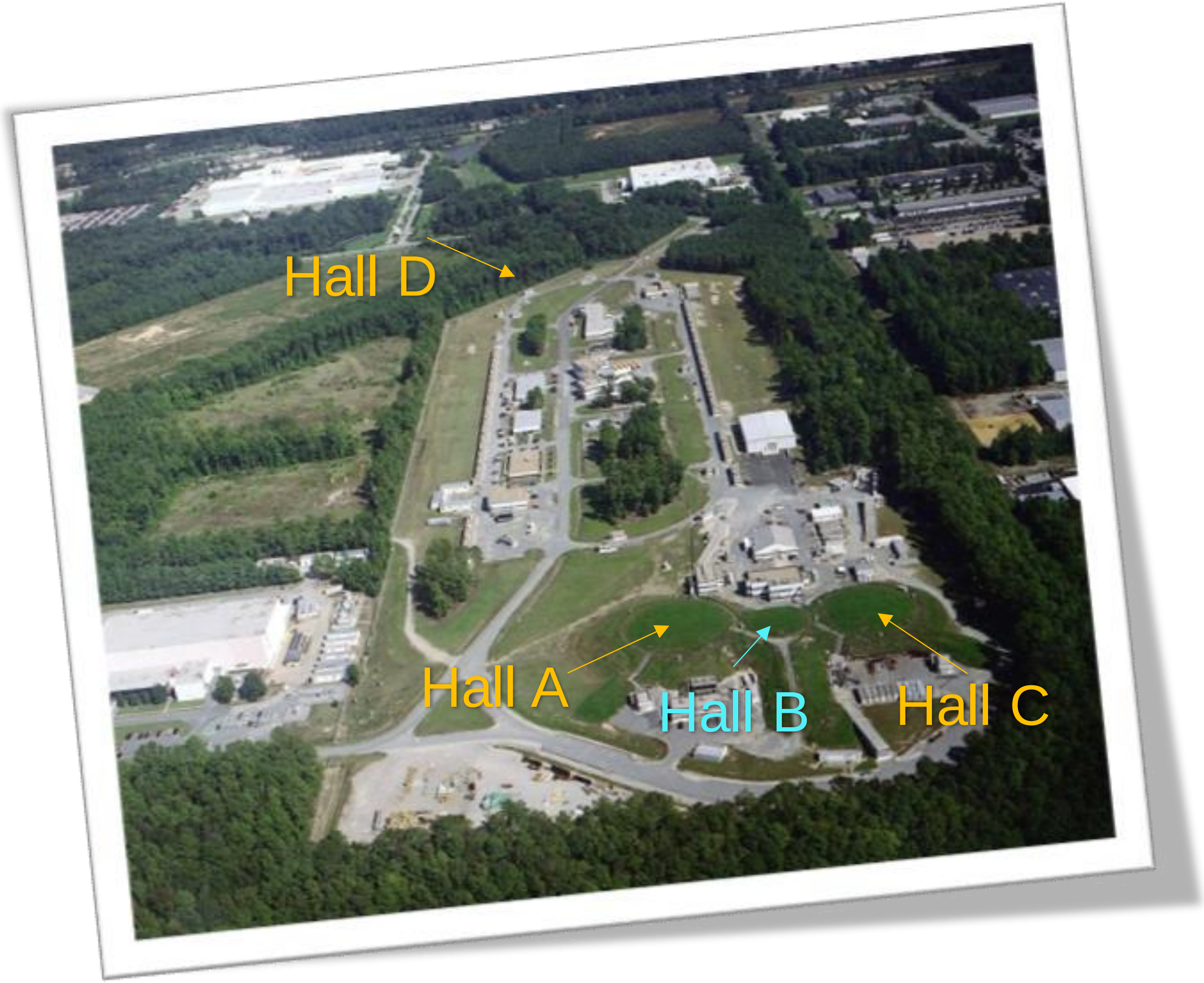
Spin observables in Deep Processes with CLAS12 at Jefferson Lab

Gregory Matousek

September 25th 2023

Jefferson National 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 (~85%), high luminosity (up to 120μA) electron beams at 10.6 – 12 GeV to four experimental halls

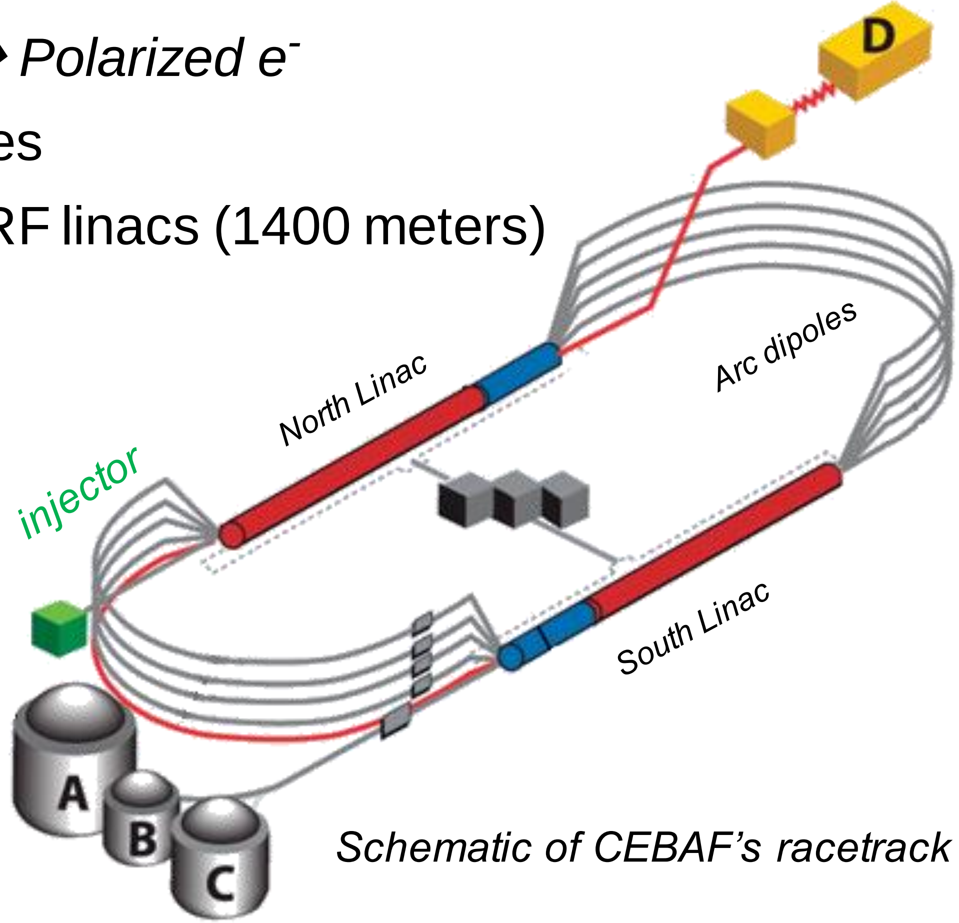
Injector: *Circularly Pol. Light → GaAs photocathode → Polarized e⁻*

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)

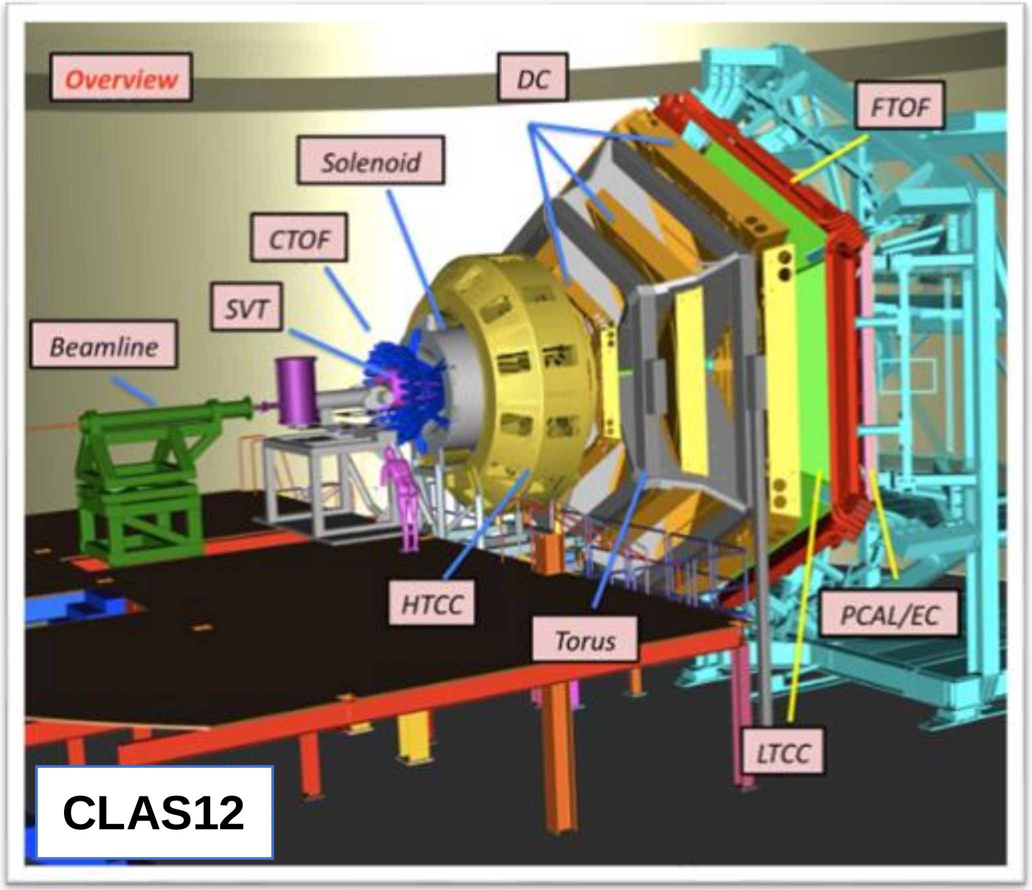
Arc Dipoles



Schematic of CEBAF's racetrack

CEBAF Large Acceptance Spectrometer (CLAS12)

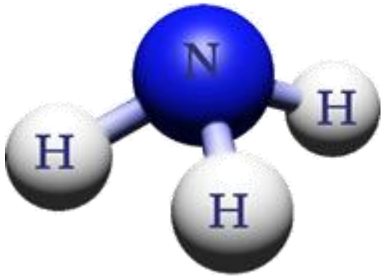
- Wide coverage detector system capable of ranging particle ID (*e, p, n,* γ, π, *K*)
  - Near full coverage in azimuthal ϕ , $\sim 5° - 140°$ in lab scattering θ
- Fixed-target experiment **(RG-C is the first polarized target experiment at Hall-B in the 12 GeV era)**
- ~10.5 GeV, ~85% longitudinally polarized electron beam at ~4-8nA beam current



CLAS12 Detector System

Run Group C @ CLAS12

- Polarized fixed target experiment (June 2022 – March 2023)
  - Dynamically polarized **NH_3 (proton)** and **ND_3 (deuteron)** targets
  - Calibration targets **C**, **CH_2** and **CD_2**



- <u>Physics Goals</u>

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

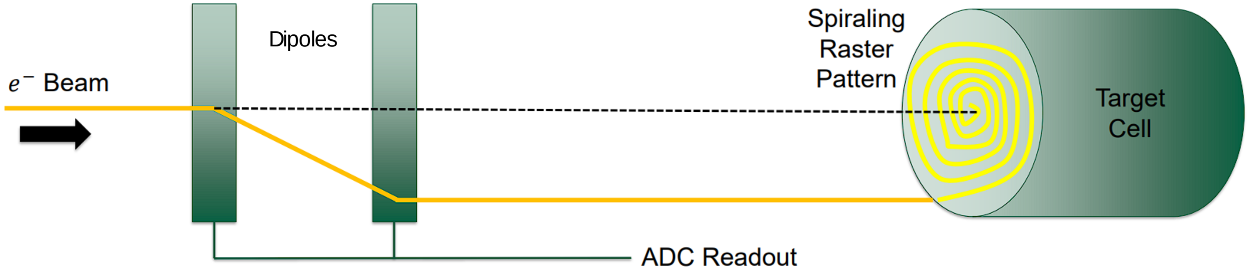
Experiment Title	Key Observables	Preliminary
Longitudinal Spin Structure of the Nucleon	Polarized parton distributions, gluon helicity, higher twist	---
DVCS on the neutron with polarized deuterium target	Neutron Compton Form Factors	---
DVCS on longitudinally polarized proton target	Helicity dependent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

RG-C Experimental Configuration

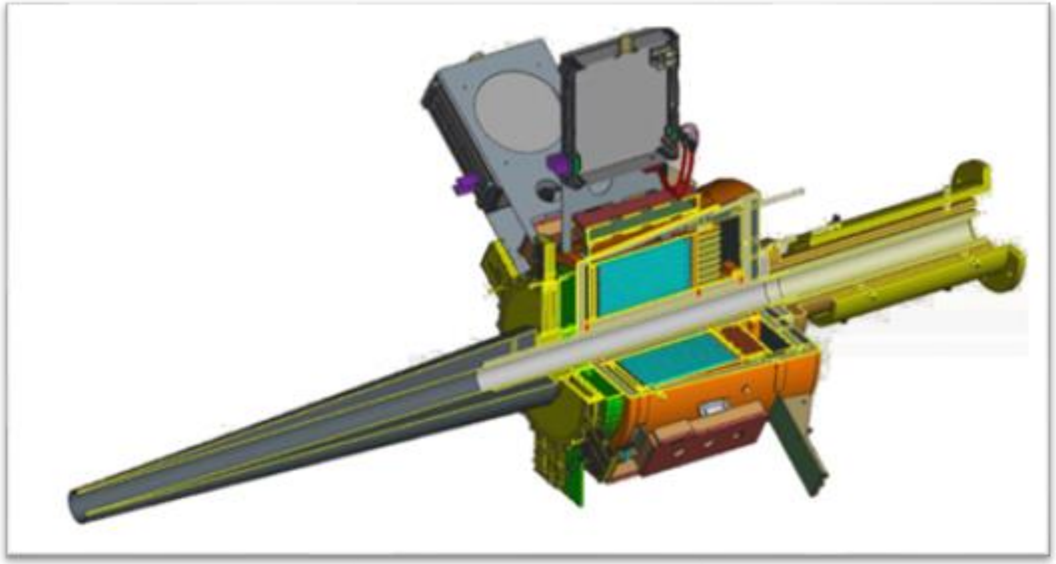
- Standard CLAS12 forward detectors ($5^\circ < \theta < 35^\circ$)
  - ❖ **NEW** 2nd azimuthal sector RICH detector installed

- Two beam current configurations
  - *(~4-4.5 months)* **4nA:** Forward tagger installed ($2^\circ < \theta < 5^\circ$) widen kinematic 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



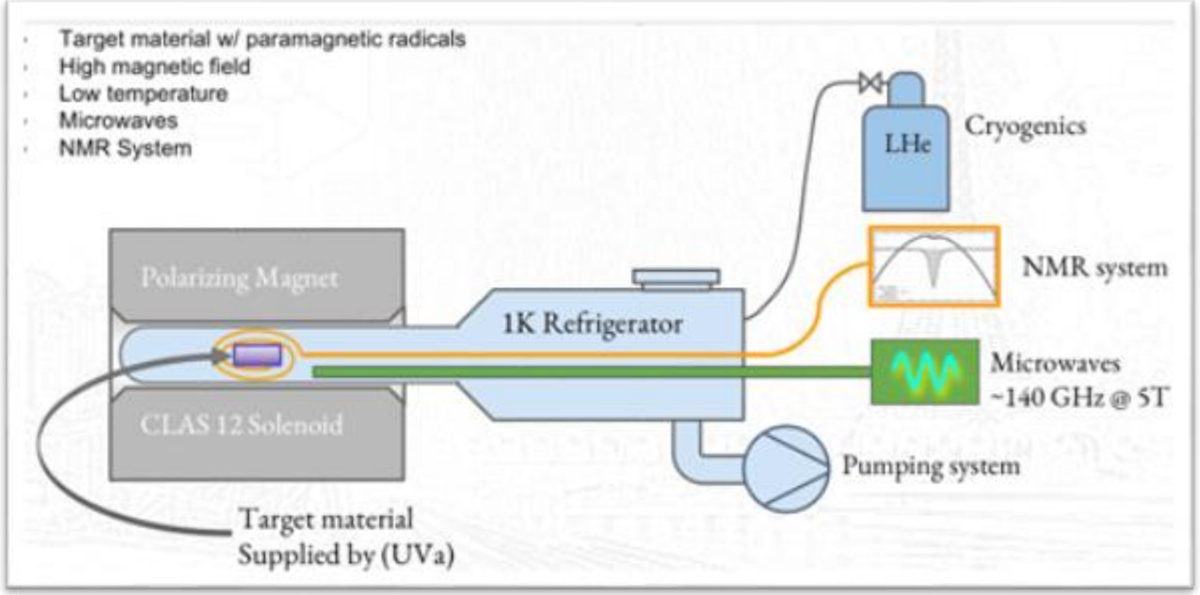
(Bottom) Schematic of the CLAS12 forward tagger

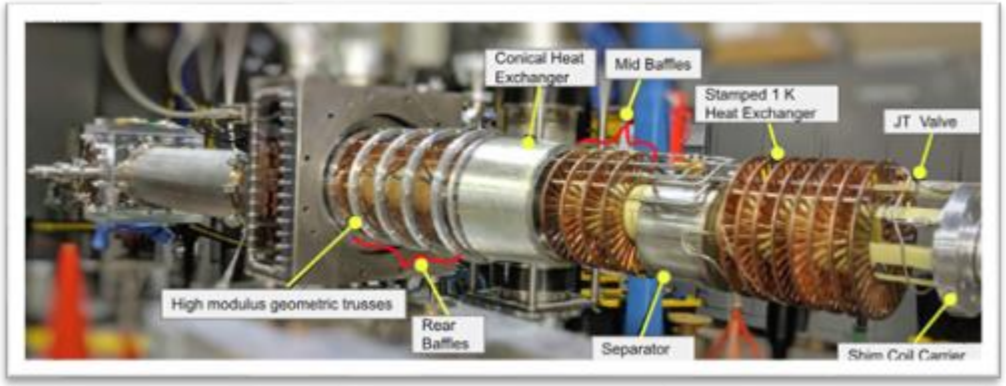
RG-C's Polarized Target

Provides longitudinally polarized p and d

Design Features

- 1K Trolley with swappable 5cm long target cartridges (videos in Pushpa's Tues. talk!)
- 5T solenoid magnet + 140GHz μwave waveguide cavity
- Nested NMR system for live target polarization readings





Cryogenics

- Cryostat: 4.2m long horizontal 1K evaporation refrigerator
- Liquid helium supplied from JLab's End Station Refrigerator (ESR)

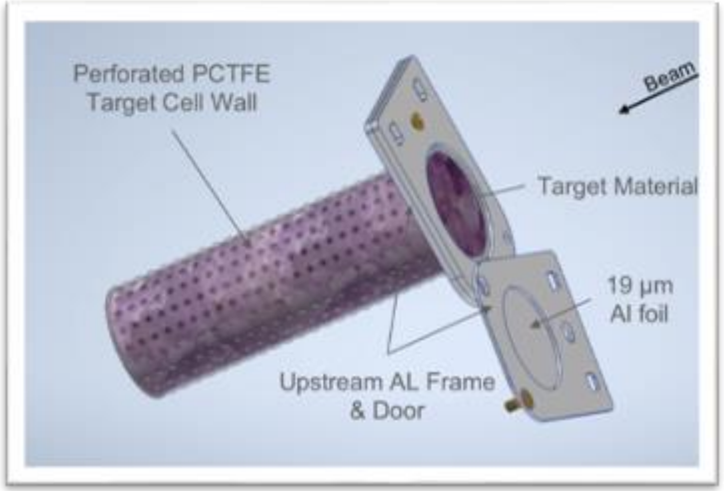
RG-C's Polarized Target

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

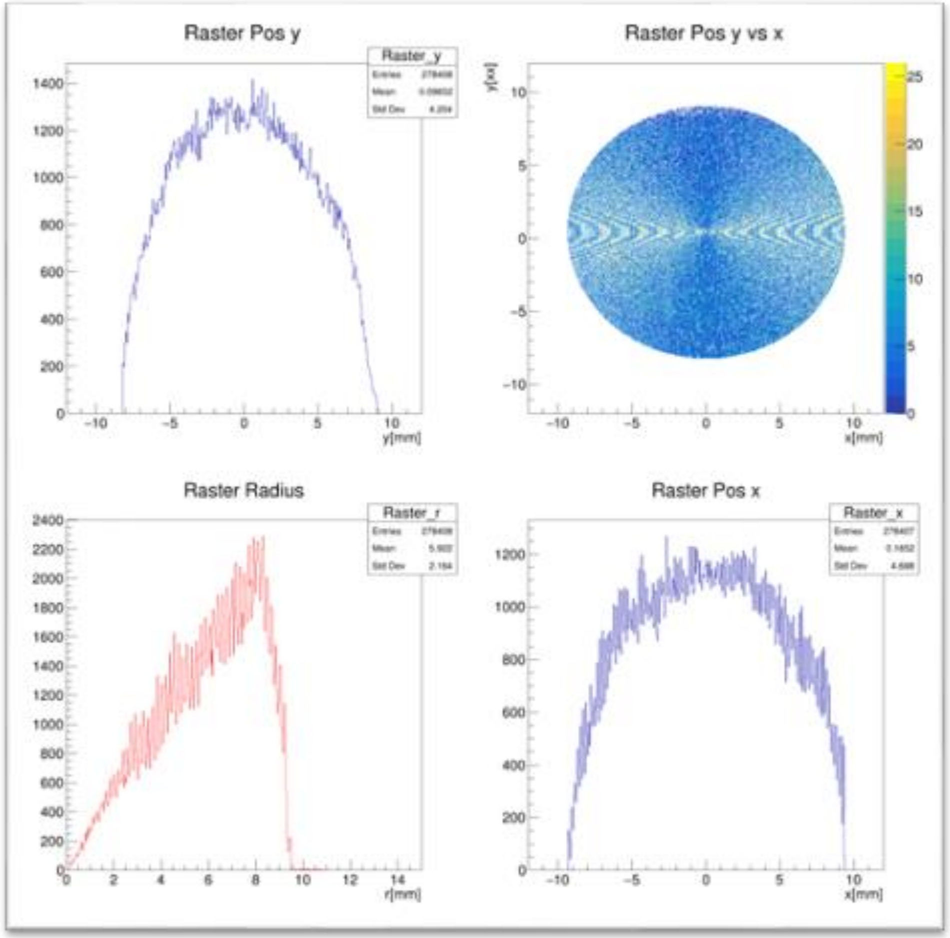
- Crushed pellet-sized beads
- Perforated cell walls

} ***Heat removal***

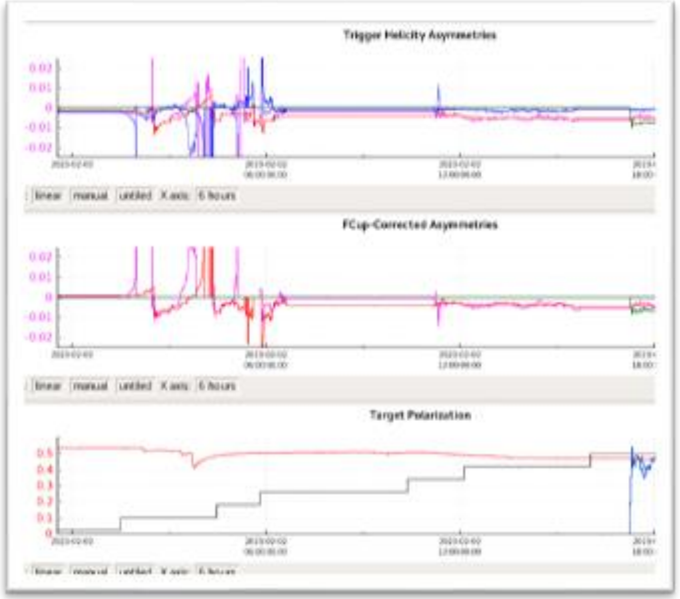
Ammonia beads sent by collaborators at University of Virginia (UVa)



Online Monitoring



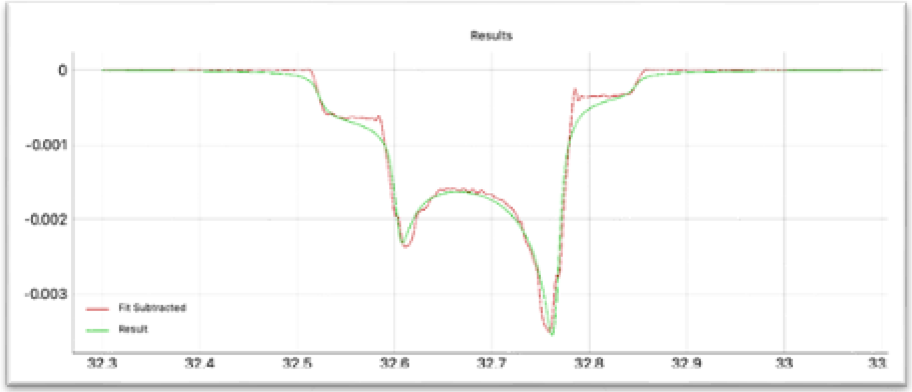
Live updating raster monitoring



Scattered e^- trigger asymmetries

Accumulated beam charge asymmetries

NMR Target Polarization monitoring



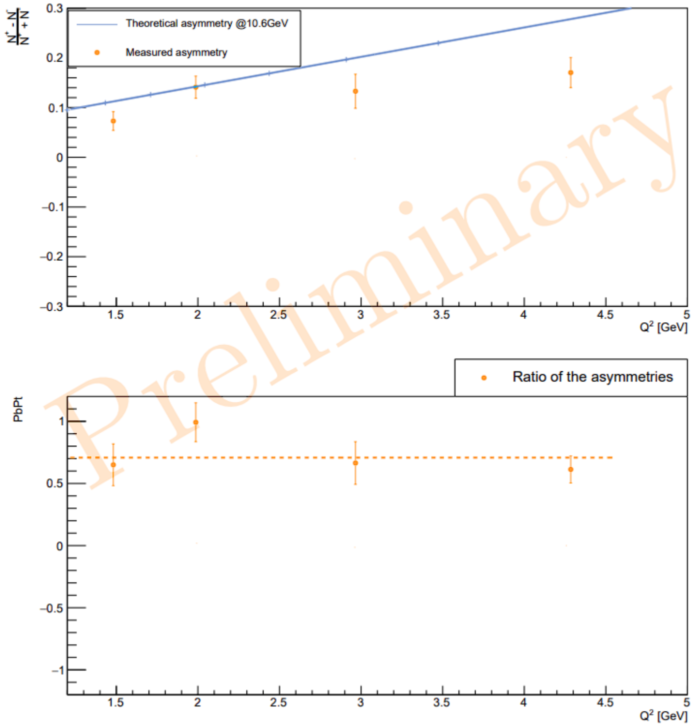
NMR software measuring d polarization

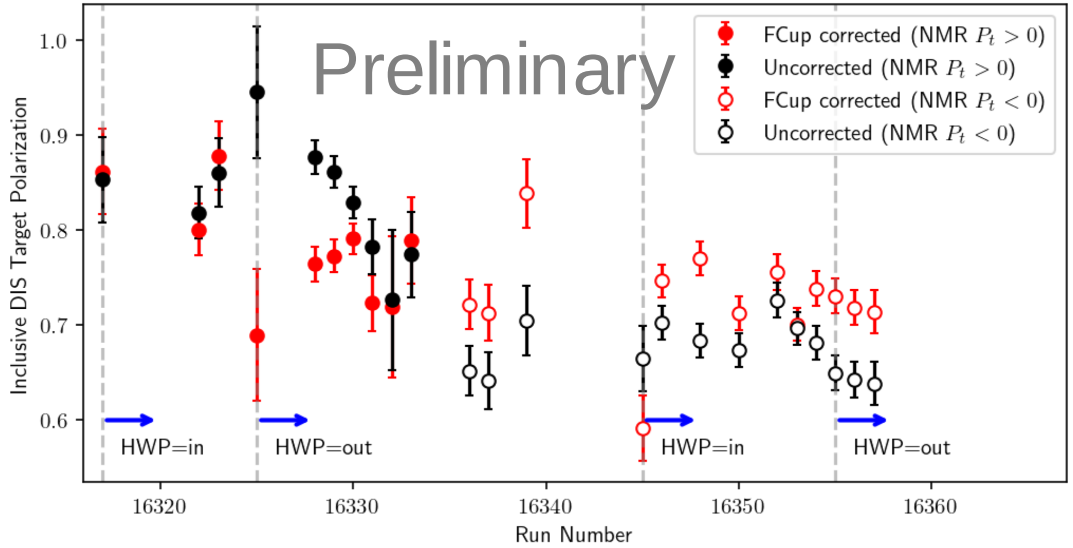
Offline Monitoring

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





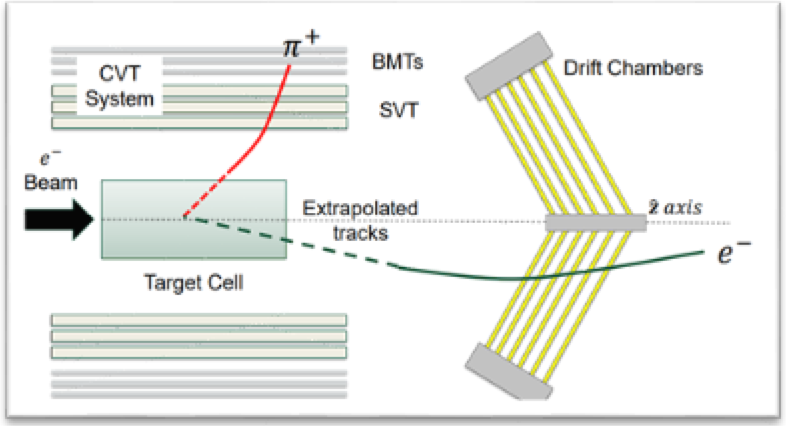
(Top) Deep inelastic scattering asymmetries from NH_3 (Gregory Matousek)

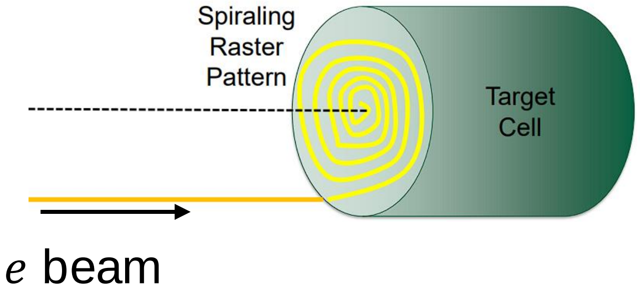
(Left) Elastic scattering asymmetries from NH_3 (Noémie Pilleux)

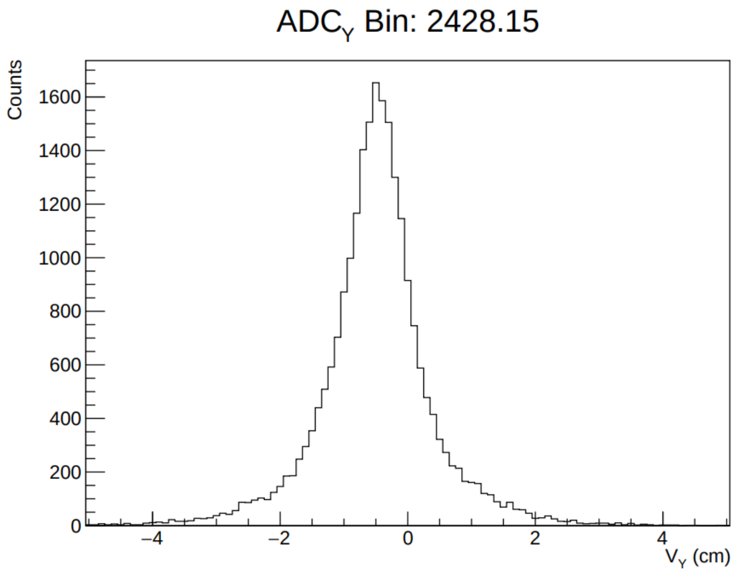
Calibration Efforts

Target Raster Calibration *(Derek Holmberg)*

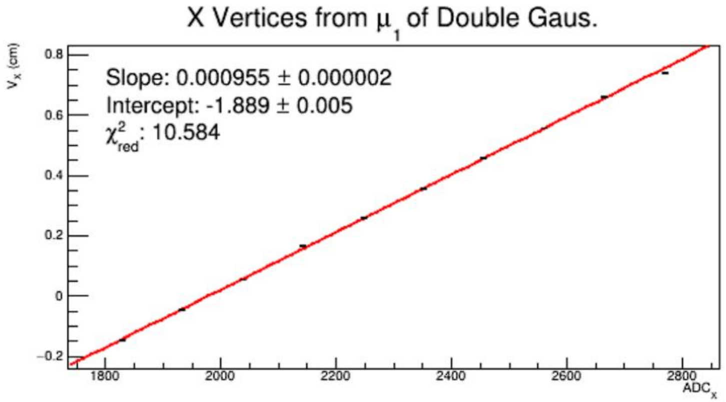
- Analyze extrapolated track vertices and raster $ADC_{x,y}$
- Look at multiple track species (e, π) and detector subsystems (forward, central)
- *** Determine event-by-event beam position in xy-plane for future analyses to utilize ***







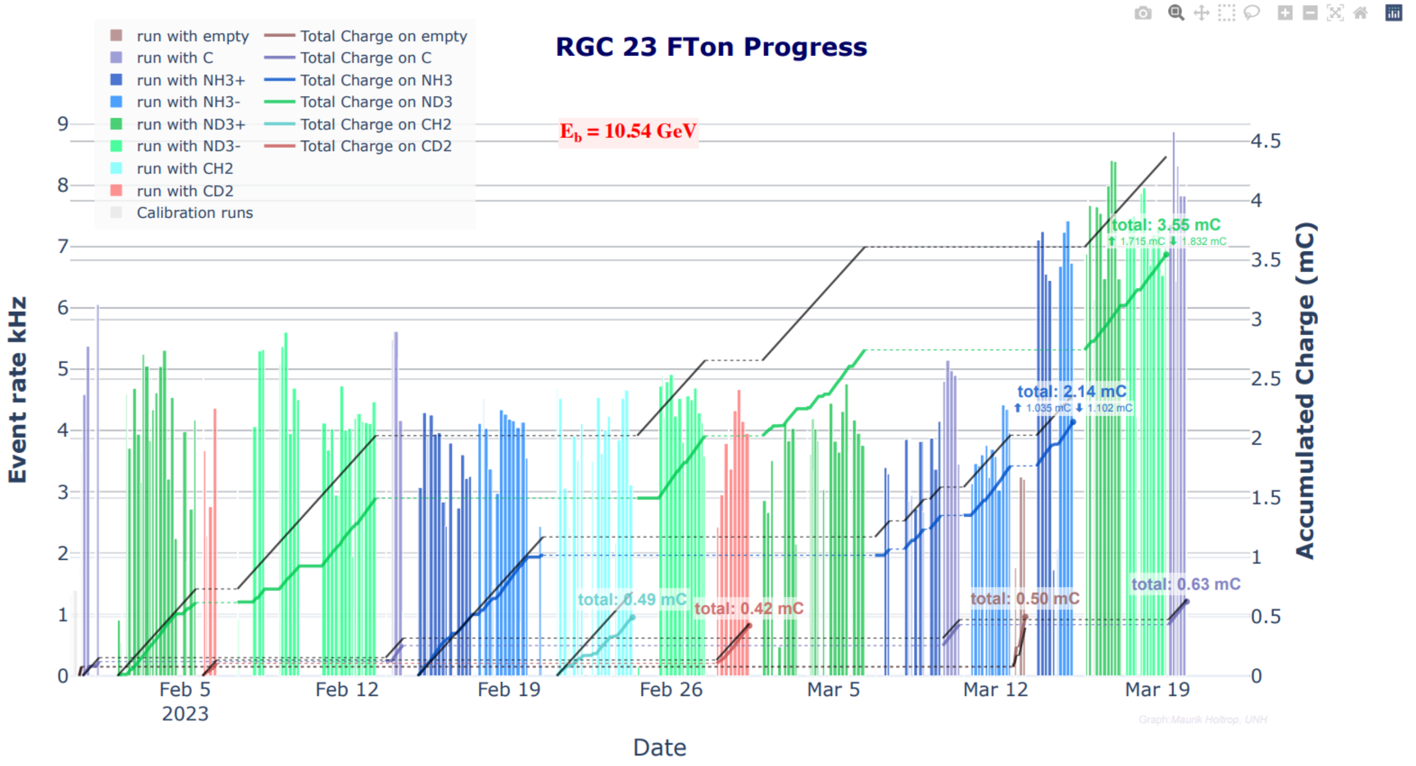
Track vertex *given* ADC signal strength



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

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: ~1.85mC
- ~5% of collected data has been processed for analysis



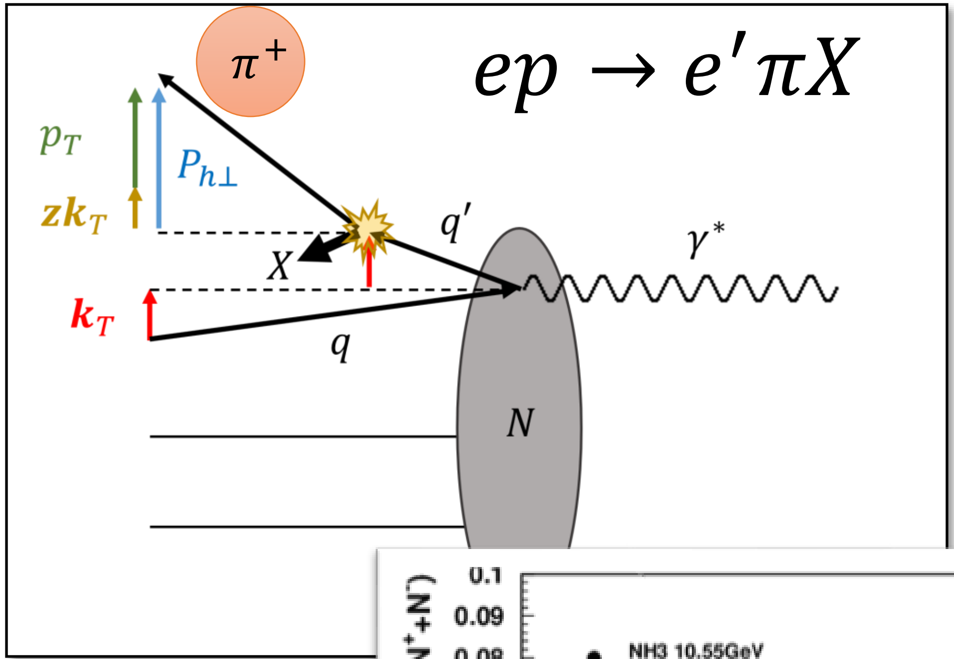
★ Preliminary analyses featured ★ correspond to a ***fraction*** of the total RG-C NH3 data

~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**

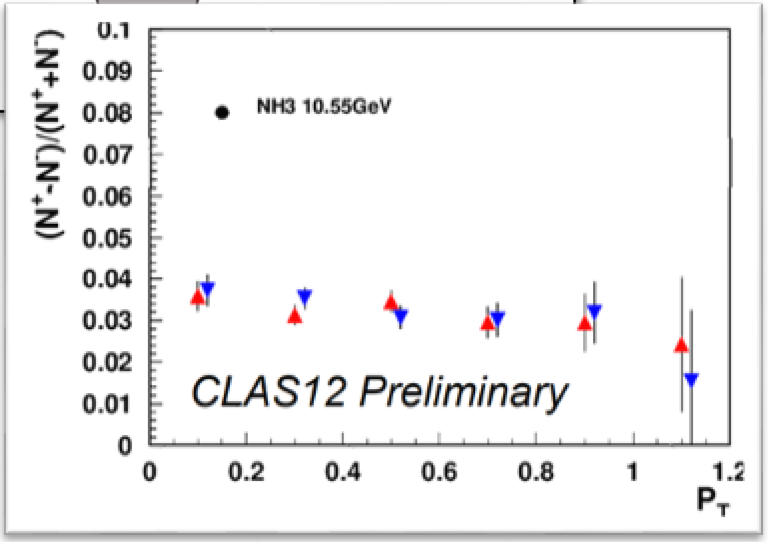


- Measuring **double-spin asymmetry** (F_{LL})
- P_T-dependence → Access the k_T-dependence of the helicity distributions $\boldsymbol{g_1(x, k_T)}$

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

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

Proton helicity *Electron helicity*



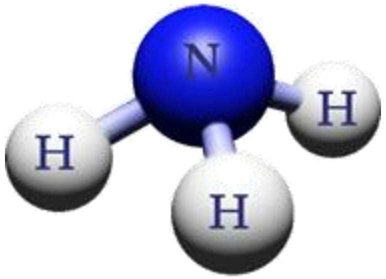
$N^+ \to \lambda S_{||} = 1$

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

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

Convolution over transverse momentum space

Preliminary Analysis: **Pion SIDIS**



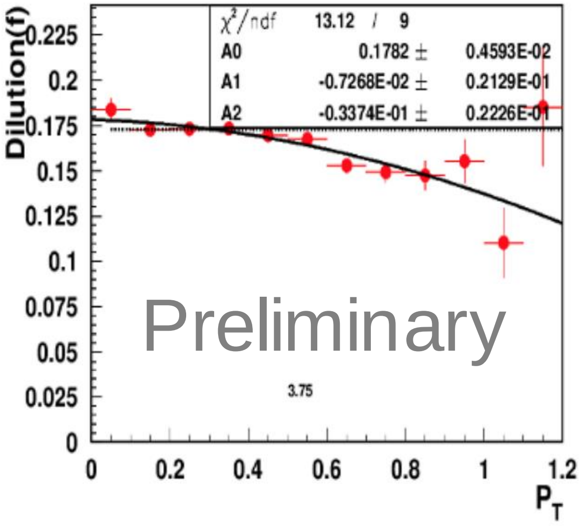
$$A_{LL} = \frac{N^+ - N^-}{N^+ + N^-} \rightarrow \left(\frac{1}{f \times P_b \times P_t \times D(y)}\right)\frac{N^+ - N^-}{N^+ + N^-}$$

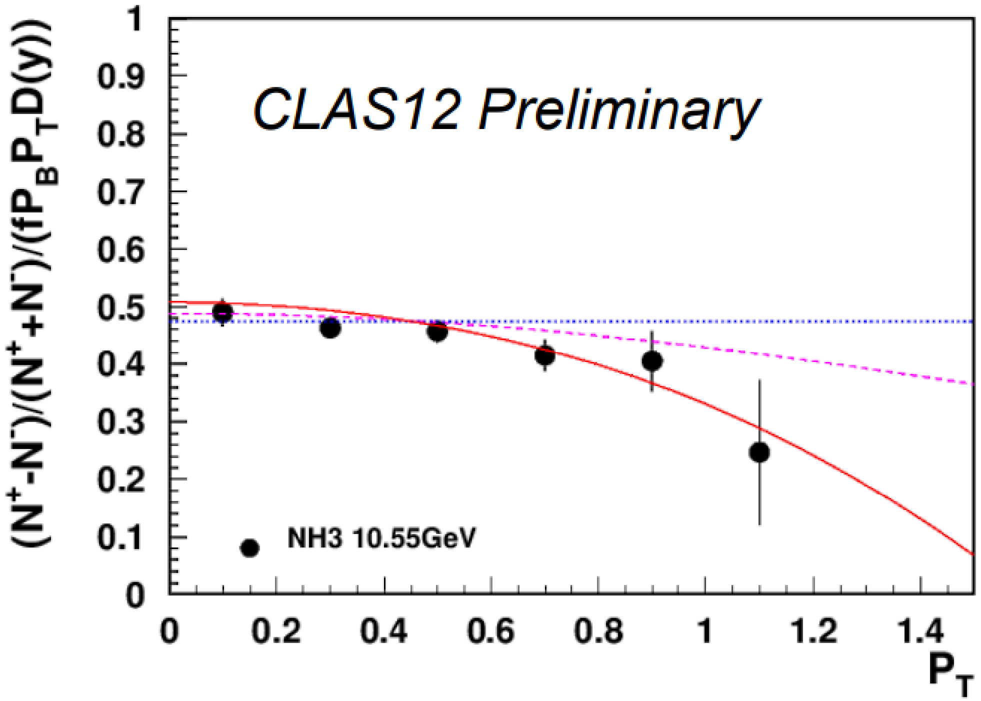
Beam/target polarization

Depolarization factor

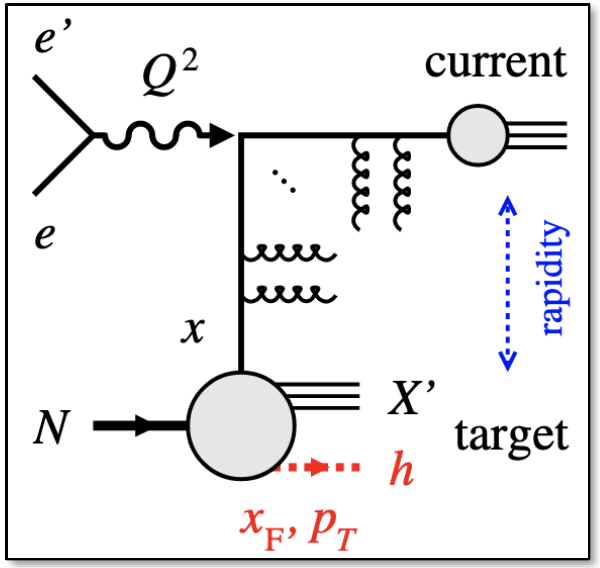
- Bin-by-bin determination of dilution factors
  - Analyze NH_3 vs. C yields
  - Calculate %-age of proton cross section contribution to NH_3

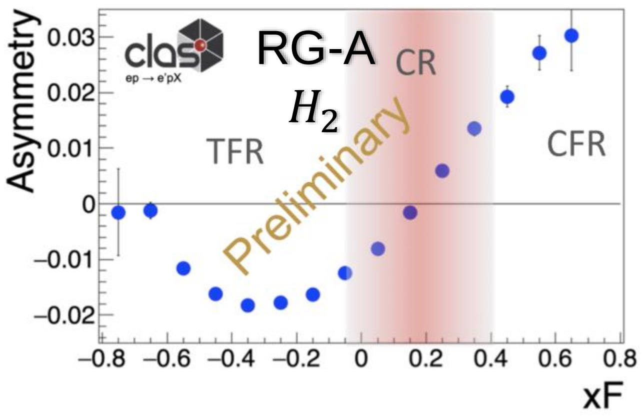
$$f = 1 - \frac{N_C}{N_{NH_3}}$$





Preliminary Analysis: **Fracture Functions**





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

"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

$$\frac{d\sigma^{\mathrm{TFR}}}{dx_B\,dy\,dz} = \sum_a e_a^2\,(1-x_B)\boxed{M_a(x_B,(1-x_B)z)}\frac{d\hat{\sigma}}{dy}$$

- Direct relationship to traditional **PDFs** by integrating over fractional longitudinal nucleon momentum ζ

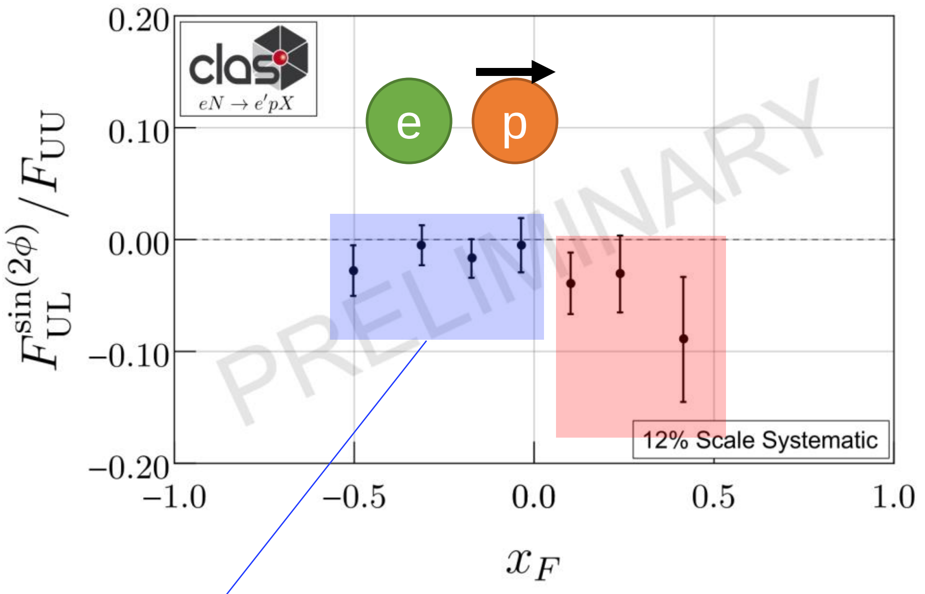
$$\sum_h \int_0^{1-x} d\zeta\,\zeta\,\hat{u}_1(x,\zeta) = (1-x)\,f_1(x)$$

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

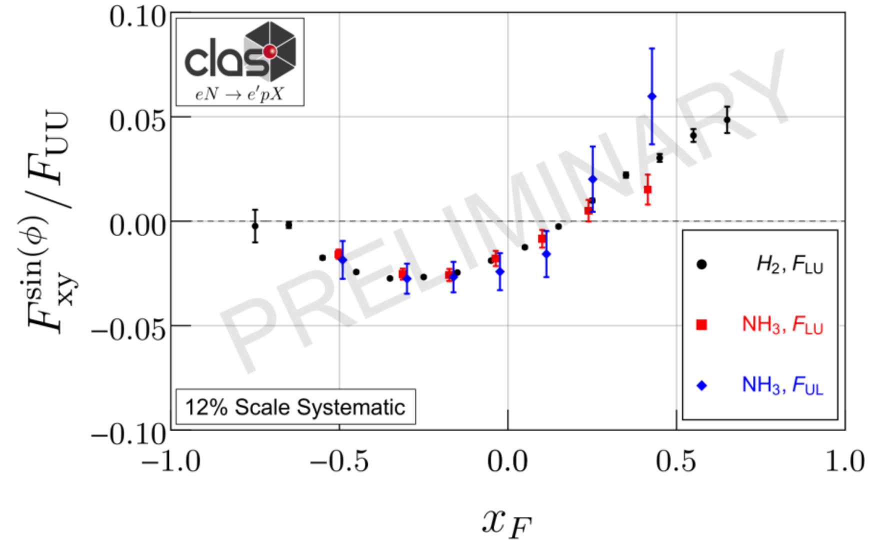
- Key for understanding how to separate *current* vs. *target* fragmentation
- **RG-C** is a great laboratory for testing TFR phenomena
  - No Collins mechanism in TFR → $F_{UL}^{\sin 2\phi} \approx 0$ and simpler structure functions
  - Test nuclear medium modification in NH_3's F_{LU} vs. H_2's F_{LU} (RG-A)
  - Access familiar TMD/PDFs with different systematics

Preliminary Analysis: **Fracture Functions**

$$ep \to e'p\,X$$

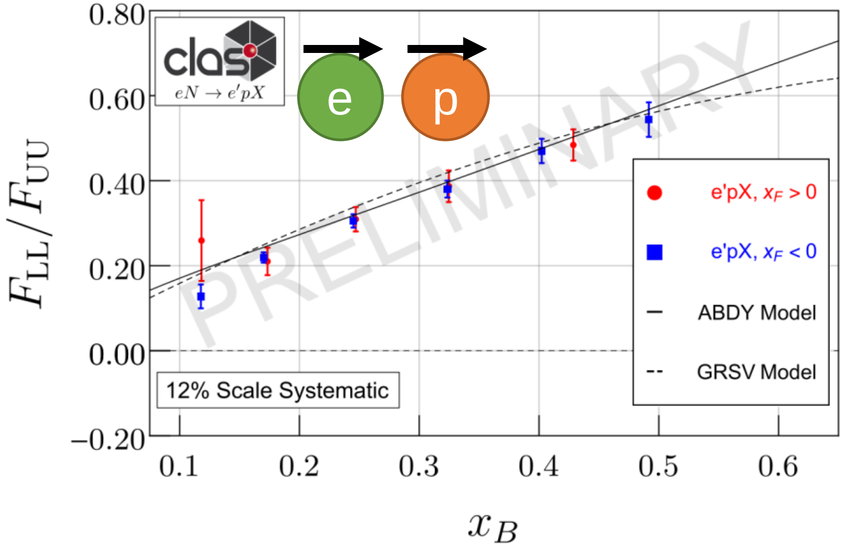


No Collins mechanism
in **TFR** → $F_{UL}^{\sin 2\phi} \approx 0$



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

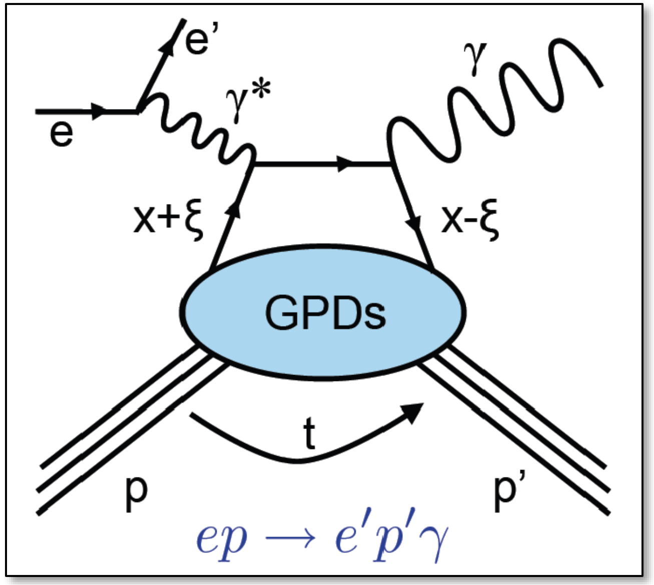
Minimal nuclear medium modification



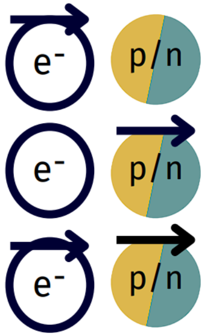
TFR Access to helicity distribution g_{1L}

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

Preliminary Analysis: **pDVCS on NH_3**



- 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



$$\Delta\sigma_{LU} \simeq \sin(\phi)\Im\left[F_1\mathcal{H} + \xi(F1+F2)\tilde{\mathcal{H}} - \xi\frac{t}{4M^2}F_2\mathcal{E}\right]$$

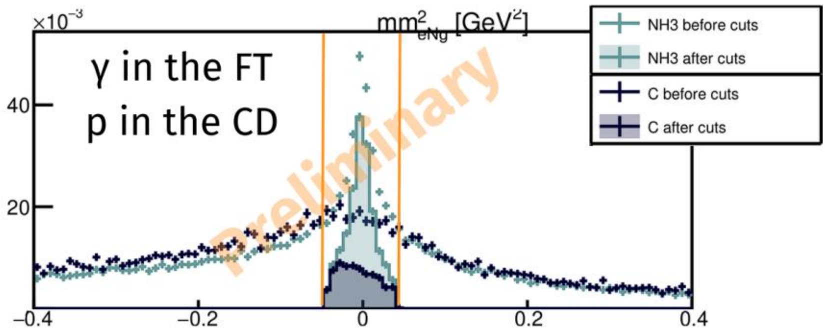
$$\Delta\sigma_{UL} \simeq \sin(\phi)\Im\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$

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

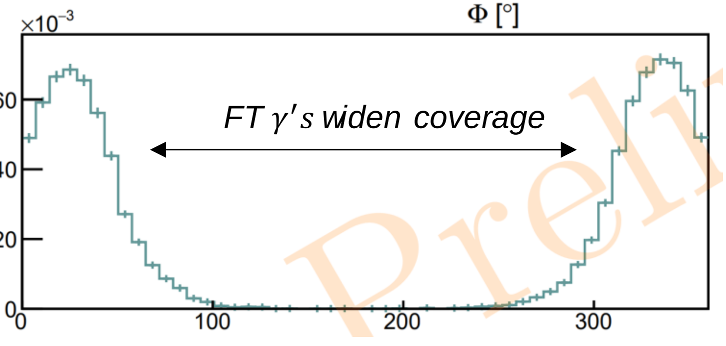
$$\mathcal{F}_p(\xi,t) = \frac{4}{9}\mathcal{F}_u(\xi,t) + \frac{1}{9}\mathcal{F}_d(\xi,t)$$

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

★ *Flavor Decomposition* ★



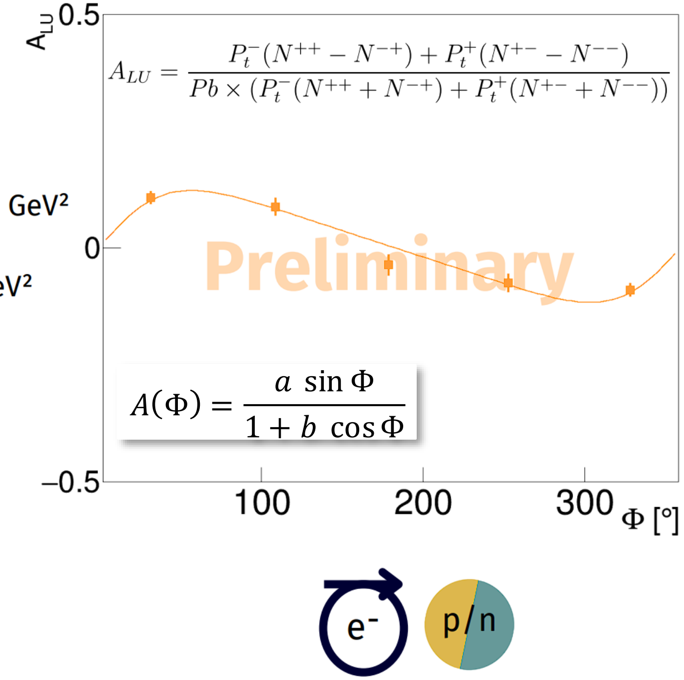
$(e'\gamma p')$ Missing Mass (exclusivity)

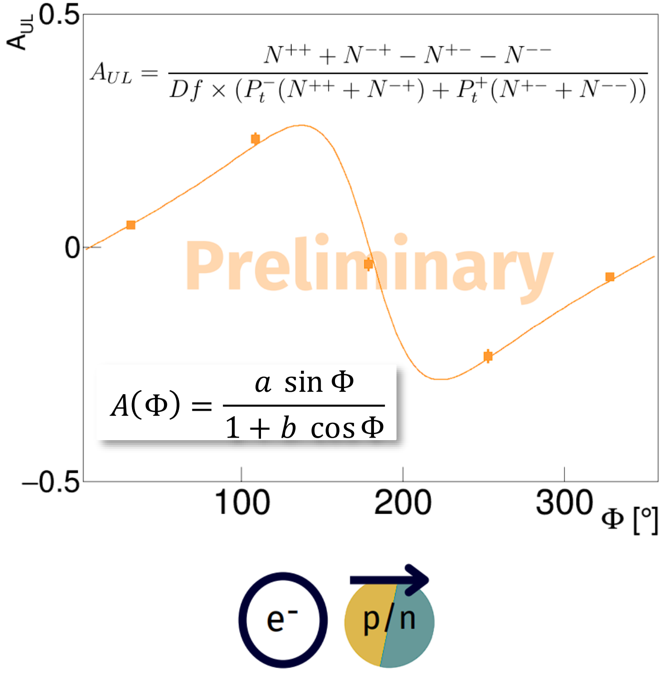


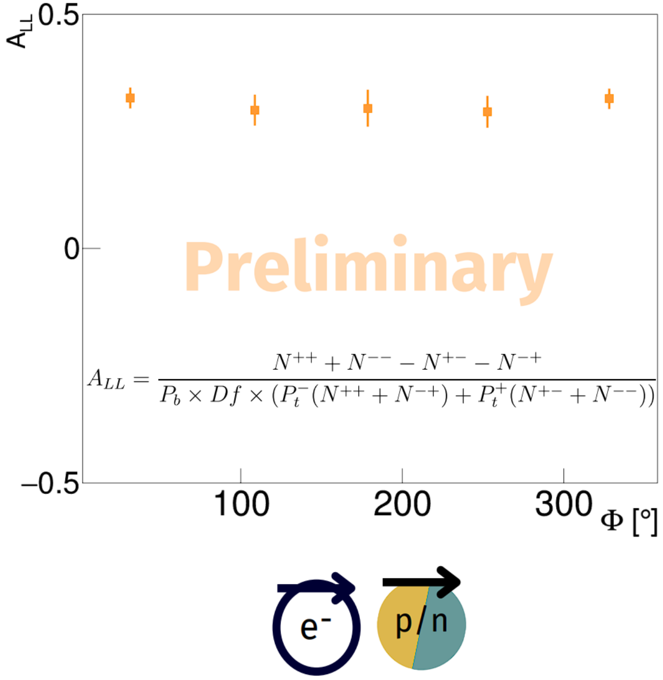
Forward-Tagger Photon Φ distribution

Preliminary Analysis: **pDVCS on NH_3**

- $\langle Q^2 \rangle = 2.5\ \text{GeV}^2$
- $\langle x_{bj} \rangle = 0.2$
- $-t = 0.5\ \text{GeV}^2$







Run Group C Summary

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

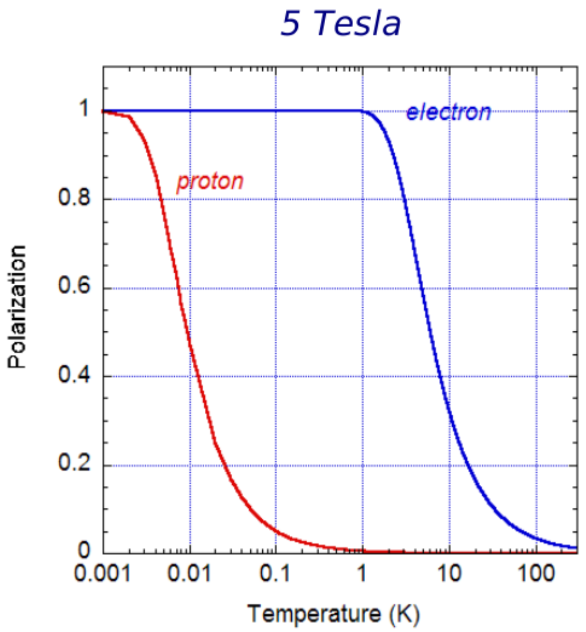
- Broad physics program: Structure functions, TMDs, GPDs
- Polarized *p* and *n* --> quark flavor sensitivity
- Large acceptance to explore a wider kinematic phase space
- Unprecedented polarized target & beam statistics capable of performing multidimensional binning of observables
- Preliminary 5% of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

Thanks for listening!

Extra Slides

Dynamic Nuclear Polarization

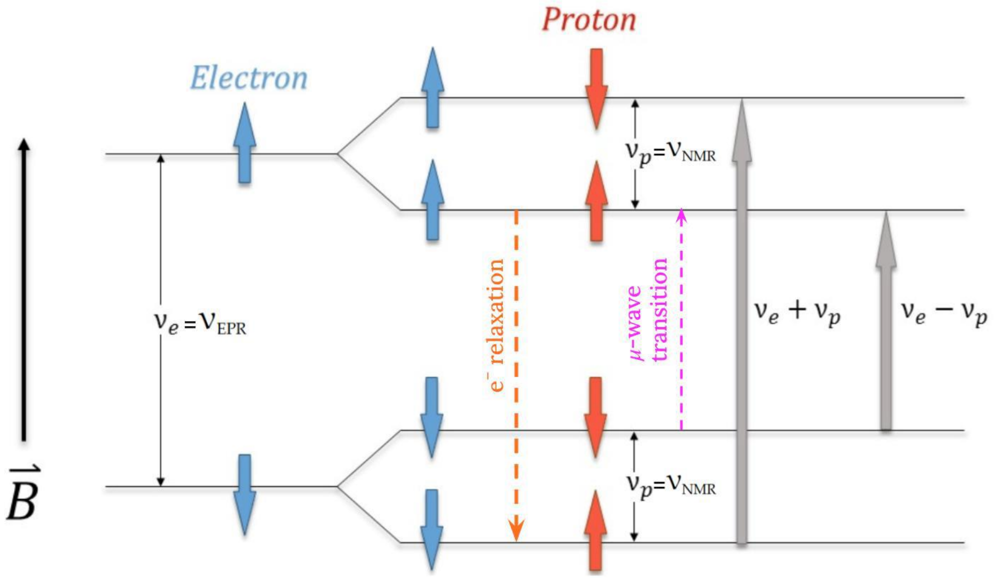
Step 1: Brute Force polarization of free e^- with 5T solenoid field



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

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

$P_p \approx 95\%$
$P_d \approx 50\%$



- *Learn more at Pushpa Pandey's talk on Tuesday!*