Fixed-target Drell Yan -- Present & Future

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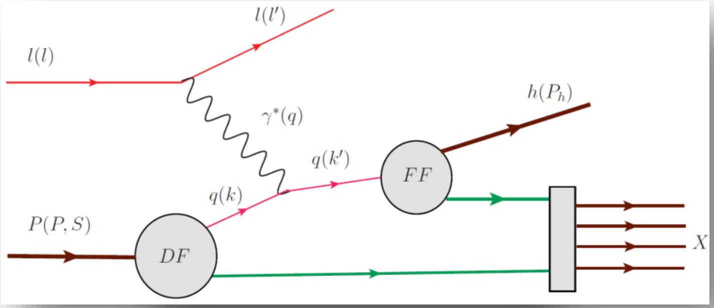
This work is supported by

Complementarity between SIDIS and Drell Yan

- SIDIS and Drell-Yan have similar physics reach:
  - ➡ tools to probe quark and antiquark structure of nucleon
  - ➡ electromagnetic probes

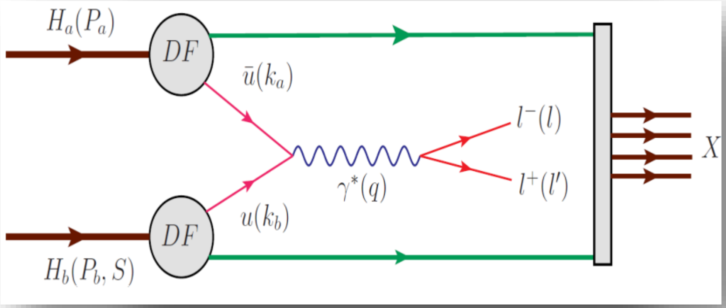
SIDIS (spacelike) virtual photon



Quintessential probe of hadron structure:

- ➡ relatively simple to measure and calculate
- ➡ QCD final state effects
- ➡ fragmentation process
- ➡ **no quark-antiquark selectivity**

Drell-Yan (timelike) virtual photon



credit: A. Kotzinian

Cleanest probe to study hadron structure:

- ➡ no QCD final state effects
- ➡ no fragmentation process
- ➡ production of two TMD parton distribution functions
- ➡ **ability to select sea quark distribution**
- ➡ hadron beam: $\sigma(DY) / \sigma(\text{nuclear}) \approx 10^{-7}$

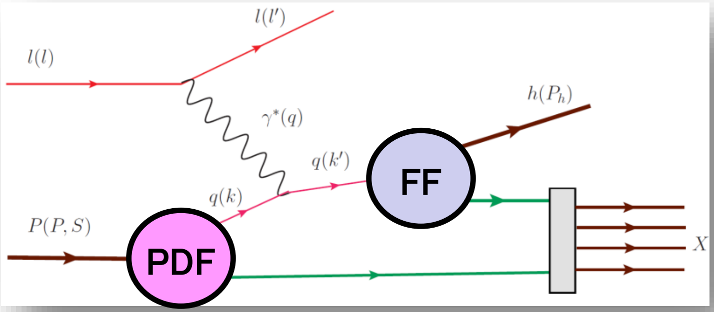
Factorization and Universality (SIDIS - DY)

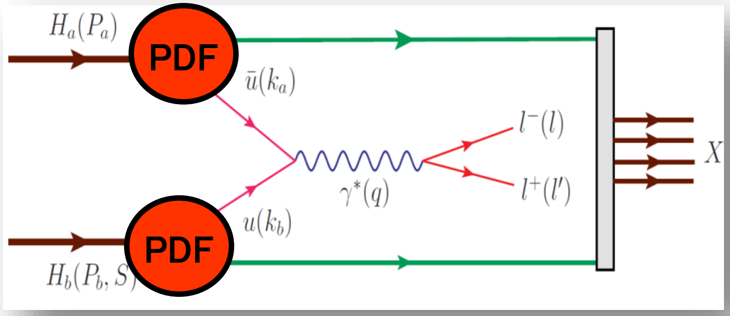
SIDIS

PDF ⊗ FF

DY

PDF ⊗ PDF





credit: A. Kotzinian

Probe Universality

are TMD PDFs in SIDIS identical to TMD PDFs in DY?

Test using unpolarized experiments, transverse SSA and DSA

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

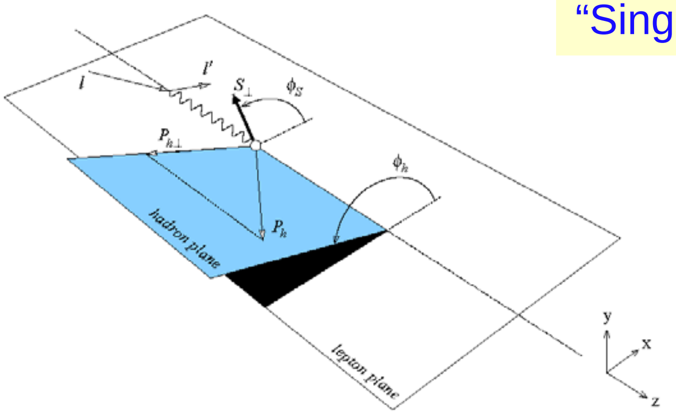
$$+ S_T\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{array}\right]$$

DY

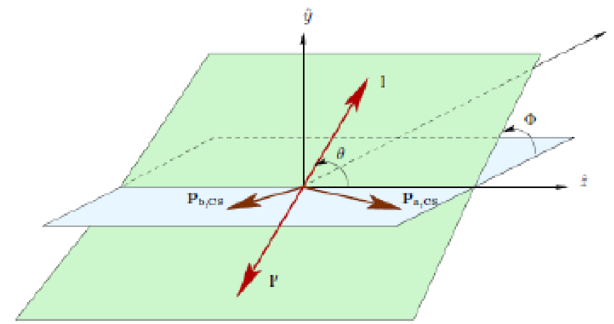
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}\right.$$

$$\left. + S_T\left[\begin{array}{l}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\left(\begin{array}{l}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{array}\right)\end{array}\right]\right\}$$

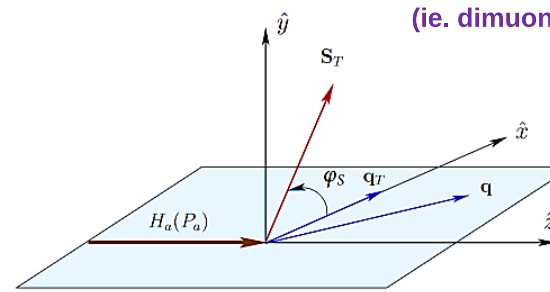
Measure magnitude of azimuthal modulations in cross section:
"Single Spin Asymmetries"



target rest frame



Collins-Soper frame
(ie. dimuon c.m. frame)



target rest frame

credit: M. Chiosso & B. Parsamyan

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Big\{\ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$+\ S_T\begin{bmatrix}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\ \sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\ \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\Big\{\ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}$$

$$+\ S_T\begin{bmatrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\begin{pmatrix}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{pmatrix}\end{bmatrix}\Big\}$$

		PDF ⊗ FF
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q}\otimes H_{1q}^{\perp h}$		BM ⊗ CF
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^{h}$		Sivers ⊗ FF
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q}\otimes H_{1q}^{\perp h}$		Transv ⊗ CF
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$		Pretz ⊗ CF

beam target

PDF ⊗ PDF	
BM ⊗ BM	$A_T^{\cos 2\varphi_{cs}} \propto h_1^{\perp q}\otimes h_1^{\perp q}$
f_1 ⊗ Sivers	$A_T^{\sin\varphi_s} \propto f_1^{q}\otimes f_{1T}^{\perp q}$
BM ⊗ Transv	$A_T^{\sin(2\varphi_{cs}-\varphi_s)} \propto h_1^{\perp q}\otimes h_{1T}^{\perp q}$
BM ⊗ Pretz	$A_T^{\sin(2\varphi_{cs}+\varphi_s)} \propto h_1^{\perp q}\otimes h_1^{q}$

within QCD TMD framework:

$$h_1^{\perp q}\Big|_{SIDIS} = -h_1^{\perp q}\Big|_{DY} \qquad f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{DY}$$

$$h_1^{q}\Big|_{SIDIS} = h_1^{q}\Big|_{DY} \qquad h_{1T}^{\perp q}\Big|_{SIDIS} = h_{1T}^{\perp q}\Big|_{DY}$$

Drell Yan Advantage

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➞ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➞ in DY: at least 2 $F_{(U)T}$ per TMD
    - → same TMDs can be measured in different $F_{(U)T}$
    - → allowing cross checks of TMD extraction & even of underlying formalism

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	PDF ⊗ FF	beam / target: PDF ⊗ PDF	
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$	BM ⊗ CF	BM ⊗ BM	$A_T^{\cos 2\varphi_{cs}} \propto h_1^{\perp q} \otimes h_1^{\perp q}$
$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers ⊗ FF	f_1 ⊗ Sivers	$A_T^{\sin \varphi_s} \propto f_1^{q} \otimes f_{1T}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transv ⊗ CF	BM ⊗ Transv	$A_T^{\sin(2\varphi_{cs} - \varphi_s)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$
$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretz ⊗ CF	BM ⊗ Pretz	$A_T^{\sin(2\varphi_{cs} + \varphi_s)} \propto h_1^{\perp q} \otimes h_1^{q}$

$$A_T^{\sin \varphi_s} = \frac{F_T^1}{F_U^1}$$

Complementarity between SIDIS and Drell Yan

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➡ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➡ in DY: at least 2 $F_{(U)T}$ per TMD
    - → same TMDs can be measured in different $F_{(U)T}$
    - → allowing cross checks of TMD extraction & even of underlying formalism TMD

- Systematic study of quark TMDs in Drell Yan
  - ➡ requires double-polarization
  - ➡ only then can all 8 leading twist TMD be measured

- Double-Spin Drell Yan
  - ➡ Measure DY with both Beam and Target polarized
    - ⟶ broad spin physics program possible
    - ⟶ truly complementary to spin physics programs at Jlab and RHIC and EIC

(Un)Polarized Drell Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity (cm^{-2} s^{-1})		P_b or P_t (f)	rFOM[#]	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 – 0.3$	2×10^{33}		$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015-2016, 2018
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s} = 4.4\text{-}6.2$	$x_b = 0.2 – 0.97$ $x_t = 0.06 – 0.6$	2×10^{31}		---	---	>2020? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}		$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021?
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}		---	---	2012 – 2017
Pol tgt DY[‡] (FNAL: E-1039)	$p + p^\uparrow$ $p + d^\uparrow$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	3.0×10^{35} 3.5×10^{35}		$P_t = 85\%$ f = 0.176	0.15	2019-2021+
Pol beam DY[§] (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}		$P_b = 60\%$	1	>2021?

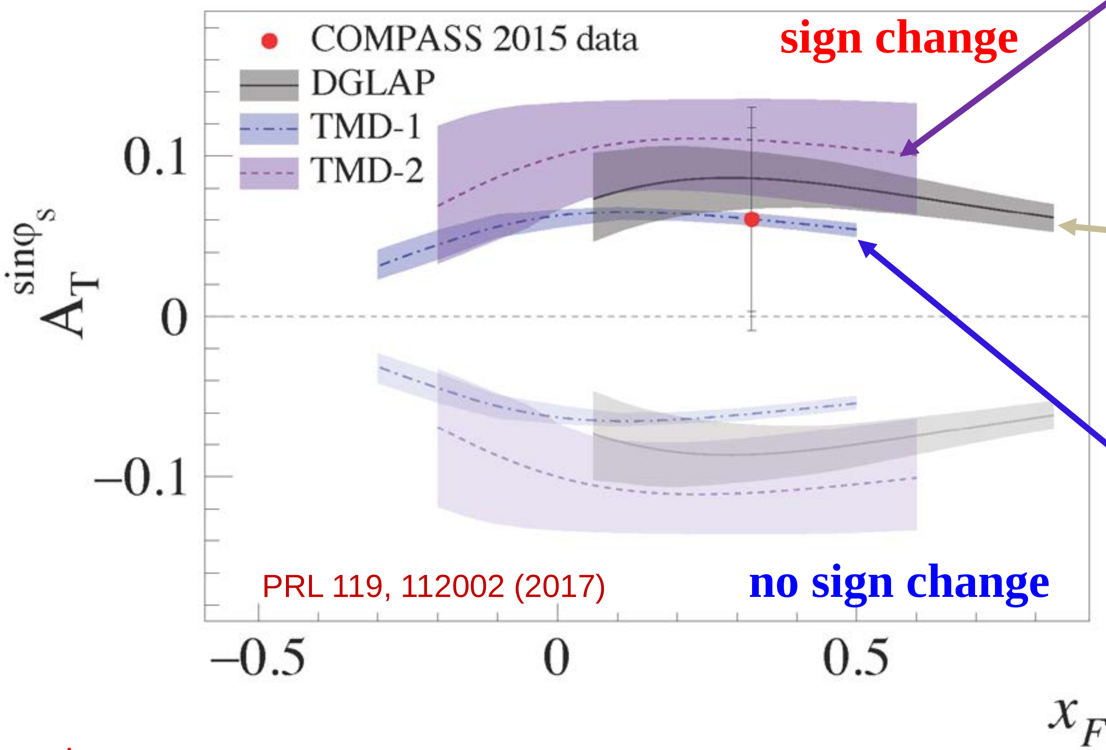
[‡] *8 cm NH_3 target* / [§] *L= 1×10^{36} cm^{-2} s^{-1} (LH_2 tgt limited)* / *L= 2×10^{35} cm^{-2} s^{-1} (10% of MI beam limited)*

**not constrained by SIDIS data* / [#] rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan) 8/2019

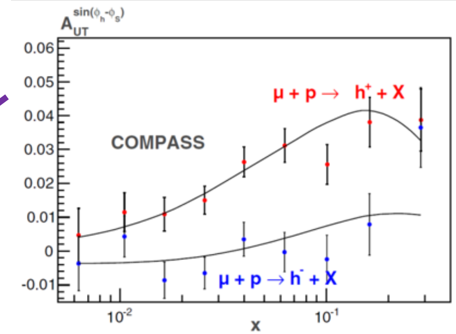
COMPASS 2015 Results

- COMPASS: 190 GeV π^- beam on transverse polarized H target (NH_3)
  - ➡ 2015 data (4 months)
  - ➡ Transverse target polarization ~80%
  - ➡ **consistent w/ sign change!**

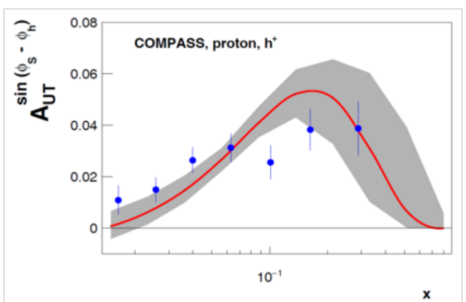


$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

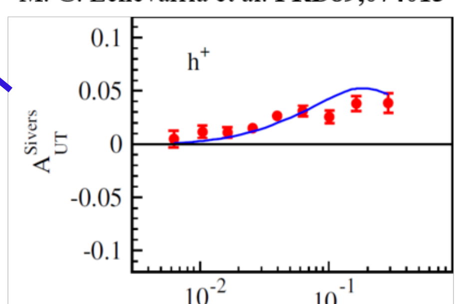
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



DGLAP (2016)
M. Anselmino et al. **JHEP 1704, 046**



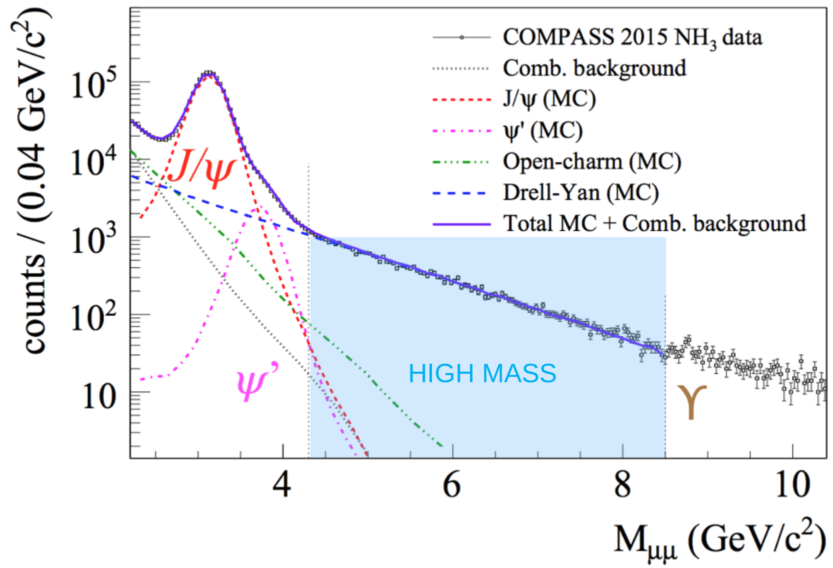
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**

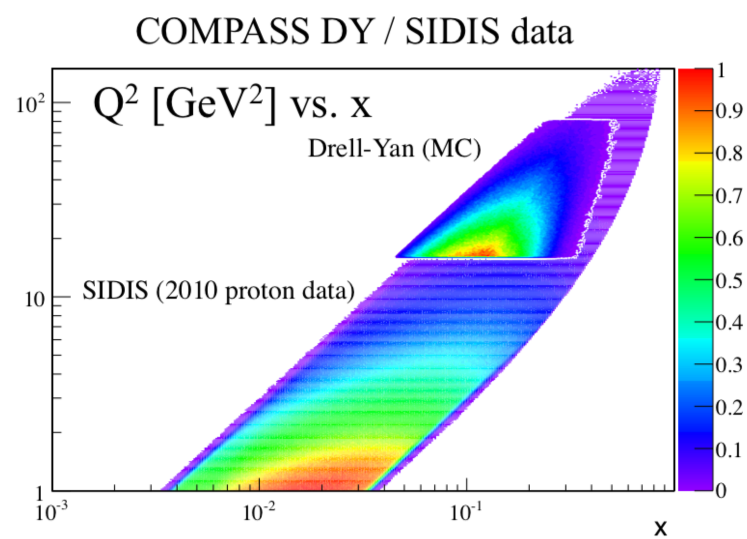


Ref: W.C. Chang (Academia Sinica) & J-C Peng (UIUC)

Kinematic Coverage

- Drell-Yan analysis: mass range 4.3 - 8.5 GeV/c^2 ("high mass range")
  - ➞ only 4% background in this mass range
  - ➞ DY events [$M(\mu^+\mu^-) > 4$ GeV/c^2): ~35,000
- Phase space for Drell-Yan and SIDIS partially overlap in the x-Q^2 plane
  - ➞ average Q^2 in Drell-Yan is about 2x that in SIDIS
  - ➞ allows to minimize the impact of uncertainties from TMD scale evolution
  - ➞ overlap in kinematic regions of COMPASS Drell-Yan and SIDIS data allows for direct comparisons of TMD amplitudes
- COMPASS probes proton's valence quarks in Drell-Yan and SIDIS

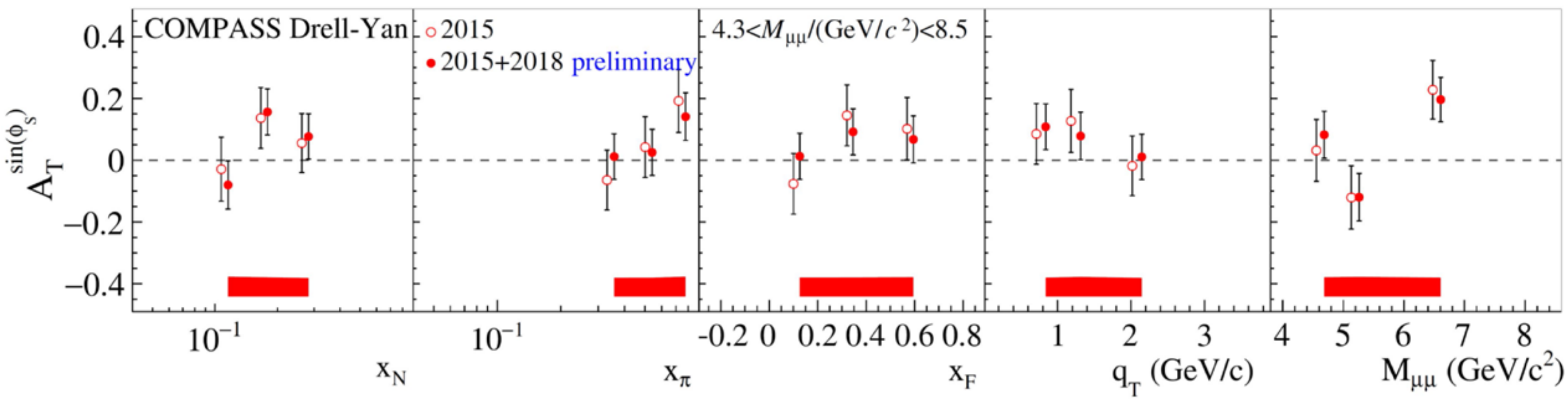




Ref: M. Meyer-Condea Sinica) & R. Heitz (UIUC)

Updated COMPASS Result

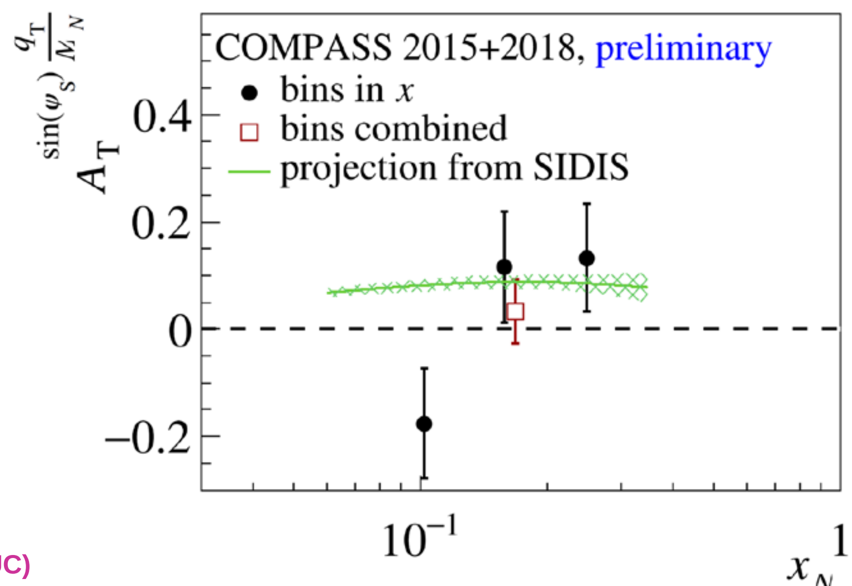
- **COMPASS 2015 (PRL 119 (2017) + 2018 (~50%)**
  - ➡ (2015 = 4 months; 2018 = 5 months of data taking)



- **q_T/M weighted asymmetries**
  - ➡ access to direct product of TMD PDFs
  - ➡ no assumption on k_T dependence of TMDs

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q(1)}$$



Ref: M. Meyer-Conde (UIUC)

COMPASS Plans (DY)

- **Sivers asymmetry:**
  - ➞ Sivers asymmetry measured both in polarized Drell-Yan and SIDIS processes with the same apparatus
  - ➞ no more sign-change data
- **Unpolarized DY:**
  - ➞ valence quark distributions for pion
  - ➞ Boer-Mulders TMD extraction
  - ➞ nuclear dependence (EMC effect, Energy loss and Cronin effect)
  - ➞ detailed study of the fundamental Lam-Tung relation violation
- **COMPASS++ / AMBER (DY program)** (LOI → Proposal: 2021+)
  - ➞ main objectives: improve significantly our knowledge of pion and kaon PDFs (2024)
  - ➞ plan to run with radio separated kaon/anti-p beam for DY and spectroscopy (>2025)
    - ✓ nucleon spin structure with anti-p beam on transversely polarized target
    - ✓ flavor separation of TMD SSAs
    - ✓ gluon TMDs in kaon
    - ✓ direct measurement of the lifetime of neutral pion

Ref: W.C. Chang (Academia Sinica) & O. Denisov (Torino)

Sivers Program at STAR

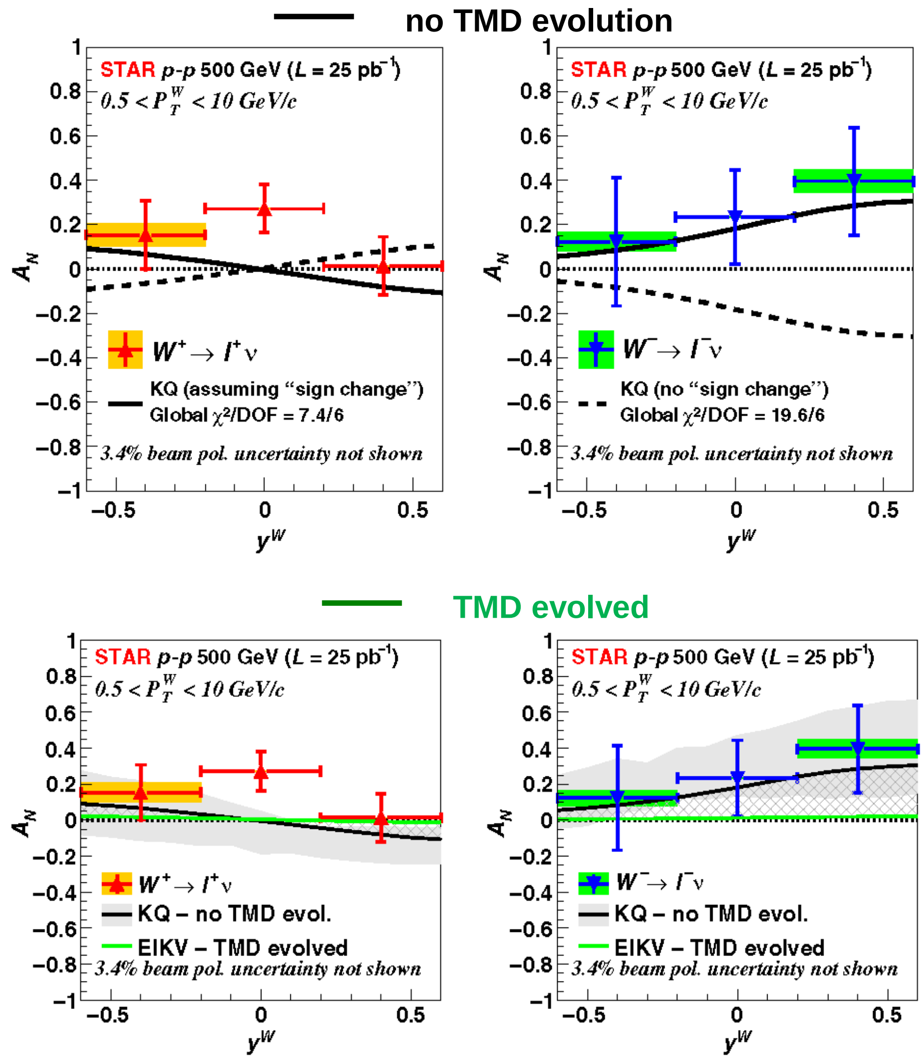
- **RHIC p+p (500 GeV):** $W^{+/-}$ TSSA

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

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

- **Sivers asymmetry:**
  - ➞ quark flavor identified
  - ➞ high Q^2
  - ➞ statistically limited: O(10%)
  - ➞ data favor sign-change

    if TMD **evolution** effects **small**
  - ➞ more data from 2017 (400 pb^{-1}) soon



PRL **116** (2016) 132301

Recent, Current and Future DY Program at FNAL

Unpolarized Beam and Target w/ SeaQuest detector

- **E-906/SeaQuest**: 120 GeV p from Main Injector on LH_2, LD_2, C, Fe, W targets
  → **high-x Drell Yan**
- Science run: March 2014 - July 2017
  ➞ dbar/ubar asymmetry, nuclear dependence, quark energy loss, Tam-Tung relation,…

Unpolarized Beam and polarized Target (w/ upgraded SeaQuest detector)

- **E-1039/SpinQuest**: SeaQuest w/ pol NH_3/ND_3 targets: 2019-2021
  ➞ probe sea quark distributions

Polarized Beam and polarized Target

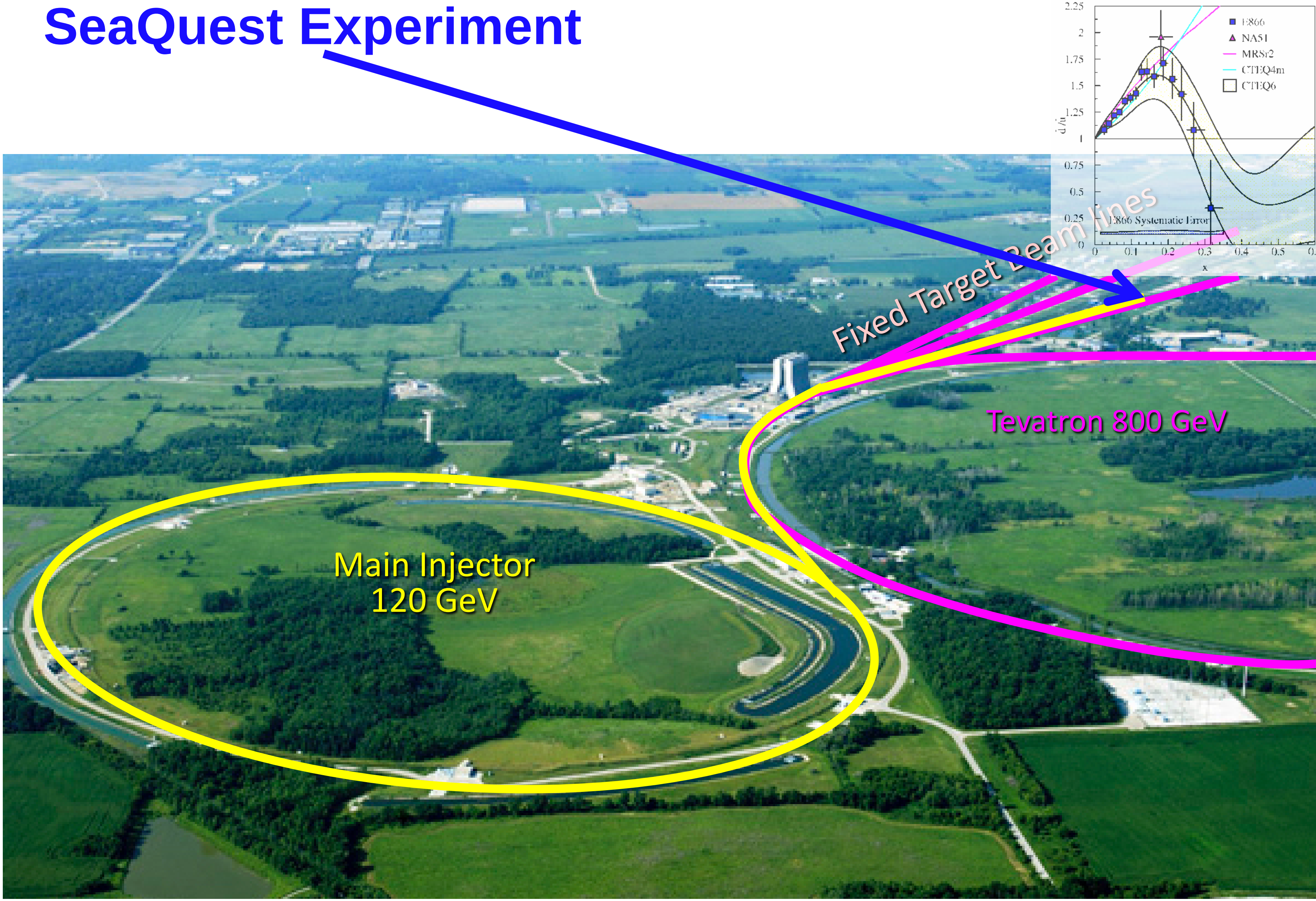
→ development of **high-luminosity** facility for **polarized Drell Yan**

- **E-1027**: pol p beam on (un)pol tgt (2021+?)
  ➞ **Sivers sign change** (valence quark)
  ➞ TMD physics program complementary to future EIC program

Other opportunities

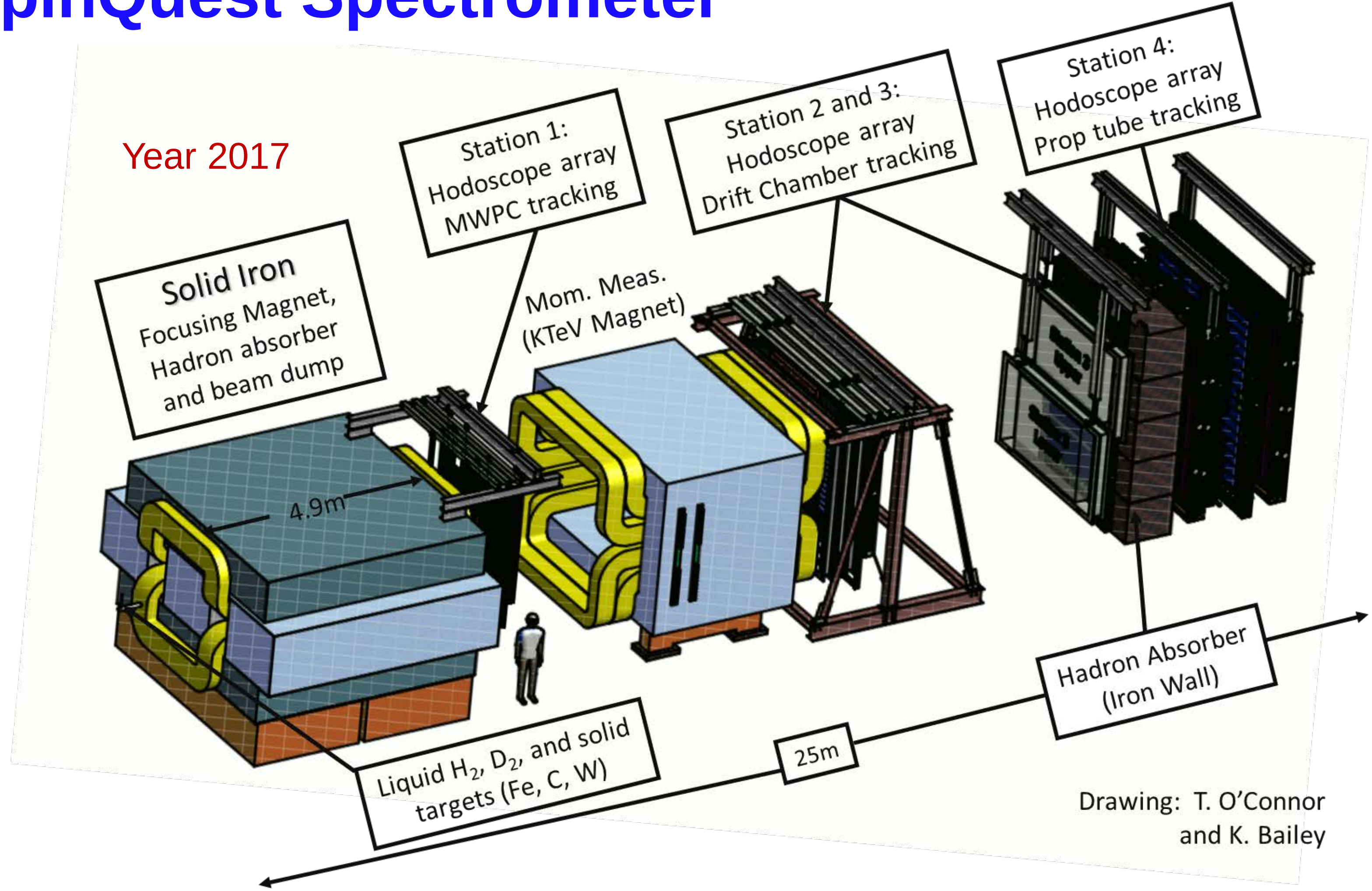
- **E-1067/DarkQuest**
  ➞ parasitic dark photon search (2016-2021+)
  ➞ dedicated run? (2021+?)

SeaQuest Experiment



10% of available beam to SeaQuest / 90% to neutrino program

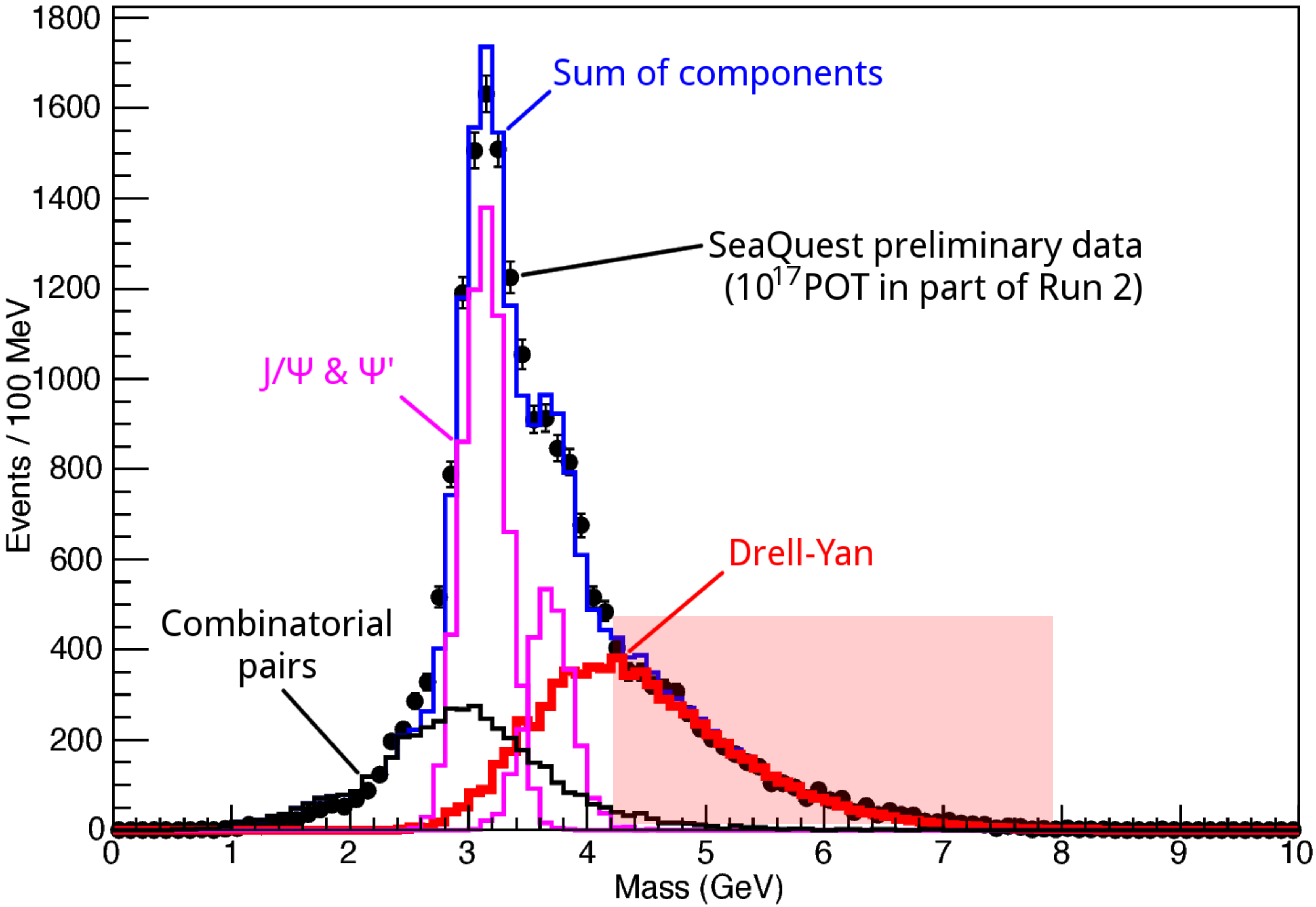
SpinQuest Spectrometer



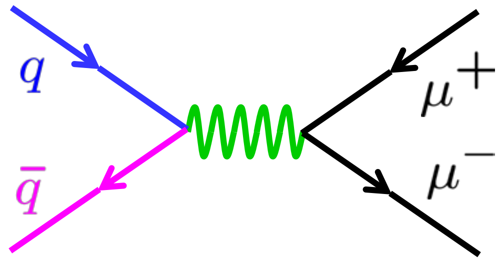
120 GeV protons from the Main Injector

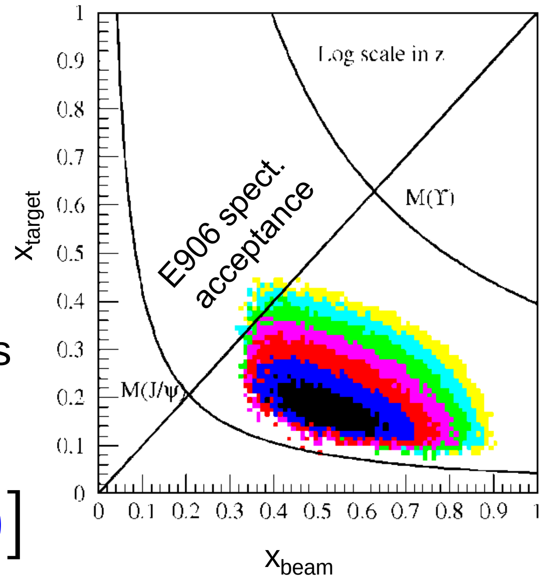
- 4.3s beam spill every 60 sec
- 19ns RF, ~10Ks p/RF bucket
- 5×10^{12} p/spill
- Total integrated POT for E1039 (2-year): 1.4×10^{18} POT

Dimuon Mass from SeaQuest



Fixed Target DY at SeaQuest: A Sea Quark Laboratory





- Cross section: convolution of beam and target parton distributions

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

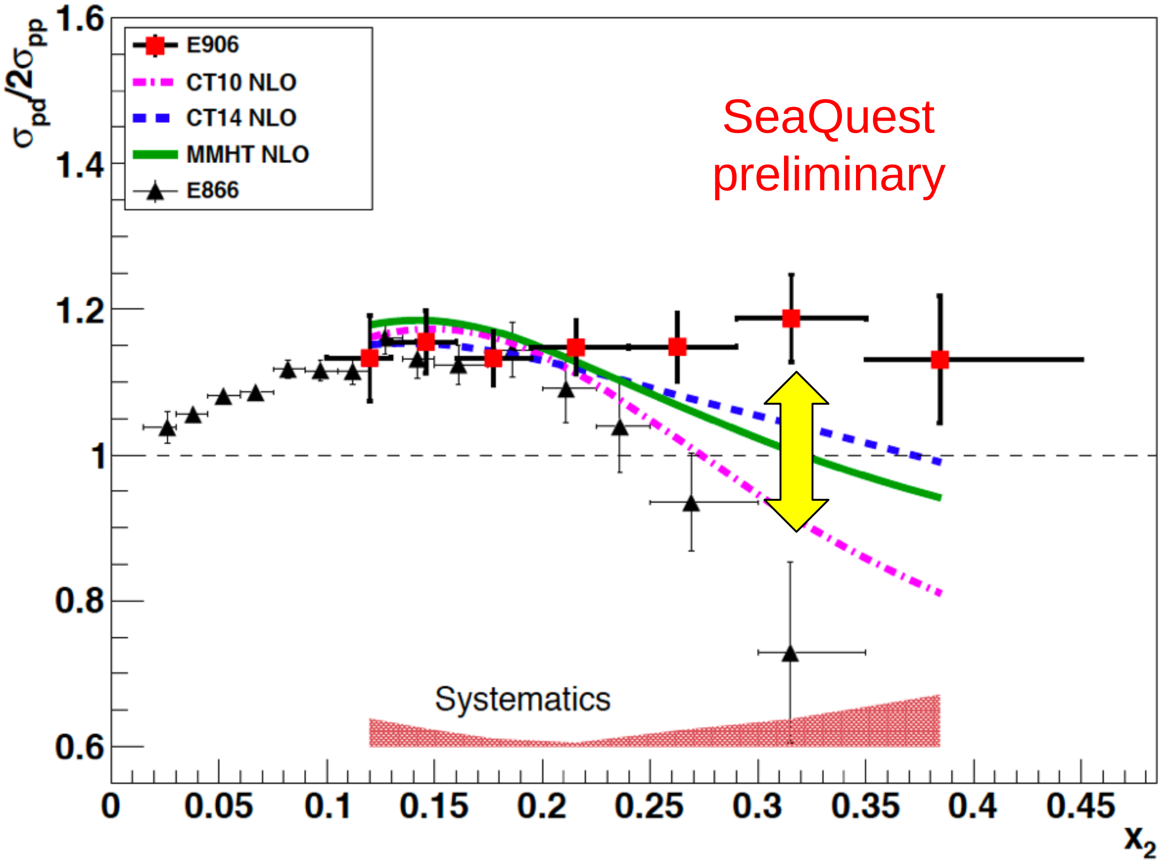
beam: valence quarks at high x

target: sea quarks at low/intermediate x

$$\frac{\sigma^{\mathrm{pd}}}{2\sigma^{\mathrm{pp}}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

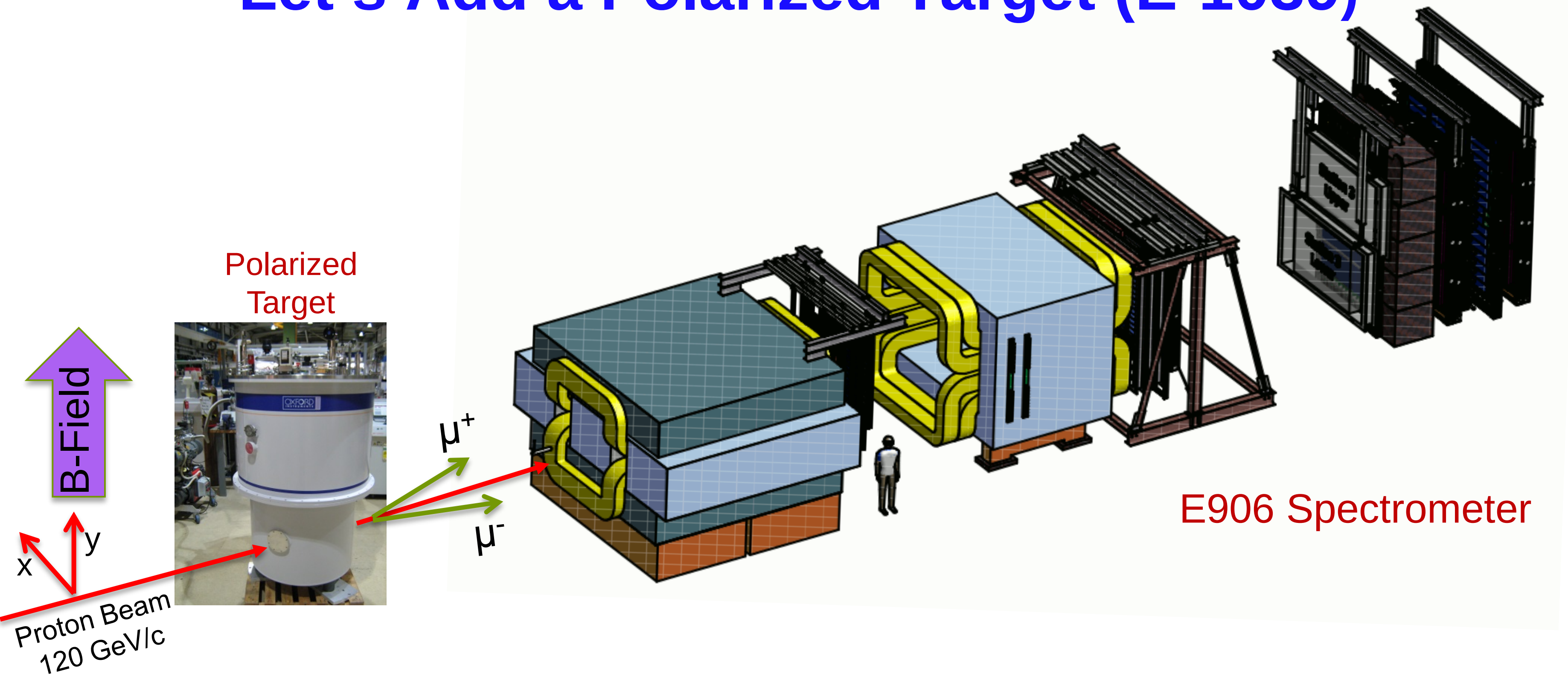
Fixed target kinematics favors sea-quarks from target – **a sea quark laboratory!**

Flavor Asymmetry of SeaQuarks



- E866 data is for $Q^2 = 54\ GeV^2$ while SeaQuest data has $Q^2 \approx 29\ GeV^2$
  - difference should be insignificant
- is there disagreement at high x?
- dbar / ubar coming soon!

Let's Add a Polarized Target (E-1039)



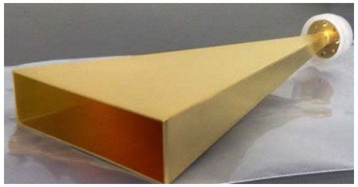
- replace unpolarized w/ polarized target
  → LANL and UVA effort
- move polarized target ~3m upstream
  → improves target-dump separation
  → moves acceptance to lower x_2

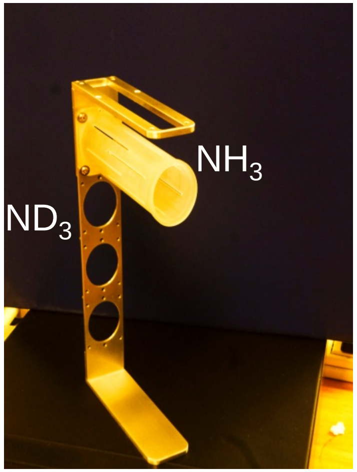
L_{int} = **1.82 *10^{42}/cm^2 NH_3 / 2.11 *10^{42}/cm^2 ND_3** for 2 years

Ref: Andi Klein (LANL)

Polarized Target Developed for DY Sivers

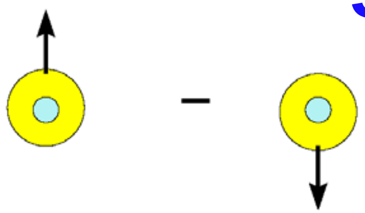
- field: 5T @ 1K
- targets: NH_3 and ND_3
- elliptical: 1.9 cm x 2.1 cm (x,y), l:7.9 cm (z)
- 3 active cells, 1 empty
- helium consumption 100 l/day





Ref: Andi Klein (LANL)

Sivers Function and Spin Crisis

$f_{1T}^{\perp} =$ 

cannot exist w/o quark **OAM**

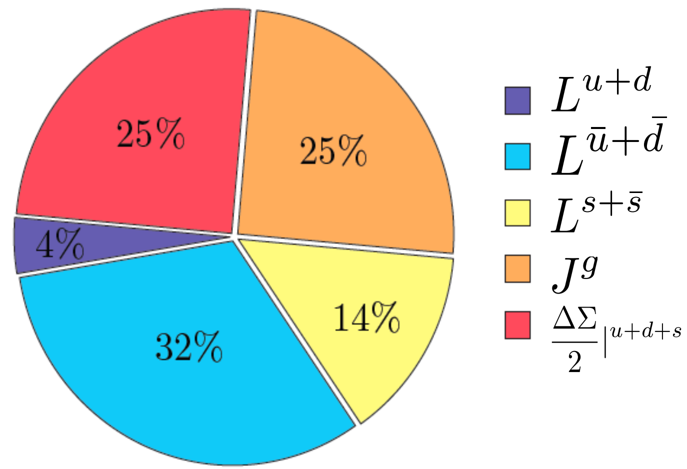
- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- connection b/w Sivers function and OAM is yet model-dependent

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$\frac{1}{2}\Delta\Sigma \approx 25\%;\quad \Delta G \approx 20\%$

$L \approx$ unmeasured

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

$2\,L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\,J_g \approx 25\%$

K.-F. Liu *et al* arXiv:1203.6388

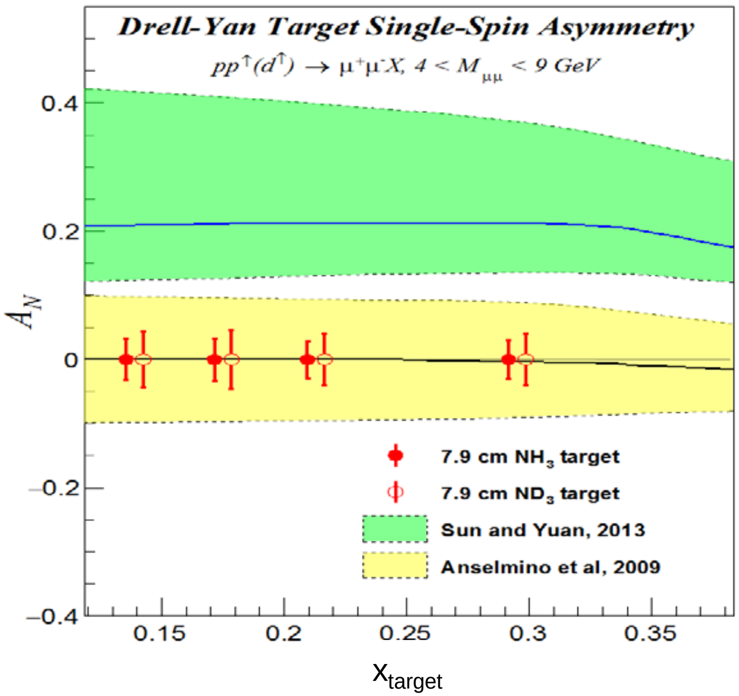
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD: Transverse Momentum Distribution

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

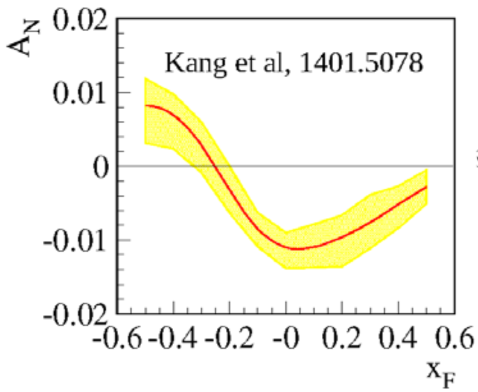
Projected DY Transverse Single Spin Asymmetry

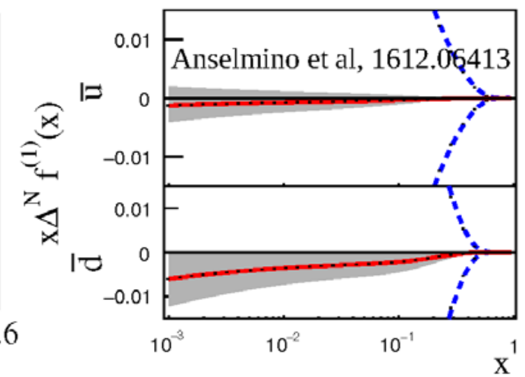
E1039 proposal



- existing SIDIS data poorly constrain sea-quark Sivers function (Anselmino)
- significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)

More recent calculations





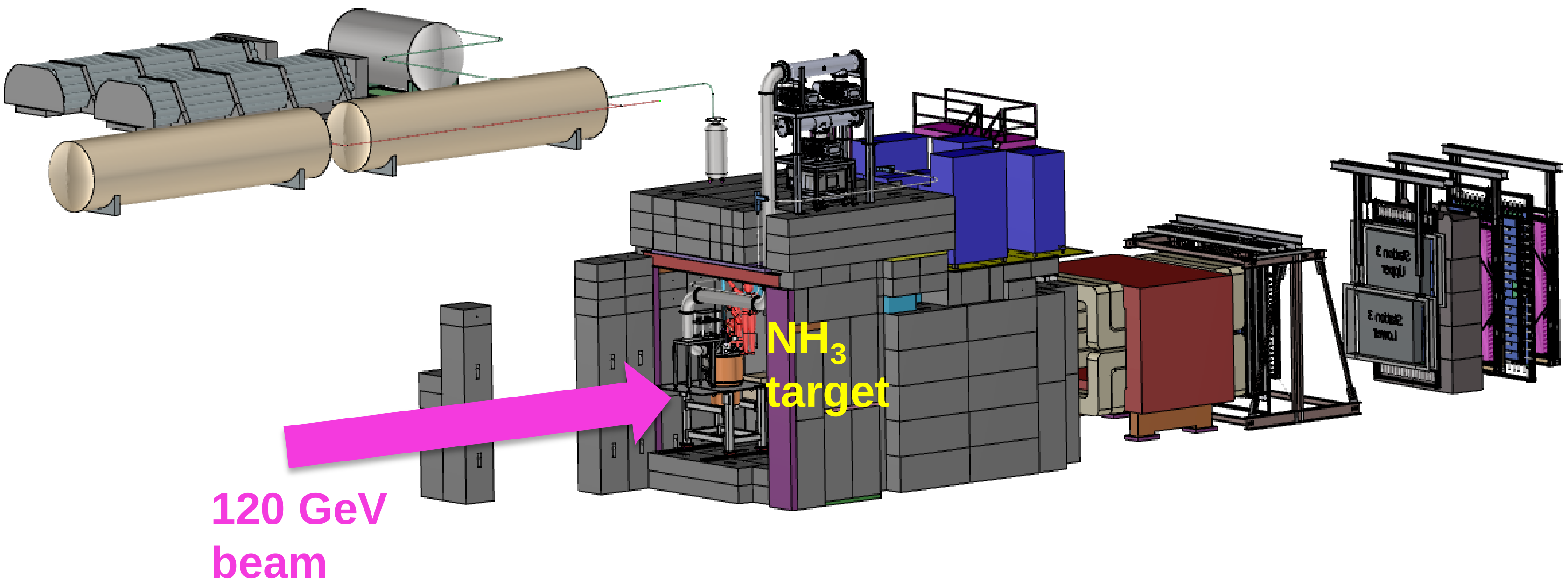
- **determine sign and value of sea quark Sivers asymmetry**
- **measure sea quark Sivers flavor dependence (H & D targets)**

If $A_N \neq 0$, **major discovery**:
“Smoking Gun” evidence for $L_{\bar{u},\bar{d}} \neq 0$

E1039 Status & Plans

- DOE approval, March 2018
- Fermilab stage-2 approval, May 2018
- E906 decommissioned, June 2018
- Polarized target to be installed by fall of 2019

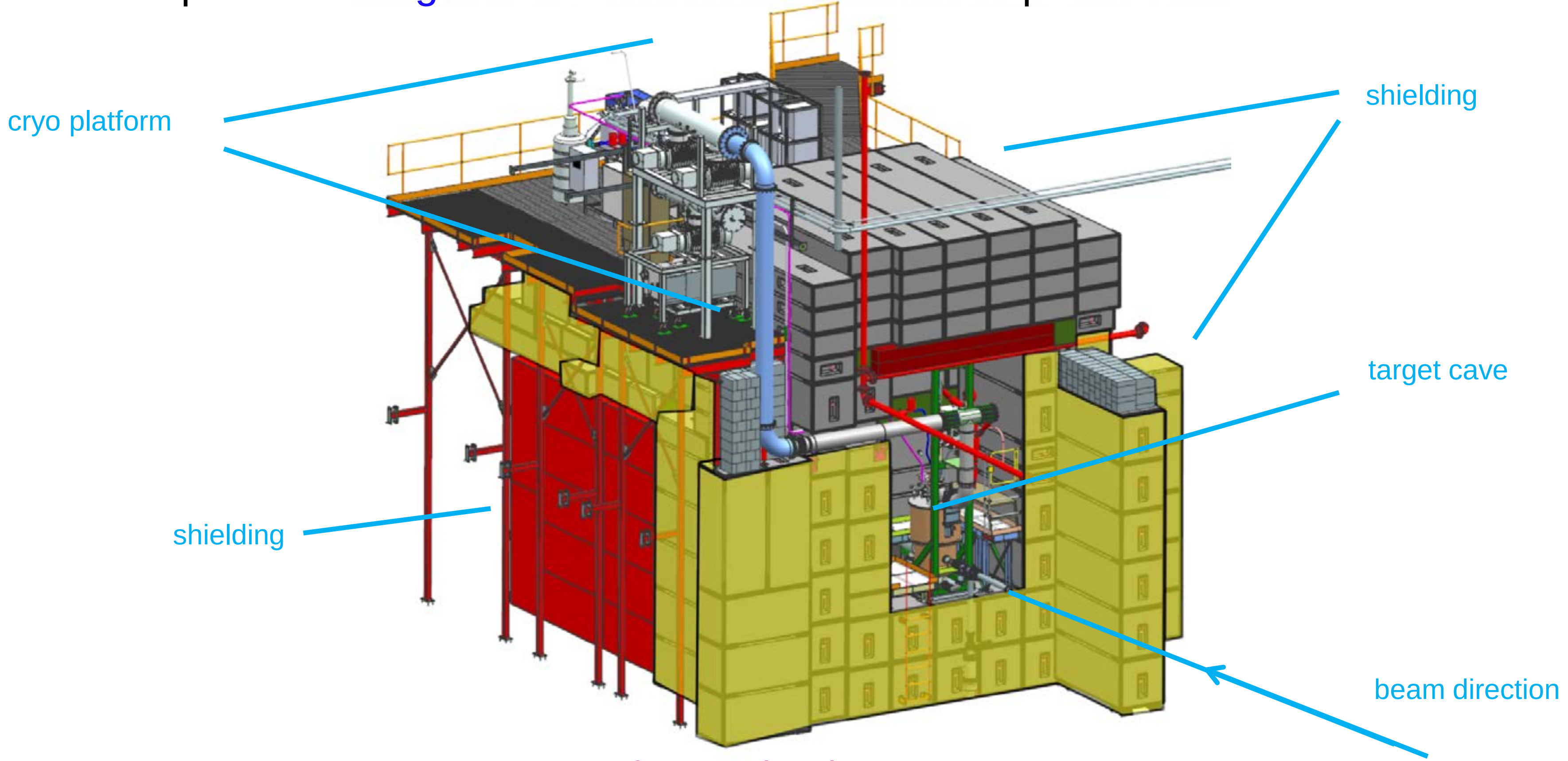
- E1039 commissioning starts in late 2019
- Run for 2+ years, 2019-2021+



Ref: M. Liu (LANL)

E1039 Milestones - Fermilab

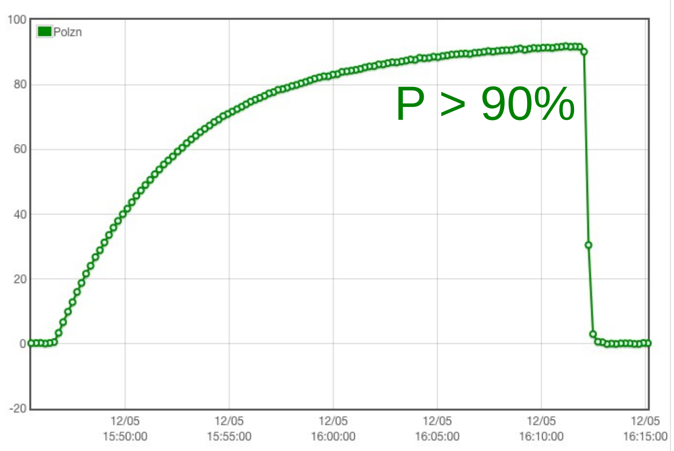
- major modifications in experimental hall (special thanks to Fermilab)
  - ➞ beamline: new collimator
  - ➞ new radiation shielding design
  - ➞ new cryo platform for polarized target infrastructure
  - ➞ polarized target cave: new location 300 cm upstream of FMAG



Ref: M. Yurov (LANL)

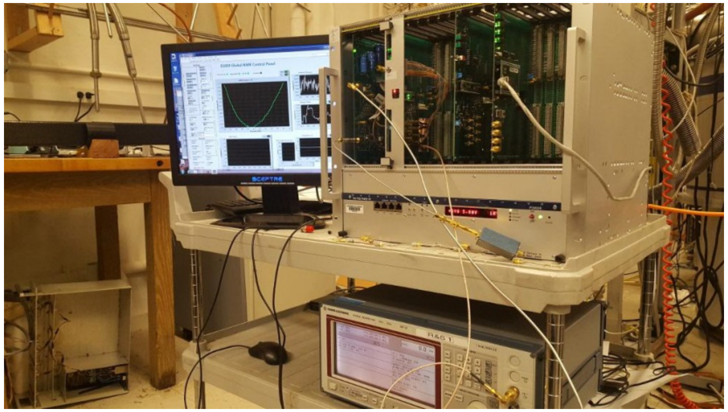
E1039 Milestones - Collaboration

- new polarized target construction: LANL and UVA effort
  - ➡ rebuild magnet; change field direction
  - ➡ modify 1K refrigerator and insert
  - ➡ new pump set; high cooling capacity
  - ➡ new high power microwave source
  - ➡ polarization of NH_3 > 90%



- new NMR system
  - ➡ replacing Liverpool Q-meter
  - ➡ cold NMR

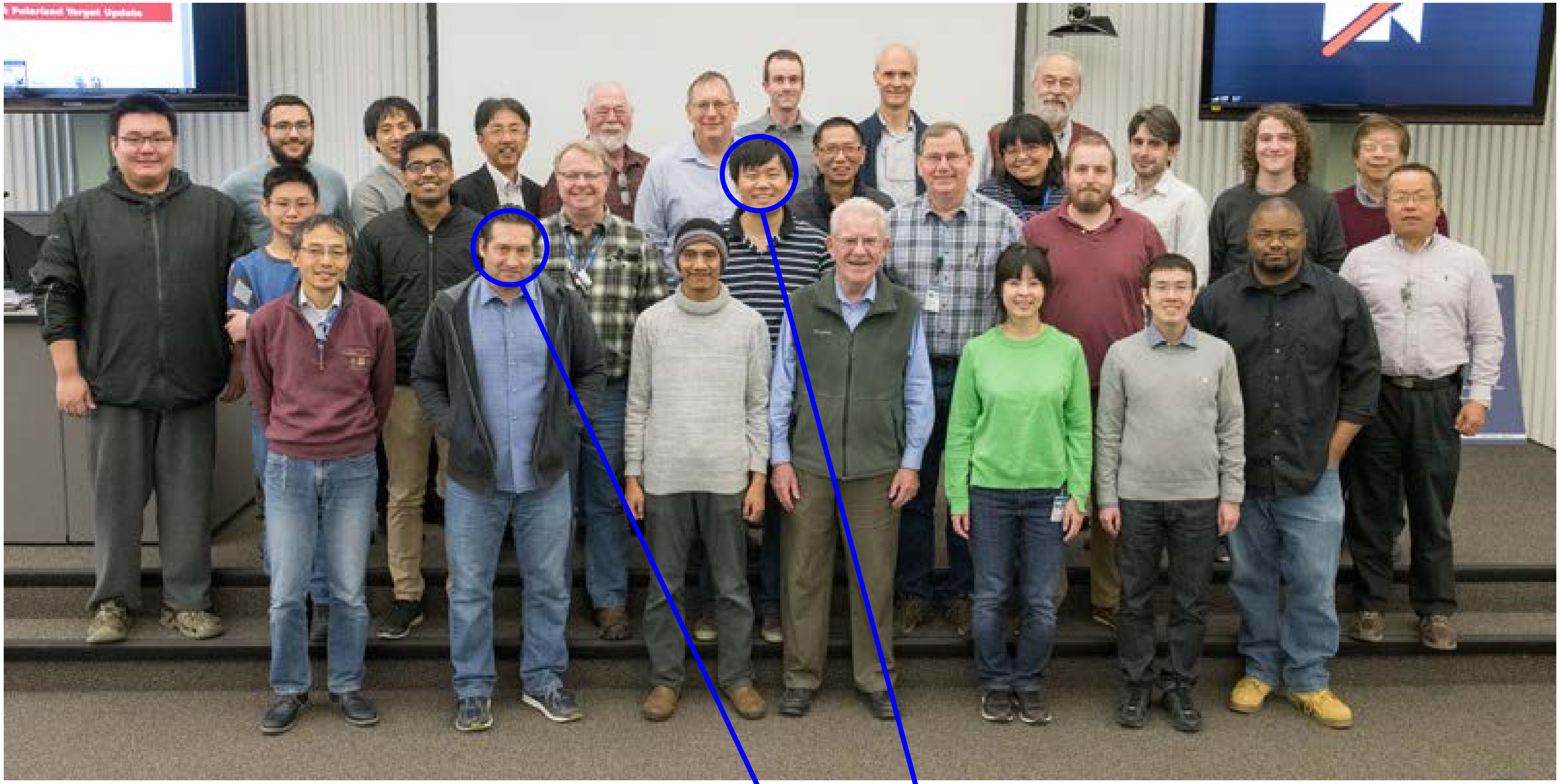
- He liquefier for liquid helium recirculation
  - ➡ constructed by "Quantum technologies"
  - ➡ ~200 L/day capacity



new LANL NMR setup

Ref: M. Yurov (LANL)

E1039 Collaboration



Contact Spokespersons:

Kun Liu (liuk@fnal.gov) - LANL

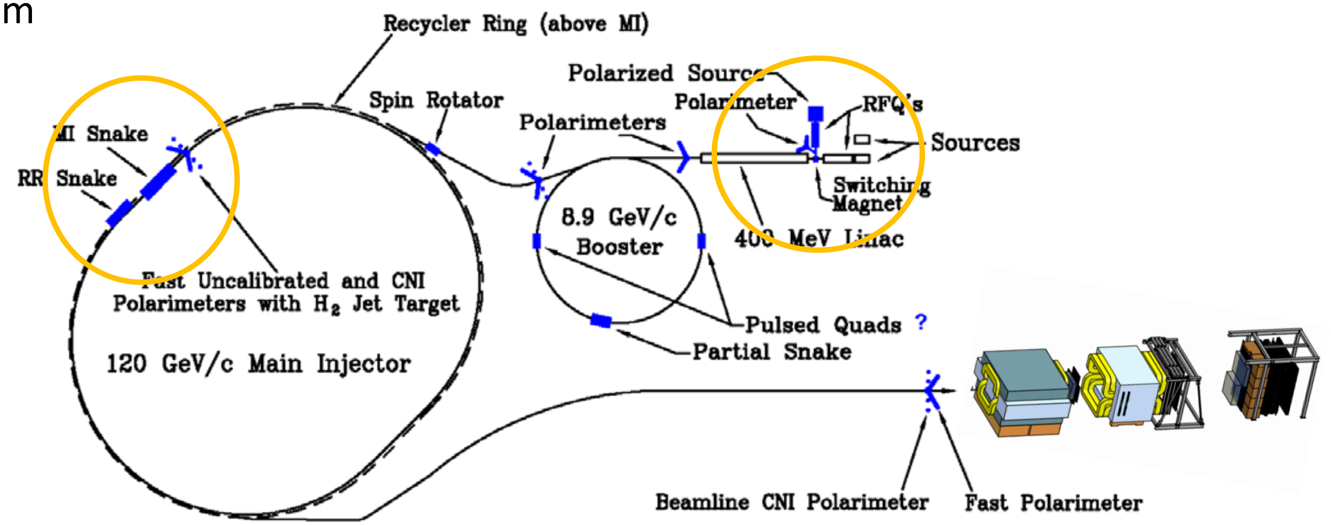
Dustin Keller (dustin@jlab.org) - UVA

Learn more about SpinQuest/E1039:
https://spinquest.fnal.gov/

Let's Polarize the Beam at Fermilab (E-1027)

The Plan:

- Use SpinQuest Spectrometer
- Add polarized beam

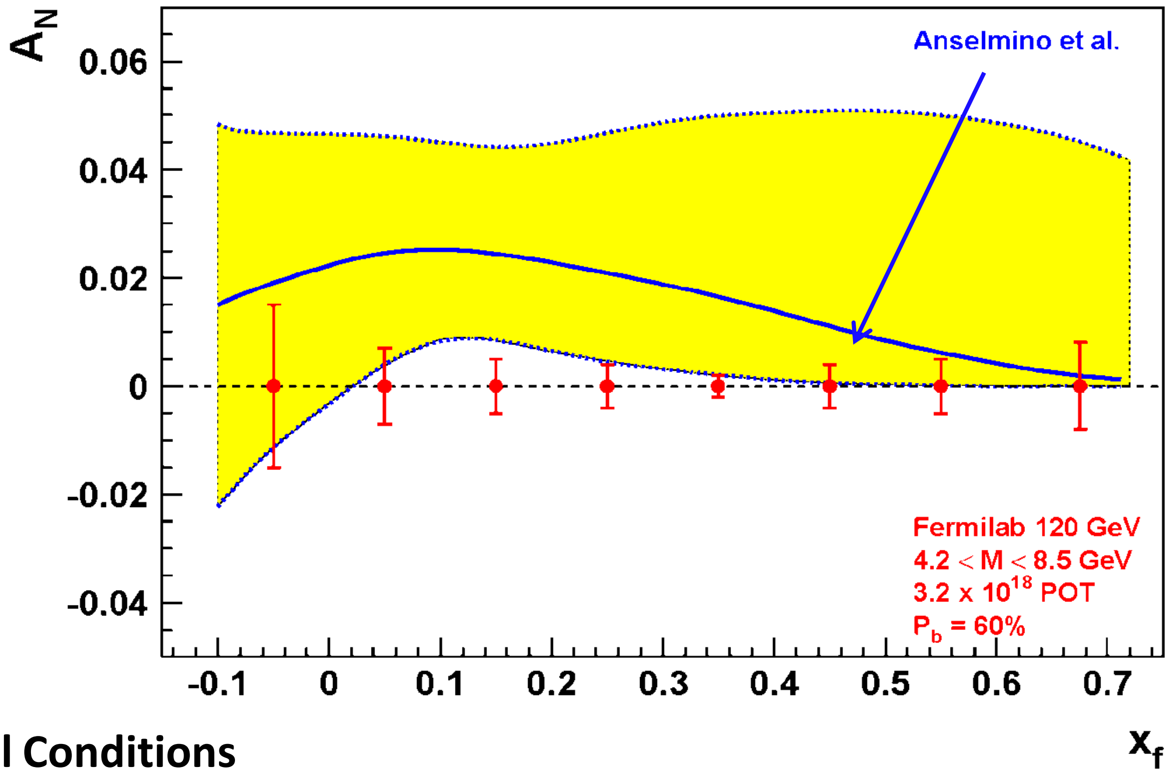


- **Fermilab (best place for polarized DY):**
  ⟶ very high luminosity, large x-coverage (primary beam, fixed target)
- **Measure sign-change in Sivers Function:**
  ⟶ sign, size and shape of Sivers function
  ⟶ and TMD evolution
- **Access to both valence and sea quarks**
- **Complementary to future EIC TMD Physics**

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

Expected Precision from E-1027 at Fermilab

- Probe **Valence Quark Sivers Asymmetry** with a polarized proton beam at SeaQuest



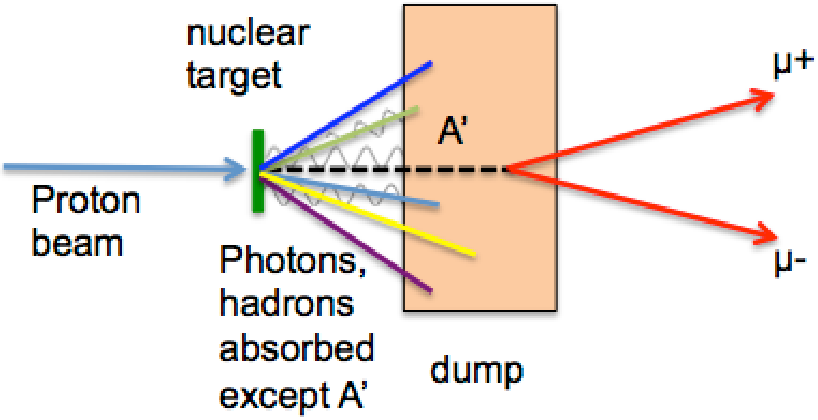
1.3 Mio DY events with no dilution

- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with $P_b = 60\%$

Can measure not only sign, but also the size & probably shape of the Sivers function! as well as TMD evolution!

Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment

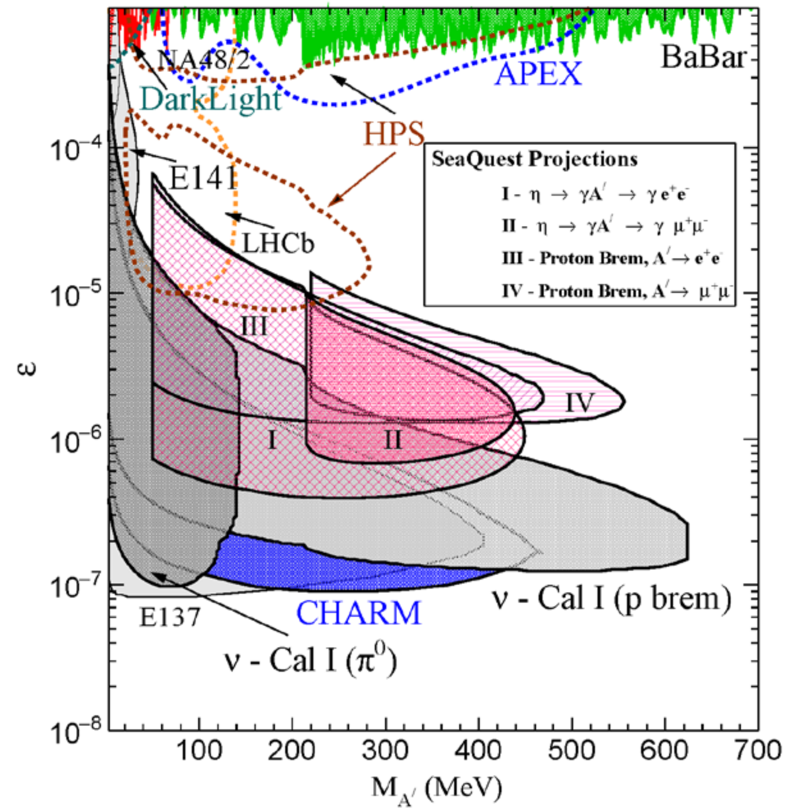


- Minimal impact on Drell-Yan program

  → run parasitically during E906 & E1039

$$l_o \approx \frac{0.8\,cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$

J. D. Bjorken et al, PRD **80** (2009) 075018



SeaQuest experimental parameters:

- → E_0 = 5 - 110 GeV for Proton Bremsstrahlung
- → N_{eff} = 2
- → l_0 = 0.17m – 5.95m

Polarized Proton Beams and Searches for Dark Forces

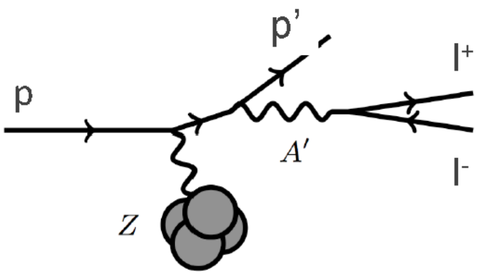
Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

$$\mathcal{L}_{\rm darkZ} = -(\varepsilon e J^{\mu}_{\rm em} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\rm NC}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

If the A' is a dark Z, then ...

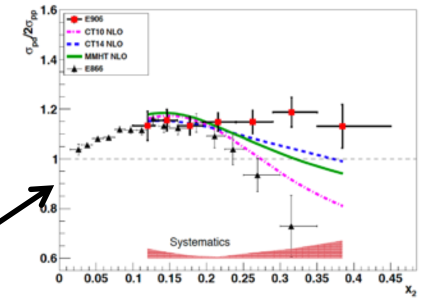


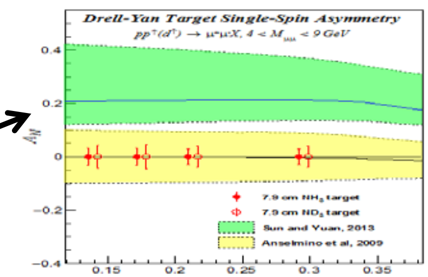
The dilepton yield can change with proton polarization: the asymmetry can be O(1)!

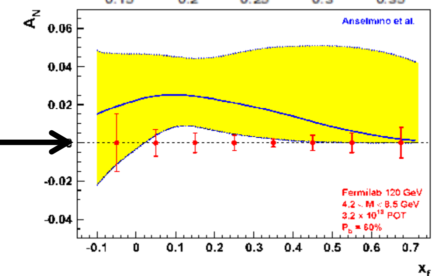
Ref: S. Gardner (Kentucky U)

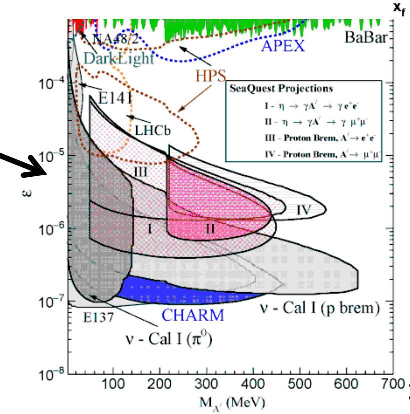
Fermilab - Summary and Outlook

Experiments	Timeline	Interactions	Physics
E906 (SeaQuest)	2014 - 2017	p + LH_2 / LD_2 p + C, Fe, W	dbar/ubar, nucl dep quark dE/dx
E1039 (SpinQuest)	2019 – 2021+	p + pol NH_3 p + pol ND_3	sea-quark Sivers, TMD
E1027	2021+ (?)	pol p + LH_2 or pol p + pol NH_3	valence quark Sivers, sign change, TMDs
E1067 (DarkQuest)	2016 - 2021+ (para.) 2021+ (dedicated?)	p + any target	dark photon, dark Higgs, dark Z, …









Ref: M. Liu (LANL)

Conclusions

- There is an exciting Drell-Yan program with polarized/unpolarized beams and targets underway
  - → although experimentally more challenging, it has some clear advantages over SIDIS
- Different labs offer complementary probes and processes to study hadronic landscape
  - → focus on strength of each lab to (minimize cost and) optimize physics output
- Future opportunities look very promising
  - → support from hadronic community (was and remains) vital to move forward
  - → opportunities to join the Fermilab program
- We have seen first results from COMPASS and STAR on the sign-change
  - → statistics still poor
- Now entering an era where we will have first measurement of a sea quark Sivers function (answer some of the questions):
  - → How much do the quarks and gluons contribute to the nucleon spin?
  - → In particular, what is the role of the sea quarks?
  - → Is there significant orbital angular momentum?
  - → Does TMD formalism work? Does Sivers function change sign (but keep shape and size)?

Thank You

SpinQuest/E1039 Collaboration

- Relatively small collaboration
  - → 36 full members, 76 affiliate members
  - → 14 institutions and Fermilab

Abilene Christian University
Argonne National Laboratory
KEK
Los Alamos National Laboratory
Mississippi State University
New Mexico State University
RIKEN
Tokyo Institute of Technology
University of Colorado, Boulder
University of Illinois, Urbana-Champaign
University of Michigan
University of New Hampshire
University of Virginia
Yamagata University

- US collaborators supported by NSF and DOE Medium Energy

- New collaborators actively sought
  - → contribute and lead major detector and physics efforts
  - → contact co-spokespersons