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Title: A Future Polarized Drell-Yan Experiment at Fermilab

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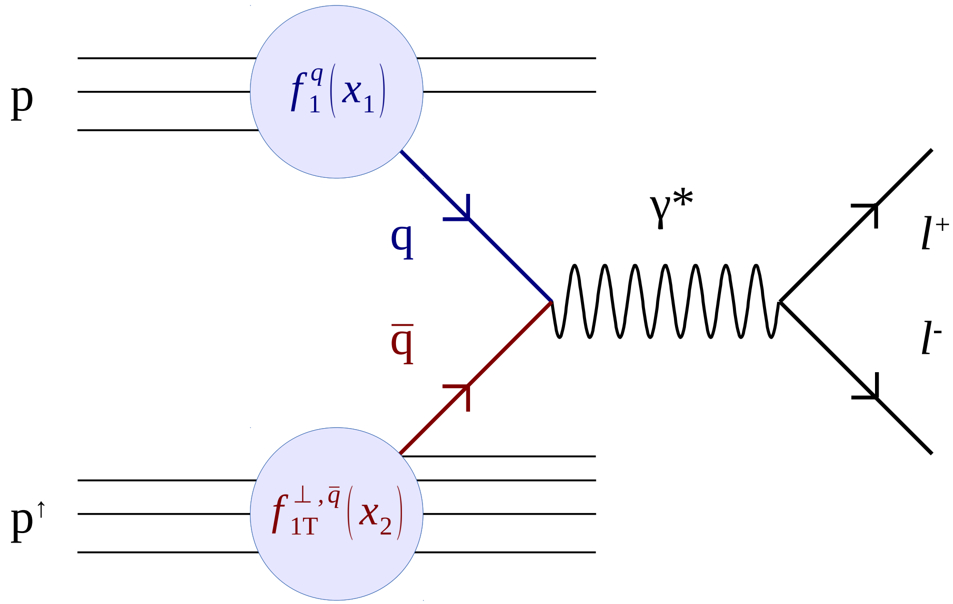
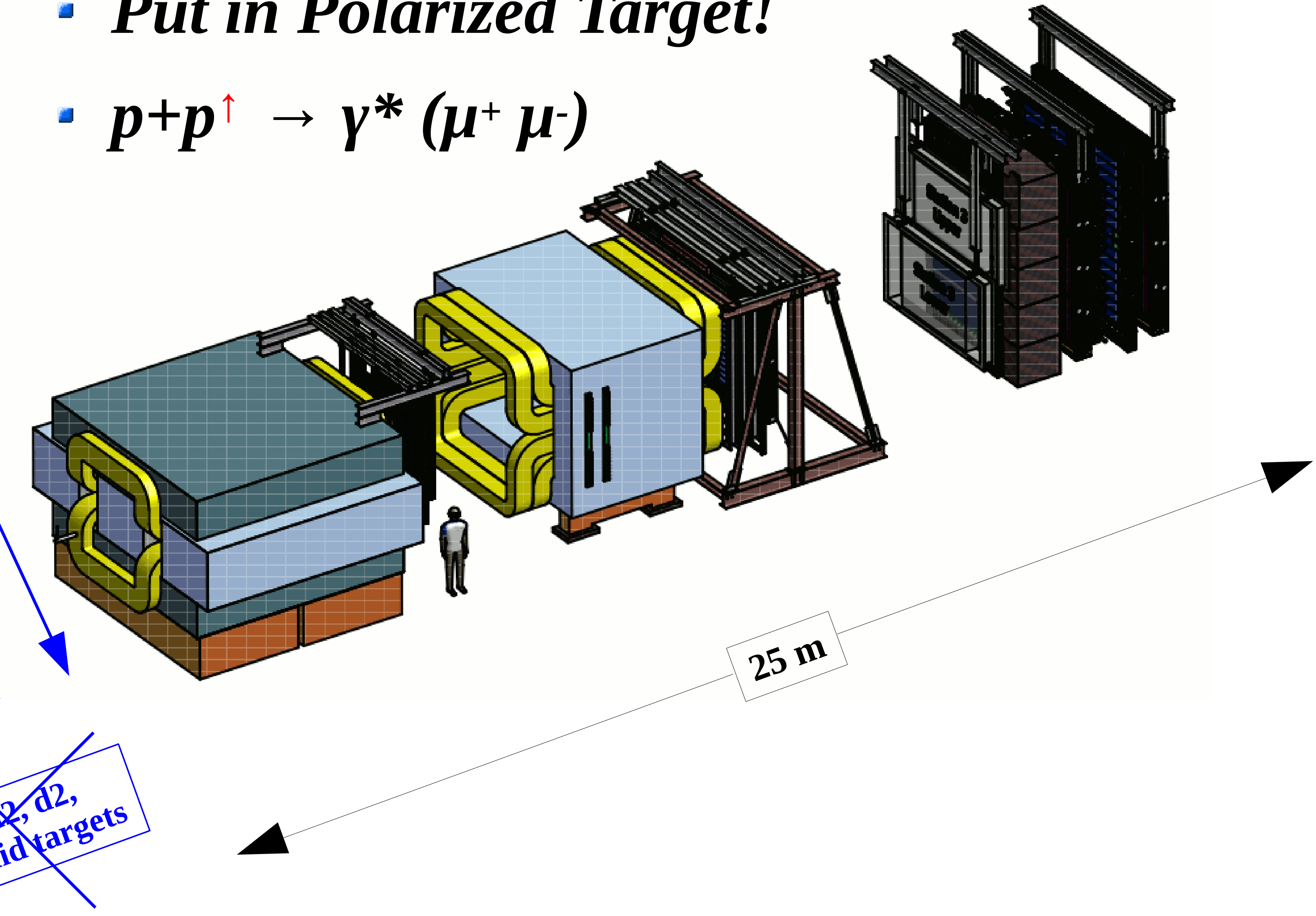


A Future Polarized Drell-Yan Experiment at Fermilab

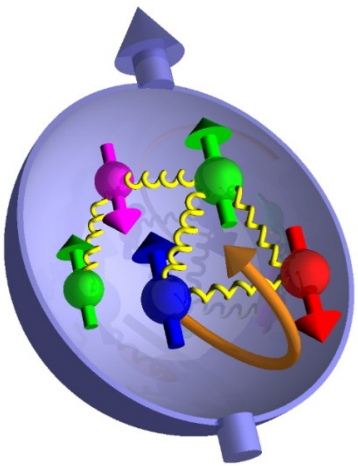
David Kleinjan
Los Alamos National Laboratory
E906/E1039 Collaboration

E906 (Seaquest) → E1039 in a Nutshell

- ***Put in Polarized Target!***
- ***$p+p^{\uparrow} \rightarrow \gamma^* (\mu^+ \mu^-)$***

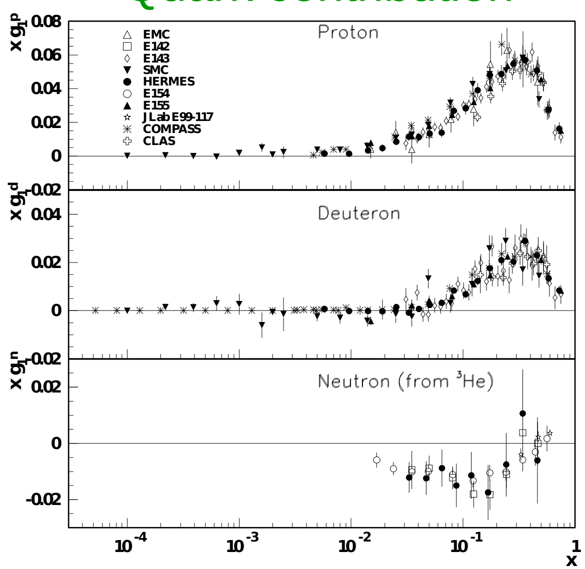


Nucleon Spin Puzzle



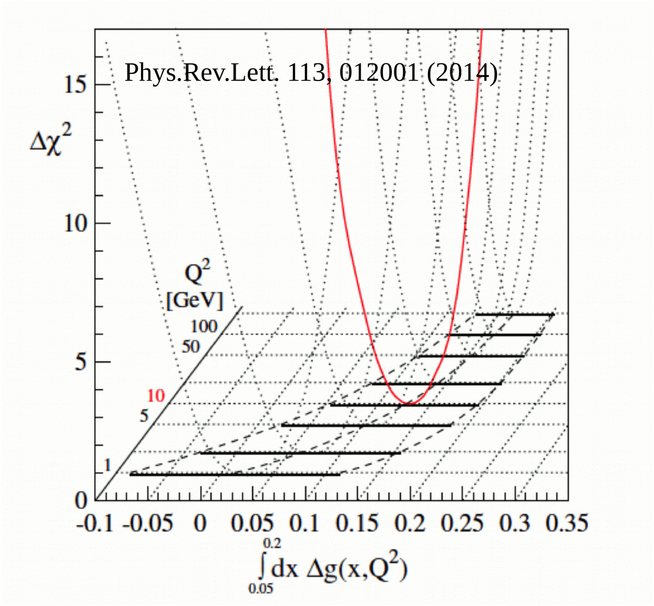
$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Quark contribution



$$\Delta\Sigma \approx 0.25\pm\ldots$$

Gluon contribution



$$\int_{0.05}^{0.2} dx\,\Delta g(x) = 0.2\pm0.06$$

~50% Missing?

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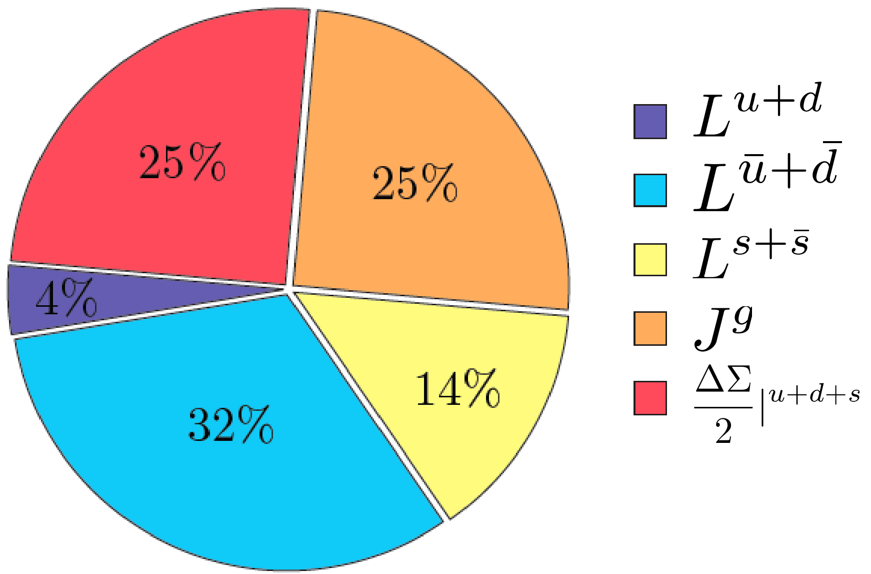
Nucleon Spin Puzzle

$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_g + L_q + L_{\bar{q}}$$

- Lattice QCD calculations indicate as much as 50% come from quark O.A.M.
- **$\Delta L_{valence}$ ≈ Small**
- *Hints of sea quark O.A.M already seen*

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



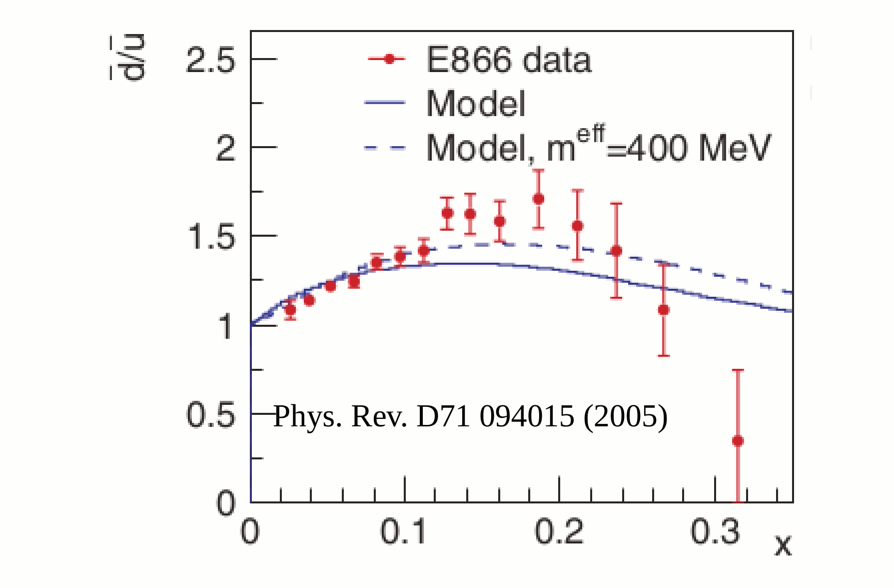
$\Delta\Sigma_q \approx 25\%$

$2\ L_q \approx 46\%[0\%(L_{valence})+46\%(L_{sea})]$

$2J_g \approx 25\%$

$L_u \approx -L_d$

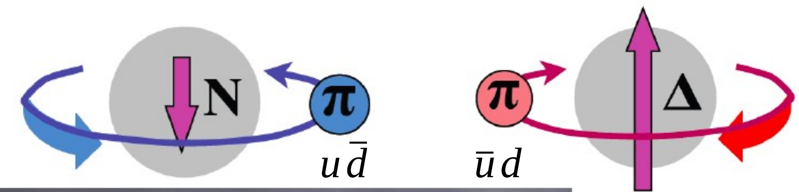
Hints of Non-zero Sea Quark O.A.M.



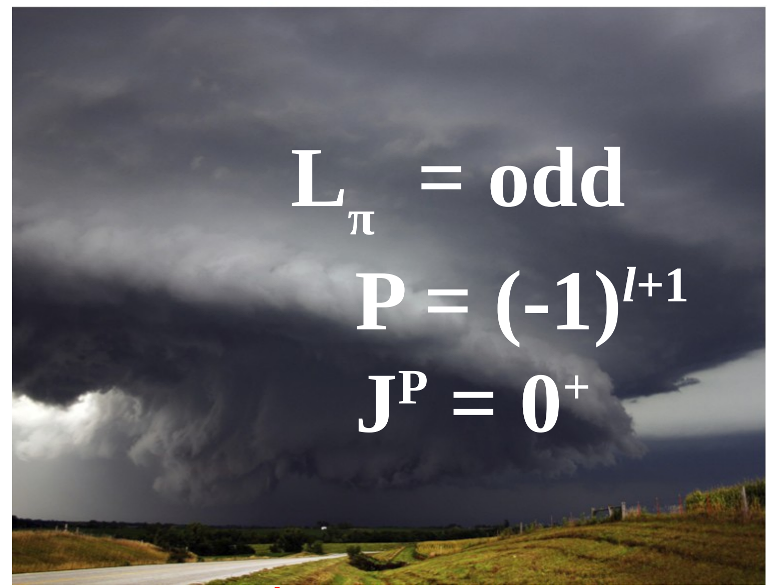
$|p\rangle = |p\rangle + |N^0\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$

Pions: $J^p=0^-$ Negative Parity

Need **L=1** to recover proton's $J^p=½^+$



- The pion cloud model
  - Simple parity conservation
  - **Pions have nonzero O.A.M.**



Sea quarks should carry orbital angular momentum.

Can be quantified via the TMD Sivers function.

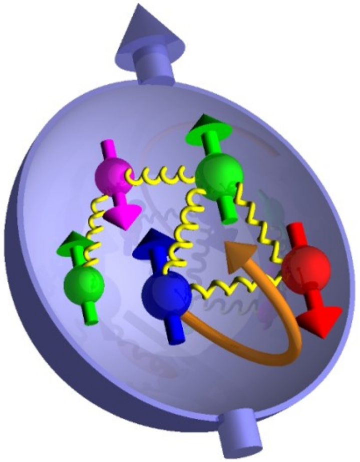
Leading Twist TMD PDFs

Nucleon \ Parton	U	L	T
U	Unpolarized $f_1(x)$		Boer-Mulders $h_1^{\perp}(x, k_T)$
L		Helicity $g_{1L}(x)$	Worm-Gear $h_{1L}^{\perp}(x, k_T)$
T	**Sivers** $f_{1T}^{\perp}(x, k_T)$	Worm-Gear $g_{1T}^{\perp}(x, k_T)$	Transversity $h_{1T}(x)$ Pretzelosity $h_{1T}^{\perp}(x, k_T)$

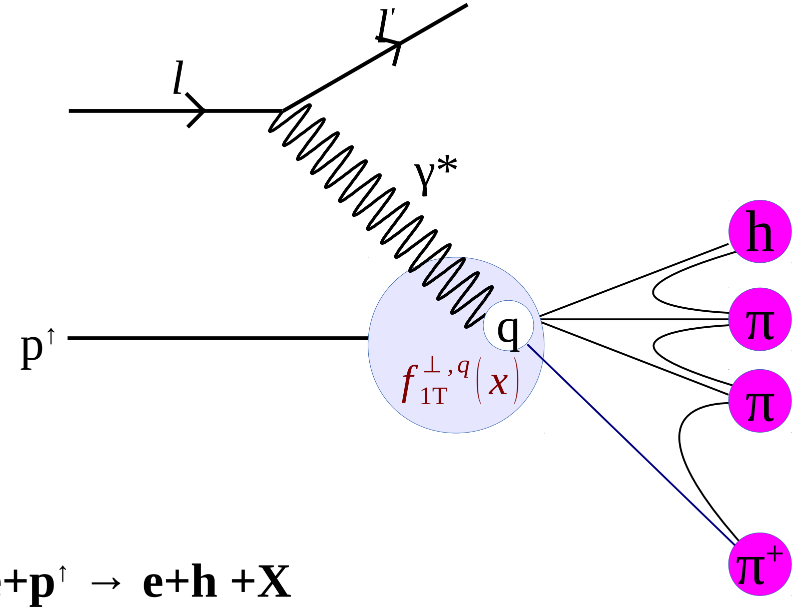
Legend
- Nucleon
- Parton
- Parton TMD

Quark Orbital Momentum and the Sivers Function

- One of 8 TMD PDFs: $f_{1T}^{\perp}(x, k_T)$
  - Correlation between proton's transverse spin and transverse parton momentum
- Quark Sivers Function Directly accessible with:

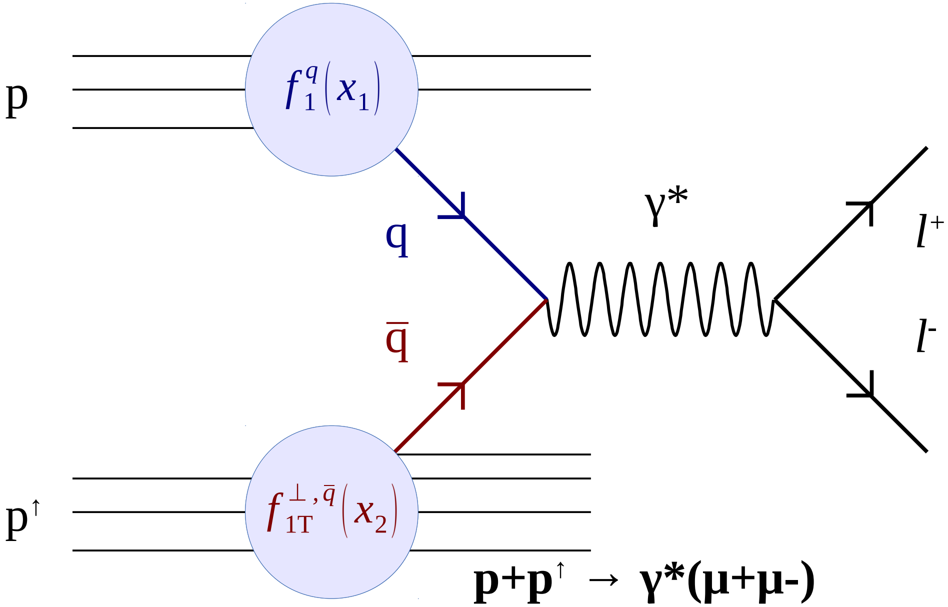


Polarized Semi-Inclusive DIS



$e+p^{\uparrow} \rightarrow e+h+X$

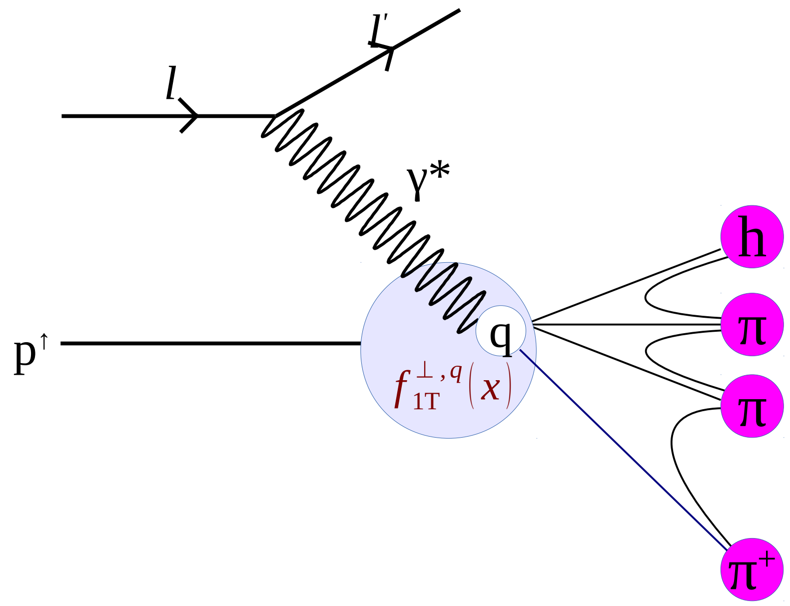
Polarized Drell-Yan



$p+p^{\uparrow} \rightarrow \gamma^*(\mu+\mu-)$

Accessing Quark Sivers distribution

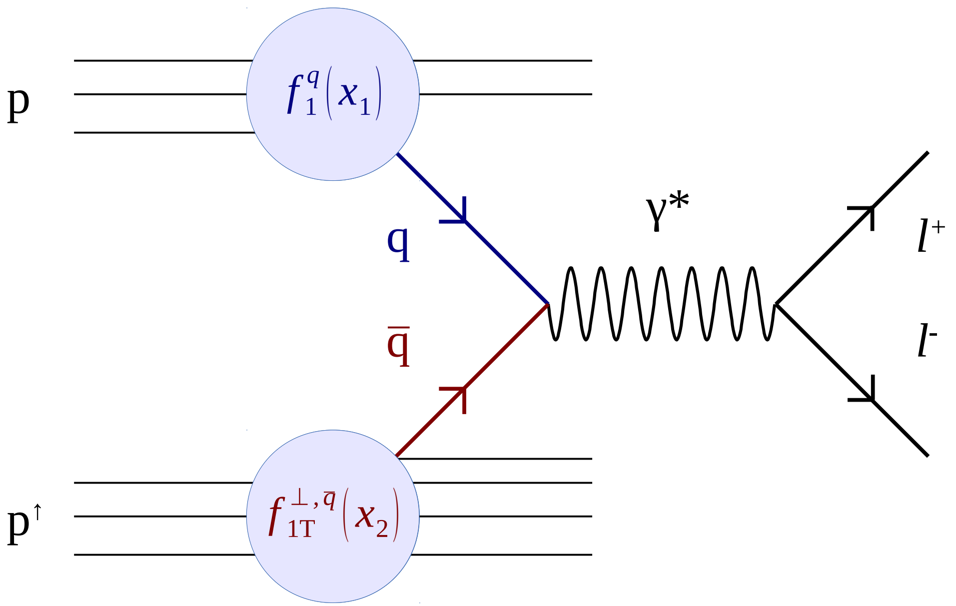
Polarized Semi-Inclusive DIS



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

- L-R asymmetry in hadron production
- Quark to Hadron Fragmention function
- Valence-Sea quark: Mixed

Polarized Drell-Yan

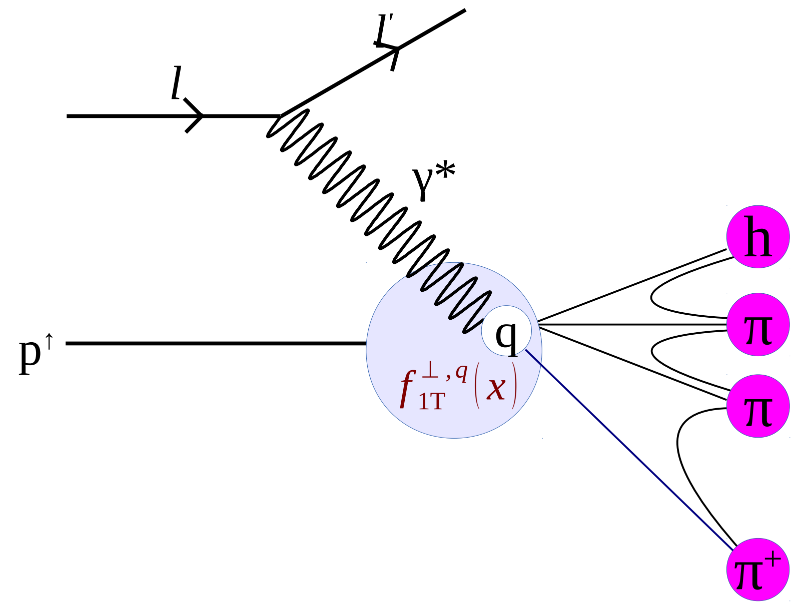


$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}$$

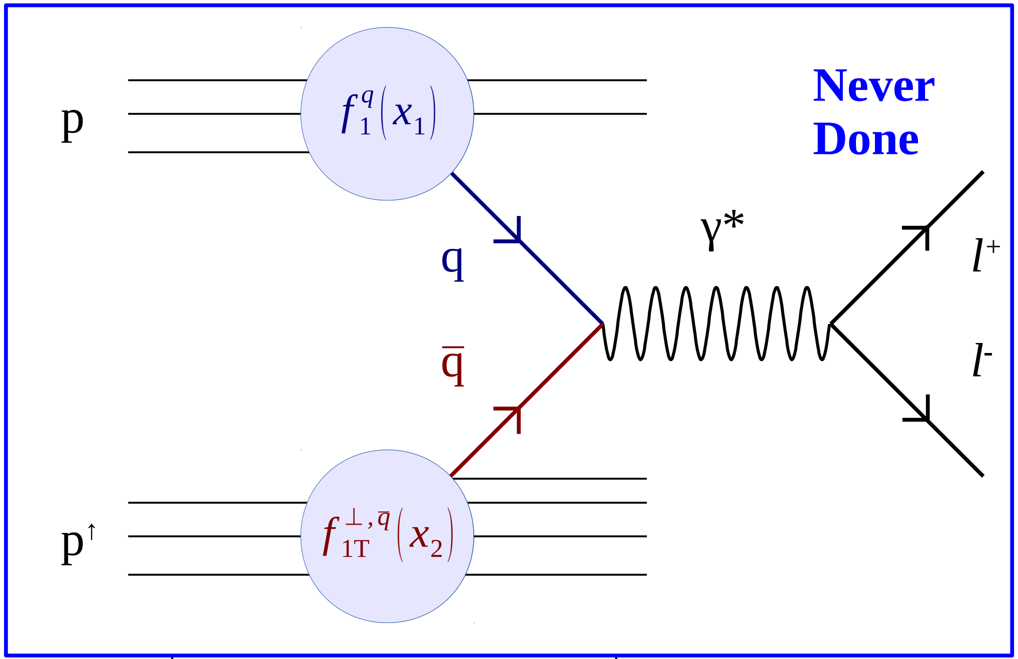
- L-R asymmetry in Drell-yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated**

Accessing Quark Sivers distribution

Polarized Semi-Inclusive DIS



Polarized Drell-Yan

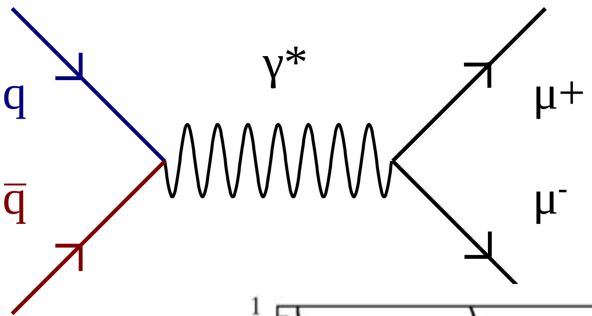


$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$

- **Cornerstone Prediction of QCD**
  - The same Sivers distribution in both processes
  - But with opposite sign
    - T-Odd
    - Initial state, Final state switch

Quark	SIDIS	DY
Valence	Known $f_1^u(x) \approx -f_1^d(x)$	Unknown (COMPASS)
Sea	Poor Sensitivity	Unknown (E1039)

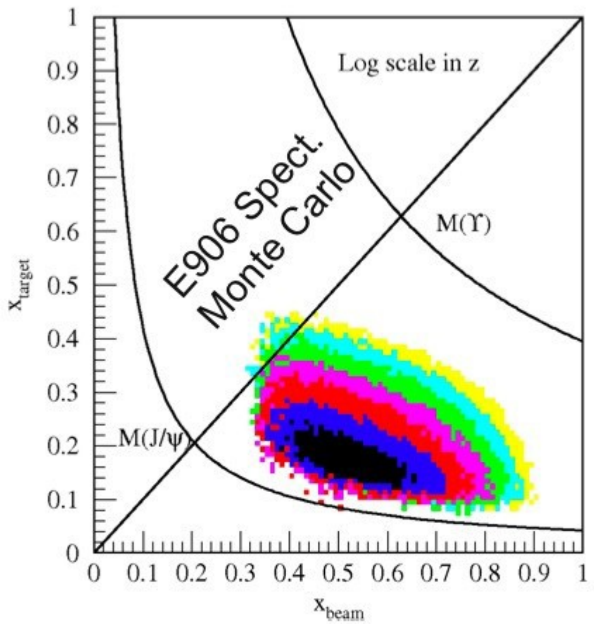
Accessing Sea quarks via Drell-Yan

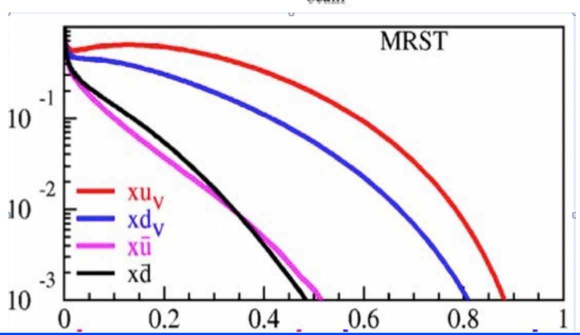


dominates   small

$$\frac{d^2\sigma(q\bar{q}\rightarrow\mu^+\mu^-)}{dx_b\,dx_t}=\frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)\,q_b(x_b)+\cancel{q_t(x_t)\,\bar{q}_b(x_b)}\right]$$

target sea quark   beam valence quark





- Fixed Target Drell-Yan
  - Seaquest Experiment
- In p+p kinematics
  - Quark from Beam
  - AntiQuark from Target
- Excellent Acceptance Sea Quark Region of interest ($0.1 < x_B < 0.4$)

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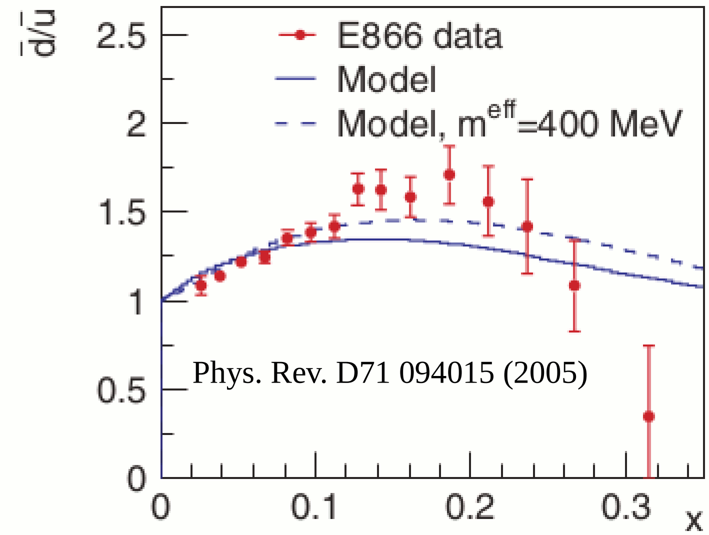
E1039 Physics Summary

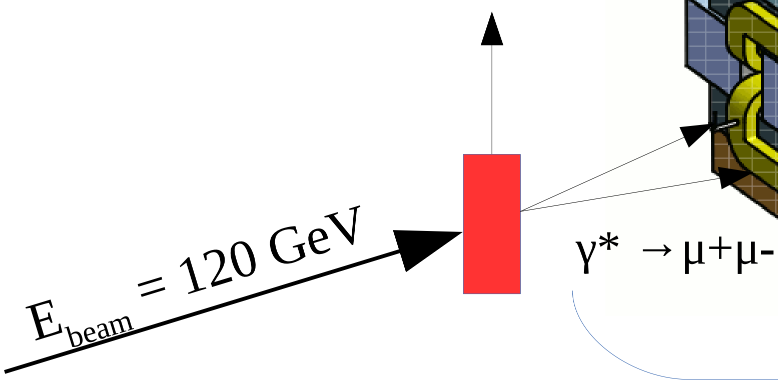
- Little is known about Sea Quark Angular Momentum
- E866 data, interpreted by the pion cloud model points to non-zero sea quark angular momentum
- The E1039 Polarized Target Drell-Yan Experiment provides opportunity to study possible Sea Quark O.A.M.
  - **Continuation of Seaquest Experiment**
  - Measure:

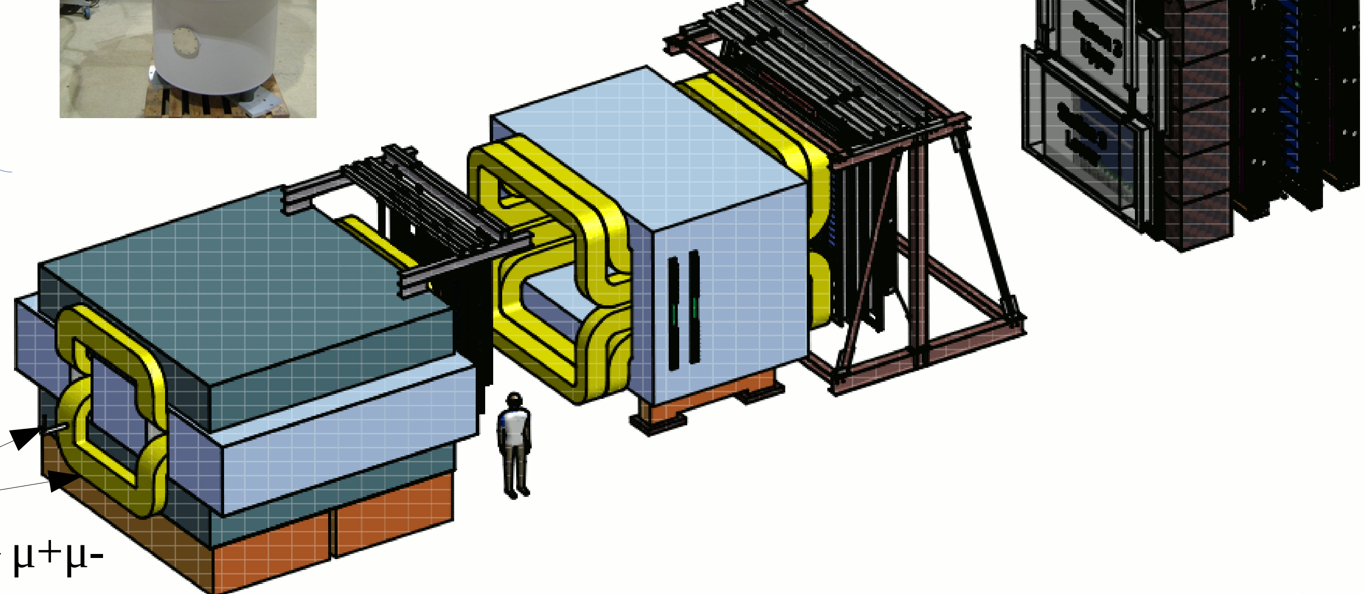


$$A_N\left(p_{beam}+p^{\uparrow}_{target}\rightarrow DY\right)\propto\frac{N_L^{DY}-N_R^{DY}}{N_L^{DY}+N_R^{DY}}\propto\frac{f_{1T}^{\perp,\bar{u}}\left(x_t\right)}{f_1^{\bar{u}}\left(x_t\right)}$$

What is needed for E1039

- **Proton Beam**
  - **Improved Focusing**
  - **In Development at FNAL**
- **Polarized Proton Target**
  - **In Development at LANL, UVa**
  - **New Shielding by FNAL**
- **Dimuon Spectrometer**
  - **Seaquest experiment**
- **Collaboration**





FNAL proton beam

Polarized Target

Successfully running Seaquest Dimuon Spectrometer
Elan McClellen's Talk Previous

Procedure to Polarize Protons

- Utilize Dynamic Nuclear Polarization
  - Thermal Equilibrium Polarization from Boltzman Distribution, Zeeman Splitting of Spin States

$$P_{(s=1/2,i)} = \tanh\left[\frac{\mu_i g_i B}{2 k_B T}\right]$$

    - T = 1 Kelvin, B = 5 Tesla
      - $P_{electron} = 0.998$
      - $P_{proton} = 0.005$, since $\mu_N/\mu_B \sim 10^{-3}$
- *Can polarize protons in Paramagnetic material through RF transitions*
  - Target Material: Irradiated NH_3

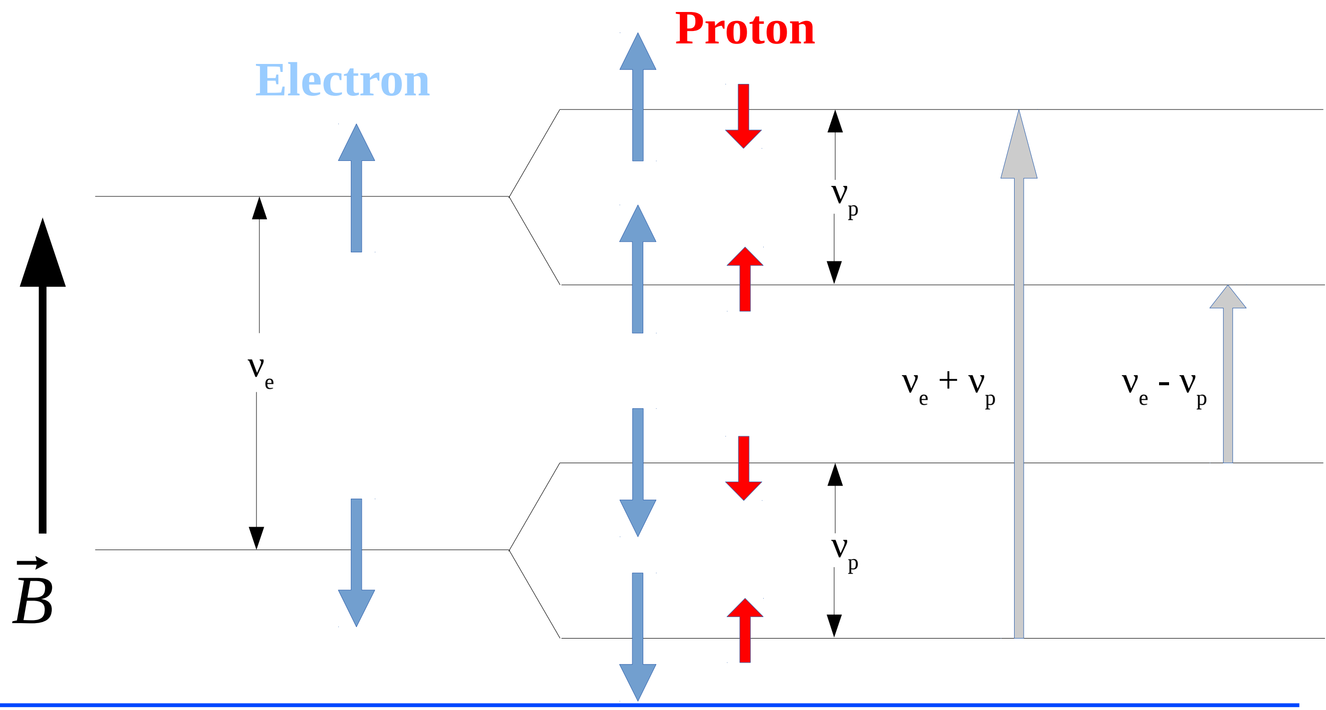
JLab Target

Procedure to Polarize Protons

- *Can polarize protons in Paramagnetic material through RF transitions*
  - Irradiate NH_3 to Create Paramagnetic Centers
  - Dipole-Dipole interaction between electron-proton
  - Pump on electrons @ Larmor Frequencies $\nu_e \pm \nu_p$ = 140.127 ± 0.213 GHz

$$P_{(s=1/2,i)} = \tanh\left[\frac{\mu_i g_i B}{2 k_B T}\right]$$

- $\tau_e \ll \tau_p$ (relaxation time)
- Polarization up to 90%
- **Measure How?**



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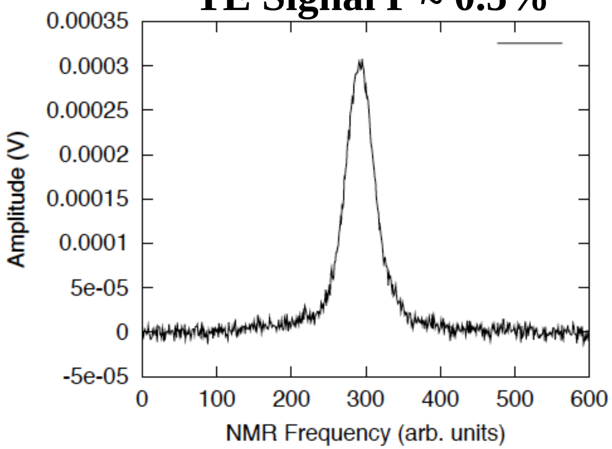
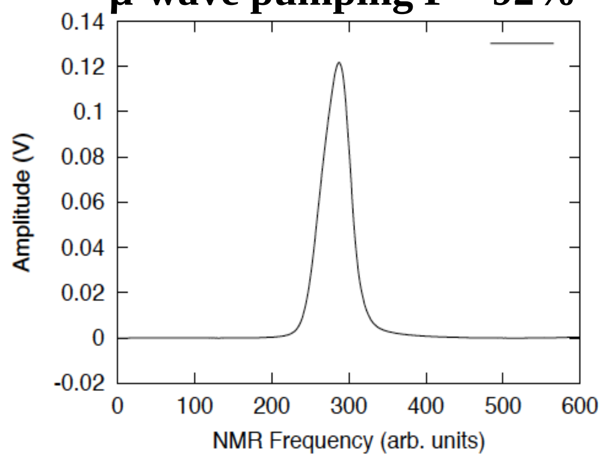
Proton Polarization Measurement using NMR

- Polarization measurement using NMR technique, basics
  - Apply RF at proton Larmor frequency, $\nu_p \approx 213$ MHz, to RLC circuit
  - Measured with an inductor coils around target
  - Measures Polarization of Protons by absoption or emission of RF
  - Voltage increases for absorption, decreases for emission (spin flip up/down)
- *213 MHz RF high gain system*
- *Stable, low noise system required to detect TE signal*

TE Signal P ≈ 0.5%



μ-wave pumping P ≈ 92%



JLab Target

NMR Coil (inductor) around target.

Keith et al. NIM A 501 (2003), 327 JLAB
Well established technology: SLAC, JLAB, PSI…

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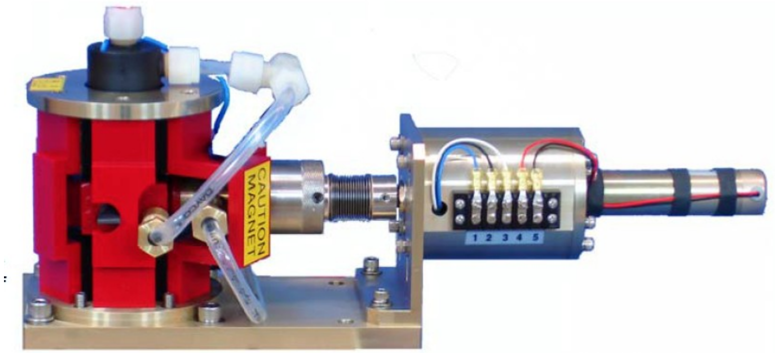
What is Needed for Polarized Target



- 5T magnetic Field
  - Liquid ^{4}He cooled Superconducting magnet
- 1K Temperature
  - Liquid ^{4}He cooled using evaporation techniques
- RF transition provider
  - 140 Ghz Microwave tube
- Polarization Measurement
  - NMR apparatus

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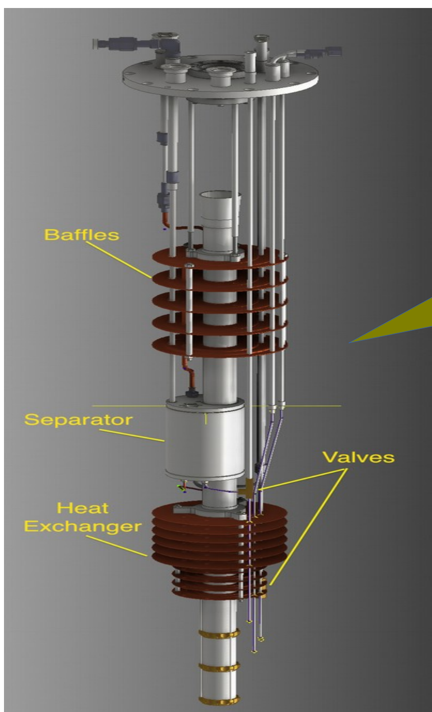
Polarized Target System

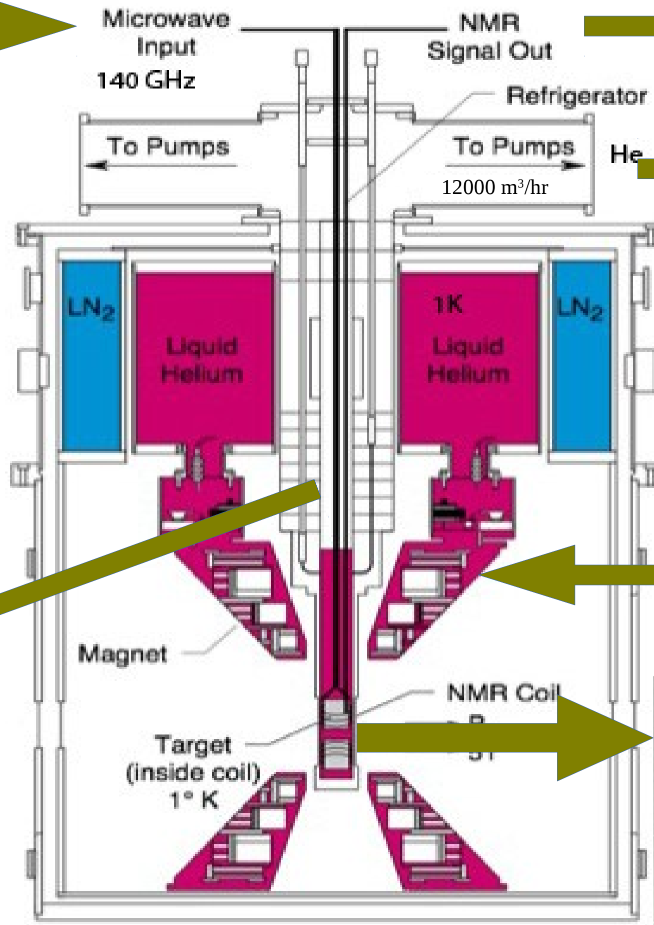
Microwave signal to
Induce spin flips

NMR Polarization
Measurement

Roots pump system used to
pump on liquid ^4He
evaporation to reach 1K

Cryostat: UVa





Superconducting
Coils for Magnet: 5T

JLab Target
(example)

μ-wave
horn

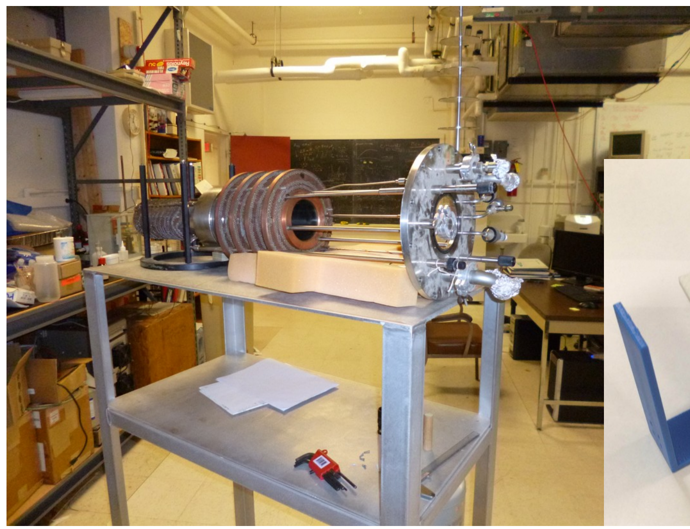
Target Material NH_3
Irradiated at NIST

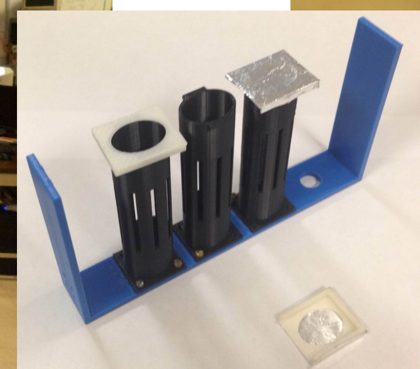
Status of E1039 Experiment

<u>Magnet:</u>

- Oxford Instruments
- Refurbished
  - New electronics, gauges, meters
- Acceptance Tests performed flawlessly

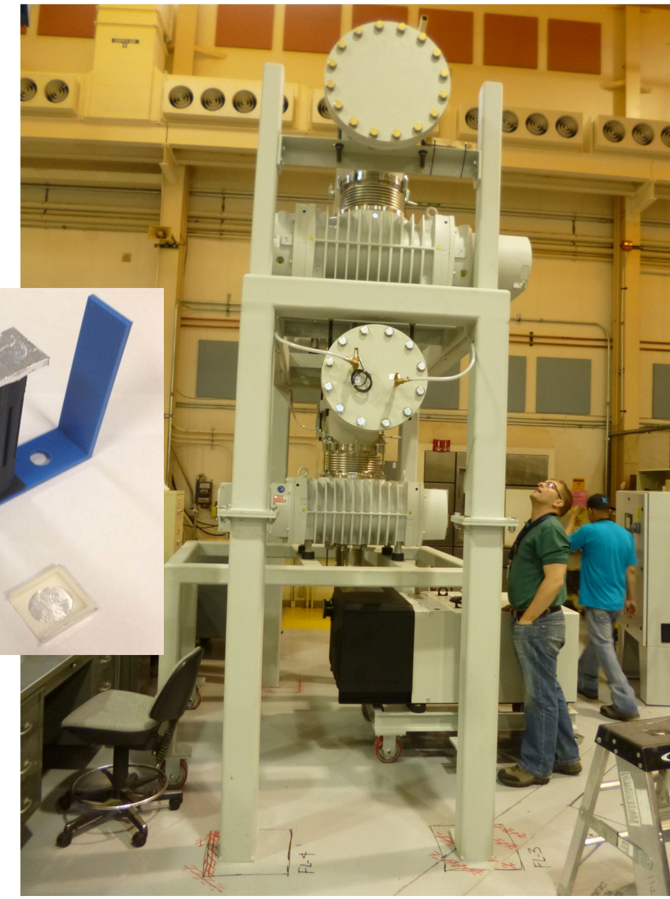
<u>Cryostat + Target Stick:</u>





- Design at UVa
- Elliptical tube 8cm long
- Will have two target sticks with two-three cells each

<u>Pumps:</u>

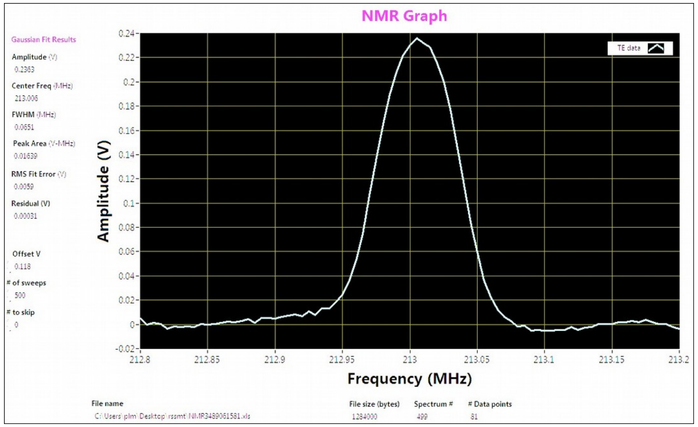


- Performance tests underway at LANL

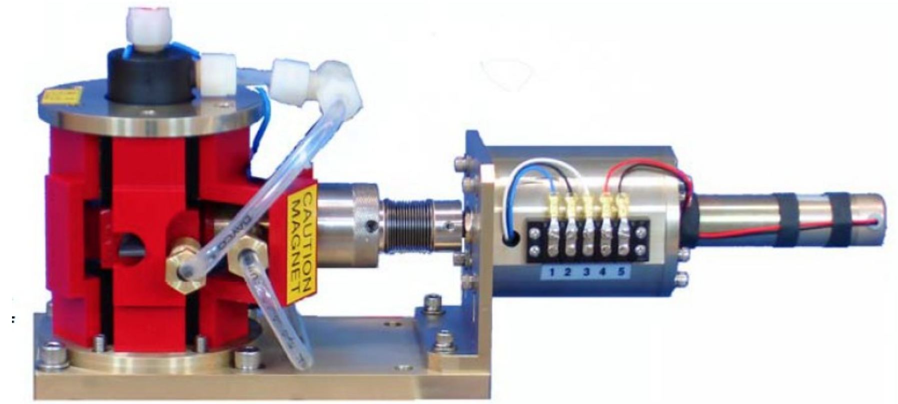
Status of E1039 Experiment

NMR System:

- Designed and Developed at LANL
- Tested 7/2014, worked well
- Layout for VME crate cards finished



Microwave Tube:



- New 140GHz tube purchased
- New Power supply purchased
- Backup Tube U of Mich
- Backup Power Supply UVa

Yield and Asymmetry Estimates

- One year L = 5.22x10^{42} cm^{-2}
- Target and Accelerator Efficiency: 50%
- Spectrometer Efficiency: 80%
- Cross Section σ_{DY} = 0.024 nb
  - Kinematic Range: 4 < M < 9 GeV, -0.2 < x_F 0.8

N^{DY} = eff.*L*σ_{DY}

Cuts	Acceptance/ Efficiency	Events
All DY in kinematic range	100%	5.01E+07
$\mu+\mu-$ geometric acceptance	2.2%	1.10E+06
Trigger Efficiency	58%	6.39E+05
$\mu+\mu-$ Pair Reconstruction Efficiency	57%	3.68E+05

Based on Present Beam and Spectrometer Performance at Seaquest

$$A_N^{DY} = \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}}$$

$$\boxed{\Delta A_N^{DY} = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N_{total}}}}$$

- f ≈ 3/17
- P ≈ 0.80

E1039 Est.

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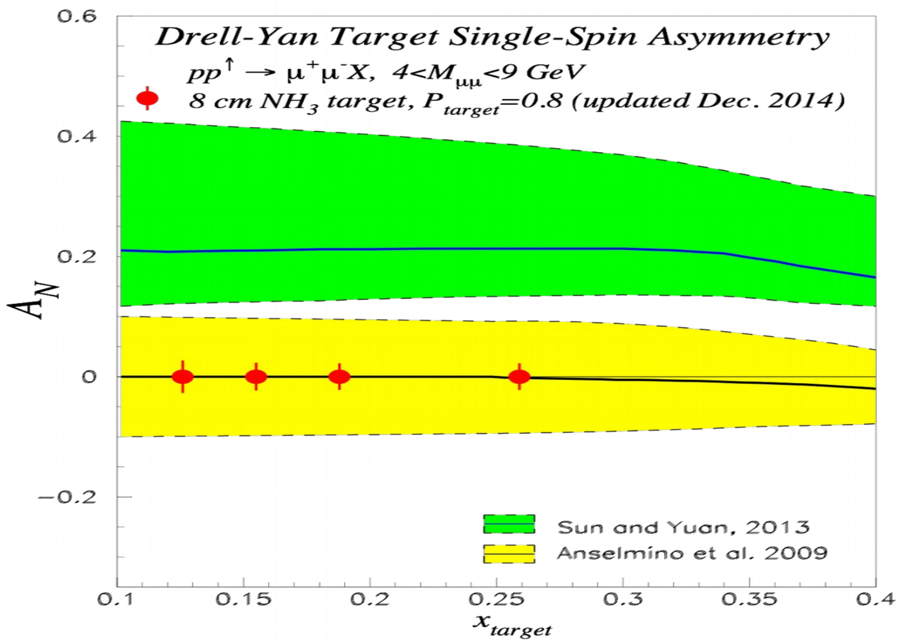
Summary and Conclusion



Statistics shown for one calendar year of running :
L = 5.2 *10^{42} cm^{-2}, POT = 9.7*10^{17}
Running will be two calendar years of beam time

Begin Setup Fall 2016
Start taking data Spring 2017!

$$A_N^{DY} \propto \frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

- First measurement of sea quark Sivers (ū)
- Sign and value
- If $A_N \neq 0$
  - Major discovery
  - Evidence for $L_{sea} \neq 0$
- If $A_N = 0$
  - $L_{sea} = 0$? Where is nucleon spin?
  - Source of Sea flavor asymmetry a mystery

Thank you On behalf of E906/E1039 Collaboration

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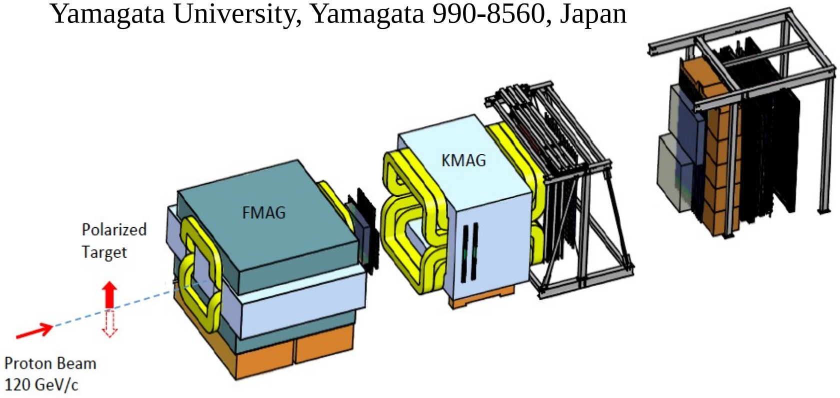

Backup

Systematics

- Systematics control
  - Reverse pol direction once a day
  - Reverse Fmag,Kmag every two days
  - Reverse 5T magnet every target replacement
  - Background measurements every shift with target out
- Absolute 1%
  - Luminosity precision on different pol directions

Leading Twist TMD PDFs

Nucleon \ Parton	U	L	T
U	Unpolarized` $f_1(x)$		Boer-Mulders $h_1^{\perp}(x, k_T)$
L		Helicity $g_{1L}(x)$	Worm-Gear $h_{1L}^{\perp}(x, k_T)$
T	**Sivers** $f_{1T}^{\perp}(x, k_T)$	Worm-Gear $g_{1T}^{\perp}(x, k_T)$	Transversity $h_{1T}(x)$ Pretzelosity $h_{1T}^{\perp}(x, k_T)$

Outline

- Motivation
  - Nucleon Spin Puzzle
  - Quark Orbital Momentum and the Sivers Function
  - Accessing Sivers via *Polarized* Drell-Yan ($p+p^{\uparrow} \rightarrow \mu^{+}\mu^{-}$)
- Transition of Seaquest (E906 → E1039)
  - Building a Polarized proton Target
  - Status of Polarized Target
- Outlook