DVCS on Polarized Nucleons with the CLAS12 experiment at Jefferson Lab

31st International Workshop on Deep Inelastic Scattering - Grenoble (France)

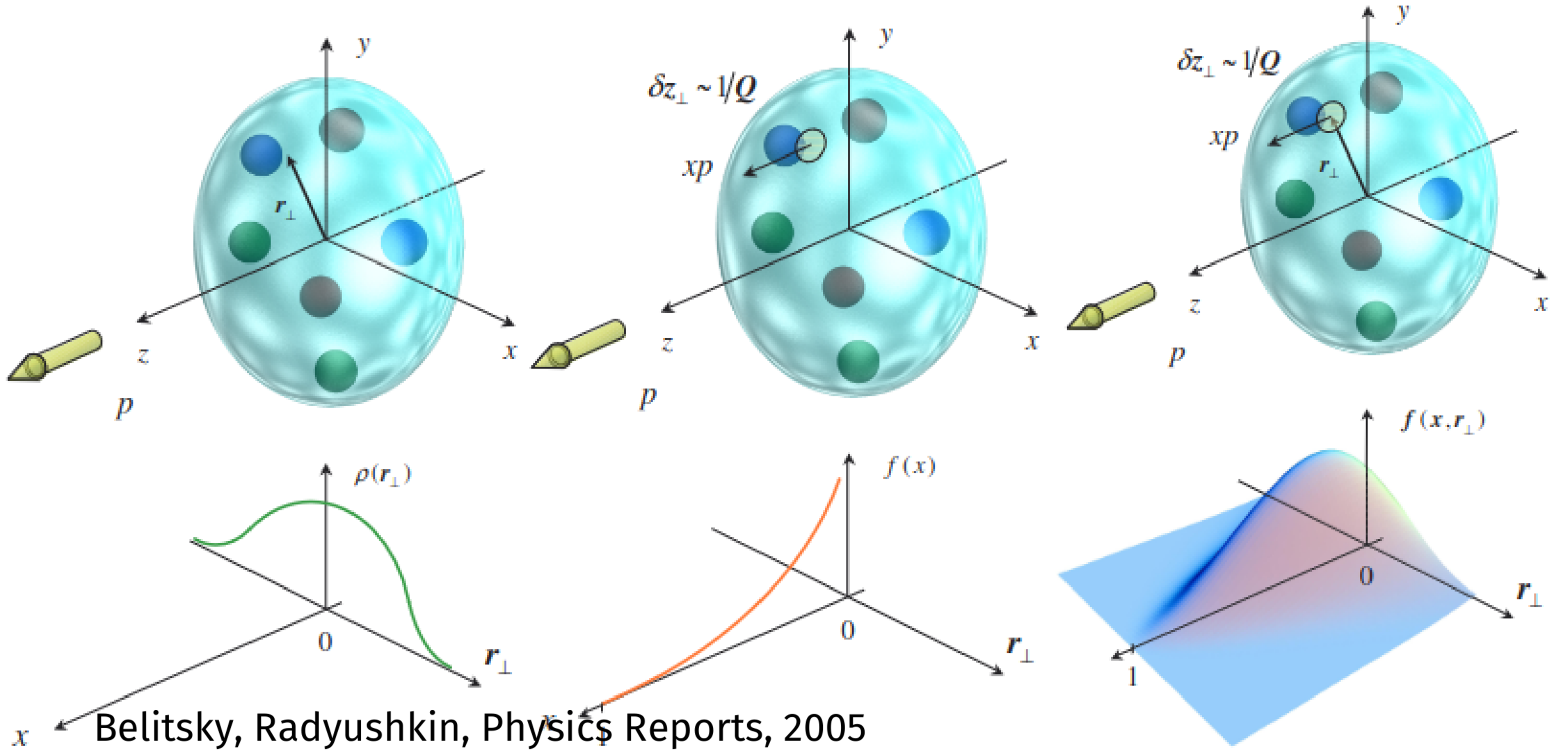
Pilleux Noémie - IJCLab, Paris Saclay University, France

10th April 2024

Understanding the Structure and Properties of Nucleons

- Generalized Parton Distributions (GPDs)

Transverse position, longitudinal momentum and their correlations

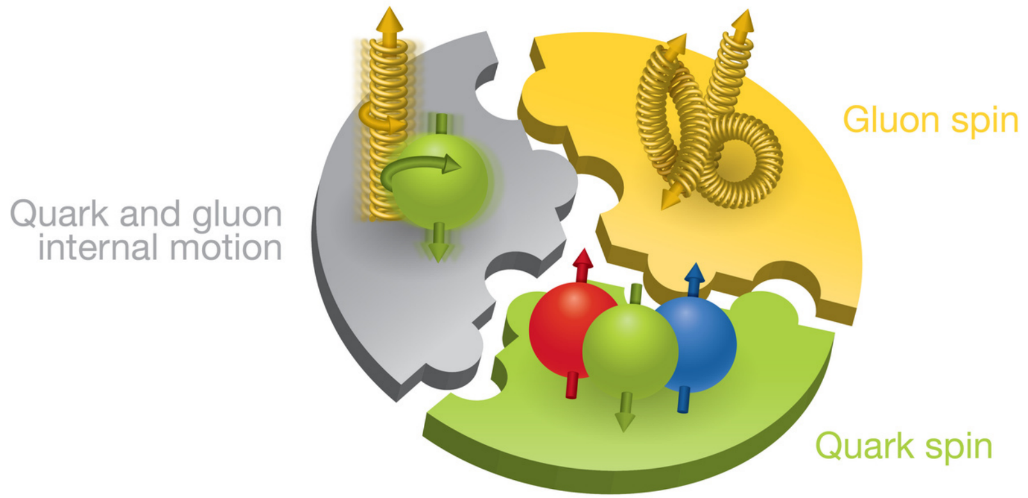


Belitsky, Radyushkin, Physics Reports, 2005

- Proton spin decomposition

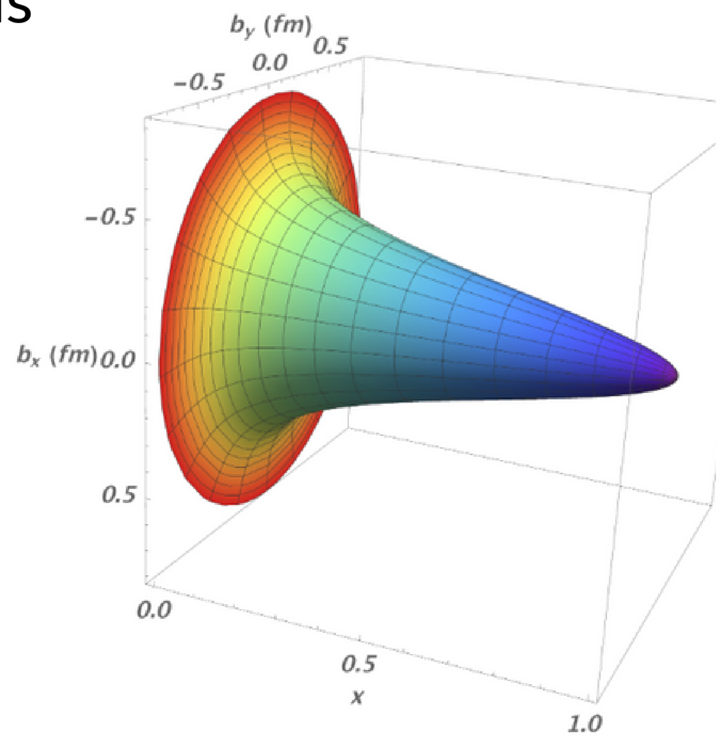
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = \frac{1}{2}\Delta\Sigma + \Delta L$$

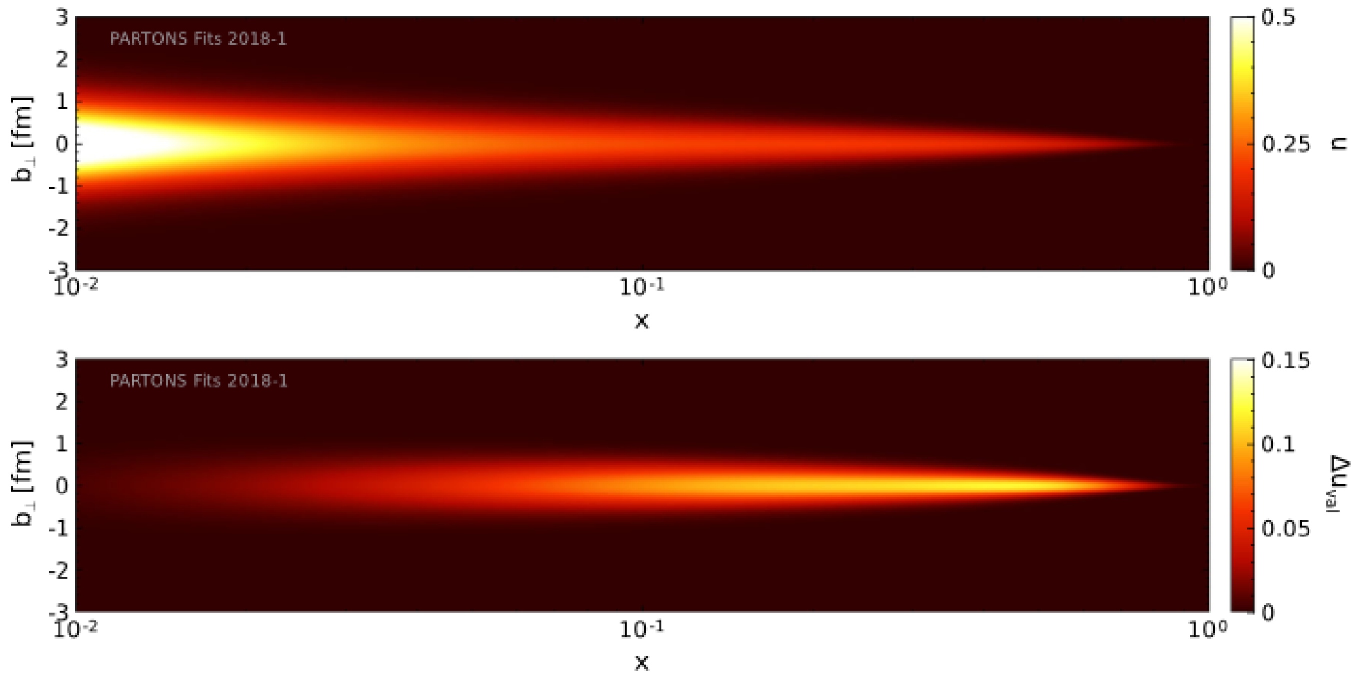


- Towards 3D imaging of nucleons

Dupré, Guidal, Vanderhaeghen, PRD95, 2017

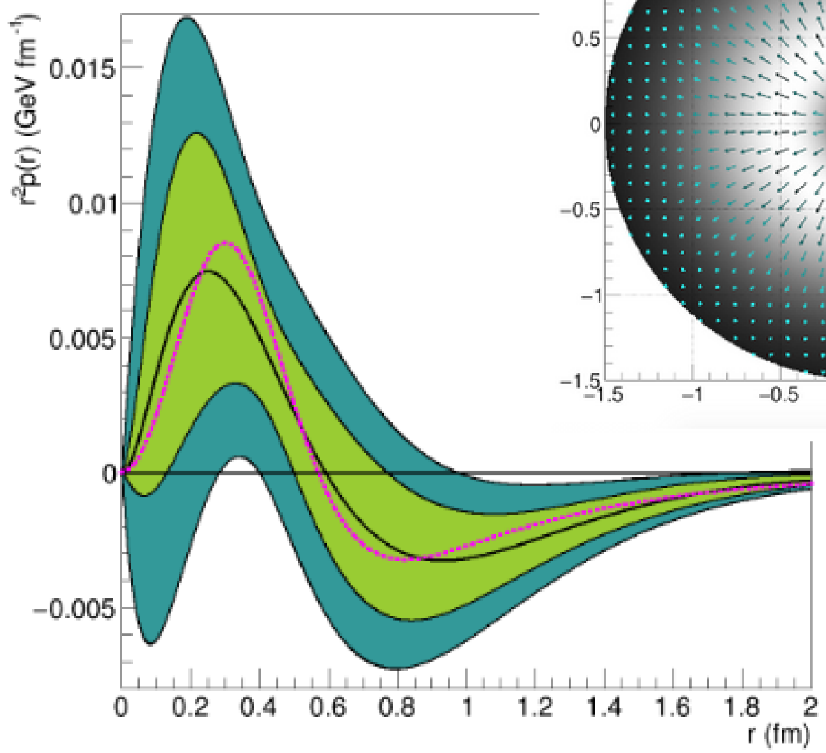


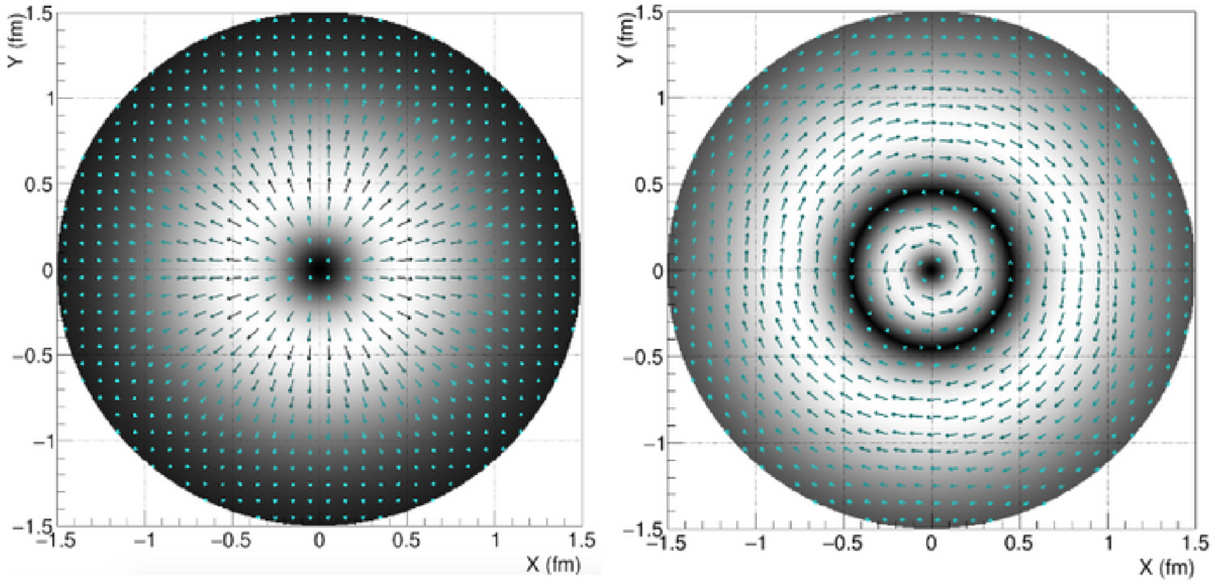
Moutarde, Sznajder, Wagner, EPJC 2018



- Forces and pressure inside nucleons

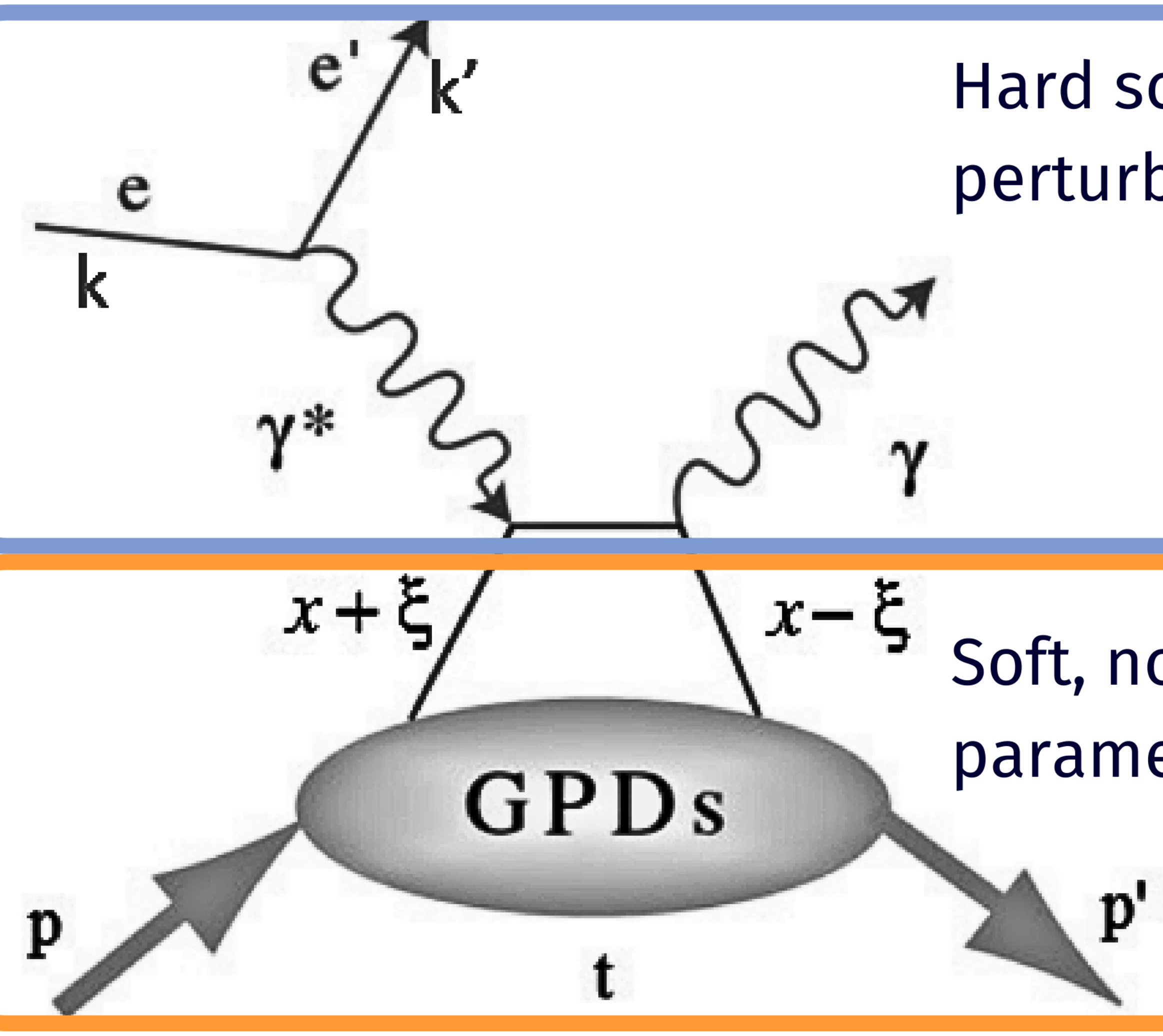
Burkert et al. 2018





Burkert et al. 2021b

Deeply Virtual Compton Scattering (DVCS)

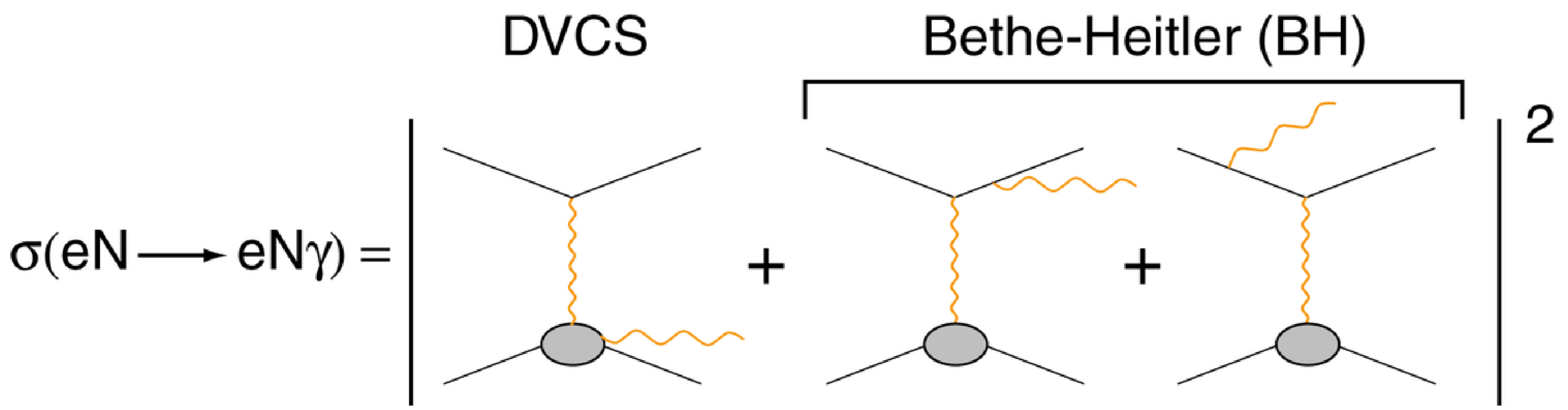


Hard scattering, perturbative

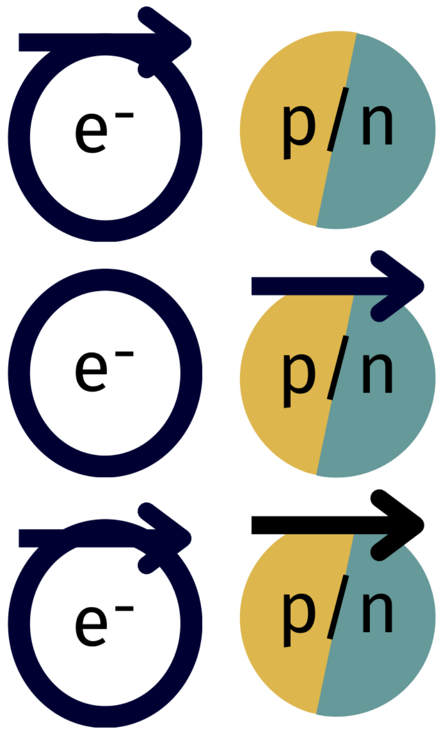
Soft, non perturbative, parametrized by GPDs

Gives access to Compton Form Factors

$$\mathcal{F}(\xi,t) = \int_{-1}^{1} dx F(\mp x,\xi,t)\left[\frac{1}{x-\xi+i\epsilon} \pm \frac{1}{x+\xi-i\epsilon}\right]$$



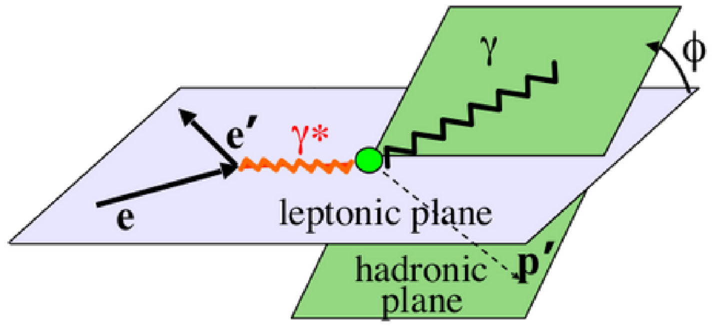
Access to linear combinations of CFFs and Form Factors thanks to the interference of BH and DVCS.



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

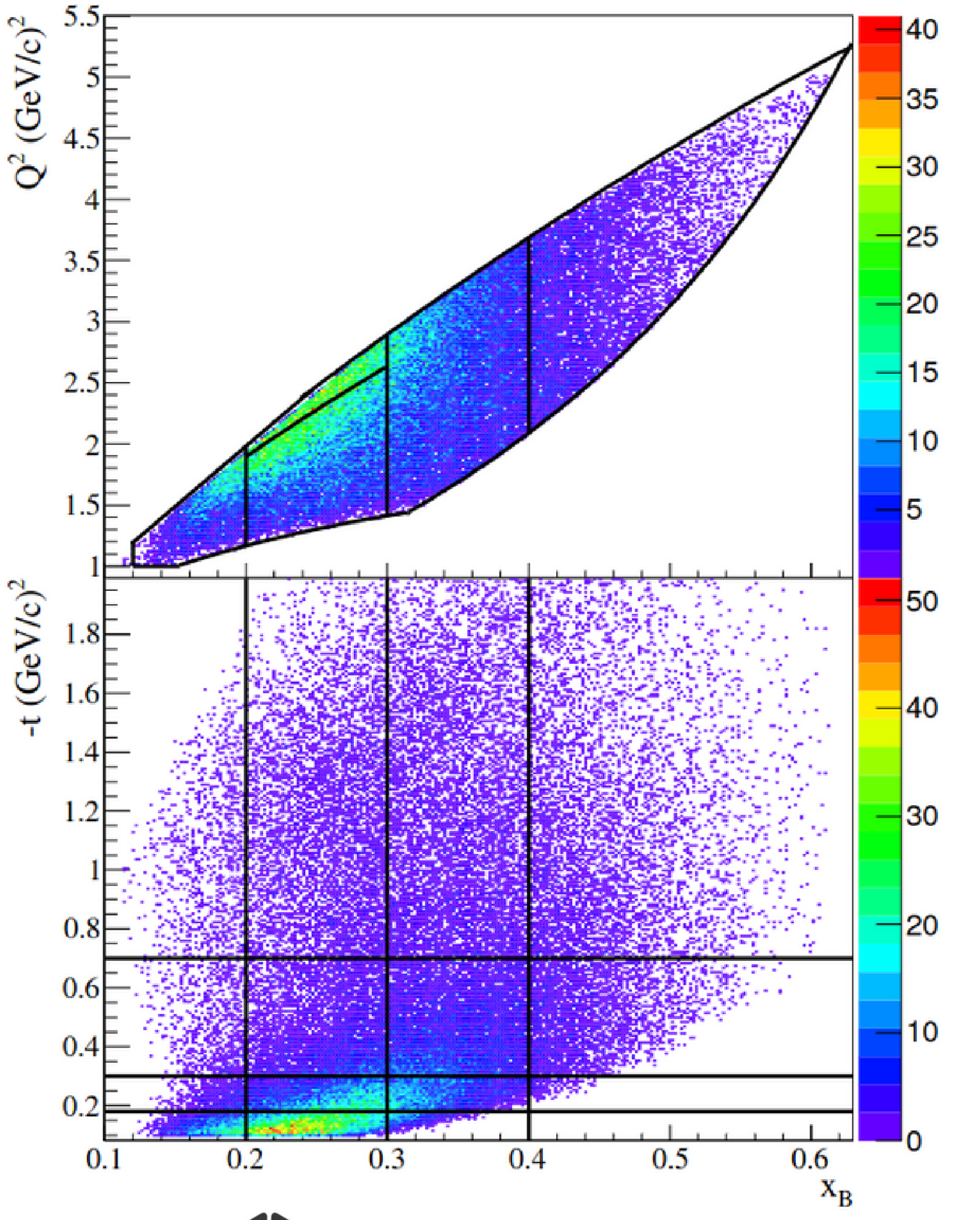
$$\Delta\sigma_{UL} \simeq \sin(\phi)\Im\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$

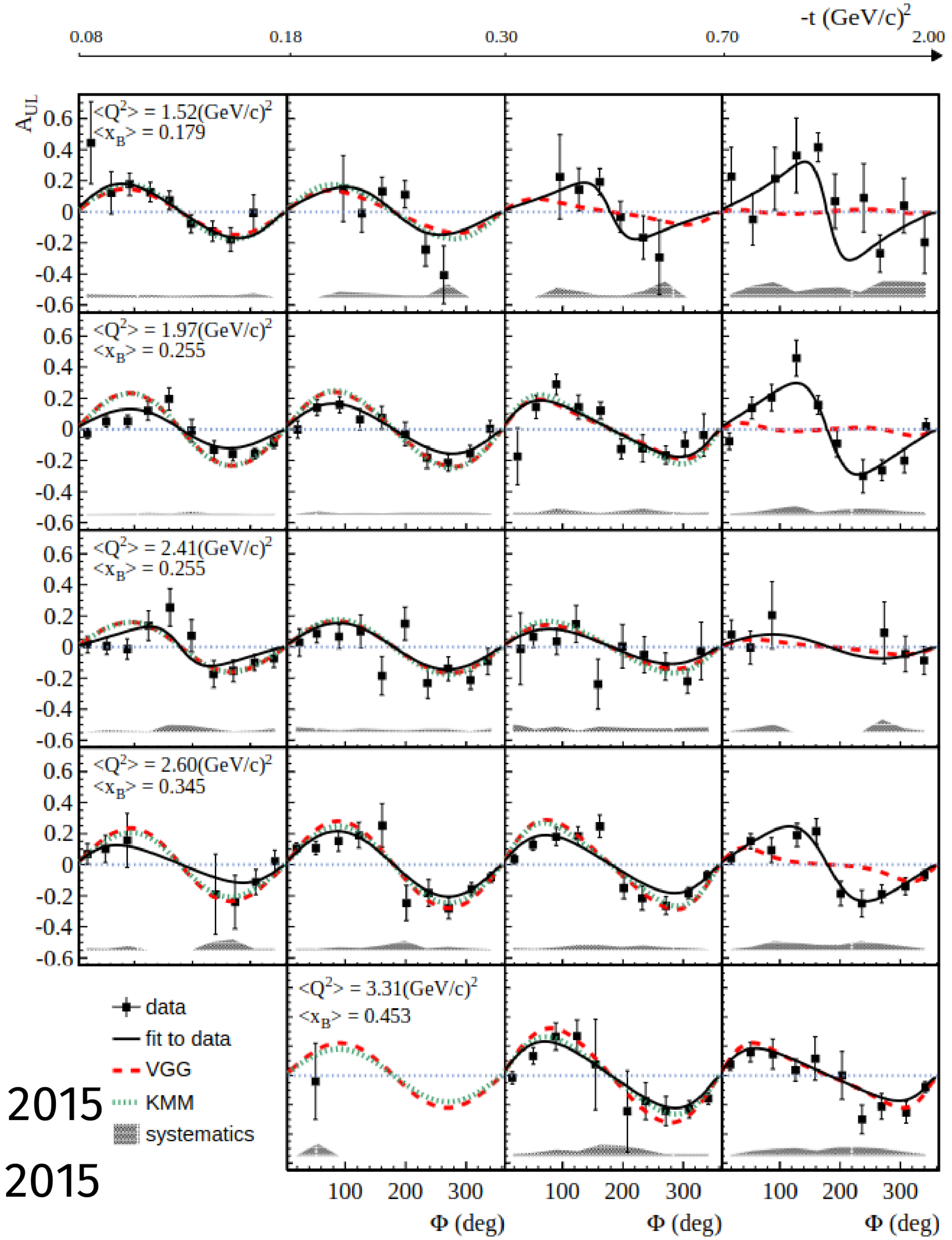
$$\Delta\sigma_{LL} \simeq (A+B\cos(\phi))\Re[F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+\frac{x_{bj}}{2}\mathcal{E})-\xi(\frac{x_{bj}}{2}F_1+\frac{t}{4M^2}F_2)\tilde{\mathcal{E}}]$$

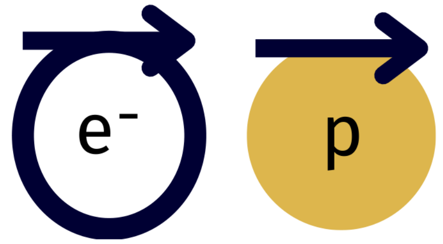


Existing CLAS Measurement of DVCS on Polarized Protons

- First measurement in 2006 with the CLAS detector (JLab) at 6 GeV (S.Chen et al. PRL97, 2006)
- Few years later, dedicated CLAS measurement at 6 GeV with an upgraded detector

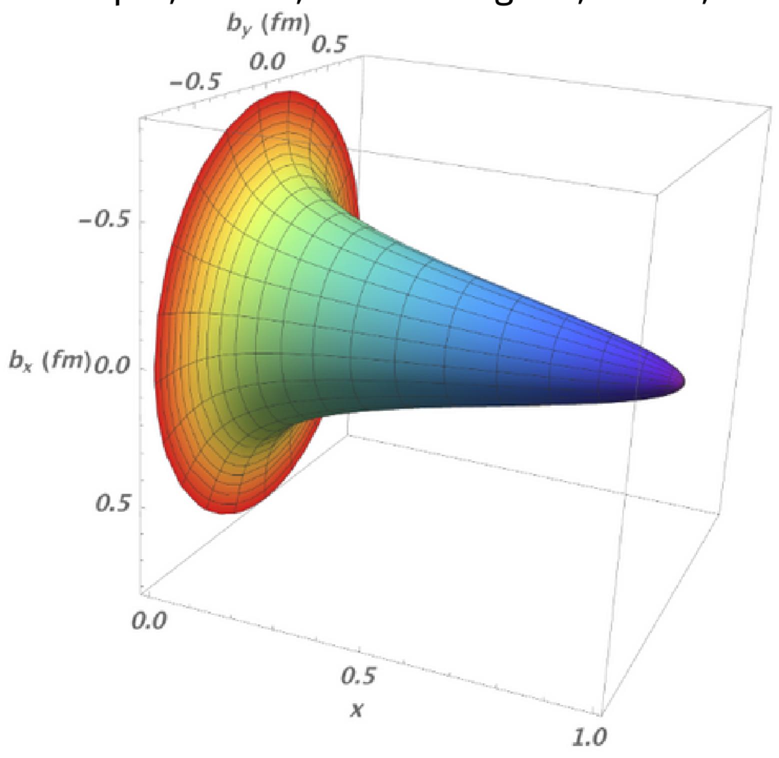


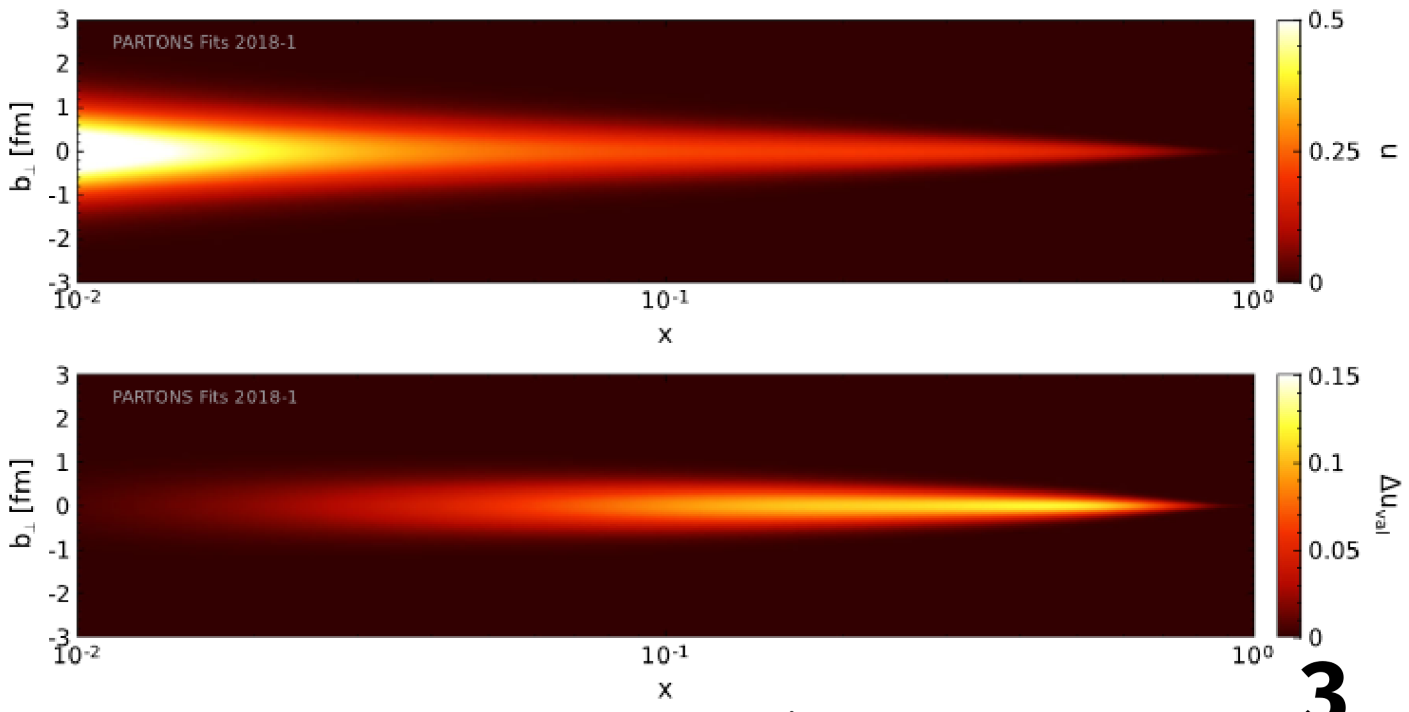




$H, \tilde{H}$

Dupré, Guidal, Vanderhaeghen, PRD95, 2017





Moutarde, Sznajder, Wagner, EPJC 2018

Pisano, et al., PRD91, 2015

Seder, et al., PRL114, 2015

The CLAS12 Program for Polarized DVCS

CLAS12 measurement of BSA, TSA and DSA with **polarized H/D**

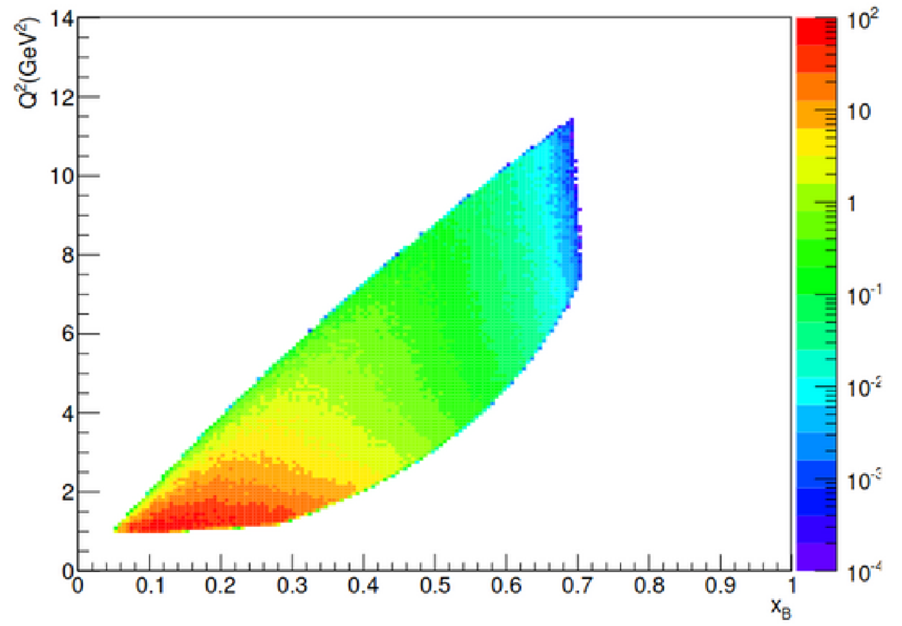
Opportunities for polarized pDVCS :

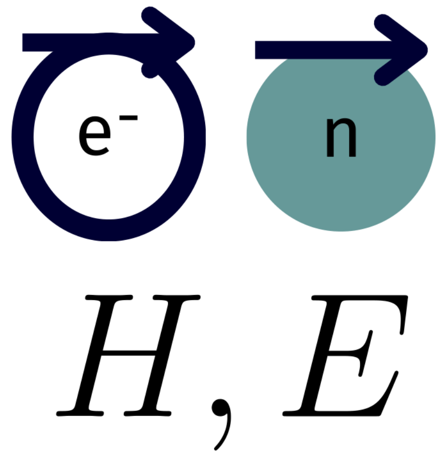
- Extend the 6 GeV measurement, vast phase space
- Comparison between H and D data to understand in-medium effects

Opportunities for polarized nDVCS :

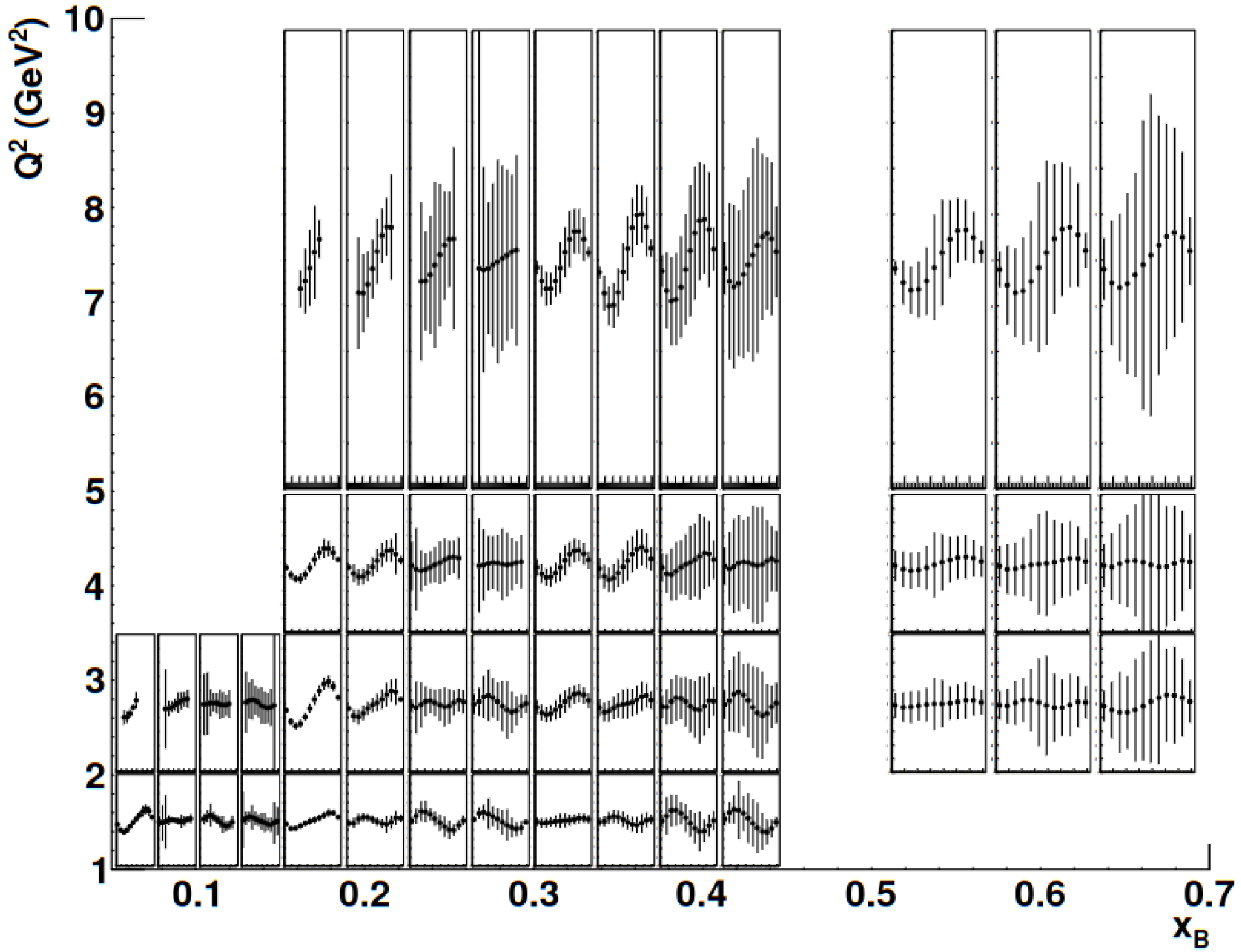
- Measurement of new observables to access poorly-known H(n)
- Flavor decomposition of CFFs

Projected kinematics for ndvcs

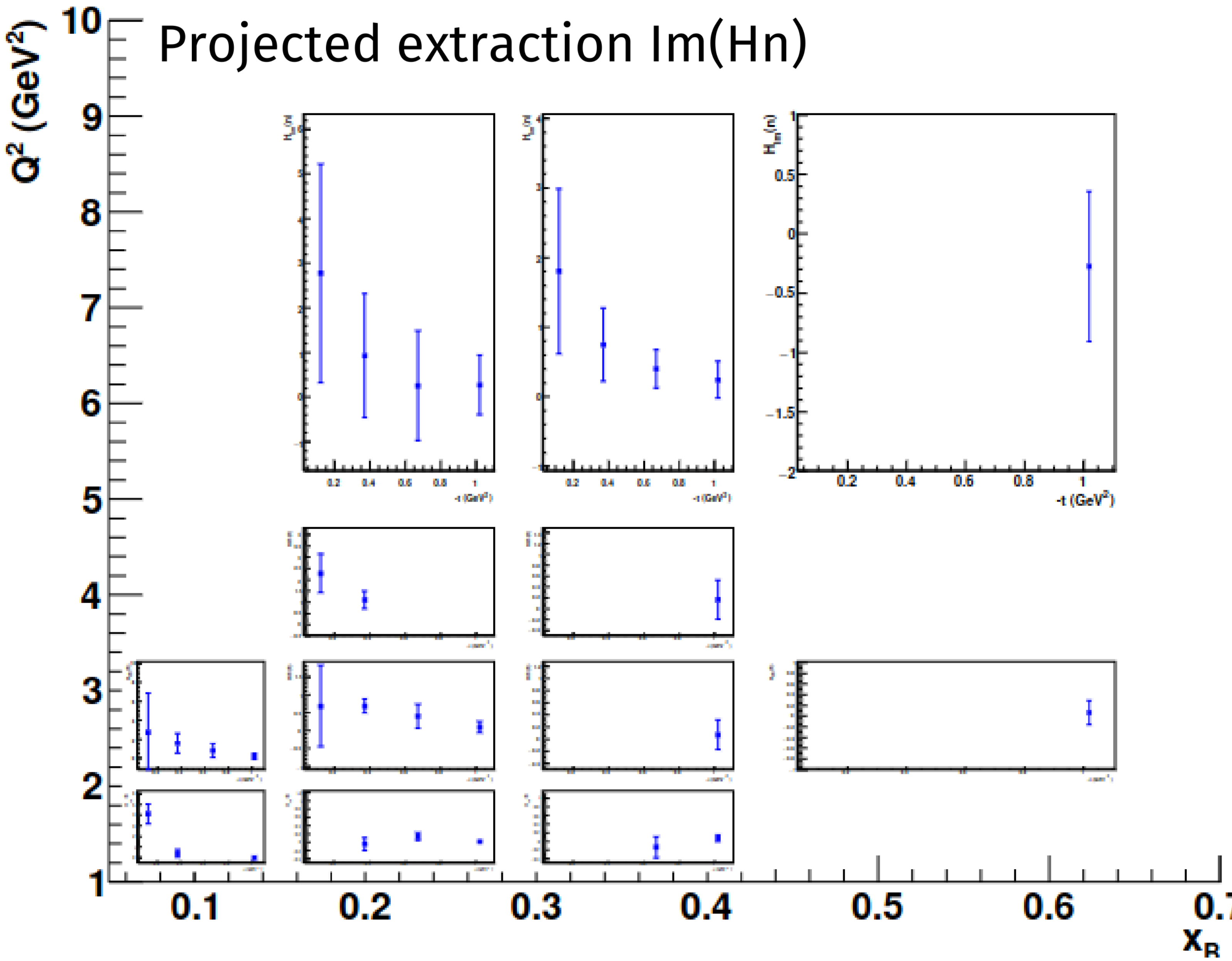




Projected TSA



Projected extraction Im(Hn)

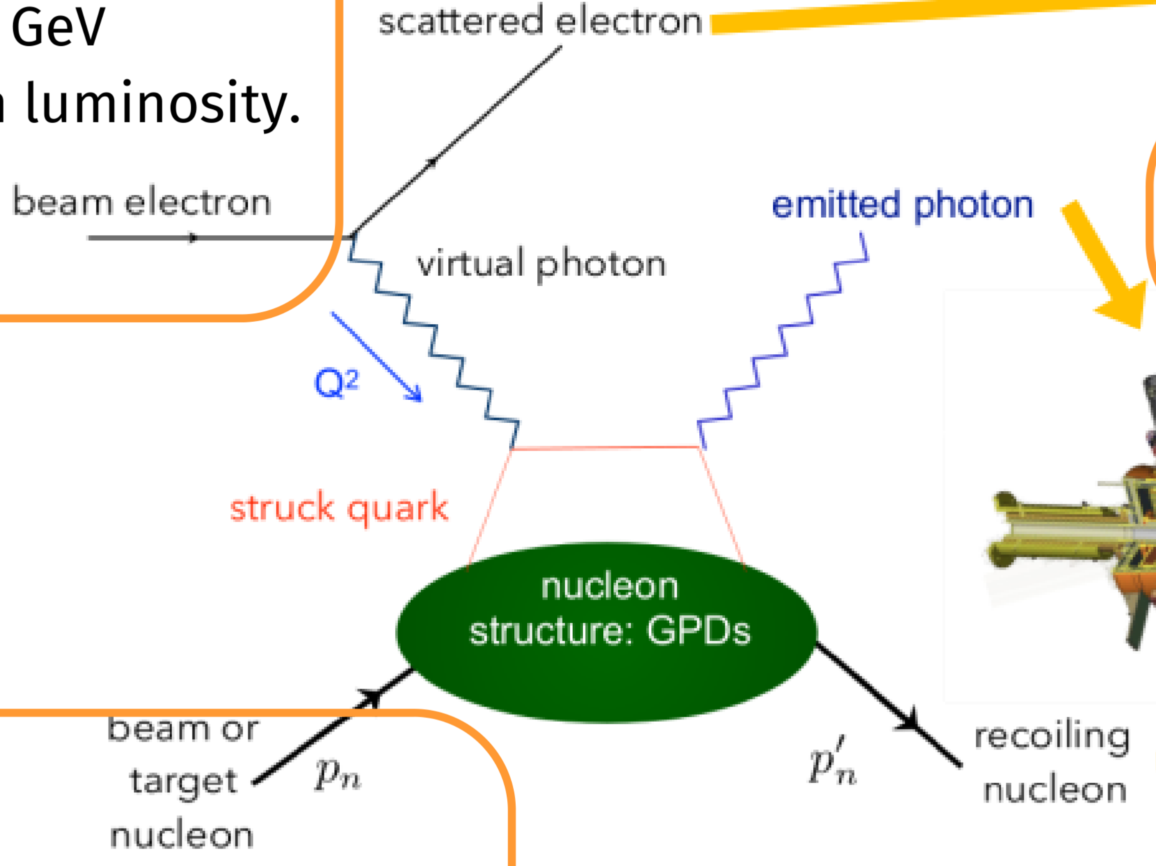


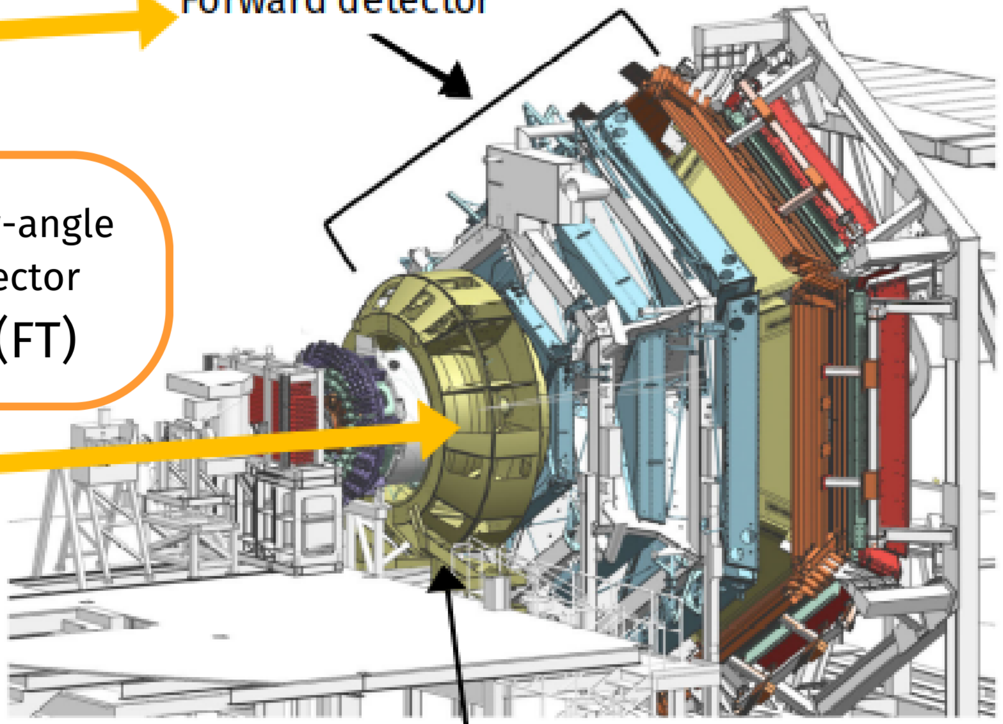
Experimental Setup

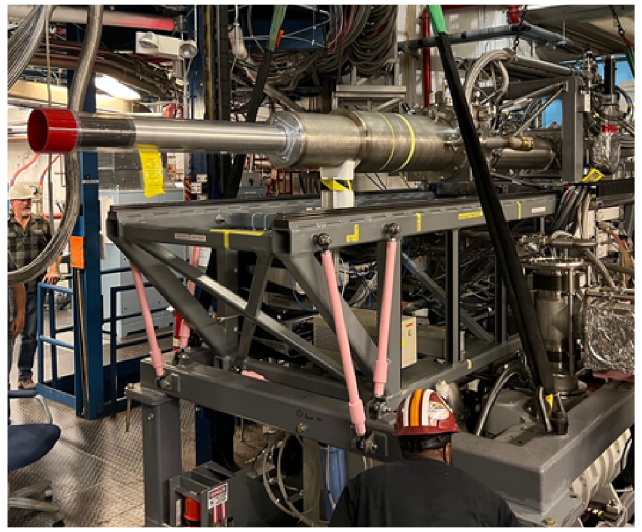
Measuring Polarized DVCS with CLAS12

- Polarized beams (CEBAF)
- DVCS measurement (CLAS12, Hall B)
- Polarized targets → Run Group C (RGC) June 2022 - March 2023

CEBAF, JLab
- highly polarized
- 10.5 GeV
- high luminosity.

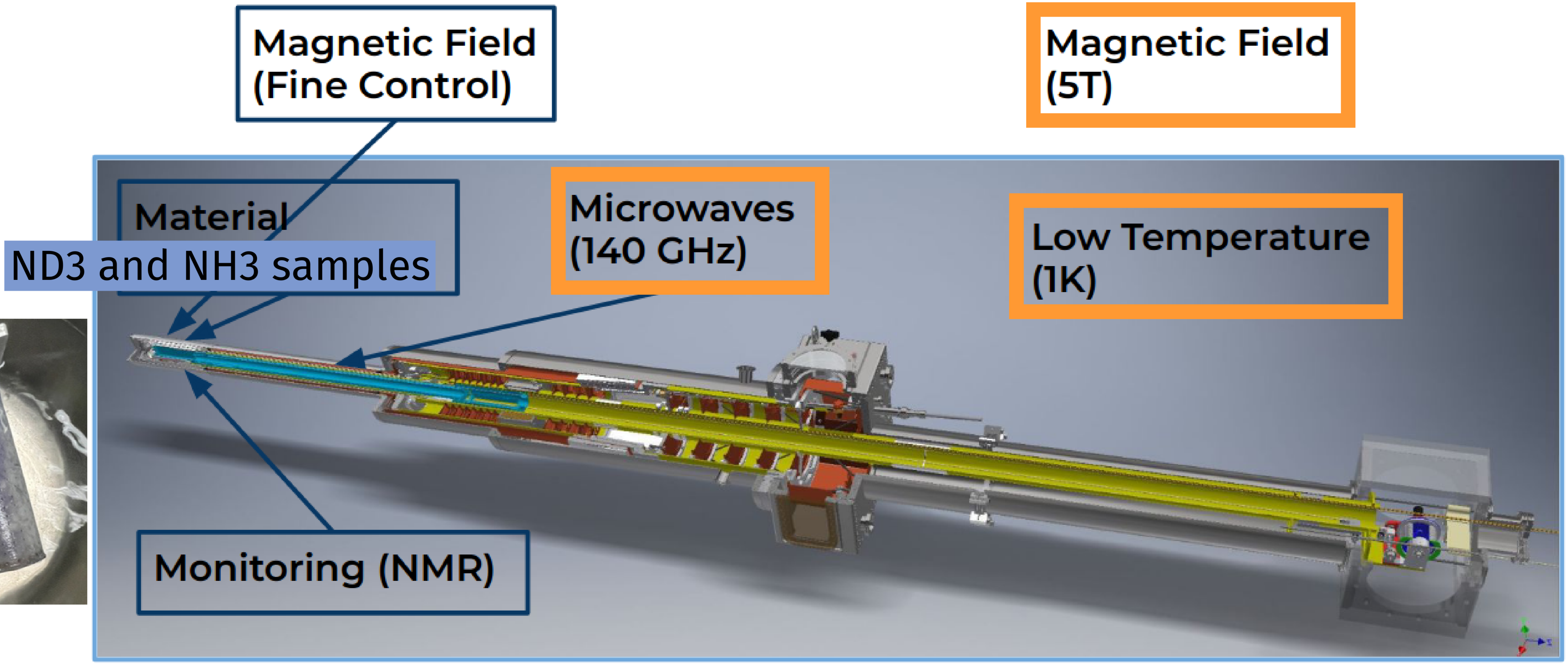






Run Group C: longitudinally polarized target

The RGC Polarized Target



The target performed very well during the long 9 months data-taking thanks to the expertise of the JLab target group, a great experimental success !

Measuring the Target Polarization

Target Polarization Measurement

- Using elastic events ep → e'p'
- The double-spin asymmetry is well known

$$A_{th} = \frac{2\tau G[\frac{M_p}{E_b} + G(\tau\frac{M_p}{E_b} + (1+\tau)\tan(\frac{\theta}{2})^2)]}{1+G^2\frac{\tau}{\epsilon}}$$

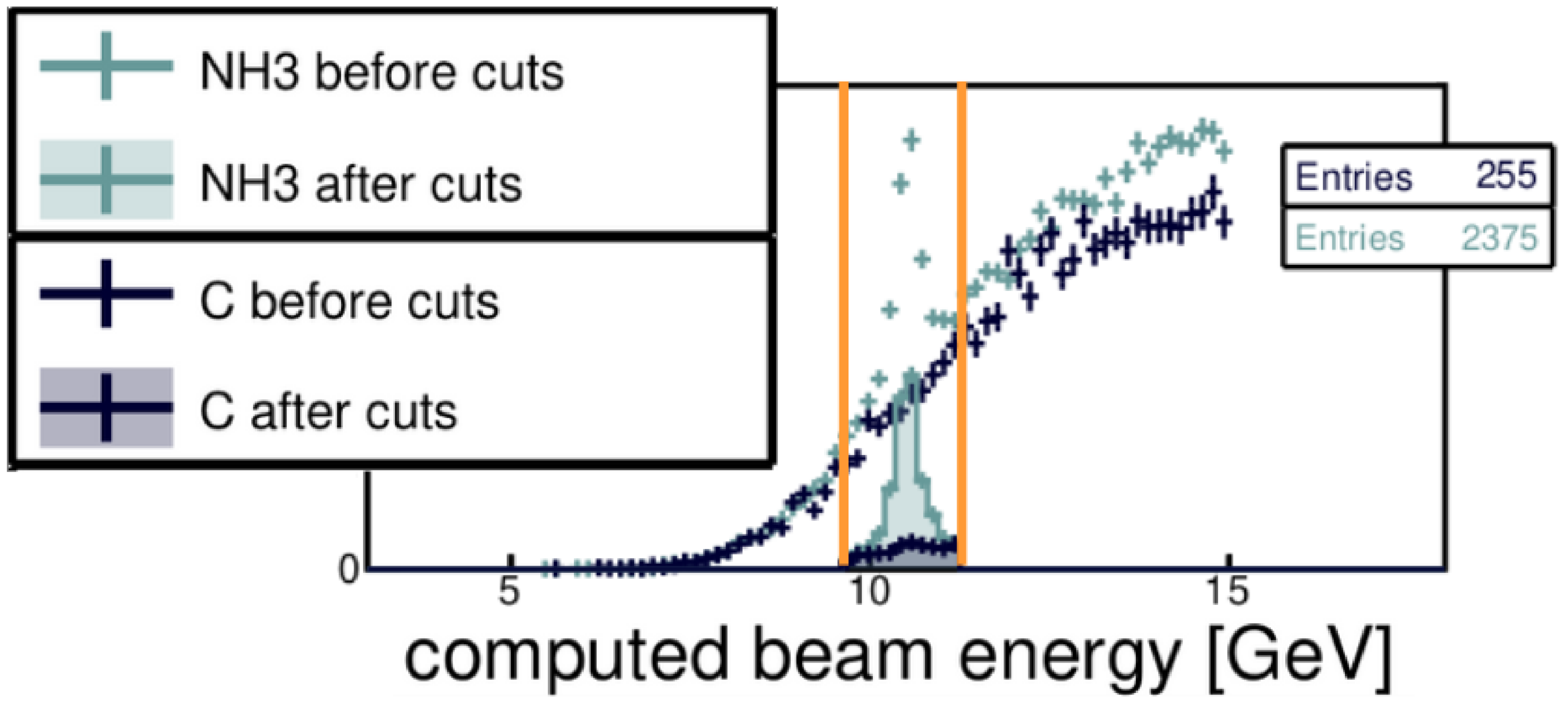
- Comparing with the measured asymmetry allows to assess the fraction of polarized electrons and protons.

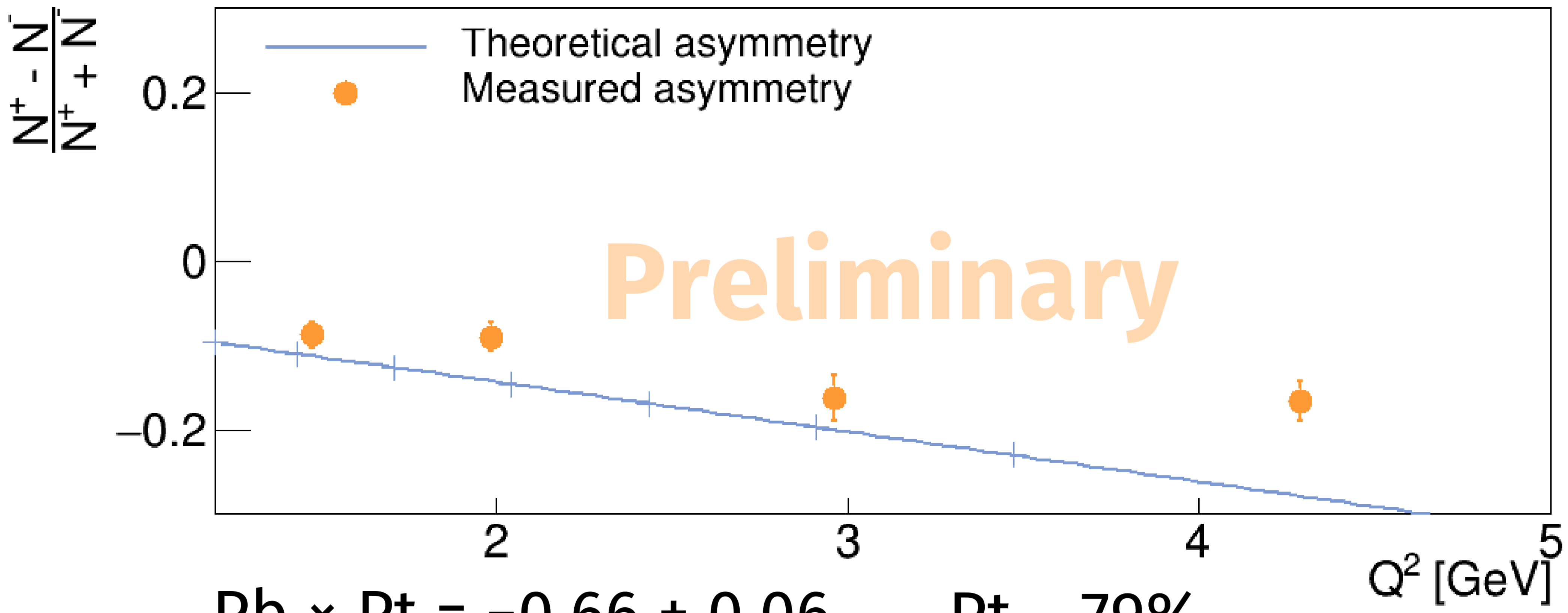
$$\rightarrow P_b P_t = \frac{A_{meas}}{A_{th}}$$

dilution factor

$$P_b P_t = \frac{\sum_{i=0}^{N_{bins}} f_i A_{th,i}(N_i^+ - N_i^-)}{\sum_{i=0}^{N_{bins}} f_i^2 A_{th,i}^2 (N_i^+ + N_i^-)}$$

yields with positive/negative beam helicity





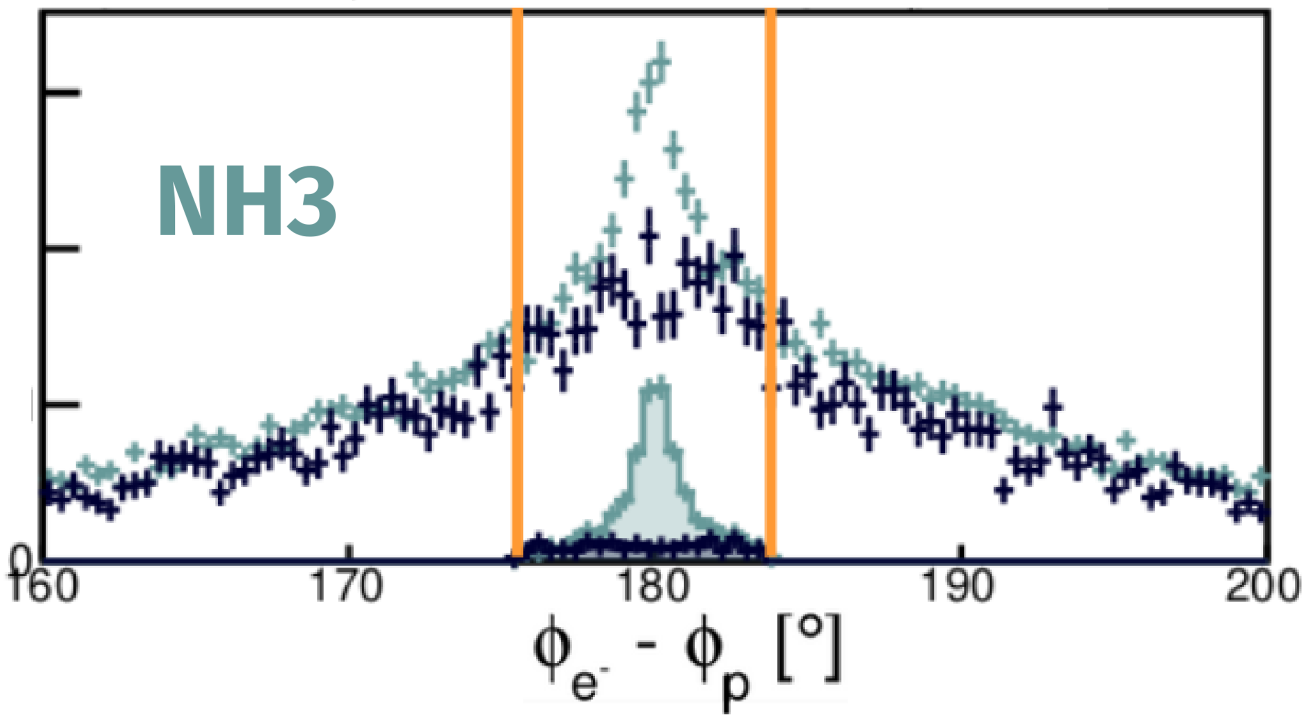
Pb × Pt = −0.66 ± 0.06 ⟶ Pt ~ 79%

Challenges with Deuterium Data

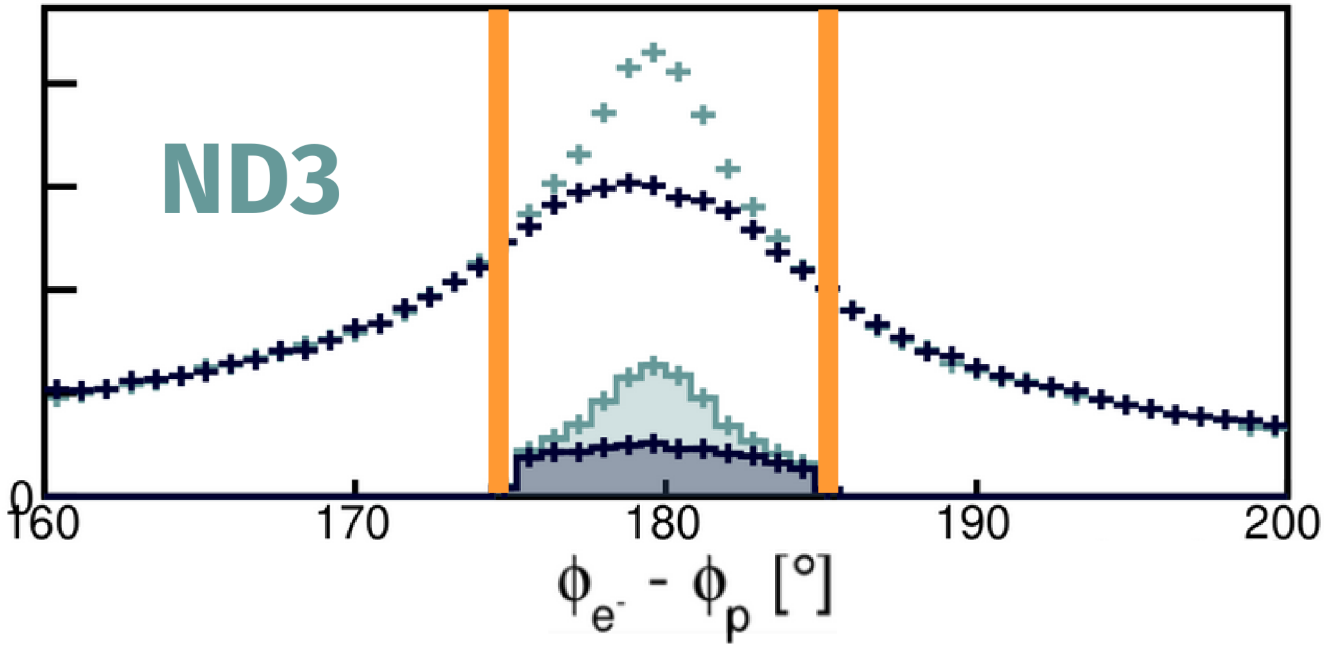
Ongoing analysis concerns p and n in D.

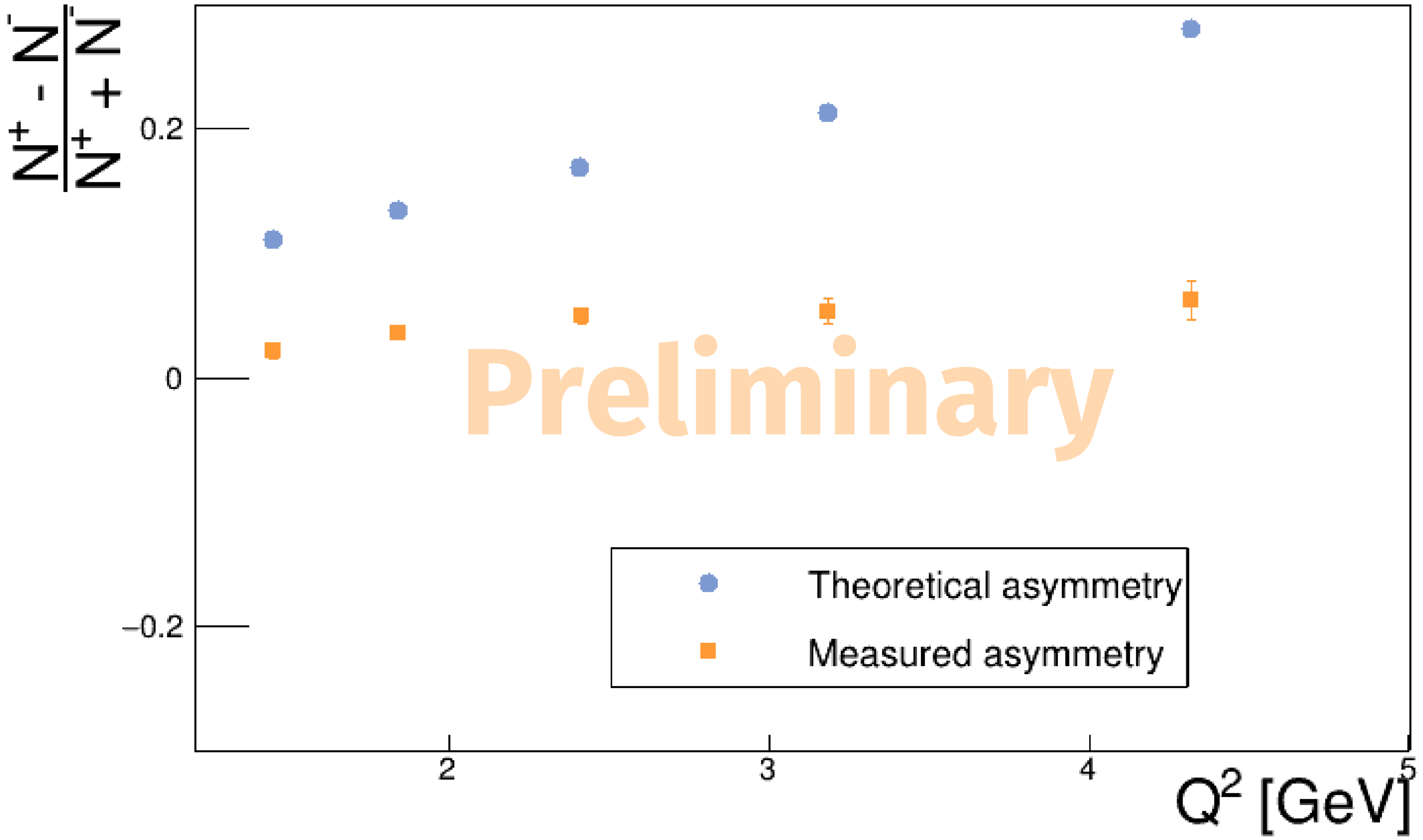
Fermi Motion makes it more complicated !

Partially calibrated data on NH3



Calibrated data on ND3





Pb × Pt = −0.25 ± 0.04 ⟶ Pt ~ 30%

Target polarizations are lower for D.

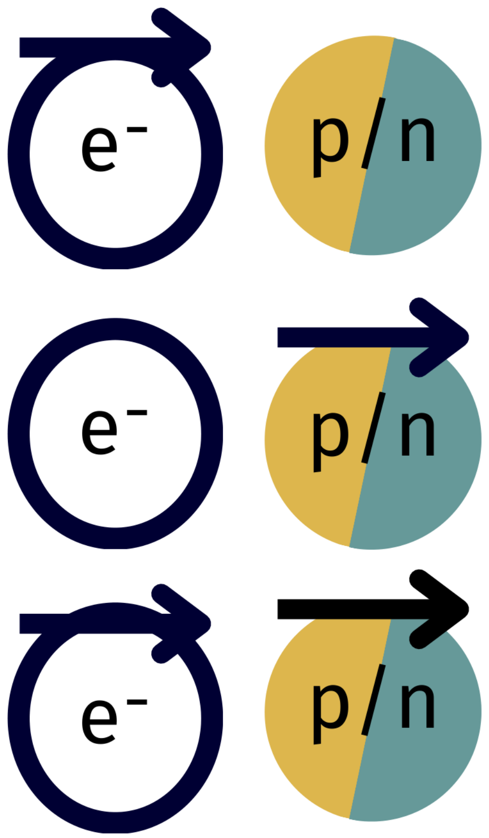
Measuring DVCS

Disclaimer: All data that is shown next is preliminary.

The calibrations have not been completed.

All presented DVCS asymmetries are raw and contain various contaminations.

Experimental Definition of the DVCS Asymetries



$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{Pb \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

$$A_{UL} = \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

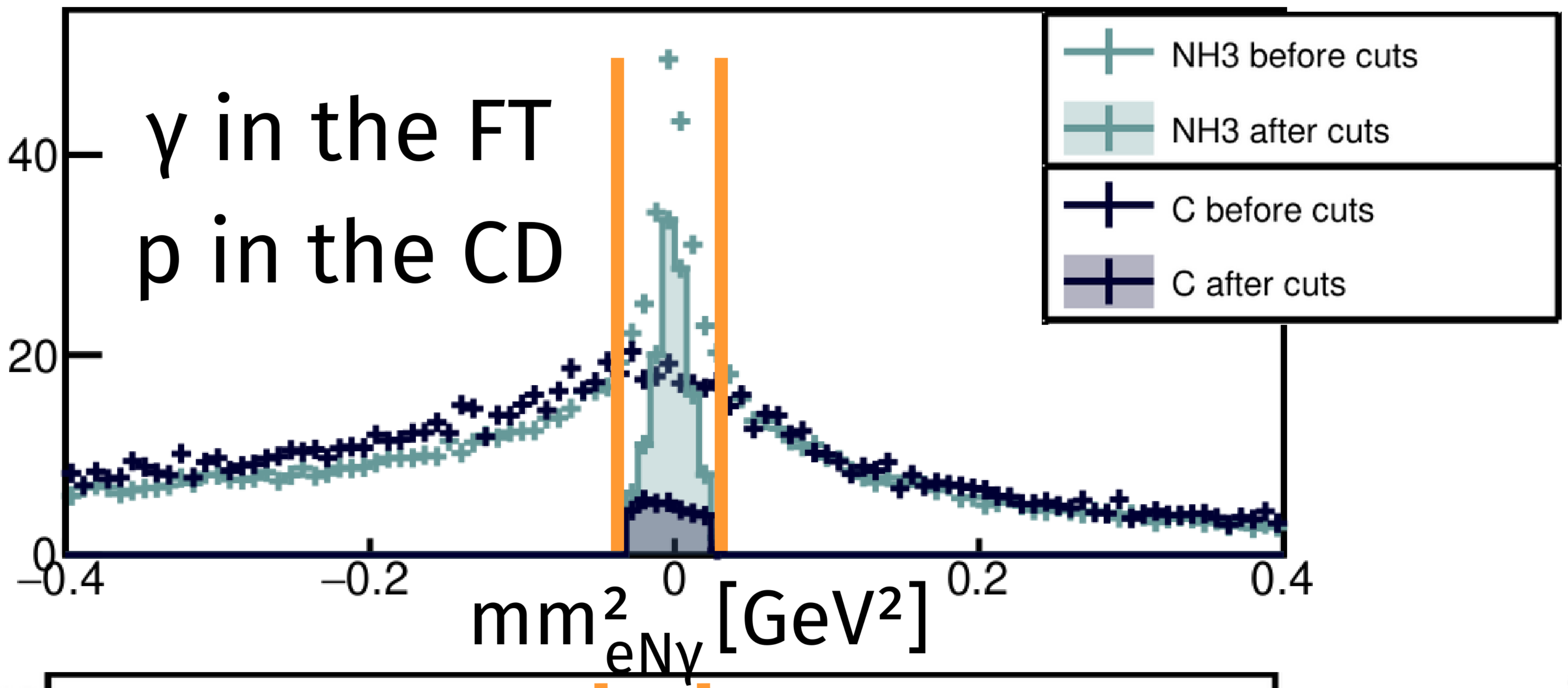
$$A_{LL} = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_b \times Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

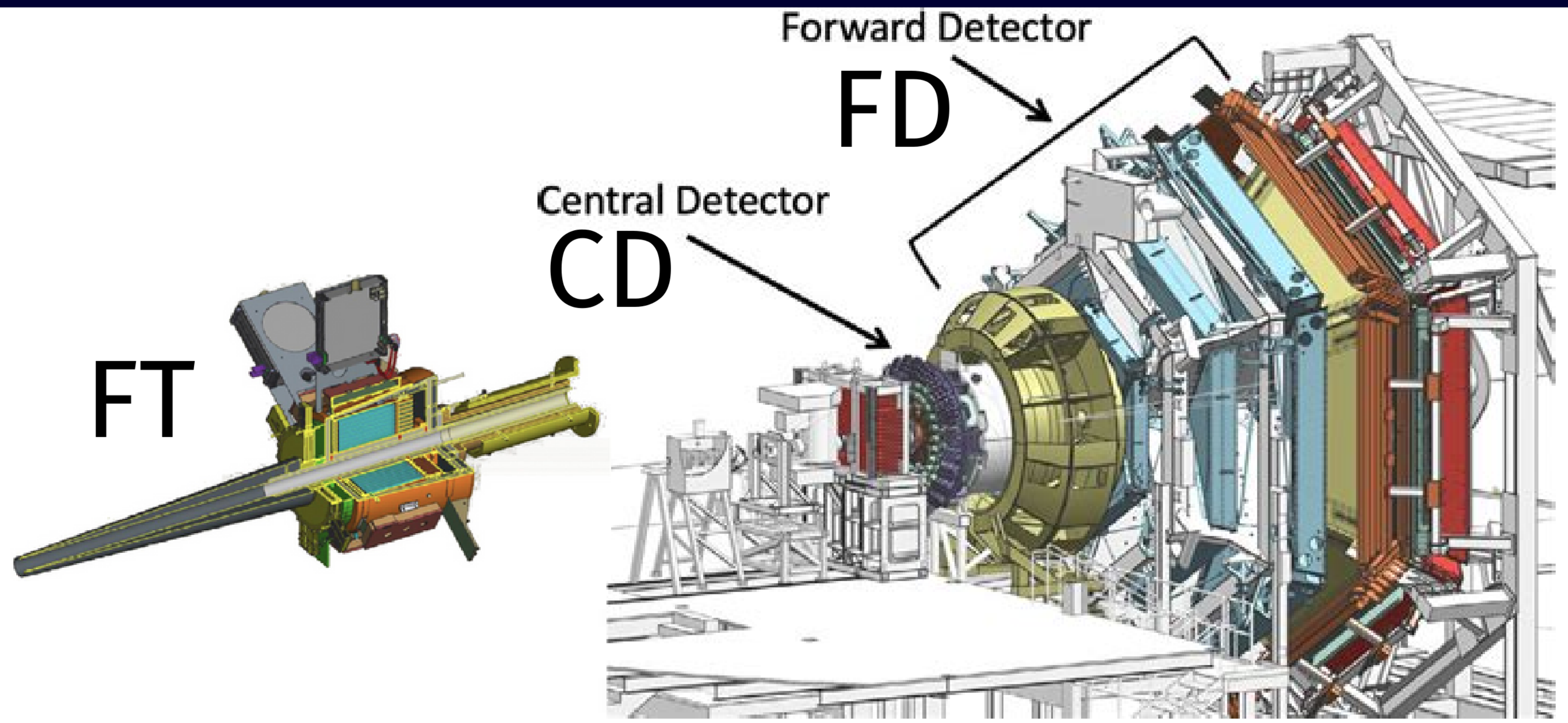
$$N^{b,t}$$

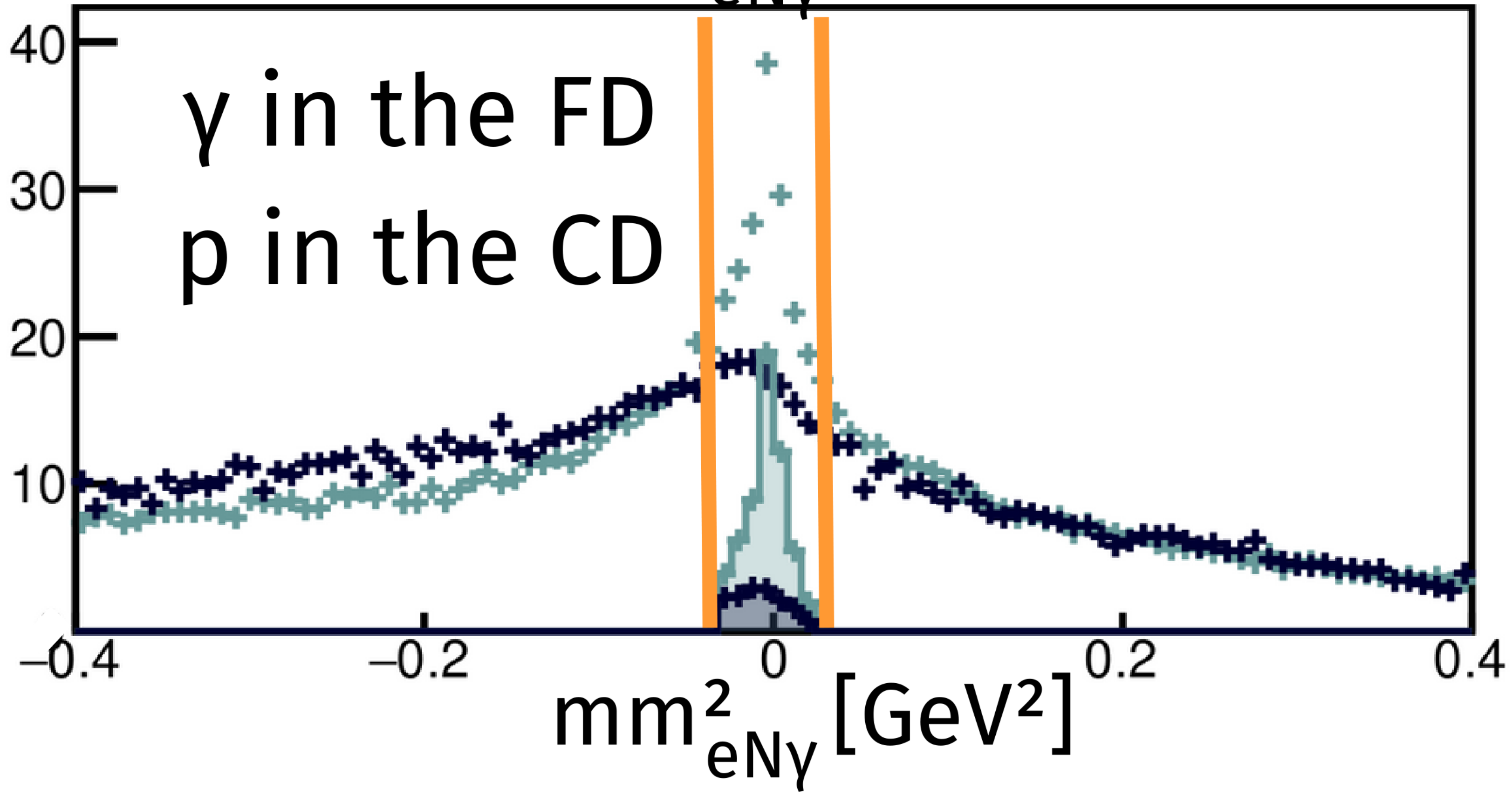
- Pb is the beam polarization, measured using Moller scattering during the experiment (~83%).
- Pt is the target polarization assessed with the elastic analysis.
- Df is the dilution factor for DVCS that accounts for the unpolarized N background.

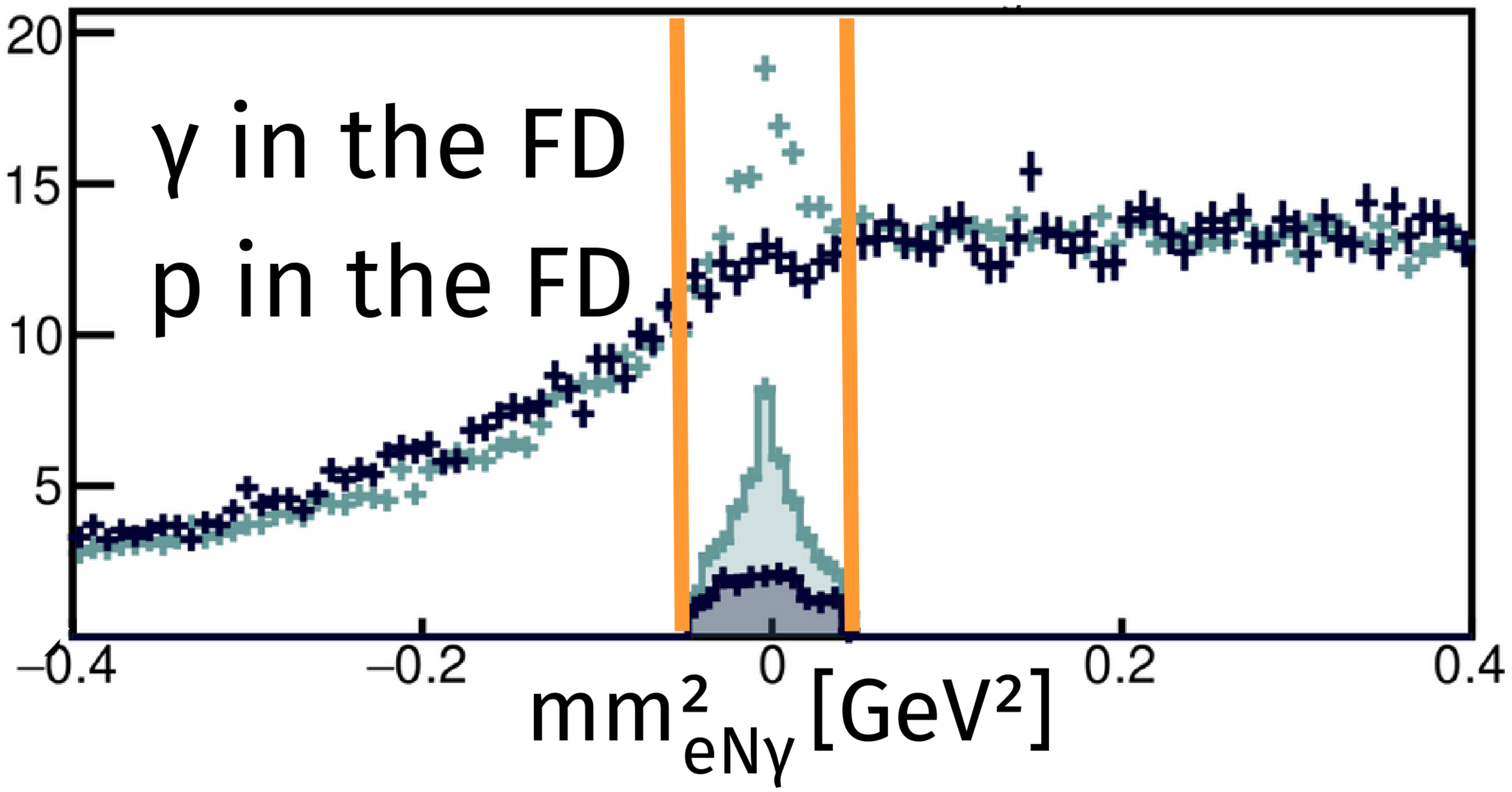
Next slides: pDVCS with an NH3 target

Event Topologies





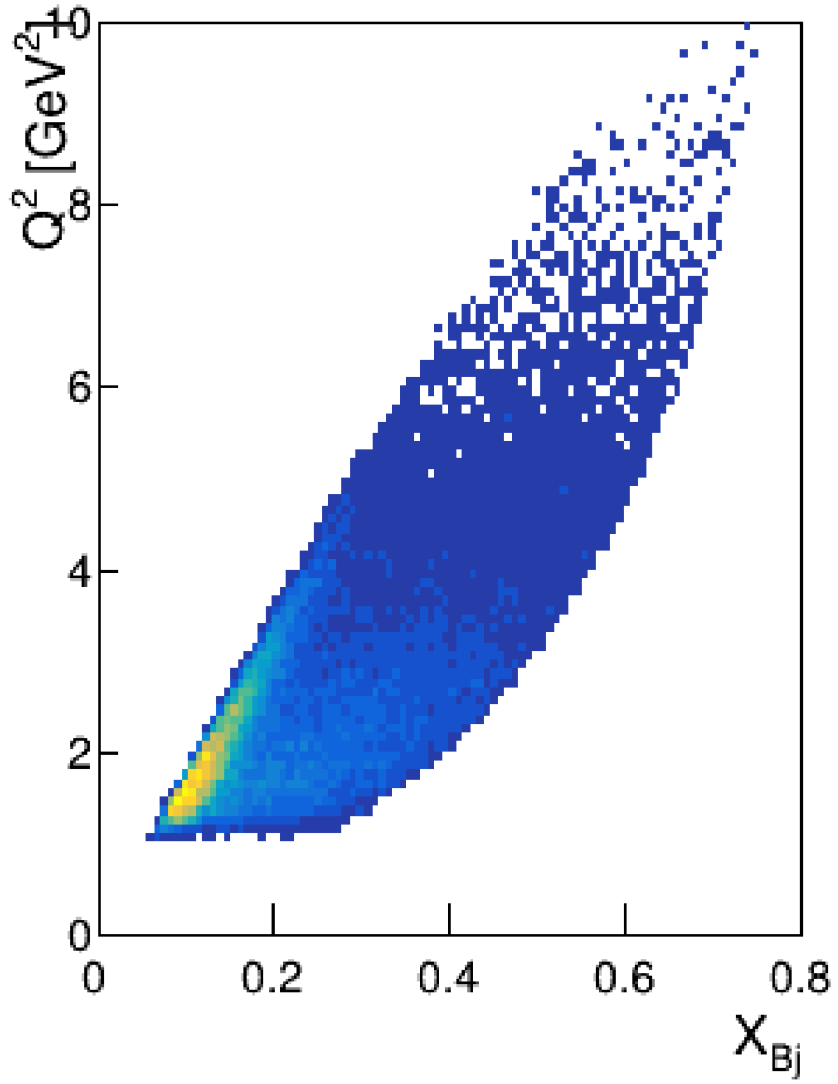


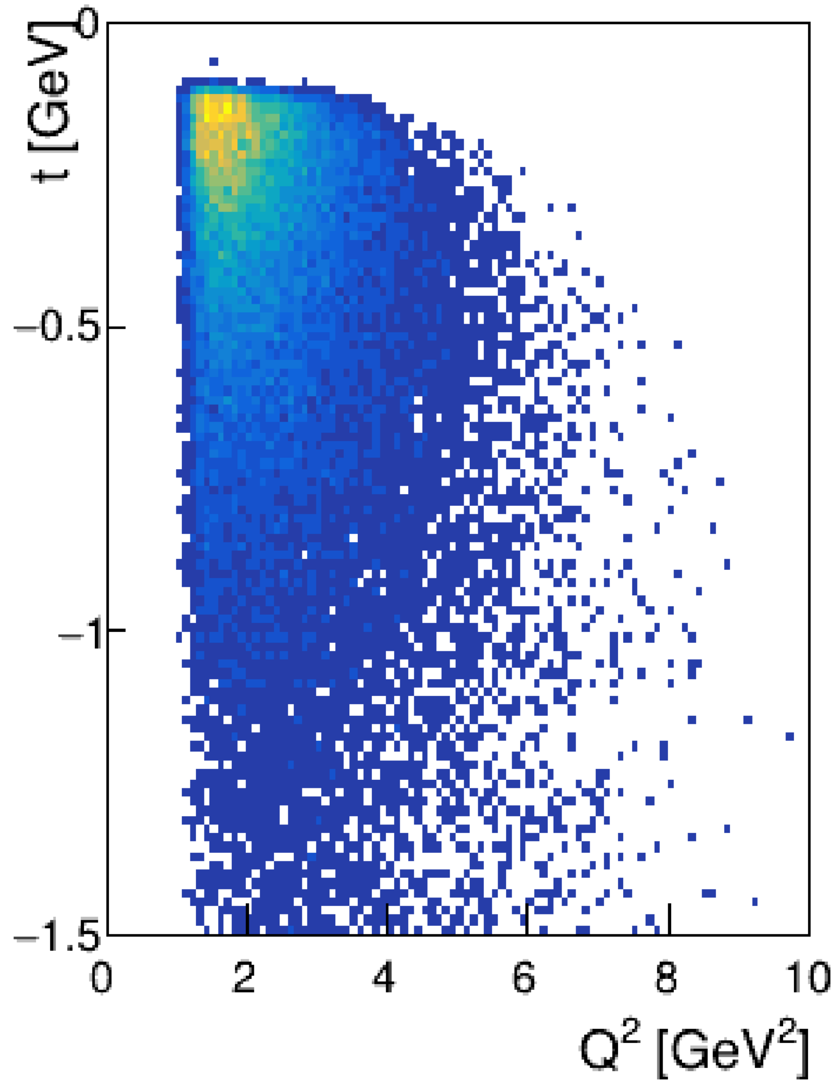


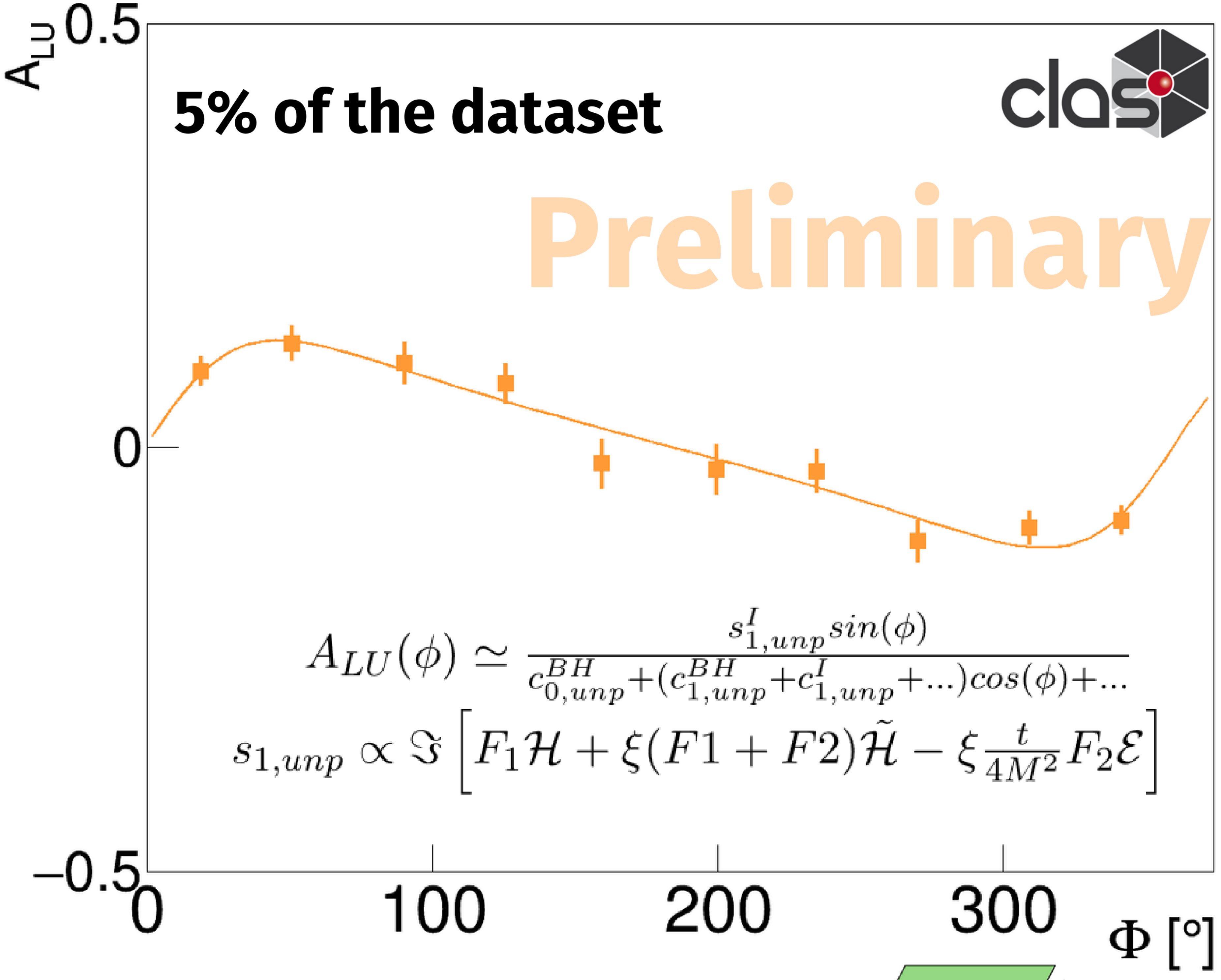
- Resolutions are different for particles detected in different part of CLAS12
- Total set of exclusivity cuts on missing masses, $\Delta\phi$, Δt.

Raw Beam Spin Asymmetry

$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_b(P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

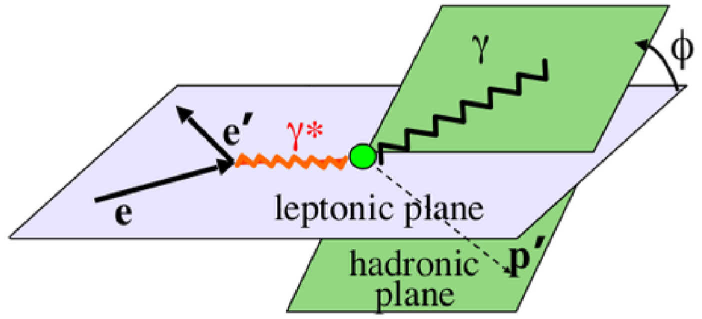






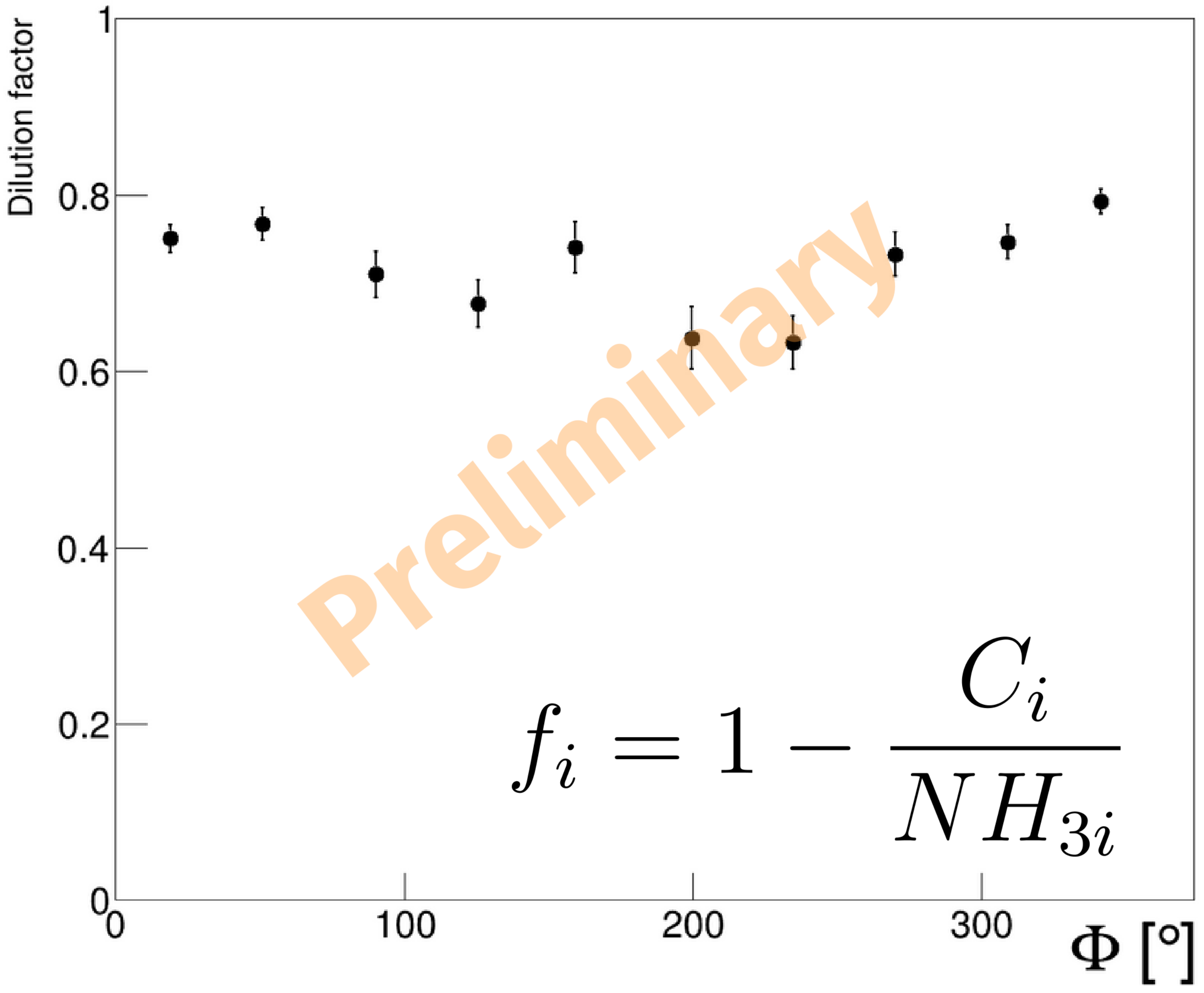
$$A_{LU}(\phi) \simeq \frac{s^I_{1,unp} sin(\phi)}{c^{BH}_{0,unp} + (c^{BH}_{1,unp} + c^I_{1,unp} + ...)cos(\phi) + ...}$$

$$s_{1,unp} \propto \Im\left[F_1\mathcal{H} + \xi(F1 + F2)\tilde{\mathcal{H}} - \xi\frac{t}{4M^2}F_2\mathcal{E}\right]$$



Raw asymmetry, no background subtraction yet.
In particular, contamination from N and from
$eN \to e'N'\pi^0 \to e'N'\gamma(\gamma)$

Raw Target Spin Asymmetry

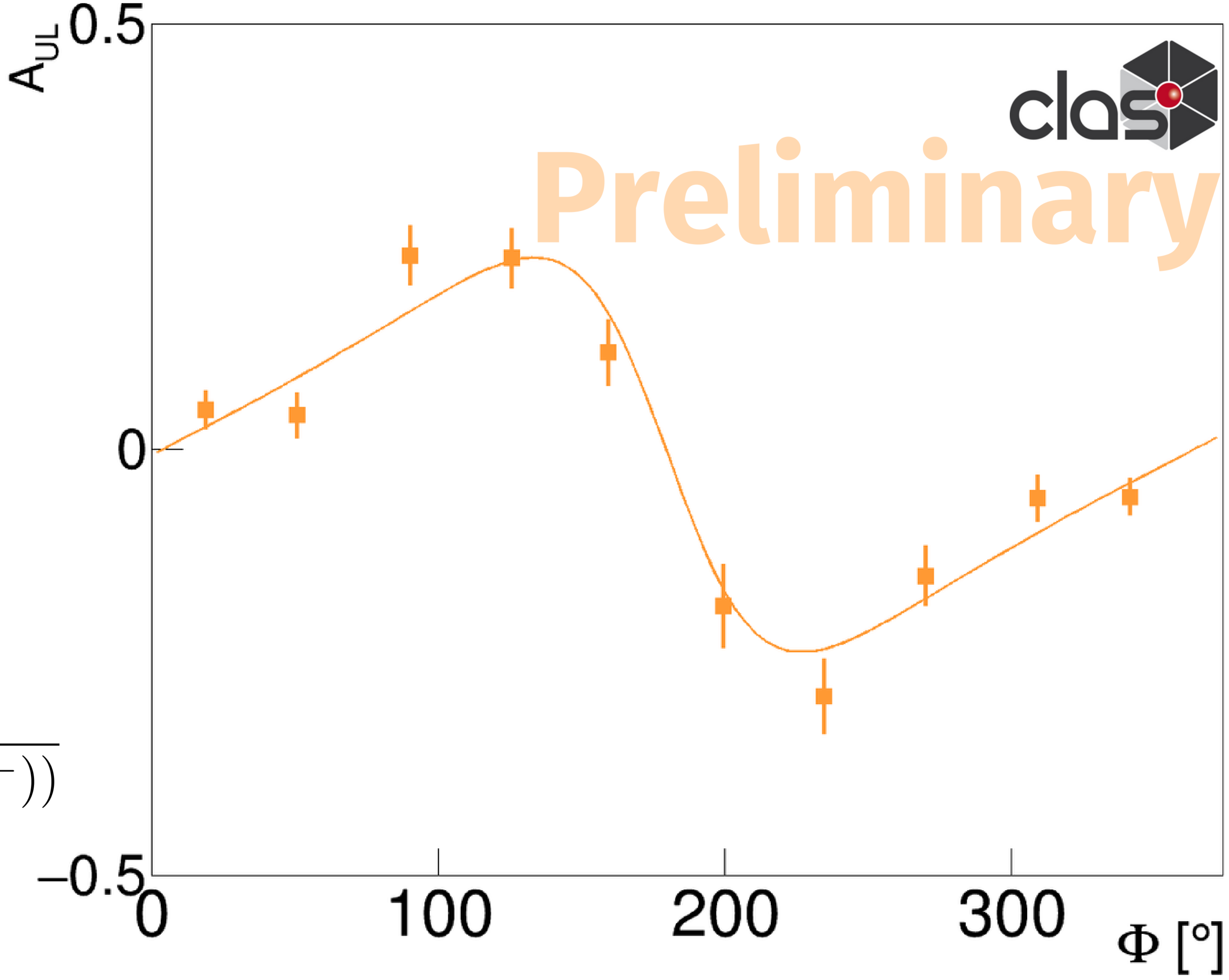


$$f_i = 1 - \frac{C_i}{NH_{3i}}$$

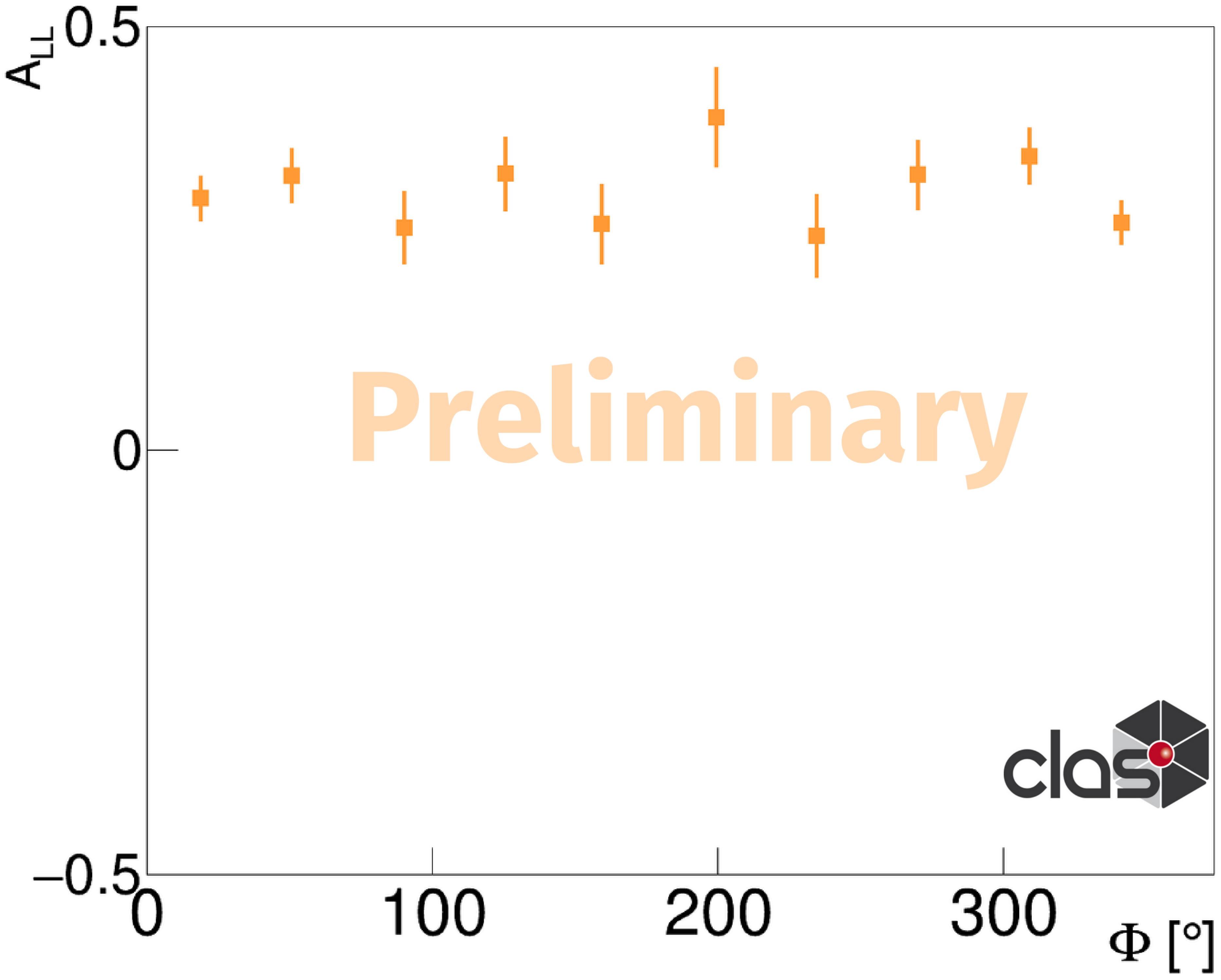
$$A_{UL} = \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

$$A_{UL}(\phi) \simeq \frac{s^I_{1,LP} sin(\phi)}{c^{BH}_{0,unp} + (c^{BH}_{1,unp} + c^I_{1,unp} + ...) cos(\phi) + ...}$$

$$s_{1,LP} \propto \Im\left[F_1\tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$



Raw Double Spin Asymmetry

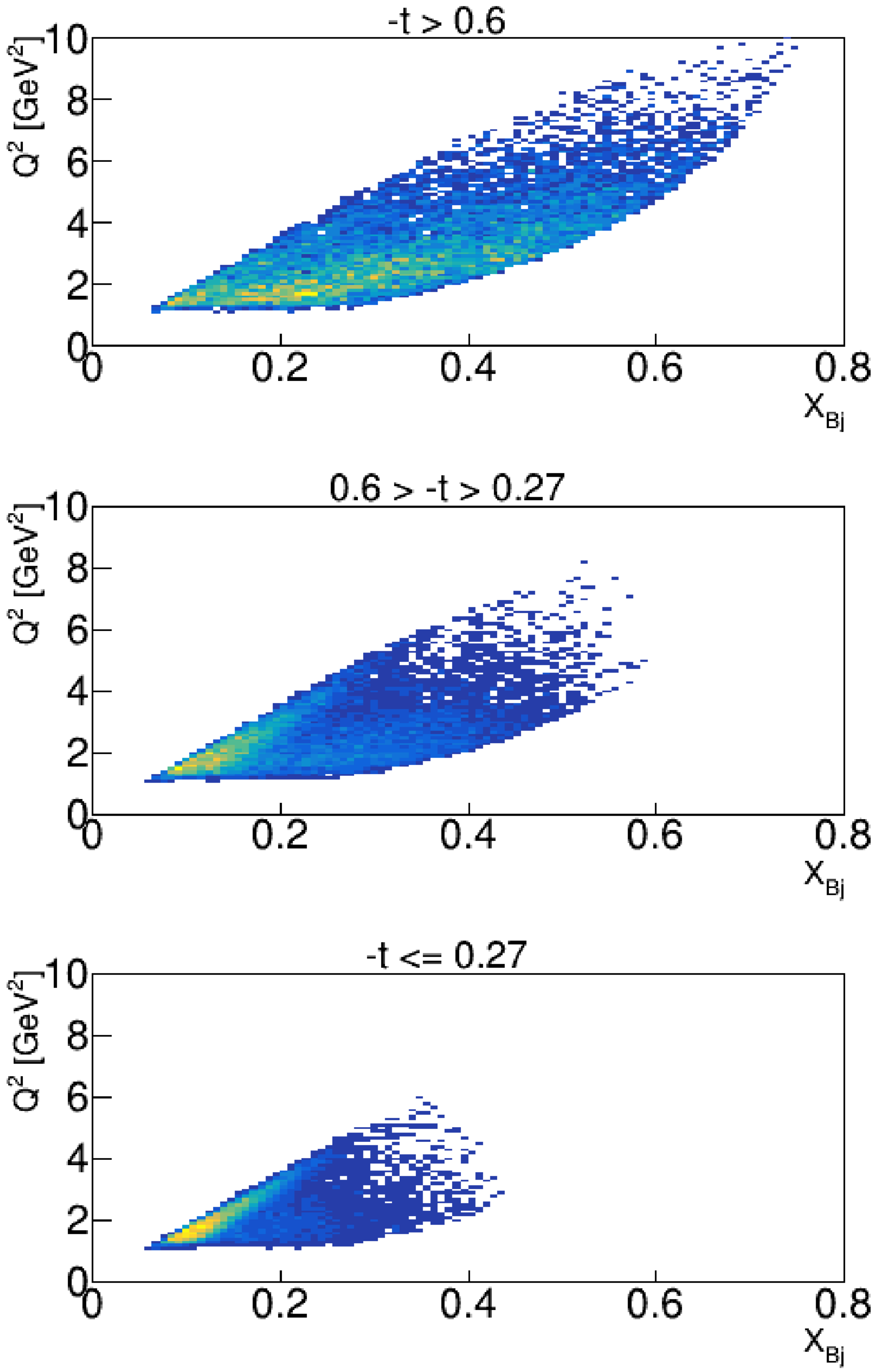


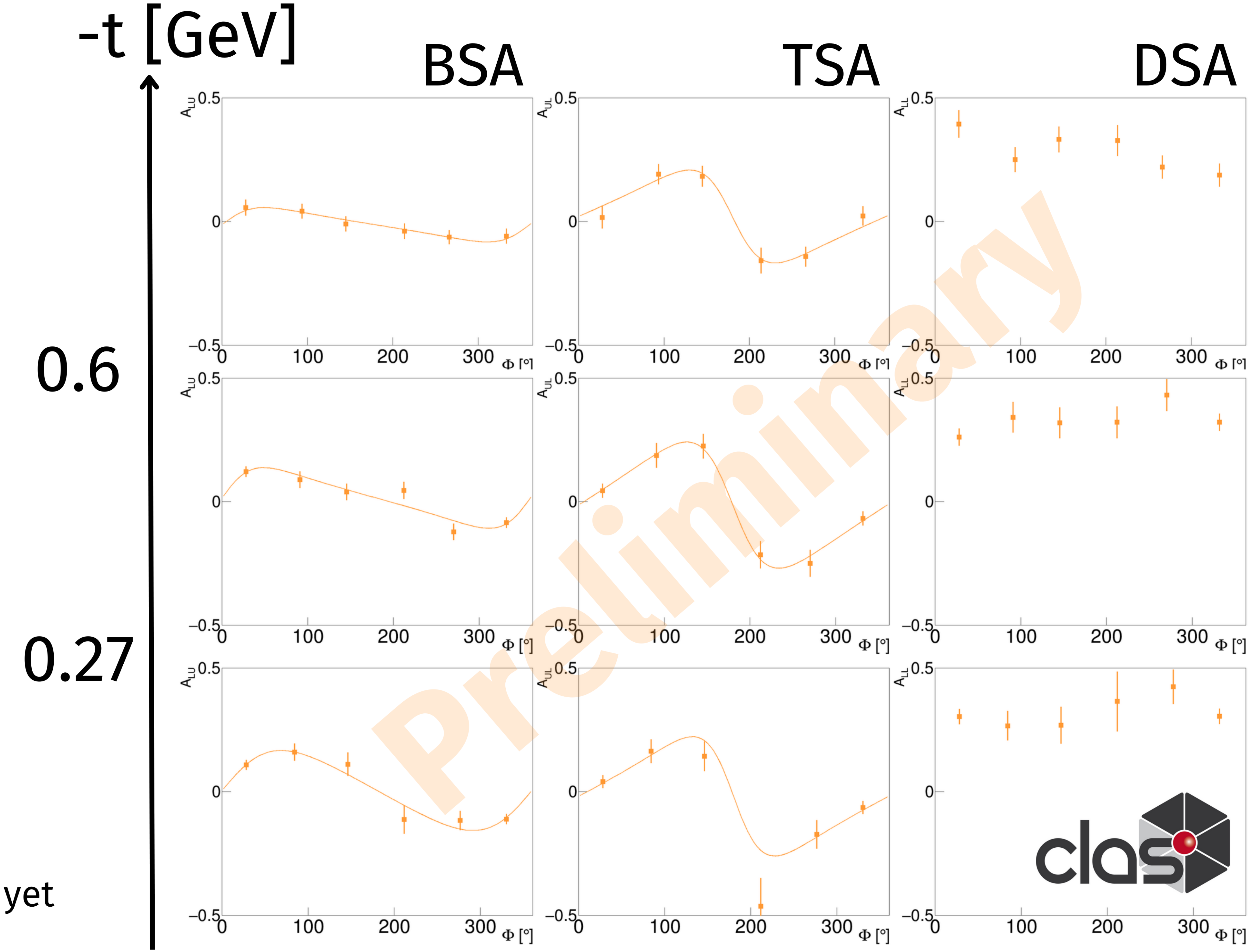
$$A_{LL} = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_b \times Df \times (P_t^{-}(N^{++} + N^{-+}) + P_t^{+}(N^{+-} + N^{--}))}$$

$$A_{LL}(\phi) \simeq \frac{c^{BH}_{0,LP} + c^{I}_{0,LP} + (c^{BH}_{1,LP} + c^{I}_{1,LP})cos(\phi)}{c^{BH}_{0,unp} + (c^{BH}_{1,unp} + c^{I}_{1,unp} + ...)cos(\phi) + ...}$$

$$c^{I}_{0,LP}, c^{I}_{1,LP} \propto \Re\left[F_1\tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$

t-Dependence





Raw asymmetries

No background subtraction yet

Challenges for nDVCS

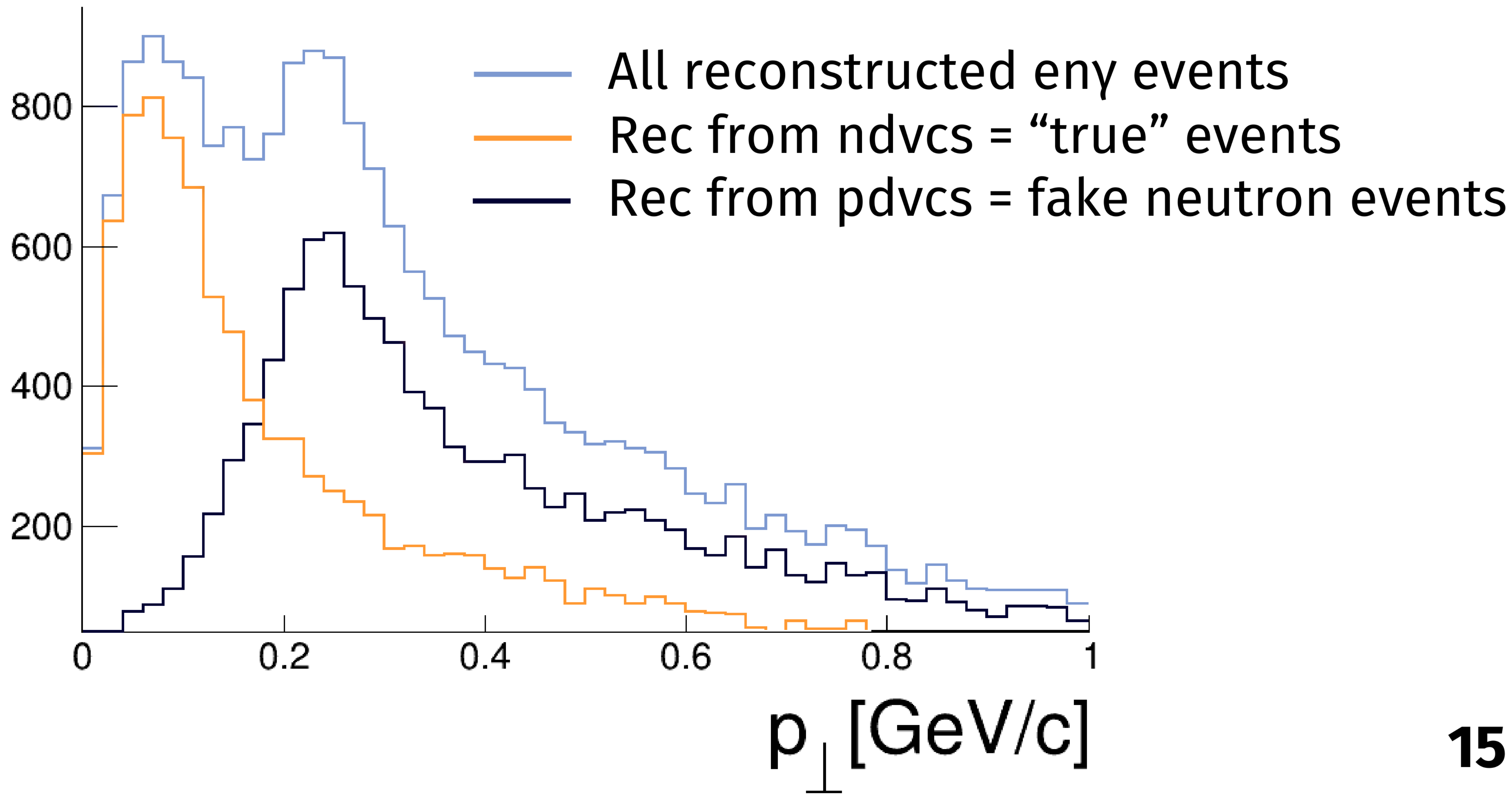
Fake n Bakground

Additional source of background for ndvcs:

- Neutron PID are identified as particles with hits in scintillators not associated with tracks in the tracking system
- Tracking system is not 100% efficient: protons misidentified as neutrons.
- They are assigned a straight track, their momentum is not well reconstructed: they appear in exclusivity variables !

GENEPI event generator :

- GPD-based
- BH + DVCS + $eN \to e'N'\pi^0 \to e'N'\gamma(\gamma)$
- Fermi Motion of nucleons in nuclei has been implemented at kinematics level

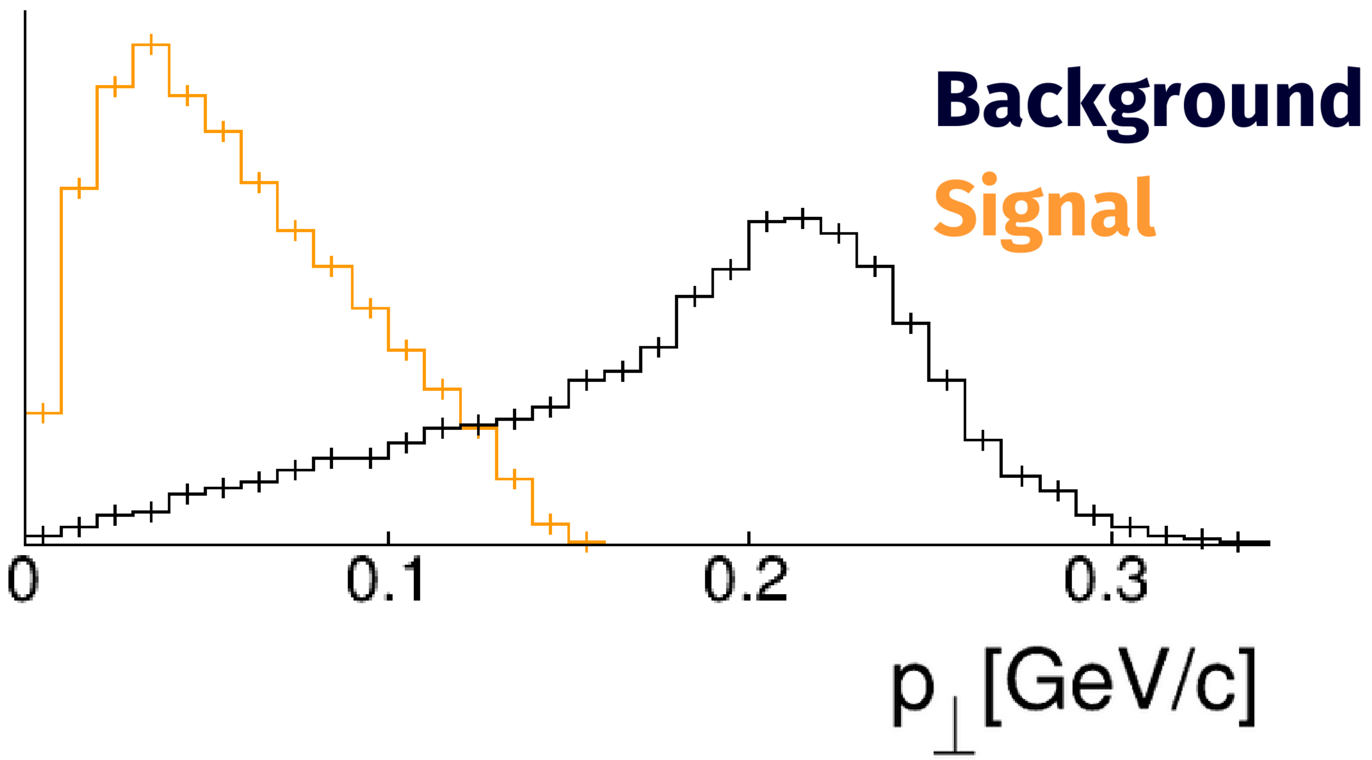


A Machine Learning Approach

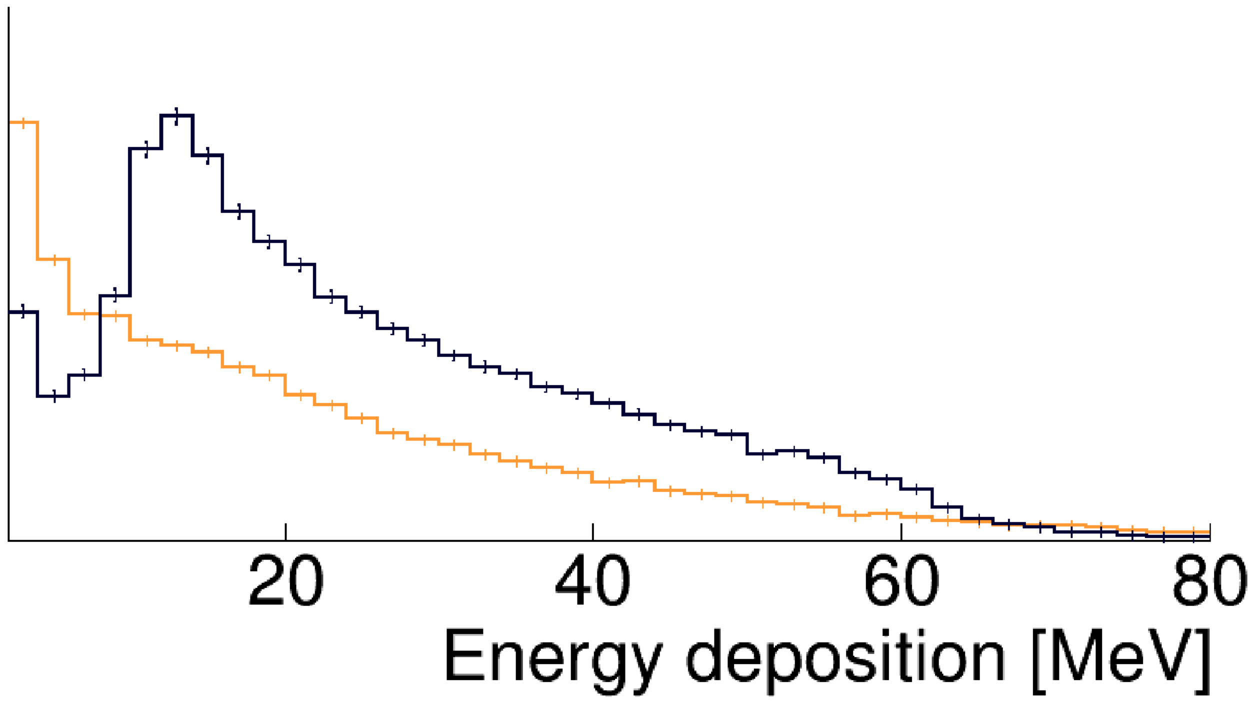
To try and reduce this source of background, a machine learning approach is tested.

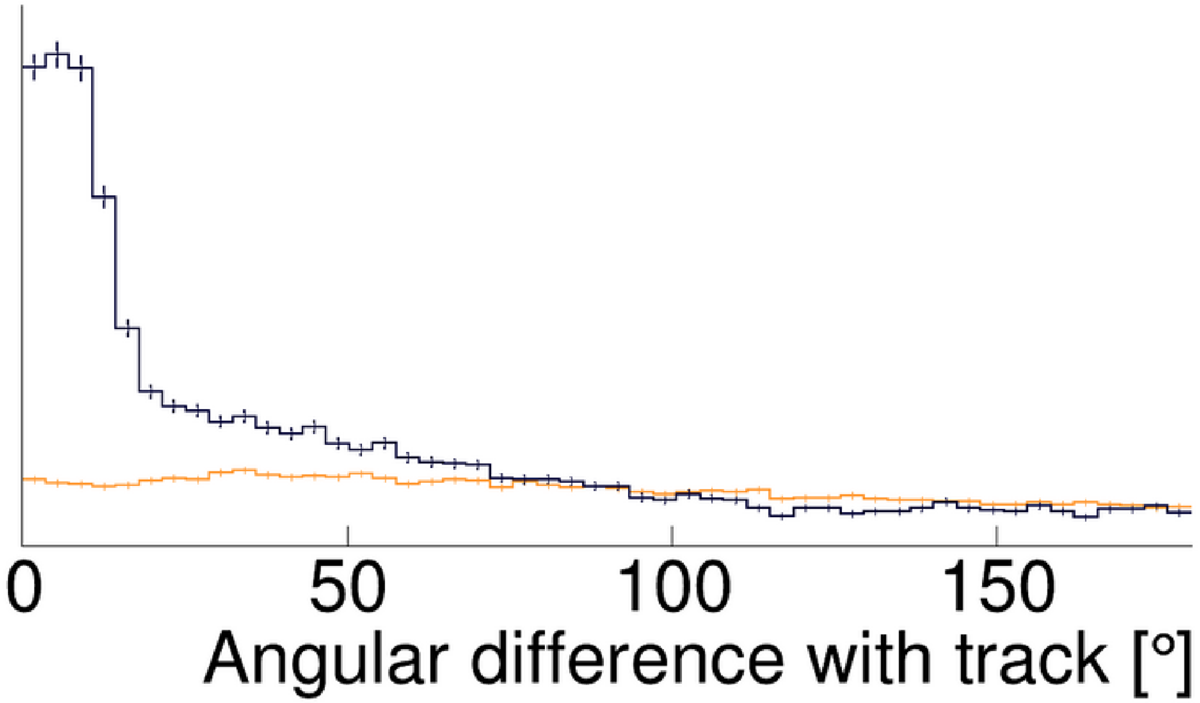
Using CLAS12 data on an H target.

- True neutrons sample: $ep \to en\pi^+$
- Fake neutrons sample: $ep \to en\gamma$



Ideal goal: improving PID at detector-level

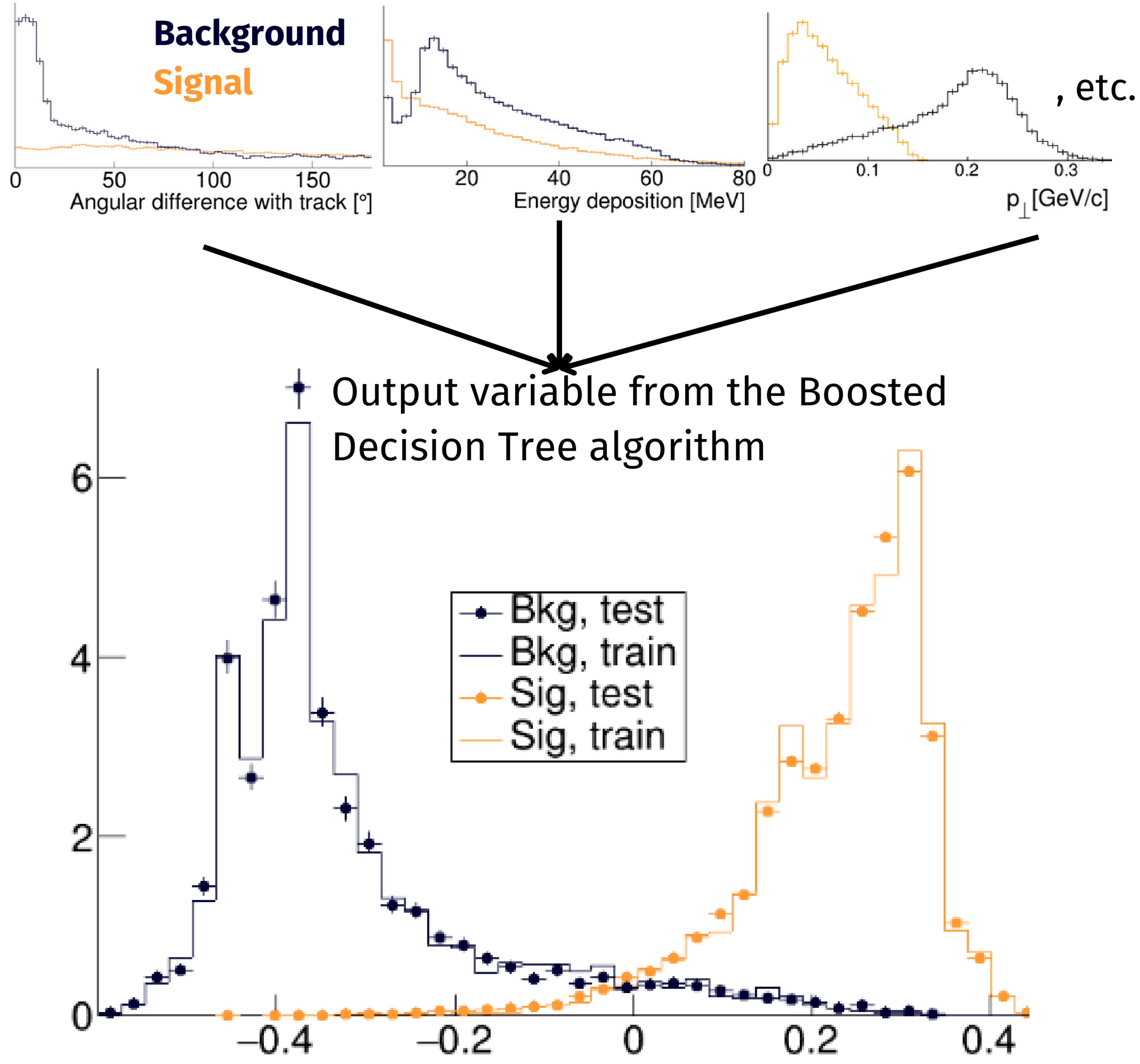




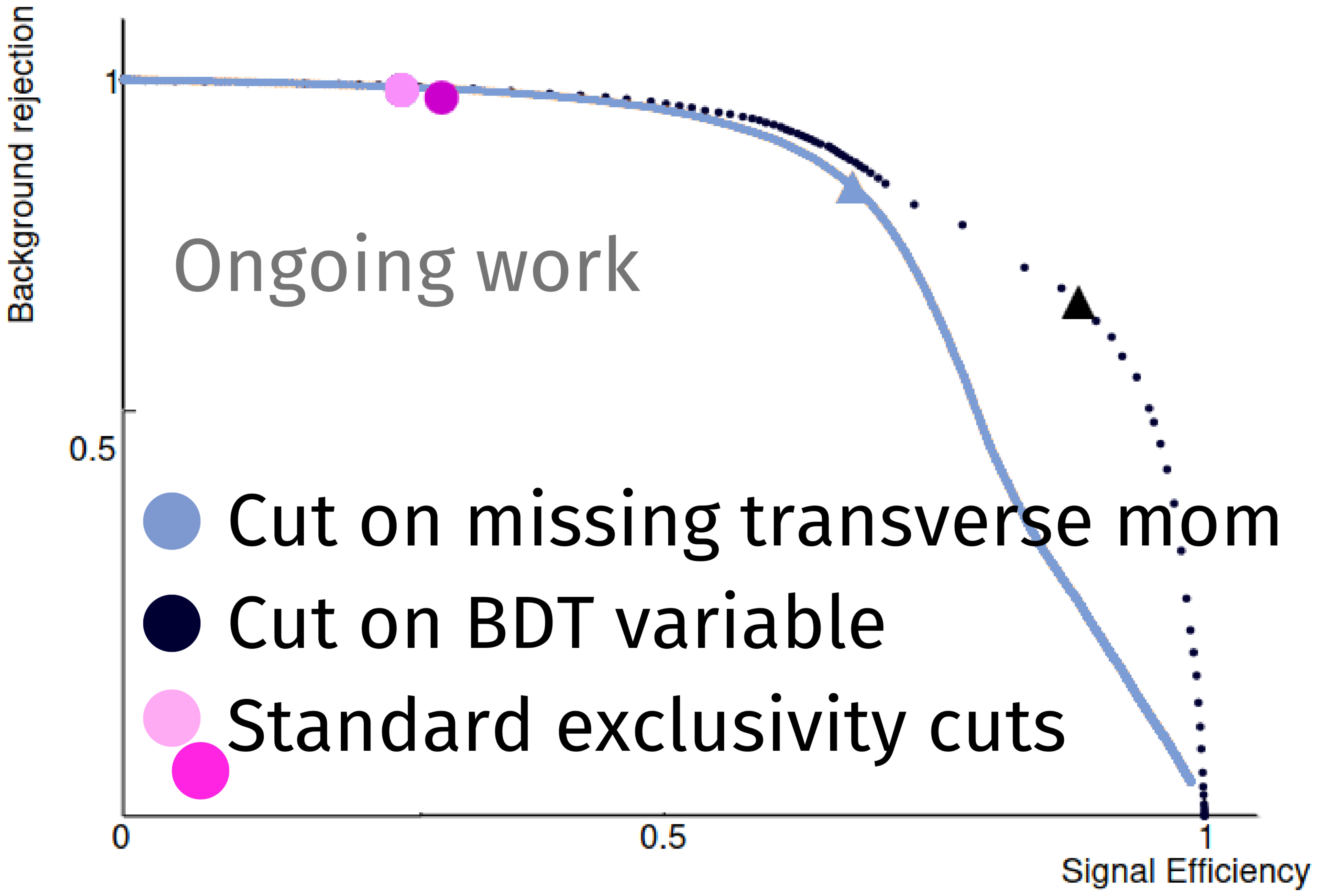
, etc.

A ML Approach

For now, we keep using an exclusivity variable.



Applied to RGC simulations



Outlook

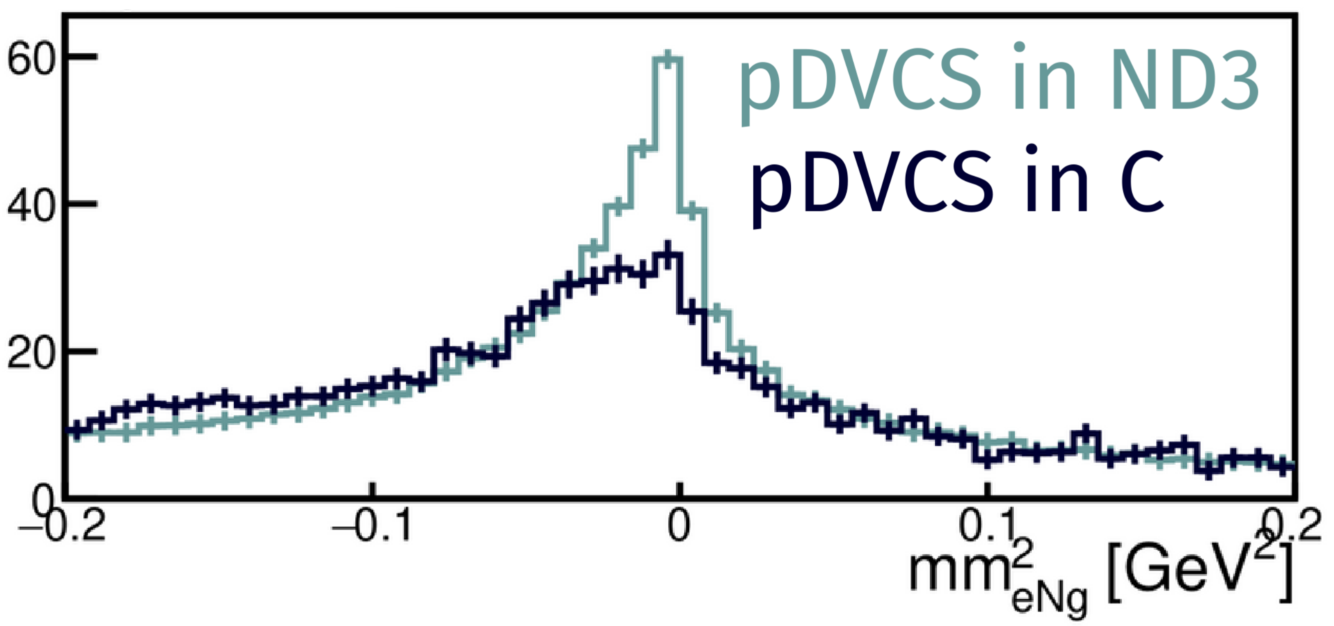
- The first polarized DVCS experiment with the CLAS12 detector will allow to access proton and neutron Compton Form Factors and extract their flavor dependency.

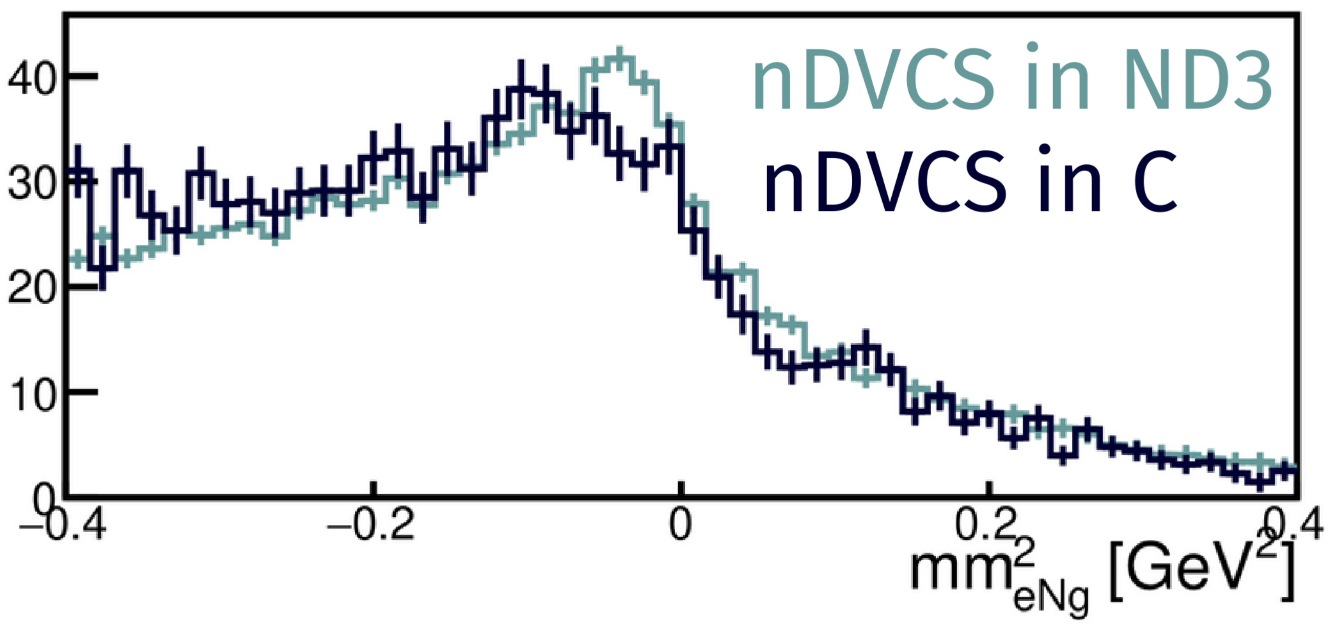
- Data taking took place between 2022 and 2023, the star of the show is the CLAS12 polarized target !

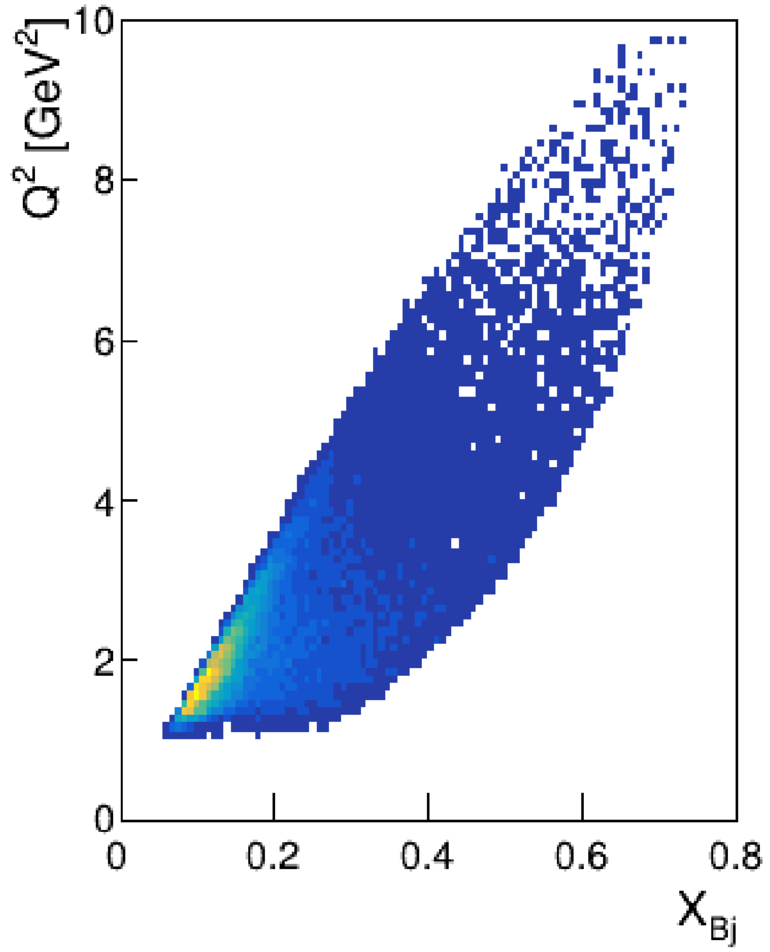
- Data analysis is ongoing, showing a healthy state of the analysis especially with the tools that are implemented to deal with a polarized nuclear target.

- Many challenges to come with neutron detection, neutral pion background, etc.

- First part of the data is being processed these days, exciting results are on the way !





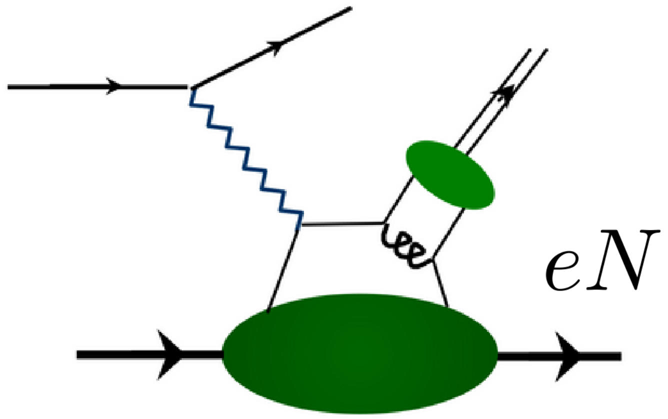


Backup

Simulation Framework

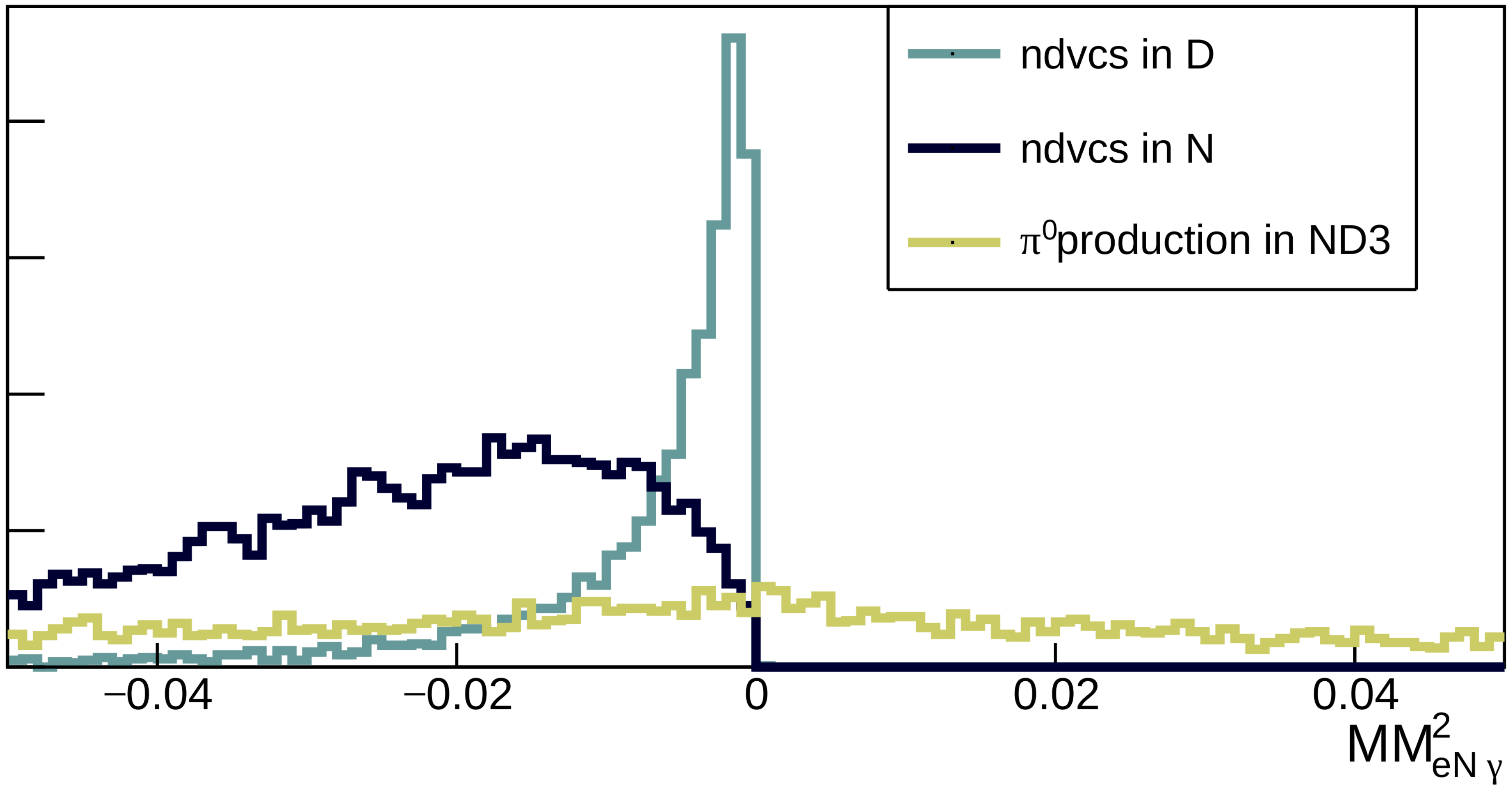
GENEPI event generator :

- GPD-based
- BH + DVCS + Deeply Virtual Meson Production
- Fermi Motion of nucleons in nuclei has been implemented at kinematics level

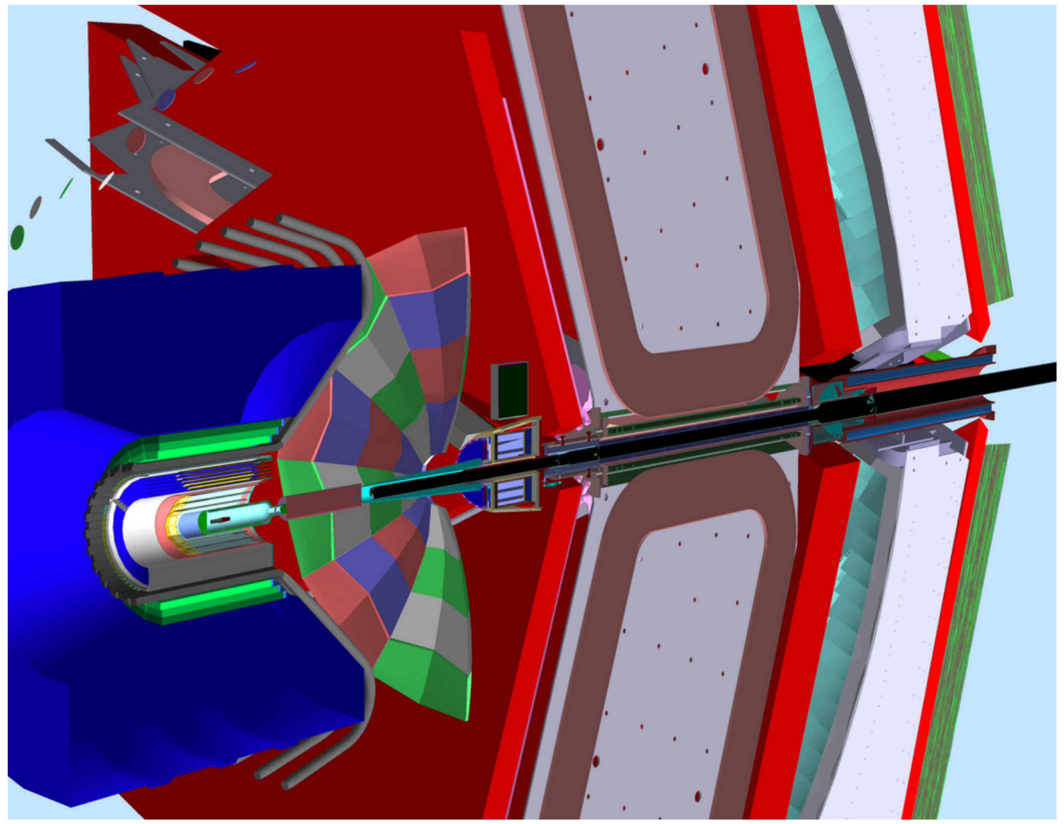


$$eN \to e'N'\pi^0 \to e'N'\gamma(\gamma)$$

Generated events



Standard CLAS12 GEANT4-based simulation and reconstruction algorithm



Simulations for nDVCS in ND3

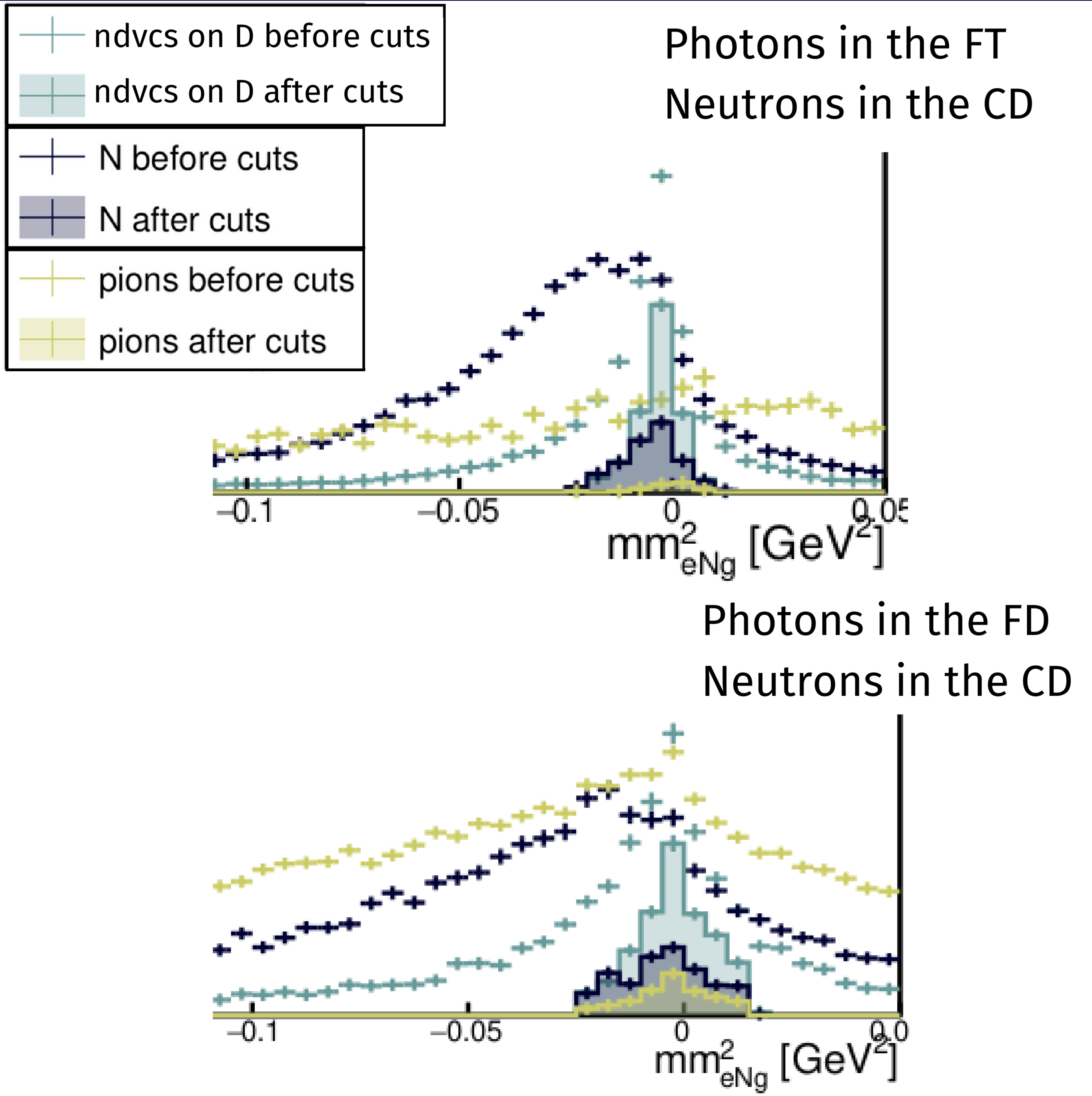
Simulations are used to optimize exclusivity cuts and study backgrounds

- 75% of DVCS events are detected with γ in the FT
- Most pion events are detected with γ in the FD which has lower resolution : more contamination
- Dilution factor

$$1 - \frac{N}{N+D} \simeq 65\%$$

Photons in the FT
Neutrons in the CD

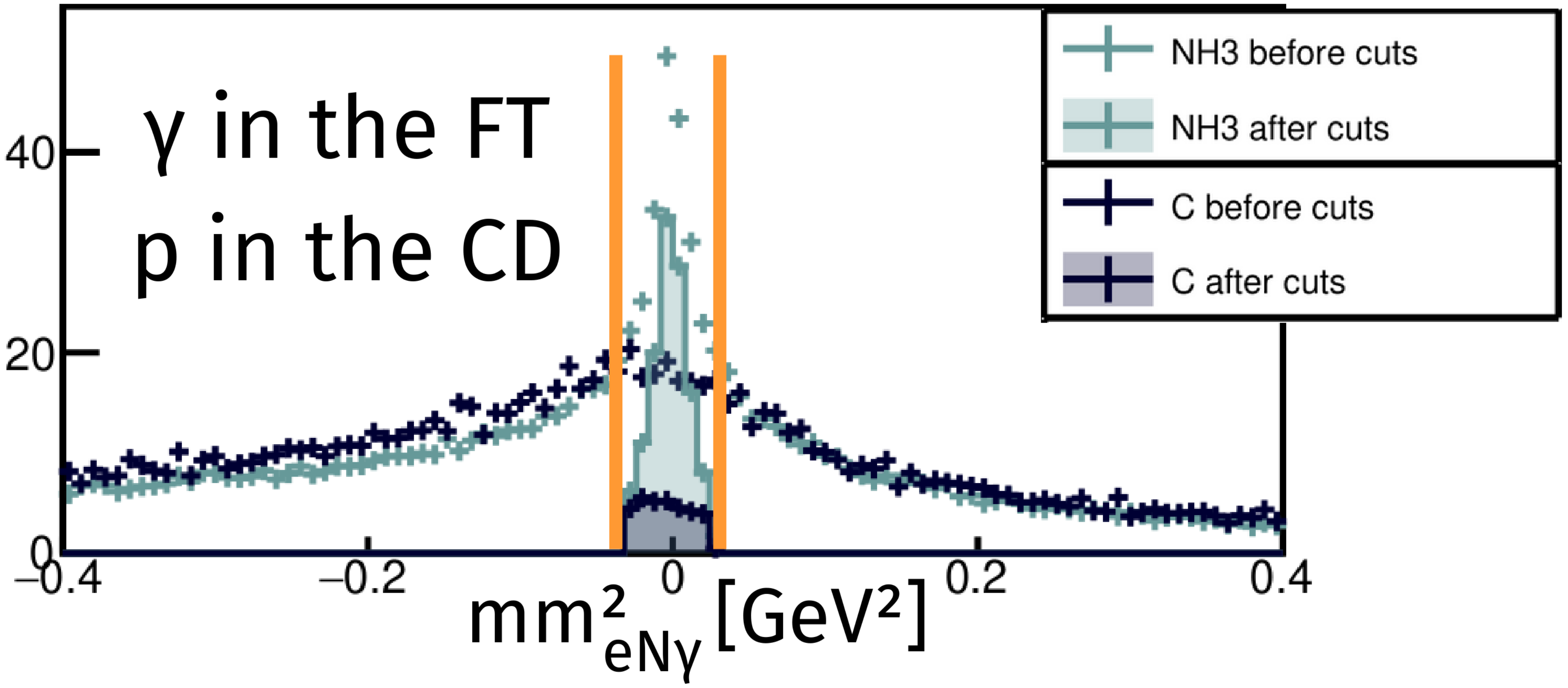
Photons in the FD
Neutrons in the CD

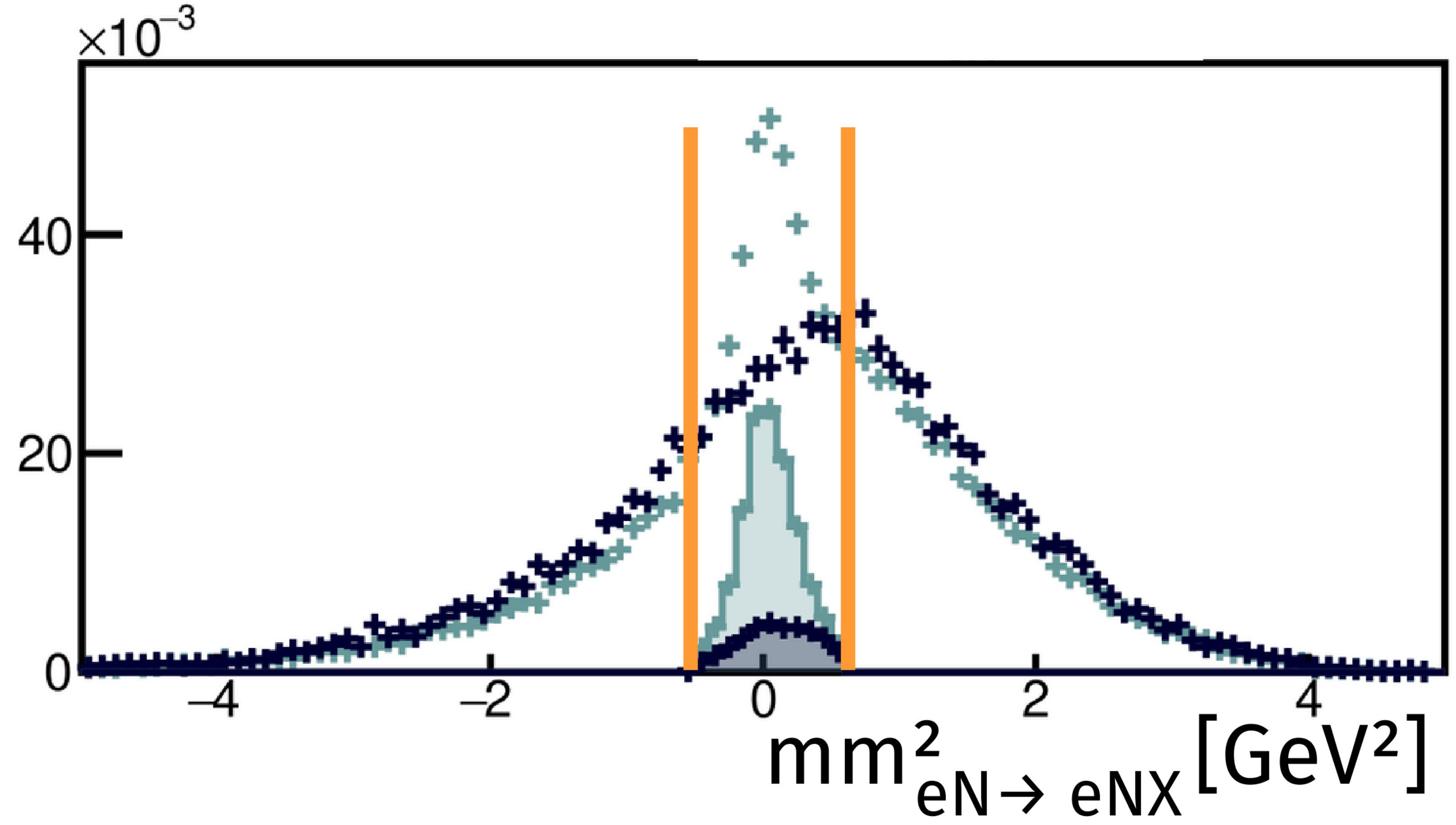


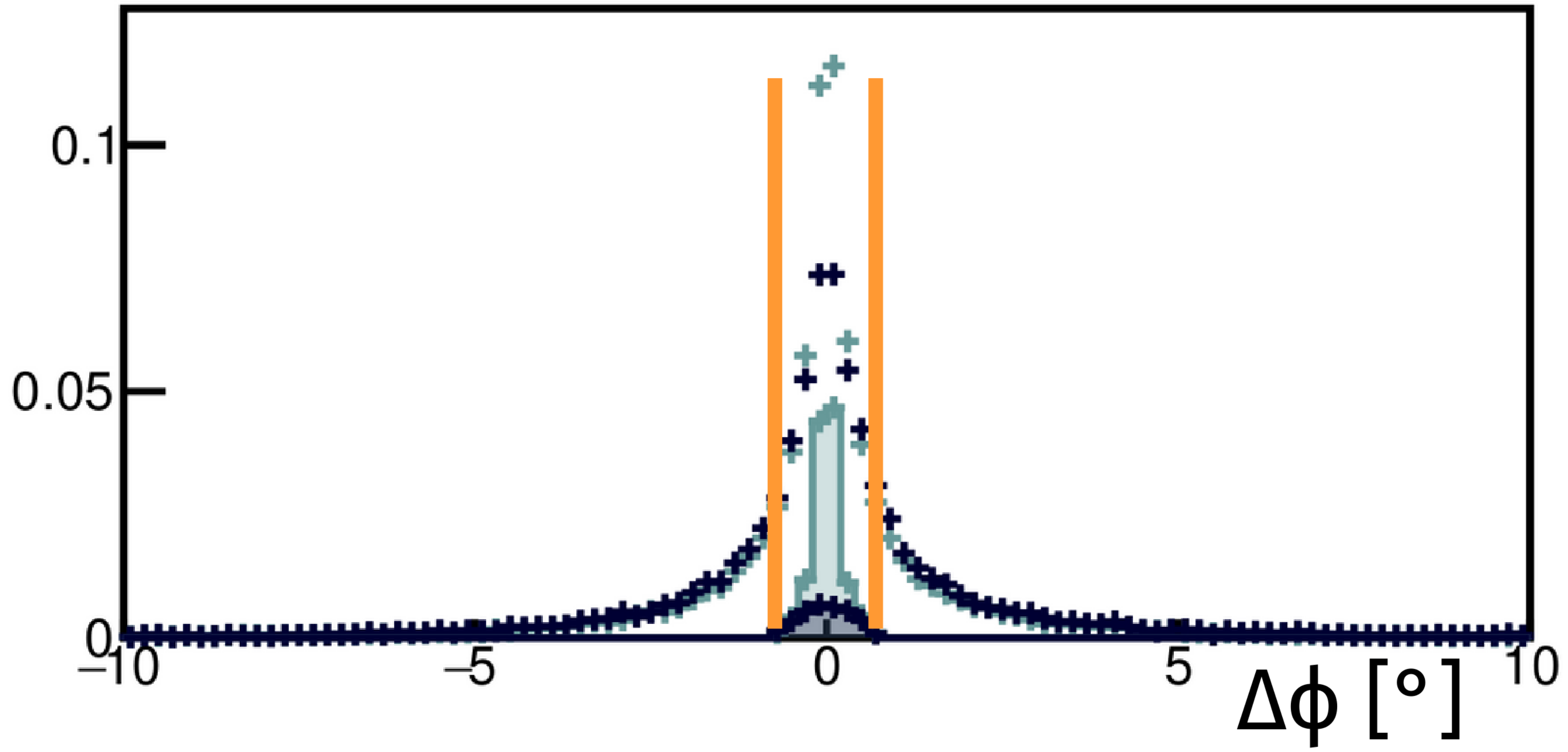
/!\ Relative scale between DVMP and DVCS does not reflect actual cross sections

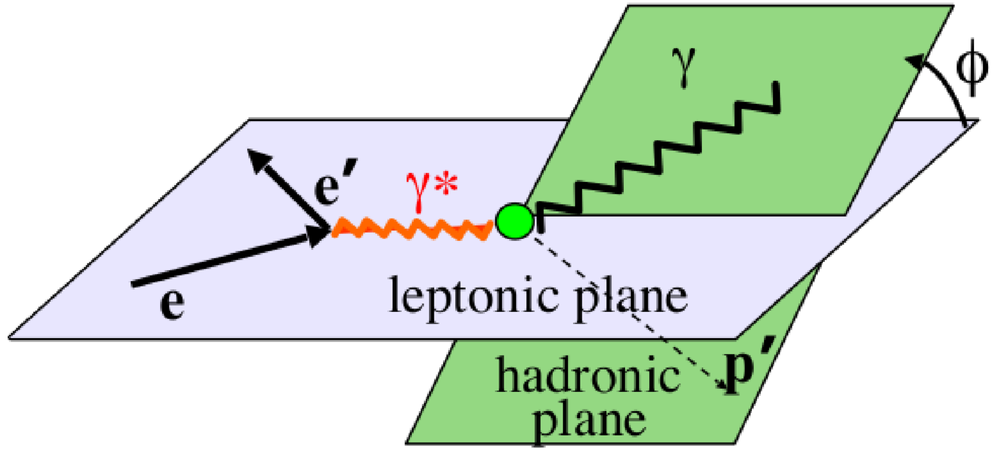
pDVCS Event Selection ep → e'p'γ

Pre-selecting events with at least 1 proton, 1 e⁻ and 1 γ

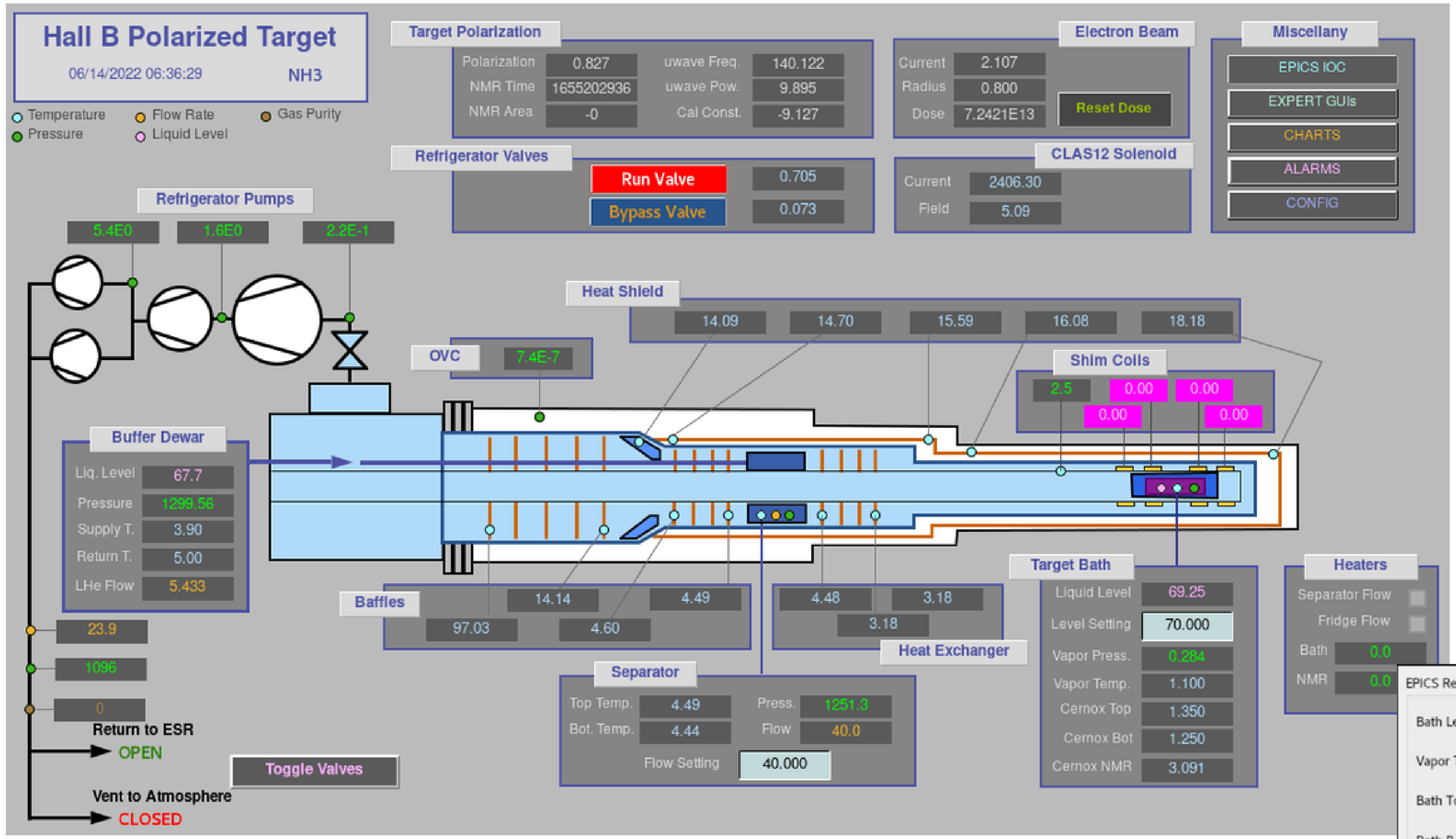


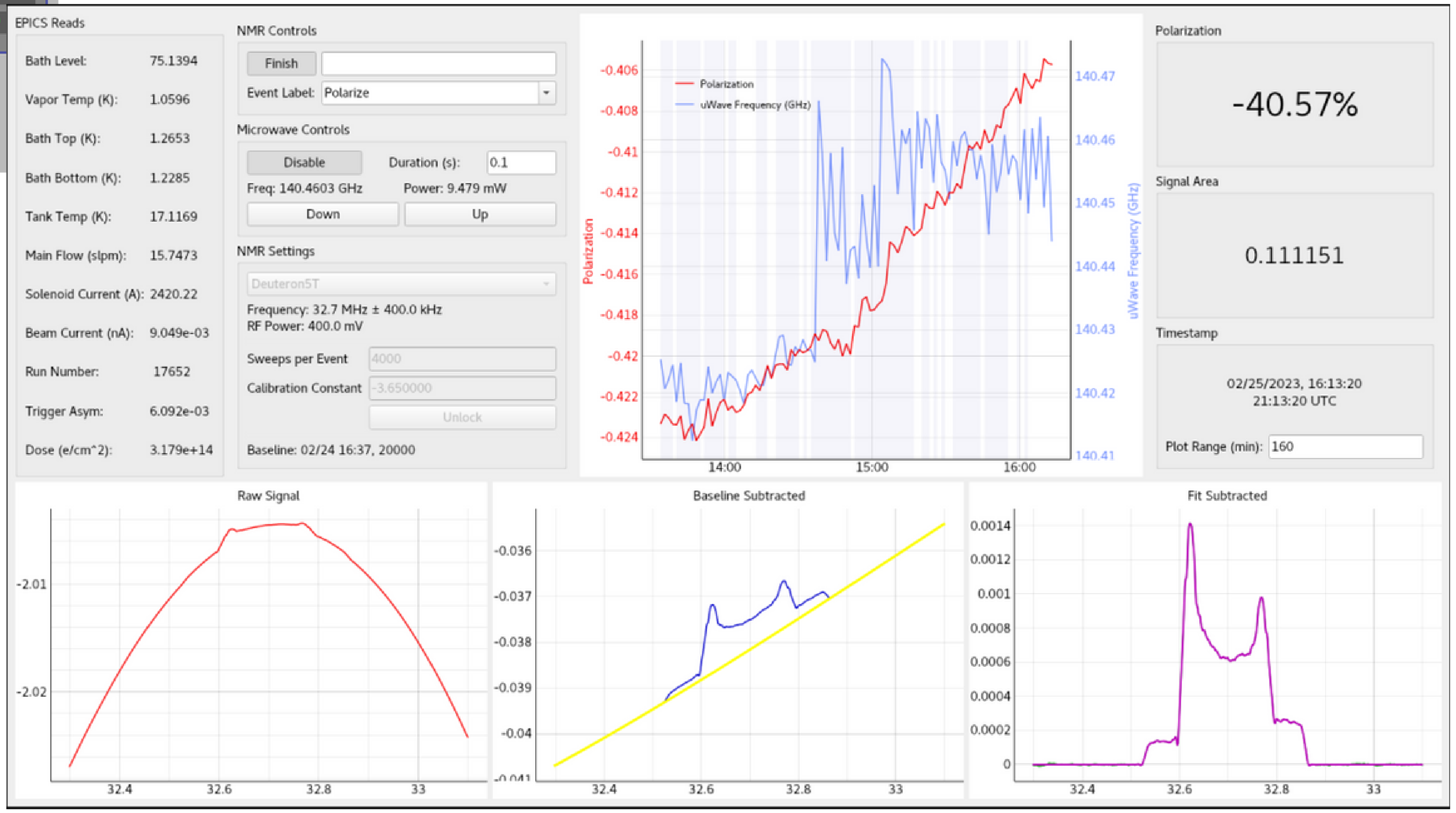




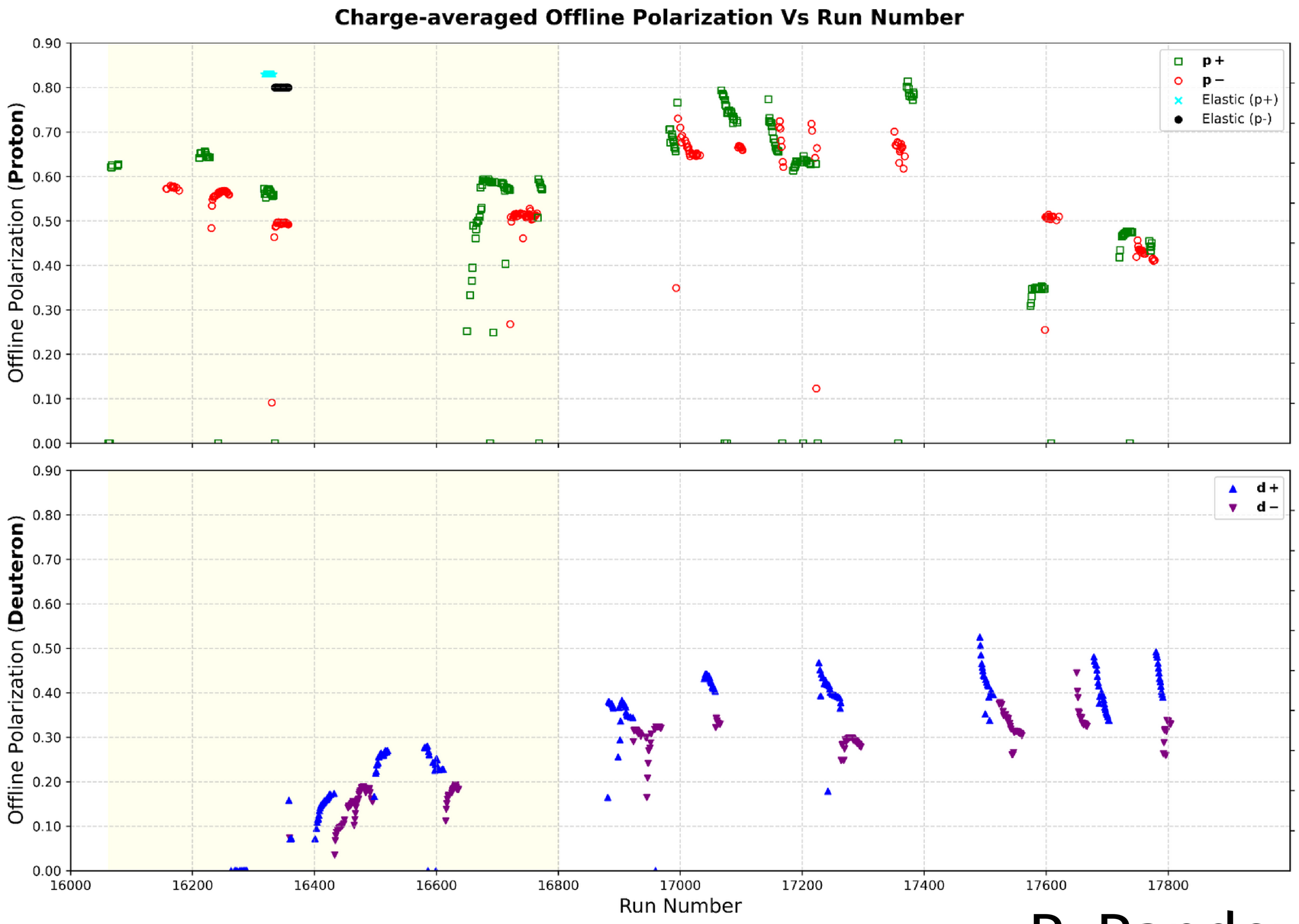


The RGC Target



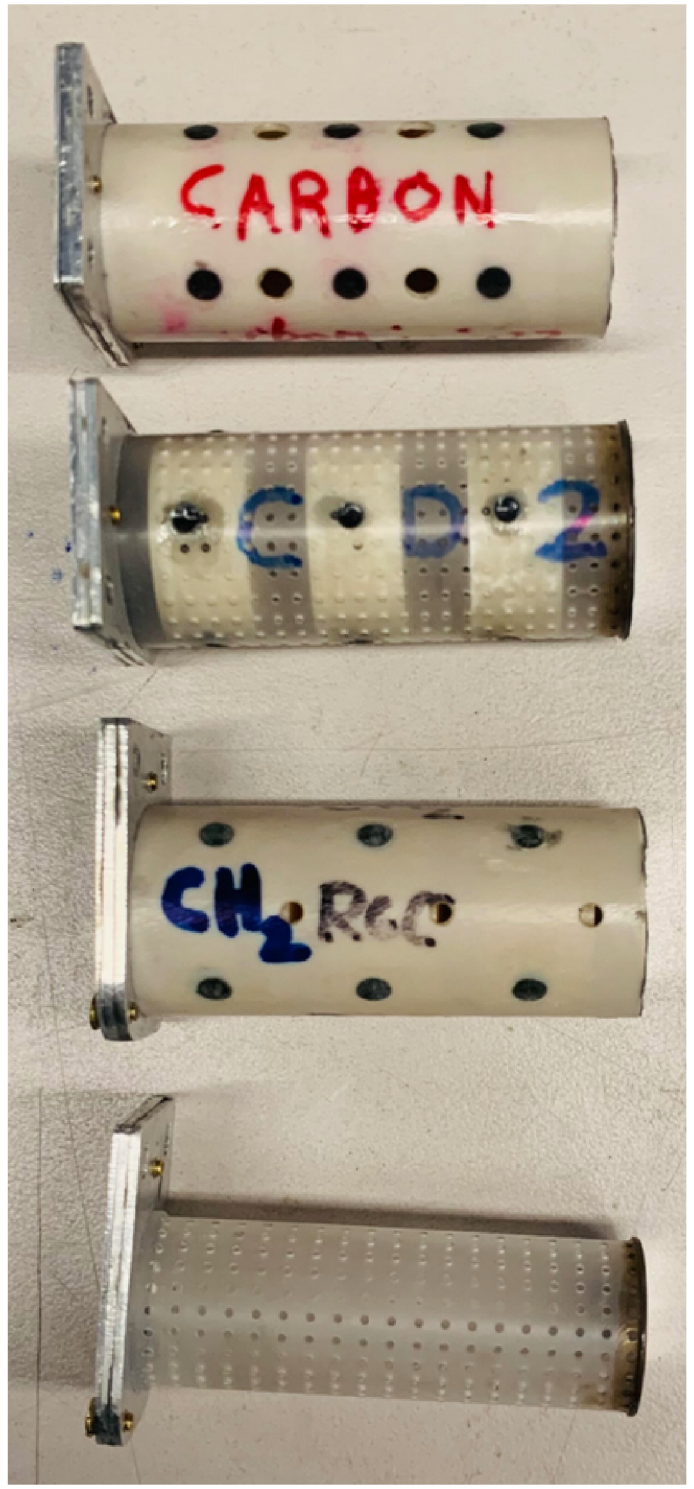


NMR Target Polarization Measurement



P. Pandey

Dilution Factor



$$N_A = X_A f_c \left[l_F \rho_F \Delta\sigma_F + (L - l_A)\rho_{He} \Delta\sigma_{He} + l_A \rho_A \left(\frac{7}{6} \Delta\sigma_C + 3\Delta\sigma_H \right) \right]$$

S.E. Kuhn

Al foils, empty target

Liquid helium, empty +LHe

N background, Carbon target (same n/p ratio and similar binding energy as N)

H/D in ammonia

RGC Experiments

Longitudinal Spin Structure of the Nucleon	Kuhn
DVCS on the neutron with polarized deuterium target	Niccolai
DVCS on longitudinally polarized proton target	Sabatie
Spin-Orbit Correlations with longitudinally polarized target	Avakian
Study of partonic distributions using SIDIS K production	Hafidi
Spin-Orbit correlations in K production with polarized targets	Avakian
Studies of Dihadron Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets	Dilks
Studies of Single Baryon Production in the Target Fragmentation Region with a Longitudinally Polarized Target	Hayward

Ongoing:
p and n DVCS in D - This work
TCS on p - K.Gates
pDVCS in H - S.Polcher
pion SIDIS - H. Avakian
Di-hadron SIDIS - G.Matousek
Fragmentation Region SIDIS - T.Hayward
DIS - D.Holmberg

The RGC Beamline

Dealing with a polarized necessitates specific design for the whole experiment

- Rastered beam for uniform depolarization
- Need to protect the detectors around:
  - When the FT is used, running at low current
  - When it is off, specific shielding