UVA Solid Polarized Targets

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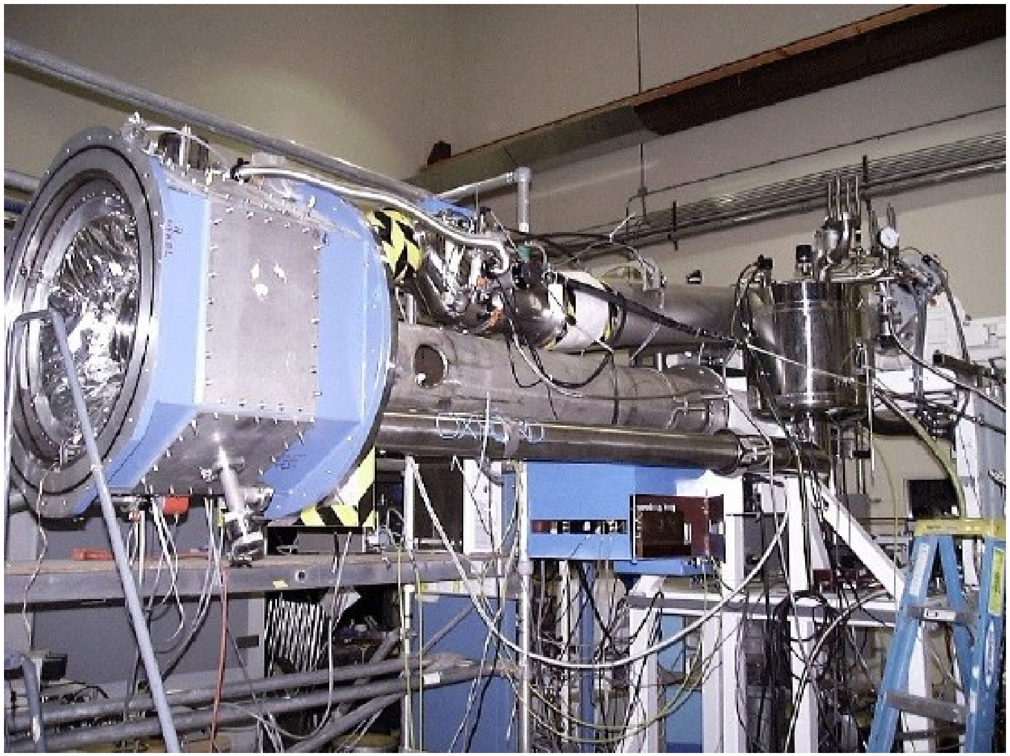
UNIVERSITY of VIRGINIA

Outline

- Introduction to The Target
- The Modern Effort and Upcoming Experiments
- A Couple of Example Projects
- Conclusion

What is a Polarized Target



- A marriage of sciences for the purpose of optimizing the over all figure of merit of Nuclear/Particle Spin Physics
- Use of high density, high polarizability, with high interaction rate in fixed target experiments

A Bit of History

Overhauser   Abragam

Overhauser effect 1953
Electrons in metals (First DNP)

- 1958: First demonstration in ^{6}LiF
- 1959: Many Substances *~20%*

S. Bernstein
Oakridge 53
Static

Jeffries

Abragam and Proctor

Solid Effect 1957
Electron to nuclear

- 1962: Jeffreis/Schmugge: First high polarization observed
- {Nd} LMN(24H2O)→ Lanthanum Magnesium Nitrate
- Highest polarization ~70%
- Very narrow EPR line → Resolved Solid Effect
- Niinikoski NH3 ~90%, very cold, time
- Crabb over 90% at 1K

Provotorov and Kozhushner

Thermal Mixing 1961

- Lineshape Theory
- Full NMR picture
- Accurately Measure Polarization
- Leads to evolution of Solid-State NMR

Abragam   Borghini

First DNP Polarized Target (Saclay) 1962

Borghini

Spin-Temperature Theory 1968

- Bulk Spin dynamics
- Frozen organic liquids
- Materials studies

The Dynamic Nuclear Polarized Target System

- -Evaporation Fridge: (e-beam: 1-100 nA)

  -Dilution Fridge: (g-beam and charged low intensity)
- ~10^{35}cm^{-2}s^{-1}
- Dilution factor *f*<50%

$$f = \frac{\text{\# of polarizable nuclei}}{\text{total \# of nuclei in target}}$$

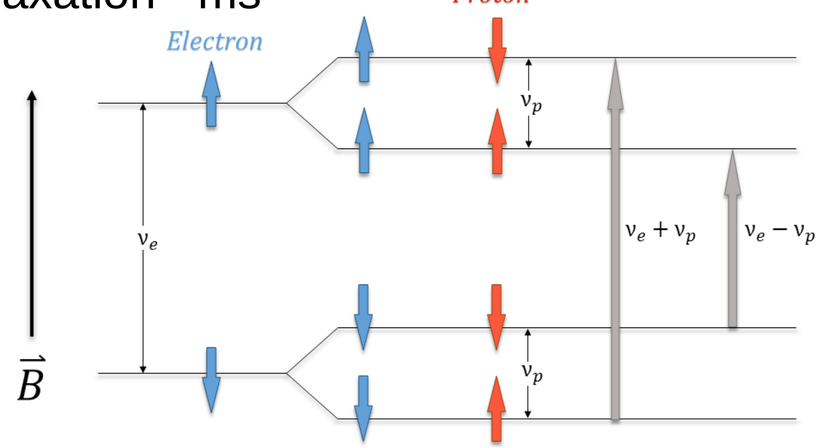
- DNP using Microwave to enhance polarization
- Cryogenic system (1.5-0.03 K)
- Material Specific to Experiment
- NMR Q-meter system for polarization data

$$FOM=n_t f^2 P^2$$

Dynamic Nuclear Polarization

Add Free Radicals, cool sample, RF-sample in B-field

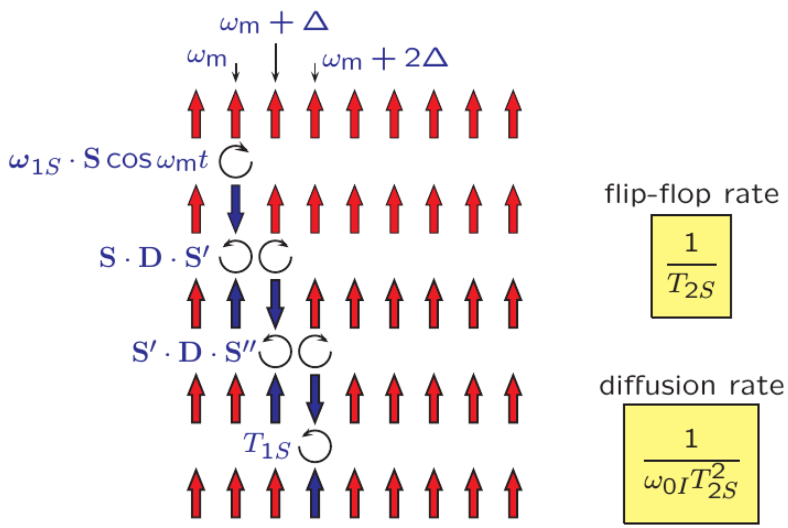
e$^-$ relaxation ~ms

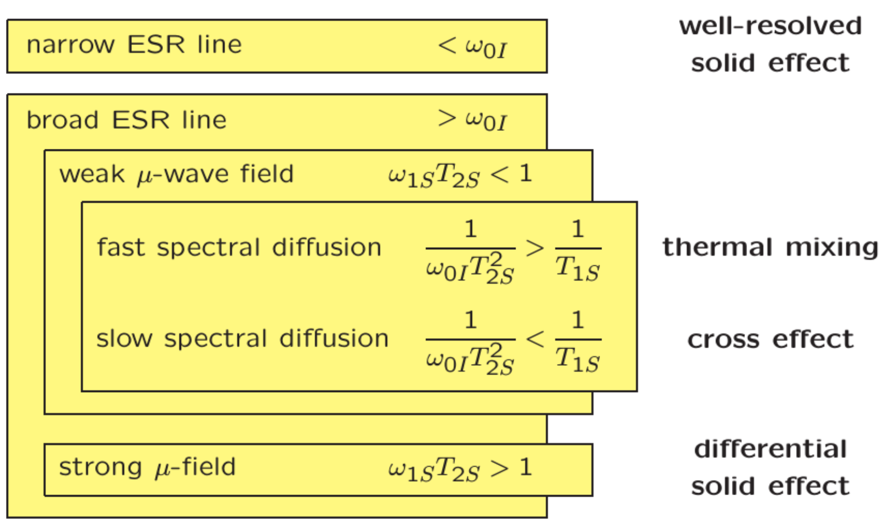


Zeeman Splitting

5T: 140 GHz

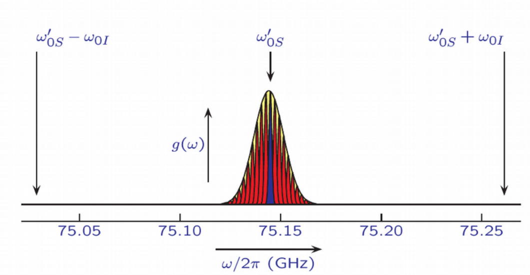
2.5: 70 GHz





- Transfer of spin polarization from electrons to nuclei
- Electrons 1K 2.5T ~92%

  Protons 1K 2.5T ~0.25%
- Narrow ESR width will help optimize



$$P = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

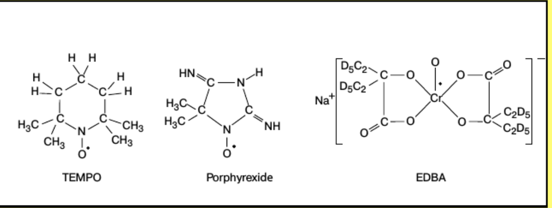
DNP-Process

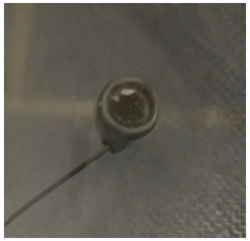
- Add Free Radicals
- Cool sample
- RF in B-Field

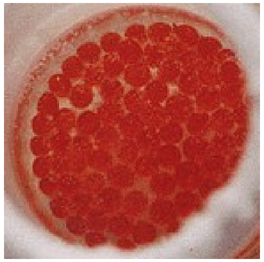
DPPH
PAC
BPA
Shape BPA
Violanthrene
Porphyrexide
TEMPO
Ziegler
Anthracene Na^+
TMR
PB
PR
TMPD
Tri-tetra-bythlphenyl
Tetramethyl 1,3 cyclobutadien
DTBM
etc.

BPA + DPPH
BPA + Cob. Oleale
Ziegler + DPPH
Ziegler + Cob. Oleale
Ziegler + BPA
etc.

neutron irradiation
^{60}Co-γ irradiation
γ - irradiation







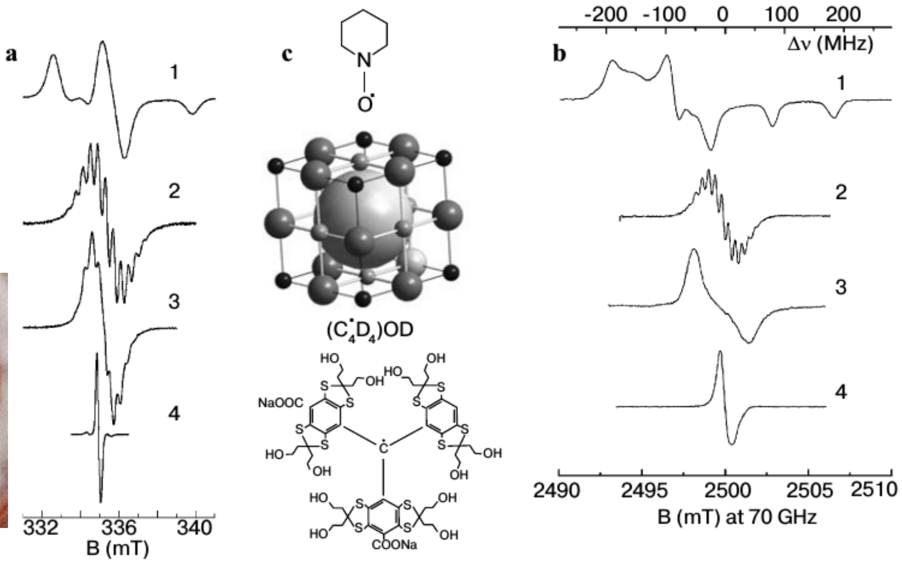
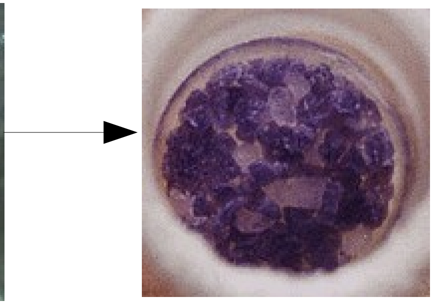


Fig. 6. X-band (**a**) and V-band (**b**) ESR spectra of TEMPO-doped d-butanol (1), irradiated ^{6}LiD (2), irradiated d-butanol (3), and trityl-doped d-propanediol (4). **c** Corresponding radicals.



Warm Irradiation

- NIST (10^{17} e-/cm^2)
- MIRF 14 MeV 10μA
- under LAr bath (~87K)
- Store in LN_2

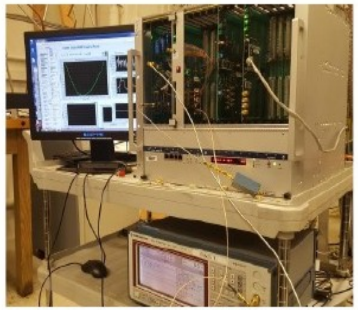
Spin Temperature Theory: Narrow paramagnetic resonance (EPR) line enables Creation of high inverse spin temperatures – High Polarizations

General DNP System

Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)
Deuteron (6.5 MHz/T)



NMR

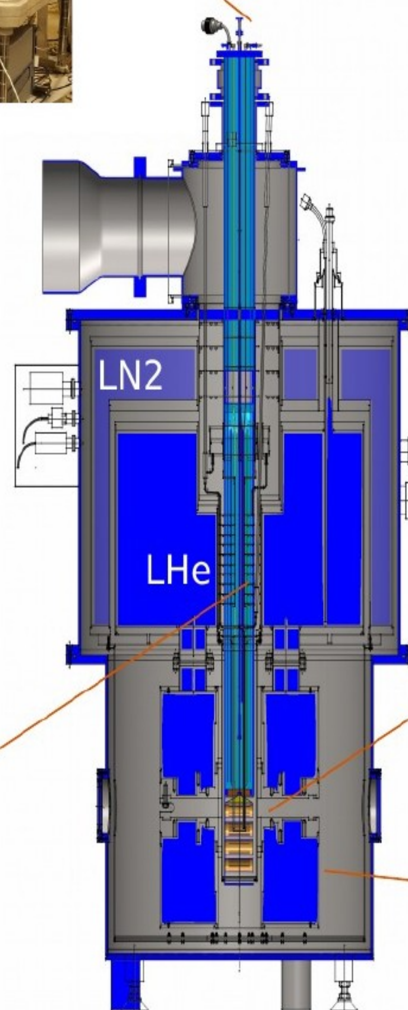
Larmor-ESR

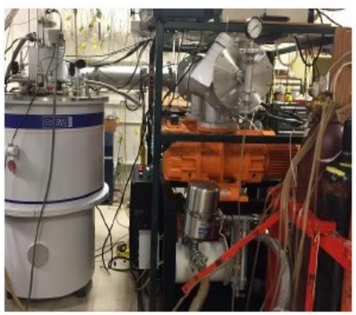
50-185 GHz

~140 GHz at 5T

Microwave

Insert





Pumps

Target material

$^{14}NH_3$ and $^{14}ND_3$
$^{15}NH_3$ and $^{15}ND_3$
^{7}LiD, ^{6}LiD, ^{7}LiH, ^{6}LiH

C_4H_9OH, C_4D_9OH

C_2H_4, C_2D_4, CH_2, CH_2

BH_3NH_3, $C_5H_{12}O$

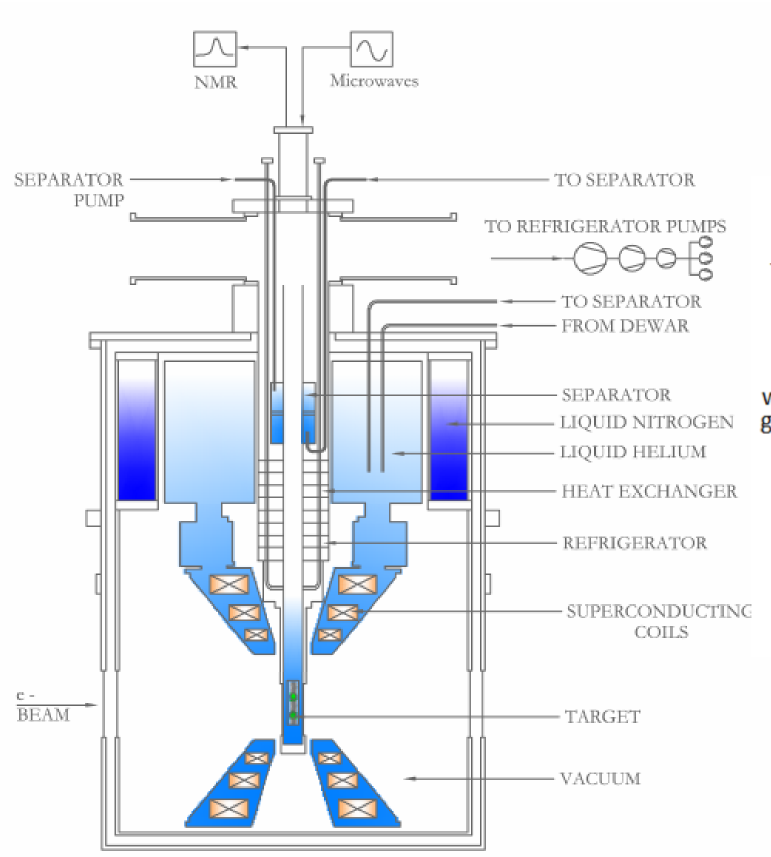
Fridge

Magnet

T=0.03-1.5K

Dilution-Evaporation

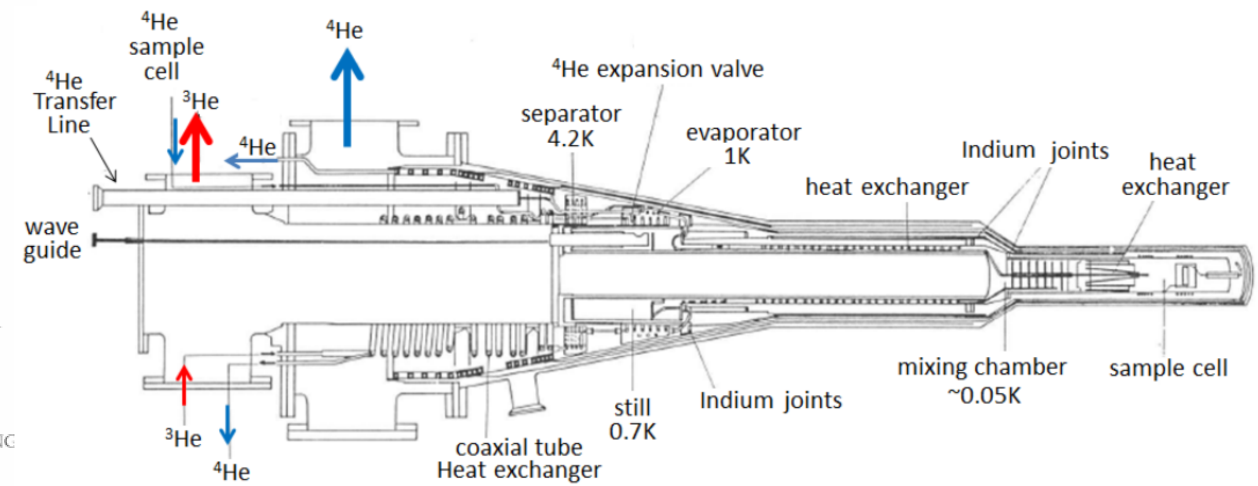
Cryogenic Systems



^{4}He Evaporation Fridge

- Charged beam up to 100nA
- Relaxation Rate (20-30 min.)
- Cooling Power (1W @ 1K)
- Run at around 80-90% p and 25-45% d

Clas12/HallA-C/SoLID/DY



^{3}He/^{4}He Dilution Fridge

- Photon beam or low intensity charge beam
- Relaxation Rate (500 hours)
- Cooling Power (5-10μW @ 30-50mK)
- Run at around 90-95% p 70-75% d

TUNL/Frost/GlueX/HD-Ice

What We Have at UVA

Much older equipment in need of repairs and maintenance

UVA Polarized Target System

Microwave

Target Insert

Pumps

Two Parallel
2063H 63 m^3/Hour

ROOTS: 600 m^3/Hour

ROOTS: Two Parallel
2000 m^3/Hour

1W (~0.121 Torr)

Magnet

Lab B28

Lab B17

Some Spin Physics Projects

- ORNL: DNP proton crystallography with a neutron beam at Spallation Neutron Source (DNP-SNS)
- LHCb: QCD-spin physics in nucleon structure and hadron spectroscopy (SMOG, LHC-SPIN)
- Fermilab: New spin physics program with polarized target and liquefier (E906, E1027, E1039)
- HIGS-TUNL: Spin physics program at Duke with polarized beam and soon polarized target (P-12-16, P-20-09)
- Next Gen HIGS: New design with higher energy and intensity with an active polarized target (HIGS2)
- NIST: Scattering production of paramagnetic complex and target sample experiments (NIST-PTexp)

Spokesperson

Project Involvement

JLAB Experiments

- Hall A

(E12-11-108) SIDIS with transversely polarized proton target

(E12-11-108A) Target single spin asymmetries using SoLID

(LOI-12-16-004) Timelike Compton Scattering with SoLID

- Hall B

(E12-06-109) Longitudinal spin structure of the nucleon

(E12-07-107) Spin-Orbit Correlations with a longitudinally PT

(E12-09-009) Spin-Orbit Correlations in kaon electroproduction in DIS

(E12-12-001) EMC effect in spin structure functions

(C12-15-004) DVCS on the neutron with a longitudinally PT

(C12-11-111) SIDIS on a transversely polarized target

(C12-12-009) Di-hadron production in SIDIS on transversely PT

(C12-12-010) DVCS on a transversely polarized target in CLAS12

- Hall C

(E12-14-006) Helicity correlations in wide-angle Compton scattering

(E12-17-008) Polarized Observables in WACS

(C12-13-011) The deuteron tensor structure function b1

(C12-15-005) Tensor Asymmetry in the x<1 Quasielastic Region

(C12-18-005) Timelike Compton Scattering with T-PT at 11 GeV

(LOI-12-14-001) Search for exotic gluonic states in the nucleus

- Hall D

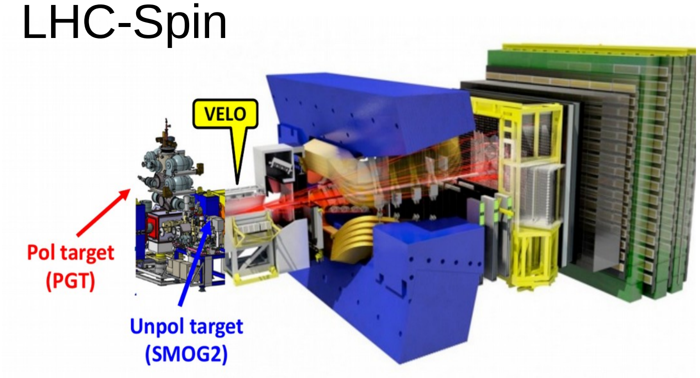
(LOI-12-15-001) Physics Opportunities with Secondary KL beam at JLAB

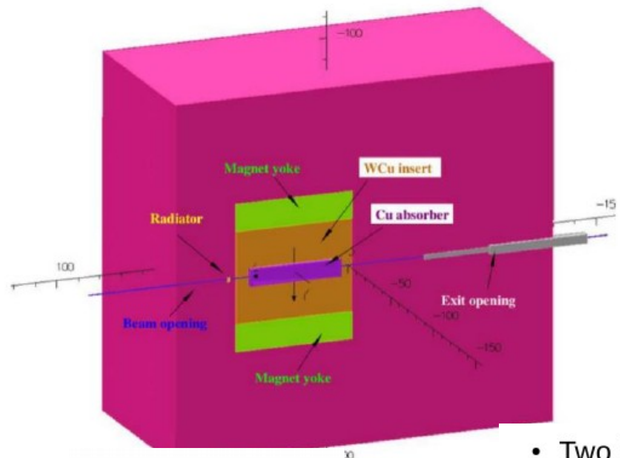
(LOI12-16-005) Target Helicity Correlations in GlueX

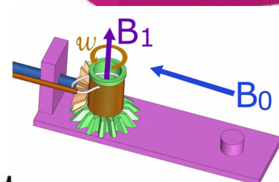
Spokesperson　　　　Project Involvement

Quick Look at Some Projects

LHC-Spin

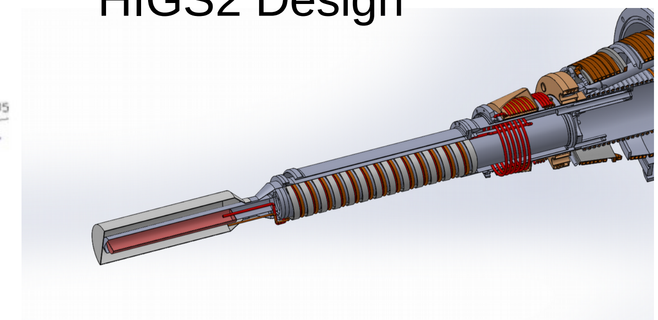




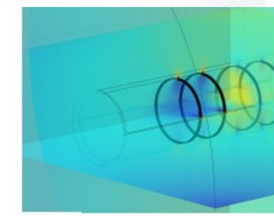


CPS

HIGS2 Design

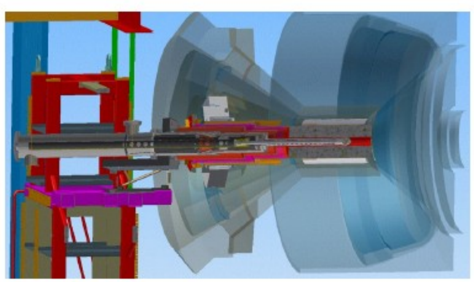


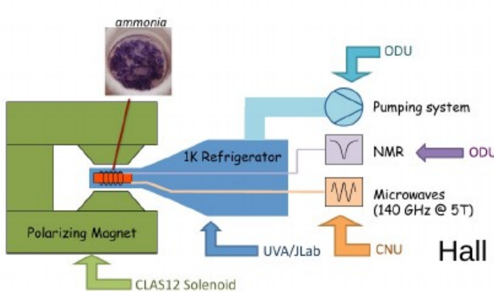
- Two Helicity State Target System
- Single Microwave Line for both
- Use set of DC coils in holding field



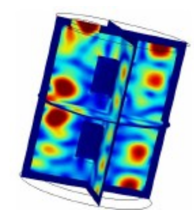
Preliminary models indicate that the ±80 gauss fields can be generated with 2-3 layers of 0.14 mm superconductor at <5 amps.

The CLAS12 Polarized Target

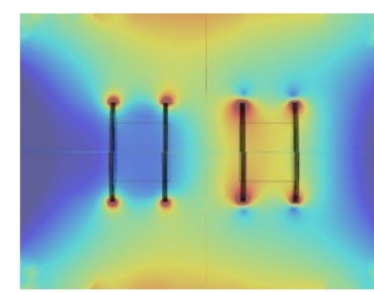




Hall B



COMSOL Multiphysics
Simulation Software



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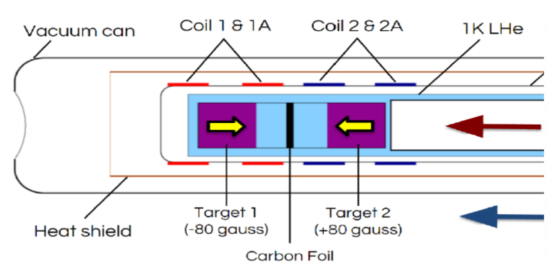

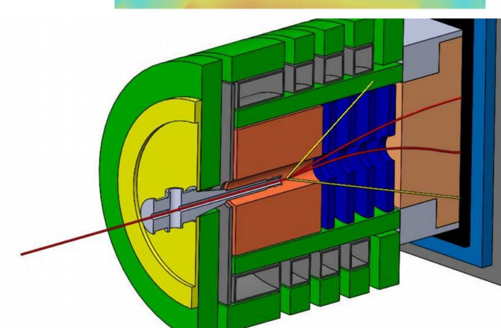

Recent Solicitations

- Erhard Steffens, Cern LHC-Spin (Physics, Target)
- Michael Snow, Indian University NOPTREX (Target)
- Yuji Goto, RIKEN RCNP (Physics, Target)
- Will Brooks, UTFSM PT (Physics, Target)
- Oleg Denisov, Cern Compass (Target)
- Zia Ashkenazi, Tel Aviv University IsoDar2 (Target)

How to do all this work?

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We are supposed to be a big group

How to do all this work?

We are supposed to be a big group

- Lead

  - Scientist

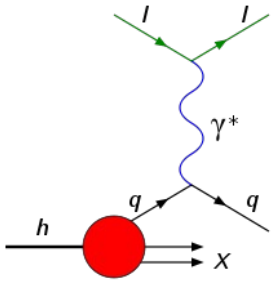
  - 2 postdocs

  - PT Tech

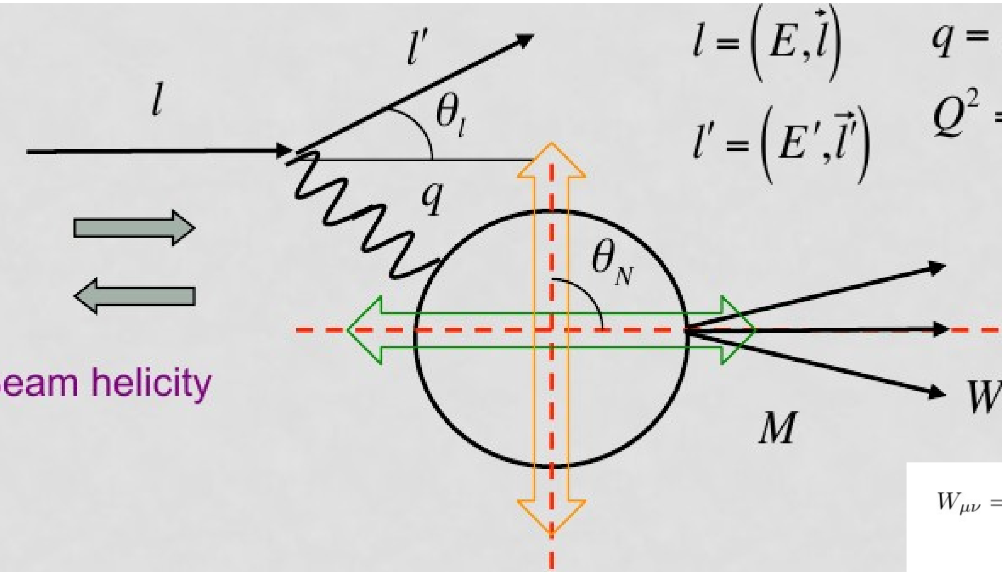
  - Grad students

Couple of Examples

b_1-Structure Function



Polarized DIS



$$l = (E, \vec{l}) \qquad l' = (E', \vec{l}')$$

$$q = l - l'$$

$$Q^2 = \vec{q}^{\,2} - \nu^2 = 2EE'(1 - \cos(\theta_{l'}))$$

$$x = \frac{Q^2}{2M\nu}$$

$$\nu = E - E'$$

$$y = \frac{\nu}{E}$$

$$W^2 = M^2 + 2M\nu - Q^2$$

Longitudinal Target Polarization $\theta_N = 0$

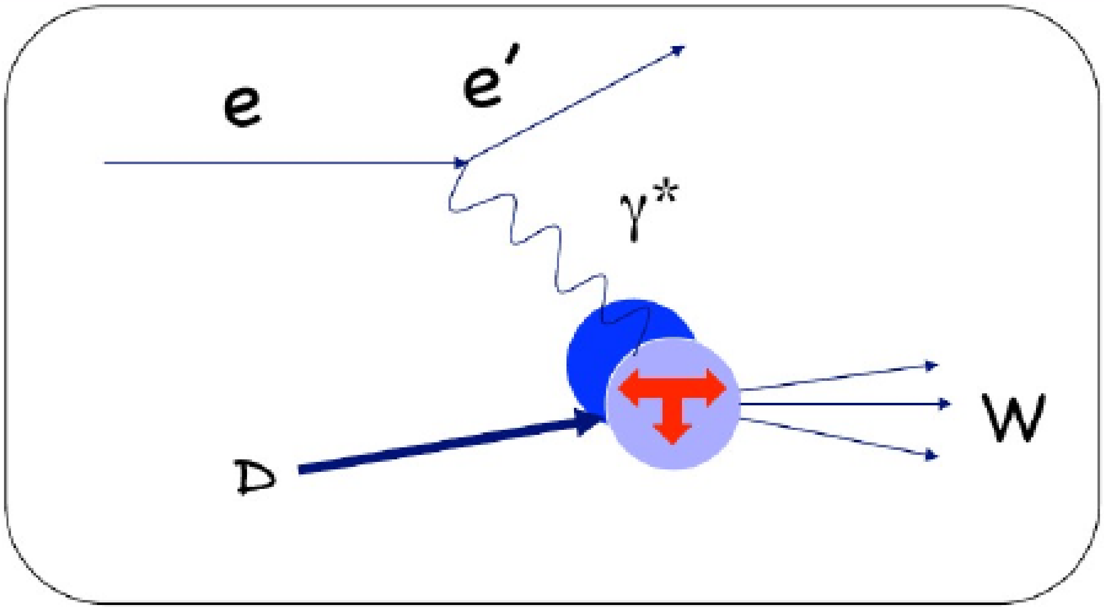
Transverse Target Polarization $\theta_N = \pi/2$

$$\begin{aligned} W_{\mu\nu} = & \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{p}_\mu \hat{p}_\nu}{p \cdot q} F_2(x,Q^2) + i\epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha p^\beta}{2p \cdot q} F_3(x,Q^2) \\ & - i\epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha s^\beta}{p \cdot q} g_1(x,Q^2) - i\epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha \left(p \cdot q\, s^\beta - s \cdot q\, p^\beta\right)}{(p \cdot q)^2} g_2(x,Q^2) \\ & + \frac{1}{p \cdot q} \left[\frac{1}{2}\left(\hat{p}_\mu \hat{s}_\nu + \hat{p}_\nu \hat{s}_\mu\right) - \frac{s \cdot q}{p \cdot q} \hat{p}_\mu \hat{p}_\nu\right] g_3(x,Q^2) \\ & + \frac{s \cdot q}{p \cdot q} \left[\frac{\hat{p}_\mu \hat{p}_\nu}{p \cdot q} g_4(x,Q^2) + \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) g_5(x,Q^2)\right], \end{aligned}$$

Asymmetries in the scattering of polarized leptons on polarized nucleons most sensitive to spin structure functions g_1 and g_2

$$\frac{d^2\sigma^{\uparrow\Uparrow(\Downarrow)}}{d\Omega dE'} = \frac{d^2\sigma}{d\Omega dE'} - (+) \frac{2\alpha^2 E'}{Q^2 E} \left(\frac{E + E'\cos\theta}{M\nu} g_1(x,Q^2) - \frac{Q^2}{M\nu^2} g_2(x,Q^2) \right)$$

Novel Targets for Novel Physics



Construct the most general Tensor W consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

	Nucleon	Deuteron
F_1	$\frac{1}{2}\sum_q e_q^2\,[q_\uparrow^{\frac{1}{2}} + q_\uparrow^{-\frac{1}{2}}]$	$\frac{1}{3}\sum_q e_q^2\,[q_\uparrow^1 + q_\uparrow^{-1} + q_\uparrow^0]$
g_1	$\frac{1}{2}\sum_q e_q^2\,[q_\uparrow^{\frac{1}{2}} - q_\downarrow^{\frac{1}{2}}]$	$\frac{1}{2}\sum_q e_q^2\,[q_\uparrow^1 - q_\downarrow^1]$
b_1	$--$	$\frac{1}{2}\sum_q e_q^2\left[2q_\uparrow^0 - (q_\uparrow^1 + q_\uparrow^{-1})\right]$

$$
\begin{aligned}
W_{\mu\nu} \quad = \quad & -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\
& + i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\
& -b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
& + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})
\end{aligned}
$$

} Tensor Polarization

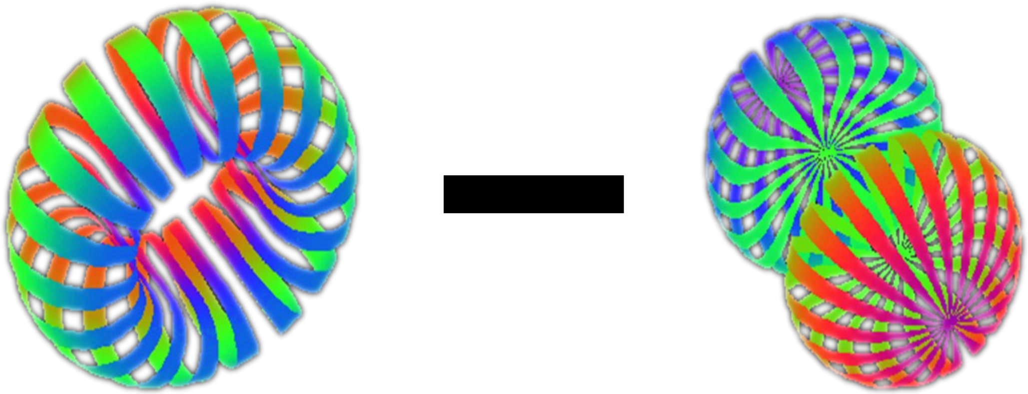
Probing Polarization of Partons

Resulting in the spin structure observed in the nuclear spin

q^0 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state *m=0*

q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |*m*| = *1*

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

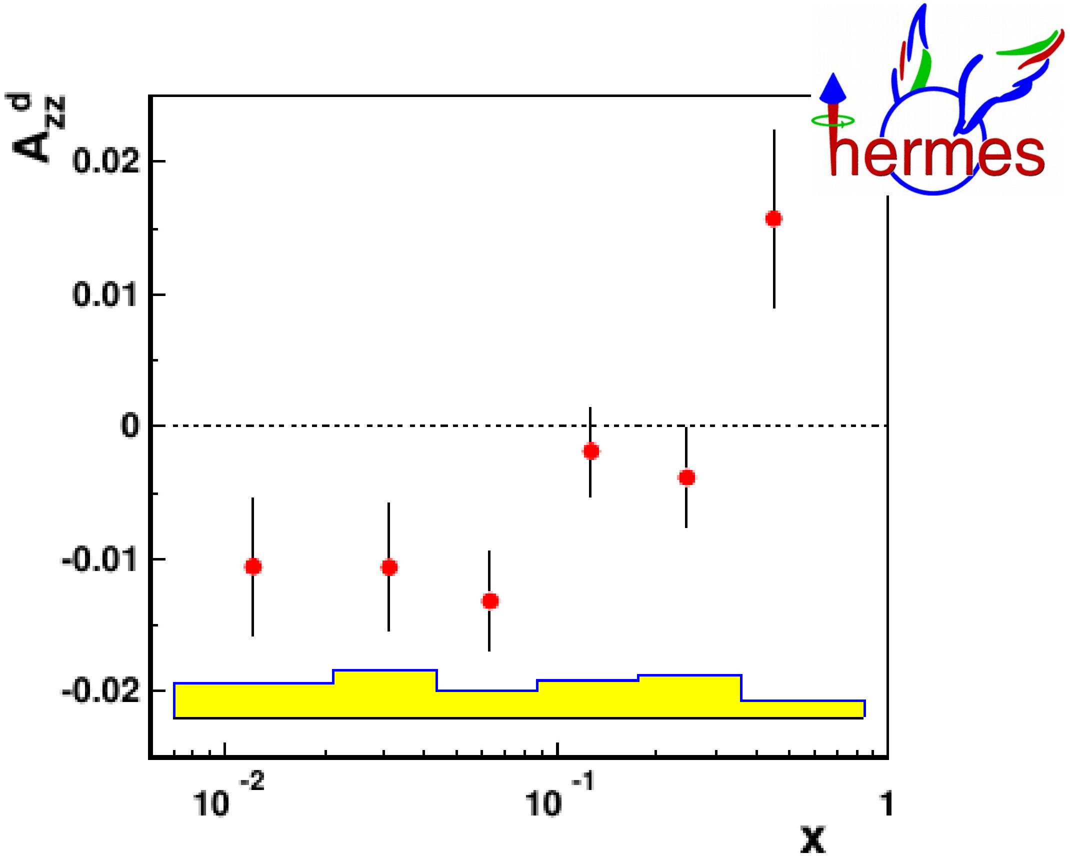


Extraction of Observable

$$A_{zz} = \frac{2}{fP_{zz}} \frac{\sigma_{\dagger} - \sigma_0}{\sigma_0}$$

$$= \frac{2}{fP_{zz}} \left(\frac{N_{\dagger}}{N_0} - 1 \right)$$

$$T = \frac{N_T}{R_T} = \frac{16}{P_{zz}^2 f^2 \delta A_{zz}^2 R_T}$$



Atomic-gas target

$\sigma_{\dagger}$: Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

P_{zz} : Tensor Polarization

	Hermes	JLAB
P_{zz}	0.8	0.2
Dilution	0.9	0.30
$L(cm^{-2}s^{-1})$	10^{31}	10^{35}

$$b_1 = -\frac{3}{2} F_1^d A_{zz}$$

Extraction of Observable

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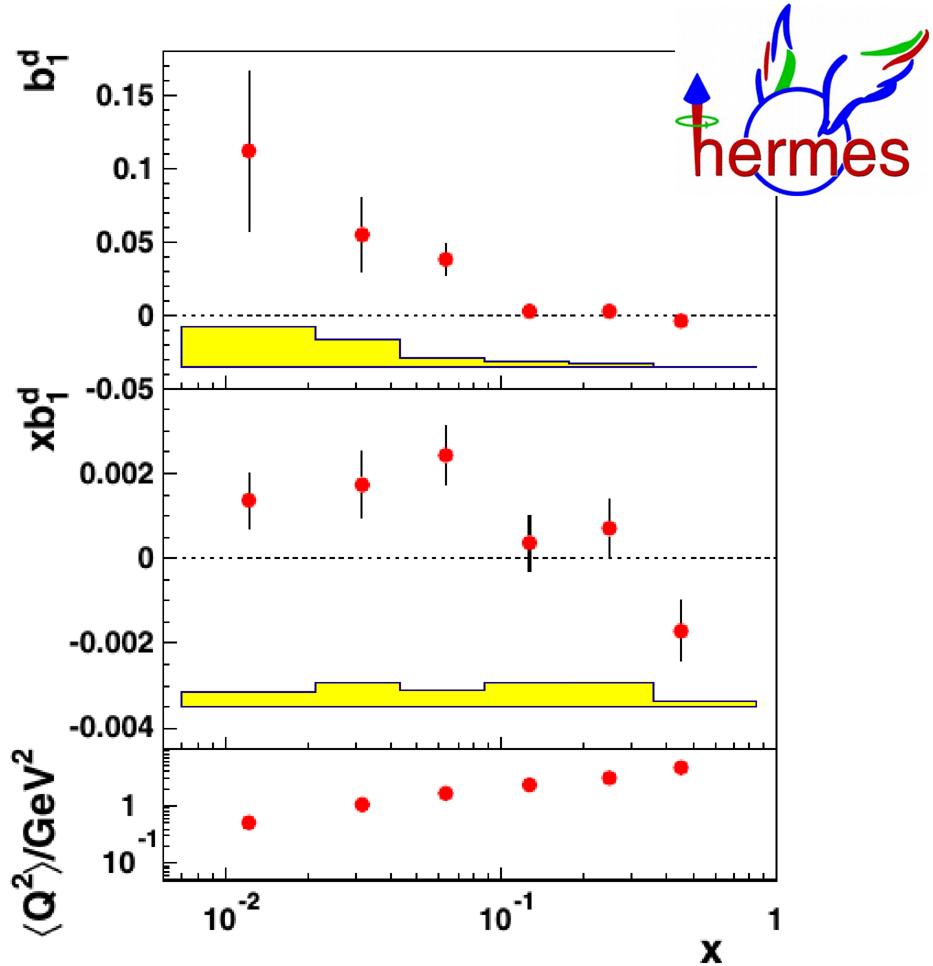

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$L(cm^{-2}s^{-1})$	10^{31}	10^{35}

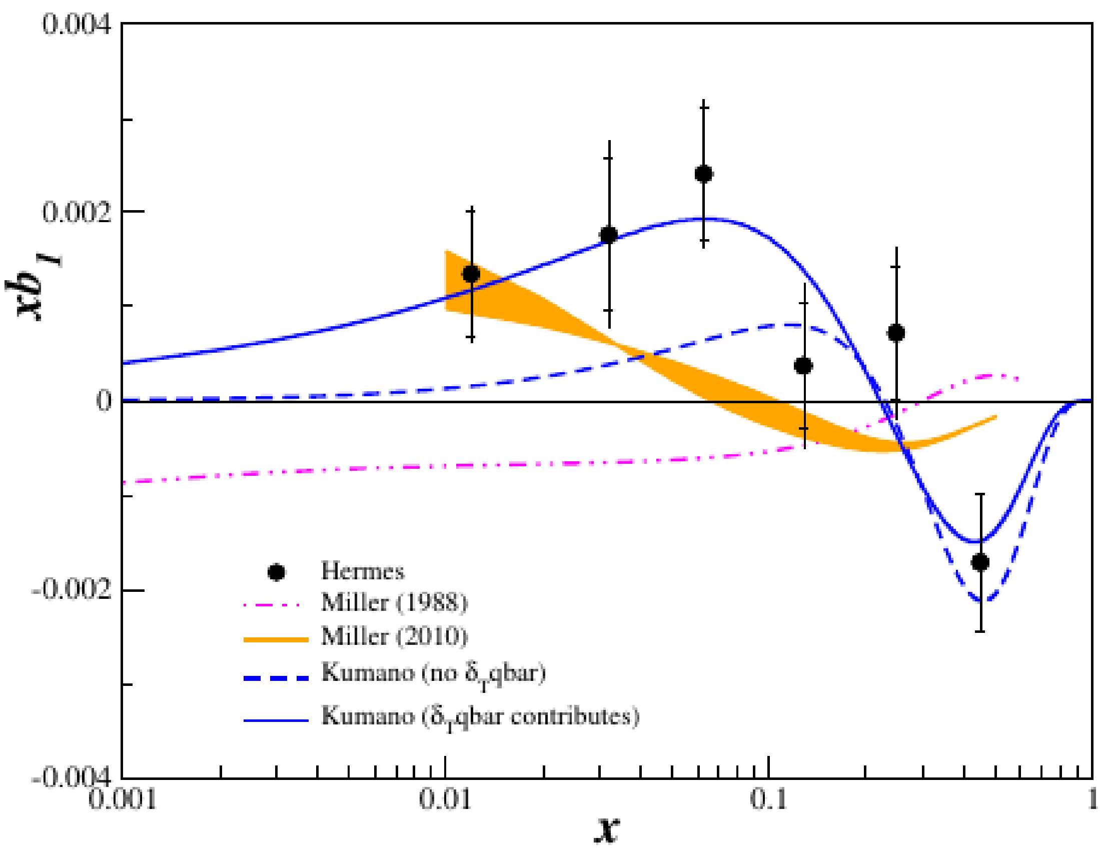
$$b_1 = -\frac{3}{2} F_1^d A_{zz}$$

Very Unexpected Result

$$\int b_1(x)dx = 0$$

if the sea quark tensor polarization vanishes

$$\int_{0.0002}^{0.85} b_1(x)dx = 0.0105 \pm 0.0034 \pm 0.0035$$



Efremov and Teryaev (1982, 1999)

Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

2nd moment more likely to be satisfied experimentally since the collective glue is suppressed compared to the sea

Study of b_1 allows to discriminate between deuteron components with different spins (quarks vs gluons)

no conventional nuclear mechanism can reproduce the Hermes data

Systematics

$\delta\xi$

Charge Determination

< 2 x 10^{-4}, mitigated by thermal isolation of BCMs and addition of 1 kW Faraday cup

Luminosity

< 1 x 10^{-4}, monitored by Hall C lumi

Target dilution and length   step like changes observable in polarimetry

< 1 x 10^{-4}

Beam Position Drift effect on Acceptance

< 1 x 10^{-4} (we can control the beam to 0.1 mm, raster over 2cm diameter)

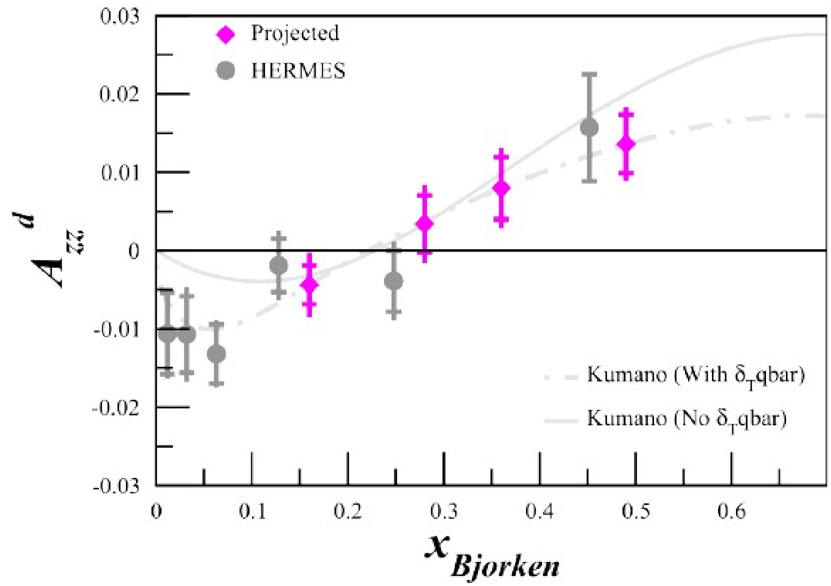
Effect of using polarized beam

< 2.2 x 10^{-5}, using parity feedback

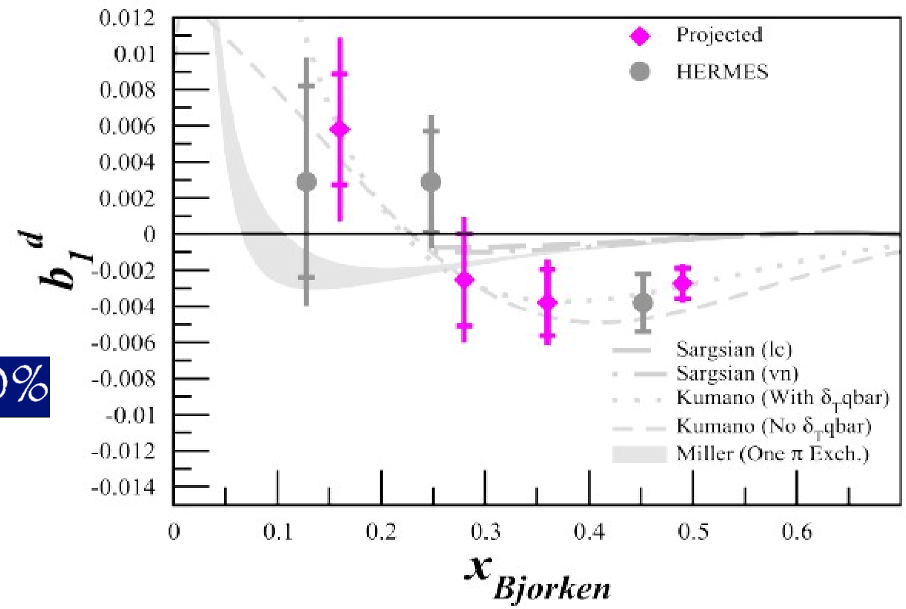
Impact on the observable

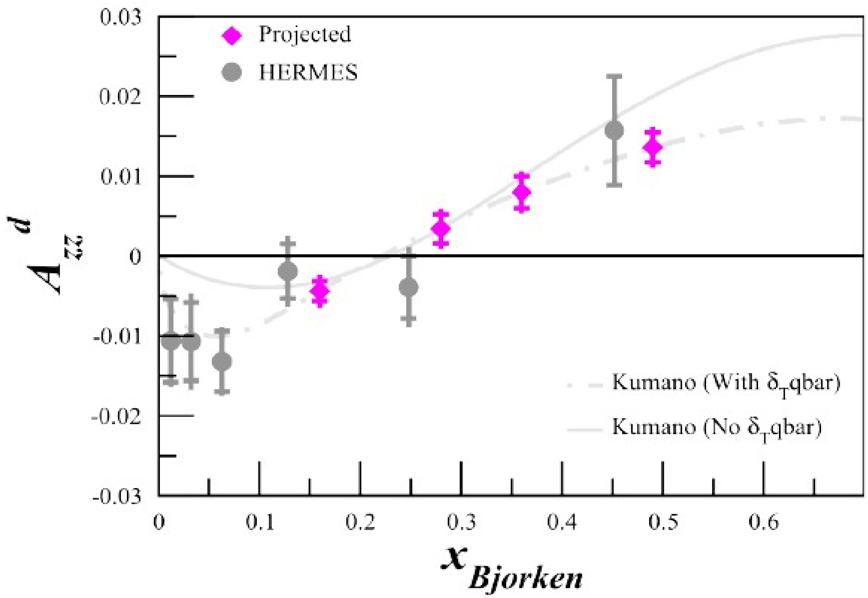
$$\delta A_{zz} = \pm \frac{2}{f P_{zz} \sqrt{N_{cycles}}} \delta\xi$$

Projected Results

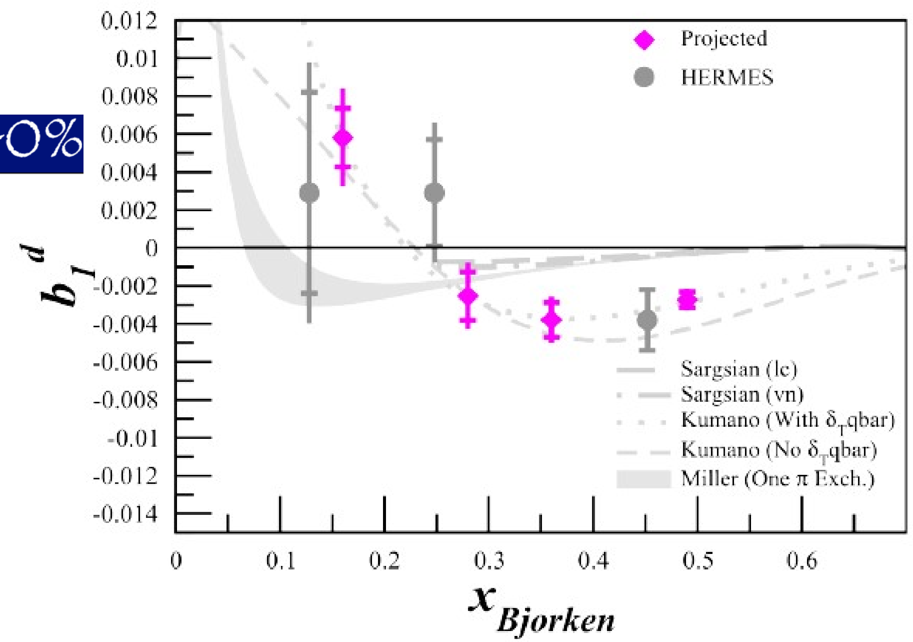


P_{zz}=20%





P_{zz}=40%



PAC Conditions

Scientific Rating: A-
Recommendation: Conditional Approval (C1)

- E12-13-011 (*The Deuteron Tensor Structure Function b1*)
- E12-15-005 (*Tensor Asymmetry in Quasielastic Region*)

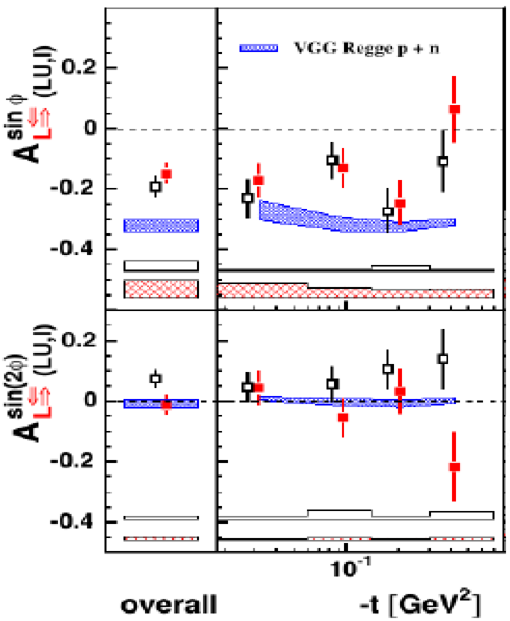
Issues:
In order to obtain conclusive data with sufficient precision it is crucial to achieve a tensor polarization significantly higher than the value of 20% assumed in the proposal. While methods such as RF- "hole burning" are known to increase the tensor polarization above the thermal equilibrium value, these techniques including the polarization measurement have to be developed further to allow for a reliable operation under experimental conditions.

Conditions:
The experiment is conditionally approved with the condition that a tensor polarization of at least 30% be achieved and reliably demonstrated under experimental conditions.

Other Possible Projects

- Spin-1 SIDIS, Spin-1 DVCS, Spin-1 TCS, photo-disintegration T20, T21, T20, Unnatural Parity exchange, Polarized gluons in the nucleon, tensor polarized meson photoproduction, gluon transversity, ...

C_{BT}^{21}, C_{BT}^{20}



□ **unpolarized**

$\mathcal{R}e(\mathcal{H}_1)$

■ **tensor-polarized**

$\mathcal{R}e(\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5)$

DVCS A_{LZZ} (tensor asymmetry) sinϕ amplitude:

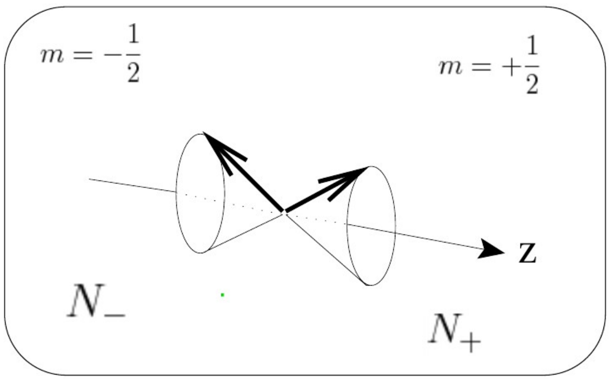
(no plot shown)

0.074 ± 0.196 ± 0.022

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{d\sigma_0}{d\Omega}\{1 - \sqrt{3/4}P_z \sin\theta_{d\gamma}\sin\phi T_{11}\left(\theta_p^{cm}\right) \\ &+ \sqrt{1/2}P_{zz}[(3/2\cos^2\theta_{d\gamma} - 1/2)T_{20}\left(\theta_p^{cm}\right) \\ &- (\sqrt{3/8}\sin 2\theta_{d\gamma}\cos\phi T_{21}\left(\theta_p^{cm}\right) \\ &+ (\sqrt{3/8}\sin^2\theta_{d\gamma}\cos 2\phi T_{22}\left(\theta_p^{cm}\right)]\},\end{aligned}$$

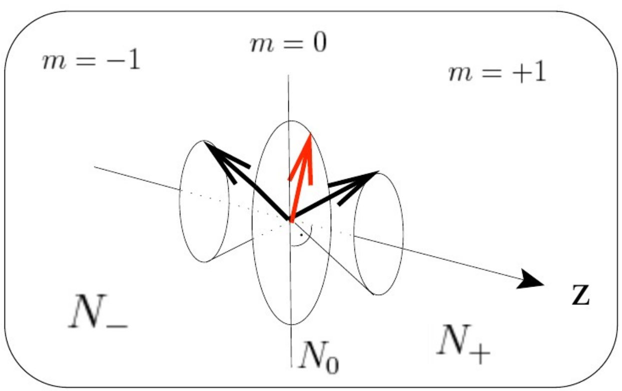
Tensor Polarization

Spin-1/2 system in B-field leads to 2 sublevels due to Zeeman interaction



$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

$-1 < P_z < +1$



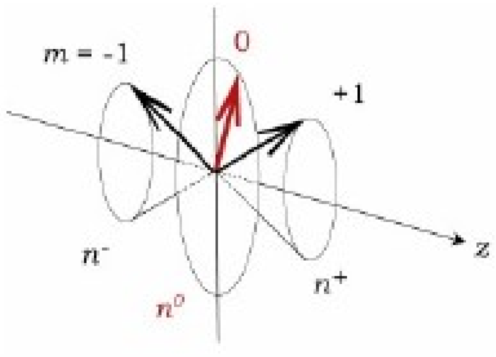
$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

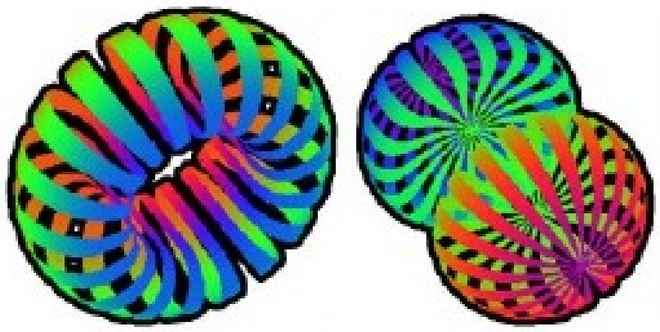
$$P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-}$$

For Spin-1 Target

- Three magnetic sublevels
- Two transitions +1→0 and 0→-1
- Deuteron electric dipole moment eQ
- Interaction with electric field gradient

Novel Targets for Novel Physics

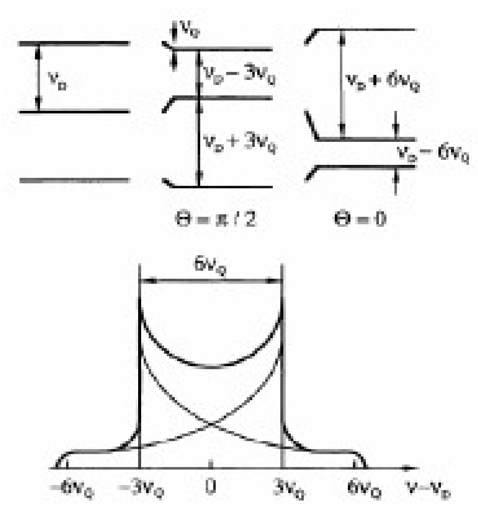


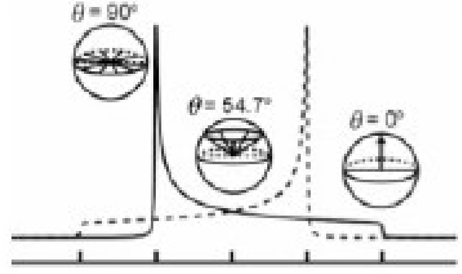


Densities of the deuteron in its two spin projections $I_z = 0$ and $I_z = 1$

$$P = \frac{n_+ - n_-}{n_+ + n_- + n_0} \quad (-1 < P_z < 1)$$

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0} \quad (-2 < P_{zz} < 1)$$



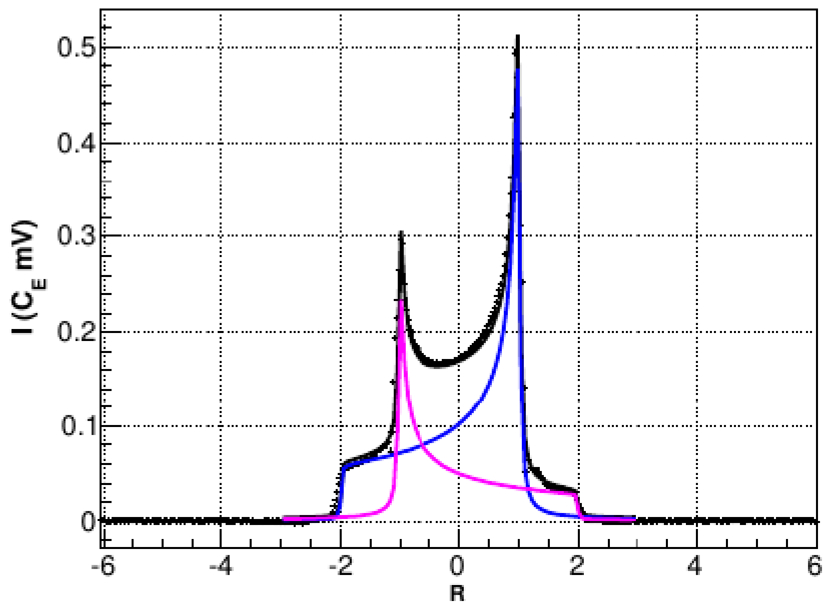


- Using Spin-1 (ND_3) Target
- Three Magnetic substates (+1,0,-1)
- Two Transitions ($+1 \rightarrow 0$) and ($0 \rightarrow -1$)
- Deuterons electric quadrupole moment eQ
- Interacts with electric field gradients within lattice

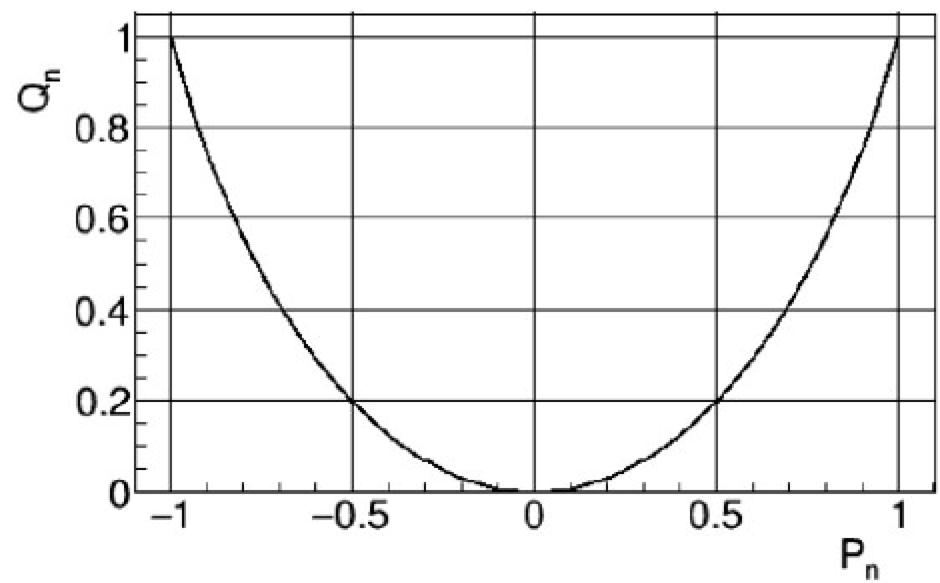
Options of Enhancement

- Increase the B-Field
- Manipulate using AFP
- Additional Microwave Sources
- Different Materials
- RF CW-NMR Manipulation

Natural Equilibrium Polarization



$R = \frac{\omega - \omega_d}{3\omega_q}$



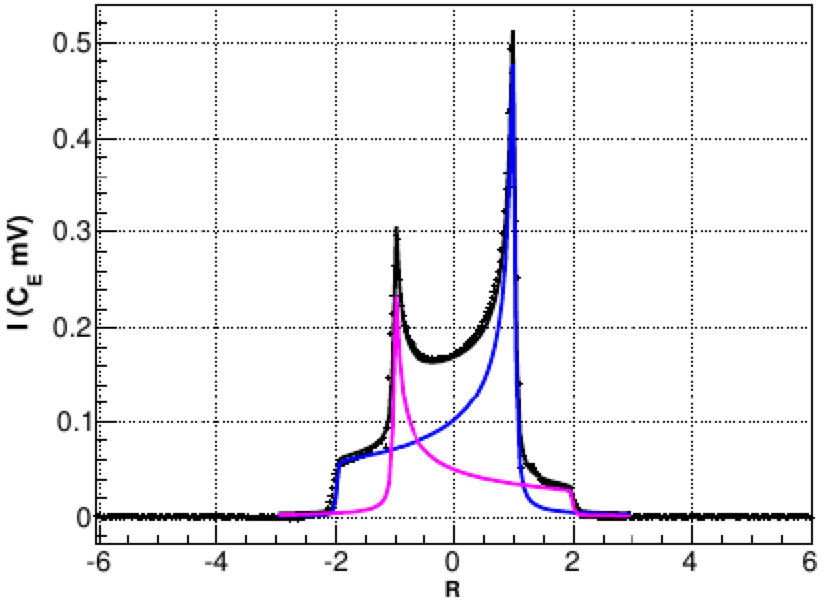
$$P_n = \frac{2\hbar}{g^2\mu_N^2\pi N}\int_{-\infty}^{\infty}\frac{3\omega_Q\omega_D}{3R\omega_Q+\omega_D}\chi''(R)dR$$
$$= \frac{1}{C_E}\int_{-\infty}^{\infty} I_+(R)+I_-(R)dR,$$

$$Q_n = (I_+ - I_-)/C_E$$

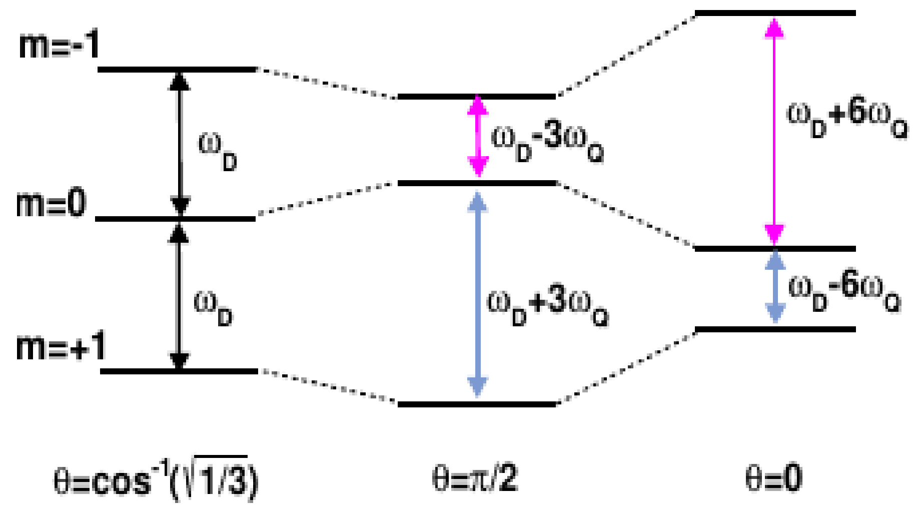
$$Q_n = 2 - \sqrt{4 - 3P_n^2}$$

- Under Boltzmann equilibrium the relationship between vector and tensor polarization always exists
- Under this same condition the Height of each peak maintains a relationship to each other that contains all polarization information
- The ratio of the peak intensities can be used to calculate relative population in each magnetic sub-level

Natural Equilibrium Polarization



$R = \frac{\omega - \omega_d}{3\omega_q}$



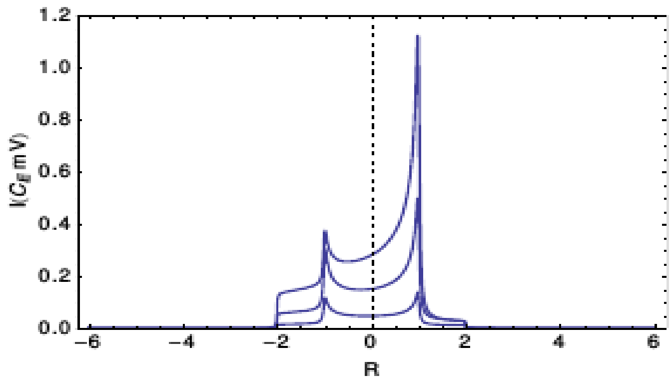
$$P_n = \frac{2\hbar}{g^2\mu_N^2\pi N}\int_{-\infty}^{\infty}\frac{3\omega_Q\omega_D}{3R\omega_Q+\omega_D}\chi''(R)dR$$
$$= \frac{1}{C_E}\int_{-\infty}^{\infty} I_+(R)+I_-(R)dR,$$

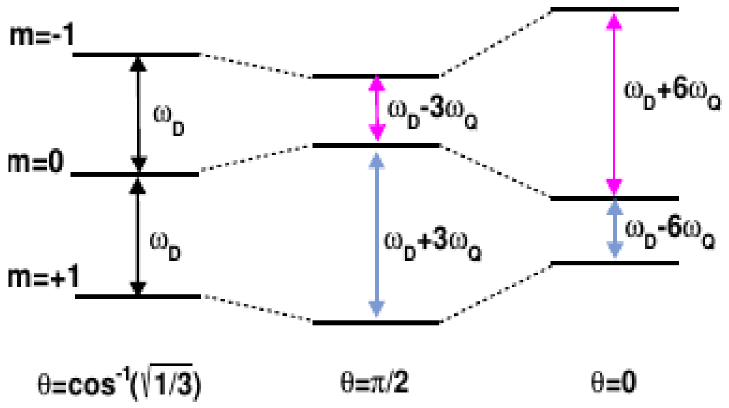
$$Q_n = (I_+ - I_-)/C_E$$
$$= (a_+ - a_0) - (a_0 - a_-)$$

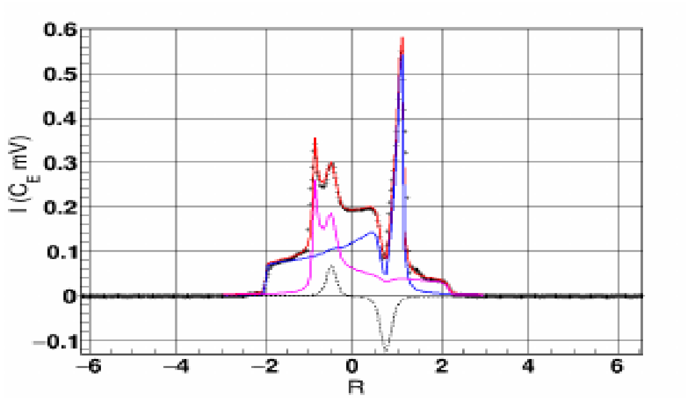
$$Q_n = 2 - \sqrt{4 - 3P_n^2}$$

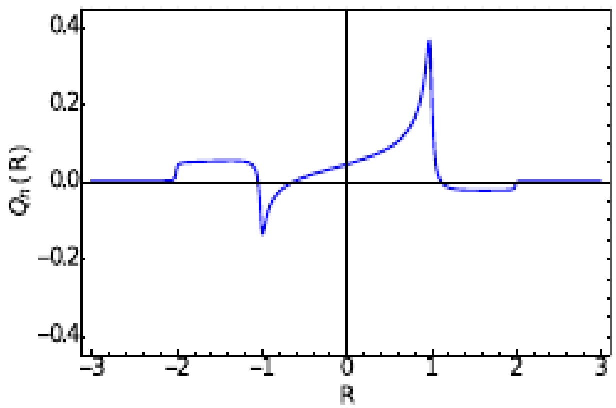
- Under Boltzmann equilibrium the relationship between vector and tensor polarization always exists
- Under this same condition the Height of each peak maintains a relationship to each other that contains all polarization information
- The ratio of the peak intensities can be used to calculate relative population in each magnetic sub-level

Selective Semi-saturation



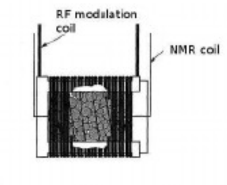




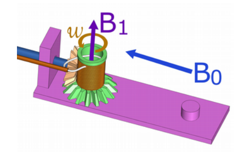


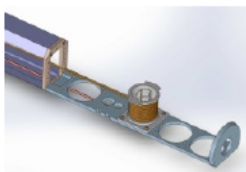
- Selective RF manipulation of the CW-NMR line
- Enhanced by mitigating the amplitudes below zero
- Can be implemented in parallel to DNP

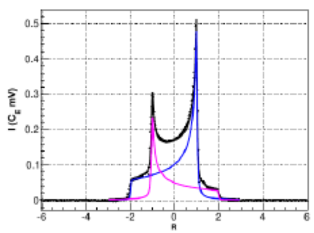
Novel Targets for Novel Physics

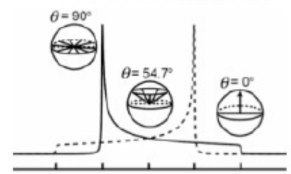


RF Manipulation







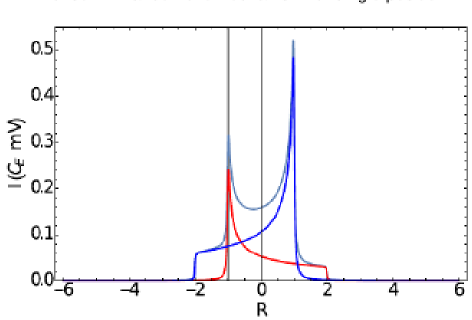


- RF irradiation at the Larmor frequency induces transitions between m=0 and other energy levels
- RF induced transitions at a single θ has a resulting effect on two positions in the line R and $-R$ through conservation of energy
- This can be implemented to shrink one transition lines area and enhancing the other resulting in tensor polarization manipulation

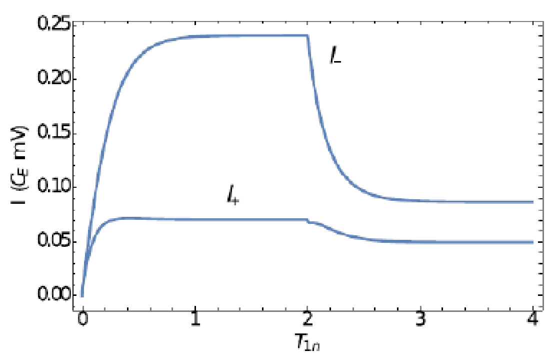
- Study Optimization Analytically
- Develop Simulated Lineshape under RF
  - Empirical info from RF-power profile and Spectral diffusion
  - Rate Eq for overlap ratio
  - Generate theoretical lineshape manipulated by RF
- Develop fitting procedure for measurement
  - Unique constraints for overlapping regions are provided by MC
  - Fit semi-saturated (optimized d-Ammonia)
  - Test measurements with specialized NMR and scattering experiments
- Further Optimized Enhancement
  - Slow Perpendicular Rotation with semi-saturating RF
  - Heavily Reliant on MC for measurements
  - Tested with d-but. but not yet for ammonia

Novel Tensor Enhanced Target

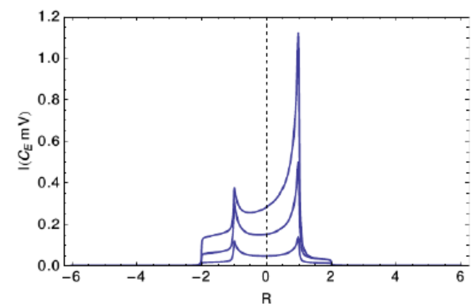
Tensor Enhancement Mechanism for single position



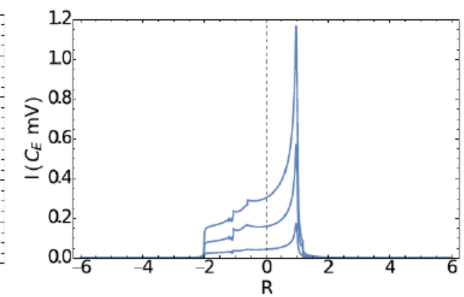
Selective Semi-saturation : Use power appropriate for position optimizing tensor polarization for all R



For peak Semi-saturation significant enhancement occurs by reduction of negative tensor polarization at R as well as adding to positive tensor polarization at $-R$

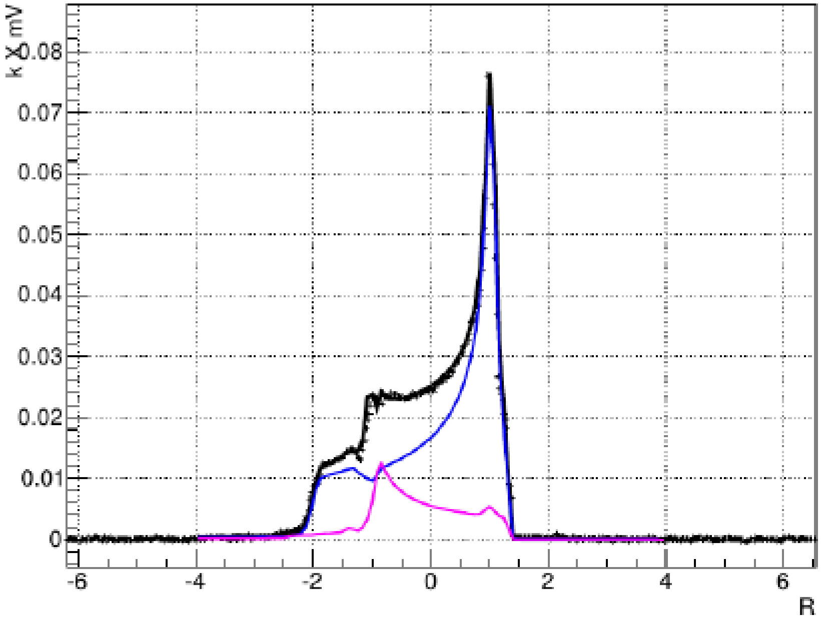


Simulated Examples of regular lineshape (13,42,78%)

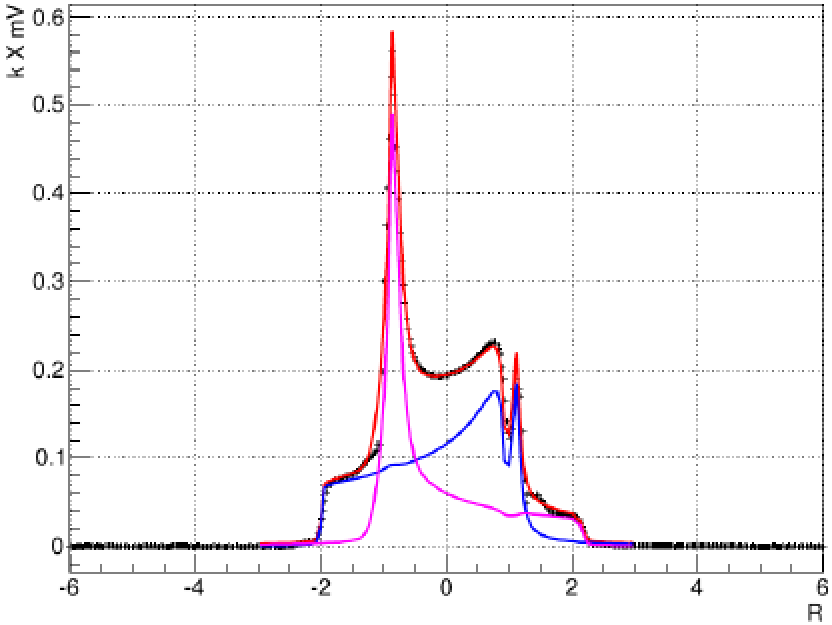


Examples Optimized Tensor Polarization Examples (1.3→5.4,13.6→23.8,52→58%)

Selective Semi-saturation
(or just hole burning)



MC overlap with d-but. NMR experimental points (Pn=51→45,Qn:20→31%)

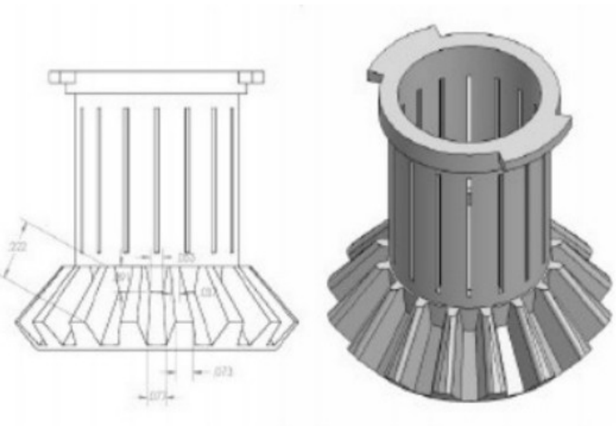


MC with fit and d-but. NMR experimental points (Pn=48→46,Qn:18→6%)

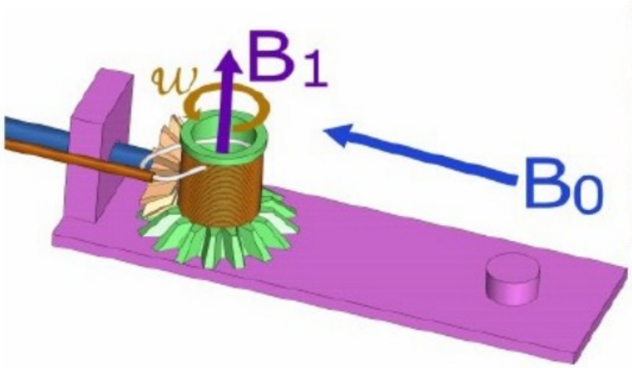
$$R = \frac{\omega - \omega_d}{3\omega_q}$$

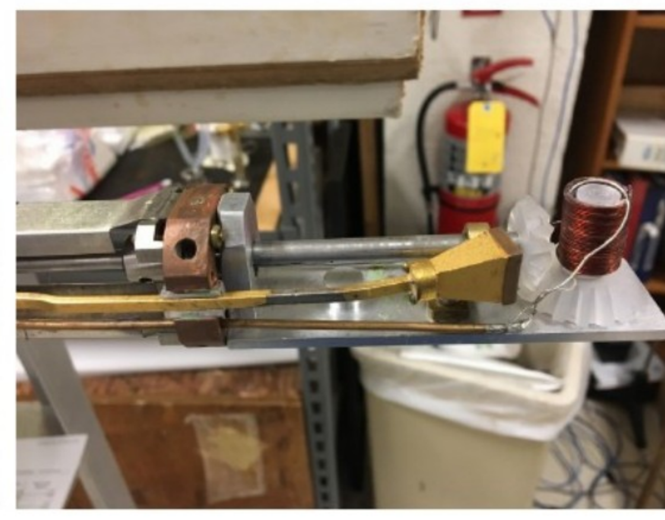
DK Eur.Phys.J. A53 (2017) no.7, 155 arXiv:1707.07065

What Things Look Like

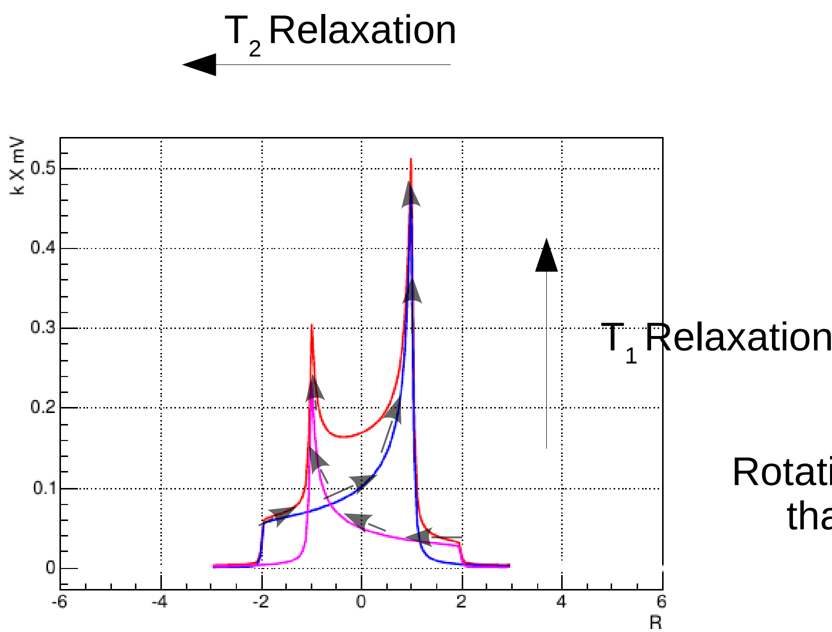


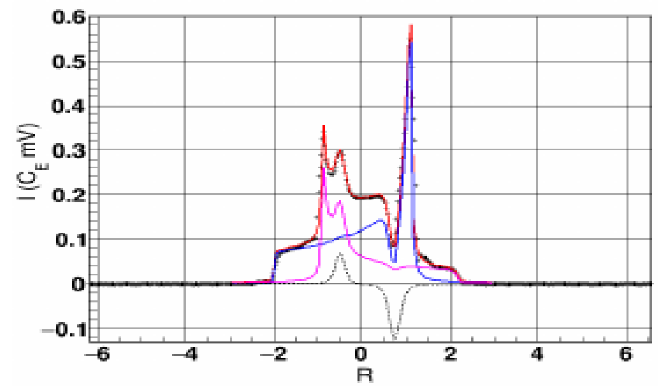
- Kel-F $(C_2ClF_3)_n$ cup and driving gear
- Motor outside cryostat
- NMR coil around cup
- Already used with several designs at UVA
- 1 Hz achieved with no problem
- Fixed beam spot



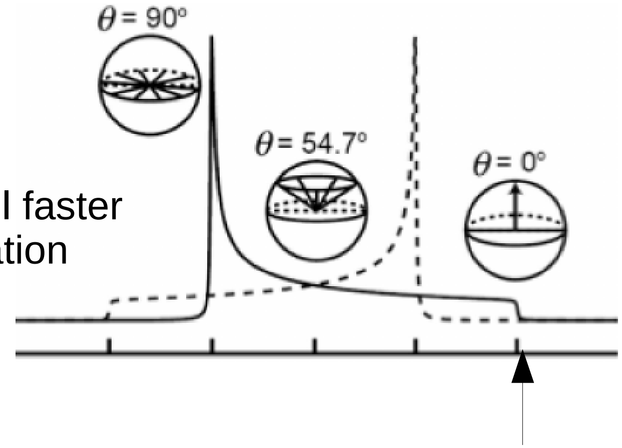


Rotating Target Concept





Rotational rate sill faster than T_2 Relaxation



SSS with slow rotation

- Selective saturation/pumping while rotating
- Saturated domain moves with rotation
- Can enhance Q or go -Q

$$Q_n = (I_+ - I_-)/C_E$$
$$= (a_+ - a_0) - (a_0 - a_-)$$

RF-Manipulated Signals

Fast target helicity flips through Adiabatic Fast Passage (AFP)

AFP at UVA

performed AFP on different materials (5T, 1K)

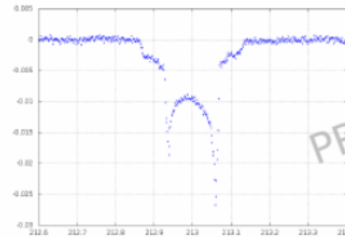
15NH3, D-butanol, butanol+tempo

preliminary results on flip efficiency

Table 1
Results from AFP experiments with various nuclei in differ
target materials

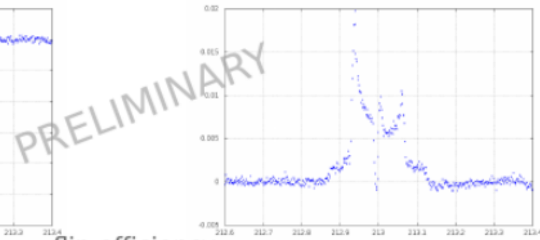
Nuclei	Substance dopant	e^- conc. (spins/g)	δP^{max}
^{1}H	1-butanol EHBA-Cr(V)	2.0×10^{19}	−0.76
^{7}Li ^{1}H	^{7}LiH (irradiated)	low	−0.90 −0.90
^{19}F ^{1}H	8-fluoro-1-pentanol TEMPO	1×10^{20}	−0.37 −0.40
^{2}H	1-butanol-d_{10} EHBA-Cr(V)-d_{22}	2.36×10^{19} 6.35×10^{19}	−0.92 −0.90

NIM 356 (1995) 108



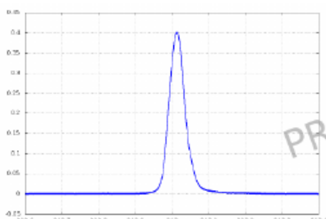
before

flip efficiency >0.8



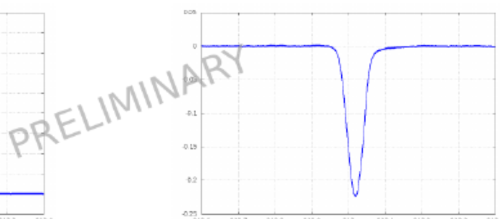
after

15NH3

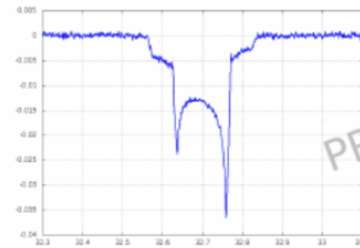


before

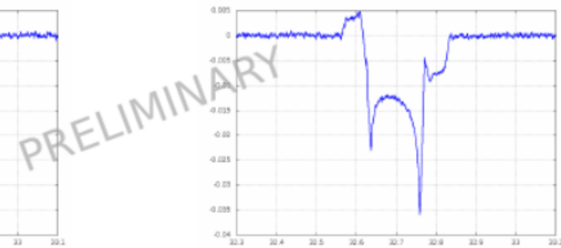
flip efficiency 0.55



after



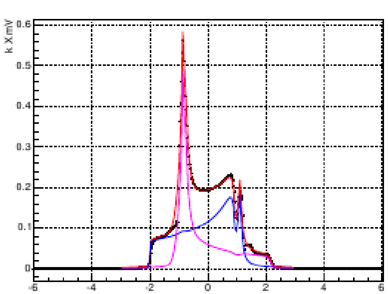
before

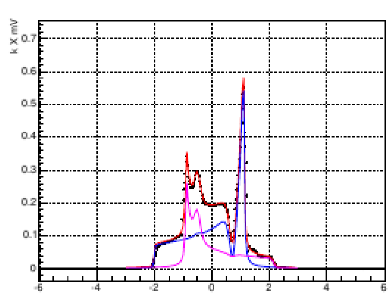


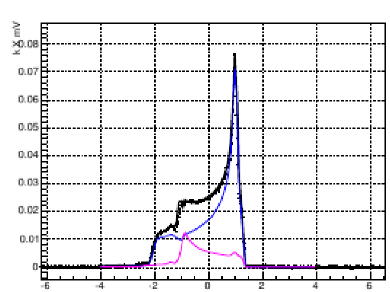
after

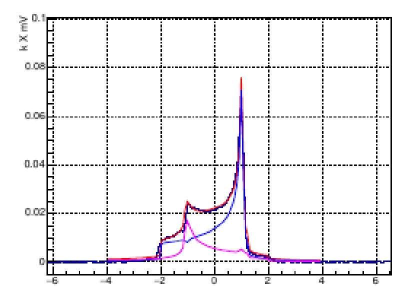
AFP produces rotation of the macroscopic magnetization vector by sweeping through resonance in a short time compared to the relaxation time

- Set record for Tensor Polarization for Deuteron (d-b only) Q>31% @1K 5T
- Set record for AFP flip with Proton e>50% @ 1K 5T









Achieved So Far

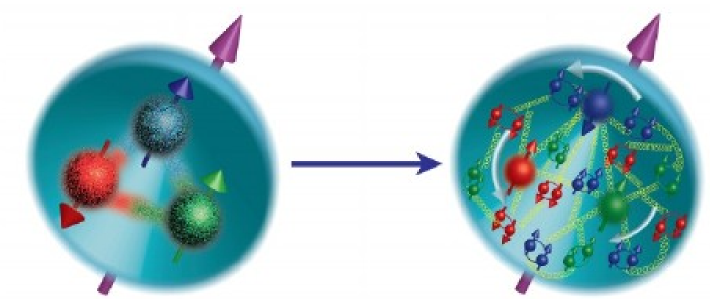
- Before recent research (1984): ~20%
- Recent studies SSS: (2014-2015): ~30%
- AFP with SSS (2016): ~34%
- Rotation with SSS: ~39%

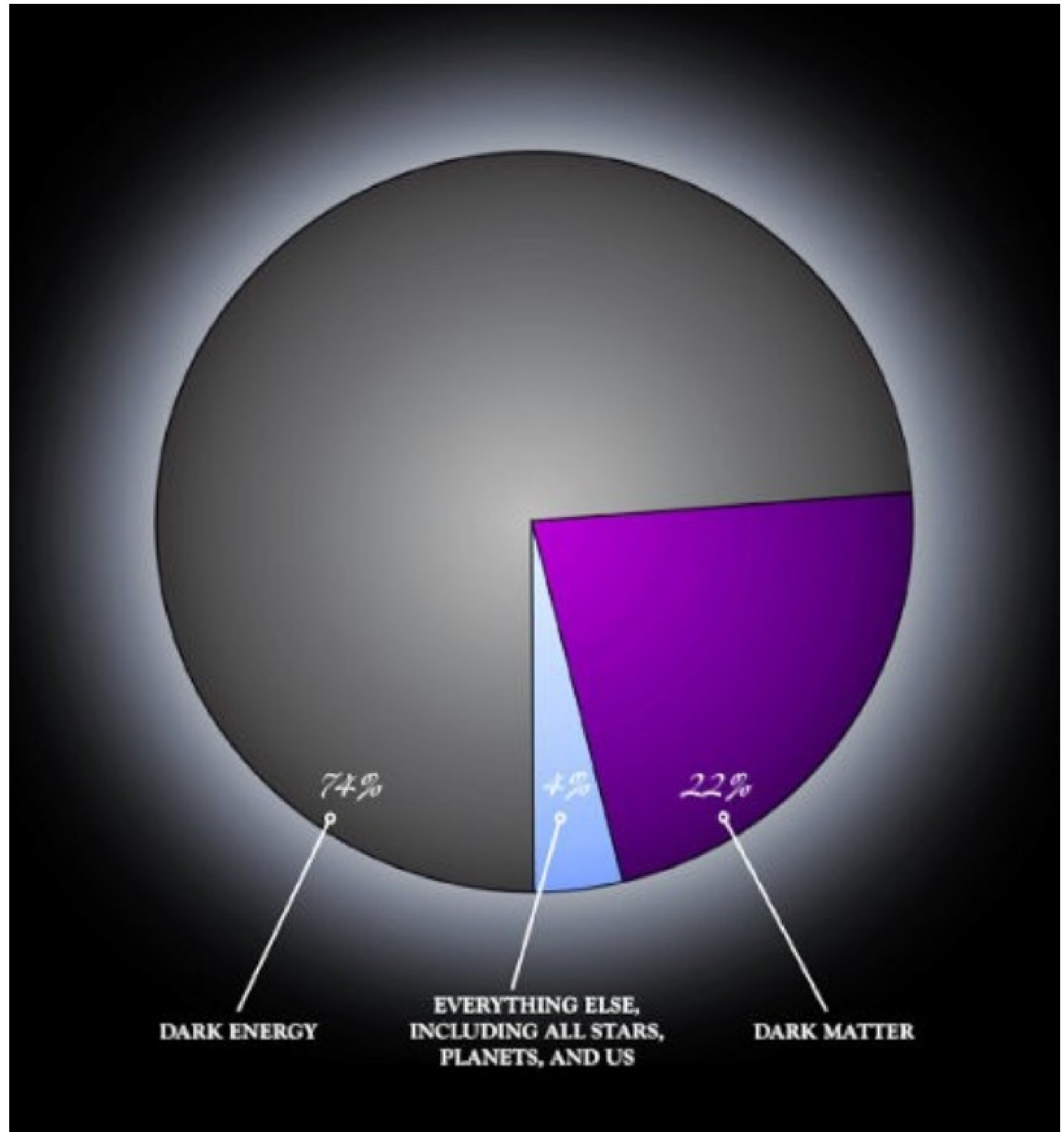
DK **Eur. Phys. J. A (2017) 53: 155**
DK PoS, PSTP2015:014 (2016)
DK J.Phys.Conf.Ser., **543**(1):012015 (2014)
DK Int.J.Mod.Phys.Conf.Ser., **40**(1):1660105 (2016)

SpinQuest Experiment

What We Think We Know

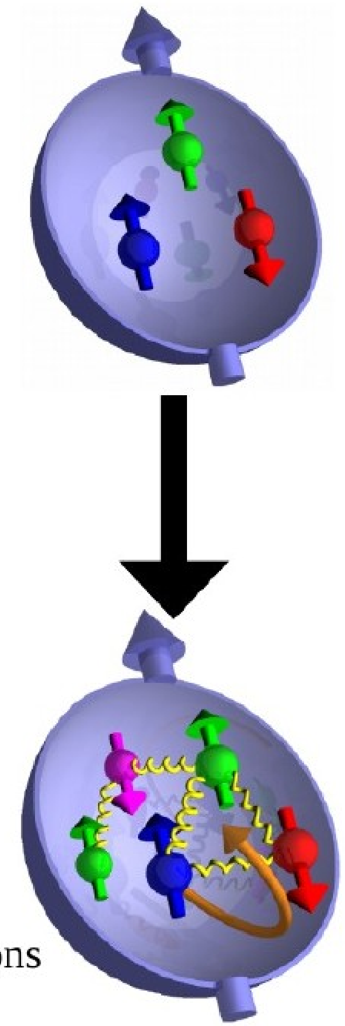
- Of the 4-5%, Higgs helps to understand 1% of this
- The mass generated by the Higgs mechanism is very far in value from the characteristic scale of strongly interacting matter
- Where is the rest of the Mass in hadrons
- Where is the rest of the Spin
- Valence quarks masses contribute only about 1% of the proton mass
- Valence quarks contribute 20-30% to the proton spin





Proton Spin Puzzle

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



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

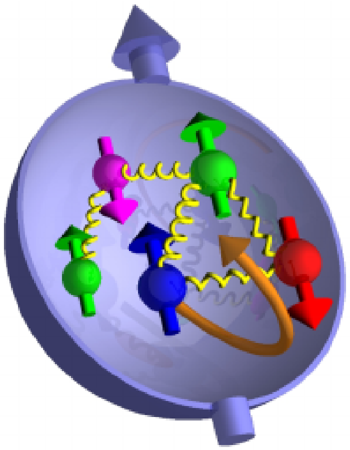
Quark Spin
(Including sea quarks)

Gluon Spin

Orbital Angular
Momentum Contributions

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

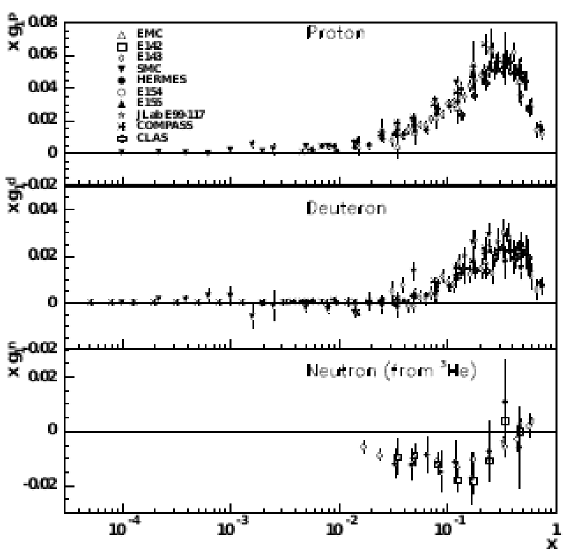
Nucleon Spin Puzzle



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

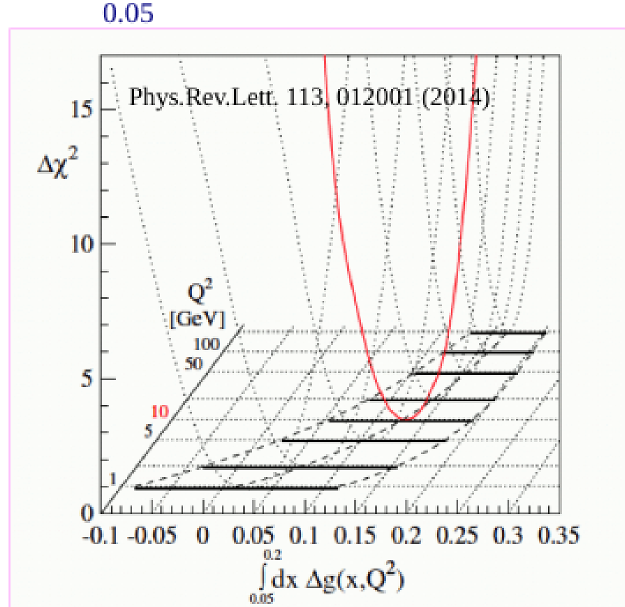
Quark contribution

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



Gluon contribution

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



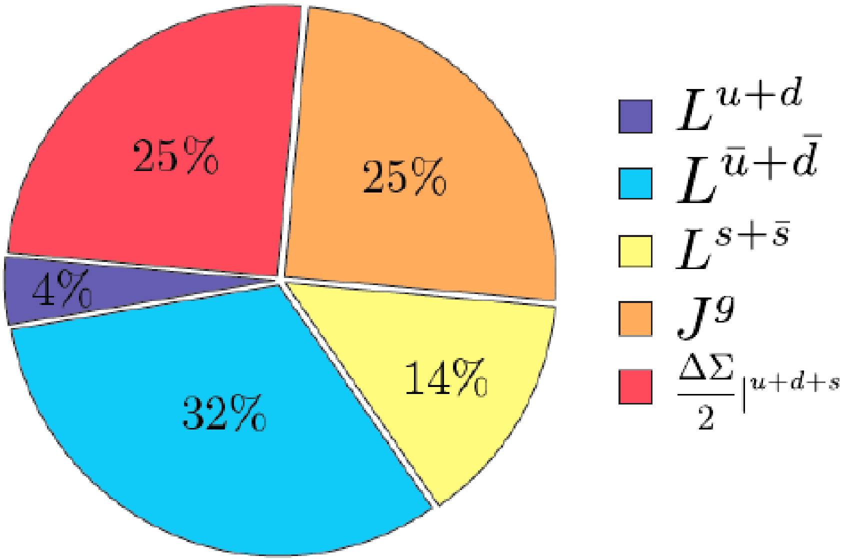
~50% Missing?

Where is the Missing Spin

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

- Lattice QCD calculations indicate as much as 50% come from quark orbital angular momentum (OAM)
- **$\Delta L_{valence}$ ≈ Small**
- *Sea Quark OAM remains largely unexplored*
- *Hints of sea quark OAM have been seen*

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



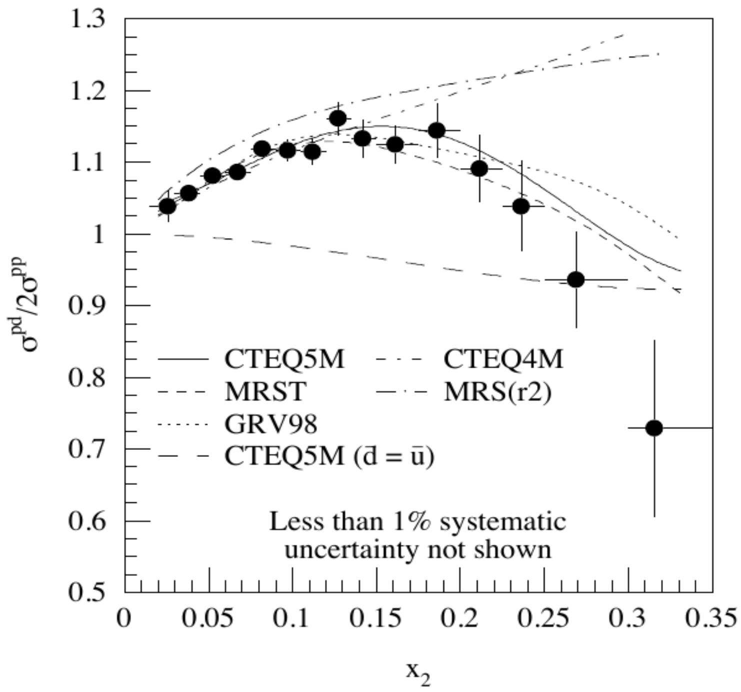
$\Delta\Sigma_q \approx 25\%$ $L_u \approx - L_d$

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

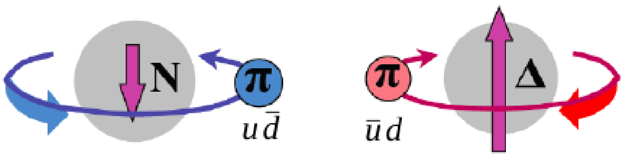
$2\ J_g \approx 25\%$

HERMES, COMPASS, Jlab: SIDIS

Hints of Non-zero Sea Quarks OAM



|p>=|p> + |N$^0\pi^+$>+ |$\Delta^{++}\pi^-$> +…



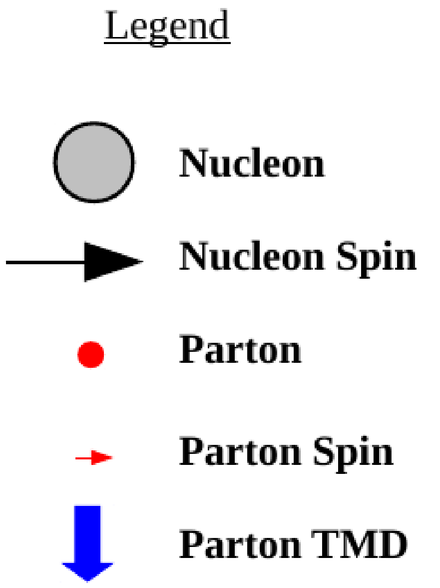
Pions: $J^p=0^-$ Negative Parity
Need **L=1**,3,... to recover proton's $J^p=½^+$

- Flavor asymmetry in sea quarks
- The pion cloud model
  - Simple parity conservation
  - **Pions have nonzero O.A.M.**

E866 Drell-Yan cross section ratio for deuterium verse hydrogen. The dashed line shows the ratio for a symmetric sea

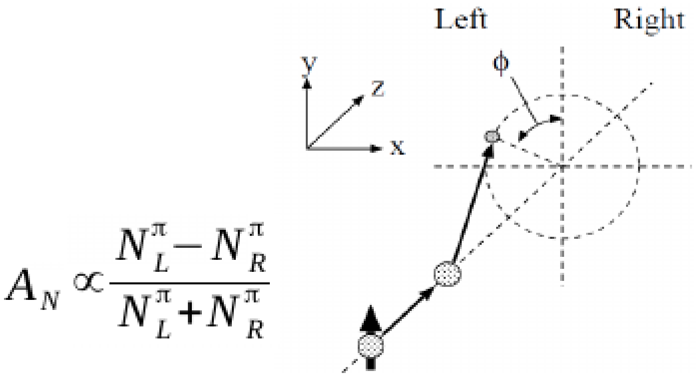
Eight Leading order TMDs

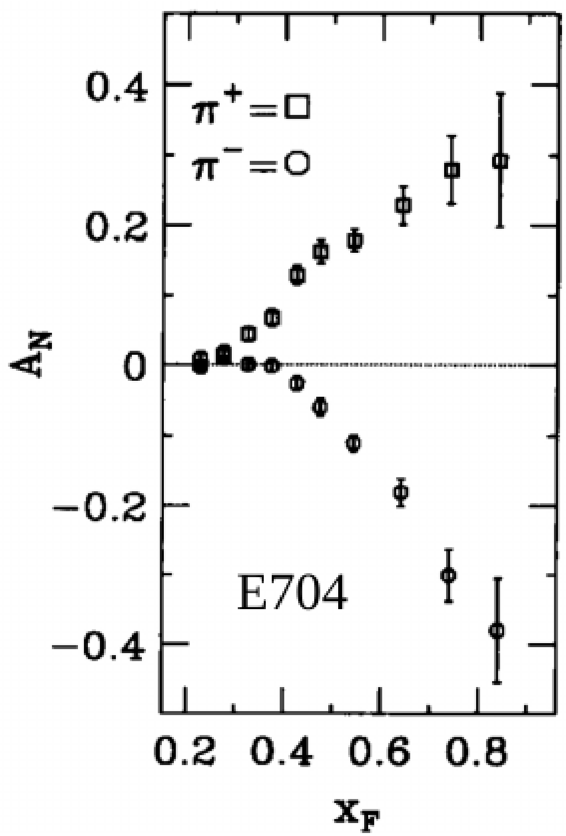
Nucleon \ Parton	U	L	T
U	Number Density $f_1(x)$		Boer-Mulders $h_1^{\perp}(x,k_T)$
L		Helicity $g_{1L}(x)$	Worm-Gear $h_{1L}^{\perp}(x,k_T)$
T	**Sivers** $f_{1T}^{\perp}(x,k_T)$	Worm-Gear $g_{1T}^{\perp}(x,k_T)$	Transversity $h_{1T}(x)$ Pretzelosity $h_{1T}^{\perp}(x,k_T)$



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

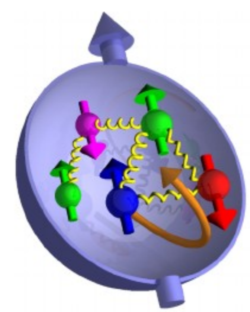
Transverse Momentum and The Sivers TMD

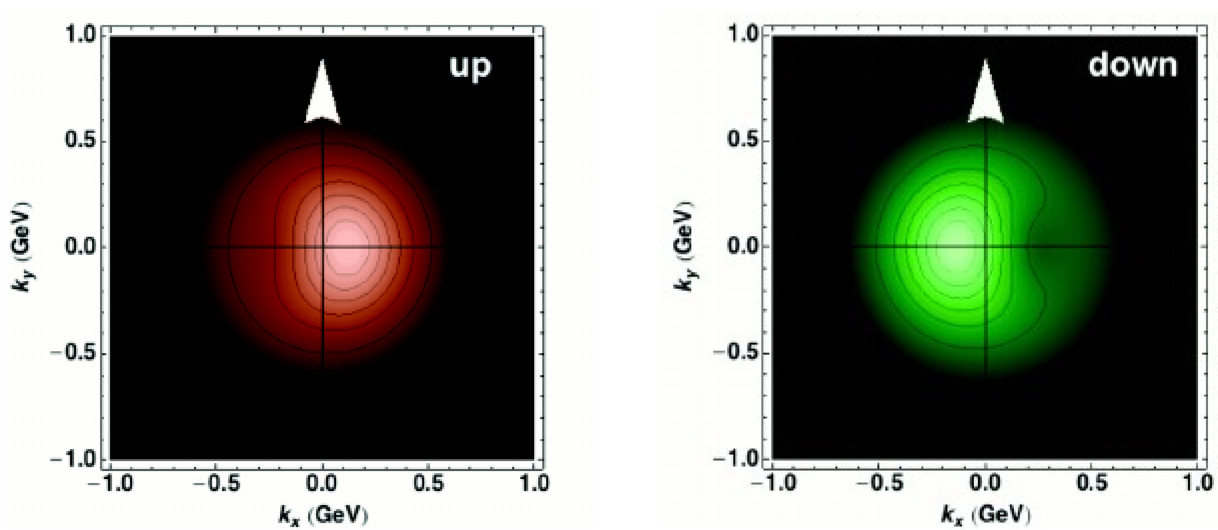




- The Sivers Function:
  - One of 8 TMD PDFs: $f_{1T}^{\perp}(x, k_T)$
  - Correlation between proton's transverse spin and transverse parton momentum

- Quark Sivers Function
  - Polarized SIDID
  - Polarized Drell-Yan

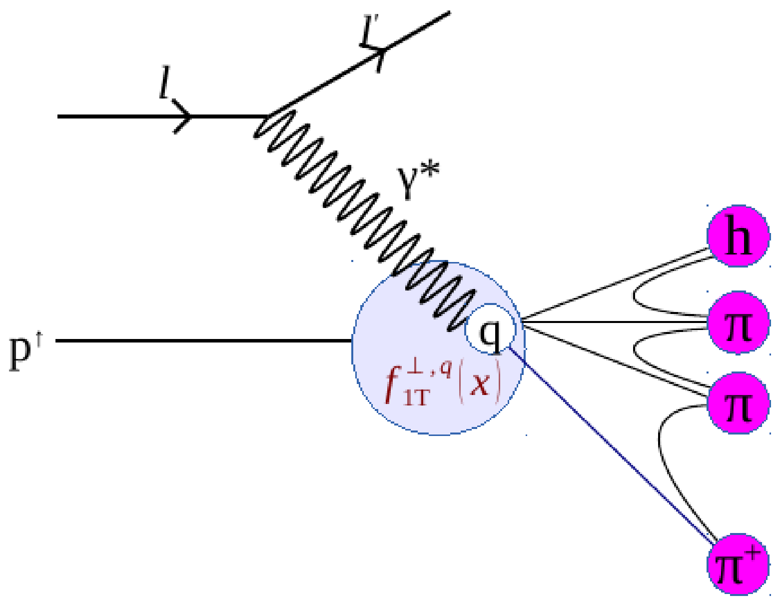




A. Bacchetta and M. Contalbrigo Il Nuovo Saggiatore, vol. 28, pp. 16–27, 2012

Accessing Quark Sivers TMDs

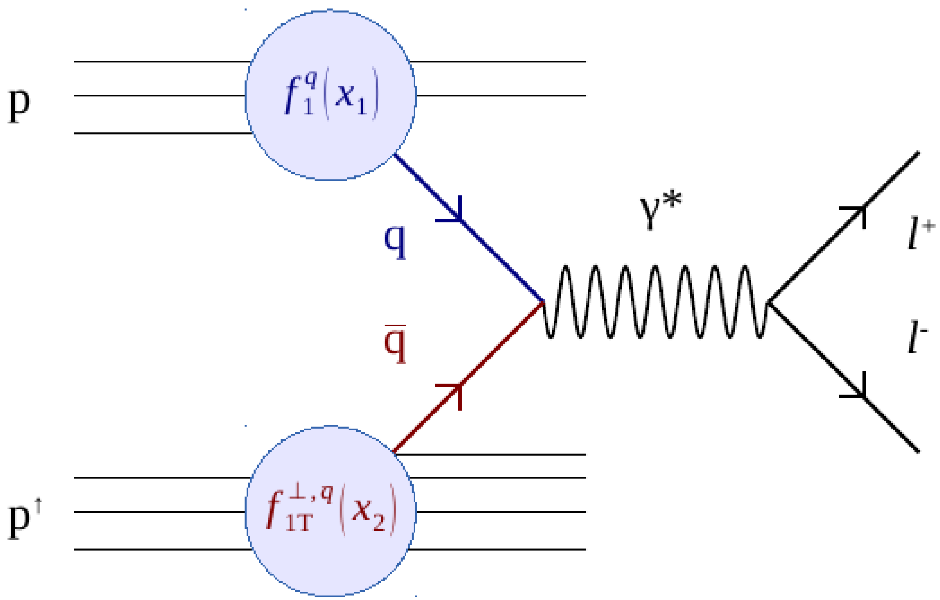
Polarized Semi-Inclusive DIS



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

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

Polarized Drell-Yan

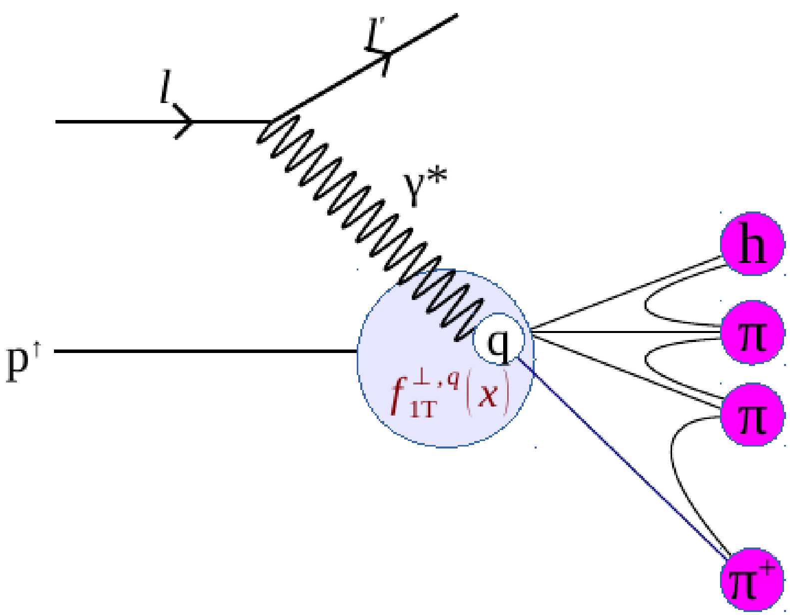


$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

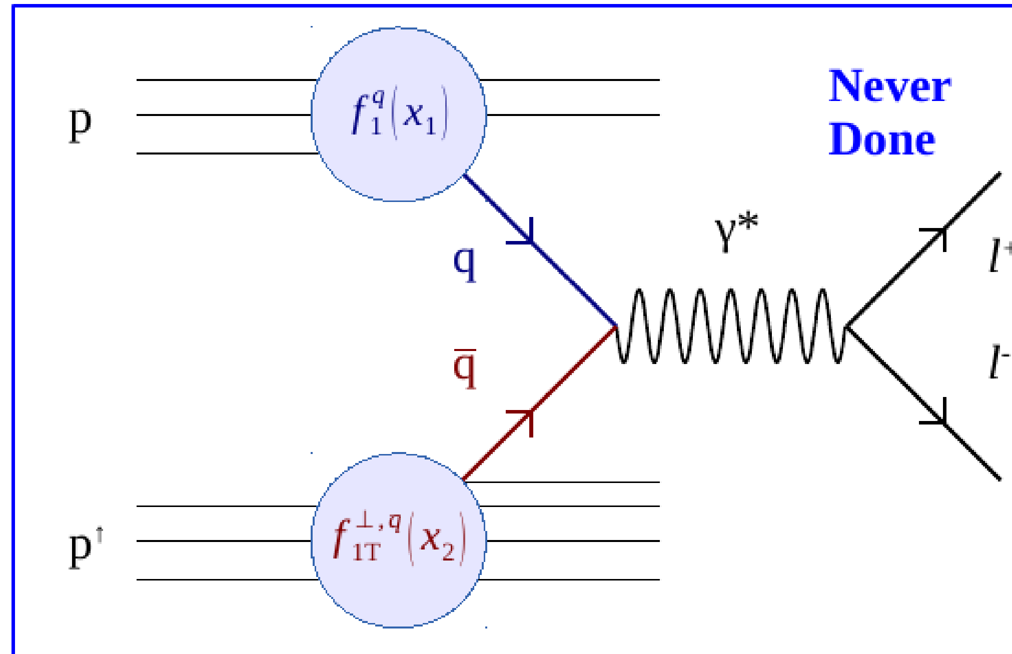
- L-R asymmetry in Drell-yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated**

Accessing Quark Sivers TMDs

Polarized Semi-Inclusive DIS



Polarized Drell-Yan



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

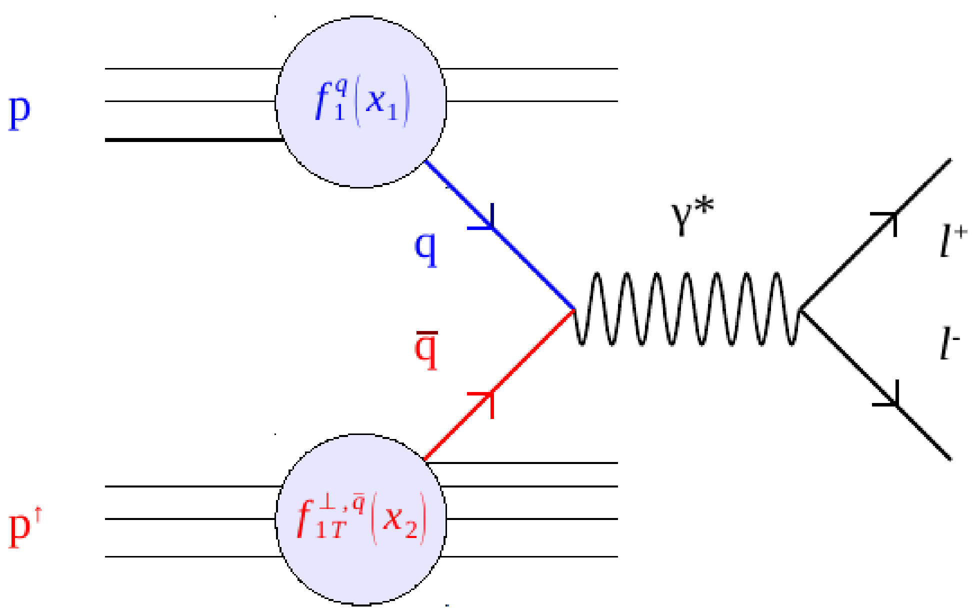
- **Cornerstone Prediction of QCD**
  - The same Sivers distribution in both processes
  - But with opposite sign
    - T-Odd
    - Initial state, Final state switch

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

Accessing Sea Quarks Sivers TMDs

- Quark Sivers TMD directly accessible using Polarized SIDIS, **Polarized Drell-Yan**

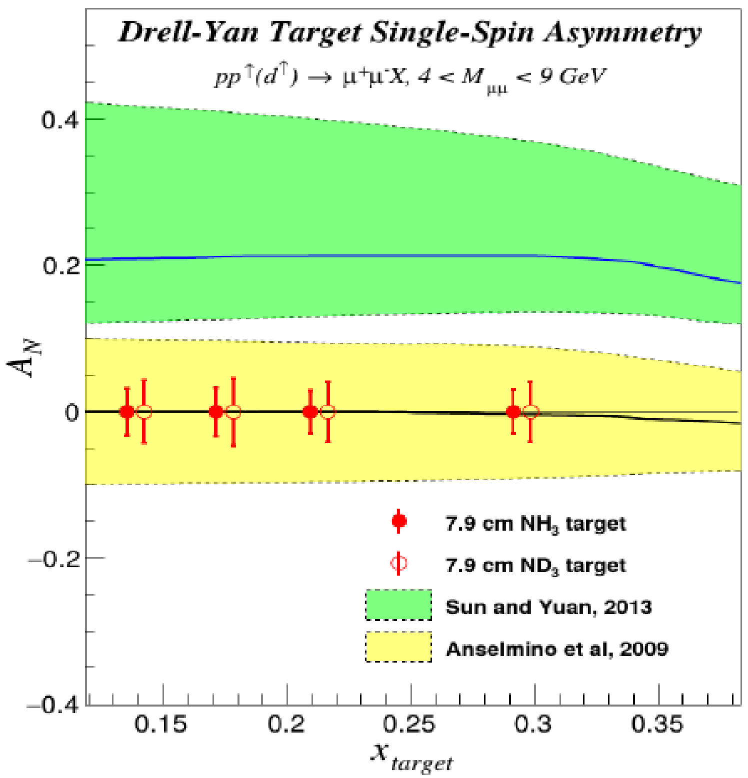
Polarized Drell-Yan

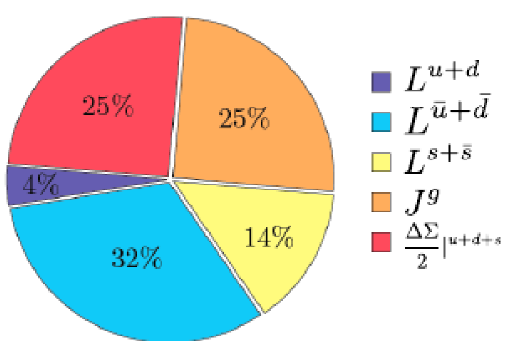


$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}$$

- L-R single spin asymmetry in Drell-Yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated.**

The Measurement



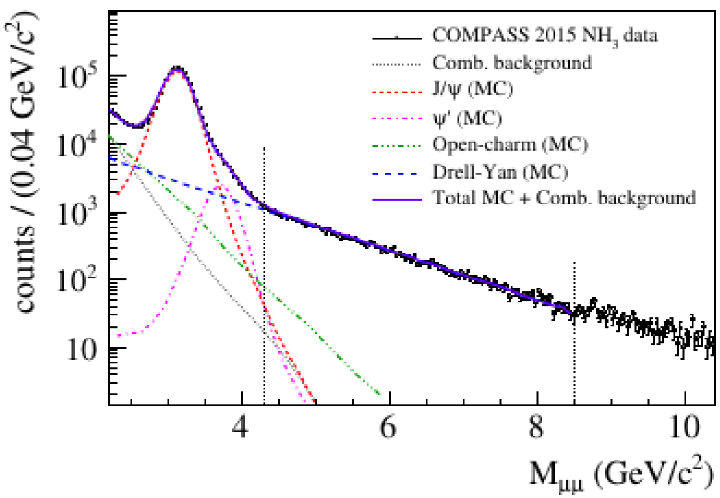


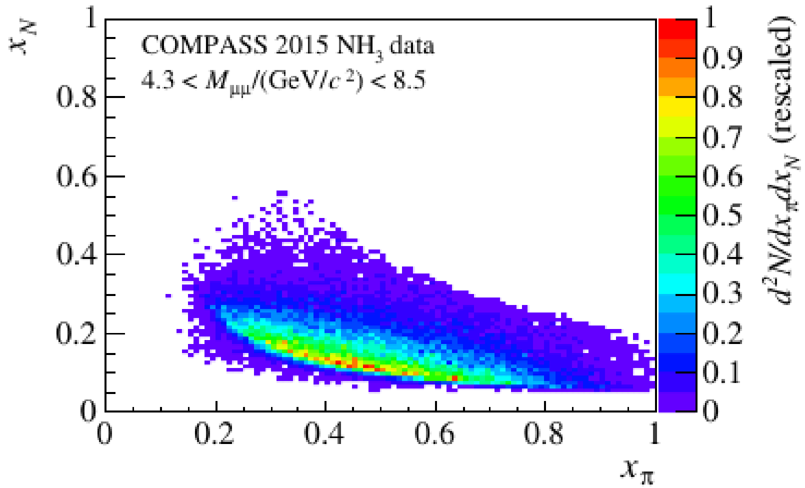
$$A_N\left(p_{beam} + p^{\uparrow}_{target} \rightarrow DY\right) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

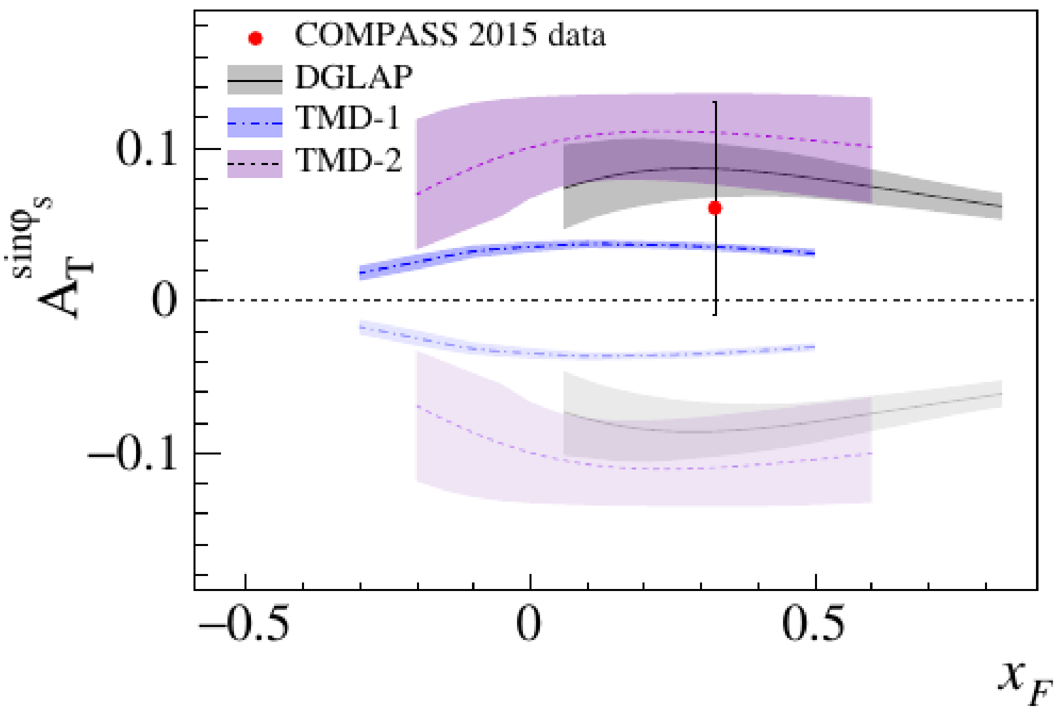
$$A_N\left(p_{beam} + d^{\uparrow}_{target} \rightarrow DY\right) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{d}}(x_t)}{f_1^{\bar{d}}(x_t)}$$

- First measurement of sea quark Sivers ($\bar{u}$, $\bar{d}$)
- Sign and value
  - Result has strong implications for O.A.M. in spin puzzle
- If nonzero, “smoking gun” for Sea quark O.A.M.
- If zero, where is proton spin coming from?

Compass Results







Fits to COMPASS, HERMES, Jlab SIDIS model predictions for different Q^2 evolution predictions

Other Physics

- Sea Quark Sivers
- Transversity
- Gluon Sivers
- J/psi TSSA
- Heavy Photon and Dark Higgs

Proton Beam at FNAL

- 120 GeV proton beam
- √s = 15.5 GeV
- Projected Beam for E1039
  - Beam: 5×10^{12} p/spill; spill is 5 s/min
  - Protons on target per year
    - 9.7×10^{17}

Advantage of the Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^1H, ^2H, and nuclear targets
- 800 GeV proton beam

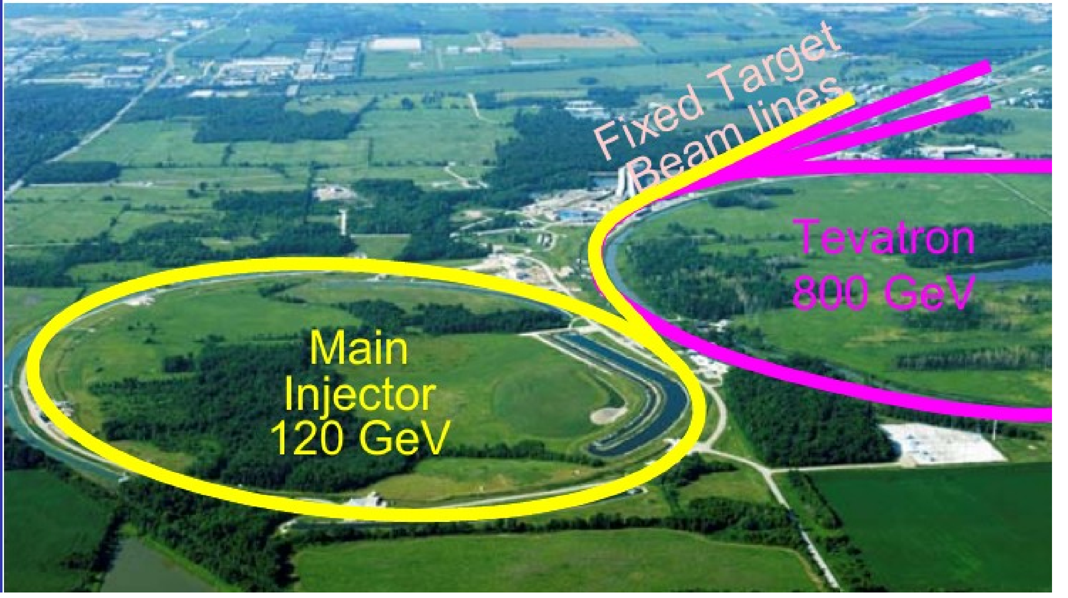
Fermilab E906

- Data in 2010
- ^1H, ^2H, and nuclear targets
- 120 GeV proton Beam

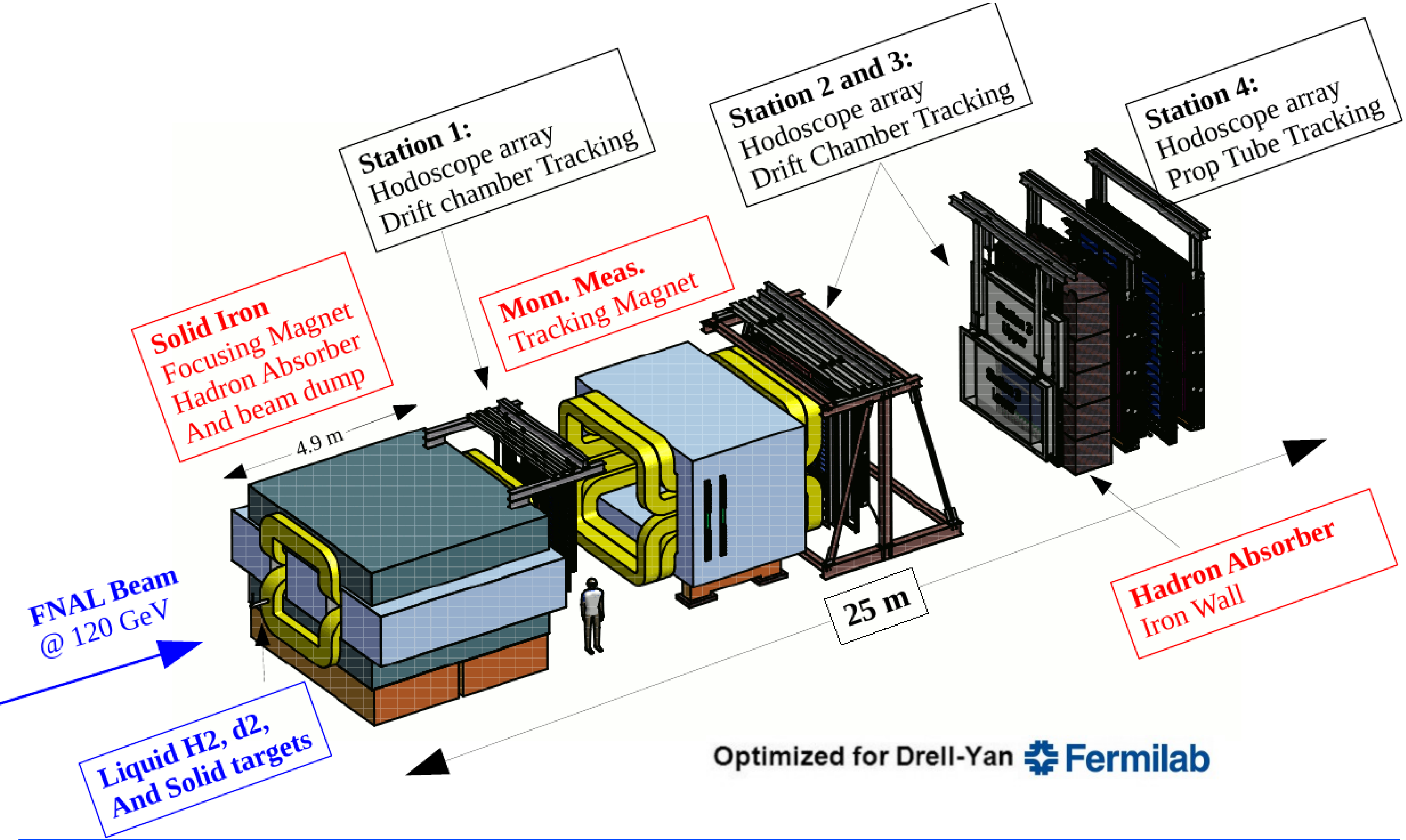
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- Cross section scales as 1/s
  - *7× that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7× Luminosity for same detector rate as 800 GeV beam*

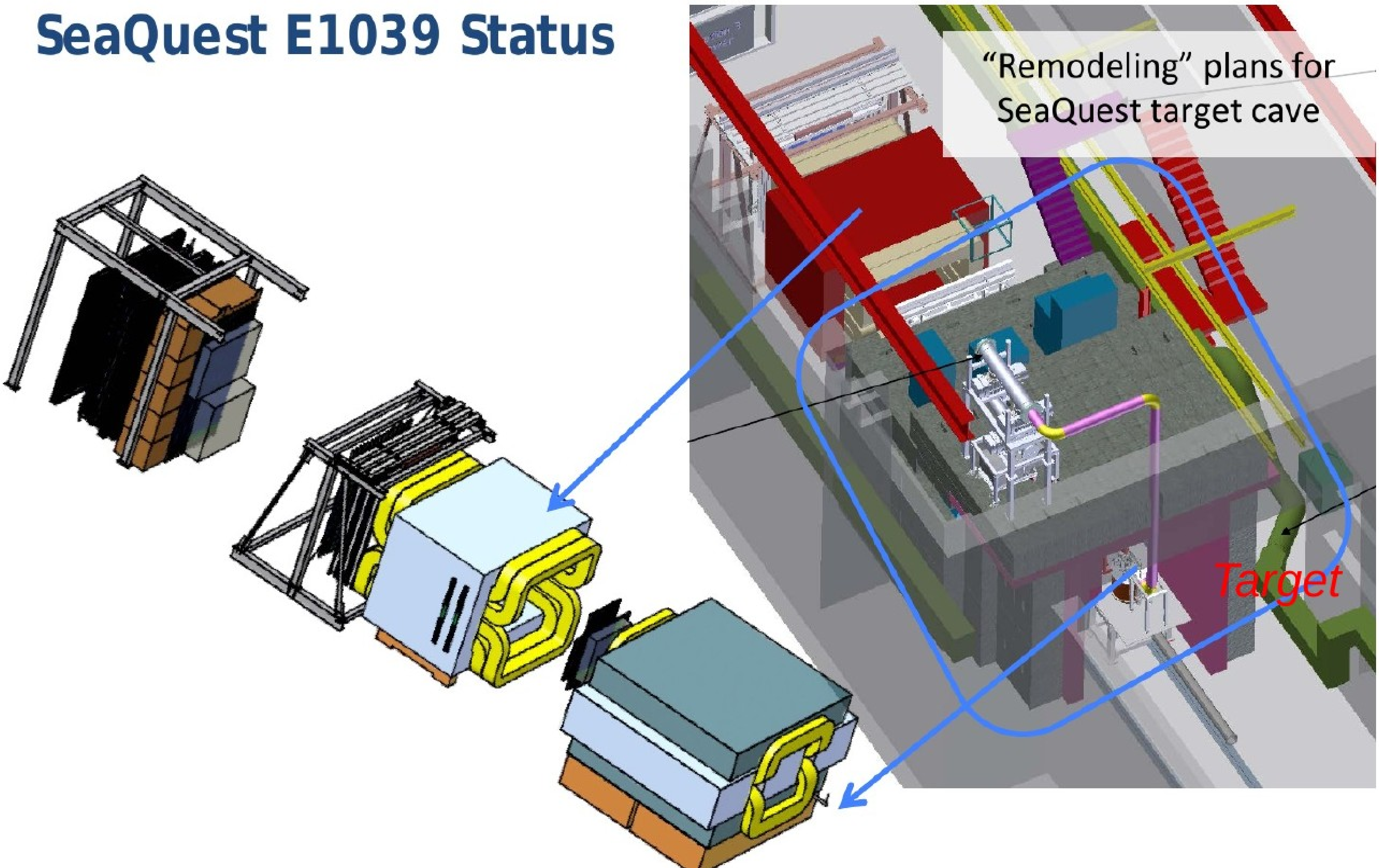
50× statistics!!



Muon ID at SpinQuest



Experimental Setup



Firsts for Polarized Targets

UVA-LANL: Three completely new NMRs

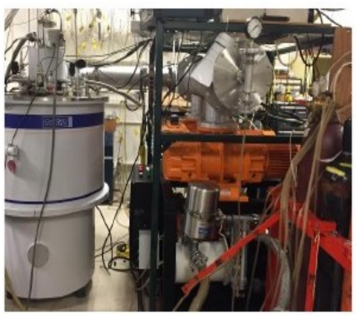
NMR

UVA: Design

Insert

Microwave

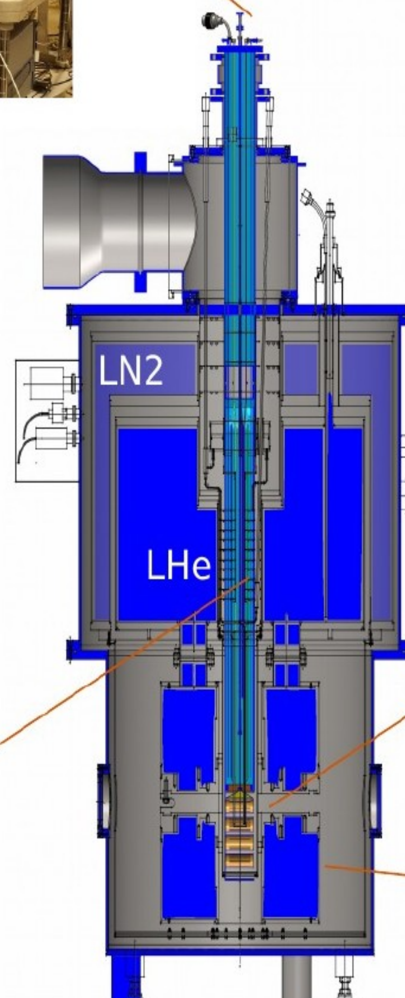
UVA: Tune System and Automation



Pumps

oerlikon

14,000 providing the highest cooling power for 1K system



Target material

UVA: Target Insert with longest cell at 8 cm for 5T

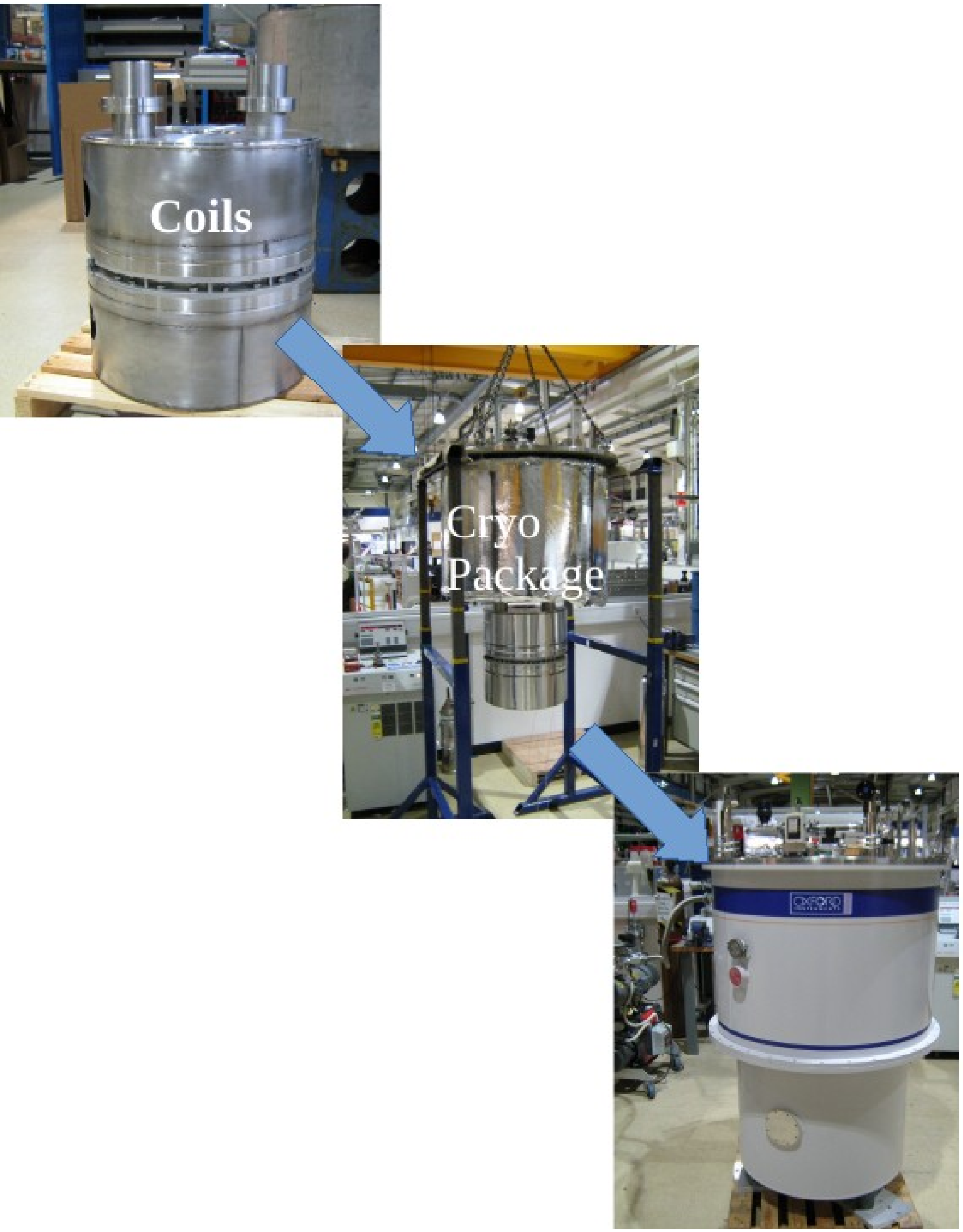
Fridge

UVA: Configure Fridge and Insert, Commission for Optimal running, setup with Actuator

Magnet

UVA: Commisioning, Slow Controls, Quench Study, Beamline interface,...

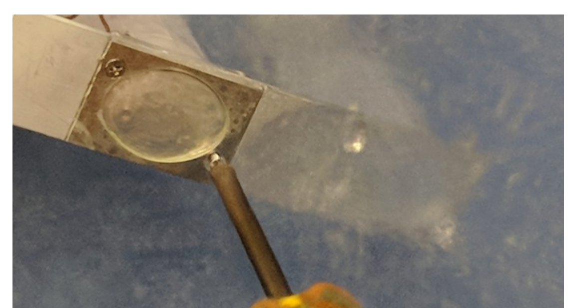
Polarized Target for E1039



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

JLab Target

Fermilab Target



Polarized Target on Intensity Frontier

Highest Intensity proton beam on polarized target with $4x10^{12}$ per 4s spill

- 8 cm long target cell of solid:

  NH_3 and ND_3

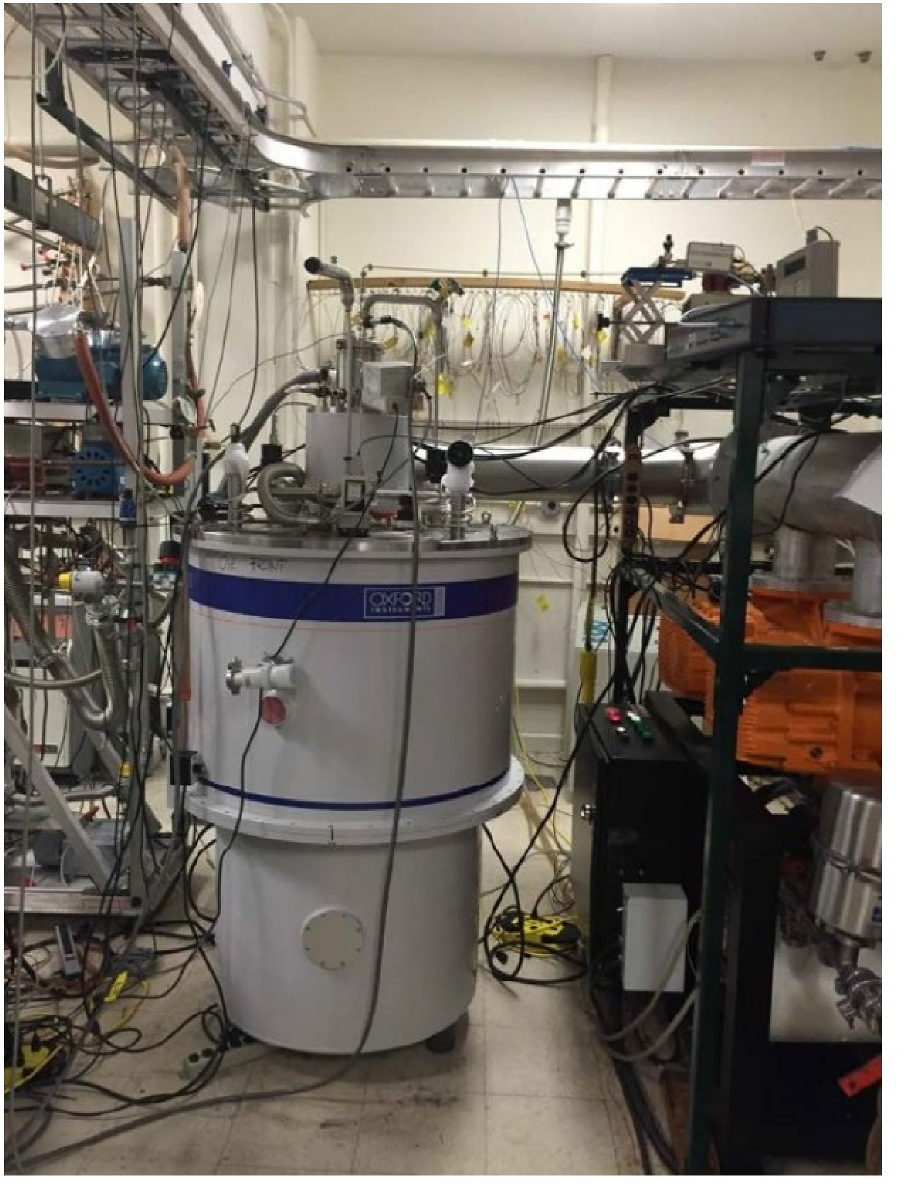
- 2 watts of cooling power:

  14,000 m^3 /hour pumping

- 5T vertically pointing SC magnet:

  Pushing critical temp each spill

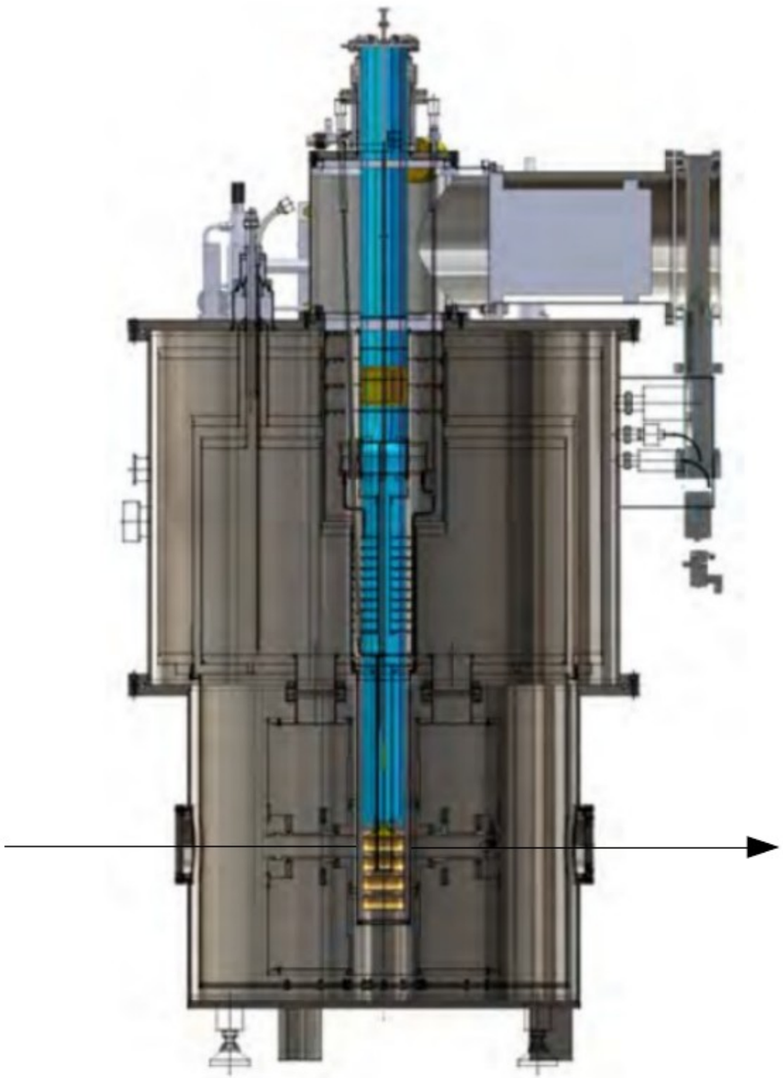
- Luminosity of around $2X10^{35}$ cm^{-2} s^{-1}



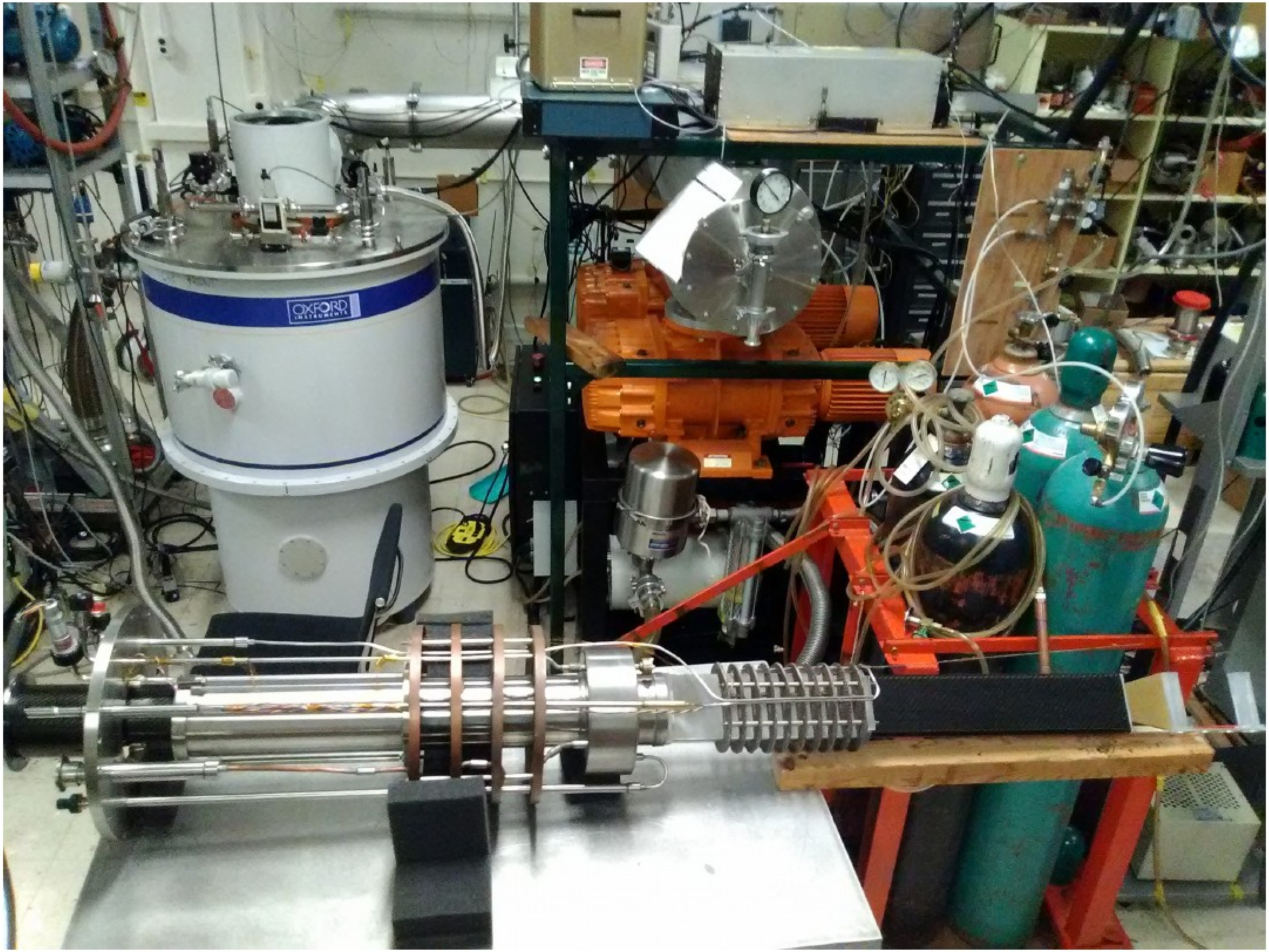
Some Challenges

- SC Magnet quench threshold (limits beam intensity)
- Target microwave uniformity (distribution and power)
- Uniformity of dose in the z-direction
- Liquefier and preservation of LHe
- Polarization measurements of long target cell
- New physics process: dilution factor (systematics)
- Radiation level of target and supporting systems
- Larger than 10^3 mSv/hr in cave and 10^4 mSv/hr in magnet

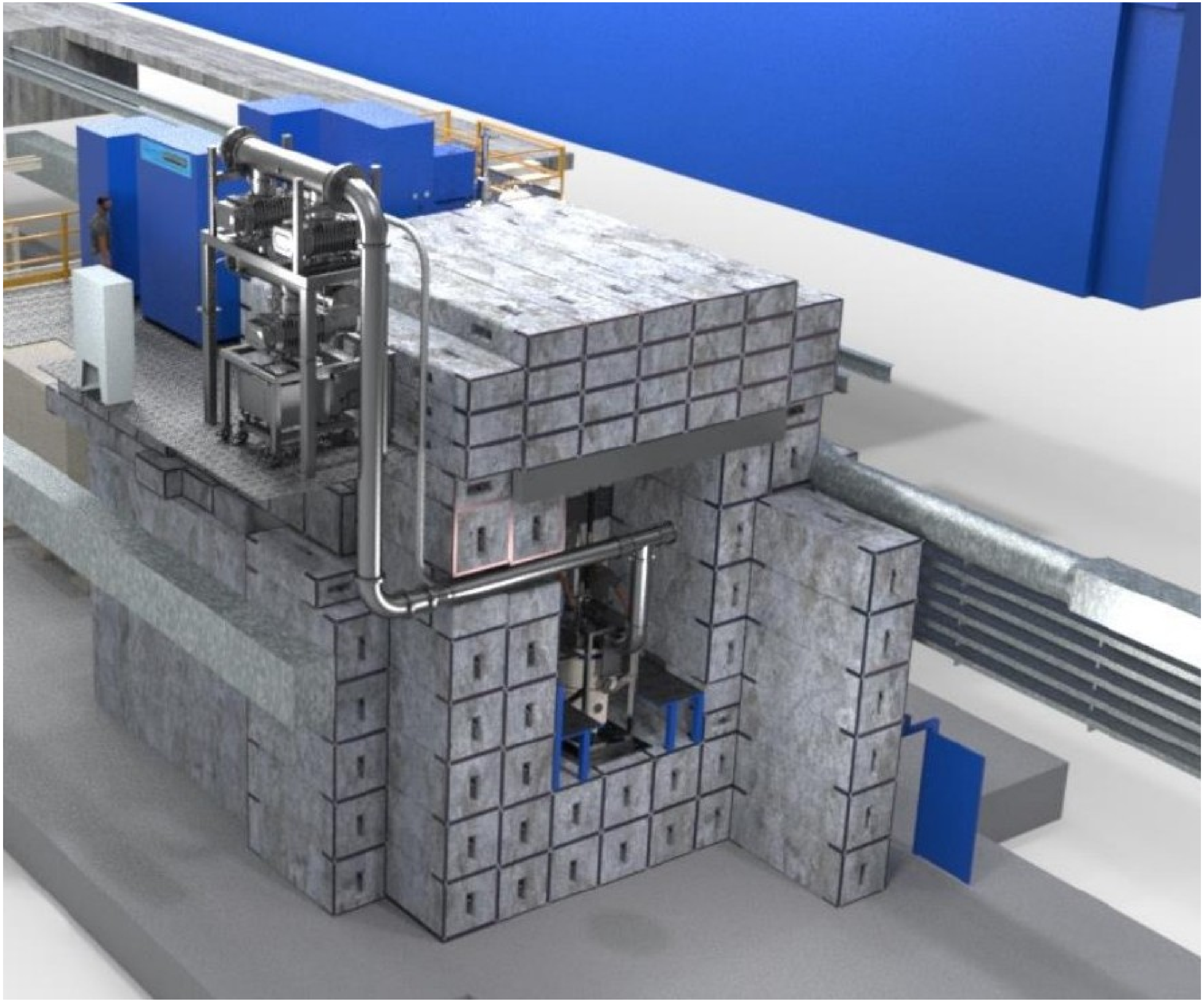
Polarized Target on Intensity Frontier



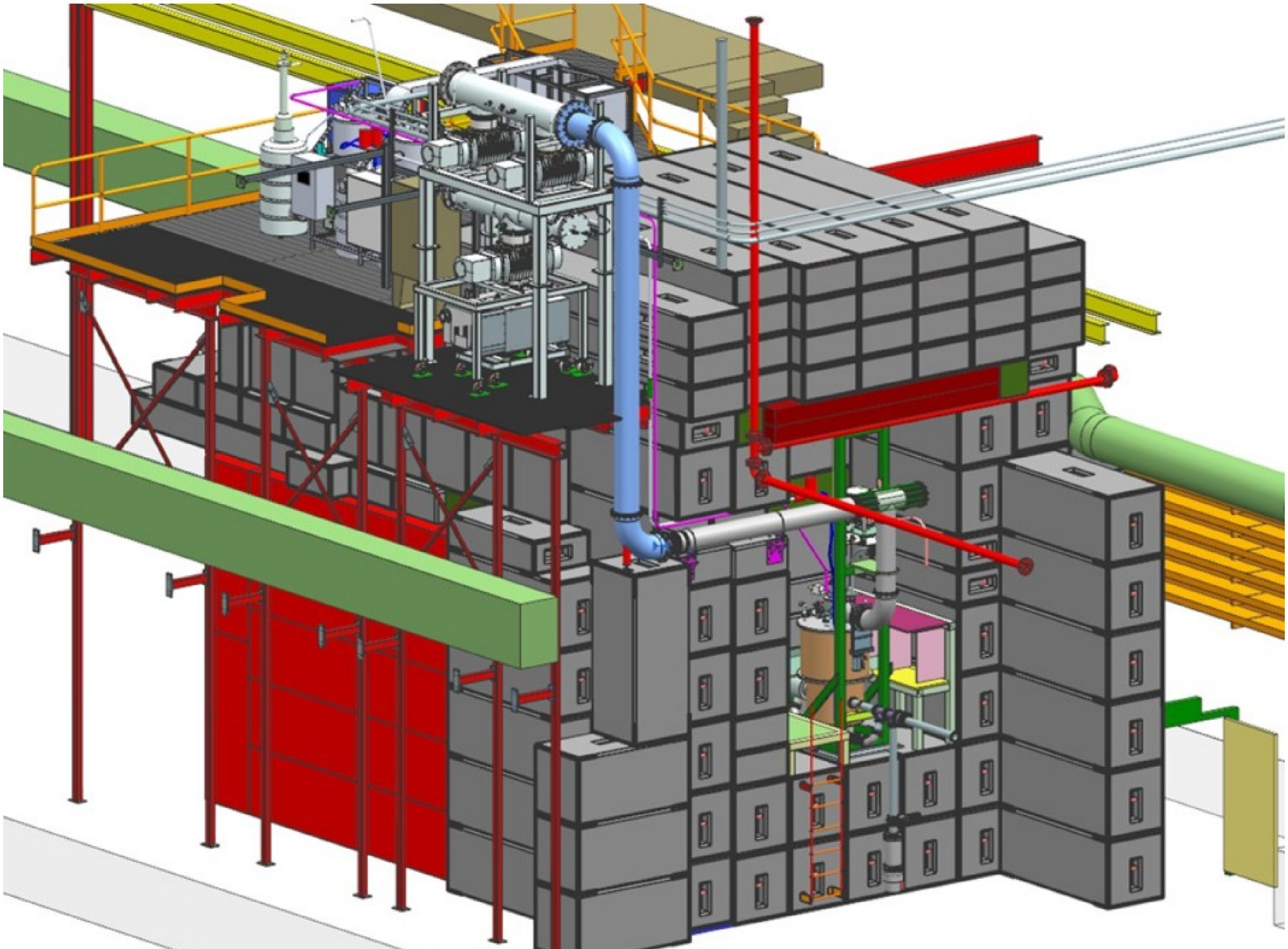
Target System



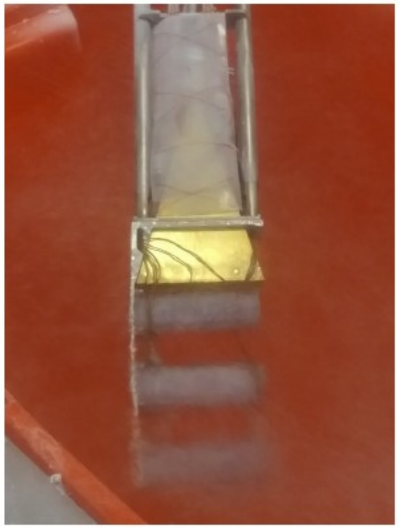
Mock-up Target Cave



Mock-up Target Cave

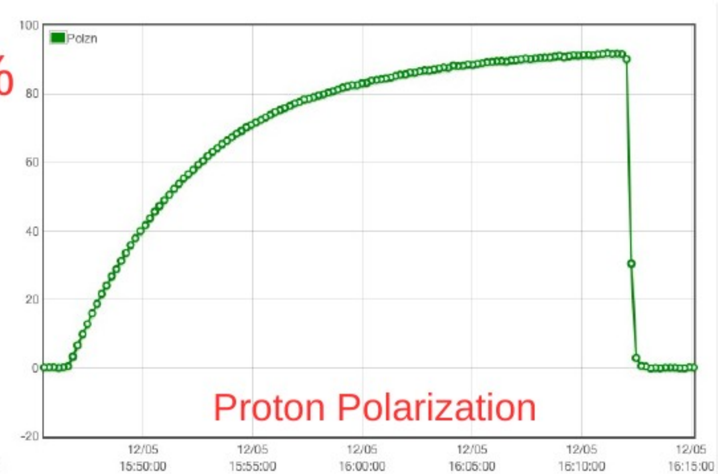


Target Performance



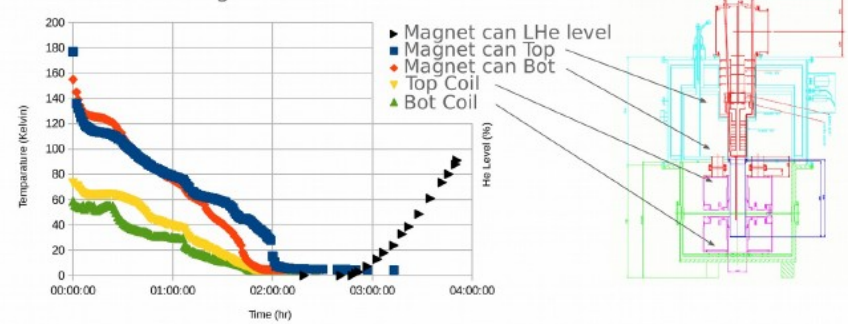
Insert in LN2

95%



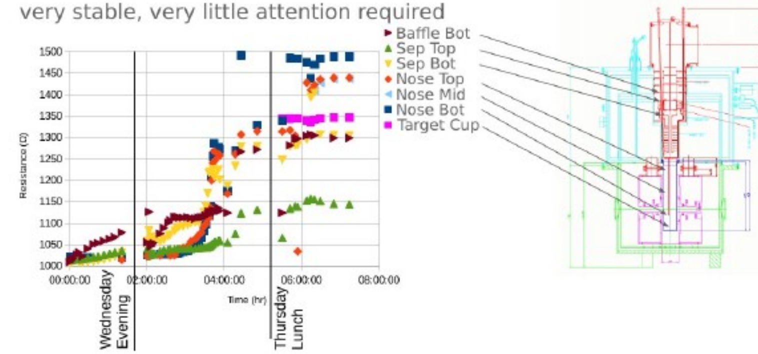
~2.5

~1 hr to to fill magnet can



~1hr to fill the nose after a night on standby

very stable, very little attention required



FNAL Summary

- **First measurement of Sivers asymmetry for light sea quarks**
  - Flavor dependence of ubar, dbar
- **Sign and Magnitude of 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**

Big Commitment

- Spokesperson
- SpinQuest Collaboration Chair
- Target Team Leader

Join The Effort

http://twist.phys.virginia.edu/E1039/

SPINQuest

Send mail to: dustin@jlab.org

A Good time to join the collaboration, experiment receives Nuclear and HEP funding, so everyone in Spin physics is welcome and there is still lots of work to go

Fermilab

Thank You