

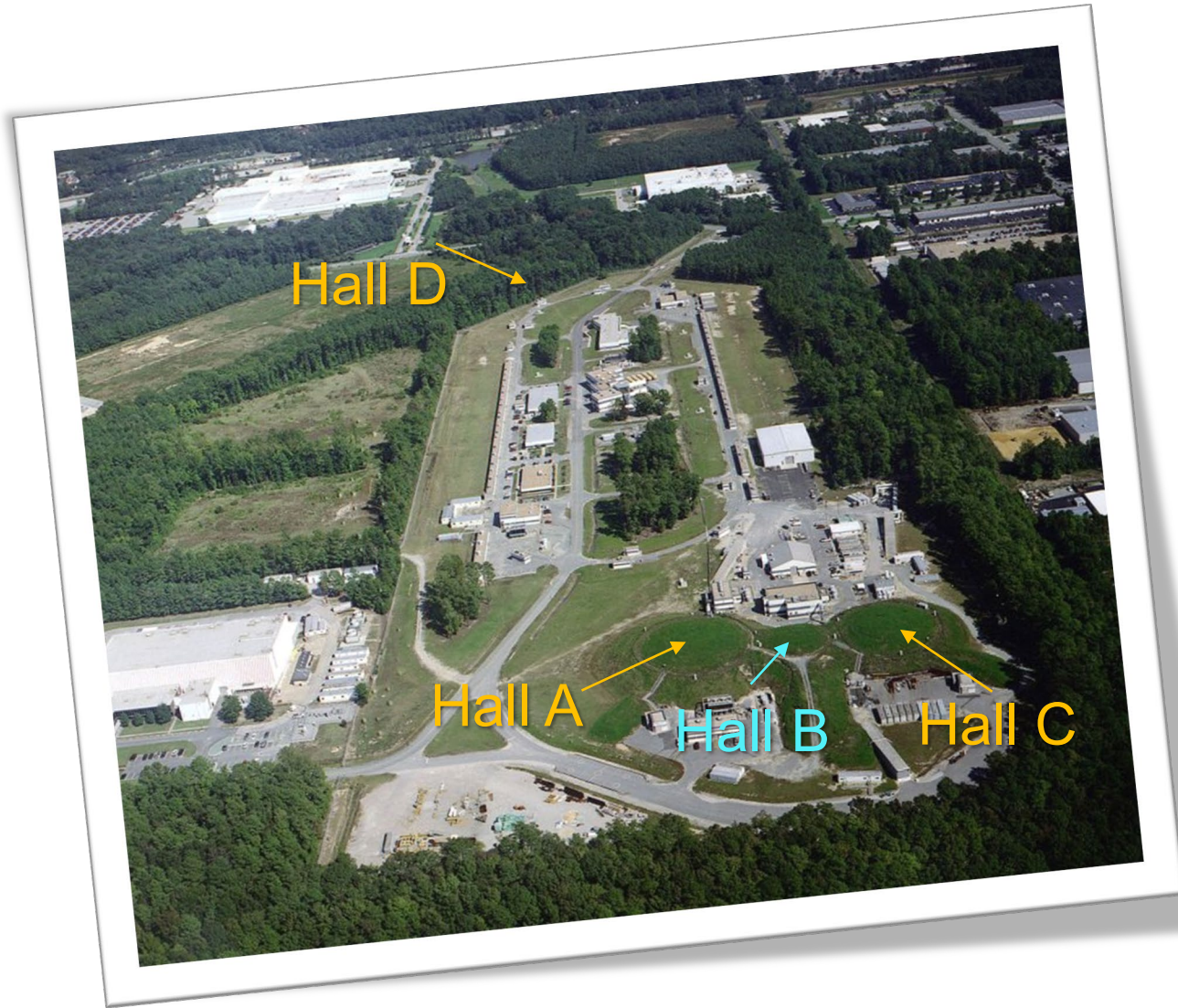
Spin observables in Deep Processes with CLAS12 at Jefferson Lab



Gregory Matousek
September 25th 2023



Jefferson Lab



- US Department of Energy funded research facility in Virginia
- Home to CEBAF (polarized electron accelerator) and 4 fixed target experimental halls



Continuous Electron Beam Accelerator Facility (CEBAF)

Provides longitudinally polarized ($\sim 85\%$), high luminosity (up to $120\mu\text{A}$) electron beams at 10.6 – 12 GeV to four experimental halls

Injector: Circularly Pol. Light $\rightarrow$ GaAs photocathode $\rightarrow$ Polarized e^-

Transport: Spreaders/recombiners, arrays of arc dipoles

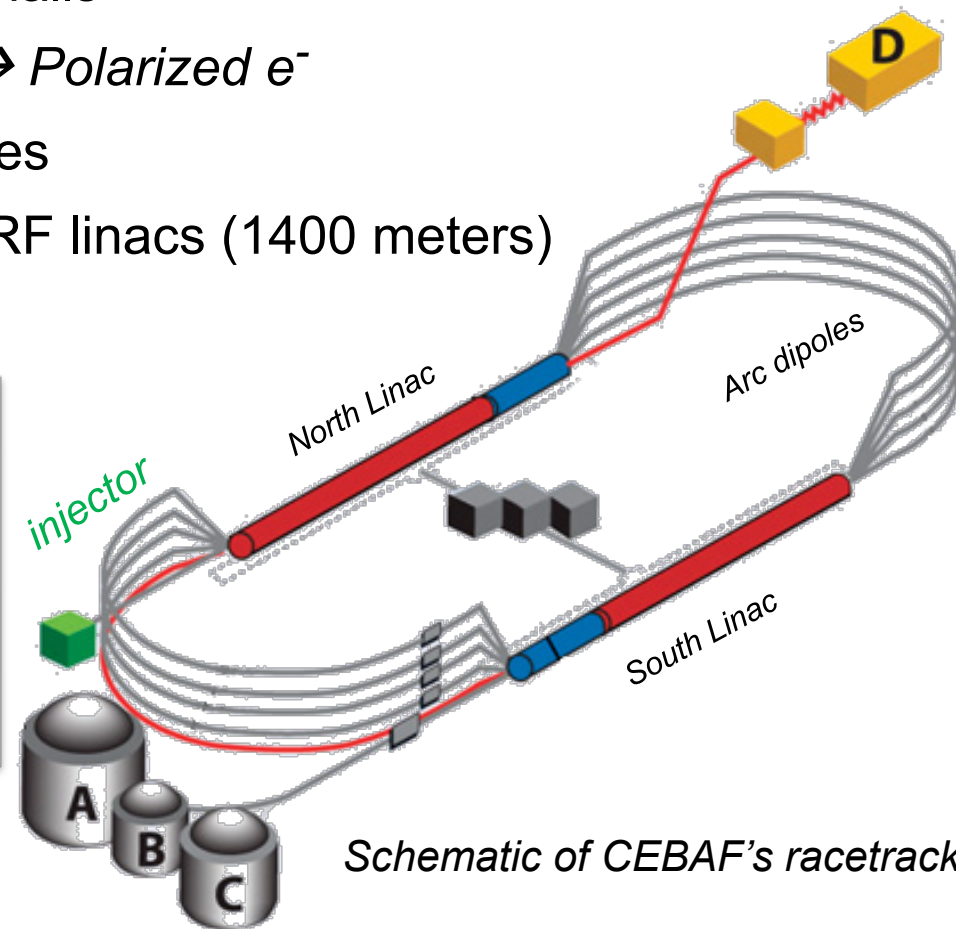
Acceleration: Liquid helium cooled, superconducting RF linacs (1400 meters)



Superconducting RF Linac
(1.09 GeV per straight-away)

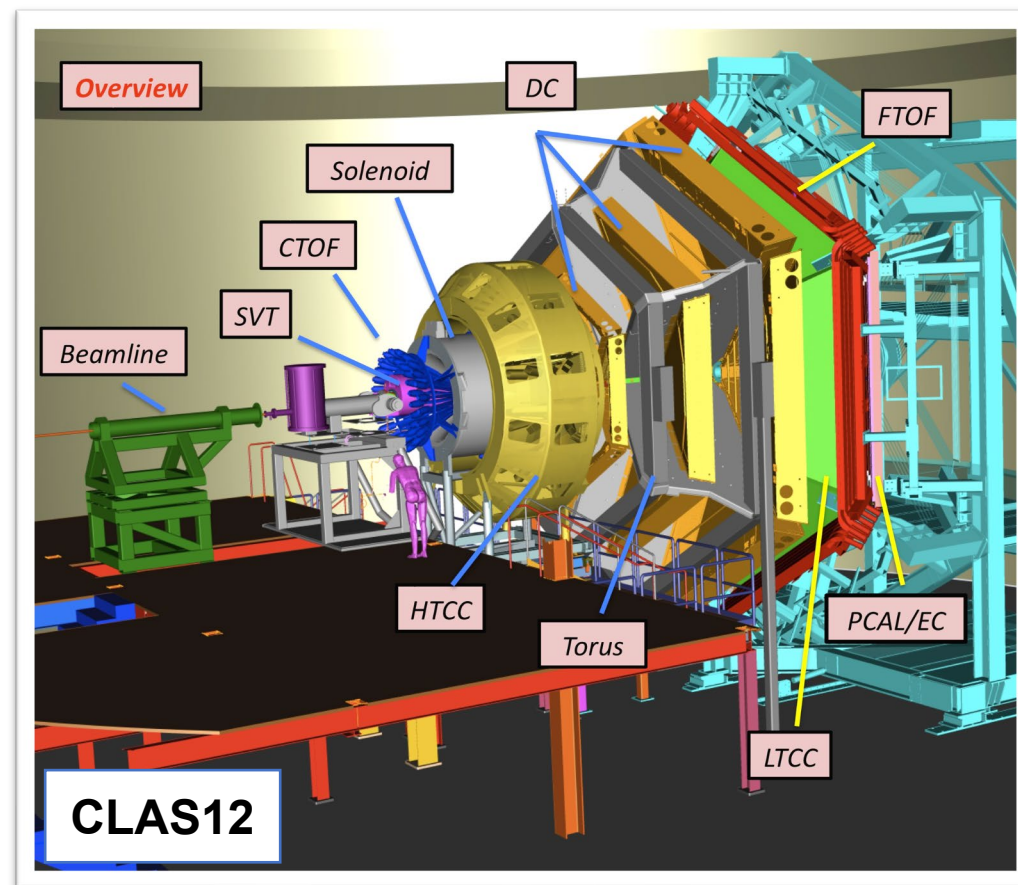
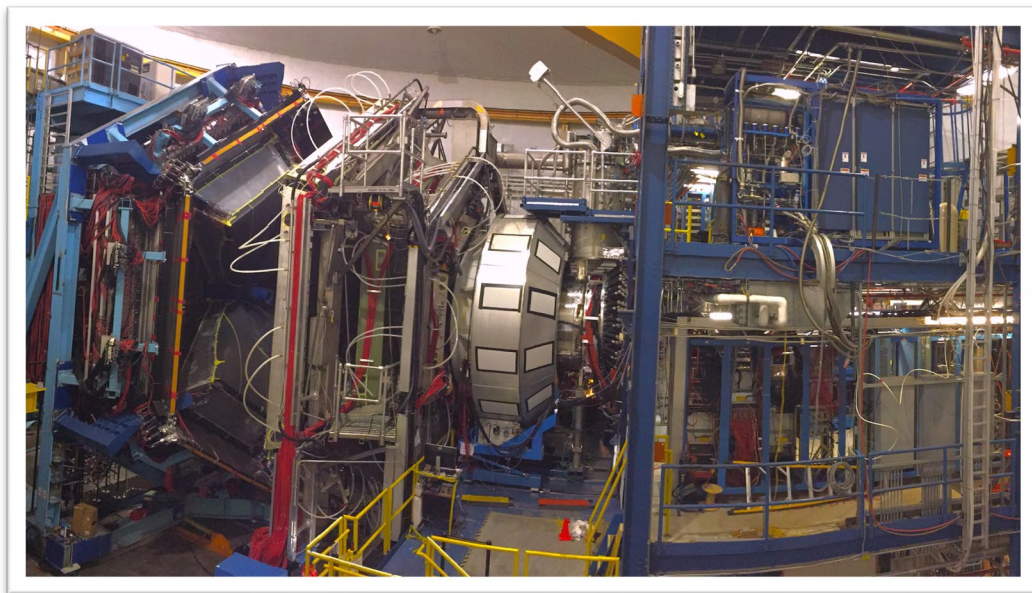


Arc Dipoles



CEBAF Large Acceptance Spectrometer (CLAS12)

- Wide coverage detector system capable of ranging particle ID (e, p, n, γ, π, K)
 - Near full coverage in azimuthal ϕ , $\sim 5^\circ - 140^\circ$ in lab scattering θ
- Fixed-target experiment (**RG-C is the first polarized target experiment at Hall-B in the 12 GeV era**)
- ~ 10.5 GeV, $\sim 85\%$ longitudinally polarized electron beam at maximum luminosity of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$



CLAS12 Detector System

Run Group C @ CLAS12

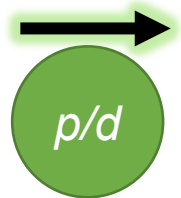
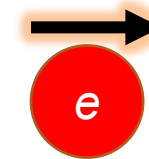
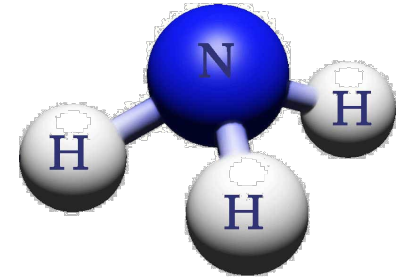
- Polarized fixed target experiment (June 2022 – March 2023)
 - Dynamically polarized **NH₃ (proton)** and **ND₃ (deuteron)** targets
 - Calibration targets **C**, **CH₂** and **CD₂**

- Physics Goals

DIS inclusive and flavor-tagged **spin structure functions**

Semi-inclusive DIS (SIDIS) to access **Transverse Momentum Distributions** (TMDs), dihadron production and backward baryon production

Deeply Virtual Compton Scattering (DVCS) & Timelike Compton Scattering (TCS) to access **Generalized Parton Distributions** (GPDs) - Measure target single and beam/target double spin asymmetries in proton and neutron DVCS.



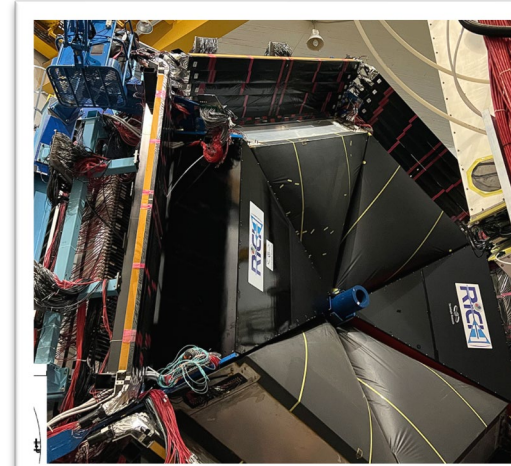
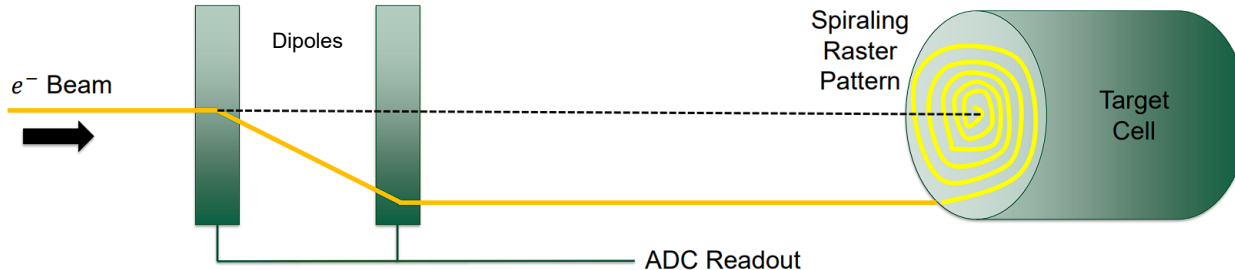
★ Longitudinal beam & target polarizations

List of RG-C Experiments

Experiment Title	Key Observables	Preliminary
<i>Longitudinal Spin Structure of the Nucleon</i>	Polarized parton distributions, gluon helicity, higher twist	---
<i>DVCS on the neutron with polarized deuterium target</i>	Neutron Compton Form Factors	---
<i>DVCS on longitudinally polarized proton target</i>	Helicity dependent cross sections, upgrade precision and coverage of previous CLAS DVCS measurements	✓
<i>Study of partonic distributions using SIDIS K production</i>	Hadron multiplicities, flavor decomposition of nucleon spin dependent quark PDFs	---
<i>Spin-Orbit Correlations with longitudinally polarized target</i>	Transverse momentum dependence of valence quark T/L spin distributions, pion SIDIS	✓
<i>Spin-Orbit correlations in K production with polarized targets</i>	Strange sea p_T distributions, kaon SIDIS (complement above)	---
<i>Studies of Dihadron Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets</i>	Spin-orbit correlations in hadronization, dihadron fragmentation functions, fracture functions, twist-3 PDFs	---
<i>Studies of Single Baryon Production in the Target Fragmentation Region with a Longitudinally Polarized Target</i>	Fracture functions, separation of current/target hadronization	✓

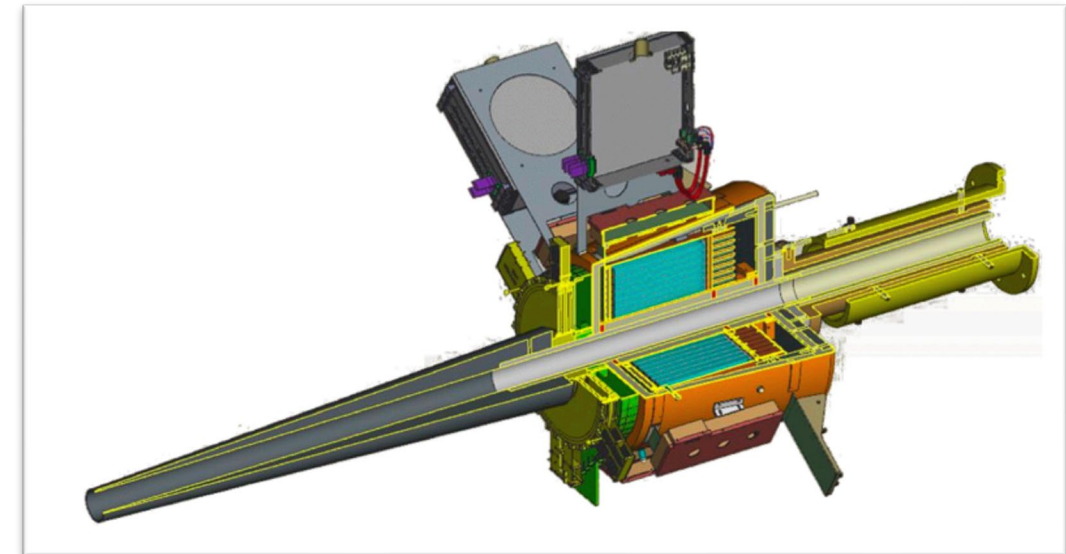
RG-C Experimental Configuration

- Standard CLAS12 forward detectors ($5^\circ < \theta < 35^\circ$)
 - ❖ **NEW** 2nd azimuthal sector RICH detector installed
- Two beam current configurations
 - (~4-4.5 months) **4nA**: Forward tagger installed ($2^\circ < \theta < 5^\circ$) for low angle e , γ reconstruction $\rightarrow$ low Q^2 , widen DVCS coverage
 - (~3 months) **8nA**: Forward tagger removed, additional e^-e^- scattering Moller shield installed
- Target raster system
 - Minimizes local depolarization of target



(Left) Back view of two installed CLAS12 RICH sectors

(Bottom) Schematic of the CLAS12 forward tagger

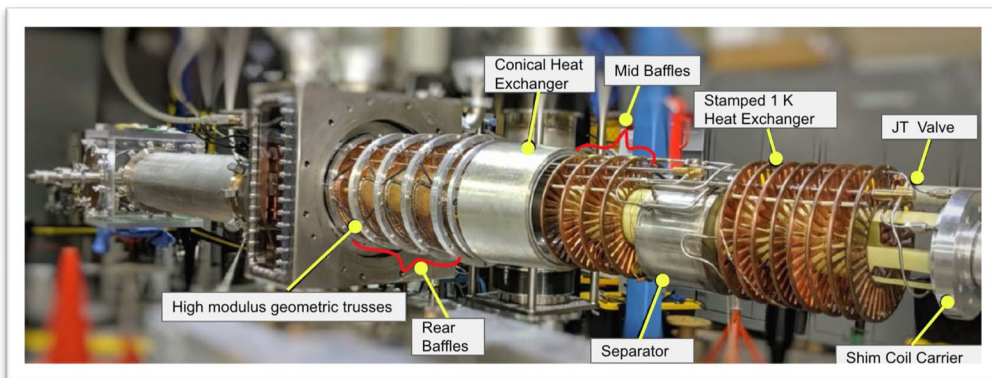
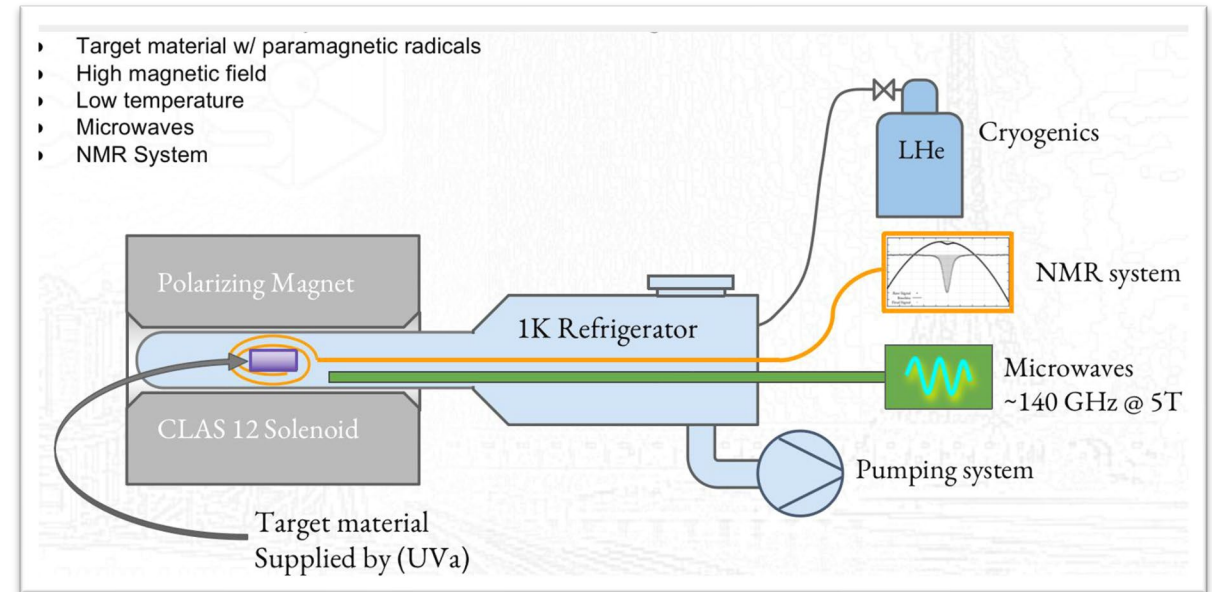


RG-C's Polarized Target

Provides longitudinally polarized p and d

Design Features

- 1K Refrigerator Trolley with swappable 5cm long target cartridges (videos in Pushpa's Tues. talk!)
- Target embedded with a 5T solenoid magnet
- 140GHz μ wave waveguide cavity to provide Dynamic Nuclear Polarization (DNP)
- Nested NMR system for live target polarization readings



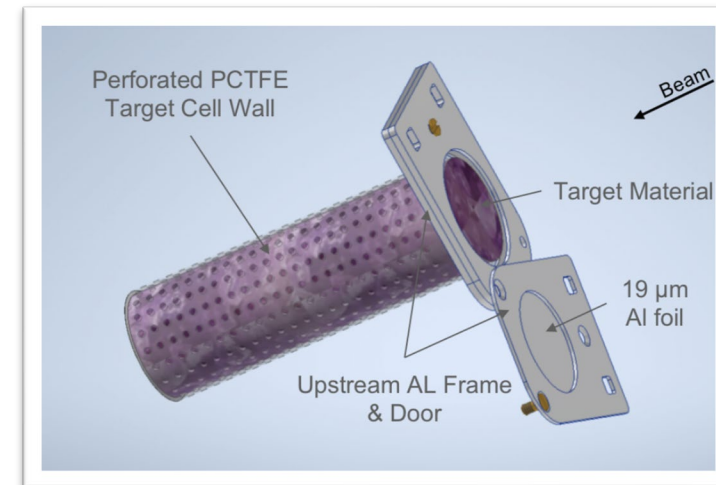
RG-C's Polarized Target



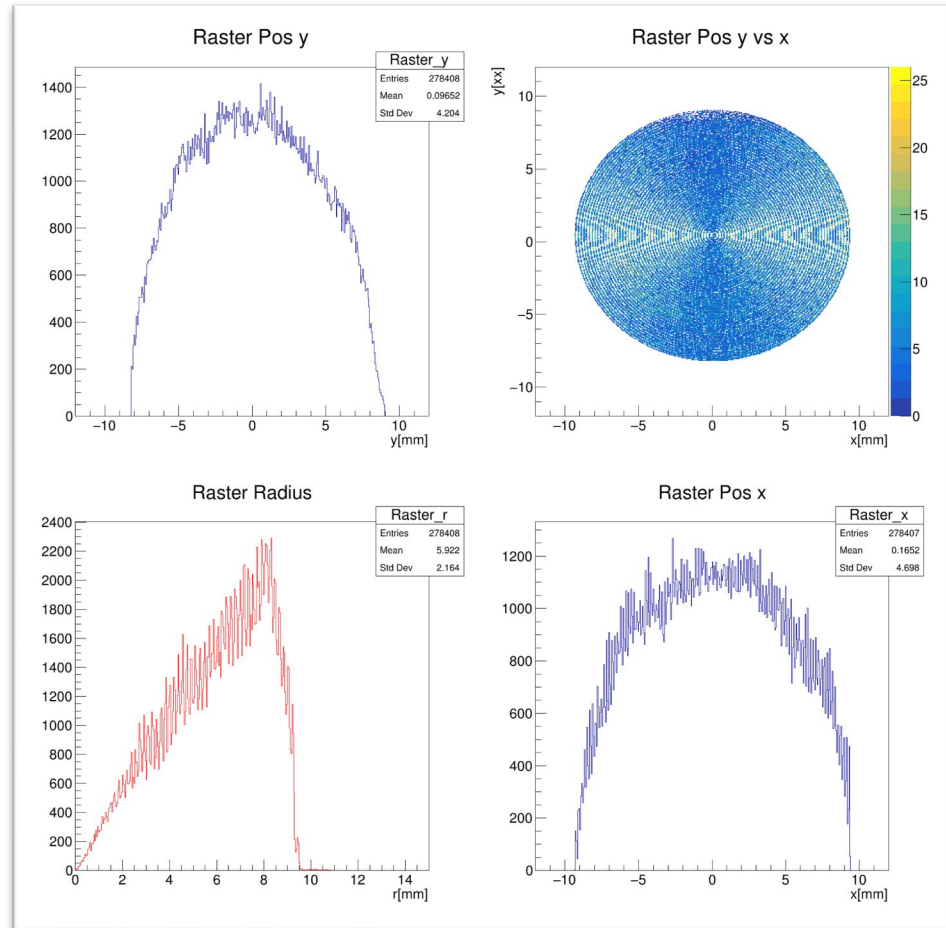
Solid target cells kept in 80K liquid Argon bath (Ammonia freezes at 195.5K)

- Crushed pellet-sized beads
 - Perforated cell walls
- Heat removal*

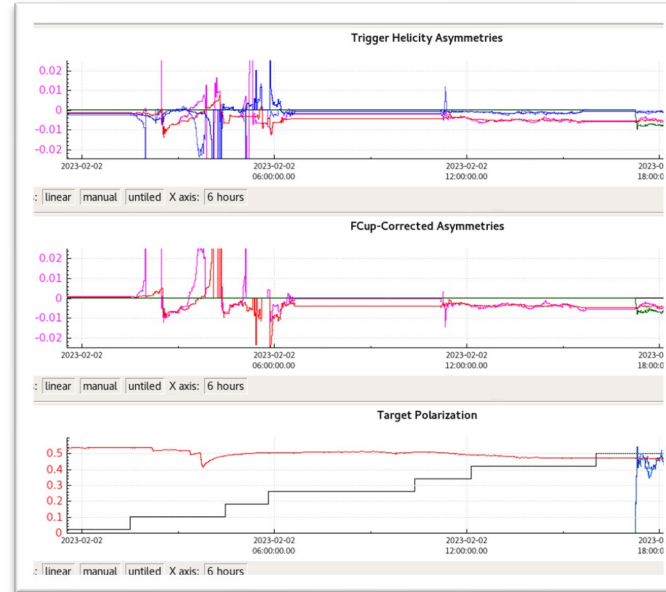
Ammonia beads sent by collaborators at University of Virginia (UVa)



Online Monitoring



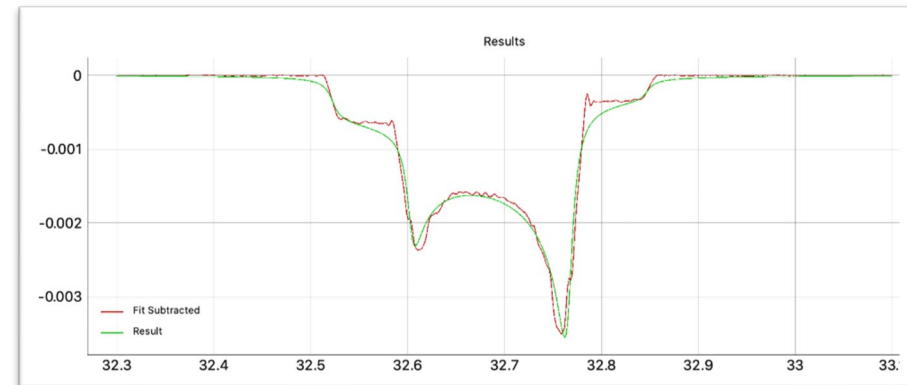
Live updating raster monitoring



Scattered e^- trigger asymmetries

Accumulated beam charge asymmetries

NMR Target Polarization monitoring



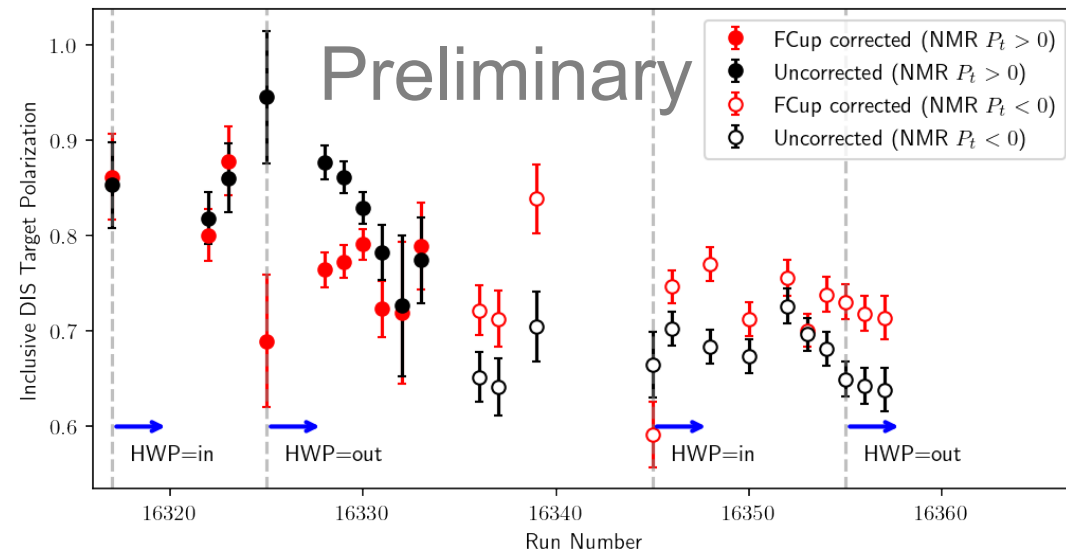
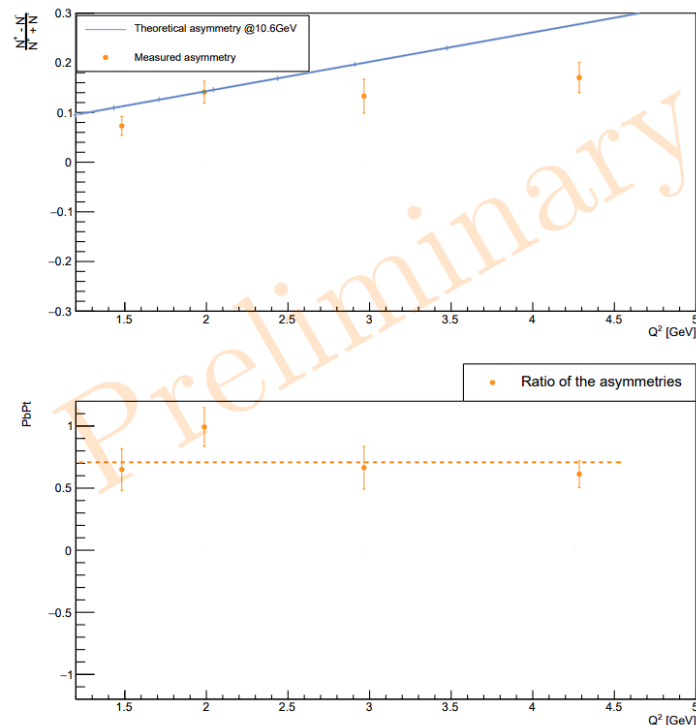
NMR software measuring d polarization

Near-Online Polarization Monitoring

Challenge: NMR unable to measure full target volume's polarization

Solution: Monitor polarization with predicted asymmetries in DIS & Elastic scattering

- Determination of dilution factors
- Corrections for beam charge asymmetries

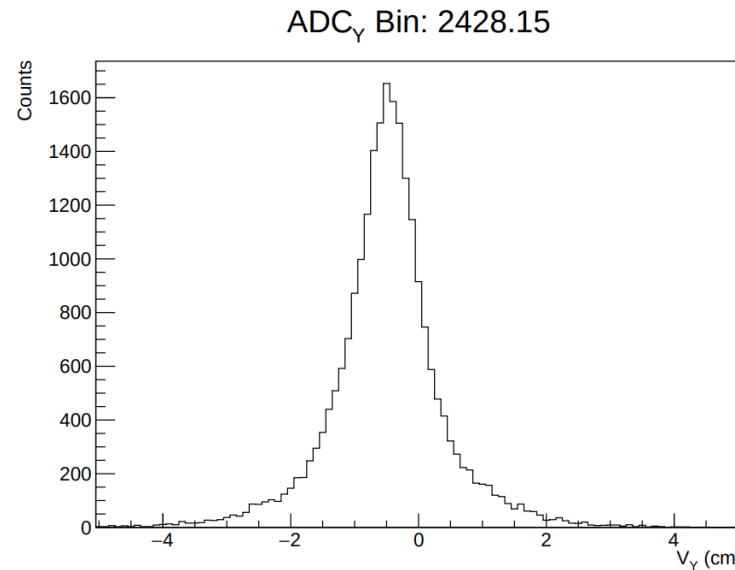
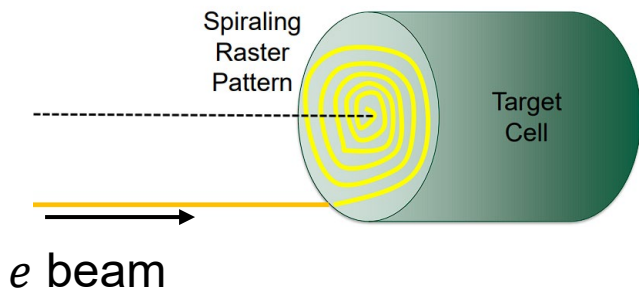
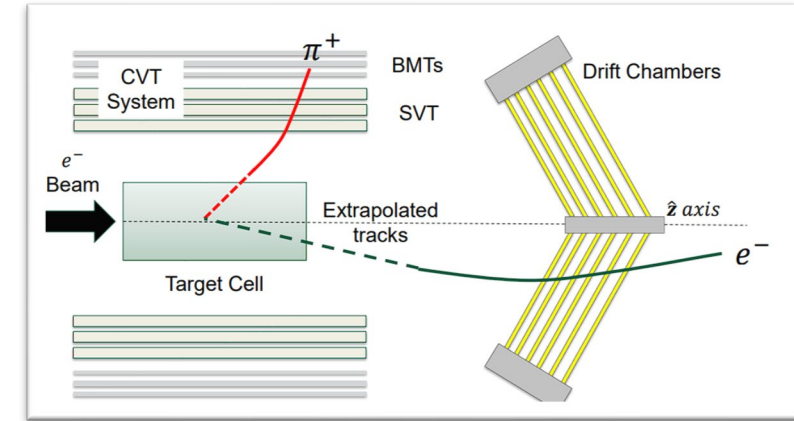


(Top) Deep inelastic scattering asymmetries from NH_3 (G. Matousek)

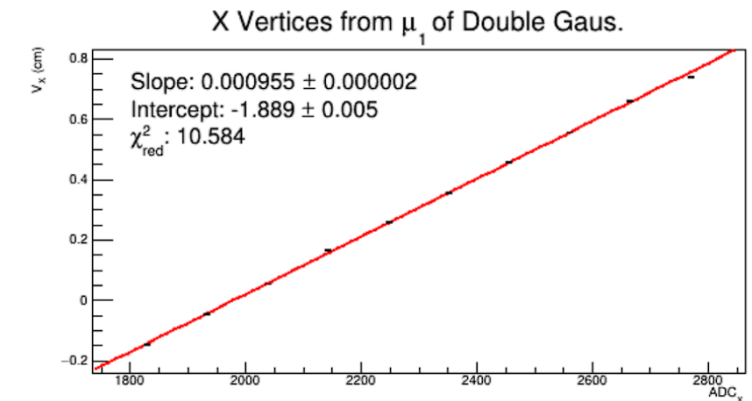
(Left) Elastic scattering asymmetries from NH_3 (N. Pilleux)

Target Raster Calibration

- Analyze extrapolated track vertices and raster $ADC_{x,y}$
- Look at multiple track species (e, π) and detector subsystems (forward, central)
- **** Determine event-by-event beam position in xy -plane for future analyses to utilize ****



Track vertex *given* ADC signal strength



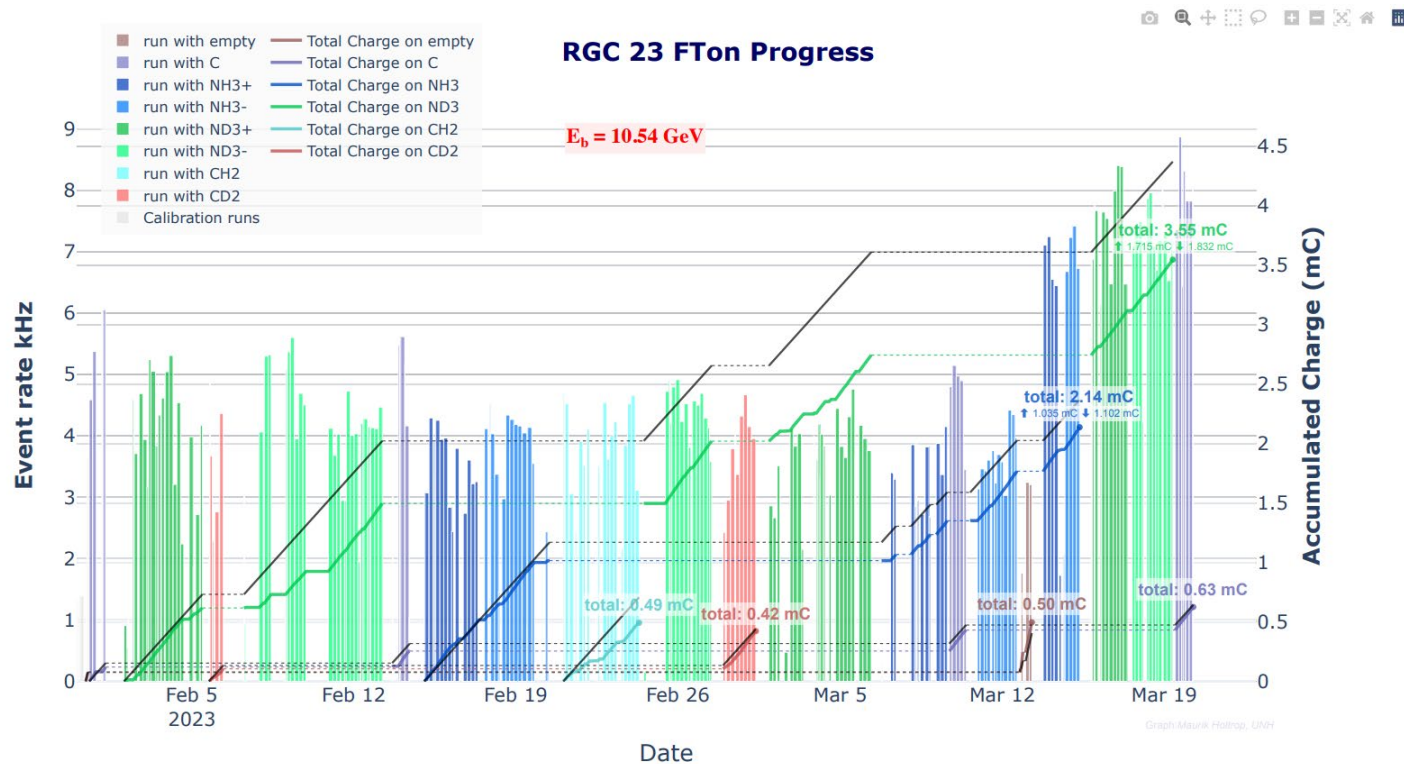
$$V_{x,y} = P_0 + P_1 * ADC_{x,y}$$

Status of Data Processing

- **Total Accumulated Beam Charges**
 - NH3: ~13.06 mC
 - ND3: ~14.19 mC
 - C: ~3.43 mC
 - CH2: ~2.88 mC
 - CD2: ~0.42 mC
 - Empty: ~1.85 mC
- ~5% of collected data has been processed for analysis

★ Preliminary analyses featured ★
correspond to a **fraction** of the total
RG-C NH3 data

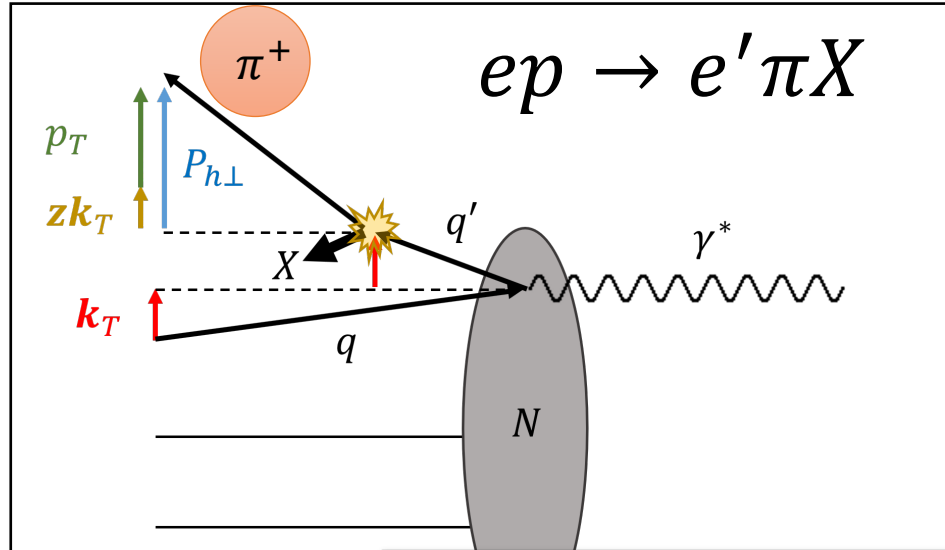
~70% target polarization
~83% beam polarization



Timeline for **Forward Tagger On** 2023

- Spikes --> *Individual runs*
- Colors --> *Target species*
 - Shades --> *Target spin*
- Diagonal lines --> *Total beam charge*

Preliminary Analysis: Pion SIDIS



- Measuring **double-spin asymmetry** (F_{LL})
- P_T -dependence $\rightarrow$ Access the k_T -dependence of the helicity distributions $g_1(x, k_T)$

$$d\sigma \propto F_{UU,T} + \epsilon F_{UU,L} + \lambda_e \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} +$$

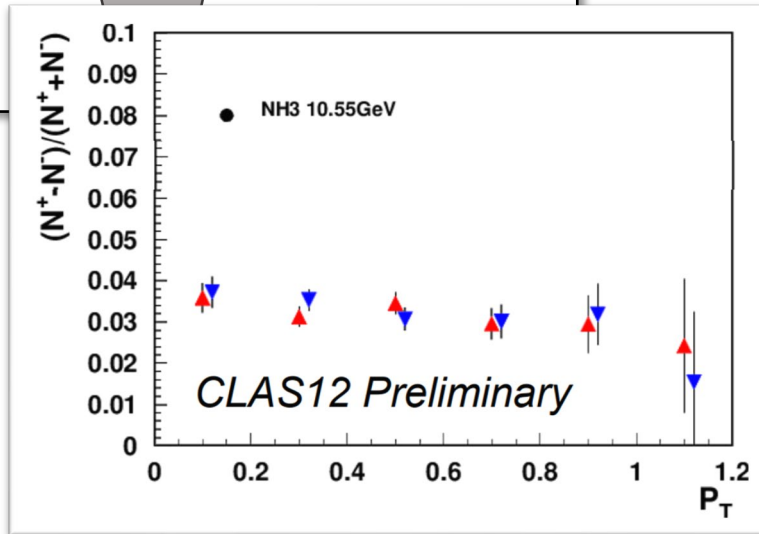
$$S_{||} \left[\sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \epsilon \sin(2\phi_h) F_{UL}^{\sin(2\phi_h)} \right] + S_{||} \lambda_e \sqrt{1-\epsilon^2} F_{LL}$$

Proton helicity

Electron helicity

$$N^+ \rightarrow \lambda S_{||} = 1$$

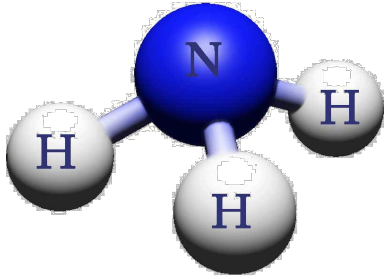
$$N^- \rightarrow \lambda S_{||} = -1$$



$$F_{LL} \propto g_1(x, k_T) \otimes D_1(z, p_T)$$

Convolution over transverse momentum space

Preliminary Analysis: Pion SIDIS



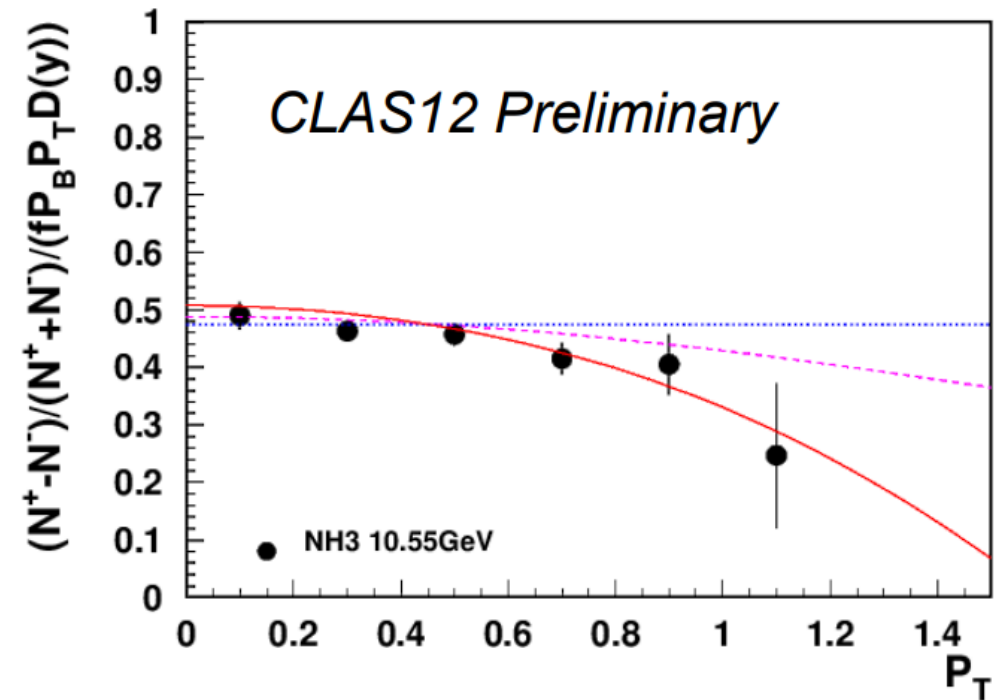
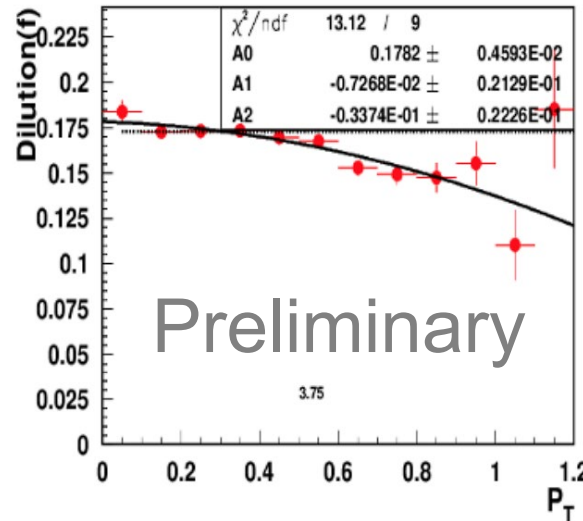
$$A_{LL} = \frac{N^+ - N^-}{N^+ + N^-} \rightarrow \left(\frac{1}{f \times P_b \times P_t \times D(y)} \right) \frac{N^+ - N^-}{N^+ + N^-}$$

f × P_b × P_t × D(y)

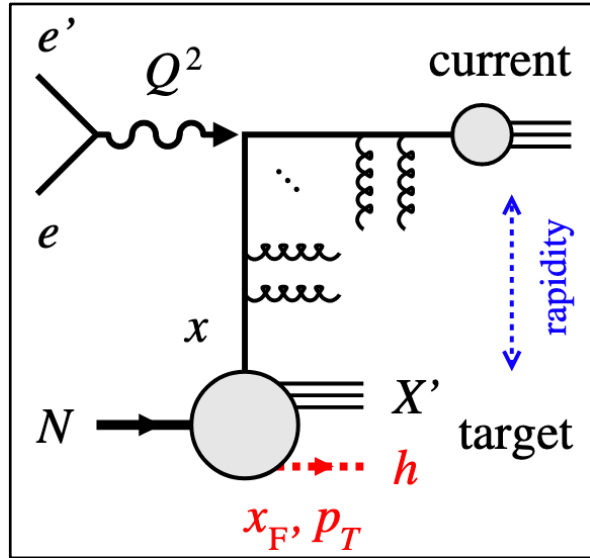
Beam/target polarization
Depolarization factor

- Bin-by-bin determination of dilution factors
 - Analyze NH_3 vs. C yields
 - Calculate %-age of proton cross section contribution to NH_3

$$f = 1 - \frac{N_C}{N_{NH_3}}$$



Preliminary Analysis: Fracture Functions

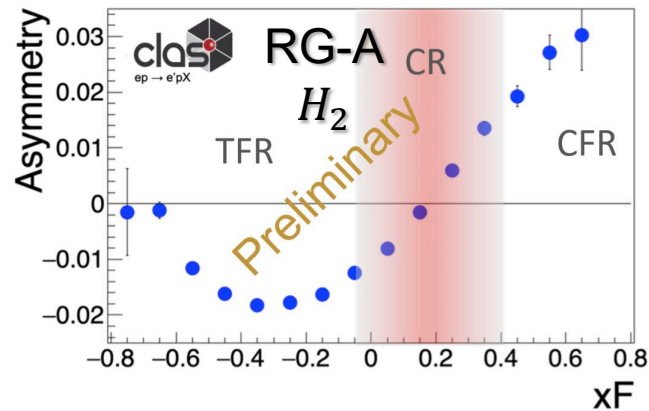


“What physics can we learn from the target remnant (TFR)?”

- **Fracture Functions** → probability for the target (p/n) remnant to form a hadron *given* ejected quark q_f
 - No hard/soft energy scale separation $\frac{d\sigma^{\text{TFR}}}{dx_B dy dz} = \sum_a e_a^2 (1 - x_B) \boxed{M_a(x_B, (1 - x_B)z)} \frac{d\hat{\sigma}}{dy}$
- Direct relationship to traditional **PDFs** by integrating over fractional longitudinal nucleon momentum ζ

$$\sum_h \int_0^{1-x} d\zeta \zeta \hat{u}_1(x, \zeta) = (1 - x) f_1(x)$$

$$\sum_h \int_0^{1-x} d\zeta \zeta \hat{l}_{1L}(x, \zeta) = (1 - x) g_{1L}(x)$$

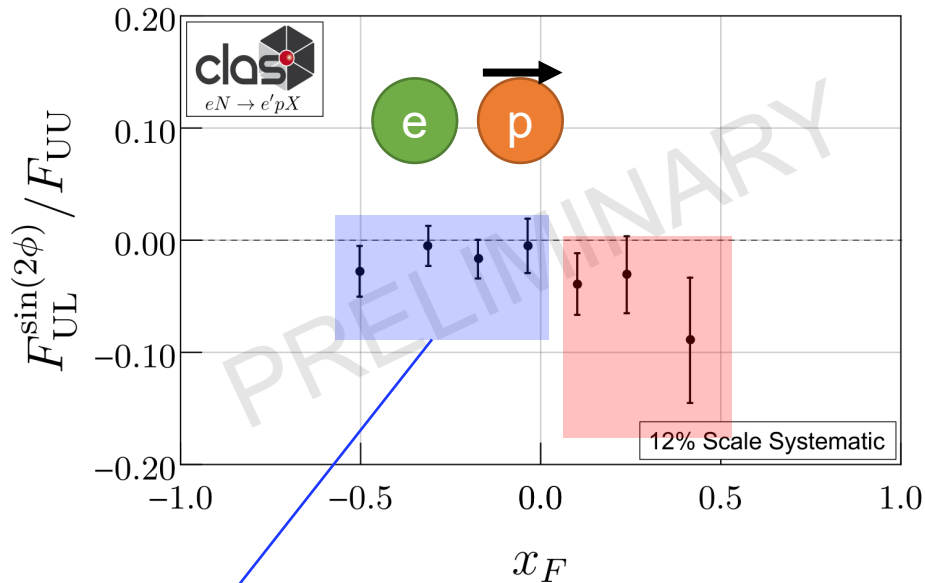


$xF \rightarrow$ Hadron p_L relative to $\gamma^* p_L$

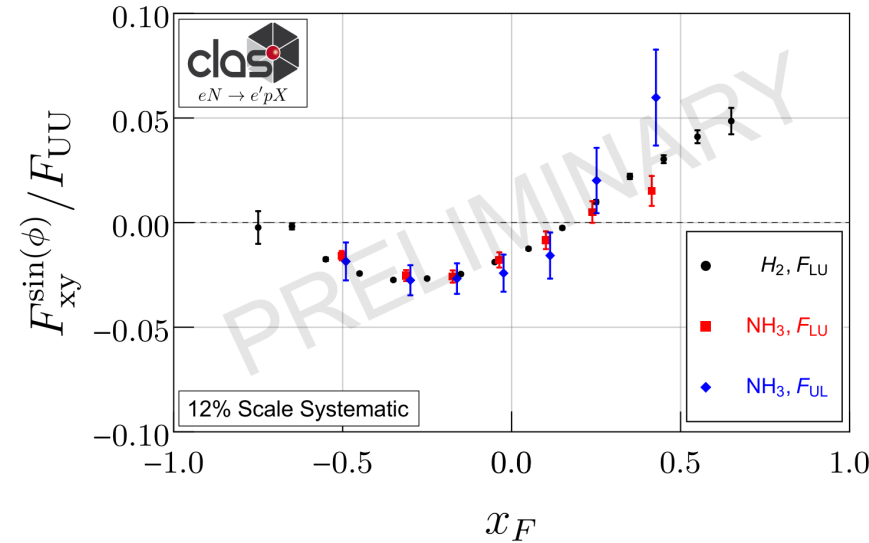
- Key for understanding how to separate *current* vs. *target* fragmentation
- **RG-C** is a great laboratory for testing TFR phenomena
 - No Collins mechanism in TFR $\rightarrow F_{UL}^{\sin 2\phi} \approx 0$ and simpler structure functions
 - Test nuclear medium modification in **NH₃'s** F_{LU} vs. **H₂'s** F_{LU} (RG-A)
 - Access familiar TMD/PDFs with different systematics

Preliminary Analysis: Fracture Functions

$$ep \rightarrow e'p X$$

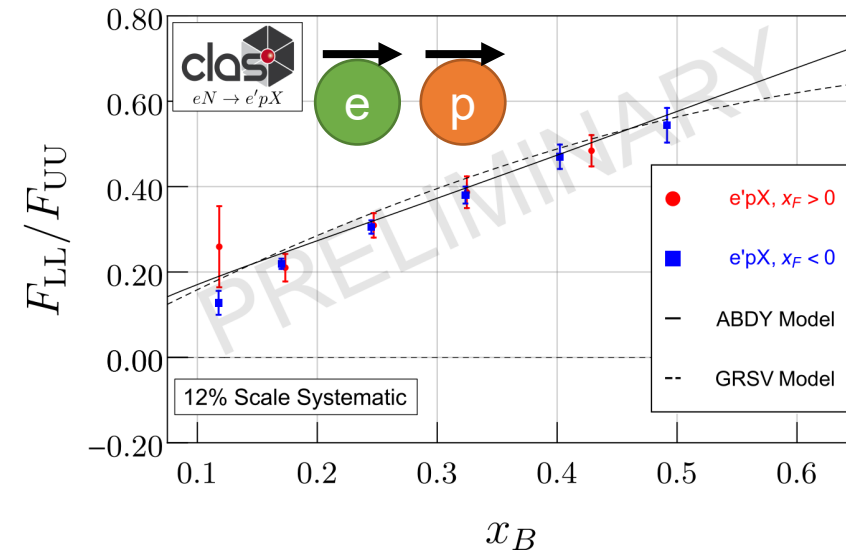


No Collins mechanism
in **TFR** $\rightarrow F_{UL}^{\sin 2\phi} \approx 0$



Visible separation
between TFR ($x_F < 0$)
and CFR ($x_F > 0$)
contributions

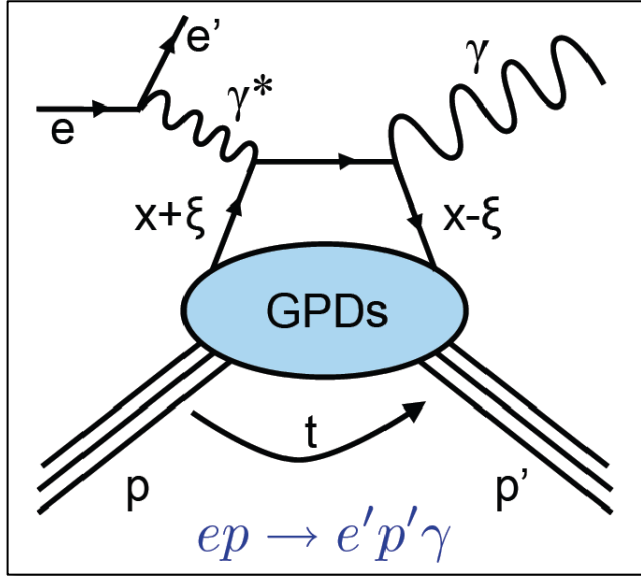
Minimal nuclear medium
modification



TFR Access to helicity
distribution g_{1L}

$$A_{LL} = \lambda_\ell S_L \frac{\sqrt{1 - \epsilon^2} F_{LL}}{F_{UU,T}}$$

Preliminary Analysis: pDVCS on NH_3



$$\mathcal{F}_p(\xi, t) = \frac{4}{9}\mathcal{F}_u(\xi, t) + \frac{1}{9}\mathcal{F}_d(\xi, t)$$

$$\mathcal{F}_n(\xi, t) = \frac{4}{9}\mathcal{F}_d(\xi, t) + \frac{1}{9}\mathcal{F}_u(\xi, t)$$

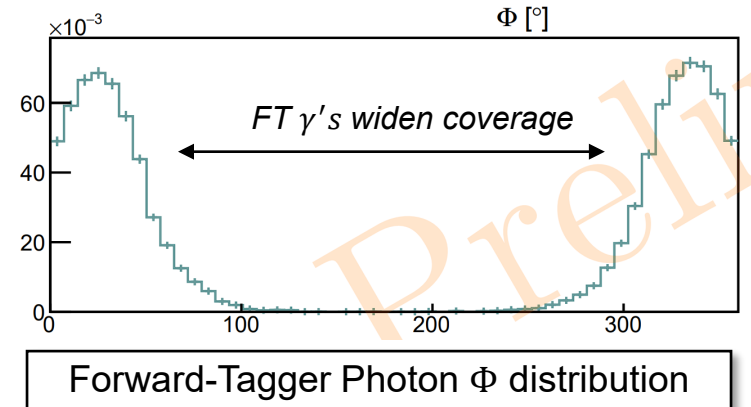
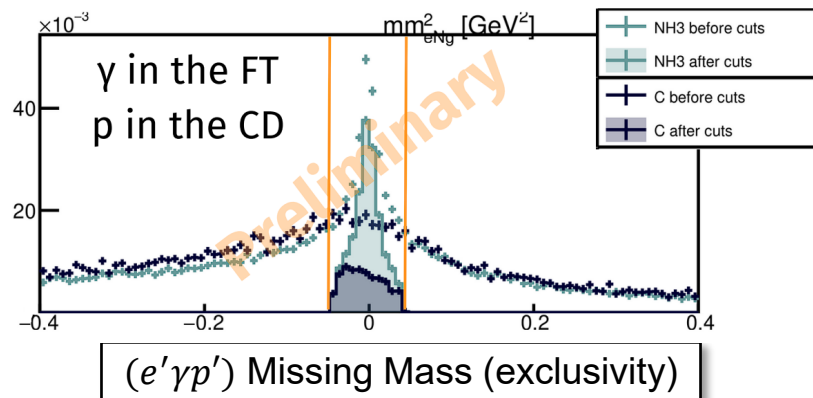
★ Flavor Decomposition ★

- GPDs give a 3-d partonic picture in terms of longitudinal momentum, transverse spatial position, and their correlations
- pDVCS (NH_3)** measurements at RG-C give access to A_{LU} , A_{UL} , A_{LL}
- With **nDVCS (ND_3)** → Separation of u , d Compton Form Factors

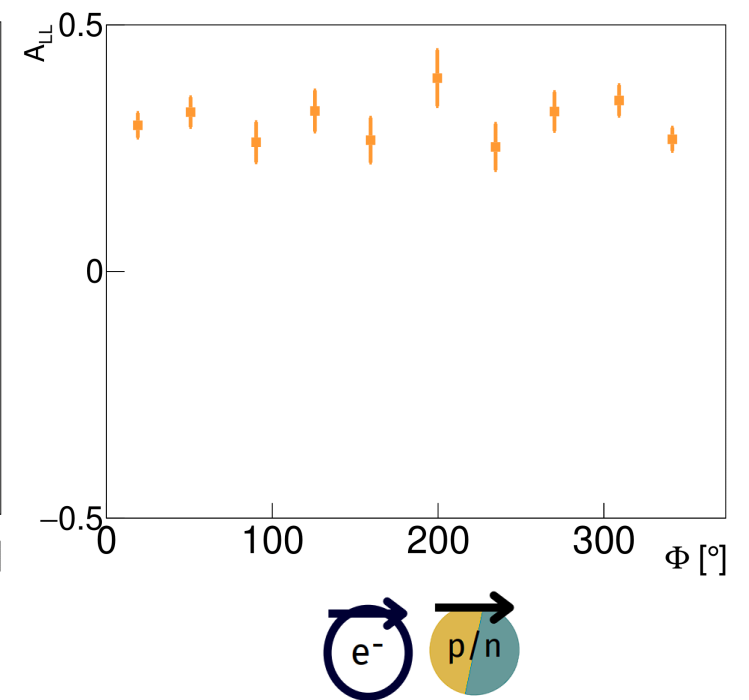
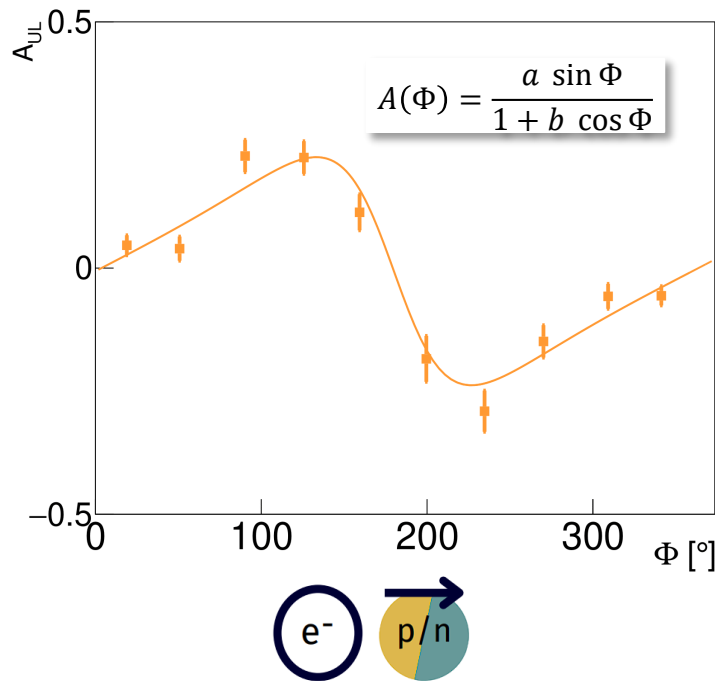
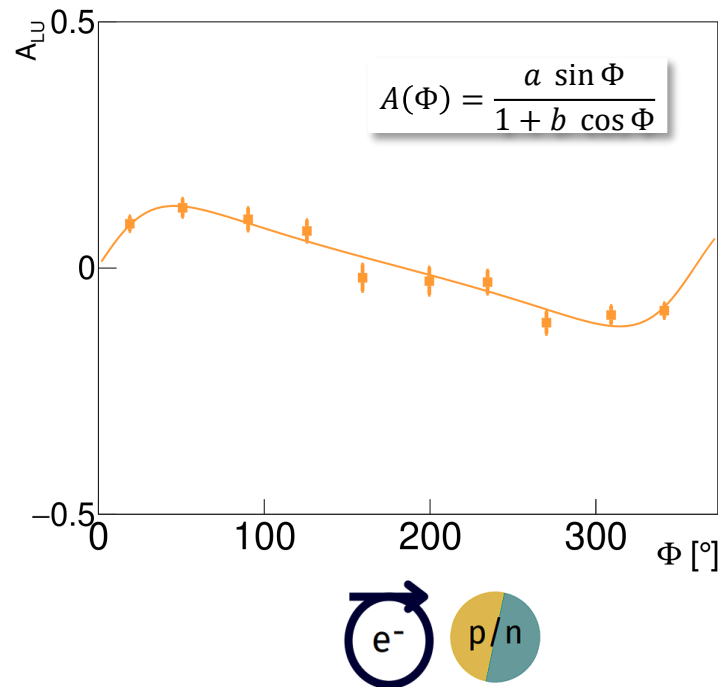
$$\textcircled{e^-} \textcircled{p/n} \quad \Delta\sigma_{LU} \simeq \sin(\phi) \Im \left[F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} - \xi \frac{t}{4M^2} F_2 \mathcal{E} \right]$$

$$\textcircled{e^-} \textcircled{p/n} \quad \Delta\sigma_{UL} \simeq \sin(\phi) \Im \left[F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2) (\mathcal{H} + \frac{x_{bj}}{2} \mathcal{E}) - \xi \left(\frac{x_{bj}}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \right]$$

$$\textcircled{e^-} \textcircled{p/n} \quad \Delta\sigma_{LL} \simeq (A + B \cos(\phi)) \Re \left[F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2) (\mathcal{H} + \frac{x_{bj}}{2} \mathcal{E}) - \xi \left(\frac{x_{bj}}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \right]$$



Preliminary Analysis: pDVCS on NH_3



Run Group C Summary

RG-C is the *first longitudinally polarized target experiment* using the CLAS12 detector system in JLab's 12 GeV era

- Large acceptance given by the capabilities of CLAS12 to explore a wider kinematic phase space
- Broad physics program: Structure functions, TMDs, GPDs
- Polarized p and d --> quark flavor sensitivity
- Unprecedented polarized target and beam statistics capable of performing multidimensional binning of observables
- Preliminary 5% of data has been processed (stay tuned!)

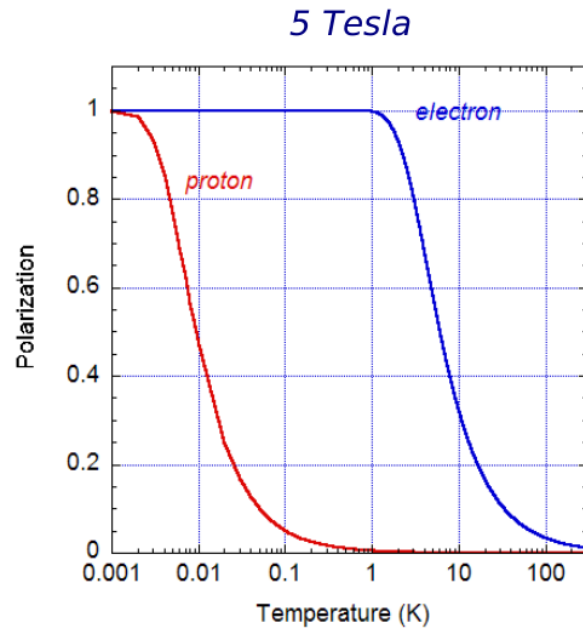
Thanks for listening!



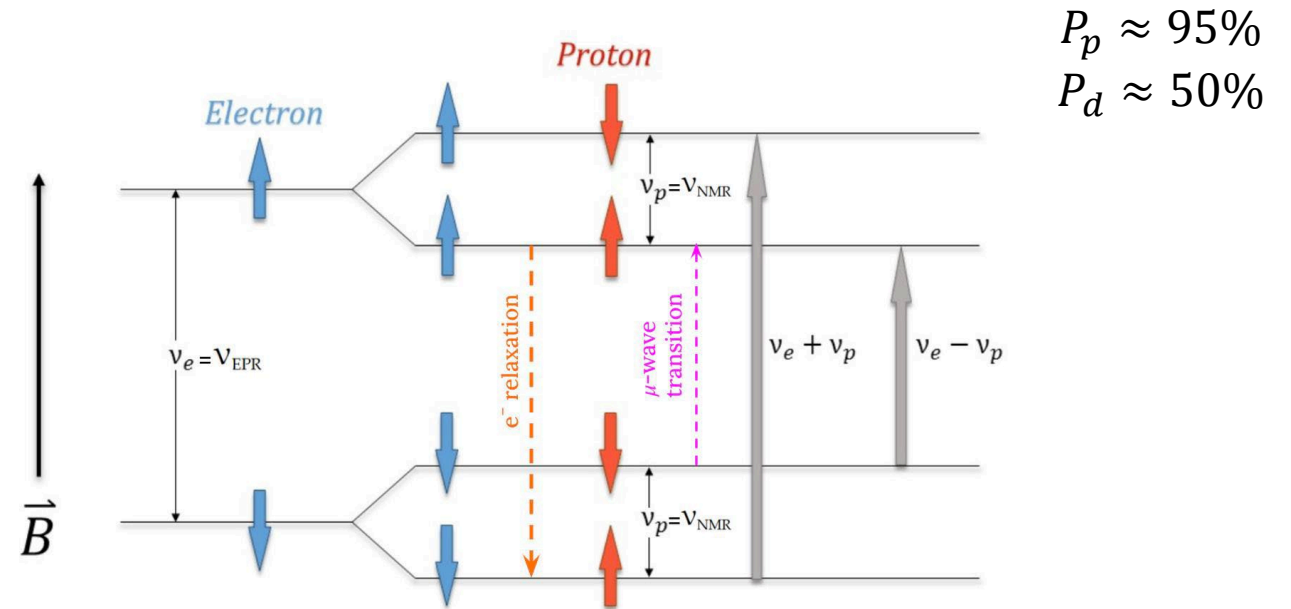
Extra Slides

Dynamic Nuclear Polarization

Step 1: Brute Force polarization of free e^- with 5T solenoid field



Step 2: Induce electron-nuclei spin exchange with 140 GHz microwaves



$$P = \tanh\left(\frac{\mu B}{k_B T}\right)$$

➤ Learn more at Pushpa Pandey's talk on Tuesday!