E1039 @ FNAL:
Measuring the Sea Quark Sivers Asymmetry

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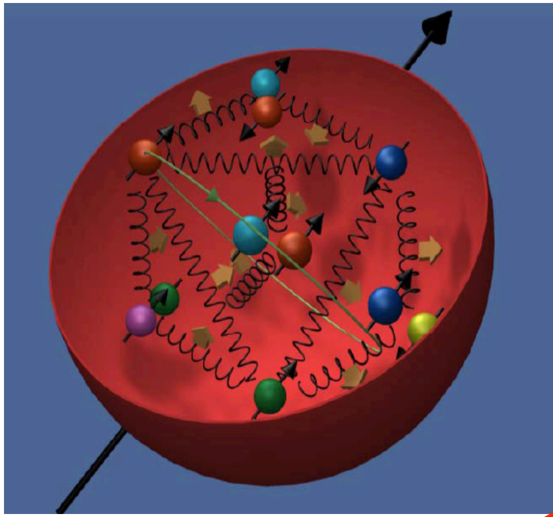


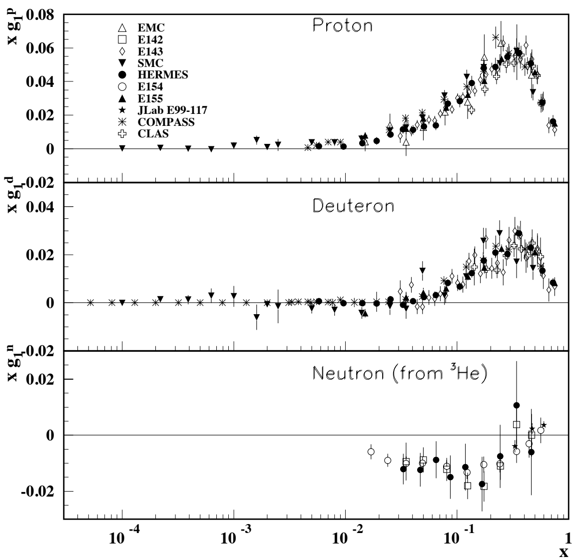
Where are we today

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

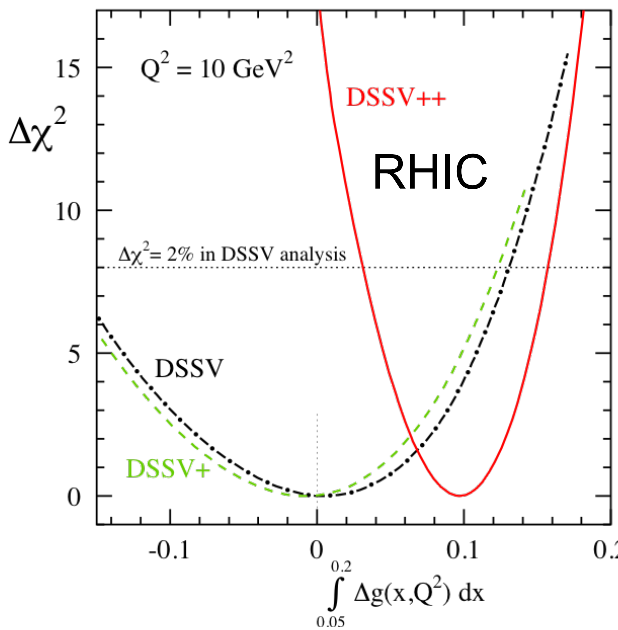
Quark contribution

Gluon contribution

Angular Momentum of q,g



Quark Polarization from all flavors



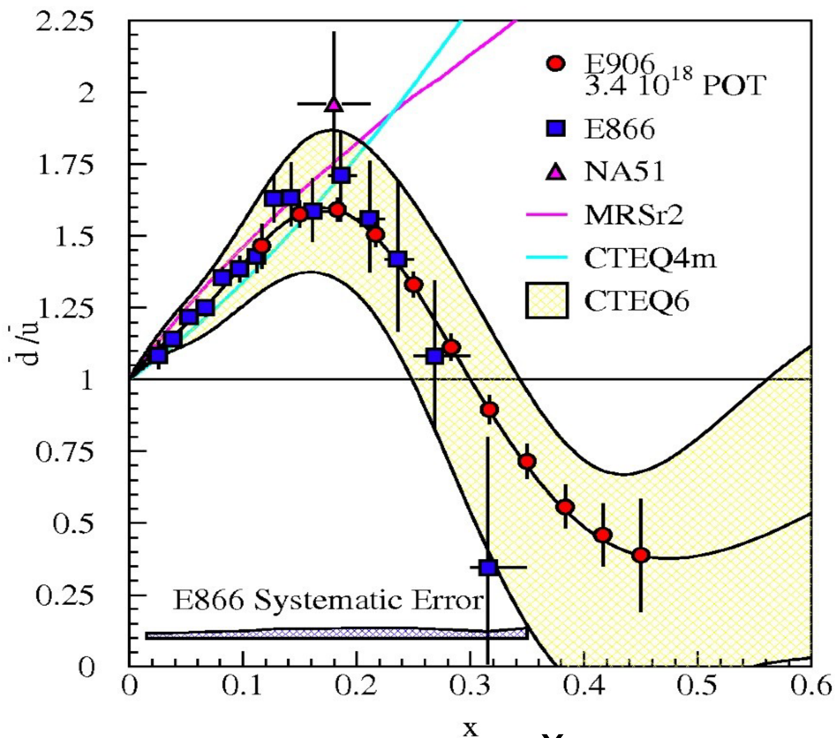
$$\Delta\Sigma_q \approx 0.25 \pm \ldots \quad + \quad \int_{0.05}^{0.2} dx\,\Delta g(x) = 0.1 \pm 0.06$$

=50% ?

Indication of Angular Momentum: Results from E866

Gottfried Sum Rule: =**1/3** ← =0

$$I_G = \int_0^1 [F_2^p(x,Q^2) - F_2^n(x,Q^2)]/x dx = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)] dx$$



x_{Target}

$$\bar{d}(x)/\bar{u}(x) \neq 1$$

$$I_G^{E866}(.100) < I_G^{NMC}(.148)$$

Why not symmetric:

- Pion cloud model

Lattice Calculations

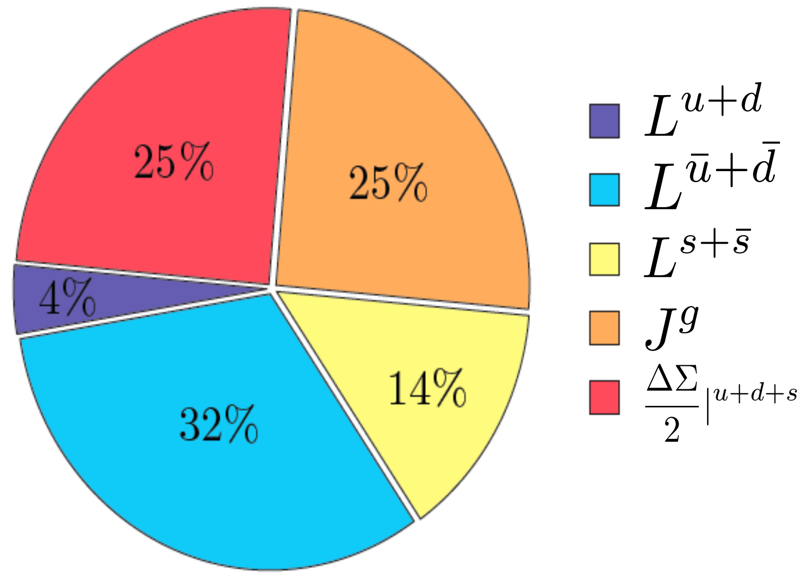
Non perturbative approach to QCD; formulated on a grid of points in space and time

- When including disconnected diagrams, most orbital angular momentum (OAM) from sea

How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD Transverse Momentum Distribution

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



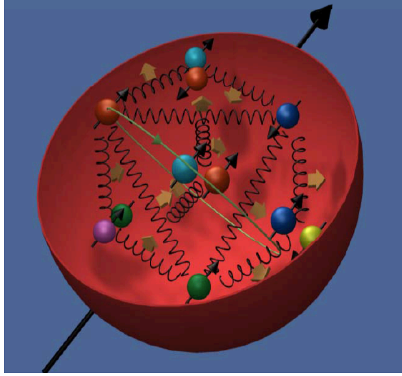
$\Delta\Sigma_q \approx 25\%$

$2\,L_q \approx 46\%$ (0%(valence)+46%(sea))

$L_u \approx - L_d$

$2\,J_g \approx 25\%$

Quark Orbital Momentum and the Sivers Function



The Sivers function is the distribution of unpolarized quarks in a transversely polarized proton, one of 8 Transverse Momentum Distributions (TMDs)

$$f(x,p_T,S) = f_1(x,p_T^2) - \frac{[p_T \times \hat{P}] \bullet S_T}{M} f_{1T}^{\perp}(x,p_T^2)$$

- S: nucleon spin
- p_T: Transverse momentum

Sivers distribution

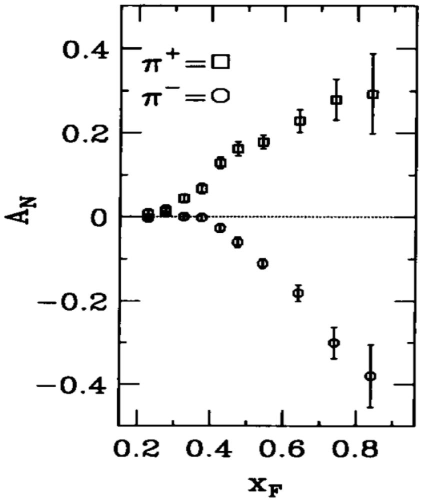
T-odd => $f_{1T}^{\perp}(x,p_T^2)$

also T-odd

First proposed to explain E704

$$f_{1T}^{\perp}(x,p_T^2) \propto f_1(x,p_T,S) - f_1(x,p_T,-S)$$

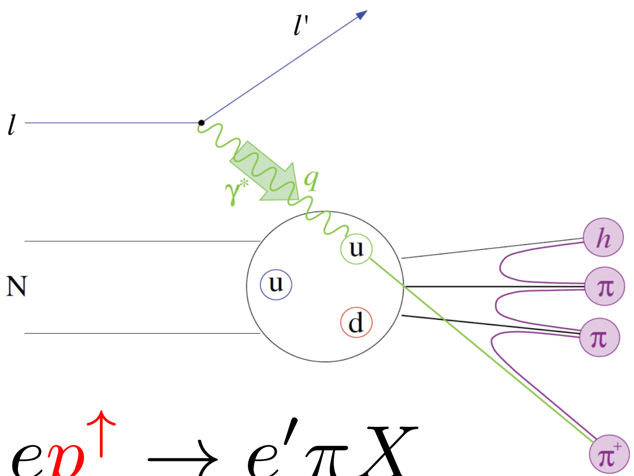
E704 $\sqrt{s}$ =20 GeV. PLB 264 (1991) 462.



Sivers effect: quark's transverse motion generates a left-right bias.
up-quarks favor the left,
down-quarks favor the right
($L_u \approx - L_d$)

Sivers function = 0 $\Leftrightarrow$ L_q=0

Asymmetry in Semi-Inclusive DIS



$$e p^{\uparrow} \rightarrow e' \pi X$$

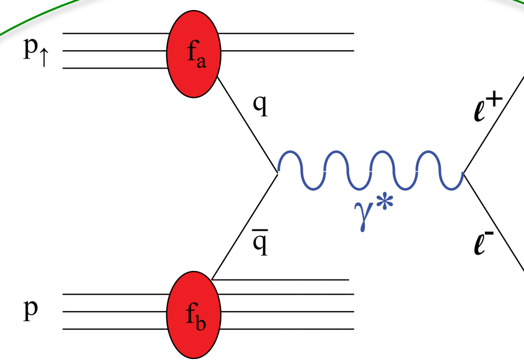
$$d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)$$

- **Involves quark to hadron frag. function.**
- **Valence and sea quarks are mixed.**

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

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

Asymmetry in Drell-Yan



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

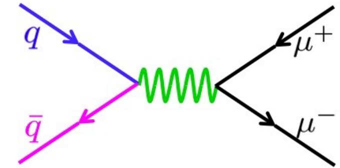
$$d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]$$

- **No quark frag. func. involved.**
- **Valence and sea quarks can be isolated**
  - **Pol. Beam➔valence quark (E-1027)**
  - **Pol. Target➔sea quark (E-1039)**

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

Result of repulsive initial state (DY) vs attractive final state (SIDIS) interaction

Drell Yan



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

target sea quark — beam valence quark — small

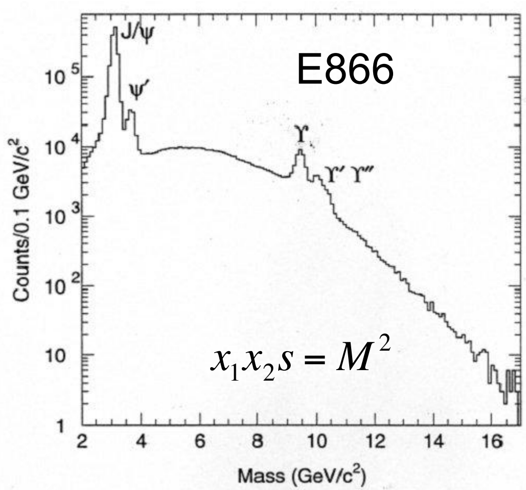
x_F= Feyman x

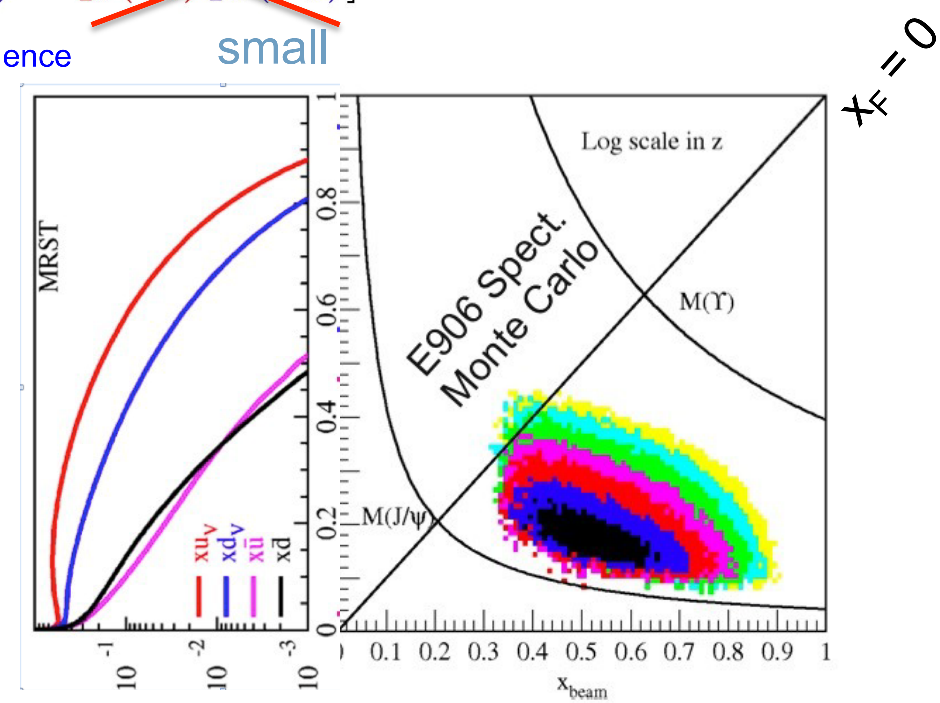
$$x_F = x_b - x_t$$

$\bar{u}_t(x_t)\cdot u_b(x_b)$ dominates

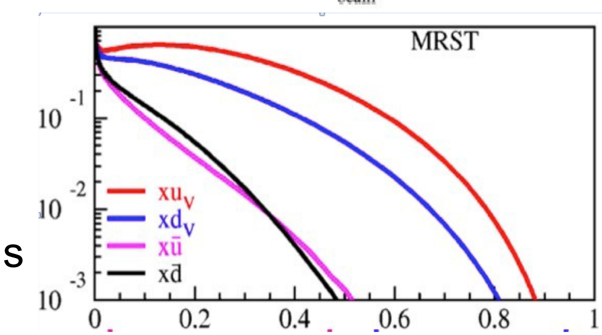
Through kinematics choose quark from beam and antiquark from target

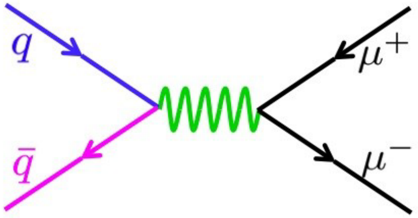
x_F>> 0



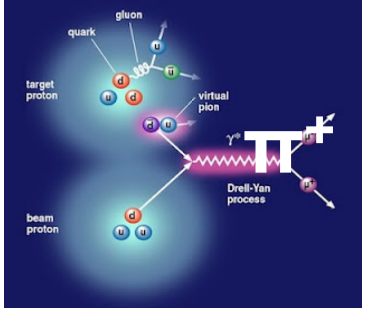


800 GeV beam
√s: 40 GeV
120 GeV:
√s: 15.5 GeV
cross section scales as s
7 times higher





Where are we?



- **We know very little about sea quarks angular momentum.**
- **E866 might point to OAM**
- **Quark orbital angular momentum leads to quark Sivers distribution.**
- **Identifying a non-vanishing sea quark Sivers distribution could lead to a major breakthrough in nucleon structure.**

- **Polarized target D-Y at Fermilab's SeaQuest provides an unique opportunity to pin down sea quark's angular momentum.**

Does Drell-Yan yield depend on target's spin direction?

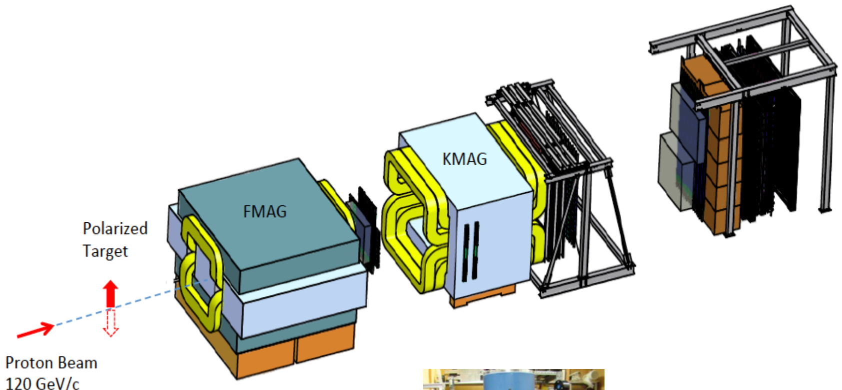
$$A_N = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \stackrel{?}{=} 0$$

$(A_N \equiv 0$ if $L_{\bar{u}} = 0)$

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

E-1039 Collaboration:

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



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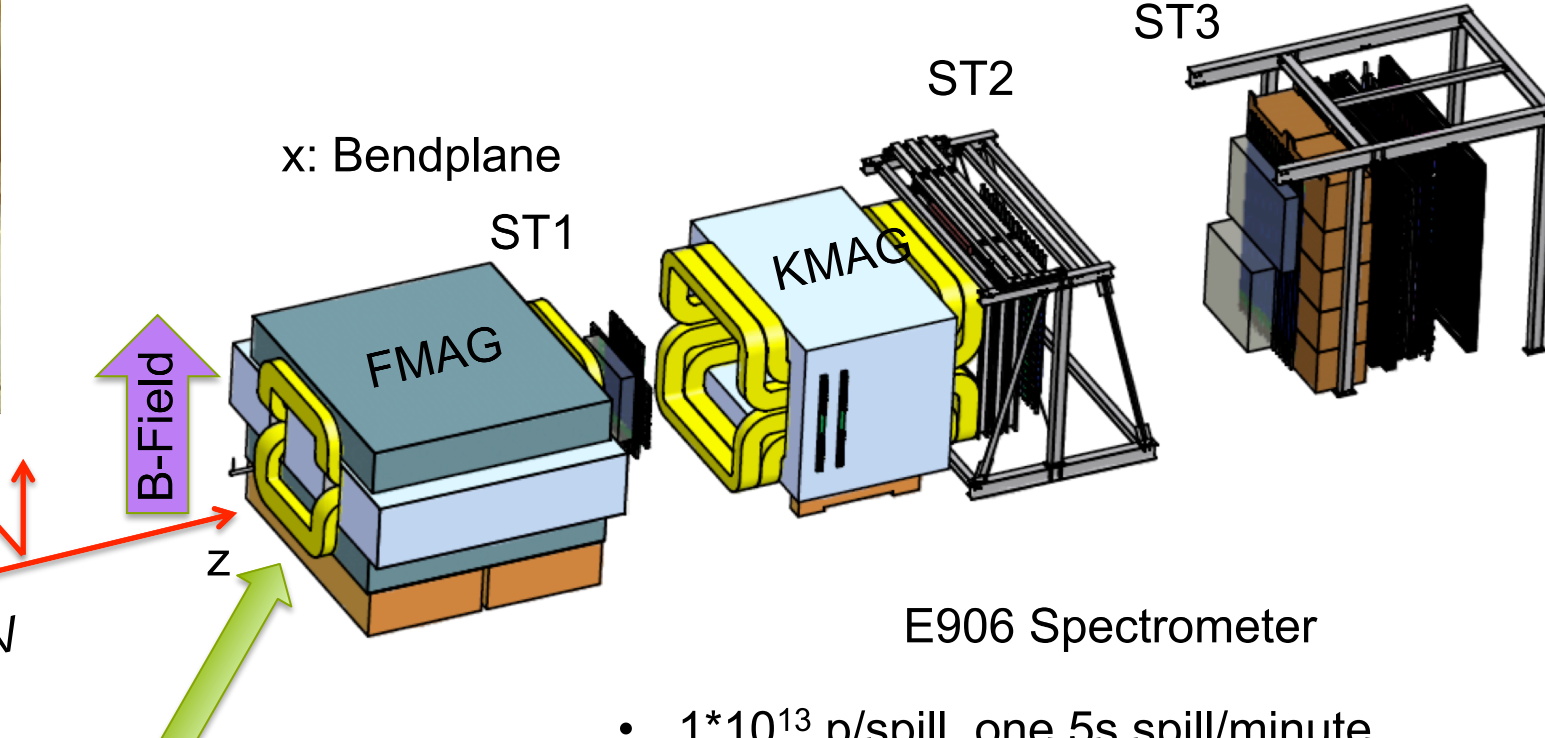
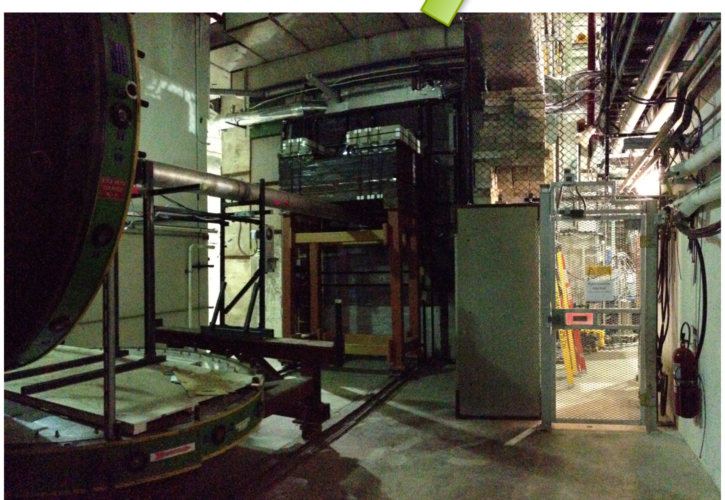
Beam @FNAL

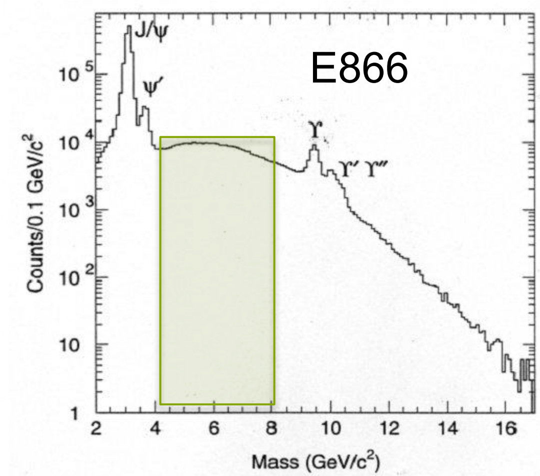
BUFFALO
FARM
WILSON
HALL
MAIN
INJECTOR
RING
TEVATRON
(3.9 MILES)

How do we measure the Sivers A

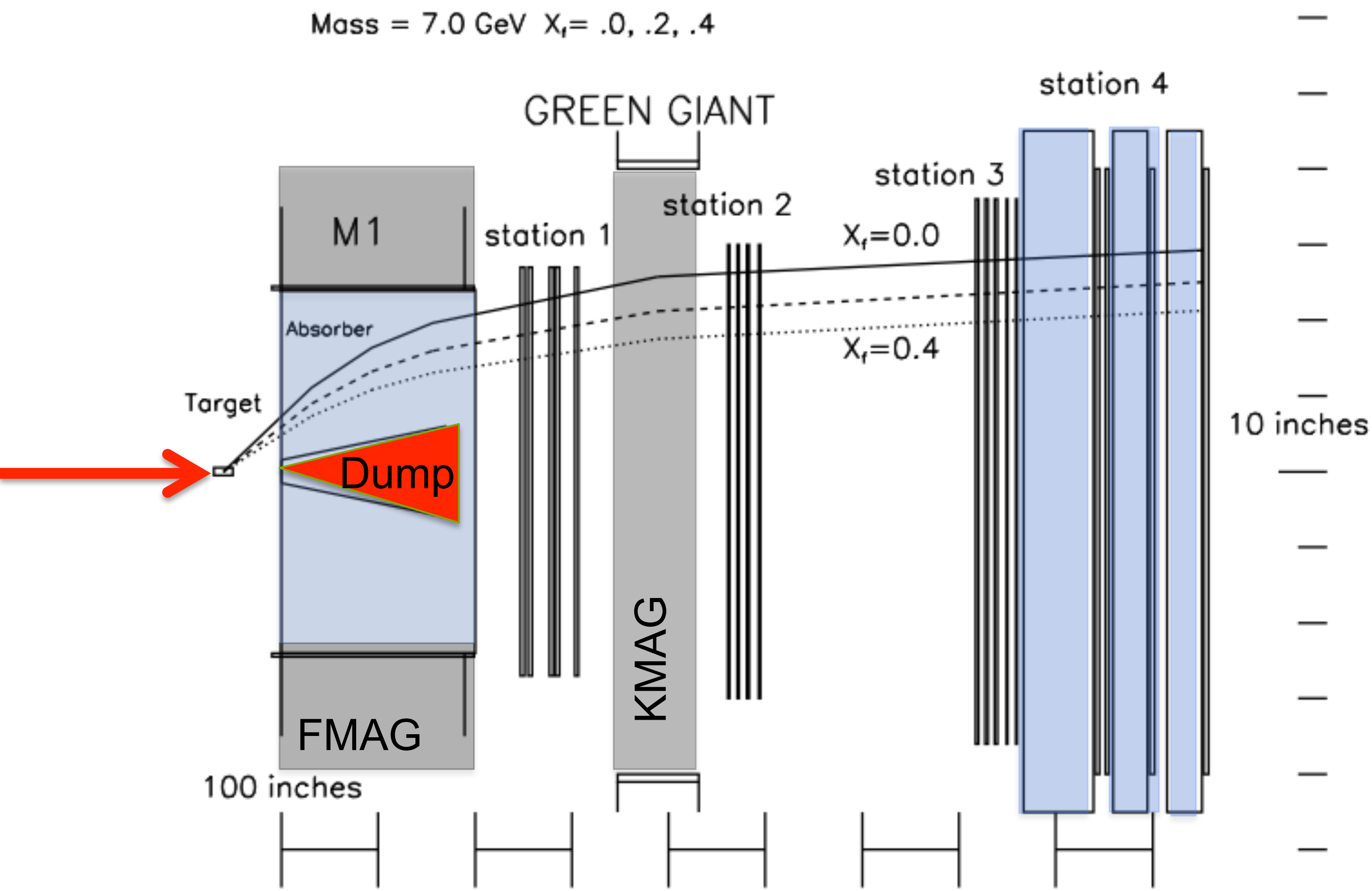




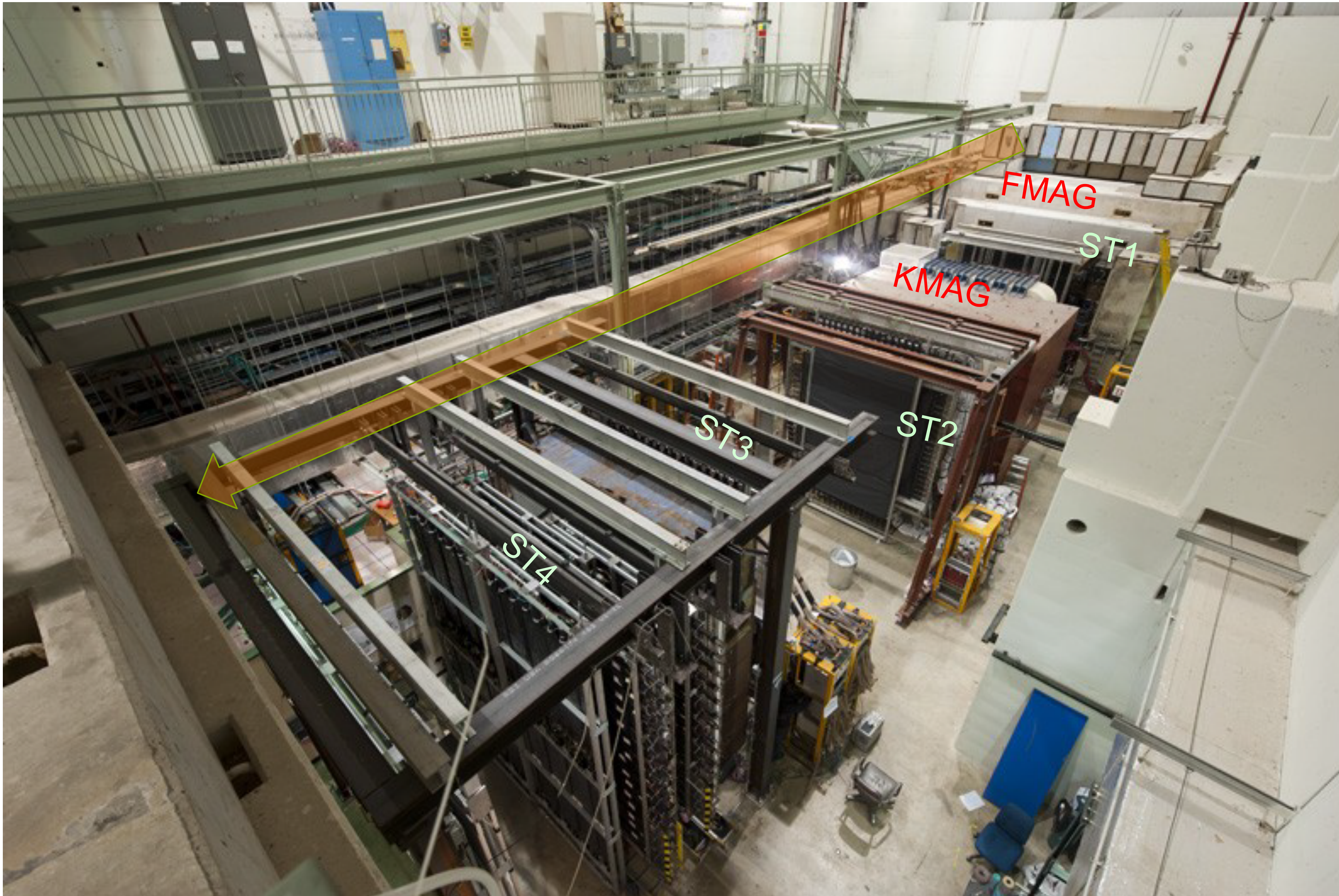
- $1*10^{13}$ p/spill, one 5s spill/minute
- Kinematic Range 4 < M <8 GeV



Schematic



- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos) MWPC


FMAG
ST1
KMAG
ST2
ST3
ST4

The Polarized Target System

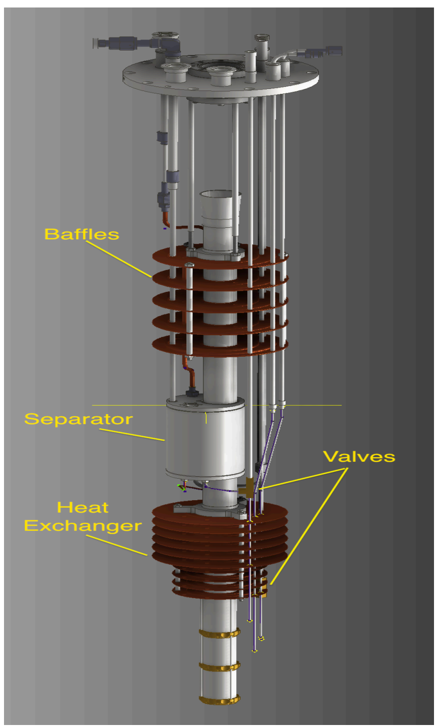
Magnet from LANL

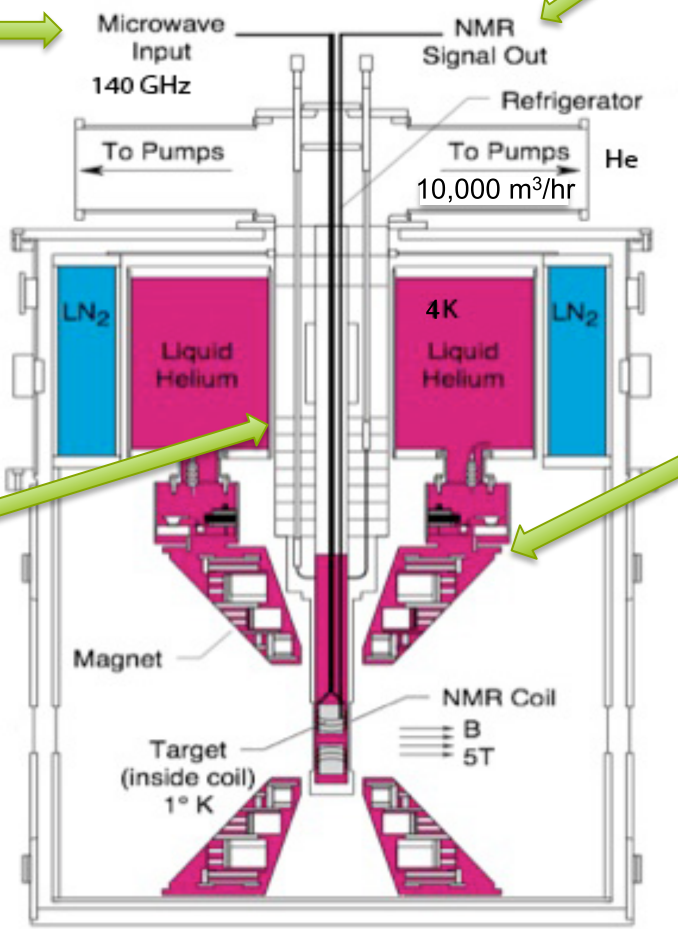
Microwave: Induces electron spin flips

- Tube + Power equip:

Measure polarization

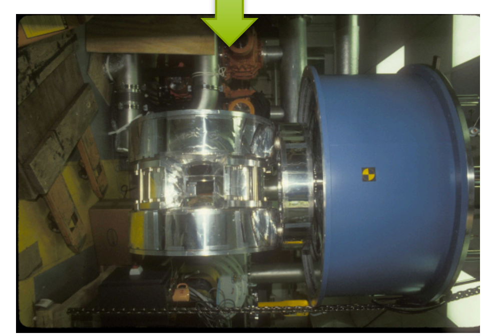
Cryostat: UVa





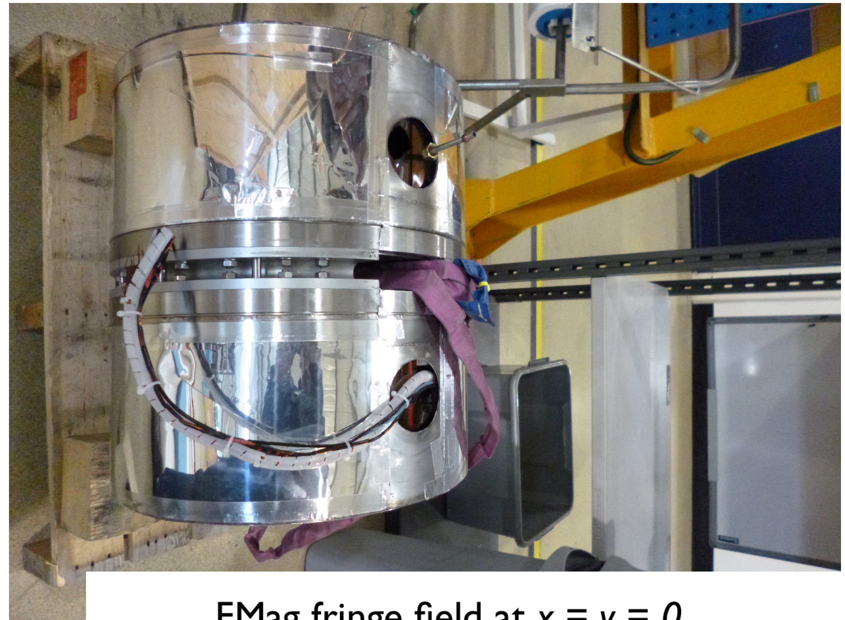
Roots pump system used to pump on ^4He vapor to reach 1K

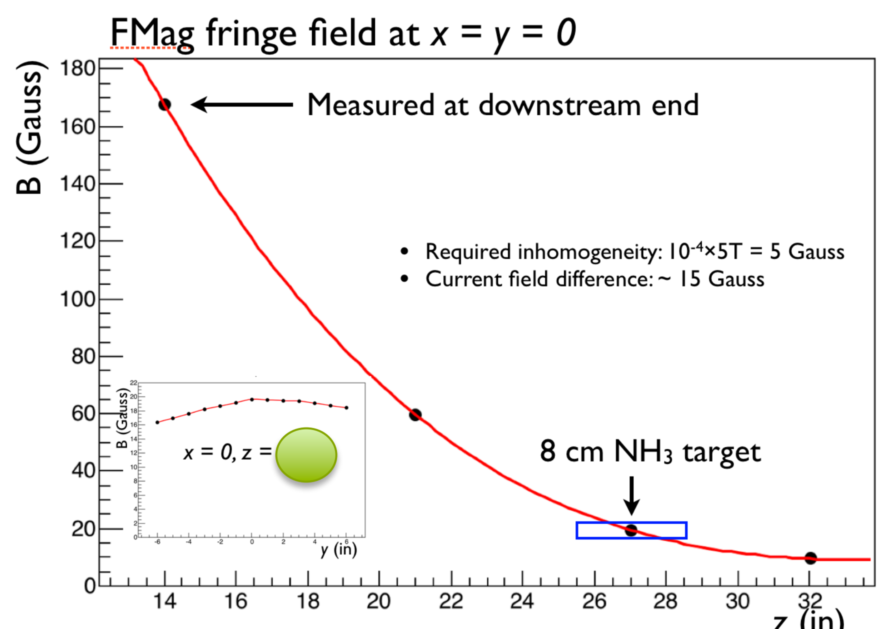
Superconducting Coils for Magnet: 5T
Rotation needed



Target material: frozen NH_3
Irradiation @ NIST

The magnet





$$\frac{d\vec{B}}{\vec{B}} < 10^{-4}$$

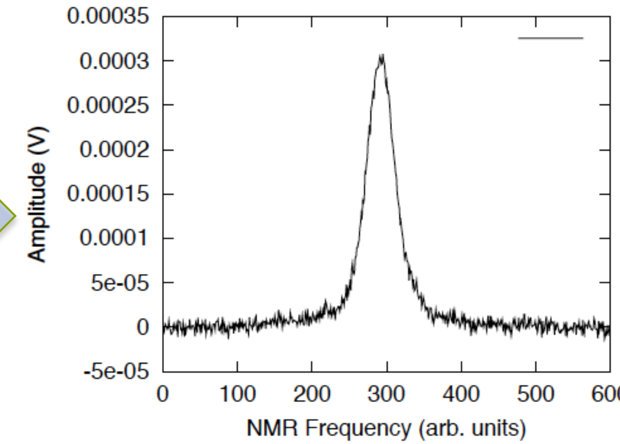
Principle of Dynamic Nuclear Polarization:

Polarization *P for paramagnetic materials:*

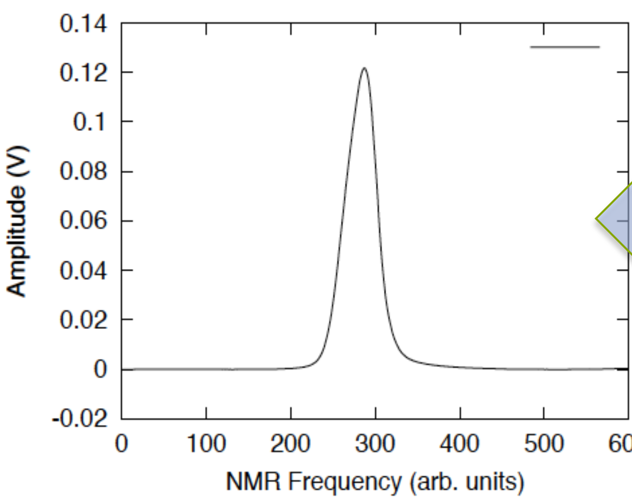
$$P_i = \left[\frac{\mu_i g_i H}{2k_B T}\right]$$

Thermal Equilibrium TE TE:
T=1K, H=5T
P_e = .998
P_p =.005 since $\mu_N / \mu_B \sim 10^{-3}$

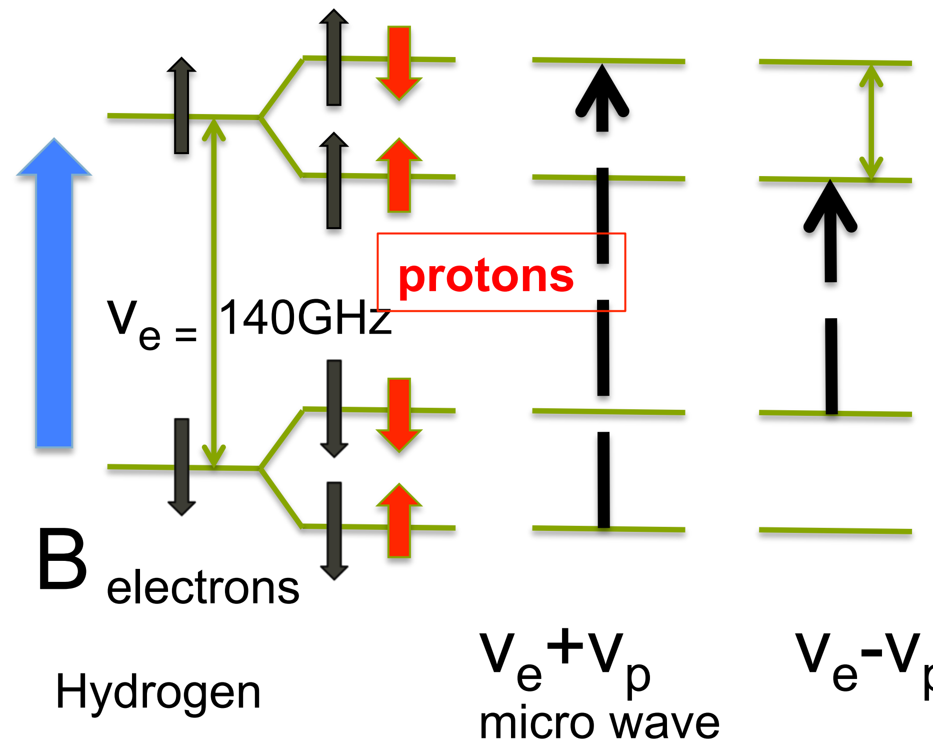
TE measurement

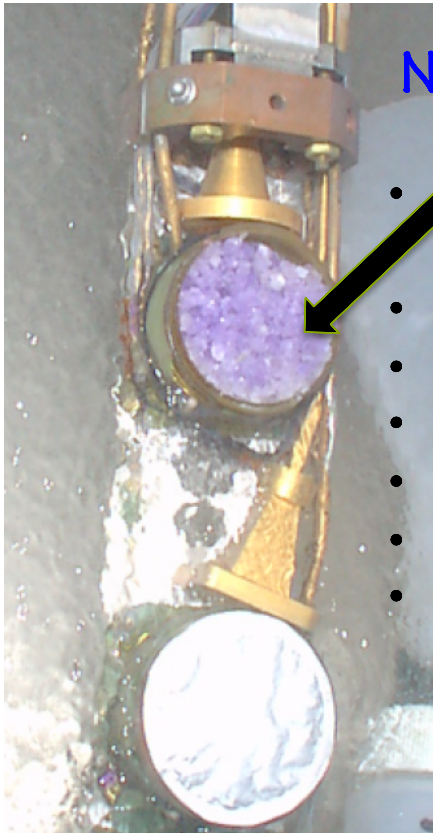


Polarization Measurement P~92 %



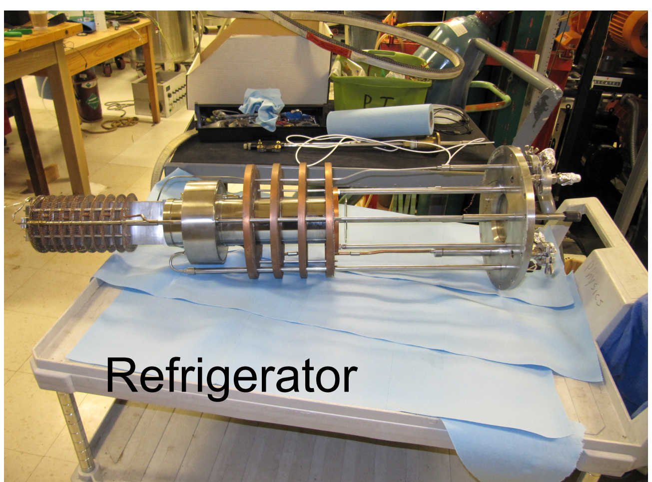
Keith et al. NIM A 501 (2003), 327 JLAB
Well established technology: SLAC, JLAB, PSI …

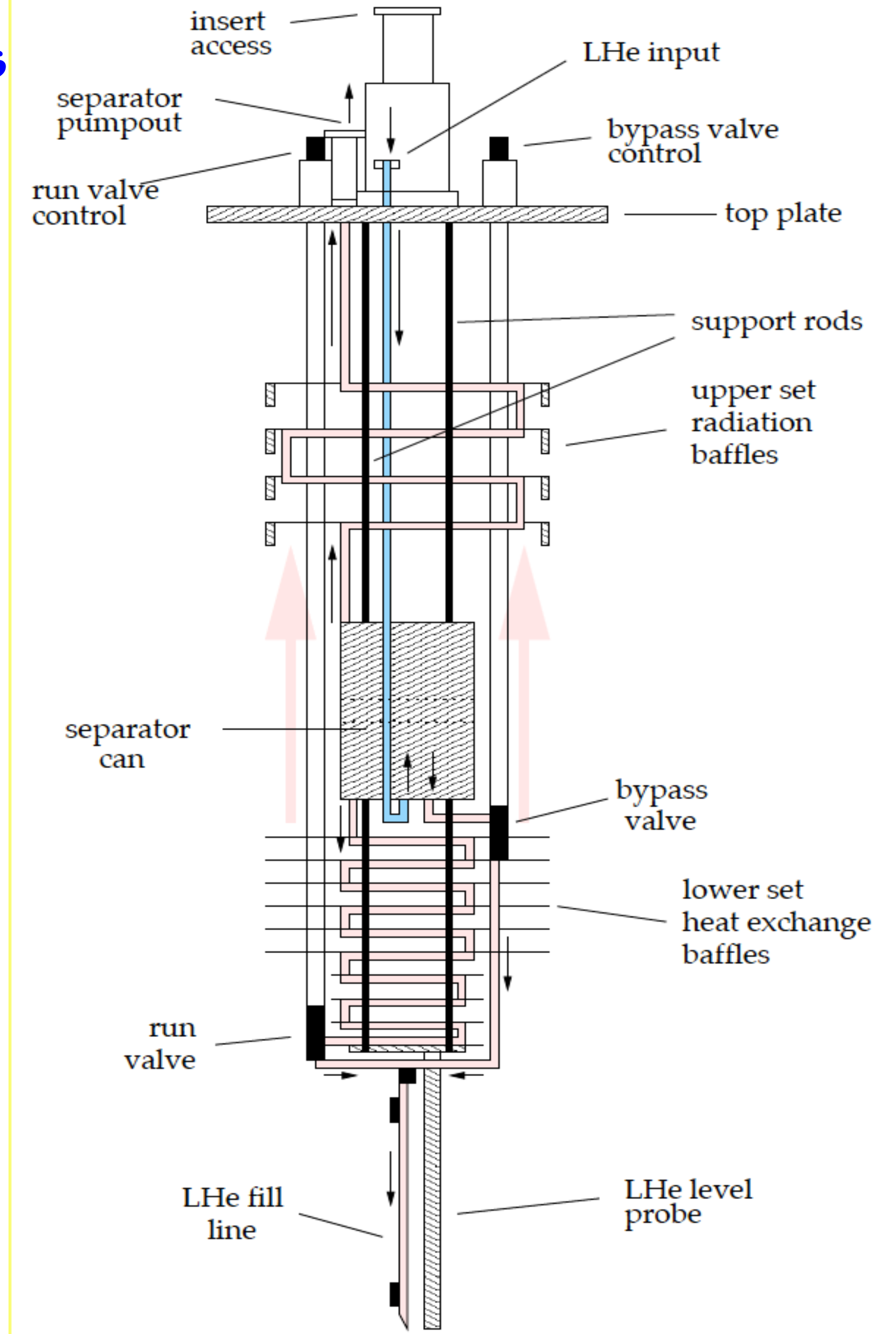




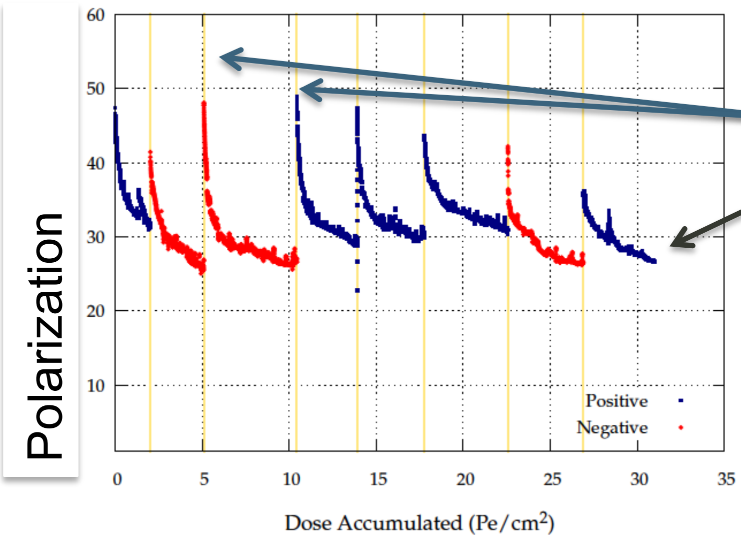
NH_3 Target Parameters

- Cylinder Φ : 2cm (x,y), length 8cm (z)
- ρ= .82 g/cm^3 NH_3
- Packing Fraction = .6
- Dilution Factor = 3/17 NH_3
- 5.1 g/cm^2 (NH_3) +
- .44 g/cm^2 He
- 4.2 * 10^{23} H/cm^2





Beam effects on polarized Target



Polarization as a function of accumulated beam dose 2.5T target (D. Crab private communication)

- Anneal every 24 hours ~ 1hr at 80K (yellow line)
- Replace target material every 10 days (two active targets) , will take one shift
  - Replace target stick
  - Cool down
  - perform TE measurement
  - Turn on microwave, measure again

Systematics control:

- Reverse Polarization Direction once a day
- Reverse magnet field of Fmag and Kmag every two days
- Reverse magnetic field of target magnet every target replacement
- Background measurements every shift with target out

Systematic errors:

- Absolute: 1% (Luminosity precision on different pol directions)
- ΔA/A ~ 4% (Dominant effect polarization measurement)

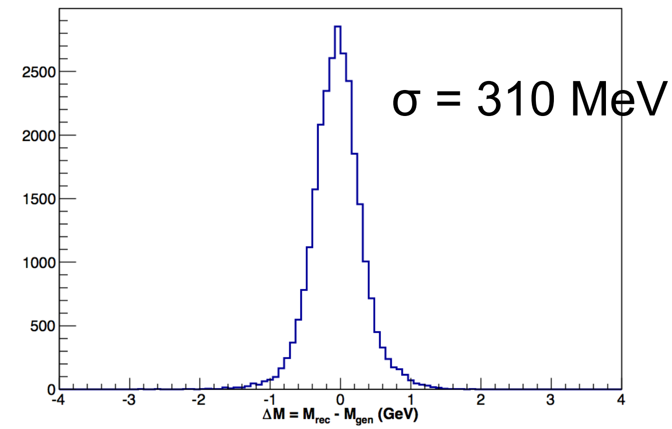
Target and Beam Performance

Target

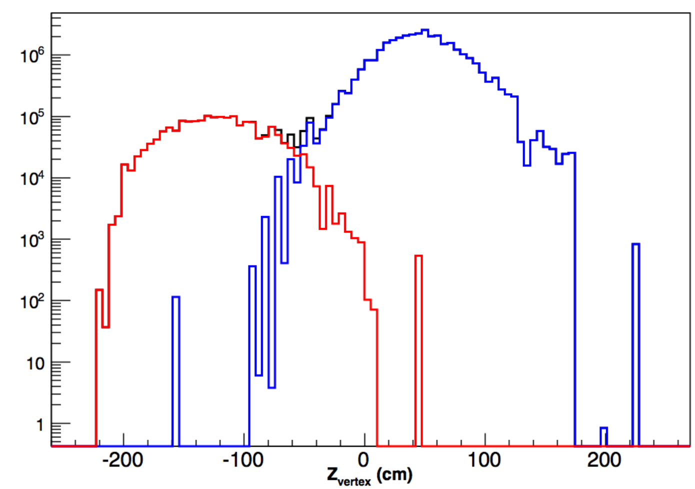
- Polarization: 88%
- Packing fraction .6
- Dilution factor: .176
- Density: .82 g/cm^3

Beam

- Beam: 1*10^{13} p/spill; spill is 5 s
- Luminosity: 4*10^{35} /cm^2/sec
- 120 GeV protons
- KTev beam line
- $\sqrt{s}$ = 15 GeV
- One year $\mathcal{L}$ = 1.1 *10^{43}/cm^2
- POT = 2.7*10^{18}



Mass Resolution



Reconstructed Vertex

Yield and Asymmetry estimates

Cuts	Efficiency	Yield
All DY in the 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

Range x_2	Mean x_2	N events	ΔA
0.1-0.14	0.123	159097.2	**0.016**
0.14-0.17	0.154	136557.6	**0.017**
0.17-0.21	0.188	123566.4	**0.018**
0.21-0.5	0.258	119508	**0.019**

Exp + Beam availability from E906 = .6
efficiency due to pol target =.8

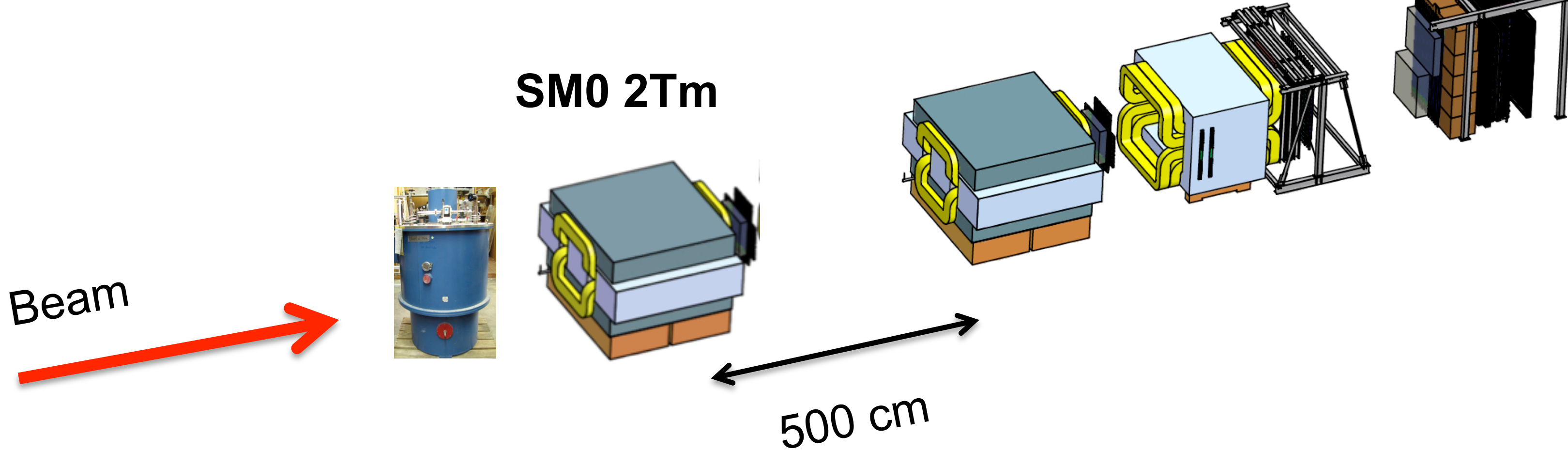
$$\Delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N_{Total}}}$$

measuring time for given ΔA

$$t^{-1} \propto \rho\left(f \bullet P\right)^2$$

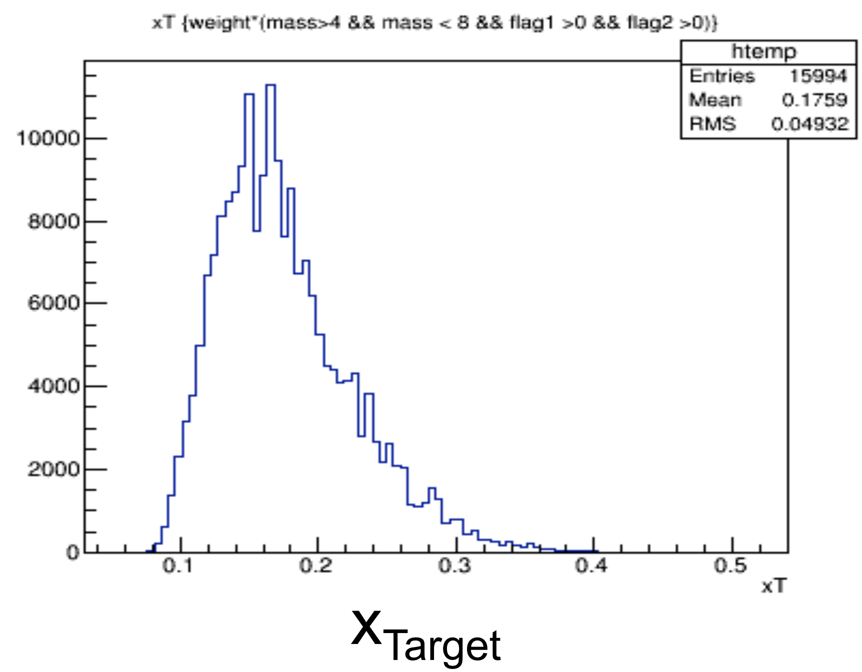
- f = .6
- P = .88

Changes under study

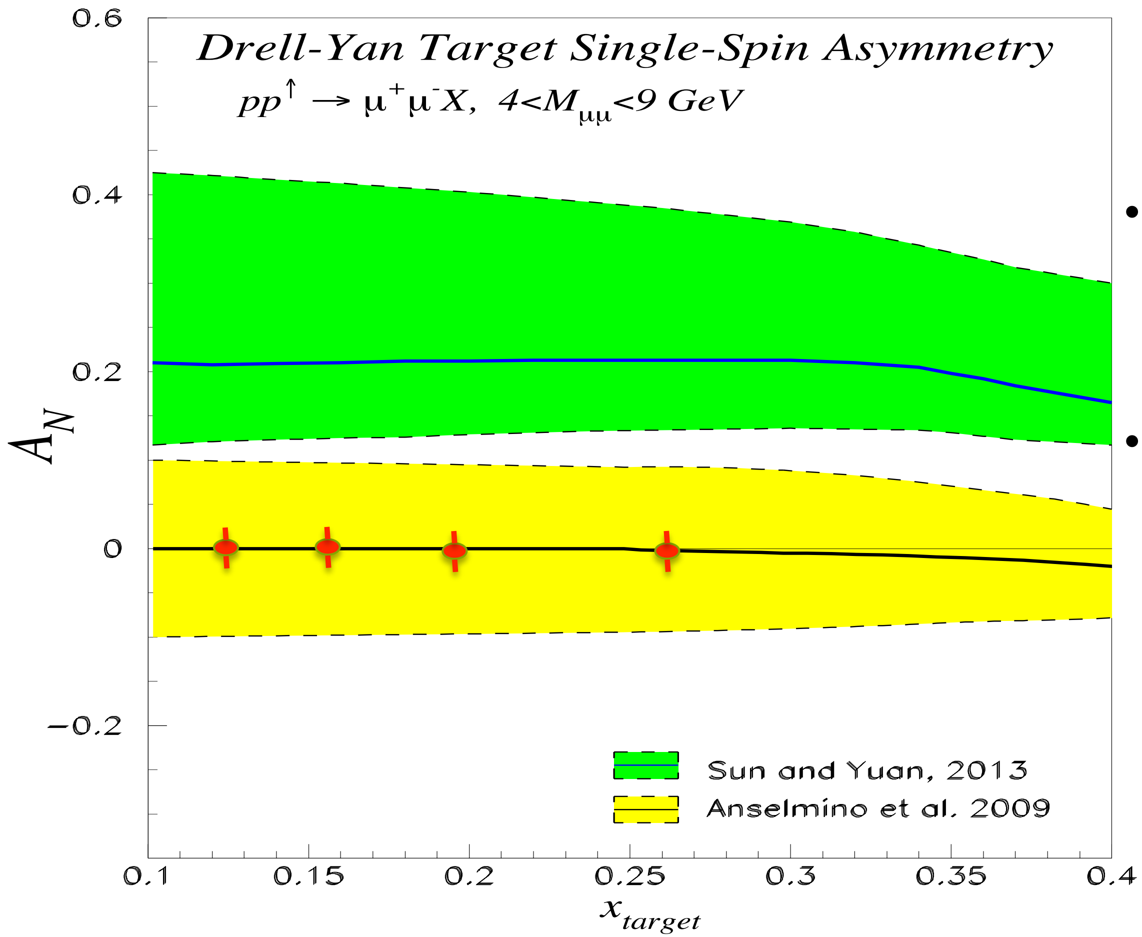


Add third magnet SM0 ~500cm upstream

- **Improves Dump-Target separation**
- **Moves $<x_2>$ from .21 to .176**
- **Reduces overall acceptance**
- **Adds shielding problems**



Projected Statistical Precision with a Polarized Target at SeaQuest



- **First Sea Quark Sivers Measurement**
- **Determine sign and value of ubar Sivers distribution**

Statistics shown for one calendar year of running :
$\mathcal{L}$ = 1.9 *10^{42} /cm^2 ←→ POT = 2.8*10^{18}

Running will be two calendar years of beam time

Existing data do not put enough constraints on the sea quark Sivers distribution, neither in sign nor value.

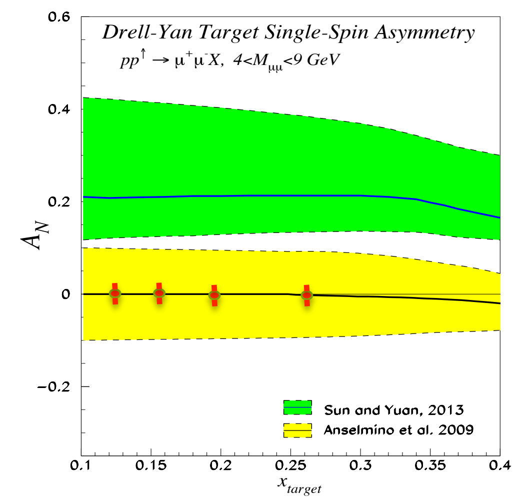
Summary

$$A_N \equiv 0 \;\; \text{if} \;\; L_{\bar{u}} = 0$$

- First Measurement of p-p Drell Yan with a polarized target.
- Measure Single Spin Asymmetry for Sea Quarks
- Access Quark Angular momentum through Sivers Distribution.
- Help solve the nucleon spin puzzle
- Establish sign of Sivers Distribution, if nonzero

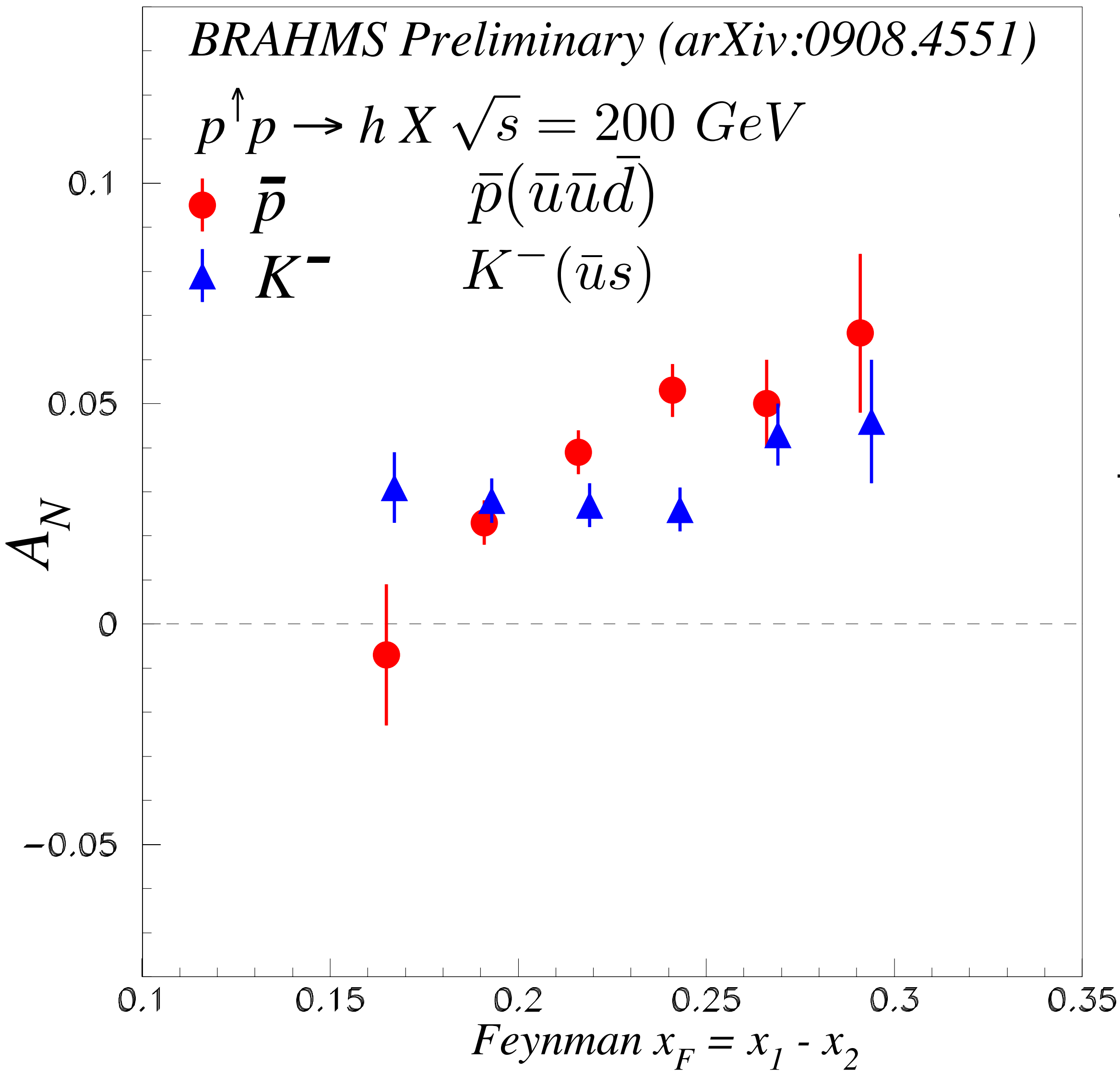
- If $A_N \neq 0$, major discovery: "Smoking Gun" evidence for $L_{ubar} \neq 0$
- If $A_N = 0$: $L_{ubar} = 0$, spin puzzle more dramatic ?

- Approved experiment E1039
- 2 calendar years of beam time
- Start of a spin program at FNAL



Backup

Hints of Non-Vanishing Sea Quark Sivers Distribution ?



Sea quark generates left-right bias ?

Left-right bias generated through fragmentation process ?

Planned Polarized Drell-Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\,s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.2 – 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2014, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 – 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f = 0.22	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 – 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 – 0.8$	1×10^{31}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2018
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s} = 500$	$x_b = 0.05 – 0.1$	2×10^{32}	0.06	$P_b = 60\%$	3.6×10^{-4}	>2018
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}	---	---	---	2012 - 2015
Pol tgt DY‡ (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 80\%$ f = 0.176	0.13	2016
Pol beam DY§ (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	2018

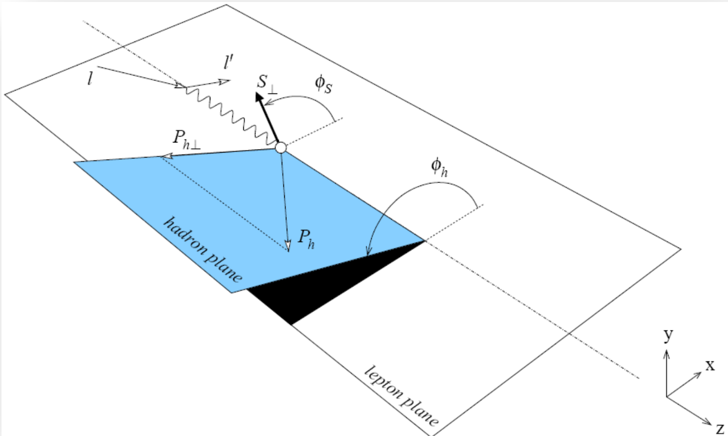
‡ *8 cm NH_3 target* § *L= 1×10^{36} $cm^{-2}\,s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2}\,s^{-1}$ (10% of MI beam limited)*
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams)

W. Lorenzon (U-Michigan)

COMPASS, E-1027, E-1039 (and Beyond)

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals (Sivers Function) sign change	size	shape	L_{sea}
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✗	✔	**valence**	✔	✗	✗	✗
E-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✔	✗	**valence**	✔	✔	✔	✗
E-1039 $p p^\uparrow \to \mu^+ \mu^- X$	✗	✔	**sea**	✗	✔	✔	✔
E-10XX $p^\uparrow p^\uparrow \to \mu^+ \mu^- X$	✔	✔	**sea & valence**	**Transversity, Helicity, Other TMDs …**			

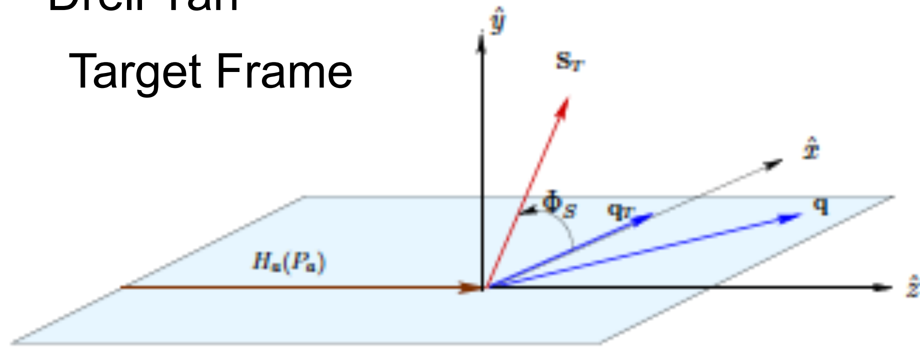
Observables and Kinematics

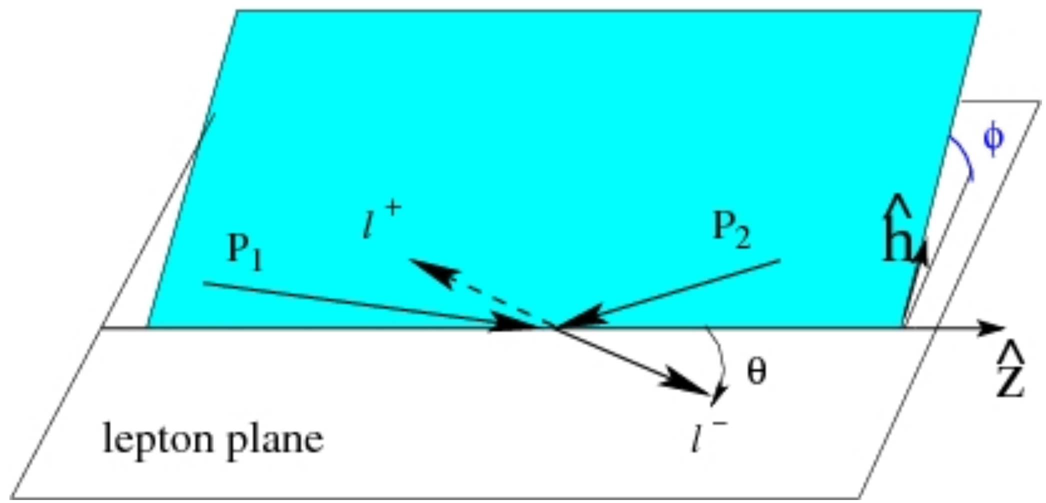


SIDIS

Drell Yan

Target Frame





Collins Soper frame: rest frame of virtual photon