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

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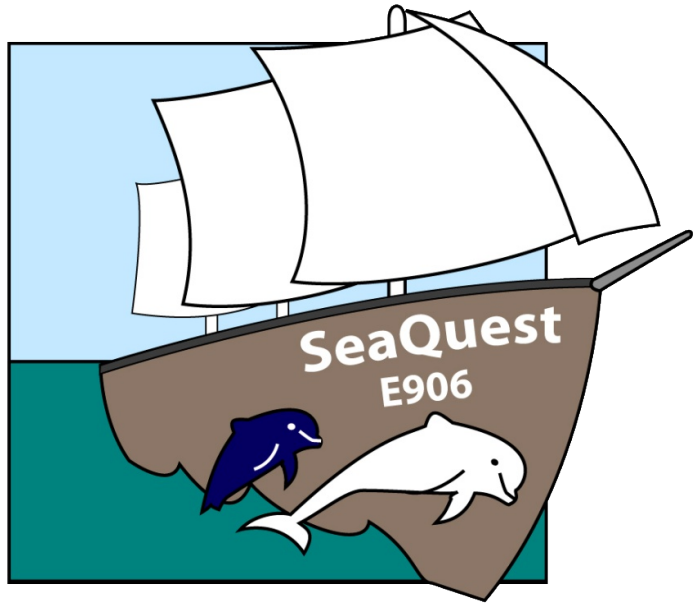
For the SpinQuest/E1029 Cillaboration

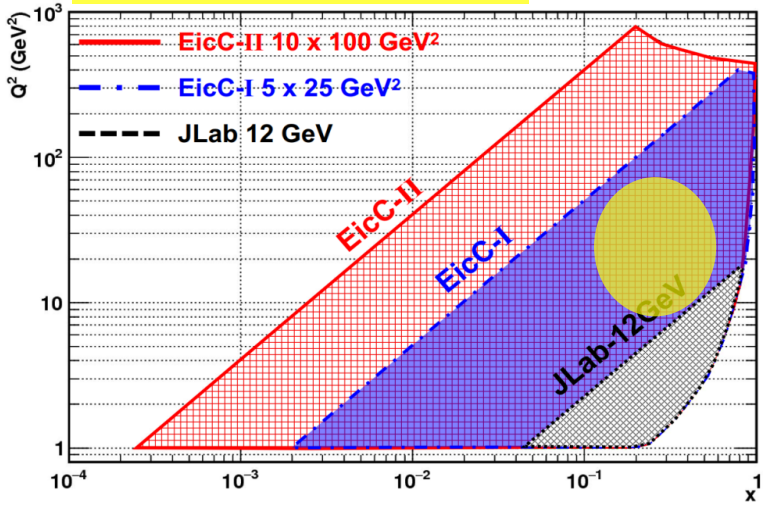
QCD Evolution 2019, May 13-17

Outline

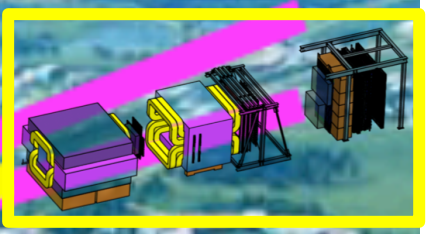
- SpinQuest experiments at Fermilab
  - E1039 polarized NH_3/ND_3 targets
  - Follow up of SeaQuest/E906 unpolarized target program
- Novel physics of sea quarks at x = 0.1 ~ 0.4
  - Flavor asymmetry
  - Sivers & OAM
- Future opportunities
  - E1067 dark photon search, 2016 - 2021+
  - E1027 polarized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



EicC: sea quarks



Fermilab High Intensity Frontier



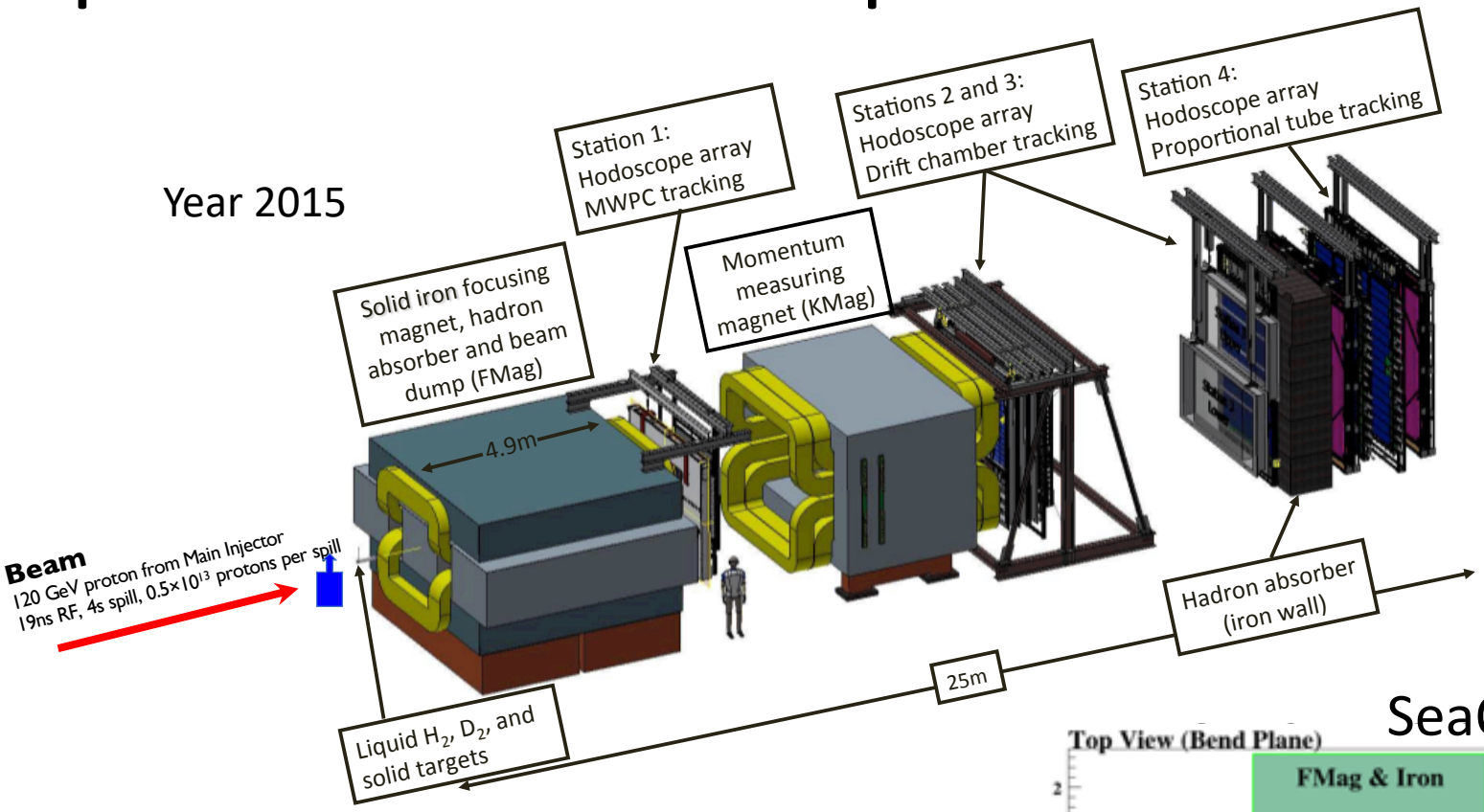
Fixed Target Beam lines

Tevatron 800 GeV

Main Injector 120 GeV

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
- $5x10^{12}$ Proton On Target (POT) per spill
- Total integrated POT for E1039 (2-year): $1.4x10^{18}$ POT

E906 unpolarized targets: 2012-2017

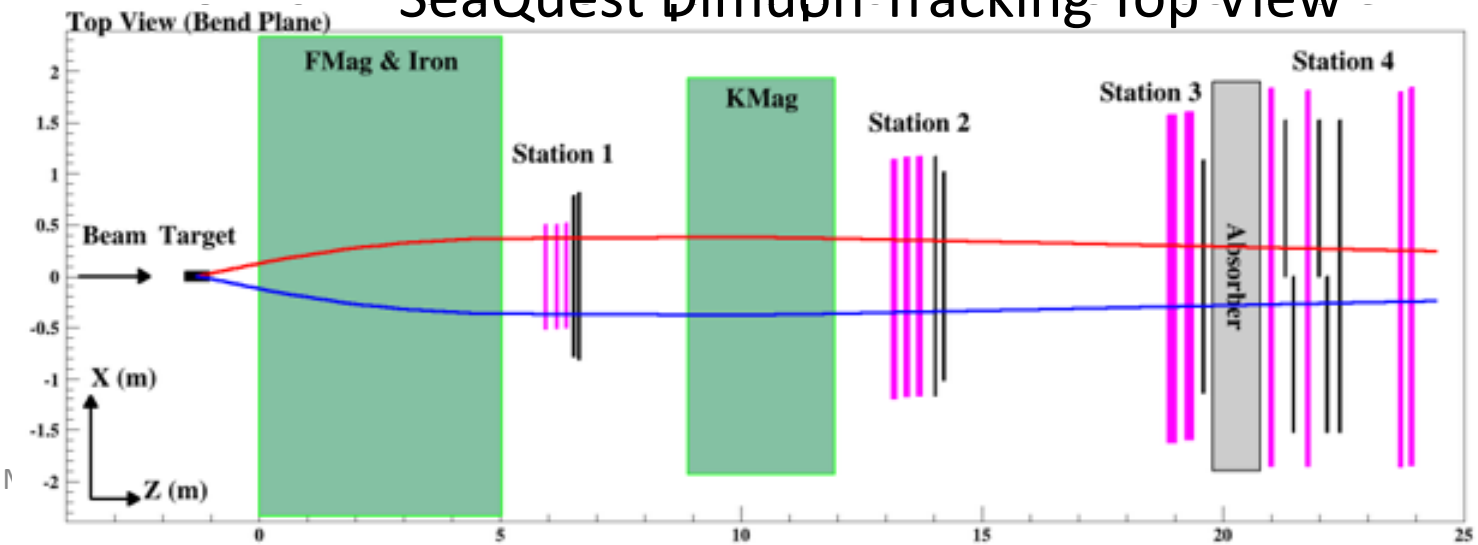
- ^{1}H, ^{2}D, ^{12}C, ^{56}Fe, ^{184}W

E1039 polarized targets: 2018 – 2021+

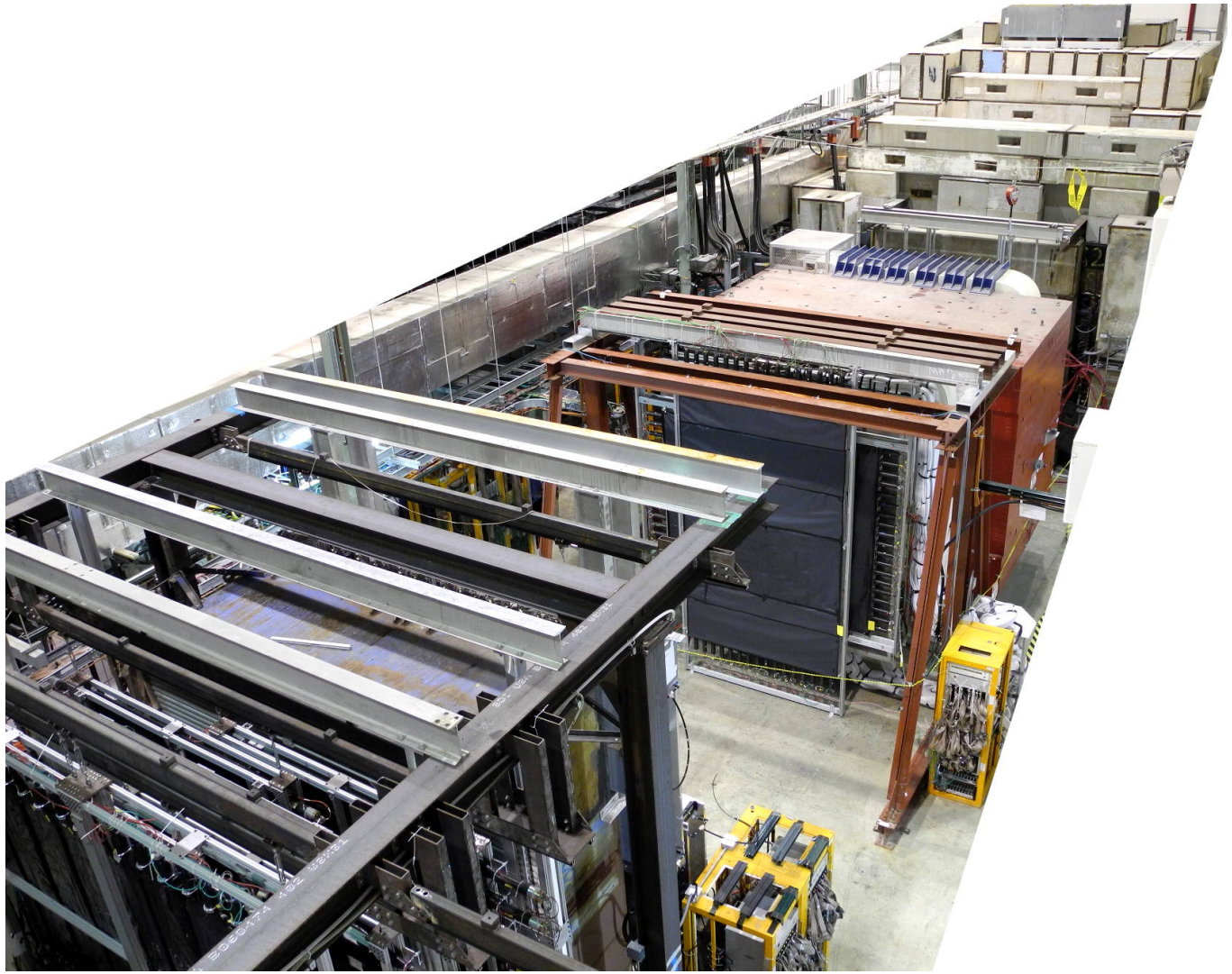
- Polarized protons (NH_3)
- Polarized neutrons (ND_3)

E1027 polarized beam

SeaQuest Dimuon Tracking Top View



SpinQuest Experimental Hall



Beam

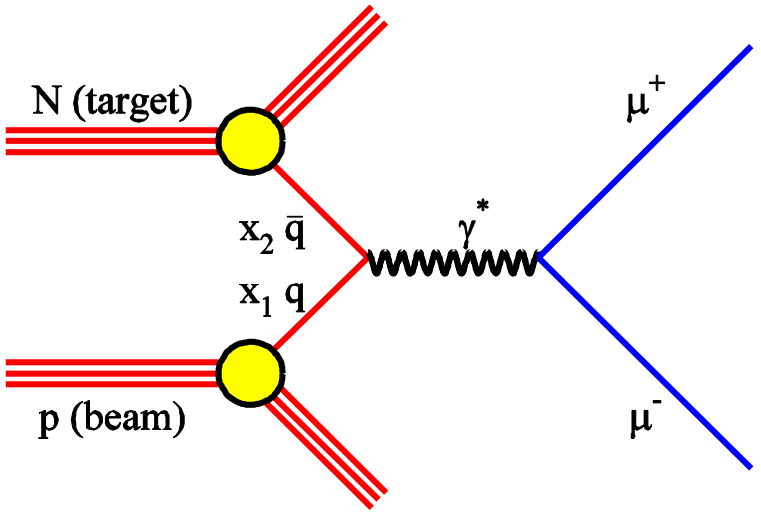
Target area

F-Mag

K-Mag

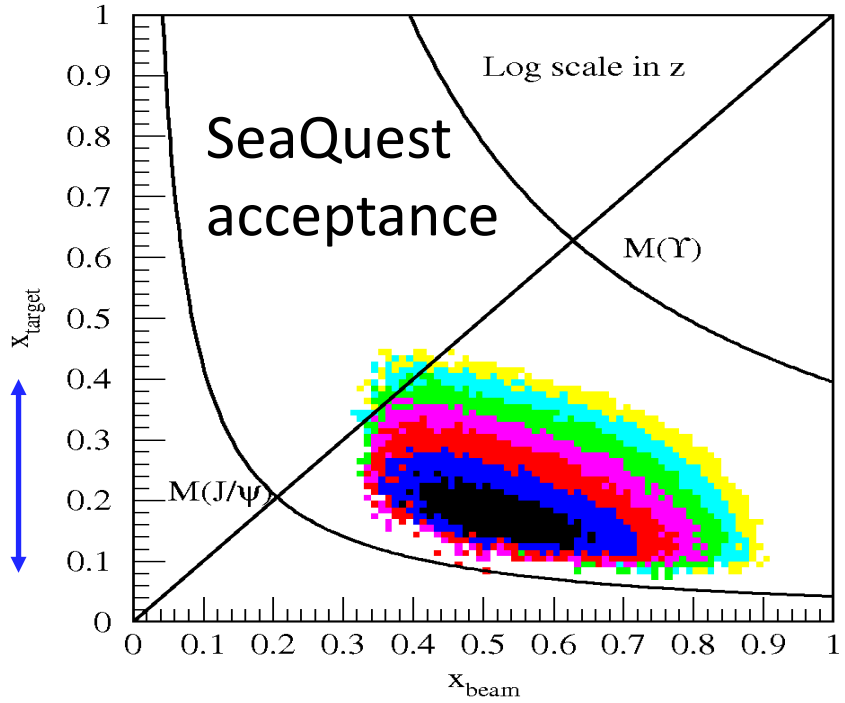
Muon-ID

Drell-Yan @SeaQuest – a Sea Quark Laboratory



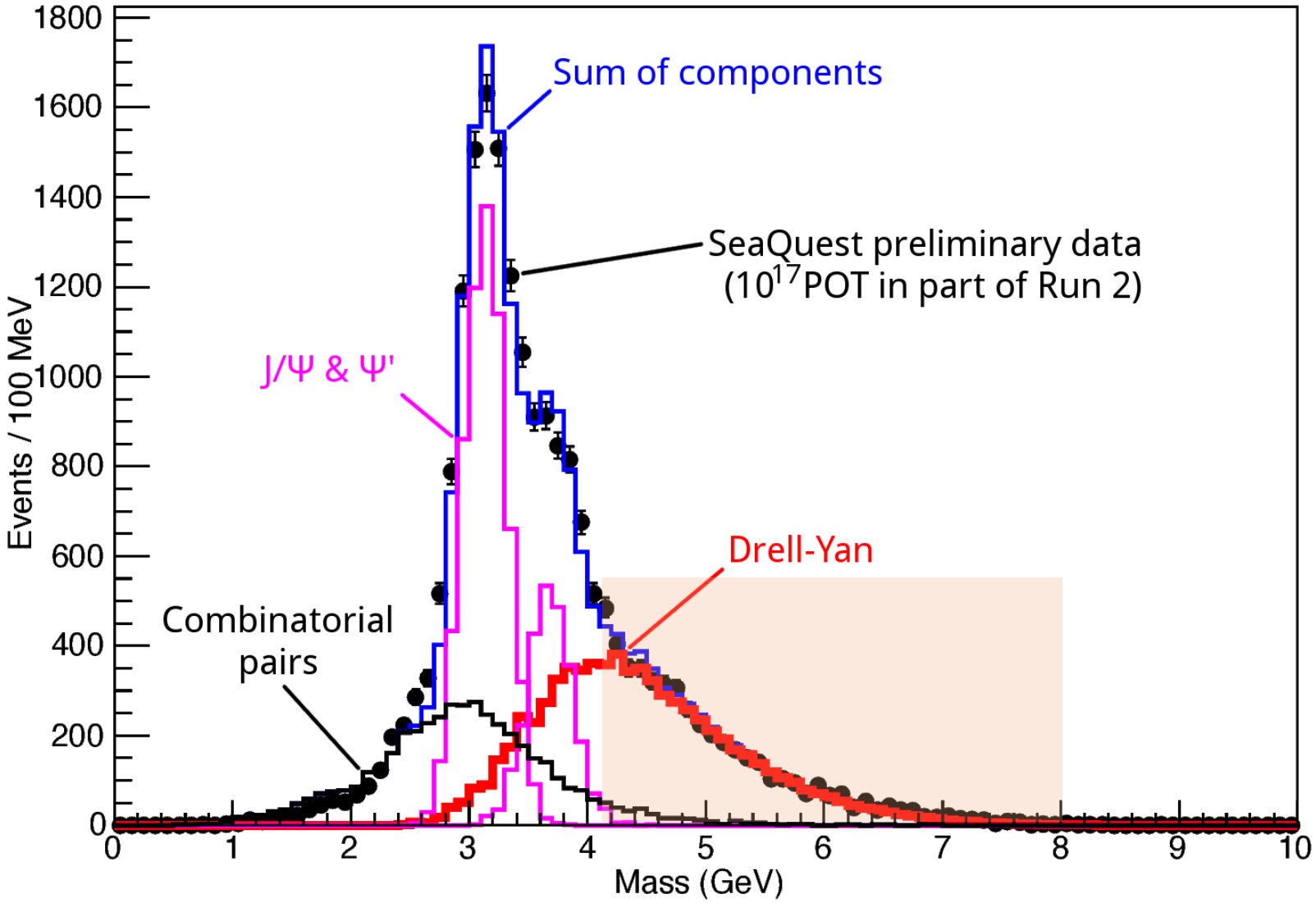
$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q(x_t)]$$

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



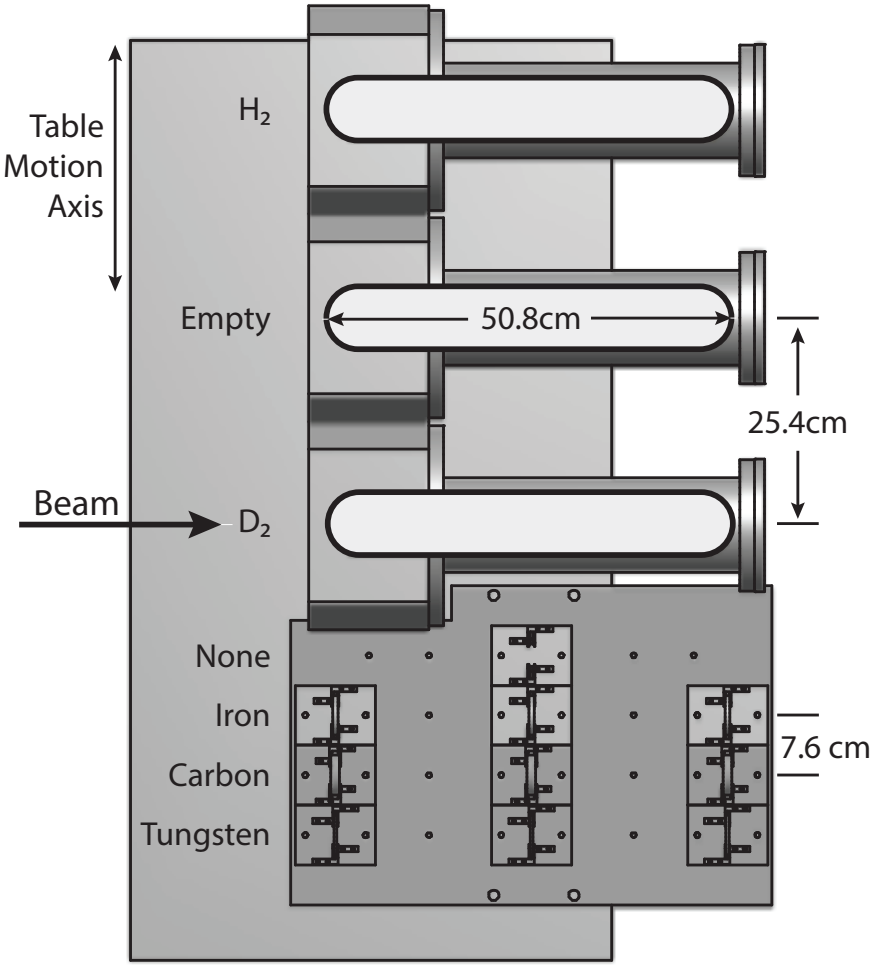
Kinematically favors sea-quarks from target – **a sea quark lab!**

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

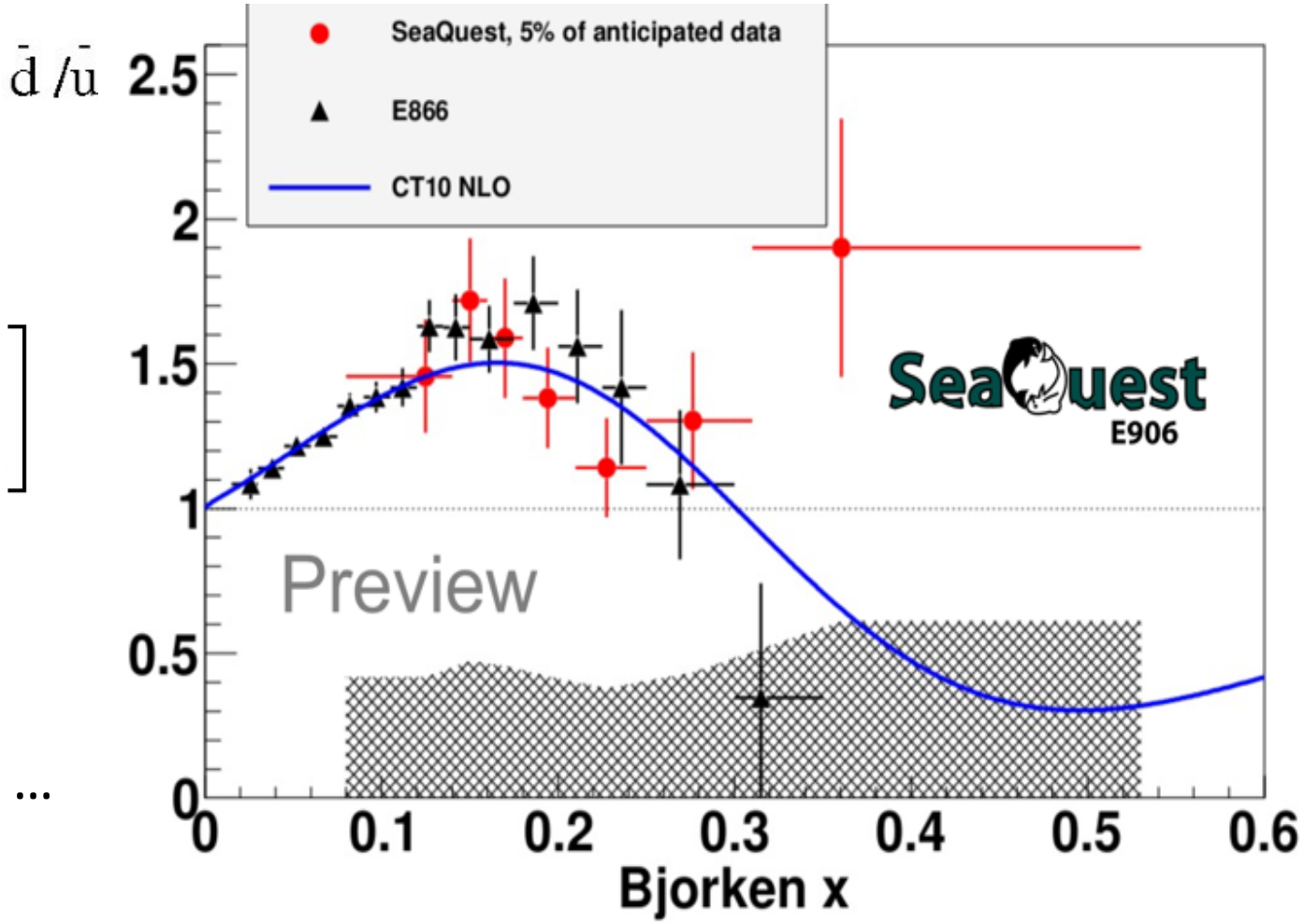


Flavor Asymmetry of Sea Quarks at Intermediate x

Update with latest plot?

Proton vs "Neutron" targets:

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



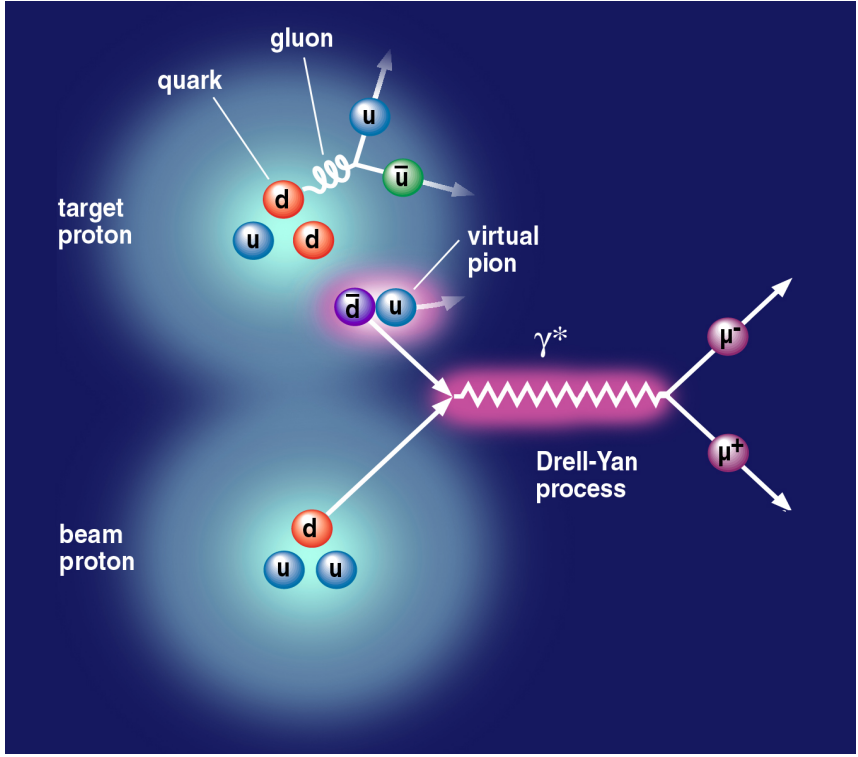
This could lead to a very interesting physics …

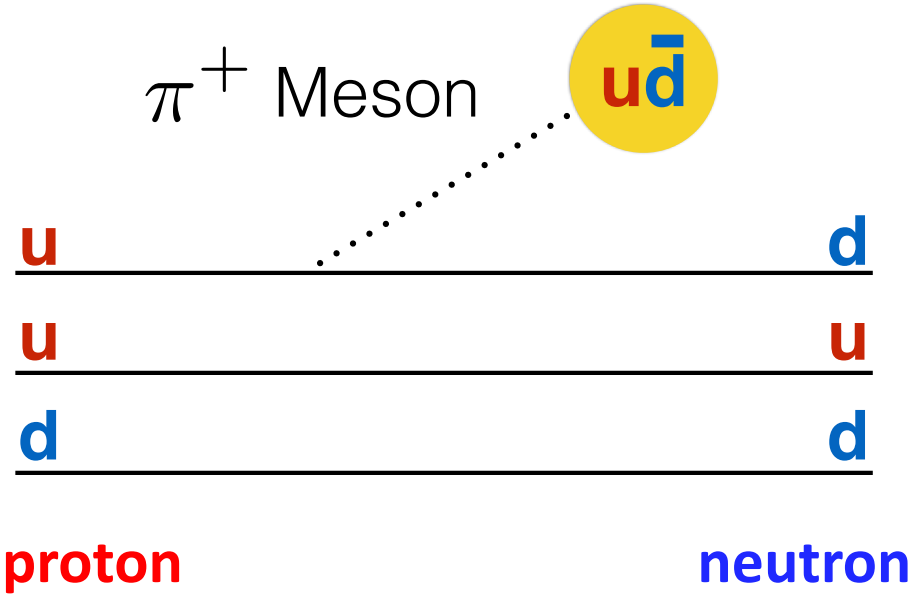
Sea Quark Flavor Asymmetry and OAM

Pion cloud model

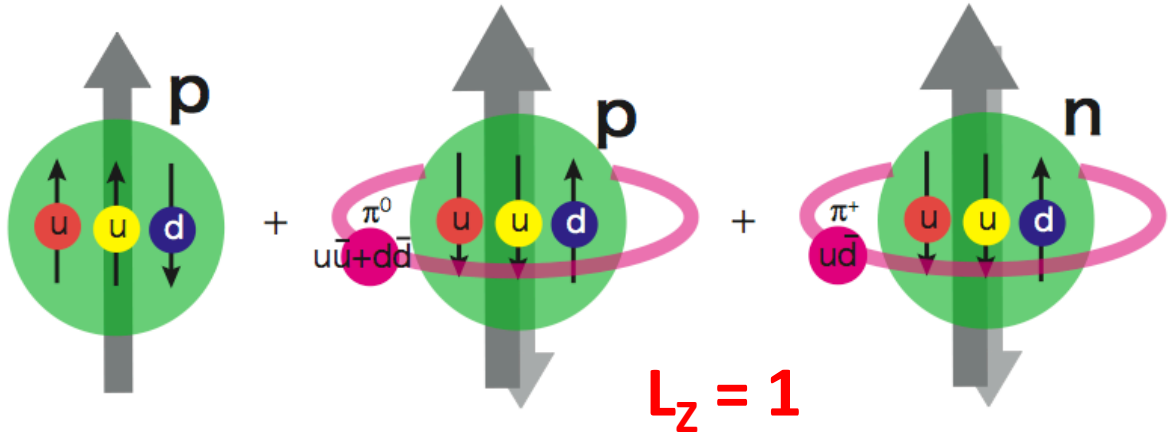
- Sea-quark flavor asymmetry
- Sea-quark orbital angular motion
- Expect large Sivers function at x = 0.0 ~ 0.4

Pion cloud and
Drell-Yan process

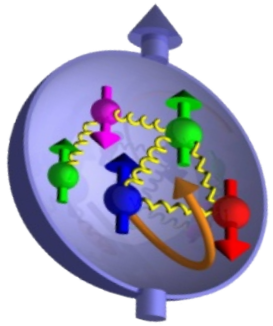




$|p\rangle = a|p_0\rangle + b|p_0 + pi^0\rangle + c|n+pi^+\rangle + \ldots$

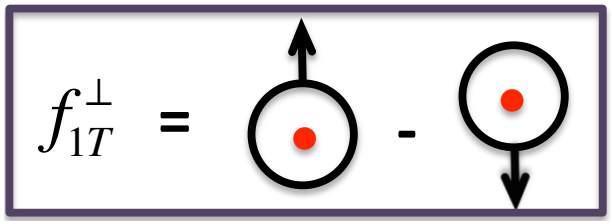


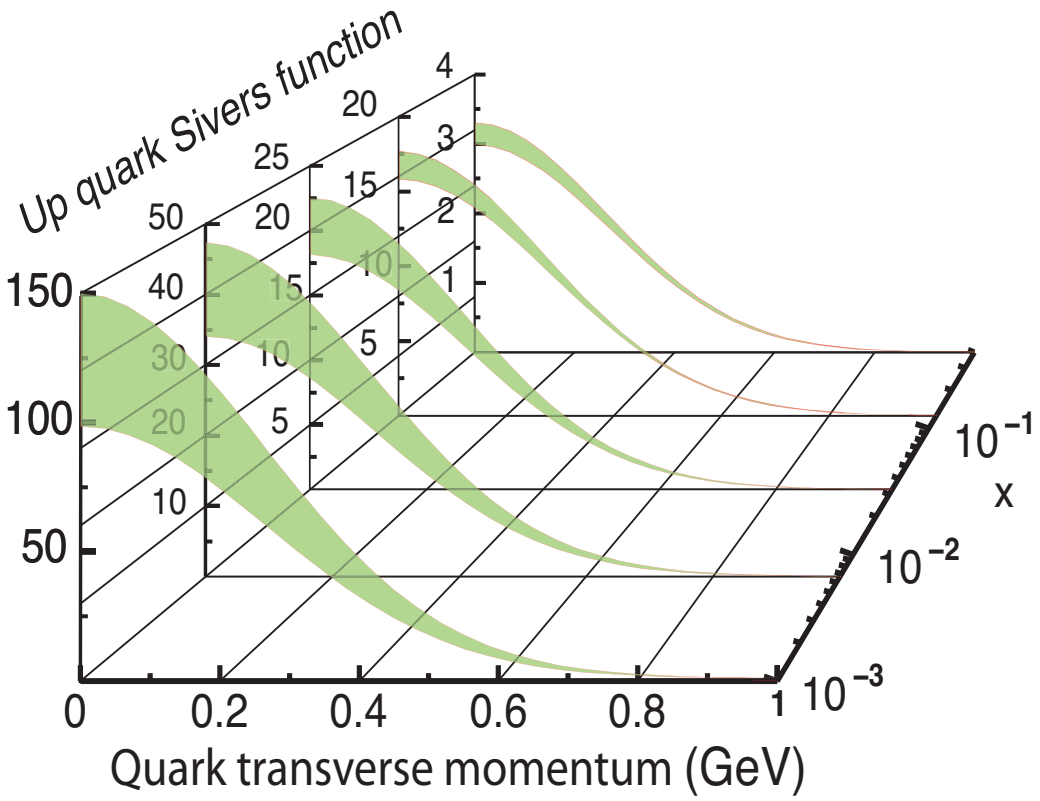
$L_z = 1$

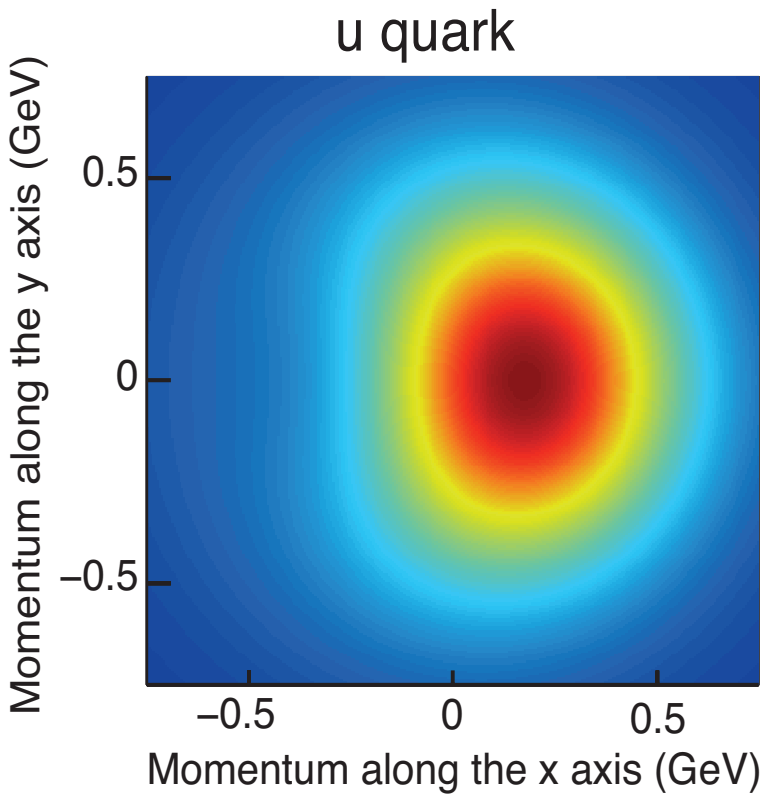


Nucleon 3-D Structure and Sivers Function

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



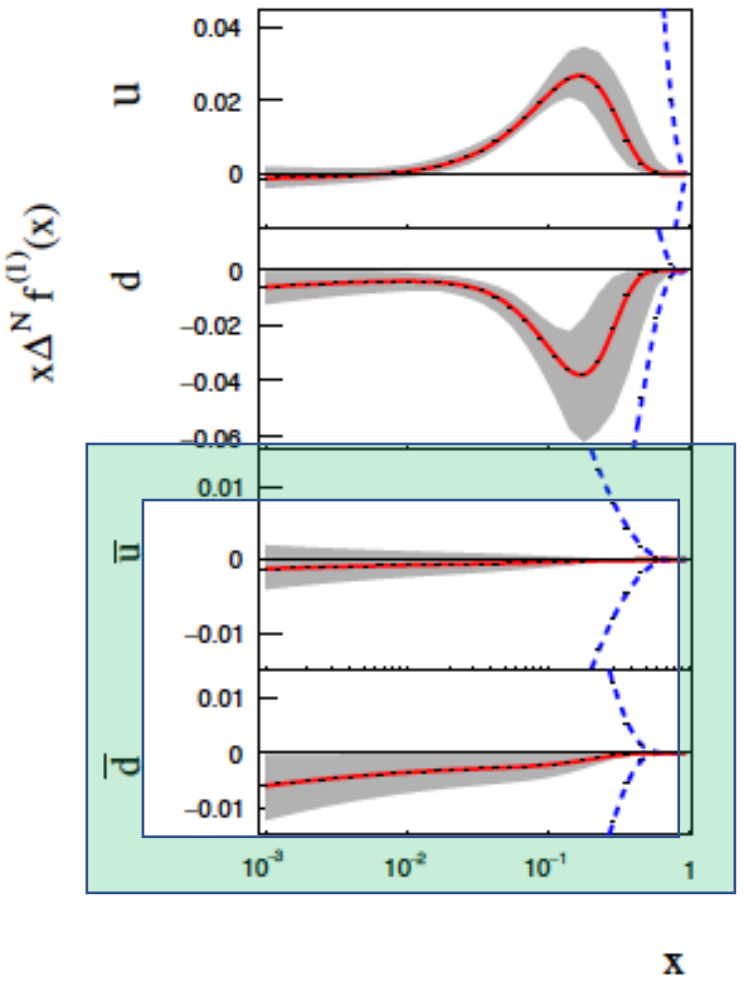




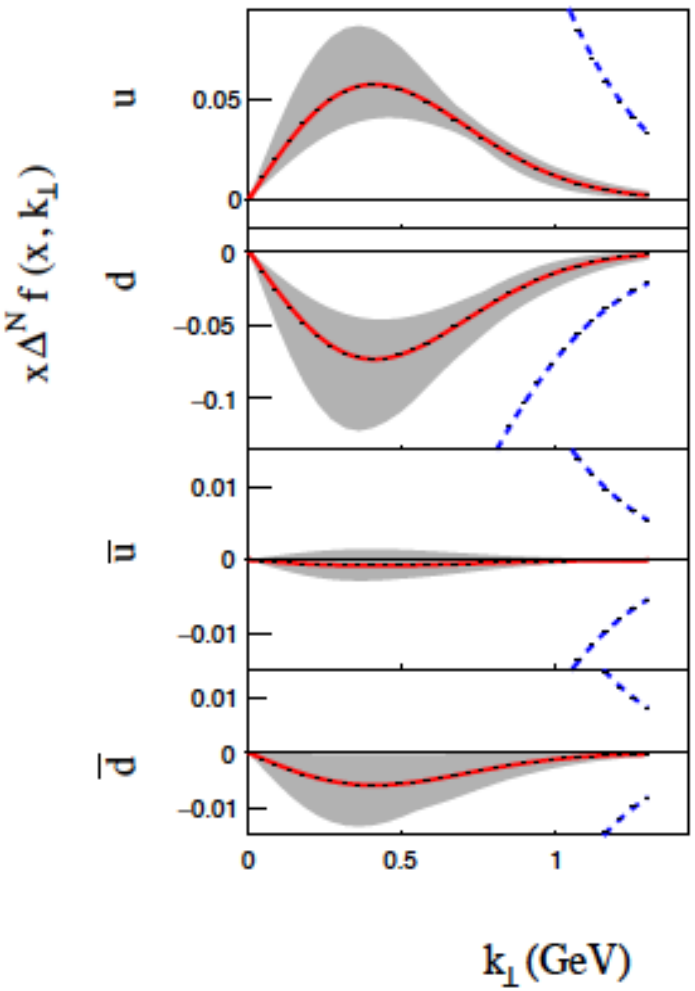
Sivers Functions from Global Fits

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

Sea quarks



1612.06413, M. Anselmino et al



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

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

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

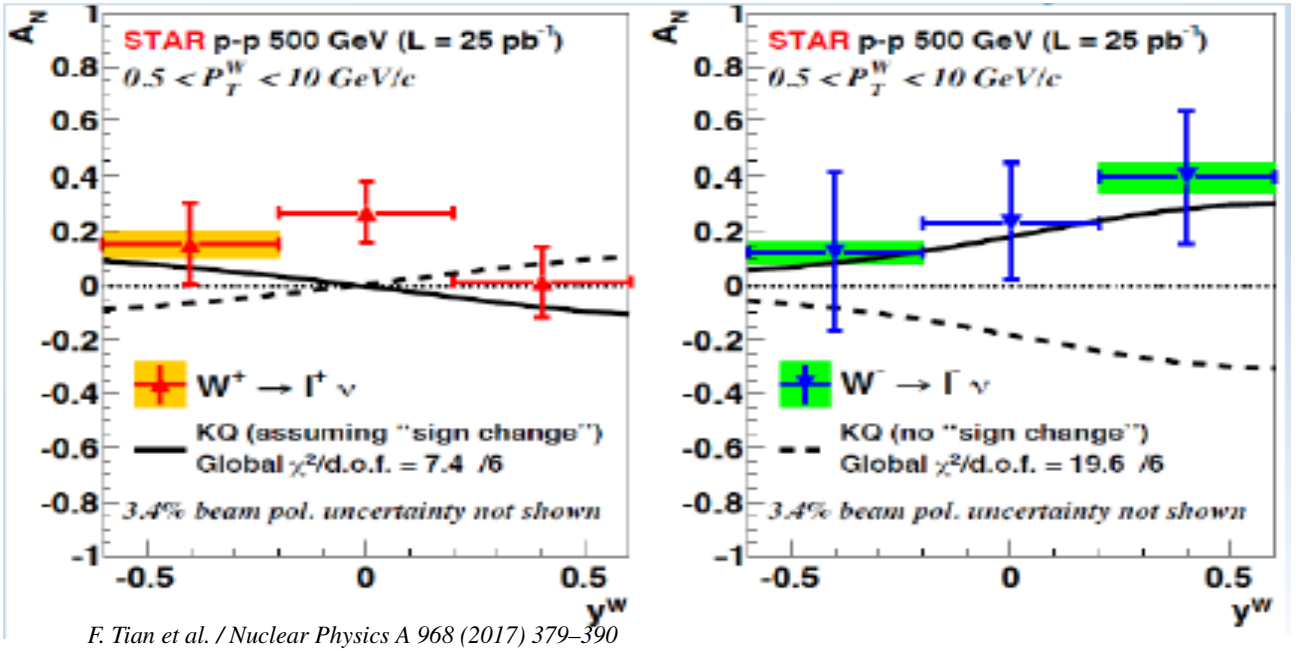
RHIC data:

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

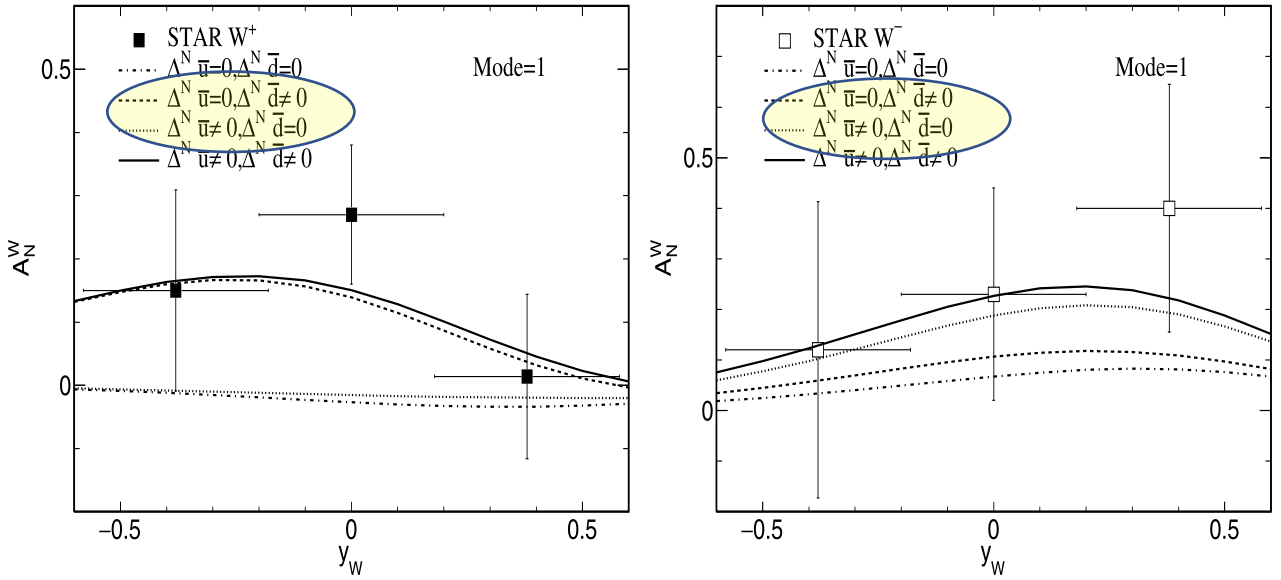
E1039:

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

Anselmino et al 2016



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



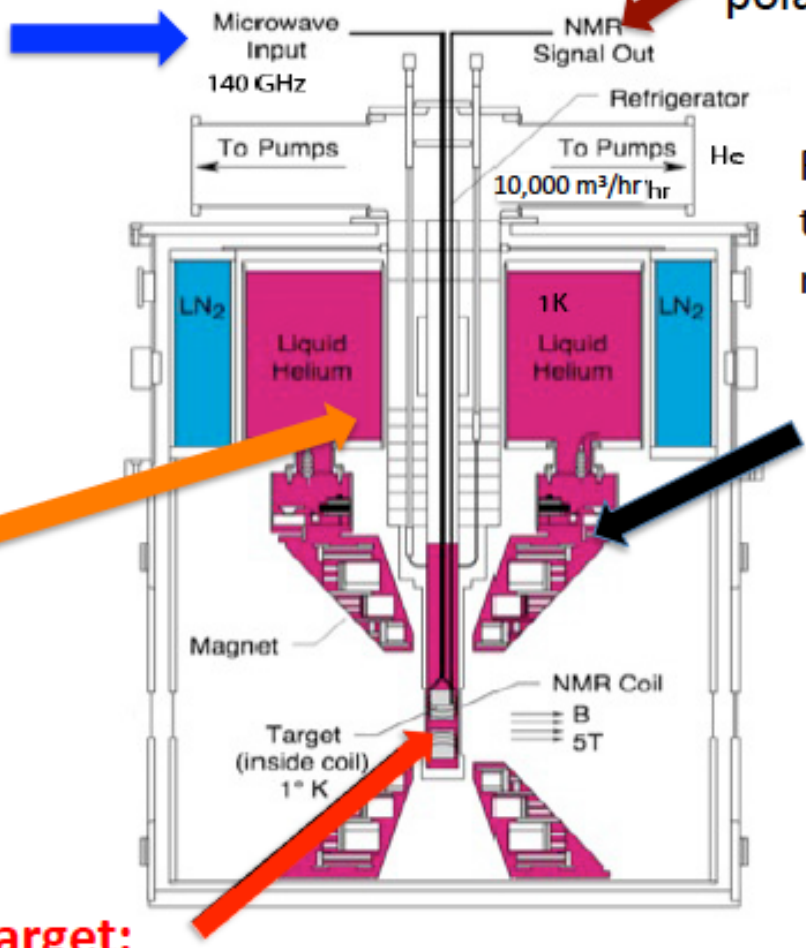
(b) $A_{W^+}^N$. (a) $A_{W^-}^N$.

Polarized NH_3 Target Developed for DY Sivers

Microwave: Induces electron spin flips

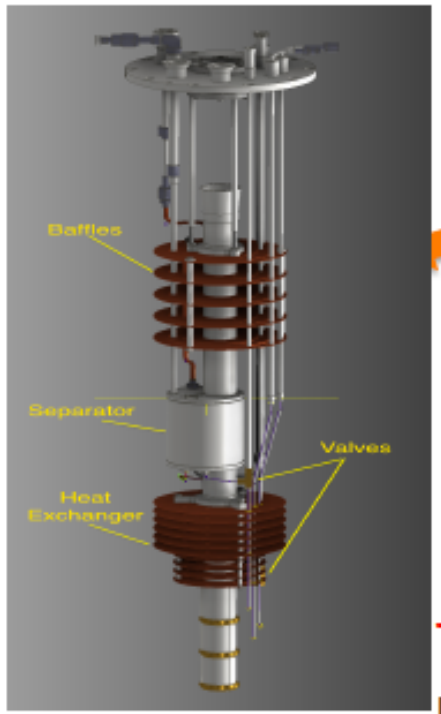
- EIO + Power equip:

NMR system: to measure polarization



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

Refrigerator:

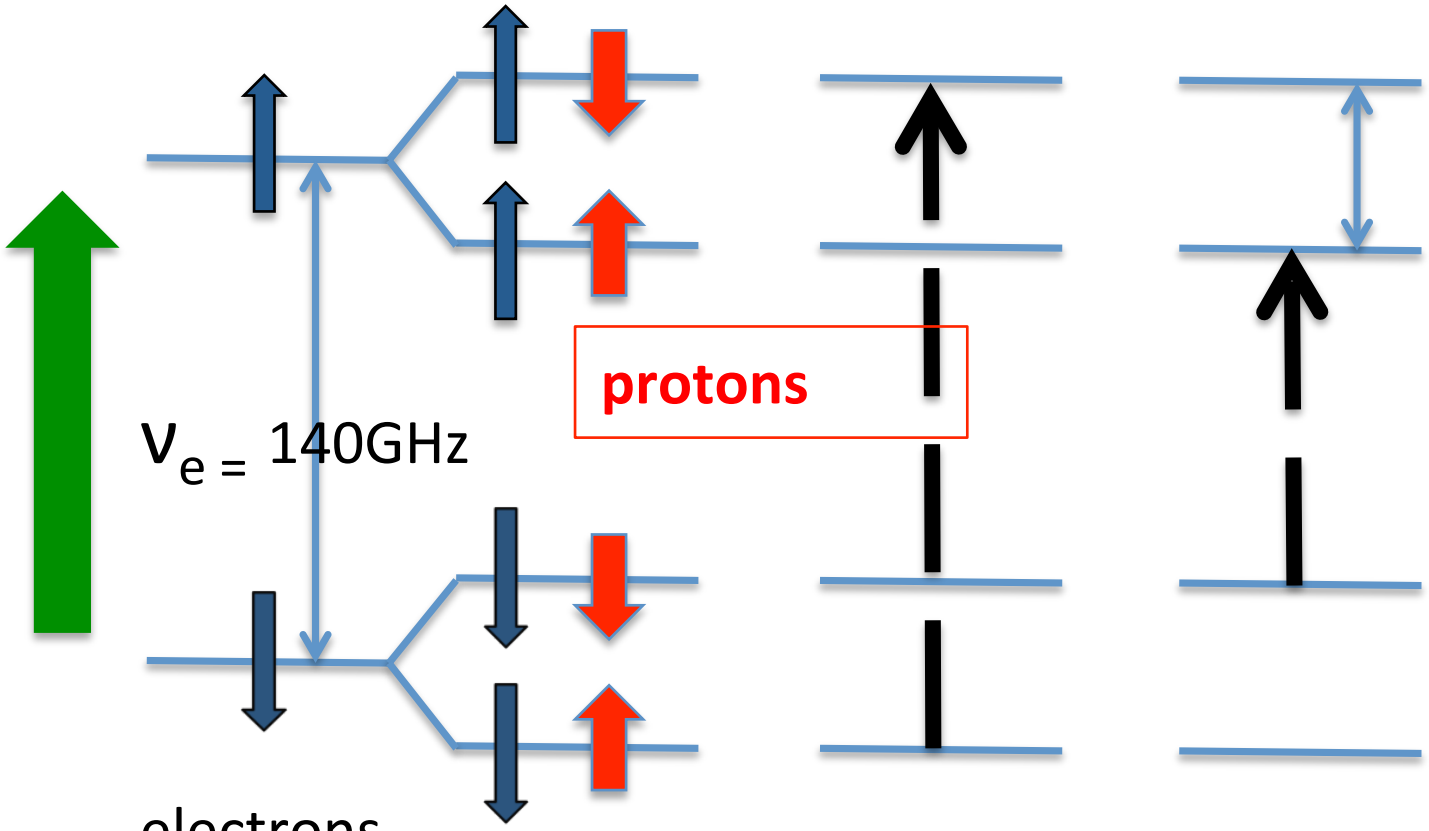


Superconducting Coils for Magnet: 5T

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%

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

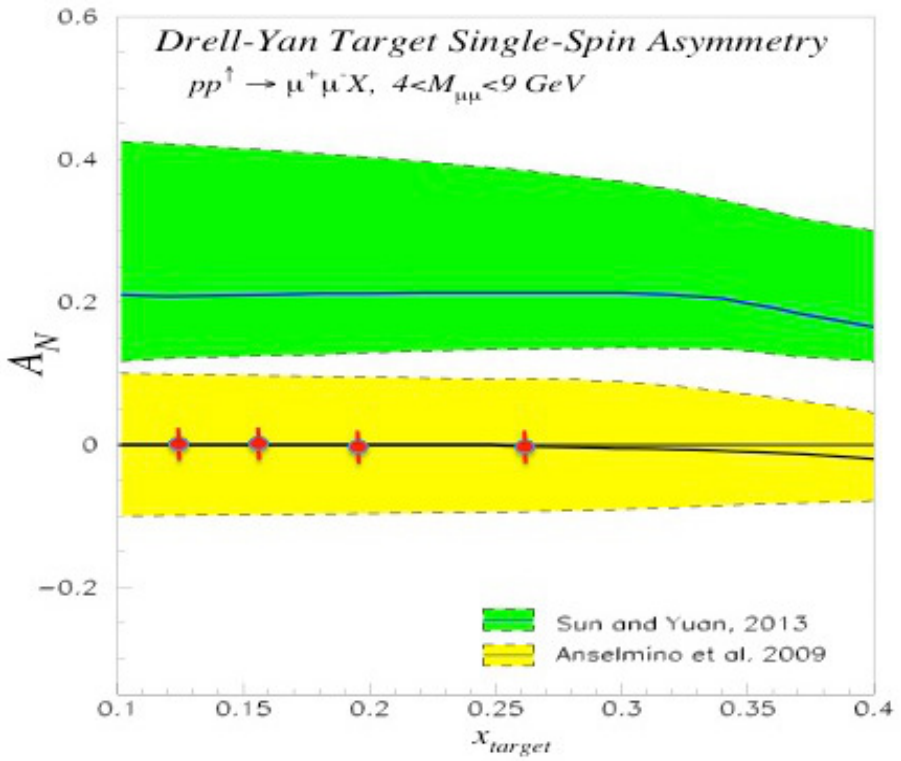
Projected SeaQuest Target and Beam Performance

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

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

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

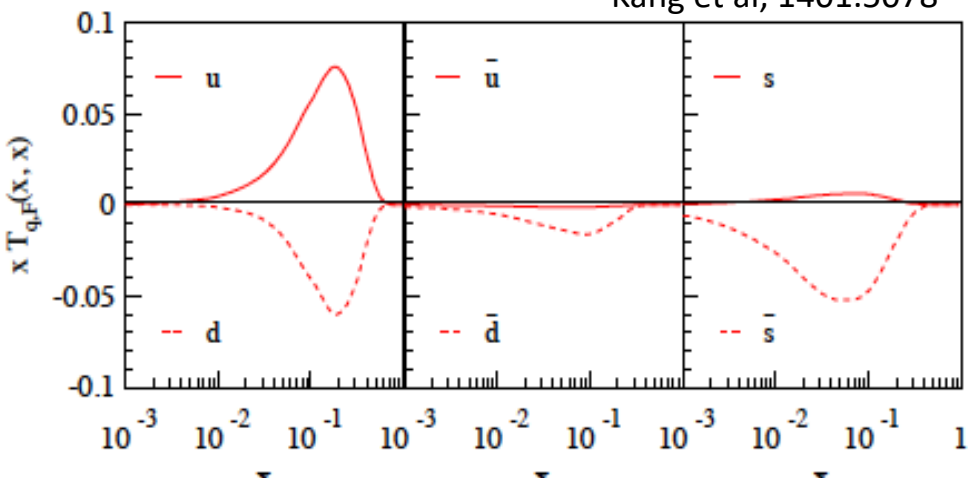


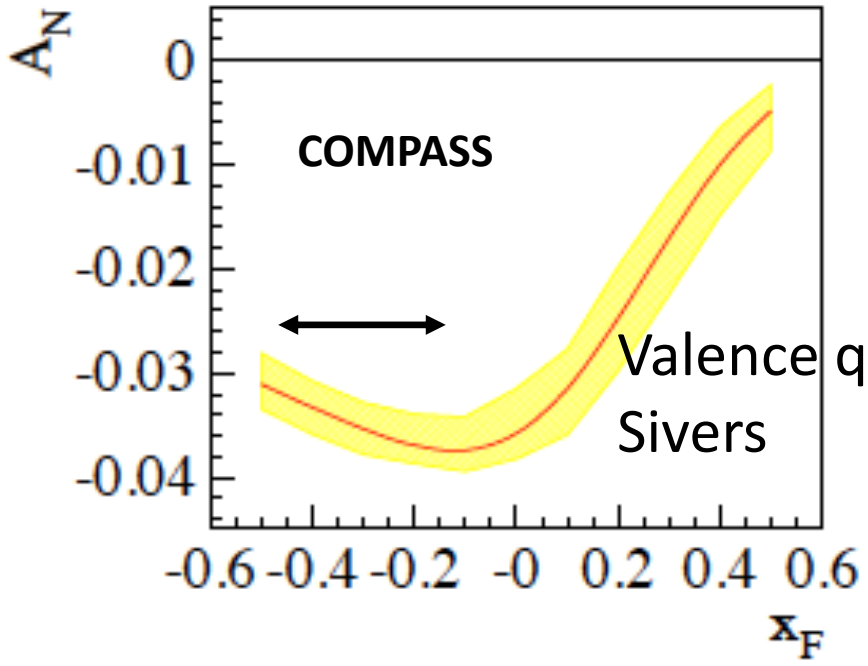
$$\Delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N^+ + N^-}}$$

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

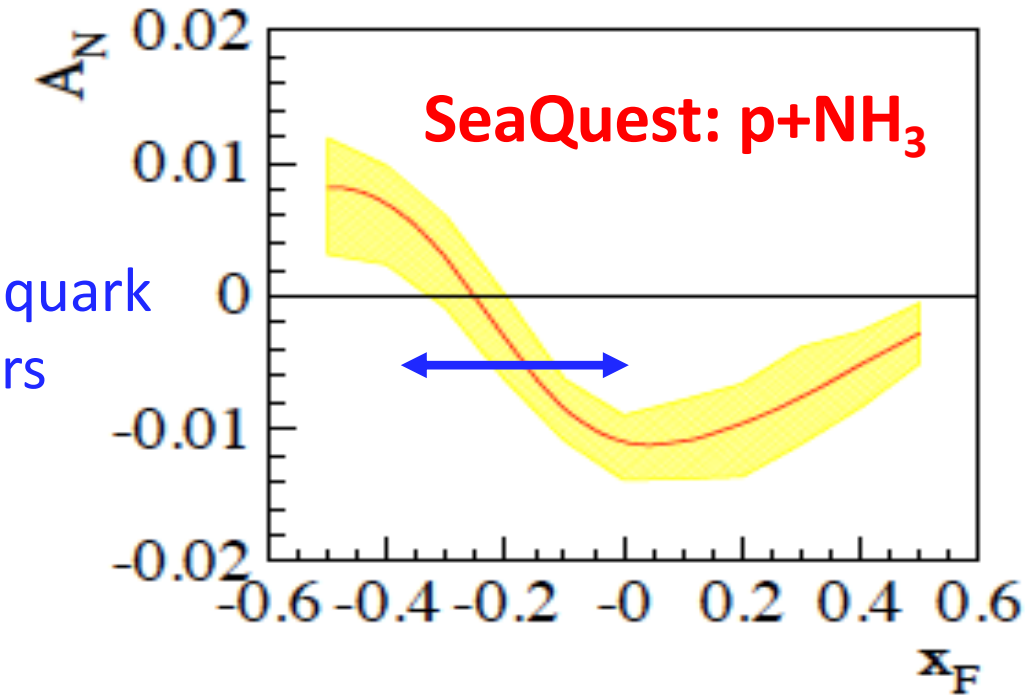
Drell-Yan Sivers Asymmetries w/ QCD Evolution

Kang et al, 1401.5078

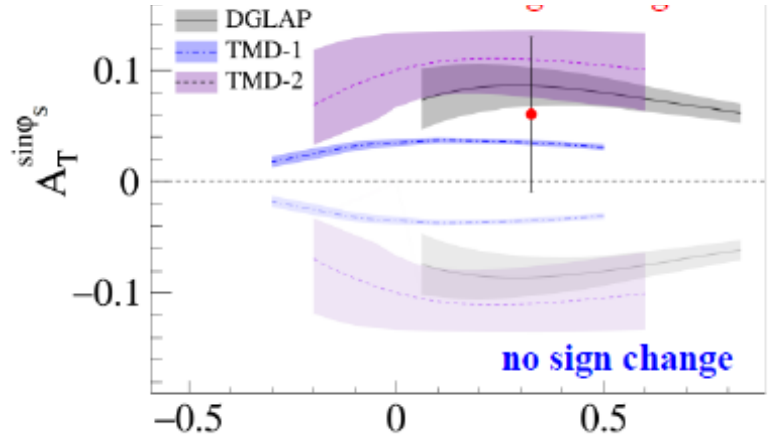




Valence quark Sivers



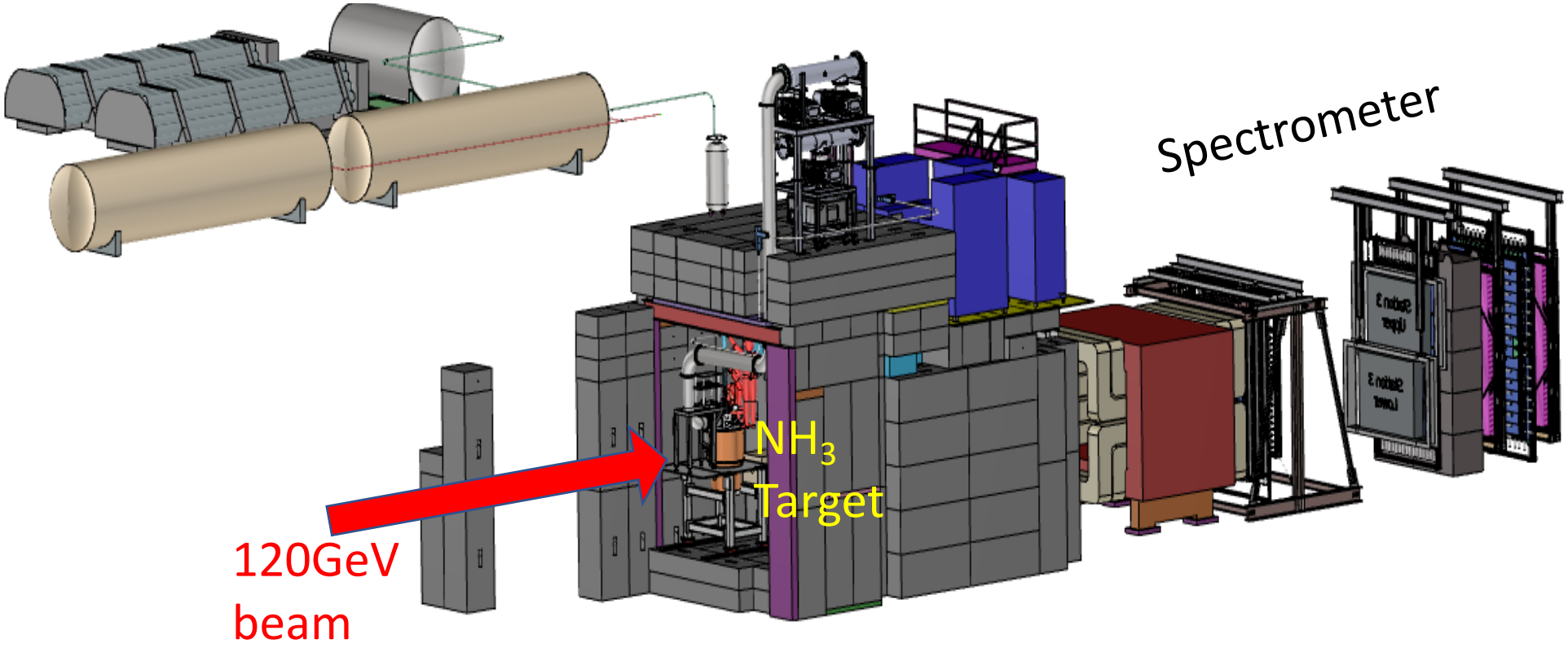
Sea quark Sivers



E1039 Status & Plan

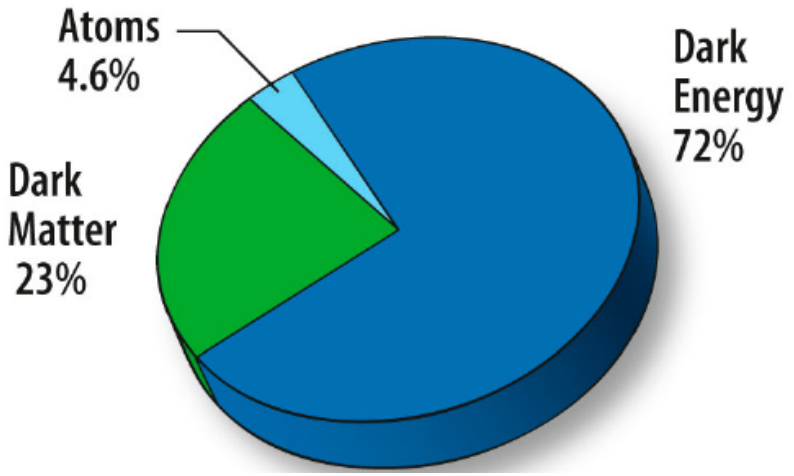
- DOE approval, March 2018
- E906 decommissioned 6/2018
- E1039 target shielding in progress
- Beam collimatorin progress
- Polarized target to be installed by fall of 2019

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

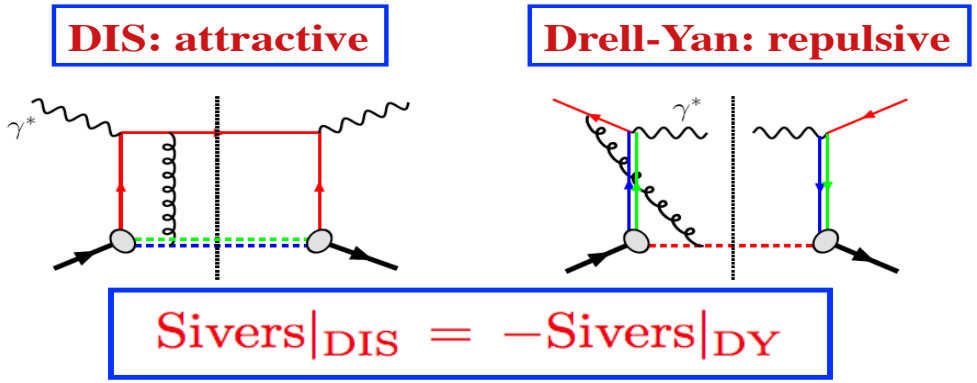


Physics Beyond E1039 Polarized DY A_N

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



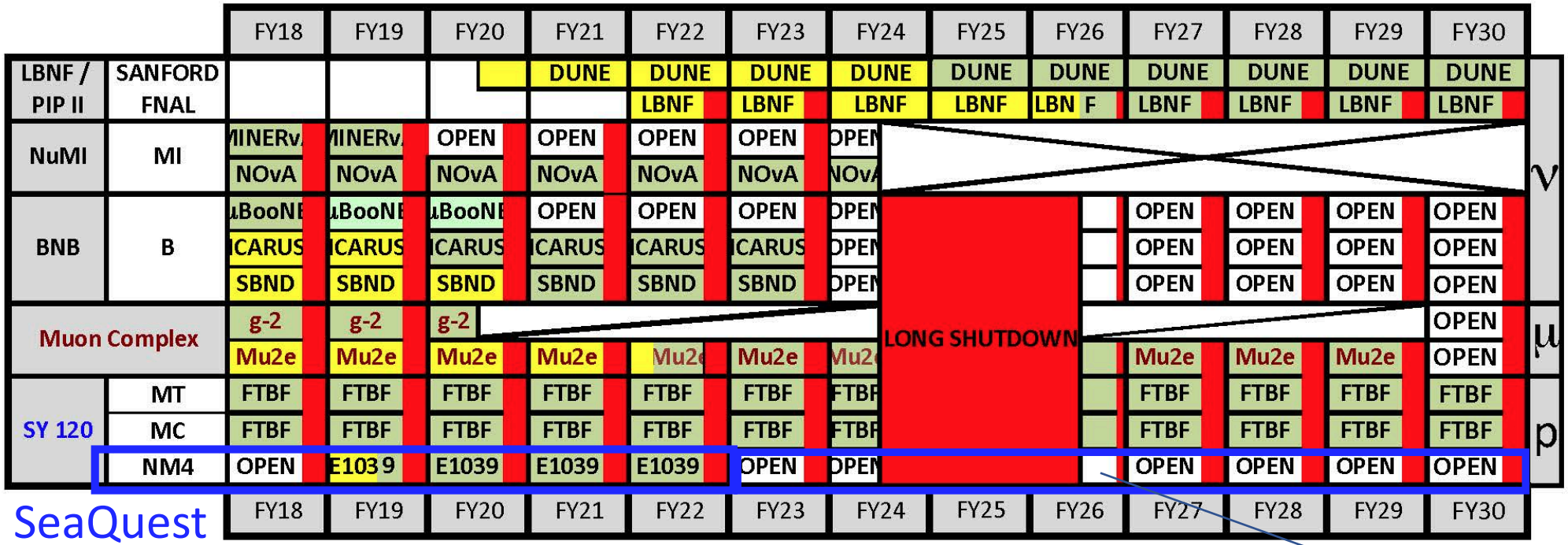
- Physics with polarized beams – E1027
  - Polarize the Main Injector 120GeV beam
  - Valence quark Sivers
  - Test QCD dynamics in DY vs DIS



Fermilab Long Range Plan

Fermilab Program Planning 5-April-18

LONG-RANGE PLAN



Construction / commissioning Run Subject to PAC review Shutdown

Capability ended Capability unavailable

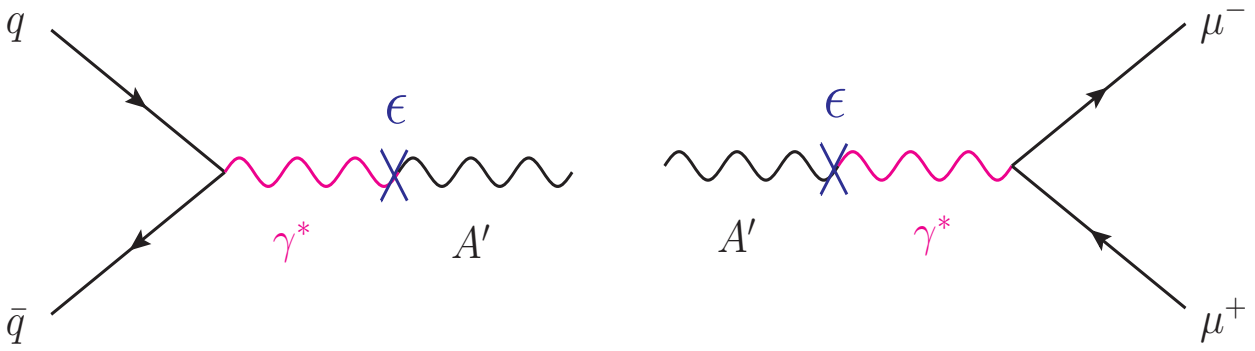
Opportunity for new programs at SeaQuest after E1039

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

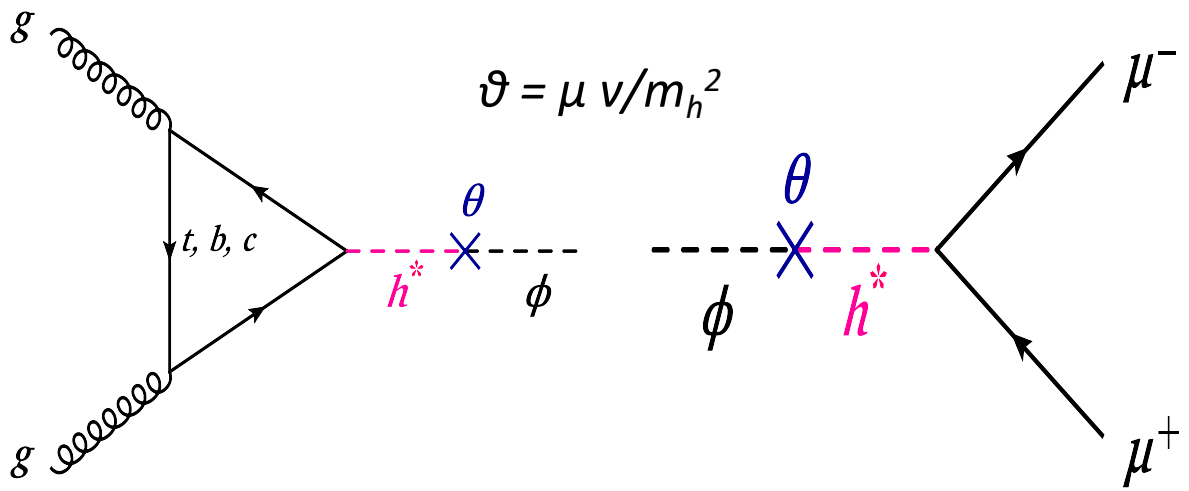
Photon portal: "vector"

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



Higgs portal: "scalar"

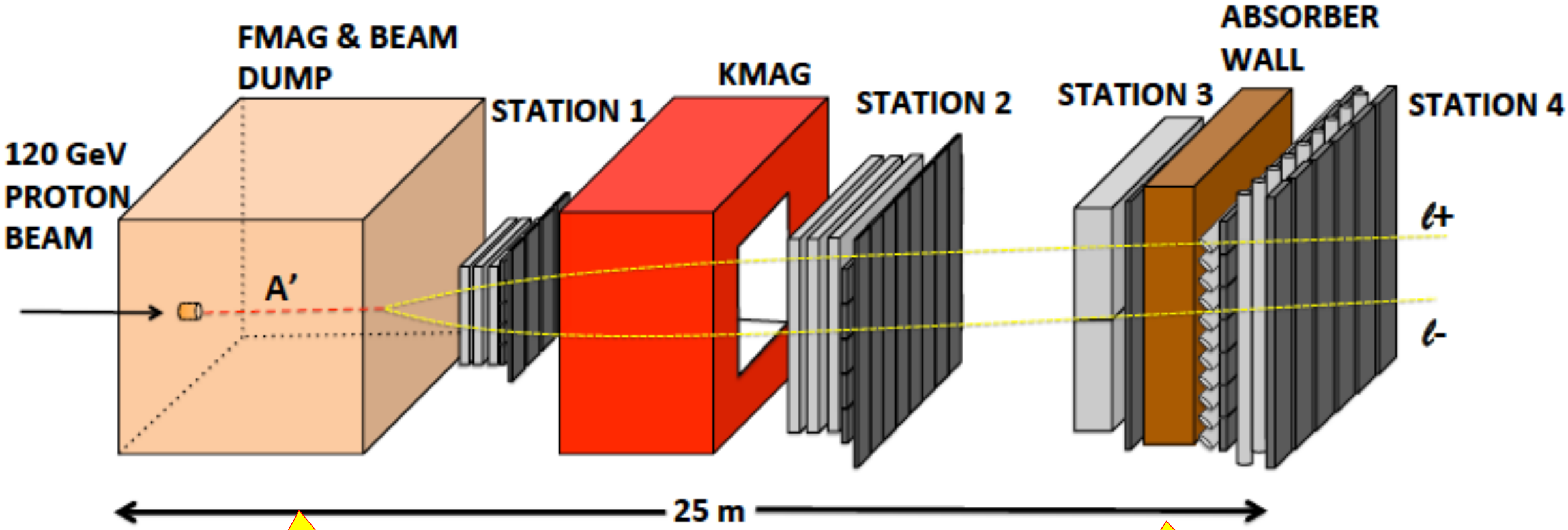
$$\mathcal{L}_{\text{mix}} = \mu\phi|H^\dagger H|$$



Advantage of hadronic collisions

Dark Sector Physics Search at DarkQuest

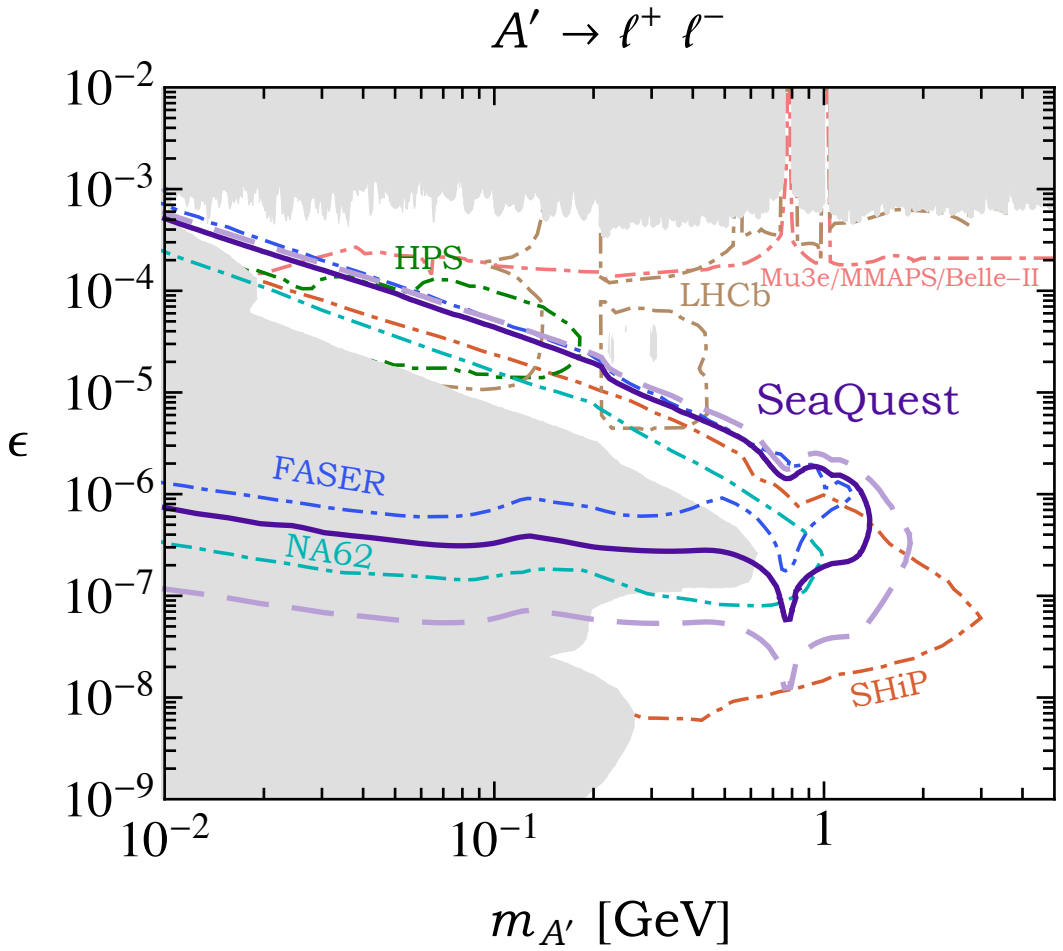
2018 ~ 2021+, proposed long term program after E1039

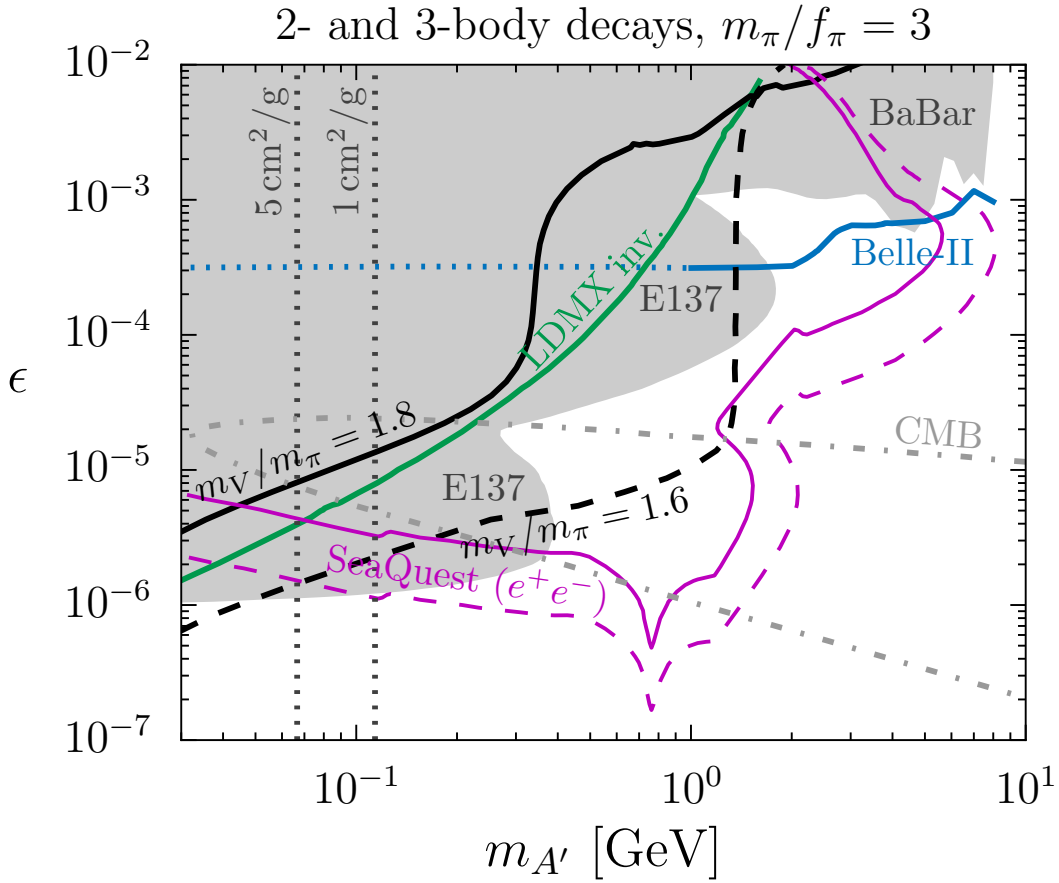


Add tracking detectors close to "target" to improve mass resolution

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

Dark Photon Search at DarkQuest with all Future Projections



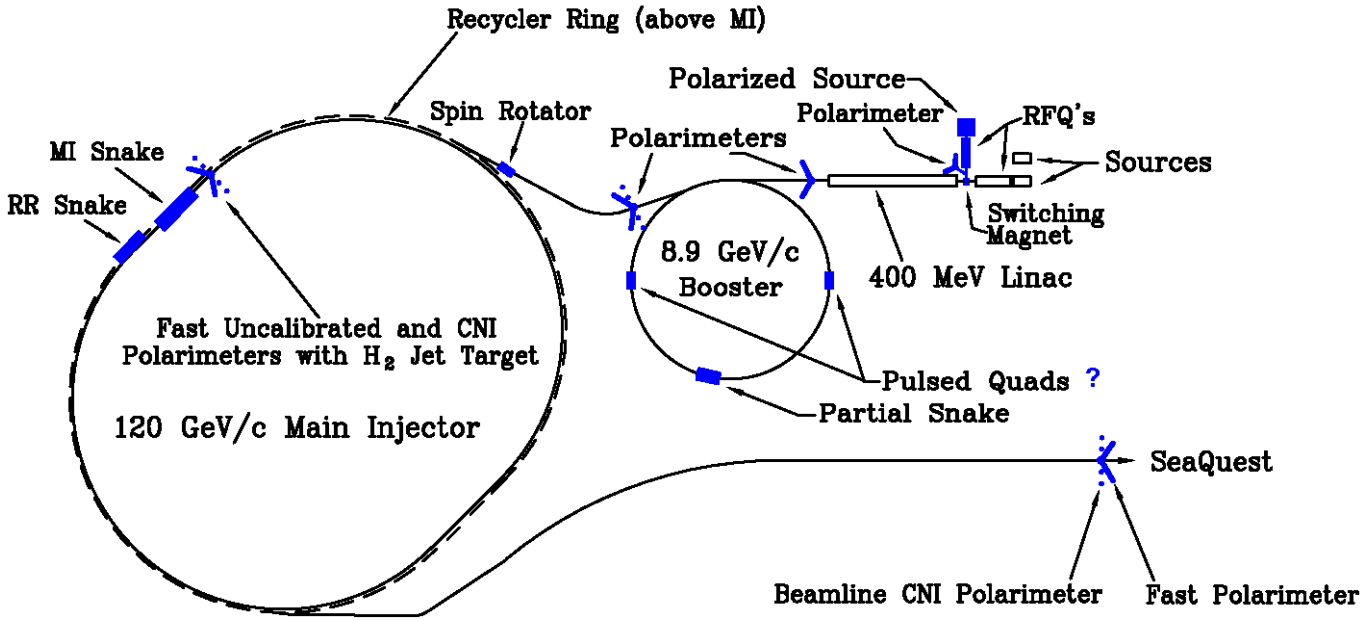


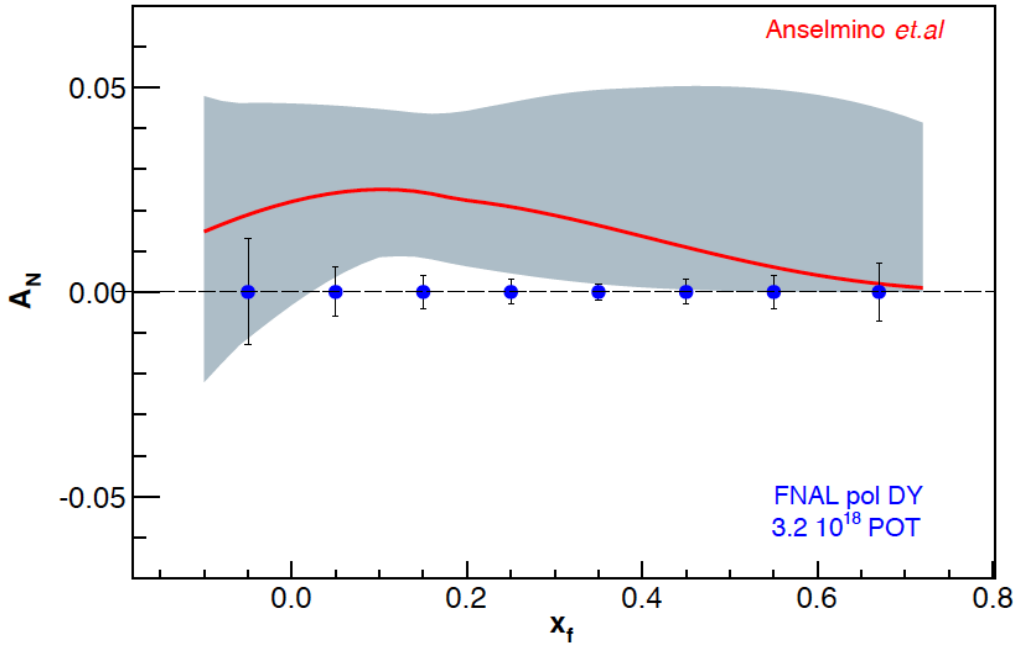
Spin physics Program with Polarized Main Injector – E1027

- 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

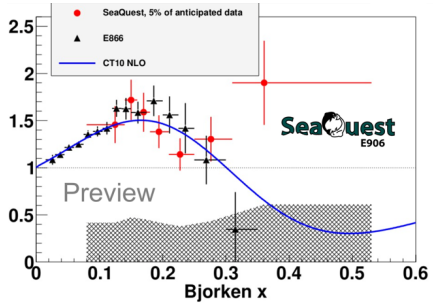
$$A_N \equiv \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \frac{f_{1T}^{\perp,u}(x_B) \cdot \bar{u}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$

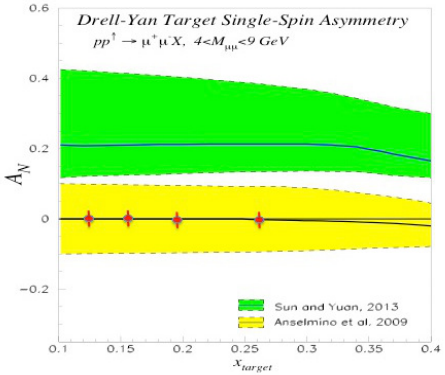


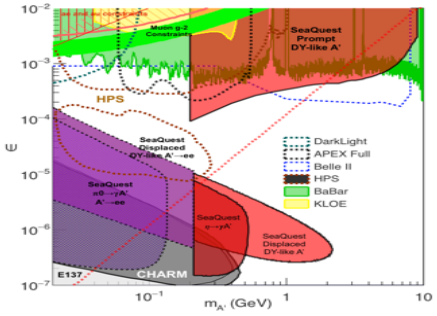


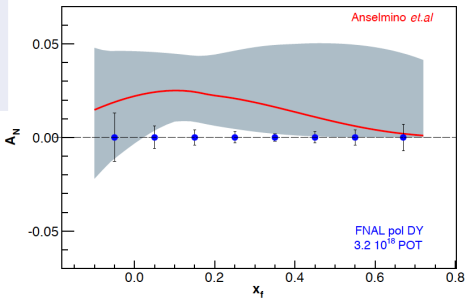
Summary and Outlook

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









SeaQuest/E1039 Collaboration – need update

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

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:

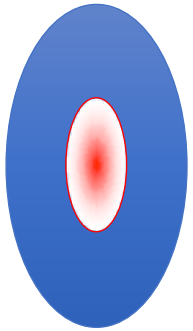
$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$ E1027

- 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

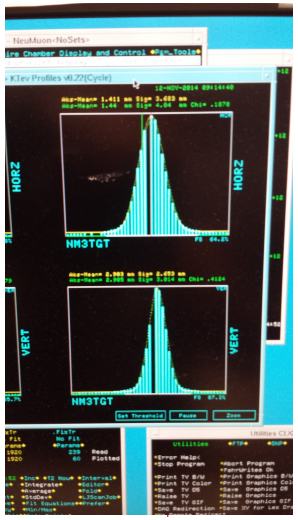


Target cross section: 18 x 28 mm^2

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

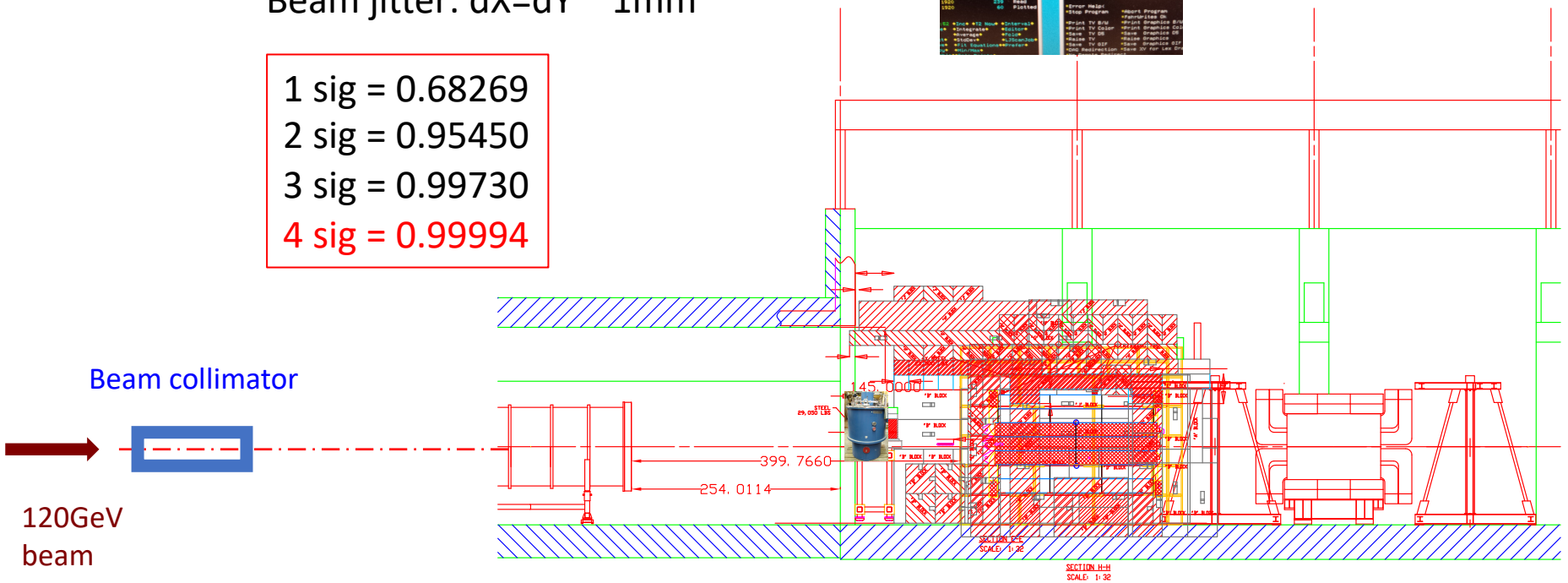
sigX = 18/2/4 = 2.2 mm
sigY = 28/2/4 = 3.5 mm
Beam jitter: dX=dY ~ 1mm

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

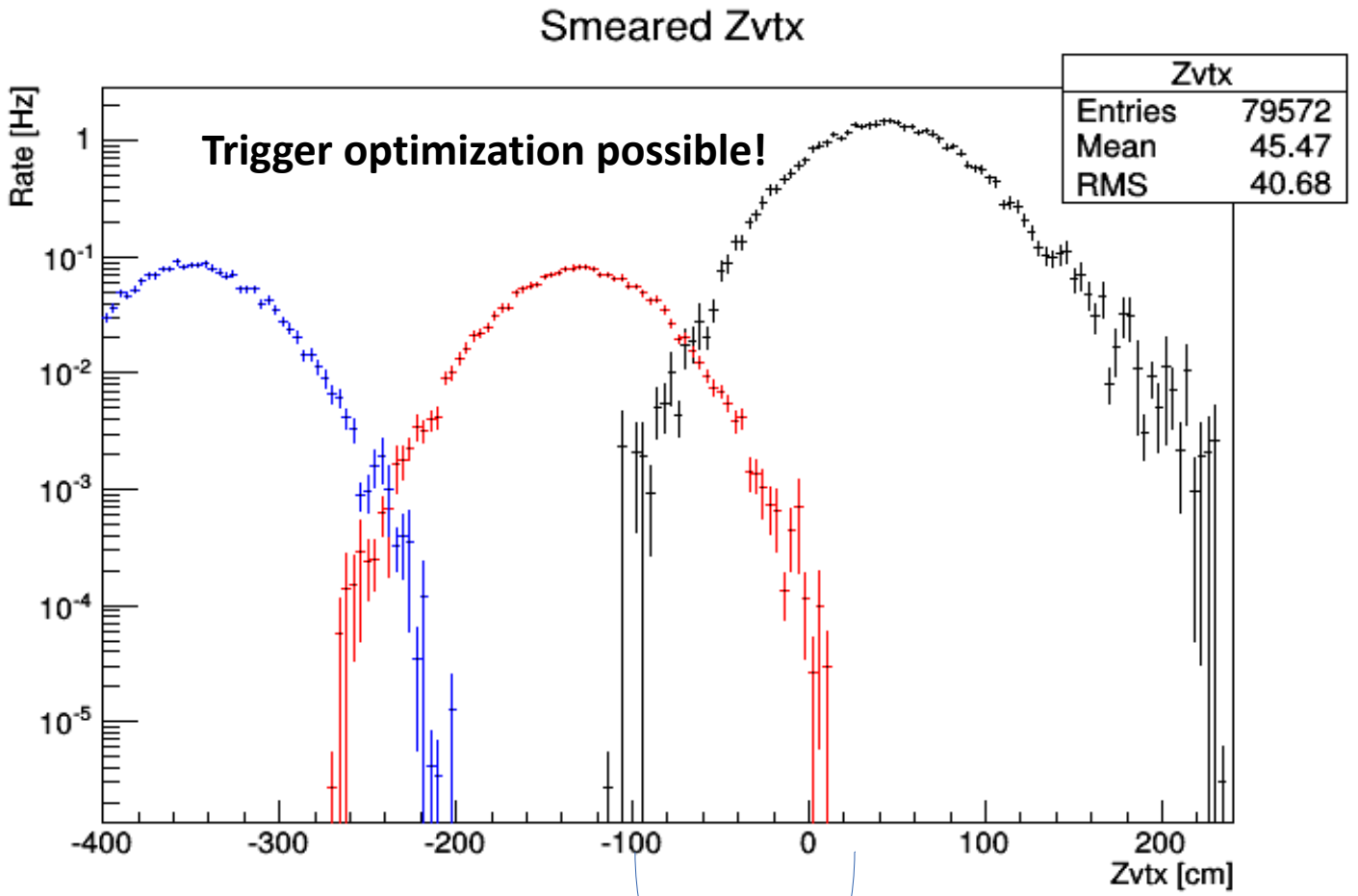


E906 beam profile:
SigX = 4.0mm
SigY = 3.0mm

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

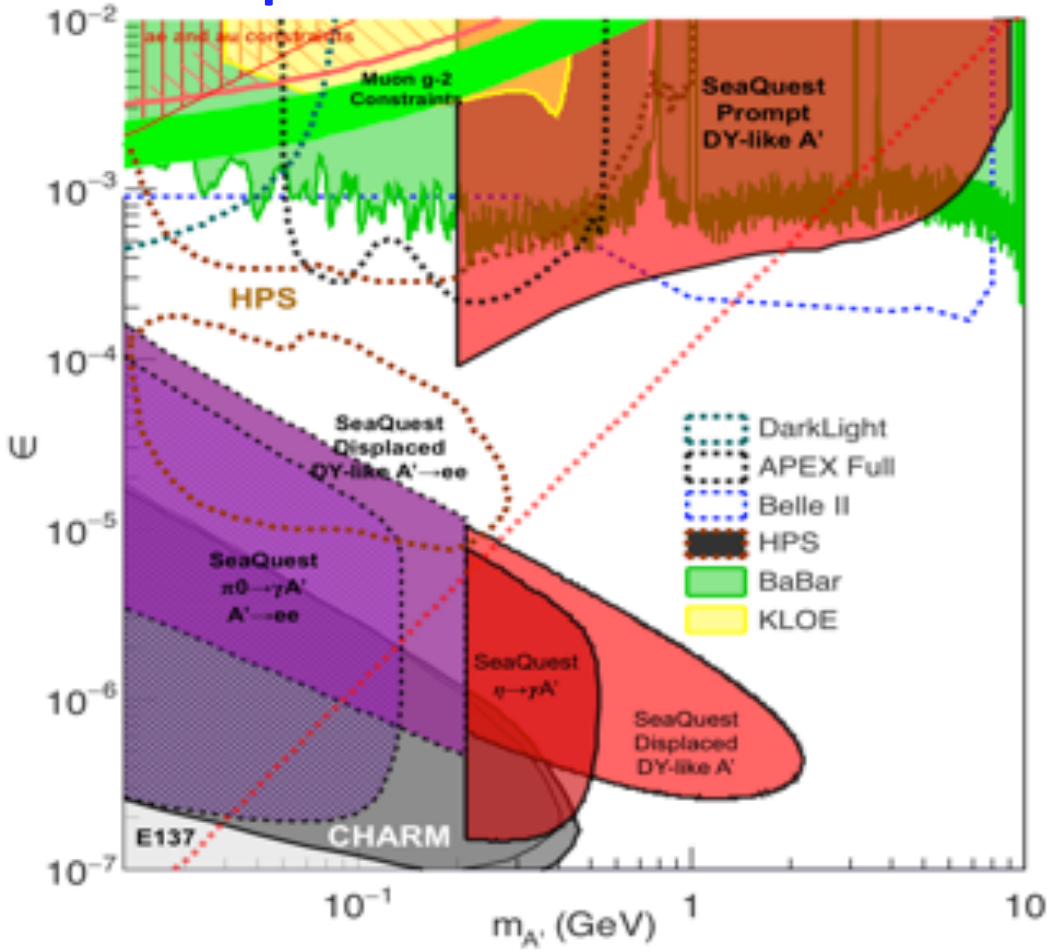


Target and Beam Dump Event Separation
target at upstream: Z=-3.5m



Projected Dark Sector Physics Search Sensitivity

Dark photon search



Dark Higgs search