Fixed-target Drell Yan -- Present & Future

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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

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: $\sigma(\text{DY}) / \sigma(\text{nuclear}) \approx 10^{-7}$

credit: A. Kotzinian

Factorization and Universality (SIDIS - DY)

SIDIS

PDF $\otimes$ FF

DY

PDF $\otimes$ 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

$$\frac{d\sigma_{SIDIS}^{LO}}{dx dy dz dp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] \\ \times (F_{UU,T} + \epsilon F_{UU,L}) \left\{ 1 + \cos 2\phi_h (\epsilon A_{UU}^{\cos 2\phi_h}) \right. \\ \left. + S_T \left[\begin{array}{l} \sin(\phi_h - \phi_S) (A_{UT}^{\sin(\phi_h - \phi_S)}) \\ + \sin(\phi_h + \phi_S) (\epsilon A_{UT}^{\sin(\phi_h + \phi_S)}) \\ + \sin(3\phi_h - \phi_S) (\epsilon A_{UT}^{\sin(3\phi_h - \phi_S)}) \end{array} \right] \right\}$$

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

target rest frame

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} \right. \\ \left. + S_T \left[\begin{array}{l} (1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \\ + \sin^2 \theta \left(\begin{array}{l} \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \\ + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \end{array} \right) \end{array} \right] \right\}$$

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

target rest frame

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma_{SIDIS}^{LO}}{dx dy dz dp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] \times (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \cos 2\phi_h (\varepsilon A_{UU}^{\cos 2\phi_h}) + S_T \left[\begin{aligned} &\sin(\phi_h - \phi_S) (A_{UT}^{\sin(\phi_h - \phi_S)}) \\ &+ \sin(\phi_h + \phi_S) (\varepsilon A_{UT}^{\sin(\phi_h + \phi_S)}) \\ &+ \sin(3\phi_h - \phi_S) (\varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)}) \end{aligned} \right] \right\}$$

PDF $\otimes$ FF

$$\begin{aligned} A_{UU}^{\cos 2\phi_h} &\propto h_1^{\perp q} \otimes H_{1q}^{\perp h} \\ A_{UT}^{\sin(\phi_h - \phi_S)} &\propto f_{1T}^{\perp q} \otimes D_{1q}^h \\ A_{UT}^{\sin(\phi_h + \phi_S)} &\propto h_1^q \otimes H_{1q}^{\perp h} \\ A_{UT}^{\sin(3\phi_h - \phi_S)} &\propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \end{aligned}$$

BM $\otimes$ CF
Sivers $\otimes$ FF
Transv $\otimes$ CF
Pretz $\otimes$ CF

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} + S_T \left[\begin{aligned} &(1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \\ &+ \sin^2 \theta \left(\begin{aligned} &\sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \\ &+ \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \end{aligned} \right) \end{aligned} \right] \right\}$$

beam target

PDF $\otimes$ PDF

BM $\otimes$ BM
 f_1 $\otimes$ Sivers
BM $\otimes$ Transv
BM $\otimes$ Pretz

$$\begin{aligned} A_T^{\cos 2\varphi_{CS}} &\propto h_1^{\perp q} \otimes h_1^{\perp q} \\ A_T^{\sin \varphi_S} &\propto f_1^q \otimes f_{1T}^{\perp q} \\ A_T^{\sin(2\varphi_{CS} - \varphi_S)} &\propto h_1^{\perp q} \otimes h_{1T}^{\perp q} \\ A_T^{\sin(2\varphi_{CS} + \varphi_S)} &\propto h_1^{\perp q} \otimes h_1^q \end{aligned}$$

within QCD TMD framework:

$$\begin{aligned} h_1^{\perp q} \Big|_{SIDIS} &= - h_1^{\perp q} \Big|_{DY} \\ f_{1T}^{\perp q} \Big|_{SIDIS} &= - f_{1T}^{\perp q} \Big|_{DY} \end{aligned}$$

$$\begin{aligned} h_1^q \Big|_{SIDIS} &= h_1^q \Big|_{DY} \\ h_{1T}^{\perp q} \Big|_{SIDIS} &= h_{1T}^{\perp q} \Big|_{DY} \end{aligned}$$

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

$$\begin{aligned}
 A_{UU}^{\cos 2\phi_h} &\propto h_1^{\perp q} \otimes H_{1q}^{\perp h} \\
 A_{UT}^{\sin(\phi_h - \phi_s)} &\propto f_{1T}^{\perp q} \otimes D_{1q}^h \\
 A_{UT}^{\sin(\phi_h + \phi_s)} &\propto h_1^q \otimes H_{1q}^{\perp h} \\
 A_{UT}^{\sin(3\phi_h - \phi_s)} &\propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}
 \end{aligned}$$

$$\text{PDF} \otimes \text{FF}$$

$$\begin{aligned}
 \text{BM} &\otimes \text{CF} \\
 \text{Sivers} &\otimes \text{FF} \\
 \text{Transv} &\otimes \text{CF} \\
 \text{Pretz} &\otimes \text{CF}
 \end{aligned}$$

beam target

$$\text{PDF} \otimes \text{PDF}$$

$$\begin{aligned}
 \text{BM} &\otimes \text{BM} \\
 f_1 &\otimes \text{Sivers} \\
 \text{BM} &\otimes \text{Transv} \\
 \text{BM} &\otimes \text{Pretz}
 \end{aligned}$$

$$\begin{aligned}
 A_T^{\cos 2\varphi_{cs}} &\propto h_1^{\perp q} \otimes h_1^{\perp q} \\
 A_T^{\sin \varphi_s} &\propto f_1^q \otimes f_{1T}^{\perp q} \\
 A_T^{\sin(2\varphi_{cs} - \varphi_s)} &\propto h_1^{\perp q} \otimes h_{1T}^{\perp q} \\
 A_T^{\sin(2\varphi_{cs} + \varphi_s)} &\propto h_1^{\perp q} \otimes h_1^q
 \end{aligned}$$

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

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 ($\text{cm}^{-2} \text{s}^{-1}$)		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 $\sqrt{s} = 4.4-6.2$	$x_b = 0.2 - 0.97$ $x_t = 0.06 - 0.6$	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 NH₃ target / [§] $L = 1 \times 10^{36} \text{ cm}^{-2} \text{s}^{-1}$ (LH₂ tgt limited) / $L = 2 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ (10% of MI beam limited)

**not constrained by SIDIS data* / [#] rFOM = relative lumi * P² * f² wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH₃)

COMPASS 2015 Results

- COMPASS: 190 GeV π^- beam on transverse polarized H target (NH₃)
 - 2015 data (4 months)
 - Transverse target polarization ~80%
 - **consistent w/ sign change!**

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

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

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 [$M(\mu^+\mu^-) > 4 \text{ GeV}/c^2$): $\sim 35,000$
- 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

COMPASS DY / SIDIS data

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

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

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

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

Sivers Program at STAR

● RHIC p+p (500 GeV): $W^{+/-}$ TSSA

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

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

● 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

Fixed Target Beamlines

Tevatron 800 GeV

Main Injector
120 GeV

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

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

beam: valence quarks
at high x

target: sea quarks at
low/intermediate x

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

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

Flavor Asymmetry of SeaQuarks

- E866 data is for $Q^2 = 54 \text{ GeV}^2$ while SeaQuest data has $Q^2 \approx 29 \text{ GeV}^2$
 - difference should be insignificant
- is there disagreement at high x ?
- $d\bar{u}$ / $u\bar{d}$ 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

$$L_{\text{int}} = 1.82 \cdot 10^{42}/\text{cm}^2 \text{ NH}_3 / 2.11 \cdot 10^{42}/\text{cm}^2 \text{ ND}_3 \text{ for 2 years}$$

Polarized Target Developed for DY Sivers

- field: 5T @ 1K
- targets: NH_3 and ND_3
- elliptical: 27 mm x 20 mm (x,y), l:80 mm (z)
- 2 active cells, 1 empty
- helium consumption ~200 l/day

Sivers Function and Spin Crisis

$$f_{1T}^\perp = \text{yellow circle with blue center and upward arrow}$$

–

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

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

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

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$L \approx$ unmeasured

How measure quark OAM ?

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

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

Lattice QCD:

$$\Delta\Sigma_q \approx 25\%$$

$$2 L_q \approx 50\% \quad (4\% \text{ (valence)} + 46\% \text{ (sea)})$$

$$2 J_g \approx 25\%$$

K.-F. Liu et al arXiv:1203.6388

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
- rebuild high cooling power evaporation refrigerator
- build two new polarized target inserts
- new pump set; high cooling capacity
- new high power microwave source
- polarization of $\text{NH}_3 > 90\%$

- 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

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

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

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

SeaQuest experimental parameters:

→ $E_0 = 5 - 110 \text{ GeV}$ for Proton Bremsstrahlung

→ $N_{\text{eff}} = 2$

→ $l_0 = 0.17 \text{ m} - 5.95 \text{ m}$

Polarized Proton Beams and Searches for Dark Forces

Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

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

[Davoudiasl, Lee, Marciano, 2014]

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

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

Fermilab - Summary and Outlook

Experiments	Timeline	Interactions	Physics
E906 (SeaQuest)	2014 - 2017	p + LH ₂ / LD ₂ p + C, Fe, W	d $\bar{u}$ /u $\bar{u}$, 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