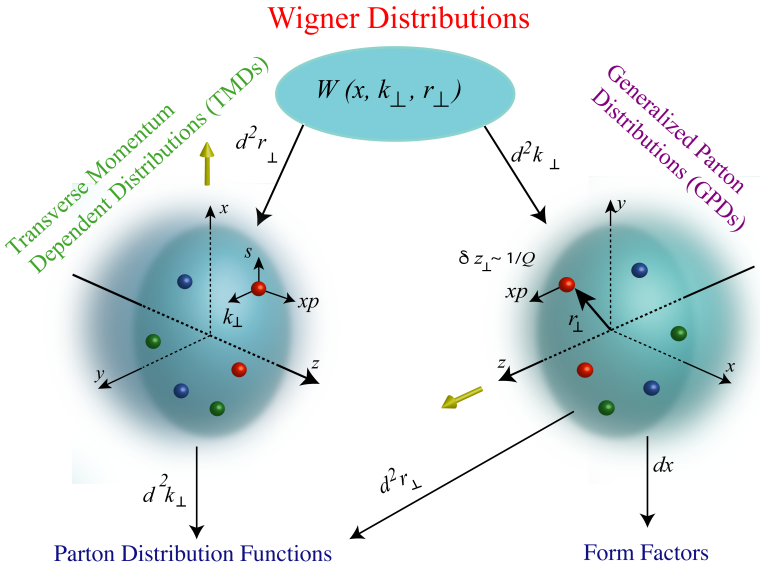
Probing Sea Quark TMD with Drell-Yan at SpinQuest/E0139 at Fermilab

Ming Liu

Los Alamos National Laboratory

For the SpinQuest/E1039 Collaboration

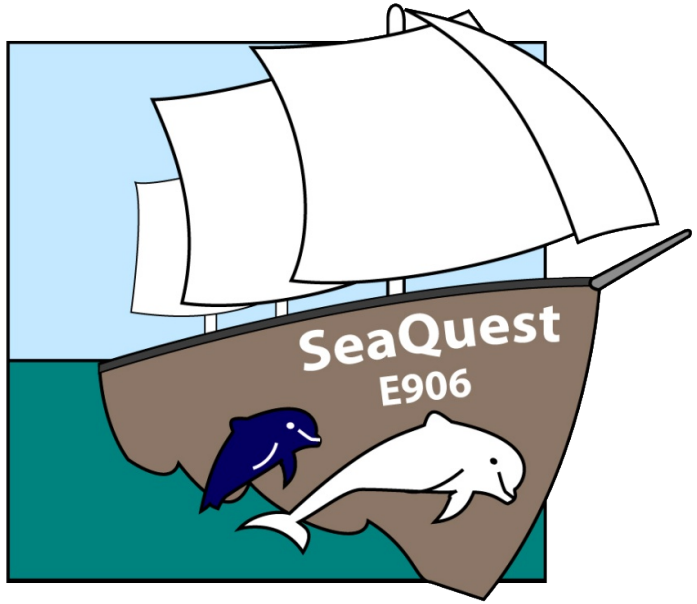


QCD Evolution 2019, May 13-17

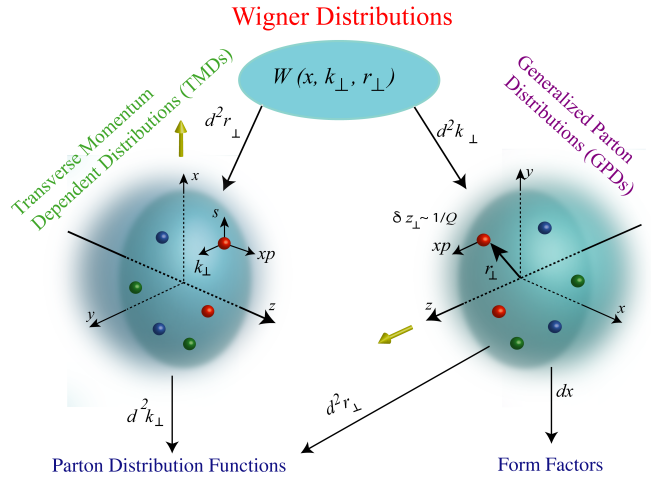
Argonne National Laboratory

Outline

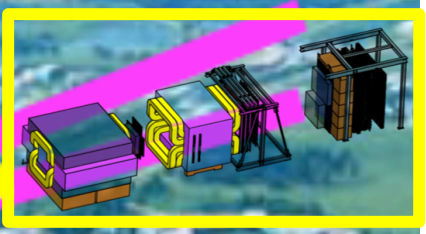
- SpinQuest/E1039 experiment at Fermilab
  - E1039 polarized NH_3/ND_3 targets
  - Follow up of SeaQuest/E906 unpolarized target program
- Novel physics of sea quarks at x = 0.1 - 0.4
  - Flavor asymmetry
  - Sivers & OAM
- Other opportunities
  - Parasitic E1067 dark photon search, 2016 - 2021+
  - Future E1027 polarized beam possibility, 2021+
  - TMD physics complementary to the future EIC program



A serials of follow up experiments:
SeaQuest, SpinQuest, DarkQuest …



Fermilab High Intensity Frontier



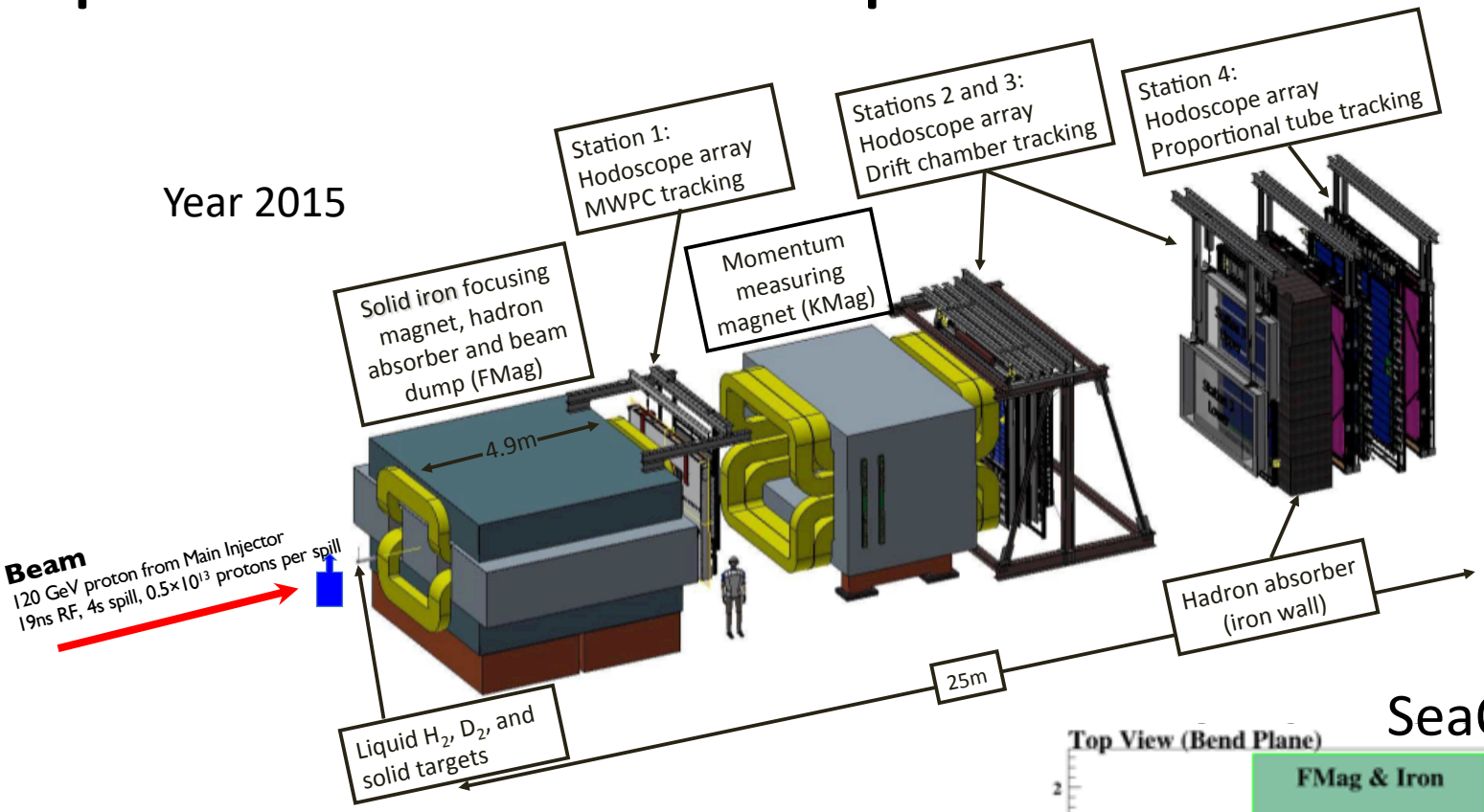
Fixed Target Beam lines

Tevatron 800 GeV

Main Injector 120 GeV

SpinQuest Dimuon Spectrometer

Year 2015



120 GeV protons from the Main Injector

- 4s beam spill very 60 sec
- 19ns RF, ~10s K protons per RF bucket
- 5×10^{12} Proton On Target (POT) per spill
- Total integrated POT for E1039 (2-year): 1.4×10^{18} POT

E906 unpolarized targets: 2012-2017

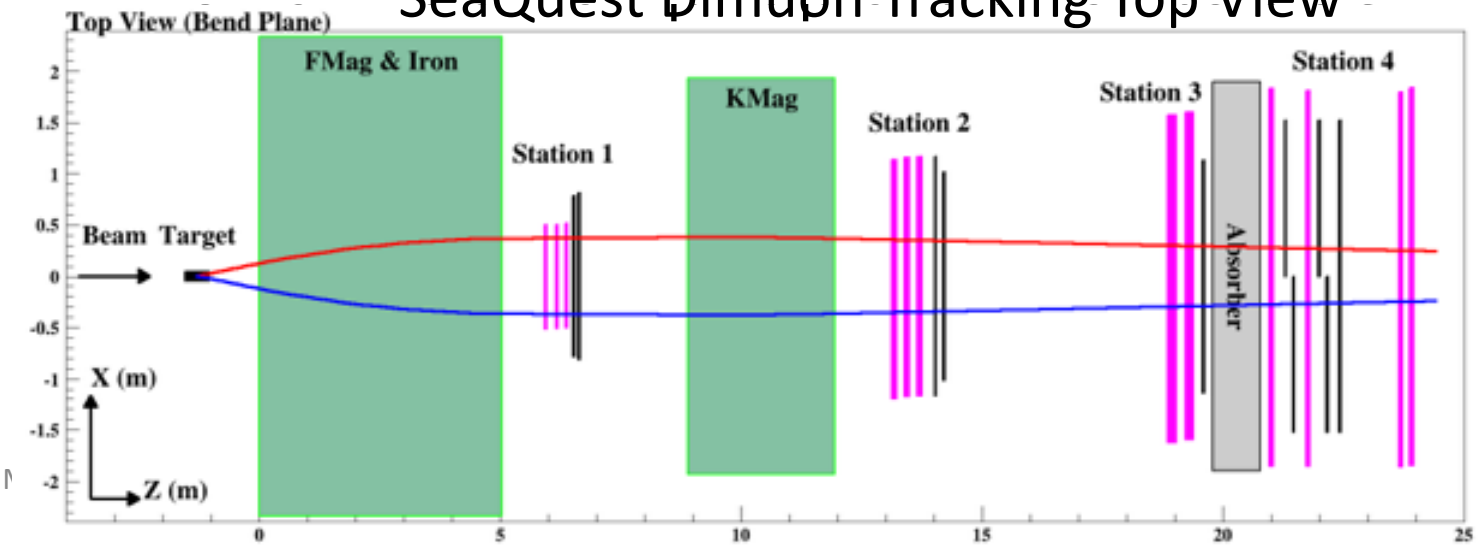
- ^{1}H, ^{2}D, ^{12}C, ^{56}Fe, ^{184}W

E1039 polarized targets: 2019 – 2021+

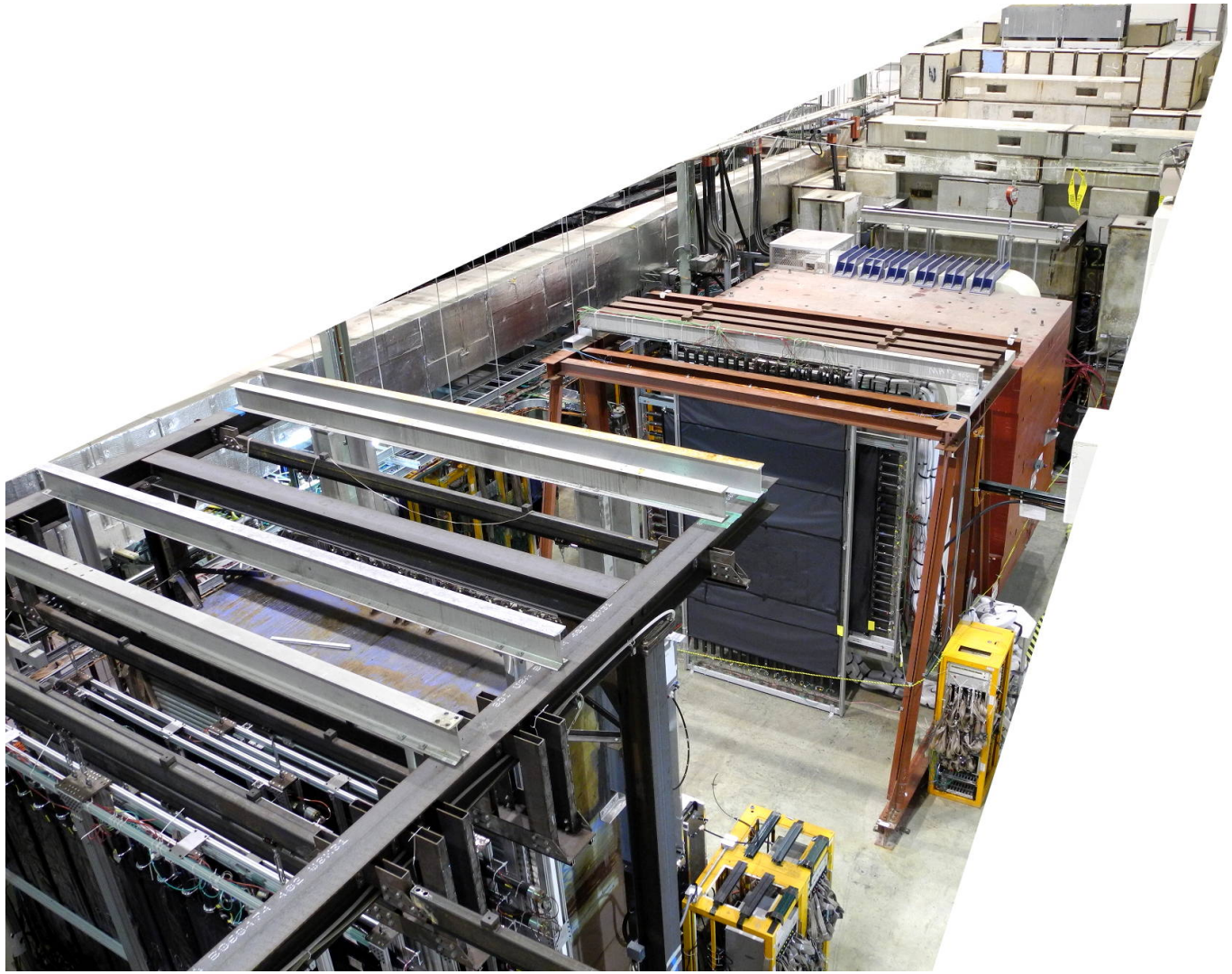
- Polarized protons (NH_3)
- Polarized neutrons (ND_3)

E1027 polarized beam

SeaQuest Dimuon Tracking Top View



SpinQuest Experimental Hall



Beam

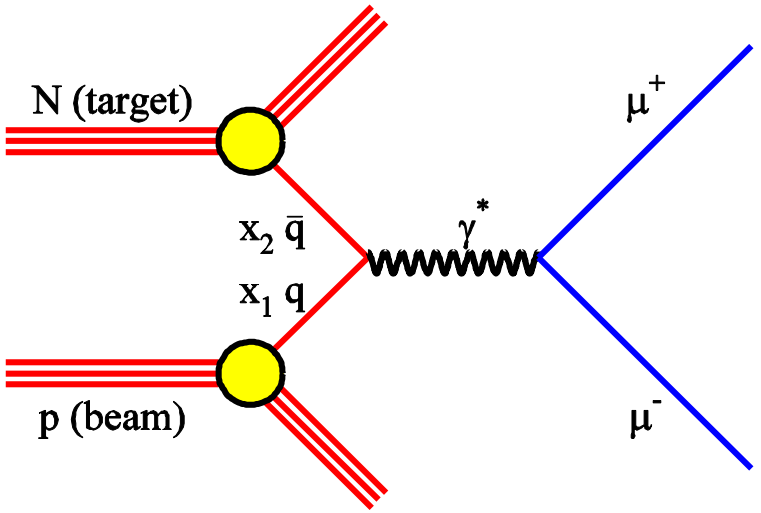
Target area

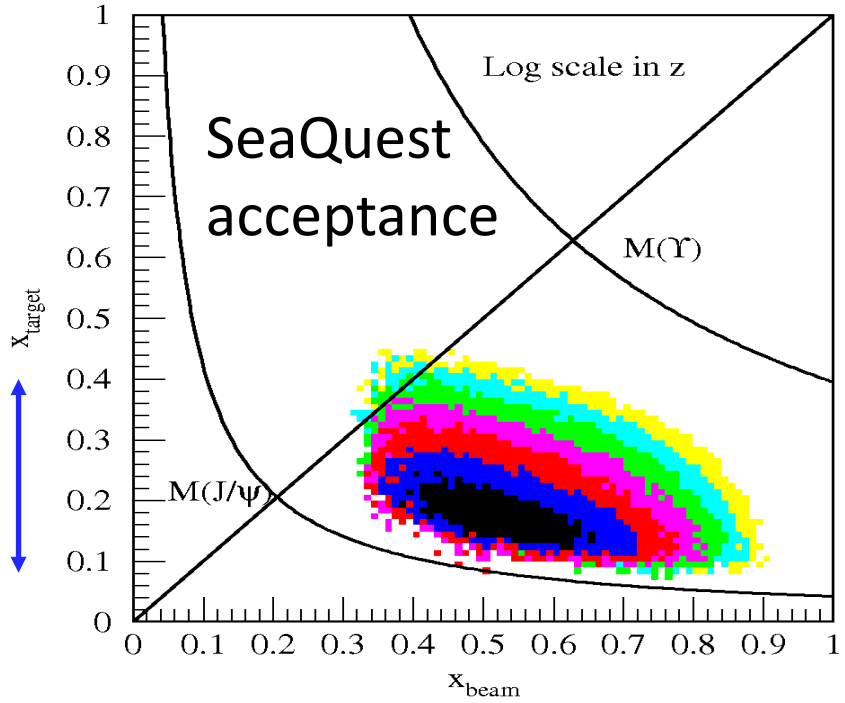
F-Mag

K-Mag

Muon-ID

Drell-Yan @SeaQuest – a Sea Quark Laboratory



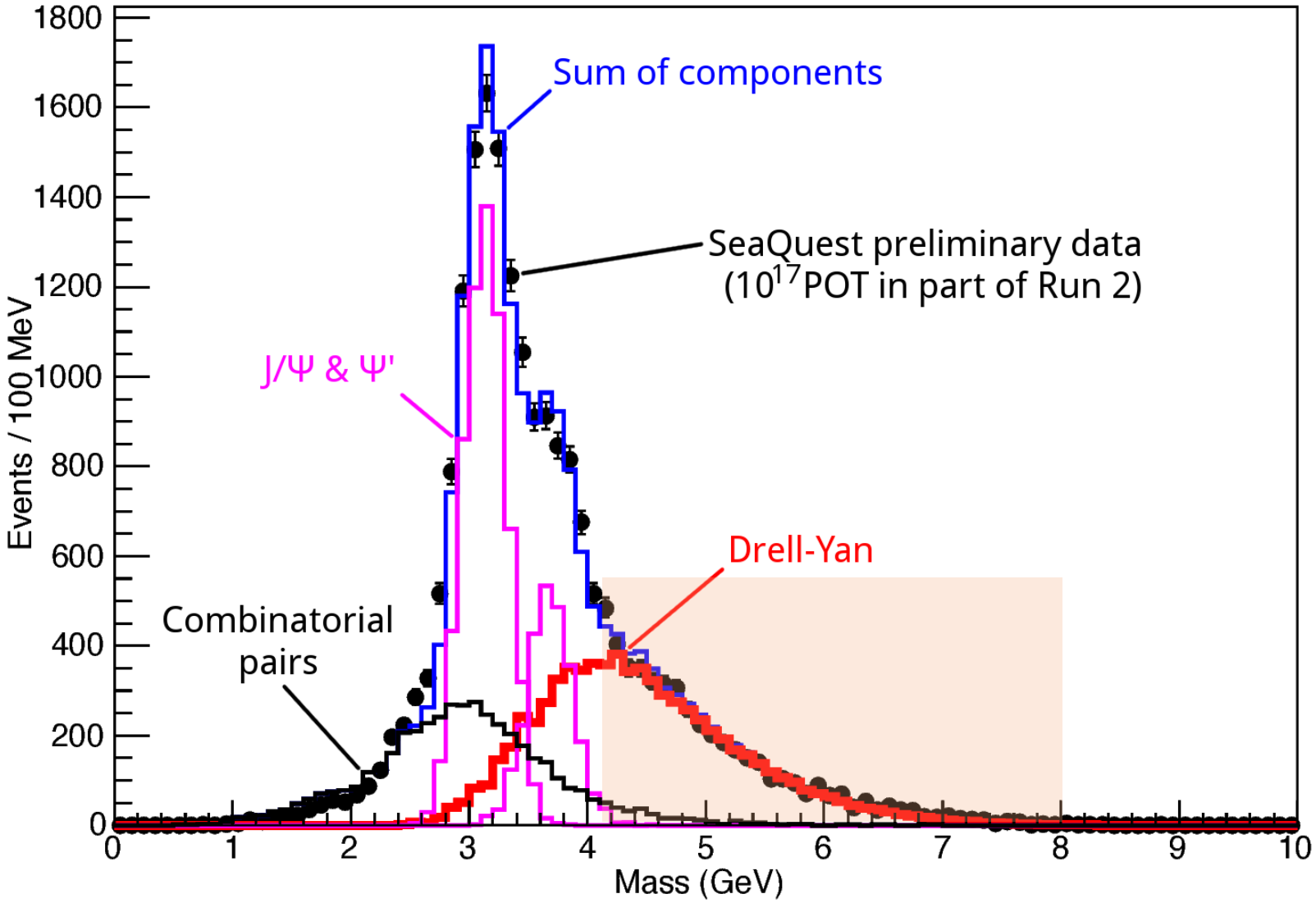


$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q(x_t)]$$

$$\approx \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t)]$$

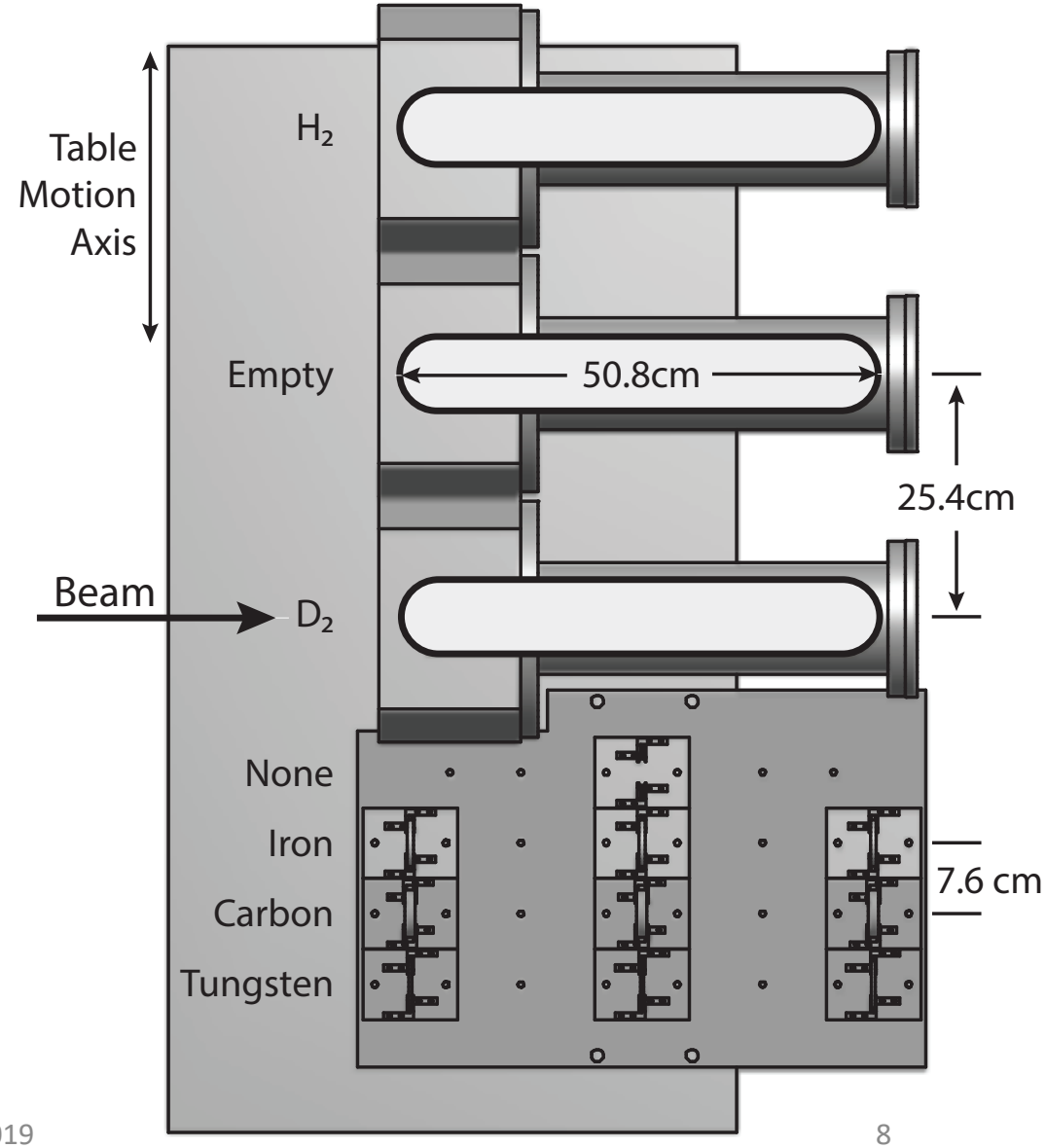
Fixed target kinematics favors sea-quarks from target – **a sea quark lab!**

Dimuon Mass from SeaQuest/E906



E906 Unpolarized Physics Program

- Thin targets: ~10% interaction length
  - Liquid H/D
  - Solid C, Fe, W
- Physics
  - Sea quark flavor asymmetry, dbar/ubar
  - Quark energy loss in p+A collisions, dE/dx
  - TMD and more …
- Experimental runs – 6 years
  - 2012 – commissioning
  - 2017 – completed

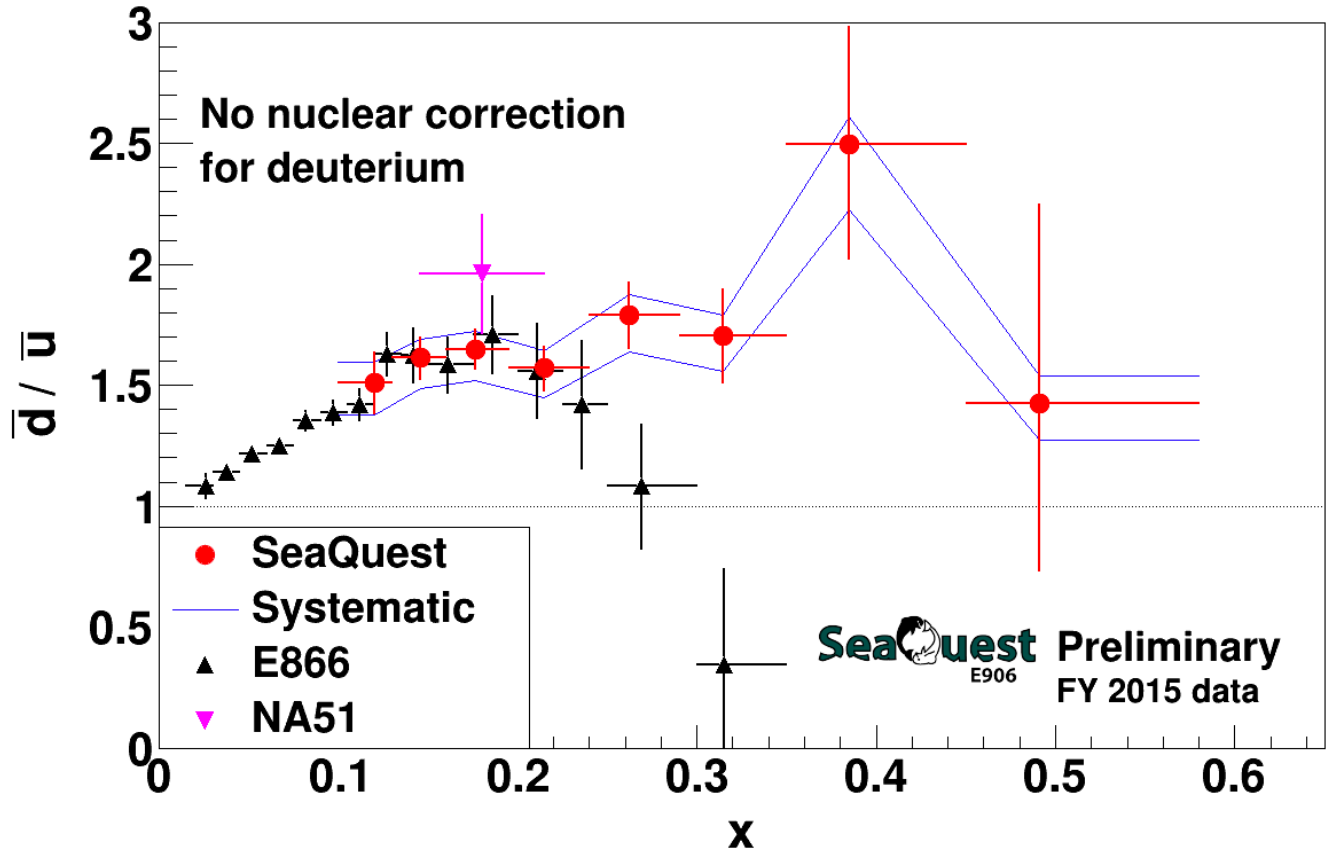


Flavor Asymmetry of Sea Quarks at Intermediate x

Proton vs "Neutron" targets:

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

This could lead to a very interesting physics …



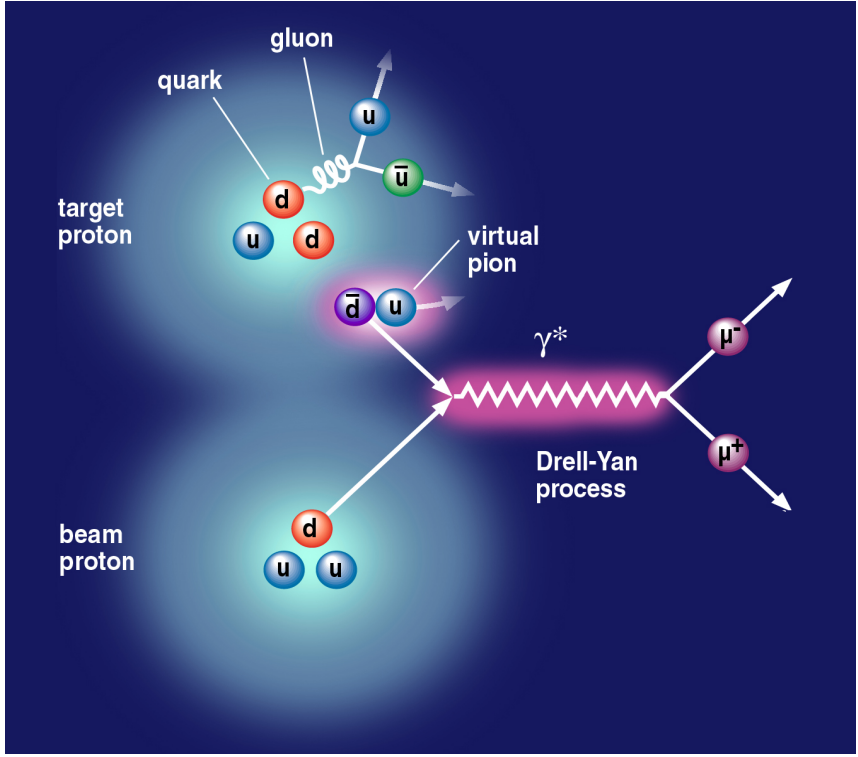
J. C. Peng et al (FNAL E866/NuSea), PRD 58, 092004 (1998)

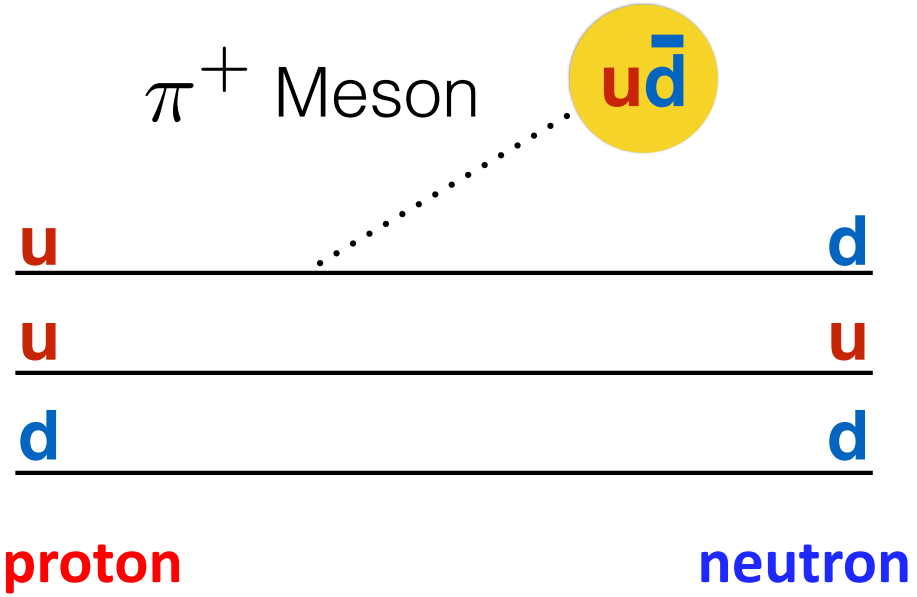
Sea Quark Flavor Asymmetry and OAM

Pion cloud model

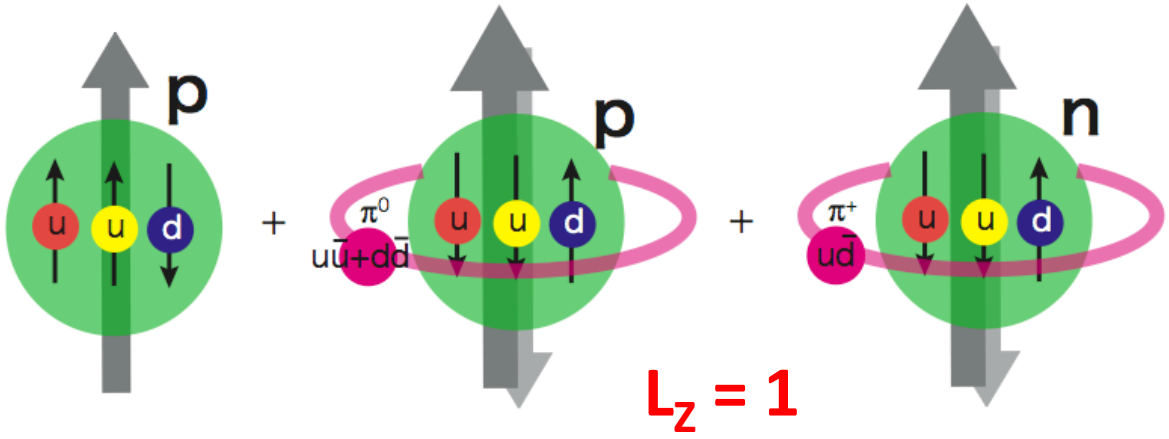
- Sea-quark flavor asymmetry
- Sea-quark orbital angular motion
- Expect large Sivers function at x = 0.1 - 0.4

Pion cloud and Drell-Yan process

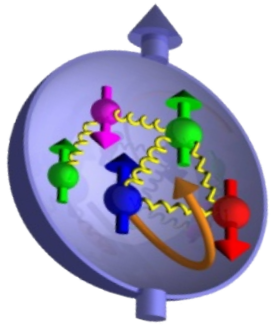




$|p\rangle = a_1|p_0\rangle + a_2|p_0 + pi^0\rangle + a_3|n+pi^+\rangle + \ldots$

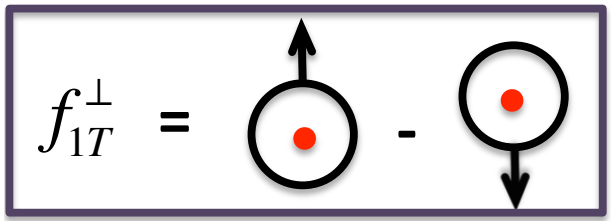


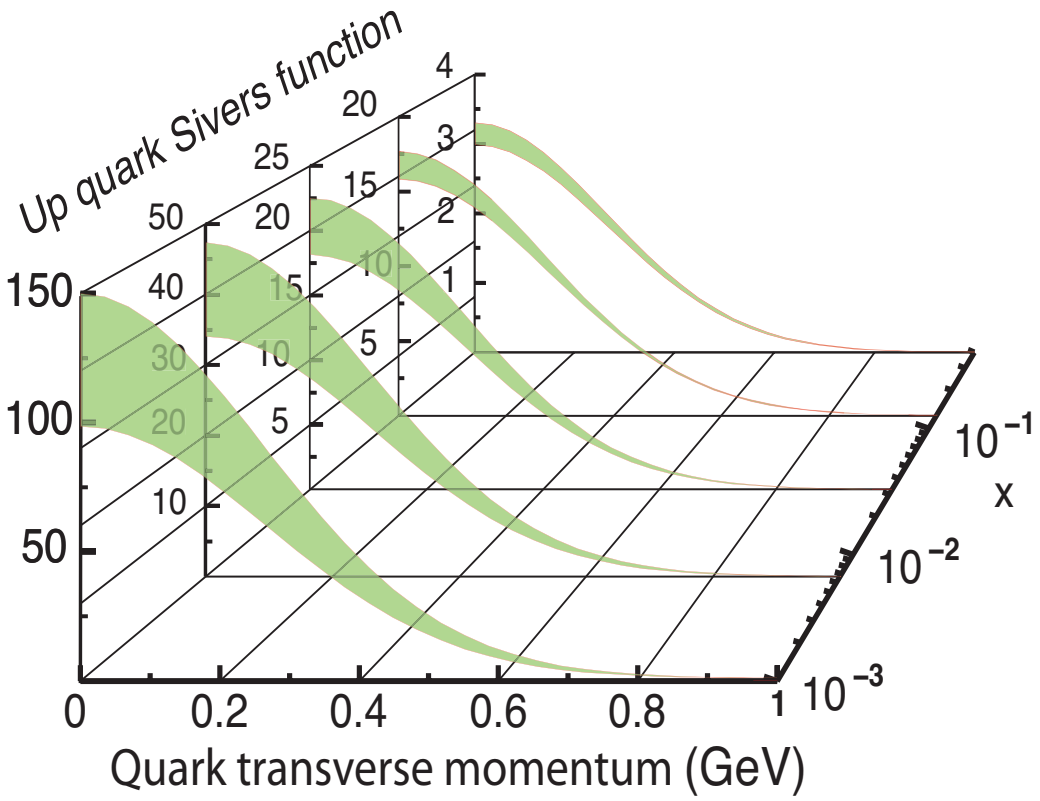
$L_z = 1$

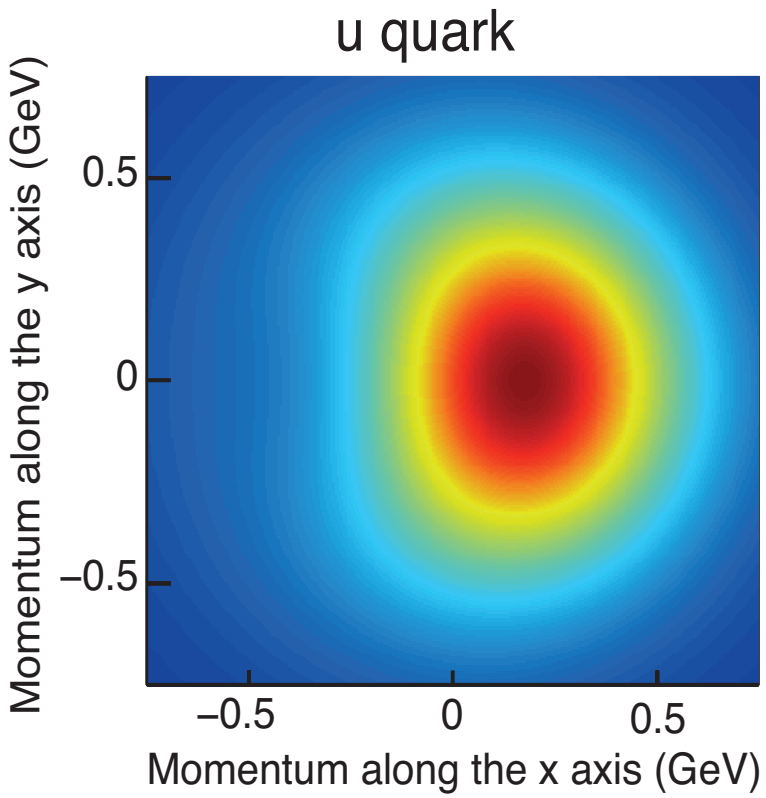


Nucleon 3-D Structure and Sivers Function

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





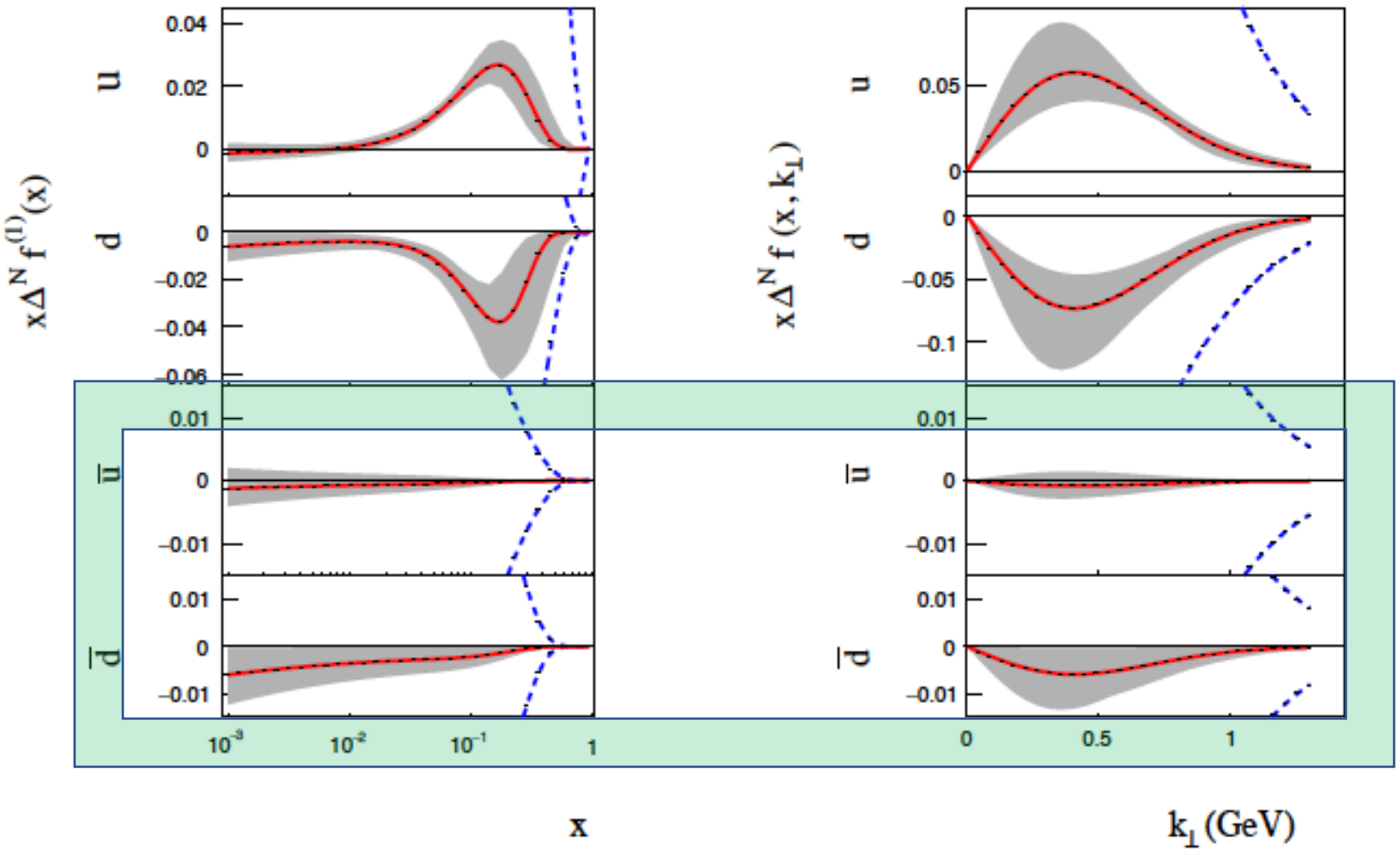


Sivers Functions from Global Fits

- 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

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

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

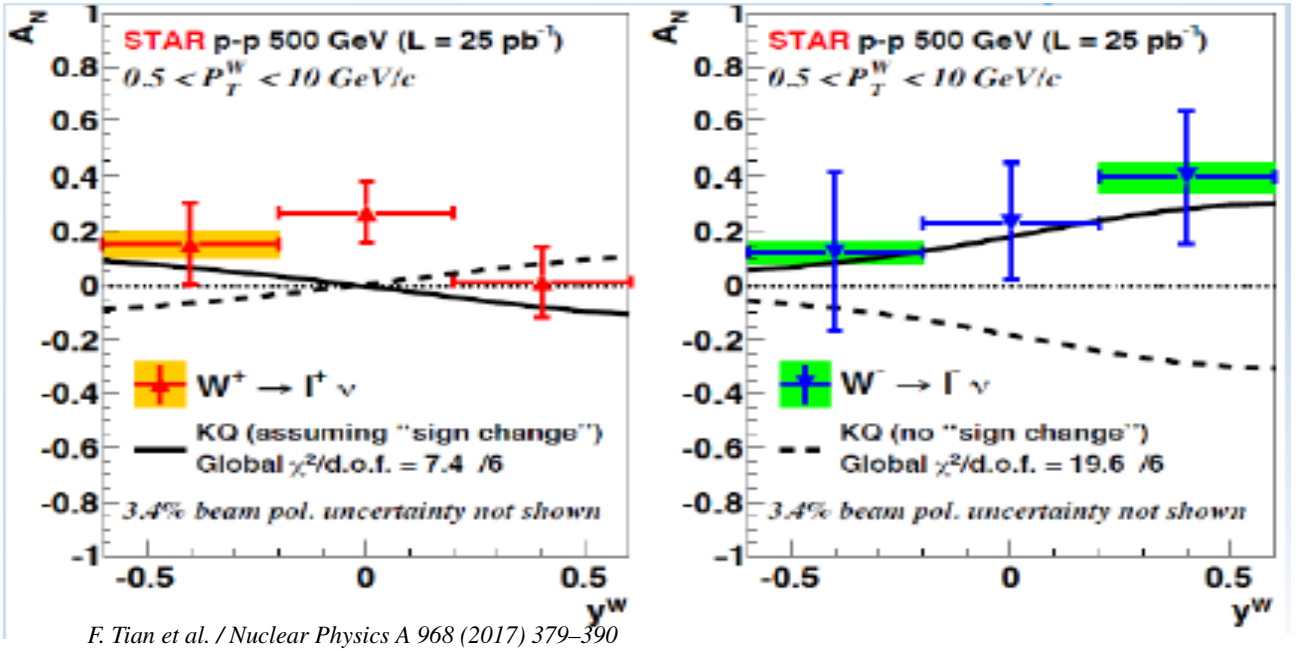
RHIC data:

- A mix of valence and sea quark Sivers
- Quark flavor identified
- High Q^2
- Statistically limited, ~0(10%)
- **Possible large dbar Sivers contributions**

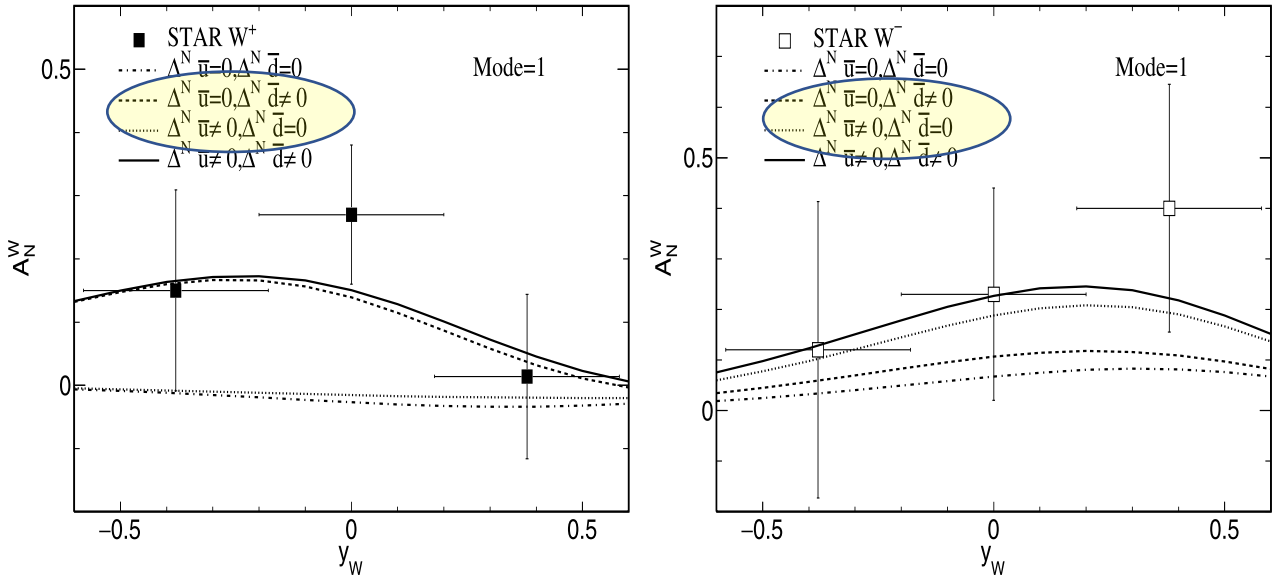
E1039:

- low Q^2
- Good statistics, ~O(1%)

Anselmino et al 2016



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



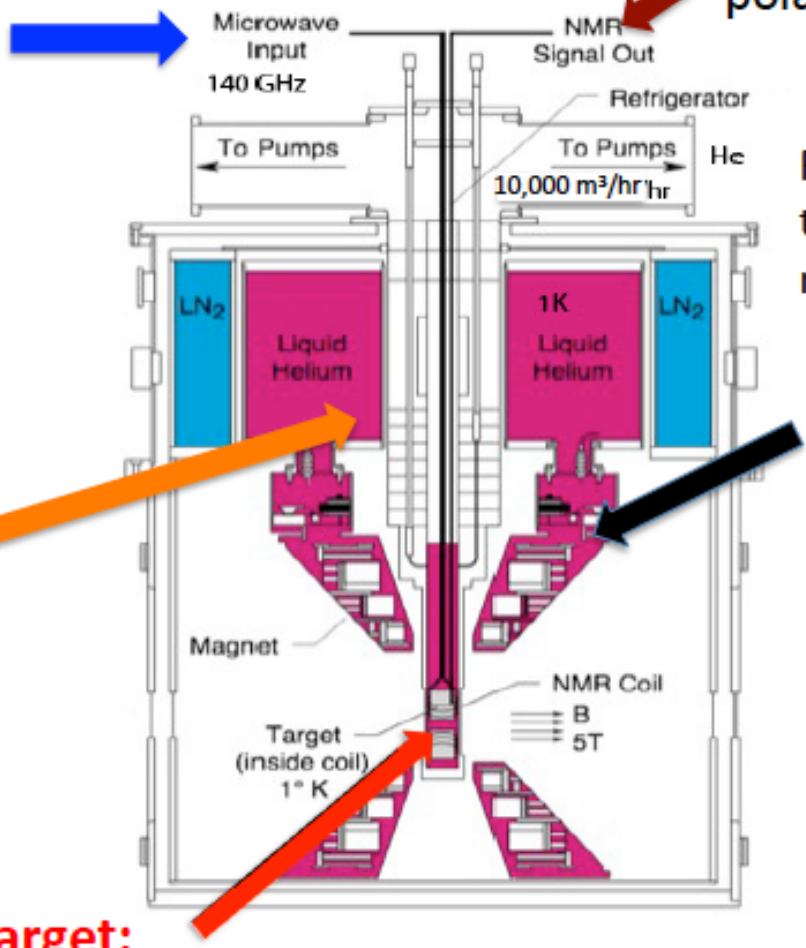
(b) $A_{W^+}^N$. (a) $A_{W^-}^N$.

Polarized NH_3 Target Developed for DY Sivers

Microwave: Induces electron spin flips

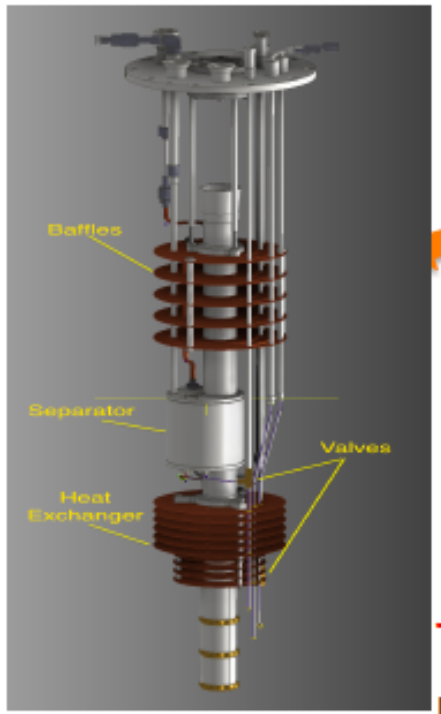
- EIO + Power equip:

NMR system: to measure polarization



Roots pump system used to pump on ^4He vapor to reach 1K

Refrigerator:

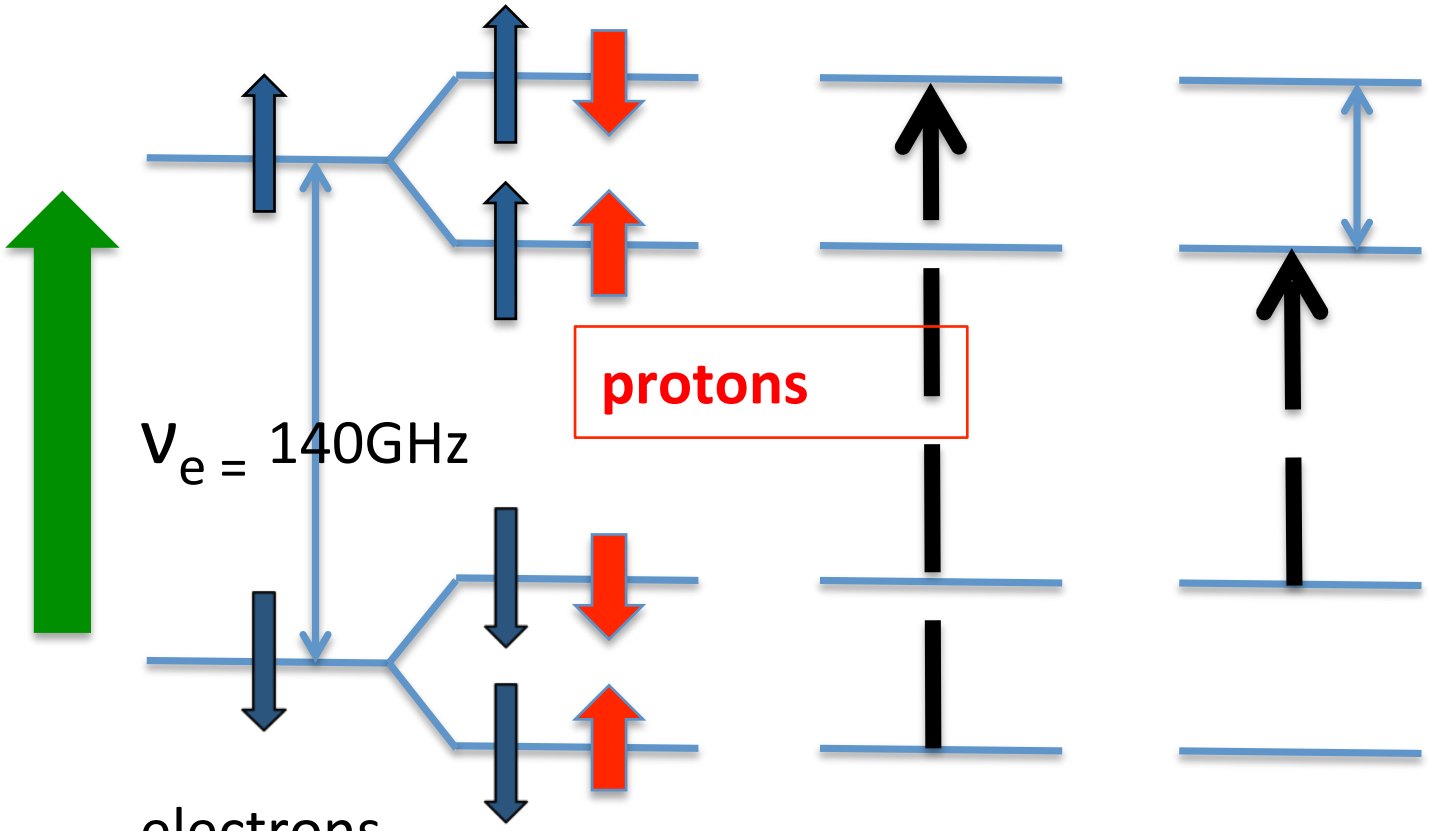


Superconducting Coils for Magnet: 5T

Target:

material: frozen NH3/ND3, Irradiation@ NIST

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%

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

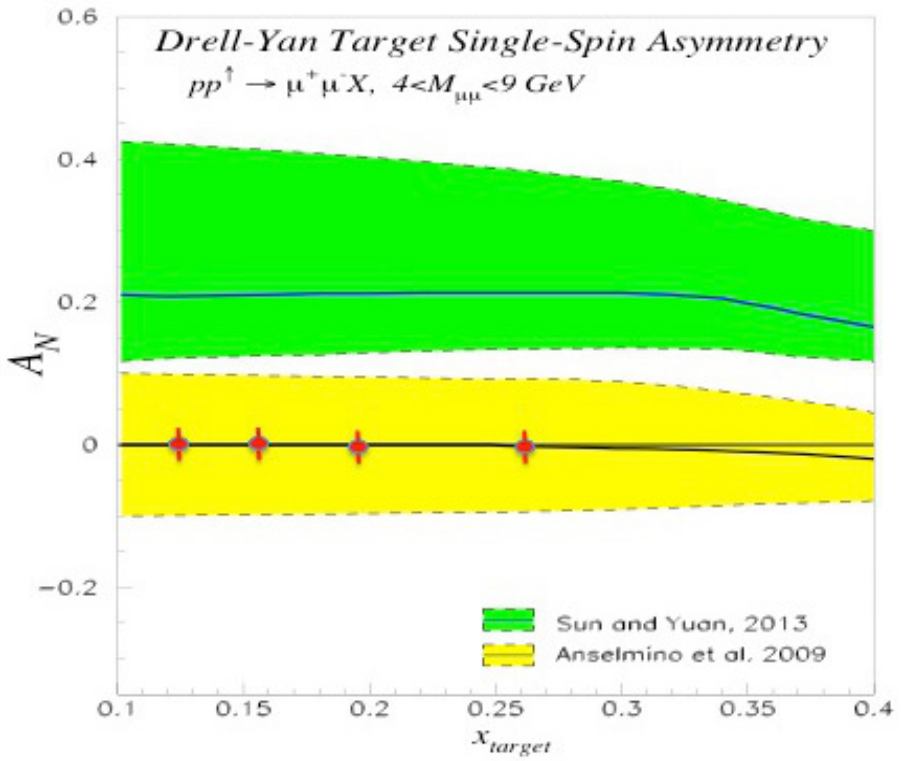
Projected SpinQuest Target and Beam Performance

$$A_{\mathrm{meas}} = f \cdot P_{\mathrm{T}} \cdot A_{\mathrm{phy}}$$

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	$4{*}10^{35}/cm^2/s$
Density NH_3	.82 g/cm^3	E_{Beam}	120 GeV
		Total $\mu^+\mu^-$ pairs	$4.59\ {*}10^5$
		Experiment available	.48

Projected Drell-Yan Transverse Single Spin Asymmetry

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

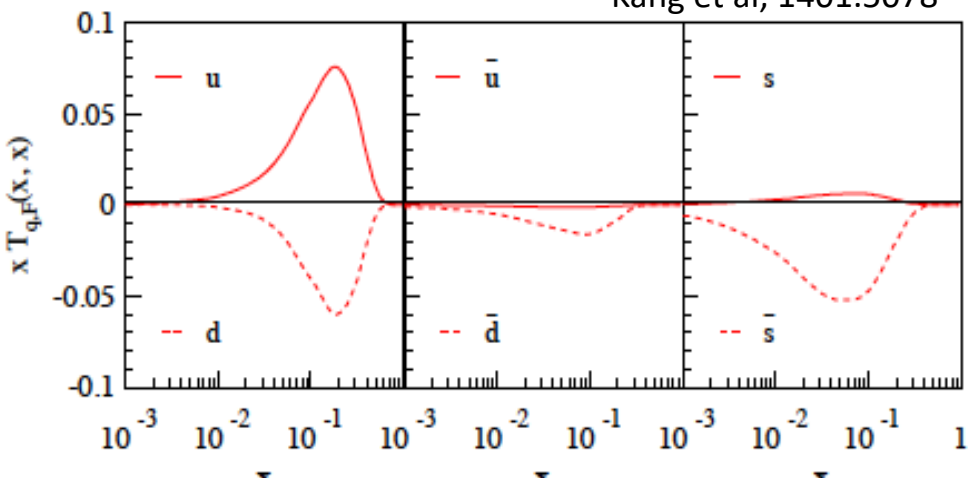


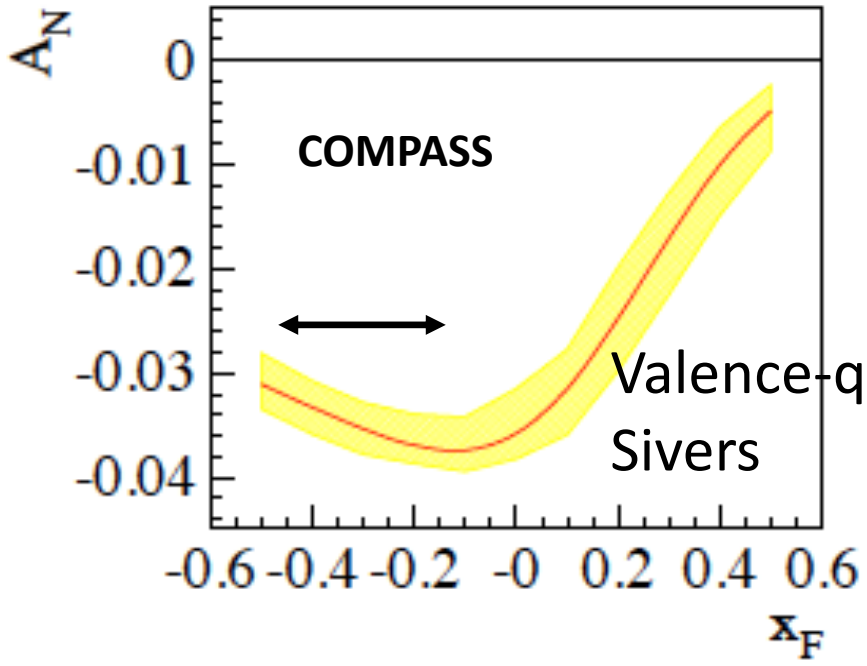
$$\delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N^+ + N^-}}$$

Range x_B	Mean x_B	Total events	ΔA
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

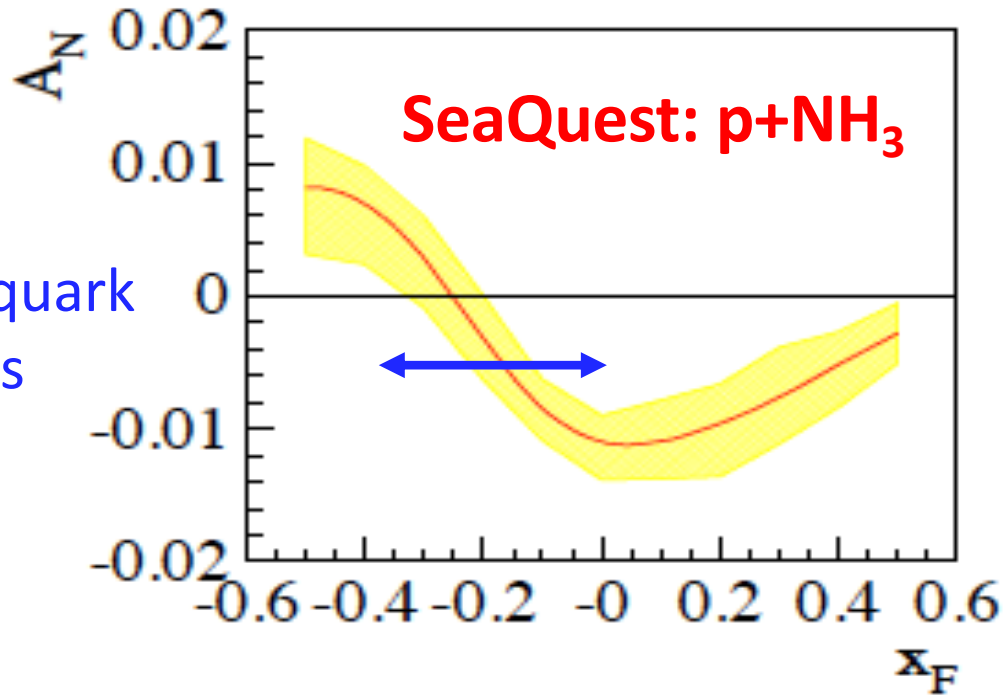
Drell-Yan Sivers Asymmetries w/ QCD Evolution

Kang et al, 1401.5078

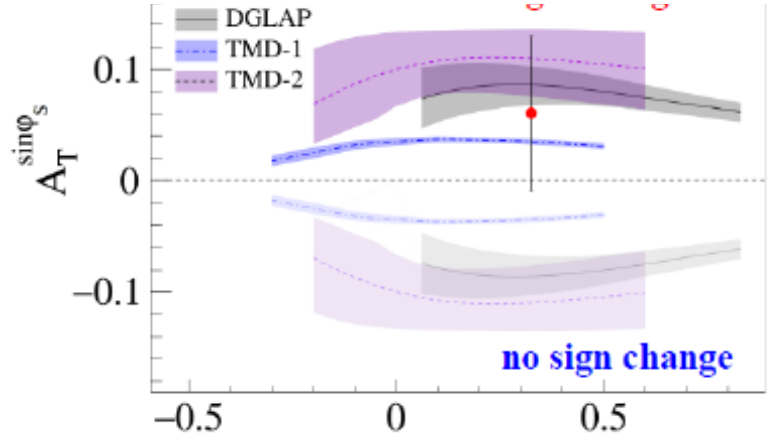




Valence-quark Sivers

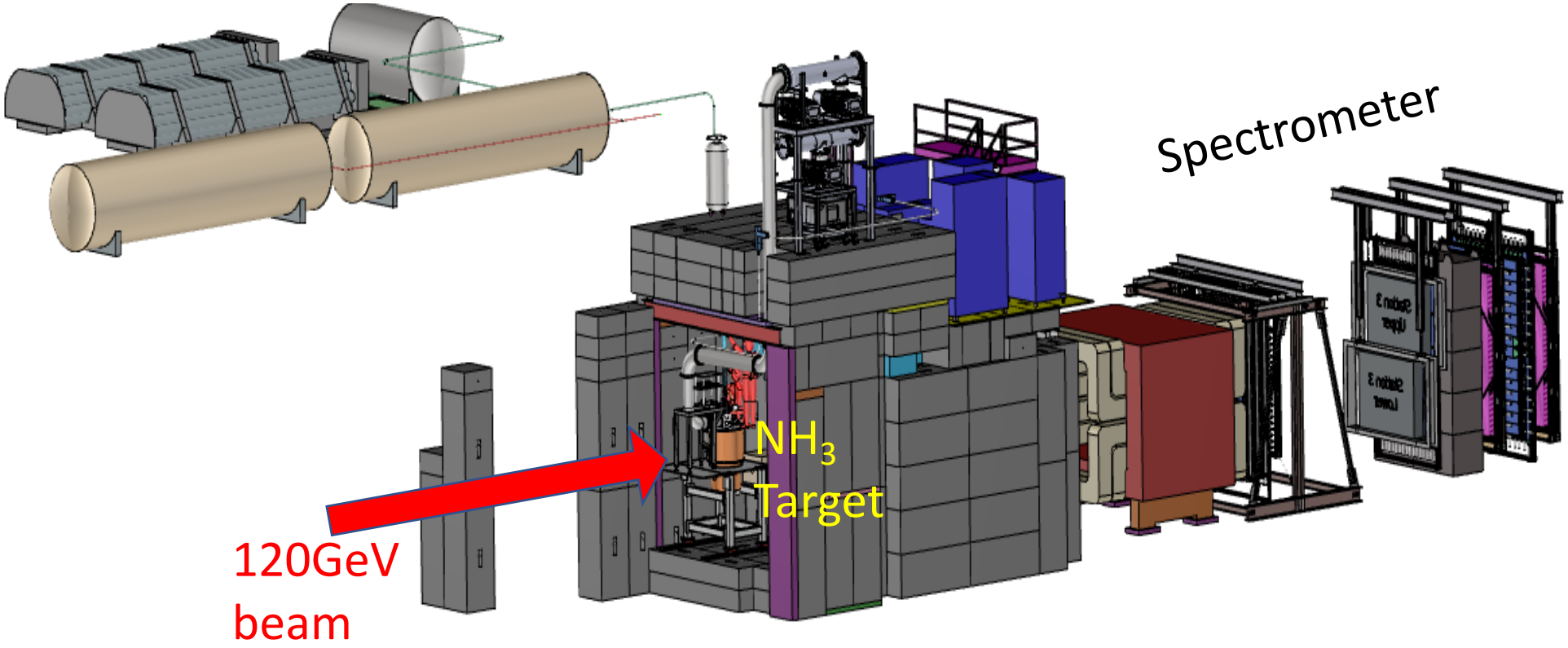


Sea-quark Sivers



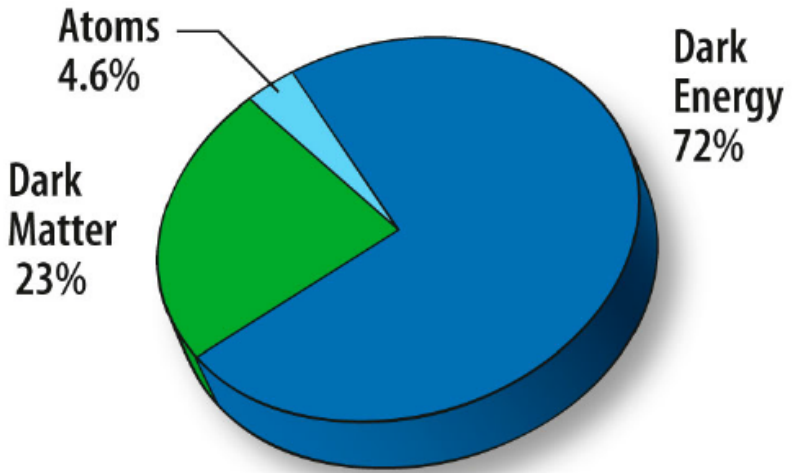
E1039 Status & Plan

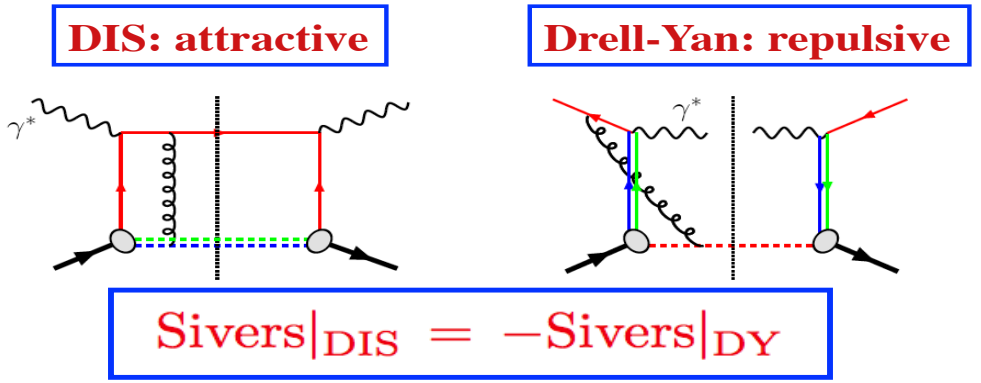
- DOE approval, March 2018
- E906 decommissioned 6/2018
- Polarized target to be installed by fall of 2019
- E1039 commissioning starts in late 2019
- Run for 2+ years, 2019-2021+



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





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 LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	DUNE LBNF	
NuMI	MI	MINERvA NOvA	MINERvA NOvA	OPEN NOvA	OPEN NOvA	OPEN NOvA	OPEN NOvA	OPEN NOvA							ν
BNB	B	μBooNE ICARUS SBND	μBooNE ICARUS SBND	μBooNE ICARUS SBND	OPEN ICARUS SBND	OPEN ICARUS SBND	OPEN ICARUS SBND	OPEN OPEN OPEN	LONG SHUTDOWN		OPEN OPEN OPEN	OPEN OPEN OPEN	OPEN OPEN OPEN	OPEN OPEN OPEN	
Muon Complex		g-2 Mu2e	g-2 Mu2e	g-2 Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	Mu2e	OPEN OPEN	μ
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

SeaQuest

Construction / commissioning Run Subject to PAC review Shutdo

Capability ended Capability unavailable

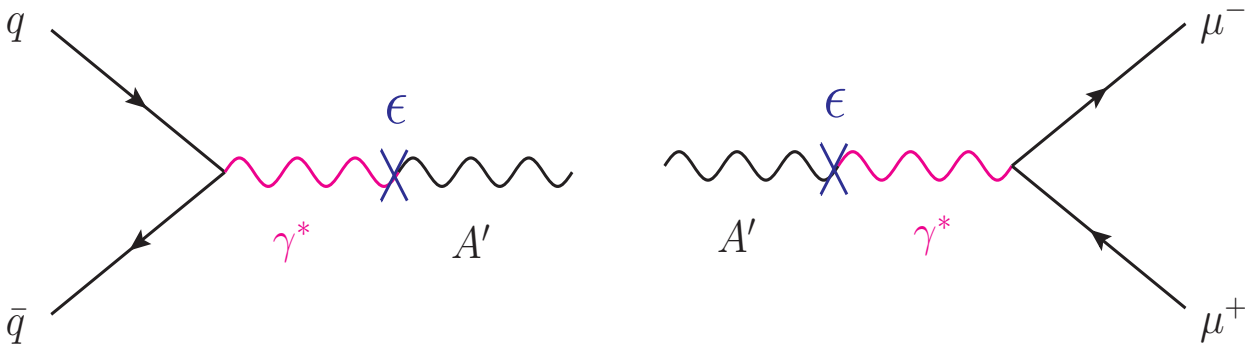
Opportunity for new programs at SeaQuest after E1039

NOTES:
1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data
2. DUNE: 1st 10kT detector module commissioned in FY24. Runs without beam FY25 to mid-FY26.
3. NOvA runs as long as possible [in the spirit of PAC Nov 2017].
4. Assume NuMI in nubar mode through FY19 - facilitates 12E20 POT for MINERvA [PAC Nov 2017]. Assumption may need re
5. Assume g-2 completed before Mu2e commissioning start mid-FY20. Very tight. Needs scrutiny.
6. 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]
7. FY19 and FY20 MicroBooNE running subject to future PAC review [PAC July 2017].

Dark Photons and Dark Higgs Search at SpinQuest/DarkQuest

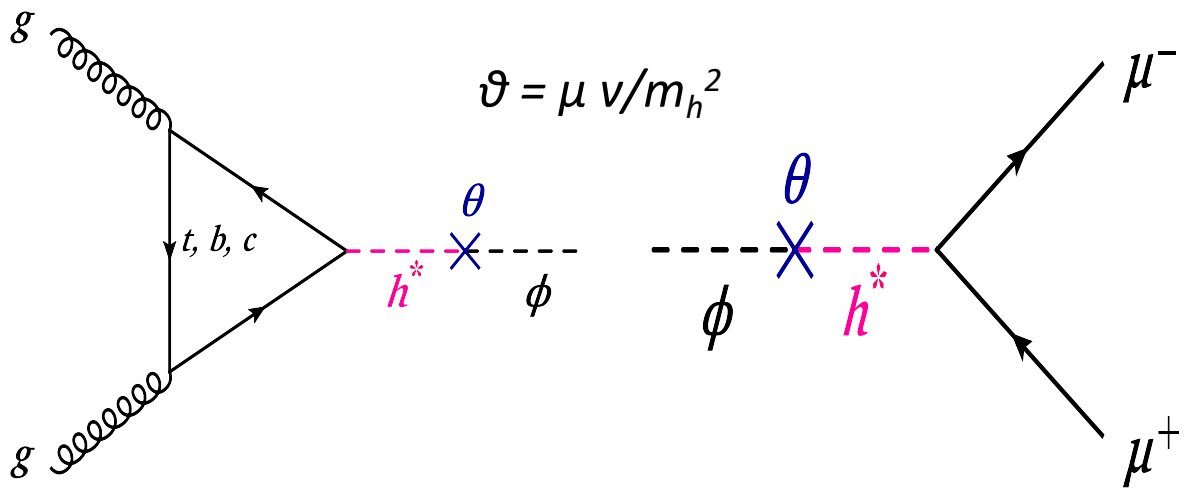
Photon portal: "vector"

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



Higgs portal: "scalar"

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

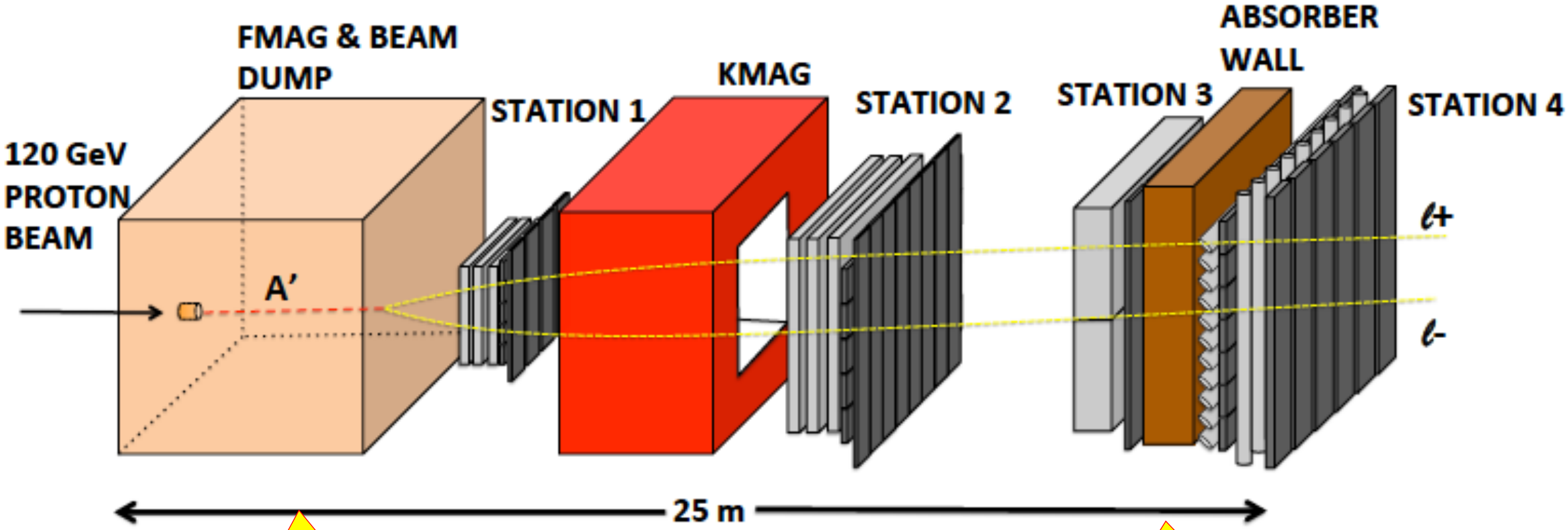


Advantage of hadronic collisions

Dark Sector Physics Search at DarkQuest

2019 ~ 2021: parasitic run for DM search

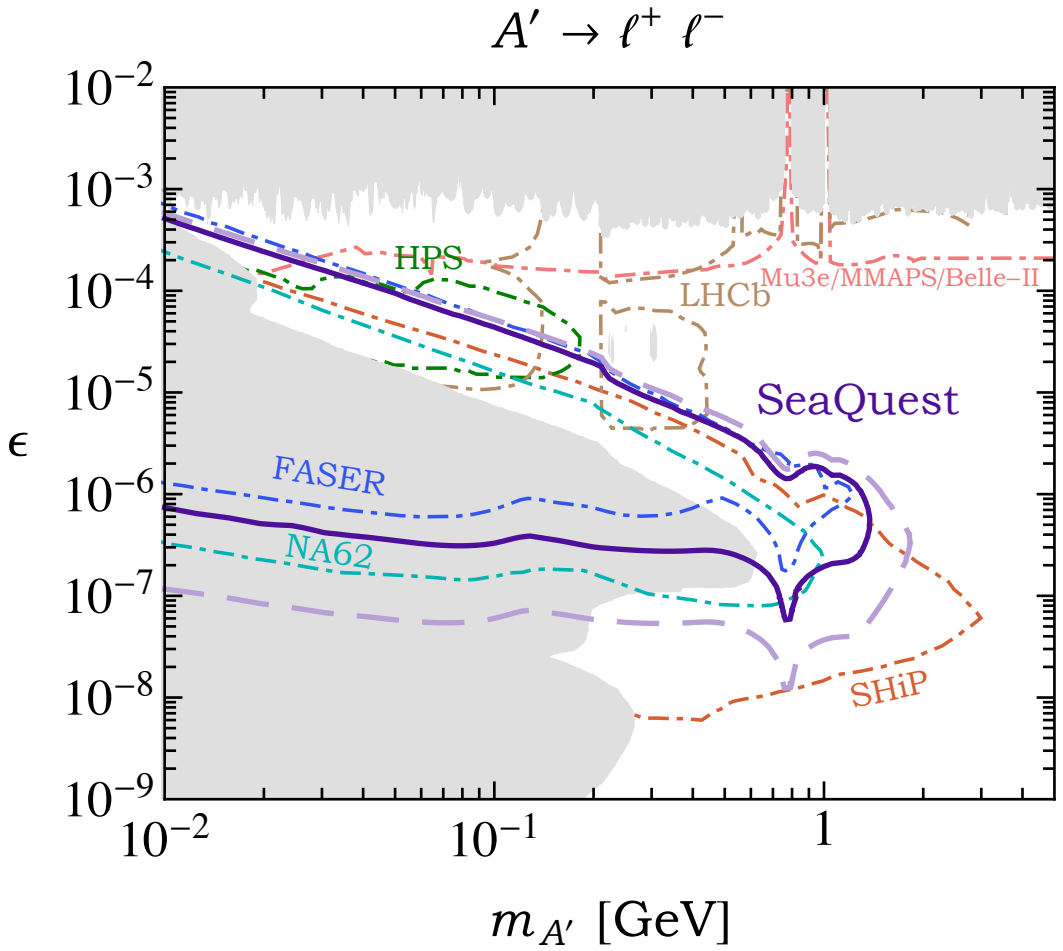
2021+: a proposal for a long term DM program after E1039; parasitic TMD physics?

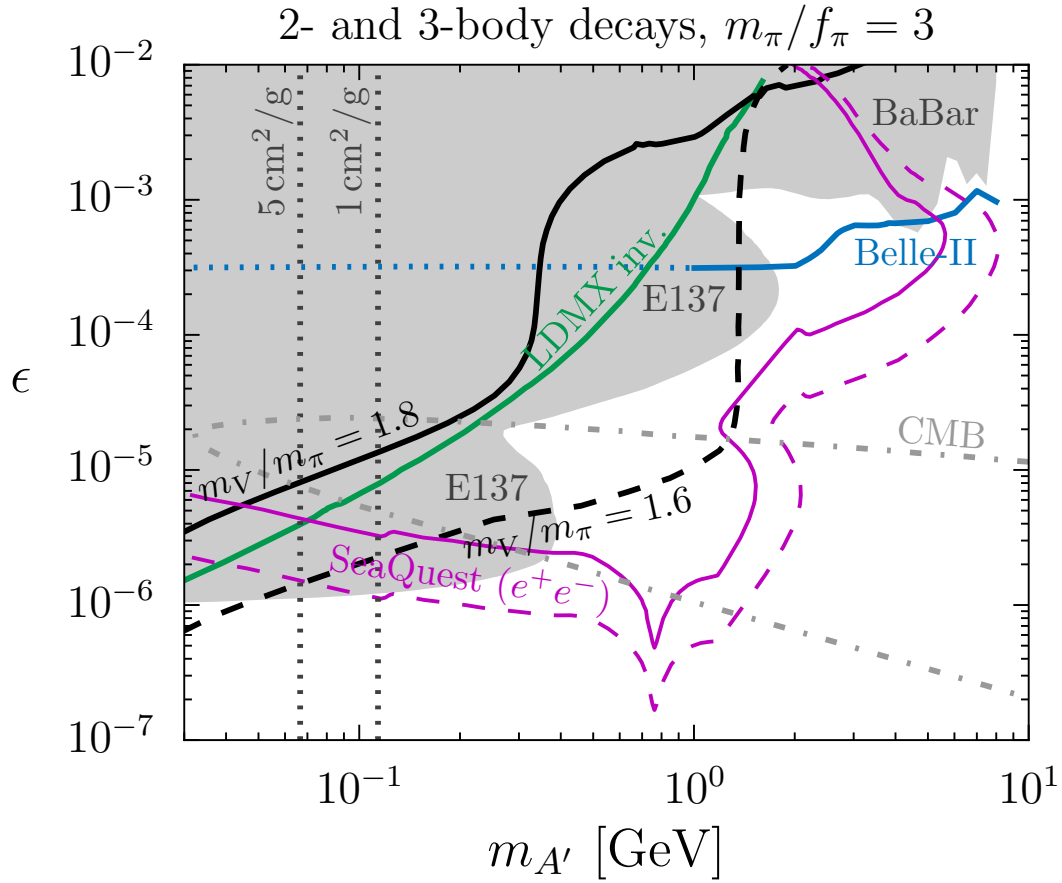


Add tracking detectors close to "target" to improve mass resolution

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

Dark Photon Search at DarkQuest with Future Projections



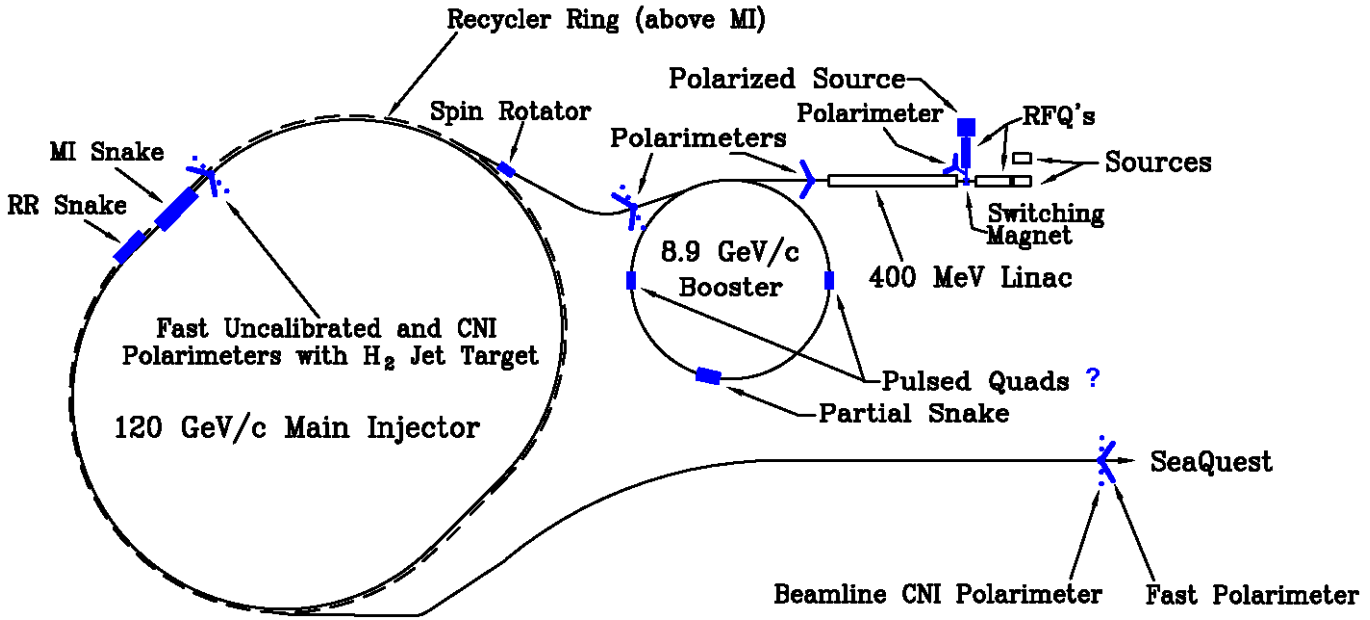


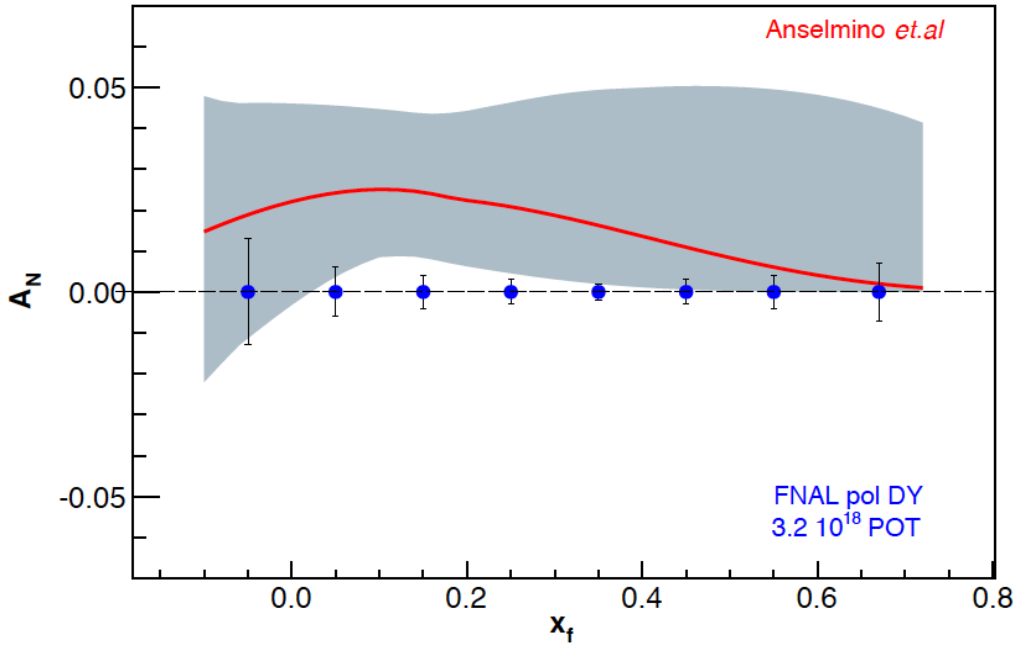
Spin physics Program with Polarized Main Injector – E1027

- 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 SeaQuest

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

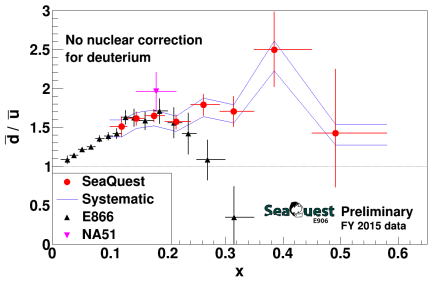
- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY

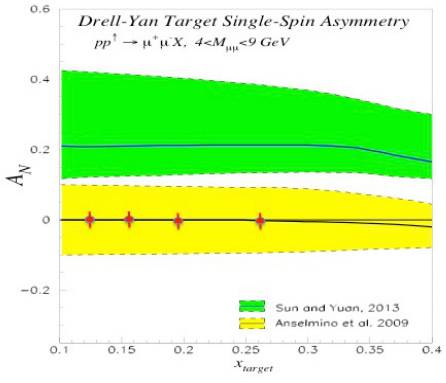
(Boer-Mulders and Sivers functions)

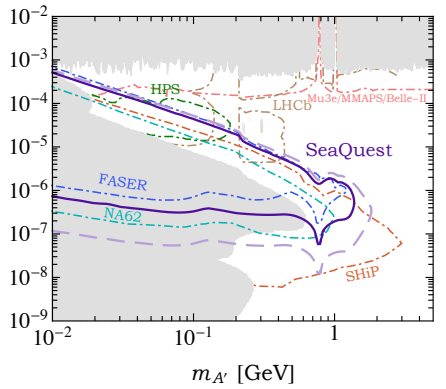
Remains to be tested experimentally! →COMPASS, RHIC, EIC/SeaQuest for sea quarks

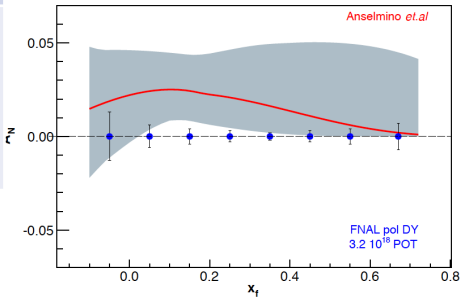
Summary and Outlook

Experiments	Run Time	Collision Types	Physics
E906	2012-2017	p + targets (H, D, C, Fe, W)	- dbar/ubar asymmetry - quark dE/dx
E1039	2018 – 2021+	p + pol. targets (NH_3, ND_3)	Sea-quark Sivers, TMDs
E1067(para.) DarkQuest	2017-2021+(para.) 2021+ (dedicated)	p + any targets	dark photon, dark Higgs, ALP …
E1027	202x	Pol. p-beam +	- quark Sivers - TMD, spin









SpinQuest/E1039 Collaboration

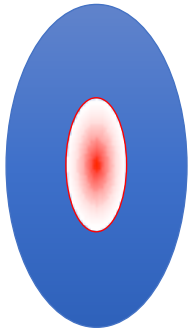
A relatively small collaboration, great opportunities for new comers to contribute and lead major detector and physics efforts

Collaboration

INSTITUTION	FULL MEMBERS	AFFILIATE MEMBERS
Abilene Christian University	Donald Isenhower (PI), Michael Daugherity, Shon Watson	Haley Stien, John Marsden, Mitchell Schneller, Nathan Rowlands, Roy Salinas, Rusty Towell, Shannon McNease, Yves Ngenzi, Thomas Fitch
Argonne National Laboratory	Paul Reimer (PI), Donald Geesaman	Kawtar Hafidi, Kevin Bailey, Thomas O'Connor, Zhihong Ye, Benjamin Zeidman
Fermi National Accelerator Laboratory	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
KEK	Shin'ya Sawada (PI)	Shigeru Ishimoto
Los Alamos National Laboratory	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
Mississippi State University	Lamiaa El Fassi (PI)	Dipangkar Dutta
New Mexico State University	Stephen Pate (PI), Vassili Papavassiliou, Haiwang Yu, Forhad Hossain	
RIKEN	Yuji Goto (PI)	
Tokyo Institute of Technology	Kenichi Nakano (PI), Toshi-Aki Shibata	
University of Colorado, Boulder	Edward Kinney (PI)	
University of Illinois, Urbana-Champaign	Jen-Chieh Peng (PI), Yen-Chu Chen	Naomi Makins, Ching Him Leung, Daniel Jumper, Jason Dove, Mingyan Tian, Bryan Dannowitz, Randall McClellan, Shivangi Prasad
University of Michigan	Wolfgang Lorenzon (PI), Minjung Kim, Noah Wuerfel	Daniel Morton, Richard Raymond, Marshall Scott
University of New Hampshire	Karl Slifer (PI), David Ruth	Maurik Holtrop
University of Virginia	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
Yamagata University	Yoshiyuki Miyachi (PI), Genki Nukazuka	Takahiro Iwata, Norihiro Doshita

backup

New Beam Collimator and Target

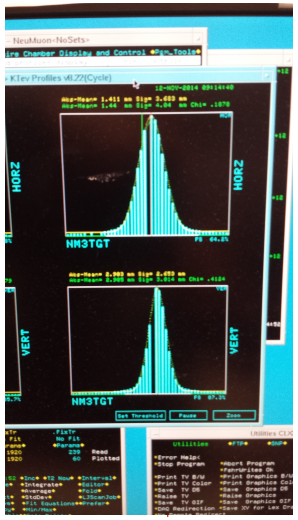


Target cross section: 18 x 28 mm^2

Beam cross section:
Need be well contained within
4 sigma, required by dR< 2x10^{-4}

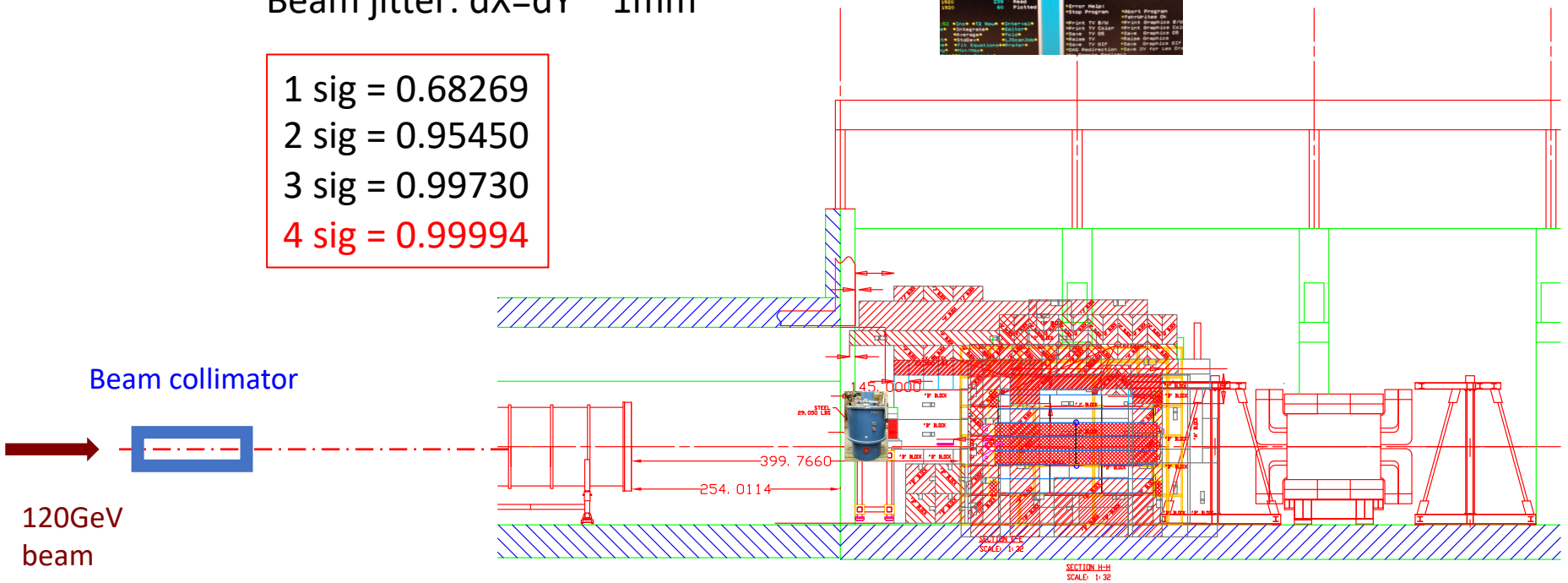
sigX = 18/2/4 = 2.2 mm
sigY = 28/2/4 = 3.5 mm
Beam jitter: dX=dY ~ 1mm

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

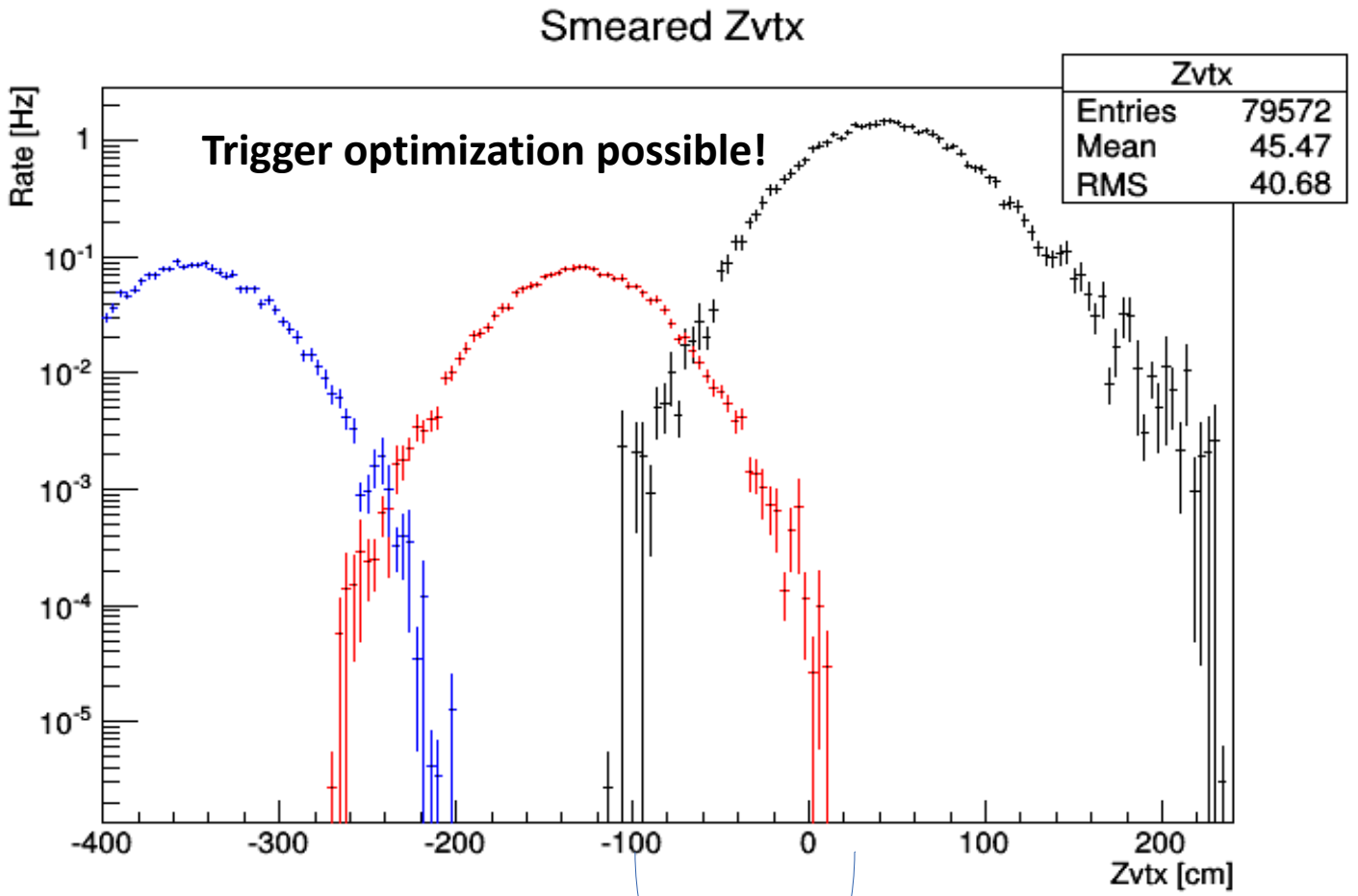


E906 beam profile:
SigX = 4.0mm
SigY = 3.0mm

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

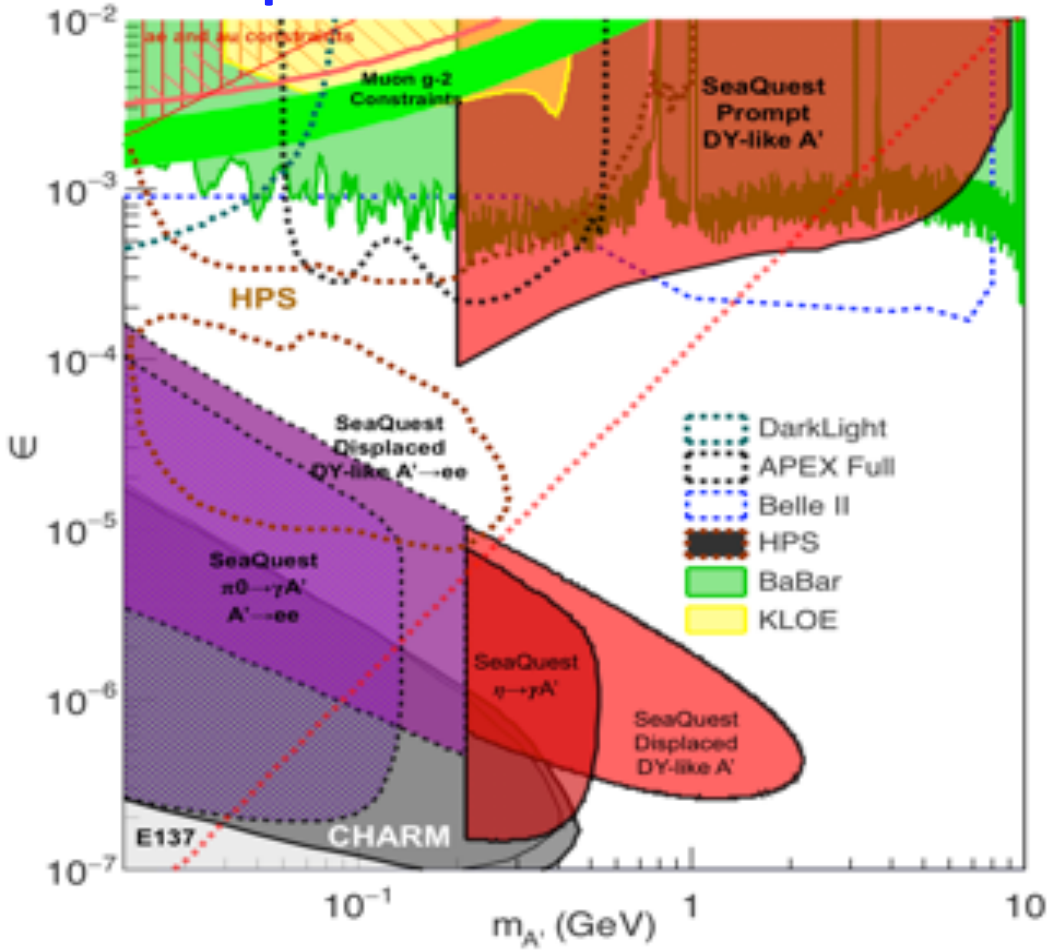


Target and Beam Dump Event Separation
target at upstream: Z=-3.5m



Projected Dark Sector Physics Search Sensitivity

Dark photon search



Dark Higgs search