

# Probing Sea Quark TMD with Drell-Yan at SpinQuest/E0139 at Fermilab

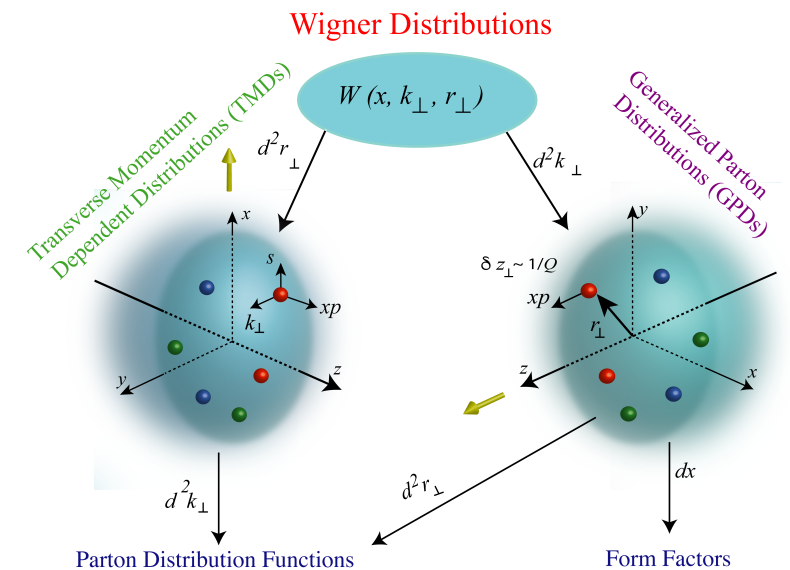
Ming Liu

Los Alamos National Laboratory

For the SpinQuest/E1039 Collaboration

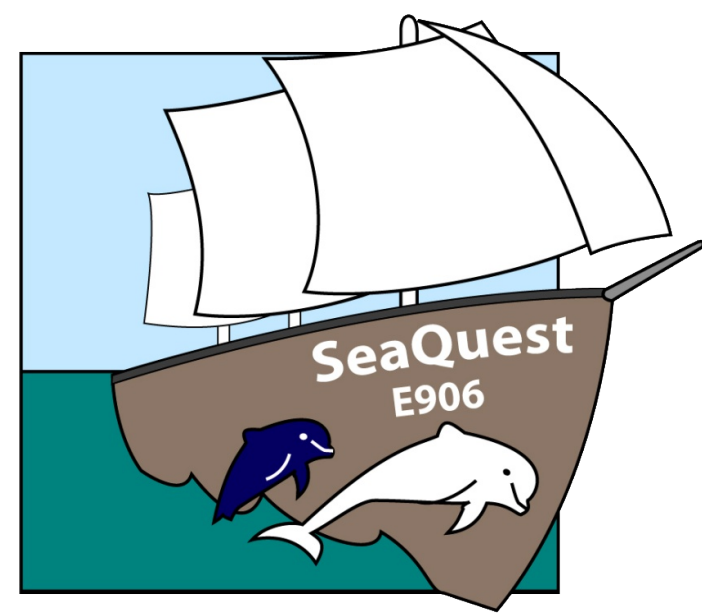
QCD Evolution 2019, May 13-17

Argonne National Laboratory

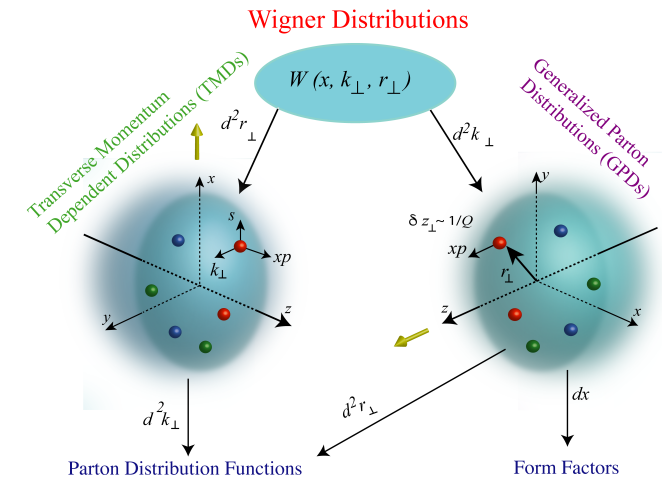


# Outline

- SpinQuest/E1039 experiment at Fermilab
  - E1039 polarized  $\text{NH}_3/\text{ND}_3$  targets
  - Follow up of SeaQuest/E906 unpolarized target program
- Novel physics of sea quarks at  $x = 0.1 - 0.4$ 
  - Flavor asymmetry
  - Sivers & OAM
- Other opportunities
  - Parasitic E1067 dark photon search, 2016 - 2021+
  - Future E1027 polarized beam possibility, 2021+
  - TMD physics complementary to the future EIC program

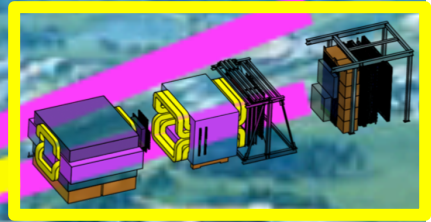


A series of follow up experiments: SeaQuest, SpinQuest, DarkQuest ...



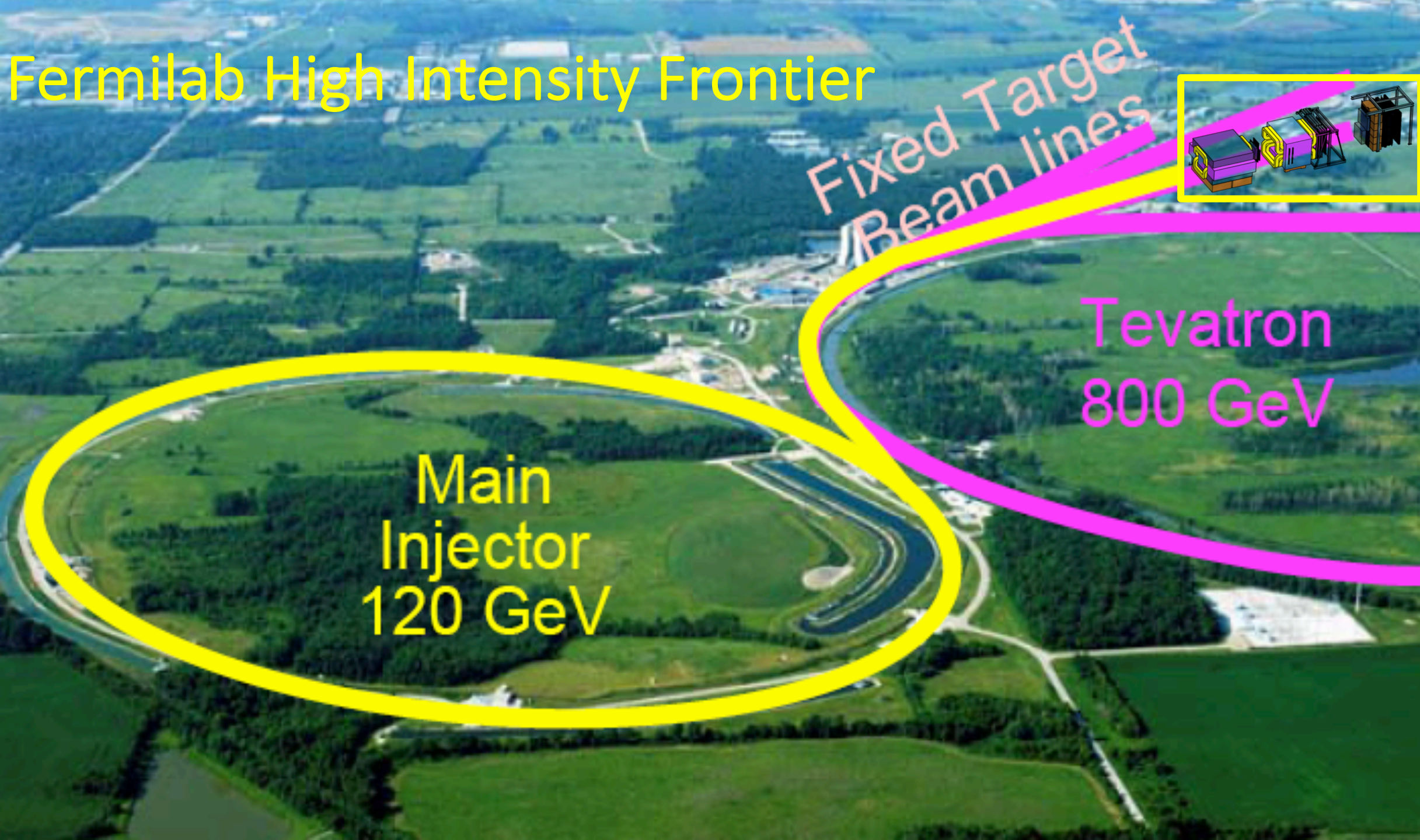
# Fermilab High Intensity Frontier

Fixed Target  
Beam lines



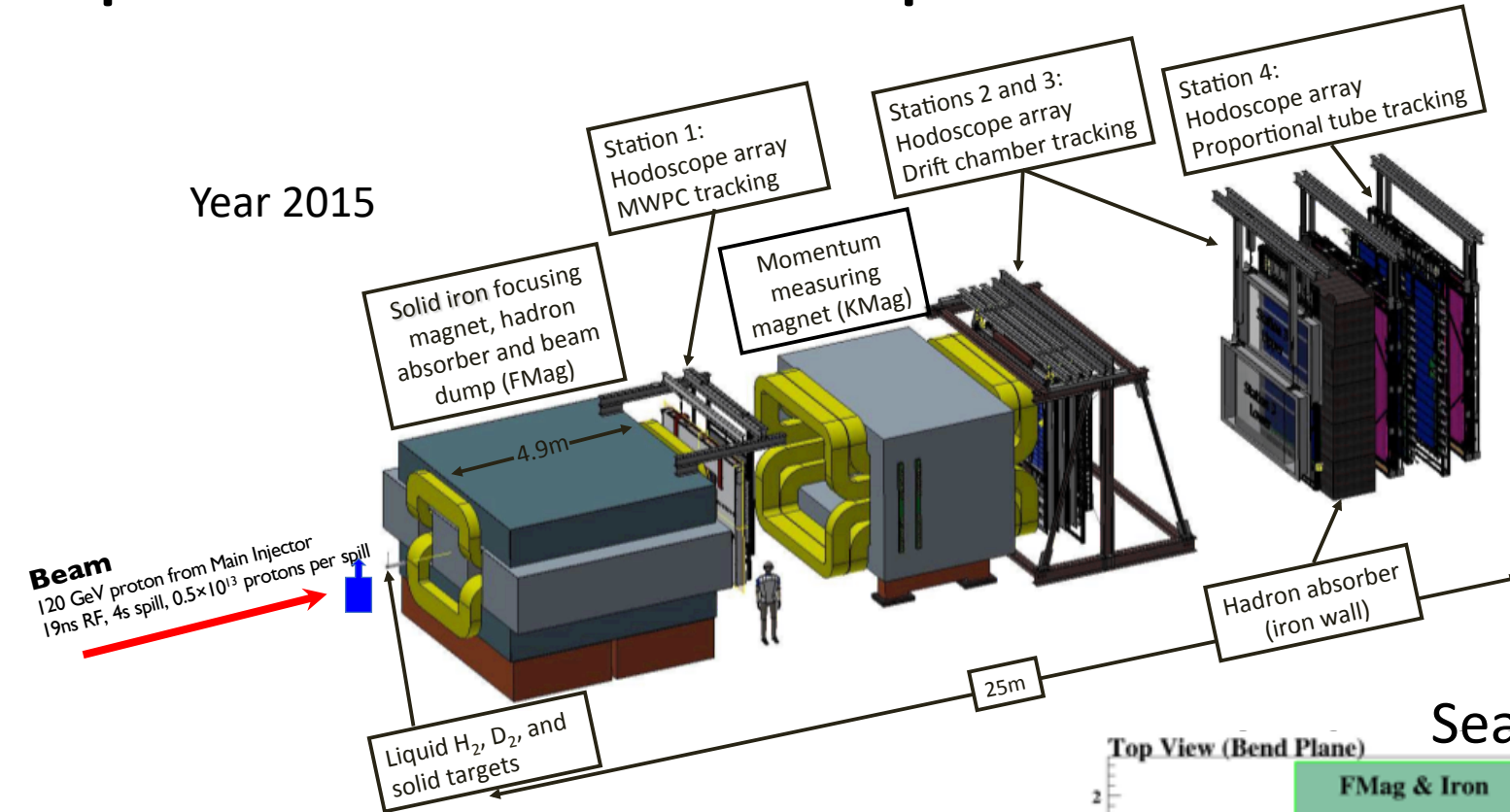
Tevatron  
800 GeV

Main  
Injector  
120 GeV



# SpinQuest Dimuon Spectrometer

Year 2015



## 120 GeV protons from the Main Injector

- 4s beam spill every 60 sec
- 19ns RF, ~10s K protons per RF bucket
- 5 × 10<sup>12</sup> Proton On Target (POT) per spill
- Total integrated POT for E1039 (2-year): 1.4 × 10<sup>18</sup> POT

## E906 unpolarized targets: 2012-2017

- <sup>1</sup>H, <sup>2</sup>D, <sup>12</sup>C, <sup>56</sup>Fe, <sup>184</sup>W

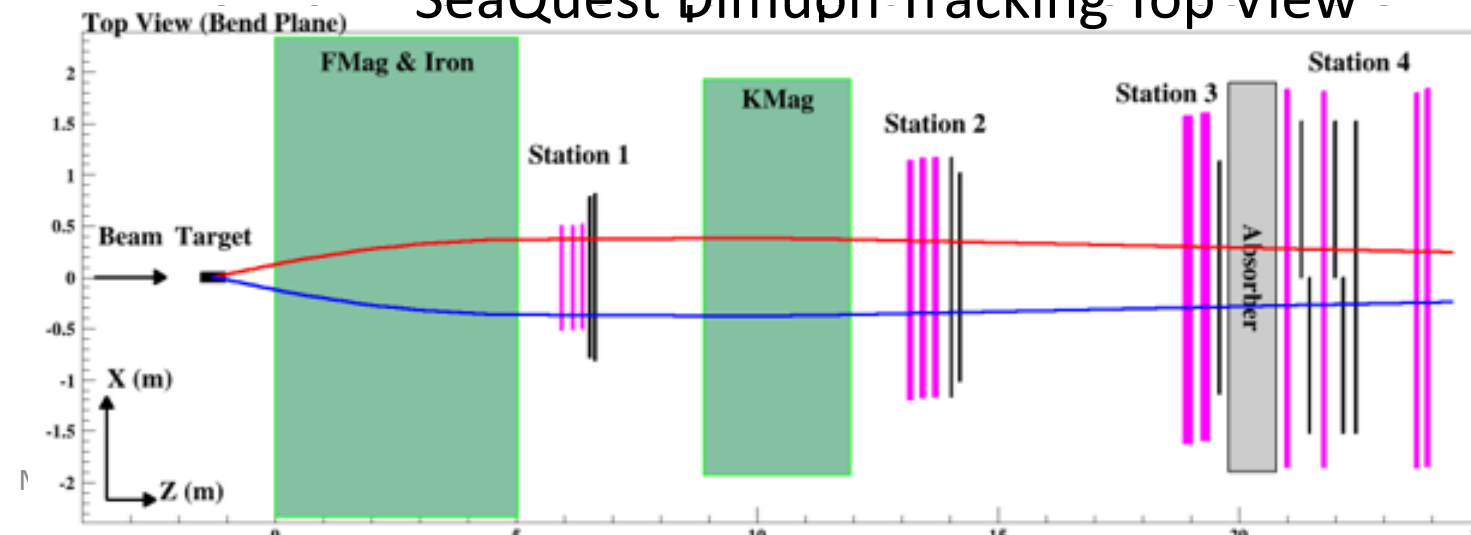
## E1039 polarized targets: 2019 – 2021+

- Polarized protons (NH<sub>3</sub>)
- Polarized neutrons (ND<sub>3</sub>)

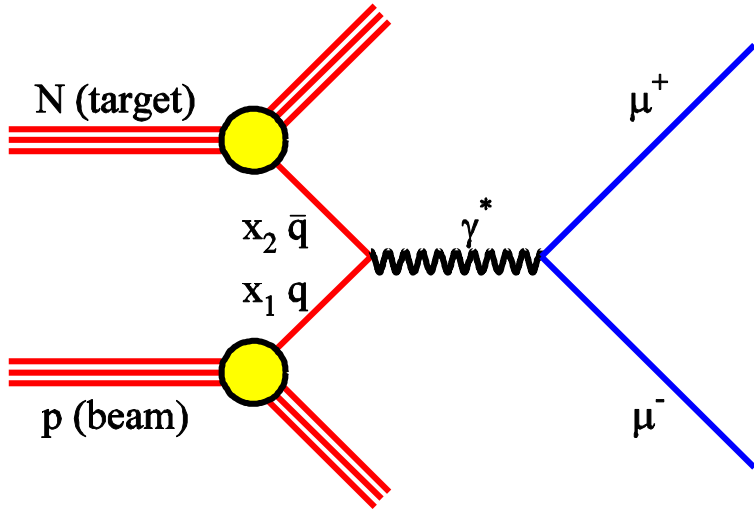
## E1027 polarized beam

5/13/19

## SeaQuest Dimuon Tracking Top View

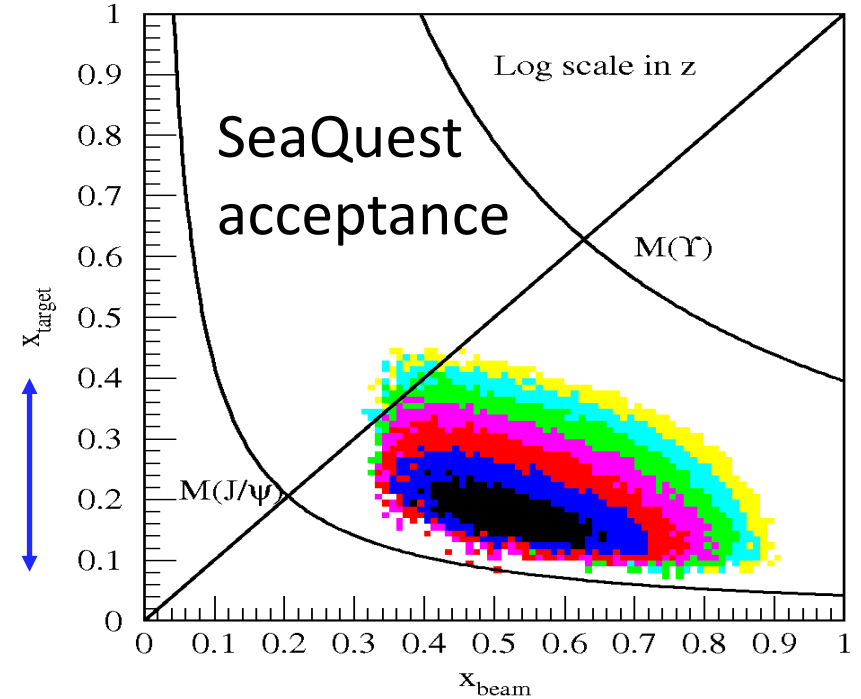


# Drell-Yan @SeaQuest – a Sea Quark Laboratory



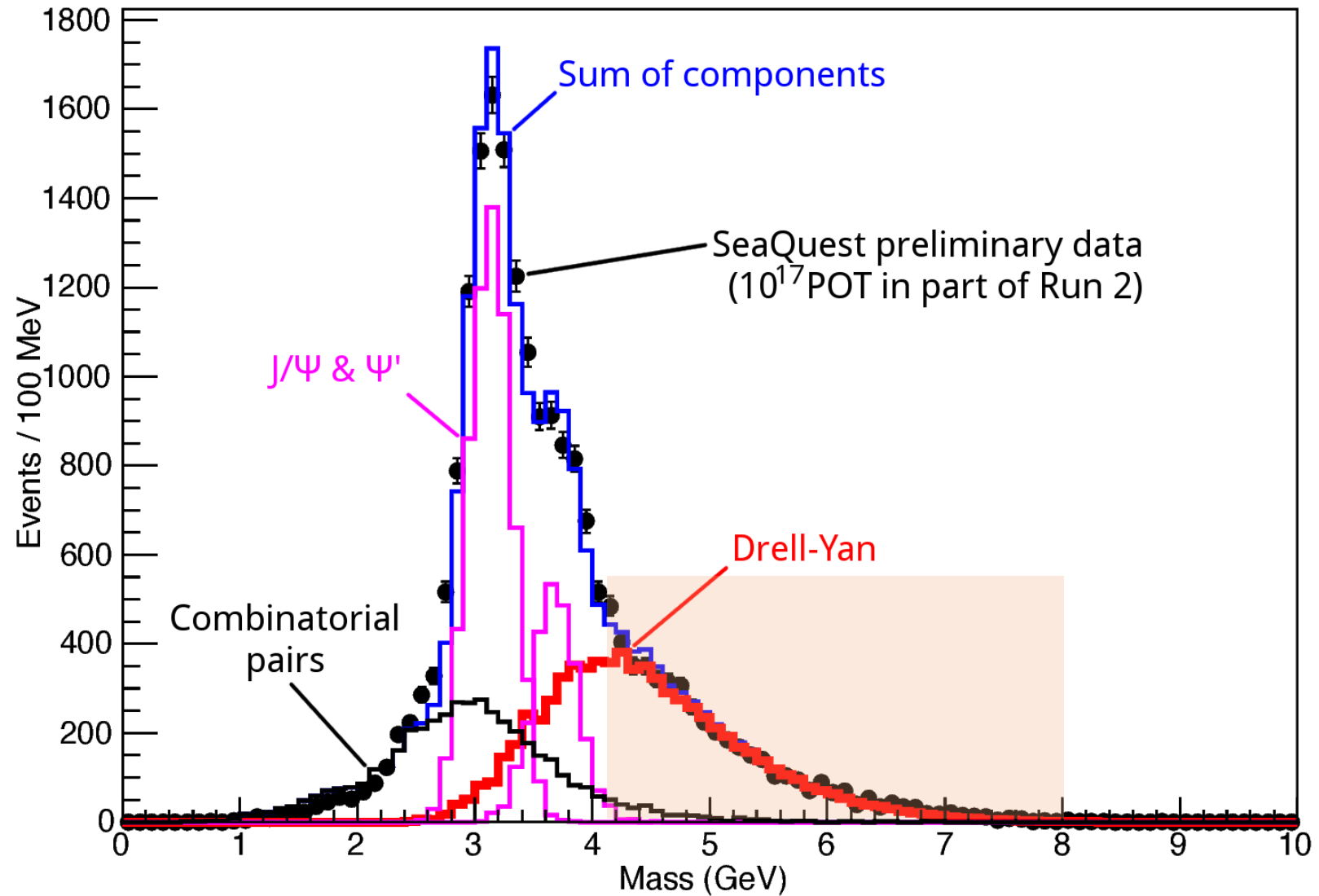
$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t) + \bar{q}_b(x_b) q(x_t)]$$

$$\approx \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t)]$$



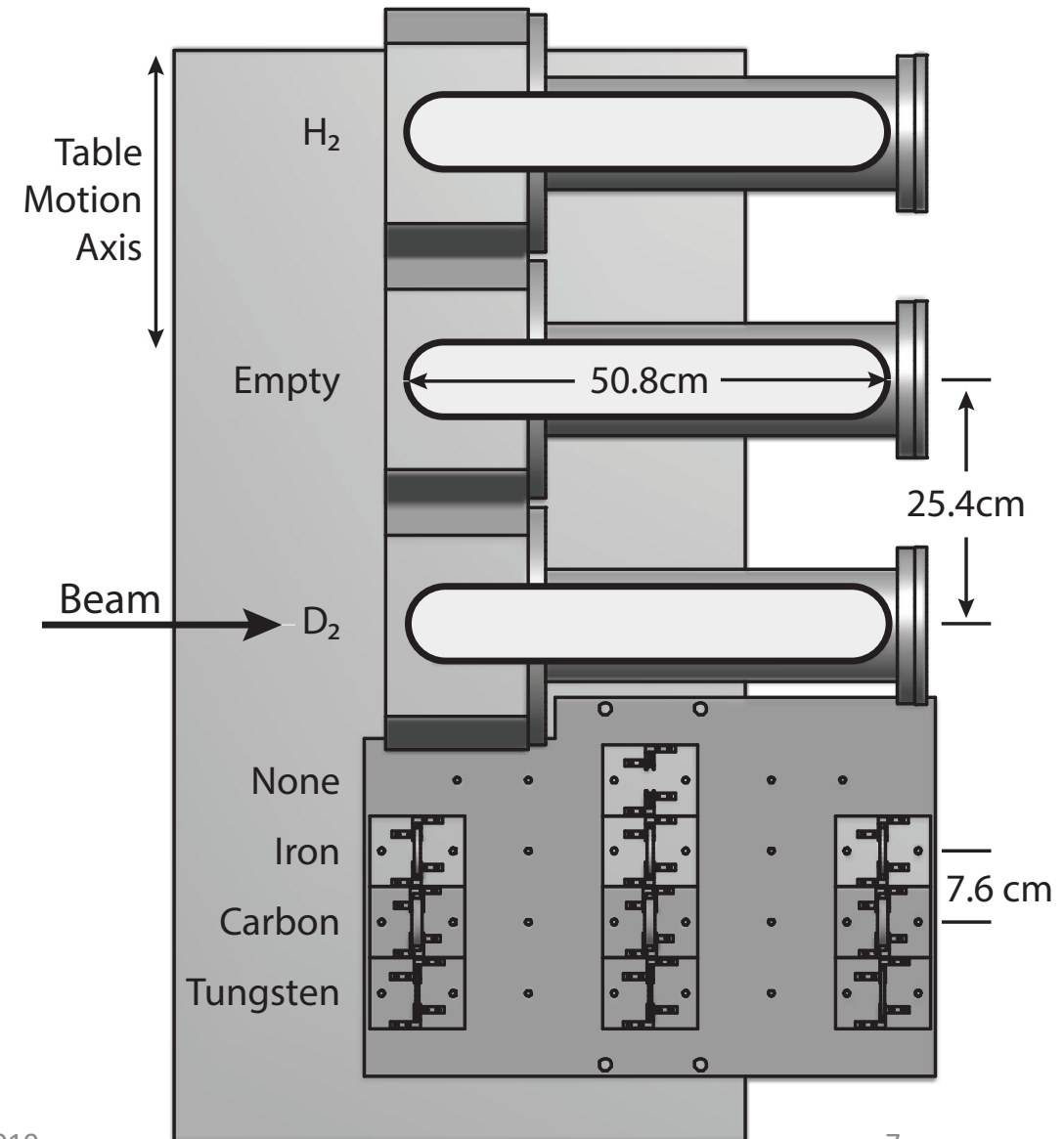
Fixed target kinematics favors sea-quarks from target – **a sea quark lab!**

# Dimuon Mass from SeaQuest/E906



# E906 Unpolarized Physics Program

- Thin targets:  $\sim 10\%$  interaction length
  - Liquid H/D
  - Solid C, Fe, W
- Physics
  - Sea quark flavor asymmetry,  $d\bar{b}/u\bar{b}$
  - Quark energy loss in p+A collisions,  $dE/dx$
  - TMD and more ...
- Experimental runs – 6 years
  - 2012 – commissioning
  - 2017 – completed



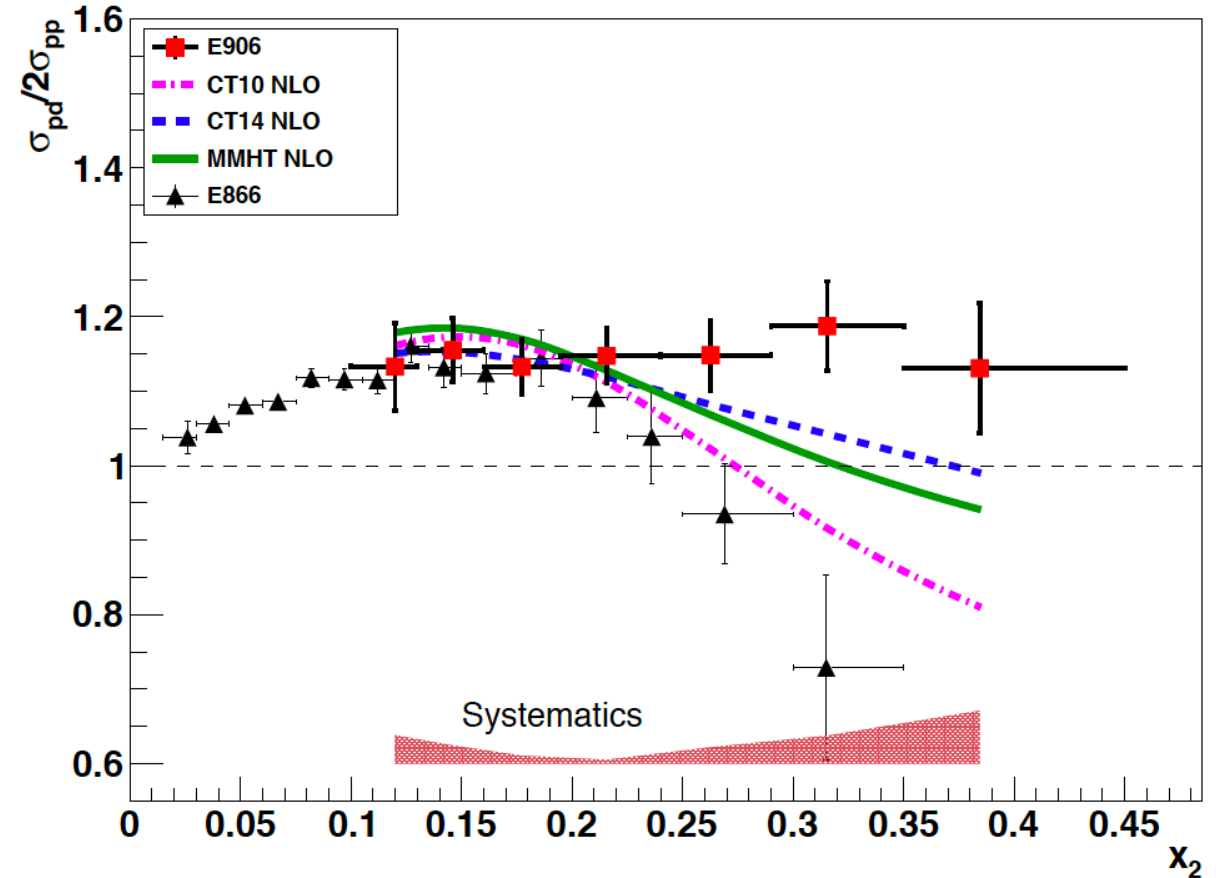
# Flavor Asymmetry of Sea Quarks at Intermediate x

Proton vs “Neutron” targets:

$$\left. \frac{\sigma_{pd \rightarrow \mu^+ \mu^-}}{\sigma_{pp \rightarrow \mu^+ \mu^-}} \right|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]$$

This could lead to a very interesting physics ...

J. C. Peng et al (FNAL E866/NuSea), PRD 58, 092004 (1998)



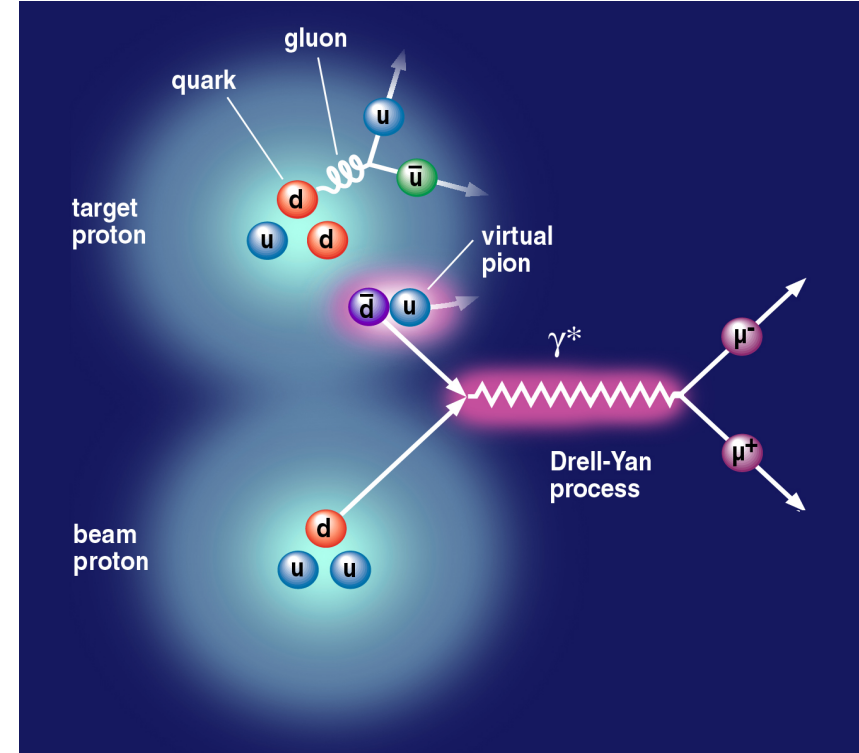


# Sea Quark Flavor Asymmetry and OAM

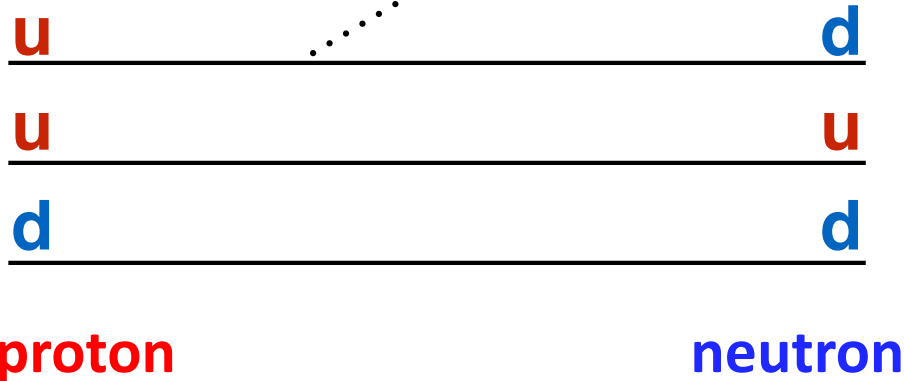
## Pion cloud model

- Sea-quark flavor asymmetry
- Sea-quark orbital angular motion
- Expect large Sivers function at  $x = 0.1 - 0.4$

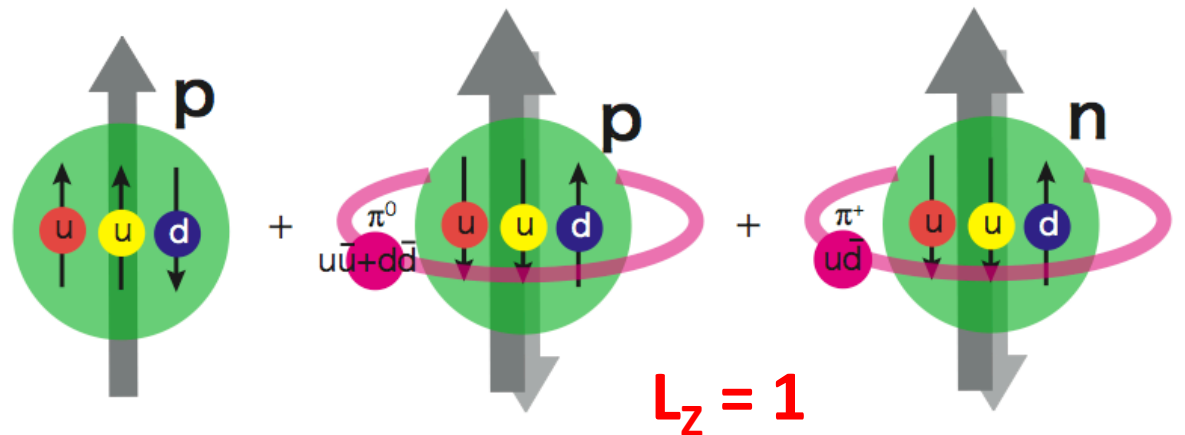
## Pion cloud and Drell-Yan process

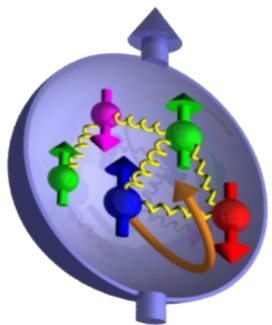


$\pi^+$  Meson



$$|p\rangle = a_1 |p_0\rangle + a_2 |p_0 + \pi^0\rangle + a_3 |n + \pi^+\rangle + \dots$$

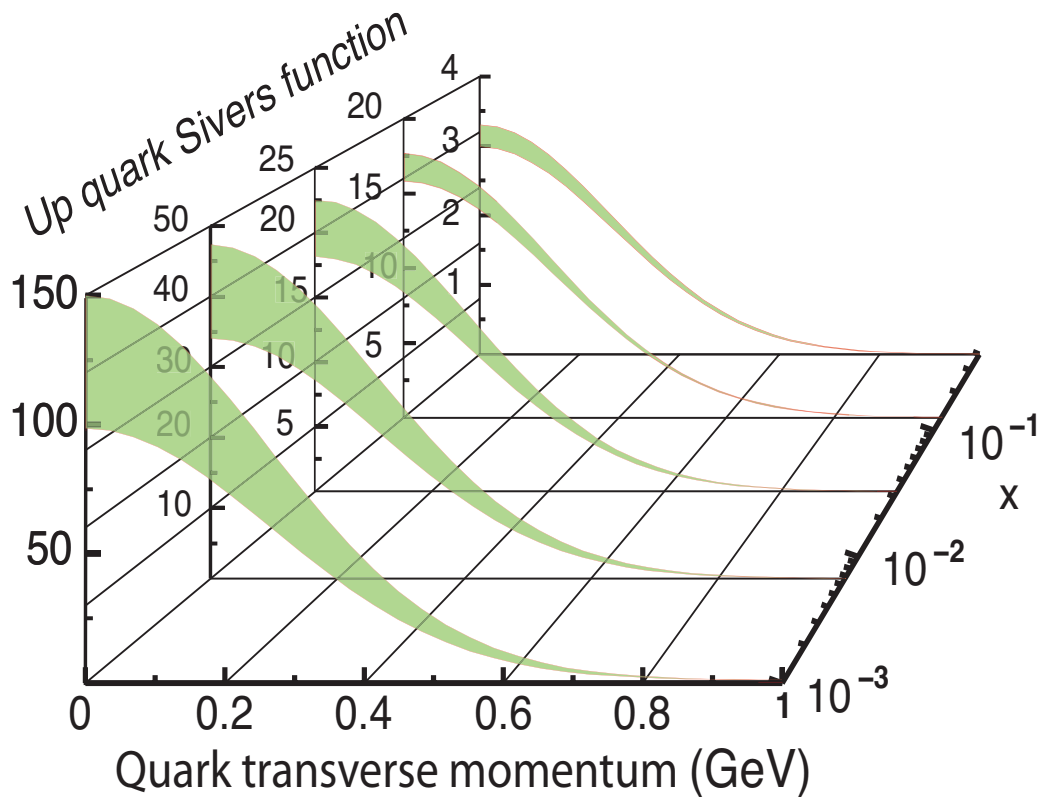




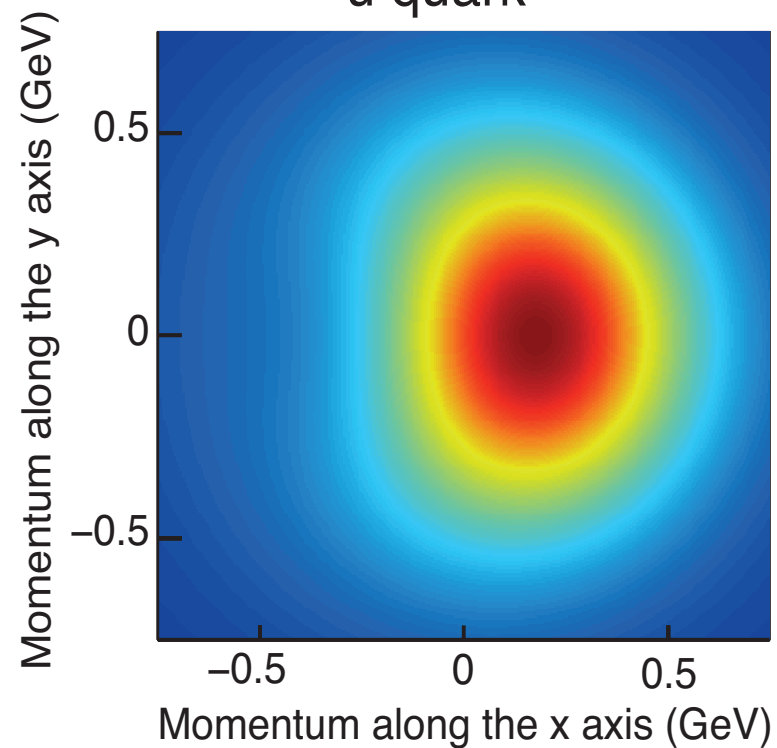
# Nucleon 3-D Structure and Sivers Function

Sivers function  $f_{1T}^\perp(x, k_T)$

$$f_{1T}^\perp = \begin{array}{c} \uparrow \\ \circ \\ \bullet \end{array} - \begin{array}{c} \circ \\ \bullet \\ \downarrow \end{array}$$



u quark

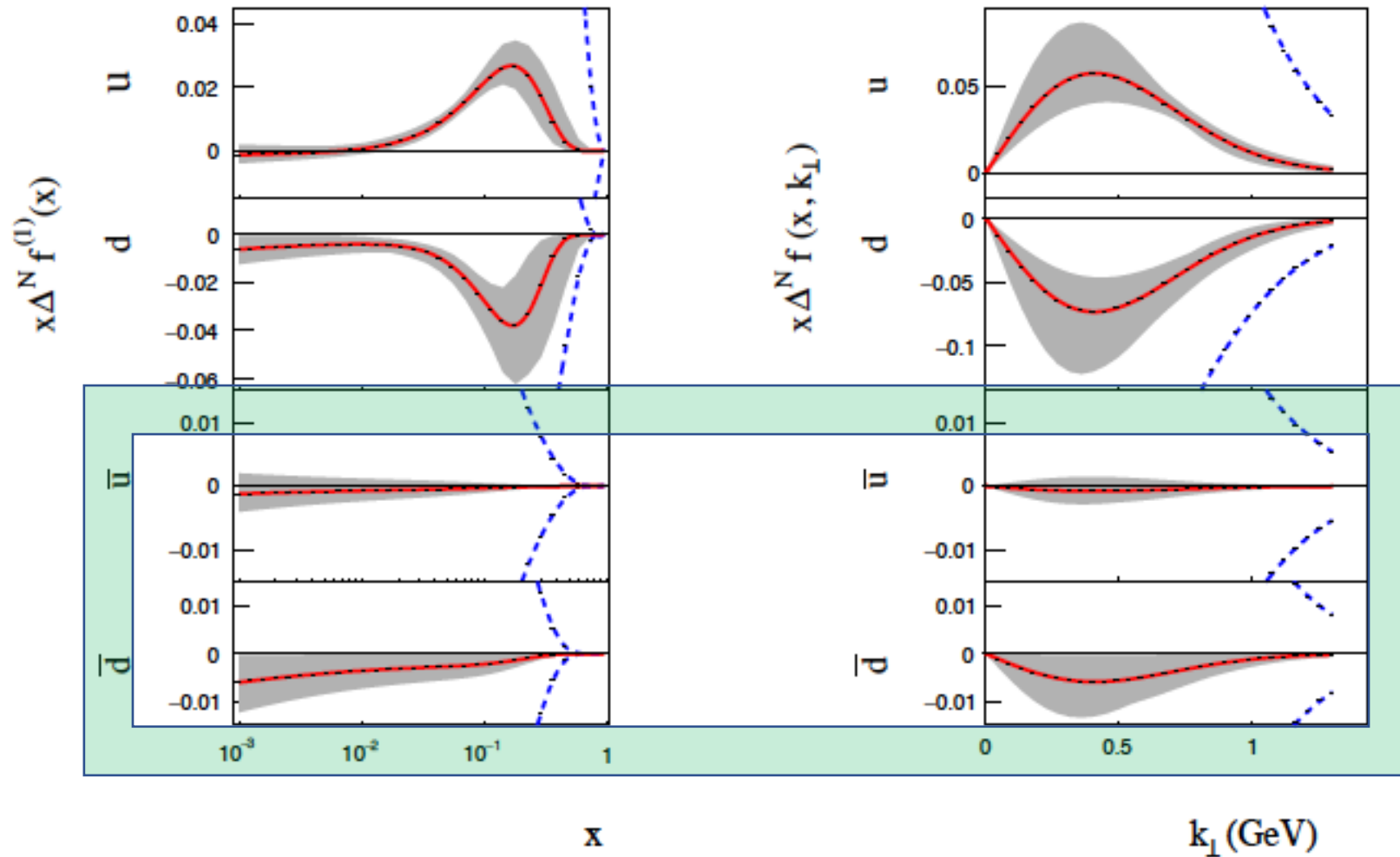


# Sivers Functions from Global Fits

- Sea Quark Sivers poorly constrained, SIDIS not sensitive to sea quarks at large  $x$

1612.06413, M. Anselmino et al

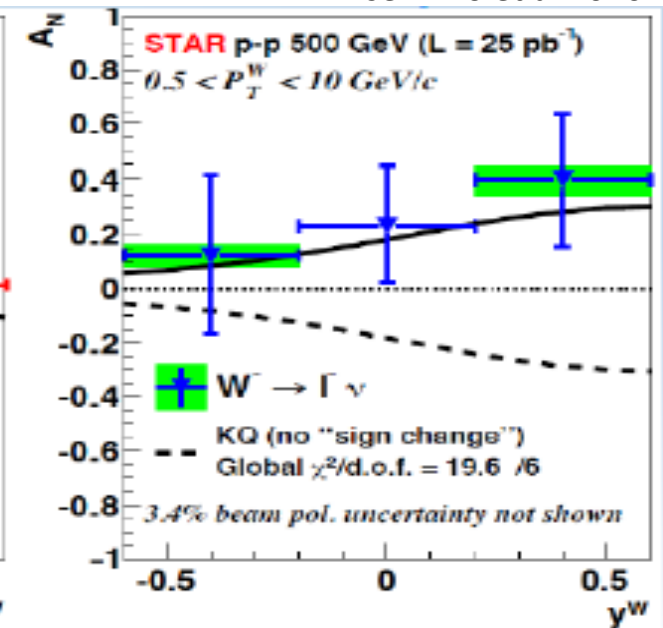
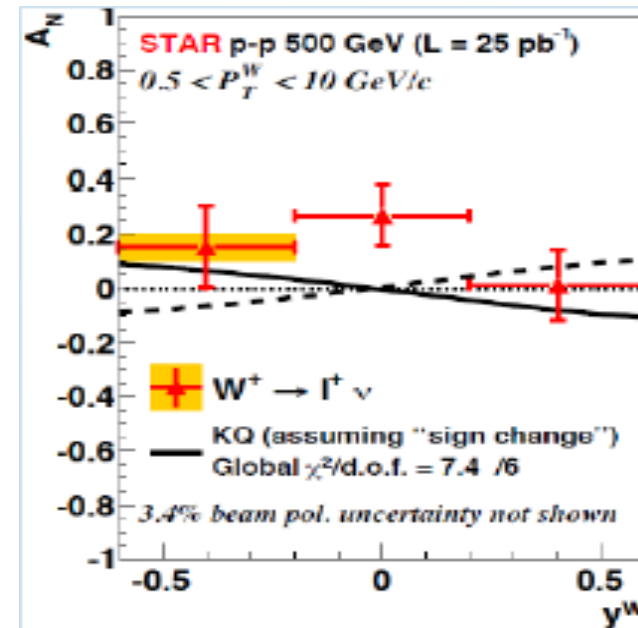
Sea quarks



# RHIC pp500GeV: $W^{+/-} A_N$

$$A_N(W^+) \sim \left( \Delta^N f_{u/p^\uparrow} \otimes f_{\bar{d}/p} + \Delta^N f_{\bar{d}/p^\uparrow} \otimes f_{u/p} \right)$$

$$A_N(W^-) \sim \left( \Delta^N f_{\bar{u}/p^\uparrow} \otimes f_{d/p} + \Delta^N f_{d/p^\uparrow} \otimes f_{\bar{u}/p} \right)$$



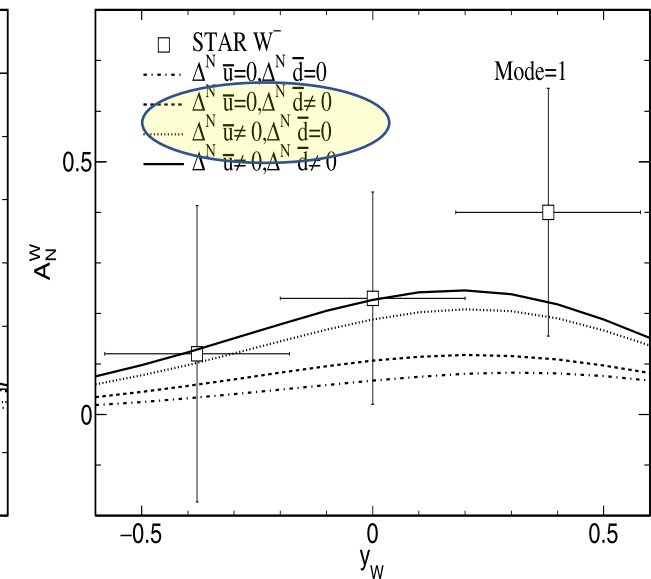
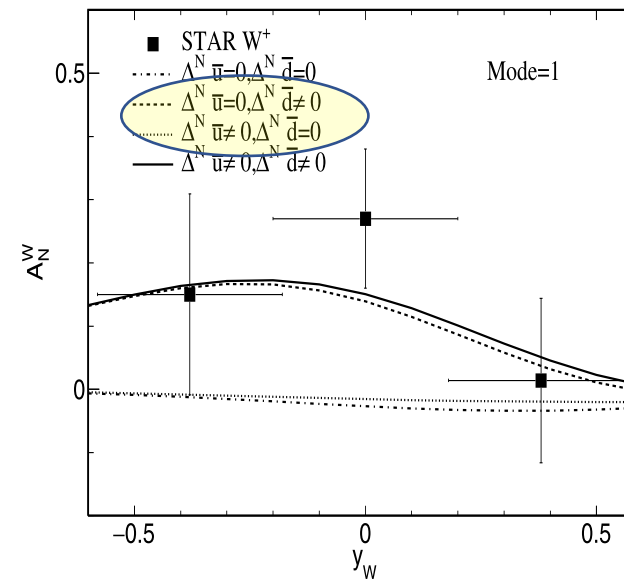
F. Tian et al. / Nuclear Physics A 968 (2017) 379–390

## RHIC data:

- A mix of valence and sea quark Sivers
- Quark flavor identified
- High  $Q^2$
- Statistically limited,  $\sim O(10\%)$
- **Hints of sizable sea-quark Sivers contributions**

## E1039:

- low  $Q^2$
- high statistics,  $\sim O(1\%)$



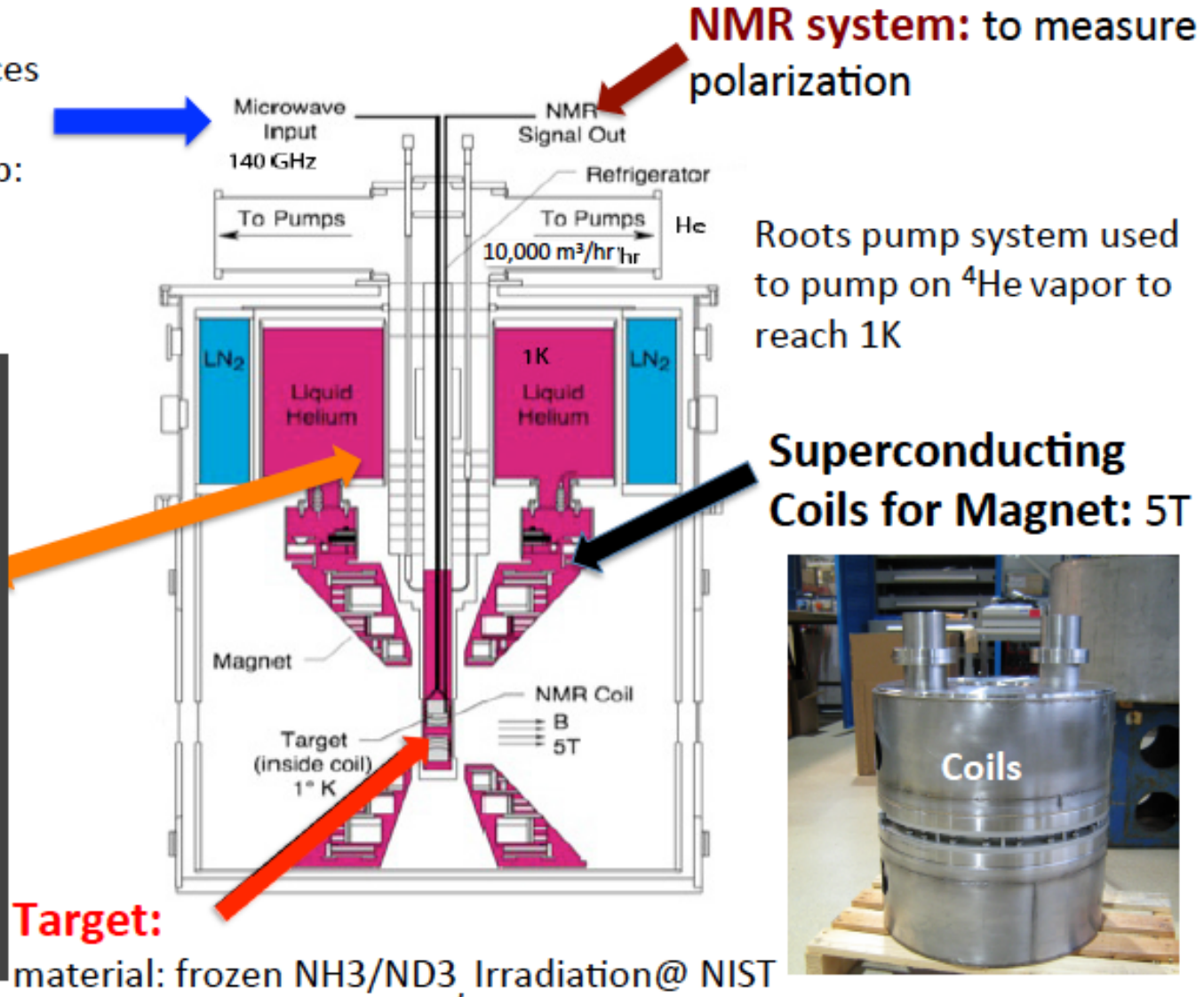
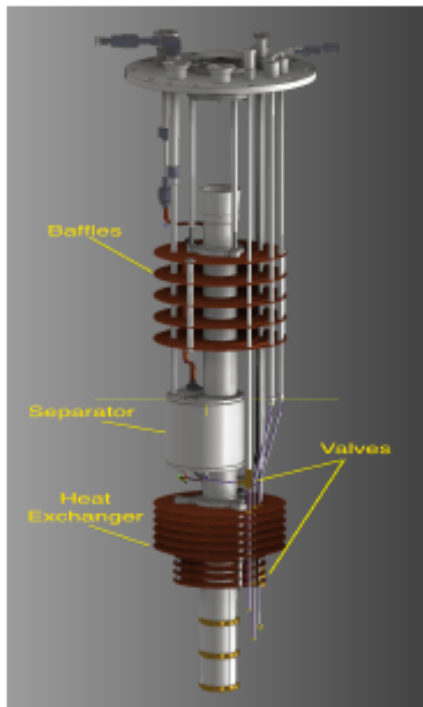
(b)  $A_{W^+}^N$

(a)  $A_{W^-}^N$  12

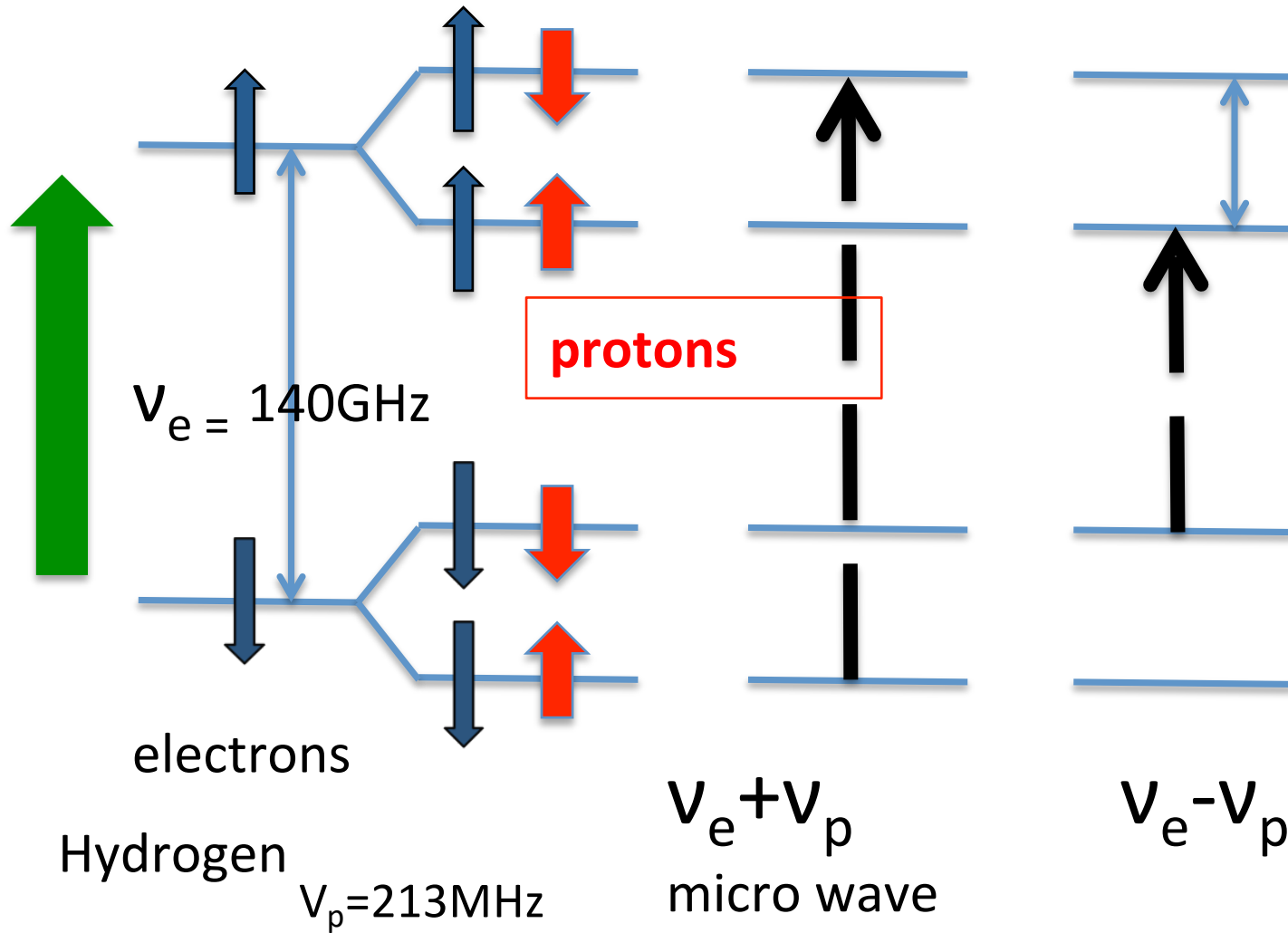
# Polarized NH<sub>3</sub> Target Developed for DY Sivers

**Microwave:** Induces electron spin flips  
• EIO + Power equip:

**Refrigerator:**



# Dynamic Nuclear Polarization: Pol. ~90%



With DNP,  
Pol. ~ 90%

W/o DNP, at thermal equilibrium:

- T = 1K
- B = 5T

Proton target polarization:

$$P_i = 0.5\%$$

$$P_i = \tanh \left( \frac{g_i \mu_i B}{2k_B T} \right)$$

# Projected SpinQuest Target and Beam Performance

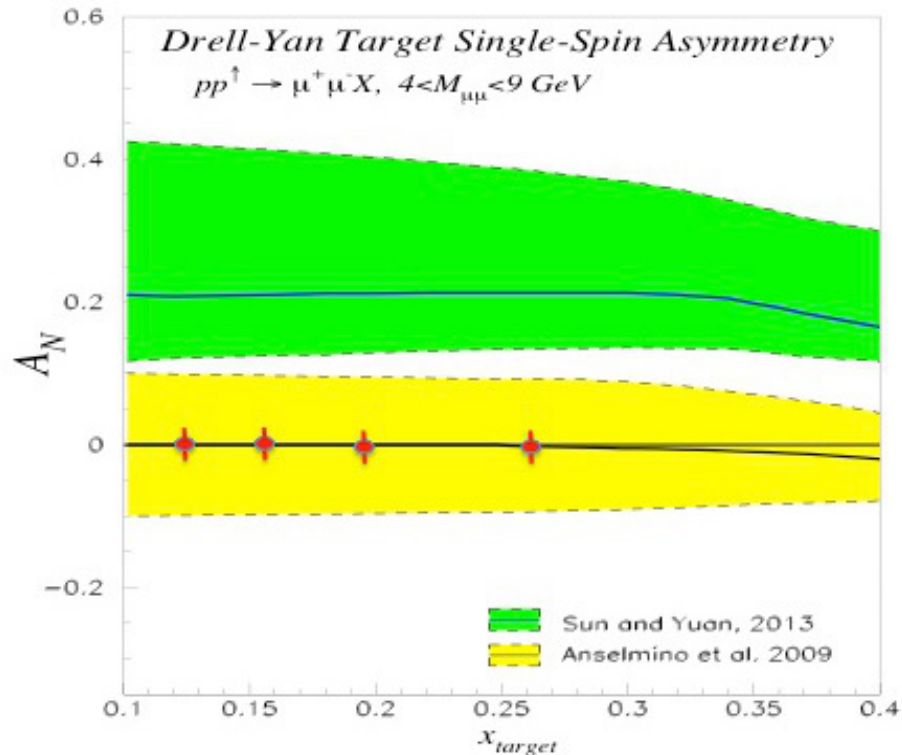
$$A_{\text{meas}} = f \cdot P_T \cdot A_{\text{phy}}$$

Target		Beam	
Polarization $P$	88%	Beam	$10^{13}$ p per spill
Packing fraction	.6	spill	5 sec , one per minute
Dilution Factor $f$	.176	Luminosity	$4 \cdot 10^{35} / \text{cm}^2 / \text{s}$
Density $\text{NH}_3$	$.82 \text{ g/cm}^3$	$E_{\text{Beam}}$	120 GeV
		Total $\mu^+ \mu^-$ pairs	$4.59 \cdot 10^5$
		Experiment available	.48

# Projected Drell-Yan Transverse Single Spin Asymmetry

$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp, \bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

$$\delta A = \frac{1}{f} \frac{1}{P} \frac{1}{\sqrt{N^+ + N^-}}$$

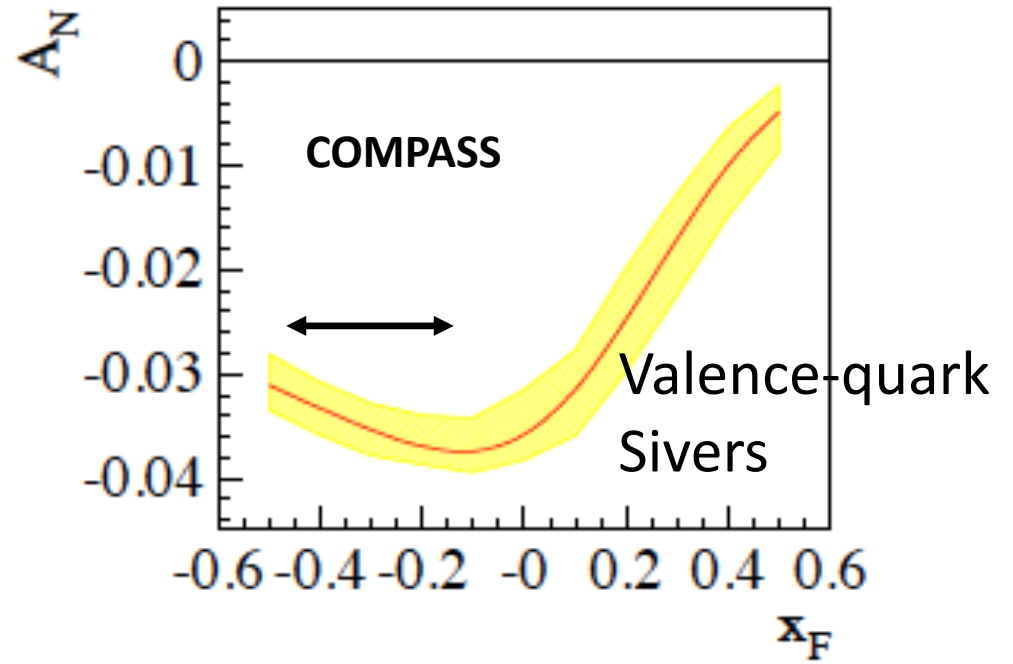
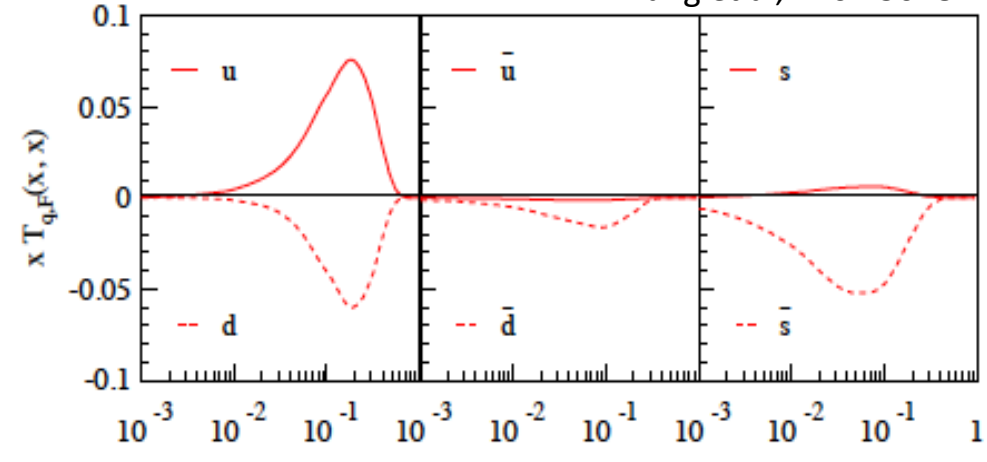


Range $x_B$	Mean $x_B$	Total events	$\Delta A$
0.10–0.14	0.123	159097	0.016
0.14–0.17	0.154	136558	0.017
0.17–0.21	0.188	123566	0.018
0.21–0.50	0.258	119508	0.019

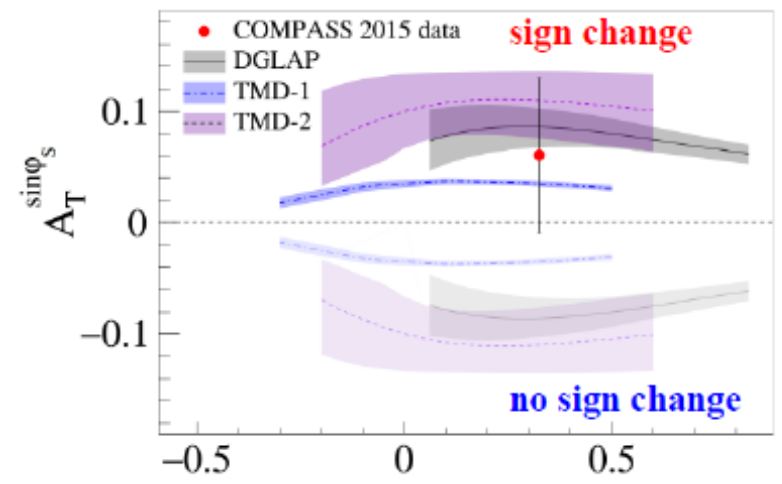
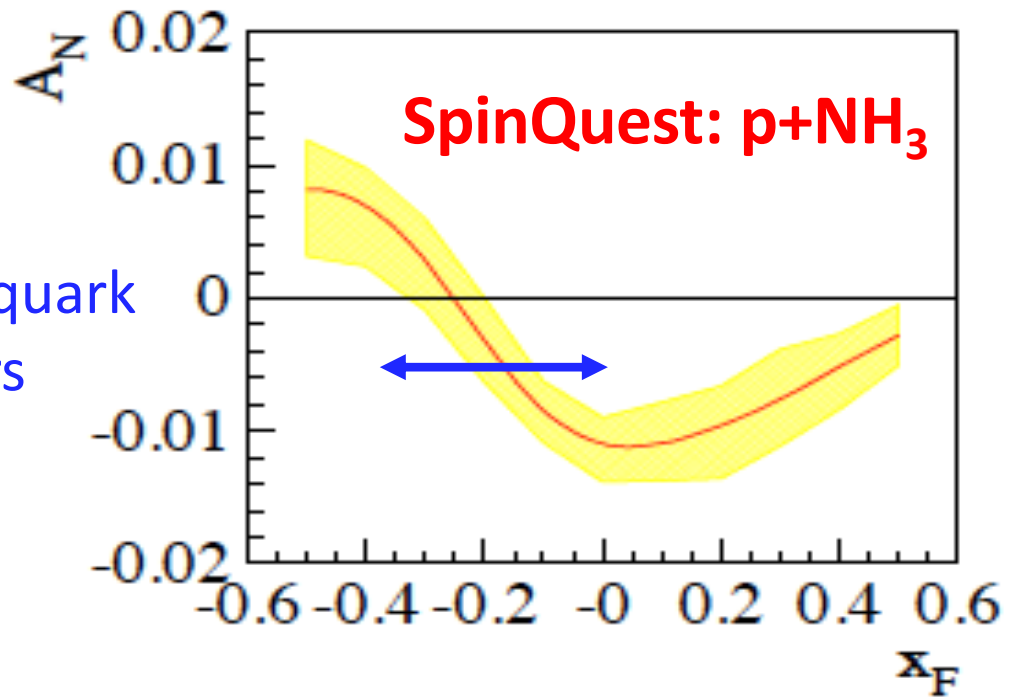


# Drell-Yan Sivers Asymmetries w/ QCD Evolution

Kang et al, 1401.5078

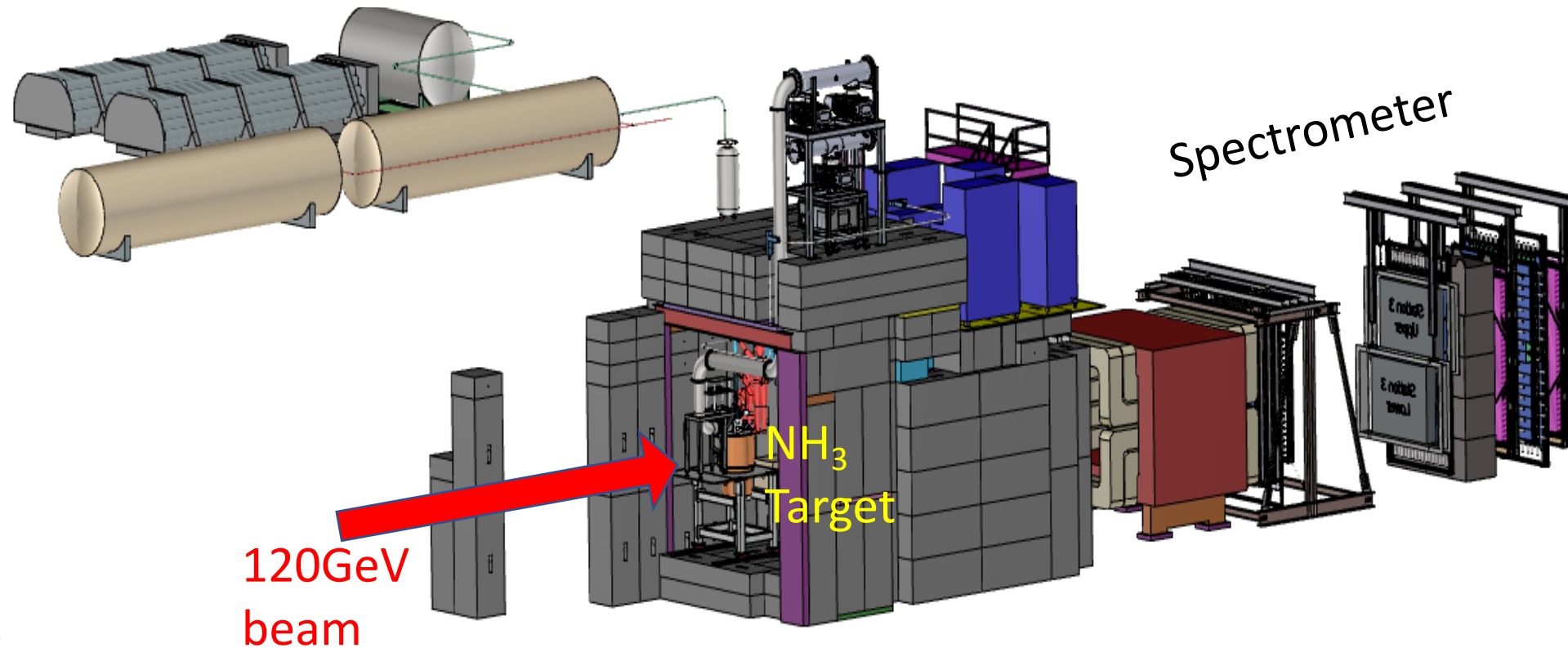


Sea-quark  
Sivers



# E1039 Status & Plan

- DOE approval, March 2018
- E906 decommissioned 6/2018
- Polarized target to be installed by fall of 2019
- E1039 commissioning starts in late 2019
- Run for 2+ years, 2019-2021+



# Fermilab Long Range Plan

Fermilab Program Planning 5-April-18

## LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
LBNF / PIP II	SANFORD FNAL				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE
						LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF
NuMI	MI	MINERvA	MINERvA	OPEN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN					
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA						
BNB	B	MicroBooNE	MicroBooNE	MicroBooNE	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN					
		CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	OPEN						OPEN
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN	OPEN	OPEN	OPEN			
Muon Complex		g-2	g-2	g-2	LONG SHUTDOWN					OPEN				
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	LONG SHUTDOWN					OPEN
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	LONG SHUTDOWN					FTBF
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	LONG SHUTDOWN					FTBF
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN	LONG SHUTDOWN					OPEN

	Construction / commissioning		Run		Subject to PAC review		Shutdown
	Capability ended		Capability unavailable				

- NOTES:
- Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data taking.
  - DUNE: 1st 10kT detector module commissioned in FY24. Runs without beam FY25 to mid-FY26.
  - NOvA runs as long as possible [in the spirit of PAC Nov 2017].
  - Assume NuMI in nubar mode through FY19 - facilitates 12E20 POT for MINERvA [PAC Nov 2017]. Assumption may need re-evaluation.
  - Assume g-2 completed before Mu2e commissioning start mid-FY20. Very tight. Needs scrutiny.
  - Assume E1039 fully approved & commissioned by mid-FY19.  
Experiment estimates 2 yrs run. Add 1 yr contingency. [Stage 1 approval PAC June 2013, update July 2017]
  - FY19 and FY20 MicroBooNE running subject to future PAC review [PAC July 2017].

Opportunity for new programs at SeaQuest after E1039

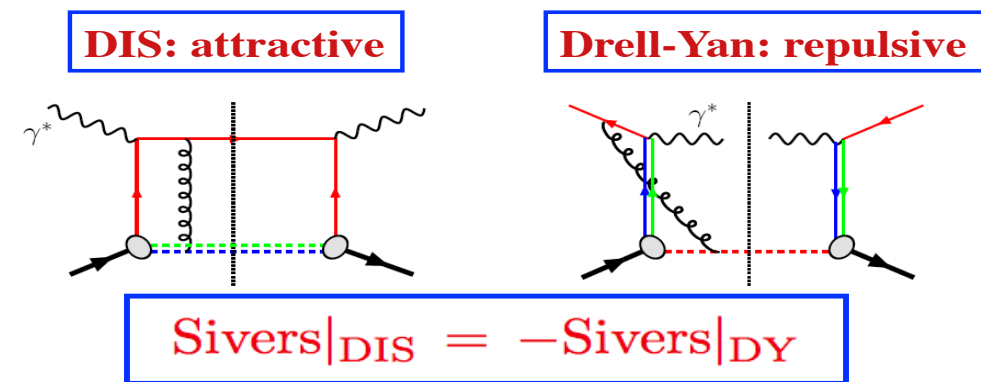
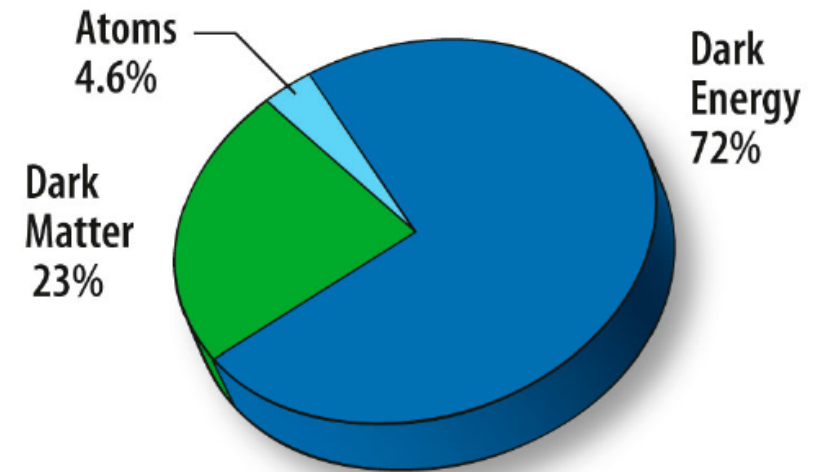
# Physics Beyond E1039 Polarized DY $A_N$

- **Dark sector physics search – DarkQuest**

- Parasitic run with E1039: 2019 – 2021+
- A new proposal for a dedicated run after E1039

- **Physics with polarized beams – E1027**

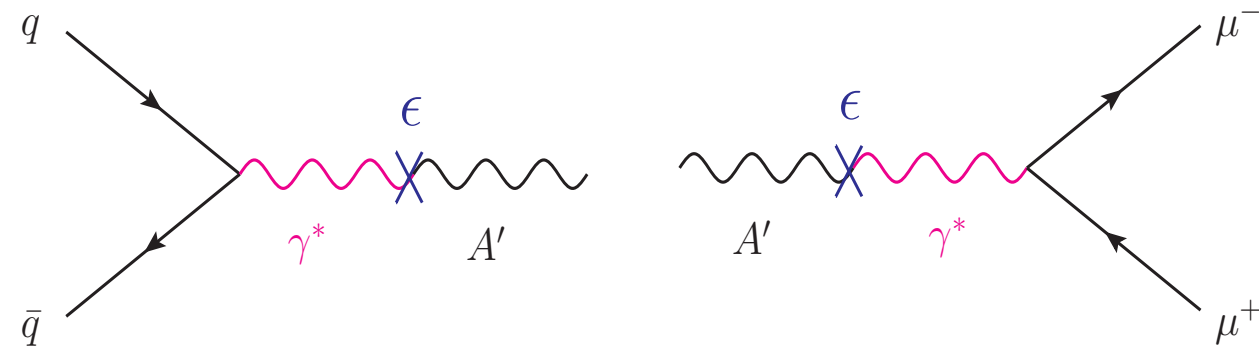
- Polarize the Main Injector 120GeV beam
- Valence quark Sivers
  - Test QCD dynamics in DY vs DIS
- TMD physics



# Dark Photons and Dark Higgs Search at SpinQuest/DarkQuest

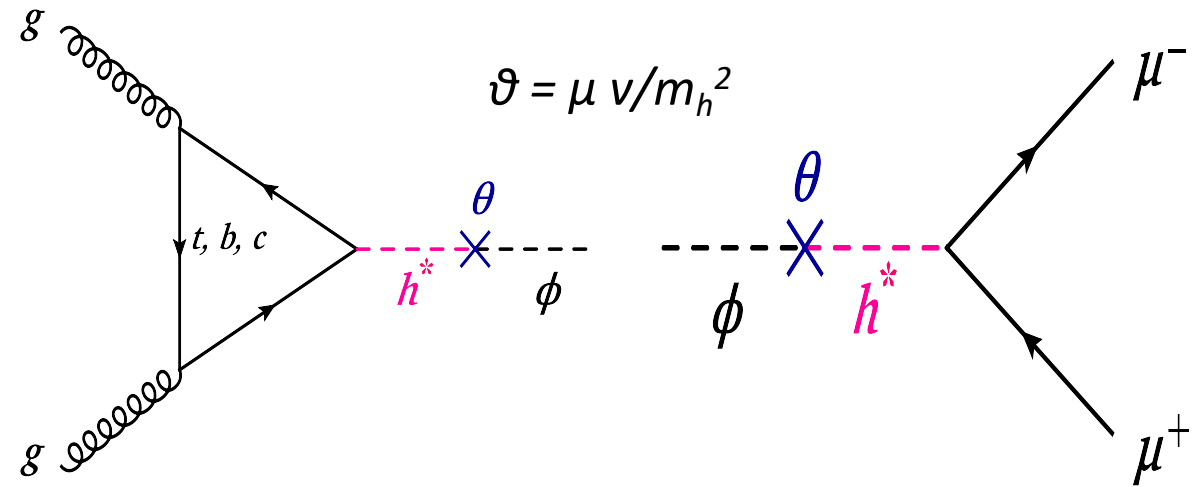
## Photon portal: "vector"

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\text{Dark}}^{\mu\nu}$$



## Higgs portal: "scalar"

$$\mathcal{L}_{\text{mix}} = \mu\phi|H^\dagger H|$$

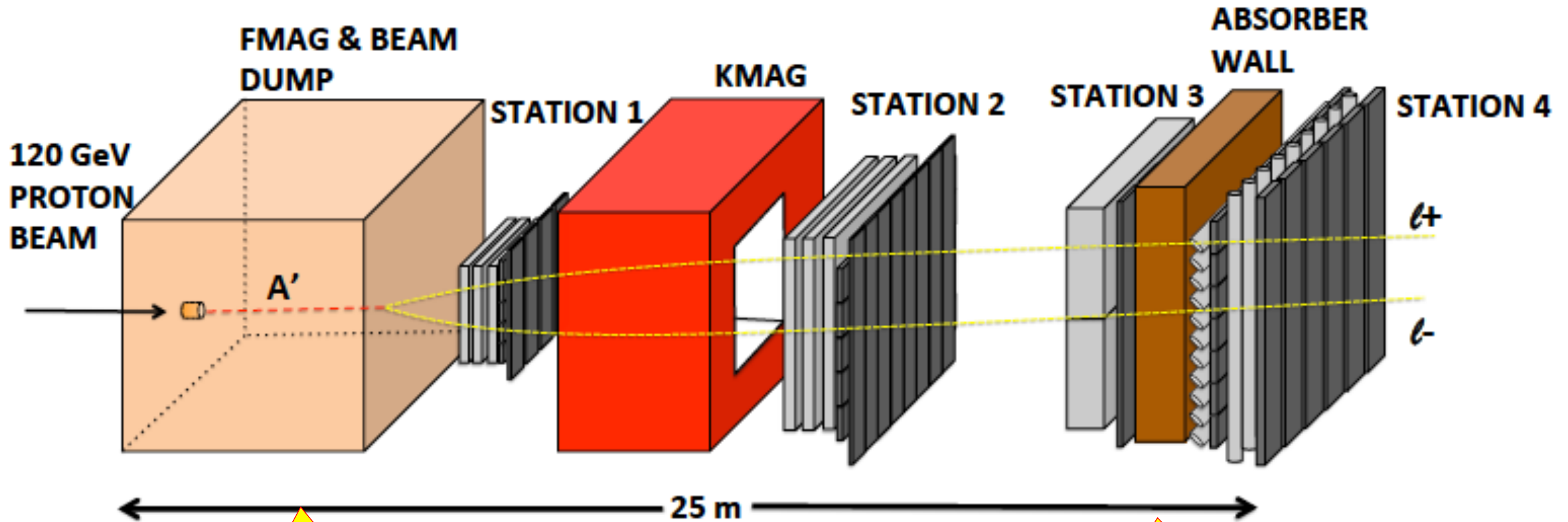


Advantage of hadronic collisions

# Dark Sector Physics Search at DarkQuest

2019 ~ 2021: parasitic run for DM search

2021+: a proposal for a long term DM program after E1039; parasitic TMD physics?

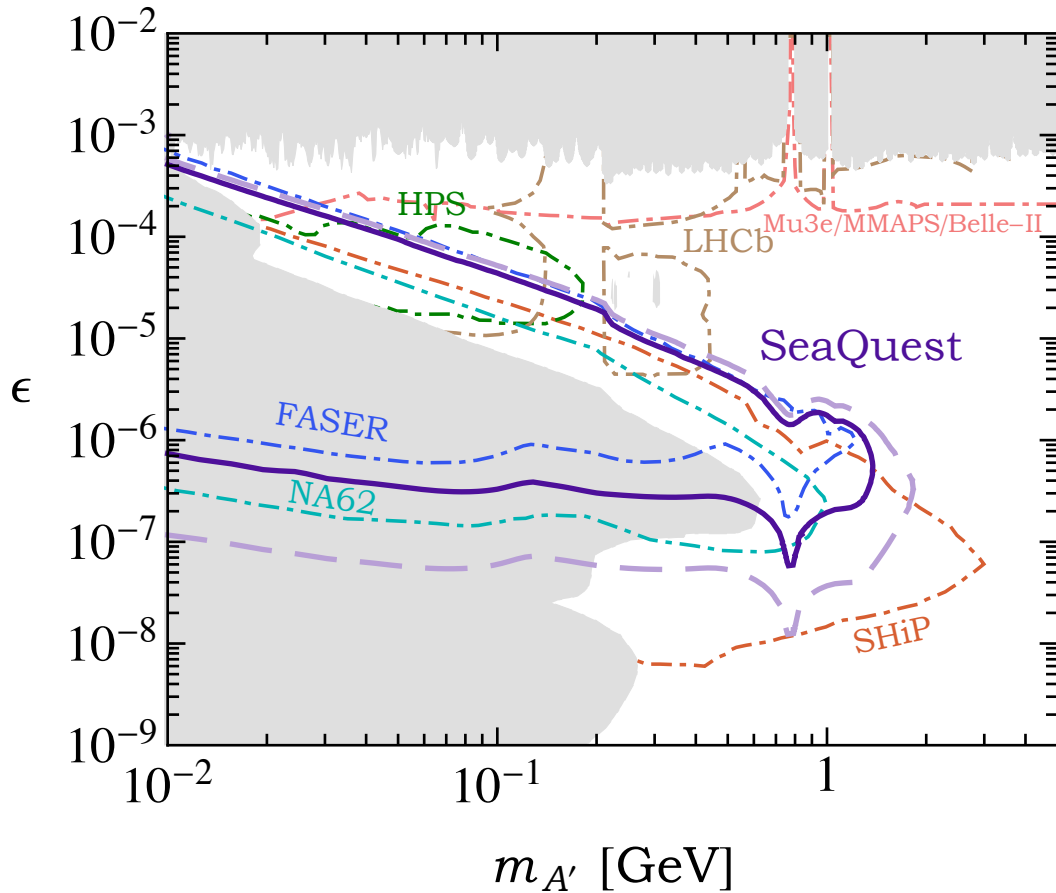


Add tracking detectors close to "target" to improve mass resolution

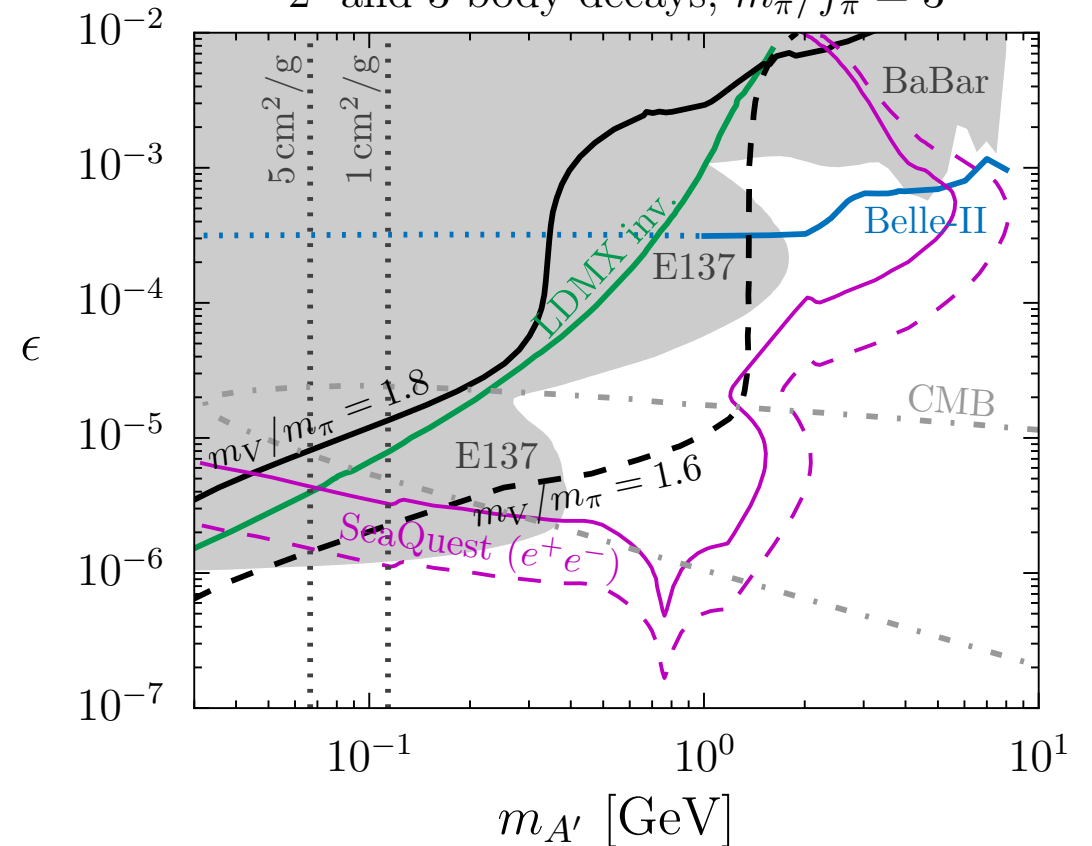
Add EMCal, PID  $e^{+/-}$ ,  $h^{+/-}$ ,  $\pi^{+/-}$

# Dark Photon Search at DarkQuest with Future Projections

$$A' \rightarrow \ell^+ \ell^-$$



$$2\text{- and }3\text{-body decays, } m_\pi/f_\pi = 3$$

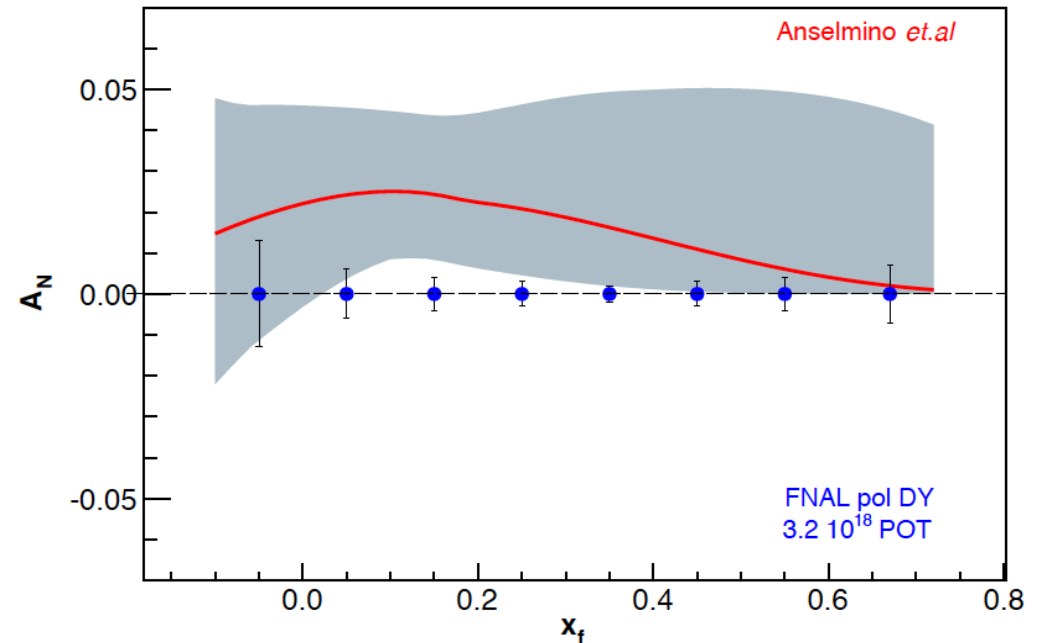
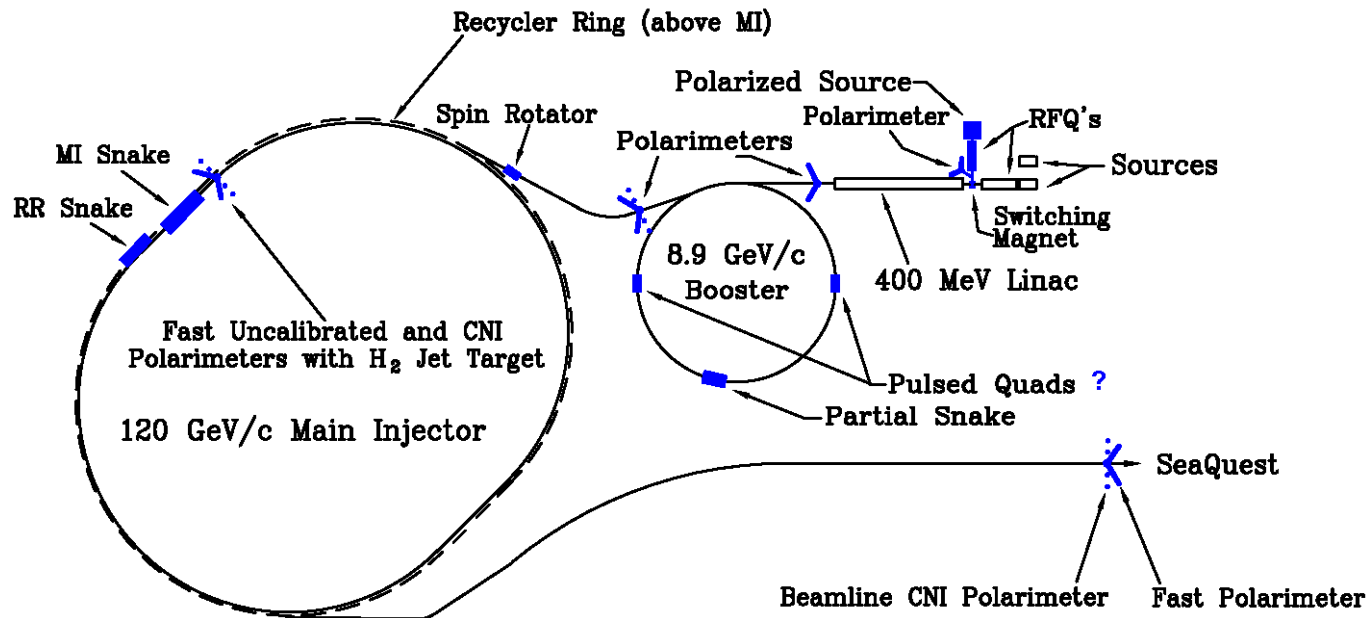


# Spin physics Program with Polarized Main Injector – E1027

- Access both polarized valence and sea quarks
- Fermilab PAC stage-1 approved
- Complementary to the future EIC TMD Physics

Test QCD processes in DY vs DIS over a broad range of kinematics

$$A_N \equiv \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \propto \frac{f_{1T}^{\perp,u}(x_B) \cdot \bar{u}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$





# TMDs probed via DY at Fermilab

## Boer-Mulders functions:

- Unpolarized Drell-Yan:  $d\sigma_{DY} \propto h_1^\perp \bar{h}_1^\perp \cos(2\phi)$

E906, E1039, E1027

## Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^\perp(x_q) f_{\bar{q}}(x_{\bar{q}})$$

E1039, E1027

## Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$$

E1027

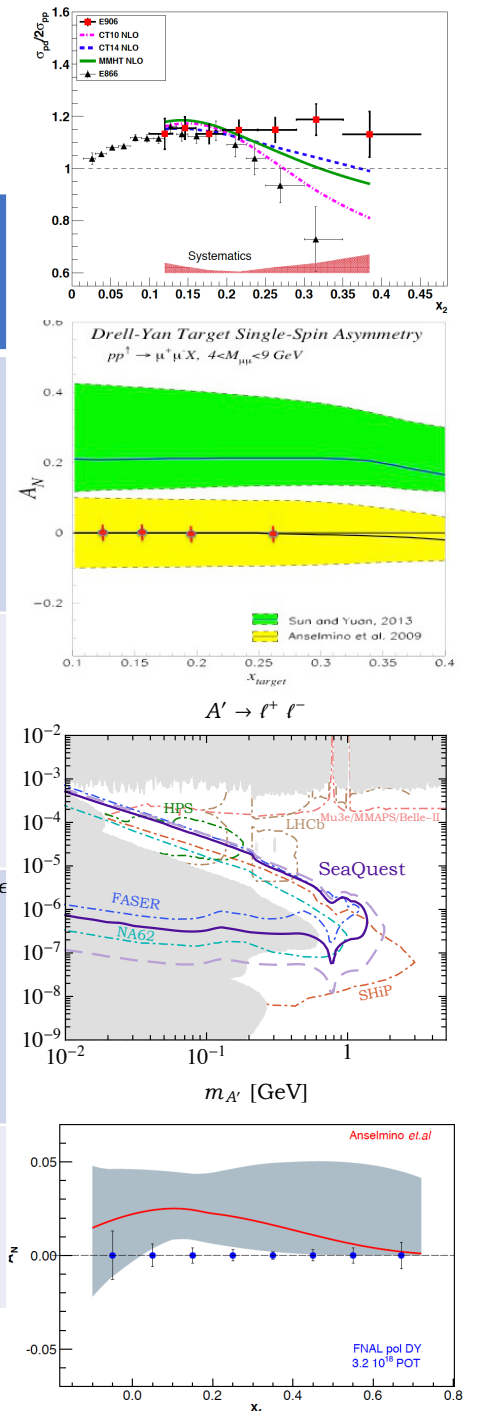
- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY

(Boer-Mulders and Sivers functions)

Remains to be tested experimentally! → COMPASS, RHIC, EIC/SpinQuest for sea quarks

# Summary and Outlook

Experiments	Run Time	Collision Types	Physics
E906	2012-2017	p + targets (H, D, C, Fe, W)	- dbar/ubar asymmetry - quark dE/dx
<b>E1039</b>	<b>2018 – 2021+</b>	<b>p + pol. targets (NH<sub>3</sub>, ND<sub>3</sub>)</b>	<b>Sea-quark Sivers, TMDs</b>
E1067(para.)	2017-2021+(para.)	p + any targets	dark photon, dark Higgs, ALP ...
DarkQuest	2021+ (dedicated)		
E1027	202x	Pol. p-beam +	- quark Sivers - TMD, spin



# SpinQuest/E1039 Collaboration

*A relatively small collaboration,  
great opportunities for new  
comers to contribute and lead  
major detector and physics  
efforts*

## Collaboration

INSTITUTION	FULL MEMBERS	AFFILIATE MEMBERS
<b>Abilene Christian University</b>	Donald Isenhower (PI), Michael Daugherty, Shon Watson	Haley Stien, John Marsden, Mitchell Schneller, Nathan Rowlands, Roy Salinas, Rusty Towell, Shannon McNease, Yves Ngenzi, Thomas Fitch
<b>Argonne National Laboratory</b>	Paul Reimer (PI), Donald Geesaman	Kawtar Hafidi, Kevin Bailey, Thomas O'Connor, Zhihong Ye, Benjamin Zeidman
<b>Fermi National Accelerator Laboratory</b>	Richard Tesarek (PI), Carol Johnstone, Charles Brown	Robert Bushek, Dave Christian, Donald Mitchell, David Northacker, Mike Geelhoed, Kathy Graden, Bridget Iverson, Ivan Vitev, Jin-Yuan Wu, Maddie Schoell, Steven Timm, Yanqiu Yin
<b>KEK</b>	Shin'ya Sawada (PI)	Shigeru Ishimoto
<b>Los Alamos National Laboratory</b>	Kun Liu (SP), Mikhail Yurov, Chun-Min Jen, Ming Liu, Xuan Li, Walter Sondheim	Jan Boissevain, Melynda Brooks, Matt Durham, David Kleinjan, Sho Uemura, Cesar Da Silva, Patrick McGaughey, Andi Klein
<b>Mississippi State University</b>	Lamiaa El Fassi (PI)	Dipangkar Dutta
<b>New Mexico State University</b>	Stephen Pate (PI), Vassili Papavassiliou, Haiwang Yu, Forhad Hossain	
<b>RIKEN</b>	Yuji Goto (PI)	
<b>Tokyo Institute of Technology</b>	Kenichi Nakano (PI), Toshi-Aki Shibata	
<b>University of Colorado, Boulder</b>	Edward Kinney (PI)	
<b>University of Illinois, Urbana-Champaign</b>	Jen-Chieh Peng (PI), Yen-Chu Chen	Naomi Makins, Ching Him Leung, Daniel Jumper, Jason Dove, Mingyan Tian, Bryan Dannowitz, Randall McClellan, Shivangi Prasad
<b>University of Michigan</b>	Wolfgang Lorenzon (PI), Minjung Kim, Noah Wuerfel	Daniel Morton, Richard Raymond, Marshall Scott
<b>University of New Hampshire</b>	Karl Slifer (PI), David Ruth	Maurik Holtrop
<b>University of Virginia</b>	Dustin Keller (SP), Joshua Hoskins, Zulkaida Akbar, Carlos Ramirez	Donal Day, Donald Crabb, Jixie Zhang, Oscar Rondon, Liliet Diaz, Arthur Conover, Brandon Kriesten, Simonetta Liuti, Ellen Brown, Blaine Norum, Matthew Roberts
<b>Yamagata University</b>	Yoshiyuki Miyachi (PI), Genki Nukazuka	Takahiro Iwata, Norihiro Doshita

backup

# SpinQuest Experimental Hall



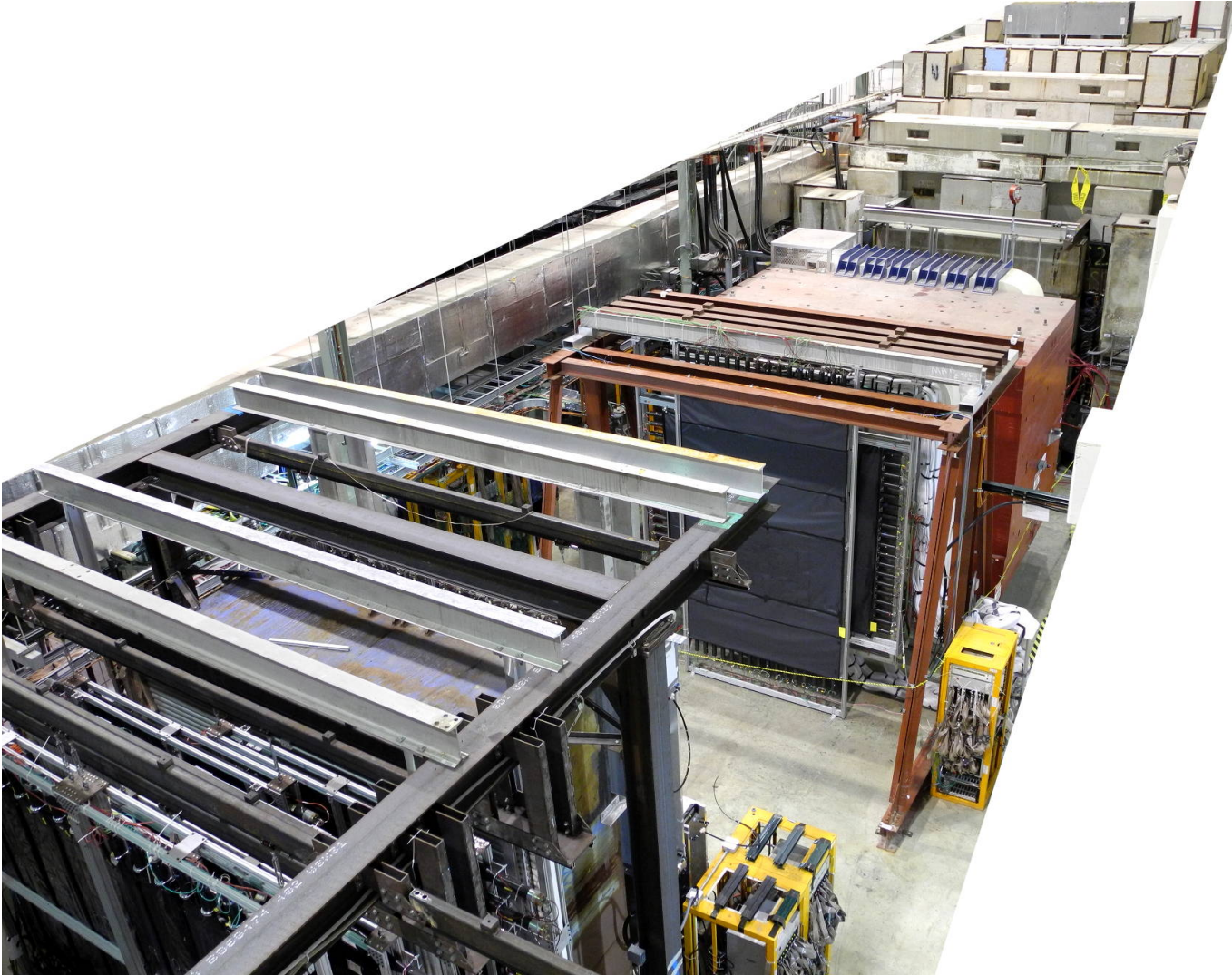
Beam

Target area

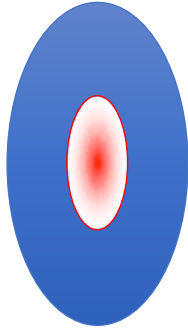
F-Mag

K-Mag

Muon-ID



# New Beam Collimator and Target



Target cross section: 18 x 28 mm<sup>2</sup>

Beam cross section:

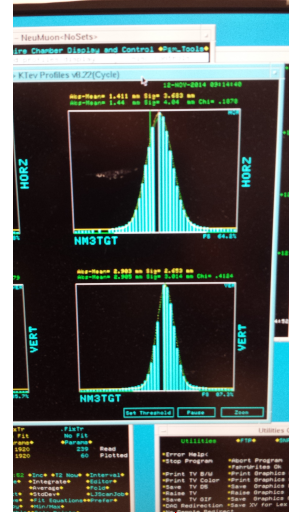
Need be well contained within 4 sigma, required by  $dR < 2 \times 10^{-4}$

sigX = 18/2/4 = 2.2 mm

sigY = 28/2/4 = 3.5 mm

Beam jitter:  $dX=dY \sim 1\text{mm}$

- 1 sig = 0.68269
- 2 sig = 0.95450
- 3 sig = 0.99730
- 4 sig = 0.99994



E906 beam profile:

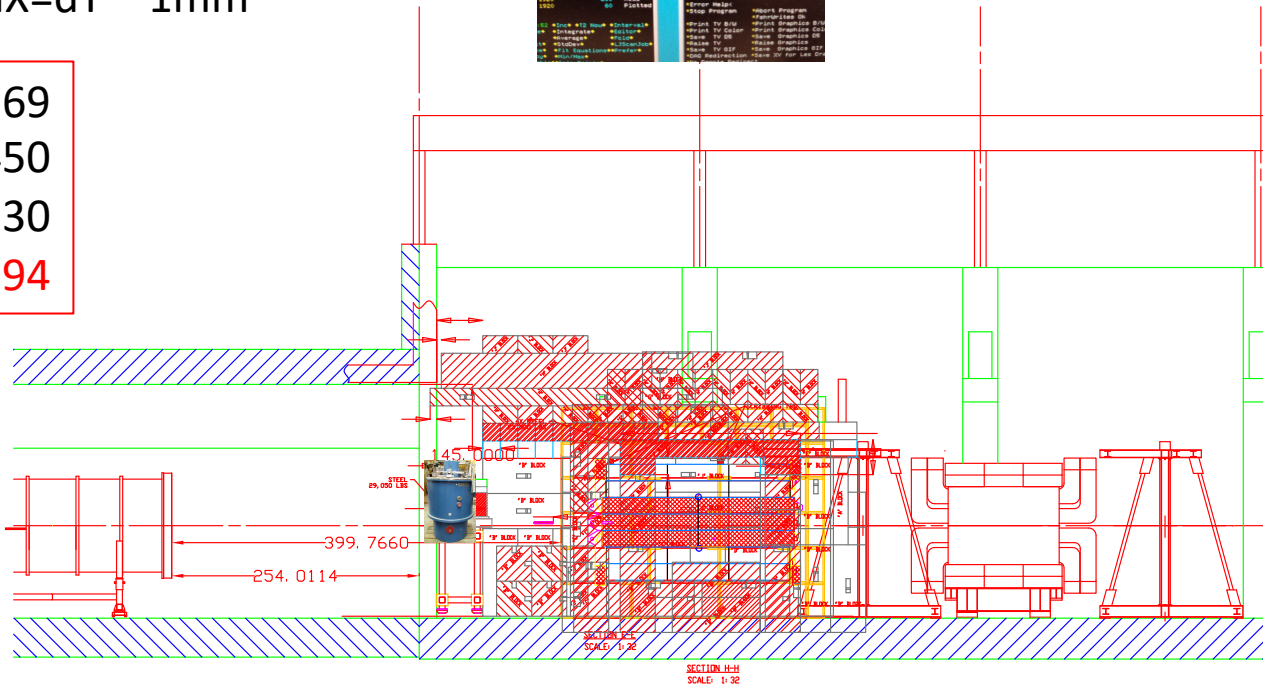
SigX = 4.0mm

SigY = 3.0mm

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

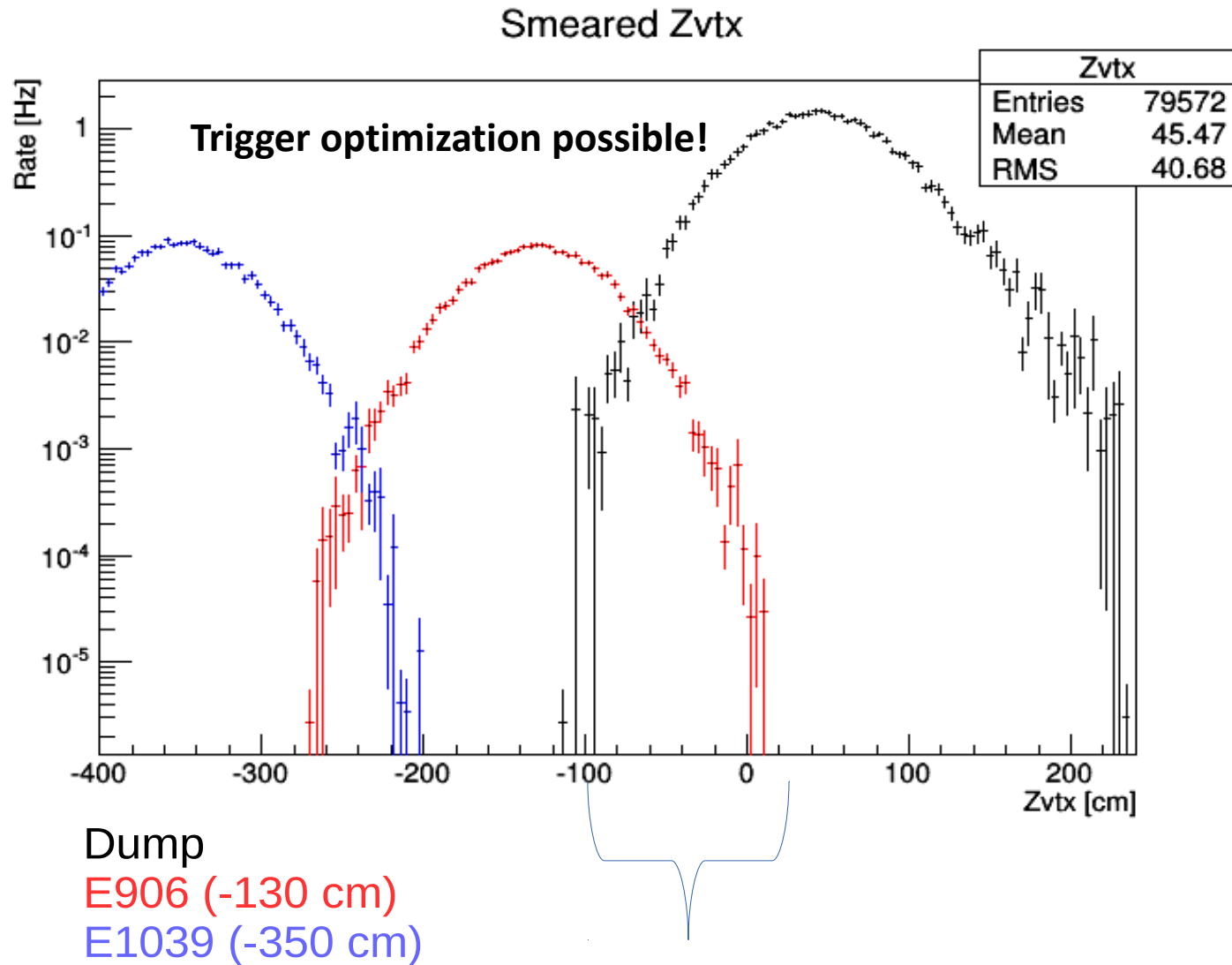
Beam collimator

120GeV beam



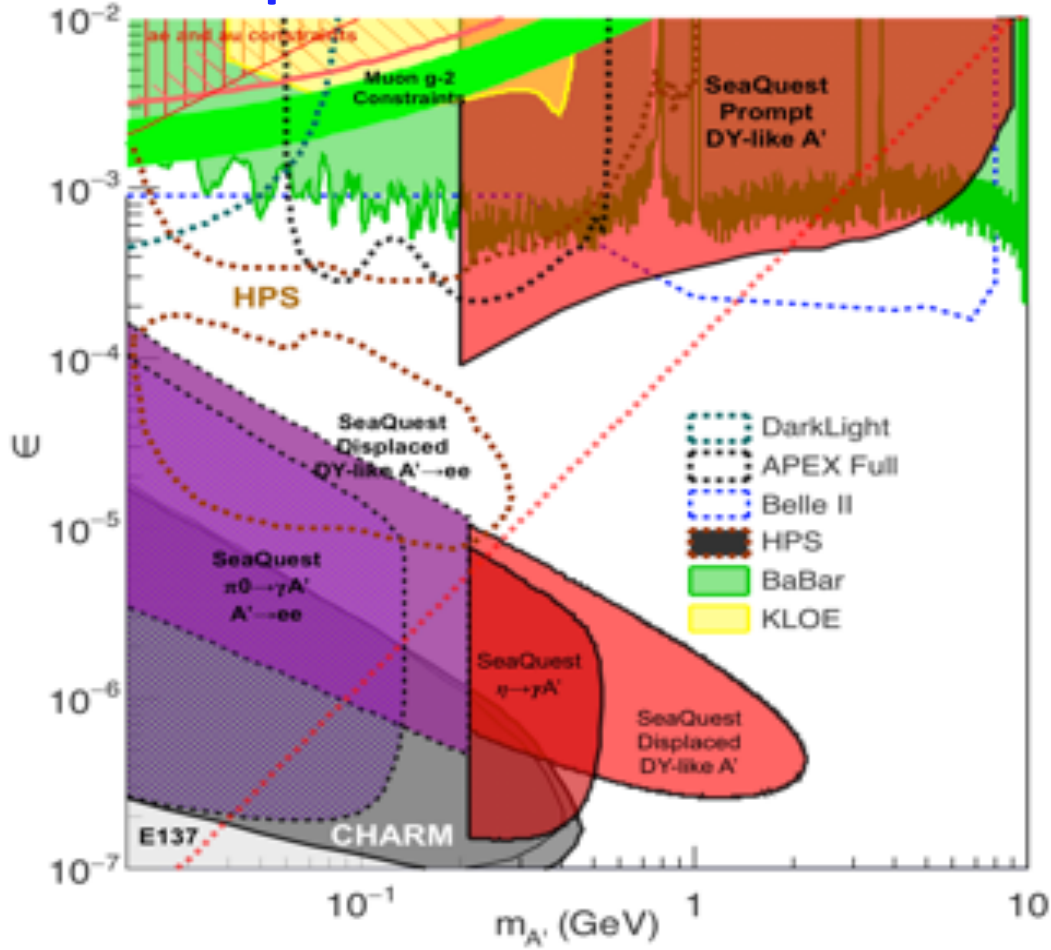
# Target and Beam Dump Event Separation

target at upstream:  $Z=-3.5\text{m}$



# Projected Dark Sector Physics Search Sensitivity

## Dark photon search



## Dark Higgs search

