

# Some Developments on Polarized Targets for Nuclear Experiments

Dustin Keller

November 19, 2014



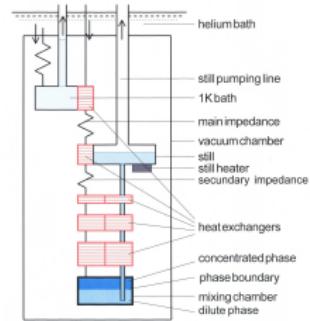
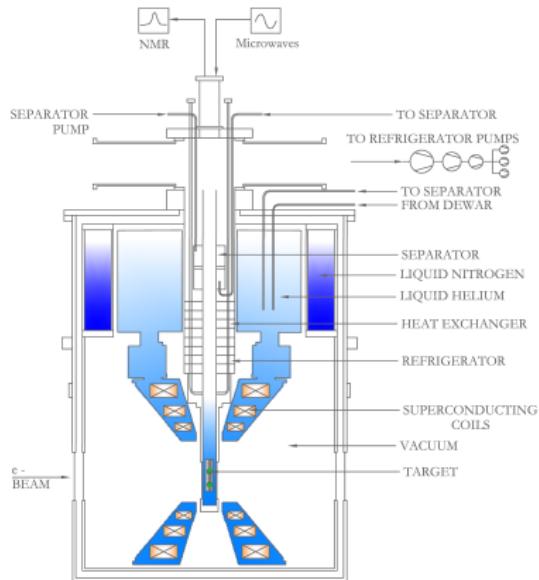
# Outline

① Introduction

② SPIN-2014

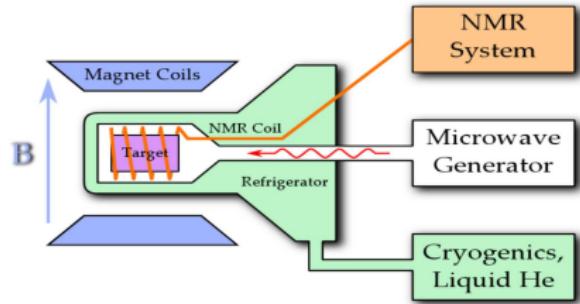
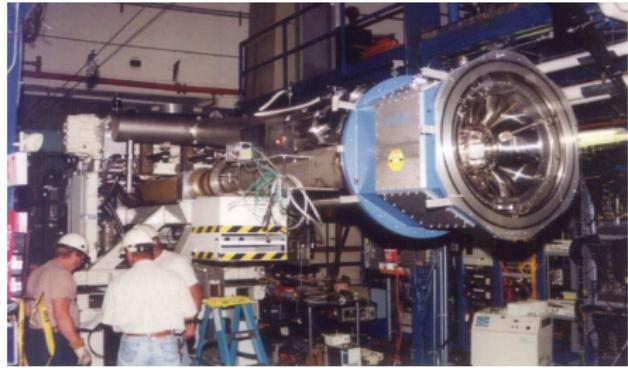
③ Solid Polarized Target Research

# Solid Polarized Target Systems



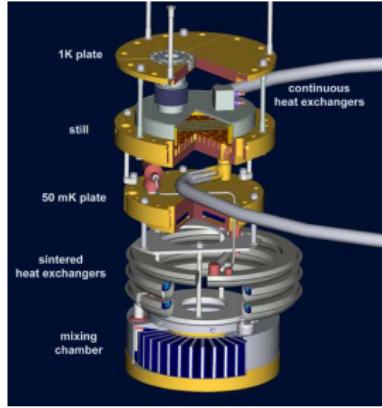
- (A)  $e^- \sim 1 \text{ nA}$ ,  $\gamma$
- (B) High Luminosity
- (C) Dilution factor  $f < 15\%$
- (D) Cryogenic System down to 30 mK
  
- (A)  $\sim 100 \text{ nA}$
- (B)  $10^{35} \text{ cm}^{-2} \text{s}^{-1}$
- (C) Dilution factor  $f < 25\%$
- (D) Cryogenic System 1.5 K

# $^4\text{He}$ Evaporation System



- Operate at 5 T
- Used with up to 100 nA
- Large Capacity pumps
- Polarizations: p~90%, d~50%

# Dilution Refrigerator



- Uses  $^3\text{He}$ - $^4\text{He}$  mixture
- Operate at 0.5 T
- Continuous/Frozen Spin mode
- Polarizations: p~95%, d~80%

# SPIN 2014

OCTOBER 20-24, 2014. PEKING UNIVERSITY, BEIJING, CHINA



The 21st International Spin Physics Symposium

- Accelerator, Storage and Polarimetry of Polarized Beams
- Applications of Spin Physics
- Fundamental Symmetries and Physics Beyond the Standard Model
- Future Facilities and Experiments
- Nucleon Structure
- Polarized Ion and Lepton Sources and Targets
- Spin Physics in Nuclear Reactions and Nuclei
- Spin Physics with Photon, Lepton and Hadron Beams
- Spin Structure of Hadrons

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B. Mihailov - University of North Carolina  
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S. Acharya - IISI  
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L. Csernai - University of Michigan  
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A. Pachucki - Warsaw  
A. Mukha - University of Alberta  
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M. Prokter - UoB  
P. Pivovaroff - University of Alberta  
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[www.phy.pku.edu.cn/spin2014/](http://www.phy.pku.edu.cn/spin2014/)



Peking University, Beijing China

<http://www.phy.pku.edu.cn/spin2014/proc.html>

12 sessions

<http://www.phy.pku.edu.cn/spin2014/proc.html>

All spin phenomena

# Spin Physics with Frozen Spin Target at Mainz

*Talk by Andreas Thomas*



DNP at 200mK and 2.5T with 70GHz microwaves.  
Frozen spin target (25mKelvin, 0.6T).  
Secondary particles punch through holding coil.  
Longitudinal and transverse holding coils.

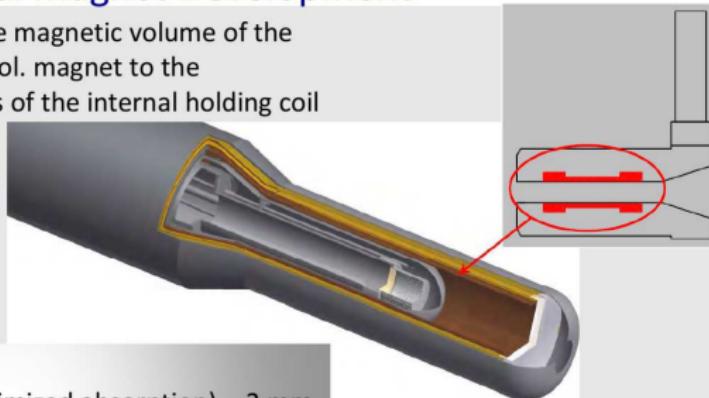
$P_{\text{proton}} \sim 85\%$   
 $P_{\text{deuteron}} \sim 75\%$   
 $\tau \sim 1000 \dots 2000 \text{ hours}$

# Spin Physics with Frozen Spin Target at Mainz

Talk by A. Thomas

## Internal Magnet Development

Idea: reduce the magnetic volume of the large external pol. magnet to the size/dimensions of the internal holding coil



- field strength: ~ 2.5 T
- as thin as possible (minimized absorption) ~ 2 mm
- homogeneity  $\Delta B/B \leq 10^{-3}$

$$B = \mu_0 \cdot N \cdot \frac{I}{l}$$

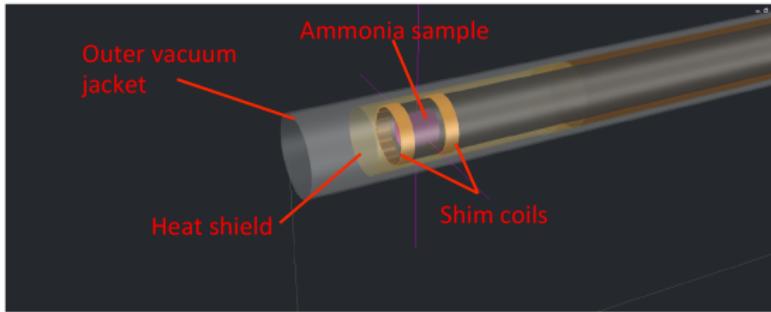
NC: ampere-turn :  $N \cdot I \sim 300 \text{ kA} \rightarrow$  superconducting wire necessary  
High current operation (~100 A) in a dilution refrigerator

# Longitudinally Polarized Target for CLAS12

Talk by Chris Keith, JLab

Polarized EMC

We intend to use internal superconducting *shim* coils to ensure  
T polarizing magnet (i.e. the CLAS12 solenoid) has  $\Delta B/B \leq 10^{-4}$

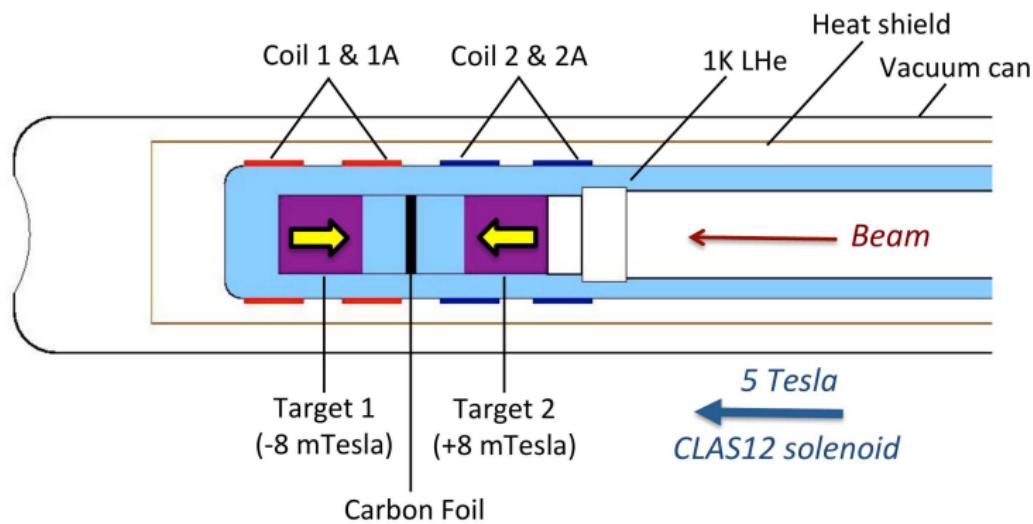


Conceptual design of superconducting shim coils  
for CLAS12 polarized target

# Longitudinally Polarized Target for CLAS12

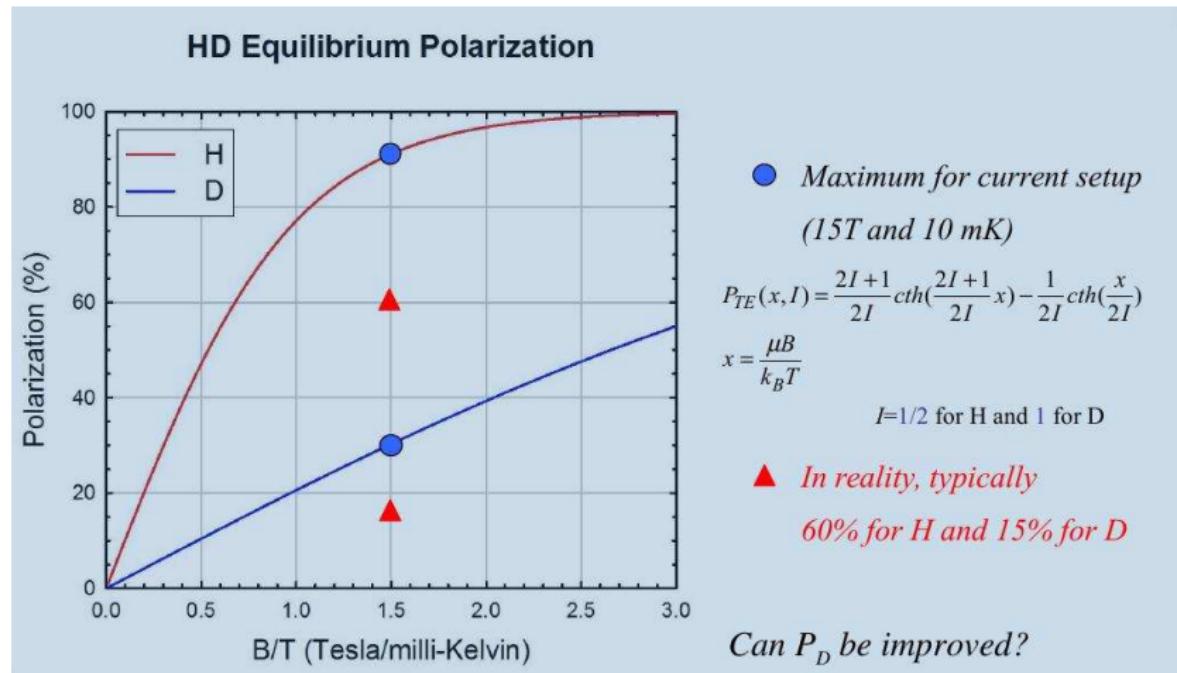
Talk by C. Keith, JLab

We also hope to use internal superconducting shim coils to adjust the polarizing field for multiple target samples, allowing independent polarizations with one microwave source



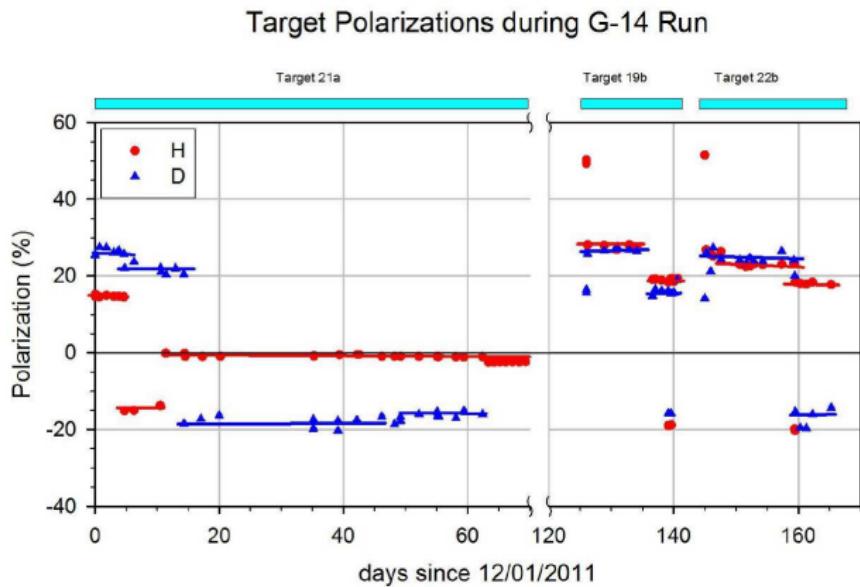
# Solid HDice Targets

Talk by Xiangdong Wei, JLab



# Solid HDice Targets

Talk by X. Wei, JLab



HDice targets used in frozen spin mode during E06-101 (G-14) photon run.

Relaxation times were longer than a year at  $B=0.9\text{T}$  and  $T<100\text{mK}$ .

# Boosting Deuteron Polarization in HD targets

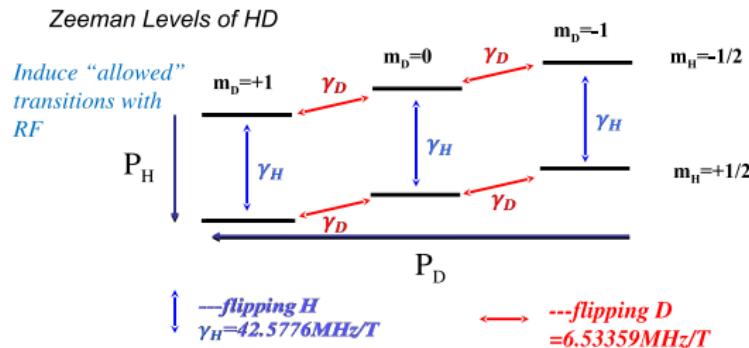
Talk by X. Wei, JLab



## Spin Manipulation Methods

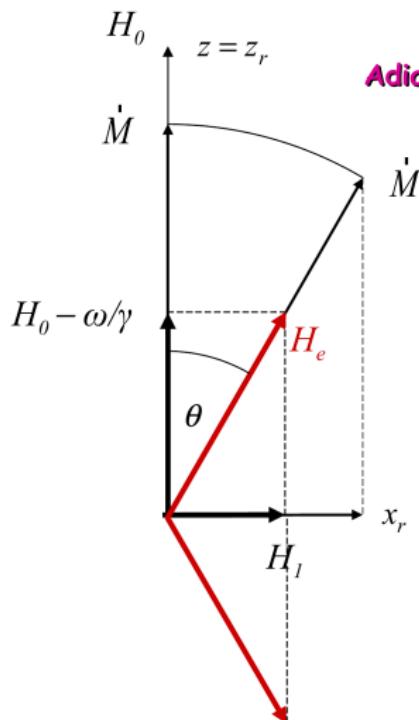
Adiabatically flipping spins of H or D with RF

- Nearly 100% efficiency for H and 70% for D so far.
  - Could be improved: uniformed RF field, stable power supply...
- Moderate RF power required (~10mW with non-tuned coils).
- Can be used with higher holding field.



- Adiabatically rotating magnetic field direction
- RF AFP

# Adiabatic Fast Passage at 1 K



**Adiabatic:**  $\frac{dH}{dt} = \gamma H_1^2$

**Fast** (faster than relaxation):  $\frac{1}{\tau} = |\gamma H_1|$

External field  $\dot{\vec{H}}$  contains **rf field**

static field:  $H_z = H_0$       rf field:  $H_x = 2H_1 \cos(\omega t)$

$$\dot{\vec{H}} = H_0 \hat{z} + H_1 \cos(\omega t) \hat{x} + H_1 \sin(\omega t) \hat{y}$$

**rotating frame**



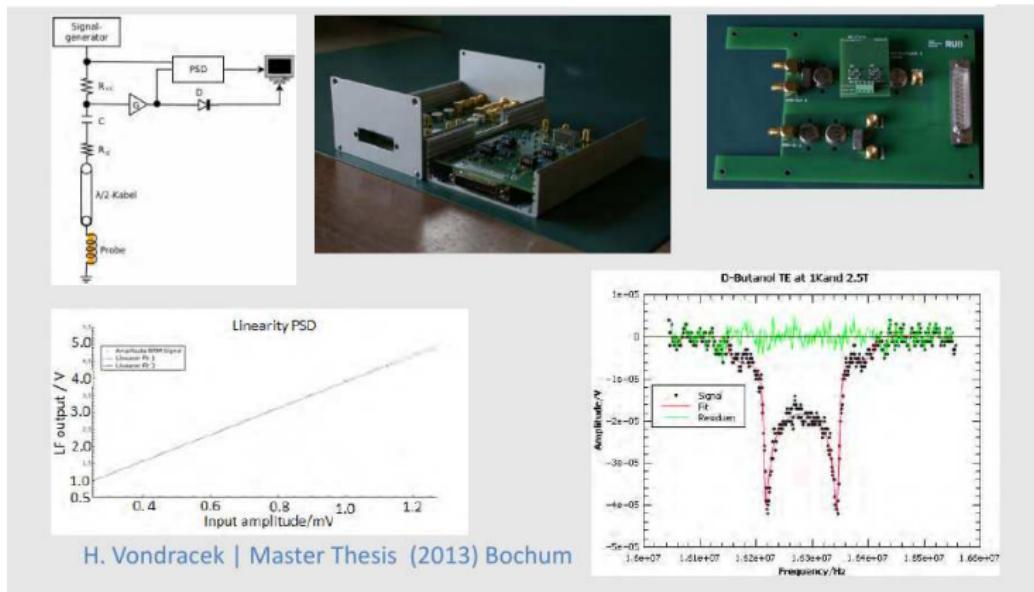
$$\vec{H}_e = (H_0 - \frac{\omega}{\gamma}) \hat{z}_r + H_1 \hat{x}_r \quad \tan \theta = \frac{H_1}{H_0 - (\omega/\gamma)} = \frac{\omega_1}{\omega_0 - \omega}$$

Larmor frequency:  $\omega_0 = \gamma H_0$

For any vector  $\vec{\mu}$  satisfying a similar equation of motion the angle between  $\vec{\mu}$  and  $\vec{H}$  remains constant provided the change of direction of  $\vec{H}$  in time is sufficiently slow

# Recent Developments at Bochum/Bonn

*Talk by Gerhard Reicherz, Bochum*

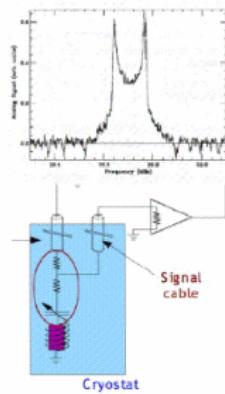
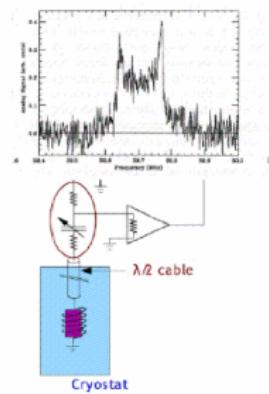
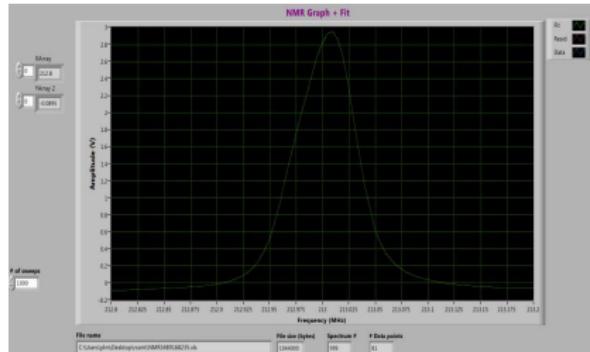


H. Vondracek | Master Thesis (2013) Bochum

# Recent Developments at LANL/UVA

## Modernized CW NMR system

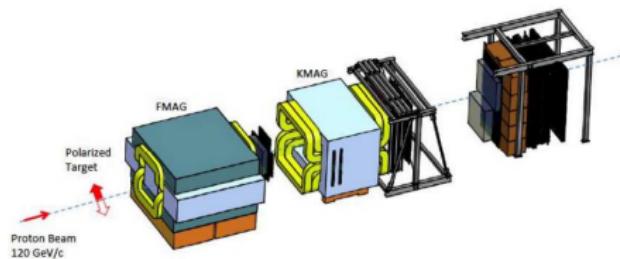
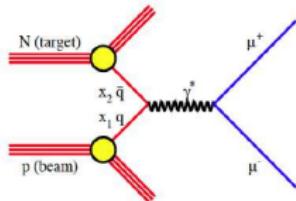
### LANL\UVA NMR Test



Cold NMR (Electrical Temp Dep.)

# Polarized Drell-Yan

Talk by Ming X. Liu, LANL

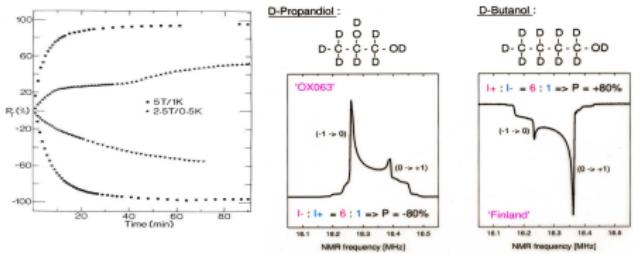
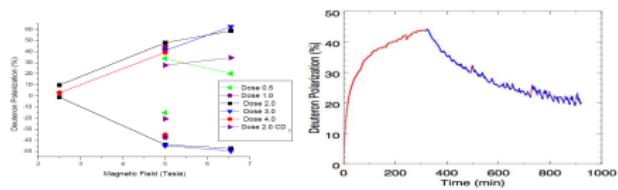


- (A) UVA cooldown magnet test
- (B) Oxford coil modification
- (C) UVA fridge modification
- (D) UVA target design

# University Virginia Solid Polarized Target

- Hardware Development and Improvements
- Radiation and Polarization Characteristics
- Measurement of Tensor Enhanced Target
- Development of Tensor Enhanced Target
- Dilution Reduction

# Material Performance



## Radiation Resistant Materials

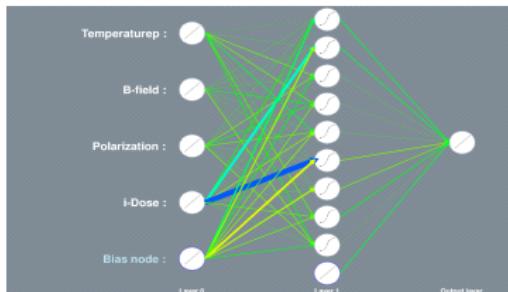
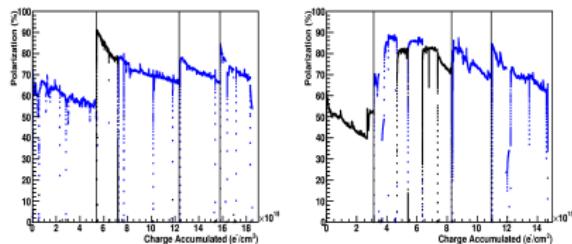
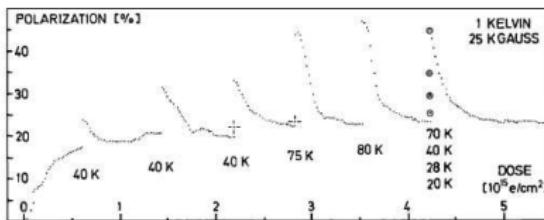
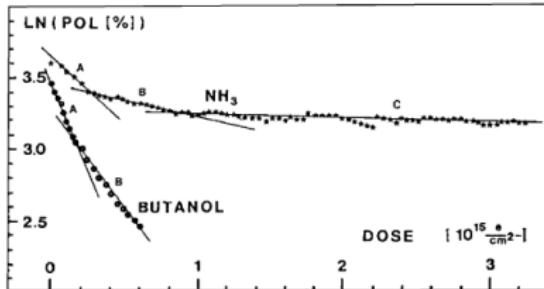
●  $^6\text{LiH}$     $^6\text{LiD}$

●  $\text{NH}_3$     $\text{ND}_3$

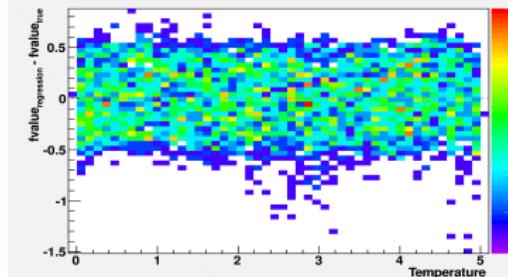
●  $\text{CH}_4$     $\text{CD}_4$

$$f = \frac{N\sigma}{\sigma N_T \sigma_T}$$

# Polarization Materials

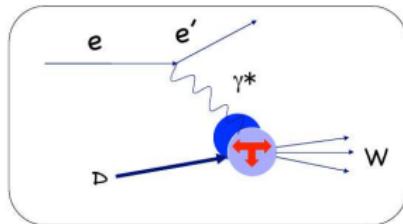
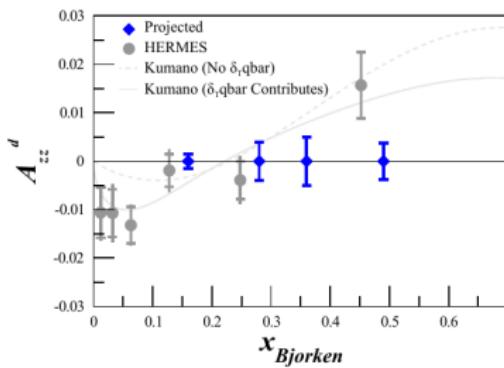


Artificial Neural Network Characteristic Flux



$$p(\Phi) = p_a + (p_0 - p_a) e^{-\Phi/\Phi_{NA}}$$

# The Need For Tensor Polarized Target



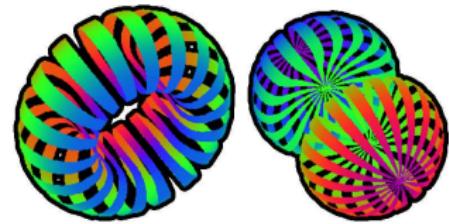
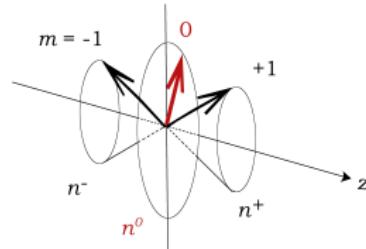
Construct the most general  
Tensor W consistent with  
Lorentz and gauge invariance

Frankfurt & Strikman (1983)  
Hoodbhoy, Jaffe, Manohar (1989)

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

Upcoming: E12-13-011(b1), LOI12-14-002, Duke Tensor-HiFrost

# Spin 1



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

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

- (a) Tensor Structure Functions
- (b) Tensor Asymmetries
- $T_{20}, T_{21}, T_{22}, A_T, b_1, b_2, \dots$

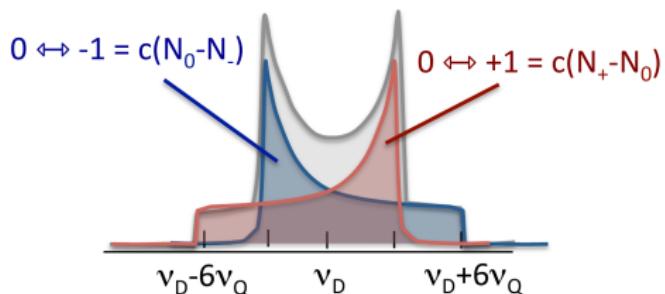
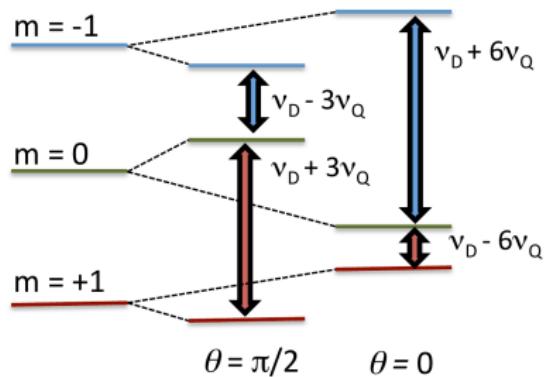
- Probe Spin 1 Observables use Spin 1 Target (Deuteron)
- Three Magnetic substates (+1,0,-1)
- Two Transitions ( $+1 \rightarrow 0$ ) and ( $0 \rightarrow -1$ )
- Deuterons electric quadrupole moment  $eQ$
- Interacts with electric field gradients within lattice

# The Need For Tensor Polarized Target

- Deuteron also has an electric quadrupole moment,  $eq_D = 2.86 \text{ e}\cdot\text{fm}^2$
- $eq_D$  interacts with electric field gradients within the lattice producing two, overlapping NMR lines (Pake doublet)

$$E_m = -hv_D m + hv_Q [3\cos^2 \theta - 1][3m^2 - I(I+1)]$$

$v_D$  = deut. Larmor freq.  
 $v_Q$  =  $ND_3$  quadrupole freq.  
 $eq$  = deuteron quadrupole moment  
 $\theta$  = angle between elec. & mag. fields



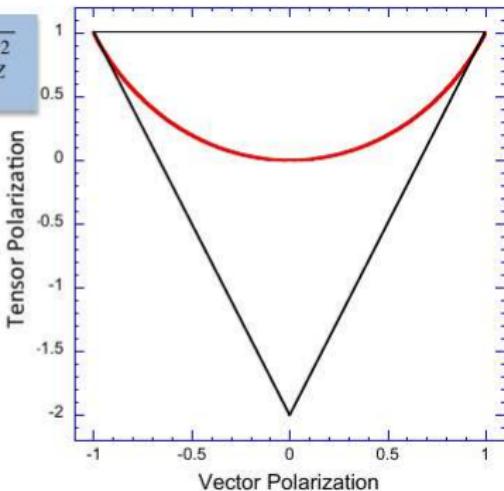
# The Need For Tensor Polarized Target

$$P_z = \frac{4 \tanh\left(\frac{\mu B}{2kT_s}\right)}{3 + \tanh^2\left(\frac{\mu B}{2kT_s}\right)}$$

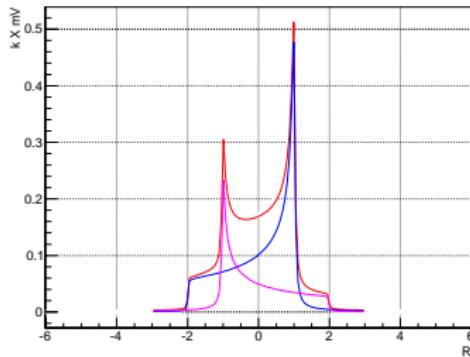
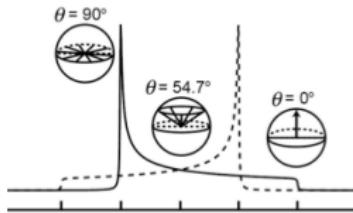
$$P_{zz} = \frac{4 \tanh^2\left(\frac{\mu B}{2kT_s}\right)}{3 + \tanh^2\left(\frac{\mu B}{2kT_s}\right)}$$

$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

- Mutually allowed values for the vector and tensor polarizations are generally restricted to be on or within the black triangle, but...
- Spin Temperature hypothesis* restricts the polarizations to only those values on the red parabola. Note: no negative  $P_{zz}$  values!



# Homogeneous Broadening



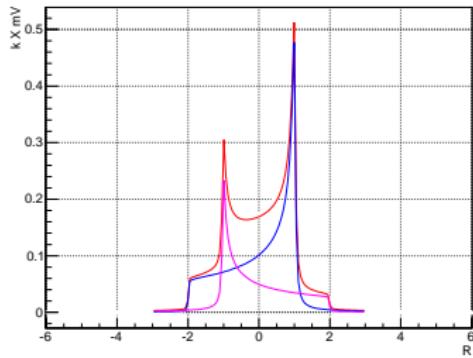
$$f_{\pm}(R, A, \eta \sim 0, \phi) = \frac{B}{2\pi\rho} \left[ 2\nu(R) \left( \arctan \frac{3 - \rho^2}{2\sqrt{3}\rho\nu'(R)} + \frac{\pi}{2} \right) + \nu'(R) \ln \left( \frac{3 + \rho^2 + 2\sqrt{3}\rho\nu(R)}{3 + \rho^2 - 2\sqrt{3}\rho\nu(R)} \right) \right]$$

$$\rho = (A^2 + [1 \pm R])^{1/4}$$

$$\nu(R) = (1 + [1 \pm R]/\rho^2)^{1/4}/2$$

$$\nu'(R) = (1 - [1 \pm R]/\rho^2)^{1/4}/2$$

# Tensor Polarization Measurement



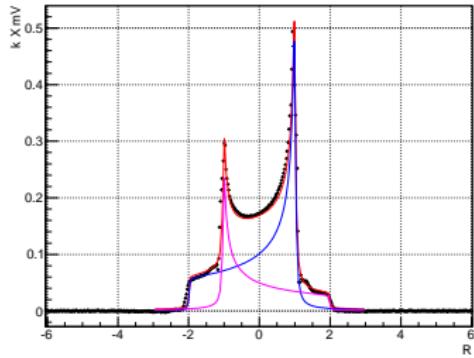
$$f_{\pm}(R, A, \eta \sim 0, \phi) = \frac{B}{2\pi\rho} \left[ 2\nu(R) \left( \arctan \frac{3 - \rho^2}{2\sqrt{3}\rho\nu'(R)} + \frac{\pi}{2} \right) + \nu'(R) \ln \left( \frac{3 + \rho^2 + 2\sqrt{3}\rho\nu(R)}{3 + \rho^2 - 2\sqrt{3}\rho\nu(R)} \right) \right]$$

$$I_+ = \int_2^2 f_+(B, R) dR = C(a_+ - a_0)$$

$$I_- = \int_2^{-2} f_-(B, R) dR = C(a_0 - a_-)$$

$$A = (\sum_m 3m^2 a_m) - 2 = (a_+ - a_0) - (a_0 - a_-) = \frac{1}{C}(I_+ - I_-)$$

# DMR line Fitting



$$f_{\pm}(R, A, \eta \sim 0, \phi) = \frac{B}{2\pi\rho} \left[ 2\nu(R) \left( \arctan \frac{3 - \rho^2}{2\sqrt{3}\rho\nu'(R)} + \frac{\pi}{2} \right) + \nu'(R) \ln \left( \frac{3 + \rho^2 + 2\sqrt{3}\rho\nu(R)}{3 + \rho^2 - 2\sqrt{3}\rho\nu(R)} \right) \right]$$

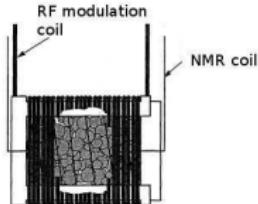
$$I_+ = \int_2^2 f_+(B, R) dR = C(a_+ - a_0)$$

$$I_- = \int_2^{-2} f_-(B, R) dR = C(a_0 - a_-)$$

Fit to find  $P = 42.3\%$  and  $A = 13.1\%$

# RF Modulation

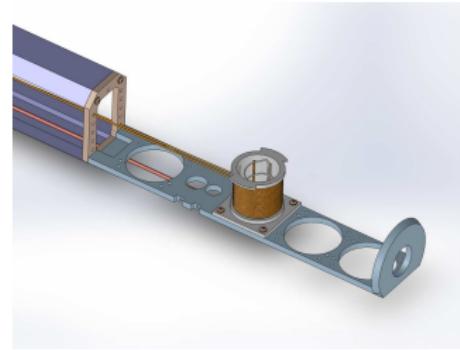
## Deuteron RF Modulation



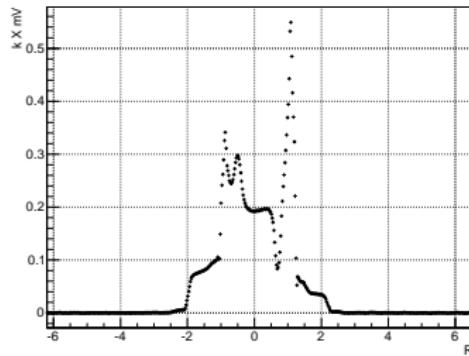
- Adjacent Spins Dynamics
- Different Resonant frequencies
- Change in  $\Gamma(\omega)$

### First Look

- ① Secondary Coil (2 mT/A)
- ② Translate NMR Area
- ③ Only Estimates
- ④ Intermittent NMR

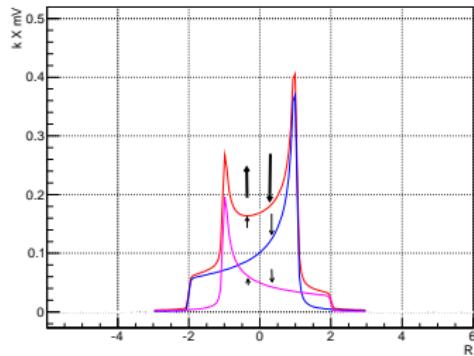


# Interpretation of the DMR line



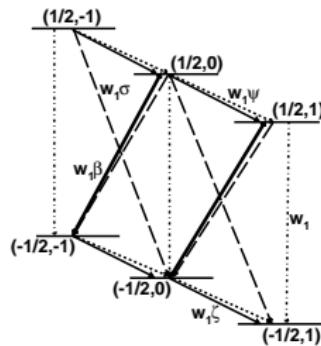
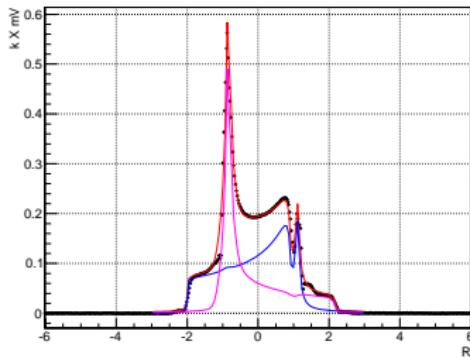
- (a) Understand change in  $I_+(\omega)$ ,  $I_-(\omega)$
- (b) Useful steady-states
- (c) Measure with uncertainty

# Interpretation of the DMR line



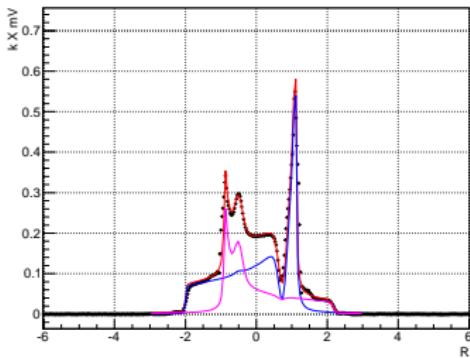
- (a) Understand change in  $I_+(\omega)$ ,  $I_-(\omega)$
- (b) Useful steady-states
- (c) Measure with uncertainty

# Steady State Solutions



- (a)  $\zeta \ll \beta$  (Minimal variation)
- (b)  $\zeta \gg \beta$  (Saturation)
- (c)  $\zeta \sim \beta$  (Family of solutions)

# The Semi-saturated Fitting



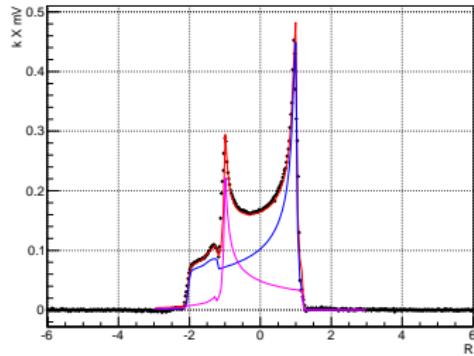
$$P = 0.490 \rightarrow 0.472 \quad P_{zz} = 0.189 \rightarrow 0.128$$

$$\hat{\mathfrak{F}}^+(R^*, A_1^*, B_1^*, \eta, \phi, h_1^*, \Gamma^*, k_1^*, \sigma^*, \delta) = f^+(R^*, A_1^*, B_1^*) - L(h_1^*, \Gamma^*, r) \otimes G(k_1^*, \sigma^*, \delta)$$

$$\hat{\mathfrak{F}}^-(R^*, A_2^*, B_2^*, \eta, \phi, h_2^*, \Gamma^*, k_2^*, \sigma^*, \delta) = f^-(R^*, A_2^*, B_2^*) + L(h_2^*, \Gamma^*, r) \otimes G(k_2^*, \sigma^*, \delta)$$

- Saturate  $\zeta$
- Use Power Profile to Gauge
- Semi-saturate to steady state

# The Saturated Fitting



$$P = 0.414 \rightarrow 0.391 \quad P_{zz} = 0.128 \rightarrow 0.156$$

$$\mathfrak{F}^+(R^*, A_1^*, A_2^*, B_1^*, B_2^*, \eta, \phi) = \begin{cases} 0 & : 1 < R \\ f_1^+(R^*, A_1^*, B_1^*) & : -1 \leq R \leq 1 \\ \sum_i f_i^+(R^*, A_i^*, B_i^*) & : -3 \leq R < -1 \end{cases}$$

$$\mathfrak{F}^-(R^*, A_3^*, A_4^*, B_3^*, B_4^*, \eta, \phi) = \begin{cases} 0 & : 1 < R \\ f_3^-(R^*, A_3^*, B_3^*) & : -1 \leq R \leq 1 \\ \sum_i f_i^-(R^*, A_i^*, B_i^*) & : -3 \leq R < -1 \end{cases}$$

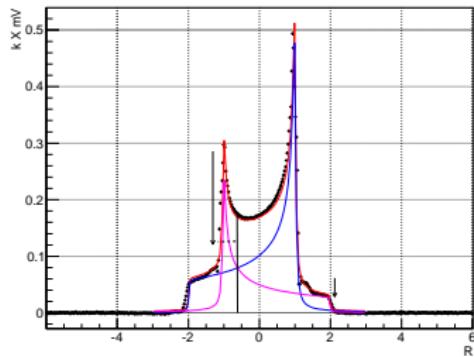
# Enhanced Tensor Polarization Measurement

## Enhancement Method

- 1 TE &  $P_{zz} = (r^2 - 2r + 1)/(r^2 + r + 1)$
- 2  $P_{zz} = 1 - 3 \frac{n_0}{N} = C(I_+ - I_-)$
- 3 Saturate Pedestal and Semi-saturate small peak
- 4  $\hat{\delta}^- + \hat{\delta}^+ \wedge \tilde{\delta}^- + \tilde{\delta}^+$

## Error Estimates

- (a) Natural distribution (4-6%)
- (b) RF Saturation (5-7%)
- (c) Semi-saturation (6-10%)



# Uncertainty in Tensor Polarization

## Standard Uncertainty Contributions

$$\left( \frac{\delta C_{TE}}{C_{TE}} \right)^2 = \left( \frac{\delta P_{TE}}{P_{TE}} \right)^2 + \left( \frac{\delta A_{TE}}{A_{TE}} \right)^2$$

$$\frac{\delta P_E}{P_E} = \left[ \left( \frac{\delta P_{TE}}{P_{TE}} \right)^2 + \left( \frac{\delta A_{TE}}{A_{TE}} \right)^2 + \left( \frac{\delta S_{TE}}{S_{TE}} \right)^2 + \left( \frac{\delta A_E}{A_E} \right)^2 + \left( \frac{\delta S_E}{S_E} \right)^2 + \left( \frac{\delta G}{G} \right)^2 \right]^{1/2}$$

- ①  $A_{TE}$  - Relative uncertainties in area acquired during TE
- ②  $S_{TE}$  - Measurement limitation during TE
- ③  $S_E$  - Systematic variation in enhanced signal
- ④  $G$  - Error from gain

D. Keller NIM 728, 133 (2013)

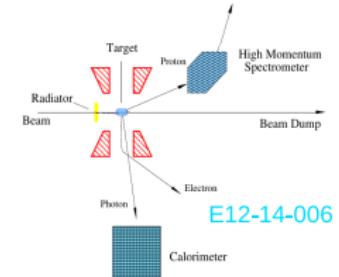
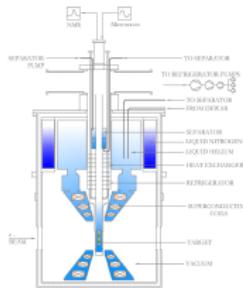
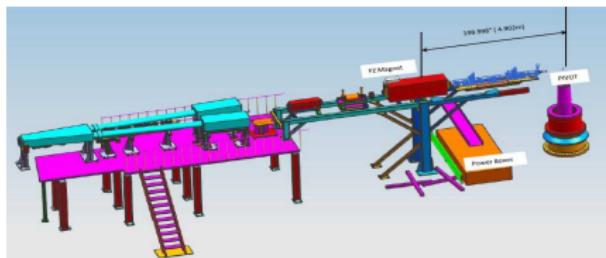
## Additional Contributions (Steady-State)

$$\delta I_{\pm} = \sqrt{(\delta C)^2 + (\delta A_{\chi^2})^2 + (\delta A_{\partial t})^2}$$

- $(\delta C)$  Standard Contributions from above
- $(\delta A_{\chi^2})$  Variation in area over covariance matrix minimization
- $(\delta A_{\partial t})$  NMR measurement limitations with respects to relaxation rate

# Wide-Angle Compton Scattering

Longitudinally Polarized Photon Beam With  
Longitudinally Polarized Target



UVA/Jlab polarized target  
Reliance on the Neutral Particle Spectrometer for photon detection

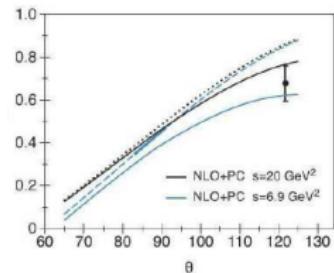
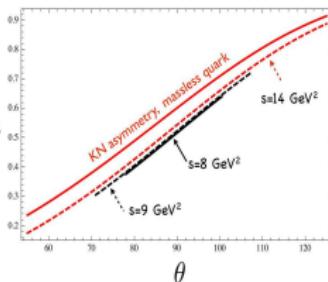
Phenomenological analysis of the WACS including the kinematic power corrections and suppressed helicity flip amplitudes in the Soft Collinear Effective Theory framework

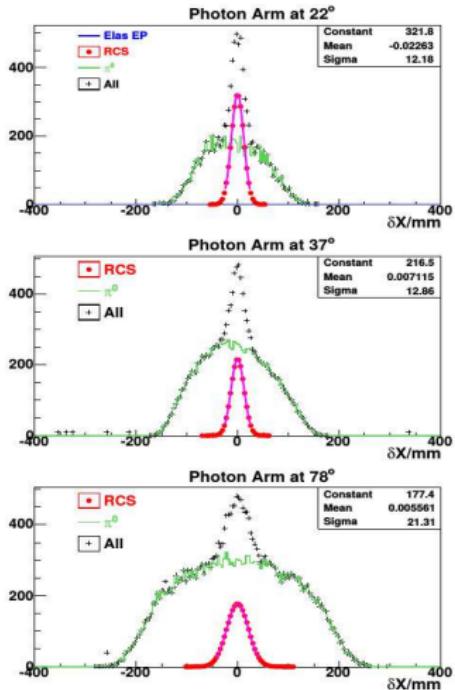
N. Kivel and M. Vanderhaeghen, JHEP 1304 (2013)

$$\text{Initial State Helicity Correlations} = \mathcal{F}_1 + \mathcal{G}_1 + H_{\text{ALL}}$$

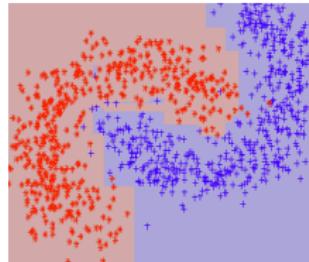
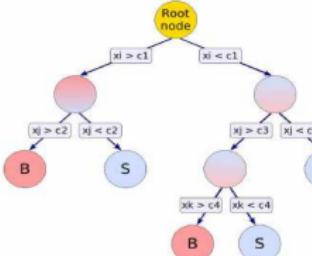
The initial State Helicity Correlations can then be used to clarify the role of the power suppressed helicity flip contribution

- New Calculation using leading order approximation
- Calculation show a weak s-dependence
- Can be checked in a new asymmetry measurement
- Extend the measurement of proton axial form factor

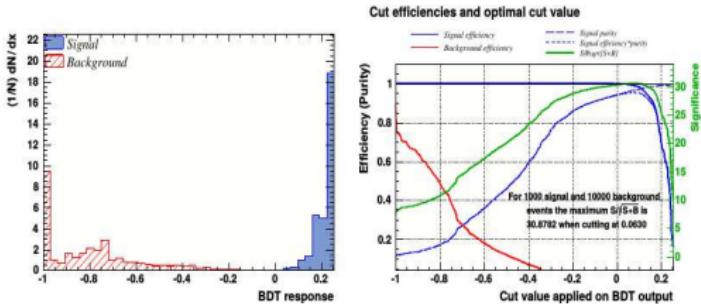




## Boosted Decision Tree



*BDT efficiency response using tagged MC*



Optimize split point: Information Entropy  $H = -\sum_c p(c)\log p(c)$

$$D = (N_{\gamma,\pi^0} + N_{\gamma,\gamma})/N_{\gamma,\gamma} \quad N_{RCS, required} = D/(P_e P_p f_{e\gamma} \Delta A_{LL})^2$$

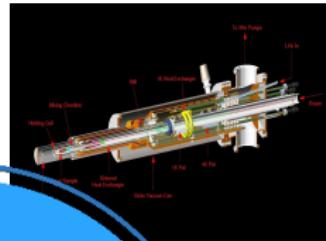
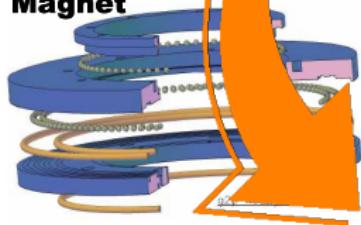
Expected dilution from simulated data:  
Normal method: D=2.0, 2.8, 3.9

BDT: D=1.01, 1.04, 1.07

Also Used for CLAS6 Frost-g9 Dilution



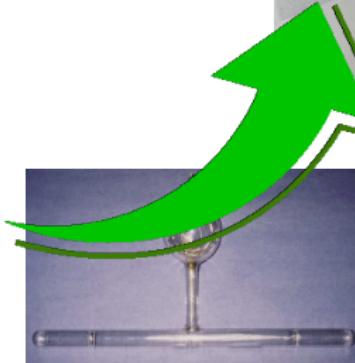
**Rotating Hall-B Magnet**



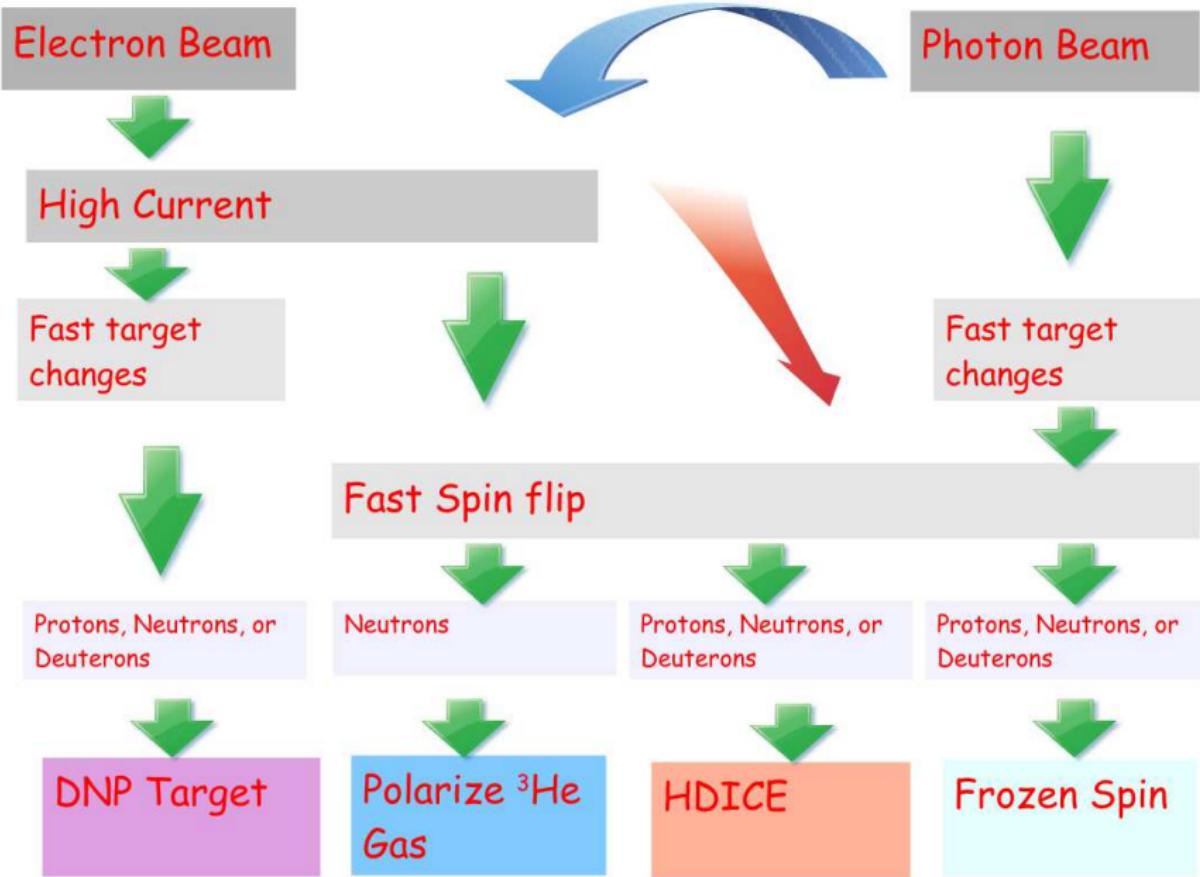
**Frozen Spin  
Dilution**



**HD Ice**



**$^3\text{He}$**



# Polarized Solid Targets at 12 GeV Jlab

- Hall A

- (E12-11-108) SIDIS with a transversely polarized proton target
- (E12-11-108A) Target single spin asymmetries using SoLID

- Hall B

- (E12-06-109) Longitudinal spin structure of the nucleon
- (E12-06-119) DVCS with CLAS at 12 GeV
- (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
- (C12-11-111) SIDIS on a transversely polarized target
- (C12-12-009) Di-hadron production in SIDIS on a 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
- (C12-13-011) The deuteron tensor structure function b1
- (LOI-12-14-001) Search for exotic gluonic states in the nucleus
- (LOI-12-14-002) Tensor asymmetry  $A_{zz}$  in the  $x < 1$  region

# Summary

- Hardware Development and Improvements
  - Radiation and Polarization Characteristics
  - Measurement of Tensor Enhanced Target
  - Development of Tensor Enhanced Target
  - Dilution Reduction
- 12 proposals Jlab