

Drell-Yan Experiment at Fermilab

Workshop on Hadron Tomography
2015.07.31 @ Kyoto Univ.

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Outline

- ▶ Drell-Yan process for (TMD) PDF measurements
- ▶ Setup & status of Drell-Yan experiments @ Fermilab
 - ▷ E906/SeaQuest ... unpolarized, ongoing
 - ▷ E1027 & E1039 ... polarized beam or target
- ▶ Physics topics & present/anticipated results
 - ▷ Anti-quark flavor asymmetry: $\bar{d}/\bar{u}$
 - ▷ Sivers function of quarks & anti-quarks
 - ▷ Tensor-polarized anti-quark distribution in deuteron
- ▶ Conclusions

Drell-Yan for (TMD) PDF Measurements

► Cross section @ LO

$$\frac{d^2\sigma}{dx_{Beam}dx_{Target}} = \frac{4\pi\alpha^2}{9x_{Beam}x_{Target}} \frac{1}{s} \sum_i e_i^2 \cdot \{q_i(x_{Beam})\bar{q}_i(x_{Target}) + \bar{q}_i(x_{Beam})q_i(x_{Target})\}$$

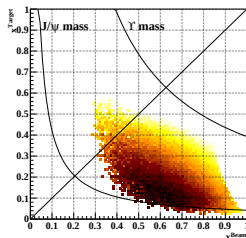
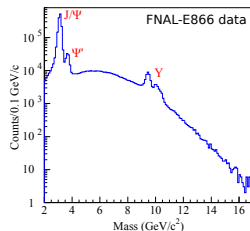
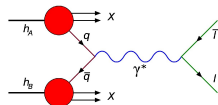
- “ $q_i(x_{Beam})\bar{q}_i(x_{Target})$ ” survives @ forward rapidity
- q w/ x_{Beam} & $\bar{q}$ w/ x_{Target} are distinguishable event-by-event
- Larger invariant mass $\Rightarrow$ larger x_{Beam} & x_{Target}

► For PDF measurements

- Cross section $\Rightarrow$ unpolarized PDFs
- Angular distribution $\Rightarrow$ Boer-Mulders
- With polarization $\Rightarrow$ Sivers, Transversity, etc.
- Nuclear targets $\Rightarrow$ nuclear effects

► Specialty w.r.t. SIDIS

- Sensitivity to $\bar{q}$
- TMD sign change



Drell-Yan Experiments @ Fermilab

SeaQuest	2013-2017	$p+p$ & $p+d$ $p+A$	$\bar{d}/\bar{u}$ Boer-Mulders of q & $\bar{q}$ Nuclear effects
E1027	in preparation	$\vec{p}+p$	Sivers of q
E1039	in preparation	$p+\vec{p}$	Sivers of $\bar{q}$
E1027+E1039		$\vec{p}+\vec{p}$	...innumerable...

- ▶ SeaQuest is running since November 2013
- ▶ Will inherit SeaQuest spectrometer to E1027/E1039
- ▶ New equipment
 - ▷ Polarized **beam** for E1027
 - ▷ Polarized **target** for E1039

Fermilab Proton Beam

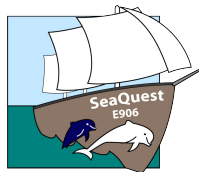


- ▶ Energy $E = 120 \text{ GeV}$
($\sqrt{s} = 15 \text{ GeV}$)
- ▶ Duty cycle
 - ▷ 5 sec for E906
 - ▷ 55 sec for ν exp.
- ▶ Bunch
 - ▷ Length: 1 nsec
 - ▷ Interval: 19 nsec (53 MHz)
 - ▷ 10^{13} protons in 5 sec
in spot size

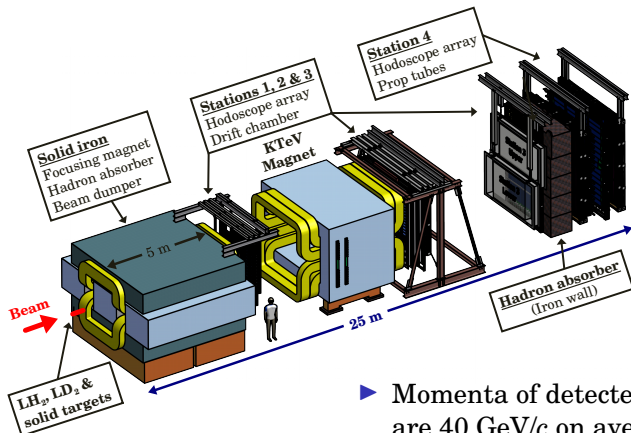
FNAL-SeaQuest Collaboration

► Institutes

- ▷ Abilene Christian Univ.
- ▷ Argonne National Lab
- ▷ Fermi National Accelerator Lab
- ▷ KEK _{Jp}
- ▷ Los Alamos National Lab
- ▷ Univ. of Michigan
- ▷ RIKEN _{Jp}
- ▷ Tokyo Tech _{Jp}
- ▷ Academia Sinica _{Tw}
- ▷ Univ. of Colorado
- ▷ Univ. of Illinois
- ▷ Ling-Tung Univ. _{Tw}
- ▷ Univ. of Maryland
- ▷ National Kaohsiung Normal Univ.
- ▷ Rutgers Univ.
- ▷ Yamagata Univ. _{Jp}



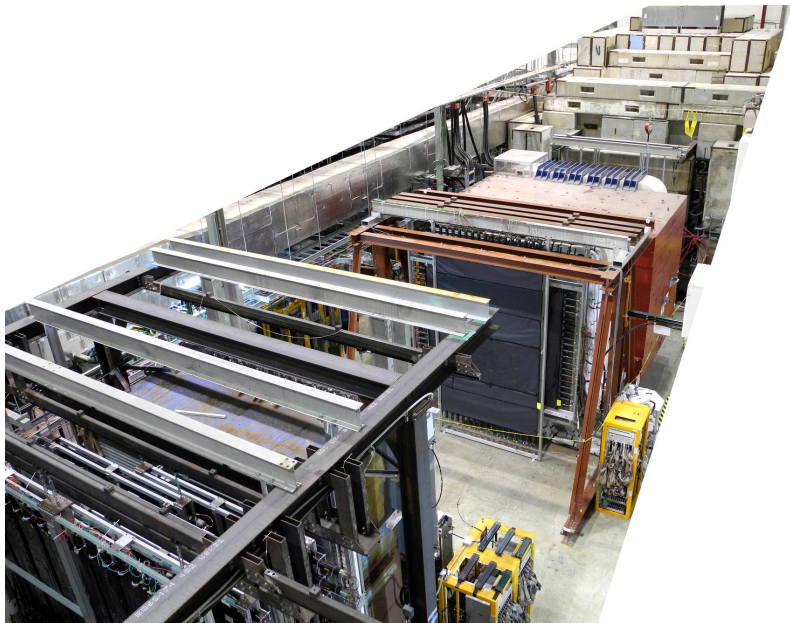
E906/SeaQuest Spectrometer



- ▶ Targets: LH₂, LD₂, C, Fe, W
- ▶ Focusing magnet (FMag) & Tracking magnet (KMag)
- ▶ Iron inside FMag, as hadron absorber & beam dump
- ▶ Detection of dimuons
 - ▷ Station 1-3 : Tracking with drift chambers
 - ▷ Station 4 : Particle identification with drift tube

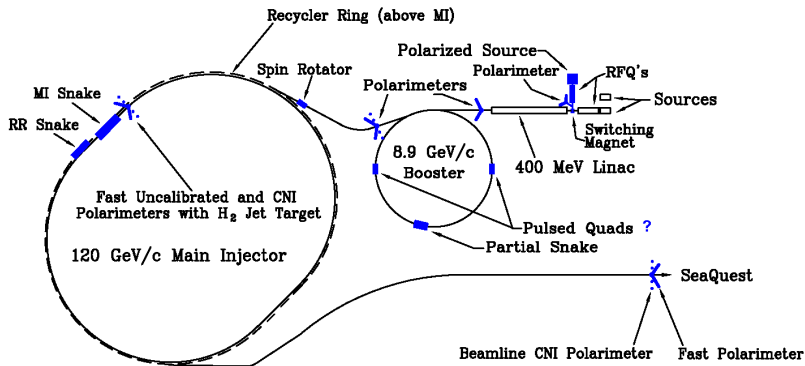
▶ Momenta of detected muons are 40 GeV/c on average

SeaQuest Hall — 2015-July-27



Polarized Beam for E1027

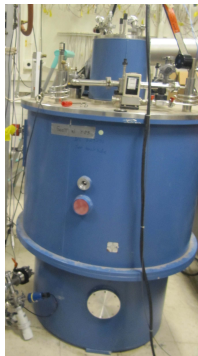
- ▶ Proposal @ <http://inspirehep.net/record/1216817>
- ▶ Use E906/SeaQuest spectrometer (w/ magnetic field adjusted)
- ▶ Upgrade source, booster & main injector
 - ▷ Based on design & experience of BNL RHIC
 - ▷ Detailed design & construction under study

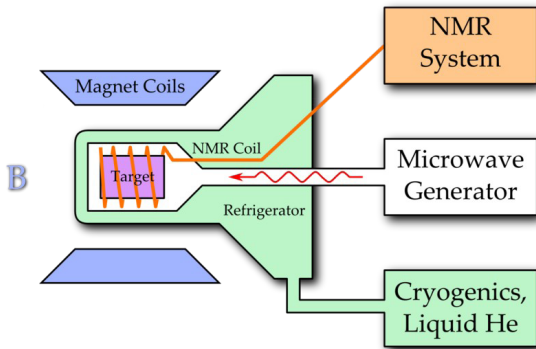
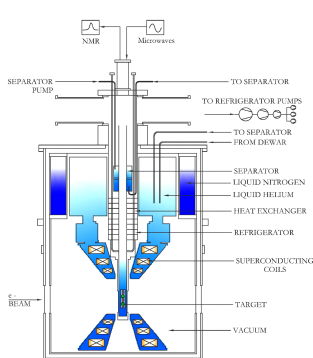


- ▶ Stage-1 approved

Polarized Target for E1039

- ▶ LoI @ http://www.fnal.gov/directorate/program_planning/June2013PACPublic/P-1039_LOI_polarized_DY.pdf
- ▶ Use E906/SeaQuest spectrometer
- ▶ Build polarized target
 - ▷ LANL LDRD project in FY2013-2016
 - ▷ NH_3 target (UVa or Hall-C polarized target) with modification
 - ▷ $L = 8 \text{ cm}$, $B = 5 \text{ T}$





- Magnet ... Transverse orientation. Uniformity ($dB/B < 10^{-4}$)
- Cryogenic system ... Fixed leaks, rewired electronics, etc. Working fine
- NMR system ... Observed TE signal. LabVIEW control software
- Polarization ... Reached 90%. Measured radiation damage

Status of SeaQuest Data Taking

► Events

Year	Month	Event
2008	12	Fermilab Stage-2 approval
2009	04	Start of spectrometer construction
2011	08	End of spectrometer construction
2012	03-04	1st data taking (commissioning)
	05-	Detector & DAQ upgrade
2013	11-	2nd data taking
2014	09-10	Accelerator works
	11-	3rd data taking
2015	07-09	Accelerator works
	10-	4th data taking
2016	08-10	Accelerator works
	11-	5th data taking (plan)

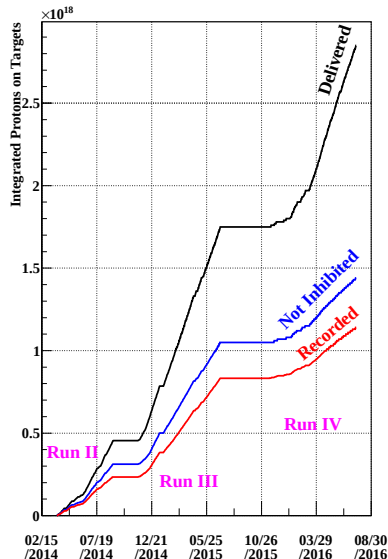
► Beam protons on targets

- 1.1×10^{18} recorded up to now
- 0.6×10^{18} analyzed for preliminary $\bar{d}/\bar{u}$

► Another data taking in FY2017

- 0.4×10^{18} to be recorded
 $\Rightarrow 1.5 \times 10^{18}$ in total
- Wider chamber acceptance at St. 1
- Faster DAQ

► Improvements on track reconstruction



Physics Topics & Present/Anticipated Results

► SeaQuest

- ▷ Anti-quark flavor asymmetry: $\bar{d}/\bar{u}$
- ▷ Boer-Mulders function via angular distribution
- ▷ Nuclear effects

► E1027 (with polarized beam)

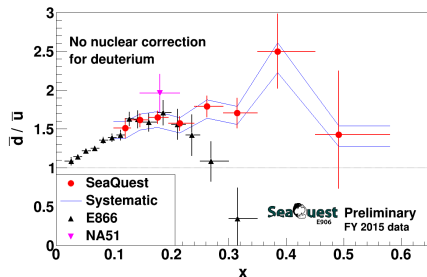
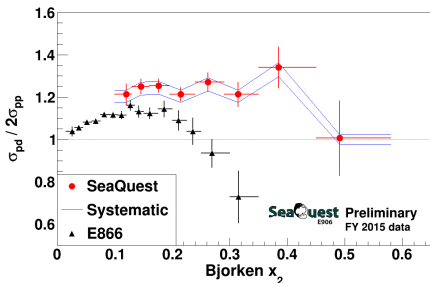
- ▷ Sivers function of quark

► E1039 (with polarized target)

- ▷ Sivers function of anti-quark
- ▷ Tensor-polarized anti-quark distribution in deuteron

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

- ▶ SeaQuest released the preliminary result in April 2016
- ▶ Talk by Kei Nagai at MENU2016: <https://indico2.riken.jp/indico/contributionDisplay.py?contribId=31&sessionId=3&confId=2174>
- ▶ Cross-section ratio vs beam- x & $\bar{d}/\bar{u}$ vs x

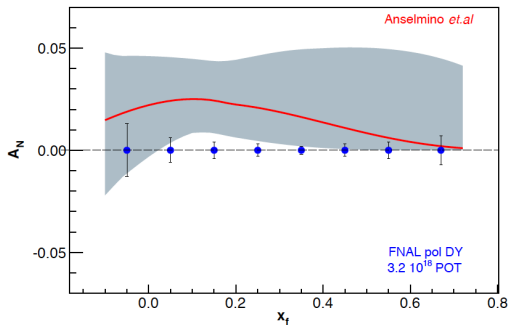


$$\frac{\sigma_{p+d}}{2\sigma_{p+p}} \approx \frac{1}{2} \left(1 + \frac{\bar{d}}{\bar{u}} \right)$$

Prospect of E1027 with Polarized Beam

- **Sivers** TMD PDF of **quark**

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



- Red line ... prediction with SIDIS (HERMES & COMPASS) result
- “Can measure not only **sign**, but also the **size** & maybe **shape** of the Sivers function”

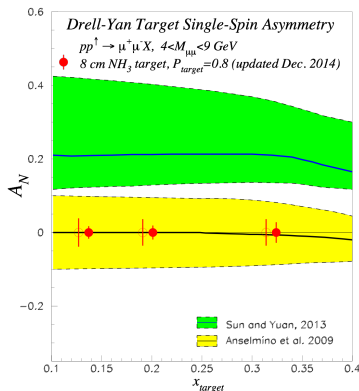
Prospect of E1039 with Polarized Target

► **Sivers** TMD PDF of **anti-quark**

► Observable:

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

- Measurement accuracy $\delta_{A_N} \sim 0.02$
- Compare with two calculations based on SIDIS data
 - Blue line takes into account the Collins-Soper-Sterman scale evolution

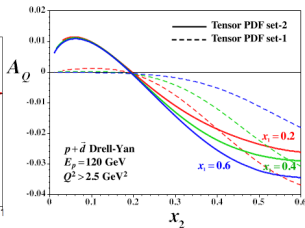
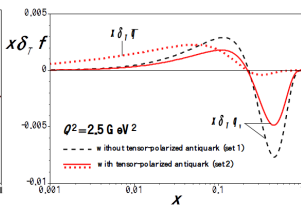
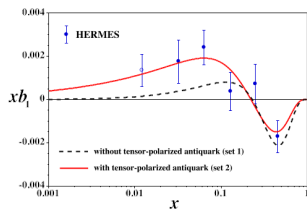


Phys. Rev. D88, 034016 (2013)

Eur. Phys. J. A39, 89 (2009)

Tensor-Polarized $\bar{q}$ Distribution in Deuteron: $\delta_T \bar{q}(x)$

- ▶ Deuteron structure is not fully known
 - ▷ Non-zero electric quadrupole moment $\Rightarrow p$ & n in D-wave slightly
 - ▷ Large(r) tensor-pol. structure function ($b_1^d(x)$) measured by HERMES
- ▶ Theoretical estimate on Drell-Yan measurement by S. Kumano & Q.-T. Song: arXiv:1606.03149
- ▶ Talk by Qin-Tao Song at MENU2016: <https://indico2.riken.jp/indico/contributionDisplay.py?contribId=70&sessionId=3&confId=2174>
- ▶ Two sets of $b_1^d(x)$ & $\delta_T \bar{q}(x)$ & Predicted A_Q



- ▶ Anticipated measurement accuracy by E1039 is being estimated

The Need For Tensor Polarized Target

- Deuteron also has an electric quadrupole moment, $eq_D = 2.86 \text{ e fm}^2$
- eq_D interacts with electric field gradients within the lattice producing two, overlapping NMR lines (Pake doublet)

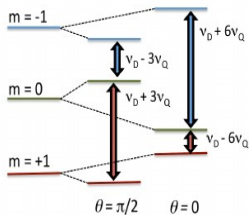
$$E_m = -h\nu_D m + h\nu_Q \left[3\cos^2\theta - 1 \right] \left[3m^2 - I(I+1) \right]$$

ν_D = deut. Larmor freq.

ν_Q = ND_3 quadrupole freq.

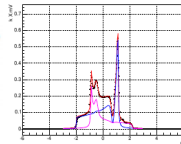
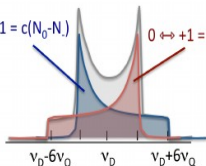
eq = deuteron quadrupole moment

θ = angle between elec. & mag. fields



$$0 \leftrightarrow -1 = c(N_0 - N_-)$$

$$0 \leftrightarrow +1 = c(N_+ - N_0)$$



A~38% for d-butanol

- Achieved with Adiabatic-Fast-Passage method
- Should be applicable to d-ammonium. Expect $A > 30\%$

Conclusions

► Drell-Yan process

- ▷ Simplest/cleanest process in $p+p$ scatterings
- ▷ Becoming more important in measuring (TMD) PDFs

► Drell-Yan Experiments @ Fermilab

▷ SeaQuest

- ▷ Recorded 1.1×10^{18} protons on targets by now
- ▷ Another data taking in FY2017 after hardware upgrades
- ▷ Analyzed 0.6×10^{18} protons for preliminary $\bar{d}/\bar{u}$

▷ E1027 & E1039 ... in preparation

- ▷ The polarized target is being commissioned well
- ▷ Negotiating with DOE NP & HEP for support

► Various present/working/possible physics topics

- ▷ Anti-quark flavor asymmetry: $\bar{d}/\bar{u}$
- ▷ Boer-Mulders function via angular distribution
- ▷ Nuclear effects
- ▷ Sivers function of quarks & anti-quarks
- ▷ Tensor-pol. anti-quark distribution with pol. deuteron