Overview of SeaQuest/E1039 Polarized Fixed Target Drell-Yan Experiment at Fermilab

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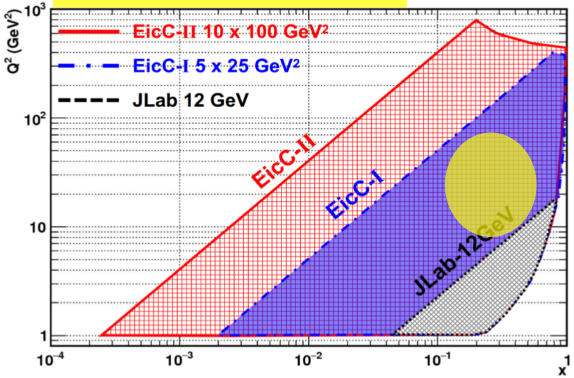
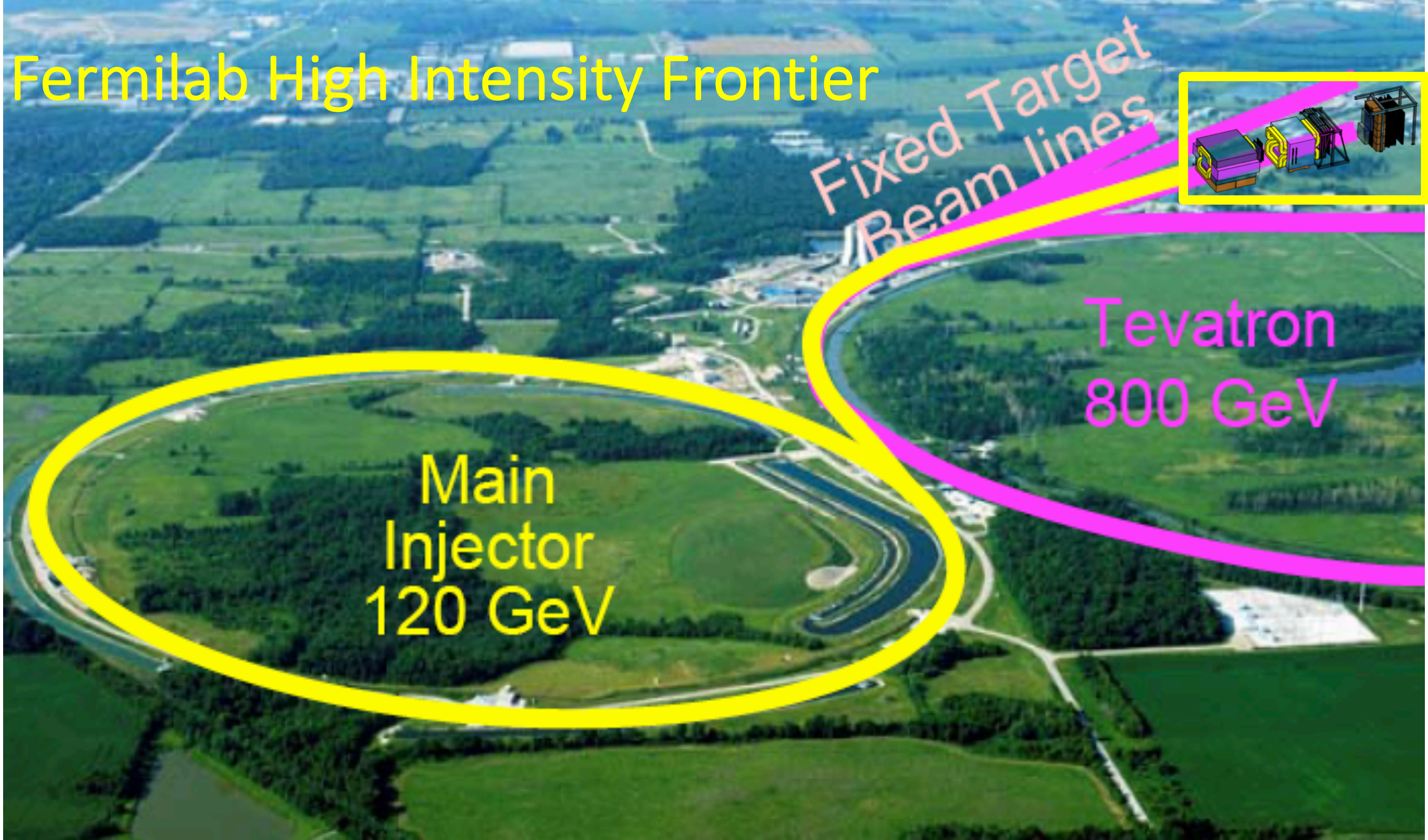
The 10th Workshop on Hadron Physics in China and Opportunities Worldwide
Shandong University, Weihai, China

Outline

- SeaQuest experiments at Fermilab
  - E906 unpolarized targets
  - E1039 polarized NH_3/ND_3 targets
- Novel physics of sea quarks at x = 0.1 ~ 0.4
  - Flavor asymmetry
  - Sivers & OAM
- Future opportunities
  - E1067 dark photon search, 2016 - 2021+
  - E1027 polarized beam,   2021+
  - TMD physics in p+p/n complementary to EIC, 2019-2021+

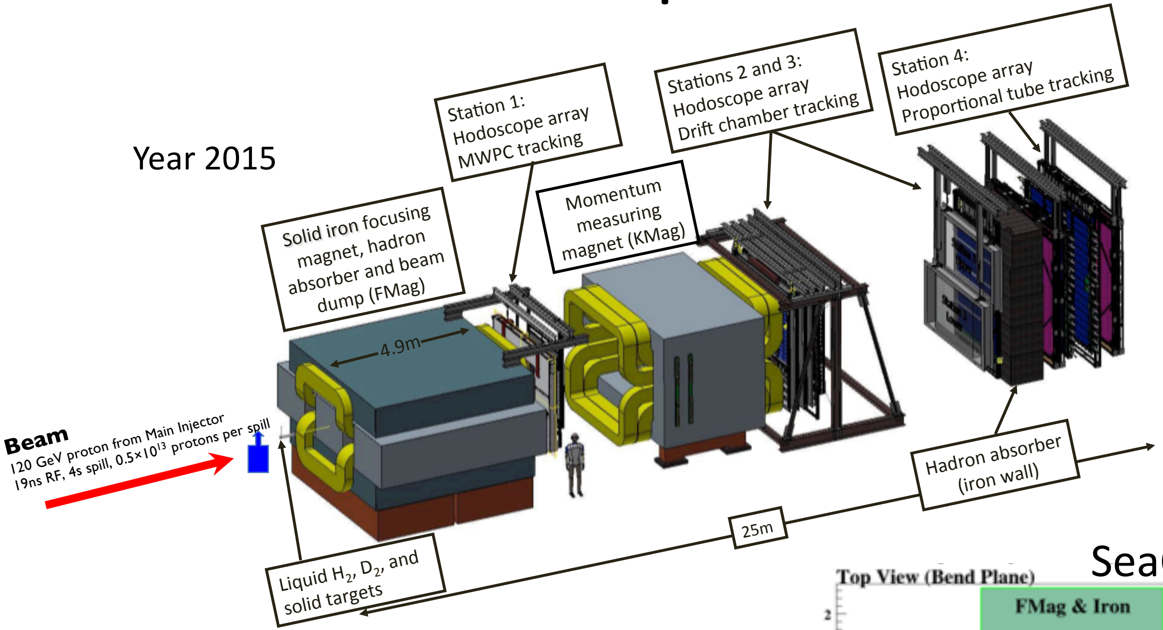
EicC: sea quarks




Fermilab High Intensity Frontier
Fixed Target
Beam lines
Tevatron
800 GeV
Main
Injector
120 GeV

SeaQuest 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

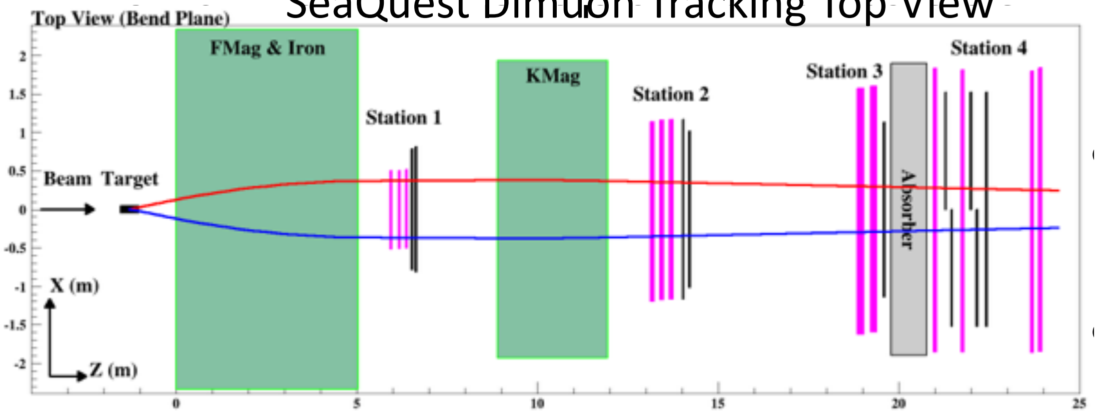
- ^{1}H, ^{2}D, ^{12}C, ^{56}Fe, ^{184}W

E1039 polarized targets: 2018 – 2021+

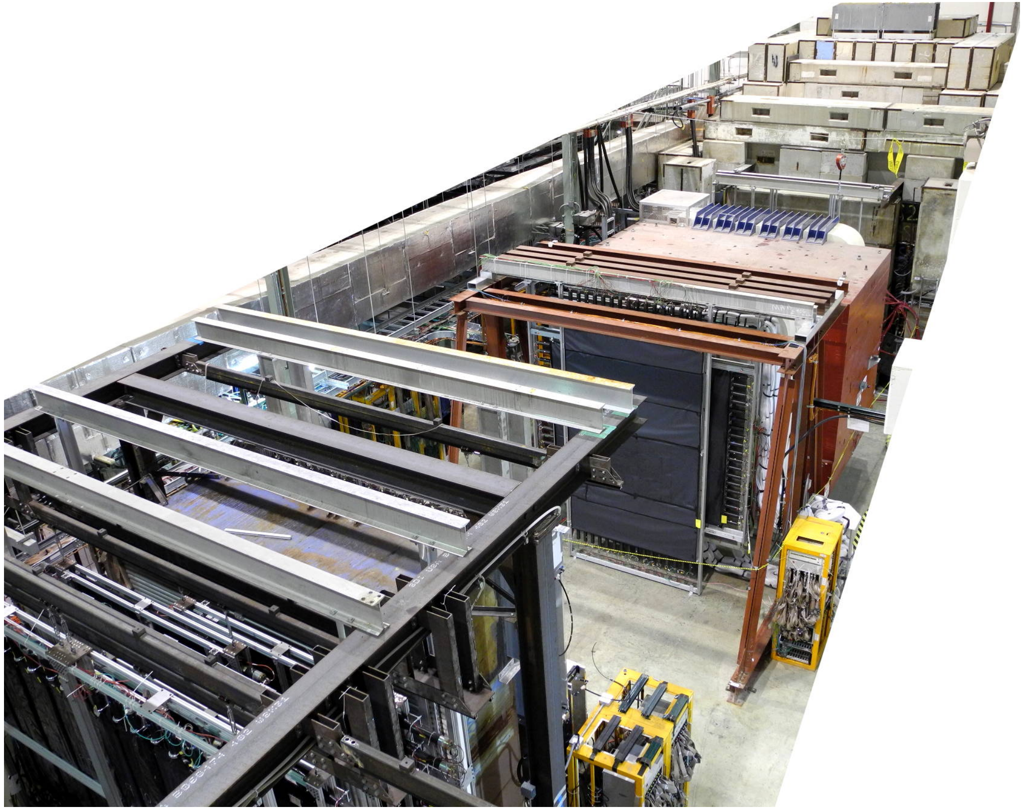
- Polarized protons (NH_3)
- Polarized neutrons (ND_3)

E1027 polarized beam

SeaQuest Dimuon Tracking Top View



SeaQuest Experimental Hall



Beam

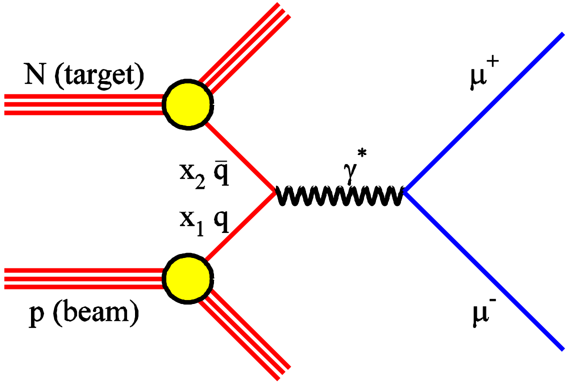
Target area

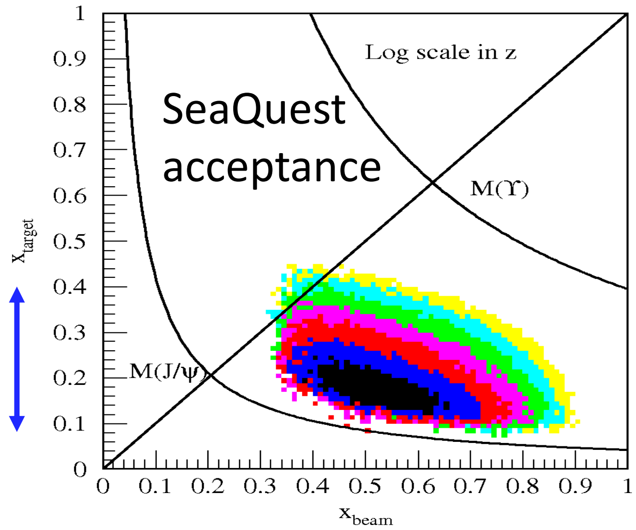
F-Mag

K-Mag

Muon-ID

Drell-Yan @SeaQuest – a Sea Quark Laboratory



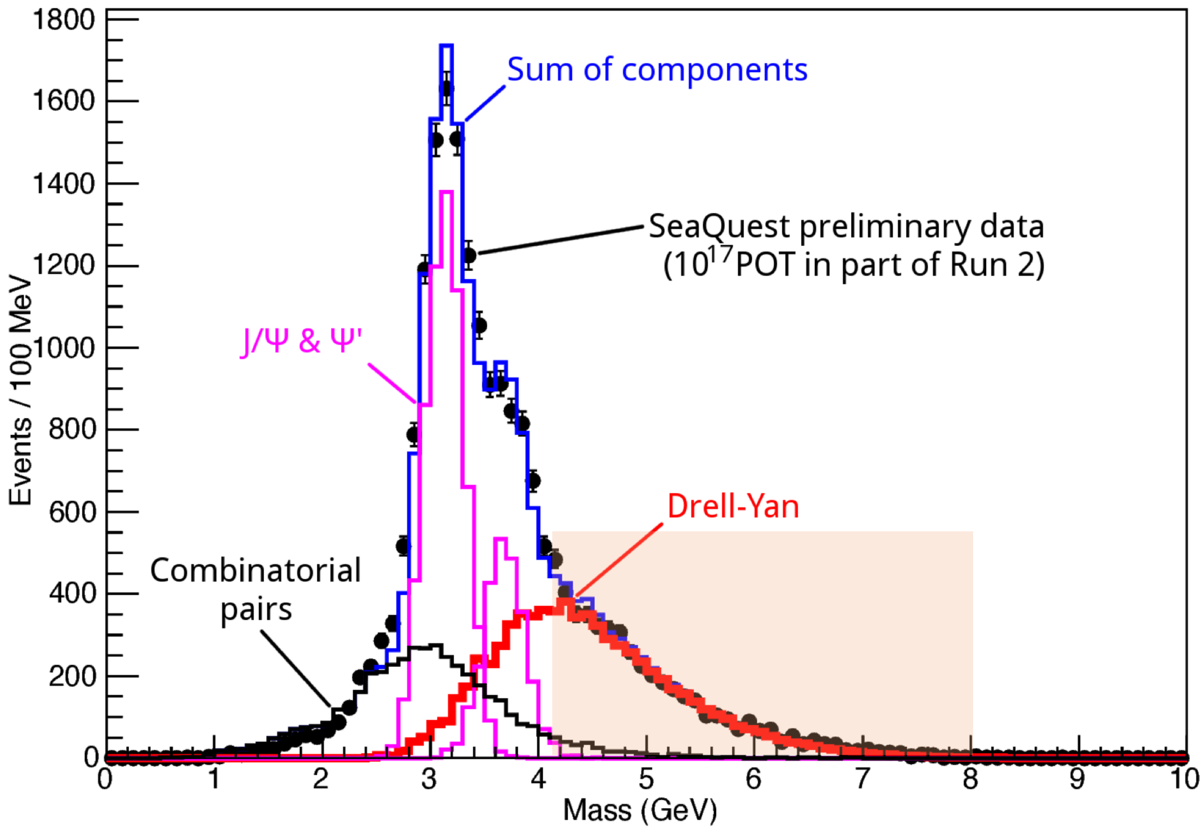


$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q(x_t)]$$

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

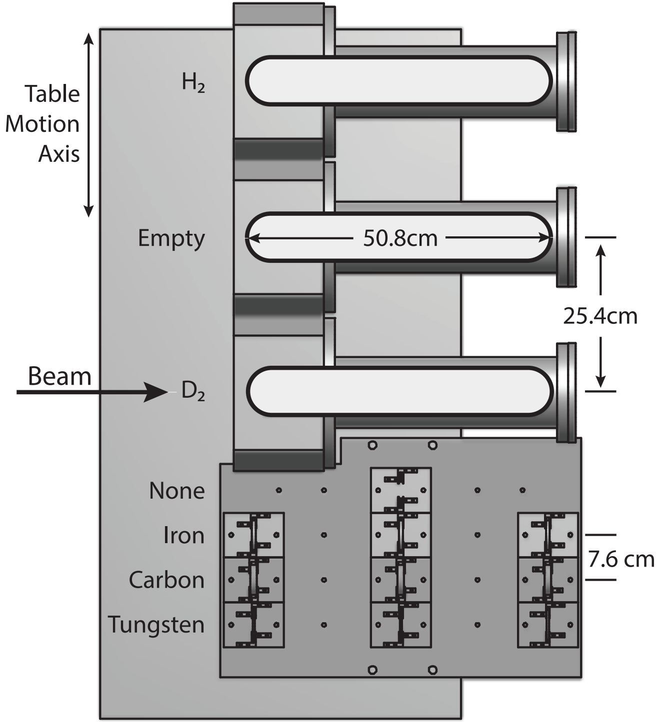
Kinematically favors sea-quarks from target – **a sea quark lab!**

Dimuon Mass from SeaQuest/E906



E906 Unpolarized Physics Program

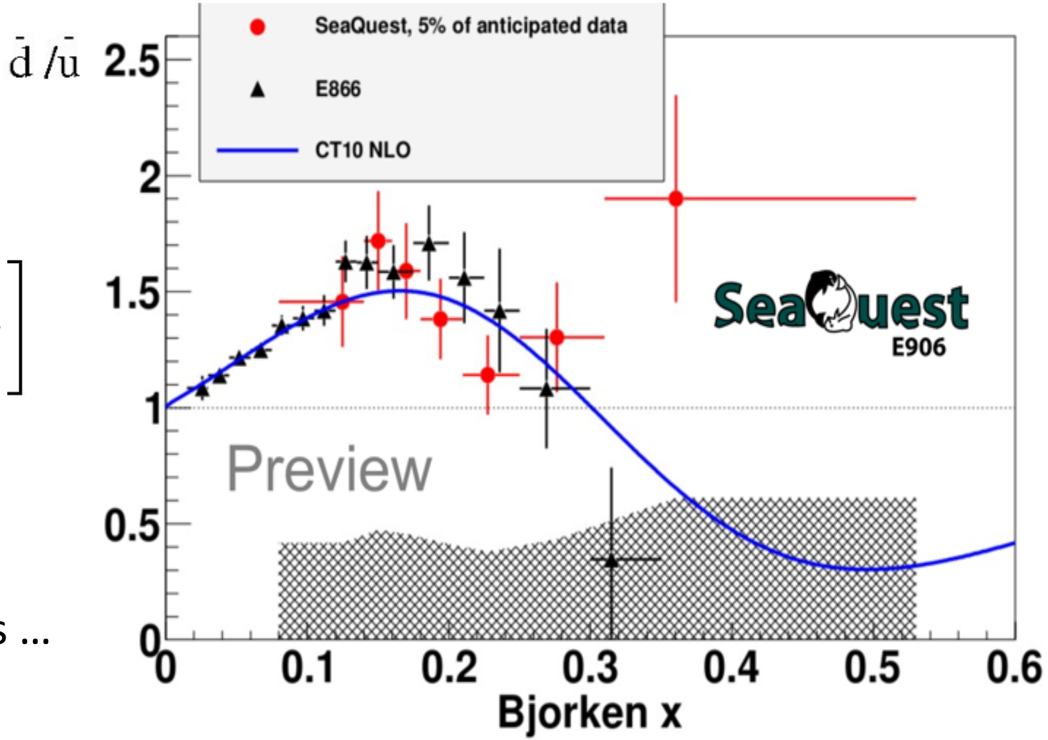
- Thin targets: ~10% interaction length
  - Liquid H/D
  - Solid C, Fe, W
- Physics
  - Sea quark flavor asymmetry, dbar/ubar
  - Quark energy loss in p+A collisions, dE/dx
  - and more …
- Experimental runs – 6 years
  - 2012 – commissioning
  - 2017 – completed



Flavor Asymmetry of Sea Quarks at Intermediate x

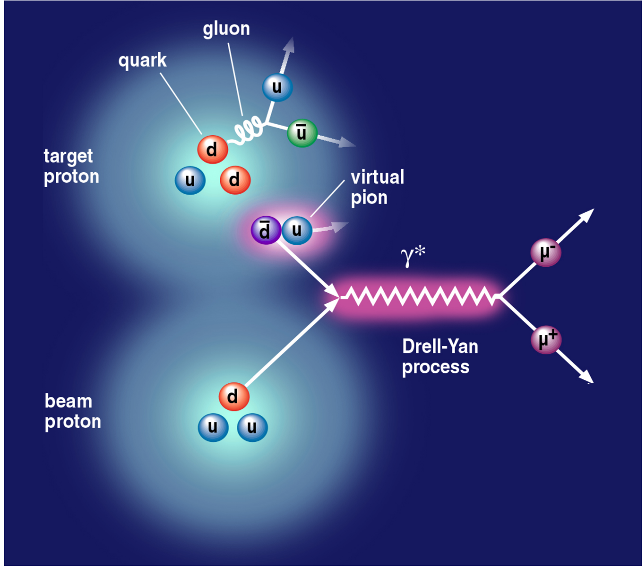
Proton vs "Neutron" targets:

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



This could lead to a very interesting physics …

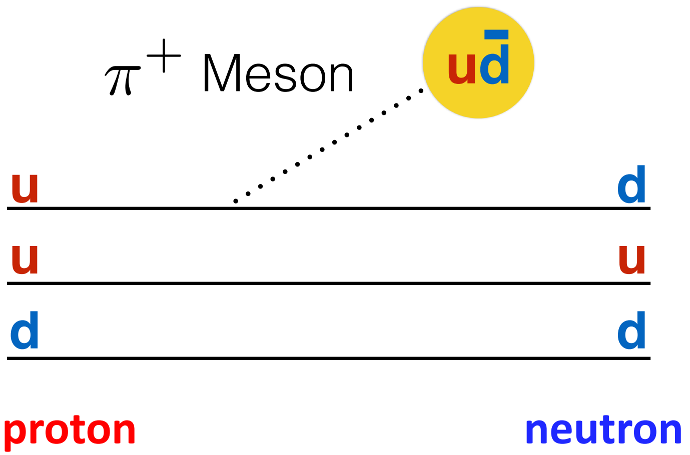
Sea Quark Flavor Asymmetry and OAM



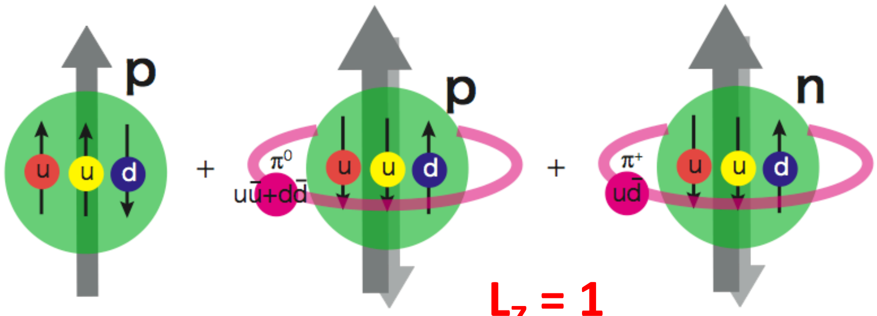
Pion cloud model

- Sea-quark flavor asymmetry
- Sea-quark orbital angular motion
- Expect large Sivers function at x = 0.0 ~ 0.4

Pion cloud and Drell-Yan process

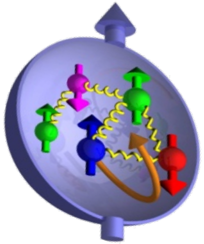


$|p\rangle = a|p_0\rangle + b|p_0 + pi^0\rangle + c|n+pi^+\rangle + \ldots$

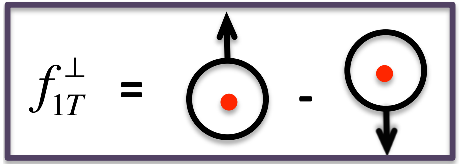


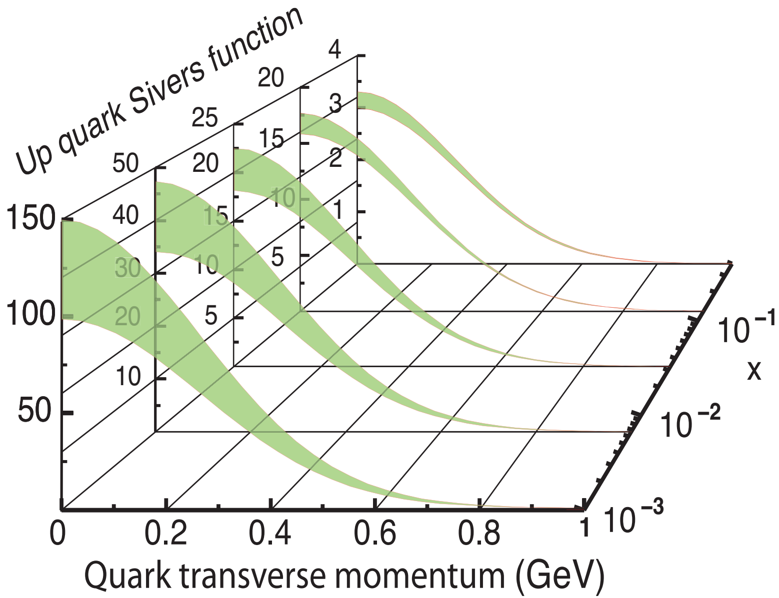
$L_z = 1$

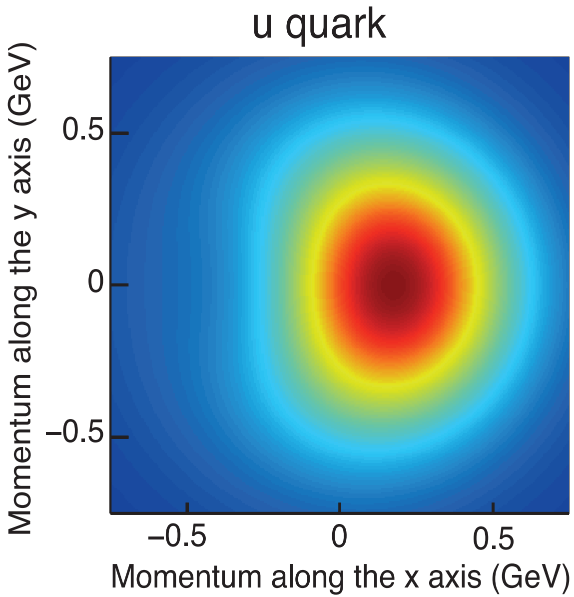
Nucleon 3-D Structure and Sivers Function



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





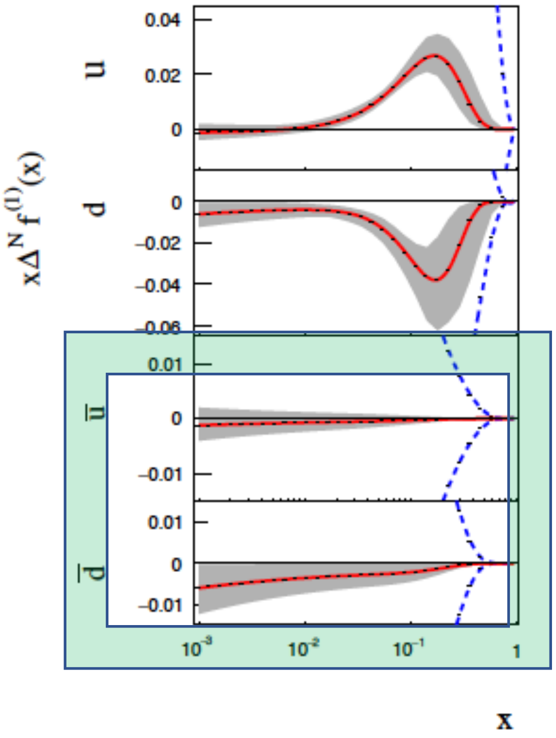


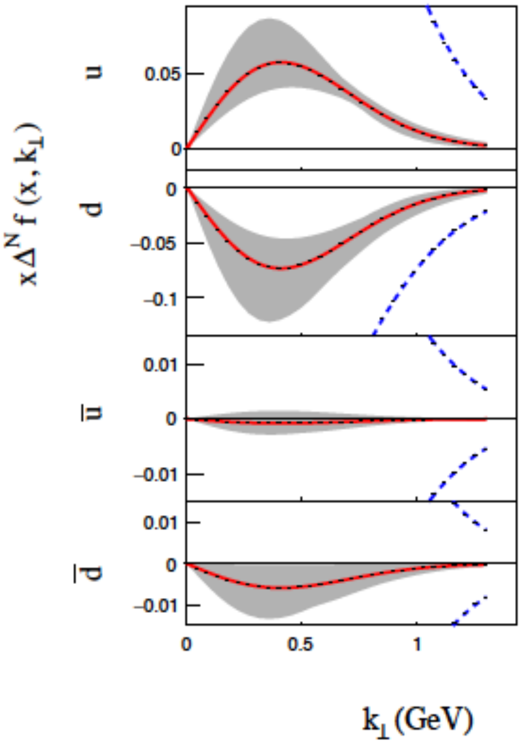
Sivers Functions from Global Fits

- 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

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

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

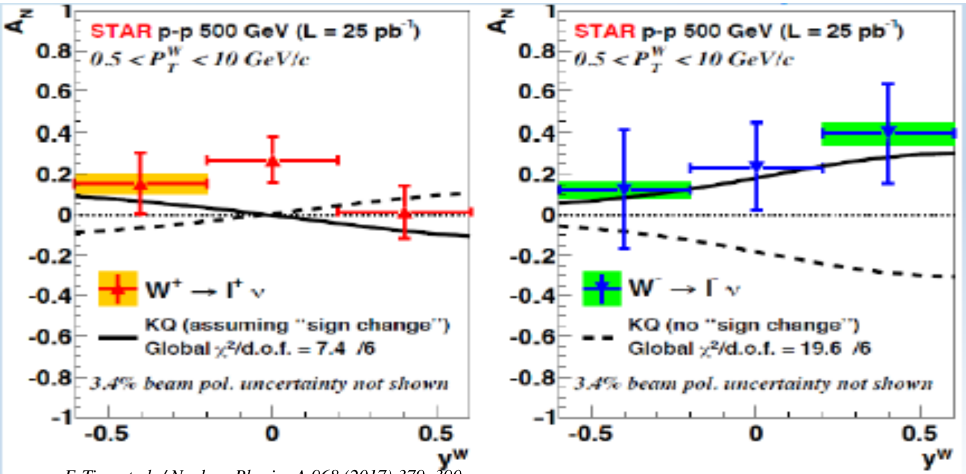
RHIC data:

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

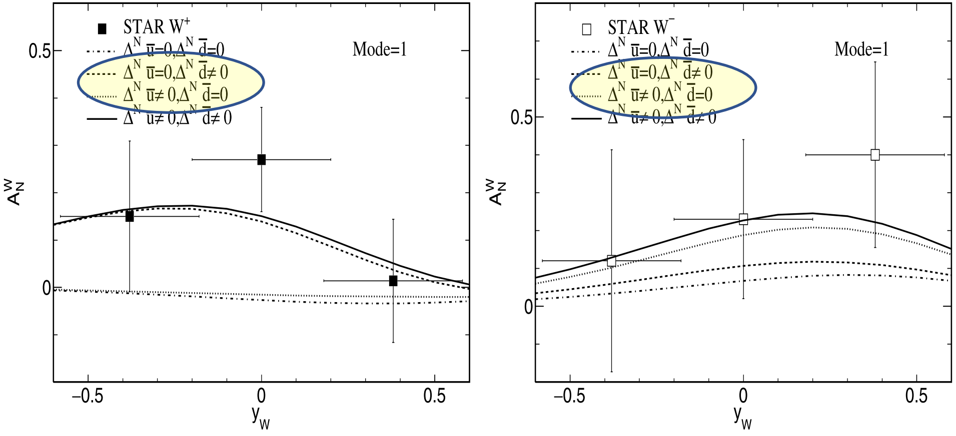
E1039:

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

Anselmino et al 2016



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



(b) $A^N_{W^+}$. (a) $A^N_{W^-}$.

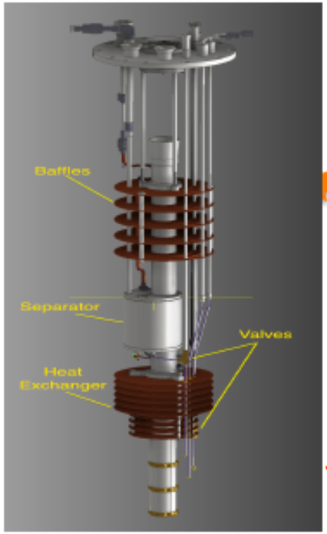
Polarized NH_3 Target Developed for DY Sivers

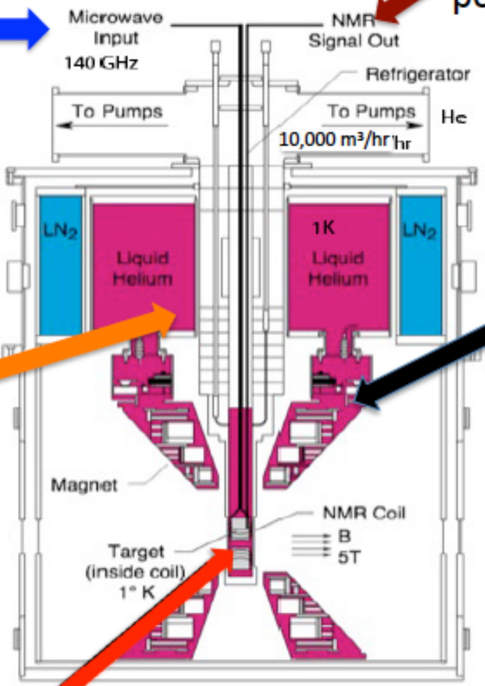
Microwave: Induces electron spin flips

- EIO + Power equip:

NMR system: to measure polarization

Refrigerator:





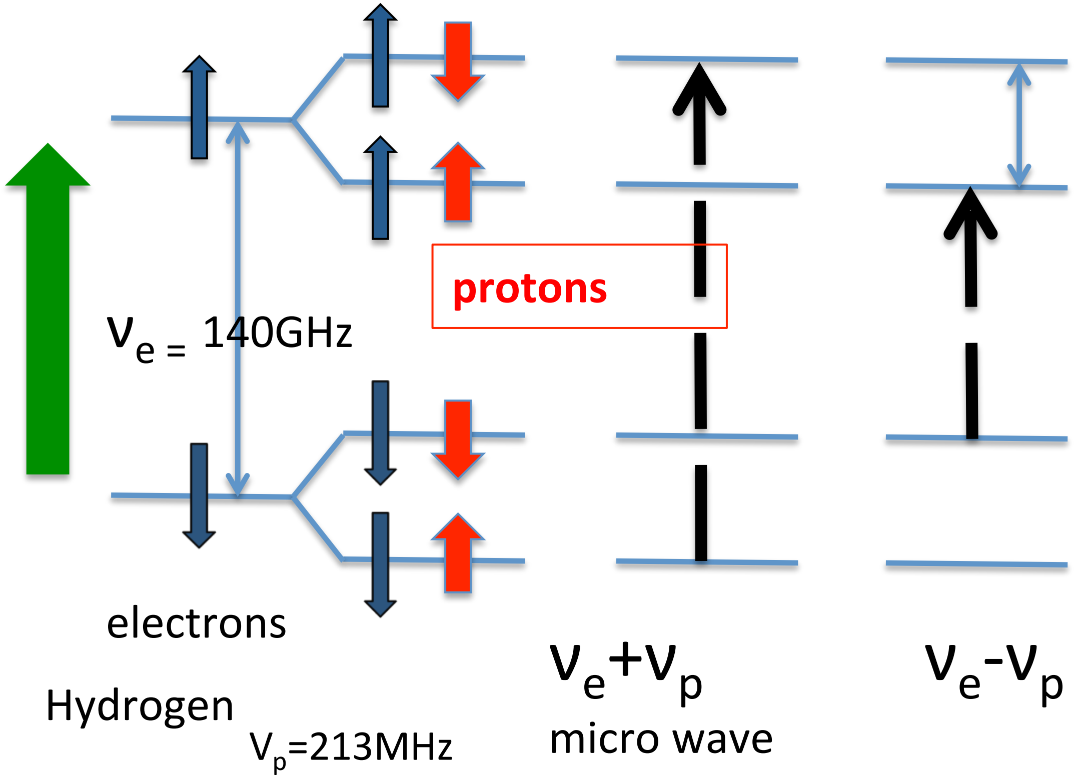
Roots pump system used to pump on ^4He vapor to reach 1K

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%

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

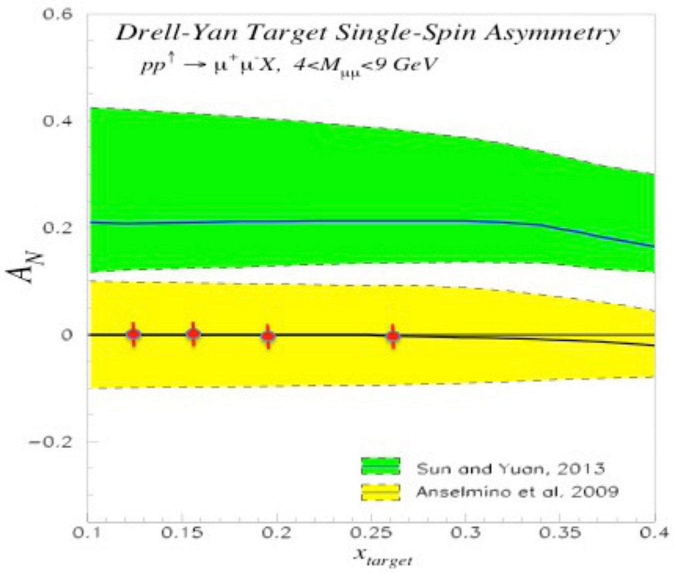
Projected SeaQuest Target and Beam Performance

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

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

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

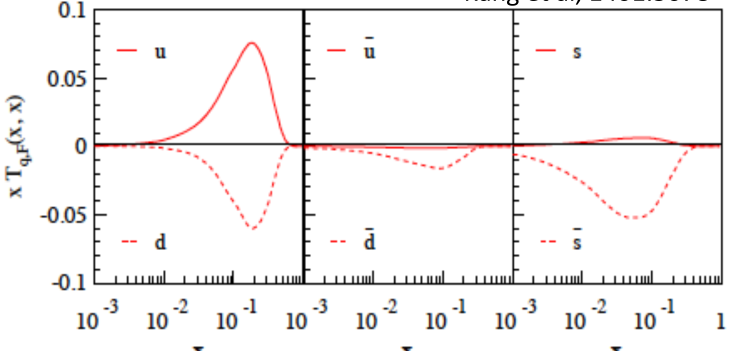


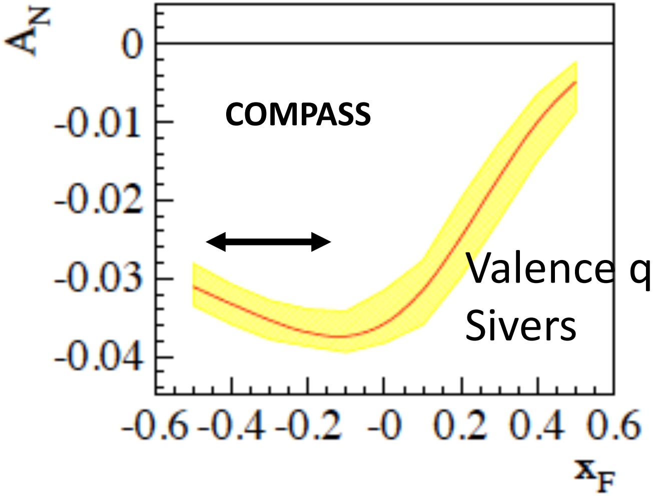
$$\Delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N^+ + N^-}}$$

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

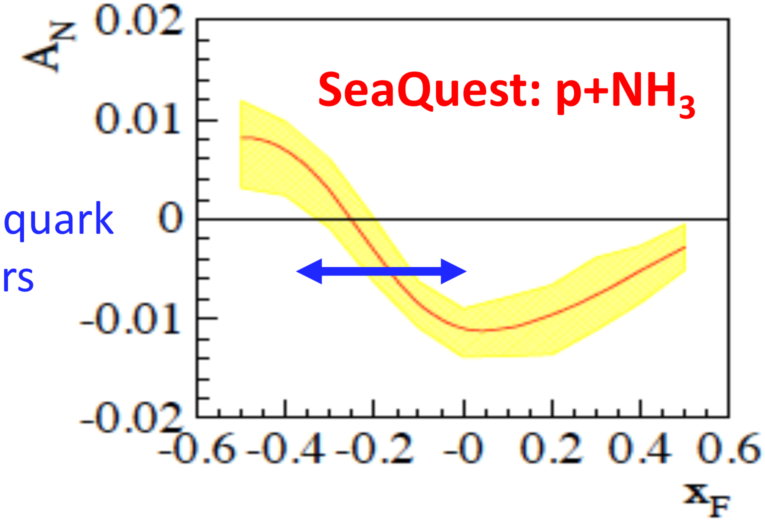
Kang et al, 1401.5078

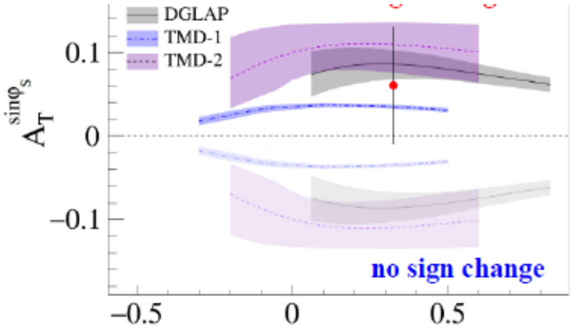




Valence quark Sivers

Sea quark Sivers

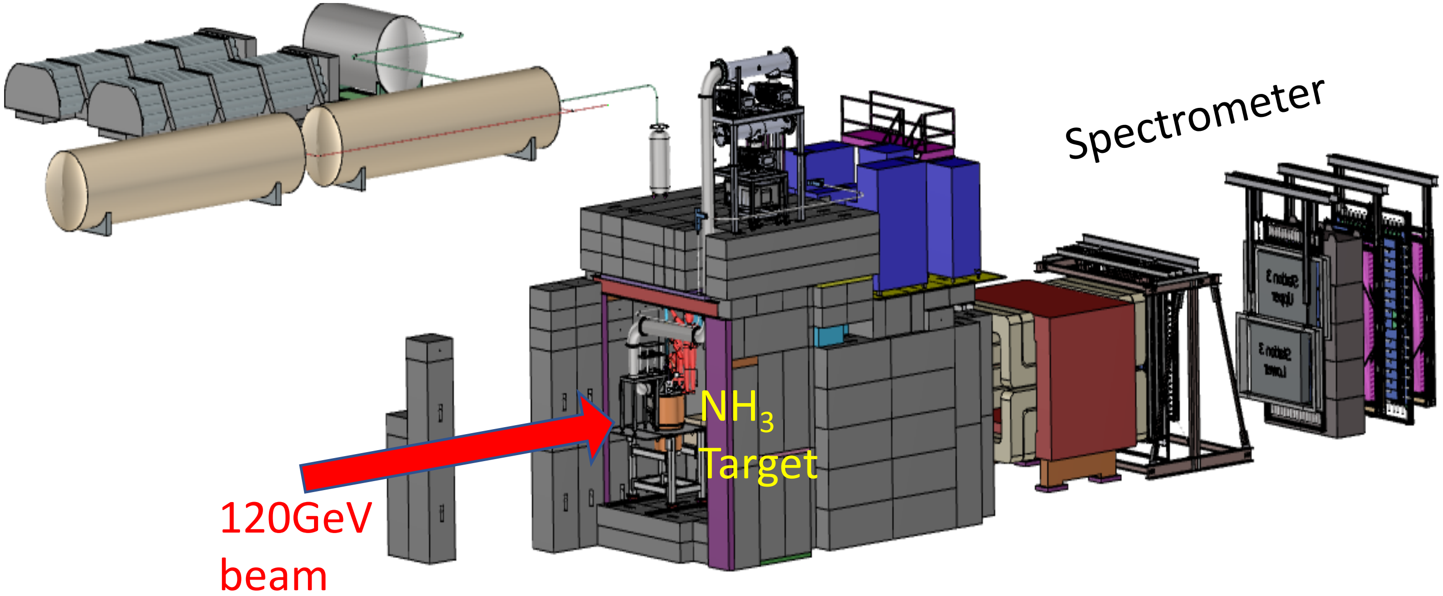




E1039 Status & Plan

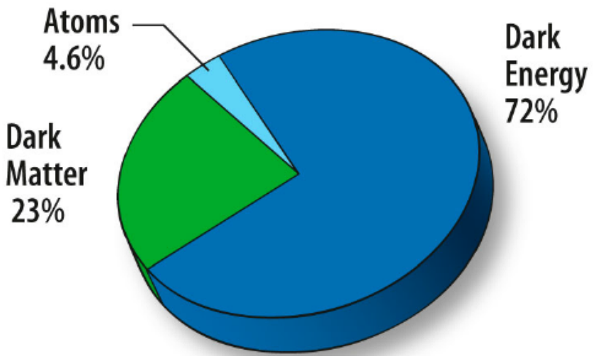
- DOE approval, March 2018
- E906 decommissioned 6/2018
- E1039 target shielding in progress
- Beam collimator in fabrication, to be installed later
- Polarized target to be installed by fall of 2018

- Fermilab Stage-2 approval, May 2018
- 2018 summer detector work in progress
- E1039 commissioning starts in late 2018
- Run for 2+ years, 2019-2021+

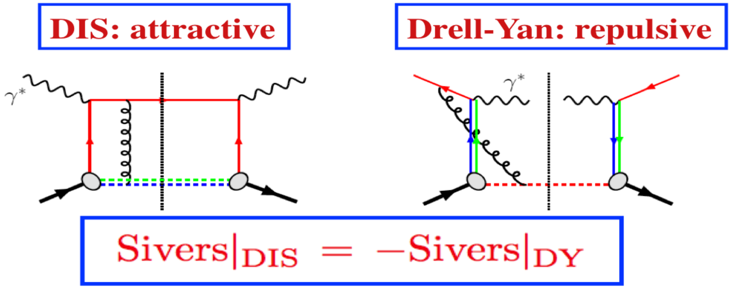


Physics Beyond E1039 Polarized DY A_N

- Dark sector physics search – E1067
  - Parasitic run with E1039: 2018 – 2021
  - Proposed dedicated run after E1039: 2021 – 2030



- Physics with polarized beams – E1027
  - Polarize the Main Injector 120GeV beam
  - Valence quark Sivers
  - Test QCD dynamics in DY vs DIS



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				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	ν
	FNAL					LBNF	LBNF	LBNF	LBNF	LBN F	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERvA	MINERvA	OPEN	OPEN	OPEN	OPEN	OPEN							
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA							
BNB	B	μBooNE	μBooNE	μBooNE	OPEN	OPEN	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	OPEN			OPEN	OPEN	OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN			OPEN	OPEN	OPEN	OPEN	
Muon Complex		g-2	g-2	g-2					LONG SHUTDOWN					OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	Mu2e	OPEN	
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

Opportunity for new programs at SeaQuest after E1039

Construction / commissioning | Run | Subject to PAC review | Shutdown

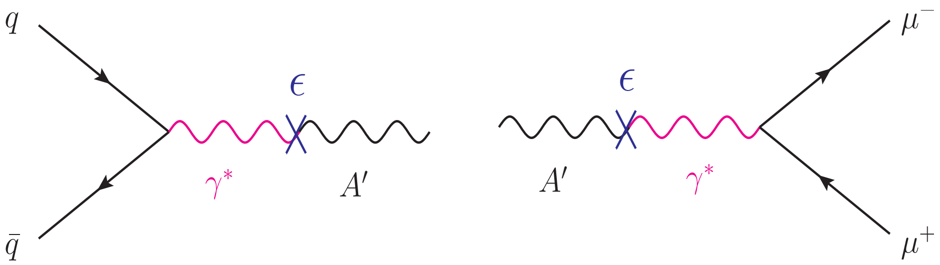
Capability ended | Capability unavailable

NOTES:
1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data taking.
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 revision.
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 SeaQuest

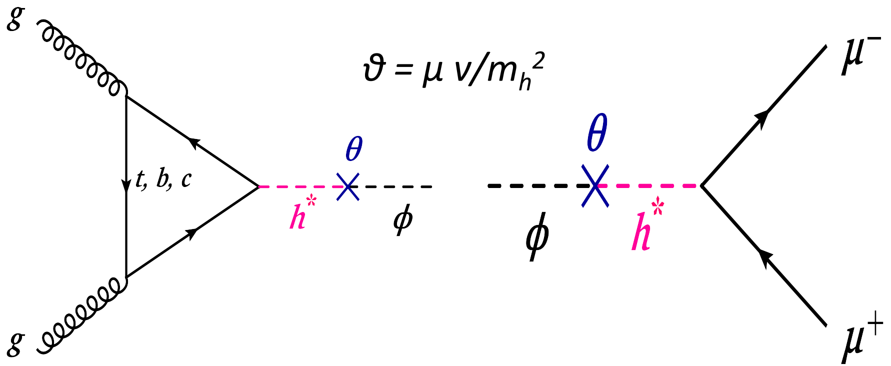
Photon portal: “vector”

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



Higgs portal: “scalar”

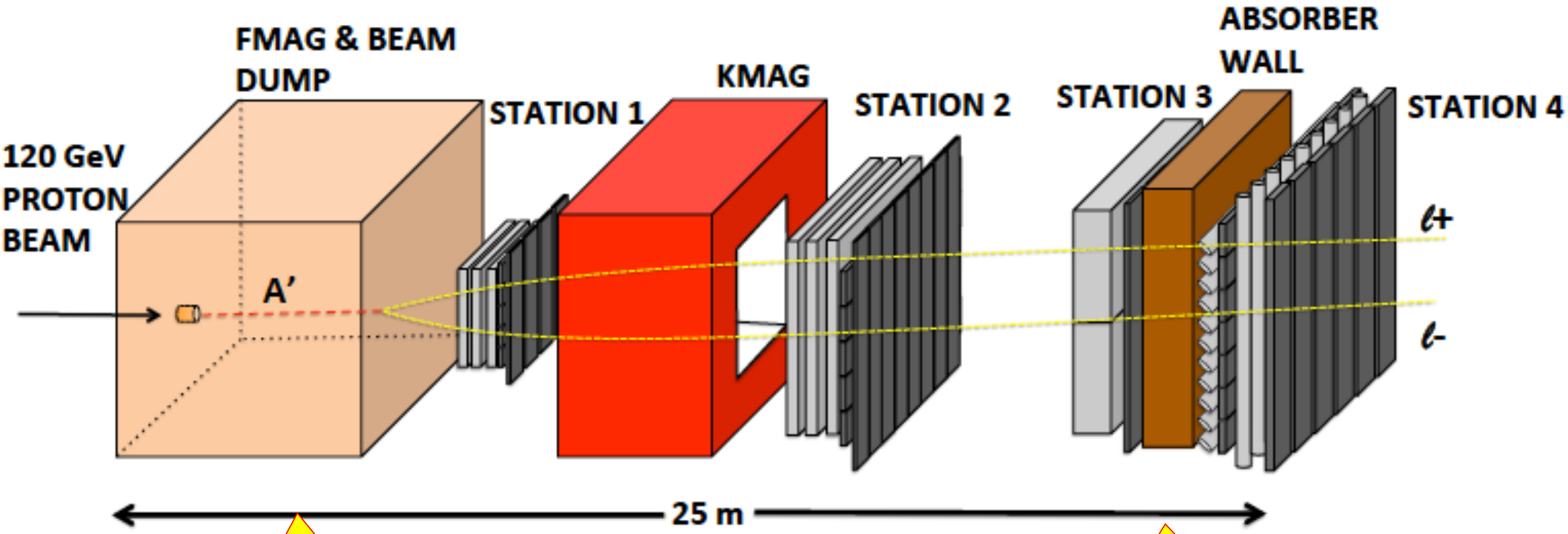
$$\mathcal{L}_{\text{mix}} = \mu\phi |H^\dagger H|$$



Advantage of hadronic collisions

Dark Sector Physics Search at SeaQuest

2018 ~ 2021+, proposed long term program after E1039

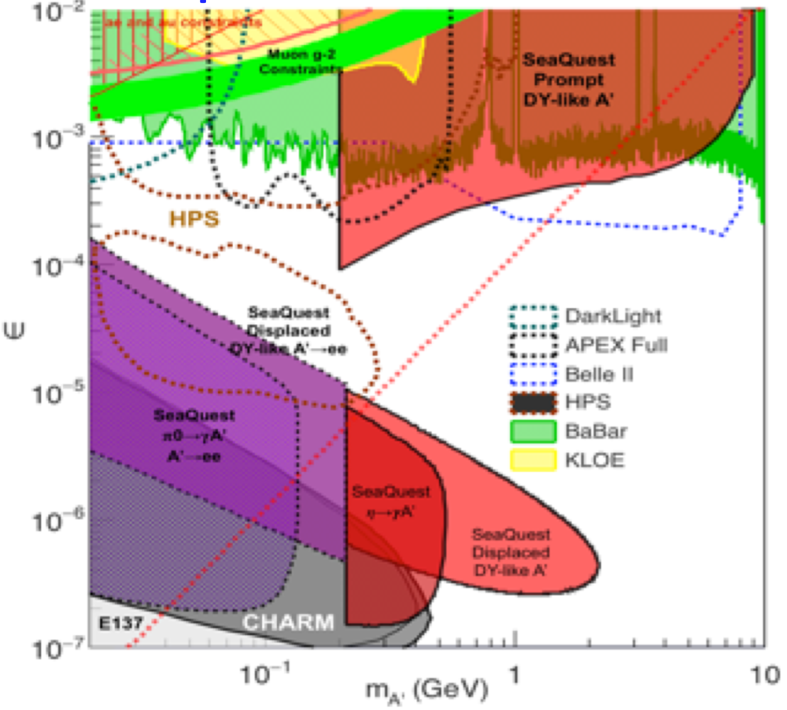


Add tracking detectors close to "target" to improve mass resolution

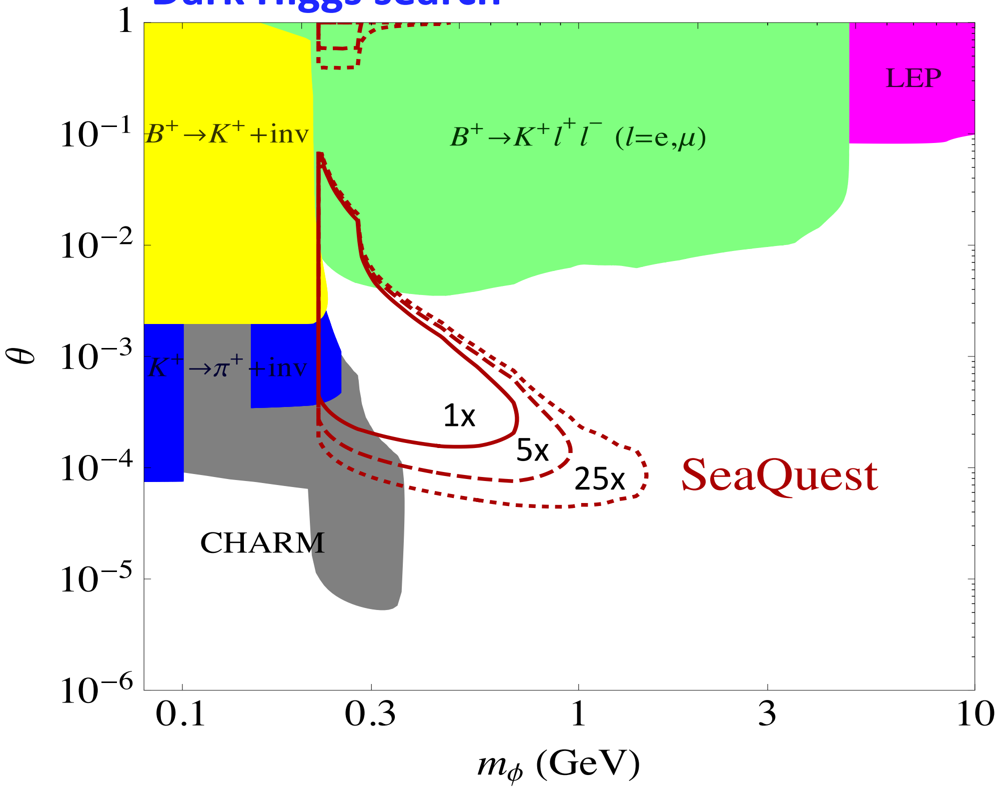
Add EMCal, PID
$e^{+/-}$, $h^{+/-}$, $\pi^{+/-}$

Projected Dark Sector Physics Search Sensitivity

Dark photon search



Dark Higgs search

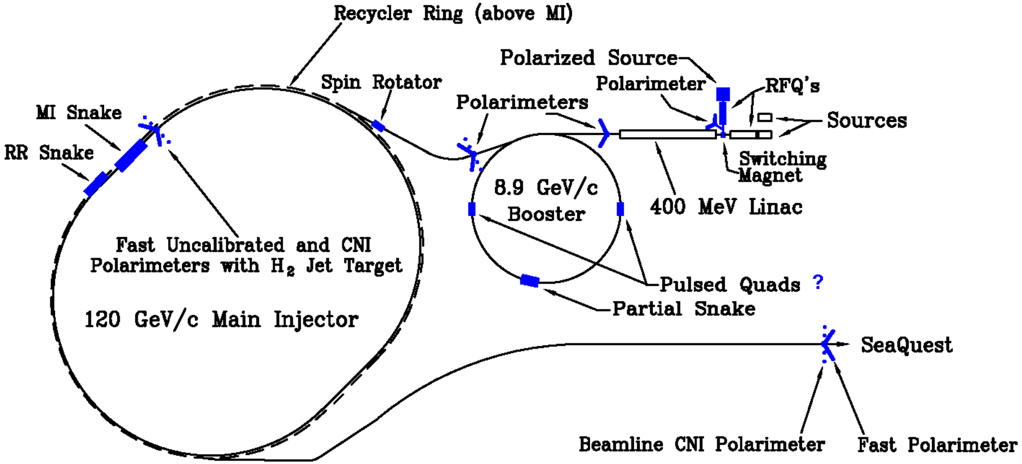


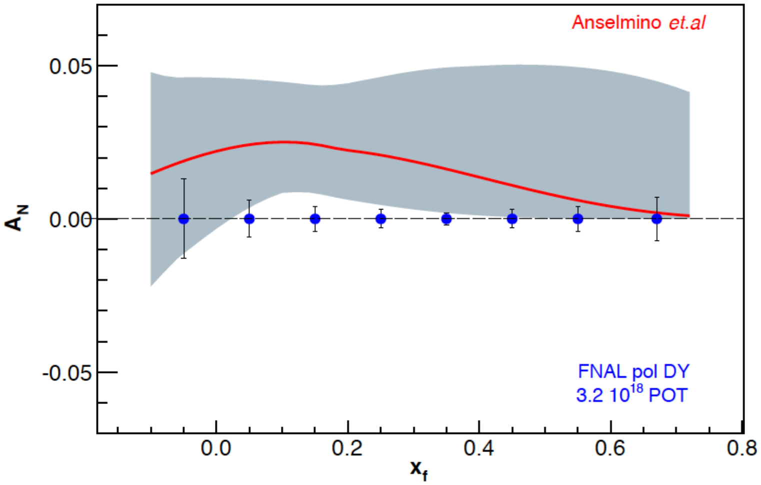
Spin physics Program with Polarized Main Injector – E1027

- Access both valence and sea quarks
- Fermilab PAC stage-1 approved
- Complementary to EIC Spin Physics

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

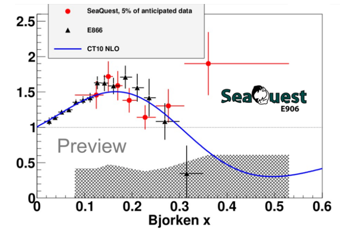
$$A_N \equiv \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \frac{f_{1T}^{\perp,u}(x_B) \cdot \bar{u}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$

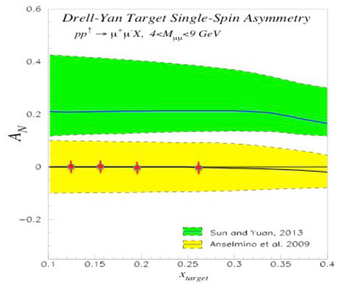


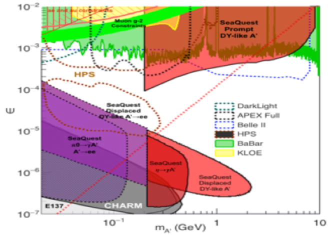


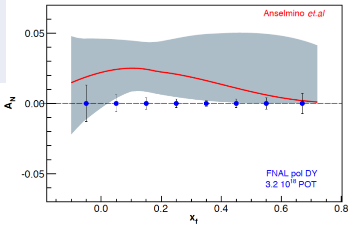
Summary and Outlook

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	2017 – 2021+	p + any targets (beam dump)	dark photon, dark Higgs
E1027	202x	Pol. p-beam + any targets	- quark Sivers - TMD, spin









SeaQuest/E1039 Collaboration

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

SeaQuest with a Transversely Polarized Target (E1039)

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Welcome to join us the fun at Fermilab *now*!

I WANT YOU

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and also during the workshop,

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backup

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

Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

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

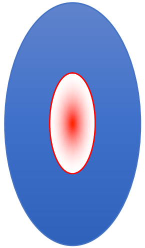
E1027

- 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

New Beam Collimator and Target

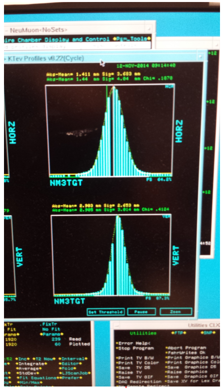


Target cross section: 18 x 28 mm^2

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

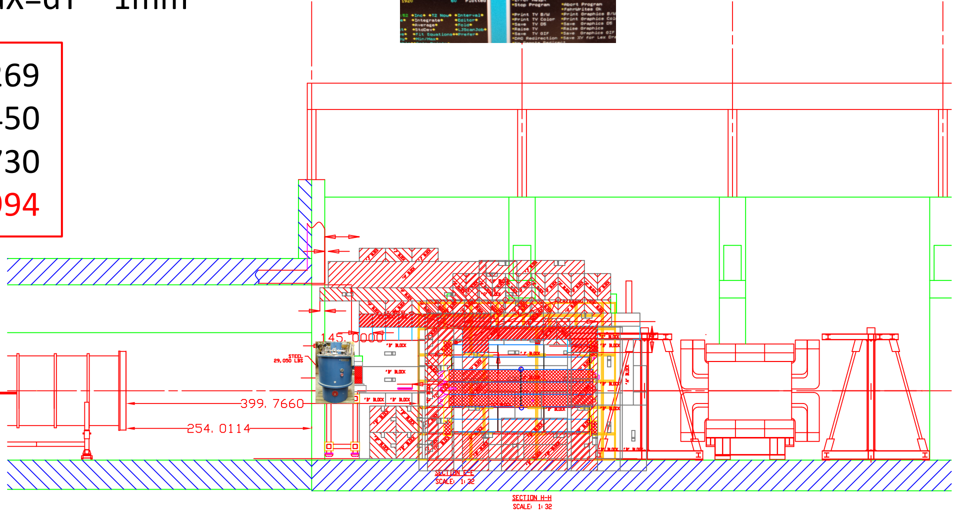


E906 beam profile:
SigX = 4.0mm
SigY = 3.0mm

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

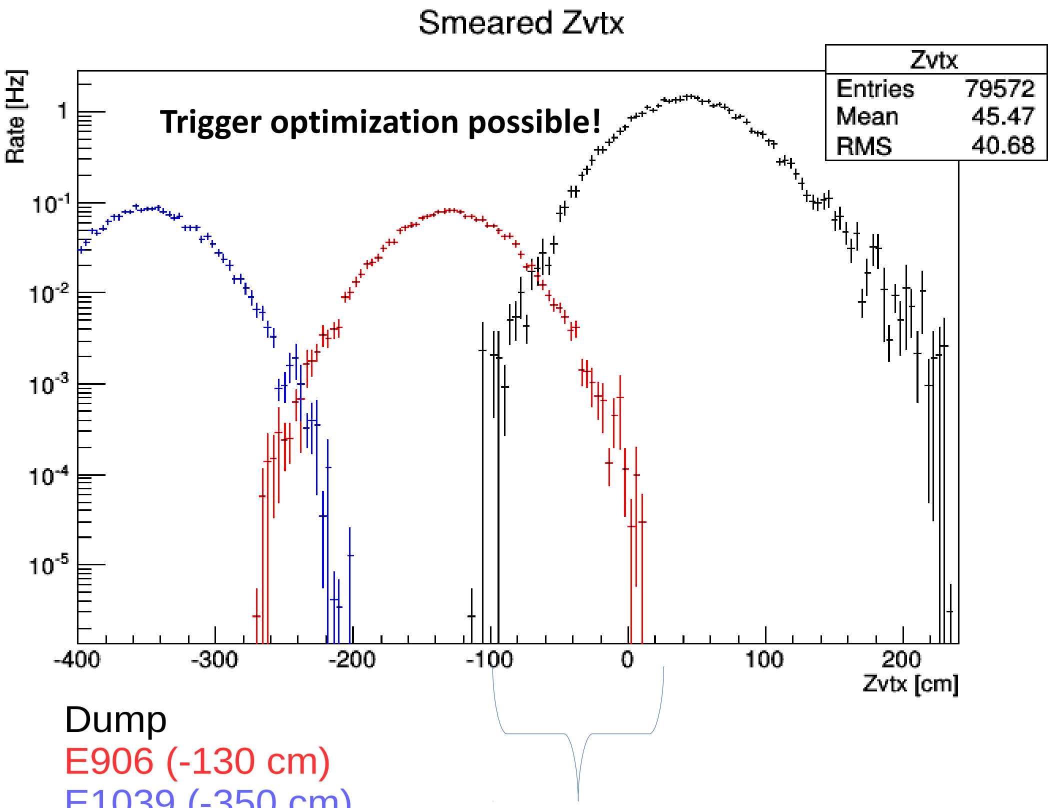
Beam collimator

120GeV
beam



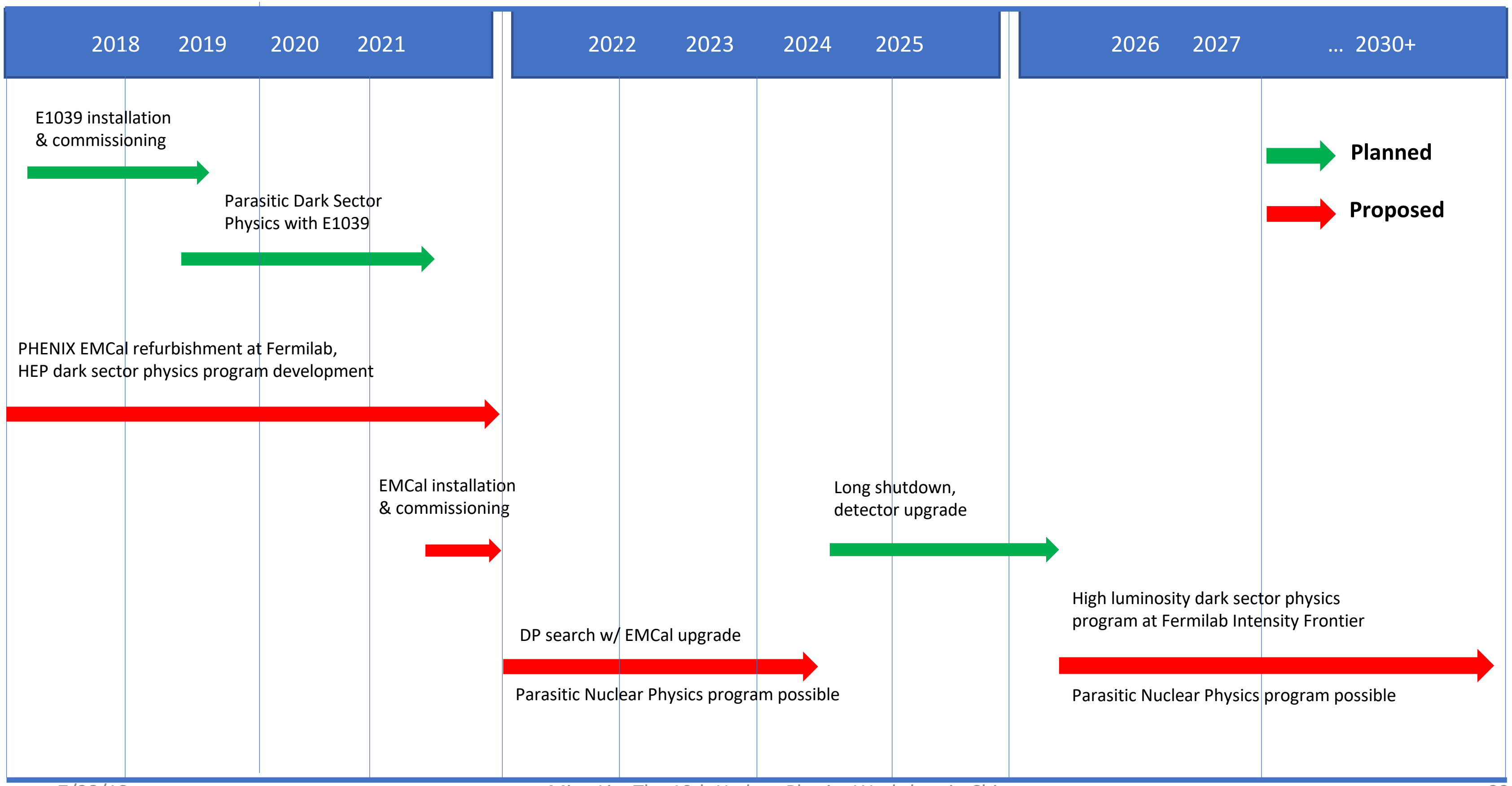
Target and Beam Dump Event Separation

target at upstream: Z=-3.5m

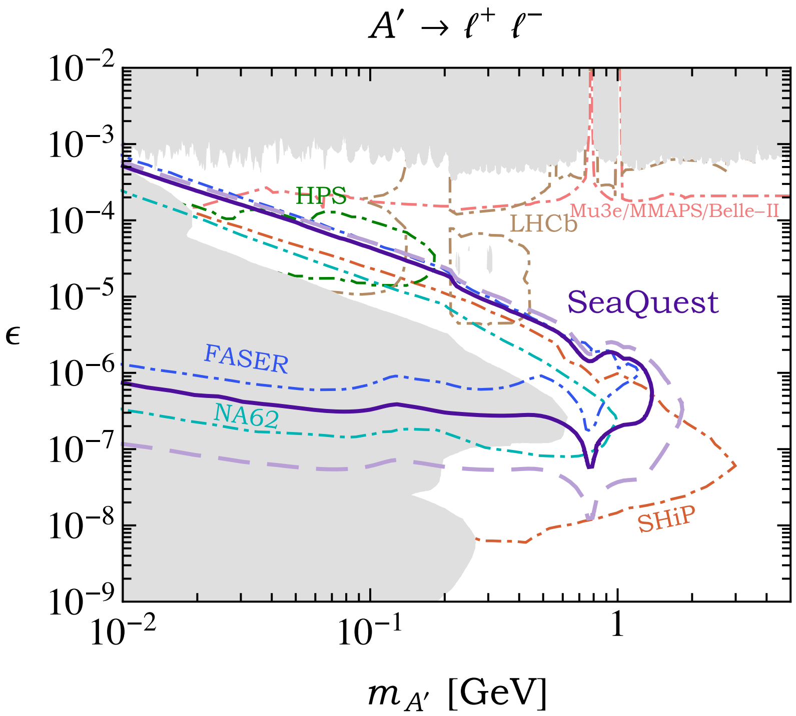


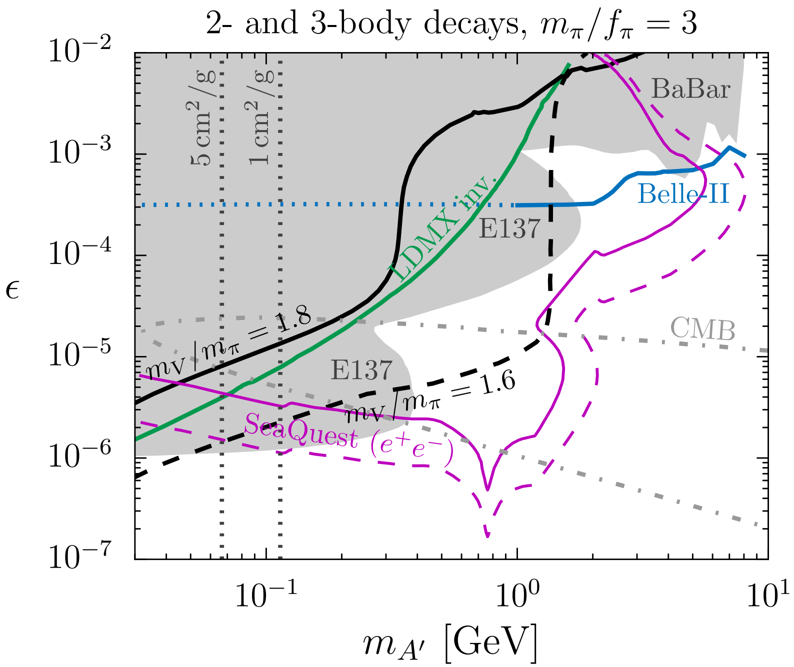
Dump
E906 (-130 cm)
E1039 (-350 cm)

Dark Sector Physics Search Program at SeaQuest



Dark Photon Search at SeaQuest with all Future Projections

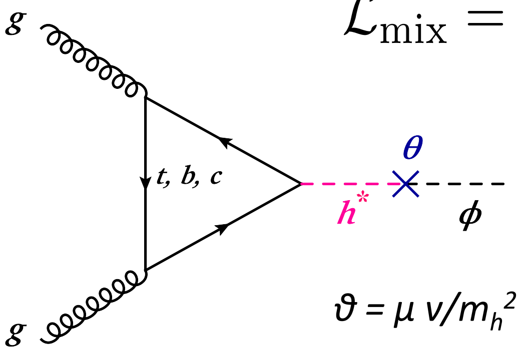




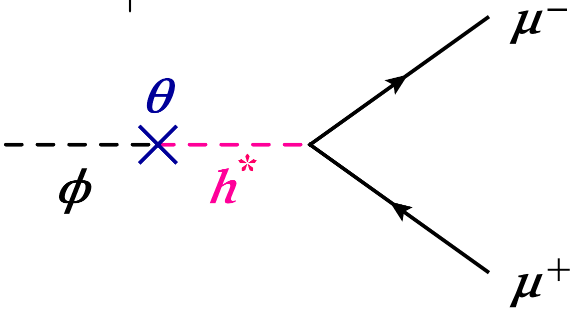
Dark Higgs

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

Y. Zhang et al, arXiv:1502.06983



$\vartheta = \mu\, v/m_h^2$



$$\sigma(p+p\to\phi+X) = \int_0^1 \frac{dx}{x} g(x) g\left(m_\phi^2/(xs)\right) \frac{\alpha_s^2 G_F m_\phi^2}{288\sqrt{2}\pi s}$$

Phase-I:

High-mass: $\mu^+\mu^-$ and hadrons

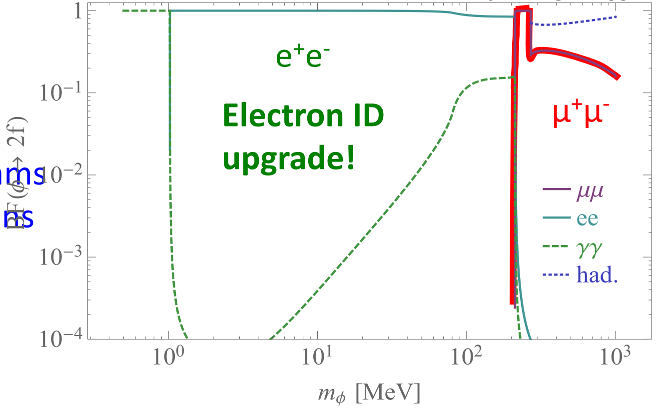
Advantage of using hadron beams with muon probes over electrons

Phase-II:

Low-mass: e^+e^-, <200MeV possible

High-mass: hadrons, (5x)

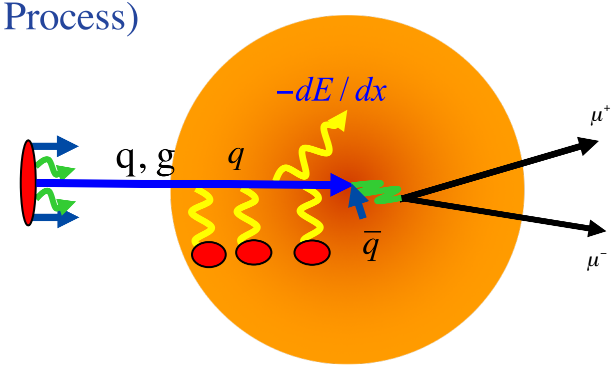
arXiv:1312.4992

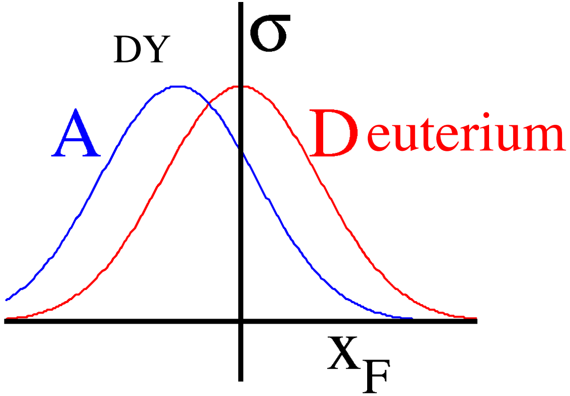


Determine and Calibrate dE/dx with DY in p+A

$$q + \bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$$ (Drell-Yan Process)

- Known initial state nuclear parton density;
- Minimal final-state interactions of the detected particles.
- E906: No shadowing correction at moderate X_t





Energy loss reduces x_b and x_F in nuclei versus proton ($x_F = x_b - x_t$)

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

Possible sea-quark shadowing effects