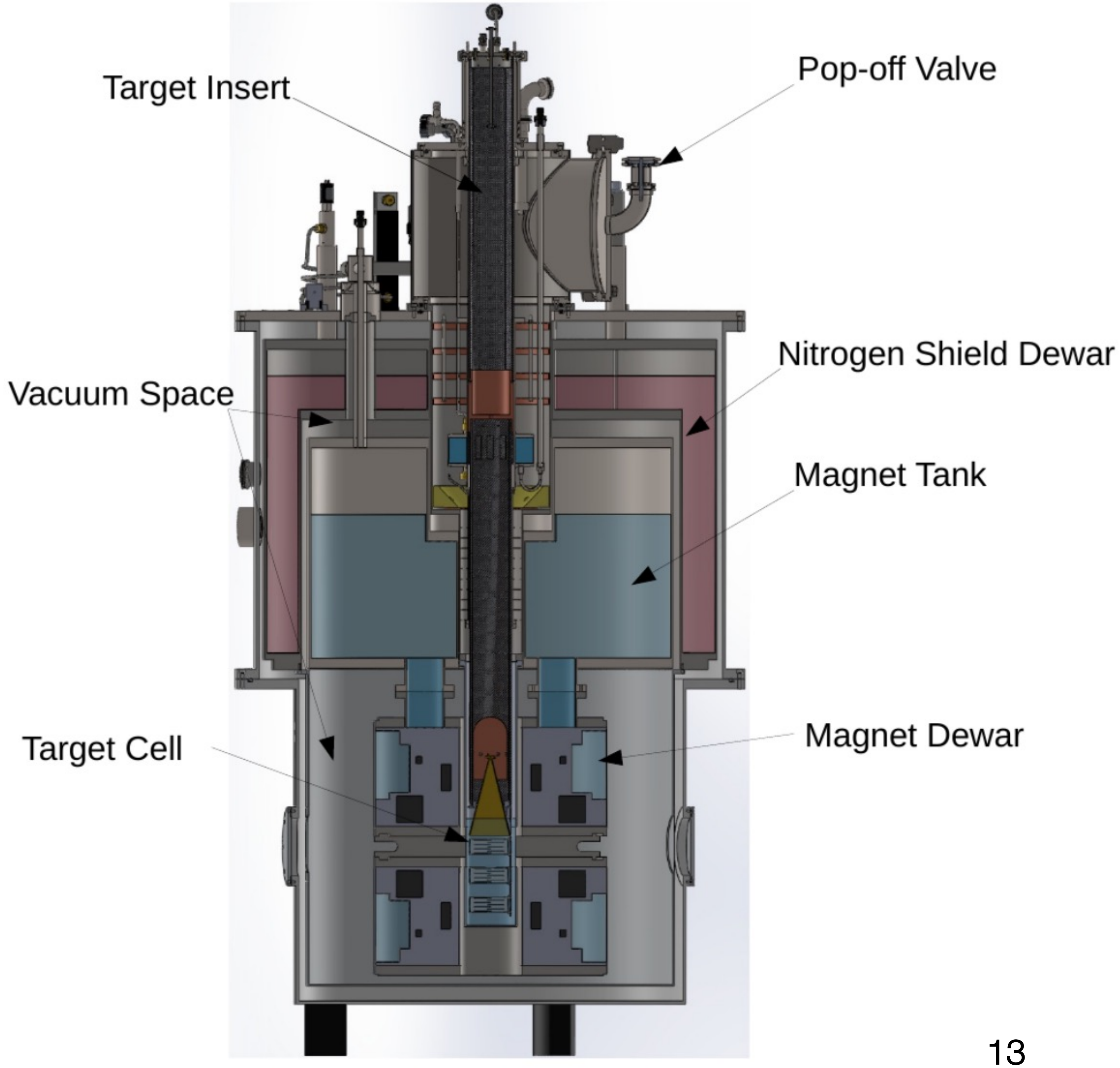


SpinQuest Target

- 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

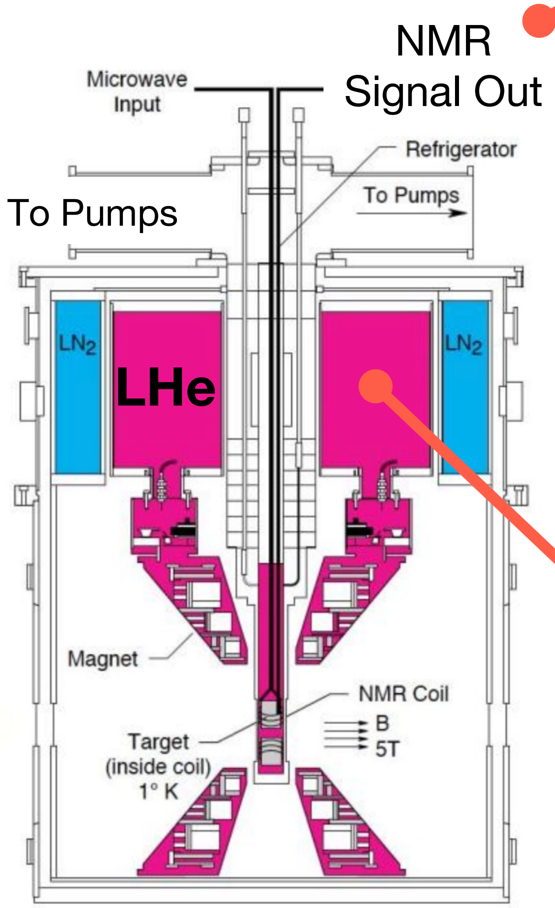
- NH_3, ND_3, and Background target.

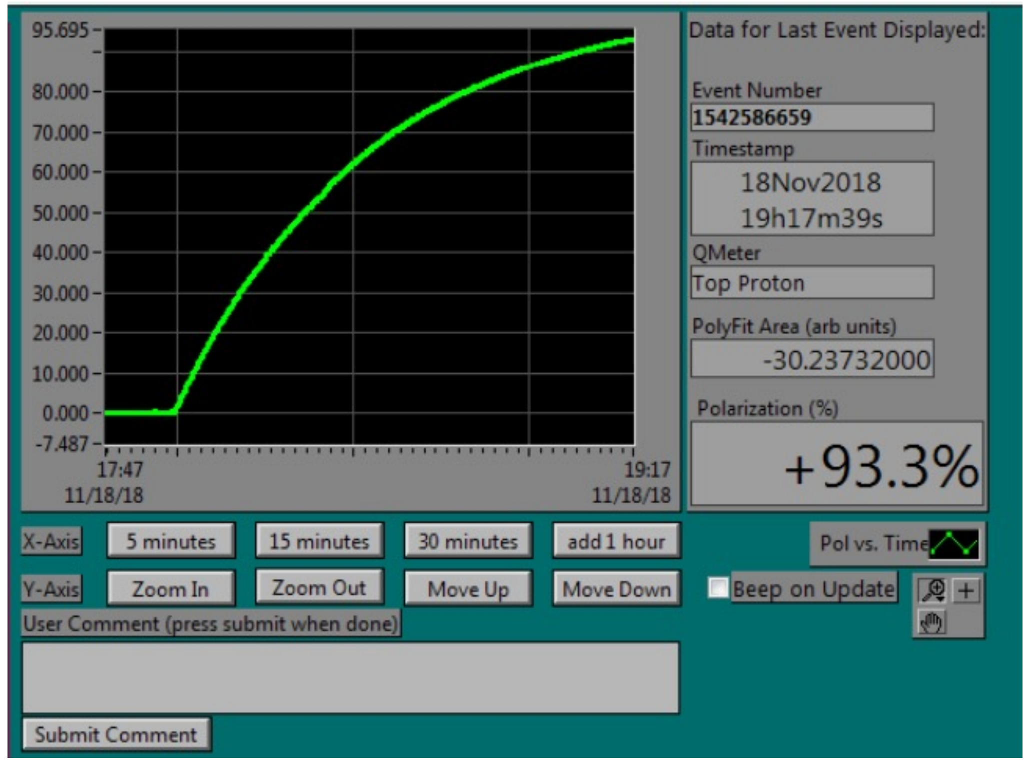


Target Status

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

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





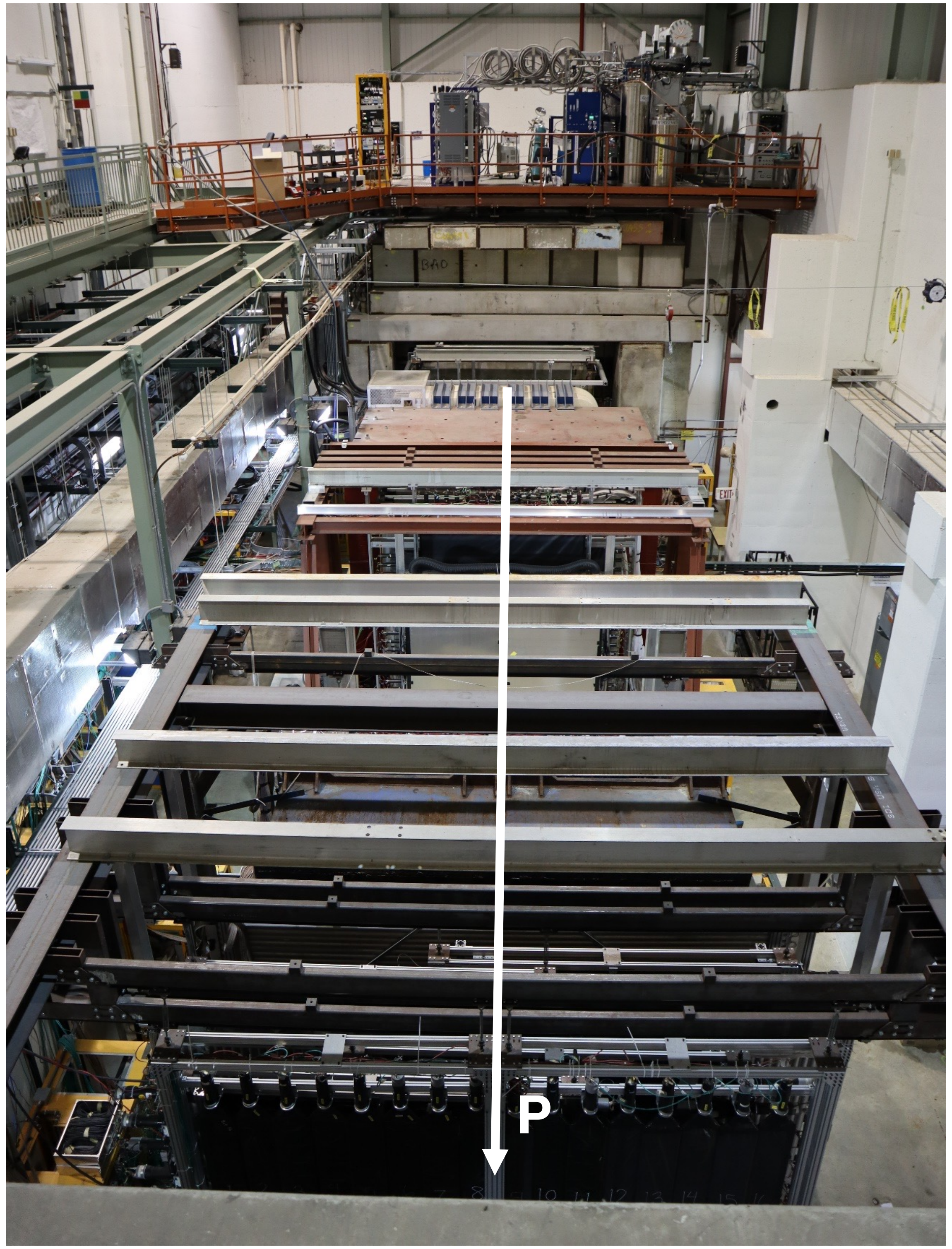
2018 UVA cooldown polarization data - Cooldown at Fermilab next month

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

Experiment Status

- 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 early 2022
- Online reconstruction running on cosmics



E1039 looking from Station 4 towards target

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

Contact Spokespeople:

Kun Liu (LANL) – liuk@fnal.gov

Dustin Keller (UVA) – dustin@jlab.org

More Info:

https://spinquest.fnal.gov/

- Quark OAM likely contributes to nuclear spin, polarized Drell-Yan can confirm it is nonzero. Major Discovery!

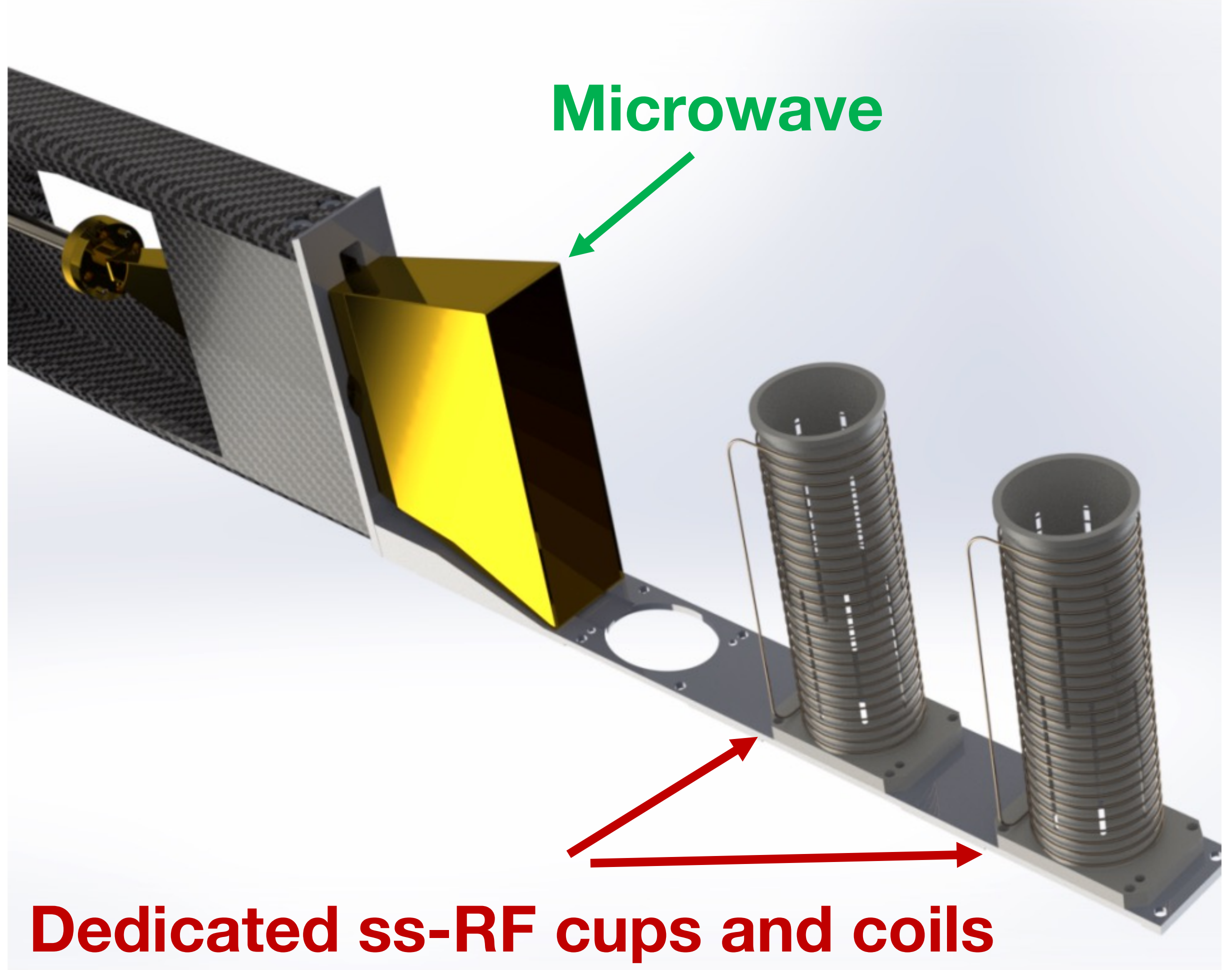
Future Transversity Studies

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.

A second, ss-RF field is needed, in addition to the **microwave DNP**, to control the Tensor Polarization – Measure NMR lineshape

arXiv:2008.09515v1

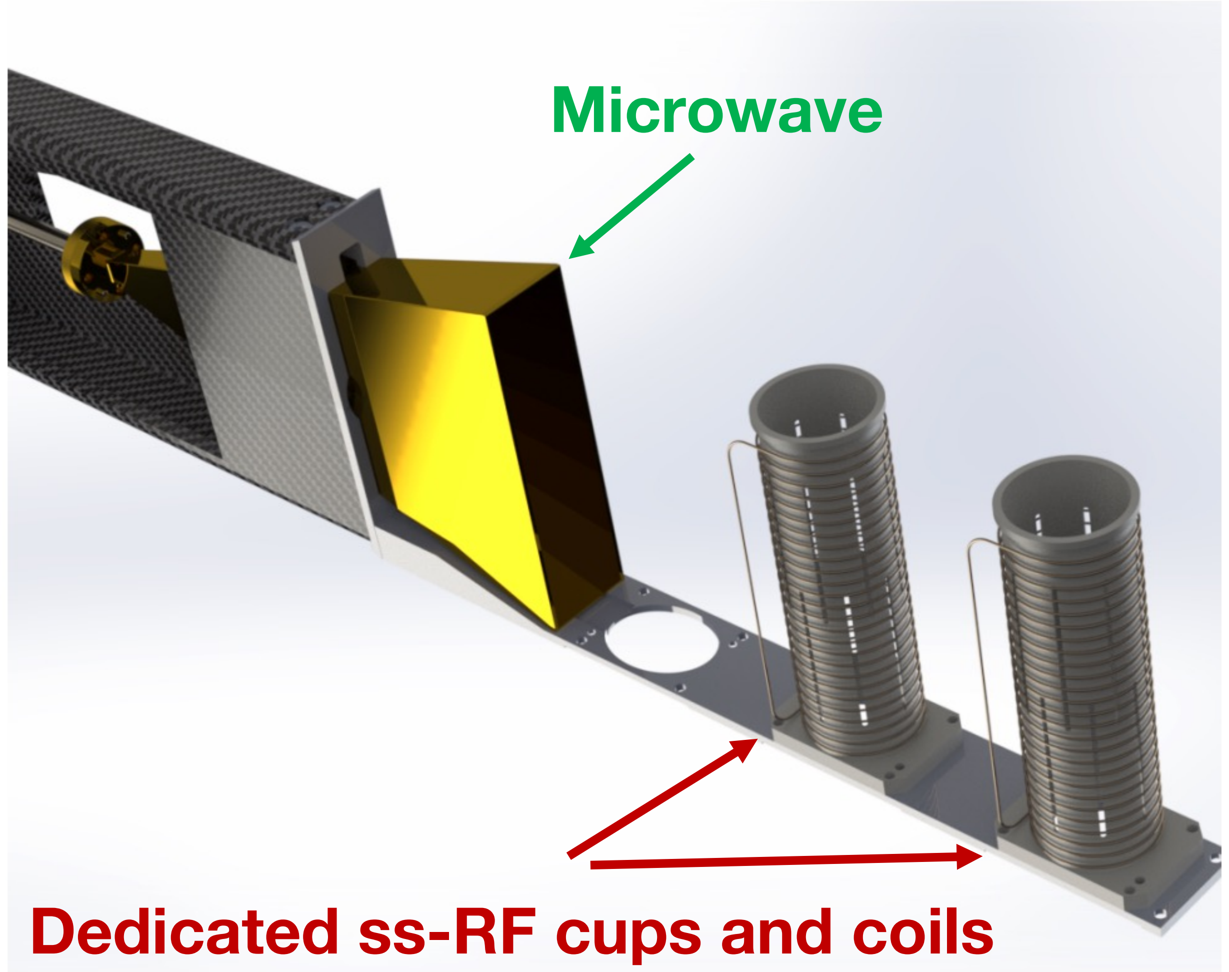
Future Transversity Studies

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

BM constrained by unpolarized DY- E906

$$A_{UT}^{\sin(\varphi_{cs}+\varphi_s)\frac{q_T}{M_N}}\Big|_{pD^\uparrow\to l^+l^-X} \simeq -\frac{\left[4h_{1u}^{\perp(1)}(x_p)+h_{1d}^{\perp(1)}(x_p)\right]\left[\bar{h}_{1u}(x_{D^\uparrow})+\bar{h}_{1d}(x_{D^\uparrow})\right]}{\left[4f_{1u}(x_p)+f_{1d}(x_p)\right]\left[\bar{f}_{1u}(x_{D^\uparrow})+\bar{f}_{1d}(x_{D^\uparrow})\right]}$$

Vector Polarized



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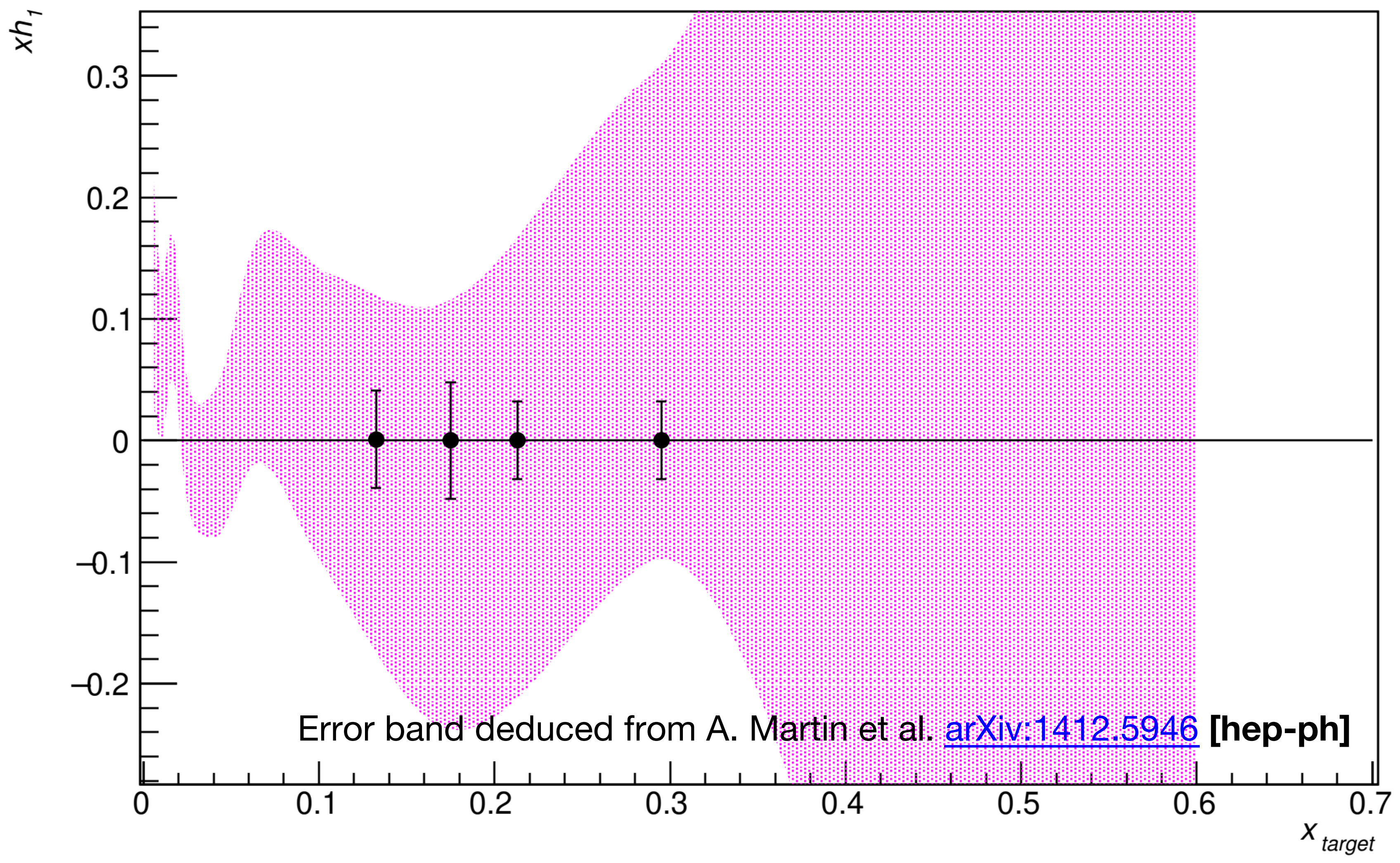
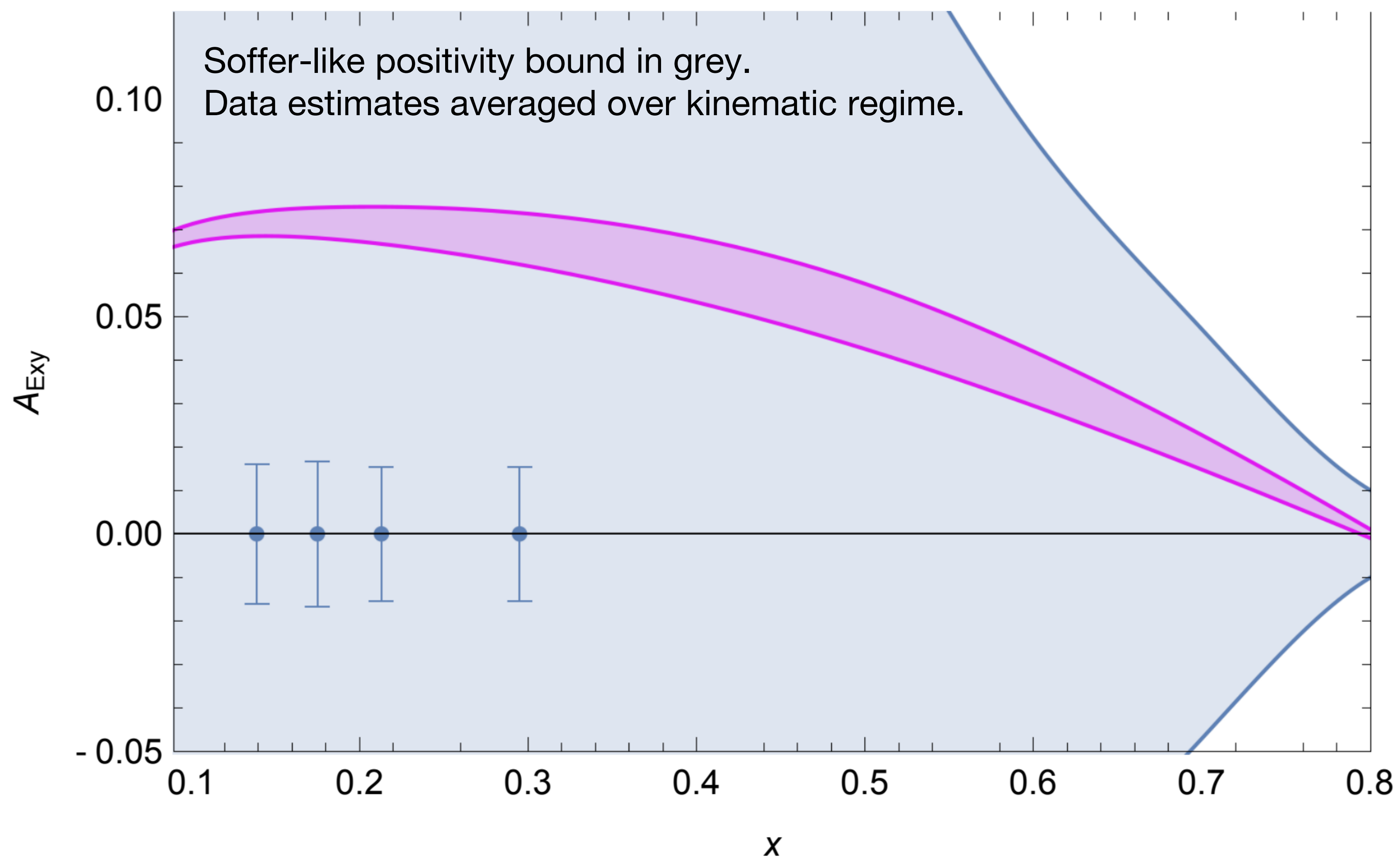


Anticipated seaquark transversity sensistivity



Anticipated linearly polarized gluon assymetry sensistivity.

Fermilab advantages:

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

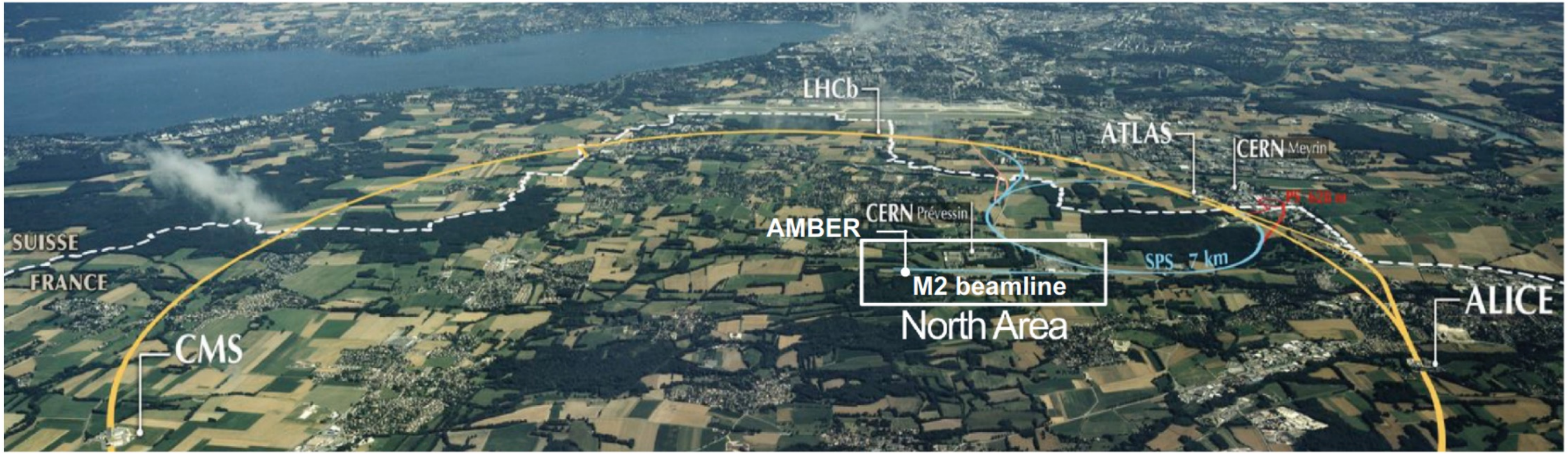
Contact:

Dustin Keller (UVA) – dustin@virigina.edu

More Info:

D. Keller arXiv:2205.01249 **[nucl-ex]**

NA66: AMBER experiment at CERN



AMBER aka Apparatus for Meson and Baryon Experimental Research

to address the question of emergence of hadron mass and confinement

2022 → **Run 3: Conv. beams** → **LS3** → **Run 4: Conv & RF-separated beams**

- Letter of Intent: CERN-SPSC-2019-003, SPSC-I-250
- Proposal for Phase-1: CERN-SPSC-2019-022, SPSC-P-360, approved December 2020✓
- Working on a proposal for Phase-2, submission goal: November 2022

Highlight on Drell-Yan measurements

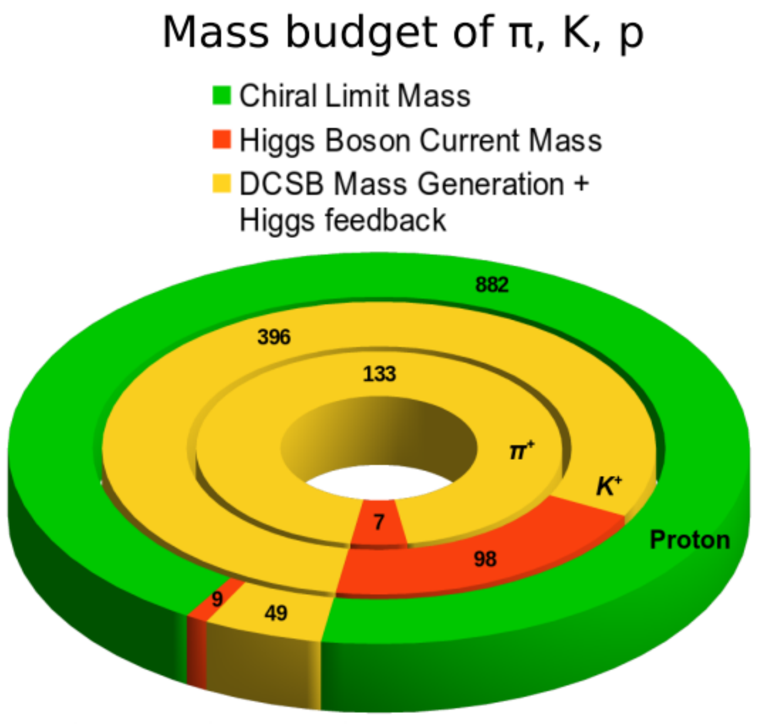
Higgs mechanism alone contributes marginally to the mass: $1\%M_p$, $5\%M_\pi$ and $20\%M_K$

Another phenomenon must exist:

- Alone: 94% of the proton mass
- Interferring with Higgs mechanism: most of π and K masses

What is the origin of the emergence of hadron Mass?

$\Rightarrow$ The answer should be encoded in the structure: PDF & PDA

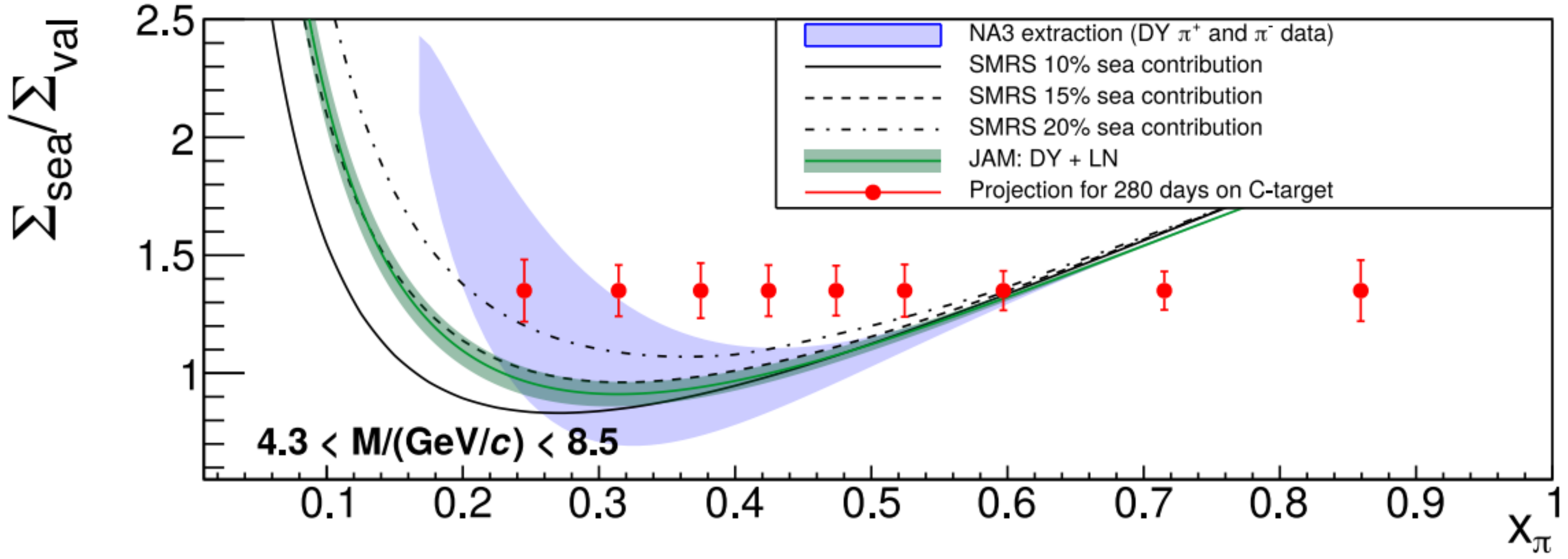


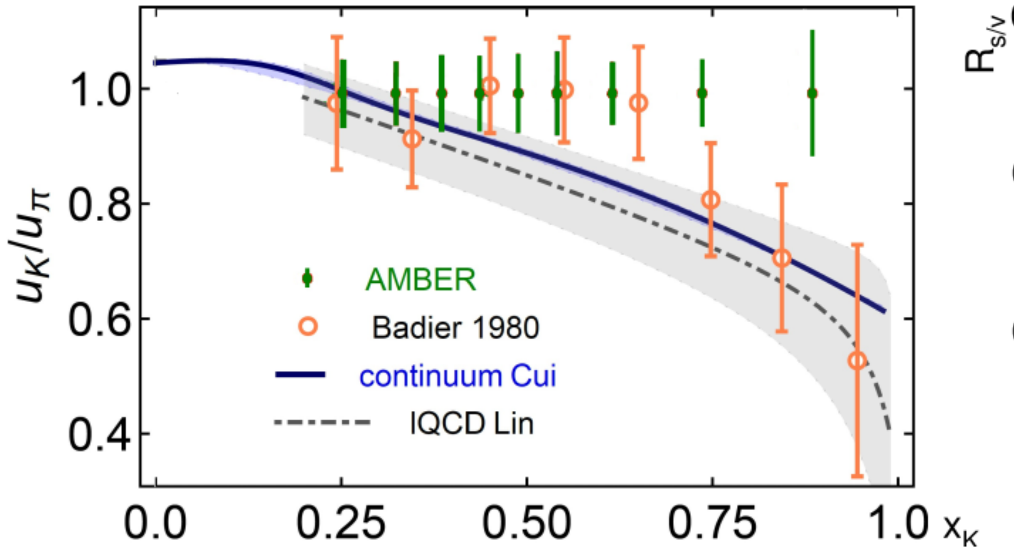
C.D. Roberts *et al.*,PPNP120(2021)103883

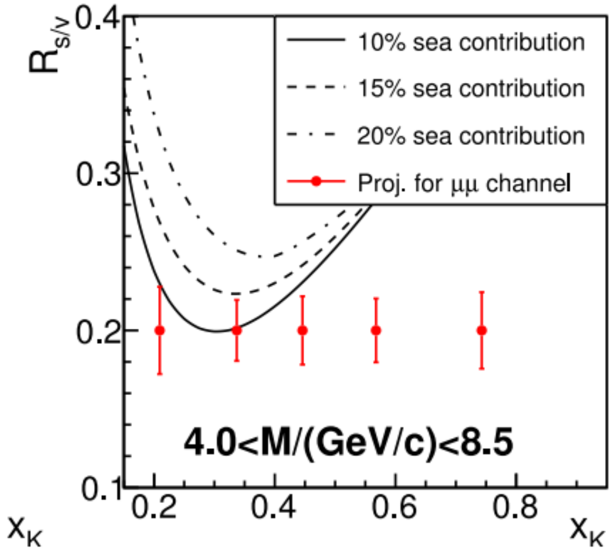
AMBER proposes to use an isoscalar target with meson beams to measure:

- **Pion** sea and valence PDFs with **10× more stats.** than available
- Valence u-quark in the **Kaon** with **3× more stats.** than available
- **First ever** separation of sea-valence contribution in the **Kaon**

Potential increase of beam intensity by a factor 2 under study







NA3: ZPC18 (1983), SMRS: PRD45,2349(1992), JAM: arXiv:1804.01965, Badier: PLB93 354 (1980), Cui: EPJC80(2020)1064, Lin: PRD103(2021)014516

When do we run?

Phase-1 approved by SPSC on December 2020

Allocation of beam time will be studied on a year basis by SPSC

Propositions:

- 2023: Anti-proton production cross section on H and He
- 2023(2024): Proton charge radius measurement
- 2025-2026: pion- and kaon-induced Drell-Yan measurement

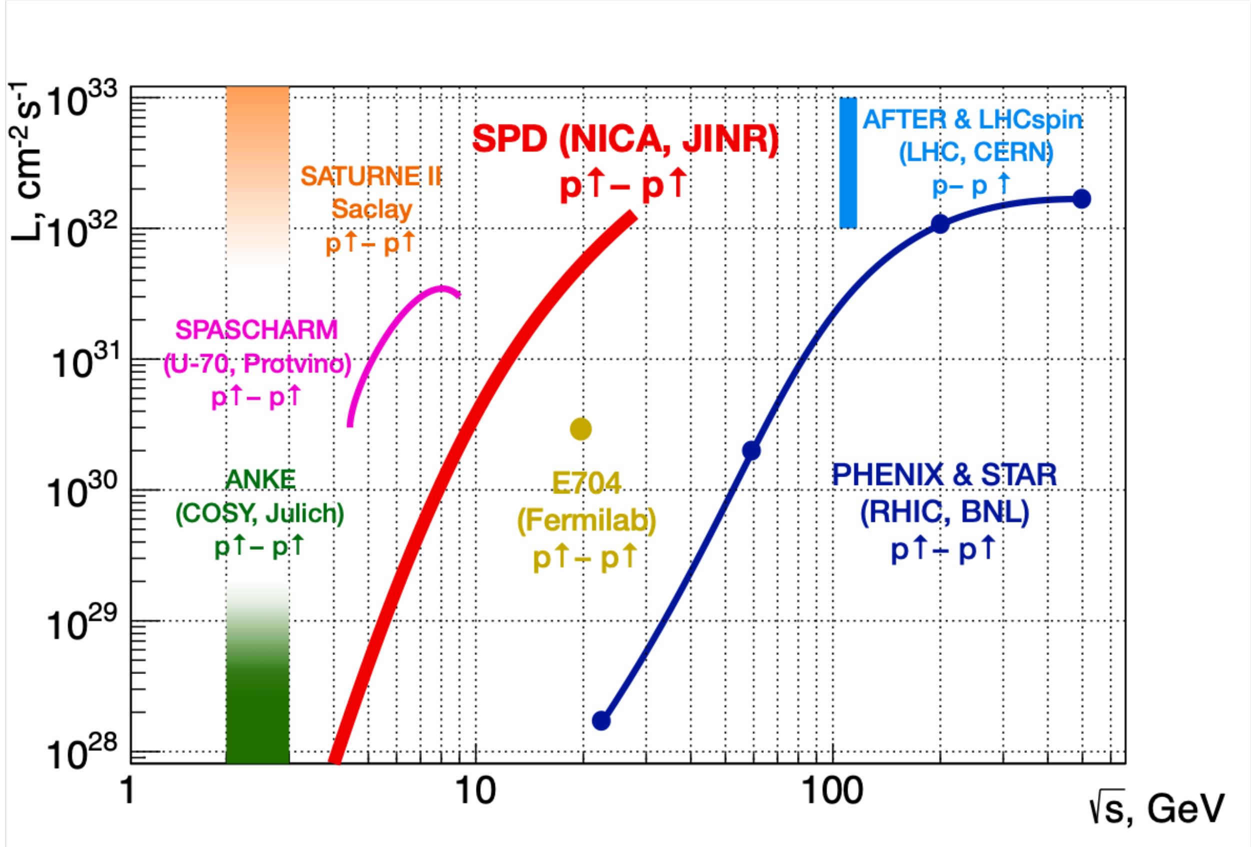
Beam time may be shared with other experiment using the M2 beamline (NA64mu and MuOnE for instance)

SPD CDR: arXiv:2102.00442

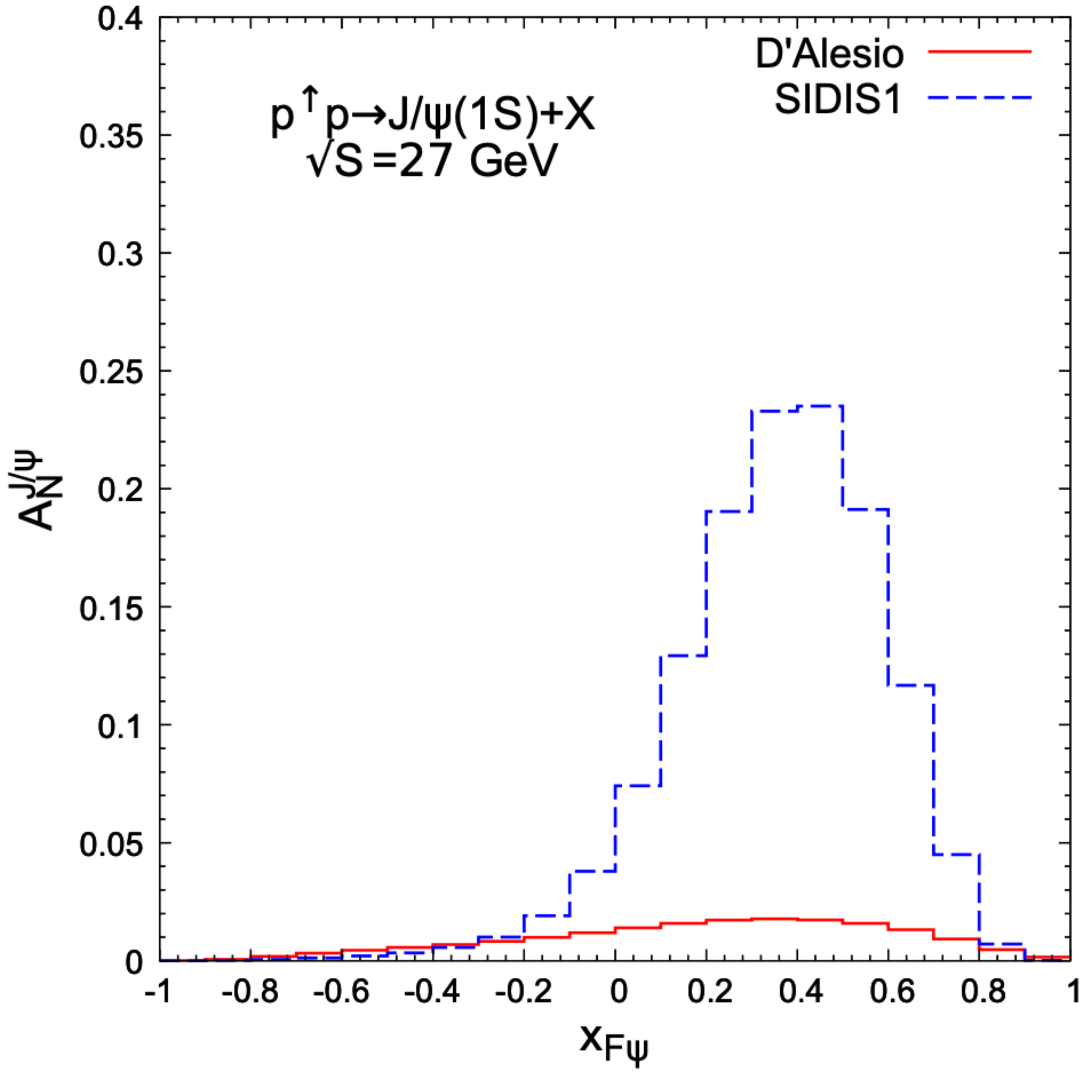
SPD physics:
Prog. Part. Nucl. Phys. 119 (2021)
Phys. Part. Nucl. 52 (2021) 6

Nuclotron-based Ion Collider fAcility – Dubna, RU

p-p and d-d collisions at √s<27 GeV, LL, TT, LT, tensor polarization for deuterons



- near-threshold J/ψ production
- J/ψ as an instrument to access polarized gluon content of proton and deuteron
  - Δg/g via A_{LL} asymmetry in LL collisions
  - TMD PDFs via azimuthal asymmetries with transverse beam polarization
  - gluon transversity in d-d collisions
  - tensor gluon PDFs in d-d collisions
- J/ψ production mechanisms
  - NRQCD factorization test
  - polarization
  - feed-down contribution
  - associated production: J/ψ J/ψ, J/ψ γ



Slide credit: Alexey Guskov (JINR)

Conclusion

- Drell-Yan is a powerful tool to study the (un)polarized hadron structure
- More data on TMD coming
  - SPD @ NICA – J/Psi as a tool to study gluon content of the proton
  - AMBER – Pion / Kaon induced DY for HADRON PDF
  - SpinQuest – Proton sivers for sea quarks + transversity

Apparatus for Meson and Baryon Experimental Research