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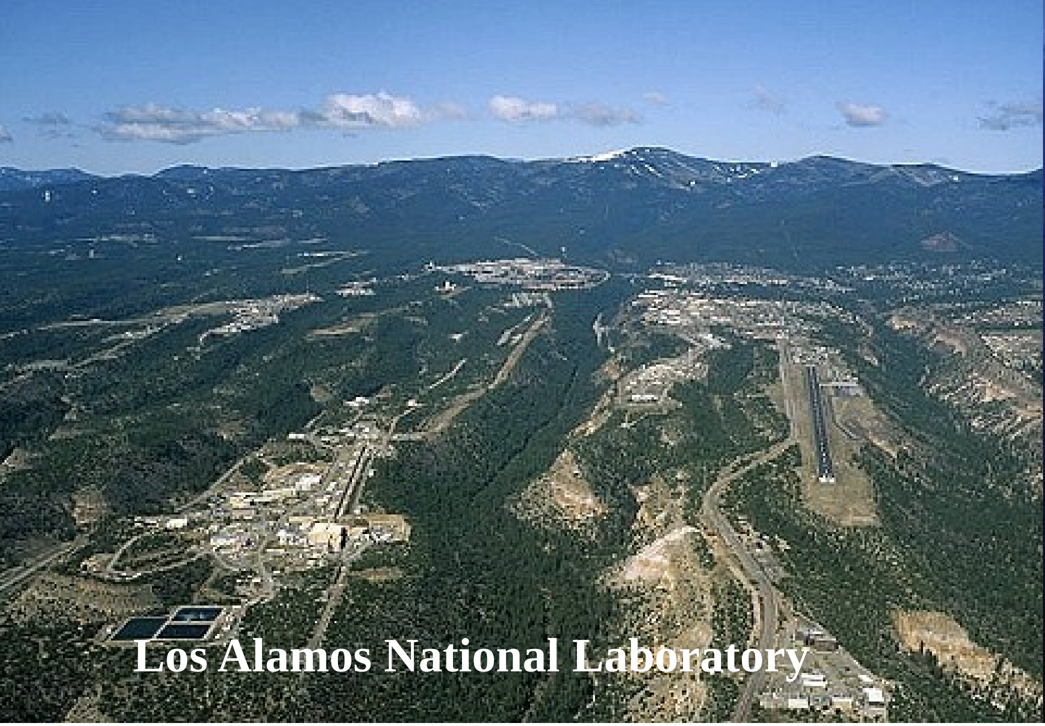


A Polarized Drell-Yan Experiment to Probe the Dynamics of the Nucleon Sea

David Kleinjan
Los Alamos National Laboratory
E1039 Collaboration

Outline

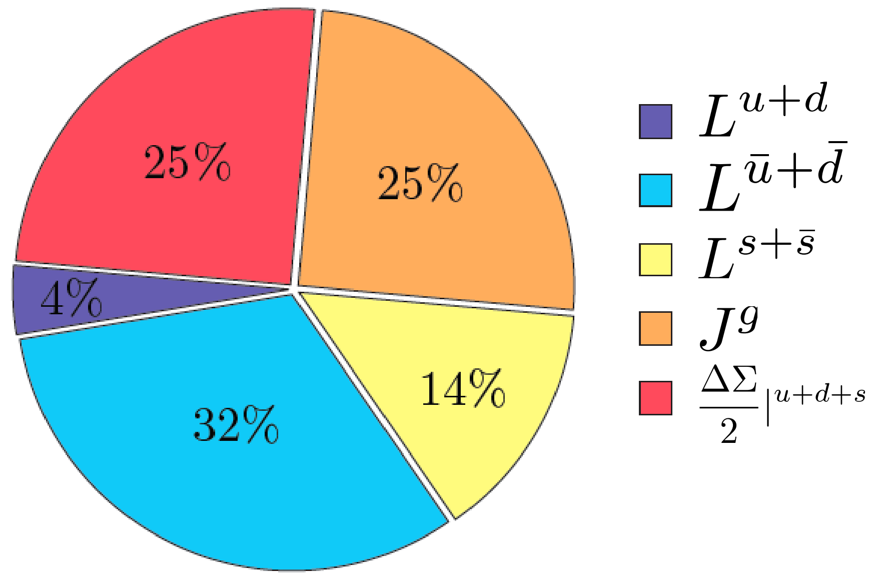
- Motivation
  - Nucleon Spin Puzzle
- Theoretical Overview
  - Sea Quark Flavor Asymmetry and Meson Cloud Model
  - Accessing Quark Angular Momentum via the Sivers Function
- A Fixed, Polarized Target Drell-Yan Experiment, E1039
- Outlook

Nucleon Spin Puzzle

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

- Quark spin from all flavor
  - $\Delta\Sigma \approx 0.25 \pm \ldots$
- Gluon spin (RHIC)
  - $\int_{0.05}^{0.2} dx\, \Delta g(x) = 0.1 \pm 0.06$
- Polarized SIDIS (HERMES/COMPASS)
  - $\Delta L_{valence} \approx$ Small
- *About half of the nucleon spin still a mystery*

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



$\Delta\Sigma_q \approx 25\%$

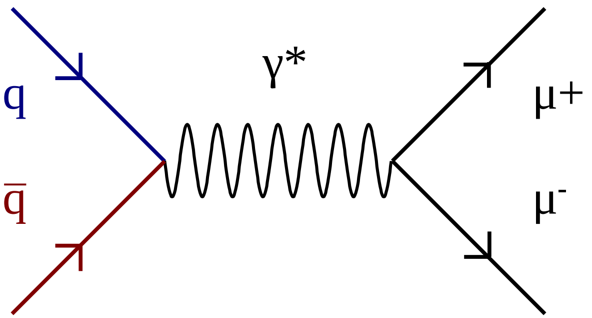
$2 L_q \approx 46\%[0\%(L_{valence})+46\%(L_{sea})]$

$2J_g \approx 25\%$

$L_u \approx -L_d$

Orbital angular momentum of sea quarks could play major role in Nucleon Spin. Hints of sea quark o.a.m. already seen....

Accessing Sea quarks via Drell-Yan



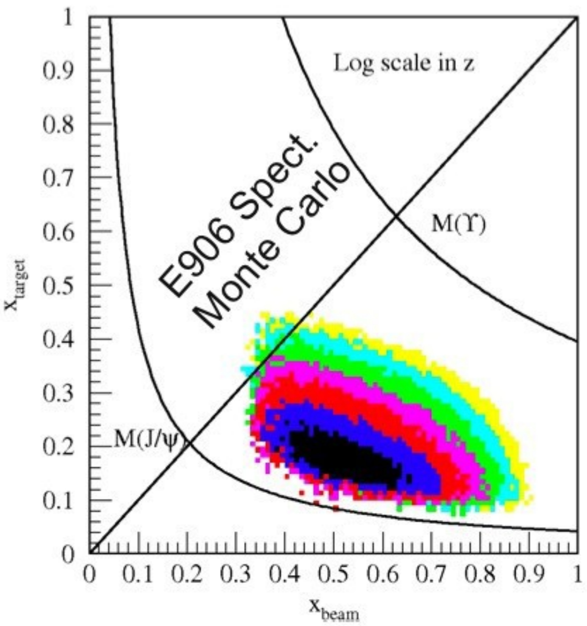
dominates small

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

target sea quark

beam valence quark

In p+p kinematics:
Quark from Beam
Antiquark from Target



- Fixed Target Drell-Yan

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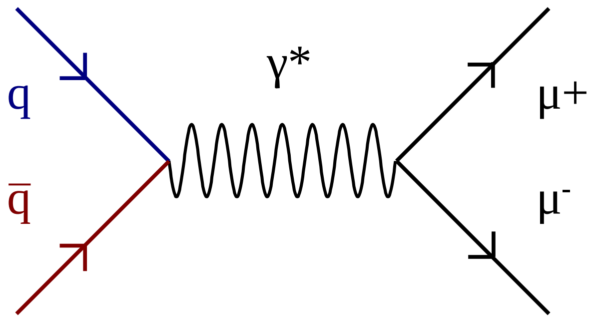
Accessing Sea quarks via Drell-Yan



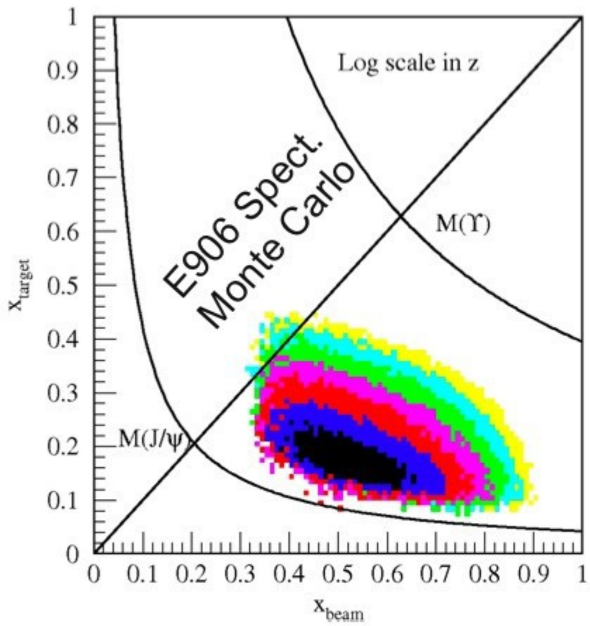
dominates small

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

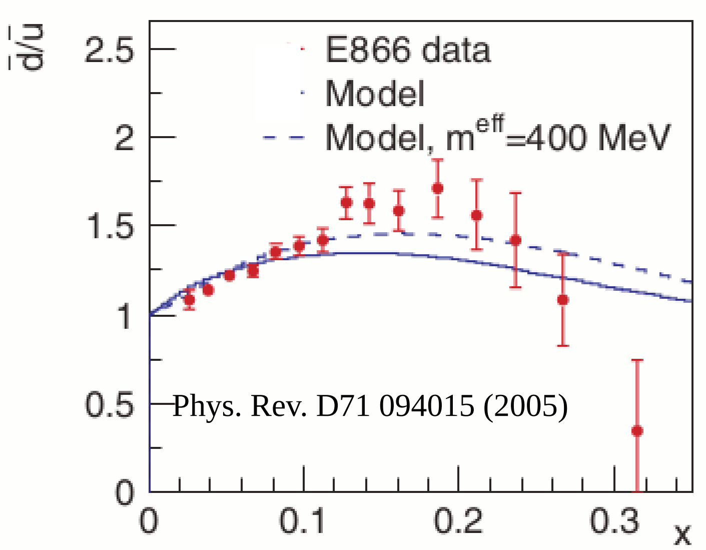
target sea quark

beam valence quark

In p+p kinematics:
Quark from Beam
Antiquark from Target



- Fixed Target Drell-Yan
- E866 saw strong flavor asymmetry seen in dbar/ubar ratio
- Meson Cloud Model may explain flavor asymmetry of sea quarks
  - Need sea quark o.a.m.



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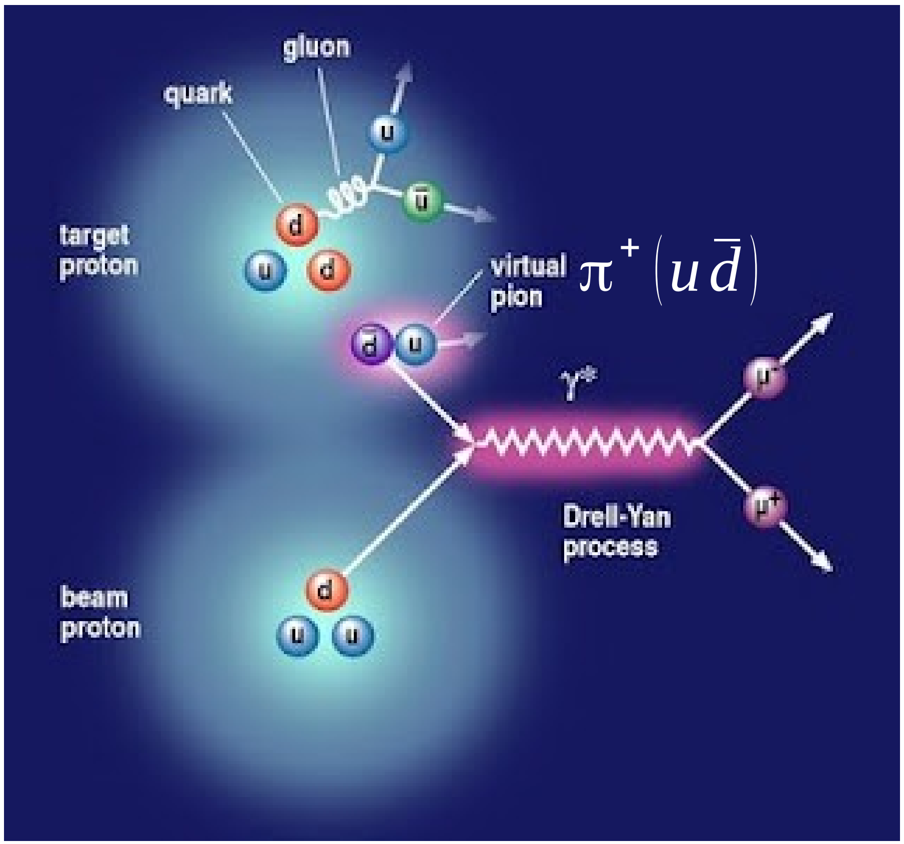
Meson Cloud Model

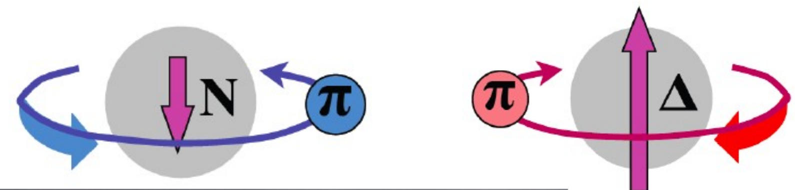
The meson cloud model explains the flavor asymmetry in the sea, by requiring sea quarks to carry angular momentum.

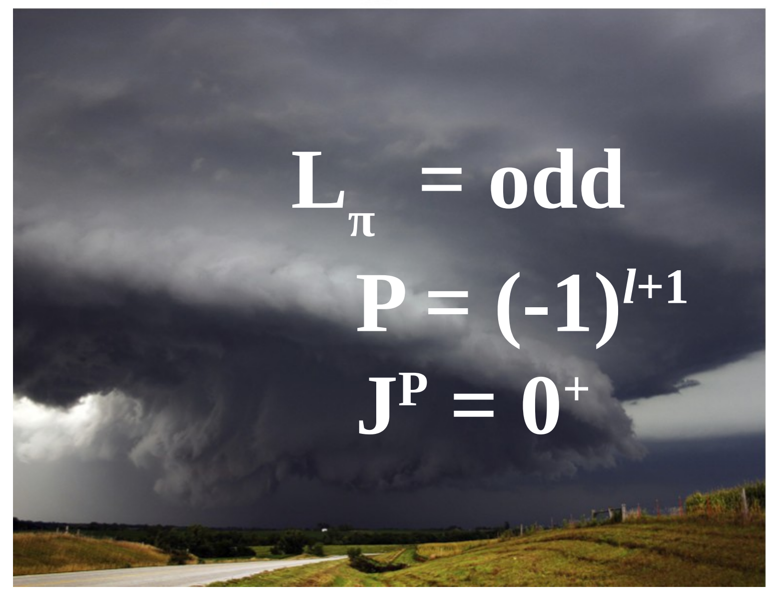
$|p\rangle = |p\rangle + |N^0\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$

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

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

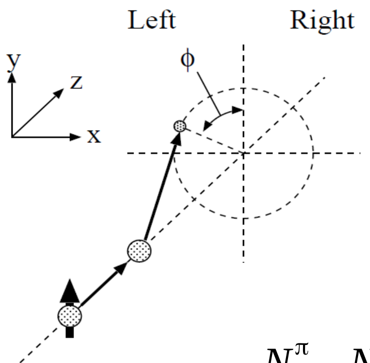




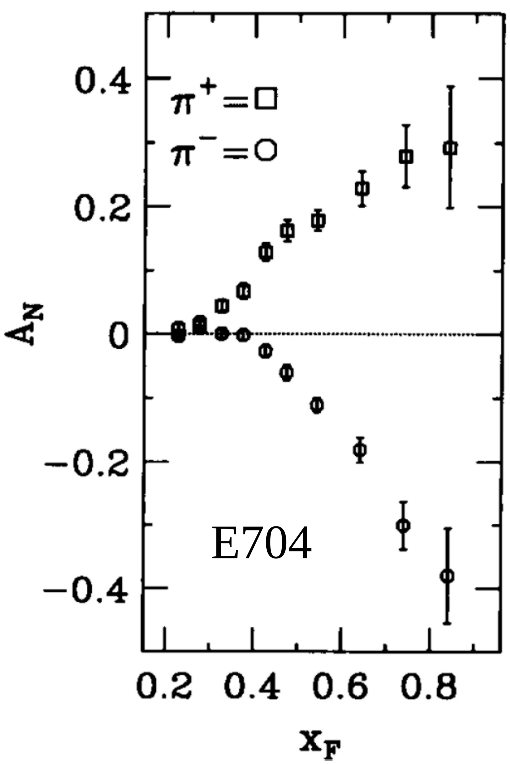


Sea quarks should carry orbital angular momentum.
Can be quantified via the TMD Sivers function.

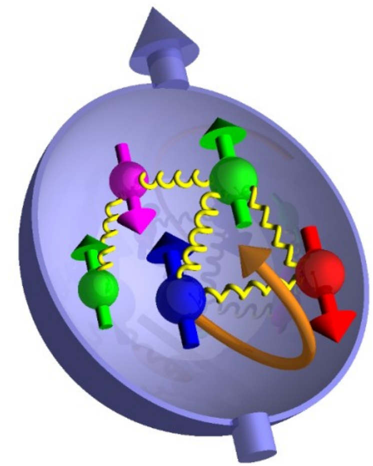
Quark Orbital Momentum and the Sivers Function

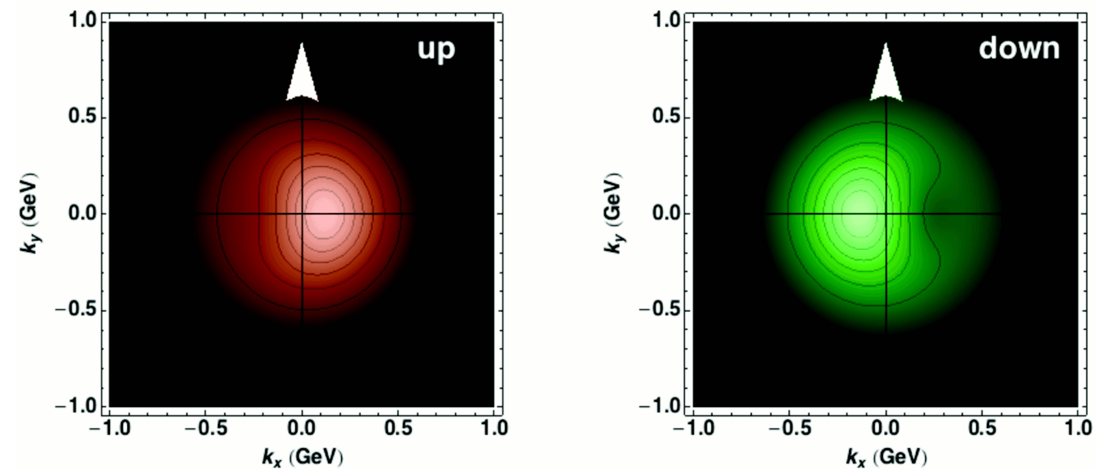


$$A_N(pp^{\uparrow} \to \pi X) \propto \frac{N_L^{\pi} - N_R^{\pi}}{N_L^{\pi} + N_R^{\pi}}$$



- The Sivers Function:
  - One of 8 TMD PDFs: $f_{1T}^{\perp}(x, k_T)$
  - Correlation between proton's transverse spin and transverse parton momentum
- Originally formulated to explain E704
  - Sivers Effect: Intrinsic k_T imbalance leads to asymmetry:



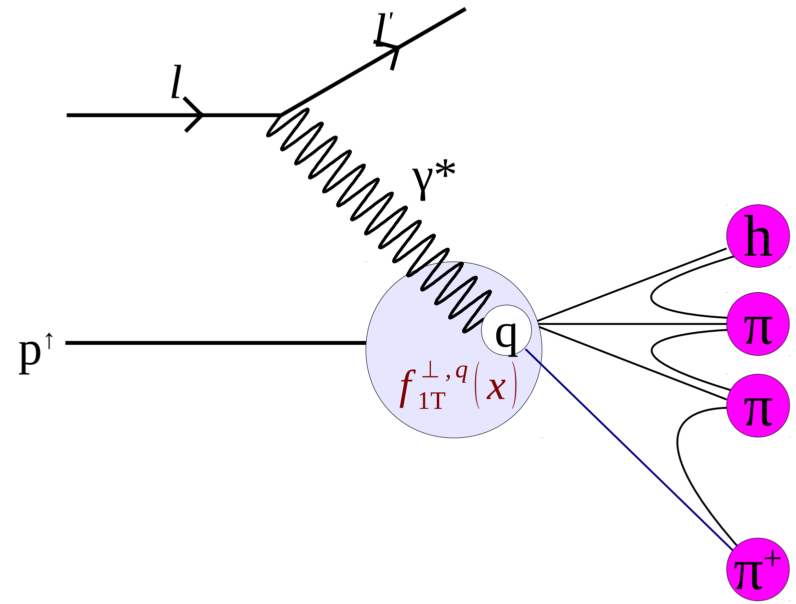


A. Bacchetta and M. Contalbrigo Il Nuovo Saggiatore, vol. 28, pp. 16–27, 2012

- **Quark Sivers Function Directly accessible with:**
  - **Polarized SIDIS [e+p↑ → e+h +X]**
  - **Polarized Drell-yan [p+p↑ → γ*(μ+μ-)]**

Accessing Quark Sivers distribution

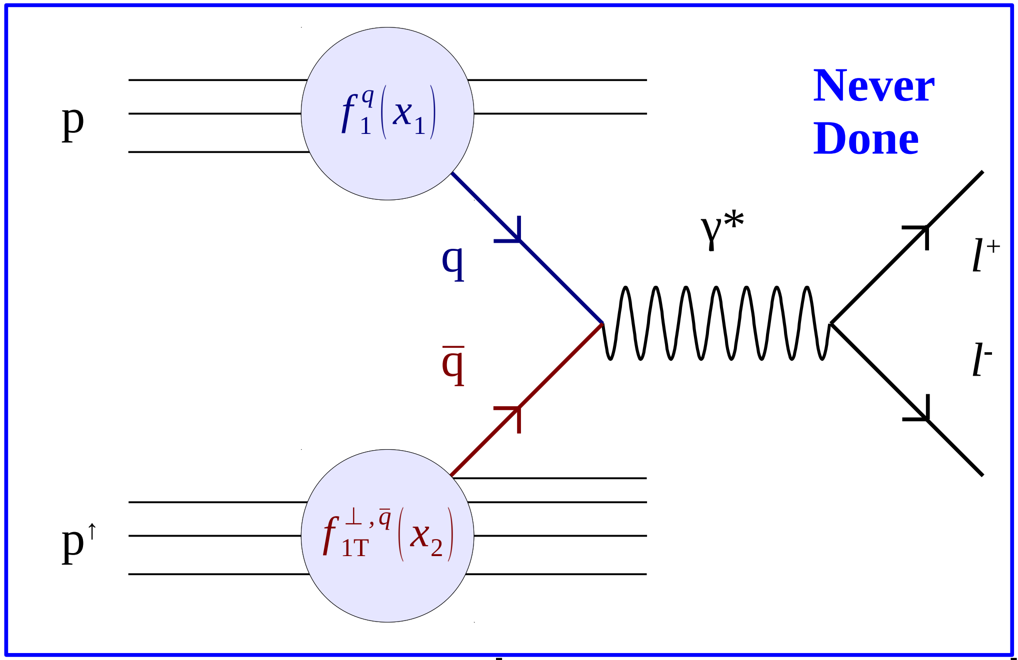
Polarized Semi-Inclusive DIS



$$A_N = \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in SIDIS on polarized nucleon
- Quark to Hadron Fragmention function
- Valence-Sea quark: Mixed

Polarized Drell-Yan

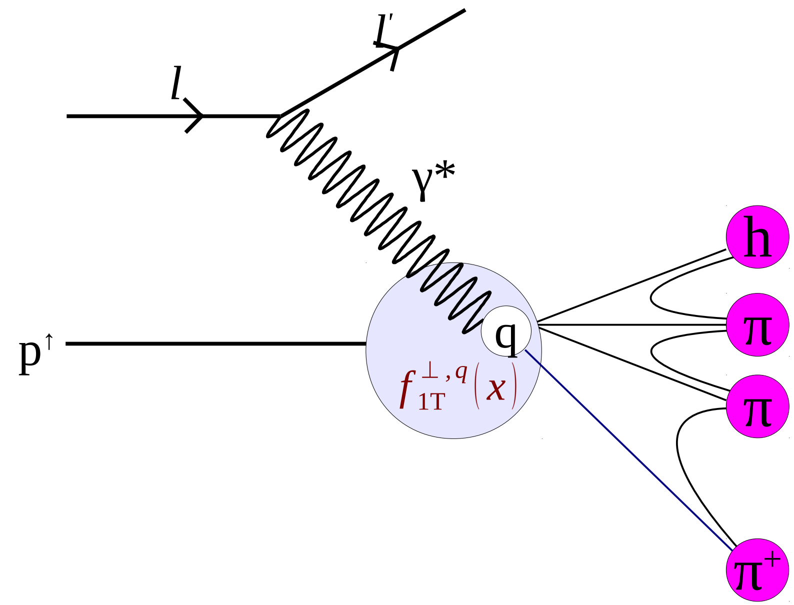


$$A_N = \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

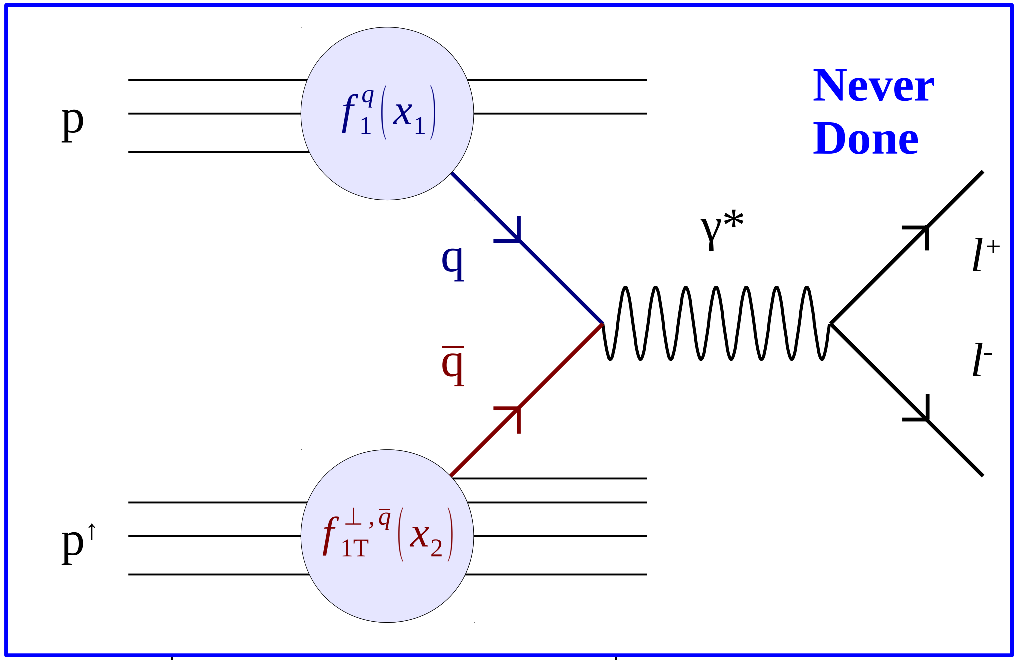
- L-R asymmetry in Drell-yan production on polarized nucleon
- **No Quark Fragmention function**
- Valence-Sea quark: **Isolated**

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 ($\Delta L_{valence} \approx 0$)	Unknown
Sea	Little Known	Unknown (E1039)

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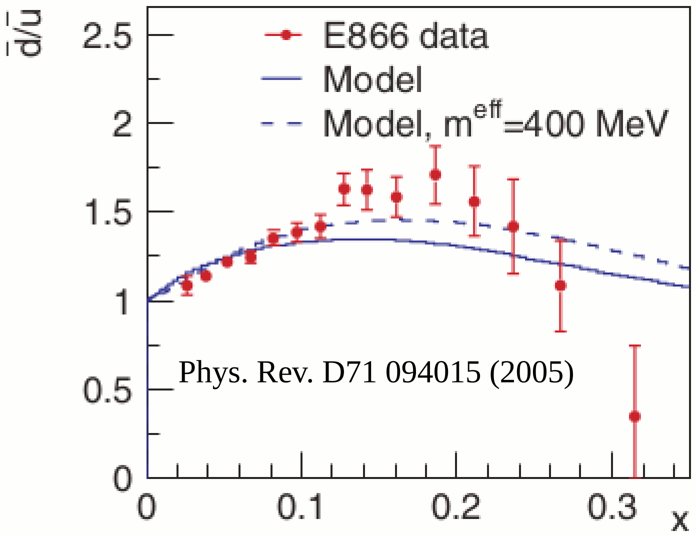
E1039 Physics Summary

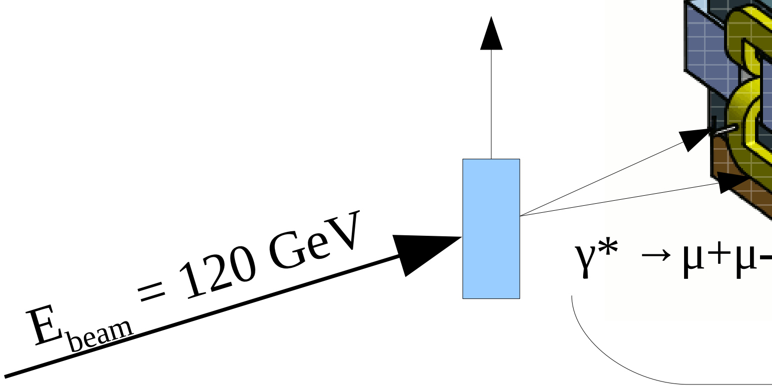


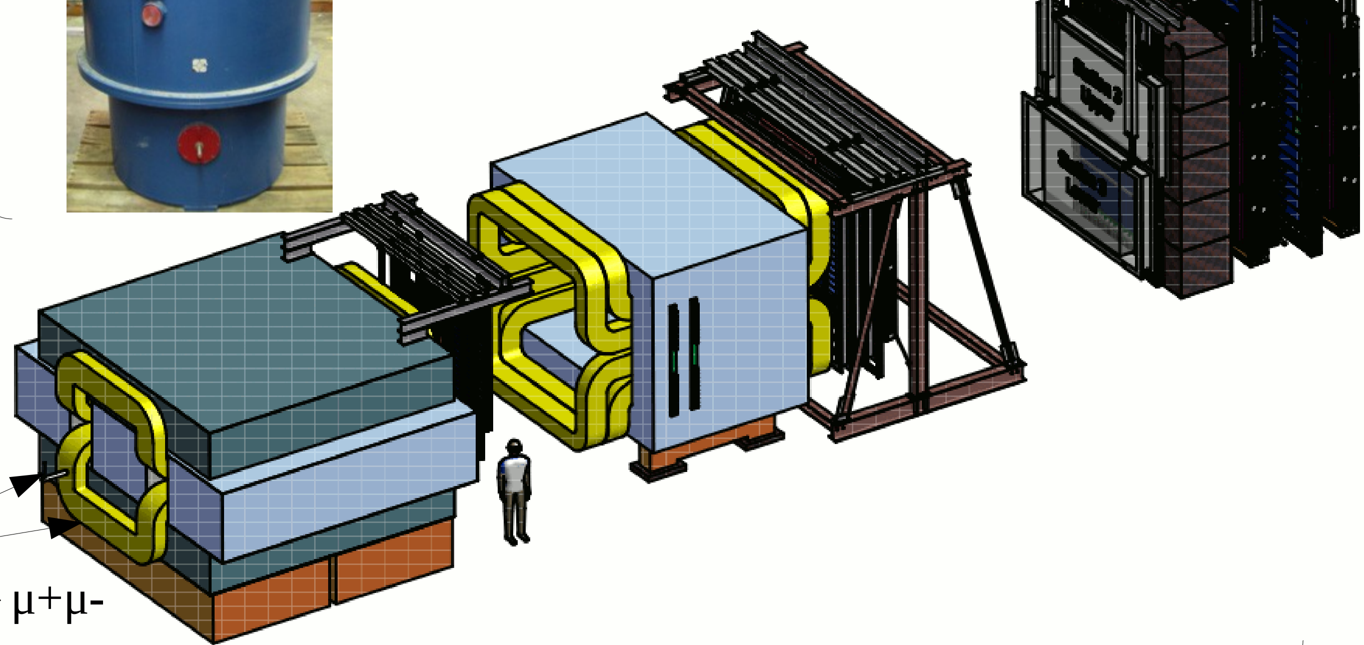
- Little is know about Sea Quark Angular Momentum
- E866 data, interpreted by the pion cloud model point to non-zero sea quark angular momentum
  - E906 (SeaQuest) extending measurement
    - x ≈ 0.45
- The E1039 Polarized Target Drell-Yan Experiment provides opportunity to study possible Sea Quark O.A.M.
  - Follow up experiment to E906
  - Measure:

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

What is needed for E1039

- **Proton Beam**
  - **Fermilab**
- **Polarized Target**
  - **In Development at LANL, UVa**
- **Dimuon Spectrometer**
  - **E906 experiment (Seaquest)**
- **Collaboration**



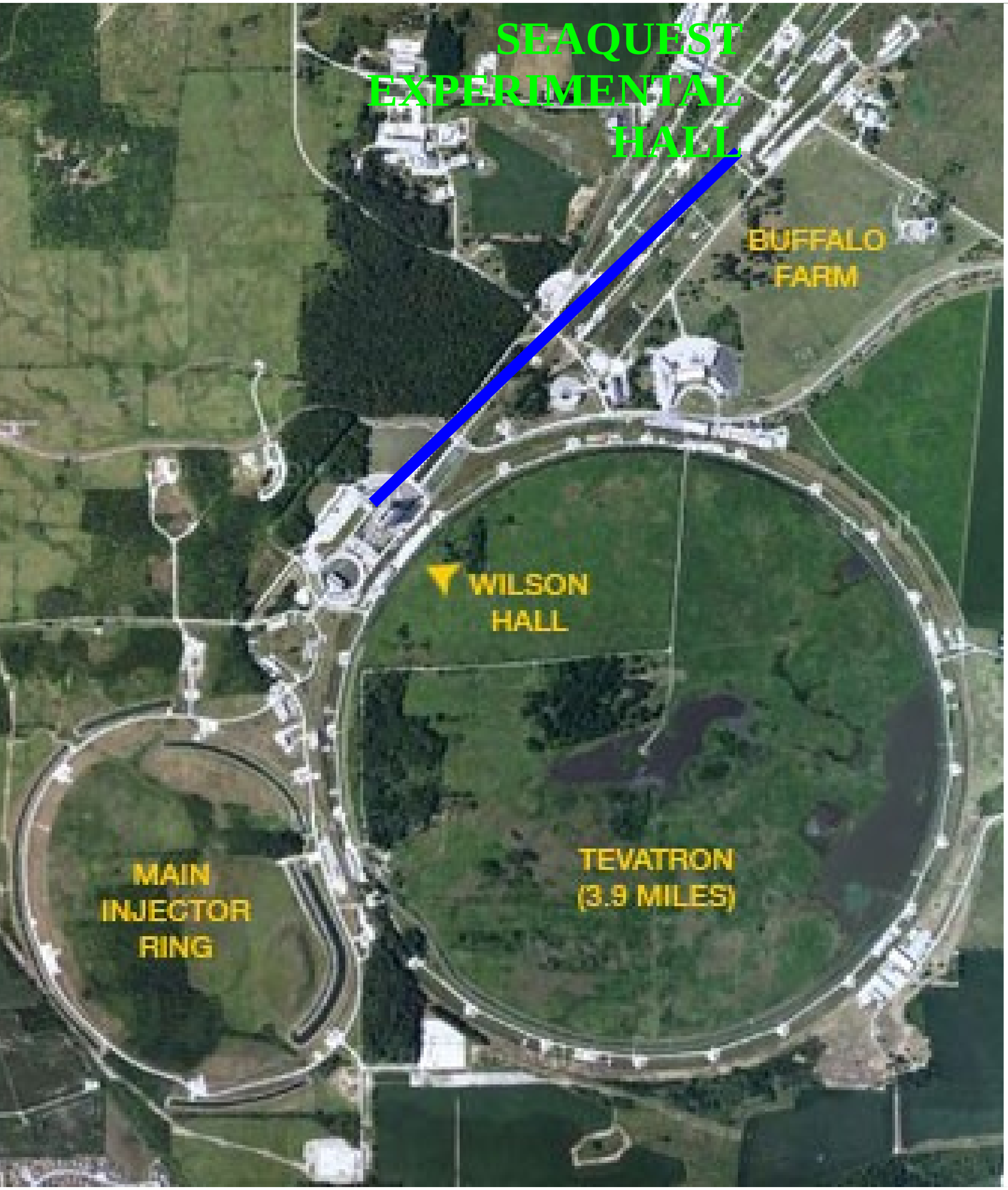


FNAL proton beam

Polarized Target

E906 Dimuon Spectrometer

Proton Beam @ FNAL



- 120 GeV protons
- KTev beam line
- $\sqrt{s} = 15.5$ GeV
- Projected Beam for E1039
  - Beam: $1\text{x}10^{13}$ p/spill; spill is 5 s/min
  - Luminosity: $4\text{x}10^{35}$ /cm^2/sec
  - P.O.T./year: $5.26\text{x}10^{18}$

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Put in Polarized target for E1039

- Refurbished 5T Magnet
- Uses ***D**ynamic **N**uclear **P**olarization (DNP)*
  - Needs low Temp, High Magnetic Field
  - Needs Paramagnetic material
  - Irradiated NH_3
- ***Proven Technology***

- Parameters of Ammonium target
  - Density: 0.917 g/cm^3
  - Length: 8 cm
  - Packing Fraction: 0.6
  - Average Polarization: 88%
  - Dilution Factor: 3/17 (NH_3)

JLab Target

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Principles of **D**ynamic **N**uclear **P**olarization

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

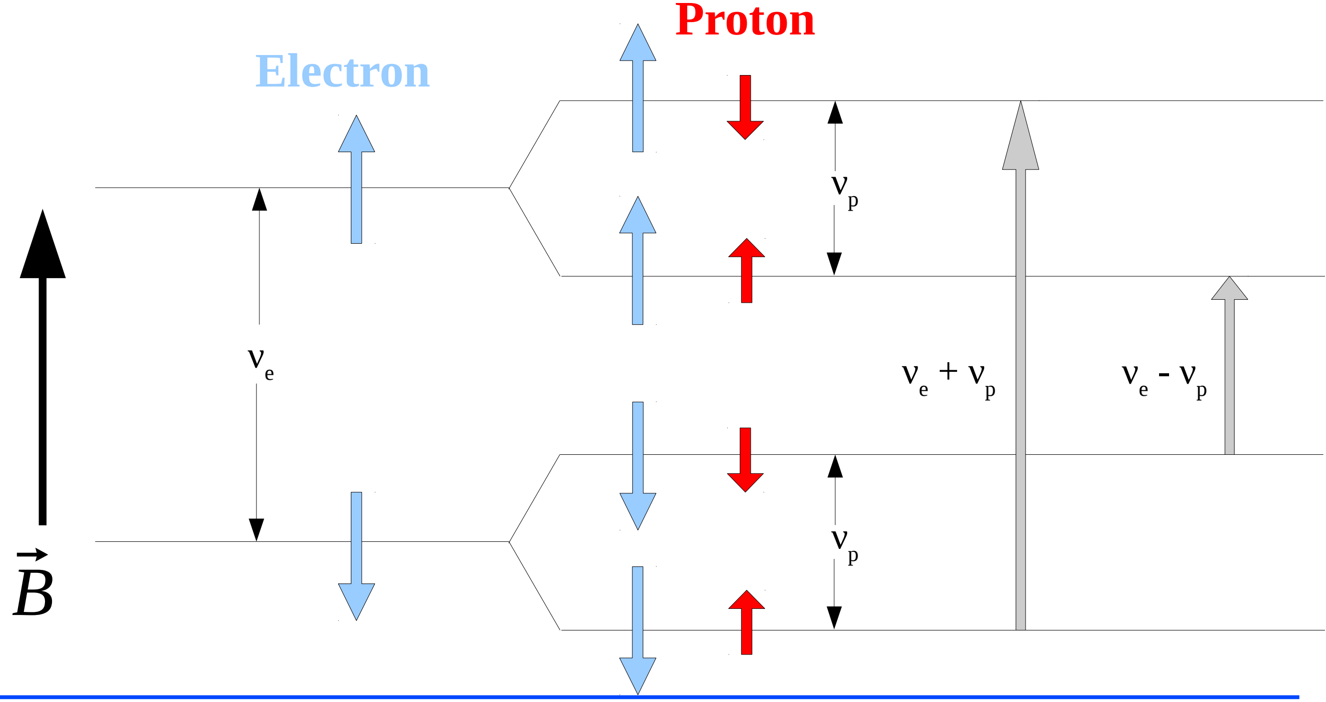
$$P_{(s=1/2,i)} = \tanh\left[\frac{\mu_i g_i B}{2 k_B T}\right]$$

  - 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*

Principles of **D**ynamic **N**uclear **P**olarization

- *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
  - $\tau_e << \tau_p$ (relaxation time)
  - Polarization > 92%

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



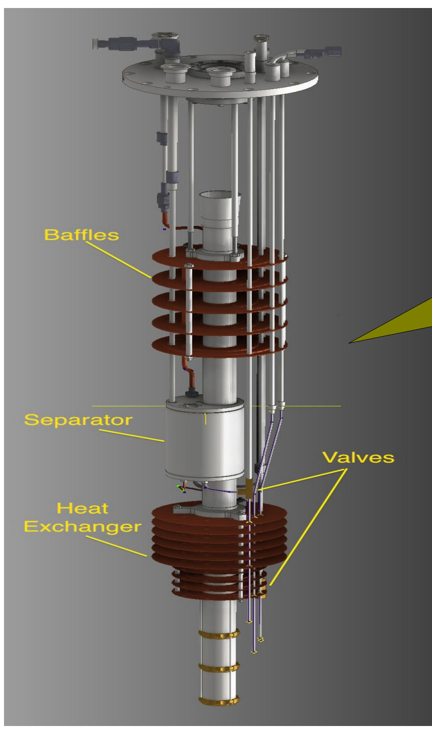
Refrigerator for Target System

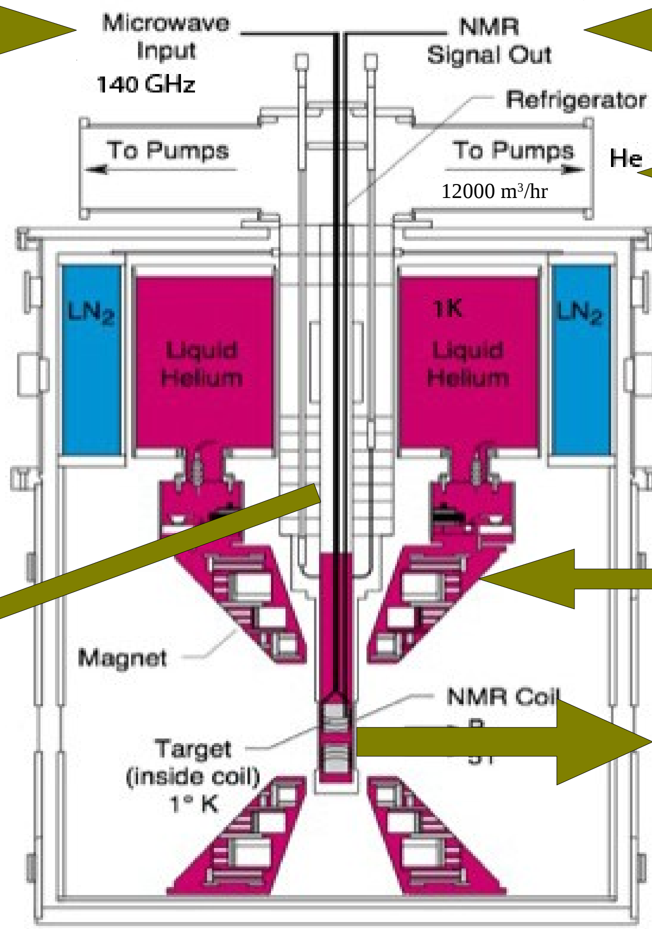
Microwave signal to
Induce spin flips

NMR Polarization
Measurement

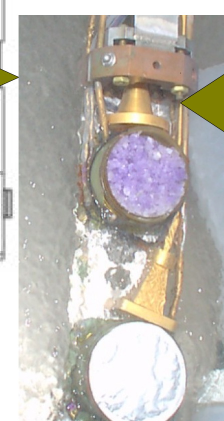
Roots pump system used to
pump on 4He vapor to
reach 1K

Cryostat: UVa





Superconducting
Coils for Magnet: 5T



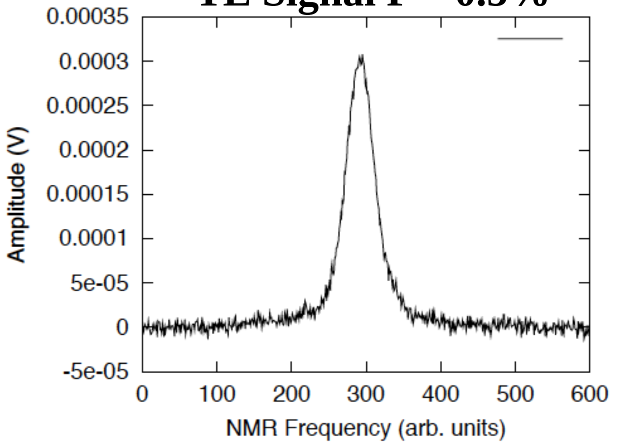
μ-wave
horn

Target Material NH_3
Irradiated at NIST

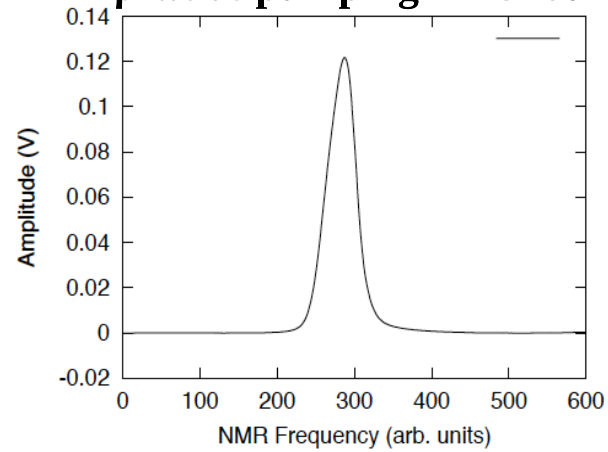
NMR Polarization Measurement, Basics

- Measure Polarization using NMR technique
  - Apply RF at proton Larmor frequency, $\nu_p \approx 213$ MHz, to RLC circuit
  - Measured with an inductor coil inside 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 + IF high gain system*
- *Stable, low noise system required to detect TE signal*

TE Signal P ≈ 0.5%



μ-wave pumping P ≈ 92%



NMR Coil (inductor) inside target.

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

Yield and Asymmetry Estimates

- One year $L = 1.40\text{x}10^{43}$ /cm^2
- Target and Accelerator Efficiency: 50%
- Spectrometer Efficiency: 80%
- Cross Section $\sigma_{DY} = 0.024$ nb
  - Kinematic Range: $4 < M < 9$ GeV, $-0.2 < x_F$ 0.8

$$N_{DY} = \text{eff.}*L*\sigma_{DY}$$

Cuts	Efficiency	Events
All DY in kinematic range	100%	1.34E+08
$\mu+\mu-$ accepted by all detectors	2%	2.78E+06
Accepted by trigger	50%	1.39E+06
$\mu+\mu-$ pair reconstructed (with target/dump separation cut)	33%	4.59E+05

$$\boxed{\Delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N_{total}}}}$$

- f = 3/17
- P = 0.88

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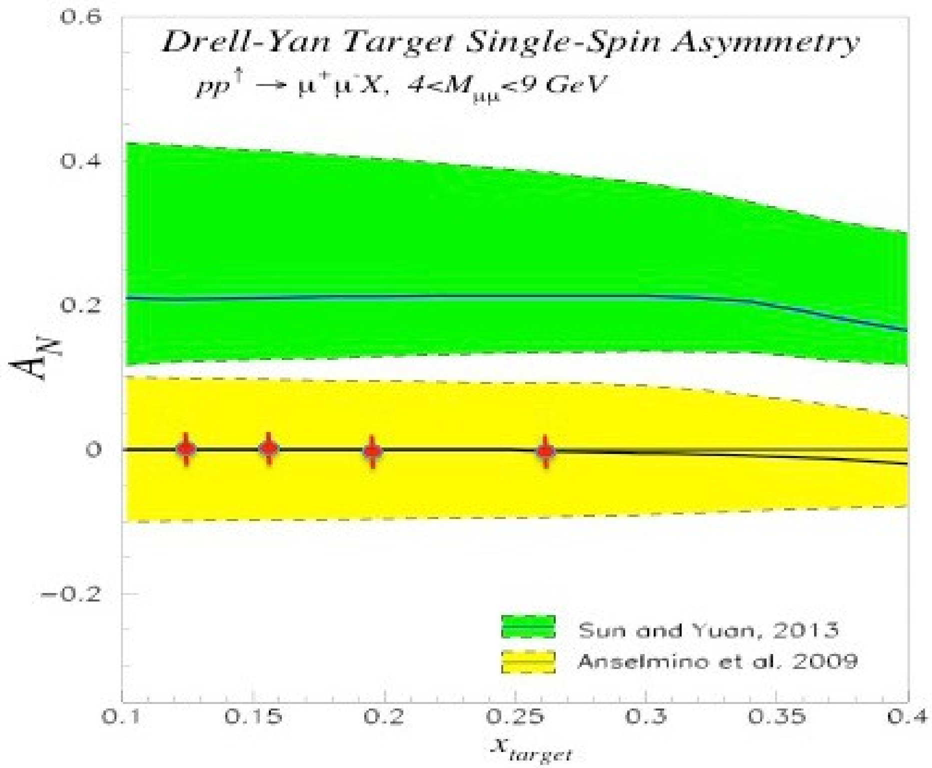
Summary and Conclusion



Statistics shown for one calendar year of running :
L = 1.4 *10^{42} /cm2, POT = 2.6*10^{18}
Running will be two calendar years of beam time

Began Setup End of 2015 to Beginning of 2016
Starting Taking data middle of 2016.

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

- 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 E-1039 Collaboration

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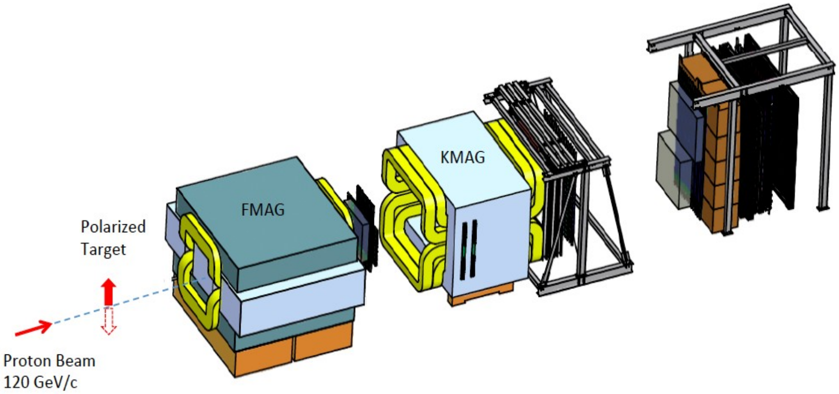
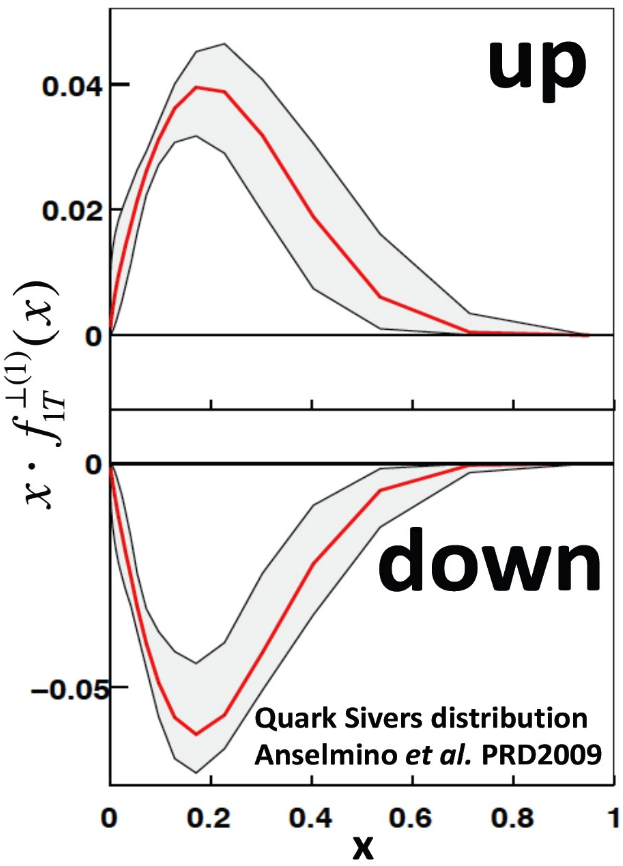


Backup

Valence quark, L_q

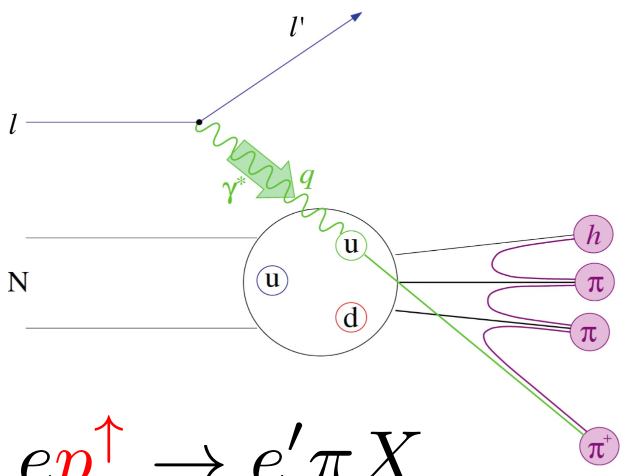
- SIDIS on polarized target
- Access to Quark Sivers Distribution
- Access to valence quark only
-
- up-quark favors left ($L_u > 0$)
- Down-quark favors right ($L_d < 0$)

- **$L_U \approx -L_d$, thus $L_q \approx 0$**
- What about sea quark O.A.M?



Valence quark Sivers from SIDIS

- Global Analysis of HERMES/COMPASS data
- Access to Quark Sivers Distribution



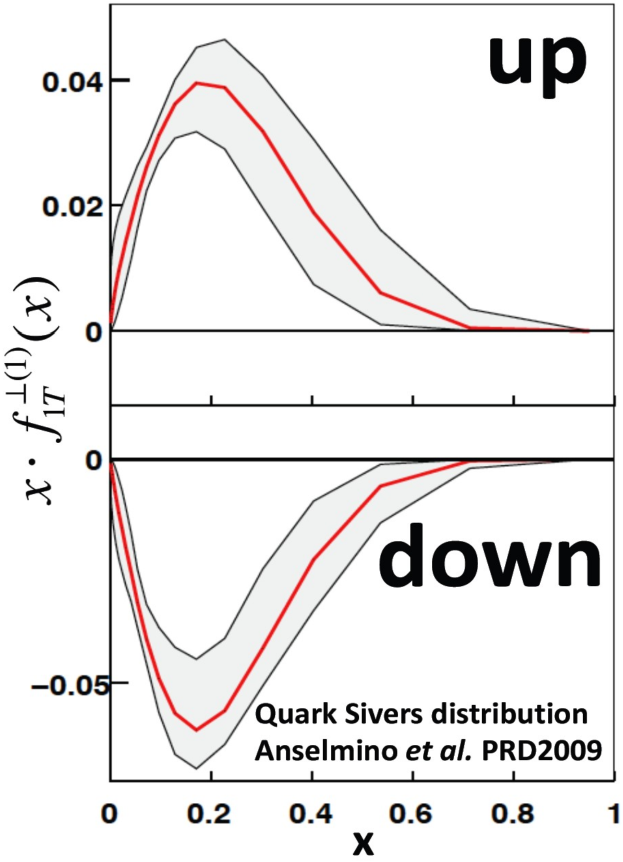
$$ep^{\uparrow} \to e'\pi X$$

∝

up-quark favors left (Lu>0),

down-quark favors right (Ld<0).

$L_u \approx - L_d$



Planned Drell-Yan Experiments

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goal
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✝	✝★	Valence quark	Sign change and size of Sivers distribution for valence quark
E-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✝★	✝	Valence quark	Sign change and size of Sivers distribution for valence quark
E-1039 $p p^\uparrow \to \mu^+ \mu^- X$	✝	★✝	Sea quark	Size and sign of Sivers distribution for Sea quarks, if DY AN≠ 0.

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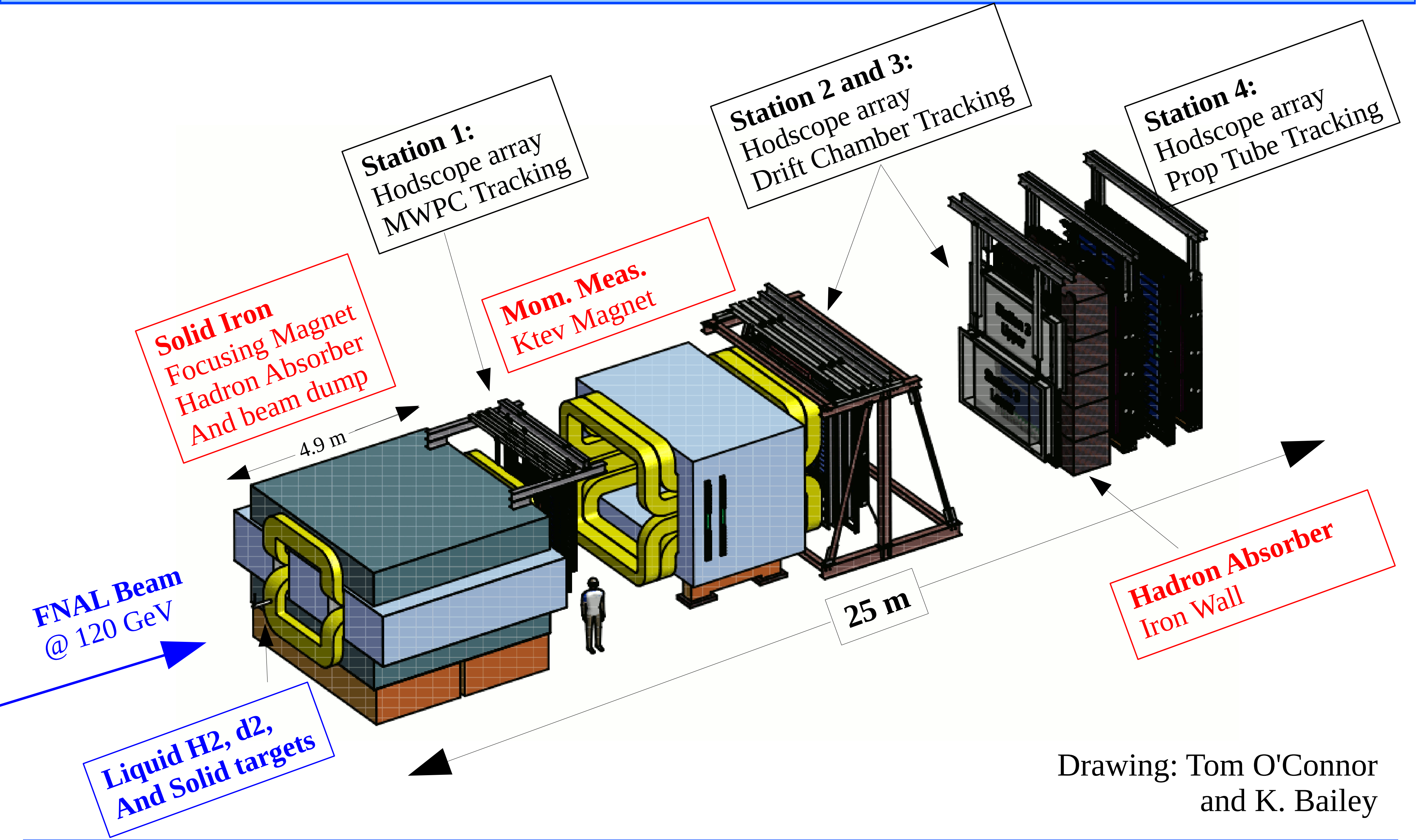
Muon ID @ E906



Drawing: Tom O'Connor
and K. Bailey

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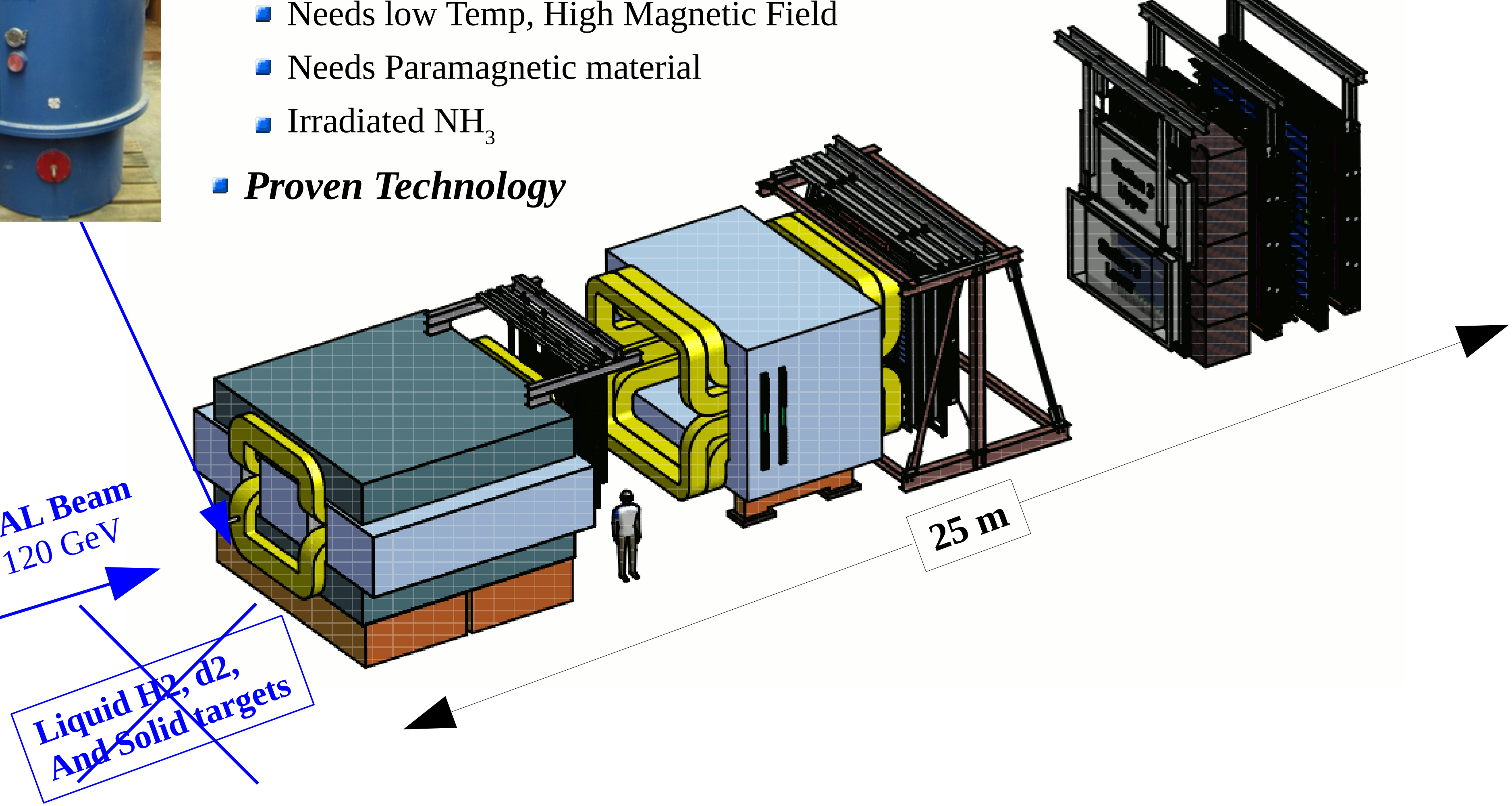
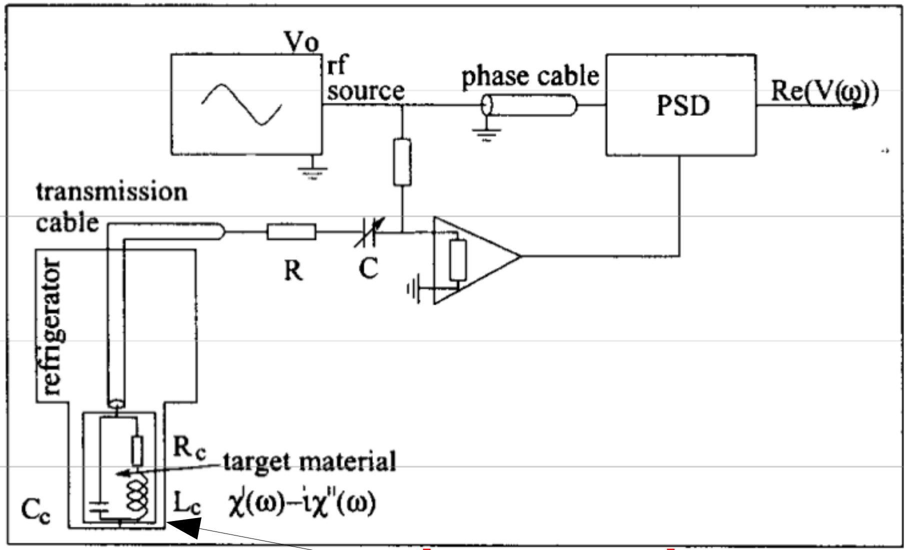
Put in Polarized target for E1039

- Refurbished 5T Magnet
- Uses *Dynamic Nuclear Polarization (DNP)*
  - Needs low Temp, High Magnetic Field
  - Needs Paramagnetic material
  - Irradiated NH_3
- ***Proven Technology***



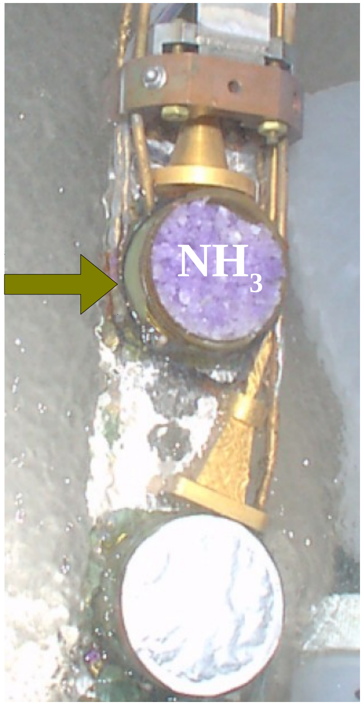
NMR Polarization Measurement, Basics

- Measured Using Q-Meter Technique
  - Apply RF at proton Larmor frequency, $\nu_p \approx 212$ MHz, to LC circuit
- Measures Polarization of Protons by absoption or emission of RF
- Voltage increases for absorption, decreases for emission (spin flip up/down)
  - $Q \approx (\omega_0 L) / R$, $V \approx 1/Q \approx P$
- *214 MHz RF + IF high gain system*
- *Stable, low noise system required to detect TE signal*



Inductor around NH_3

NMR Coil (inductor) aroundTarget.



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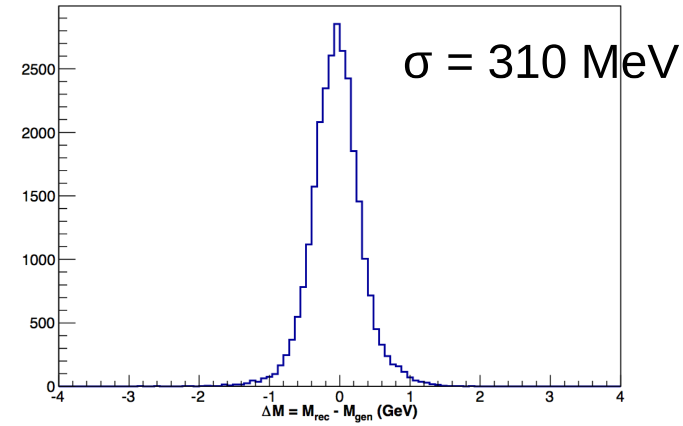
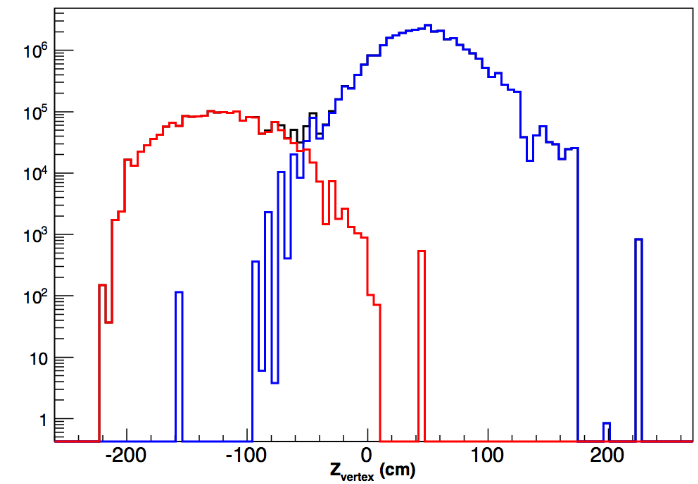
Target and Beam Performance

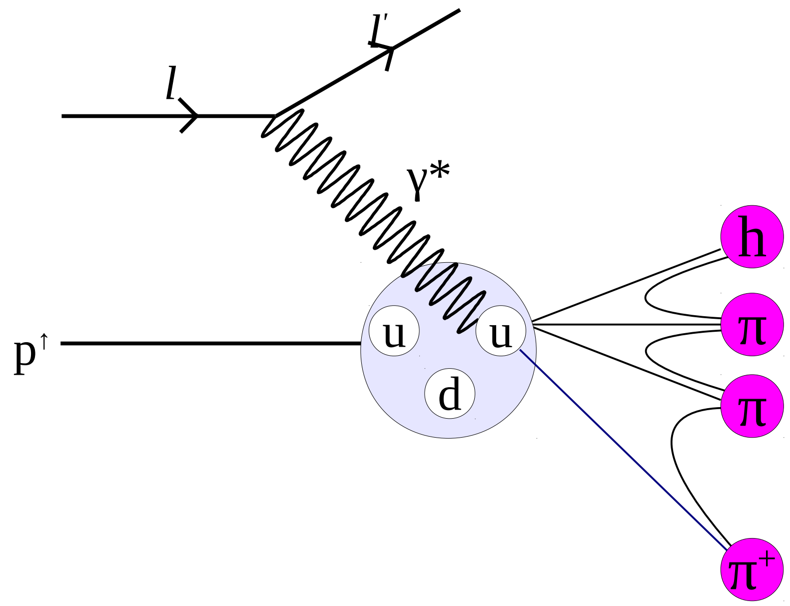
- Target
  - Polarization: 88%
  - Packing Fraction: 0.6
  - Dilution Factor: 3/17 (NH_3)
  - Density: 0.82 g/cm^3
- Beam
  - Beam: 1x10^{13} p/spill; spill is 5 s/min
  - Luminosity: 4x10^{35} /cm^2/sec
  - 120 GeV protons
  - Ktev beam line
  - √s = 15.5 GeV
  - One year L = 1.1x10^{43} /cm^2
  - POT = 2.7*10^{18}



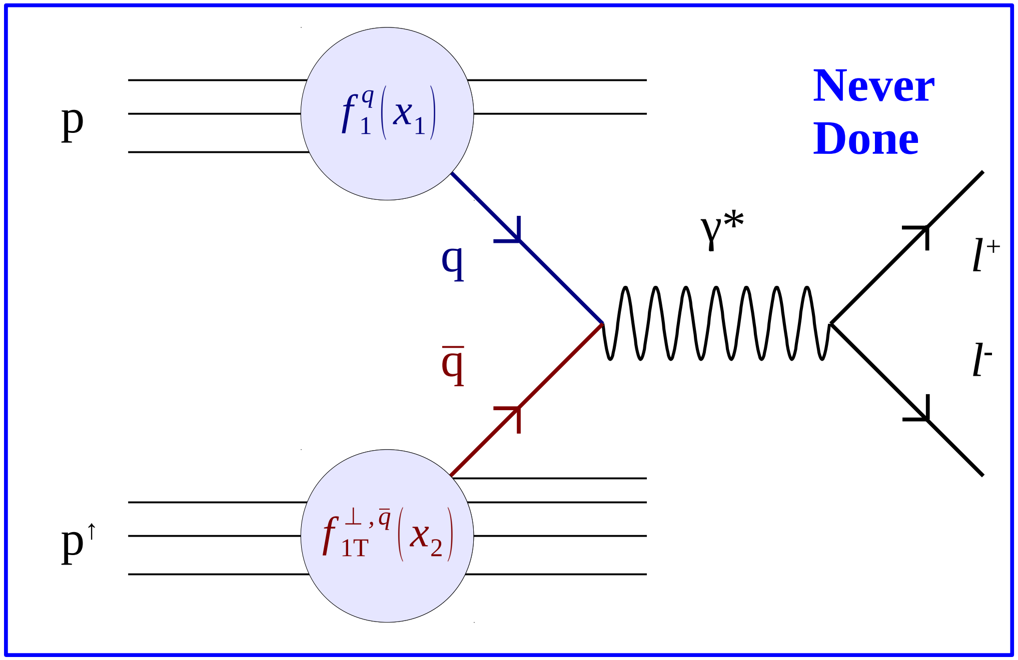
Mass Resolution



Reconstructed Vertex



l
l′
γ*
p↑
u
u
d
h
π
π
π+



p
$f_1^q(x_1)$
Never
Done
q
γ*
l^+
$\bar{q}$
l^-
p↑
$f_{1T}^{\perp,\bar{q}}(x_2)$