Fermilab E1039: Measuring the Sea Quark Sivers Asymmetry with Polarized Drell-Yan Interaction

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Motivation

- Spin Crisis- intrinsic spins of quarks not enough.
 - Contribution of intrinsic spin of valence quarks and gluons less than assumed. (C.A. Aidala et al, arXiv:1209.2803)
 - Gluon OAM contributes, but valence quark OAM near zero. (D. de Florian et al arXiv:1404.4293)
- Sea quark contribution
 - OAM of sea quarks could contribute to overall spin
 - Non-zero Siverson function implies non-zero OAM (relationship model-dependent.)

Lattice QCD:

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

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + L_{\bar{q}} + \Delta G + L_g$$

The Sivers Function

- Different polarizations represent different physics (Transverse Momentum Distributions)
- Sivers represents the correlation of the transverse momentum of an unpolarized parton with the spin of a transversely polarized nucleon.
- A non-zero DY sea quark Sivers function asymmetry is indicative of contribution by sea quark OAM.

Leading Twist TMDs

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \text{circle with red dot}$		$h_1^\perp = \text{circle with red dot and up arrow} - \text{circle with red dot and down arrow}$ Boer-Mulders
	L		$g_{1L} = \text{circle with red dot and right arrow} - \text{circle with red dot and left arrow}$ Helicity	$h_{1L}^\perp = \text{circle with red dot and up arrow and right arrow} - \text{circle with red dot and up arrow and left arrow}$
	T	$f_{1T}^\perp = \text{circle with red dot and up arrow} - \text{circle with red dot and down arrow}$ Sivers	$g_{1T}^\perp = \text{circle with red dot and right arrow and up arrow} - \text{circle with red dot and right arrow and down arrow}$	$h_1 = \text{circle with red dot and up arrow} - \text{circle with red dot and down arrow}$ Transversity $h_{1T}^\perp = \text{circle with red dot and up arrow and right arrow} - \text{circle with red dot and up arrow and left arrow}$

$f_{1T}^\perp =$

Sivers

Polarized Drell-Yan Scattering

- One way to measure Sivers function asymmetry
- Quark and antiquark annihilate into virtual photon, decays in dilepton.
- Azimuthal asymmetry due to orbit of quarks.
- Fixed target DY isolates beam quarks, target antiquarks.

$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp, \bar{q}}(x_2) + 1 \leftarrow \rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow \rightarrow 2 \right]}$$

Experimental Layout

- Fermilab main injector beam
 - 120 GeV
 - $\sim 10^{12}$ protons per 4 second spill,
 $\sim 10^{17}$ per year
- Detector is the existing E906 spectrometers.
 - 2 magnets
 - 4 tracking stations

The SpinQuest spectrometer

Target

- We will be using a target made up of ammonia beads (NH_3 or ND_3)
- Dynamic Nuclear Polarization
- Polarization will be done with a 5T magnet, ^4He evaporation refrigerator, 140 GHz microwave source, and a 14000 m^3/hr pumping system.
- Based on experience, we expect maximum 95% polarization for proton, 50% for deuteron.

Error estimates

- Statistical: 3%-5% absolute error
 - Dependent on polarization, dilution, events
 - Different in each bin
- Systematic: 6.5% relative error
 - **Target: 5.7%**
 - **Dilution: 3%**
 - **Density: 1%**
 - **Polarization: 2.5%**
 - **Packing Fraction: 2%**
 - **Polarization Homogeneity: 2%**
 - **Uneven Decay: 3%**
 - Beam: 2.5%
 - Relative Luminosity: 1%
 - Drifts: 2%
 - Scraping/Dead Time: 1%
 - Detector: 1.8%
 - DAQ: 1.5%
 - Detector: 1%

DGLAP: M. Anselmino et al arXiv:1612.06413
 TMD-1: M. G. Echevarria et al arXiv:1401.5078
 TMD-2: P. Sun and F. Yuan arXiv:1308.5003

Target Error: Packing Fraction+Density

- Archimedes' Principle
- Submerge in liquid nitrogen, measure displacement.
- Density of ammonia changes based on temperature.
- Very little data on density of ammonia at low temperatures.
- Create sealed, pre-measured targets.

Rondon, 1993

Target Error: Polarization

- Measured using Nuclear Magnetic Resonance
- 3 probes over length of target
- NMR precise to within 1%, but uncertainty between probes.
- Proton bombardment can cause uneven decay, making this measurement less accurate the longer we use one sample.

Cup length 7.62cm (3 inches)
Cups are elliptical with axes of 20.5mm and 27.7mm

Target Error: Dilution

- Dilution factors well known for individual chemicals.
- Other materials in beam path create uncertainty (Helium, Aluminium, plastic)
- Need to know DY cross section for each material in path
- Uncertainty in the dilution will likely be around 2-3%
- Measuring single-muon channel during commissioning to measure cross-sections could reduce error.

$$f = \frac{N_D \sigma_H}{N_N \sigma_N + N_H \sigma_H + \Sigma N_A \sigma_A}$$

SpinQuest Collaboration

Contact Spokespersons: Kun Liu (liuk@fnal.gov) - LANL

Dustin Keller (dustin@jlab.org) - UVA

Welcoming all collaborators!

More information: <https://wiki.shanti.virginia.edu/display/SeaQuest/>

Schedule/Status:

- Ongoing since summer 2018: Equipment commissioning
- May 2019: Beam commissioning planned start
- Fall 2019-2021: Experiment runs

Brute-force Polarization

- Probability of polarization determined by temperature and magnetic field
- For T=1K and B=5T
 - Electron Polarization 99.76%
 - Proton Polarization 0.5108%
 - Deuteron Polarization 0.1046%
 - Neutron Polarization -0.35%
- Need something else to reach desired polarization.

$$P_{TE}^{\frac{1}{2}} = \tanh \frac{\Delta E}{2kT}$$

$$P_{TE}^1 = \frac{4 \tanh \frac{\Delta E}{2kT}}{3 + \tanh^2 \frac{\Delta E}{2kT}}$$

Dynamic Nuclear Polarization

- Target doped with paramagnetic centers (electrons)
- Electrons polarized in low temp/high B field
- Microwaves transfer polarization
- Relaxation time for electrons on scale of ms, protons on scale of minutes/hours

$$e + p^\uparrow \rightarrow e' \pi X$$

① Polarized Semi-Inclusive DIS

$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp, q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R Asymmetry in Hadron Production
- Quark to hadron fragmentation function
- Valence and sea quarks mixed
- Poor sea quark sensitivity

$$p + p^\uparrow \rightarrow \mu^+ \mu^- X$$

② Polarized Drell-Yan

$$A_N^{DY} \propto \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp, \bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}$$

- L-R Asymmetry in Drell-Yan production
- No fragmentation function
- Valence and sea quarks isolated
- Potentially better sea quark sensitivity