E1039 @ FNAL:
Measuring the $\bar{u}$ and $\bar{d}$ Sivers Asymmetry

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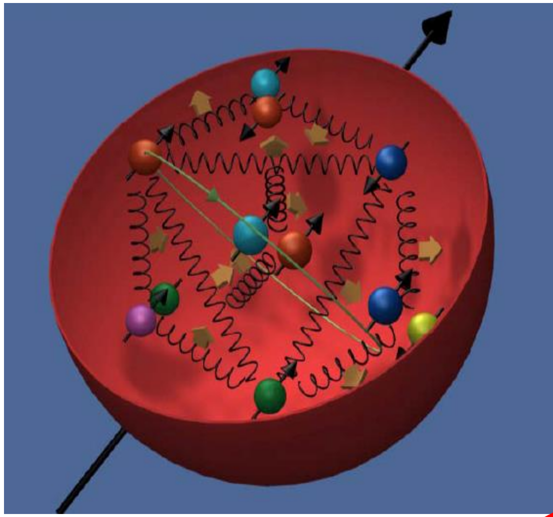
Where are we today

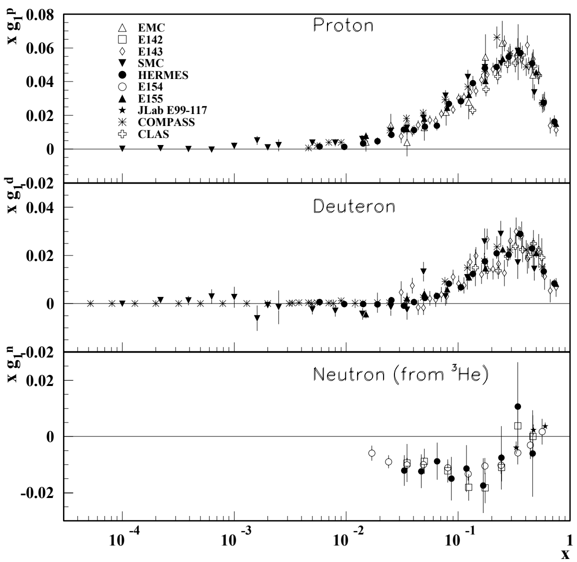


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

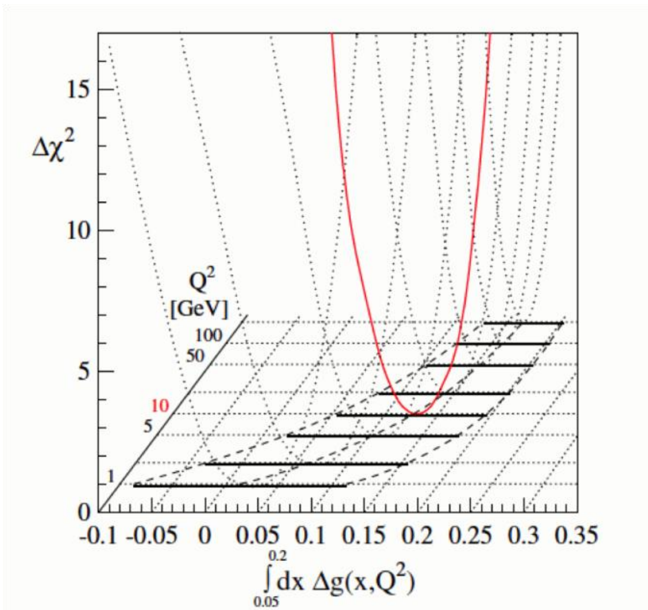
Quark contribution

Gluon contribution

Angular Momentum of q,g



Quark Polarization from all flavors

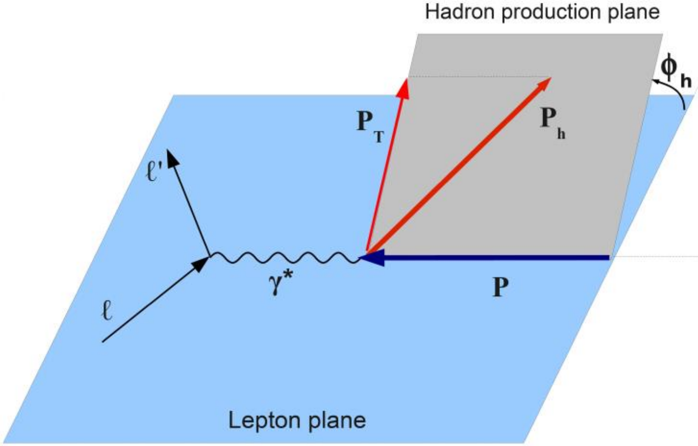


$$\Delta\Sigma_q \approx .25 + \Delta G \approx .2$$

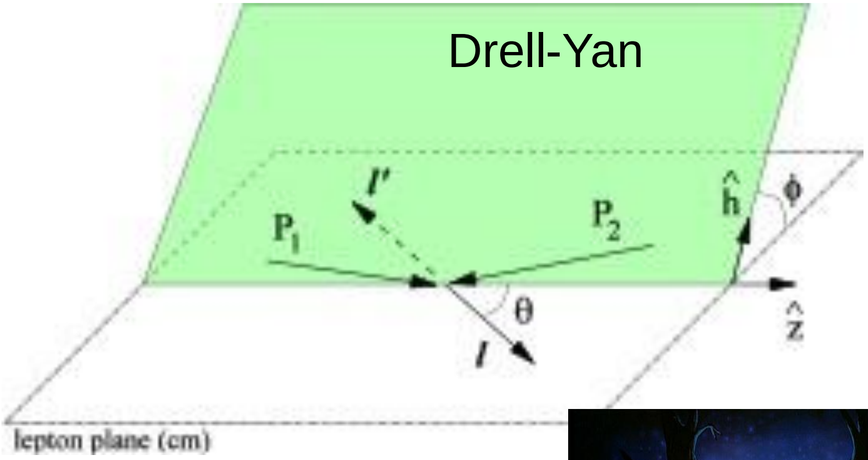
Path Forward

Leave one dimensional world of PDF and Helicity distributions which are collinear configurations.

- Heisenberg uncertainty => $k_T \sim 200 MeV/c$
- SIDIS, DY not collinear



SIDIS



- Simultaneous: longitudinal and transverse D.o.F of partons

Enter the world of **T**ransverse **M**omentum **D**istributions

The Sivers Function

$f_{1T}^{\perp}$ =

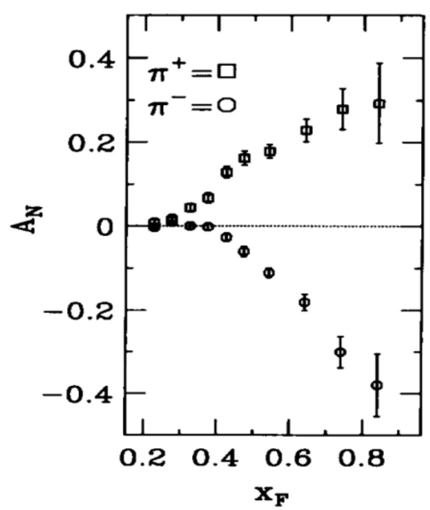
Distribution of unpolarized quarks in a transversely polarized nucleon

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

- S: nucleon spin
- p_T: Transverse momentum

Sivers function

Proposed to explain single spin asymmetries in hadron production



E704 √s =20 GeV. PLB 264 (1991) 462.

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

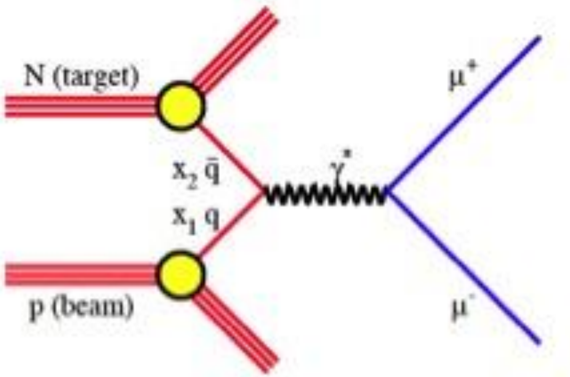
Sivers effect: quark's transverse motion generates a left-right bias.
up-quarks favor the left,
down-quarks favor the right
($L_u \approx - L_d$)

Sivers function = 0 ↔ L_q=0

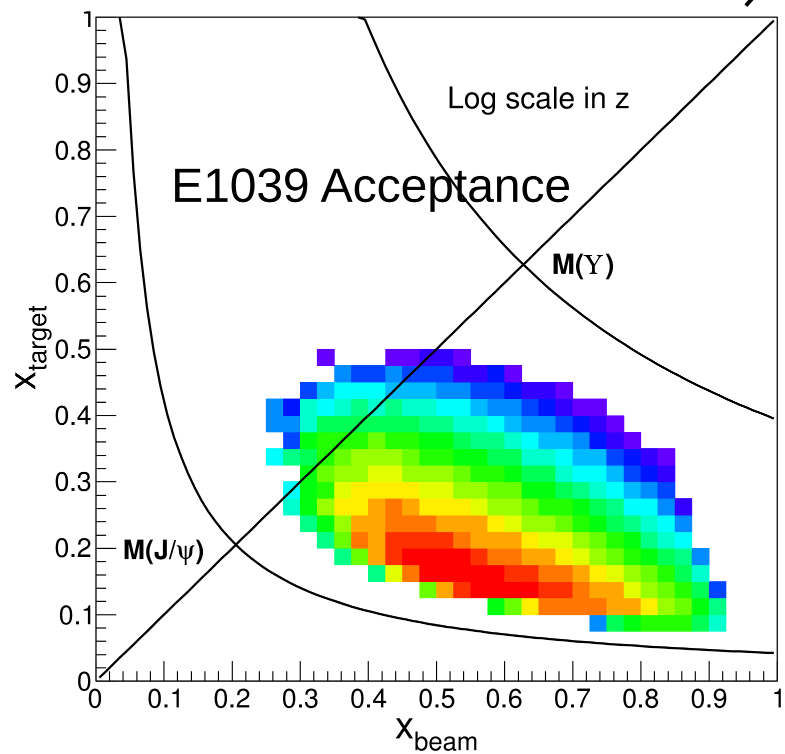
How to Access Sea Quark Sivers Distribution with Drell-Yan

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

target sea quark — beam valence quark — small (crossed-out term) = 0



Through kinematics choose quark from beam and antiquark from target



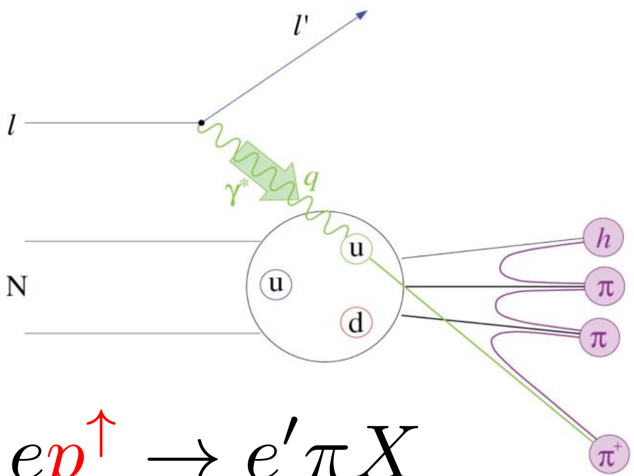
Does Drell-Yan yield depend on target's spin direction?

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

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

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

Asymmetry in Semi-Inclusive DIS



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

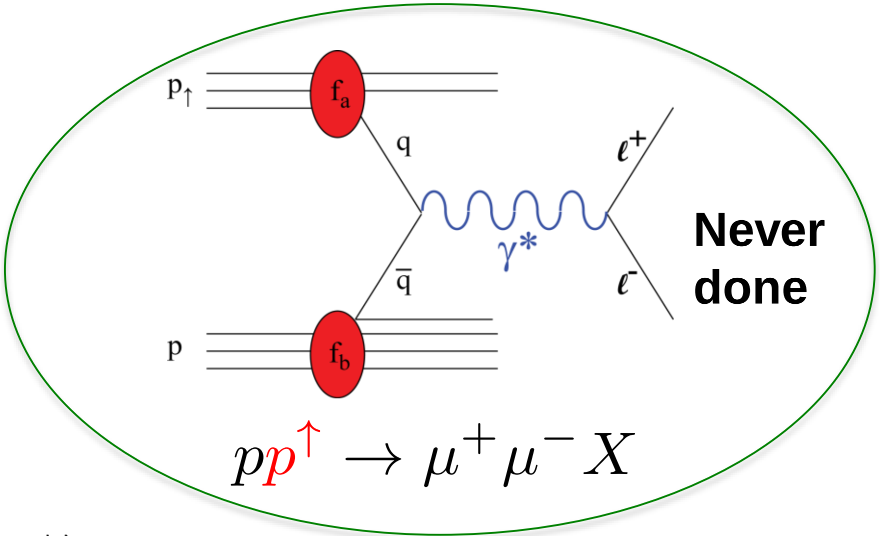
$$d\sigma^{\uparrow\downarrow} \equiv d\sigma_0 \pm \sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)$$

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

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

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

Asymmetry in Drell-Yan



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

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

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

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

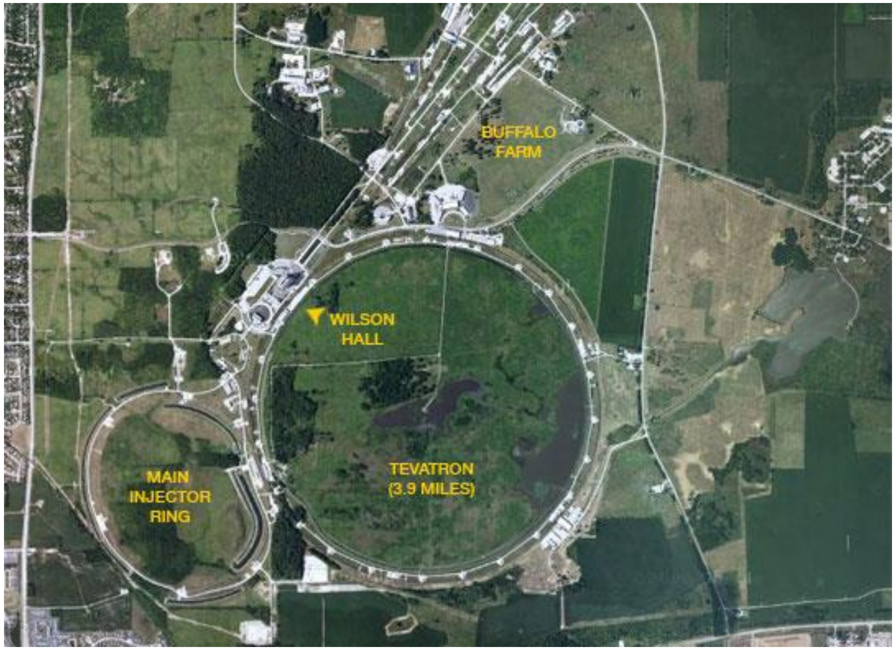
Result of repulsive initial state (DY) vs attractive final state (SIDIS) interaction

E1039

Polarized Drell-Yan with Seaquest

Measure Sivers asymmetry for :

$$\bar{u}(x)\ ,\ \bar{d}(x)$$



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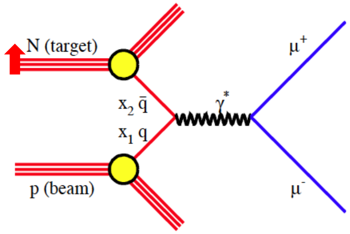
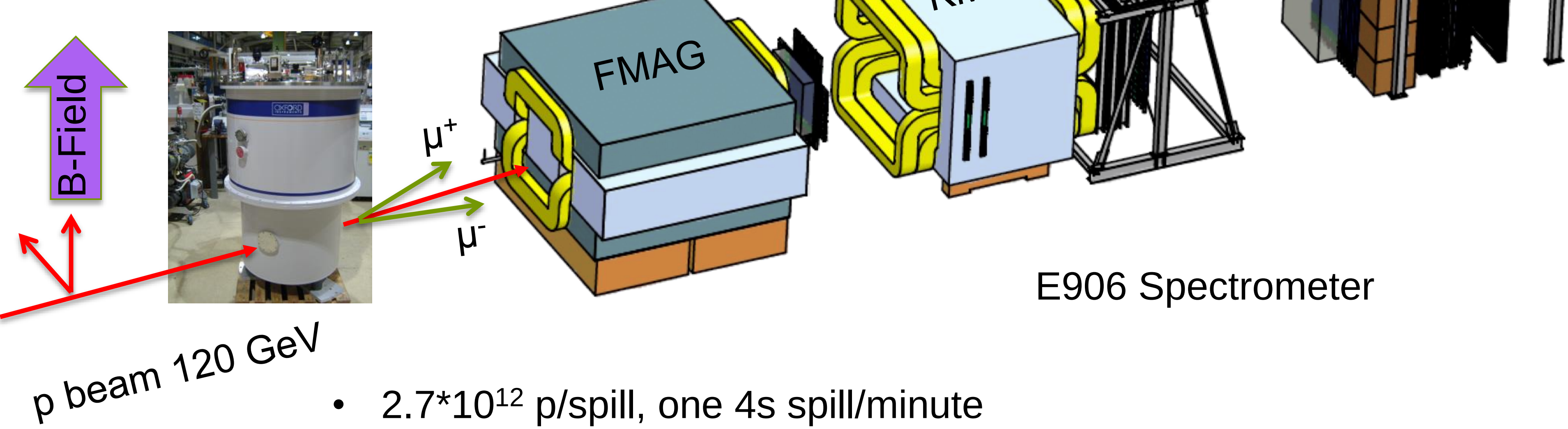
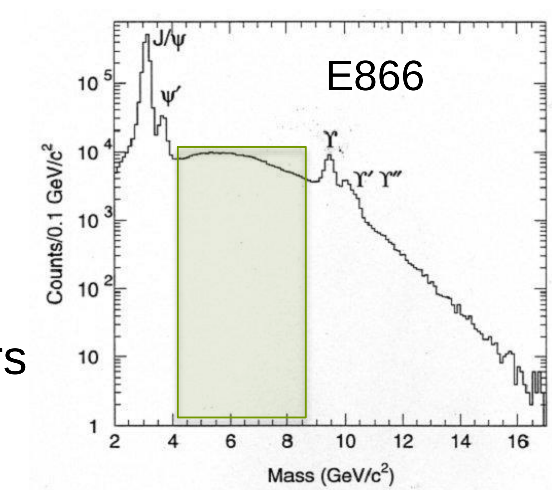
How do we measure the Asymmetry





- $2.7*10^{12}$ p/spill, one 4s spill/minute
- Kinematic Range 4 < M <9 GeV
- Luminosity: $3*10^{35}$ /cm^2/sec (NH_3)
- 120 GeV protons
- KTev beam line
- $\sqrt{s}$ = 15 GeV



- **L = $1.82*10^{42}$/cm² NH_3 , $2.11*10^{42}$/cm² ND_3** for 2 years

Polarization in a Nut Shell

Polarization *P for paramagnetic materials:*

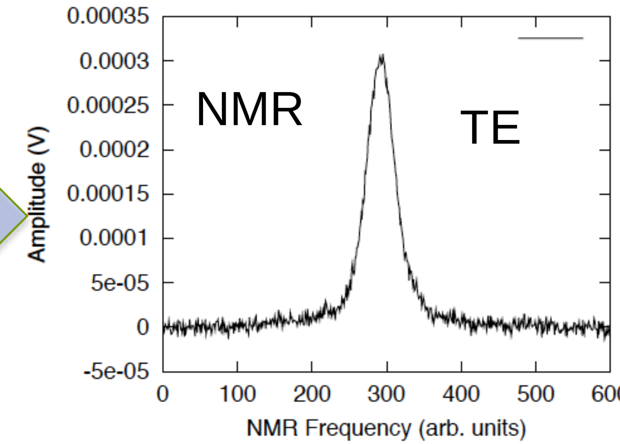
$$P_i = \tanh\left[\frac{\mu_i g_i H}{2 k_B T}\right]$$

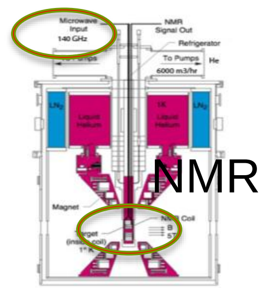
Thermal Equilibrium TE:

T=1K, H=5T

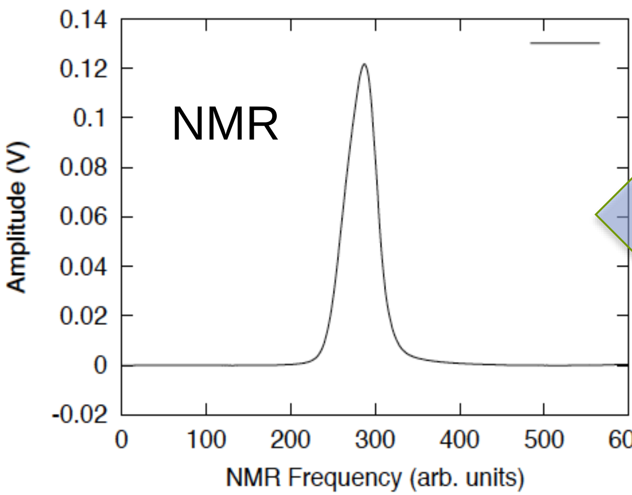
P_e = .998

P_p =.005 since $\mu_N / \mu_B \sim 10^{-3}$



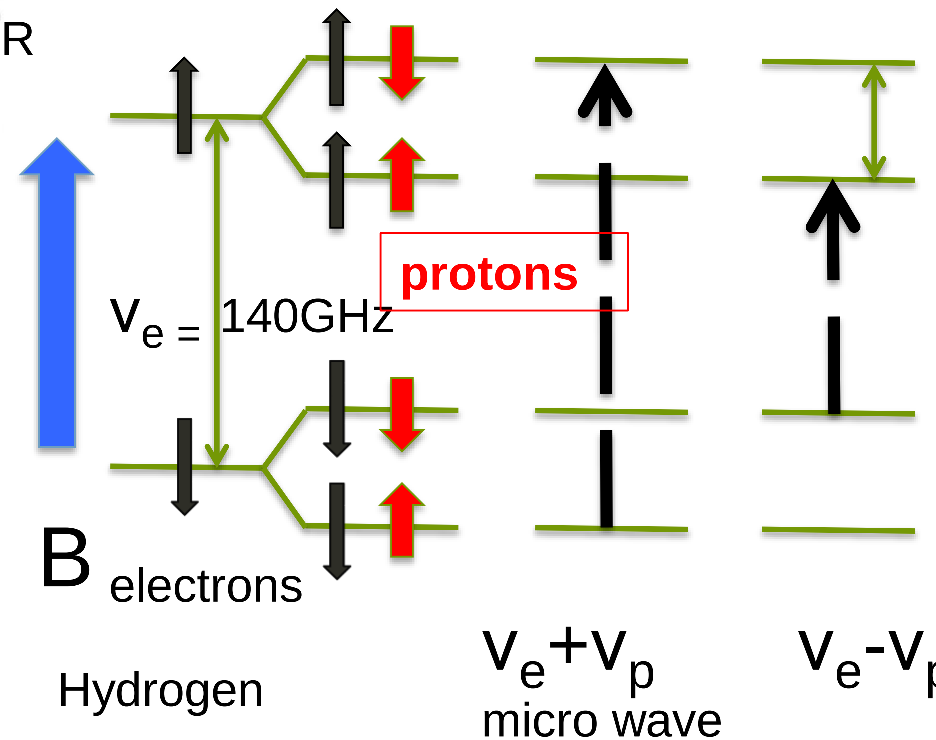


Polarization Measurement P~92



Keith et al. NIM A 501 (2003), 327 JLAB

Well established technology: SLAC, JLAB, PSI …



To summarize:

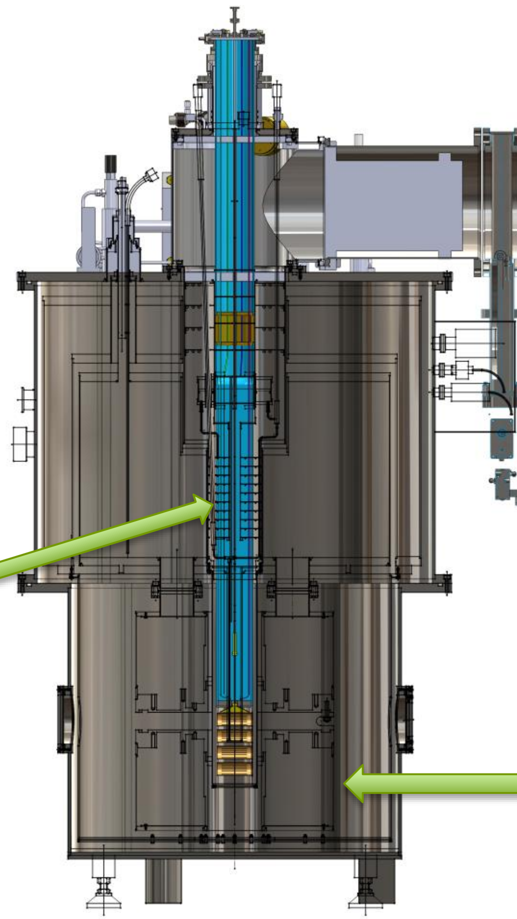
- **Low Temperature : 1K**
- **High Magnetic Field : 5T**
- **RF transitions: 140 GHz**
- **Paramagnetic Material: Irradiation of NH_3 and ND_3**

How do we get there?

The Polarized Target System

Microwave: Induces electron spin flips

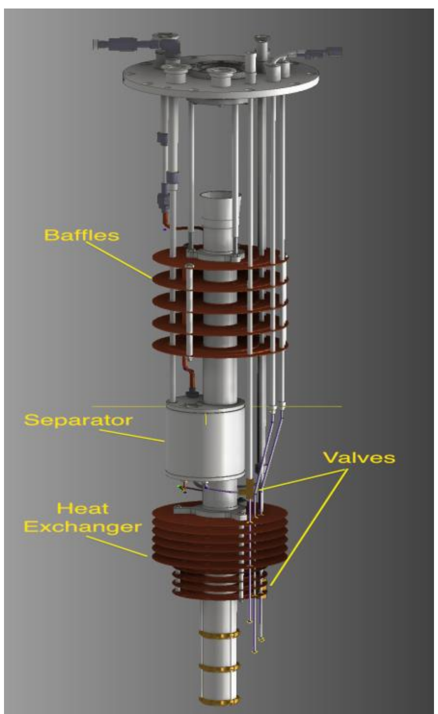
Measure polarization NMR)



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

Superconducting Coils for Magnet: 5T

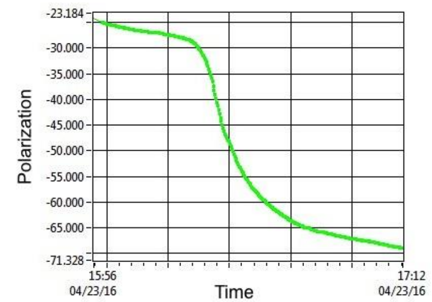
Refrigerator:

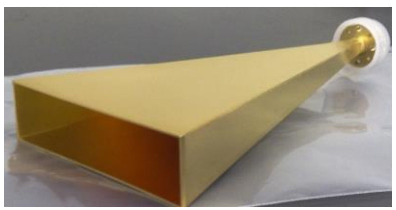


Target material: frozen NH_3
Irradiation @ NIST

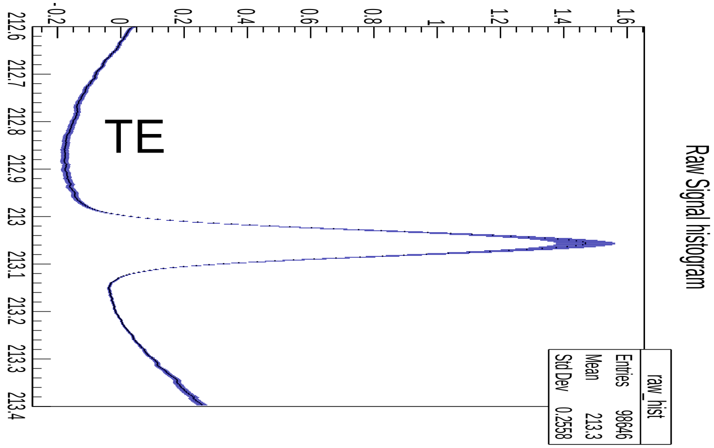
The E1039 Target

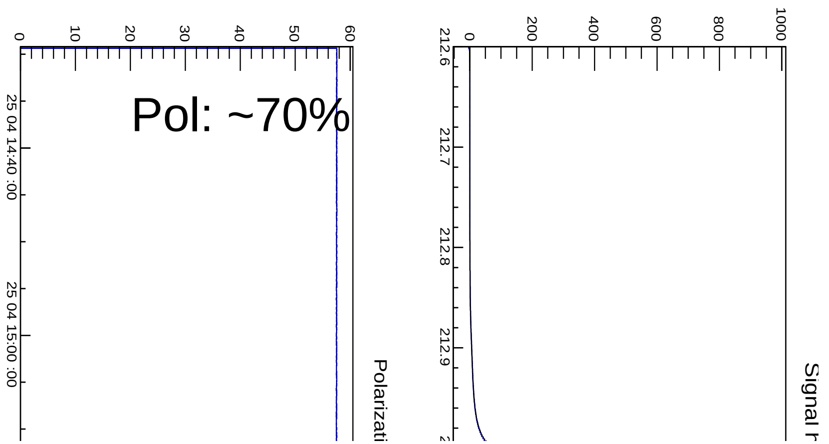
- Field: 5T @ 1K
- Elliptical: 1.9 cm x 2.1 cm (x,y), l:7.9cm (z)
- ρ= .87 g/cm^3 NH_3, 1 g/cm^3 ND_3
- Packing Fraction = .6
- Dilution Factor ~ .176 , .3
- Polarization <80%>, <32%>
- IL: 8.6% , 9.5%
- 3 active cells, 1 empty
- Helium consumption 100 l/day





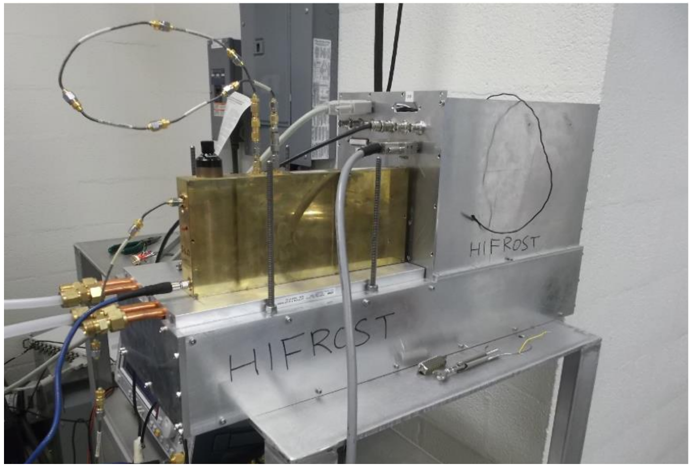
Developed new NMR system

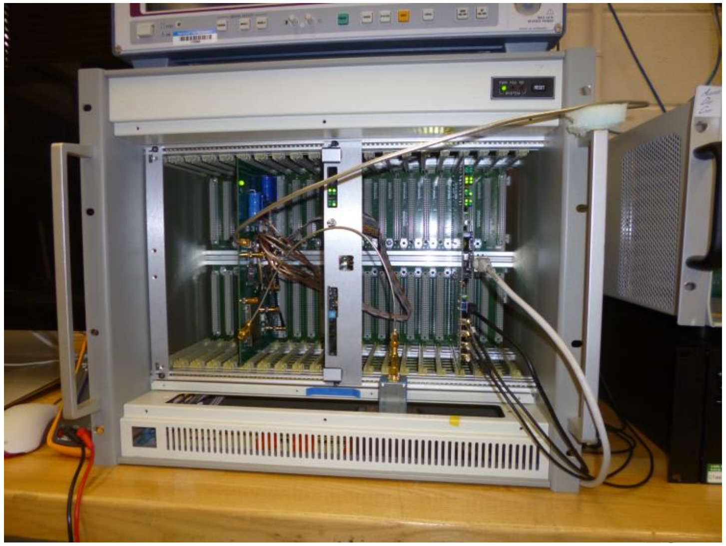




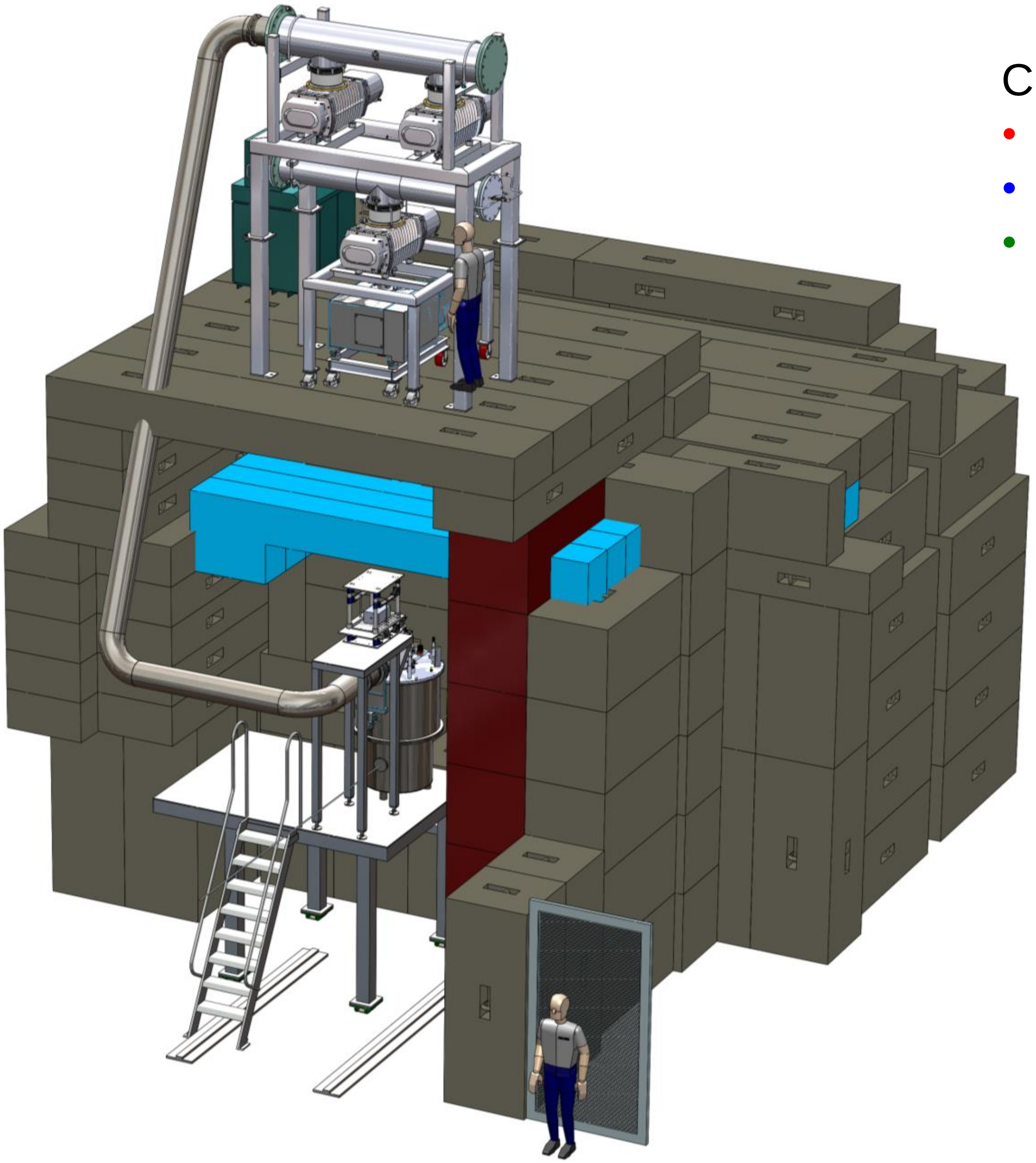
VME based system
9 coils; 3 per cell
Fully digital

Liverpool Q-meter ~1993





E1039 Target and FMAG



Changes needed :

- Collimators upstream
- Closed Loop He system
- 90 degree monitors L/R, T/B

Beam **σ_x=17mm, σ_y=19mm**

Target upstream by ~200cm

- lower x_2 Acceptance
- Better Target – Dump separation

Yield and Asymmetry estimates

Range x_2	Mean x_2	N events p	ΔA % p	N events n	ΔA % n
0.1-0.16	.139	5.0×10^4	3.2	5.8×10^4	5.4
0.16-0.19	0.175	4.5×10^4	3.3	5.2×10^4	5.7
0.19-0.24	0.213	5.7×10^4	2.0	6.6×10^4	5.0
0.24-0.6	0.295	5.5×10^4	3.0	6.4×10^4	5.1

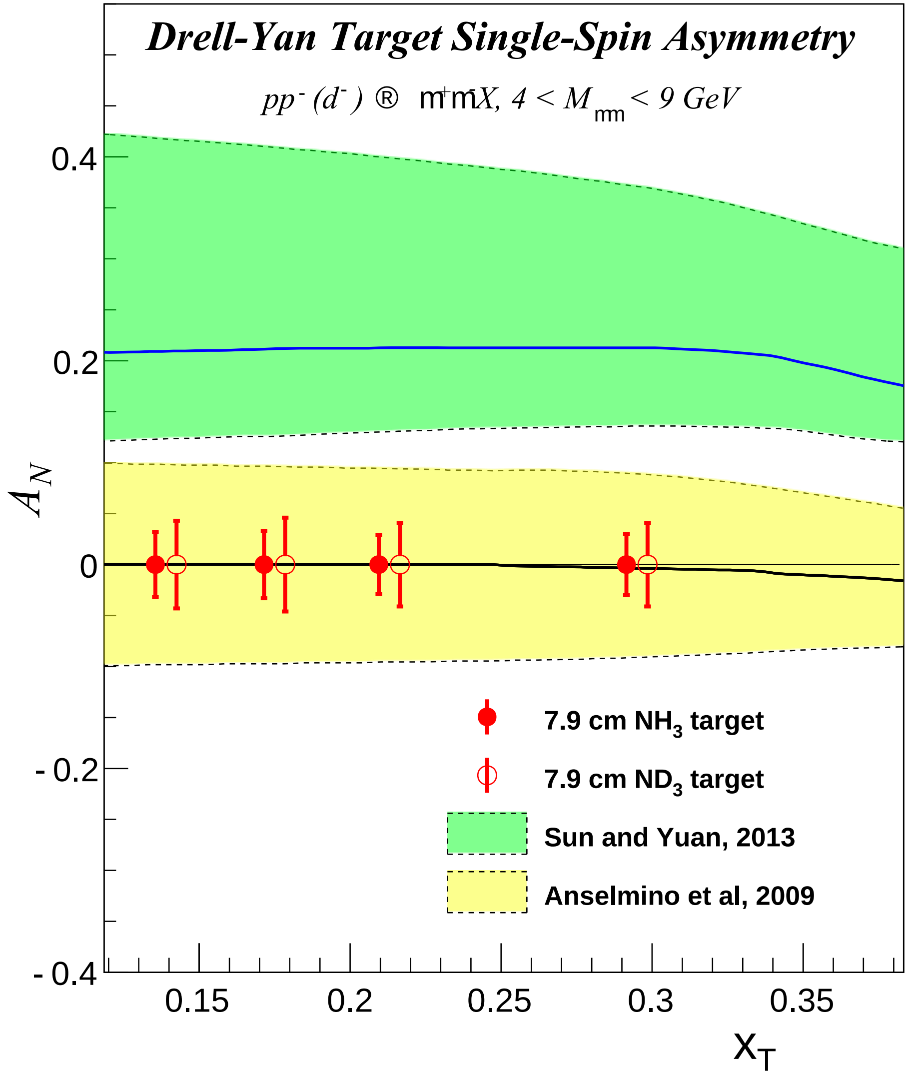
Target/Accelerator Effi: 50%
Spectrometer: 80%
Acceptance 2.2%
Trigger 90%
Reconstruction 60%
Beam: 2.67×10^{12} p/spill
Total integrated Luminosity: 1.82×10^{42} & 2.11×10^{42} cm^{-2}

$$\mathrm{DA} = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N_{Total}}}$$

$$t^{-1} \mu\, r\left(f \cdot P\right)^2$$

- f = .176 , .3
- P = .8 , .32

Projected Statistical Precision with a Polarized Target at SeaQuest



First Sea Quark Sivers Asymmetry Measurement

Determine sign and value of ubar ,dbar Sivers distribution

Statistics shown for two calendar years of running :
L = 1.82 *10^{42} /cm^2 and
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

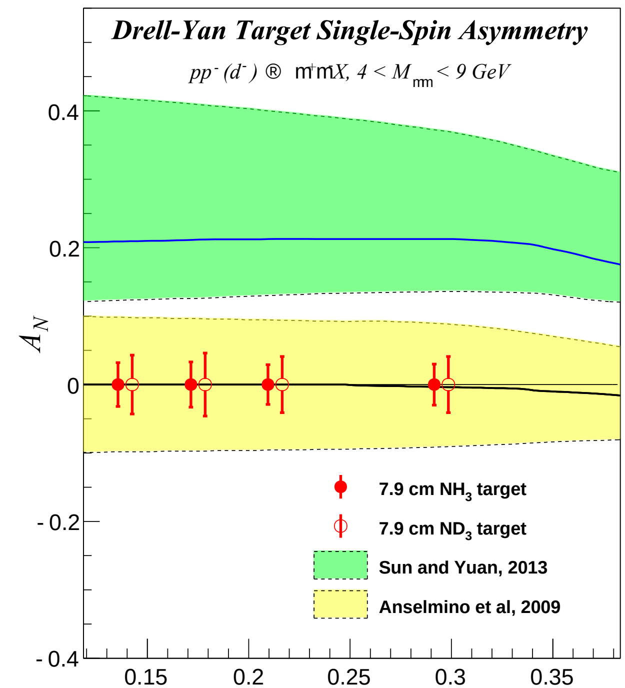
$A_N \equiv 0$ if $L_{\bar{u}} = 0$

- **First Measurement of Sivers asymmetry in Drell Yan for sea quarks**
- **Flavor dependence of the Sivers asymmetry for $\bar{u}$ and $\bar{d}$**
- **Sign and magnitude of sea quark Sivers Distribution**

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

- **Beginning of a spin program at FNAL**
  - **tensor structure function b_1**
  - **transversity with polarized beam**

- **Approved experiment E1039 (stage 1)**
- **2 calendar years of beam time**



Thank You

Tensor Polarization of Deuteron

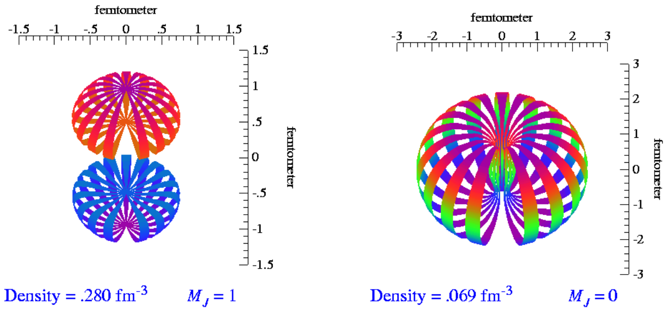
- d is spin 1 particle, opens up new physics

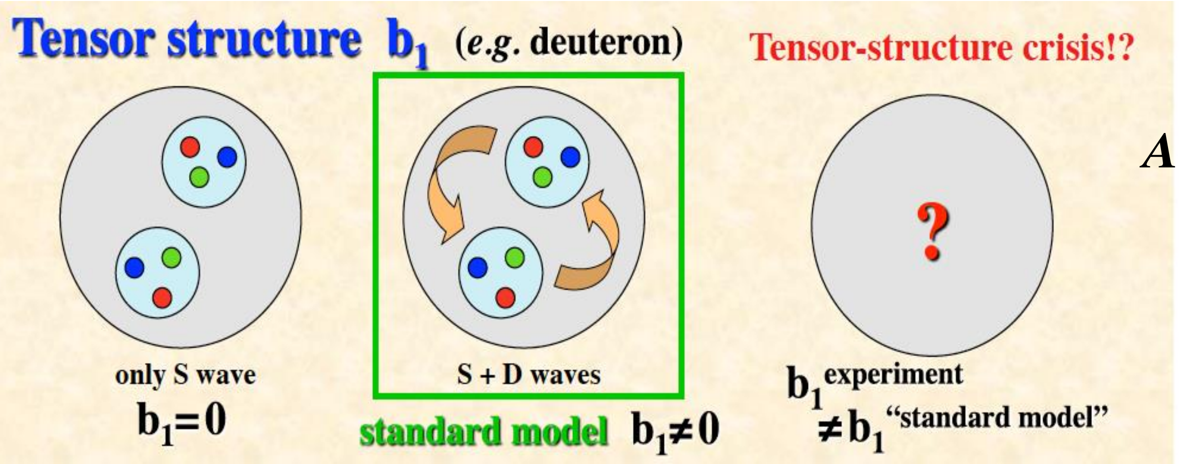
Spin-1 system in a B-field leads to 3 sublevels
 via Zeeman interaction

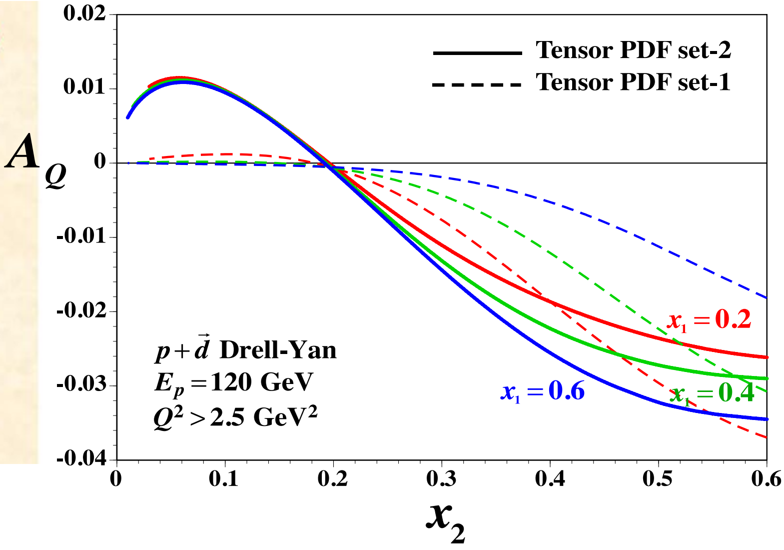
Vector polarization: (n+ - n-); -1 < Pz < +1

Tensor polarization: (n+ - n0) – (n0 - n-); - 2 < Pzz < +1

Normalization: (n+ + n- +n0) = 1







From S. Kumano, arxiv.org/1606.03149

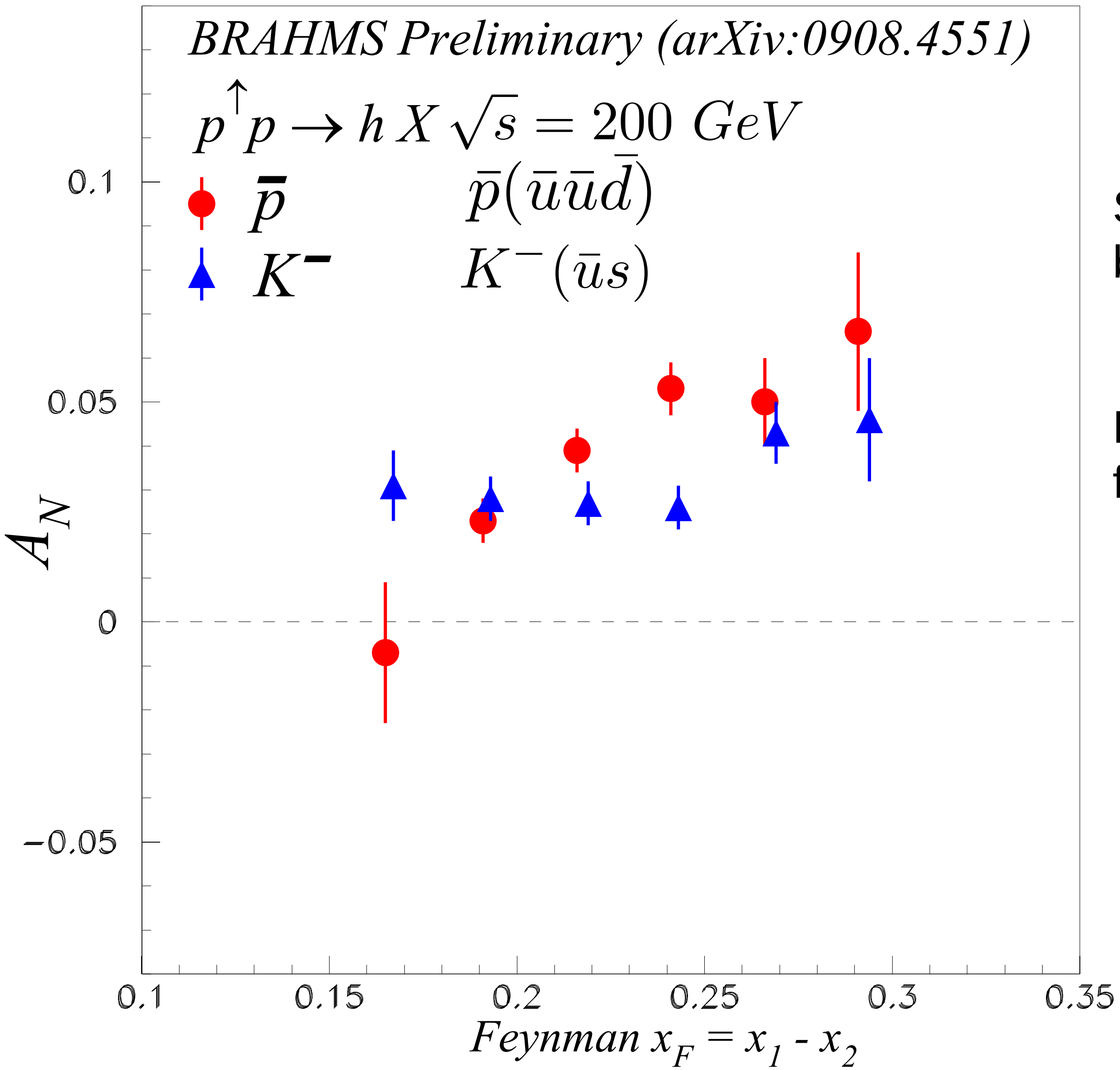
(Un)Polarized Drell-Yan Experiments

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)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 – 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015-2016, 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}	>2020?
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s} = 4.4\text{-}6.2$	$x_b = 0.2 – 0.97$ $x_t = 0.06 – 0.6$	2×10^{31}	---	---	---	>2019? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
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 - 2017
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*	$P_t = 85\%$ f = 0.176	0.15	>2018
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	>2020

‡ *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, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan) 7/2016

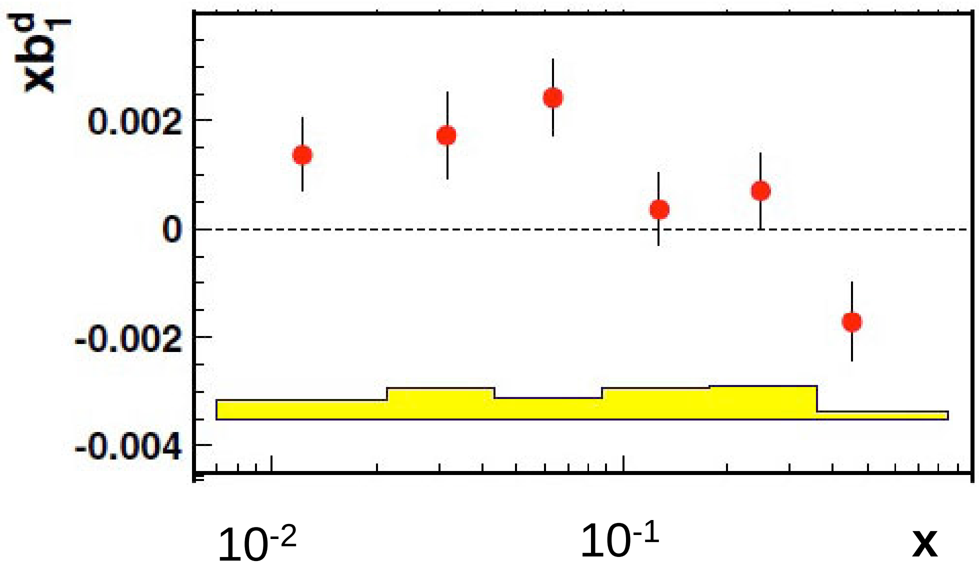
Hints of Non-Vanishing Sea Quark Sivers Distribution ?

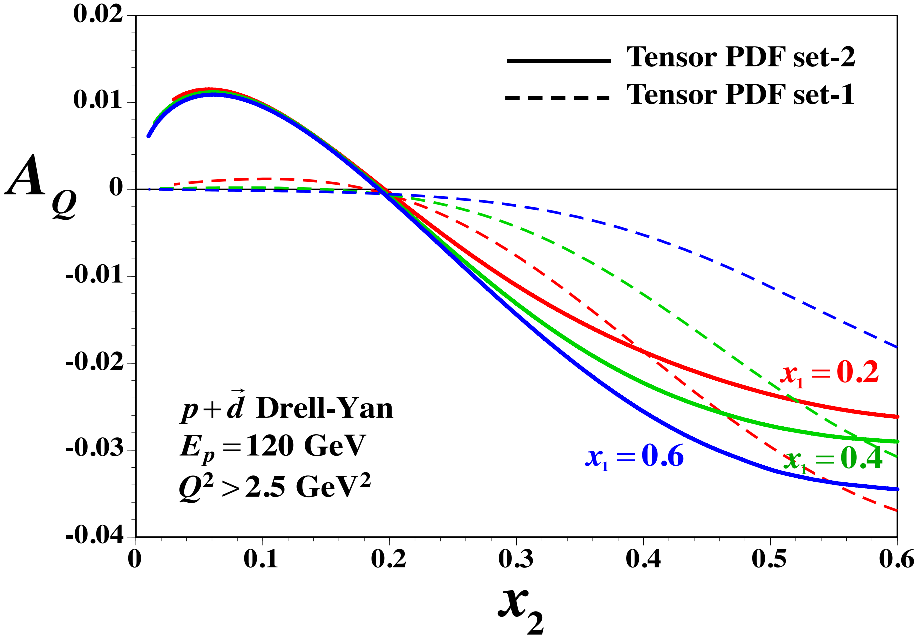


Sea quark generates left-right bias ?

Left-right bias generated through fragmentation process ?

HERMES , Phys. Rev. Lett. 95, 242001





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