LA-UR-15-24110
Approved for public release; distribution is unlimited.

Title: Understanding Proton Spin Structure via the Dynamics of its Sea Quarks

Author(s): Kleinjan, David William

Intended for: P-division Postdoc Summer Seminar Series

Issued: 2015-06-08 (rev.1)

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer,is operated by the Los Alamos National Security, LLC for the National NuclearSecurity Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Departmentof Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Understanding Proton Spin Structure via the Dynamics of its Sea Quarks

David Kleinjan
P-25, PHENIX Team
E906/E1039 Collaboration

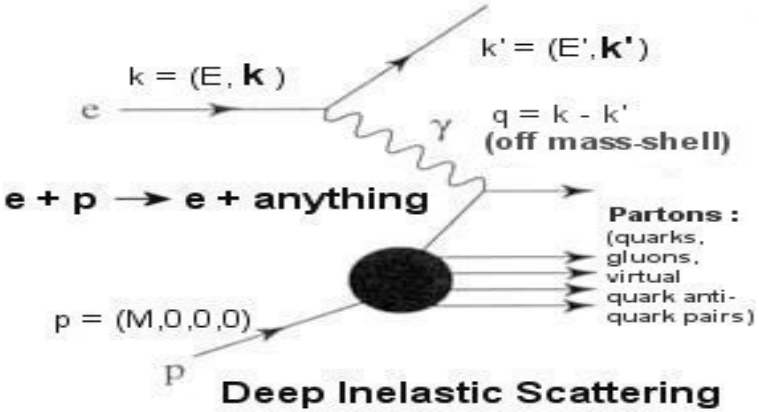
Outline

- Basics
- History of proton spin structure
- Accessing sea quark orbital Angular Momentum
  - Physics
  - Experiment

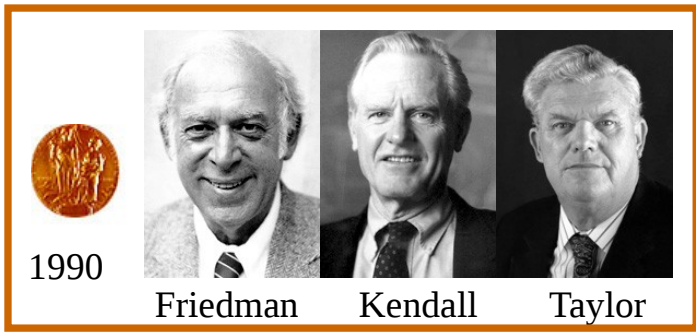
Basics

- Proton not point particle
  - R ~ 0.85 fermi
- Point particles are *partons*
  - quarks, antiquarks and gluons, confined inside proton
    - quark flavors: u, d, s, c, b, t
    - Their corresponding antiquarks: e.g. ū
- Overall Theory describing stong nuclear force and hadronic physics is Quantum Chromodynamics
- **Much still not understood about proton**
  - *If proton not point particle, why is the proton spin ½?*

Experimental Observation of Partons

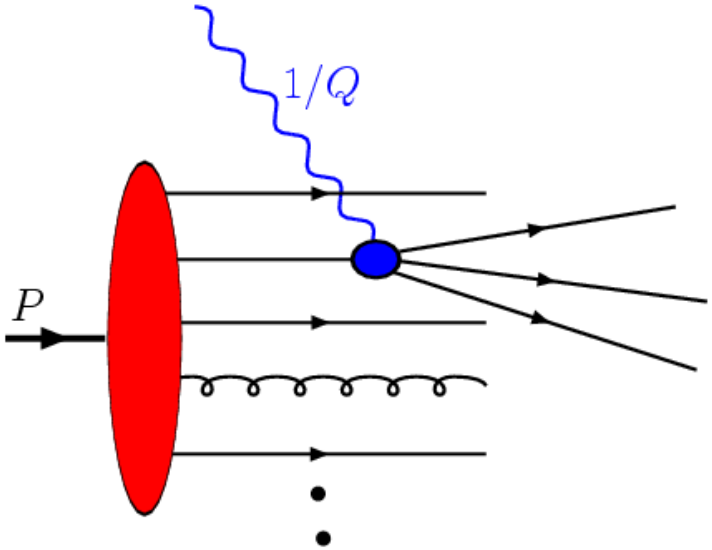


$$x = \frac{k}{P}$$

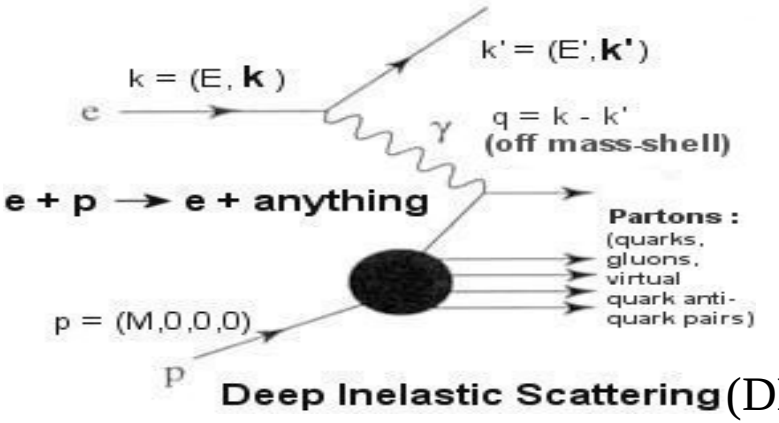


Deep Inelastic Scattering

- Point-Like Structure in proton
- Feynman Parton Model
  - Physics simplified in **infinite momentum frame**
- Bjorken scaling
  - Momentum fraction of proton attributed to partons
  - *Parton Distribution Functions*

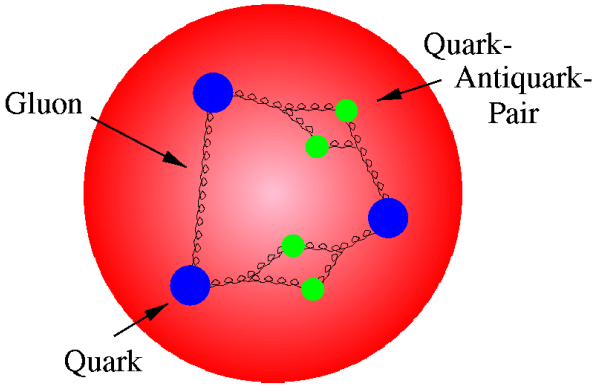


Parton Distribution Functions (PDF)



(DIS)

$$x = \frac{k}{P}$$

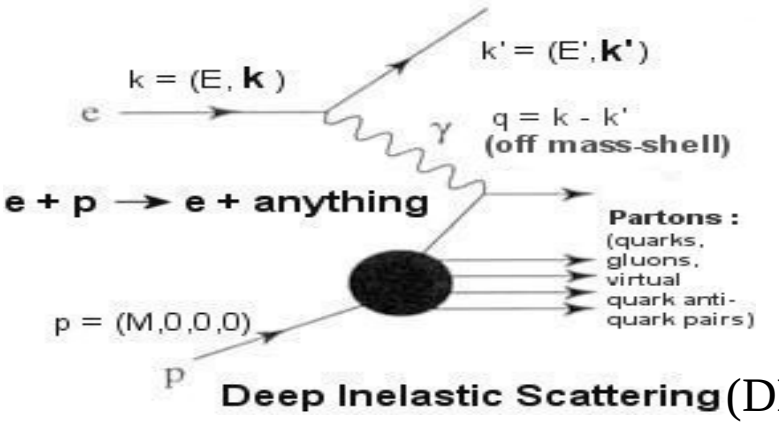


Momentum Density Functions

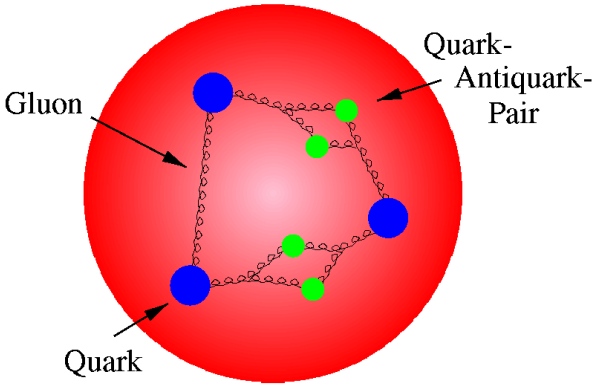
- $f(x) = \sum_{q,\bar{q},g} e_i^2 q_i(x)$

- Probability parton *q* carries momentum fraction x of proton's momentum
- Basic proton structure
  - Three valence quarks (uud) in a “sea” of quark-antiquark pairs and gluons

Parton Distribution Functions (PDF)



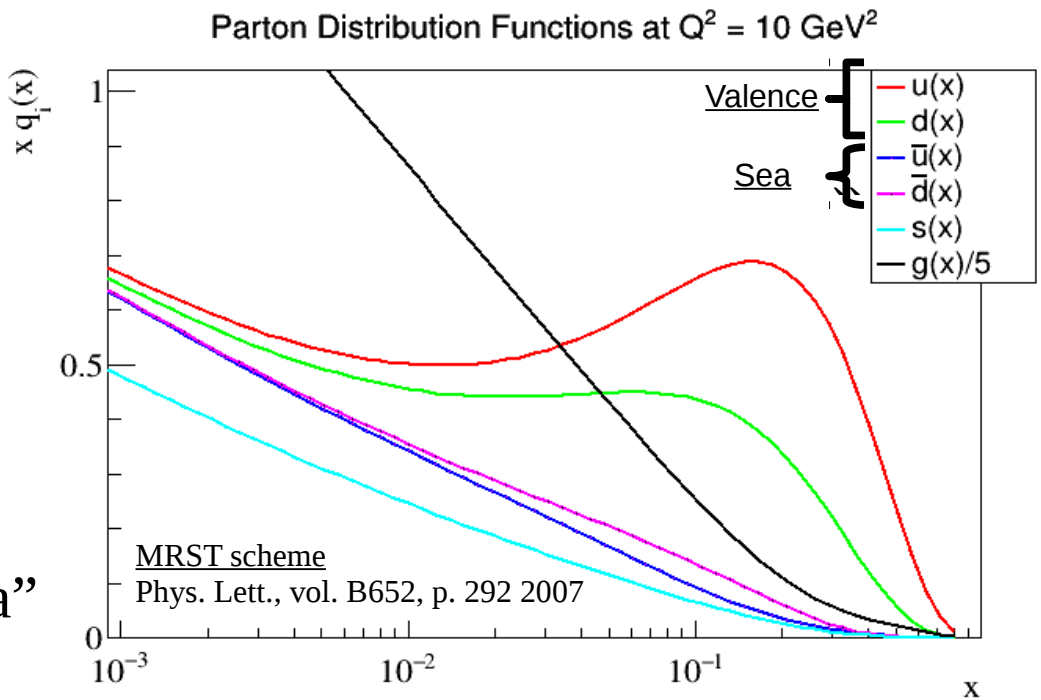
$$x = \frac{k}{P}$$



Momentum Density Functions

- $f(x) = \sum_{q,\bar{q},g} e_i^2 q_i(x)$

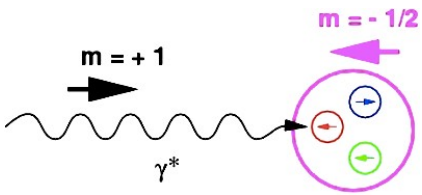
- Probability parton q carries momentum fraction x of proton's momentum
- Basic proton structure
  - Three valence quarks (uud) in a "sea" of quark-antiquark pairs and gluons



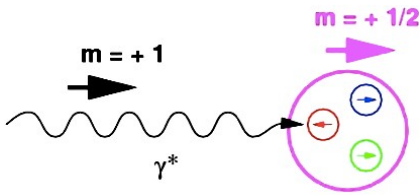
Los Alamos NATIONAL LABORATORY

Helicity PDFs

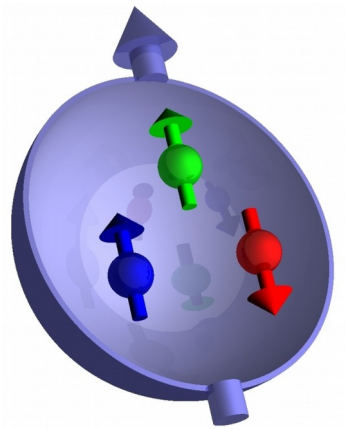
- Proton and parton spin (anti)aligned with proton infinite momentum
- Spin Density Functions
  - $g(x) = \sum_{q,\bar{q},g} \left[e_i^2 q_i^+(x) - e_i^2 q_i^-(x) \right]$
- Accessed in Polarized DIS
  - EMC Experiment @ CERN
- Naive QPM valence quarks carry proton spin



$\sigma_{1/2} \sim \sum_i e_i^2 q_i^+$



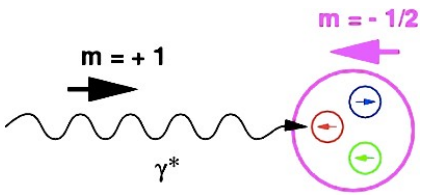
$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$



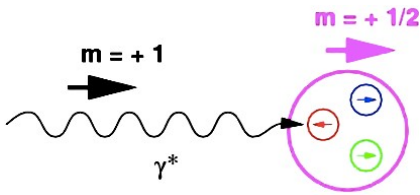
$S_p = ½ = ½ + ½ – ½$

Helicity PDFs

- Proton and parton spin (anti)aligned with proton infinite momentum
- Spin Density Functions
  - $g(x) = \sum_{q,\bar{q},g} \left[e_i^2 q_i^+(x) - e_i^2 q_i^-(x) \right]$
- Accessed in Polarized DIS
  - EMC Experiment @ CERN
- Naive QPM valence quarks carry proton spin
  - Found only ~20%
  - Proton Spin Puzzle was born

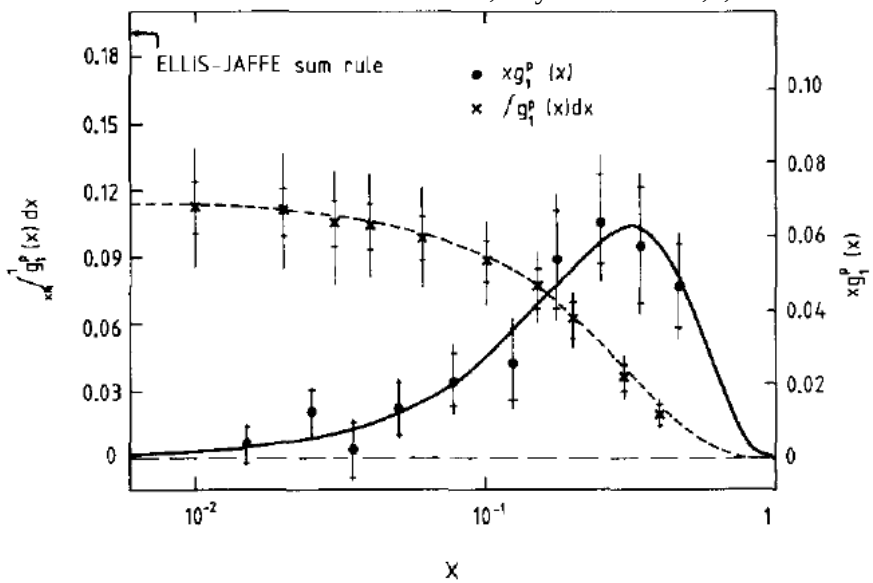


$\sigma_{1/2} \sim \sum_i e_i^2 q_i^+$

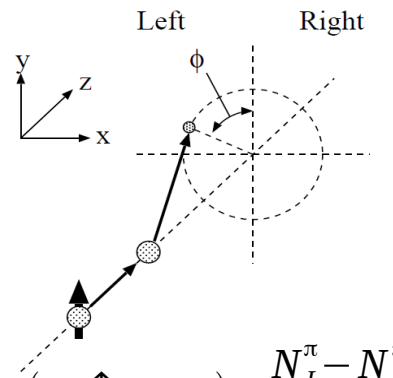


$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$

EMC, Phys. Lett. B206,2,364 1988

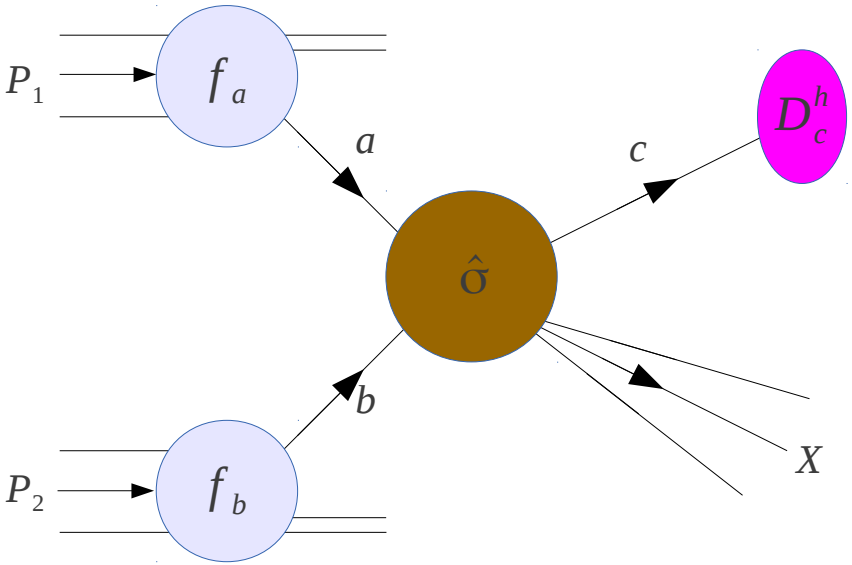


Around the same time...

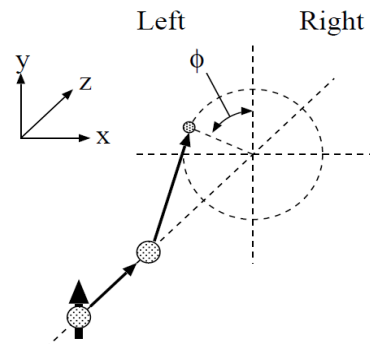


$$A_N(pp^{\uparrow} \rightarrow \pi X) \propto \frac{N_L^{\pi} - N_R^{\pi}}{N_L^{\pi} + N_R^{\pi}}$$

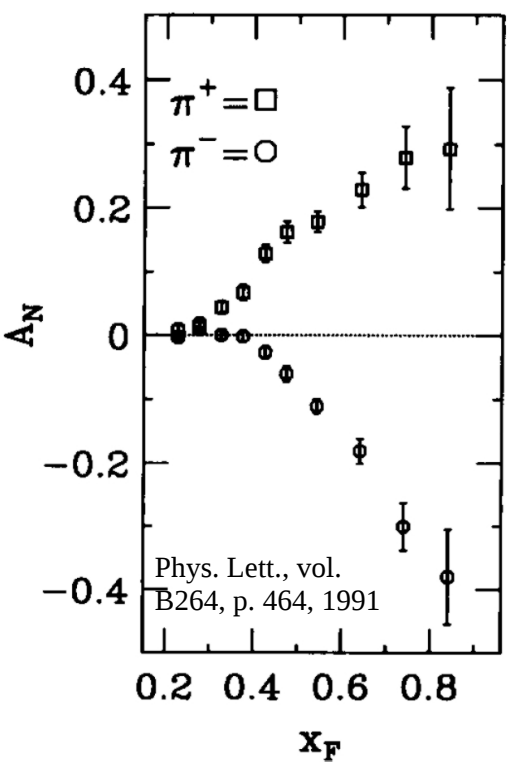
- $pp^{\uparrow} \rightarrow \pi^{\pm} + X$
- Proton spin vector transvese to momentum



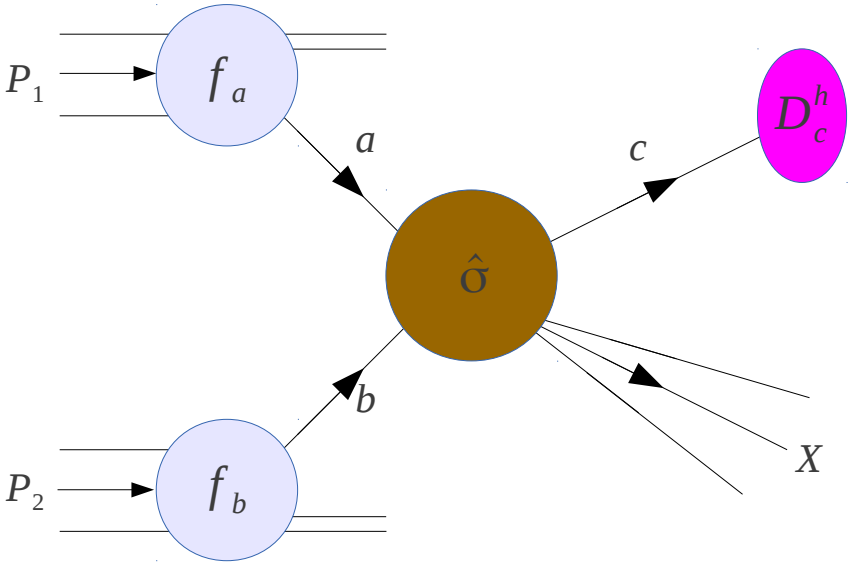
Around the same time...



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



- $pp^{\uparrow} \rightarrow \pi^{\pm} + X$
- Proton spin vector transvese to momentum



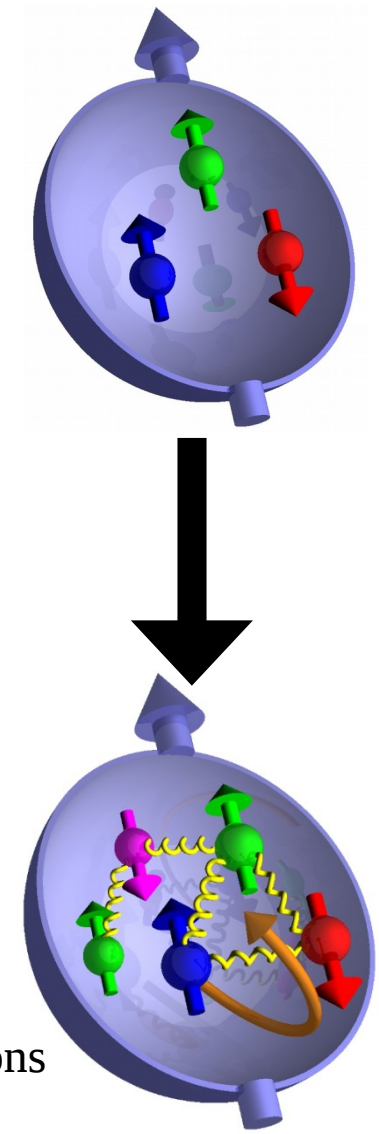
- A_N large and non-zero for $\pi^{\pm}$ production
- Collinear perturbative QCD predicted small asymmetry at hard partonic scattering (~10^{-4})
- Initial or final state effects causing asymmetry?
  - *e.g. orbital angular momentum of partons in initial state?*

x_F: fraction of proton energy given to forward momentum of hadron

Los Alamos NATIONAL LABORATORY

Proton Spin Puzzle

- Naive understanding of Proton spin not correct
- Add Gluon spin, Orbital Angular Momentum



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

Quark Spin
(Including sea quarks)

Gluon Spin

Orbital Angular
Momentum Contributions

How do we access the different parts of the spin puzzle?

We've talked about two PDFs

Parton / Proton	U	L
U	Number Density $f_1(x)$	
L		Helicity $g_{1L}(x)$

Legend

Nucleon

Nucleon Spin

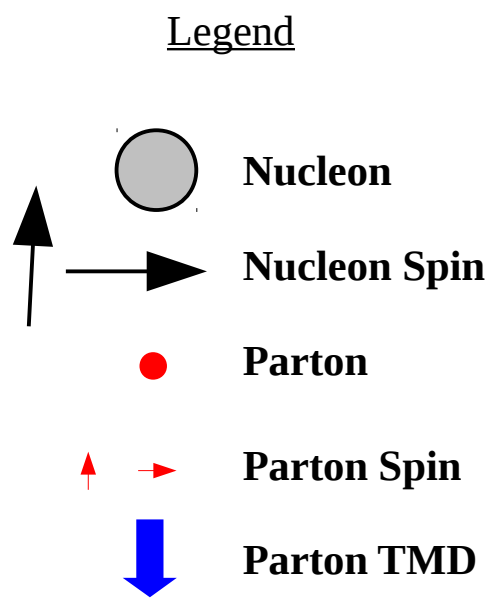
Parton

Parton Spin

- Only have proton (parton) momentum and helicity distribution

We've talked about two PDFs

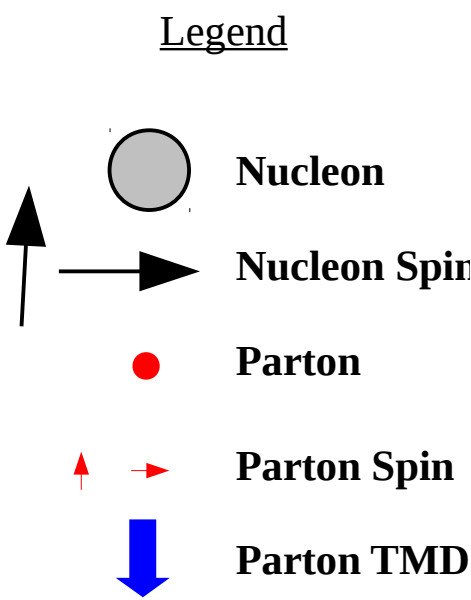
Parton / Proton	U	L
U	Number Density $f_1(x)$	
L		Helicity $g_{1L}(x)$



- Only have proton (parton) momentum and helicity distribution
- **What if Proton (parton)spin Transverse to infinite momentum?**
- **What if partons carry net transverse momentum w.r.t. proton Momentum?**

Eight leading order PDFs

Parton / Proton	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 $h_{1T}^{\perp}(x,k_T)$



- **Different PDFs shed light on different parts of the proton spin puzzle**

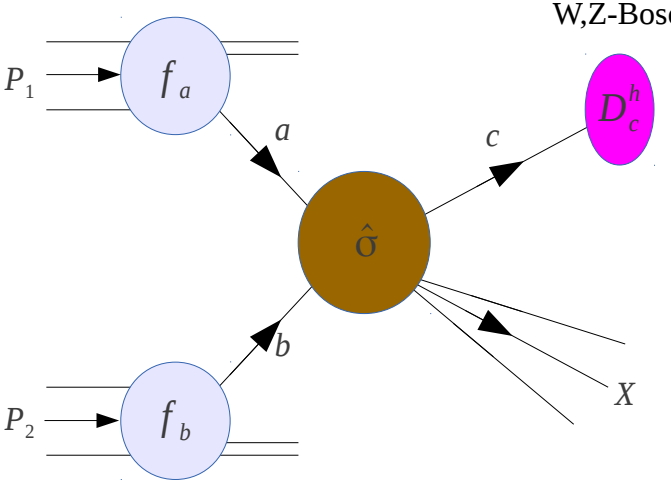
$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_q \rangle + \langle L_g \rangle$$

Los Alamos NATIONAL LABORATORY

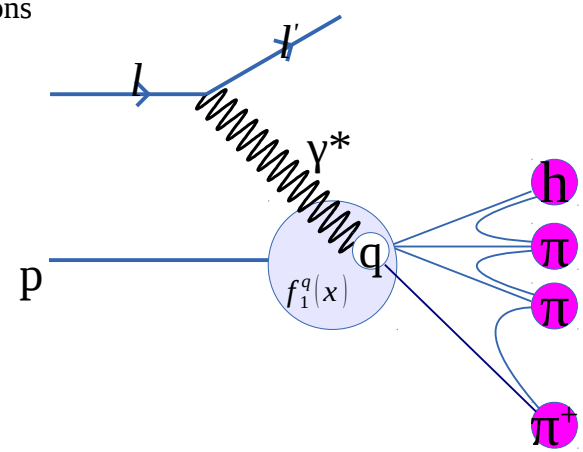
High energy probes of PDFs

Hadronic reactions

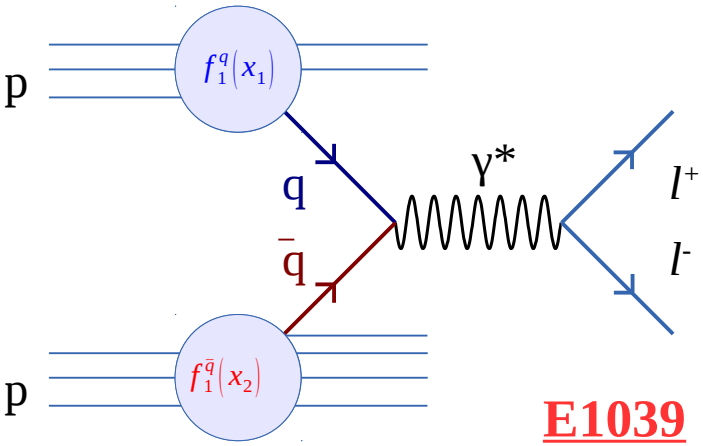
Jet/Hadron
Direct-γ
W,Z-Bosons



DIS, Semi-Inclusive DIS



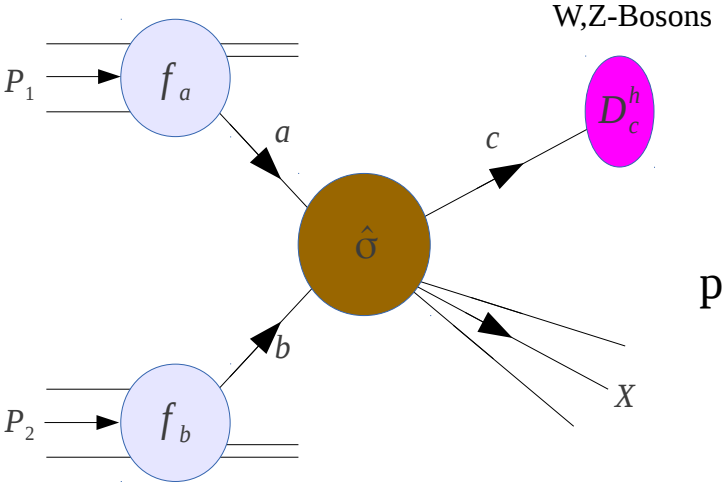
Drell-Yan



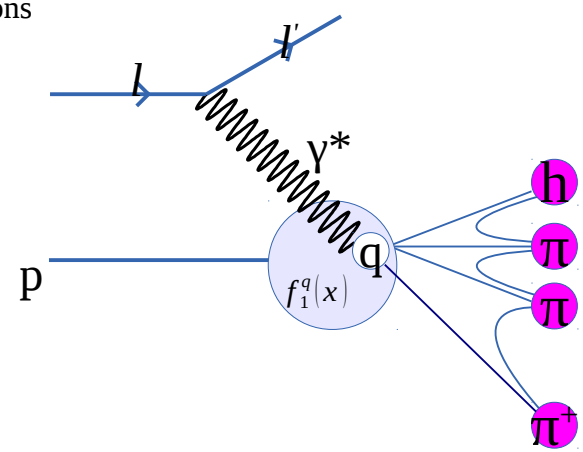
E1039

High energy probes of PDFs

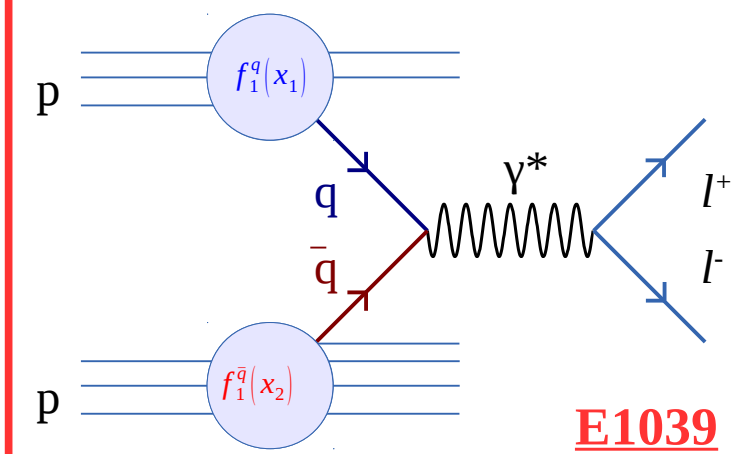
Hadronic reactions



DIS, Semi-Inclusive DIS

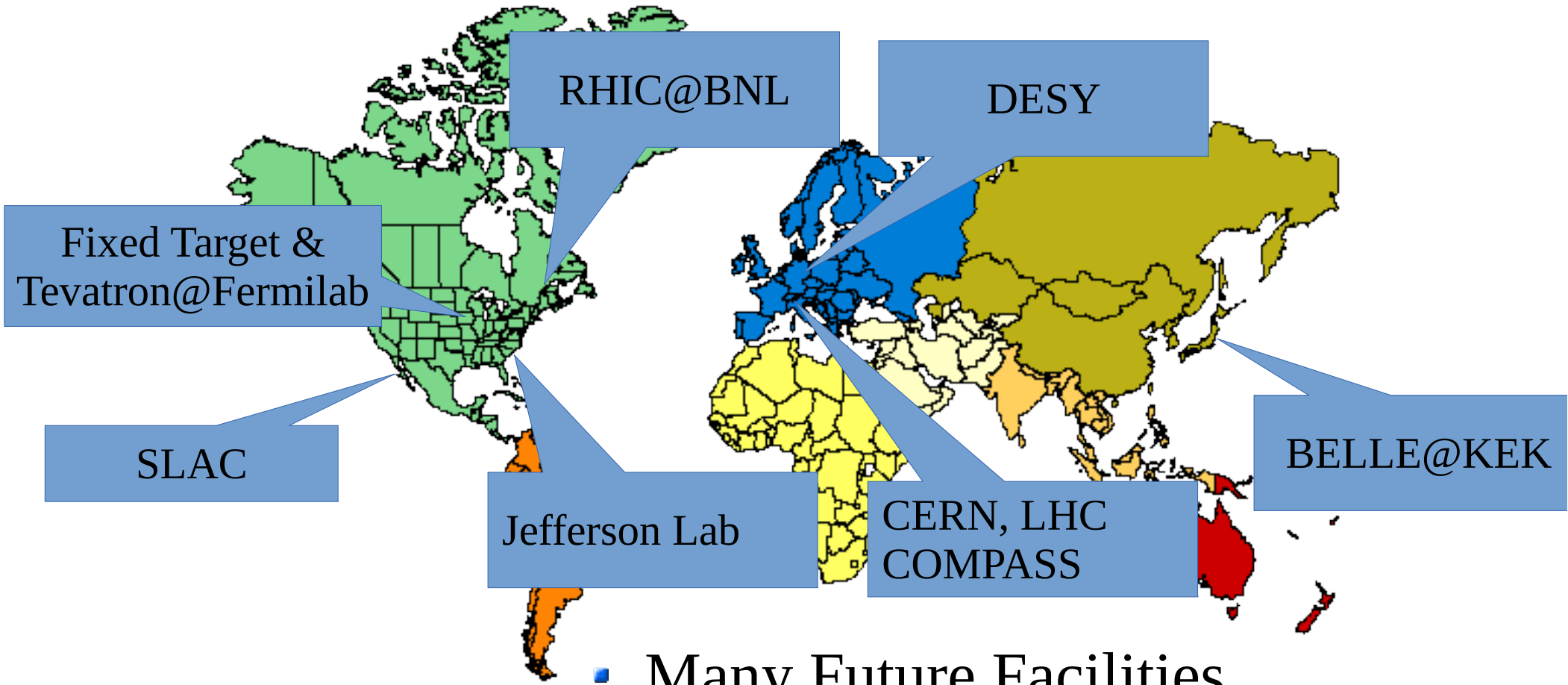


Drell-Yan



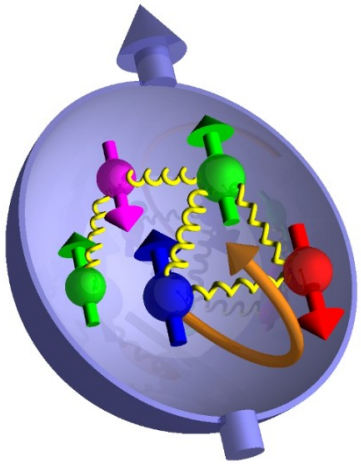
- **Different processes access different parton flavors, PDFs, momentum fraction ranges**
  - Polarize one or both participants in initial state (longitudinal and/or transverse)
- **PDFs not directly accessible from measurements**
  - Measure cross sections, particle production asymmetries (A_L, A_{LL}, A_{UT}, A_N, etc)
  - Theorists then utilize QCD factorization, universality to gain PDF info

Global effort, past and present!



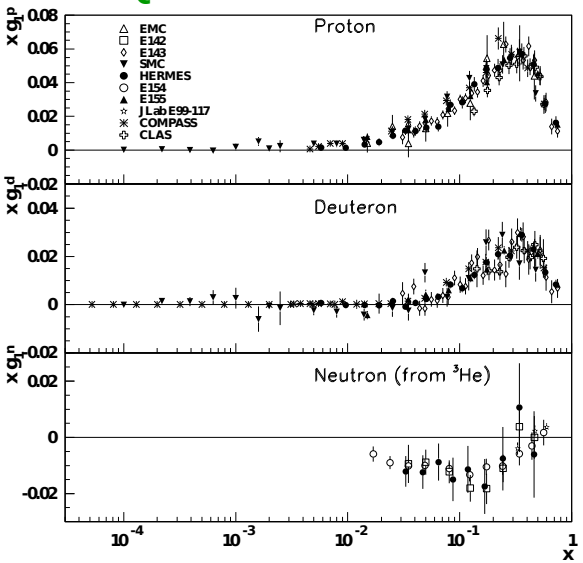
- Many Future Facilities
  - Including E1039 at Fermilab!

Status of Nucleon Spin Puzzle



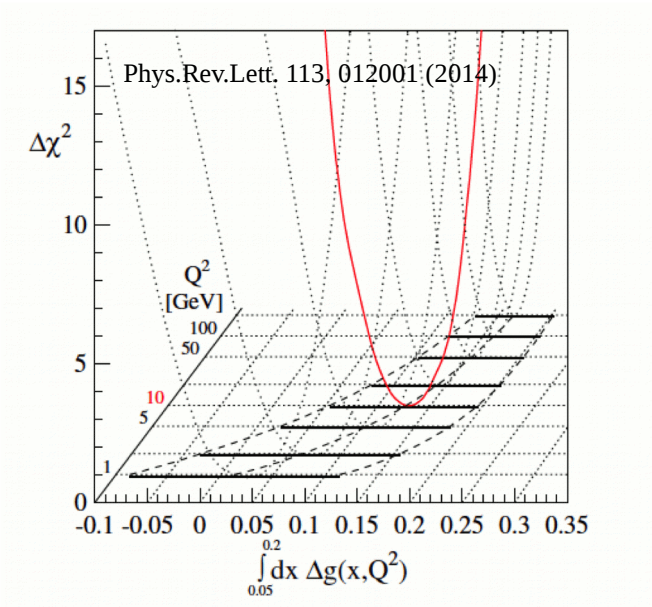
$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_q \rangle + \langle L_g \rangle$$

Quark contribution



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

Gluon contribution



$$\int_{0.05}^{0.2} dx\, \Delta g(x) = 0.2 \pm 0.06$$

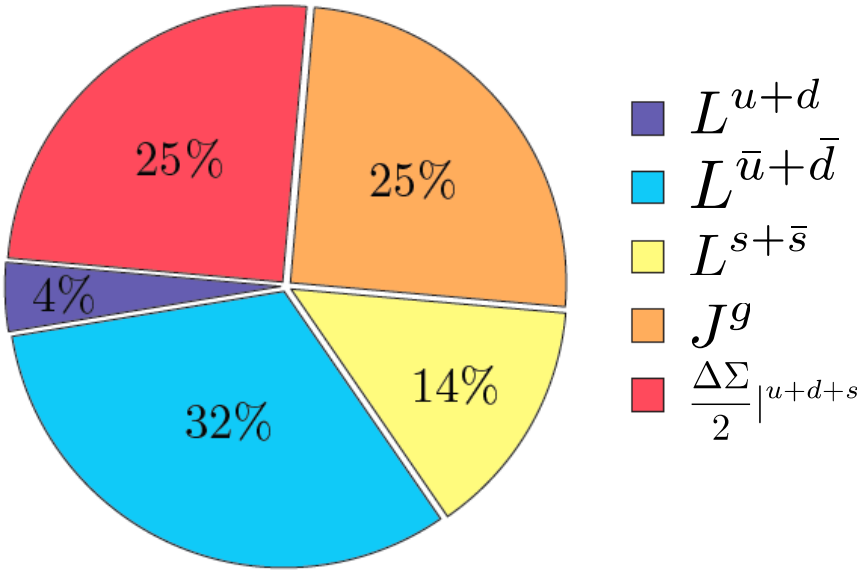
~50% Missing?

Los Alamos NATIONAL LABORATORY

Nucleon Spin Puzzle

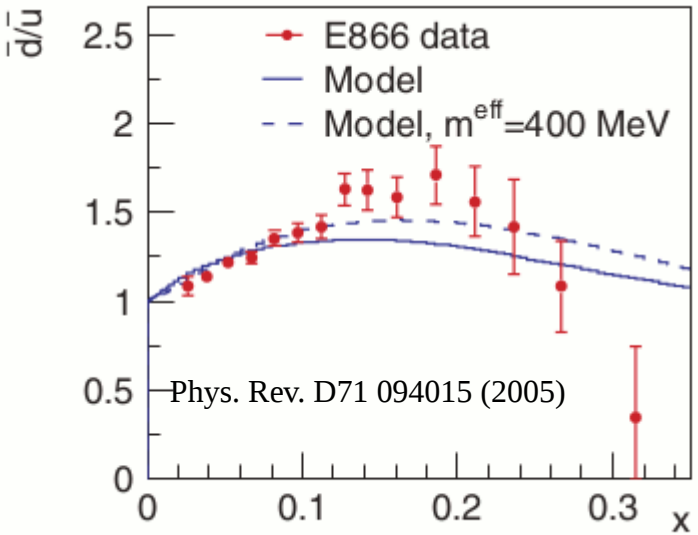
$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_g + \langle L_q \rangle + \langle L_{\bar{q}} \rangle$$

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

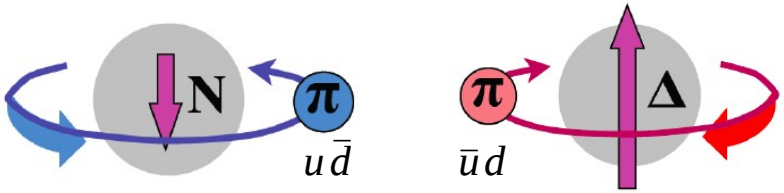


- Lattice QCD calculations indicate as much as 50% come from quark O.A.M.
- **$\Delta L_{valence}$ ≈ Small**
- *Hints of sea quark O.A.M already seen*

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

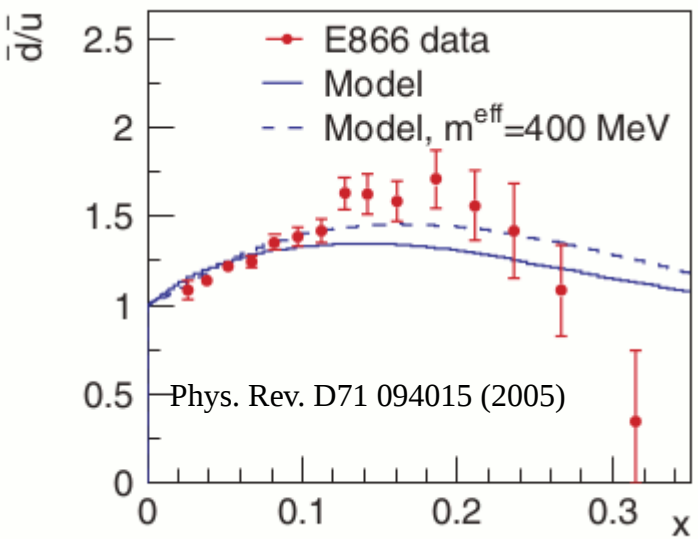


$|p\rangle = |p\rangle + |N^0\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$

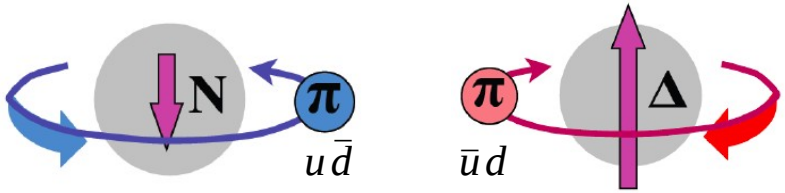


- The pion cloud model

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



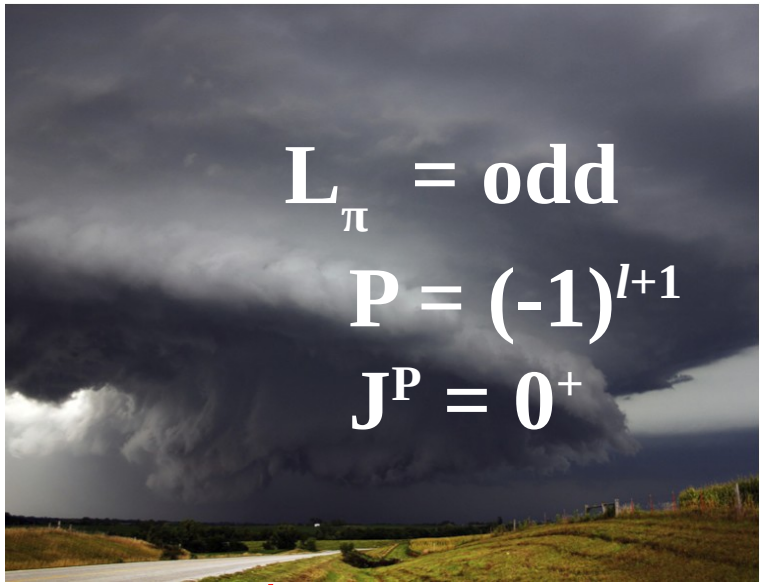
$|p\rangle = |p\rangle + |N^0\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$



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 Sivers TMD PDF.

Eight leading order PDFs

Parton / Nucleon	U	L	T
U	Number Density $f_1(x)$		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 $h_{1T}^{\perp}(x,k_T)$

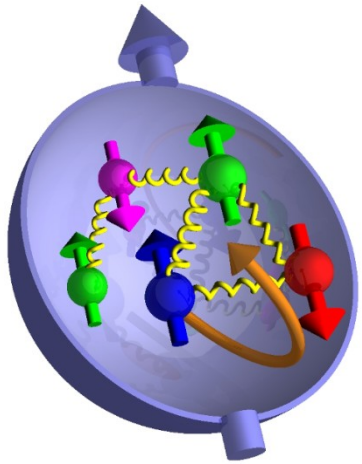
Legend

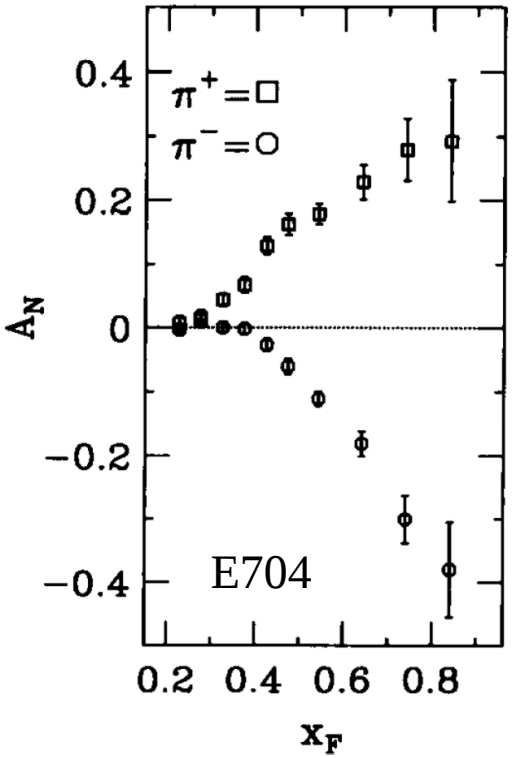
- Nucleon
- Nucleon Spin
- Parton
- Parton Spin
- Parton TMD

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

Quark Orbital Momentum and the Sivers PDF

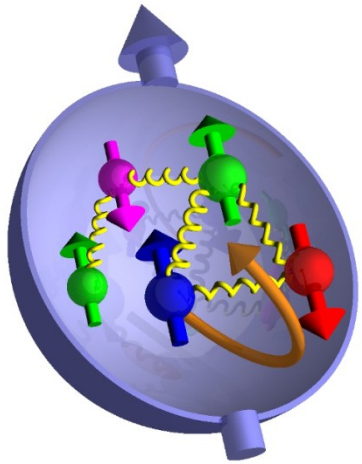
- The Sivers PDF: $f_{1T}^{\perp}(x, k_T)$
  - Correlation between proton's transverse spin and transverse parton momentum
- Originally formulated to explain E704
  - Sivers Effect: Intrinsic k_T imbalance leads to asymmetry:

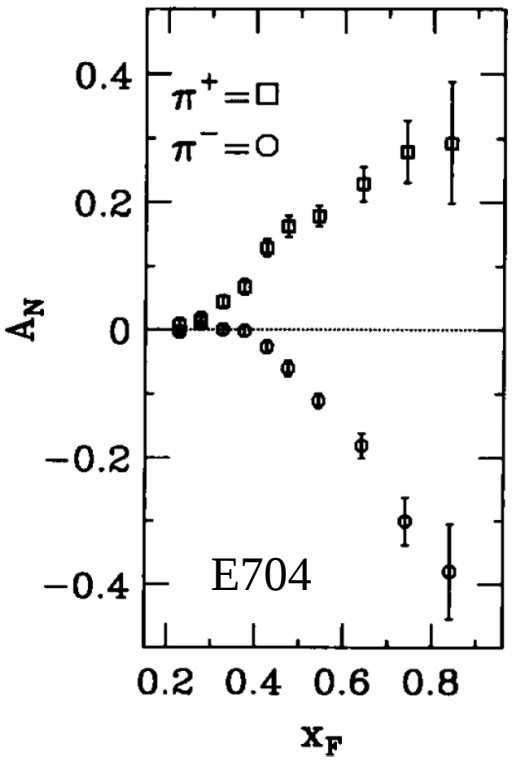


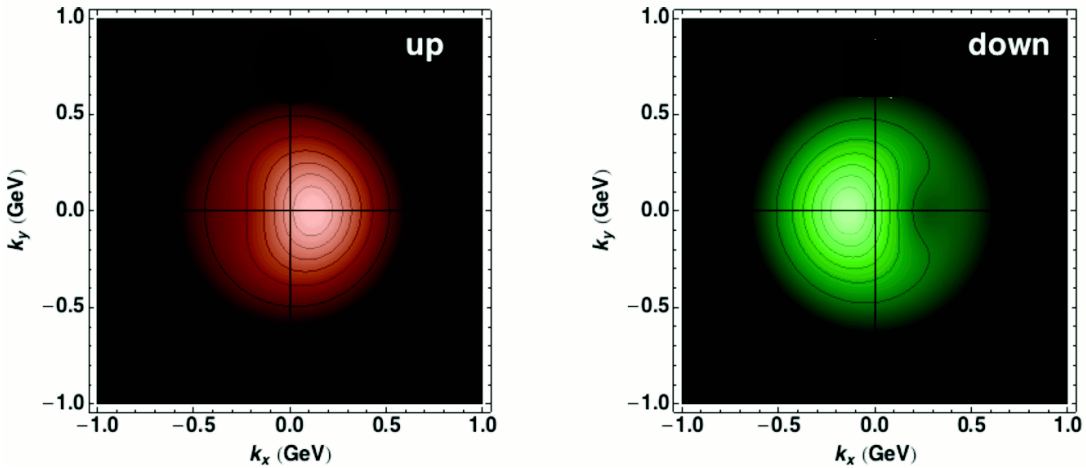


Quark Orbital Momentum and the Sivers PDF

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







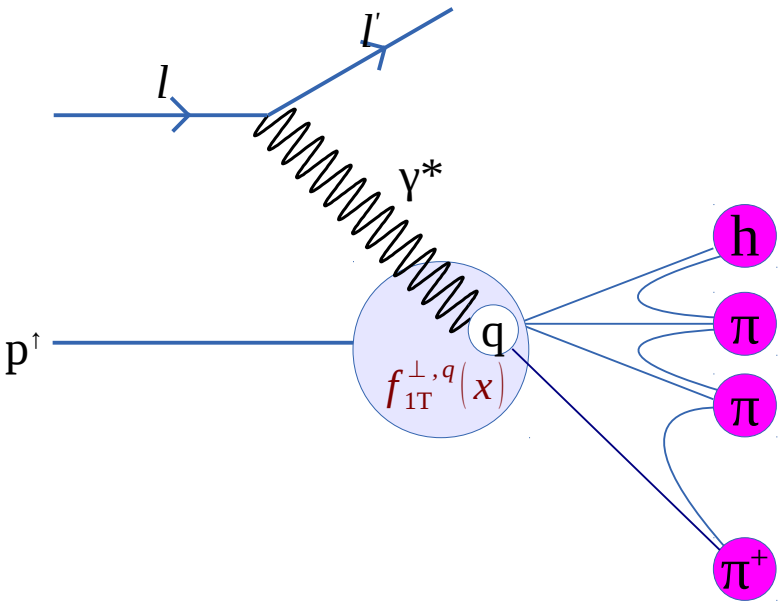
A. Bacchetta and M. Contalbrigo
Il Nuovo Saggiatore, vol. 28, pp. 16–27, 2012

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

Los Alamos NATIONAL LABORATORY

Accessing Quark Sivers PDFs

Polarized Semi-Inclusive DIS

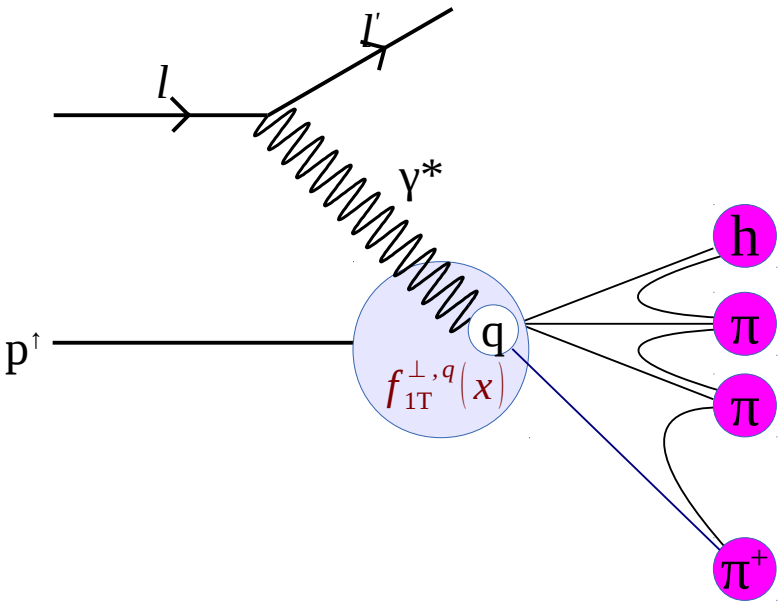


$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to Hadron Fragmention function (model dep.)
- Valence-Sea quark: Mixed

Accessing Quark Sivers PDFs

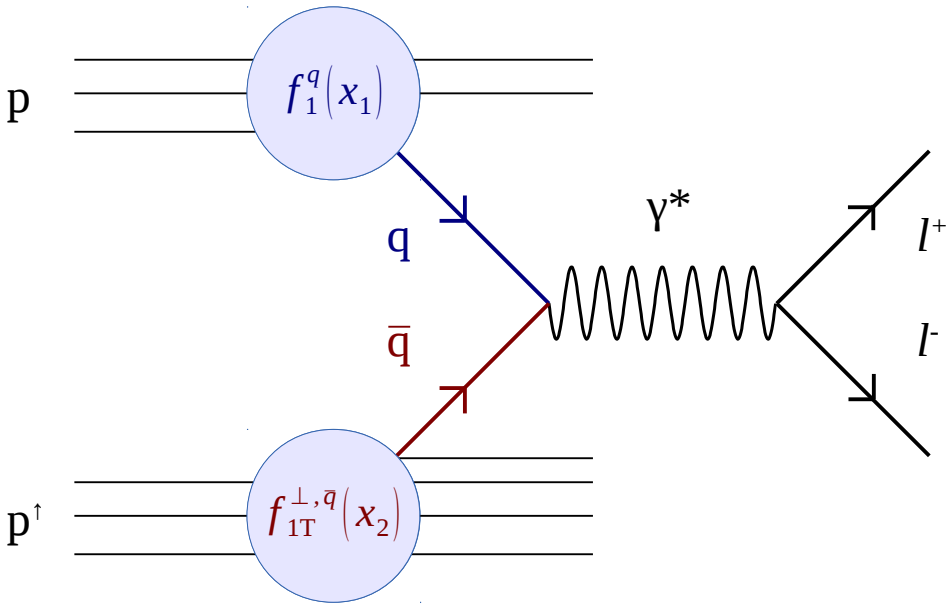
Polarized Semi-Inclusive DIS



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

- L-R asymmetry in hadron production
- Quark to Hadron Fragmention function (model dep.)
- Valence-Sea quark: Mixed

Polarized Drell-Yan

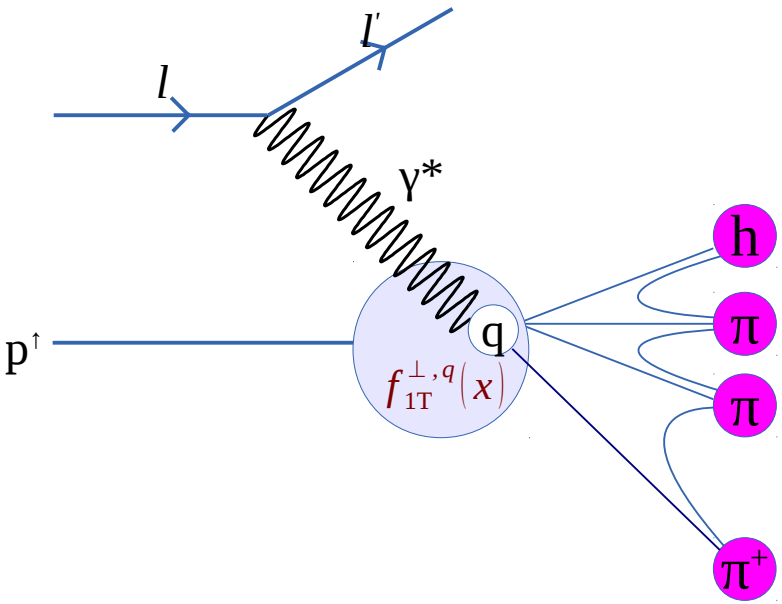


$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

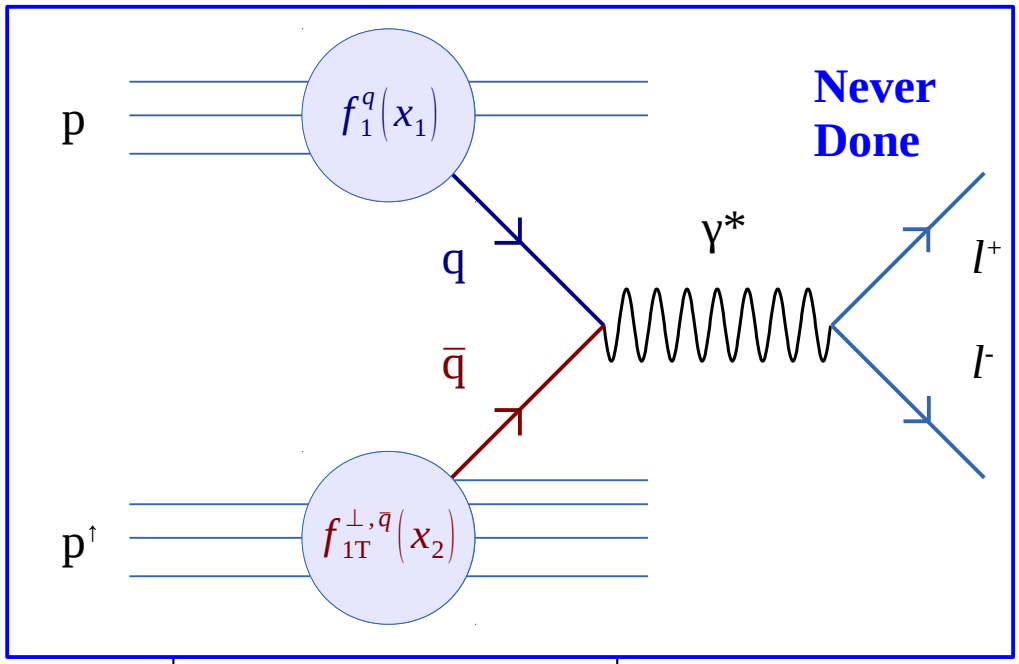
- L-R asymmetry in Drell-yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated**

Accessing Quark Sivers PDFs

Polarized Semi-Inclusive DIS



Polarized Drell-Yan

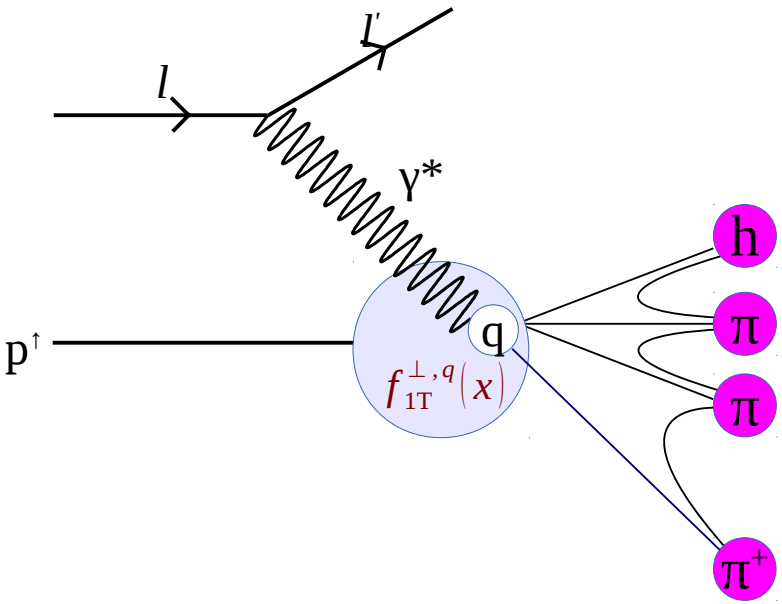


$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$

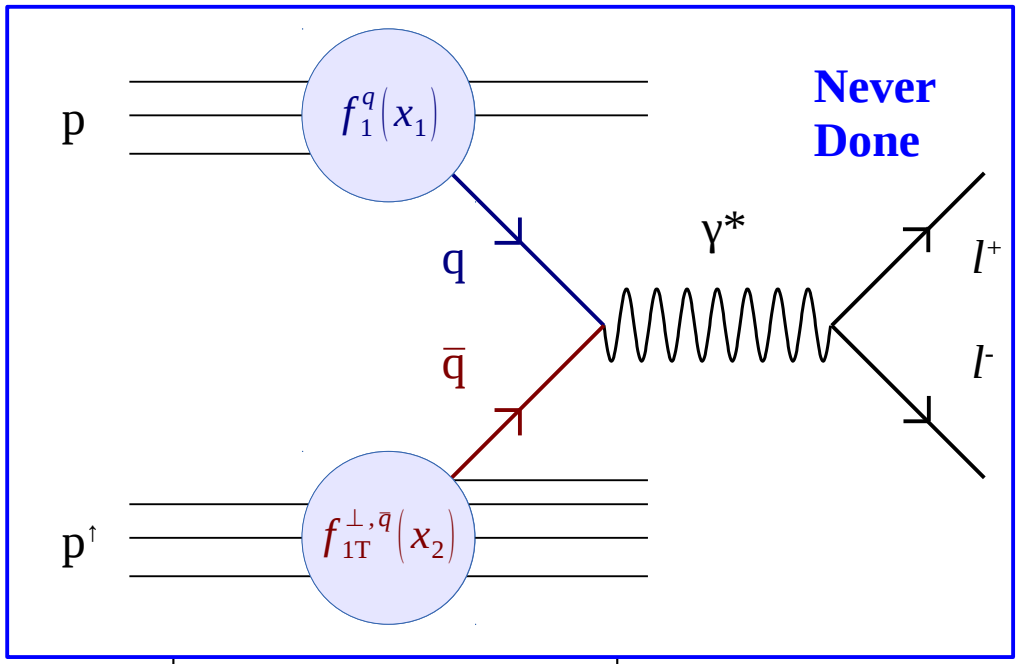
- **Cornerstone Prediction of QCD**
  - The same Sivers PDFs in both processes
  - But with opposite sign
    - T-Odd
    - Initial state, Final state switch

Accessing Quark Sivers PDFs

Polarized Semi-Inclusive DIS



Polarized Drell-Yan



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

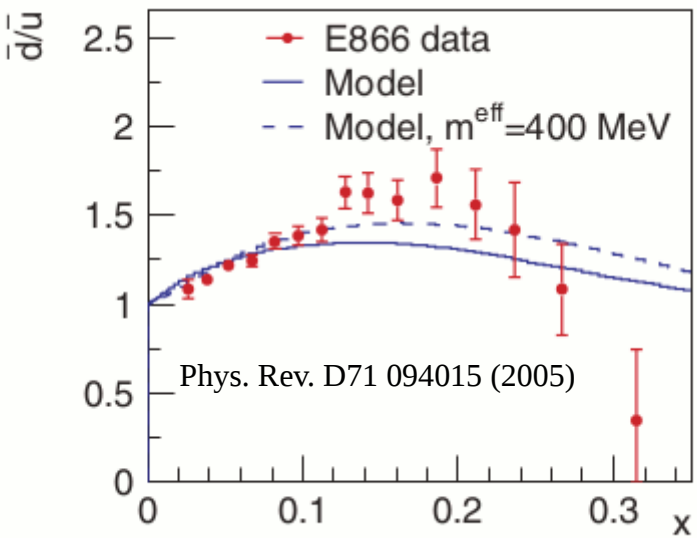
- **Cornerstone Prediction of QCD**
  - The same Sivers PDFs in both processes
  - But with opposite sign
    - T-Odd
    - Initial state, Final state switch

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

Los Alamos NATIONAL LABORATORY

E1039 Physics Summary

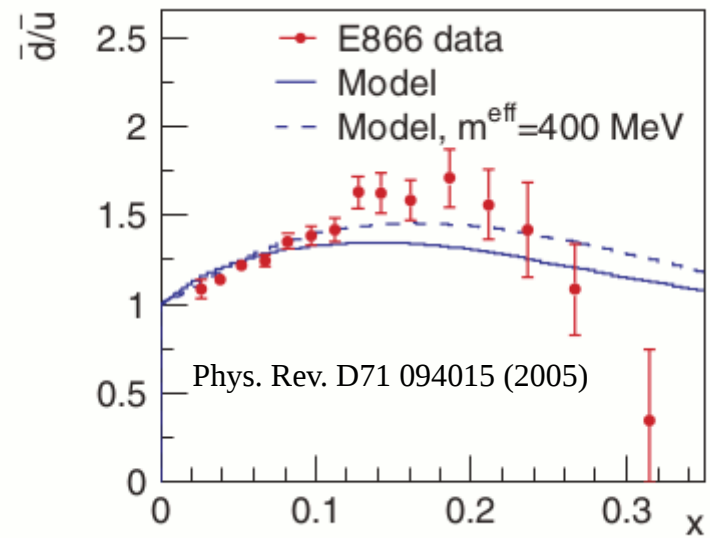
- Little is known about Sea Quark Angular Momentum
- E866 data, interpreted by the pion cloud model points to non-zero sea quark angular momentum
- The E1039 Polarized Target Drell-Yan Experiment provides opportunity to study possible Sea Quark O.A.M.

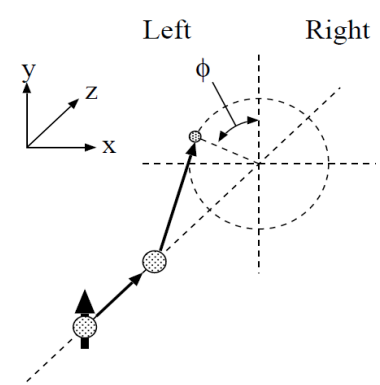


E1039 Physics Summary

- 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 E906 Seaquest Experiment**
  - Measure:

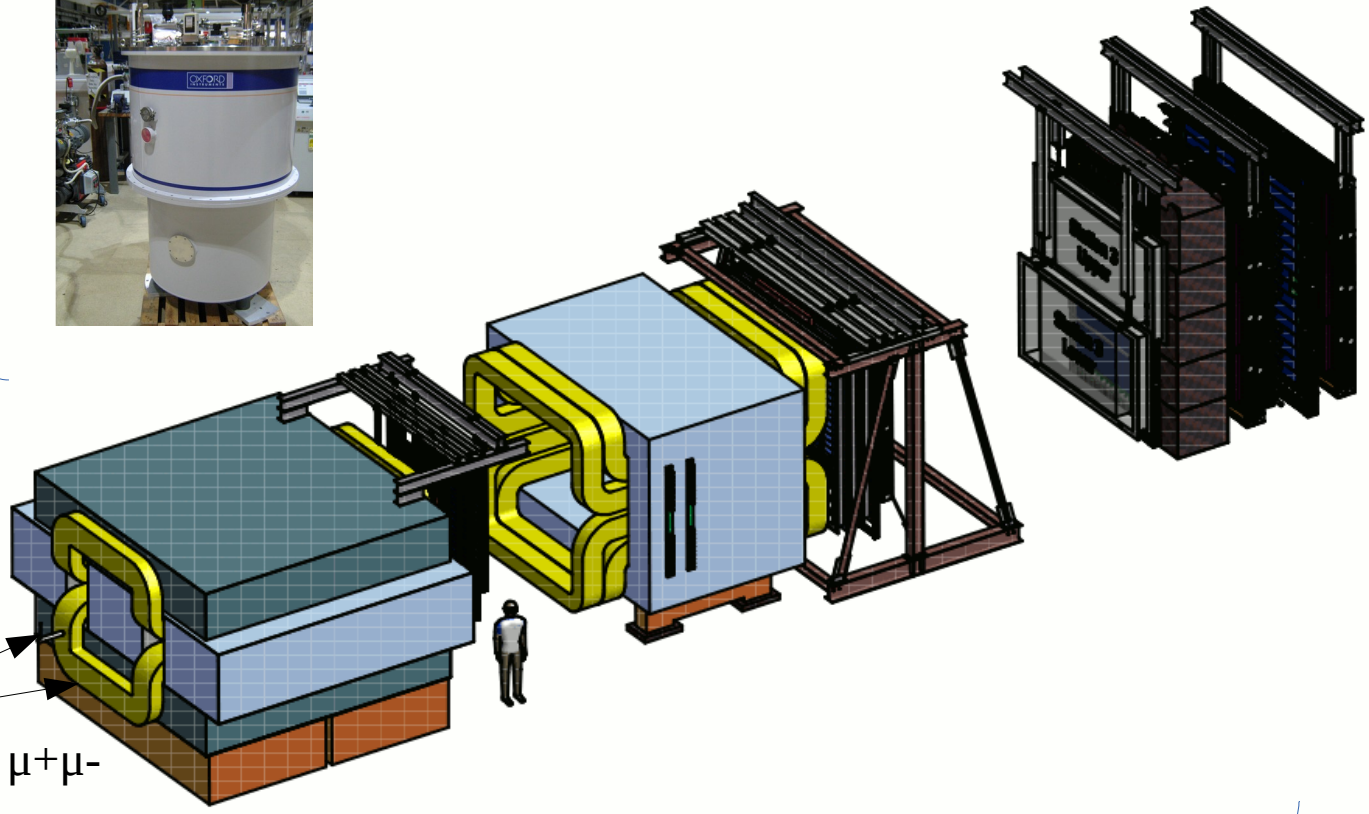
$$A_N\left(p_{beam} + p^{\uparrow}_{target} \rightarrow DY\right) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{u}}\left(x_t\right)}{f_1^{\bar{u}}\left(x_t\right)}$$

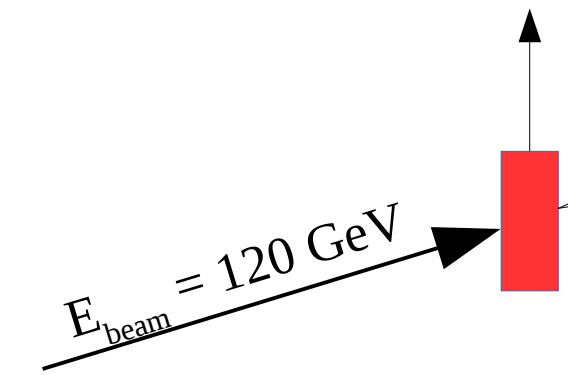




What is needed for E1039

- **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**





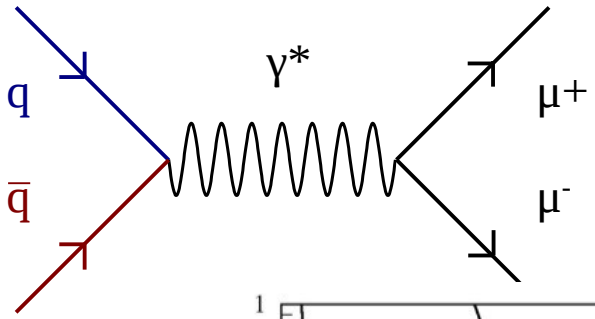
Dimuon Spectrometer

FNAL proton beam

Polarized Target

P-division Postdoc Summer Seminar Series
July 29th, 2015
Kun Liu

Sea quarks and Fixed Target Drell-Yan

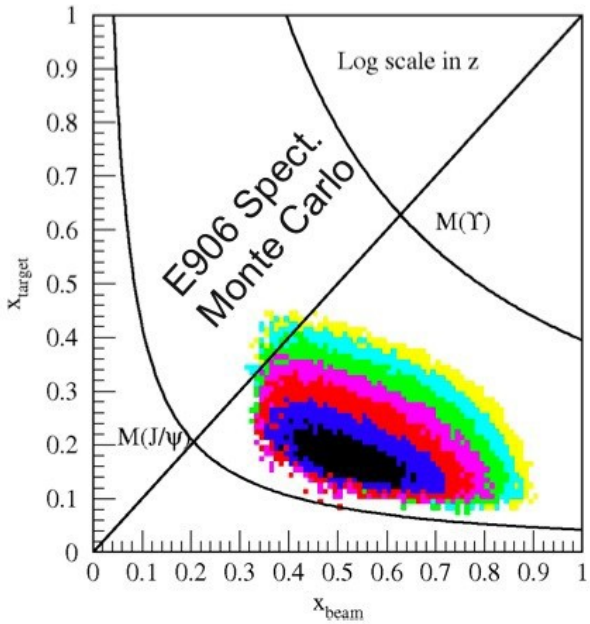


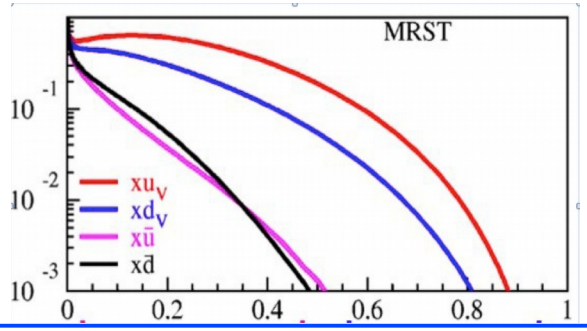
$$\frac{d^2\sigma(q\bar{q}\rightarrow\mu^+\mu^-)}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_bx_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b)+\cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

dominates small

target sea quark

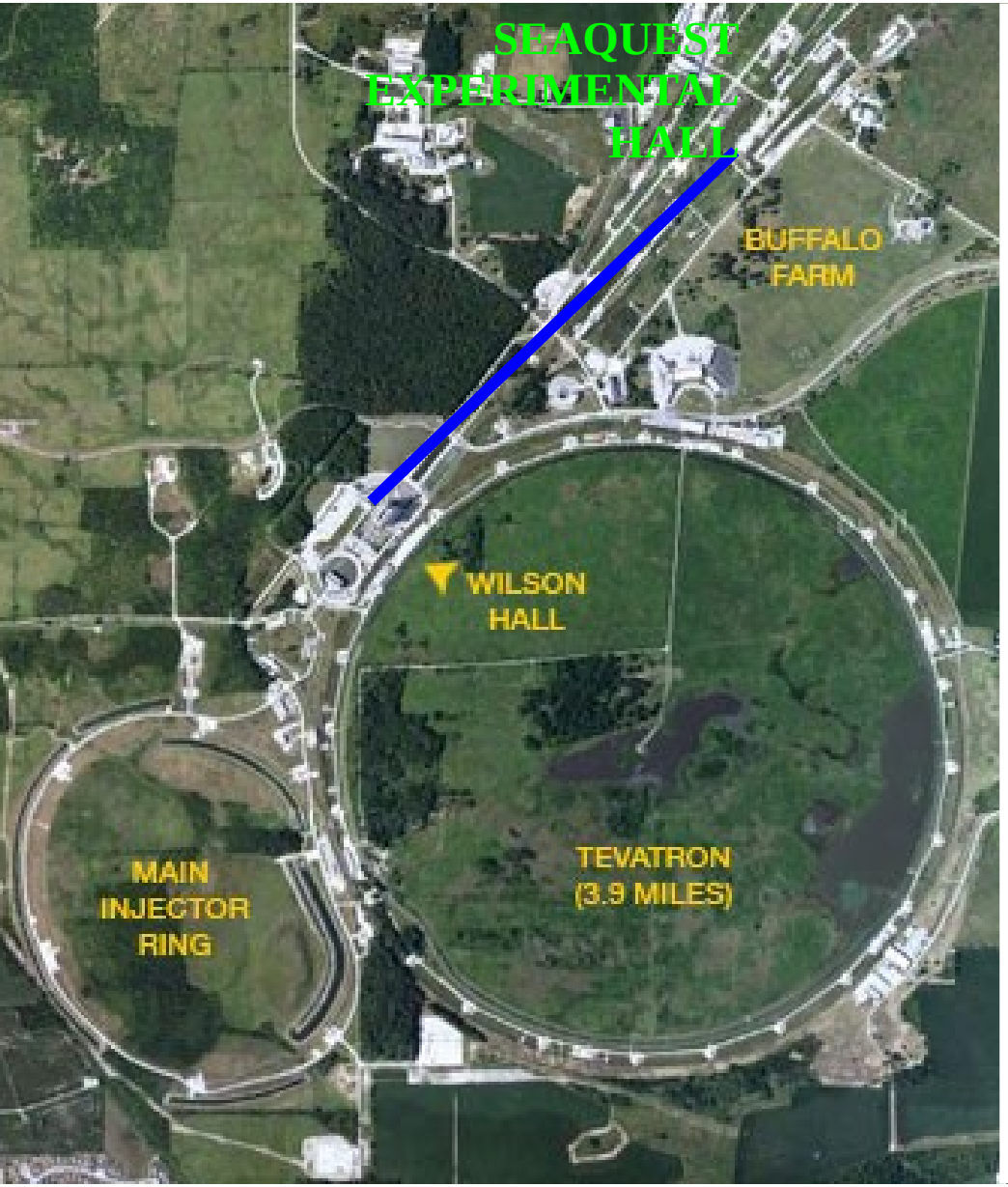
beam valence quark





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

Proton Beam @ FNAL



- 120 GeV protons
- KTev beam line
- $\sqrt{s}$ = 15.5 GeV
- Projected Beam for E1039
  - Beam: 5×10^{12} p/spill; spill is 5 s/min
  - P.O.T./year: 9.7×10^{17}

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 Ammonia target
  - Density: 0.917 g/cm^3
  - Length: 8 cm
  - Packing Fraction: 0.6
  - Average Polarization: 80%
  - Dilution Factor: 3/17 (NH_3)

JLab Target

E906/E1039 Collaboration

E1039 Co-Spokespersons: A. Klein, X. Jiang Los Alamos National Lab Laboratory

M. Daugherity, D. Isenhower, R. Towell, S. Watson
Abilene Christian University, Abilene, TX 79699

D. Geesaman, P. Reimer, B. G. Tice, J. Arrington
Argonne National Laboratory, Argonne, IL 60439

E.R. Kinney, J. Katich, P.-J. Lin
University of Colorado, Boulder, CO 80309

C. Brown, D. Christian
Fermi National Accelerator Laboratory, Batavia IL 60510

M. Diefenthaler, J.-C. Peng, N. Madkins, B. Dannowitz, B. Kerns, R.E. McClellen
University of Illinois, Urbana, IL 61081

T.-H. Chang, W.-C. Chang
Institute of Physics, Academia Sinica, Taiwan

S. Ishimoto, S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan

X. Jiang, A. Klein D. Kleinjan, M. Leitch , K. Liu , M. Liu , P. McGaughey, J. Mirabal-Martinez
Los Alamos National Laboratory, Los Alamos, NM 87545

E. Beise , K. Nakahara, Y.-C. Chen
University of Maryland, College Park, MD 20742

C. Aidala, W. Lorenzon, B.J. Ramson, R. Raymond, J.G. Rubin
University of Michigan, Ann Arbor, MI 48109-1040

T. Badman, Shujie Li, E. Long, P. Solvignon, K. Slifer , R. Zielinski
University of New Hampshire, Durham, NH 03824

R.-S. Guo, S.-Y. Wang
National Kaohsiung Normal University, Taiwan

L. El Fassi
Mississippi State University, Starkville, MS 39762

Y. Goto
RIKEN, Wako, Saitama 351-01, Japan

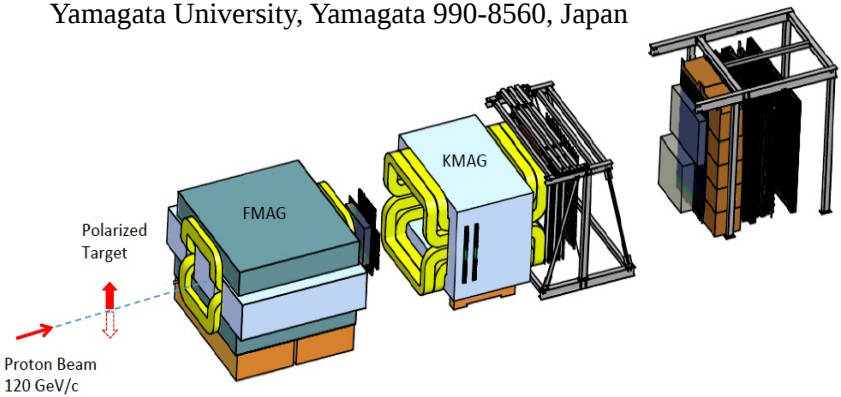
R. Gilman, K. Mesick , R. Ransome, A. Tadepalli,
Rutgers University, Rutgers NJ 08544

J.-P. Chen , C. Keith
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan

D. Crabb (FA) , D. Day , D. Keller, O. Rondon, J. Zhang
University of Virginia, Charlottesville, VA 22904

N. Doshita , T. Iwata, Y. Miyachi
Yamagata University, Yamagata 990-8560, Japan



Procedure to Polarize Protons

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

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

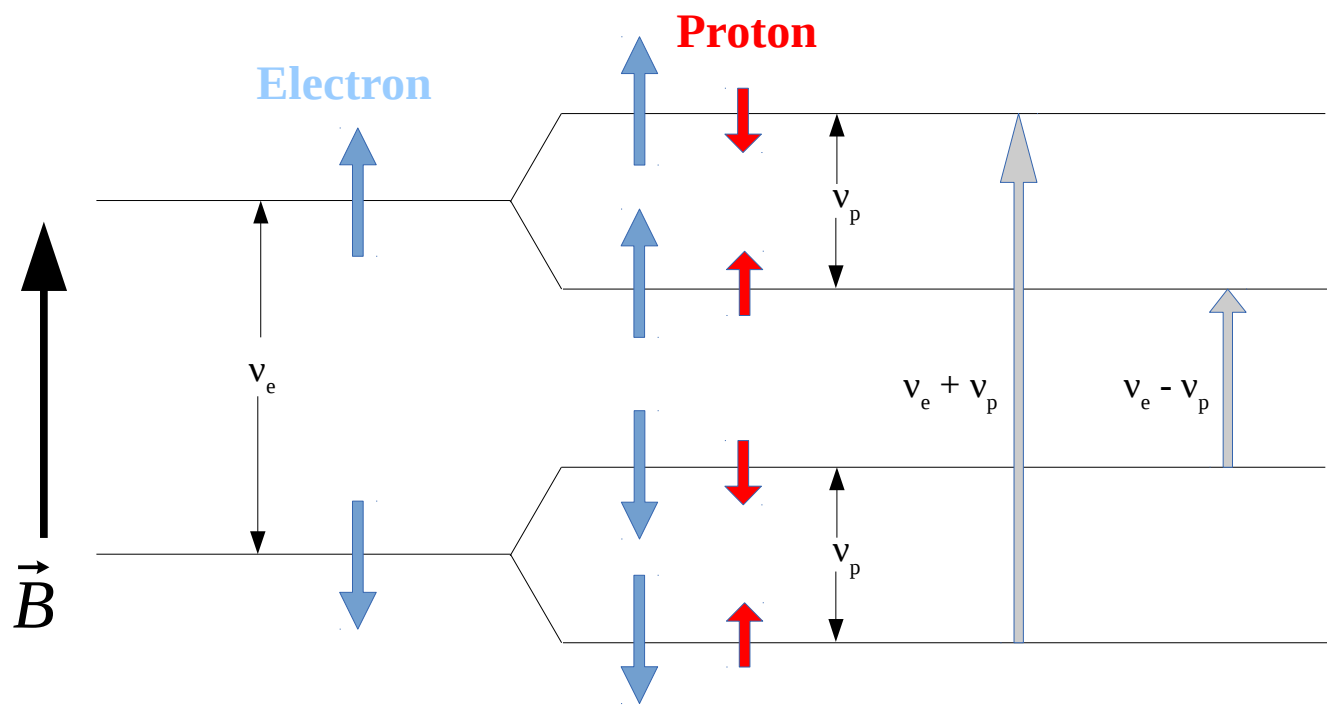
    - T = 1 Kelvin, B = 5 Tesla
      - $P_{electron} = 0.998$
      - $P_{proton} = 0.005$, since $\mu_N/\mu_B \sim 10^{-3}$
- *Can polarize protons in Paramagnetic material through RF transitions*

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

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



Proton Polarization Measurement using NMR

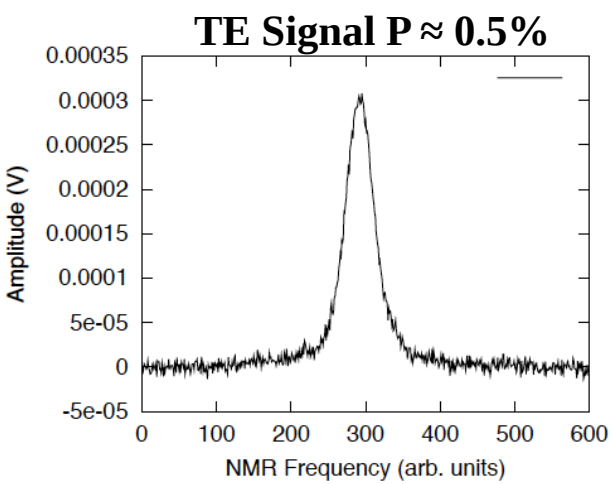
- Polarization measurement using NMR technique, basics
  - Apply RF at proton Larmor frequency, $\nu_p \approx 213$ MHz, to RLC circuit
  - Measured with an inductor coils around target
  - Measures Polarization of Protons by absoption or emission of RF
  - Voltage increases for absorption, decreases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

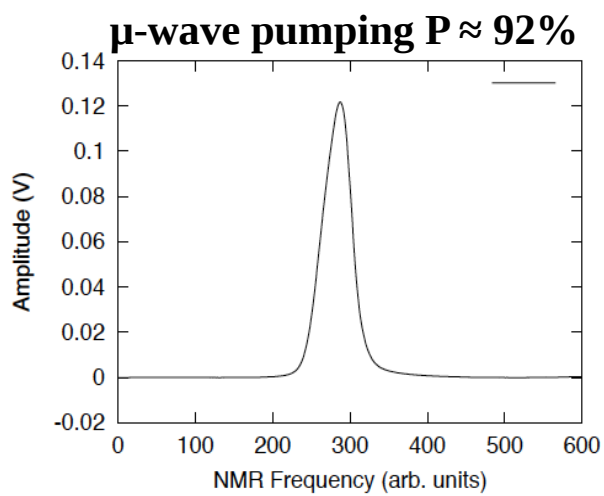
JLab Target

NMR Coil (inductor) around target.

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*



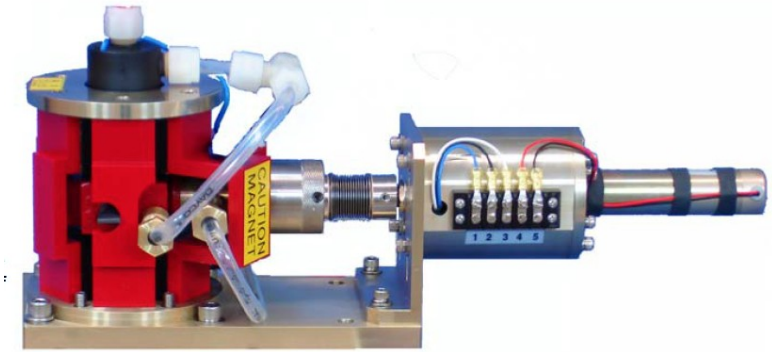


Keith et al. NIM A 501 (2003), 327 JLAB
Well established technology: SLAC, JLAB, PSI…

JLab Target

NMR Coil (inductor) around target.

What is Needed for Polarized Target



- 5T magnetic Field
  - Liquid ^{4}He cooled Superconducting magnet
- 1K Temperature
  - Liquid ^{4}He cooled using vapor pressure/pumping technique
- Spin-flip RF transition provider
  - 140 Ghz Microwave tube
- Polarization Measurement
  - NMR apparatus

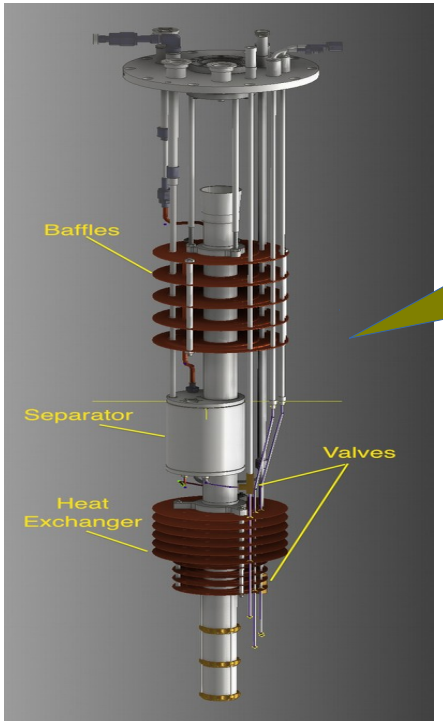
Polarized Target System

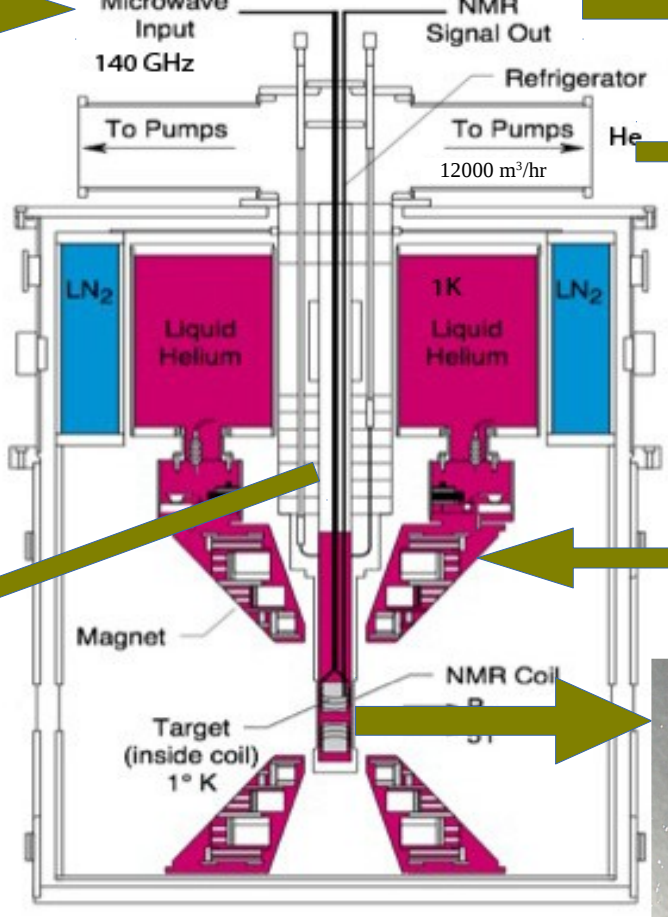
Microwave signal to Induce spin flips

NMR Polarization Measurement

Roots pump system used to pump on liquid ^{4}He vapor pressure to reach 1K

Cryostat: UVa





Superconducting Coils for Magnet: 5T

JLab Target (example)

μ-wave horn

Target Material NH_3 Irradiated at NIST

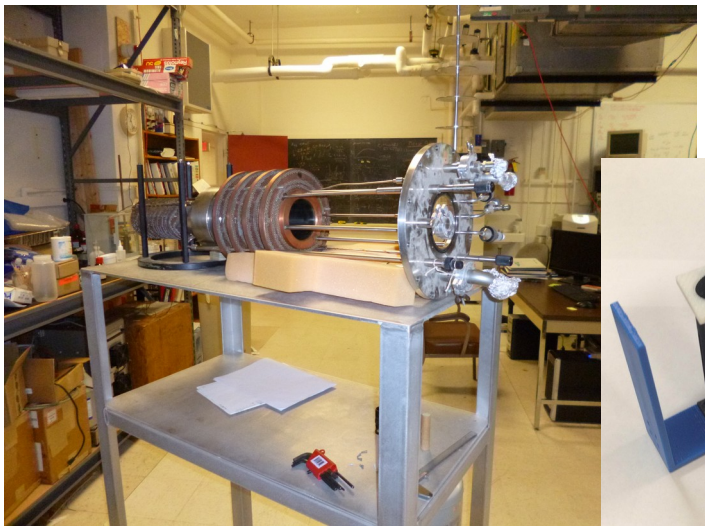
Los Alamos NATIONAL LABORATORY

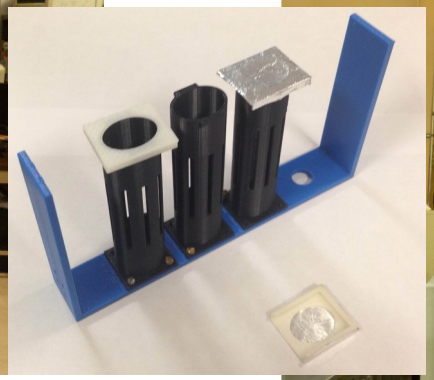
Status of E1039 Experiment

Magnet:

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

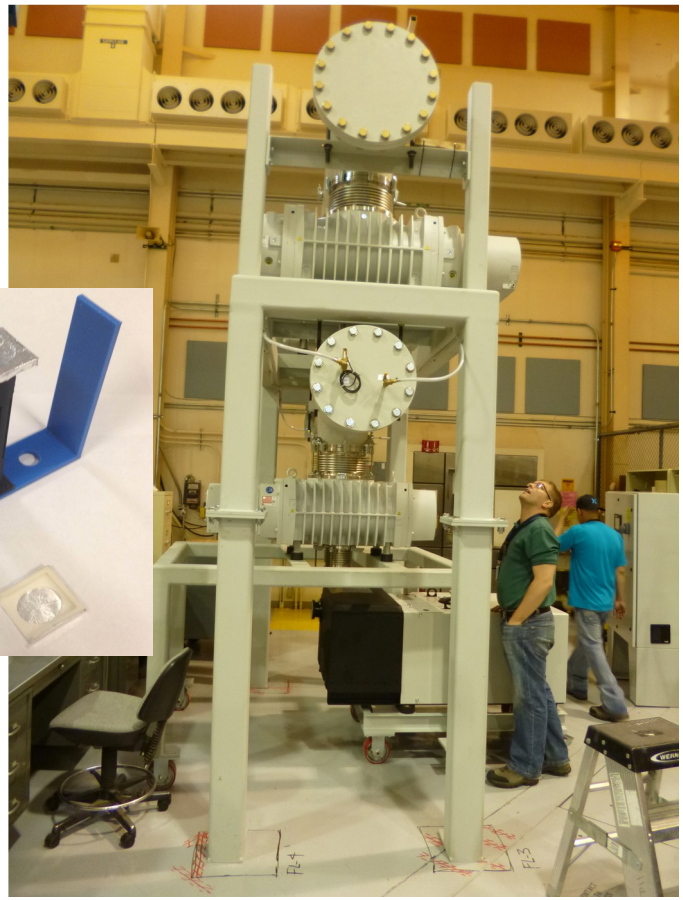
Cryostat + Target Stick:





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

Pumps:



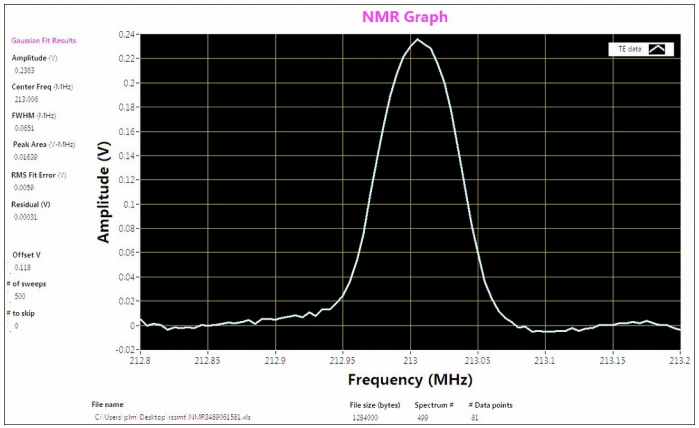
- Performance tests underway at LANL

Los Alamos NATIONAL LABORATORY

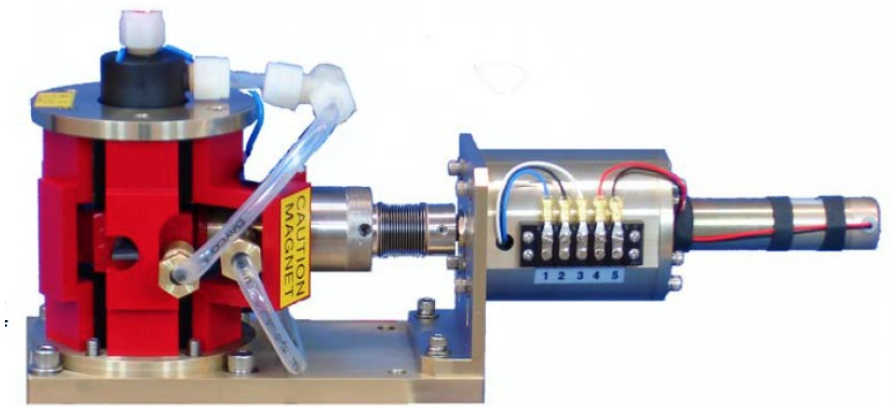
Status of E1039 Experiment

NMR System:

- Designed and Developed at LANL
- Tested 7/2014, worked well
- Layout for VME crate cards finished
  - Pat McGaughey, Jackie Mirabal-Martinez

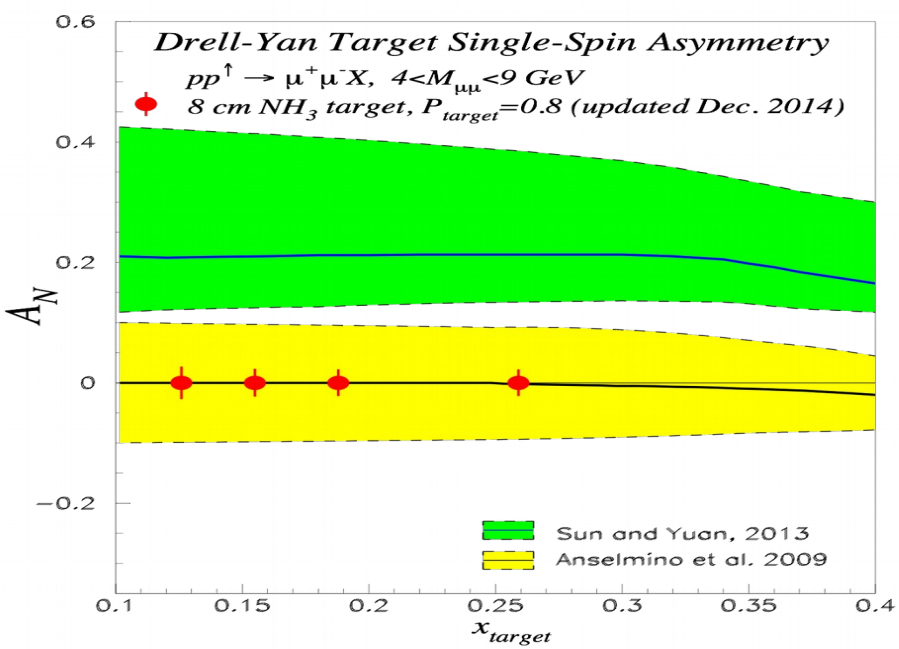


Microwave Tube:



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

Summary and Conclusion



Based on current Beam and Spectrometer performance
Statistics shown for one calendar year of running :
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 probe of sea quark ($\bar{u}$) Sivers PDF
- 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

Backup

Yield and Asymmetry Estimates

- One year $L = 5.22\text{x}10^{42}$ 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

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

Based on Present Beam and Spectrometer Performance at Seaquest

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

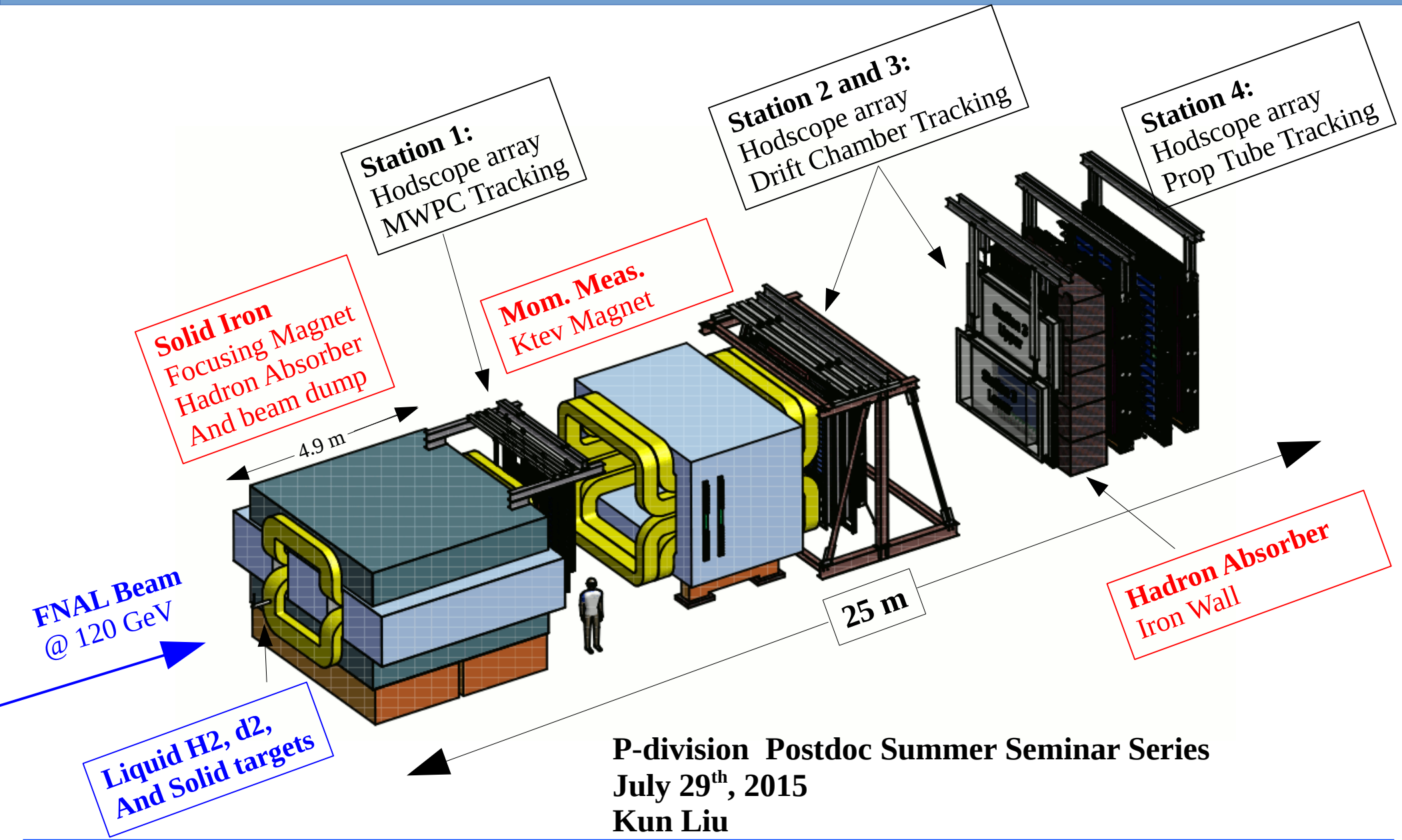
$$A_N^{DY} = \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}}$$

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

- $f \approx 3/17$
- $P \approx 0.80$

E1039 Est.

Muon ID @ Seaquest



P-division Postdoc Summer Seminar Series
July 29th, 2015
Kun Liu

Yield and Asymmetry Estimates

- One year $L = 5.22\text{x}10^{42}$ 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

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

Based on Present Beam and Spectrometer Performance at Seaquest

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

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

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

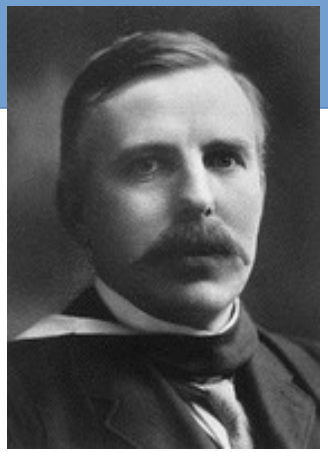
- $f \approx 3/17$
- $P \approx 0.80$

E1039 Est.

Systematics

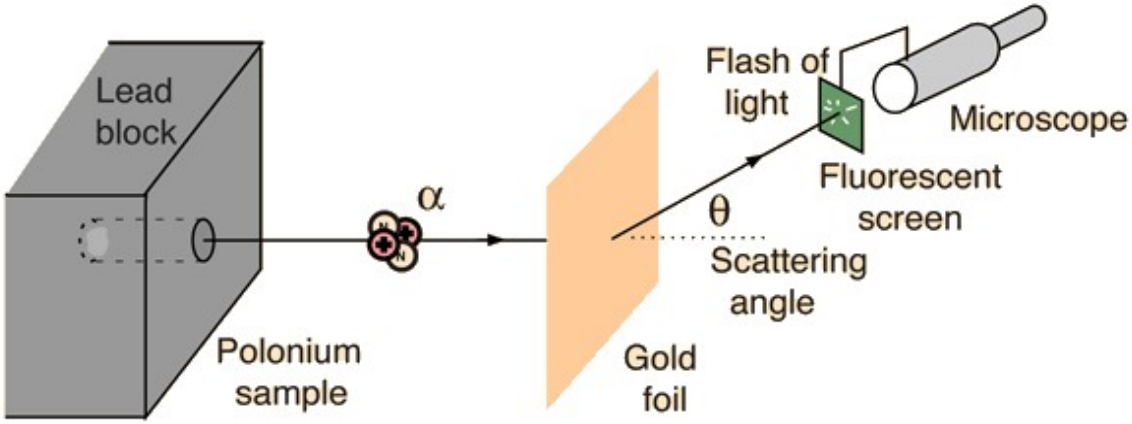
- Systematics control
  - Reverse pol direction once a day
  - Reverse Fmag,Kmag every two days
  - Reverse 5T magnet every target replacement
  - Background measurements every shift with target out
- Absolute 1%
  - Luminosity precision on different pol directions

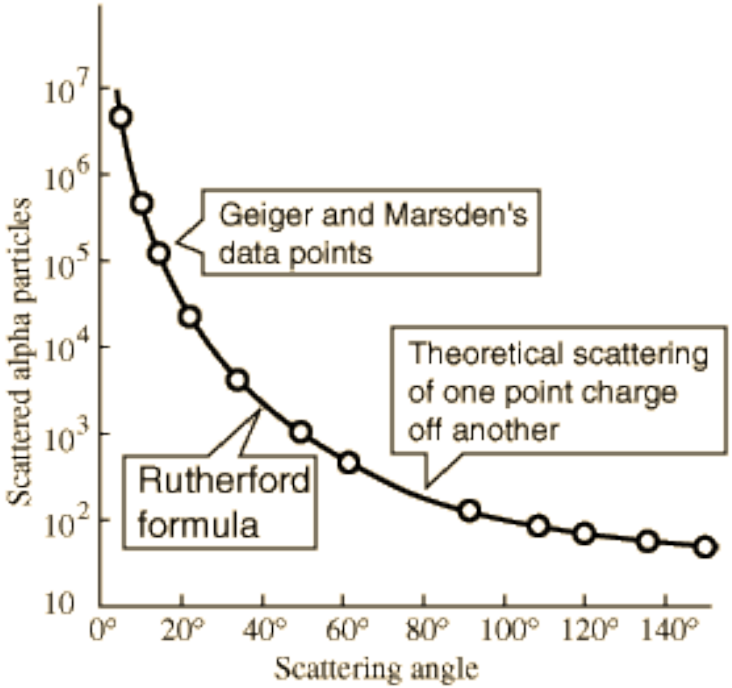
Rutherford Scattering



The Scattering of α and β Particles by Matter and the Structure of the Atom

E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688





Discovery of Nuclei

Finite size of nucleon (charge radius)

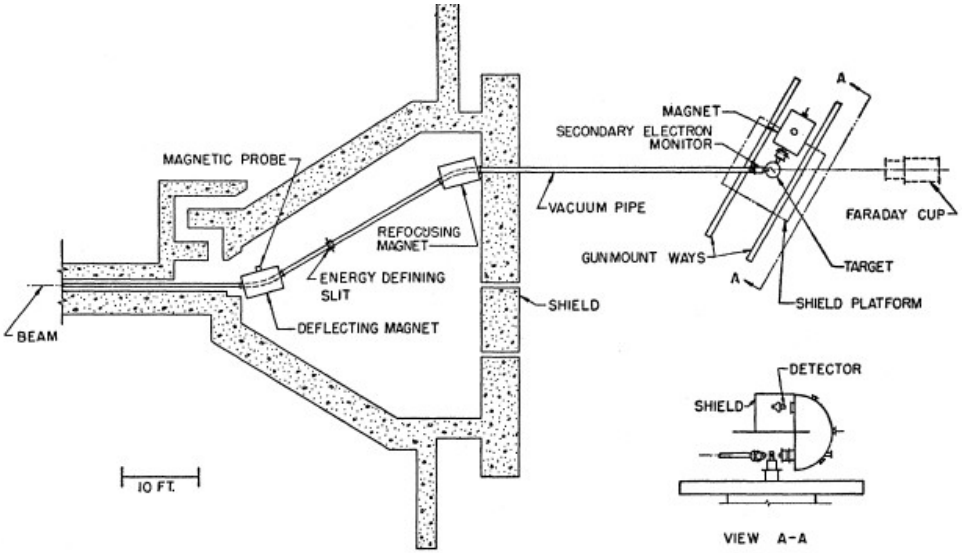
REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 3 JULY, 1956

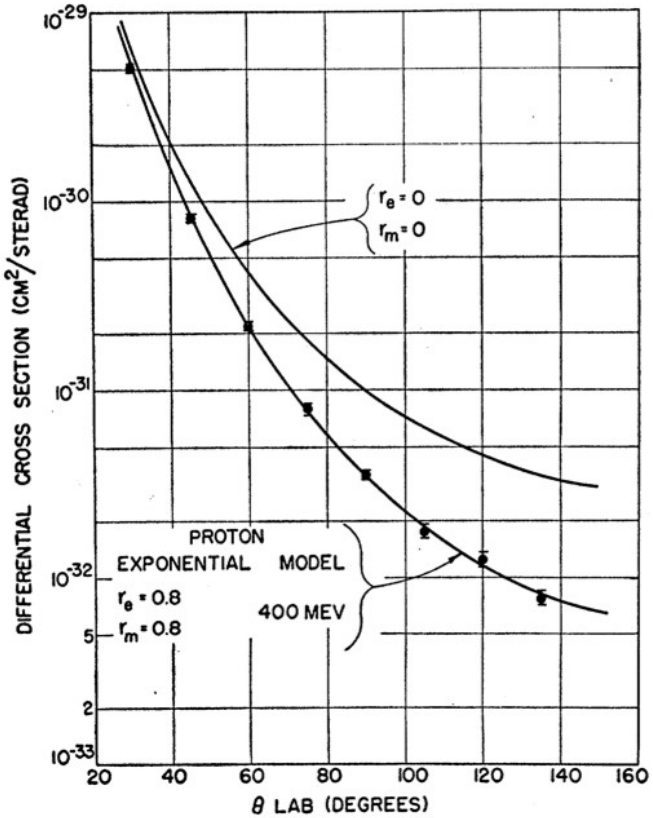
Electron Scattering and Nuclear Structure*

ROBERT HOFSTADTER

Department of Physics, Stanford University, Stanford, California

Hofstadter





Rutherford Scattering with electron

Los Alamos NATIONAL LABORATORY