Drell-Yan at FNAL

Cold QCD at Town Hall Meeting

- Past and Future Drell-Yan Program at Fermilab
- The Need for sea-quark Information
- SpinQuest (A polarized Target Experiment to explore the Sea)
- Experiment Status and Timeline
- The Transverse Structure of the Deuteron in DY

Dustin Keller **9/23/2022**

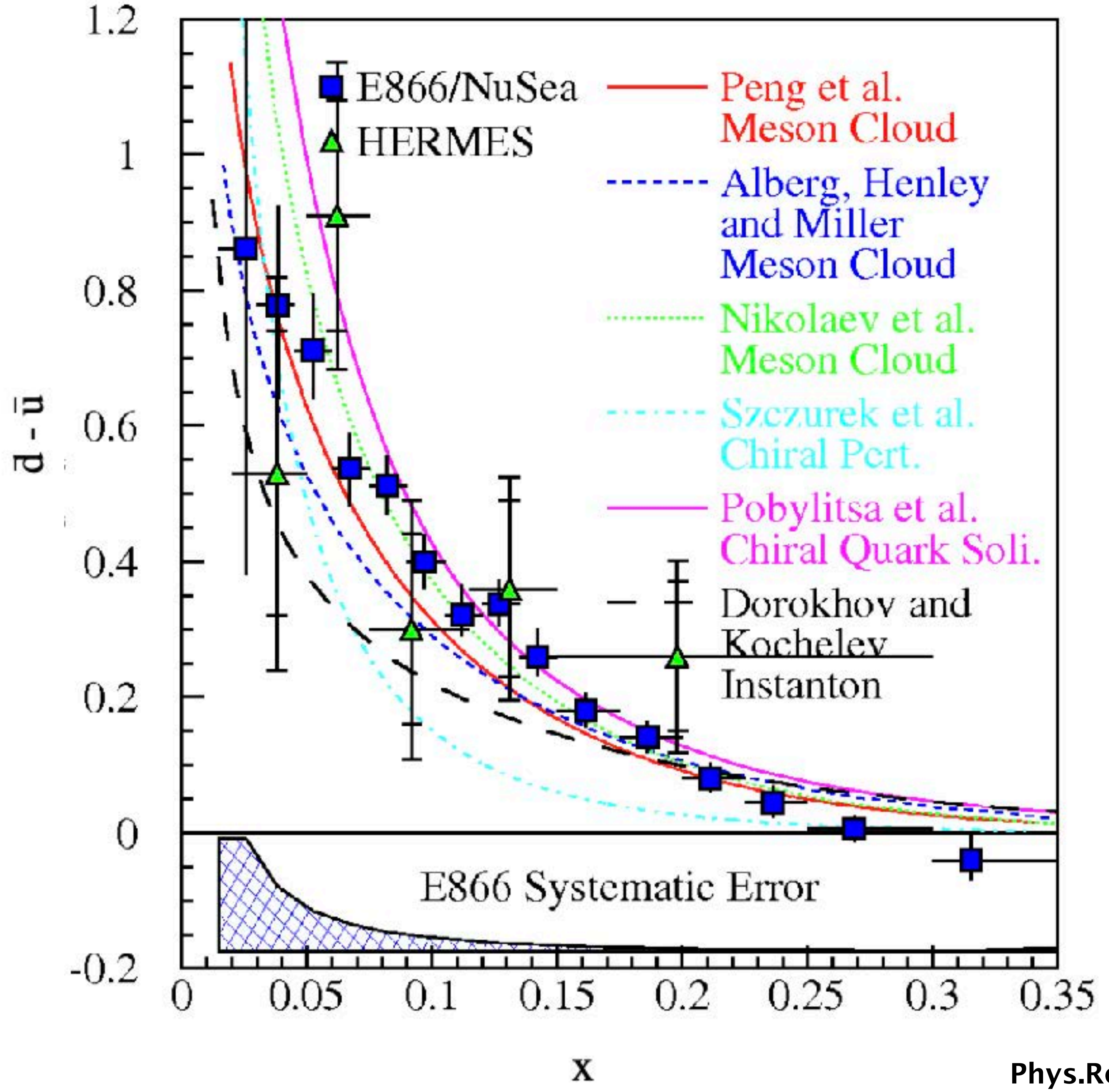
DOE contract DE-FG02-96ER40950

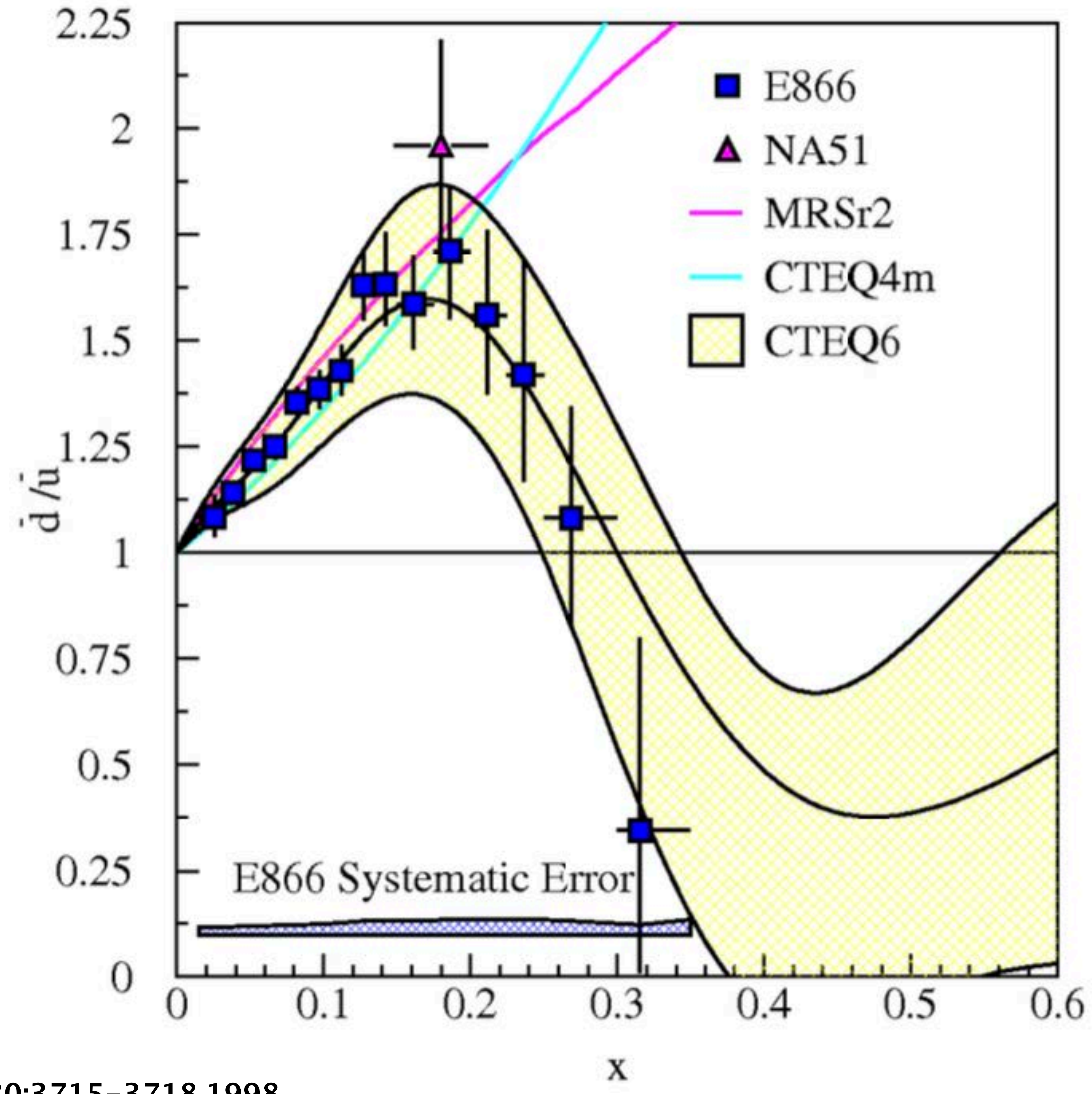
Past and Future Drell-Yan Program

At Fermilab

- E605 (1983) High Pt particle pair with Beryllium target (800 GeV)
- E772 (1988) A-dependence of the Drell-Yan process (800 GeV)
- E789 (1991) A-dependence J/psi, psi’, DY, D and B (800 GeV)
- E866 (1997) Asymmetry in nucleon sea using Drell-Yan (800 GeV)
- E906 (2017) Asymmetry in nuclear sea using Drell-Yan (120 GeV)
- E1039 (2025) Drell-Yan with a Transversely Polarized Target (120 GeV)
- L1039x (2026) Transverse Structure of the Deuteron (120 GeV)
- E1027 (??) Polarized Proton Beam Drell-Yan (120 GeV)

E866/NuSea





Phys.Rev.Lett.80:3715-3718,1998

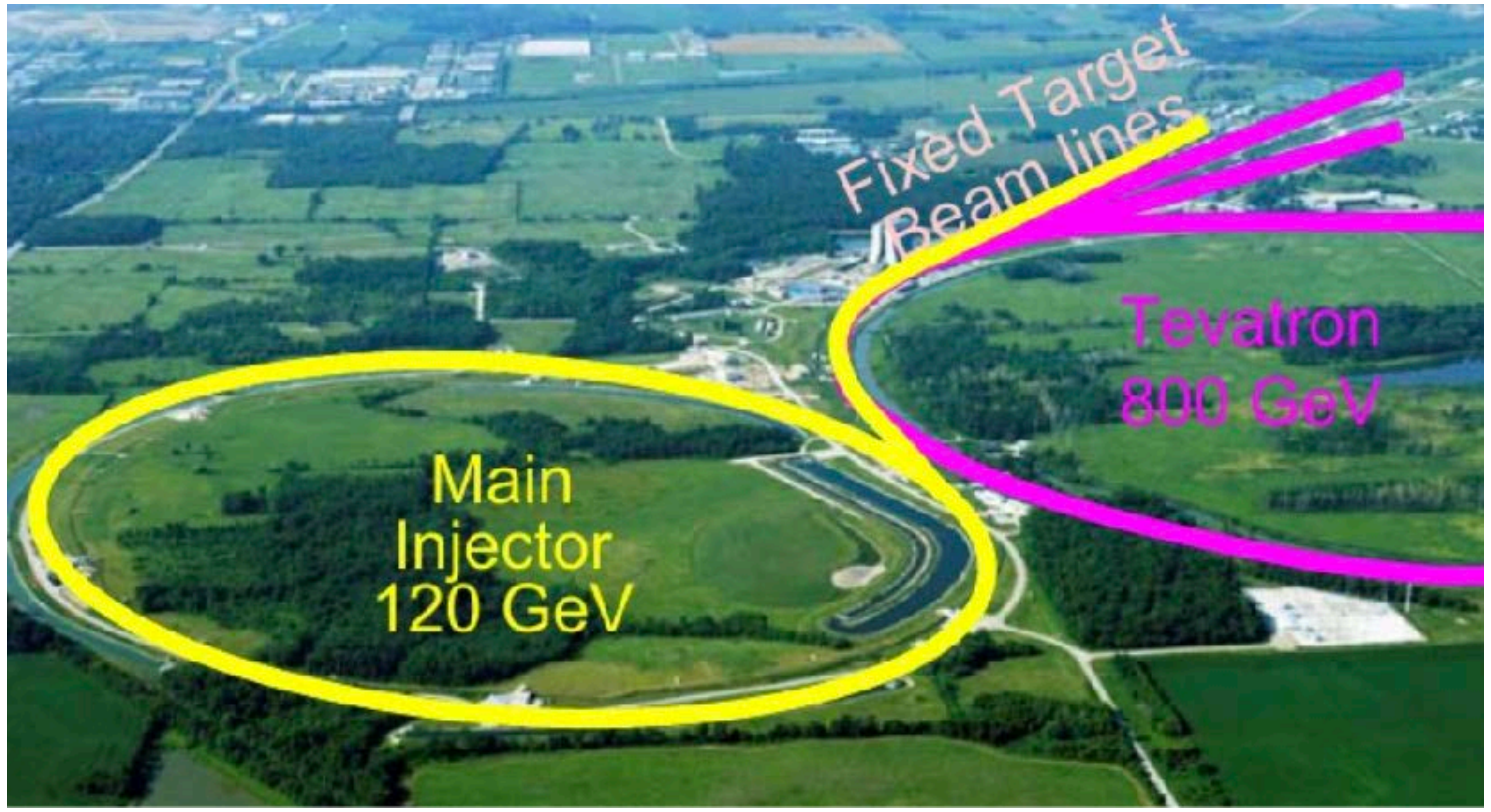
Fermilab Proton Beam Main Injector

E866/NuSea
Data in 1996-1998
^1H, ^2H and nuclear targets
800 GeV proton beam

E906/SeaQuest
Data in 2013-2017
^1H, ^2H and nuclear targets
120 GeV proton beam

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)]$$

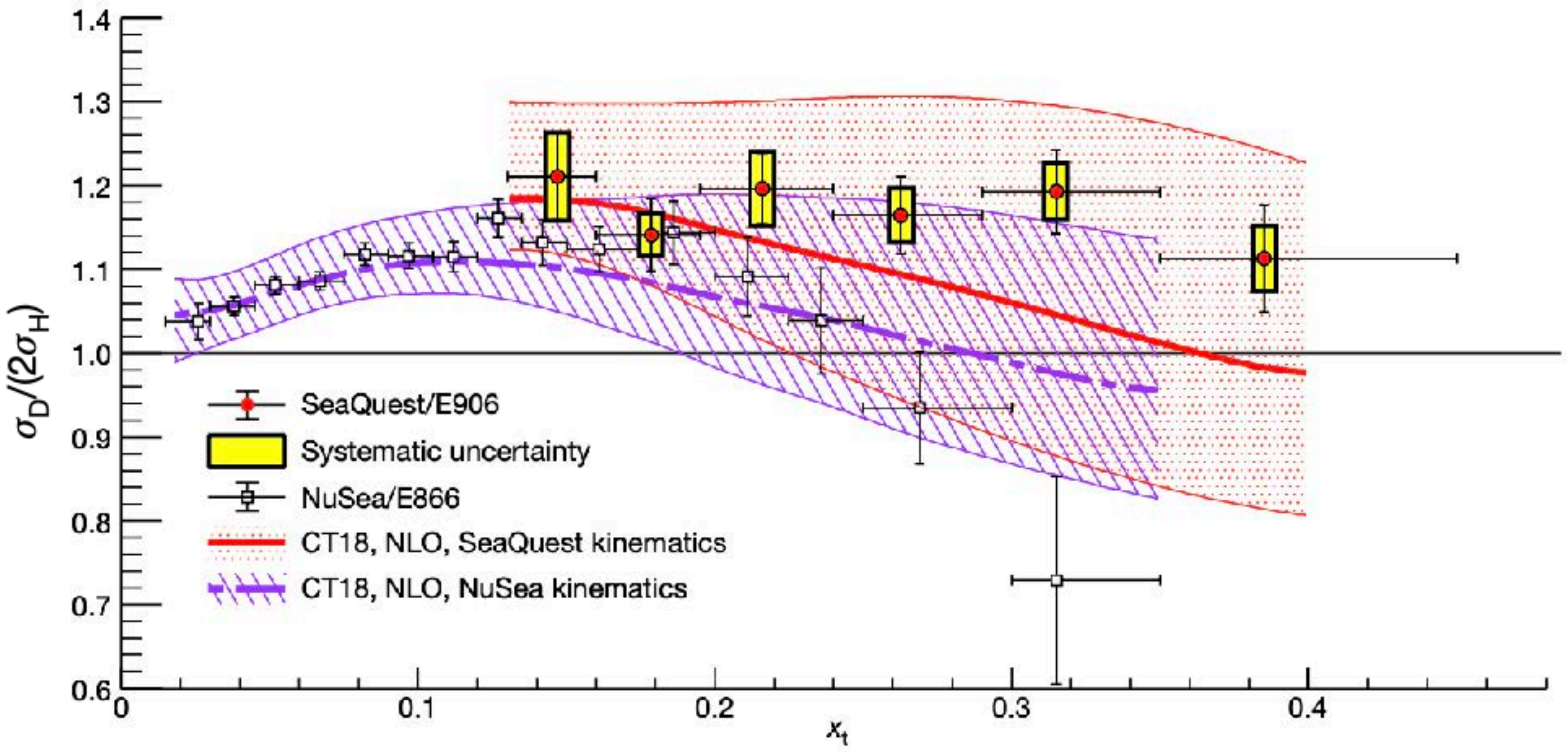
- Optimized for Improved Statistics
    - Cross-Section scales as ~7 times compared to the 800 GeV
    - Luminosity is ~7 times greater than NuSea
    - About 49 times the statistics significance

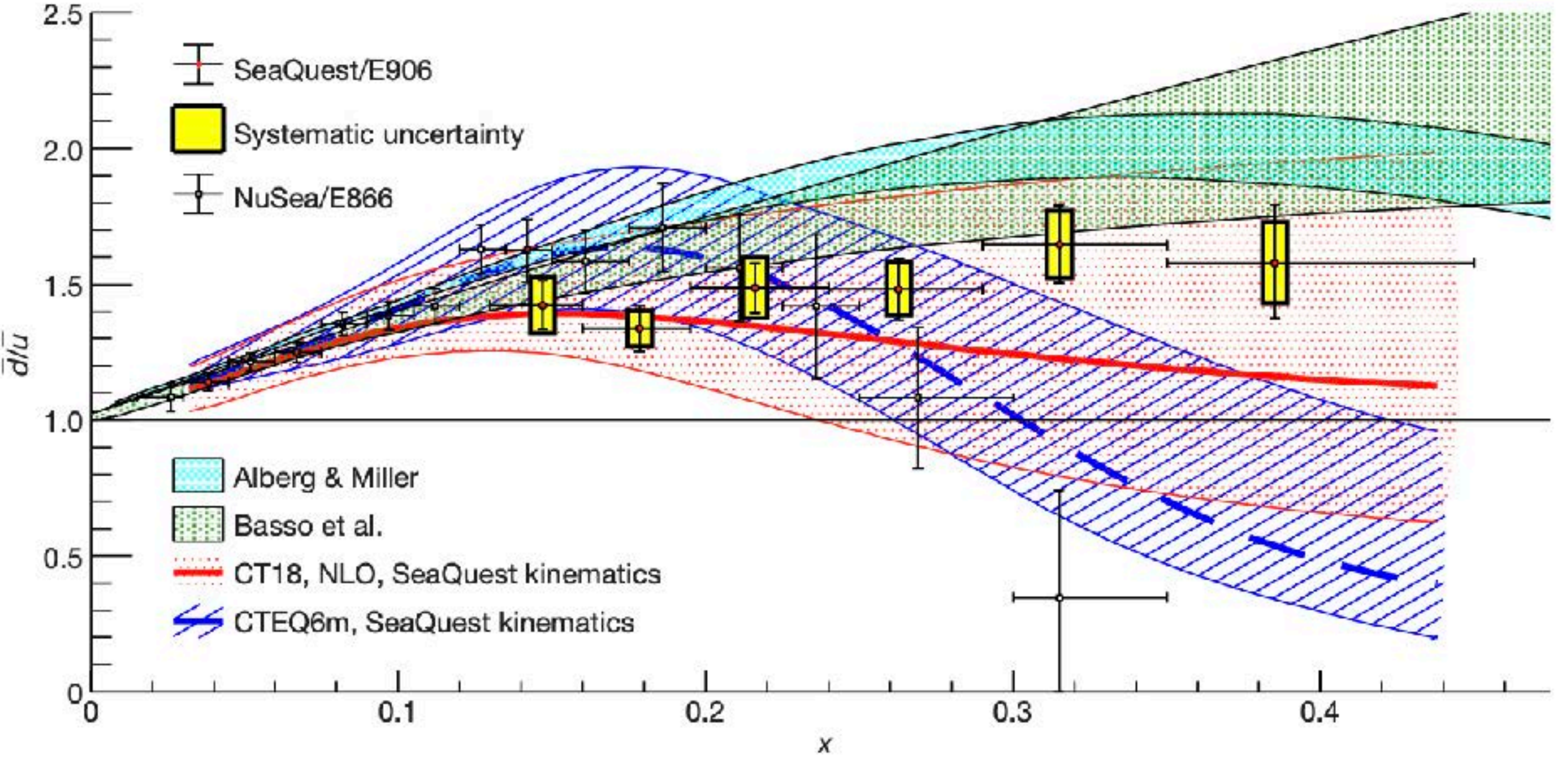


E906\SeaQuest

Asymmetry of Antimatter in the Proton

- Targets: (LH2, LD2, C, Fe, W)
- EMC study
- Nuclear P_T broadening/eloss
- Absolute cross-section
- Boer-Mulders
- J/psi physics





Nature Vol 590, 561-565 (2021)

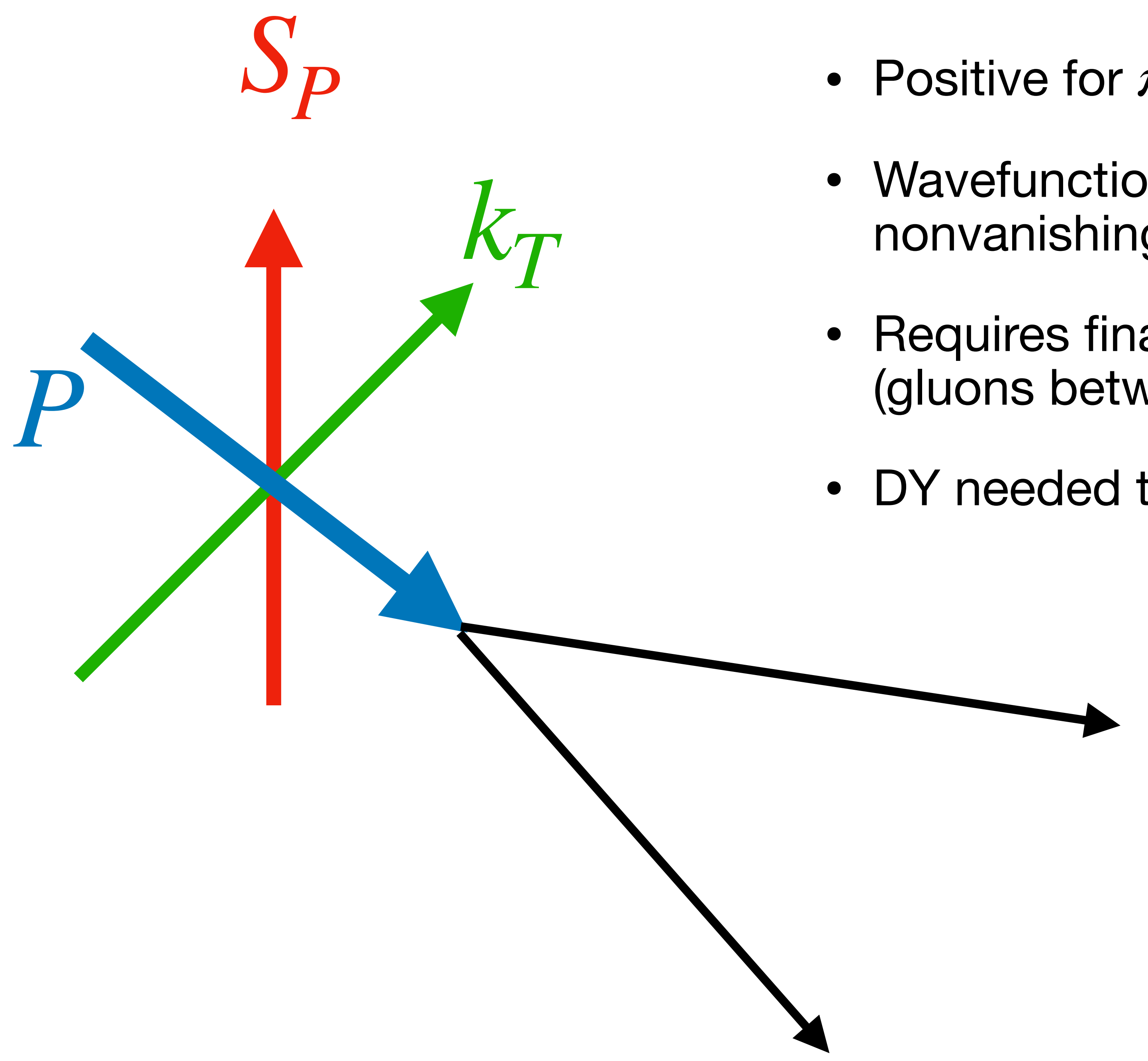
Future Investigation Must Relate Isospin and Spin Asymmetries

So What Spin Asymmetries

- What we expect from pQCD:
  - TSSA should be very small (collinear, leading twist)
- What we know from experiment:
  - Data tells a different story (E704, PHENIX, STAR)

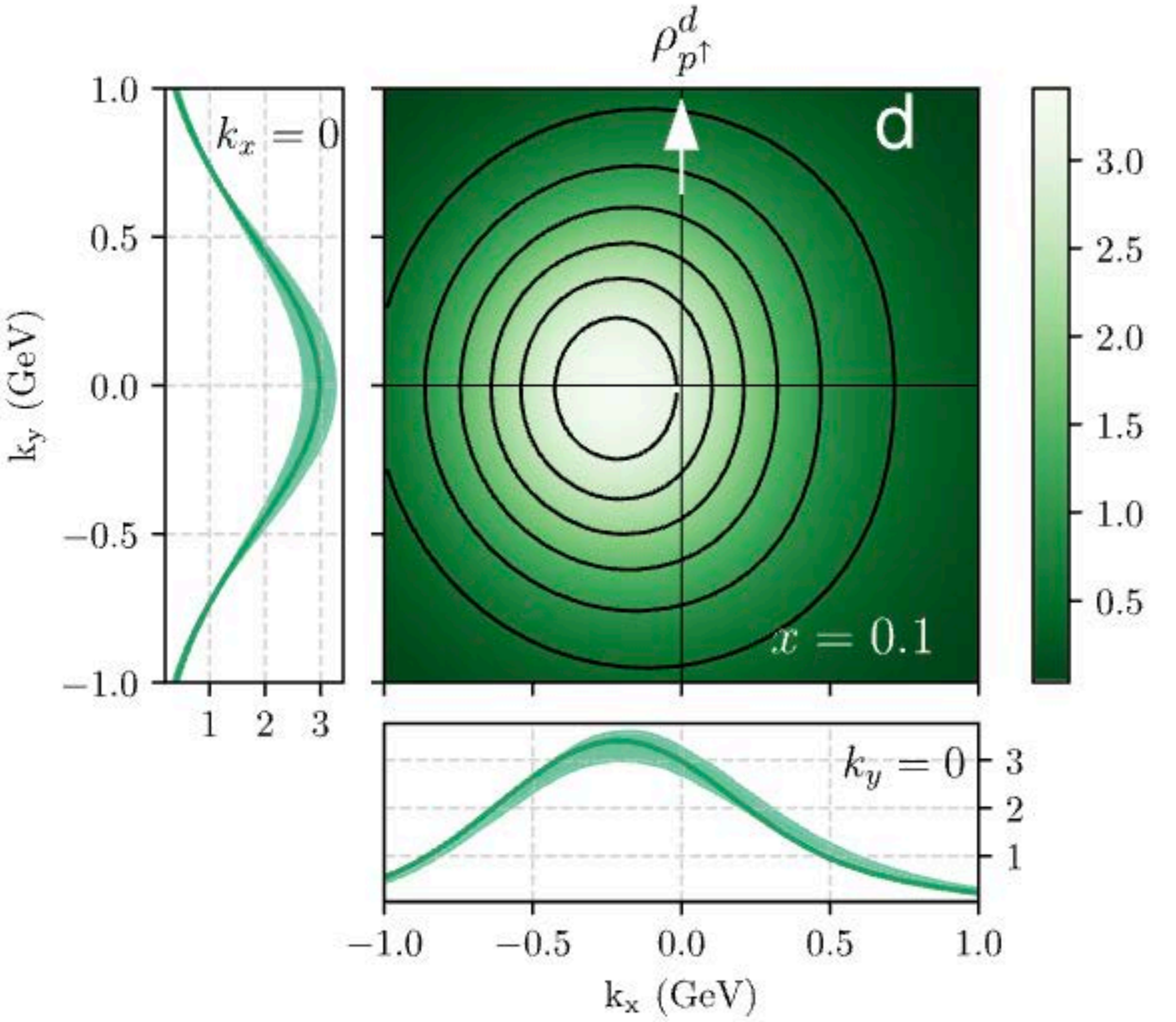
Sivers Mechanism

Data Indicates its a real (SIDIS)



- Positive for π^+ and $K^{\pm}$ (0 for π^-)
- Wavefunction have components with nonvanishing angular momentum
- Requires final-state interaction effects (gluons between quarks and proton)
- DY needed to adding constraints

Map distributions of unpolarized quarks

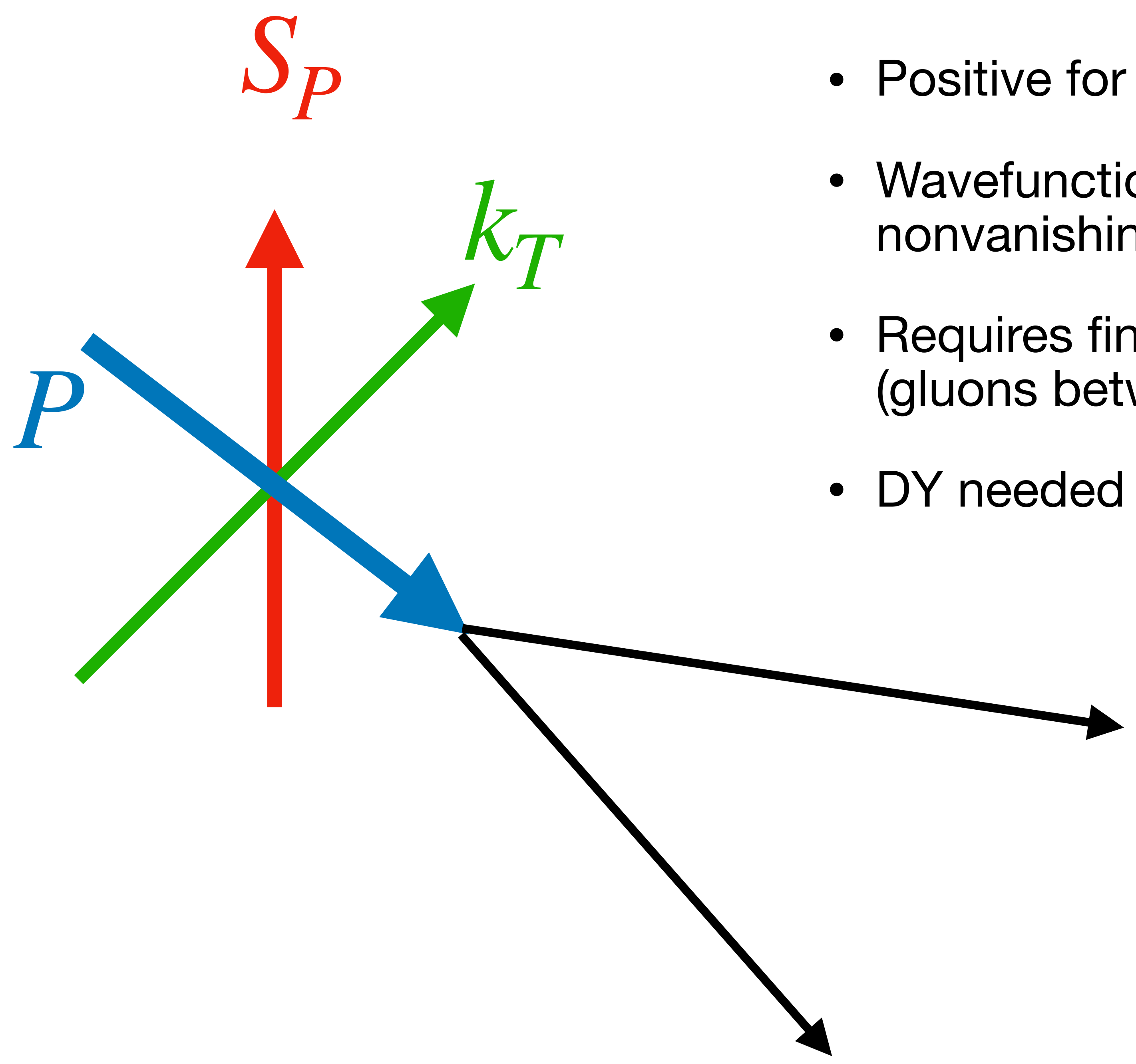


Pavia, PLB 827 136961 (2022)

Separate this mechanism from Collins (Drell-Yan)

Sivers Mechanism

Data Indicates its a real (p+p?)



- Positive for π^+ and $K^\pm$ (0 for π^-)
- Wavefunction have components with nonvanishing angular momentum
- Requires final-state interaction effects (gluons between quarks and proton)
- DY needed to adding constraints

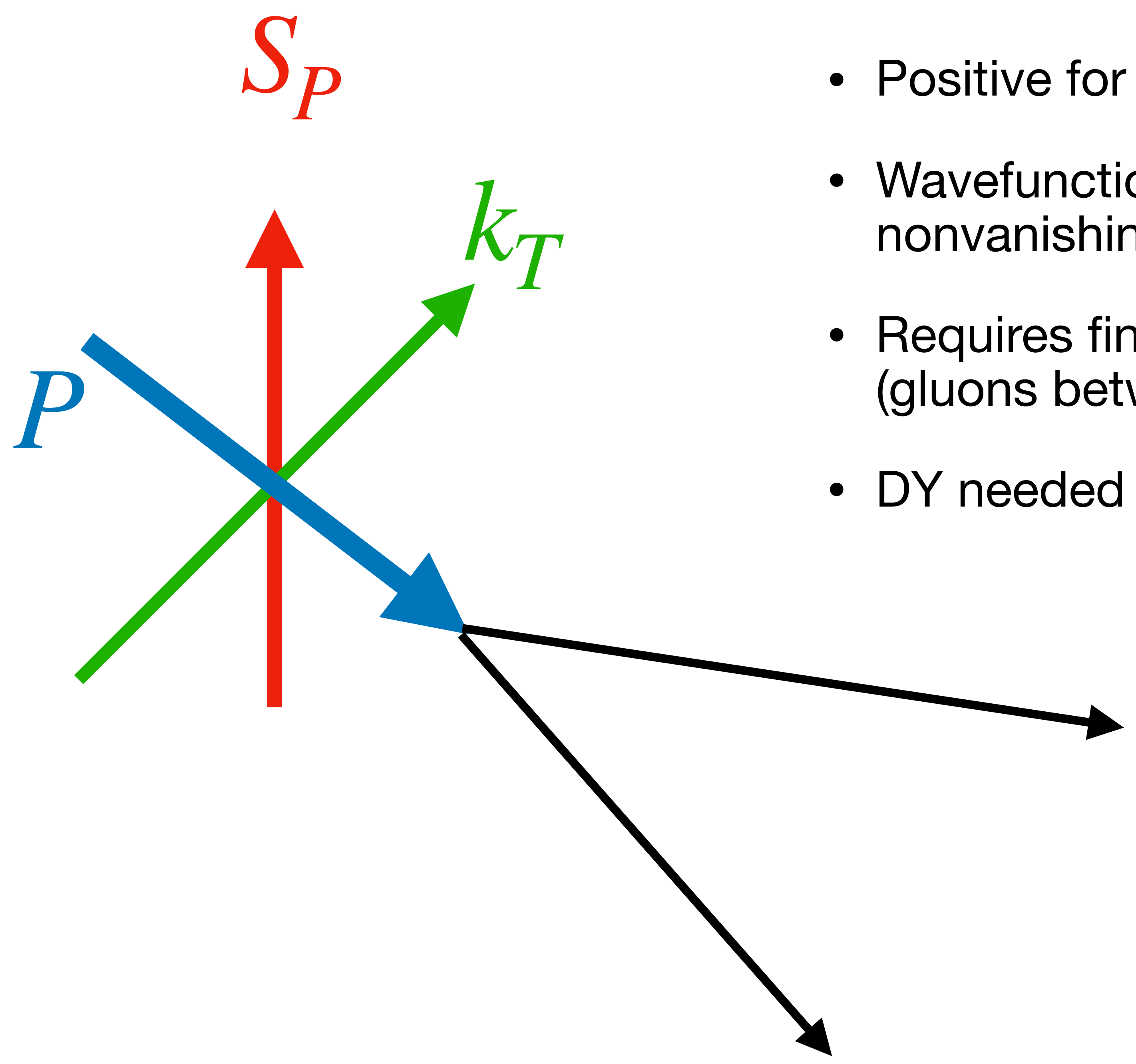
- Sivers in the most accessible TMD
  - Universality (In observables)
  - Is Factorization valid with TMDs
  - TMD Evolution

Need experimental data to determine non-perturbative part

Need to completely map phase space in both DY and SIDIS

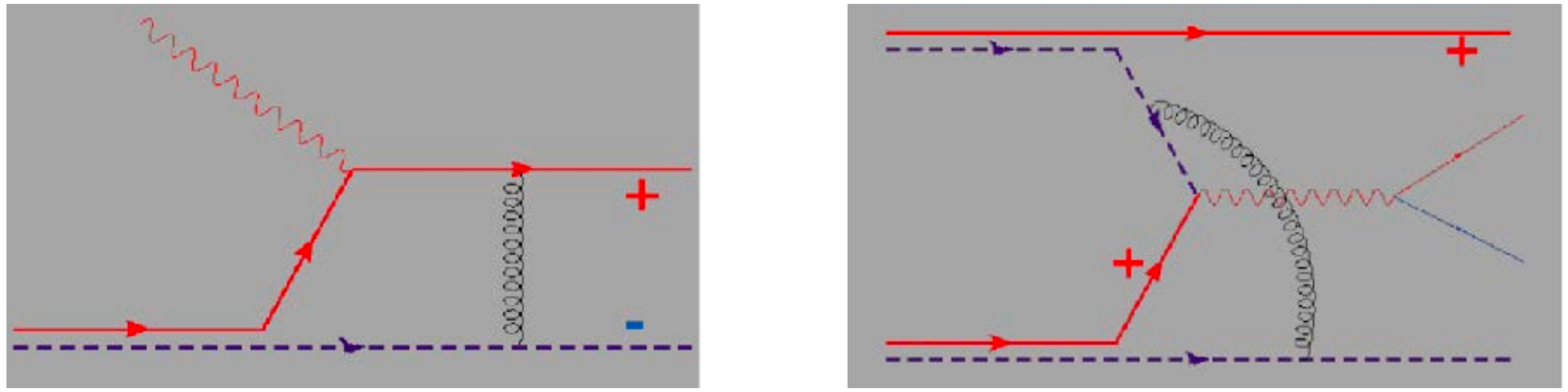
Sivers Mechanism

Data Indicates its a real



- Positive for π^+ and $K^{\pm}$ (0 for π^-)
- Wavefunction have components with nonvanishing angular momentum
- Requires final-state interaction effects (gluons between quarks and proton)
- DY needed to adding constraints

Modified Universality



- Gauge link provides the phase for the interference
- Can be interpreted as an interaction of the struck quark with the color field of the target remnant
- Colored Objects surrounded by gluons with profound consequence of gauge invariance
- Opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (DY)

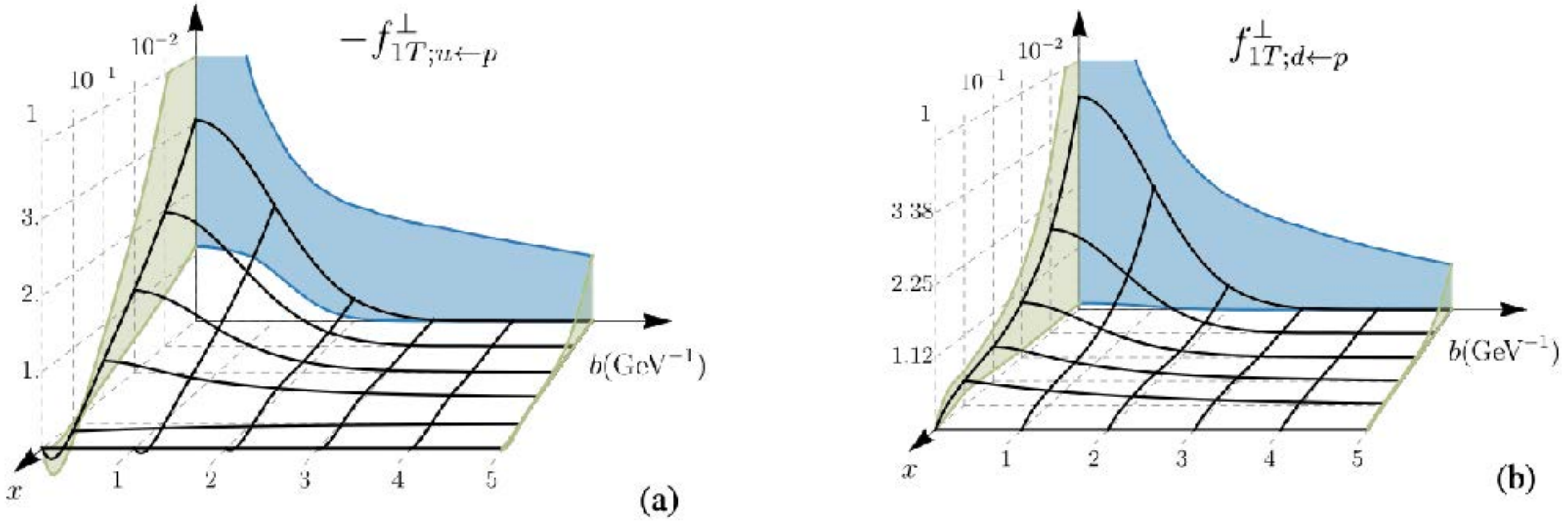
$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

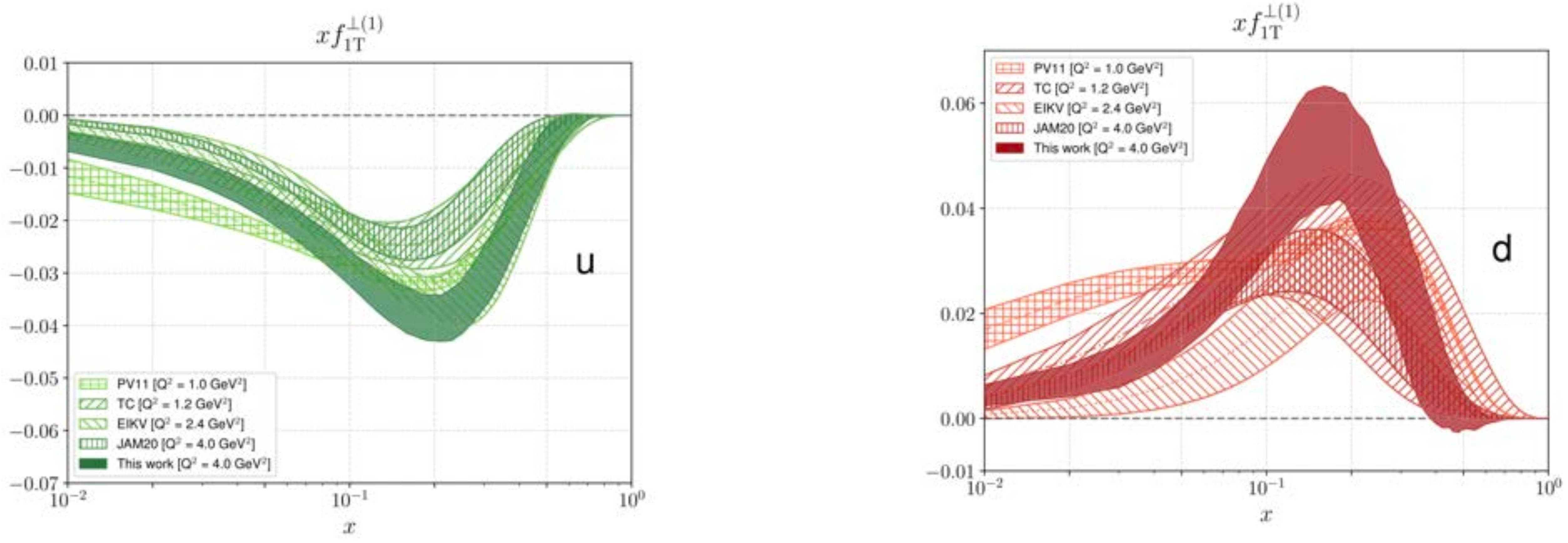
Recent Global Analysis

- Similar Results (Valence)
- Sign-change is preferred
- Statistics and Kinematics limited
- Most experiments focus on Valence
- Sea contribution suppressed in SIDIS

"…The sign of the sea-quark Sivers function plays the central role here…"

PHYSICAL REVIEW LETTERS **126,** 112002 (2021)



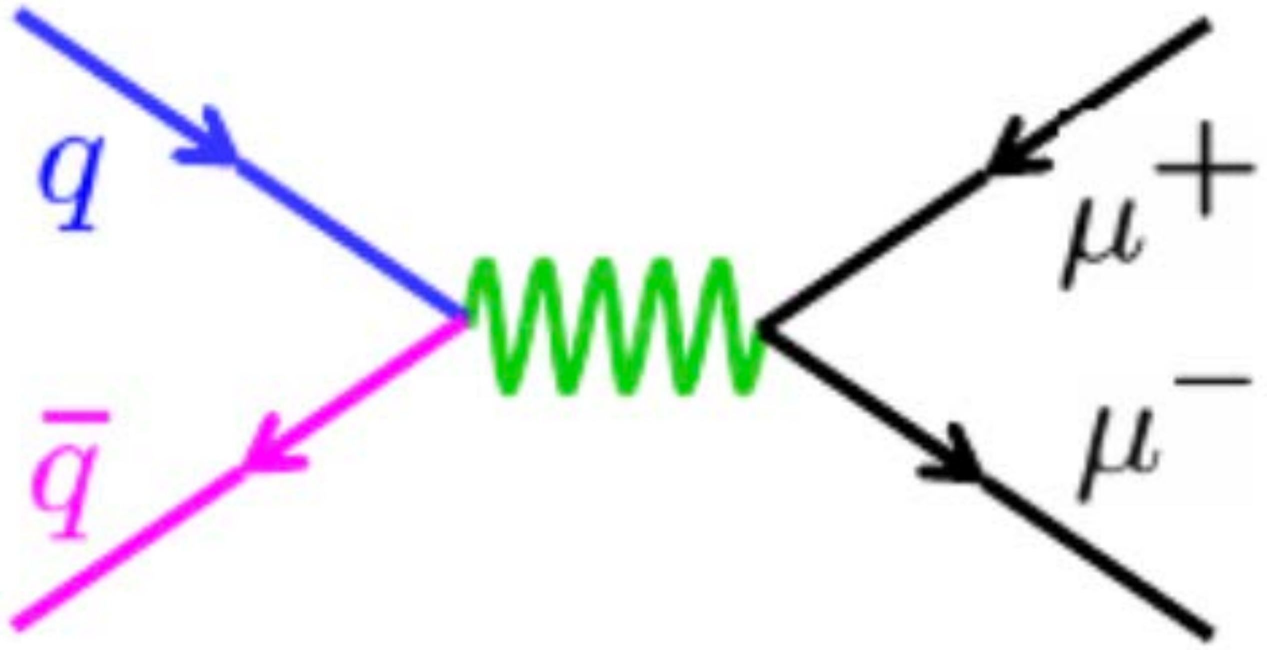


Physics Letters B 827 (2022) 136961

We really need more data!!

SpinQuest is designed for sea-quarks

Designed investigate sea-quarks in a polarized proton/neutron



beam: valence quarks at high x

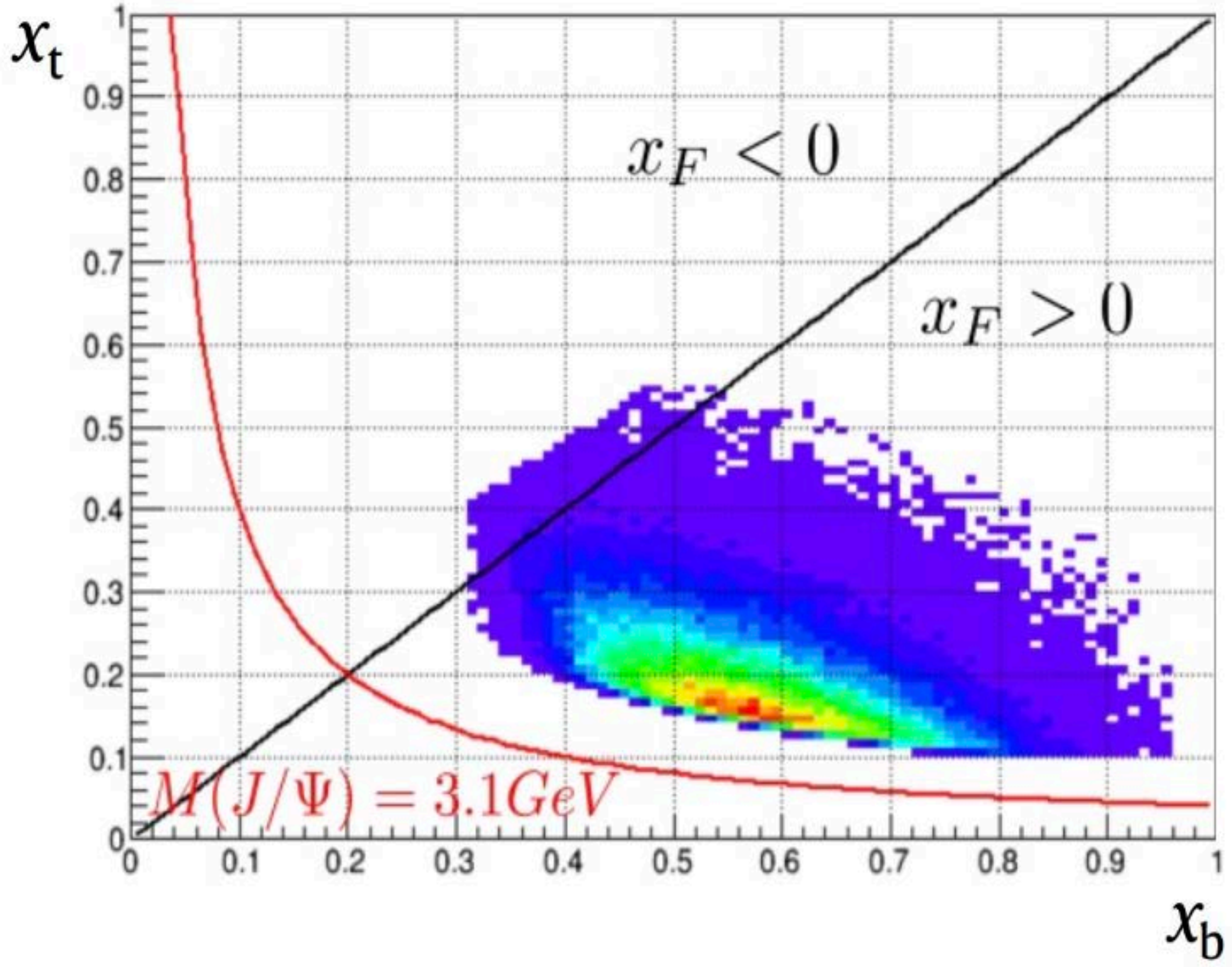
target: sea quarks at low/intermediate x

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,...\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

u-quark dominance
$(2/3)^2$ vs. $(1/3)^2$

acceptance limited
(Fixed Target, Hadron Beam)

Sample the sea-quark in the polarized target



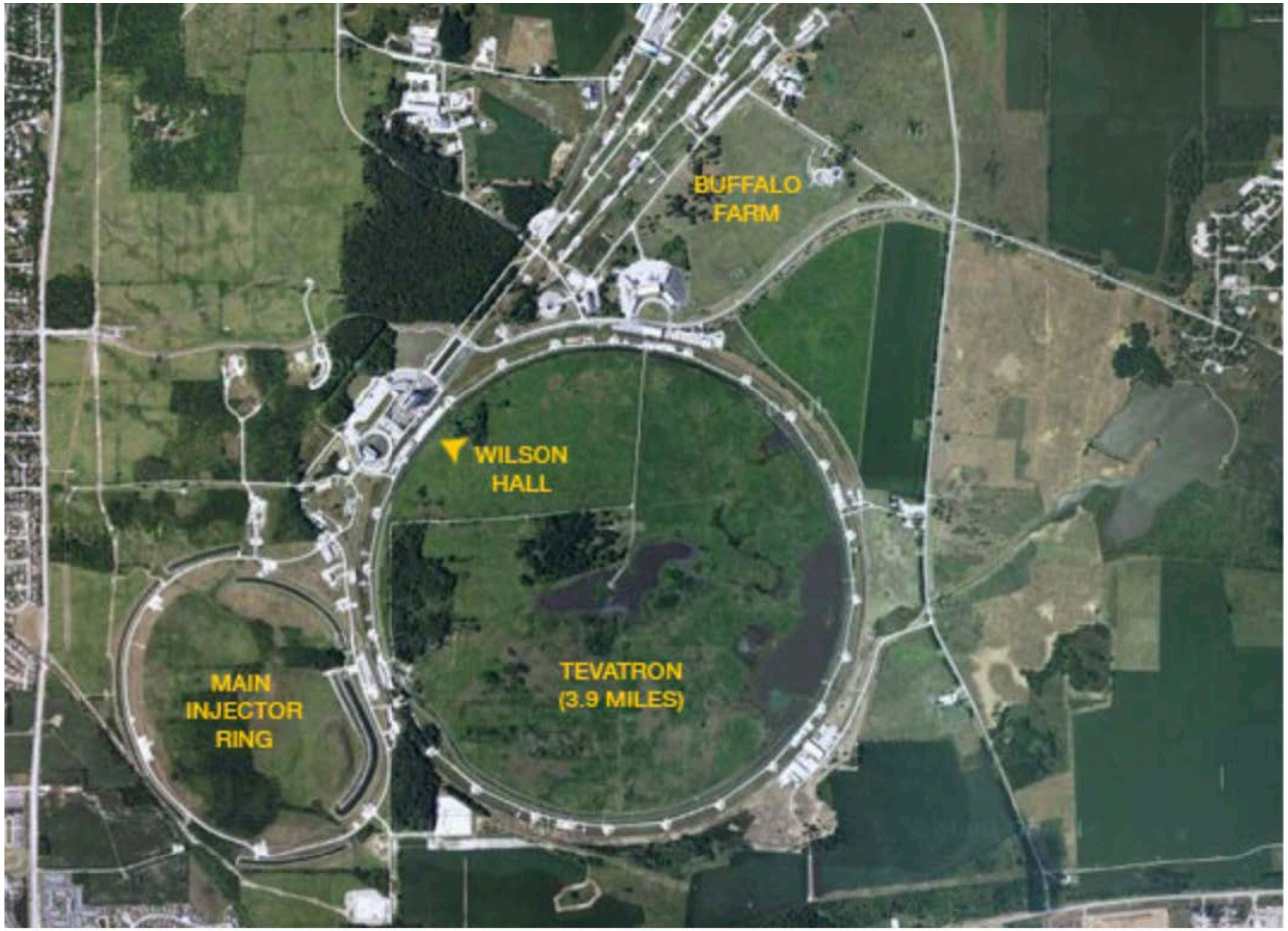
SpinQuest at Fermilab

A measurement of the contribution of the vacuum to spin

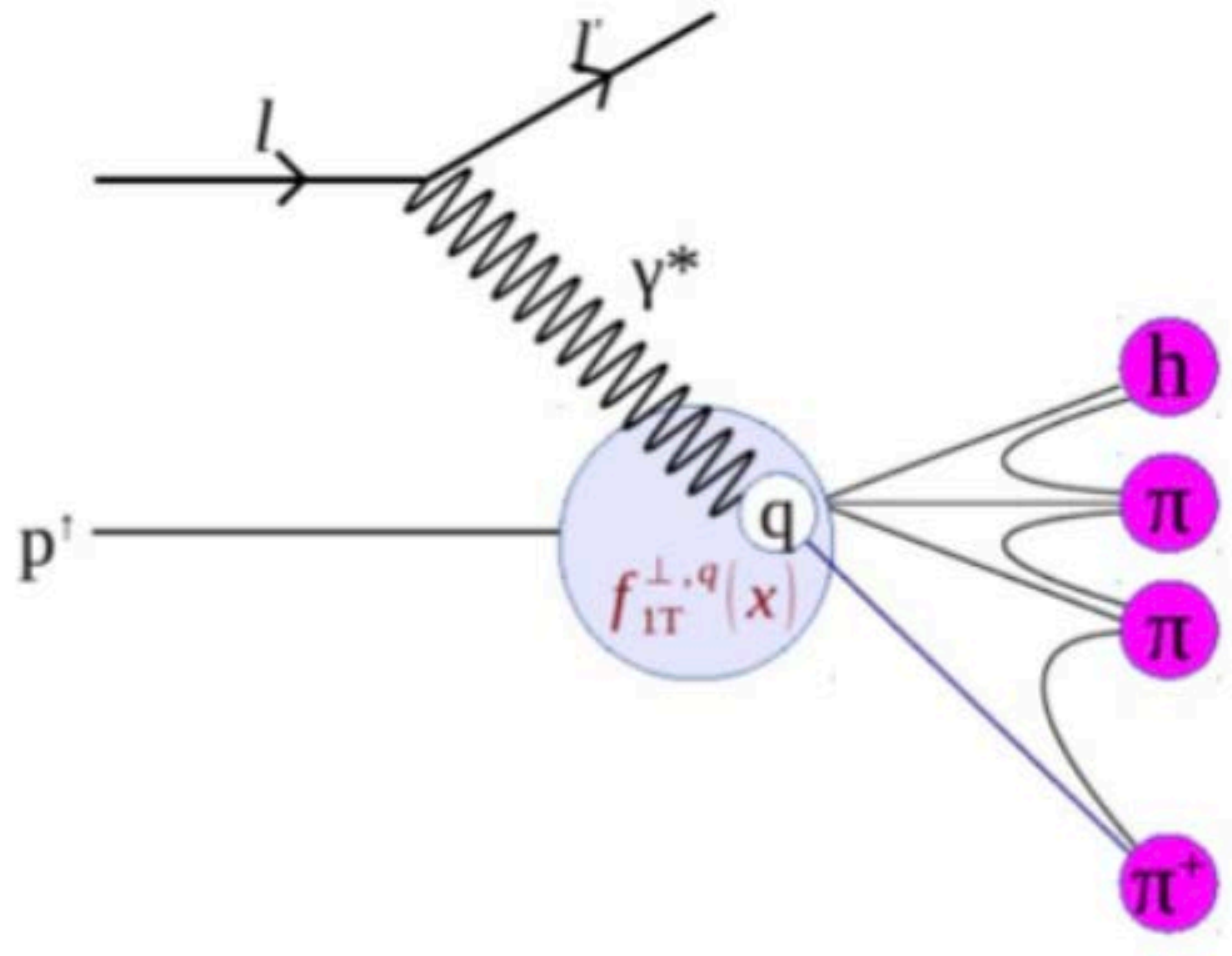
SpinQuest

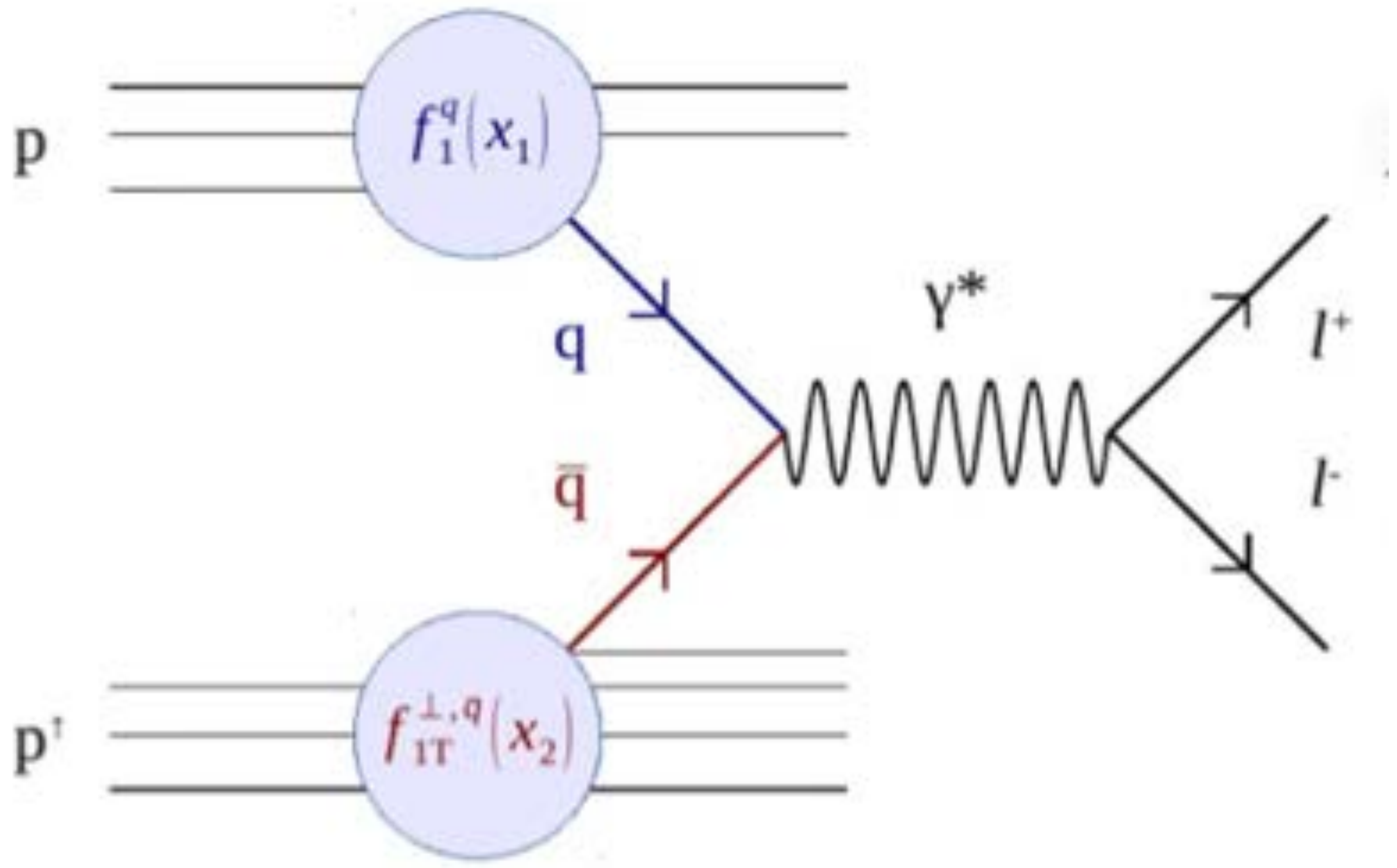
- 120 GeV proton beam
- $\sqrt{s} = 15.5$ GeV
- $\sim 1 \times 10^{12}$ pro/sec for 4.4 sec/min

  - SpinQuest will measure the correlation between the momentum of the struck sea-quark and the spin of parent nucleon
  - A none zero asymmetry is evidence of sea-quark OAM
  - SpinQuest will fill in important and critical information about the sea



Accessing TMDs





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

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

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

$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

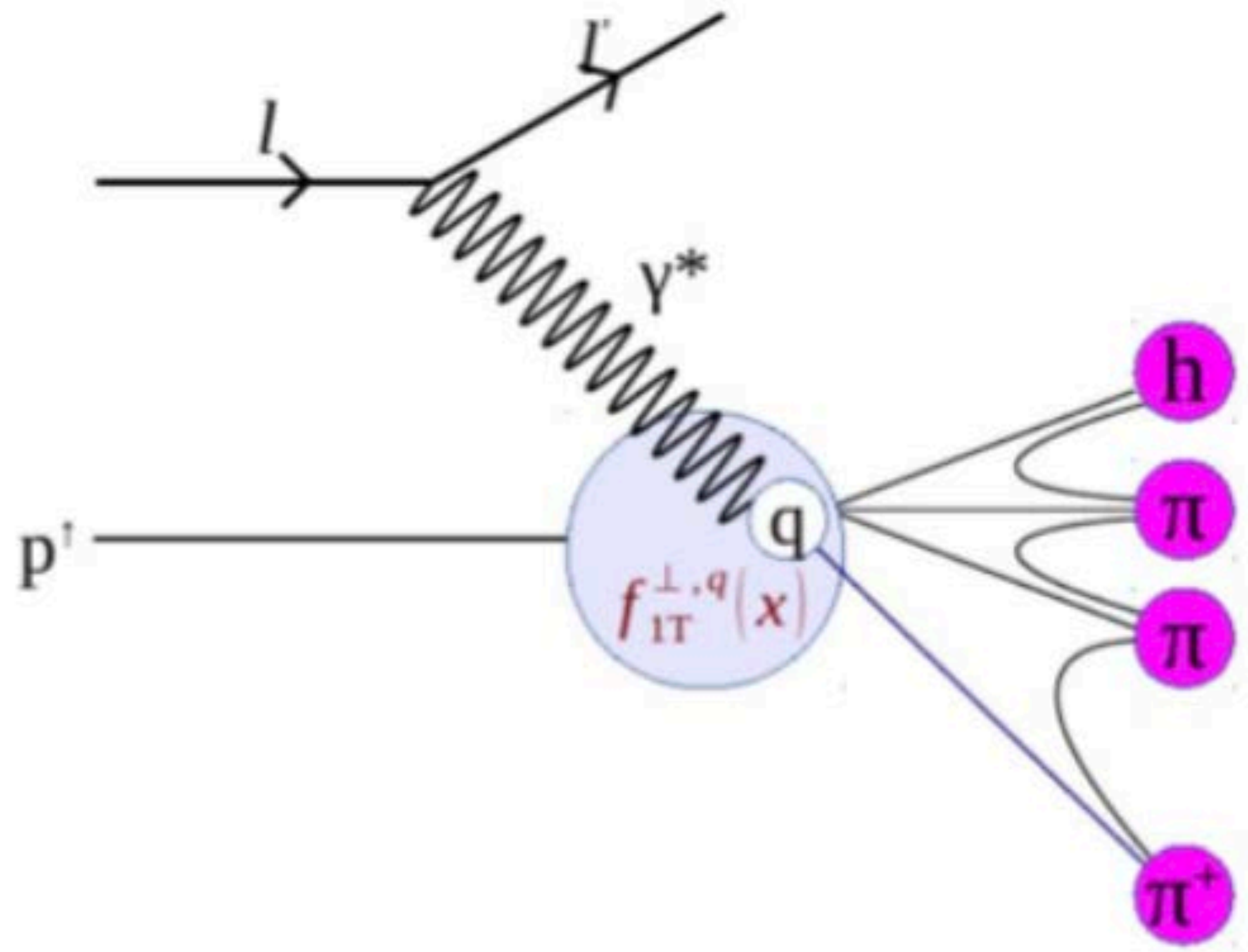
$$A_{T}^{\cos 2\varphi_S} \propto h_1^{\perp q} \otimes h_1^{\perp q}$$

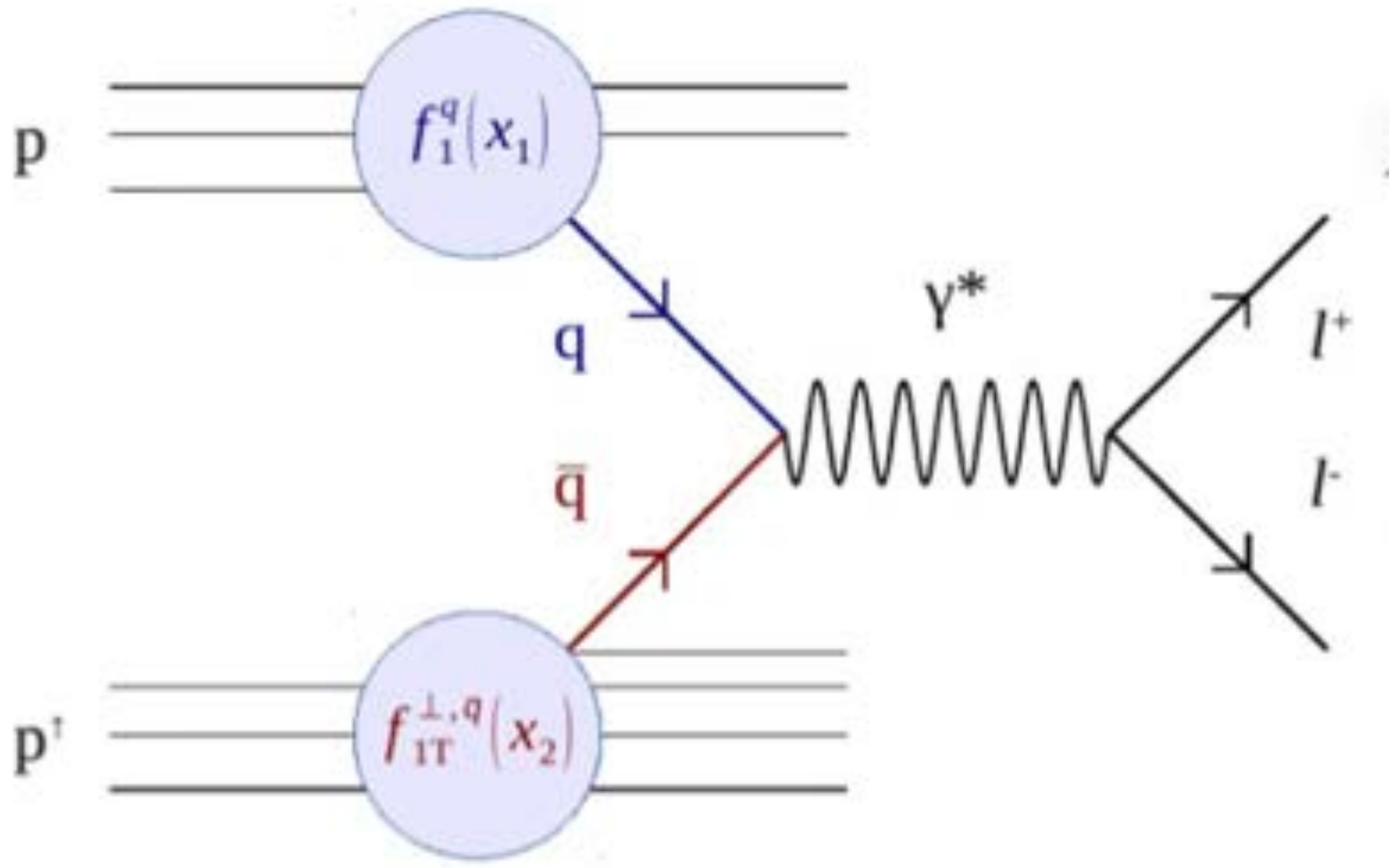
$$A_{T}^{\sin \varphi_s} \propto f_1^{q} \otimes f_{1T}^{\perp q}$$

$$A_{T}^{\sin(2\varphi_S - \varphi_s)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$$

$$A_{T}^{\sin(2\varphi_c s + \varphi_s)} \propto h_1^{\perp q} \otimes h_1^{q}$$

Accessing TMDs





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$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$h_1^q\Big|_{SIDIS} = h_1^q\Big|_{DY}$$

$$h_{1T}^{\perp q}\Big|_{SIDIS} = h_{1T}^{\perp q}\Big|_{DY}$$

$$h_1^{\perp q}\Big|_{SIDIS} = -\,h_1^{\perp q}\Big|_{DY}$$

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

$$A_T^{\cos 2\varphi_{cs}} \propto h_1^{\perp q} \otimes h_1^{\perp q}$$

$$A_T^{\sin \varphi_s} \propto f_1^q \otimes f_{1T}^{\perp q}$$

$$A_T^{\sin(2\varphi_{cs} - \varphi_s)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$$

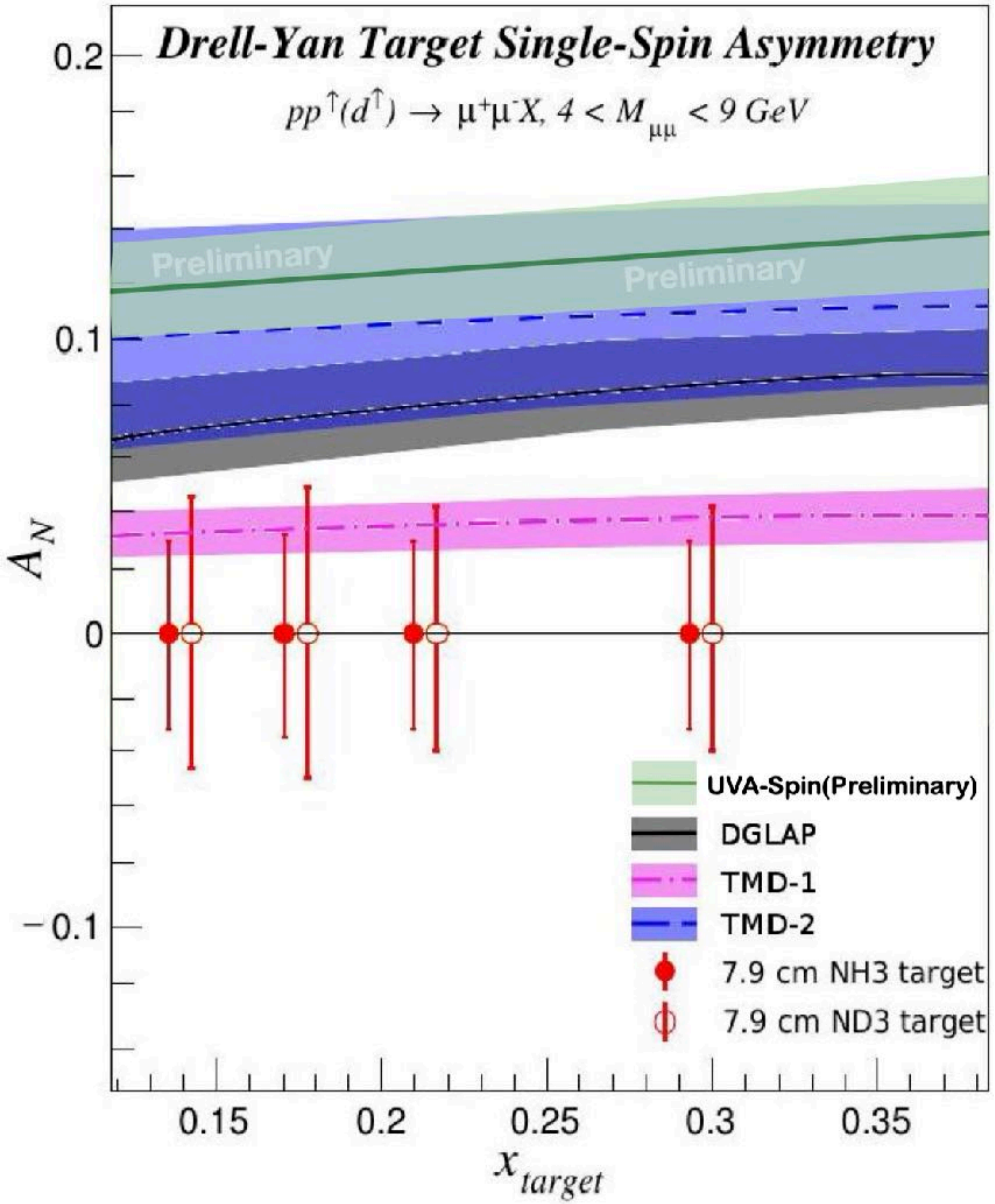
$$A_T^{\sin(2\varphi_{cs} + \varphi_s)} \propto h_1^{\perp q} \otimes h_1^{q}$$

SpinQuest Projection

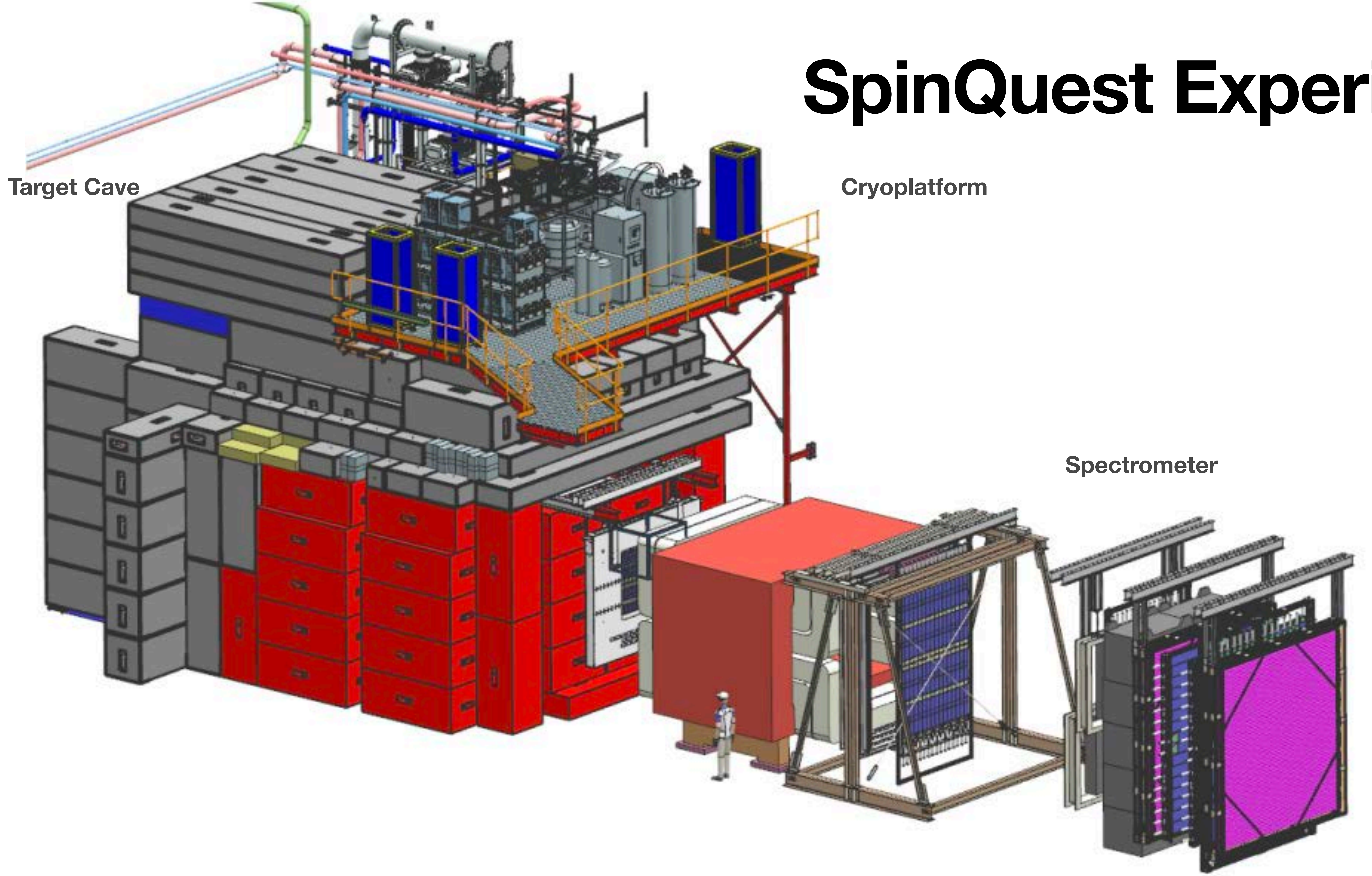
$$A_N\left(p_{beam}+p^{\uparrow}_{target}\rightarrow DY\right)\propto\frac{N_L^{DY}-N_R^{DY}}{N_L^{DY}+N_R^{DY}}\propto\frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

$$A_N\left(p_{beam}+d^{\uparrow}_{target}\rightarrow DY\right)\propto\frac{N_L^{DY}-N_R^{DY}}{N_L^{DY}+N_R^{DY}}\propto\frac{f_{1T}^{\perp,\bar{d}}(x_t)}{f_1^{\bar{d}}(x_t)}$$

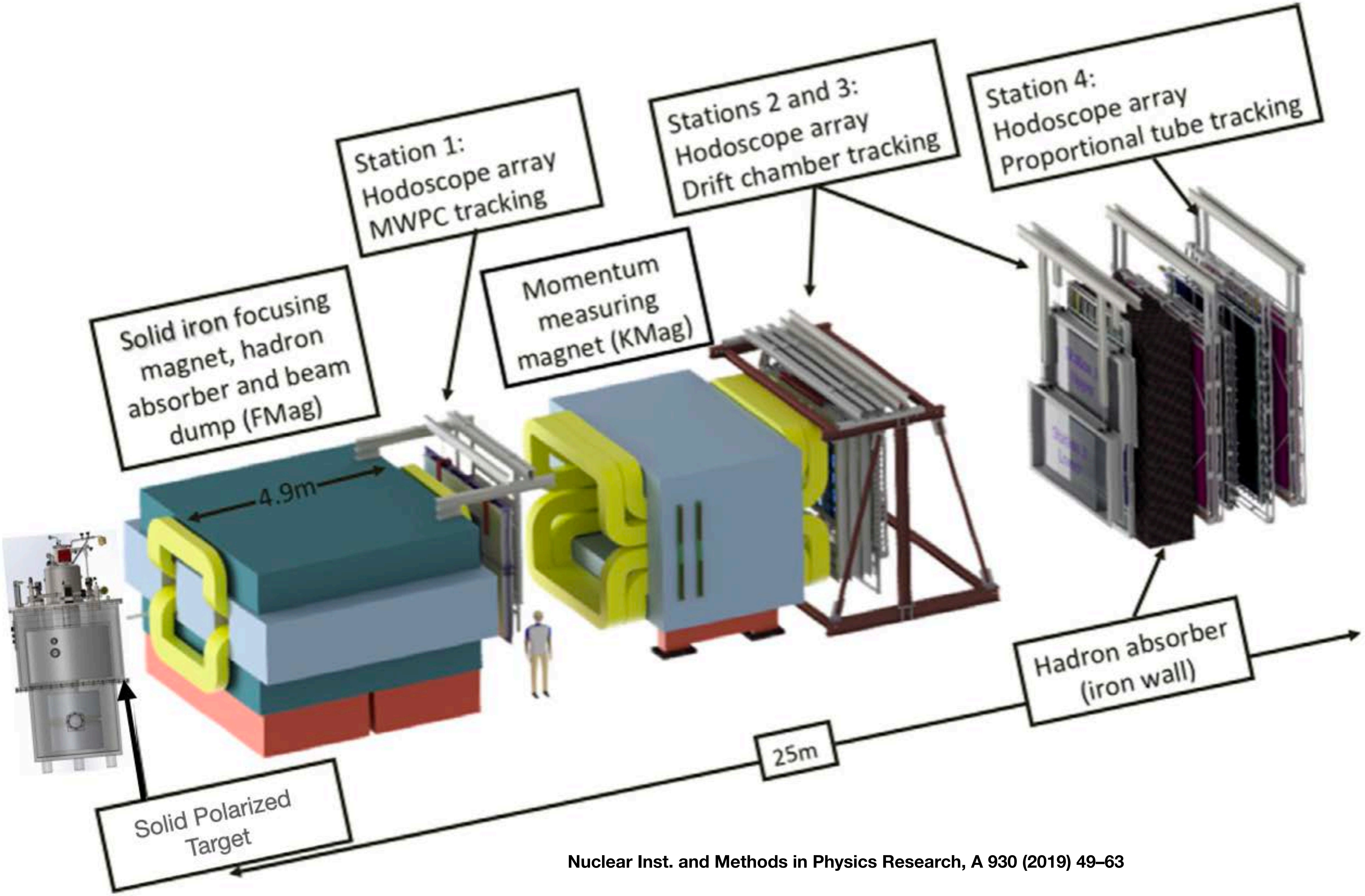
- $\sqrt{s} = 15.5$ GeV
- 4.4 seconds spill $<10^{12}$ p/s
- $\sim 10^{17}$ protons per year for 2 years
- We are set to have the highest instantaneous proton intensity on PT



SpinQuest Experiment



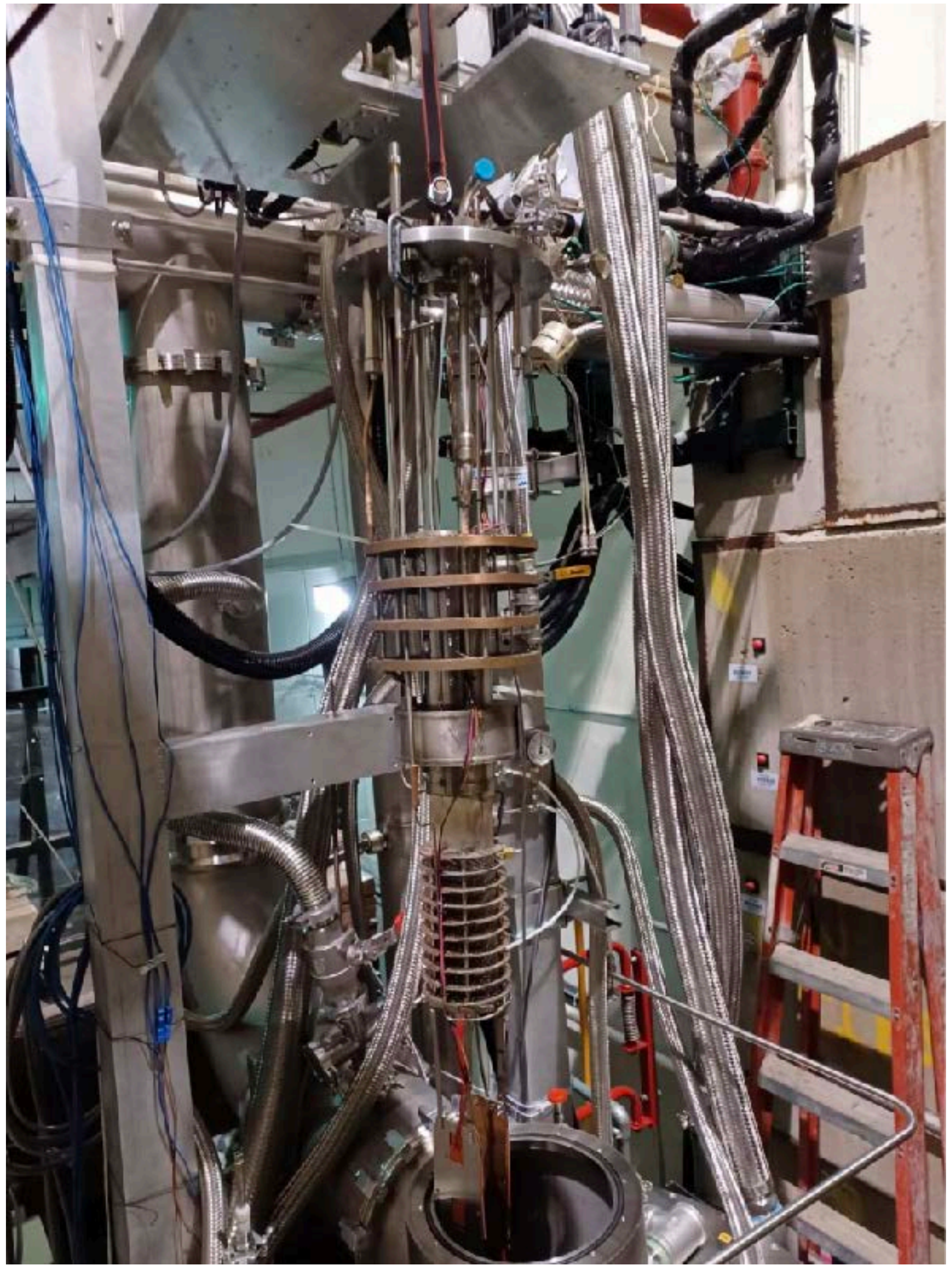
SpinQuest Experimental Setup



Nuclear Inst. and Methods in Physics Research, A 930 (2019) 49–63

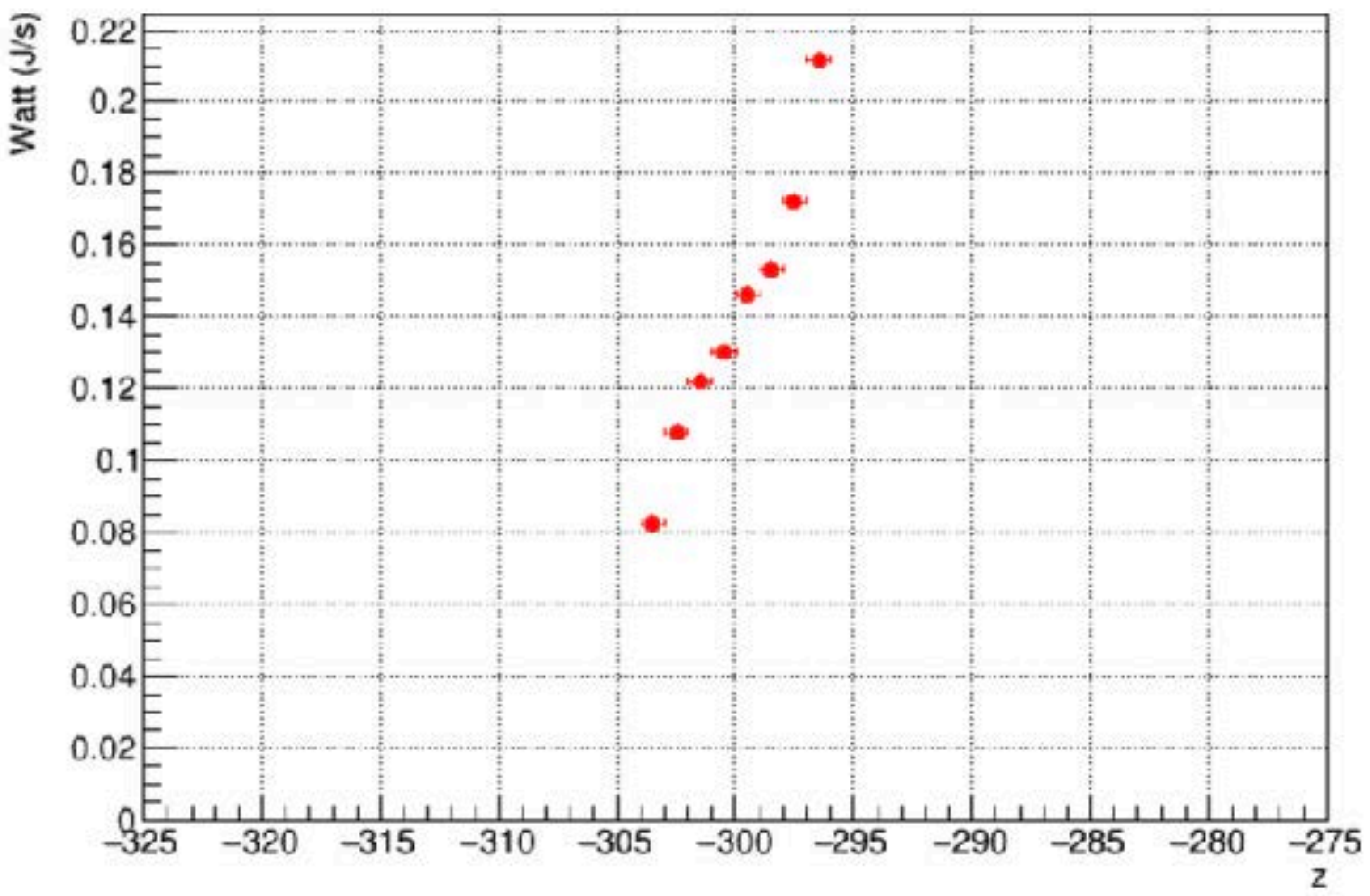
High Intensity Proton Running

With a Polarized Target



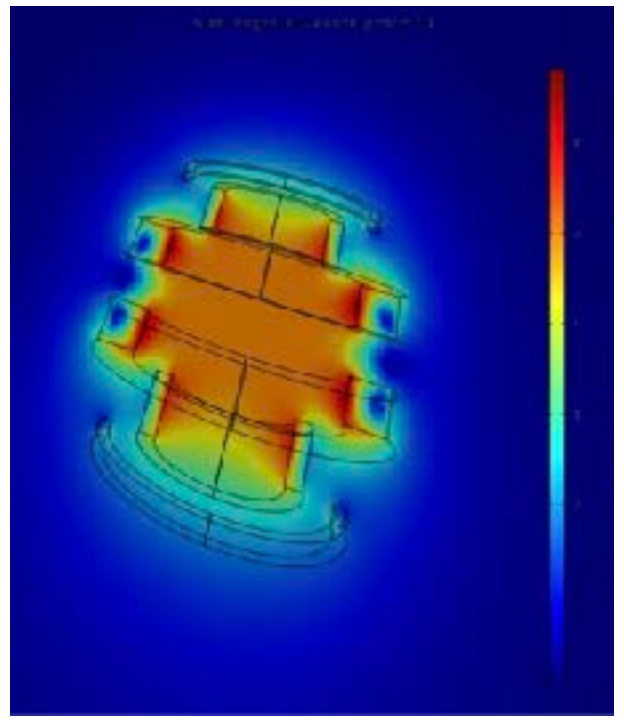
1.4 W at 1 K assuming a flow rate of 20 SLPM
but can support as high as 4 W of cooling power

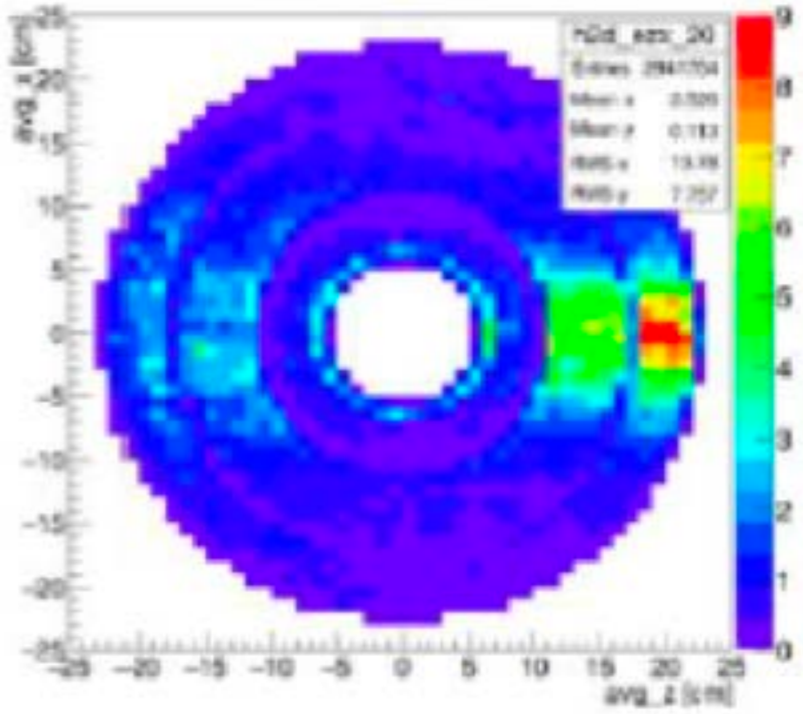
- Magnet limitation
- Fridge limitation
- Punctuated heat load
- Long target cell



High Intensity Proton Running

With a Polarized Target

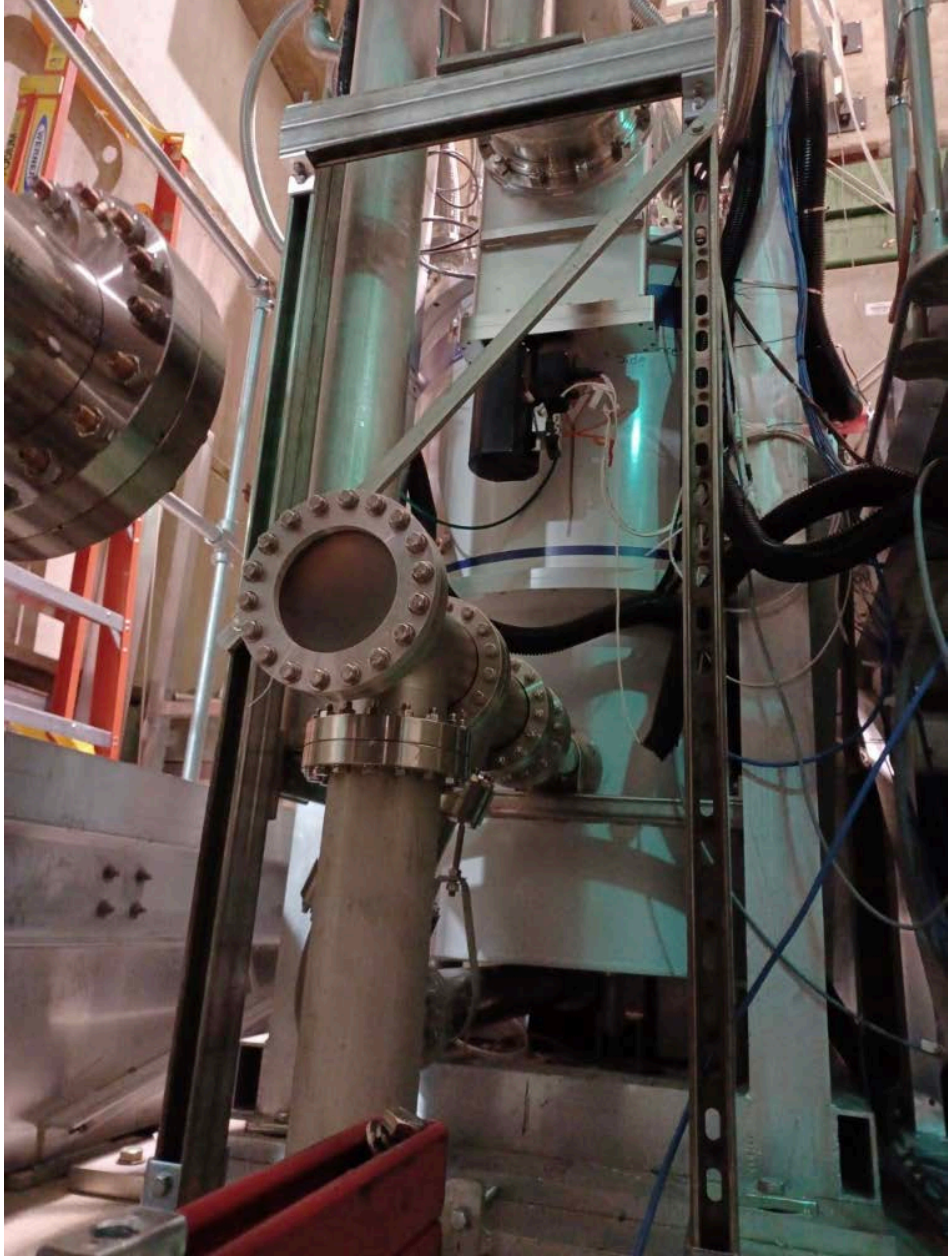




Config	pro/s	Rel. error
No Pumping	$< 1 \times 10^{12}$	10%
100 SLM	$< 3 \times 10^{12}$	20%

Roots pumps capable of 17,000 m^3/h

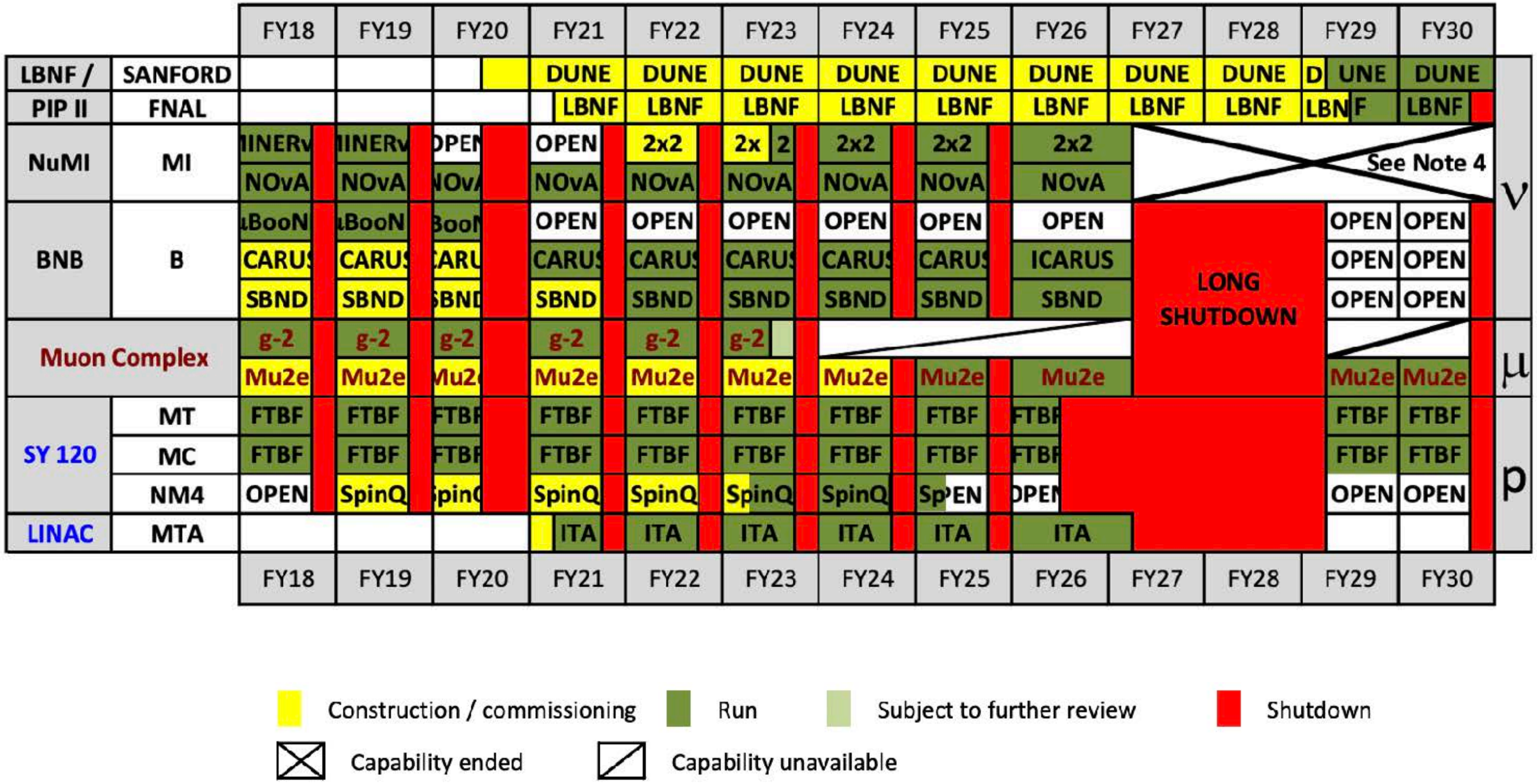

Genie



SpinQuest Important (rough) Dates

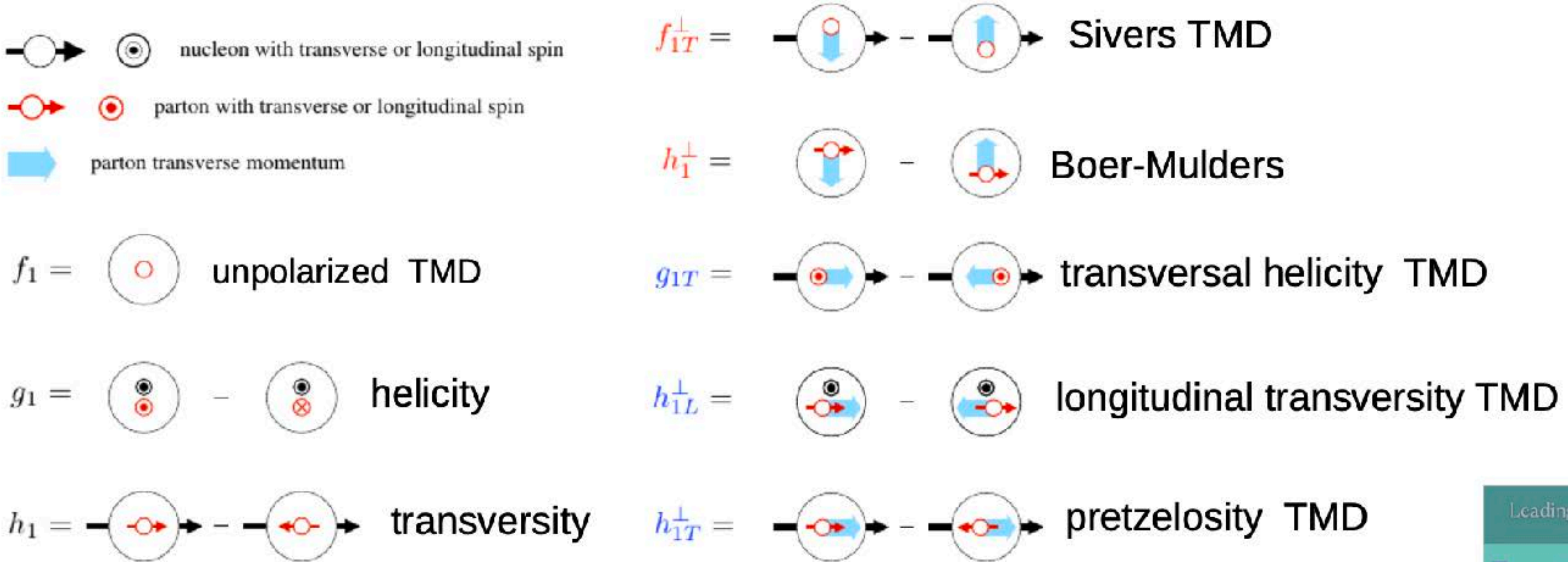
- February 2021: Started commissioning using cosmic rays
- Spring 2022: QT and Polarized target installed
- July 2022: QT Commissioning started
- September 2022: Target Magnet first cooldown
- October 2022: Accelerator Readiness Review
- November 2022: Polarized Target Commissioning
- January 2023: Polarized Target and Beam Commissioning
- March 2023: Day-1 Physics (J/psi asymmetry)
- Summer 2023: Operational Readiness Review
- Begin production runs for 2+ years

The SpinQuest Timeline (unofficial) at Fermilab



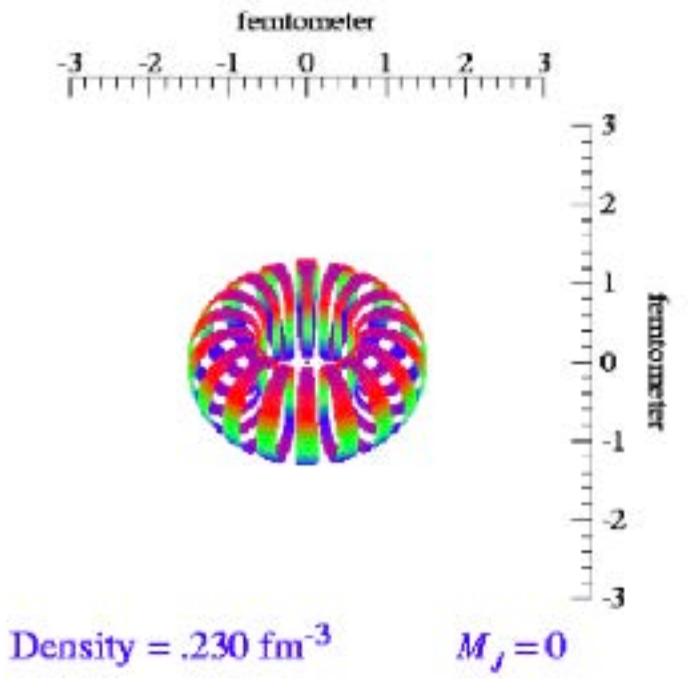
Separation of sea-quark and gluon TMDs

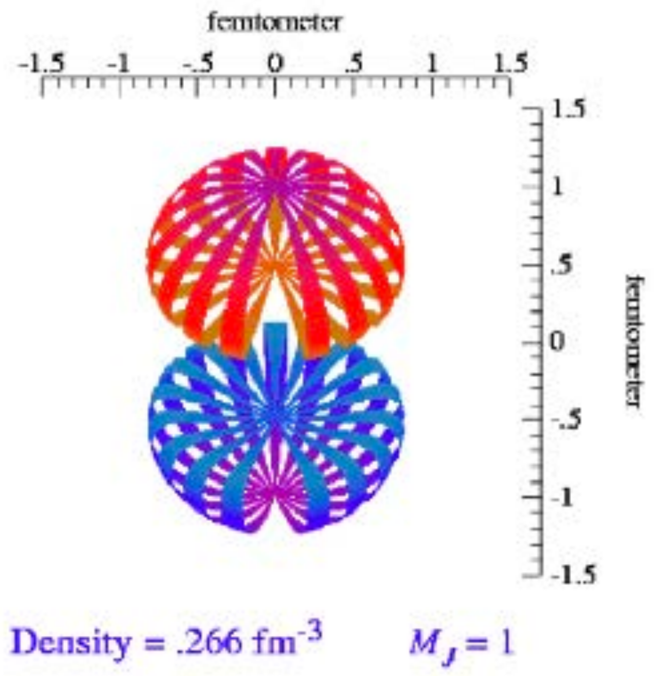
A way to extract information on the dynamics and spin structure of nuclei

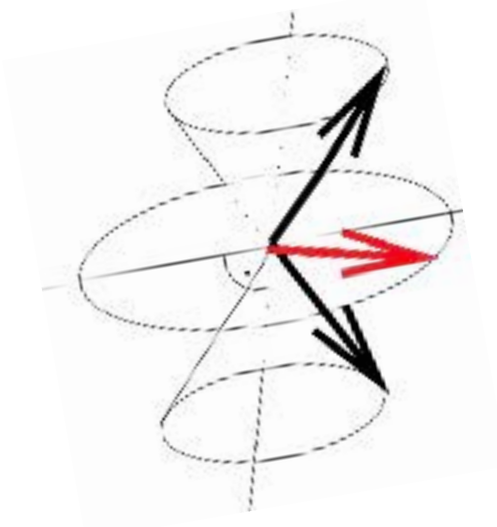


quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$







J. L. Forest et al. Phys. Rev. C54,646-667 (1996).

Gluon Operator

Target Polarization	Leading Twist	Unpolarized	Circular	Linear
Vector Polarized	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$
Tensor Polarized	LL	f_{1LL}		$h_{1LL}^\perp$
	LT	f_{1LT}	g_{1LT}	$h_{1LT}, h_{1LT}^\perp$
	TT	f_{1TT}	g_{1TT}	h_{1TT}, $h_{1TT}^\perp$, $h_{1TT}^{\perp\perp}$

The Transverse Structure of the Deuteron

With Drell-Yan

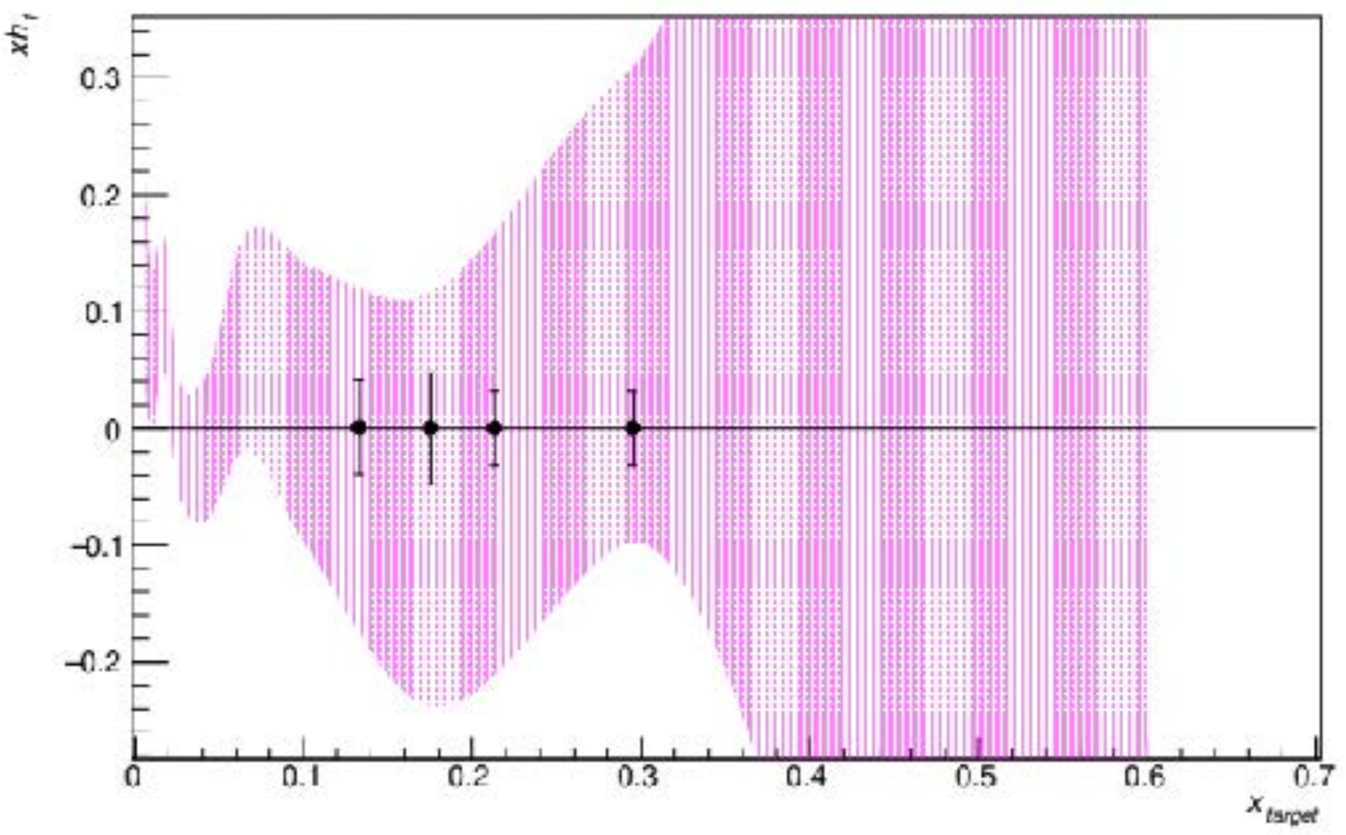
https://arxiv.org/pdf/2205.01249.pdf

- Quark transversely distributions decoupled from the gluon transversity in Q^2
- Polarized nuclei with spin ≥ 1, due to helicity-flip (chiral-odd) property
- Tensor Force Largely responsible for the geometry
- Use DY as a probe to understand this geometric properties in terms of quark gluon dynamics
- Vanish for nucleus made up of just protons and neutrons (gluon distribution not related to the nucleons: deep binding, polarized EMC, hidden color, geometry)
- Cleanly access $\bar{d}$ sea-quark and gluon transversity using novel DY-asymmetries
- A probe of linearly polarized gluons in the target using h^g_{1TT}

$$h^g_{1TT}|_{SIDIS} = h^g_{1TT}|_{DY}$$

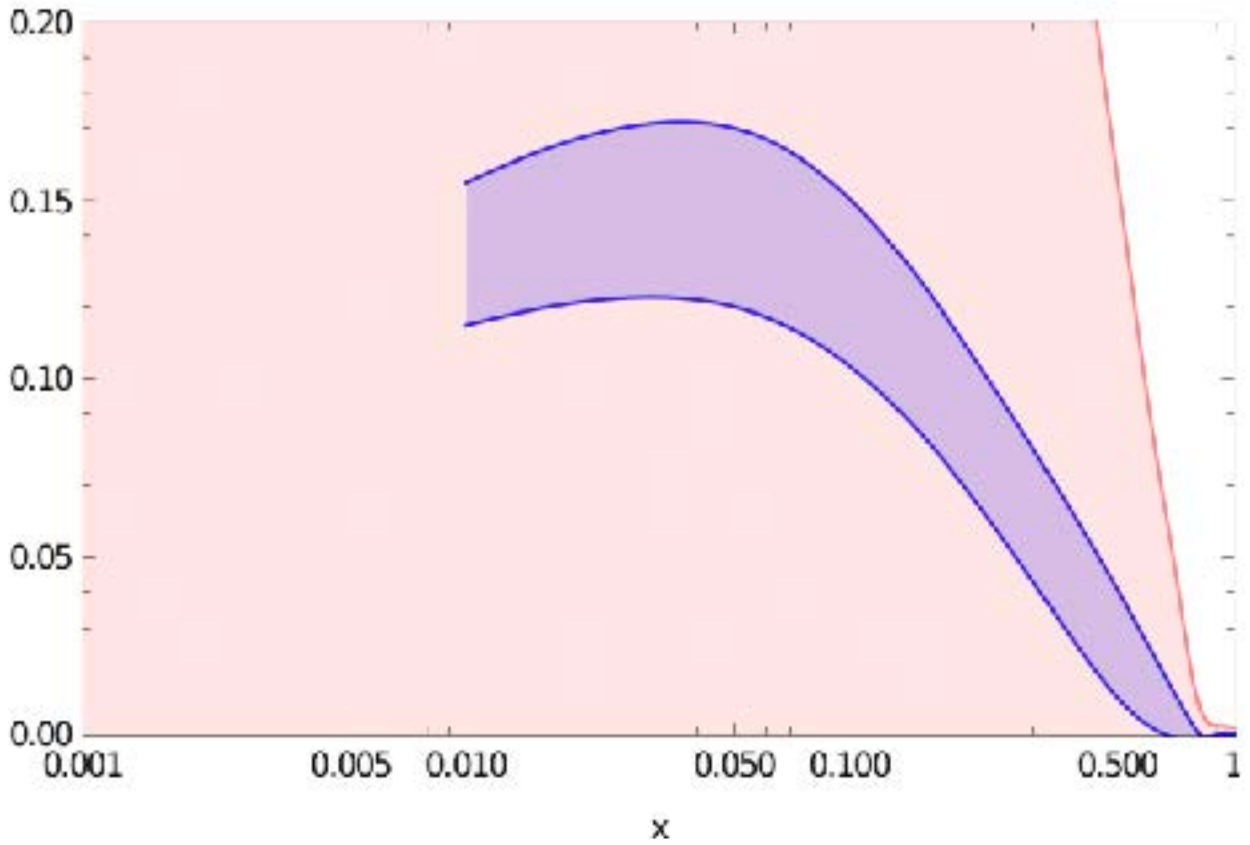
Transverse Structure of the Spin-1 Target

SeaQuark Transversity



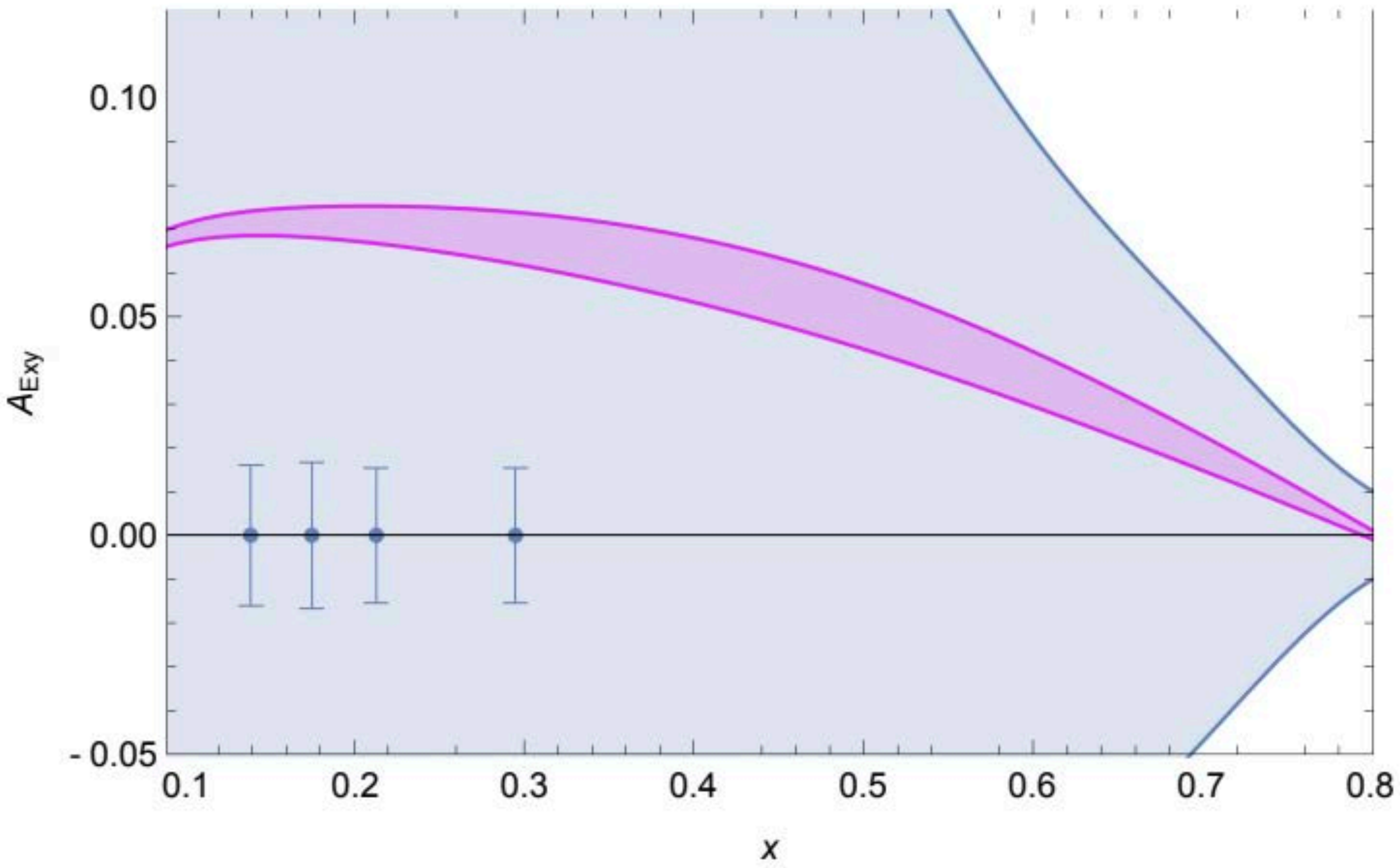
A. Martin, F. Bardamante, and V. Barone, Phys. Rev. D 91, 014034

Gluon Transversity



S. Kumano and Qin-Tao Song, Phys. Rev. D 101, 054011 (2020).

Gluon Tensor Transvers Asymmetry



- Very High Proton Luminosity from main Injector
- Large Kinematic coverage that overlaps with SIDIS JLab and Future EIC
- Beam cycle allows target RF manipulations between spills
- June FNAL PAC (Transversity/Dark) encouraged us to move forward and return to request stage-1 approval (Nov 2022)

Thank You

Thinking of Joining SpinQuest or Future Projects:

(liuk.pku@gmail.com, dustin@virginia.edu)

https://spinquest.fnal.gov/

http://twist.phys.virginia.edu/E1039/

The SpinQuest Collaboration

Fermilab

https://spinquest.fnal.gov/

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2) Argonne National Laboratory	Paul Reimer (PI), Donald Geesaman	Kevin Bailey, Thomas O'Connor
3) Aligarh Muslim University	Huma Haider (PI)	
4) Boston University	David Sperka (PI), Zijie Wan	
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17) Tsinghua University	Zhihong Ye (PI)	
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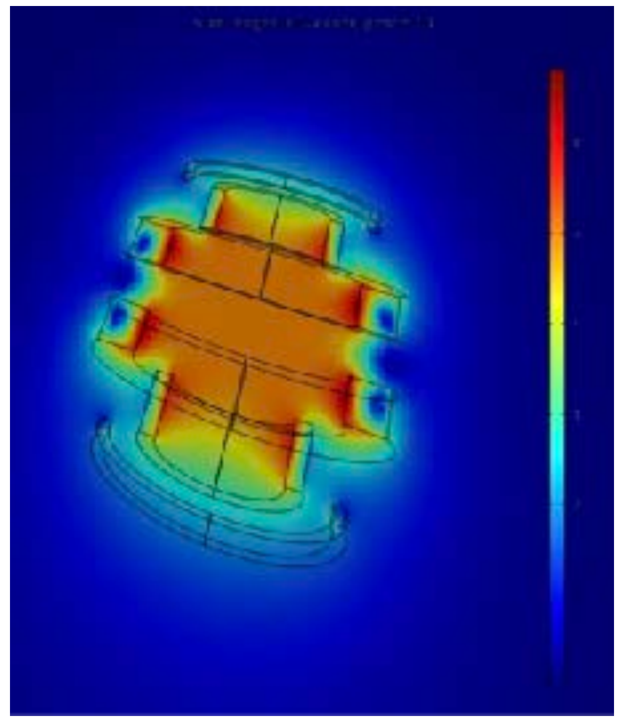
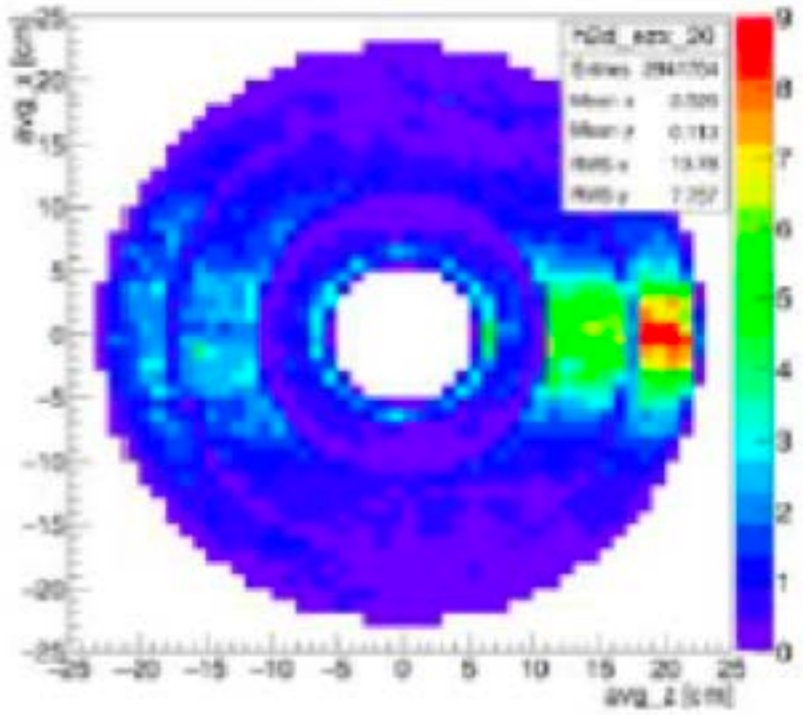
19) Yamagata University	Yoshiyuki Miyachi (PI)	Takahiro Iwata, Norihiro Doshita
20) Yerevan Physics Institute	Hrachya Marukyan (PI)	

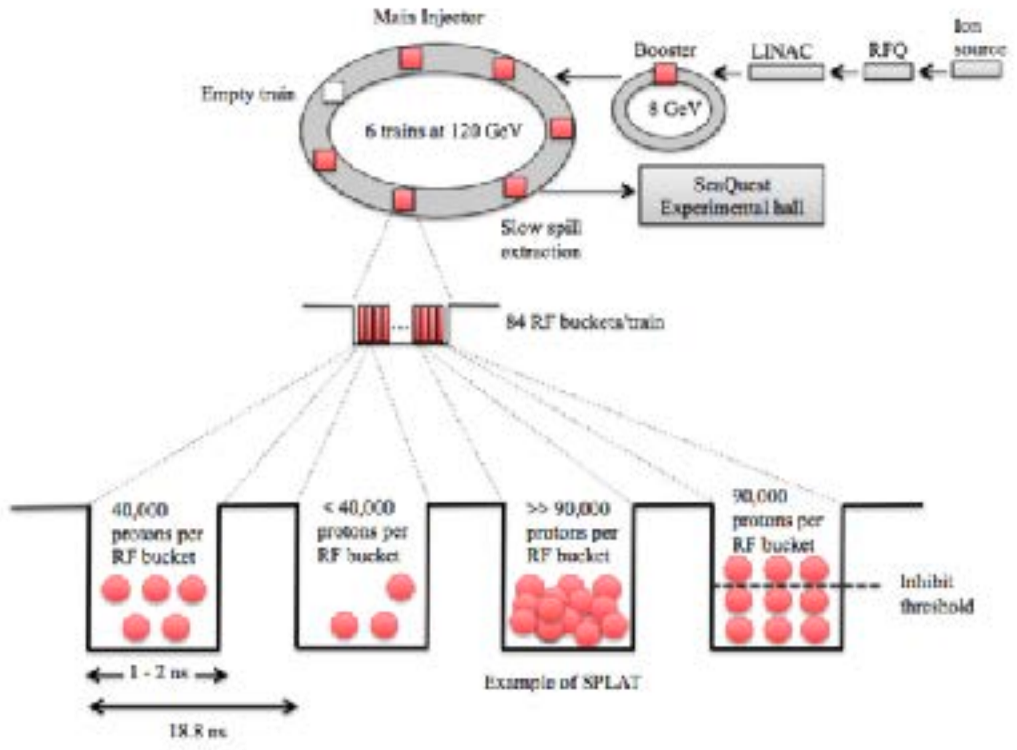
High Intensity Proton Running

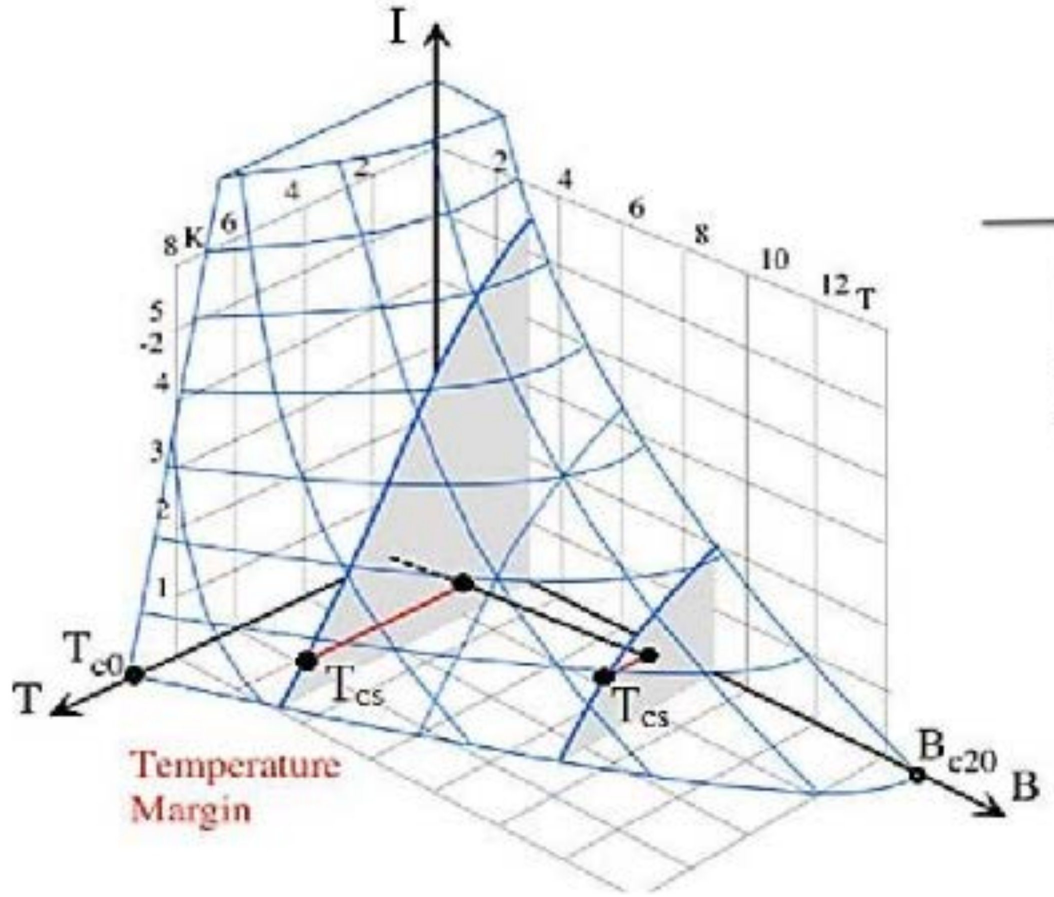
With a Polarized Target



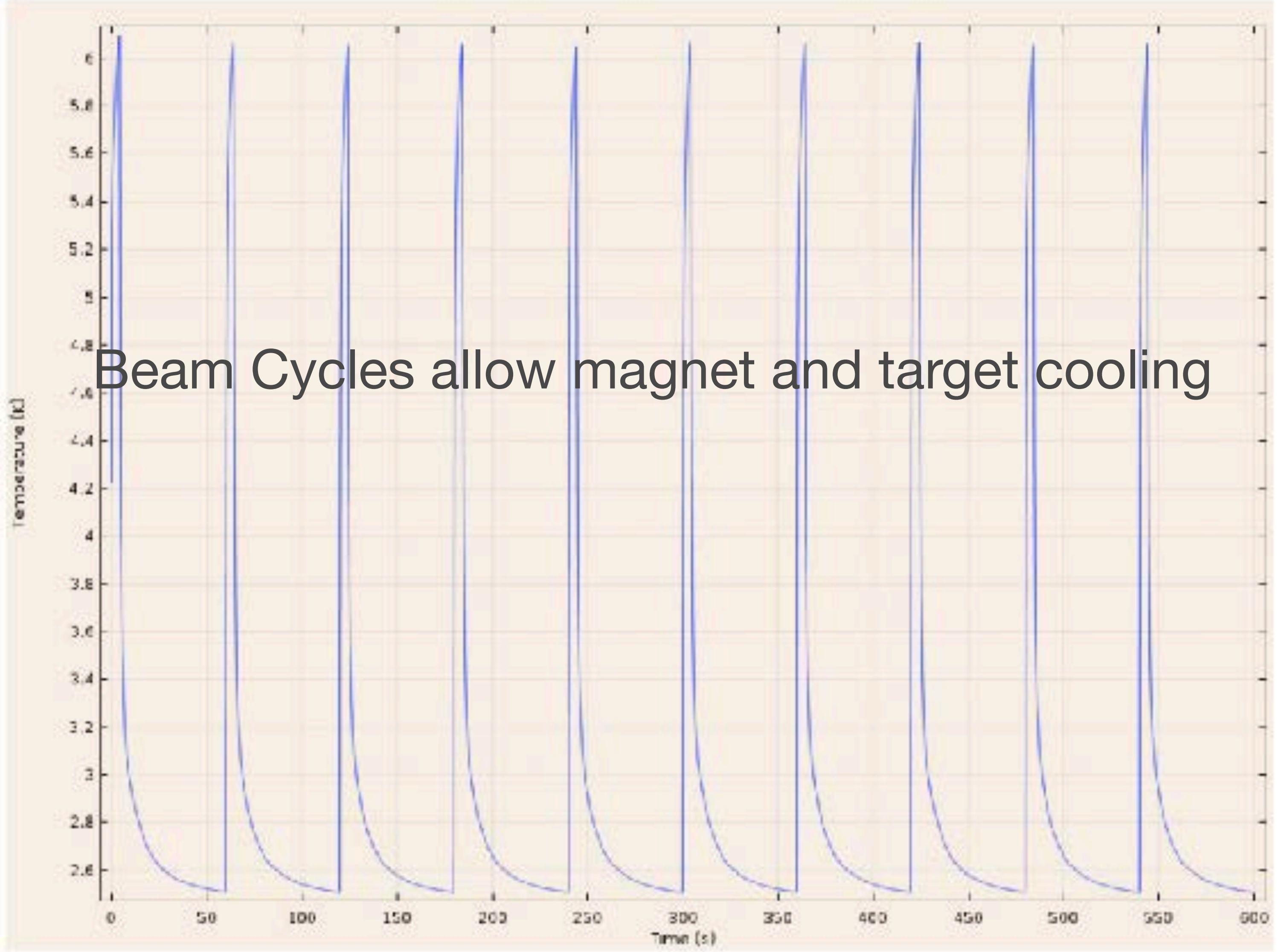


Config	prot/s	Rel. error
No Pumping	$< 1 \times 10^{12}$	10%
100 SLM	$< 3 \times 10^{12}$	20%





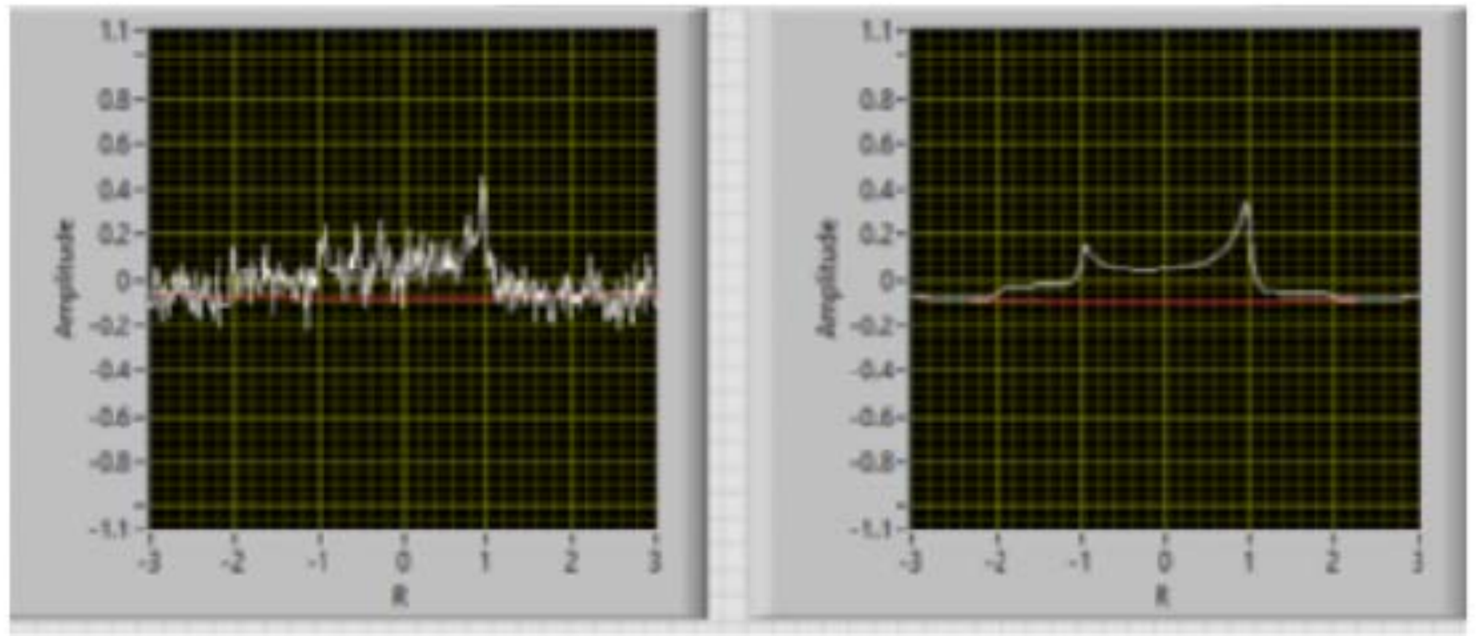
4.4s of beam
55.6s to recover



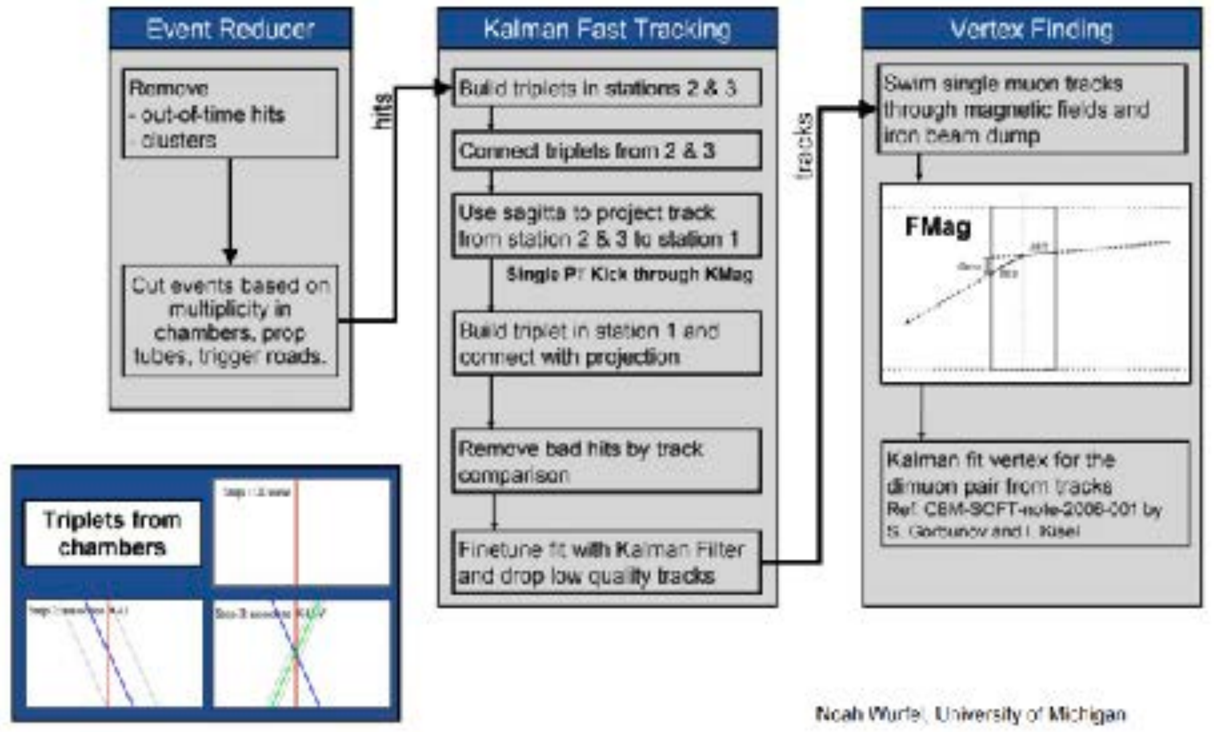
Beam Cycles allow magnet and target cooling

Simulation study: Zulkaida Akbar, UVA

Artificial Intelligence at SpinQuest



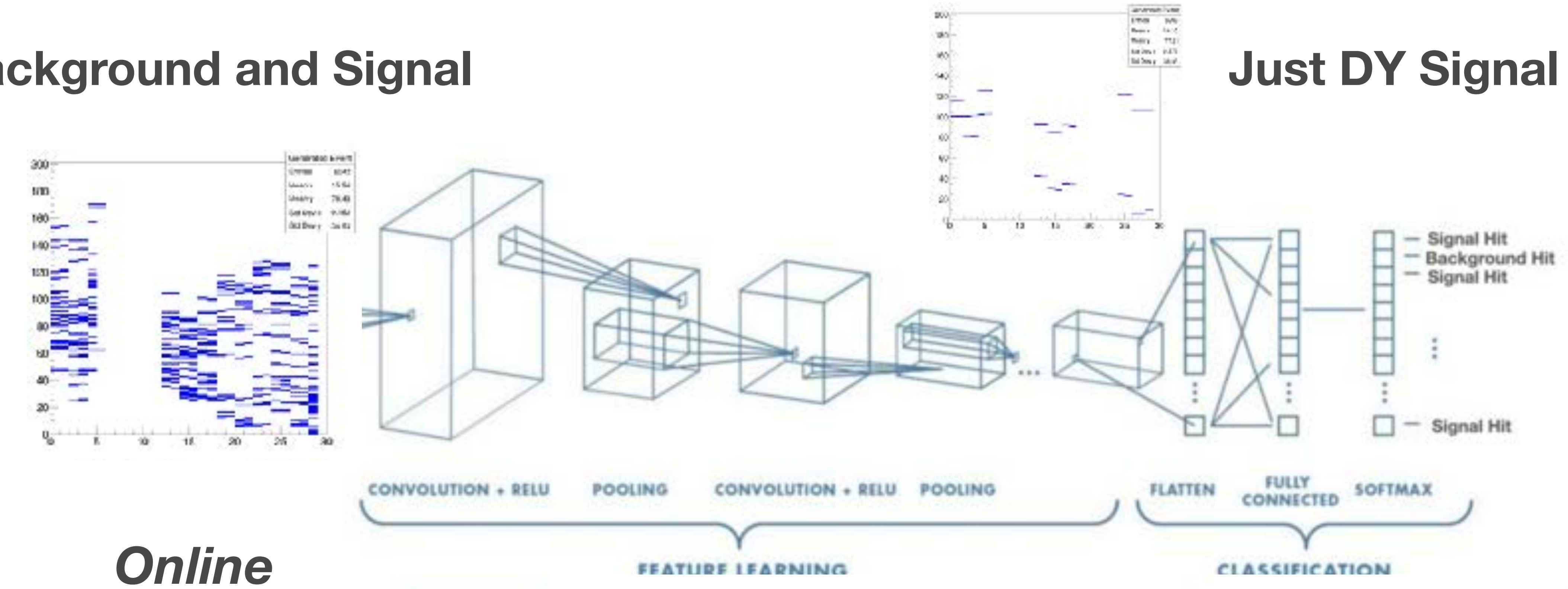
AI NMR Signal Extraction



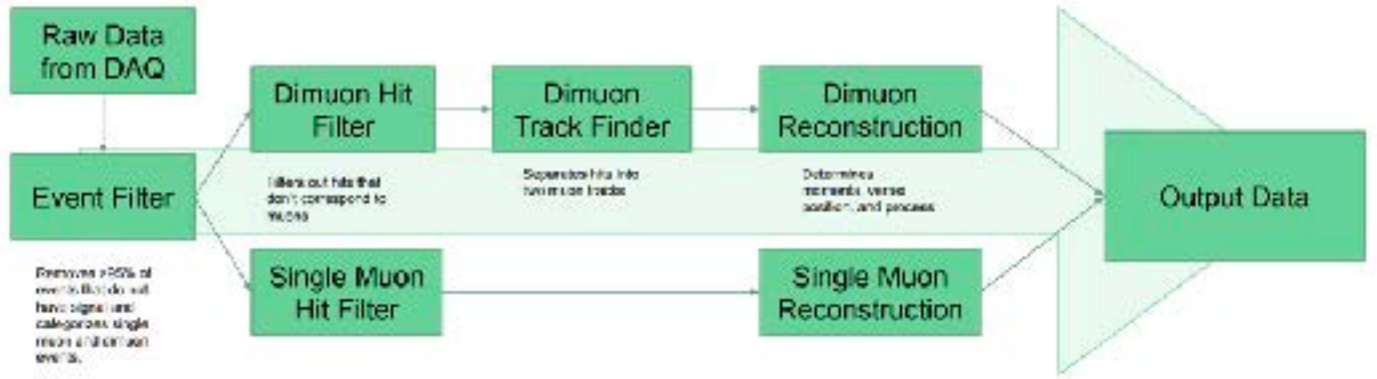
1 CPU: 110 minutes for 40K

Background and Signal

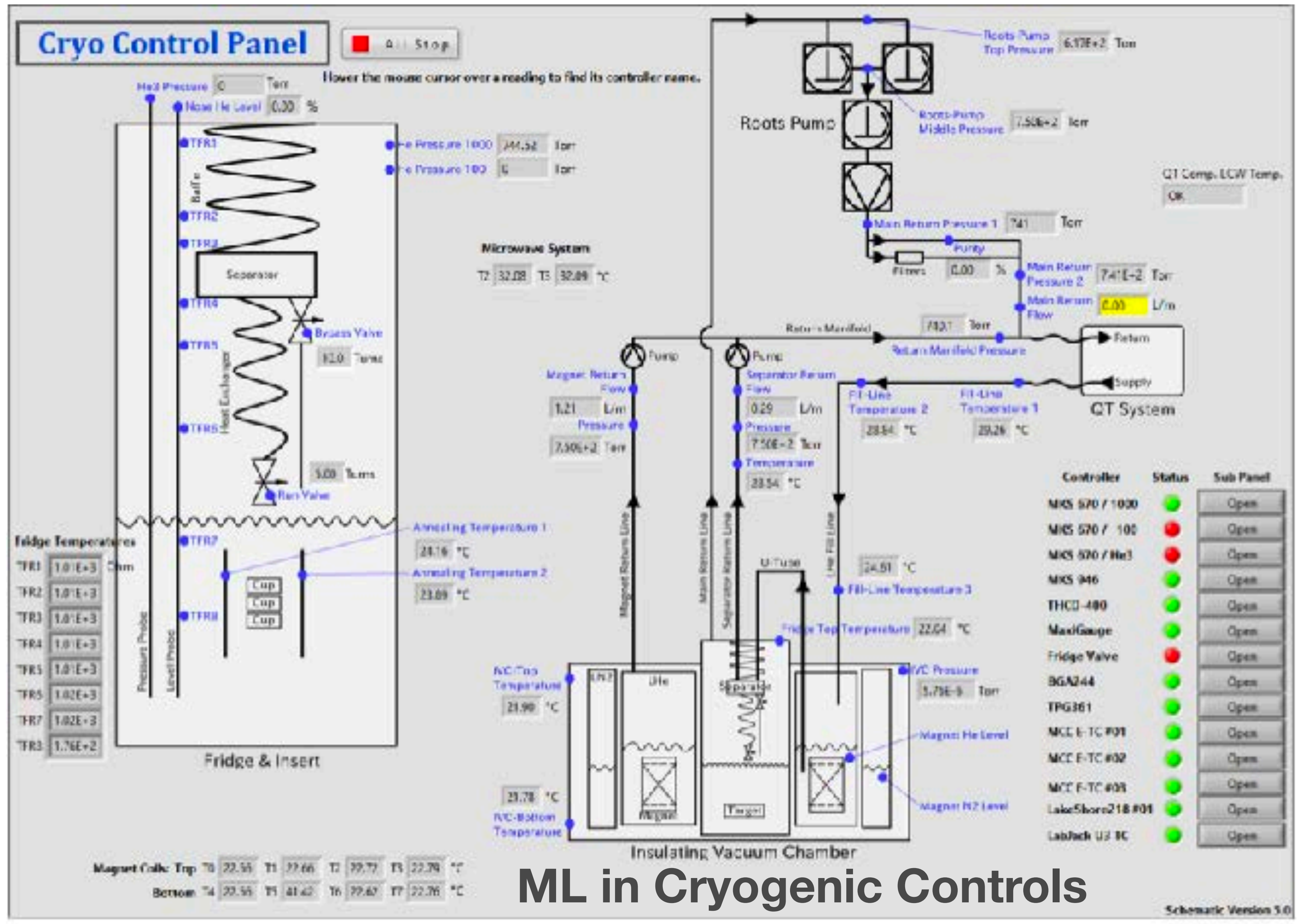
Just DY Signal



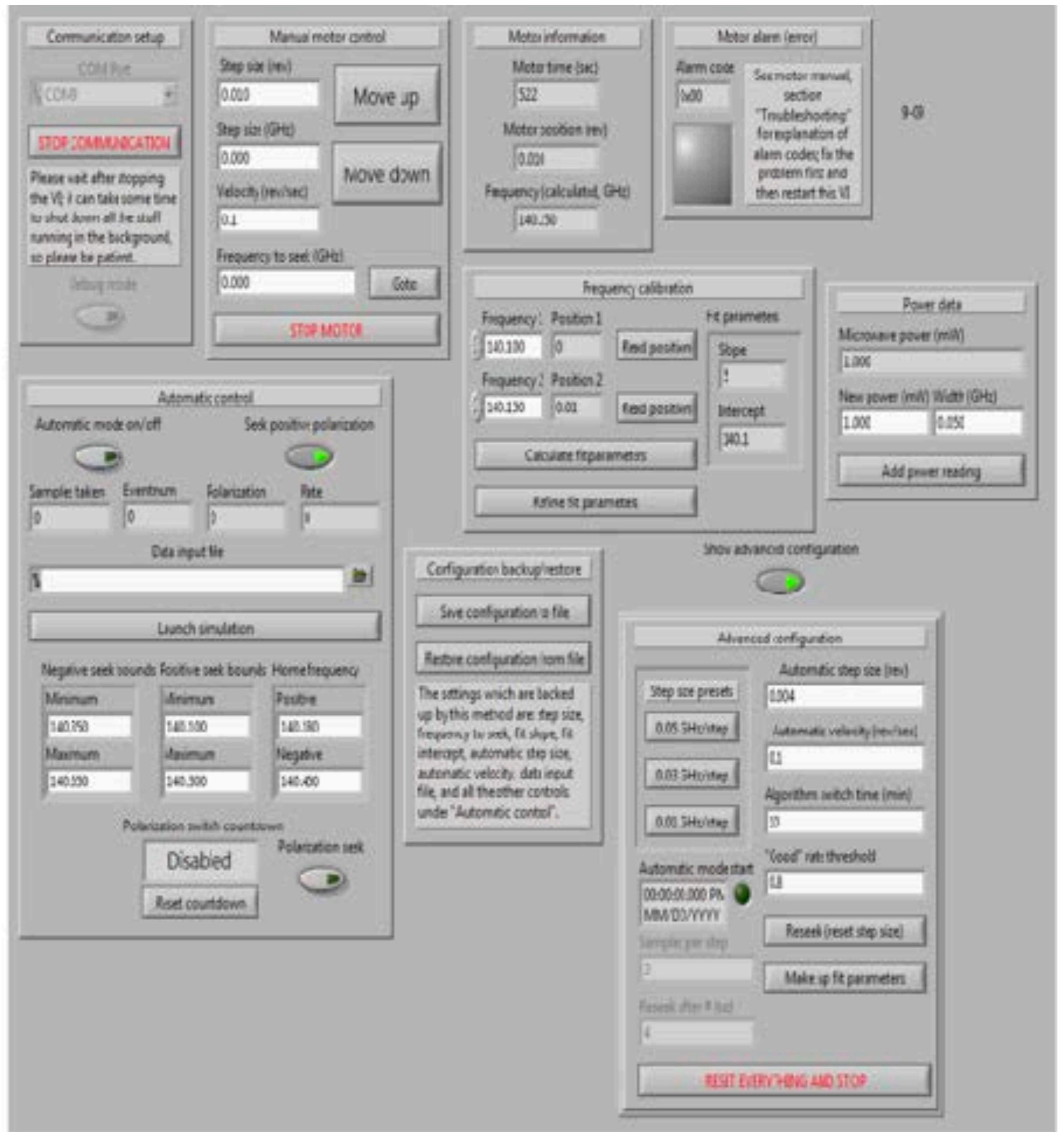
Online Reconstruction



GPU based AI: 4 seconds for 40K



ML in Cryogenic Controls

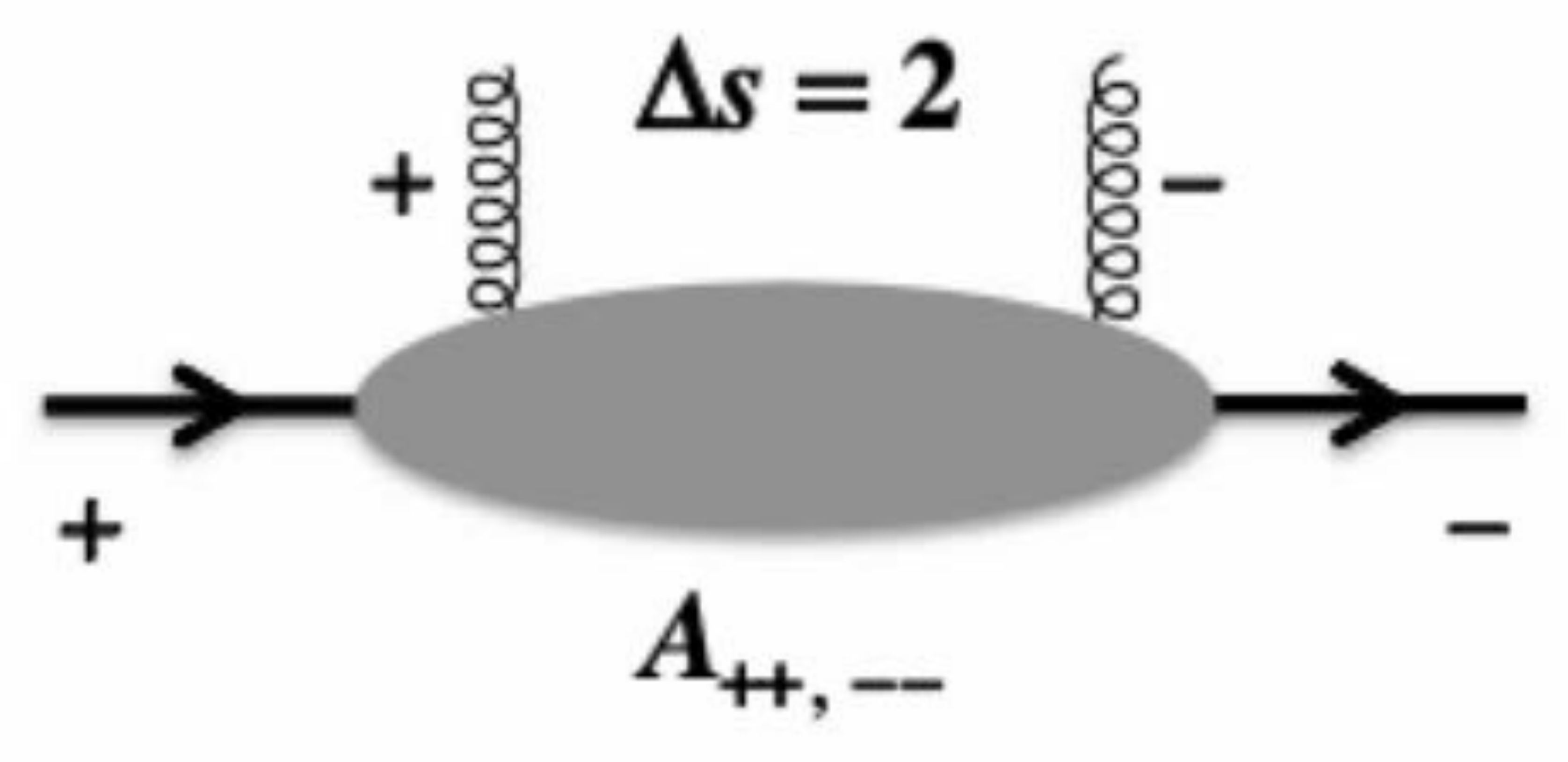


Automated Microwave System

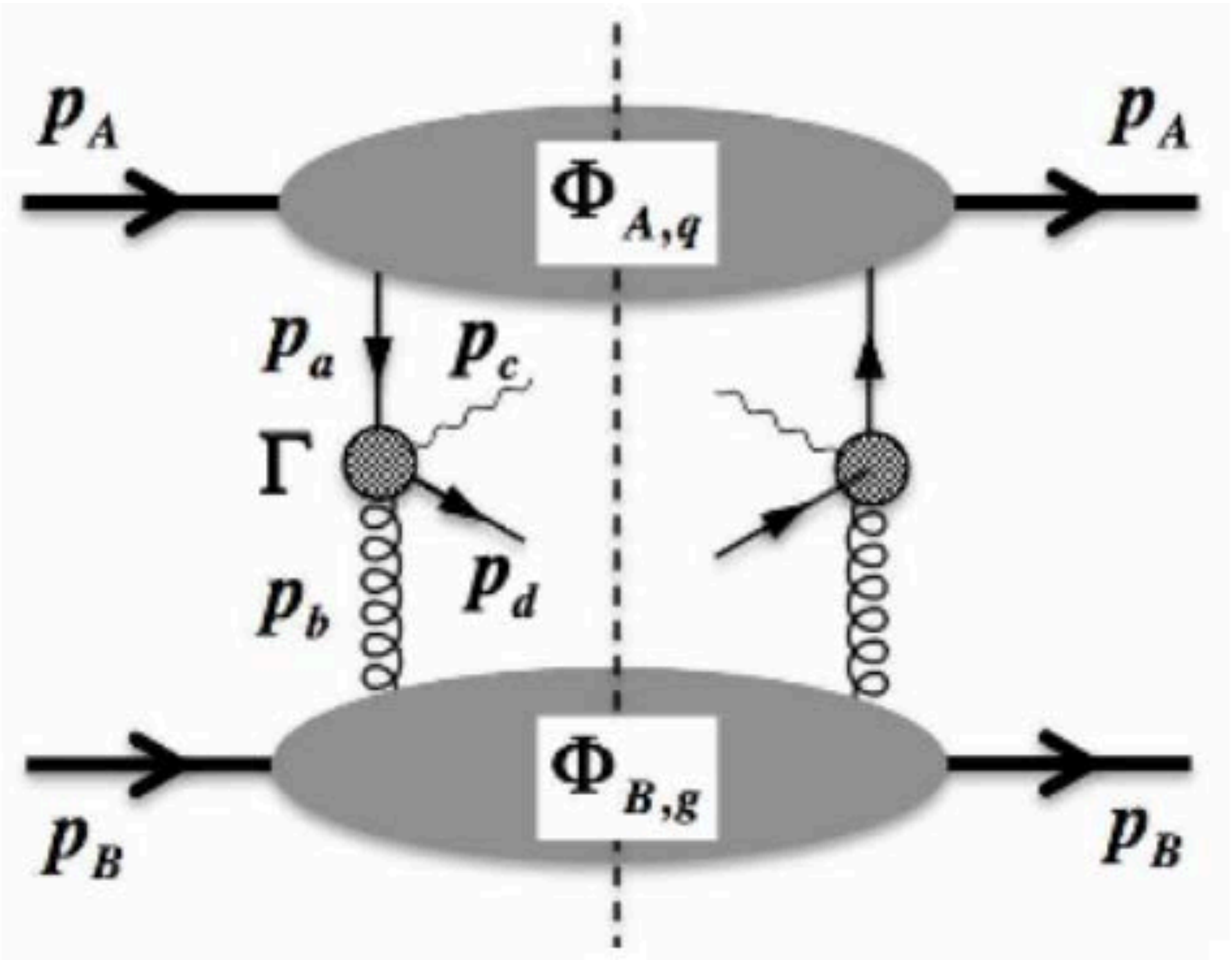
Linearly Polarized Gluons in the Target

Drell-Yan

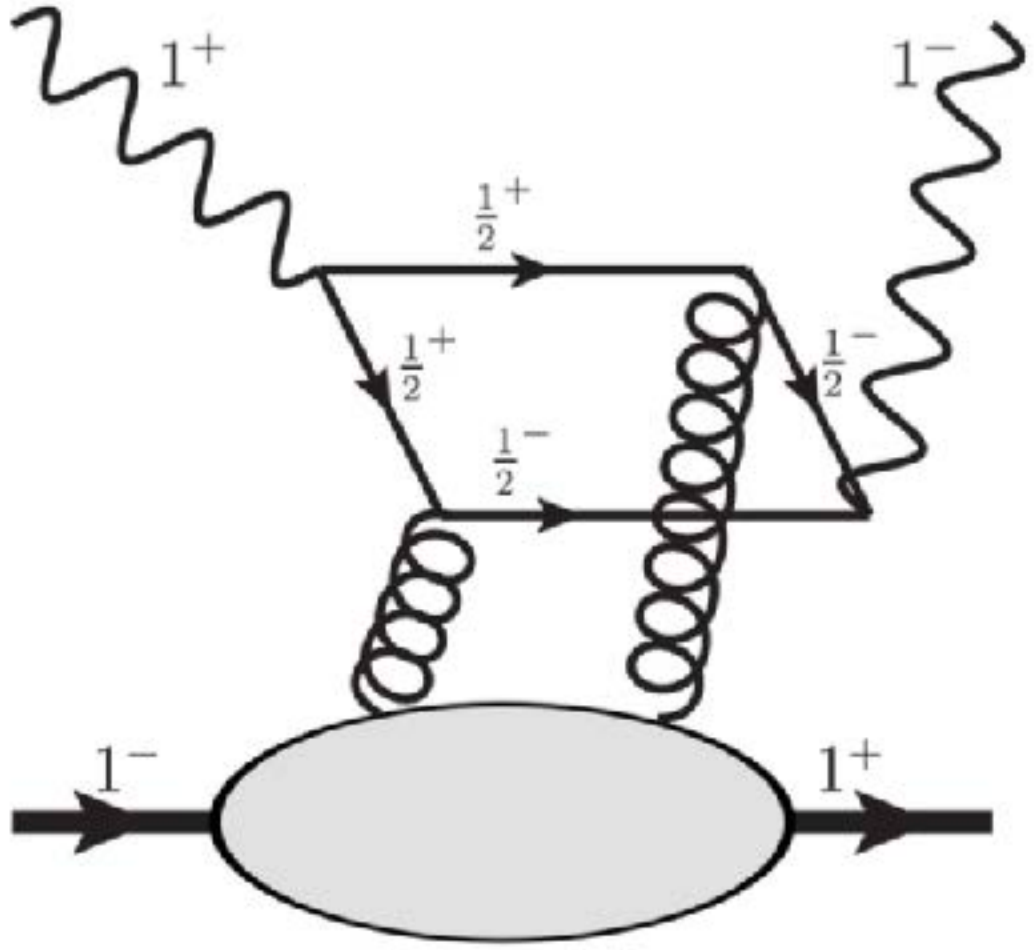
DIS



Gluon-deuteron forward scattering amplitude A++,−−
with the spin flip of 2 (Δs = 2) for gluon transversity.



The Quark-gluon process contribution to the cross-section.



One of the leading contributions in DIS

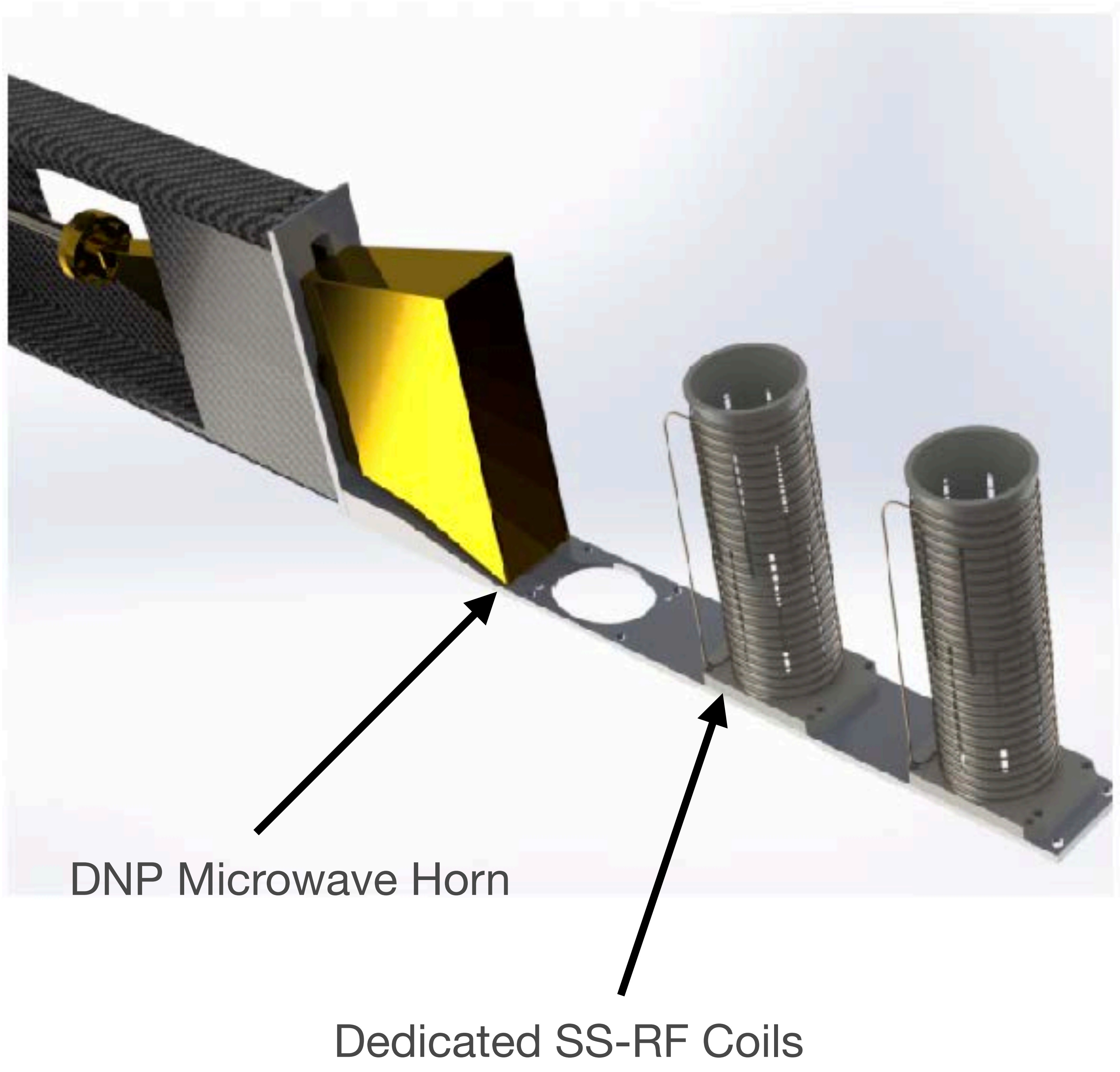
S. Kumano and Qin-Tao Song, Phys. Rev. D 101, 054011 (2020).

PHYSICAL REVIEW D 94, 014507 (2016)

Accessing Transversity

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

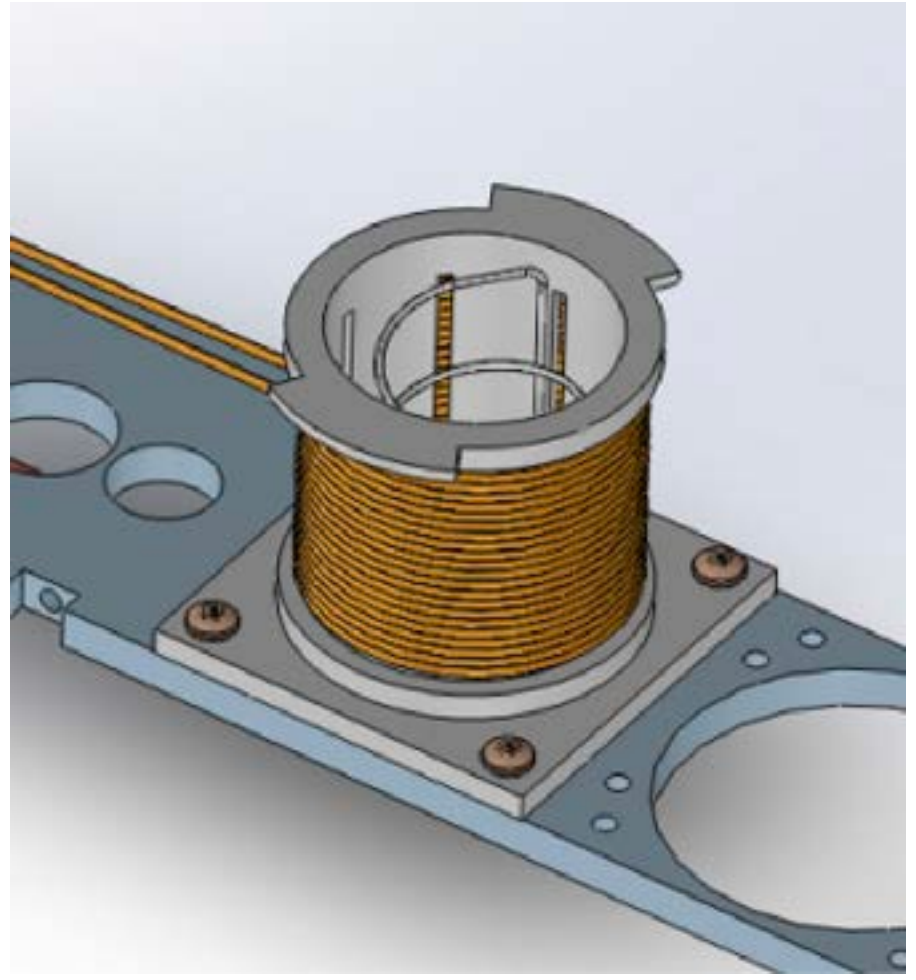
$$A_{E_{xy}} = \frac{2\sigma^{E_x}_{pd\to\mu^+\mu^-X}-\sigma^{U}_{pd\to\mu^+\mu^-X}}{\sigma^{U}_{pd\to\mu^+\mu^-X}} = \frac{1}{fP_{zz}}\frac{2N^{E_x}_{pd\to\mu^+\mu^-X}-N^{U}_{pd\to\mu^+\mu^-X}}{N^{U}_{pd\to\mu^+\mu^-X}},$$

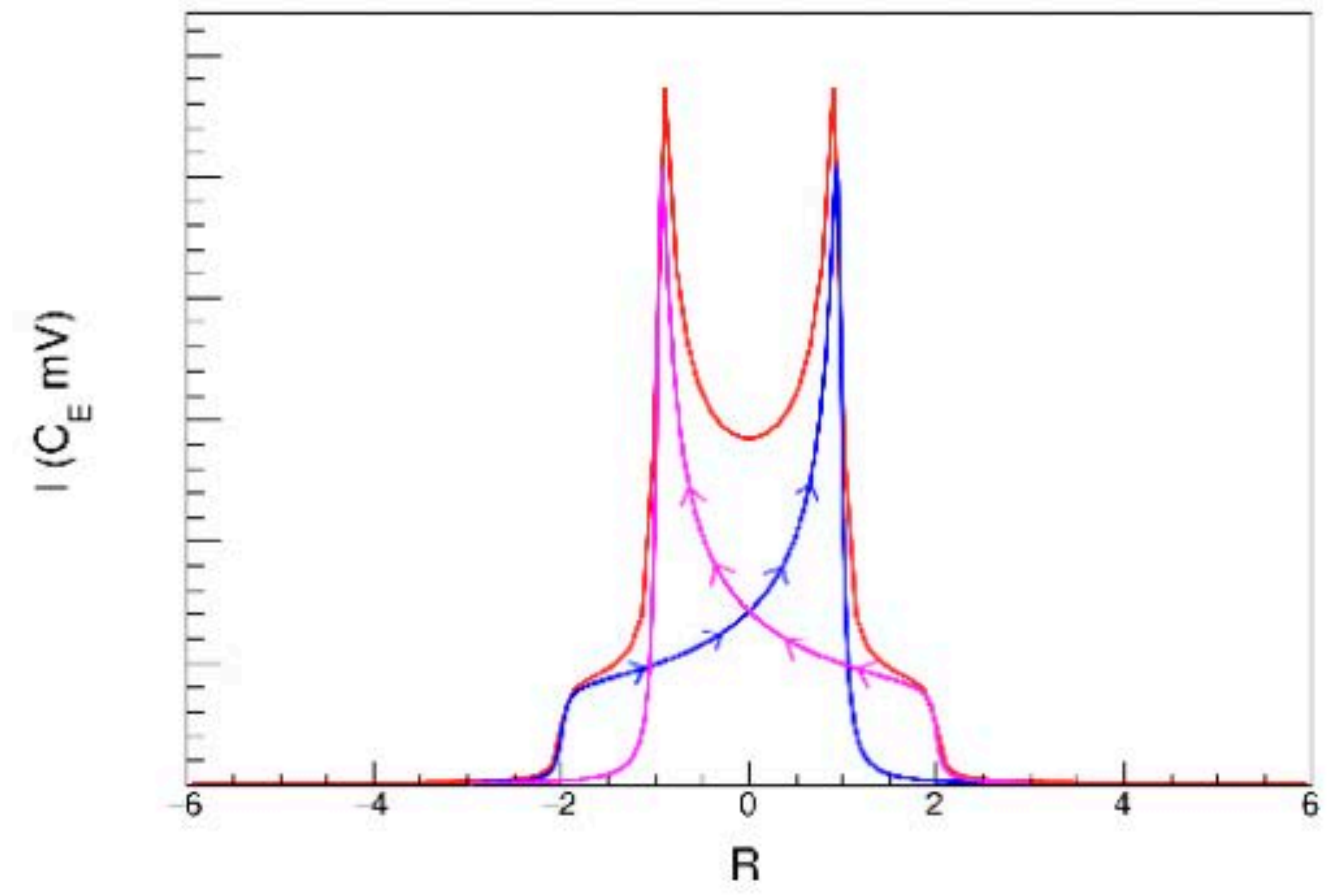


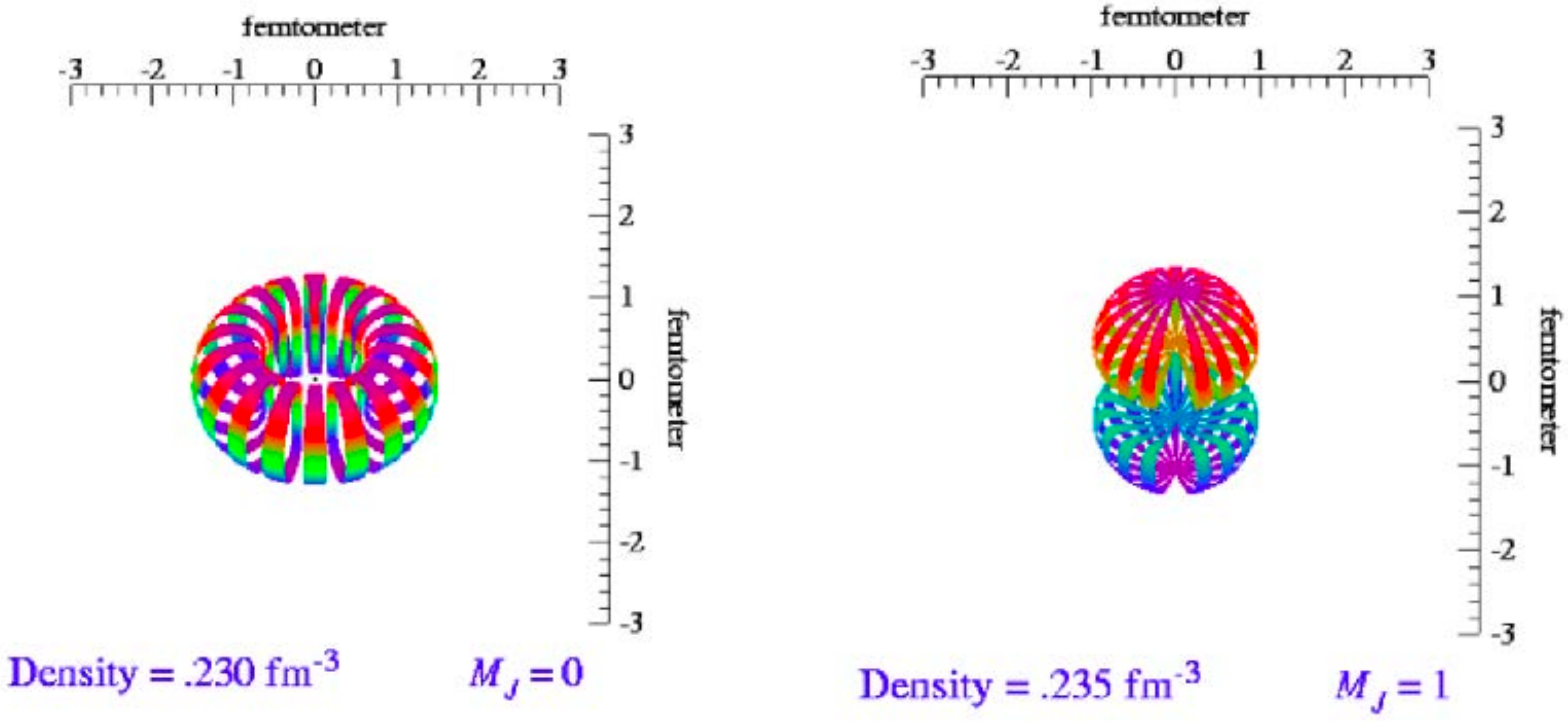
- With E906 and E1039 data $\bar{u}$ and $\bar{d}$ Transversity can be separated and extracted (only possible with the SpinQuest kinematics)
- SpinQuest-X has primary focus on Deuteron Transversity and particularly gluon Transversity but also helps with clean $\bar{d}$ Transversity for m=+/-1 states

AI in Future Experiments

Automated Spin-1 Configuration with AI Drive RF







New NMR technology developed at UVA can manipulate spin but is optimized by AI controls so that the spin manipulation and polarization measurements are continuous across the frequency domain.

For the case of spin-1 there are not an equal number of up and down quarks pairs. In the deuteron there are 1.5 pairs of down quarks and 1.5 pairs of up quarks.

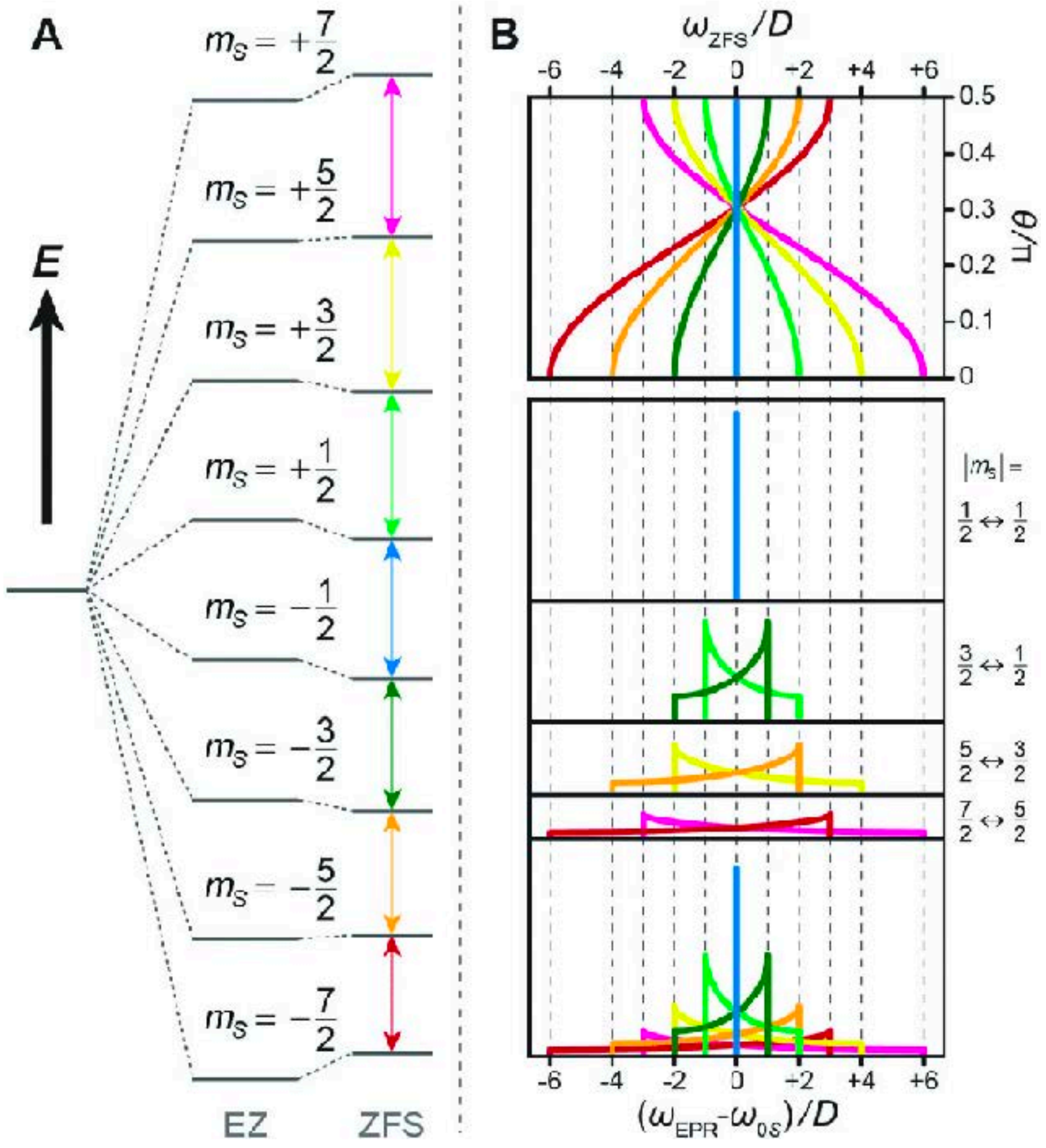
Target with integer spin like deuterium, nitrogen14, lithium6, boron10, can be be Tensor Enhanced with RF

The use of the TMDs of polarized nuclei offers the necessary connective bridge, allowing us to explore how these geometric properties emerge from quark and gluon dynamics.

More Partonic Organization with More Polarization Axes

Polarizing Higher Mass Nuclei with Spin ≥ 1

- For spin-1 there are three independent polarization components of a second-rank tensor, for higher than spin-1 you get additional polarization components
- Additional polarization components lead to more polarization axes
- Additional polarization axes leads to reduced partonic complexity and more observables
- With spin ≥ 1 for many nuclei with increase mass number
- Integer and half-integer provide different information
- New RF techniques to polarize nuclei at higher temperatures
    - Spin-1: ^{2}D, ^{6}Li, ^{14}N
    - Spin-2: ^{22}Na
    - Spin-3: ^{10}B



DY at FNAL (Much Critical Information)

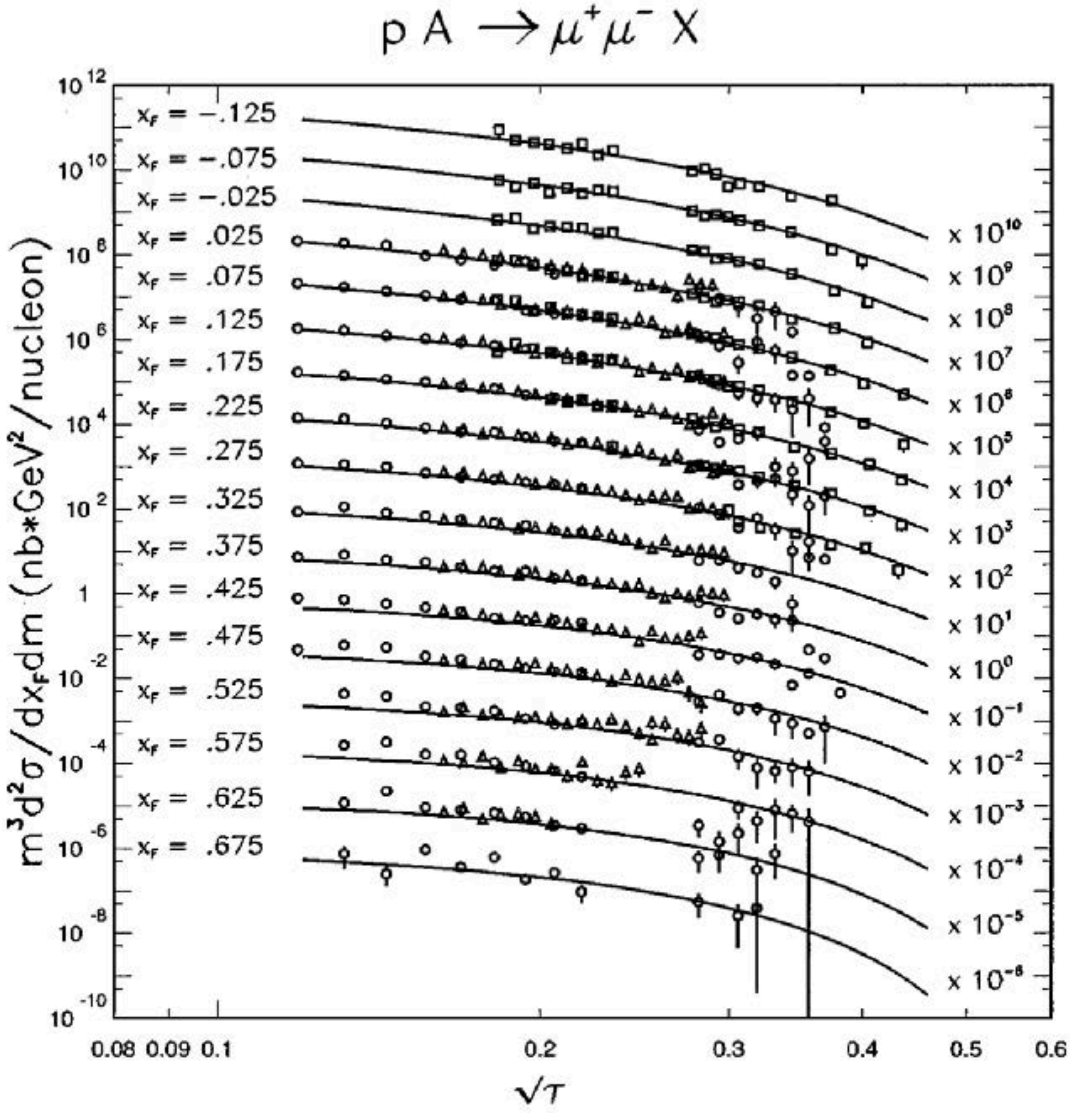


Figure 3 Proton-induced Drell-Yan production from experiments NA3 (8) (triangles) at 400 GeV/c, E605 (9) (squares) at 800 GeV/c, and E772 (10; PL McGaughey et al, unpublished data) (circles) at 800 GeV/c. The lines are absolute (no arbitrary normalization factor) next-to-leading order calculations for p + d collisions at 800 GeV/c using the CTEQ4M structure functions (11).

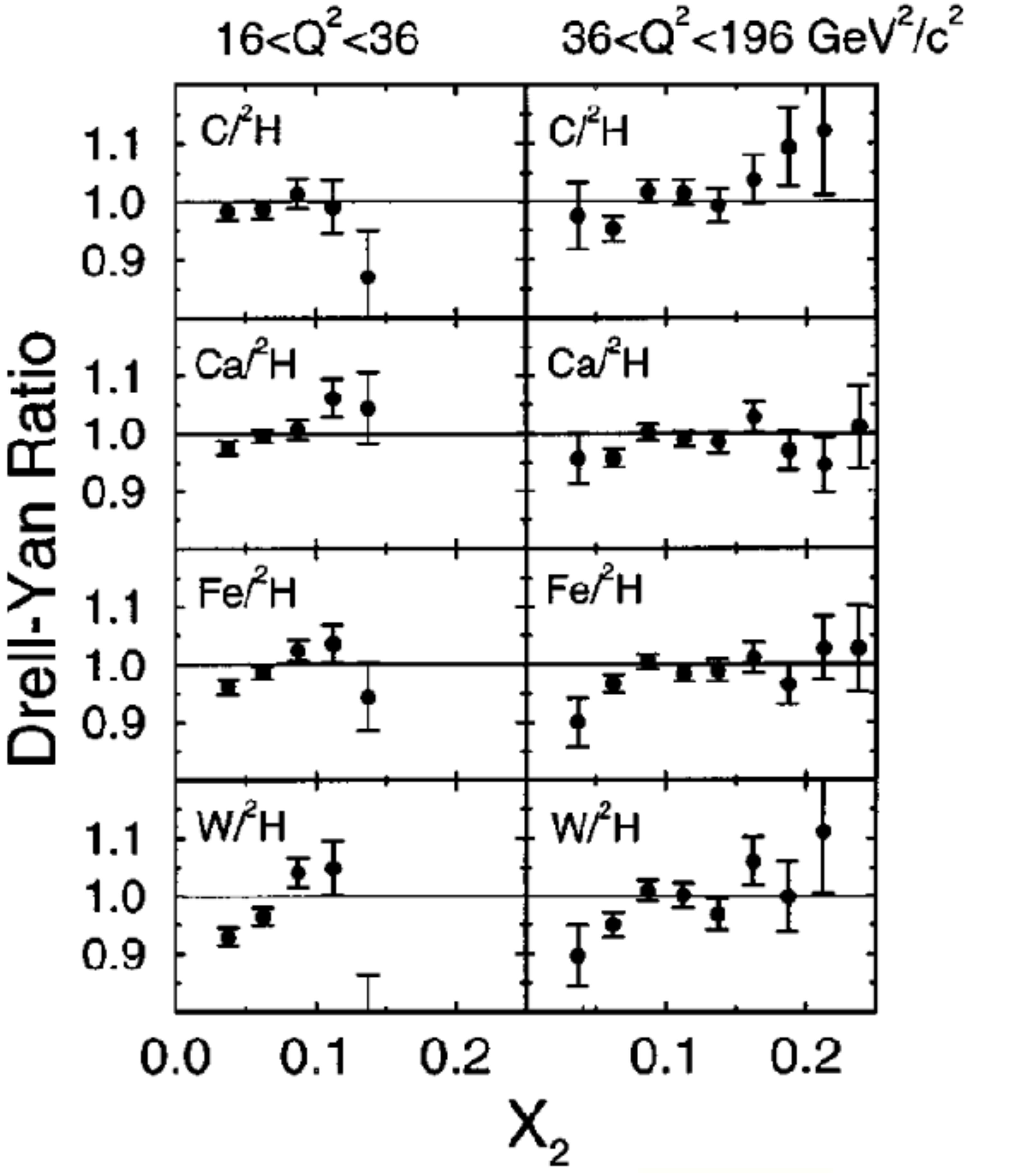


Figure 12 Ratio of Drell-Yan cross sections per nucleon for heavy nuclei to deuterium versus target momentum fraction from E772 (104). The two columns show data for different bins of $Q^2 = M^2$.

Publications of the Fermilab Drell-Yan Program

E866/NuSea

- E.A. Hawker *et al.* *Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea*, Phys. Rev. Lett. **80**, 3715 (1998).
- J.C. Peng *et al.* *d-bar/u-bar Asymmetry and the Origin of the Nucleon Sea*, Phys. Rev. **D58**, 092004 (1998).
- M.A. Vasiliev *et al.* *Parton energy loss limits and shadowing in Drell-Yan dimuon production*, Phys. Rev. Lett. **83**, 2304 (1999).
- M.J. Leitch *et al.* *Measurement of Differences between J/ψ and ψ' Suppression in p-A Collisions*, Phys. Rev. Lett. **84**, 3256 (2000).
- C.N. Brown *et al.* *Observation of Polarization in Bottomonium Production at sqrt s = 38.8 GeV*, Phys. Rev. Lett. **86**, 2529 (2001).
- R.S. Towell *et al.* *Improved Measurement of the d-bar/u-bar Asymmetry in the Nucleon Sea*, Phys. Rev. **D64**, 052002 (2001).
- T.H. Chang *et al.* *J/ψ polarization in 800-GeV p Cu interactions*, Phys. Rev. Lett. **91** 211801 (2003).
- L.Y. Zhu *et al.* *Measurement of Angular Distributions of Drell-Yan Dimuons in p + d Interaction at 800-GeV/c*, Submitted to Phys. Rev. Lett. arxiv:hep-ex/0609005.

E789 Publications:

- M.S. Kowitt *et al.* *Production of J/ψ at Large x_F in 800 GeV/c p-Copper and p-Beryllium Collisions*, Phys. Rev. Lett. **72**, 1318 (1994).
- M.J. Leitch *et al.* *Nuclear Dependence of Neutral D Production by 800 GeV/c Protons*, Phys. Rev. Lett. **72**, 2542 (1994).
- C.S. Mishra *et al.* *Search for the decay $D^0 \to \mu^+\mu^-$*, Phys. Rev. **D50**, 9 (1994).

Publications of the Fermilab Drell-Yan Program

E789 Publications (Cont.):

- D.M. Jansen *et al.* *Measurement of the Bottom-Quark Production Cross Section in 800 GeV/c Proton-Gold Collisions*, Phys. Rev. Lett. **74**, 3118 (1995).
- M.H. Schub *et al.* *Measurement of J/ψ and ψ' Production in 800 GeV/c Proton-Gold Collisions*, Phys. Rev. **D52**, 1307 (1995); Phys. Rev. D53, 570 (1996).
- M.J. Leitch *et al.* *Nuclear Dependence of J/ψ Production by 800 GeV/c Protons near $x_F = 0$*, Phys. Rev. **D52**, 4251 (1995).
- C.N. Brown *et al.* *Nuclear Dependence of Single-Hadron and Dihadron Production in p-A Interactions at sqrt s = 38.8 GeV*, Phys. Rev. **C54**, 3195 (1996).
- D. Pripstein *et al.* *Search for flavor-changing neutral currents and lepton-family-number violation in two-body D_0 decays*, Phys. Rev. **D61**, 032005 (2000).

E772 Publications:

- D.M. Alde *et al.* *Nuclear Dependence of Dimuon Production at 800 GeV*, Phys. Rev. Lett. **64**, 2479 (1990).
- D.M. Alde *et al.* *A Dependence of J/ψ and ψ' Production at 800 GeV/c*, Phys. Rev. Lett. **66**, 133 (1991).
- D.M. Alde *et al.* *Nuclear Dependence of the Production of Upsilon Resonances at 800 GeV*, Phys. Rev. Lett. **66**, 2285 (1991).
- P.L. McGaughey *et al.* *Cross sections for the production of high-mass muon pairs from 800 GeV proton bombardment of ^2H*, Phys. Rev. **D50**, 3038 (1994).
- P.L. McGaughey *et al.* *Limit on the d-bar/u-bar asymmetry of the nucleon sea from Drell-Yan production*, Phys. Rev. Lett. **69**, 1726 (1992).