Measurement of Polarized Drell-Yan Process at FNAL E1039/SpinQuest

PacificSpin2019 @ Miyazaki, Japan

2019-August-29

Kenichi Nakano

Tokyo Tech

Outline

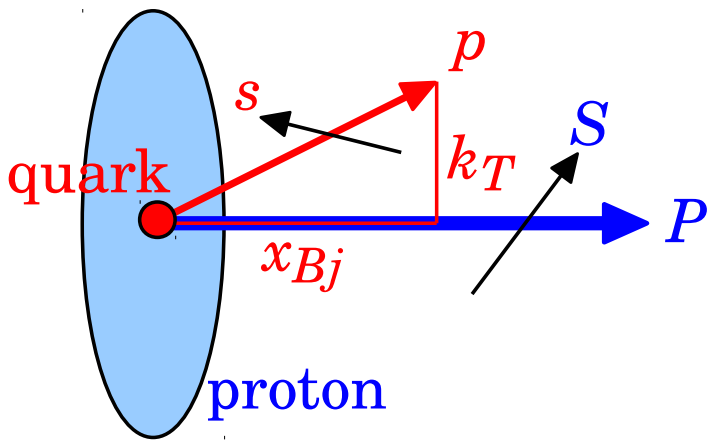
1. Introduction
   - Sivers function of anti-quarks
2. Measurement at E1039/SpinQuest
   - Measurement method
   - Anticipated sensitivity
3. Experimental status
   - Setups of target & spectrometer
   - Schedule toward data taking
4. Summary

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

- One of the eight Transverse-Momentum-Dependent (TMD) PDFs

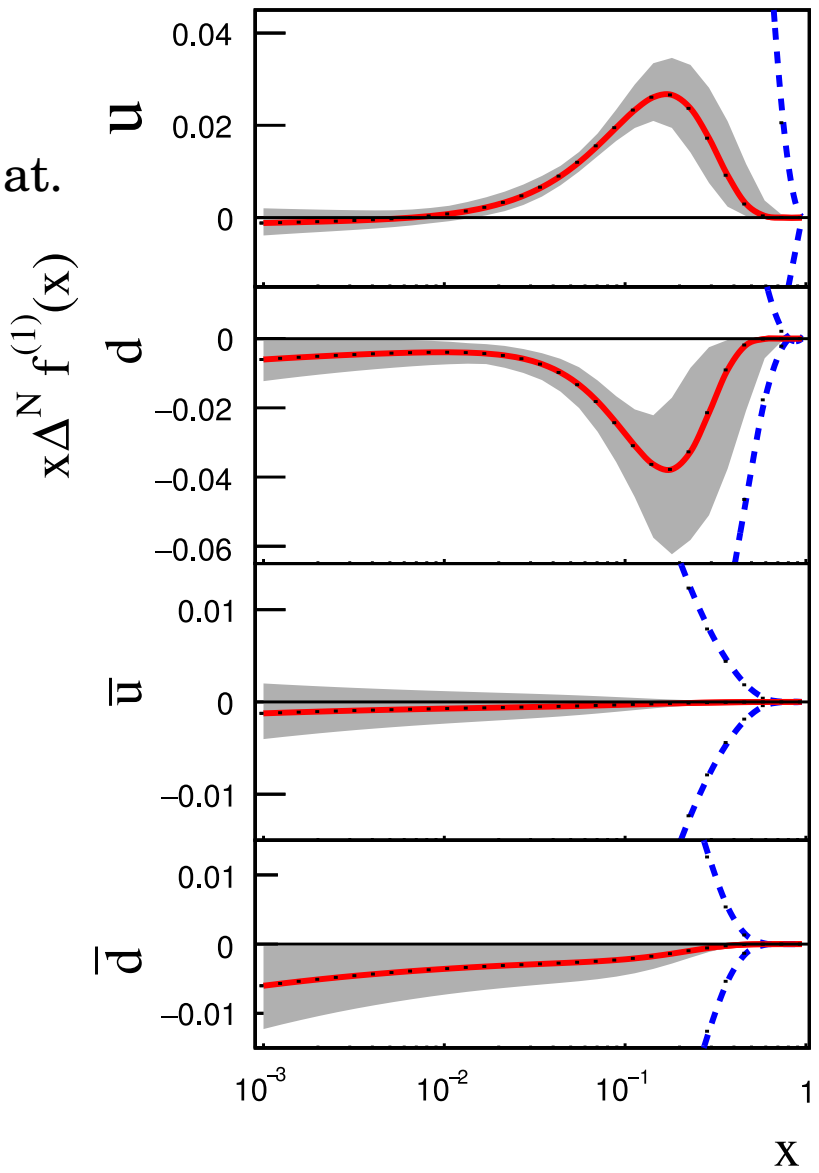
		Parton spin		
		U	L	T
Nucleon spin	U	Density f_1		Boer-Mulders $h_1^{\perp}$
	L		Helicity g_1	Worm gear #2 $h_{1L}^{\perp}$
	T	Sivers $f_{1T}^{\perp}$	Worm gear #1 g_{1T}	Transversity h_1 & Pretzelosity $h_{1T}^{\perp}$

- Correlation between the nucleon spin (S) & the parton transverse momentum (k_T)



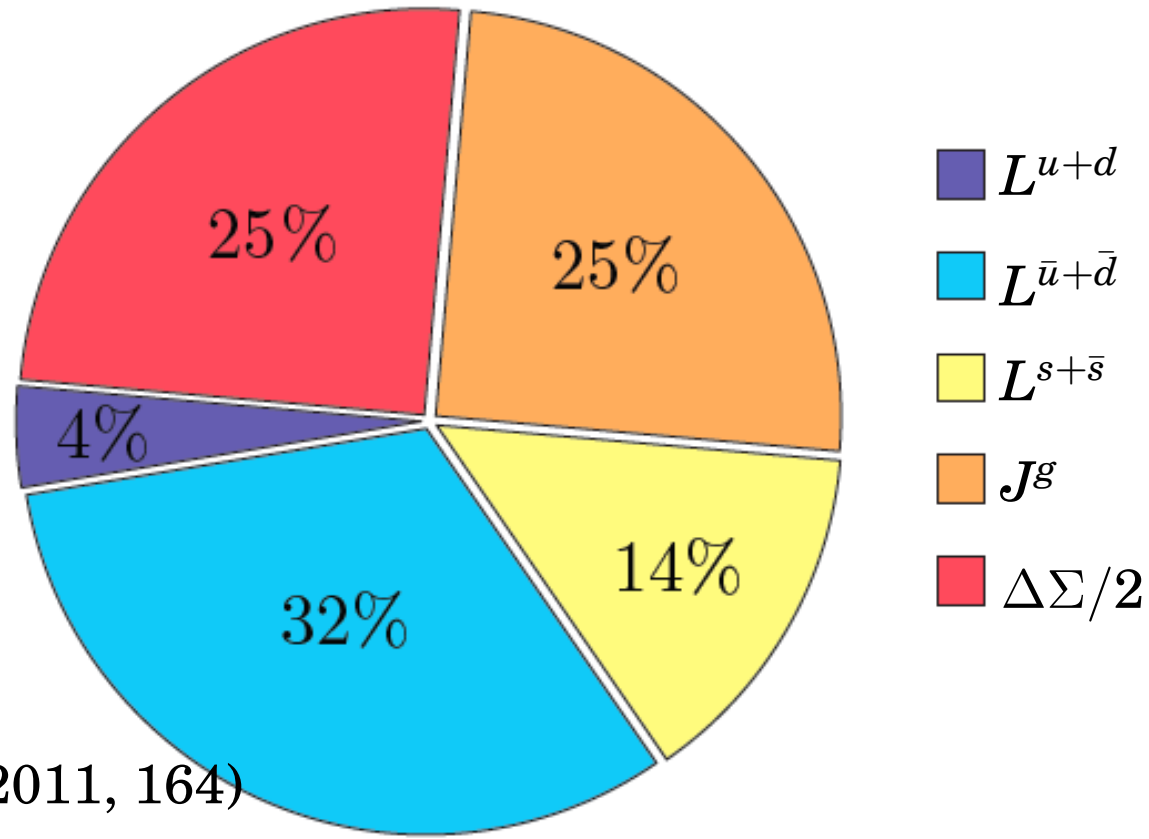
Sivers Function of Anti-Quarks

- Extraction by global analyses
  - PRD88 (2013) 114012, P. Sun & F. Yuan
  - PRD89 (2014) 074013, M. G. Echevarria et at.
  - JHEP 04 (2017) 046, M. Anselmino et al.
    - Use of HERMES, COMPASS & JLab data
    - First moment of Sivers function:
      $x\Delta^N f^{(1)}(x) \equiv -x f_{1T}^{\perp(1)}(x)$
- $f_{1T}^{\perp}(x)$ of anti-quarks is not well known
  - Since $\bar{q}$ & q are mixed up in SIDIS



Importance of Anti-Quarks

- In proton spin puzzle: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_G + L_q + L_{\bar{q}}$

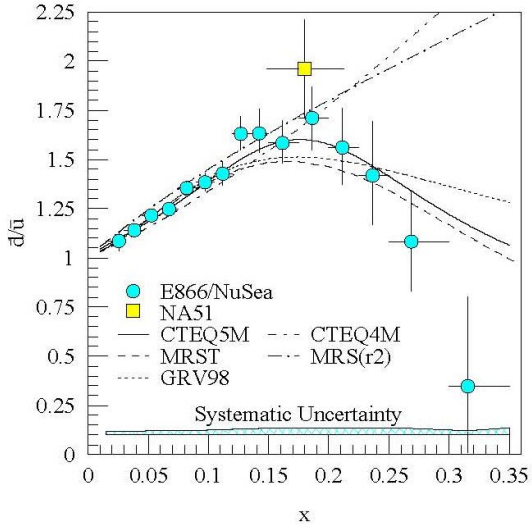


Lattice QCD
(PoS LATTICE2011, 164)

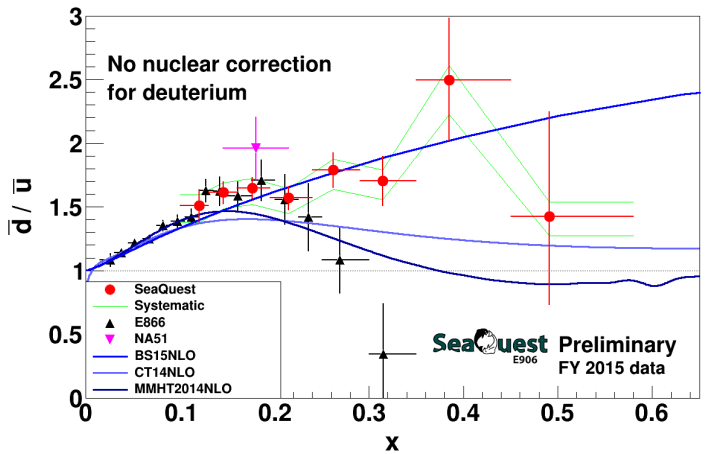
- The sea-quark orbital angular momentum is expected to be a major part of the missing spin
- Non-zero Sivers function of anti-quarks promises $L_{\bar{q}} \neq 0$!

Connection to Unpolarized PDF

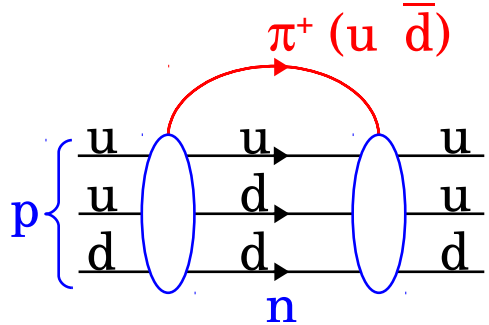
- Light anti-quark flavor asymmetry: $\bar{d}(x)/\bar{u}(x)$
  - E866/NuSea



  - E906/SeaQuest



- Meson cloud model ... *PRD58, 092004 (1998)*
  - $|p\rangle = (1-a-b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
  - It predicts the large $\bar{d}(x)/\bar{u}(x)$ asymmetry
  - It predicts also non-zero $L_{q,\bar{q}}$ like "meson tornado"
    (need $L = 1$ of π to make $J^P = 1/2^+$ of proton, as parity of π is $J^P = 0^-$)



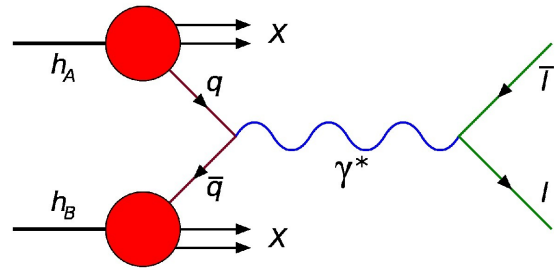
- We could reach an unified understanding about the Sivers function, the OAM & the $\bar{d}(x)/\bar{u}(x)$ asymmetry

Measurement at E1039/SpinQuest

Proton-Induced Drell-Yan Process

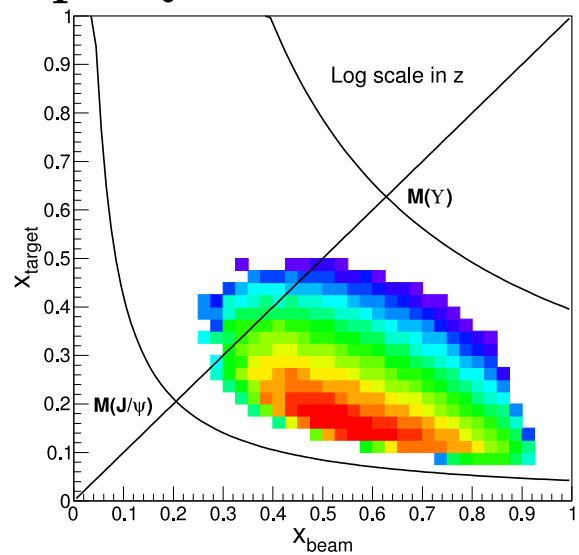
- Cross section at LO

$$\frac{d^2\sigma}{dx_{beam}dx_{target}} = \frac{4\pi\alpha^2}{9x_{beam}x_{target}}\frac{1}{s}\sum_{i=u,d,\cdots} {e_i}^2 \cdot$$
$$\{q_i(x_{beam})\bar{q}_i(x_{target}) + \bar{q}_i(x_{beam})q_i(x_{target})\}$$



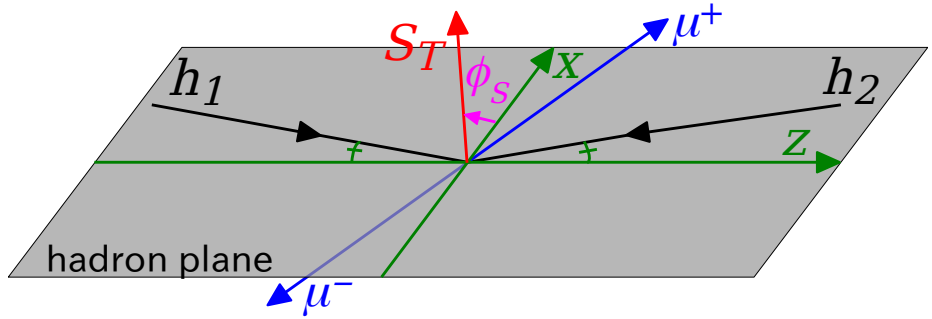
  - "$q(x_{beam})\ \bar{q}(x_{target})$" survives @ forward rapidity
  - q w/ x_{beam} & $\bar{q}$ w/ x_{target} are distinguishable event-by-event
- Proton & deuteron as targets
  - Flavor separation ($\bar{u}$ vs $\bar{d}$) based on the proton-neutron isospin symmetry
  - Polarized NH_3 & ND_3 materials

SpinQuest simulation



Sivers Asymmetry in Drell-Yan Process

- $p + N$ Drell-Yan process with transverse target polarization ($\vec{S}_T$)



  - ϕ_S: Azimuthal angle of target spin w.r.t. hadron plane

- $f_{1T}^{\perp}$-related structure function

$$\sigma \sim F_{UU}^1 + S_T F_{UT}^1 \sin\phi_S$$

$$F_{UT}^1 = -\mathcal{C}\left[\frac{\vec{q}_T \cdot \vec{k}_{T,target}}{q_T M_p} f_1(x_{beam}, \vec{k}_{T,beam}^2) f_{1T}^{\perp}(x_{target}, \vec{k}_{T,target}^2)\right]$$

  - $\mathcal{C}$: convolution over $\vec{k}_{T,beam}$ & $\vec{k}_{T,target}$

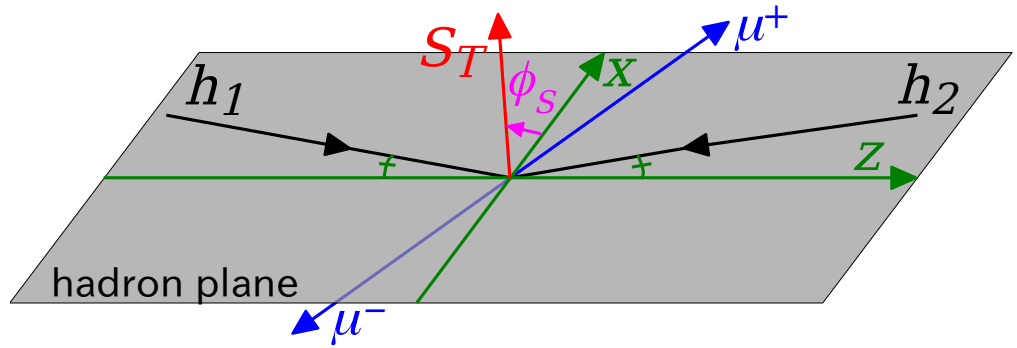
- Transverse Single Spin Asymmetry (TSSA): $A_{UT}^{\sin\phi_S}(x_{target})$
  - $N(x_{target}, \phi_S)$: measured yields of Drell-Yan process
  - Fourier projection of N on $\sin\phi_S$ modulation

$$A_{UT}^{\sin\phi_S}(x_{target}) \equiv \frac{2}{f\,|S_T|} \frac{\int d\phi_S \frac{dN(x_{target},\phi_S)}{d\phi_S} \sin\phi_S}{N(x_{target})} = \frac{F_{UT}^1}{F_{UU}^1}$$

    - f: Dilution factor for the ratio of polarizable nucleons
  - Relation to $f_{1T}^{\perp,\bar{q}}(x)$

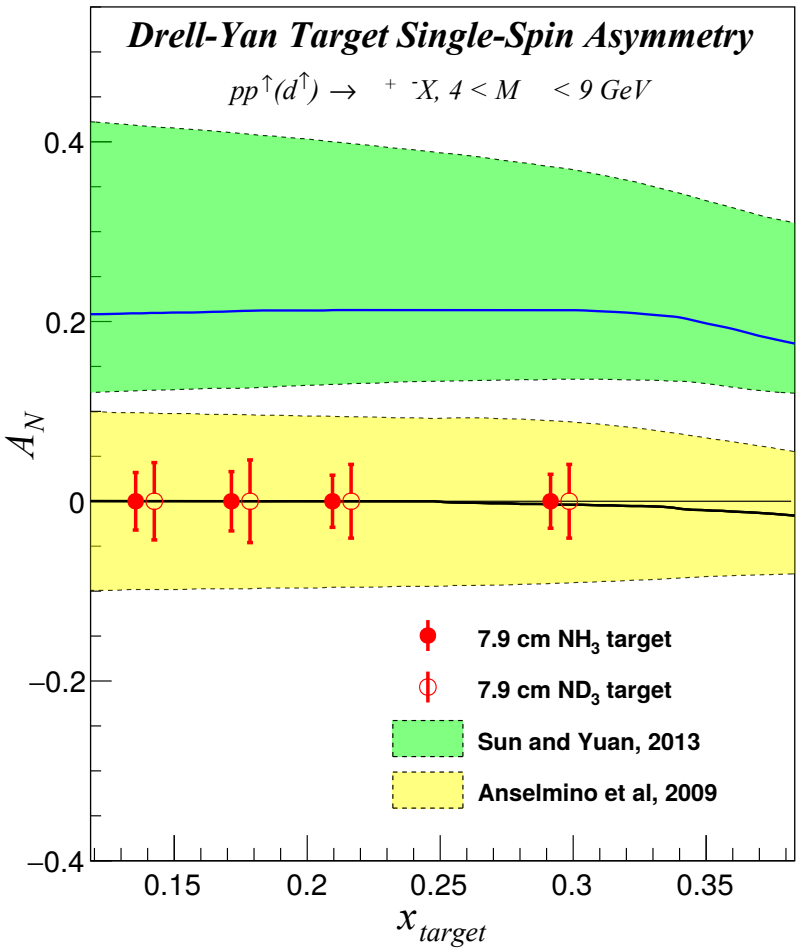
$$\frac{F_{UT}^1}{F_{UU}^1} \sim \frac{f(x_{beam}) \cdot f_{1T}^{\perp,\bar{q}}(x_{target})}{f(x_{beam}) \cdot \bar{f}(x_{target})}$$

    - Assumption for simplicity here:
      quark having x_{beam} at beam & anti-quark having x_{target} at target



Anticipated Sensitivity of E1039/SpinQuest

- Conditions
  - Two years of data taking
  - NH_3:ND_3 = 50%:50% in time
  - Details in the E1039 proposal
- TSSA: $A_{UT}^{\sin\phi_S} = A_N$
  - Measurement accuracy $\delta_{A_N} \sim 0.04$
  - Two predictions of A_N of NH_3
    - Calculations based on SIDIS data
    - Blue line takes into account the Collins-Soper-Sterman scale evolution
- Aim to observe non-zero anti-quark Sivers asymmetry!!

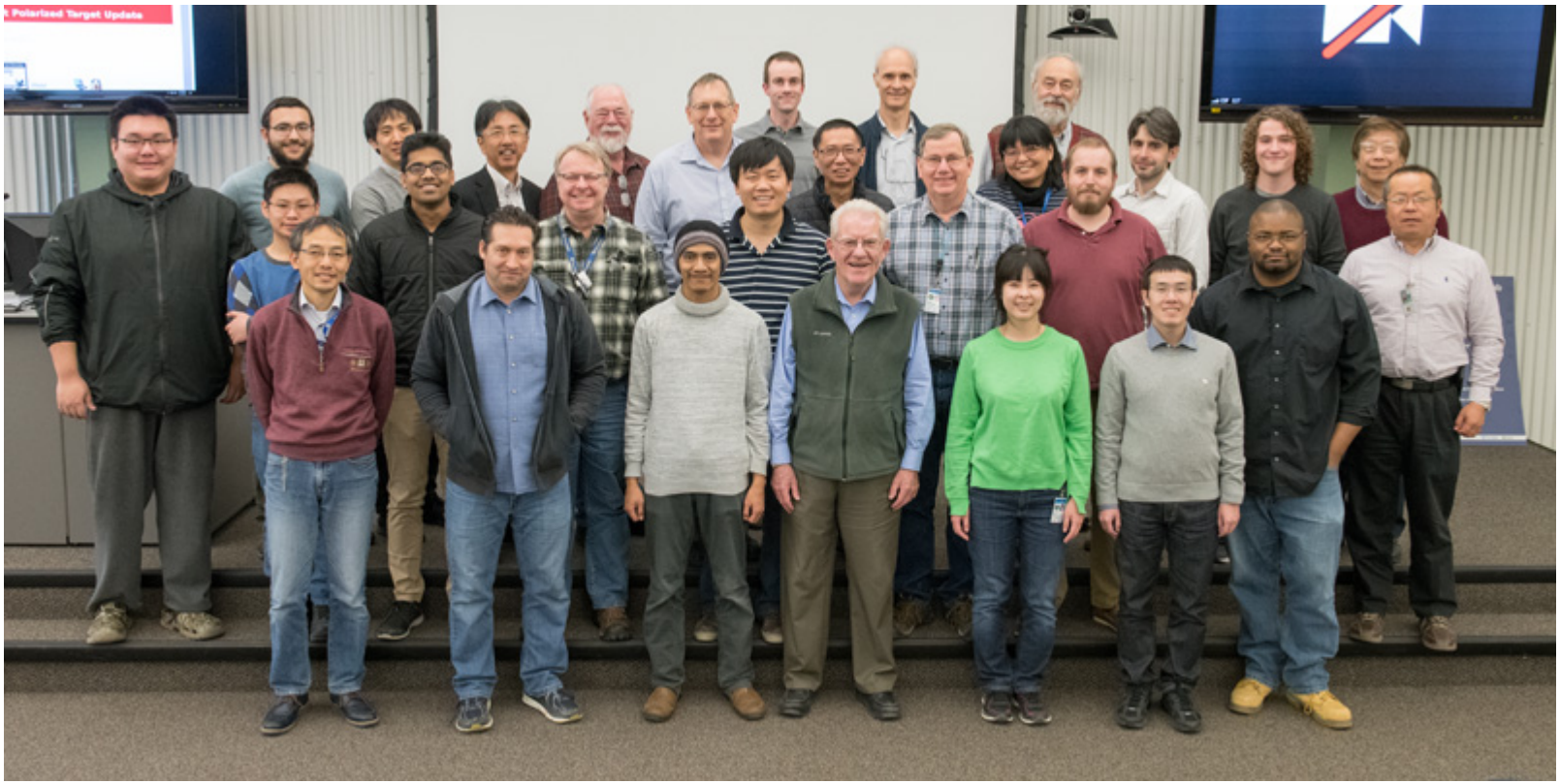


Phys. Rev. D88, 034016 (2013)

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

Experimental Status

FNAL-E1039/SpinQuest Collaboration



At Collaboration Meeting on March 7, 2019

- 15 institutions at present
- Spokespersons:

  Kun Liu <liuk@fnal.gov> (LANL) & Dustin Keller <dustin@jlab.org> (UVA)

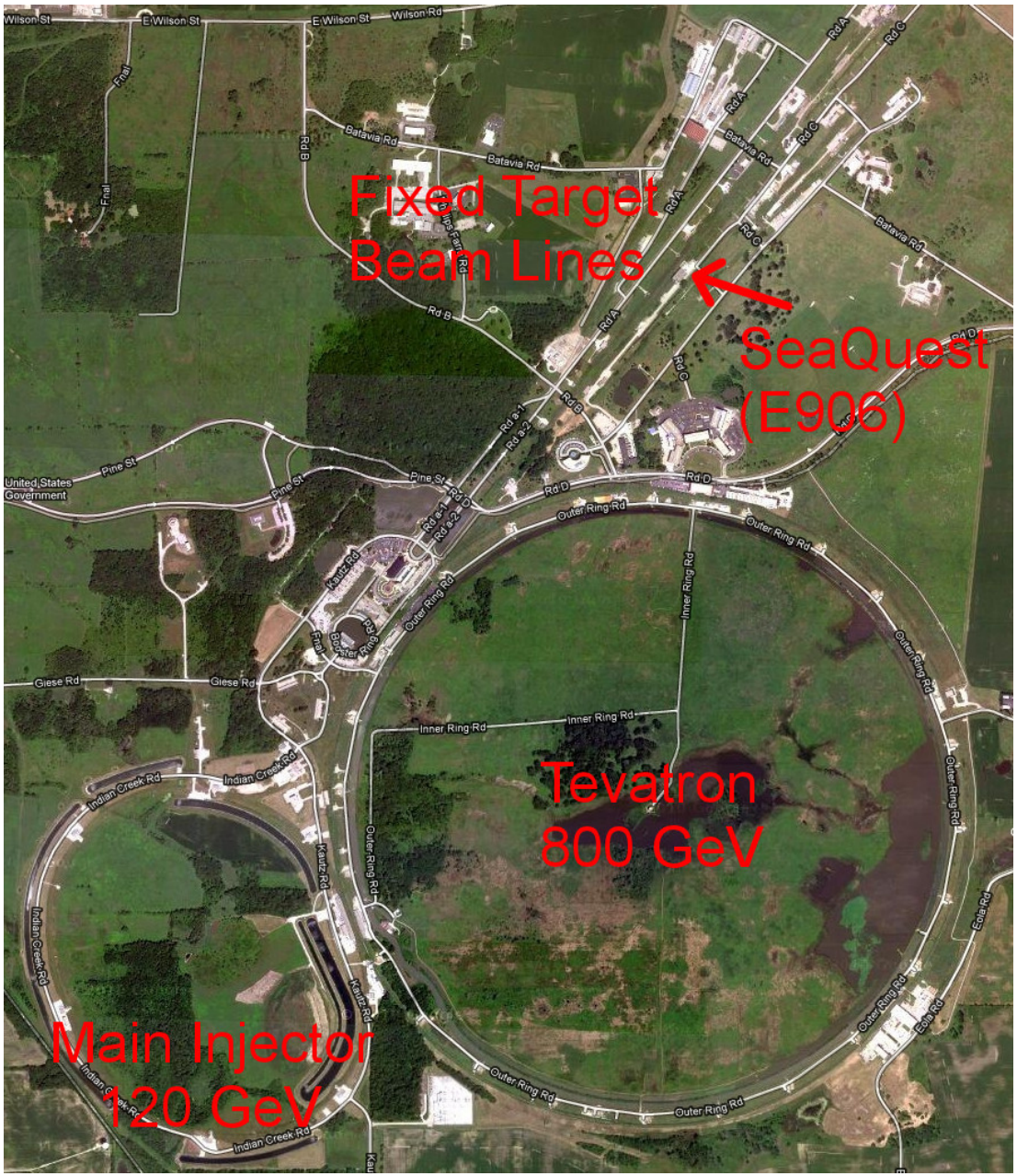
- https://spinquest.fnal.gov

E1039/SpinQuest Timeline

Year	Month	Event
2018	05	Granted Stage-2 approval from Fermilab
		Decommissioned E906/SeaQuest components
2019	06	Transfered the pol. target from UVA to Fermilab
	Now	Commission all components using cosmic rays
	Winter	Commission the whole system using proton beam
		Start the data taking
		$\Downarrow$ Run for two years
2021	Winter	Finish the data taking

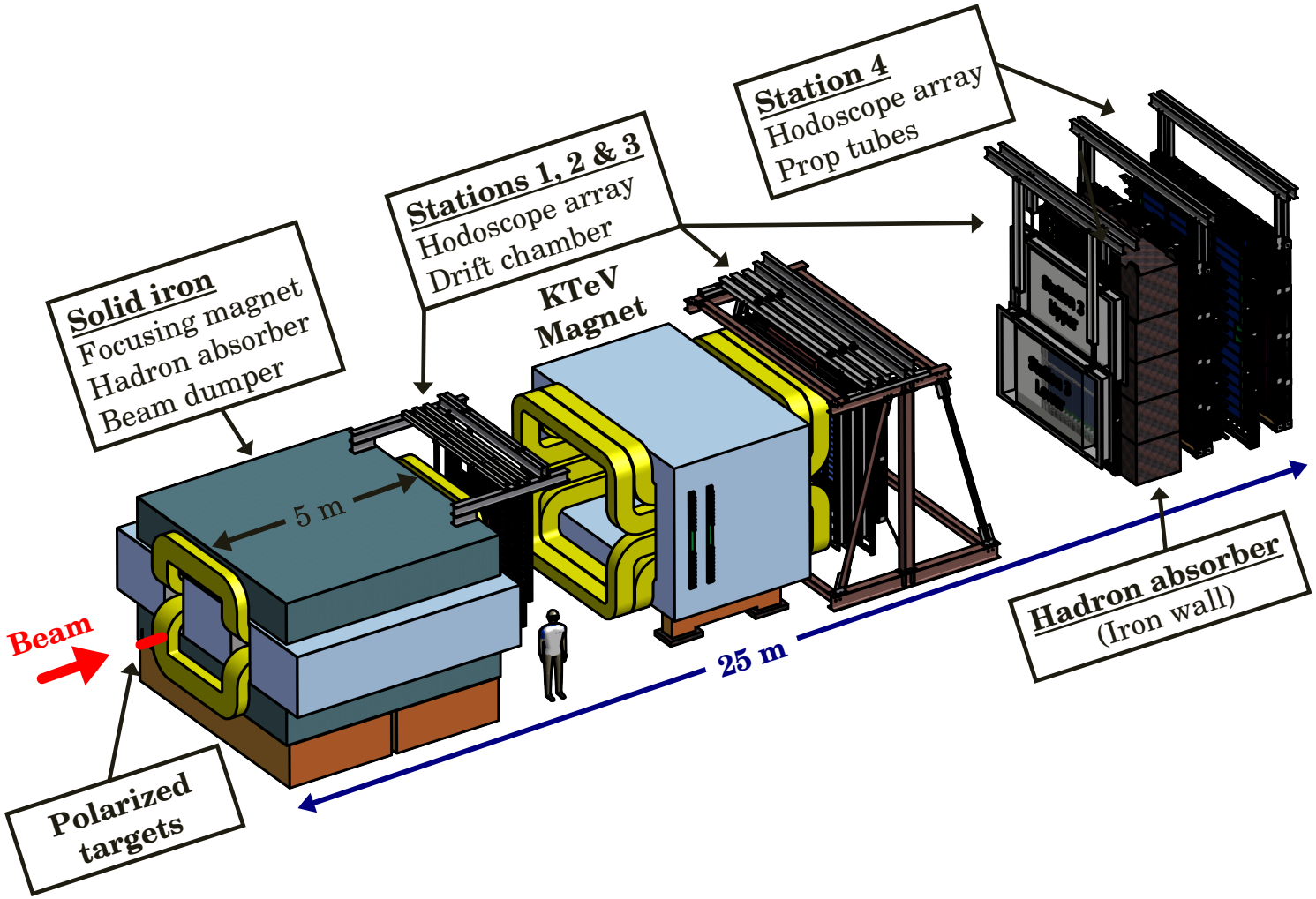
- We are considering quicker physics topics such as Transverse Single Spin Asymmetry (TSSA) of J/ψ production
  - $q + \bar{q} \gg g + g$ under E1039/SpinQuest kinematics
  - Sensitive to the Sivers function of anti-quarks and partly gluons

Fermilab Proton Beam



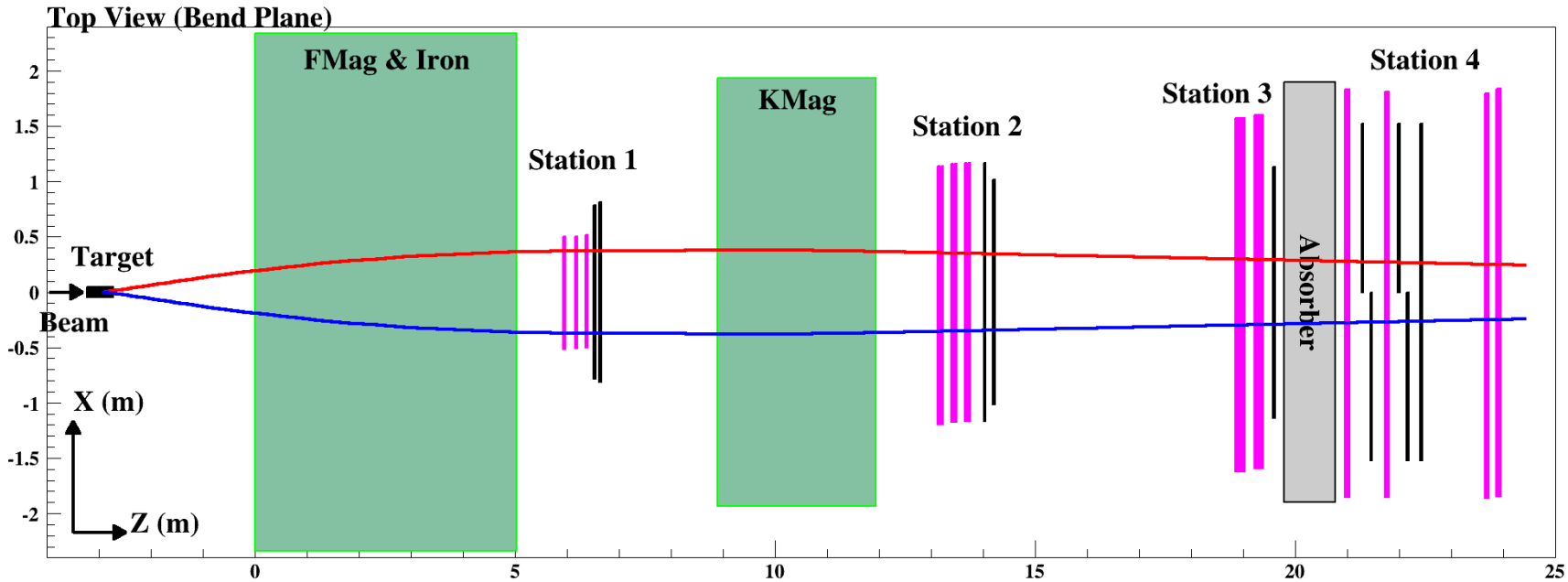
- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 4 sec for SpinQuest
  - 56 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 4×10^{12} protons in 4 sec

E1039/SpinQuest Spectrometer



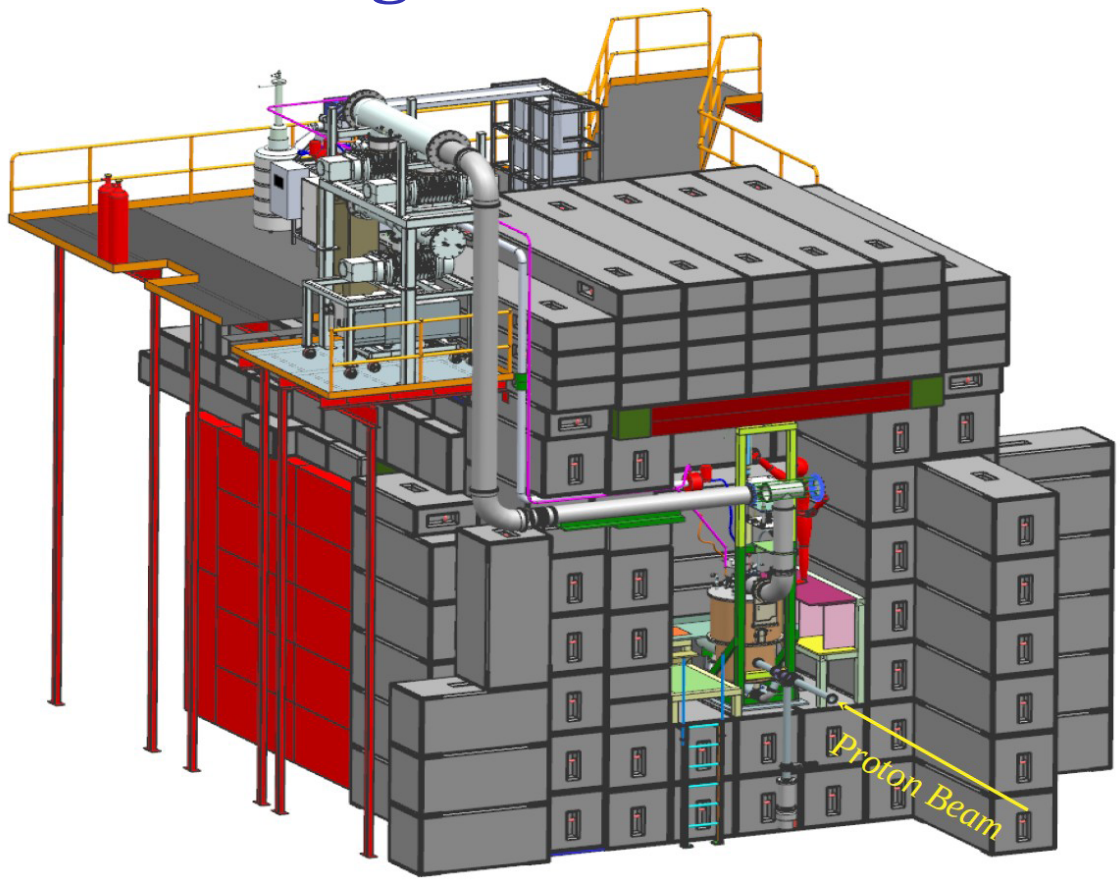
- Targets: transversely-polarized NH_3 & ND_3
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

- Typical Drell-Yan event
  - Muon momenta $\sim$ 40 GeV/c



- Detection of dimuons
  - Trigger with hodoscopes at Stations 1-4
    - $\times$7-finer hodoscopes will be installed at Stations 1 & 2 (width = 1 & 2 cm) for better random-background rejection and dark-photon search
  - Tracking with drift chambers at Stations 1-3
  - Muon identification with drift tubes at Station 4
  - Resolution: $dM/M \lesssim 10\%$ (dominated by the multiple scattering in FMag)

Beamline & Shielding



- Major modifications around target
  - More radiation shielding under new design
  - New cryo platform for target infrastructure
  - New location of target cave (300 cm upstream of FMag)
  - New collimator on beamline
- Special thanks to Fermilab accelerator division

- NM3: looking downstream

- NM4: looking upstream

  - Beam collimator
  - Target cave
  - Rad. shielding
  - Cryo platform

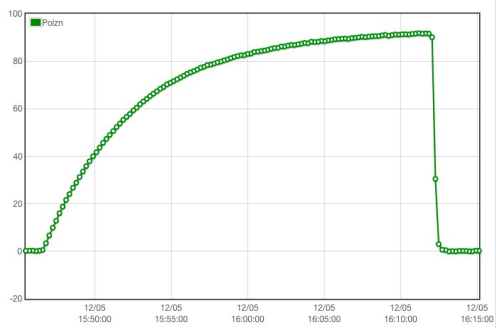
Polarized Targets

- Specification
  - Solid NH_3 & ND_3
  - Magnetic field: $B = 5$ T with $dB/B < 10^{-4}$
  - Size: L 80 mm, ϕ 40 mm

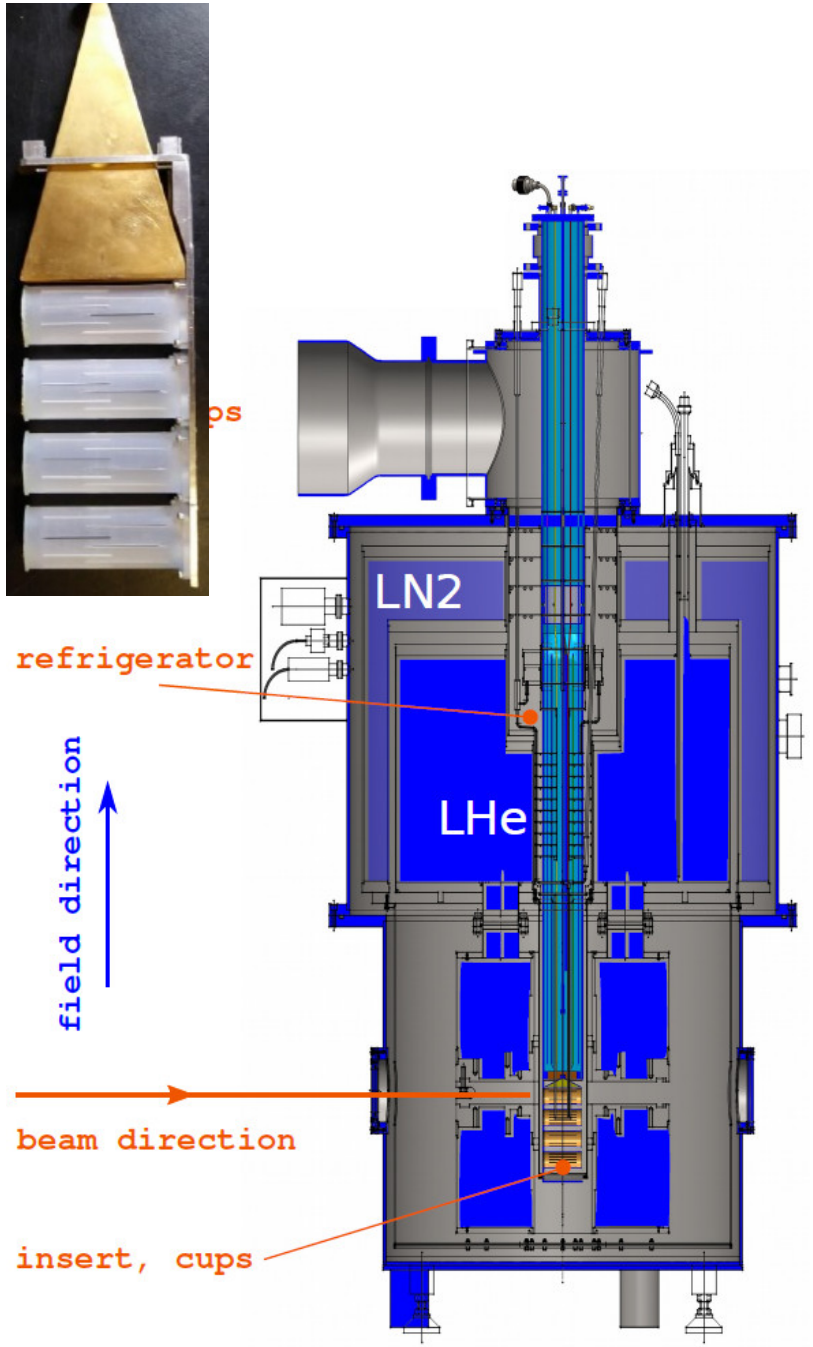
Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

- New polarized-target construction ... massive efforts by LANL & UVA
  - Change the field direction
  - Modify & insert 1K refrigerator
  - New device for cryostat
    - LHe pumps for high cooling capacity
    - He liquefier for liquid helium recirculation
  - New device for polarization
    - High power microwave source
    - NMR system

- Three material cells (+ one spare)
  - NH_3, ND_3 & Empty
  - Target materials will be replaced every $\sim$10 days due to radiation damage
- Polarization
  - Via DNP
  - $>90\%$ for NH_3



  - Flipped per day
- Performance under the beam radiation?
  - 4×10^{12} protons in 4 sec
  - Feasible based on heat-deposit simulation
  - To be tested in the beam commissioning



Summary

- The Sivers function of anti-quarks
  - Not well known, since not well separated from quark in SIDIS
  - Could be a "Smoking Gun" evidence for $L_{\bar{q}} \neq 0$
- E1039/SpinQuest at Fermilab
  - Measure TSSA of proton-induced Drell-Yan process
  - Use transversely-polarized NH_3 & ND_3 targets
  - Anticipate the measurement accuracy $\delta_{A_N} \sim 0.04$ at $0.1 \lesssim x \lesssim 0.3$
  - Extract the Sivers functions of $\bar{u}$ & $\bar{d}$ separately
- Preparation for the data taking
  - Commission all components using cosmic rays and then the proton beam
  - Start the data taking this winter for two years