



Deeply Virtual Compton Scattering on Polarized Nucleons with the CLAS12 Experiment

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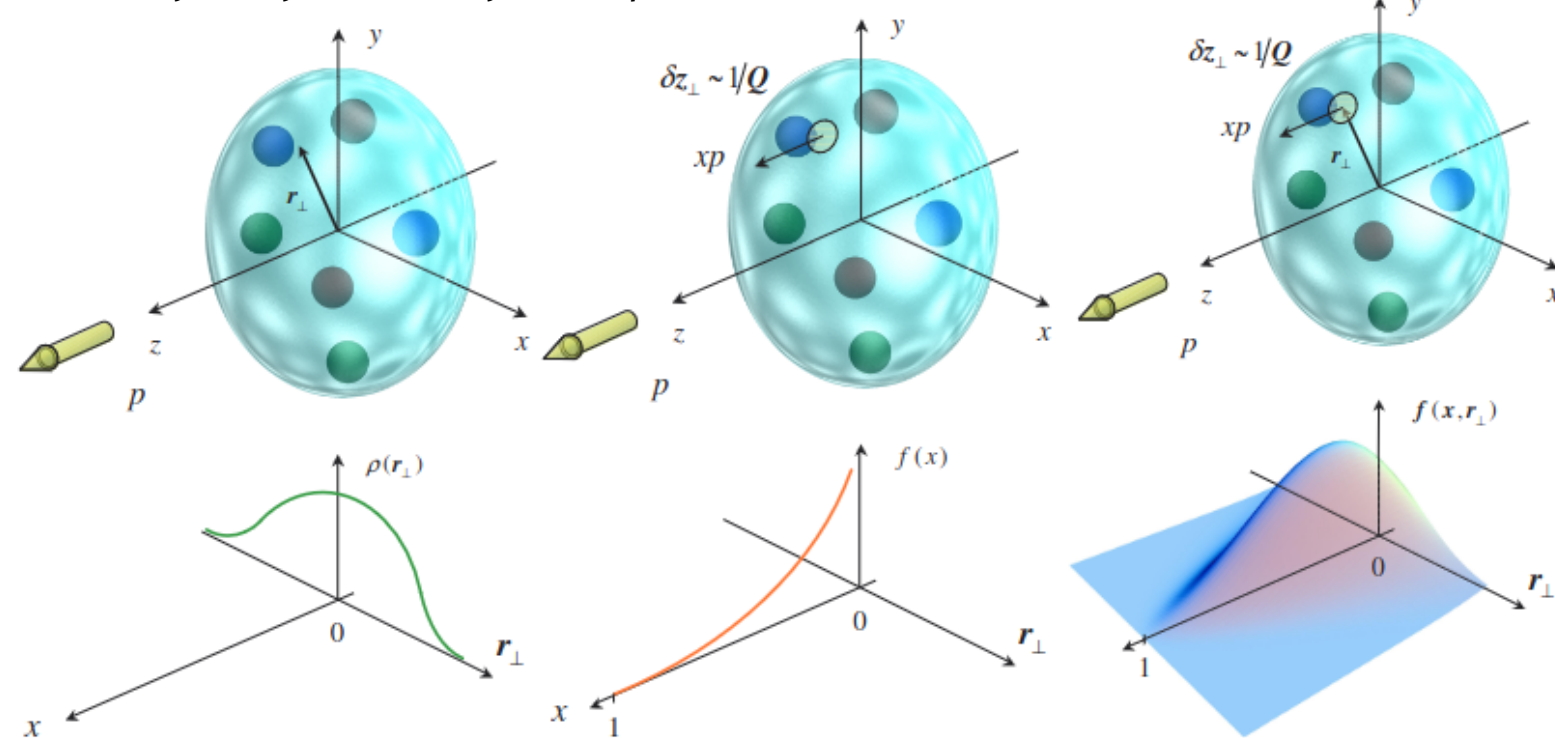
Understanding the Structure and Properties of Nucleons

QCD is non perturbative at the scale of the nucleon mass \rightarrow structure functions

Generalized Parton Distributions

Longitudinal momentum, transverse position and their correlations

Belitsky, Radyushkin, Physics Reports, 2005



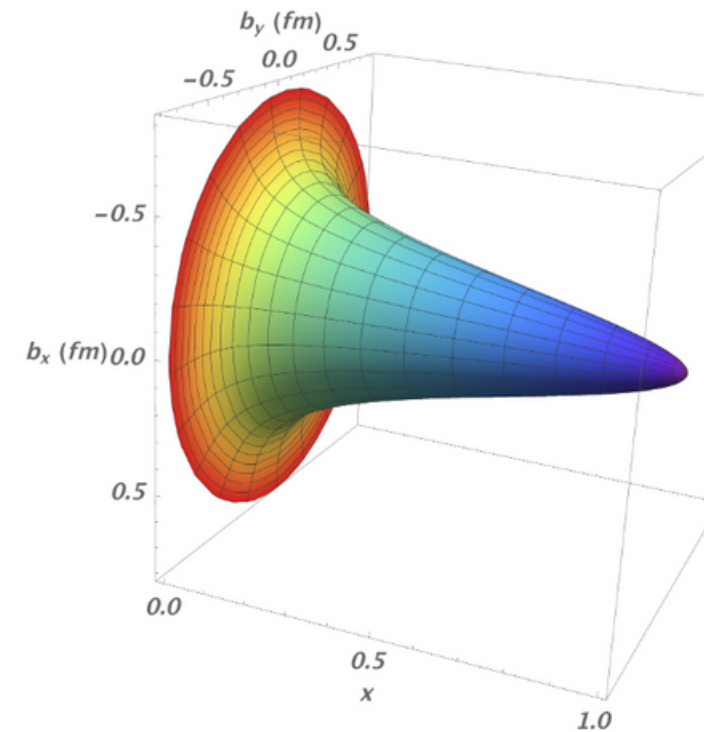
• Proton spin decomposition

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

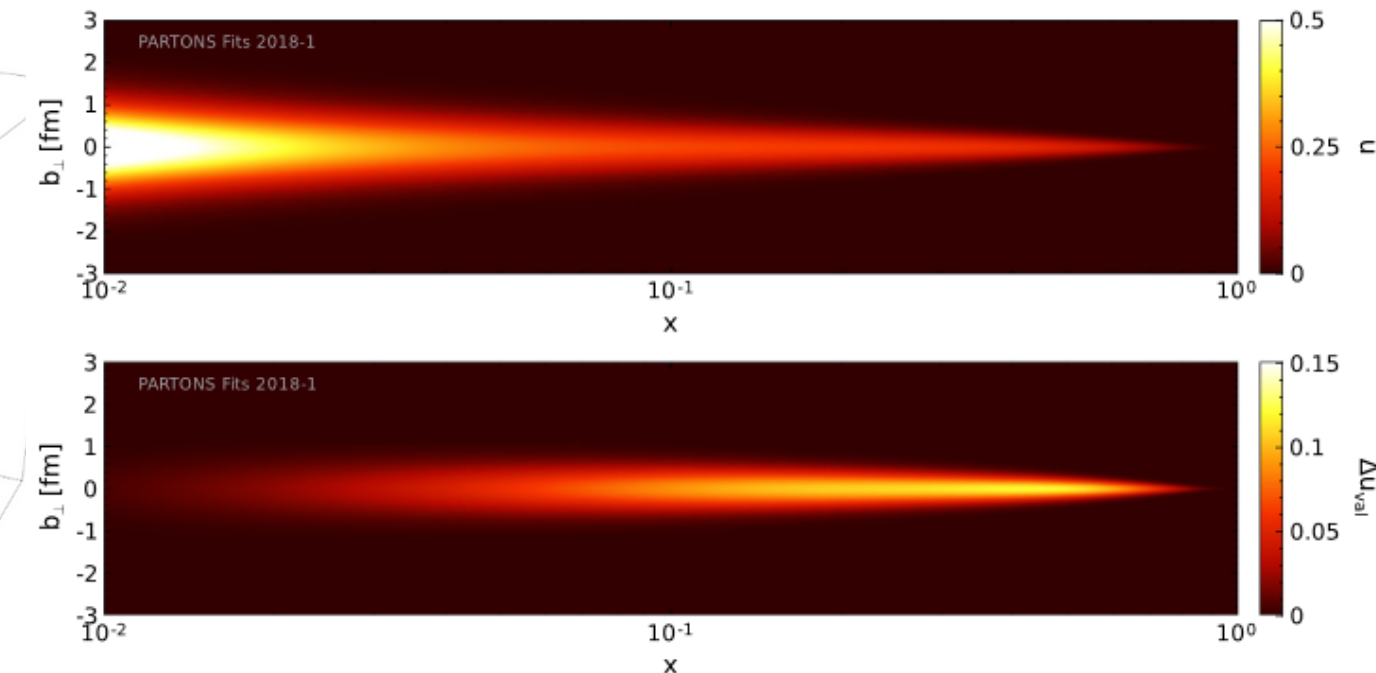
$$\frac{1}{2} \int_{-1}^1 dx (H(x, \xi, t=0) + E(x, \xi, t=0)) = \frac{1}{2} \Delta \Sigma + \Delta L$$

• Towards 3D imaging of nucleons

Dupré, Guidal, Vanderhaeghen, PRD95, 2017

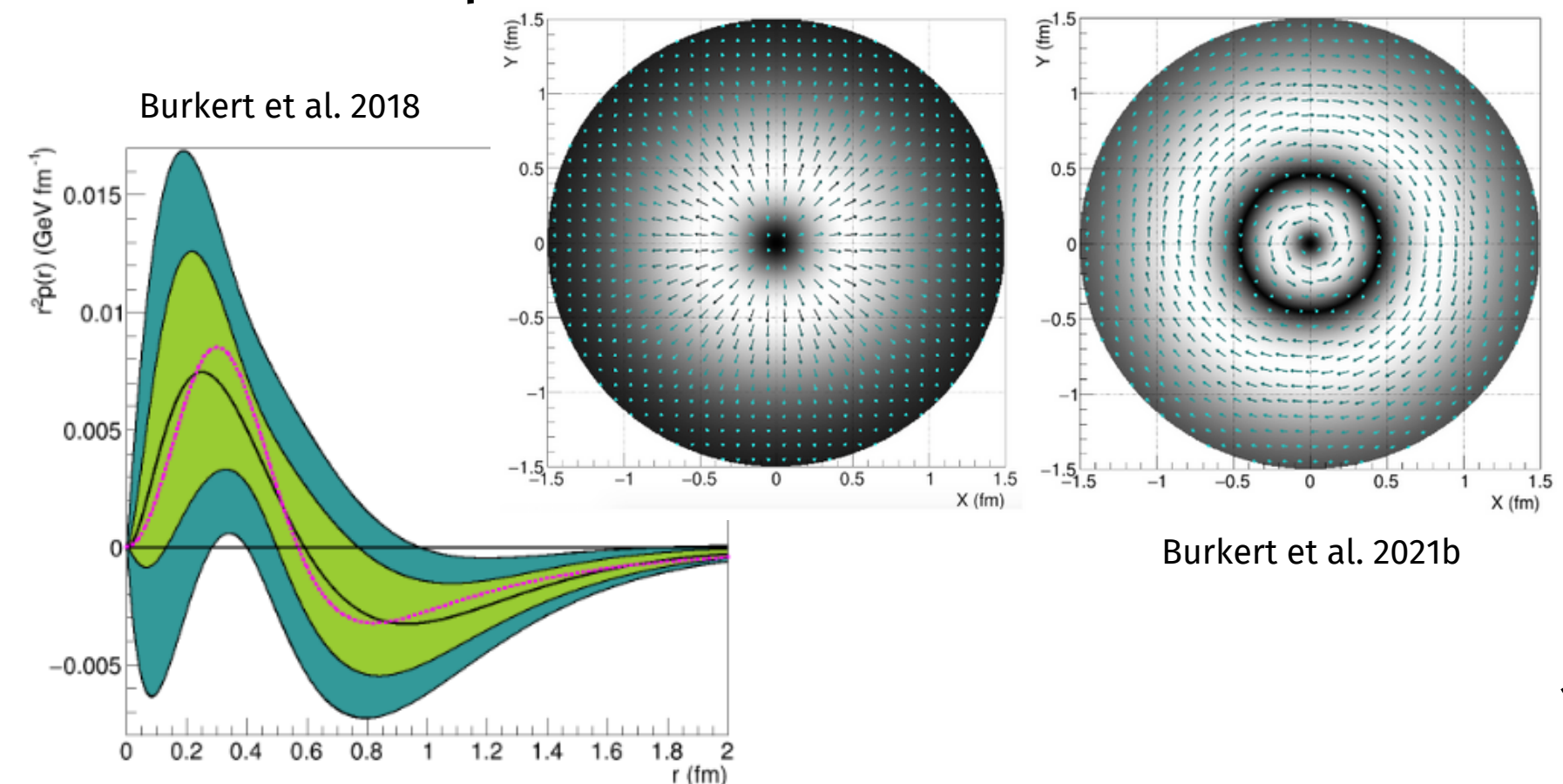


Moutarde, Sznajder, Wagner, EPJC 2018



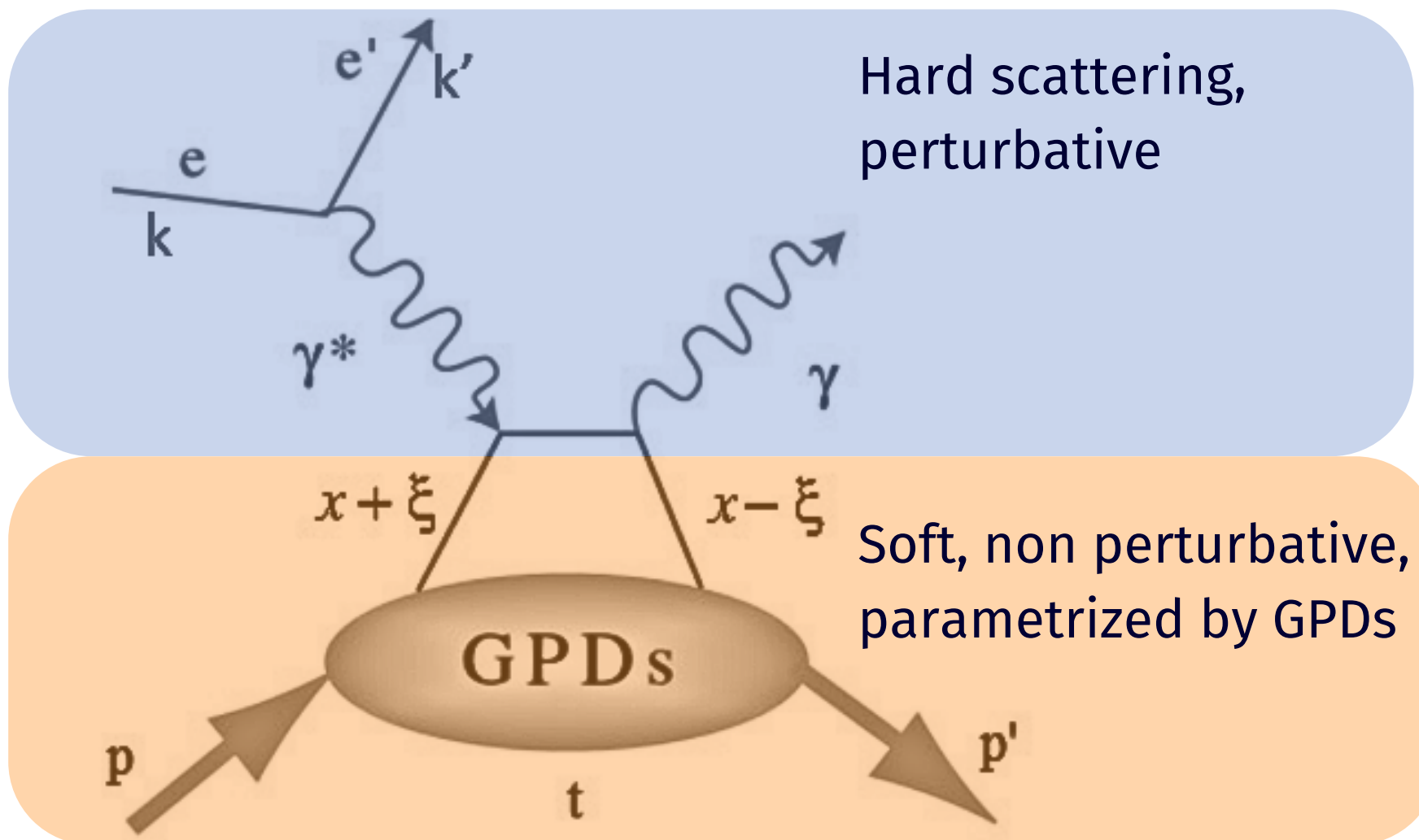
• Forces and pressure inside nucleons

Burkert et al. 2018



Burkert et al. 2021b

Deeply Virtual Compton Scattering

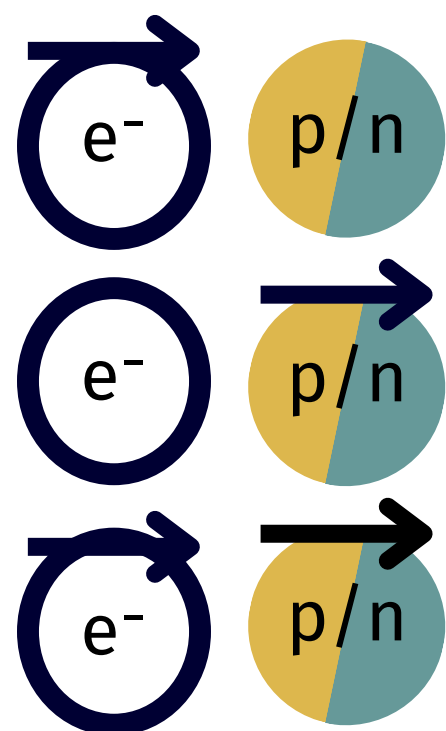


Gives access to Compton Form Factors

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

$$\sigma(eN \rightarrow eN\gamma) = \left| \text{DVCS} + \text{Bethe-Heitler (BH)} \right|^2$$

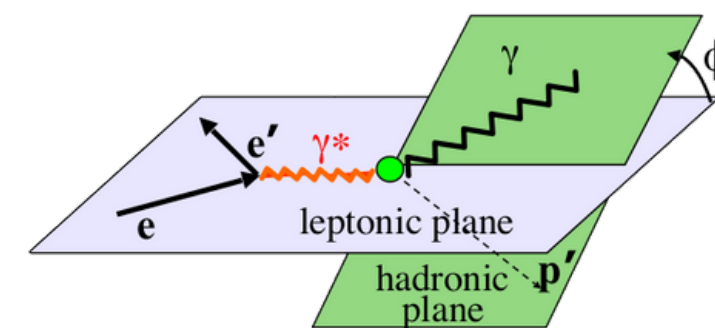
Access to linear combinations of CFFs and Form Factors thanks to the interference of BH and DVCS.



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

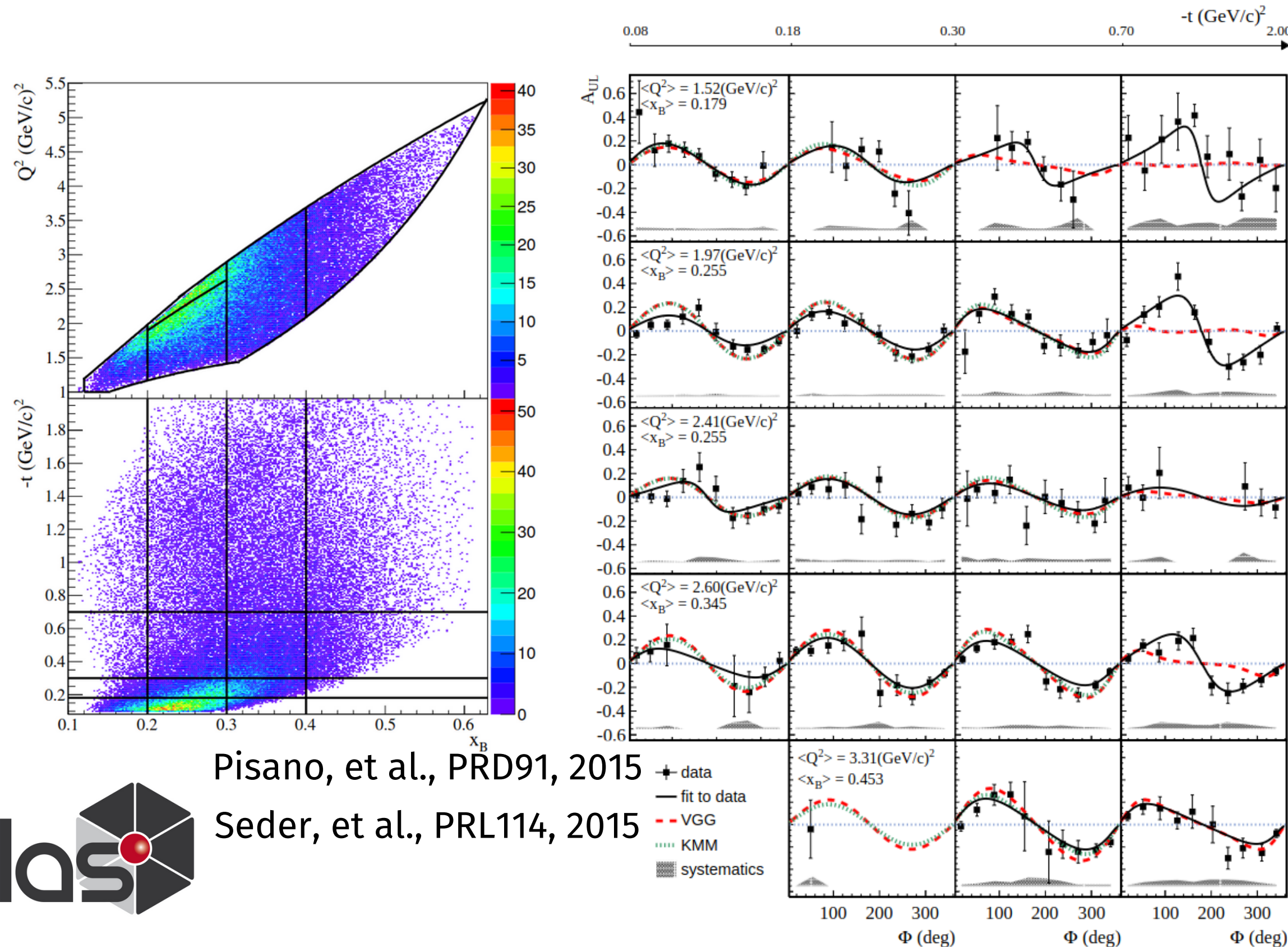
$$\Delta\sigma_{UL} \simeq \sin(\phi) \Im \left[F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2) \left(\mathcal{H} + \frac{x_{bj}}{2} \mathcal{E} \right) - \xi \left(\frac{x_{bj}}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \right]$$

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

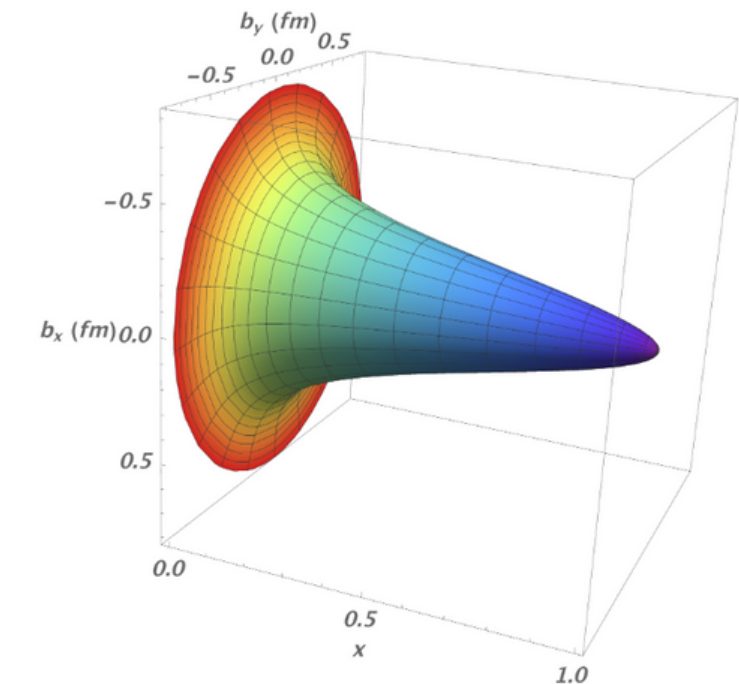


Existing CLAS Measurement of DVCS on Polarized Protons

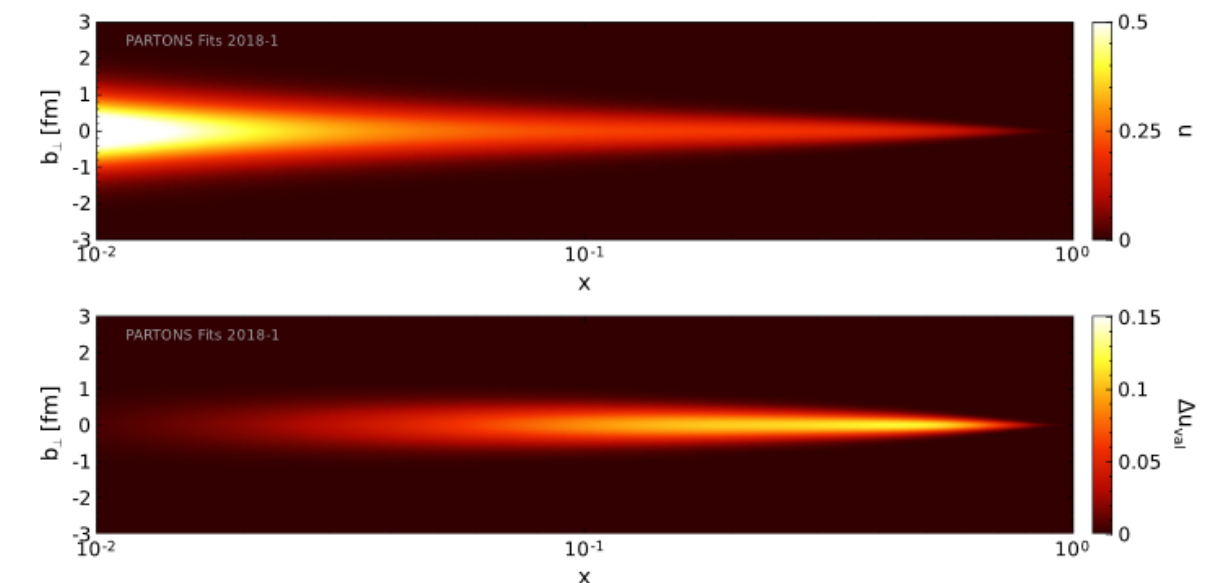
- First measurement in 2006 with the CLAS detector at 6 GeV (S.Chen et al. PRL97, 2006)
- Few years later, dedicated CLAS measurement at 6 GeV with an upgraded detector



Dupré, Guidal, Vanderhaeghen, PRD95, 2017

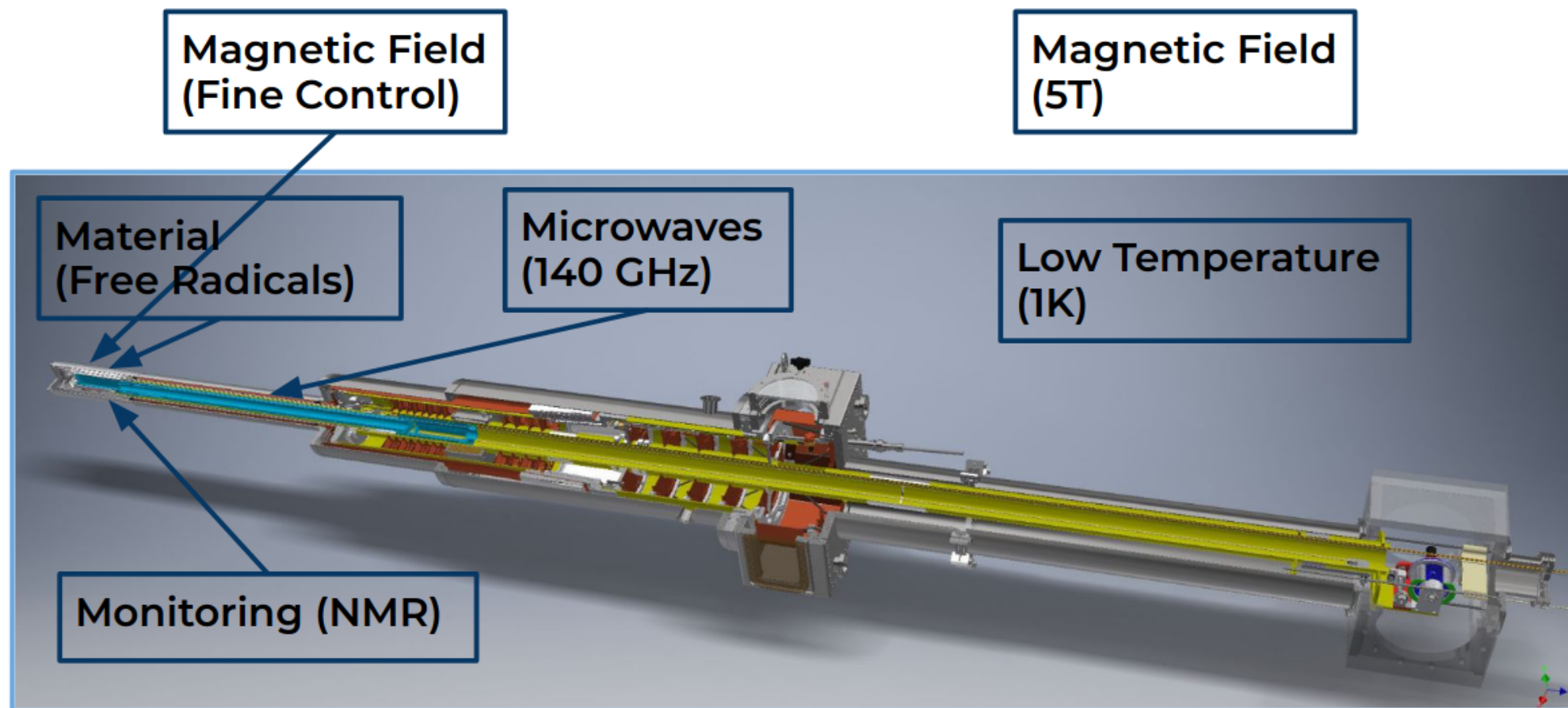


Moutarde, Sznajder, Wagner, EPJC 2018



Polarized DVCS with CLAS12, Run Group C

- Run Group C : First polarized target experiment with CLAS12
- Ran from June 2022 to March 2023
- Polarized solid NH₃/ND₃ targets
- Richness of opportunities for hadronic physics and nucleon structure studies
- G. Matousek, P.Pandey, T.Hayward, H.Avakian talks for all details and more exciting physics



Measurement of DVCS Beam-, Target- and Double-Spin Asymmetries 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

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

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

CLAS12 for DVCS

CEBAF, JLab

- highly polarized
- up to 12 GeV
- high luminosity.

beam electron

scattered electron

virtual photon

Q^2

struck quark

nucleon
structure: GPDs

beam or
target
nucleon
 p_n

p'_n
recoiling
nucleon

emitted photon

Possibility to add a low-angle
electron/photon detector
Forward Tagger (FT)

FD
Forward detector

Central detector CD

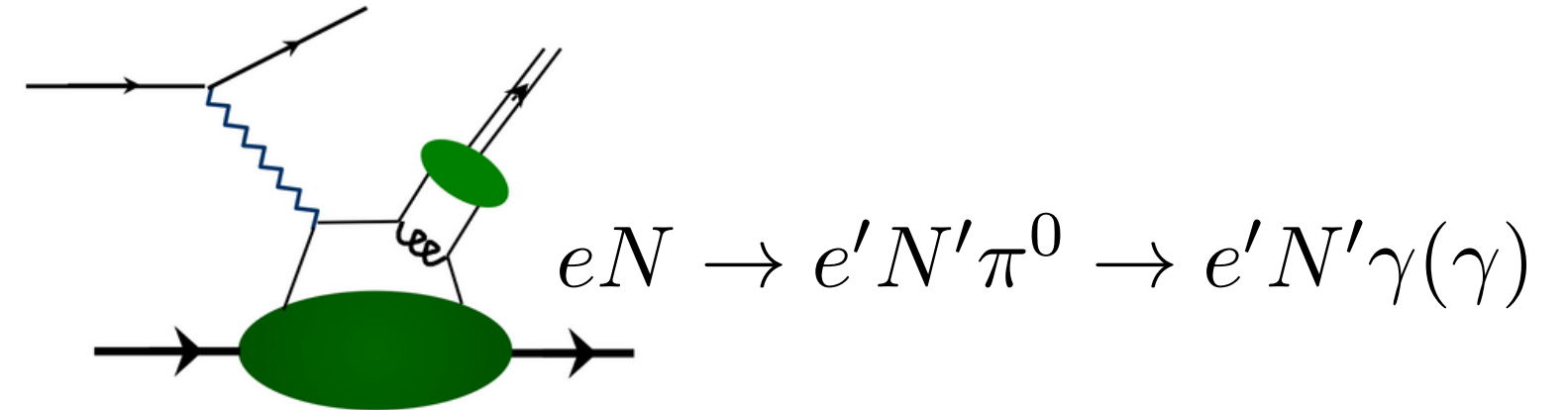
Hall B, Large Acceptance
Spectrometer

Simulation studies for pDVCS and nDVCS in D

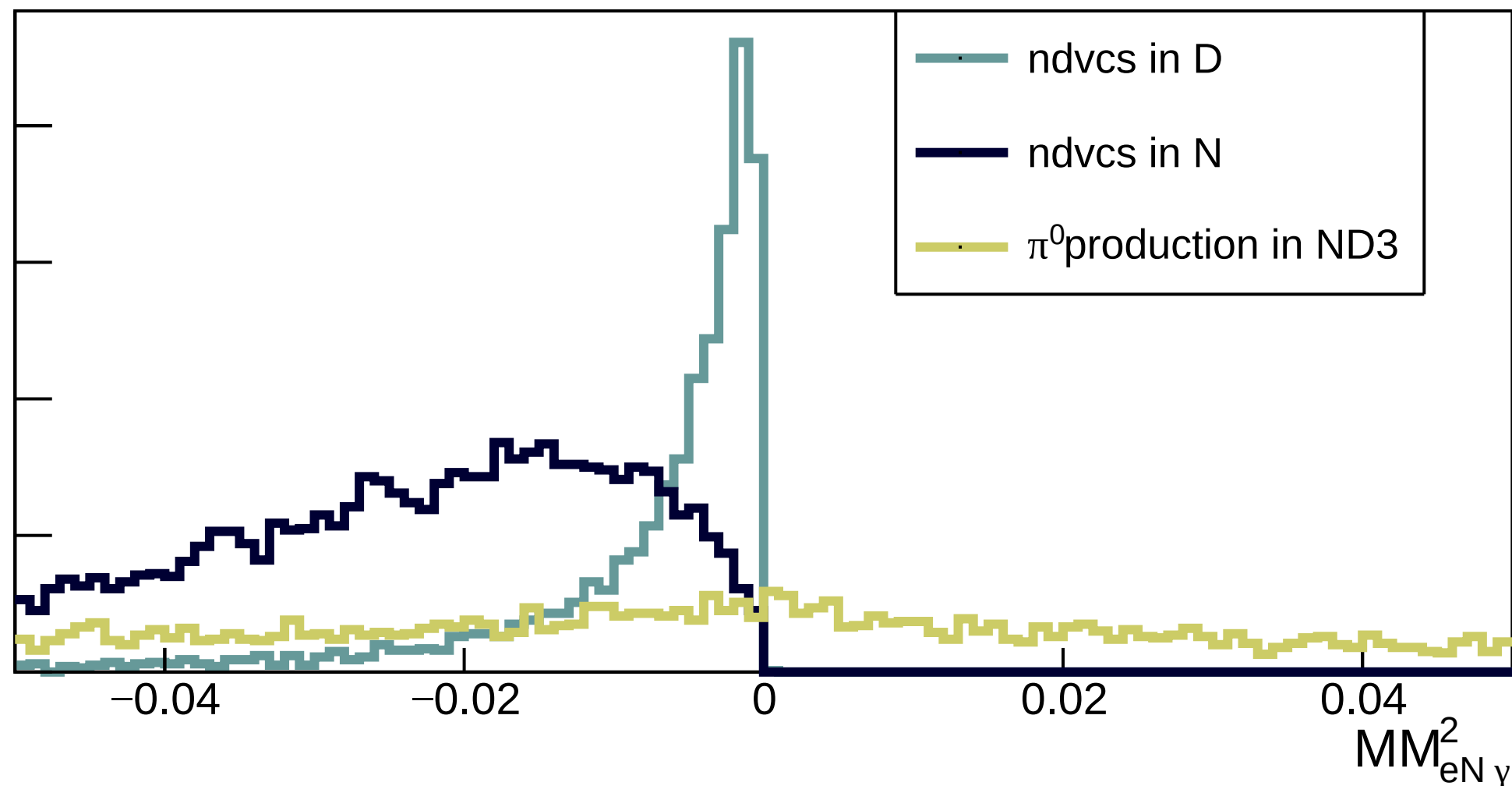
Simulation Framework

GENEPI event generator :

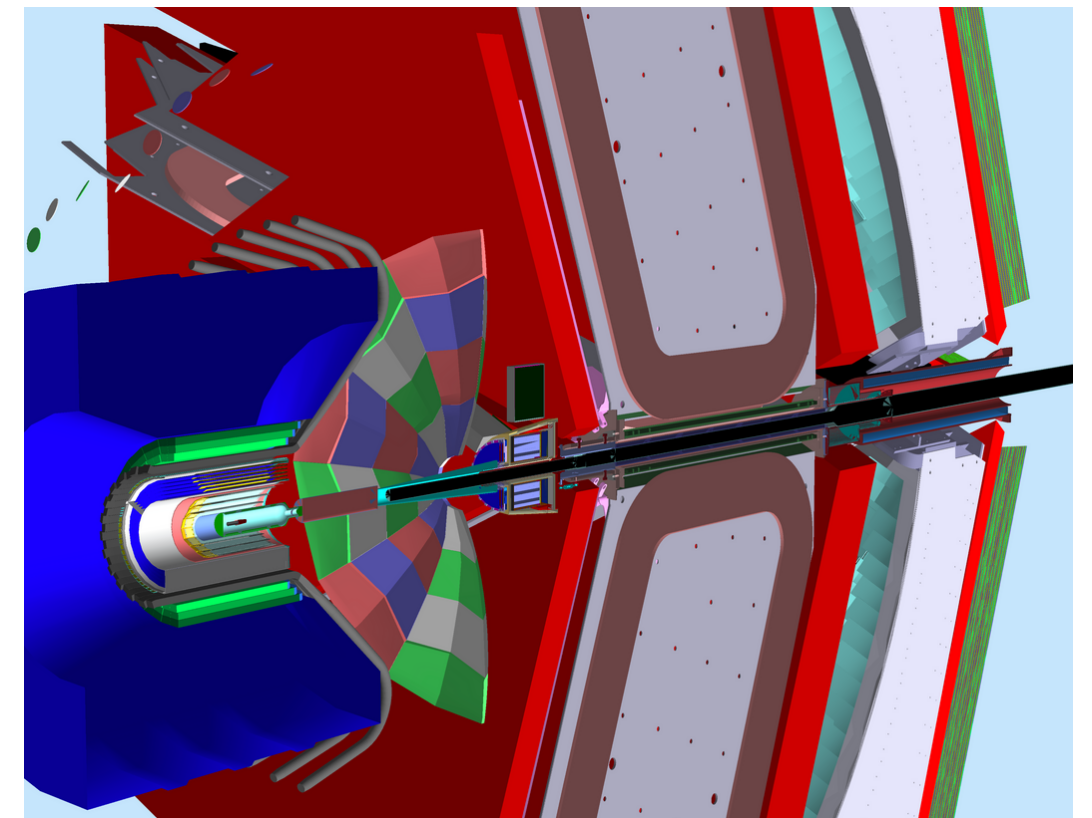
- GPD-based
- BH + DVCS + Deeply Virtual Meson Production
- Fermi Motion of nucleons in nuclei has been implemented at kinematics level



Generated events



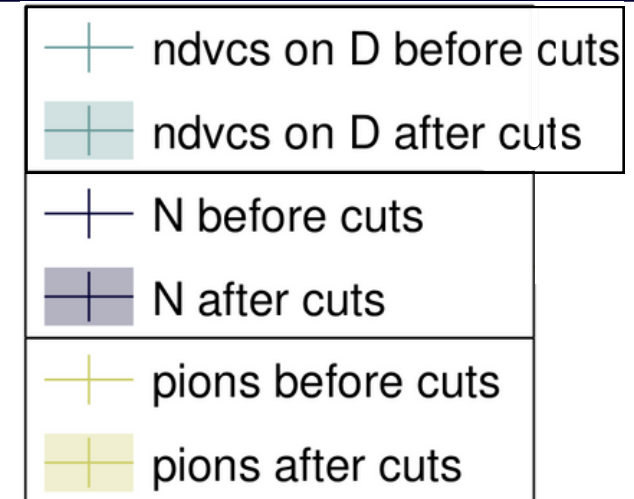
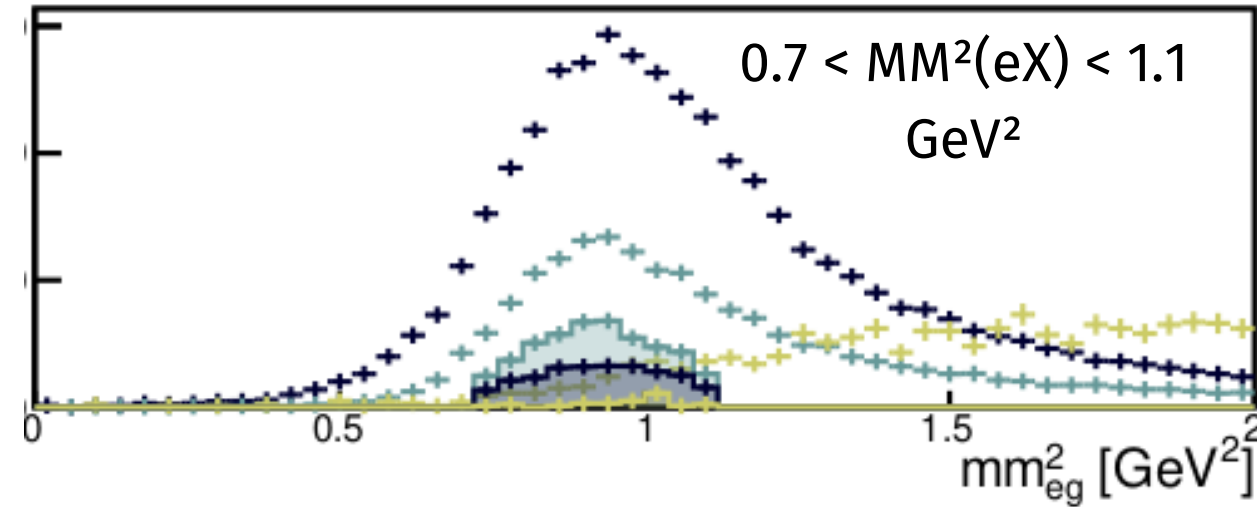
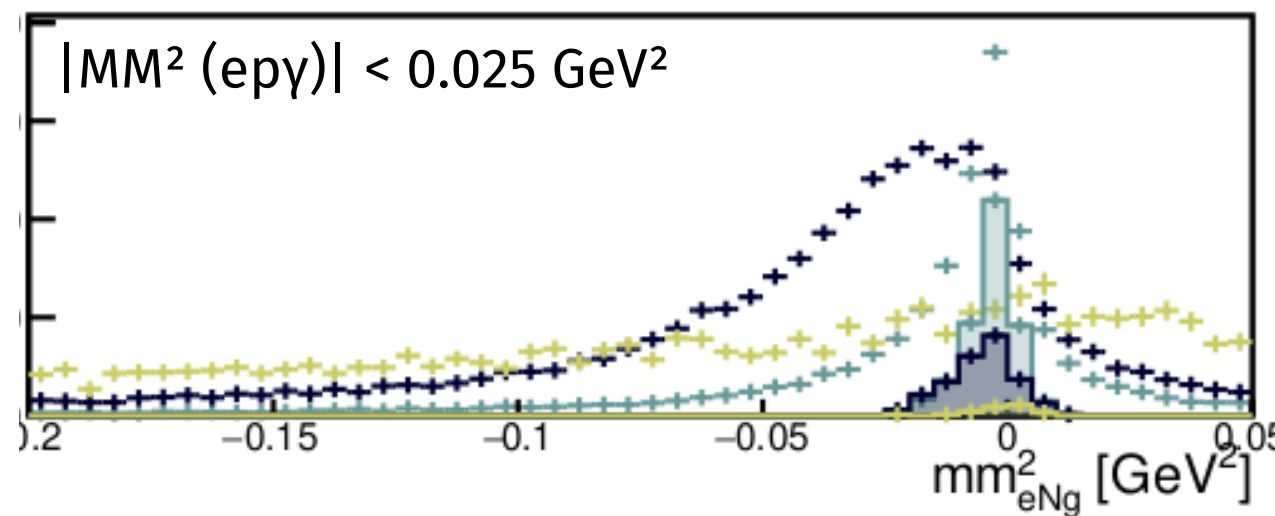
Standard CLAS12 GEANT4-based simulation and reconstruction algorithm



Simulations for pDVCS in ND3

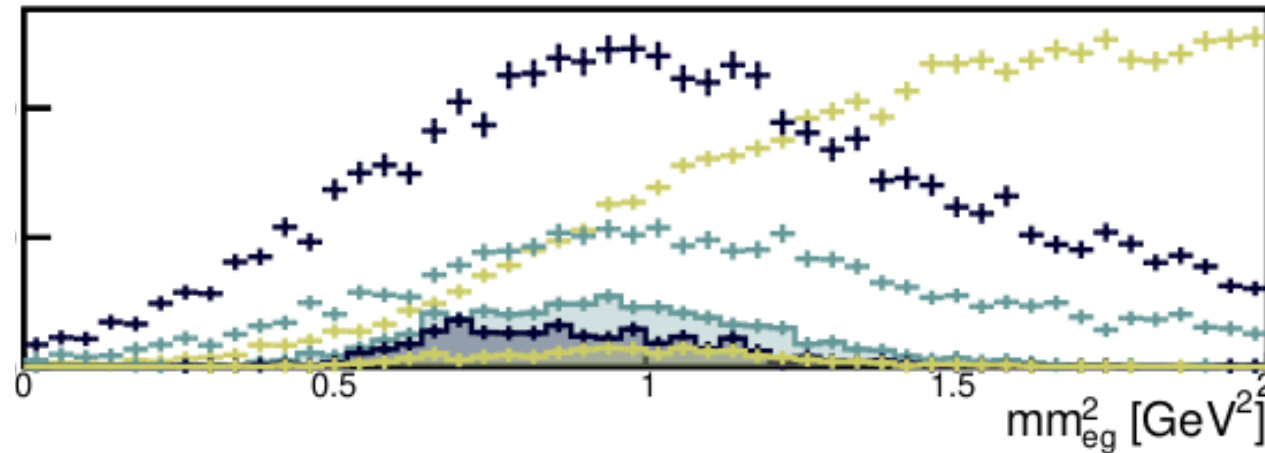
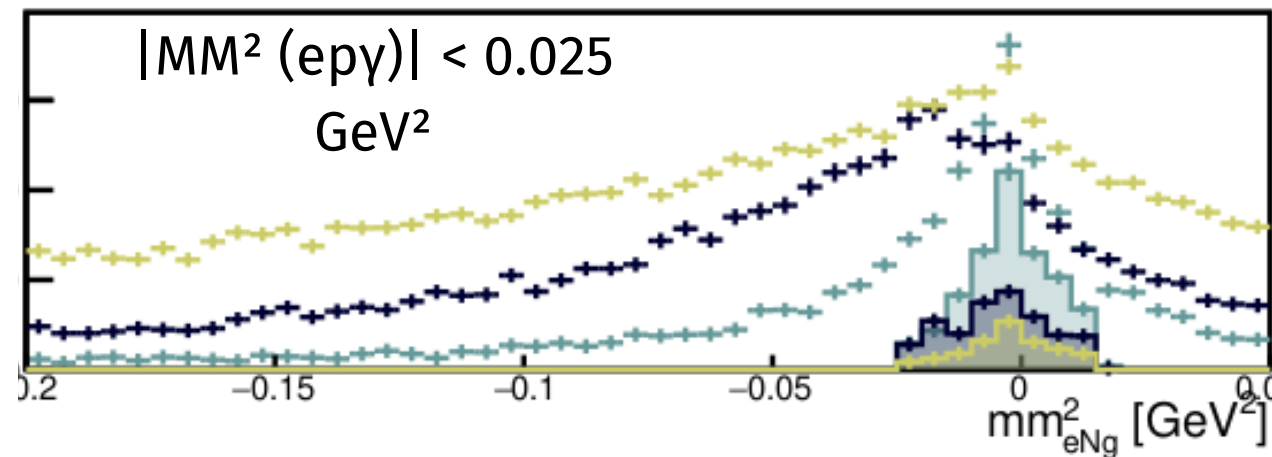
Used to optimize exclusivity cuts

Photons in the FT



- $|\Delta t| < 0.1 \text{ GeV}^2$
- $|\Delta\phi| < 0.2$
- Missing perpendicular momentum $< 0.15 \text{ GeV}/c$

Photons in the FD

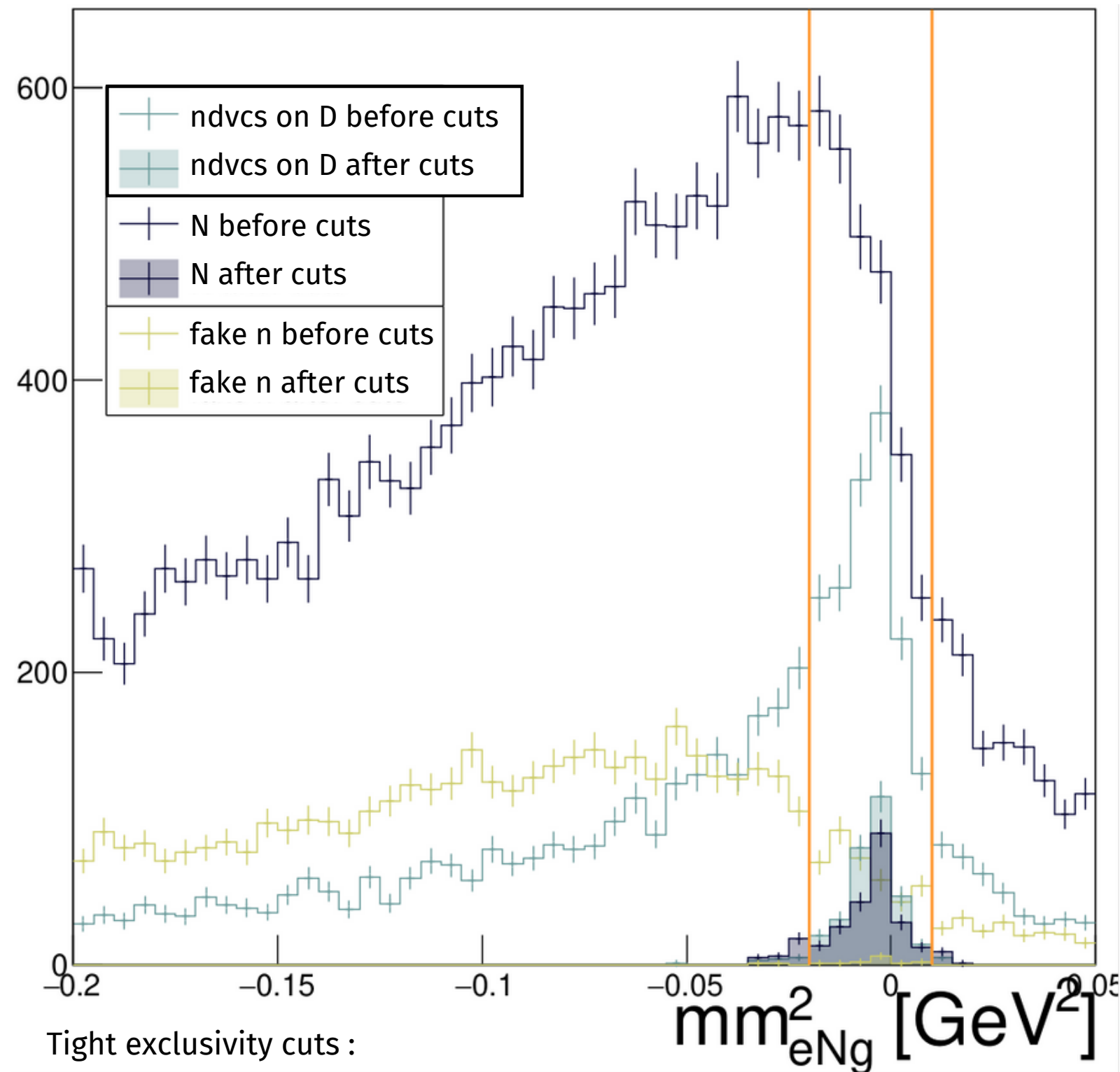


- $|\Delta t| < 0.15 \text{ GeV}^2$
- $|\Delta\phi| < 0.4$
- Missing perpendicular momentum $< 0.15 \text{ GeV}/c$

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

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

Simulations for nDVCS in ND3



Tight exclusivity cuts :

- missing perpendicular momentum < 0.1 GeV
- $|\Delta\phi| < 0.4$
- $|\Delta t| < 0.2$
- $0.6 < MM^2(egX) < 1.2$
- $|MM^2(enX)| < 1.3$

In the nDVCS case, there is an additional source of background :

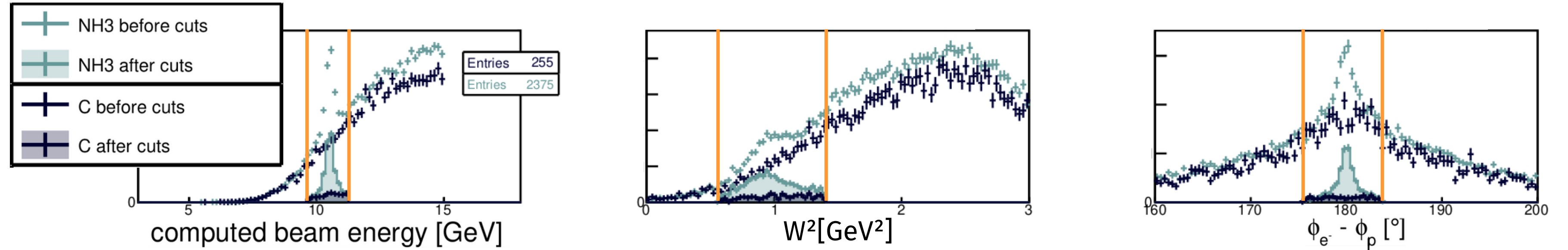
- Neutrons are identified as particles with hits in scintillators not associated with tracks in the tracking system
- Tracking system is not 100% efficient
- Protons misidentified as neutrons
- Currently improving PID with detector-level, data-driven, machine learning techniques.

First Measurements with the RGC dataset

- Preliminary study with the available NH3 data.
- Low statistics ($\approx 5\%$ of the full dataset) , not fully calibrated.
- Results are not meant to be final physics results, but to show the potential of RGC.
- All asymmetries that will be presented are raw and contain various sources of contamination.

Target Polarization Measurement

- Measuring the target polarization reliably is crucial for all RGC experiments
- Using elastic events $ep \rightarrow e'p'$



- Comparing the precisely computable theoretical asymmetry to the measured asymmetry

$$A_{th} = \frac{2\tau G \left[\frac{M_p}{E_b} + G \left(\tau \frac{M_p}{E_b} + (1+\tau) \tan^2\left(\frac{\theta}{2}\right) \right) \right]}{1 + G^2 \frac{\tau}{\epsilon}} \quad \rightarrow \quad P_b P_t = \frac{A_{meas}}{A_{th}}$$

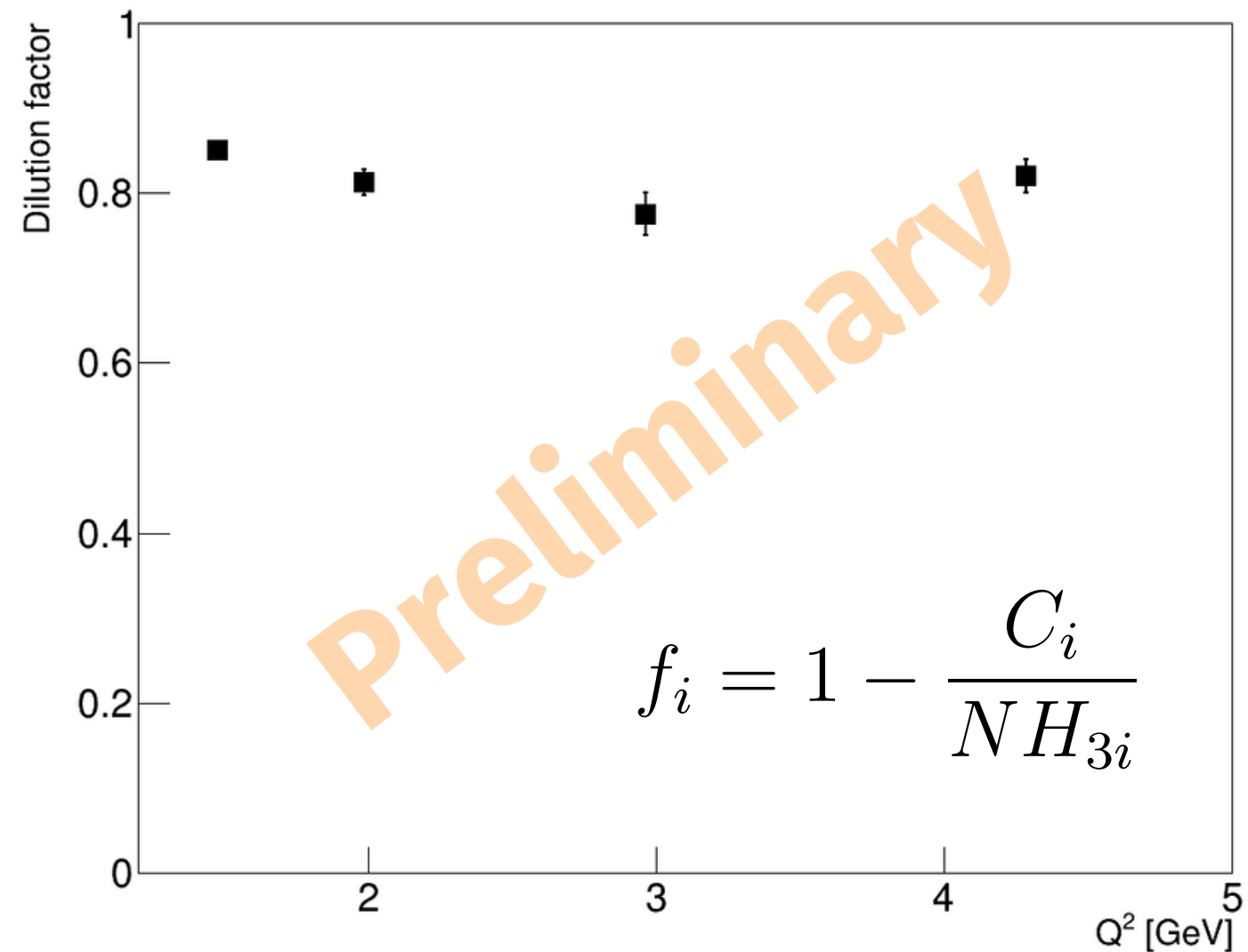
$G = \frac{G_M}{G_E}$

- Maximum likelihood estimator, from Q^2 binned yields

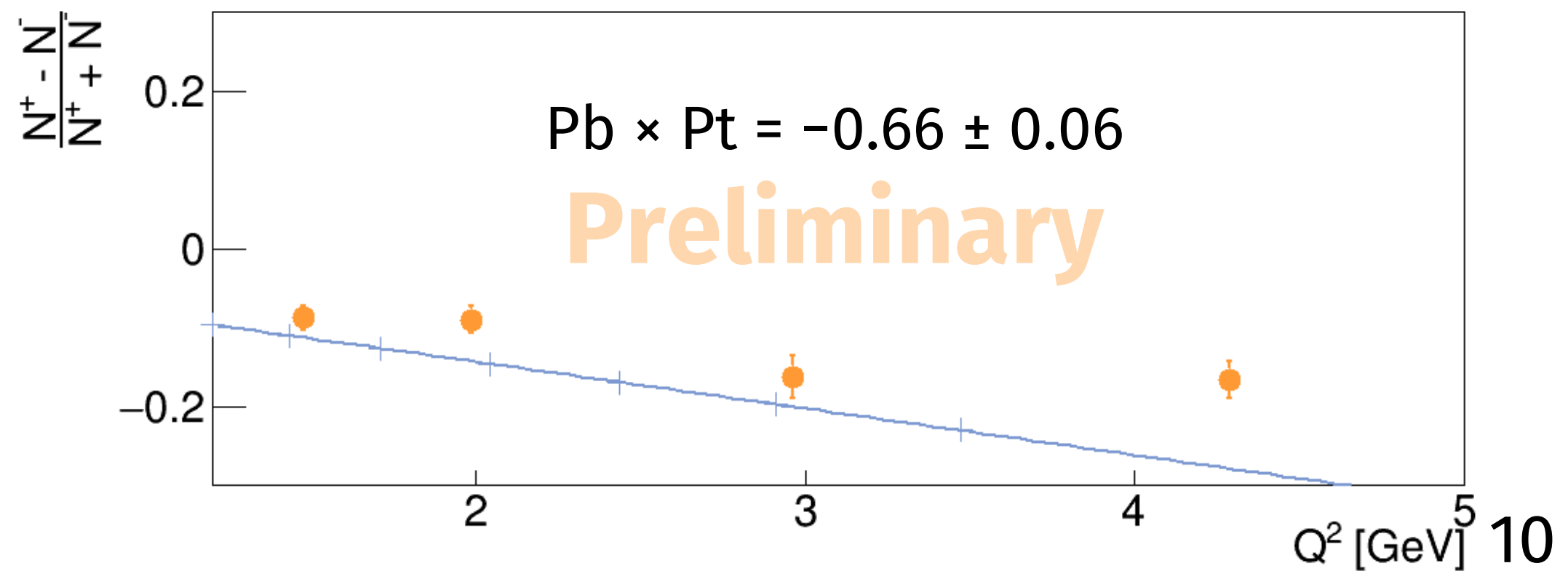
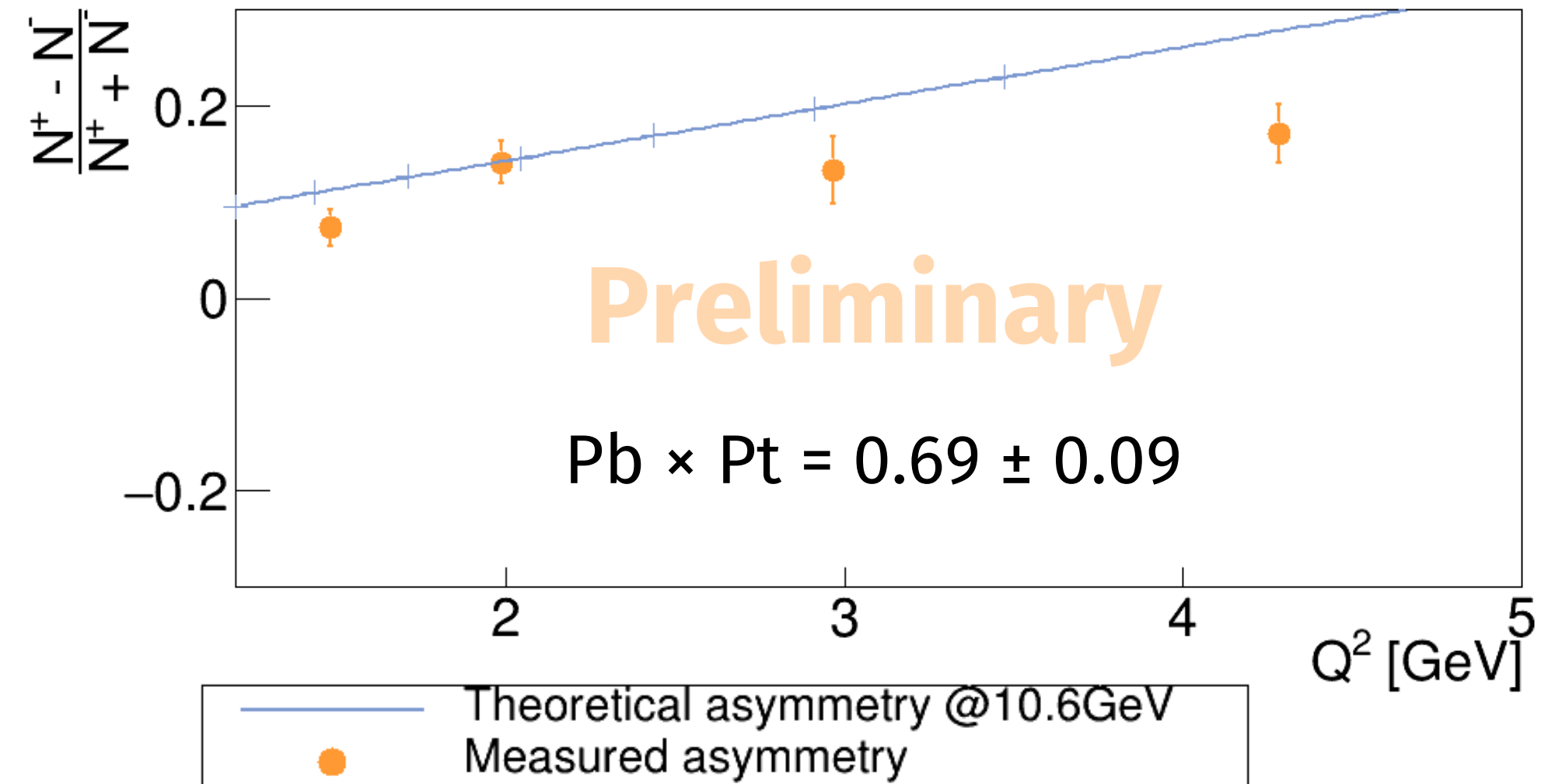
dilution factor yields with positive/negative beam helicity

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

Asymmetry $ep \rightarrow e'p'$



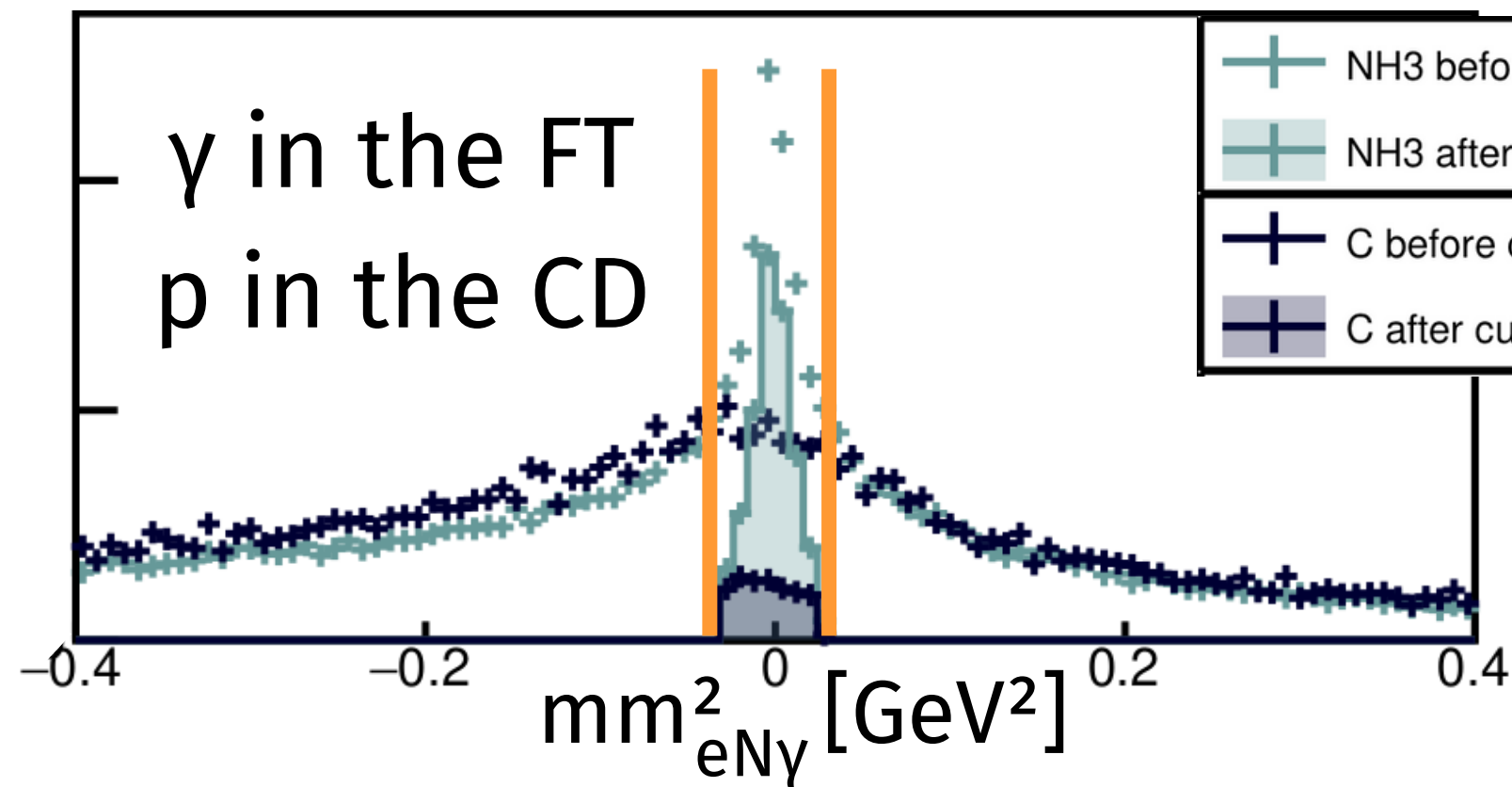
Pb has been measured with a Moller Polarimeter during the experiment.



Measurement of the pDVCS Asymmetries

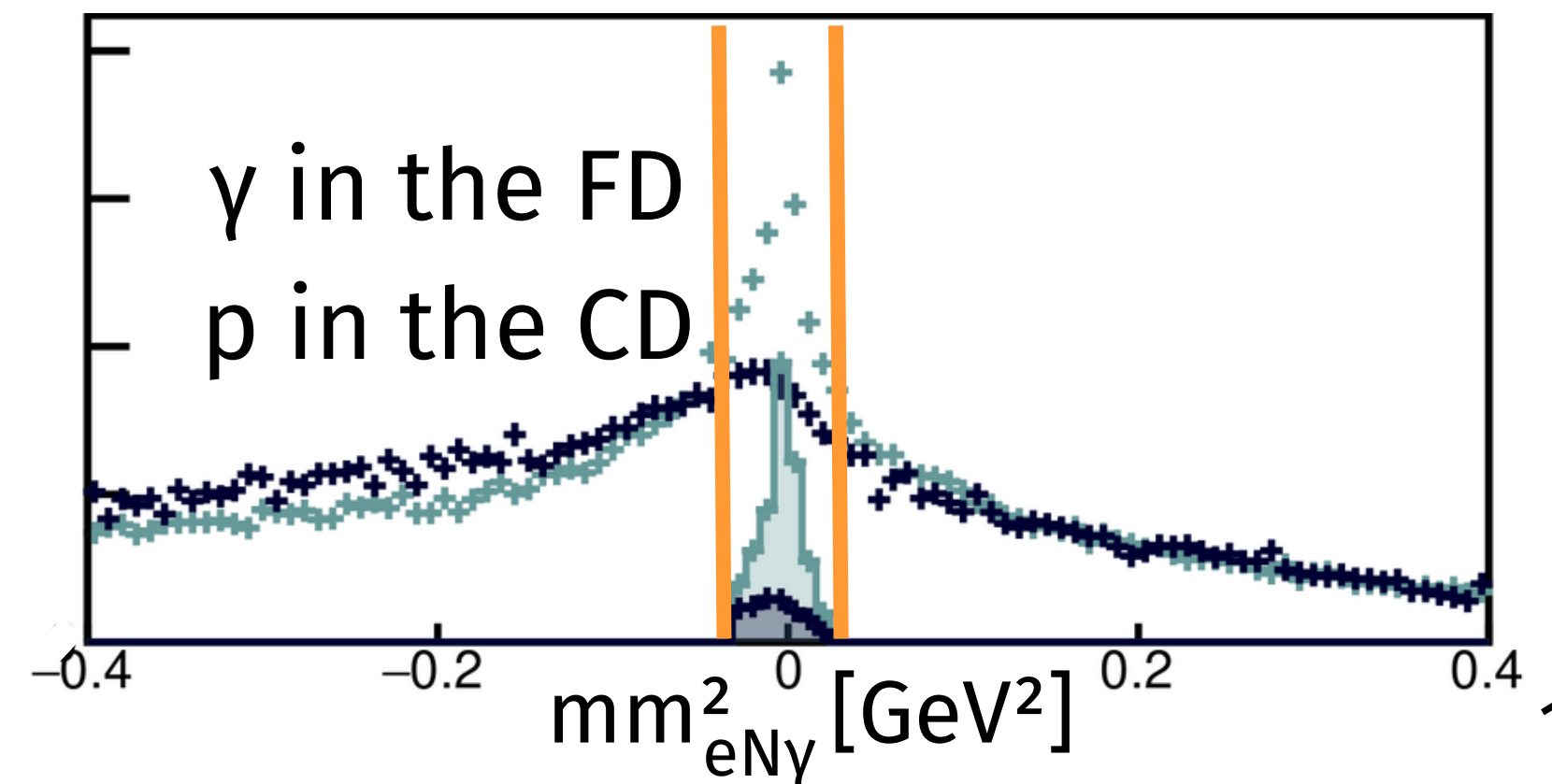
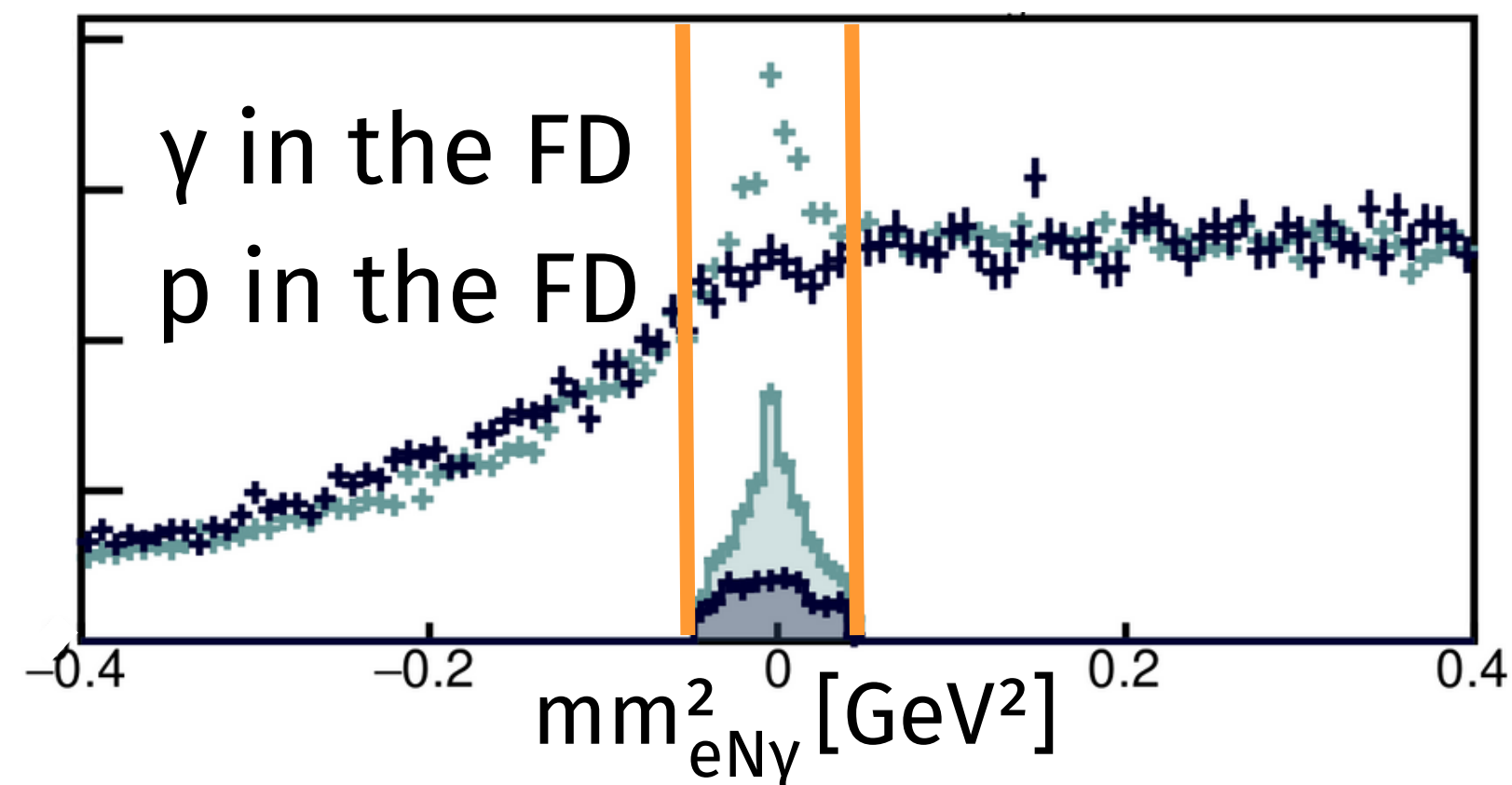
pDVCS event selection $ep \rightarrow e'p'\gamma$

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



- $Q^2 \geq 1 \text{ GeV}^2$
 - $W \geq 2 \text{ GeV}$
 - $E_\gamma \geq 1.5 \text{ GeV}$
- + exclusivity cuts :
- Missing masses $ep\gamma$, $eX\gamma$, epX
 - $\Delta\phi$
 - Δt

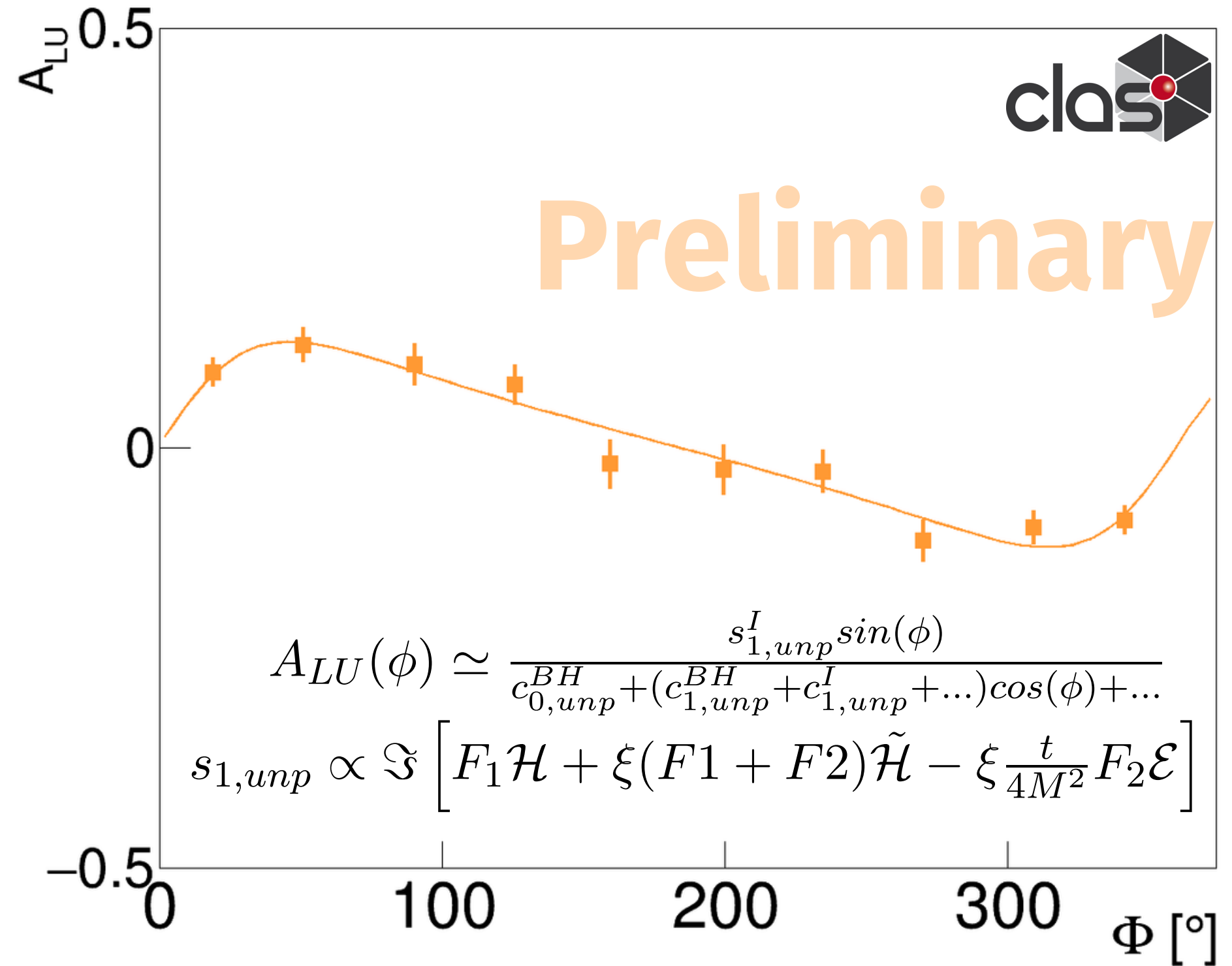
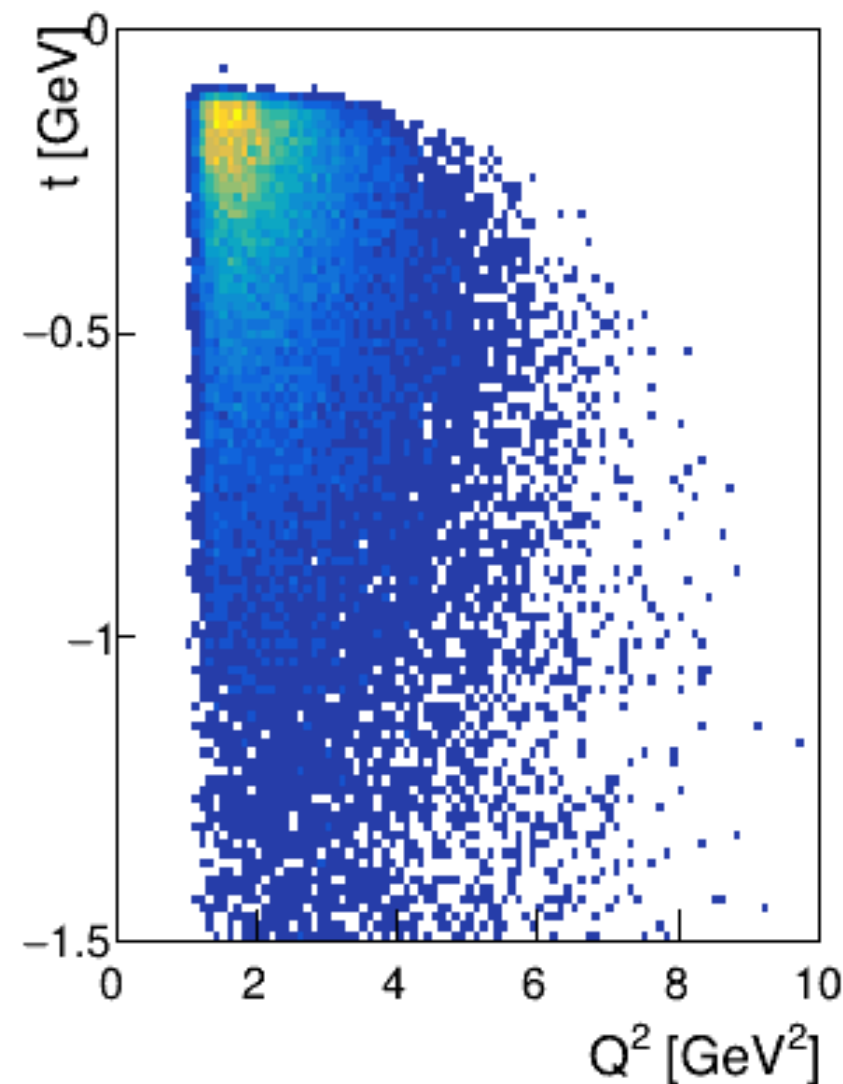
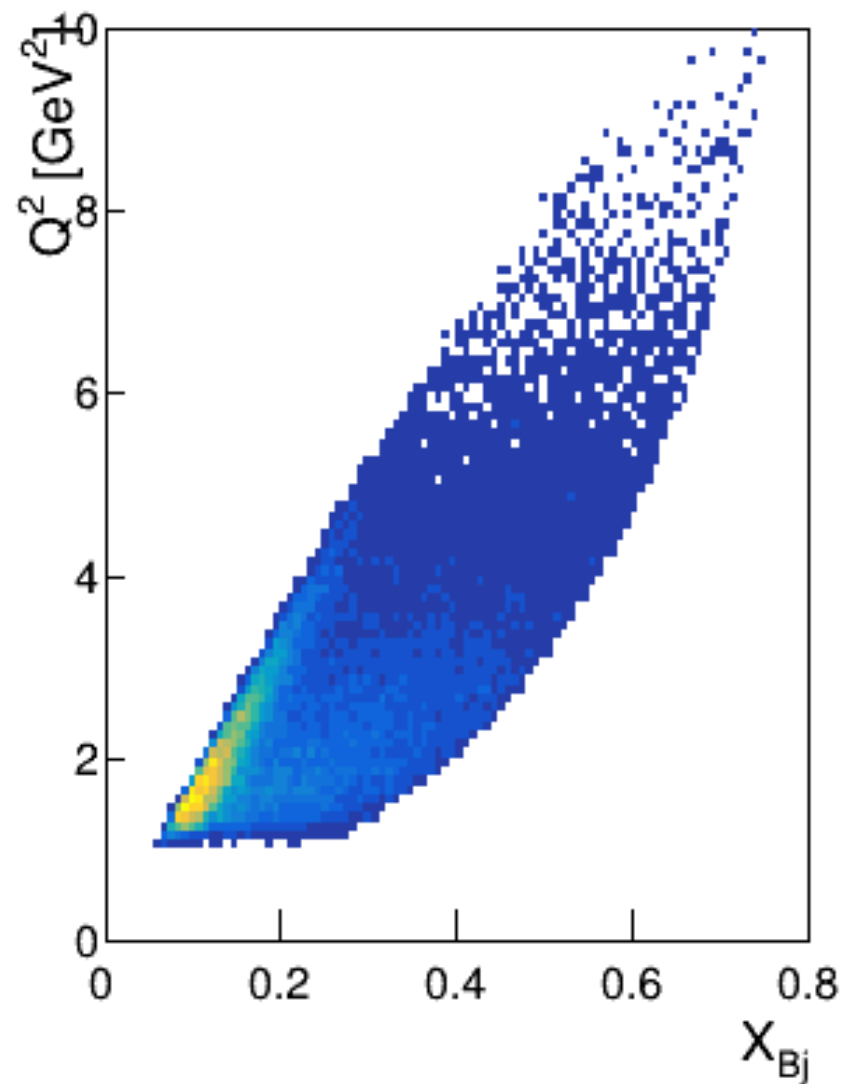
Resolutions are different for particles detected in different part of CLAS12 \rightarrow different N/H relative populations in each topology of events



Raw Beam Spin Asymmetry

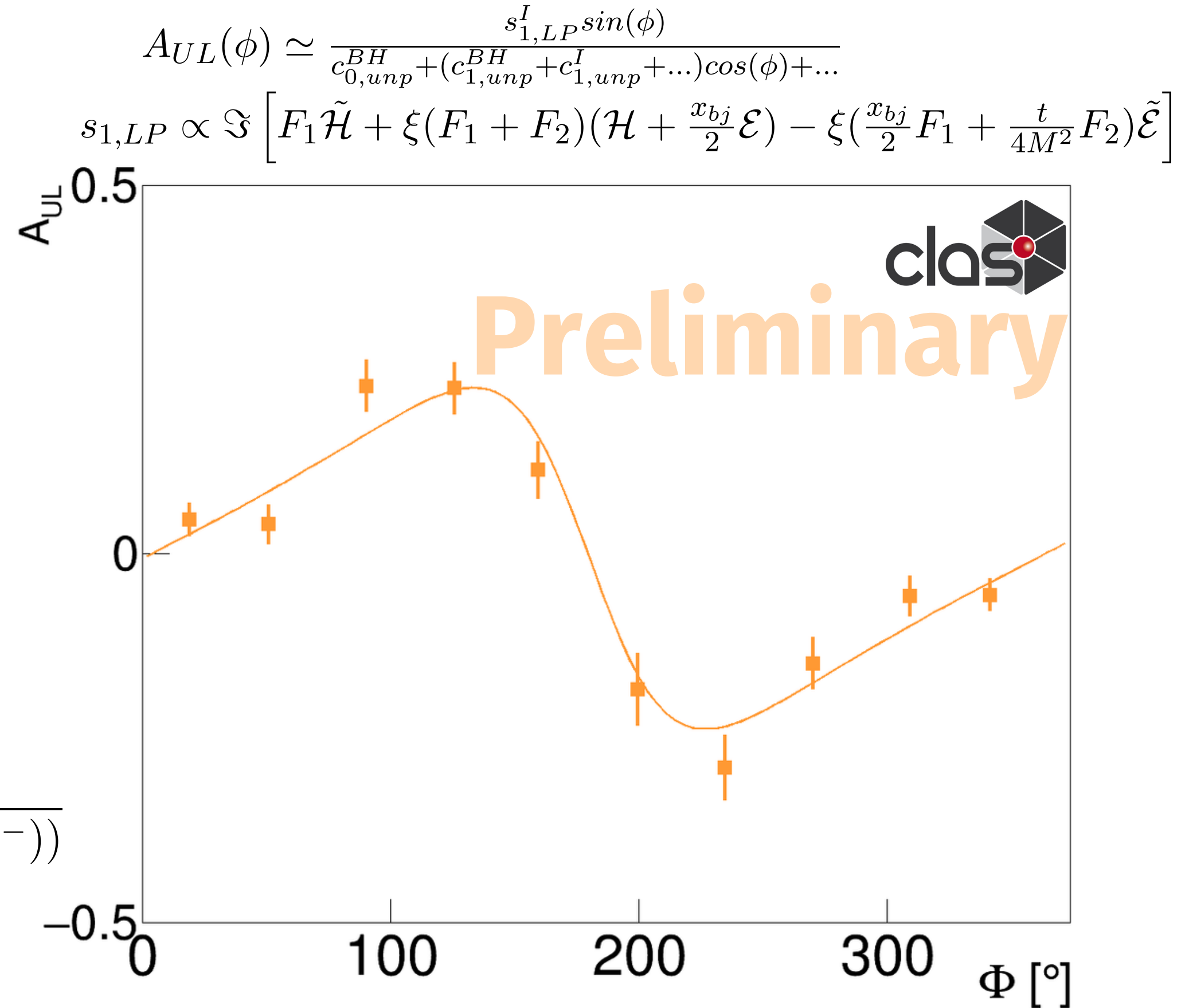
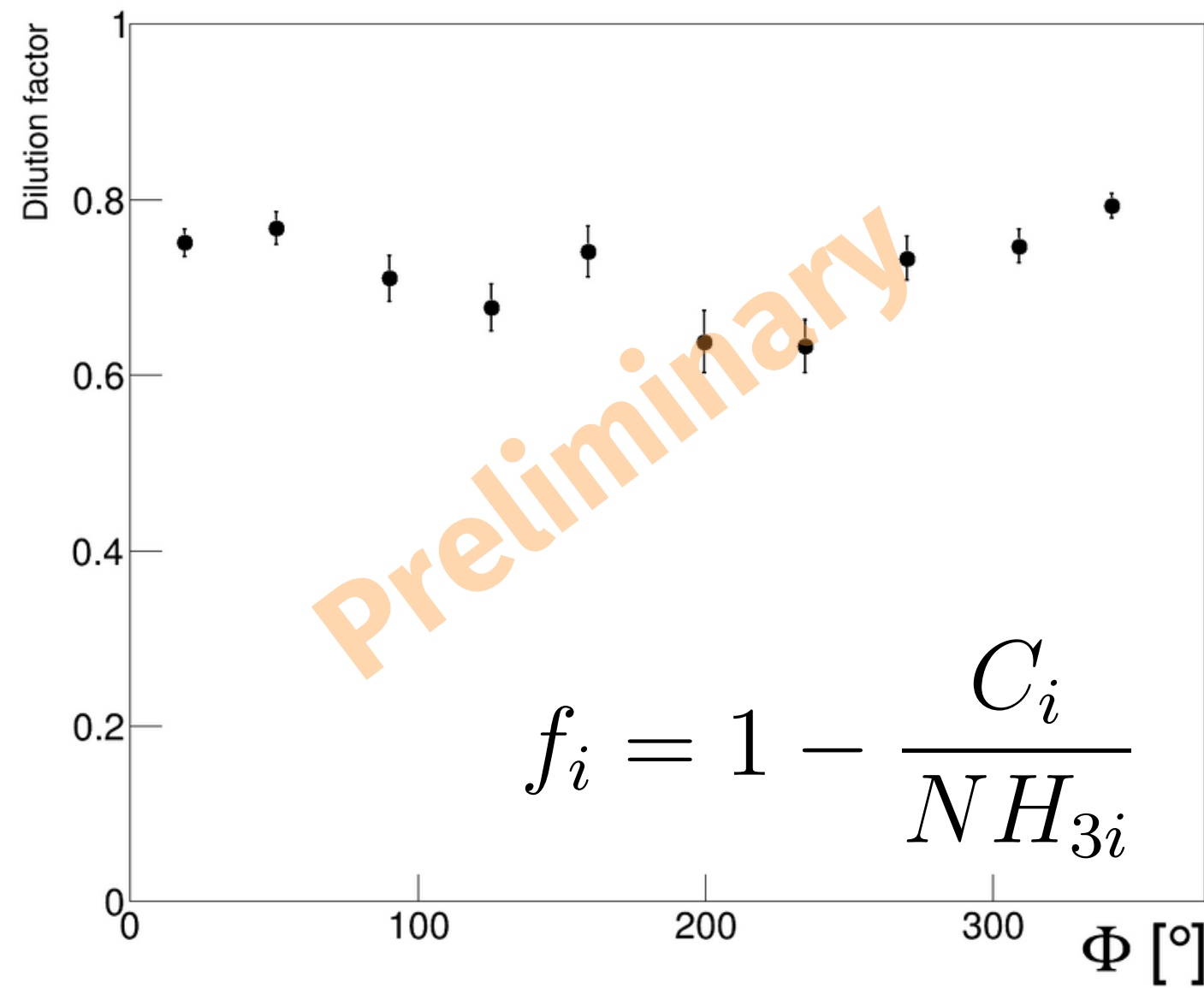
$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{Pb \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

N^{bt}



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

Raw Target Spin Asymmetry



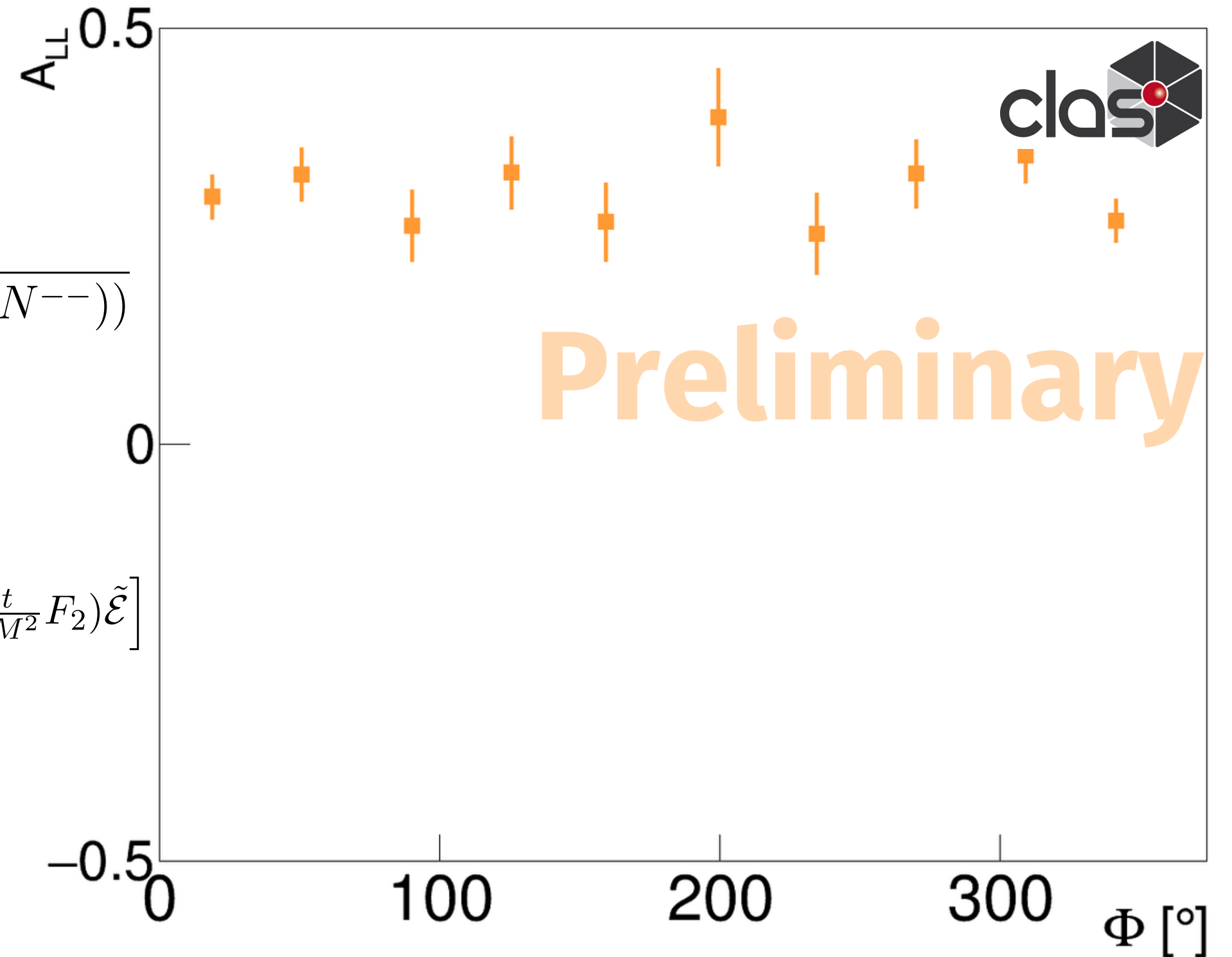
$$A_{UL} = \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

Raw Double Spin Asymmetry

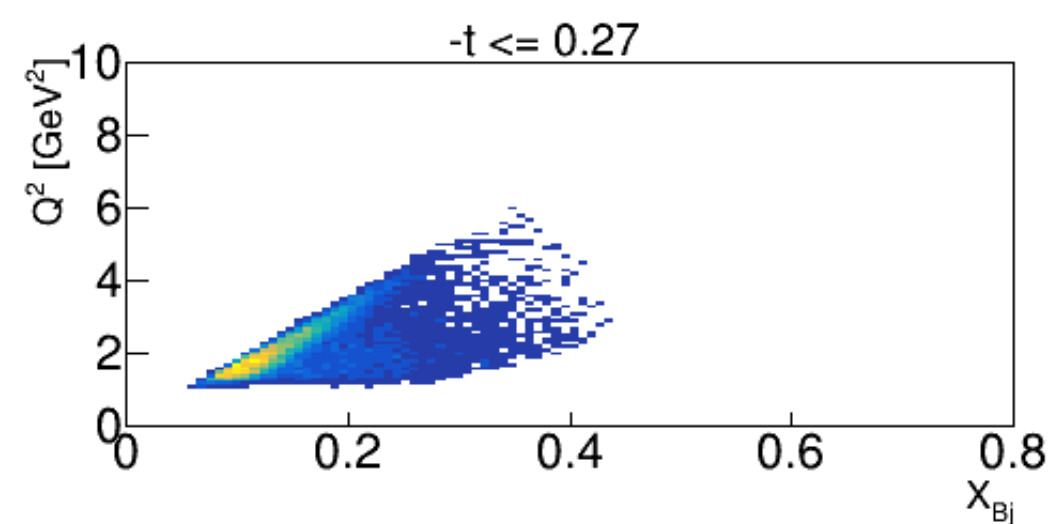
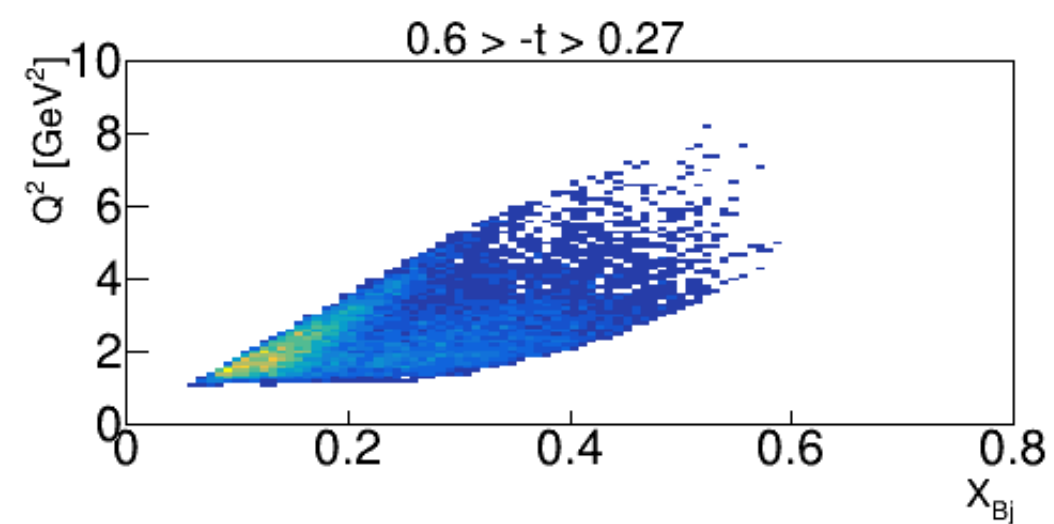
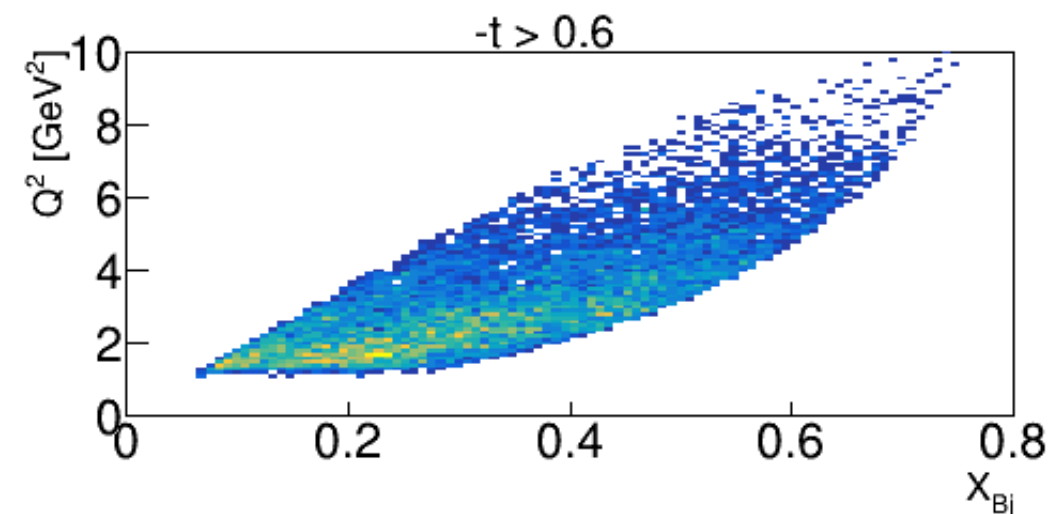
$$A_{LL} = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_b \times Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

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

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



t-Dependence

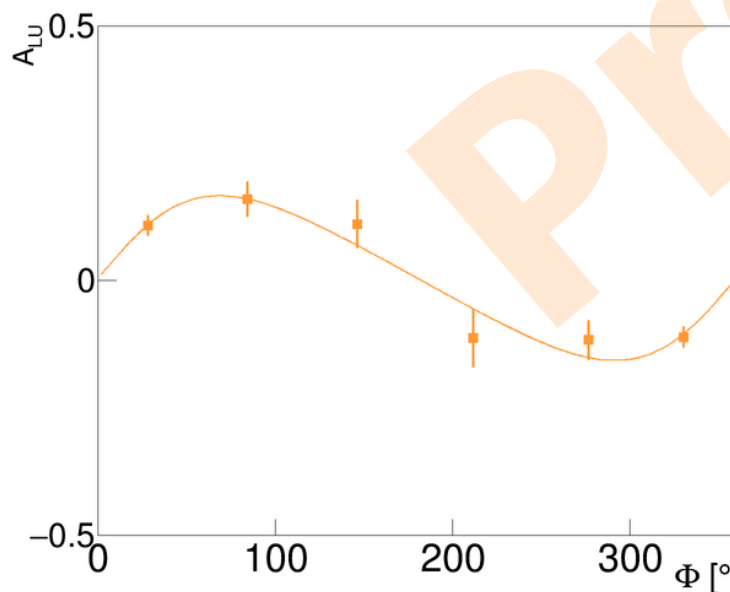
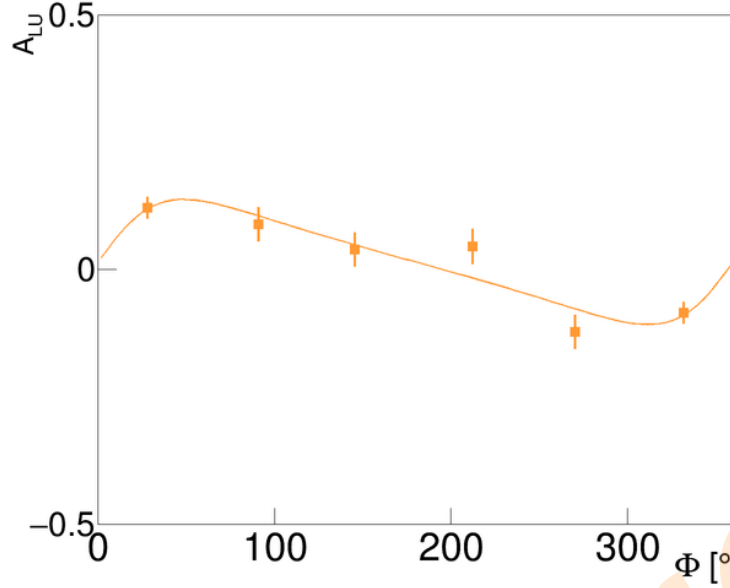
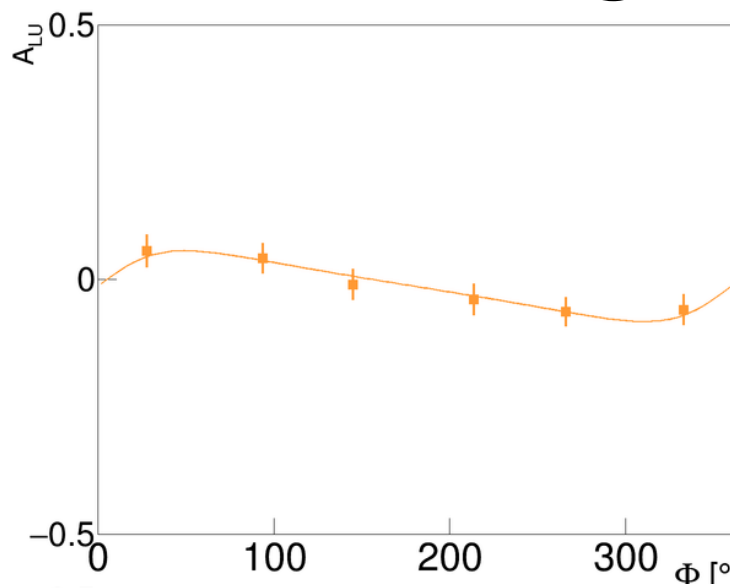


$-t$ [GeV]

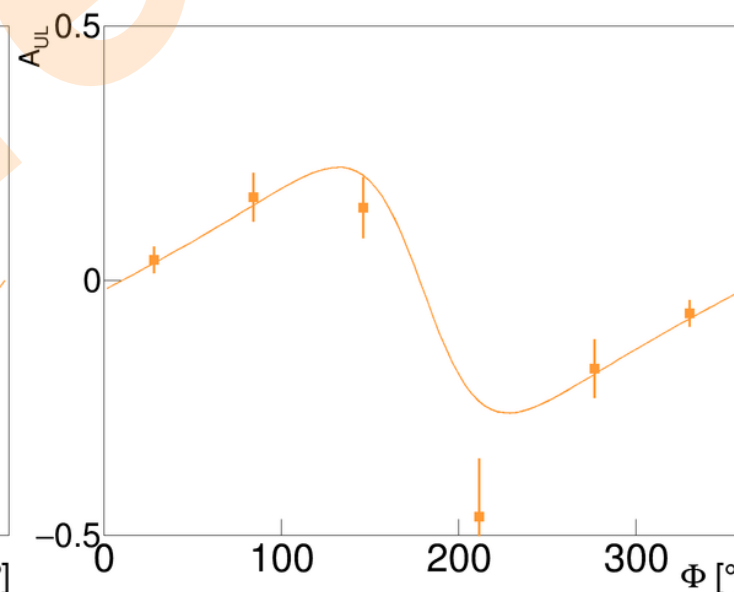
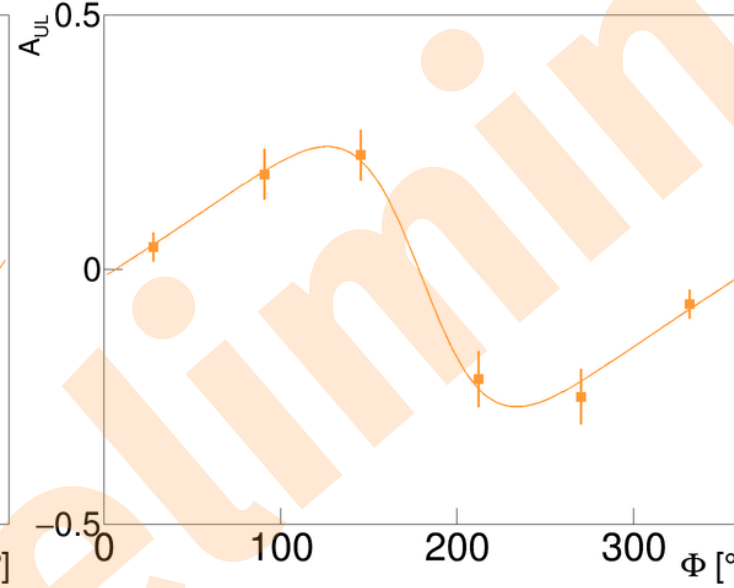
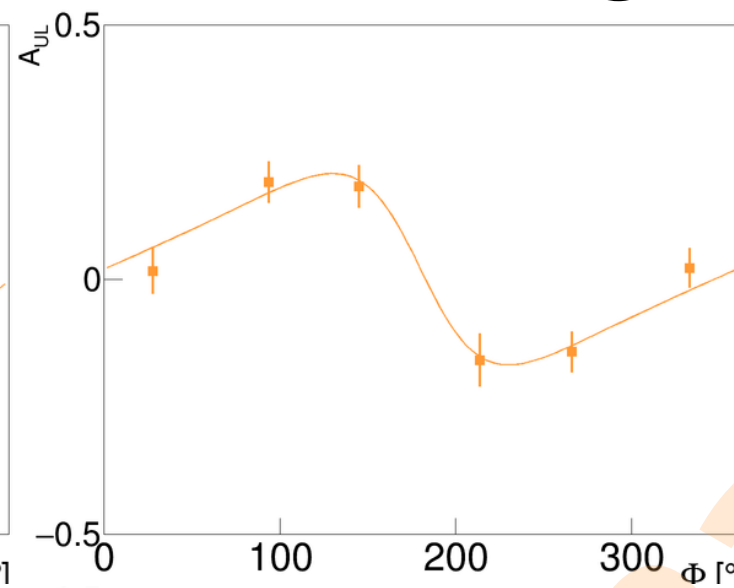
0.6

0.27

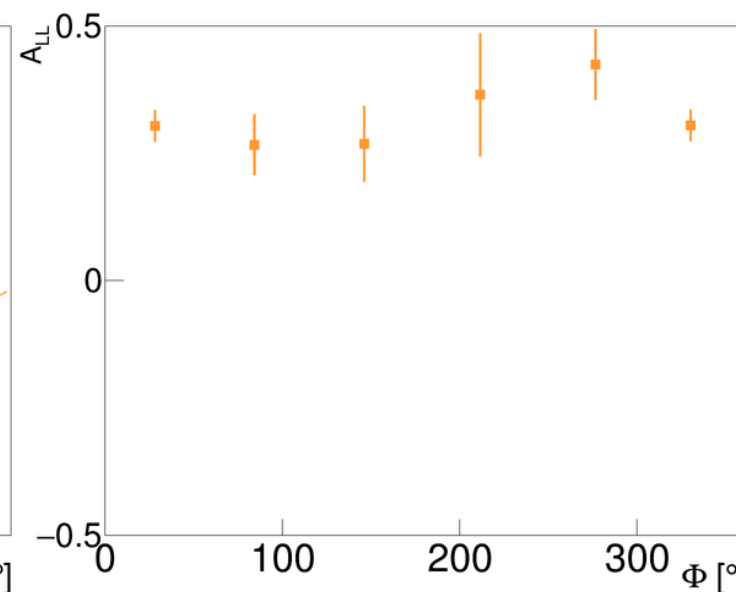
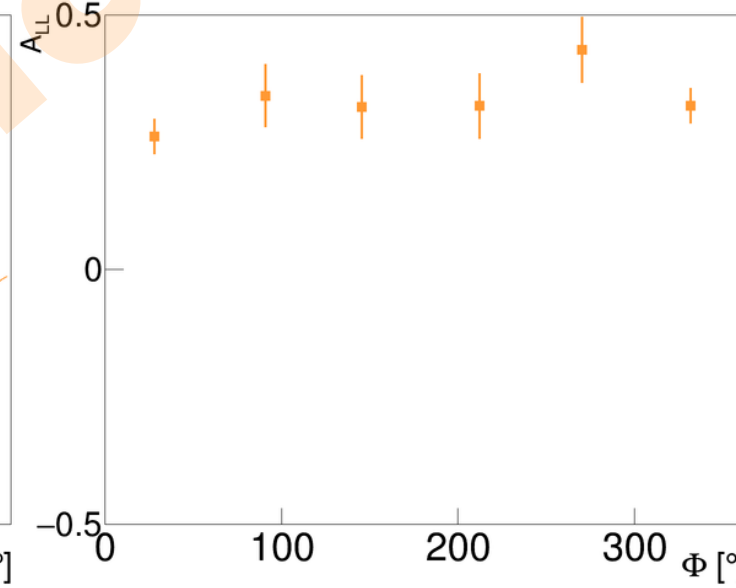
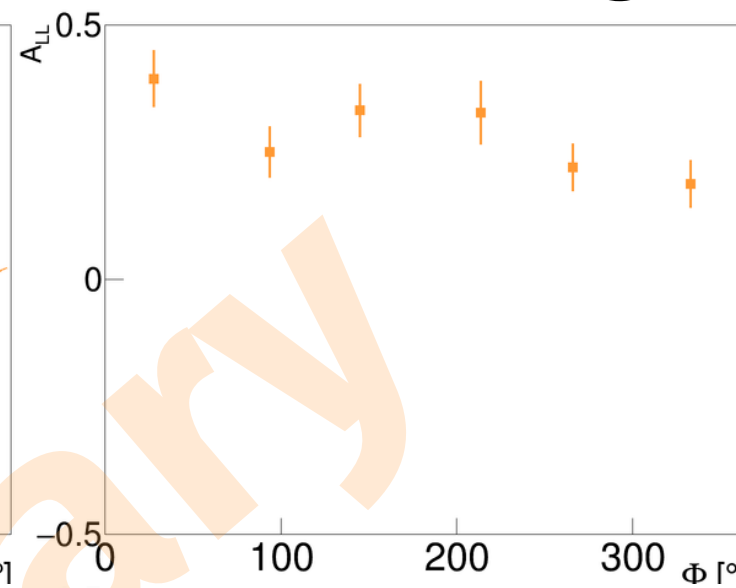
BSA



TSA



DSA

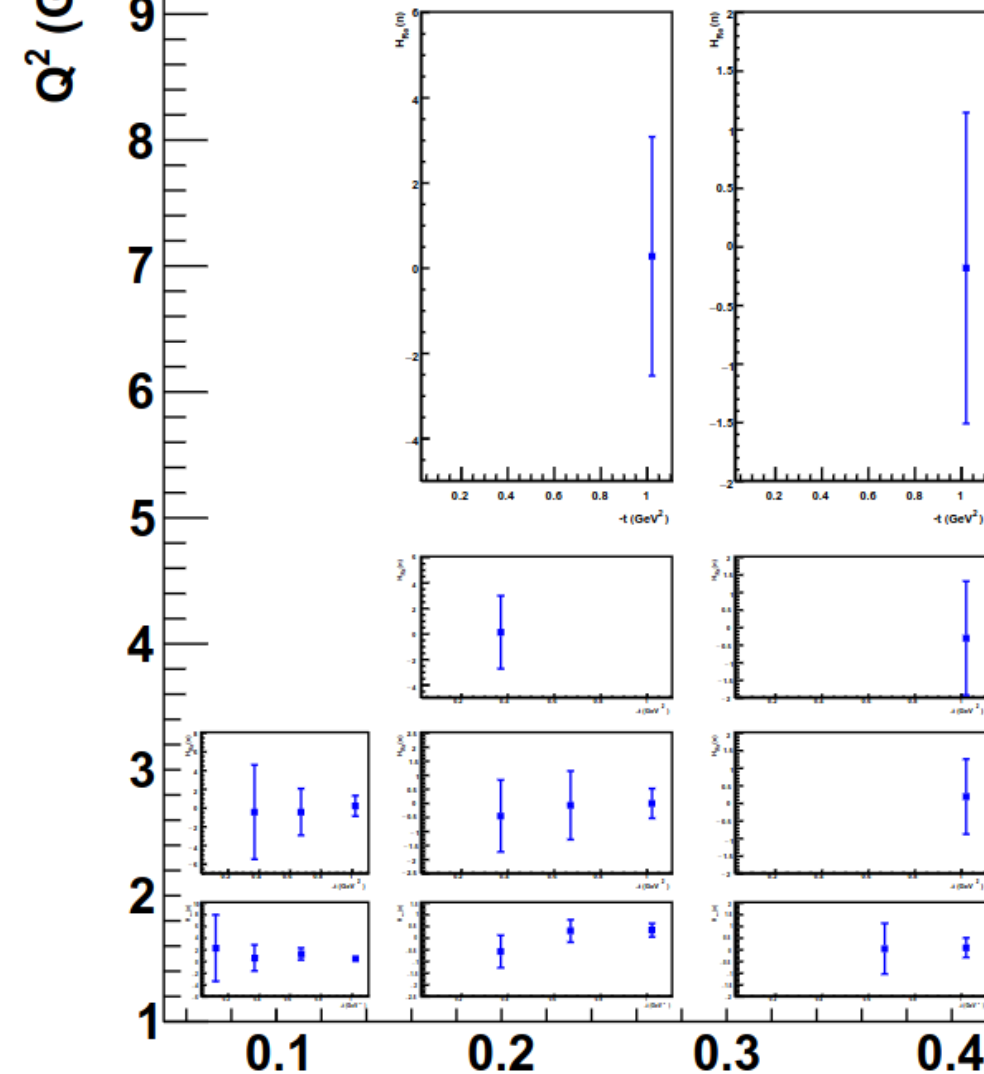


Conclusions

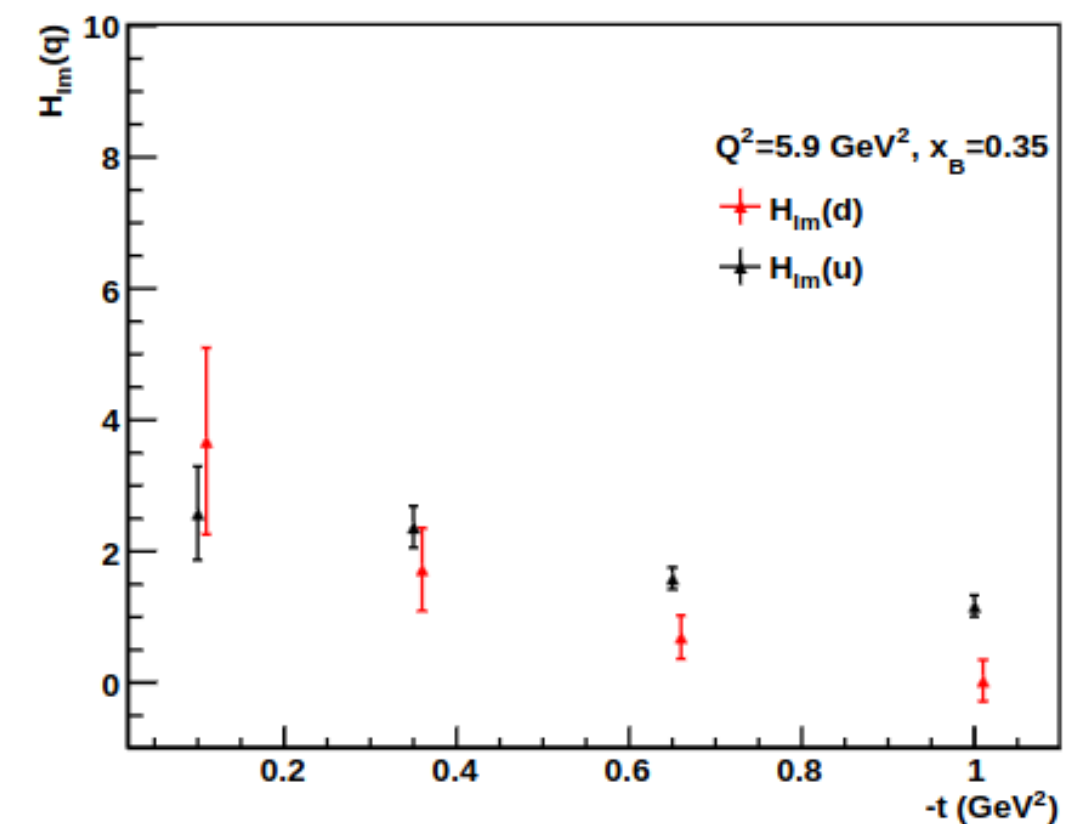
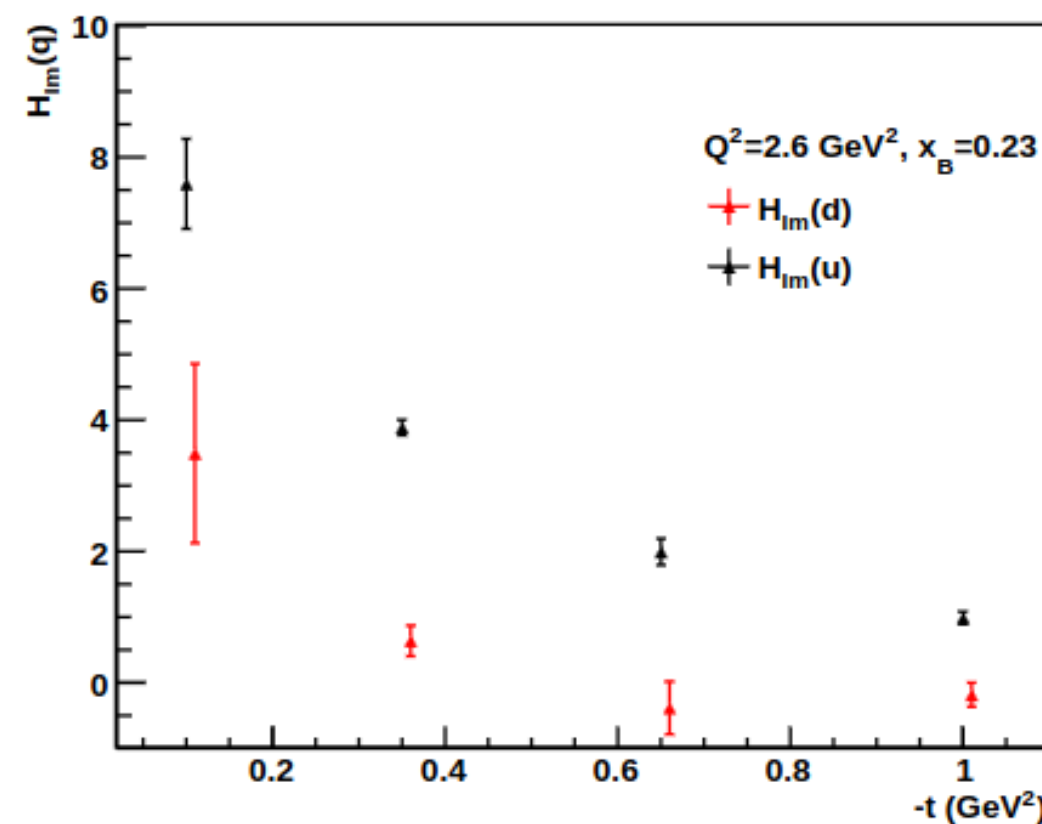


- The first polarized target experiment at CLAS12 ran successfully last year !
- It will allow for DVCS studies with polarized nucleons.
- The target polarization can be measured reliably from analysis of elastic scattering.
- First DVCS asymmetries have been extracted for polarized protons in H in an NH3 target.
- They are used as a check for sanity of the data and pave the way towards extraction of observables for polarized pdvcs and ndvcs in ND3.

RGC proposal, $\text{Re}(H)$ for the neutron from the projected measurement of the ndvcs DSA using the VGG model for GPDs



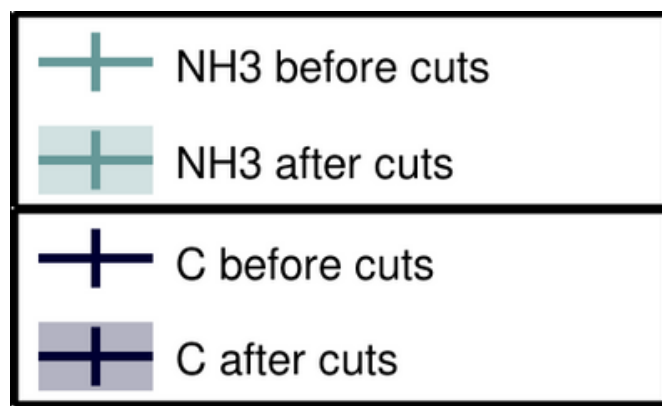
Projected CFFs flavor separation from combining pdvcs and ndvcs information on H



(S. Niccolai)

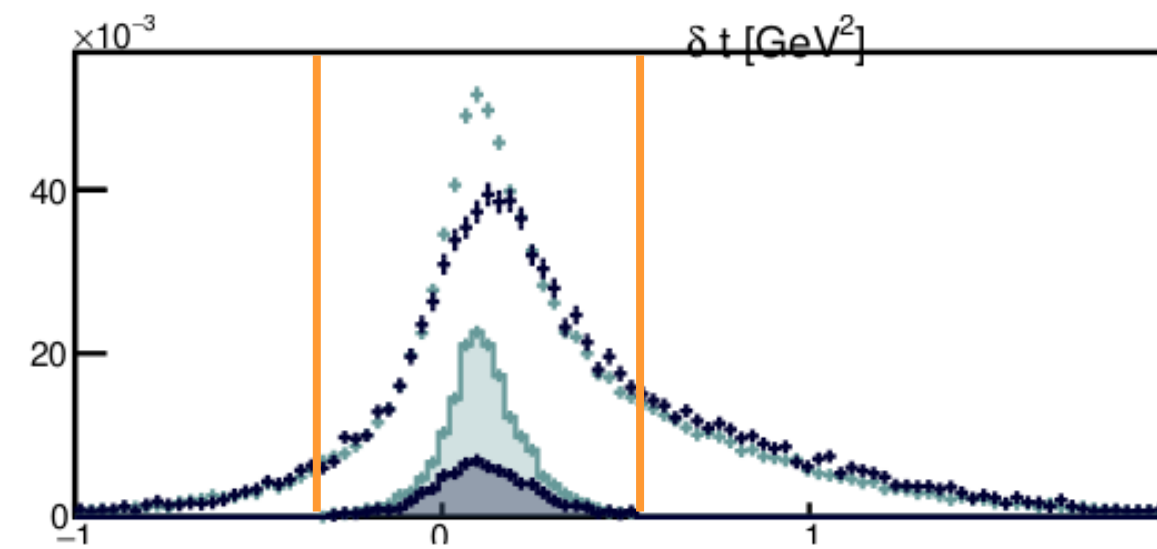
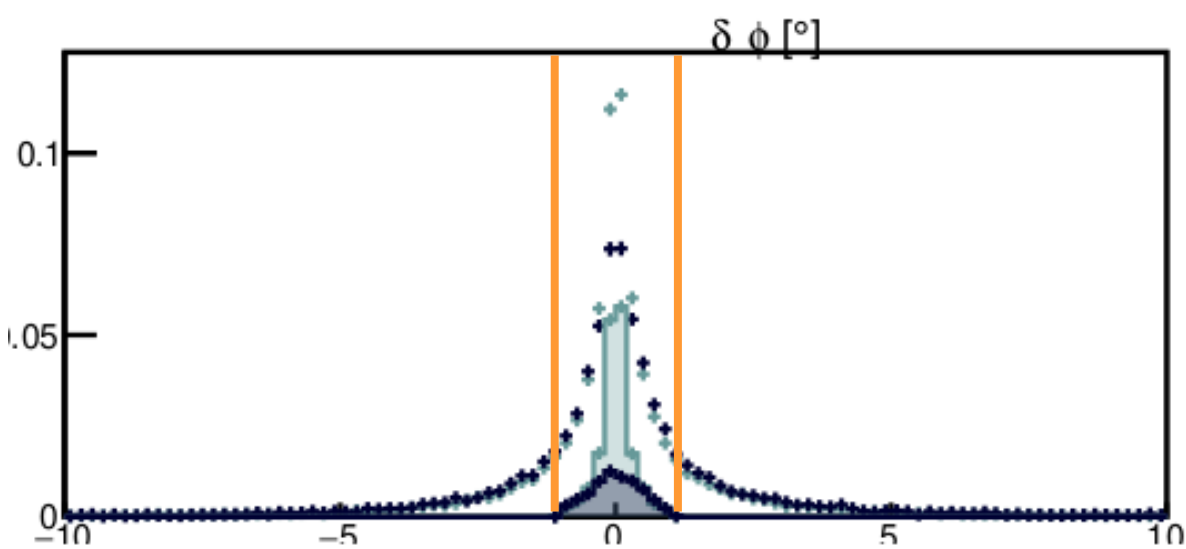
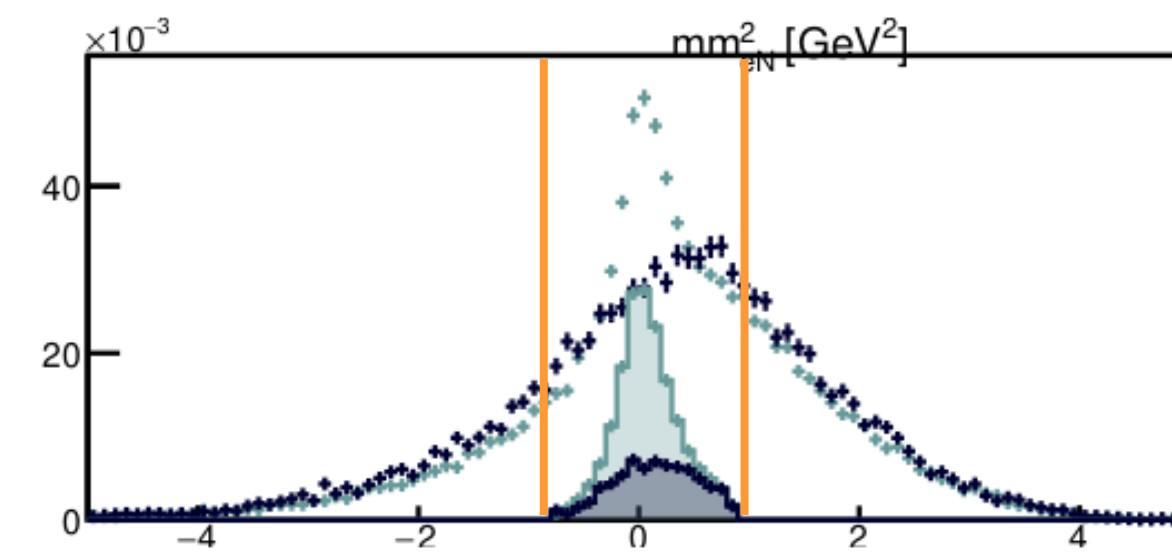
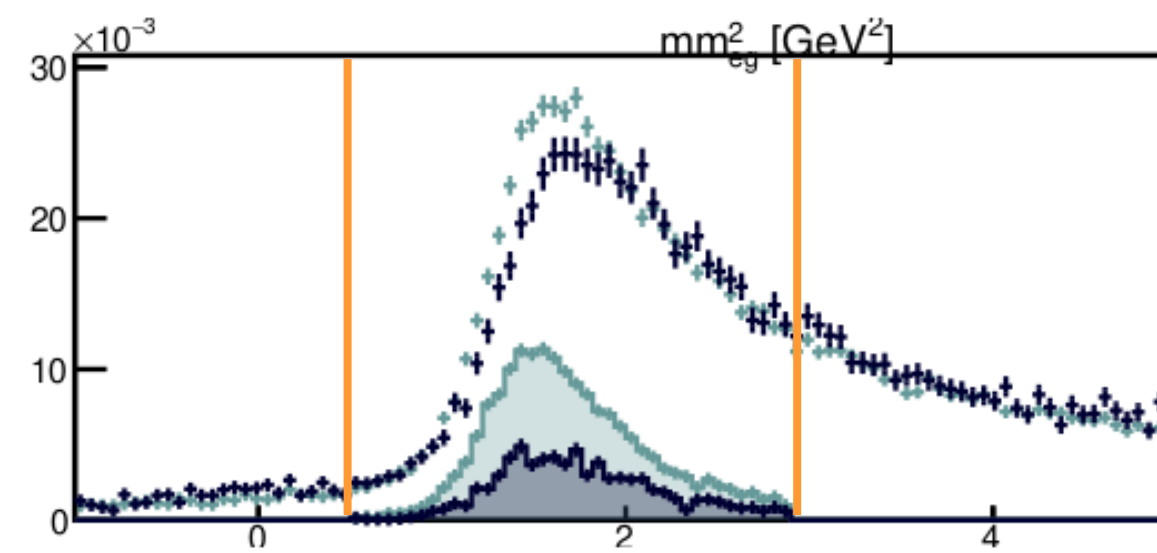
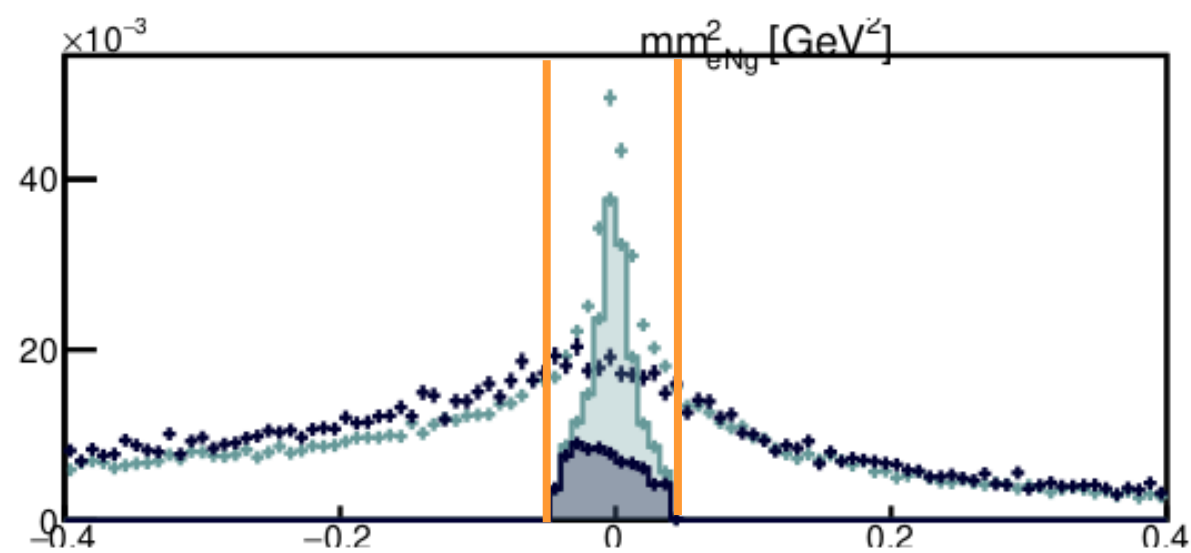
Backup

pDVCS event selection $ep \rightarrow e'p'\gamma$



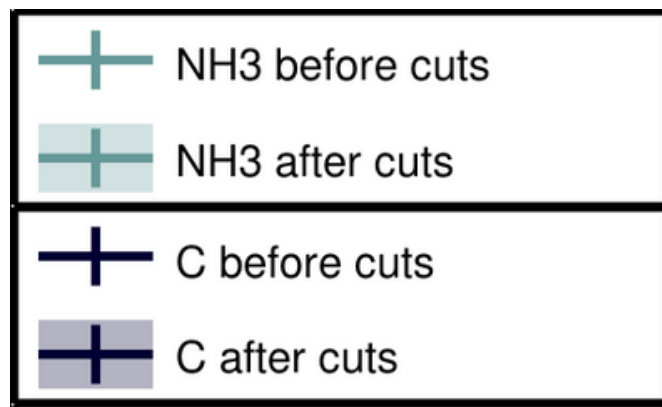
γ FT

p CD

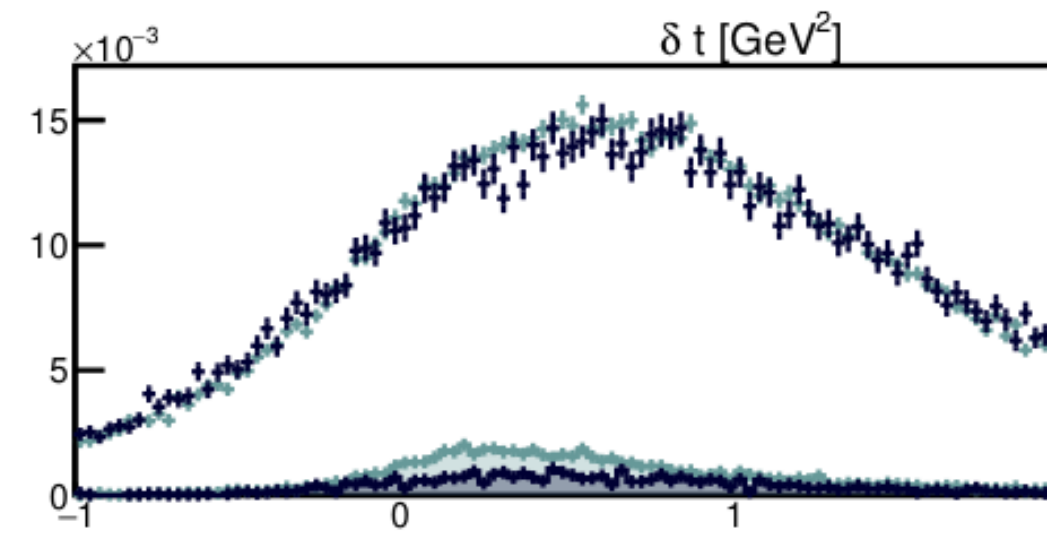
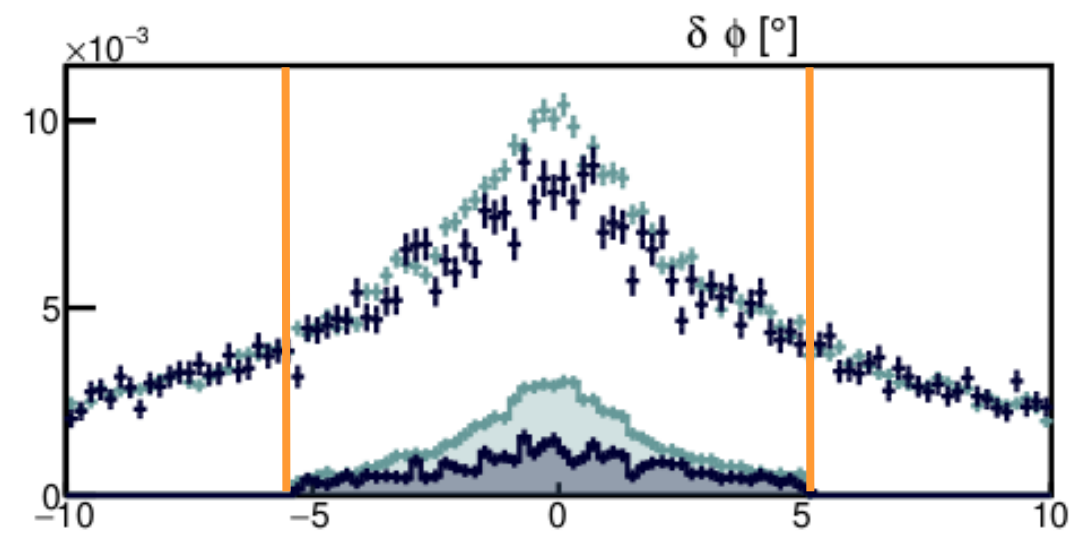
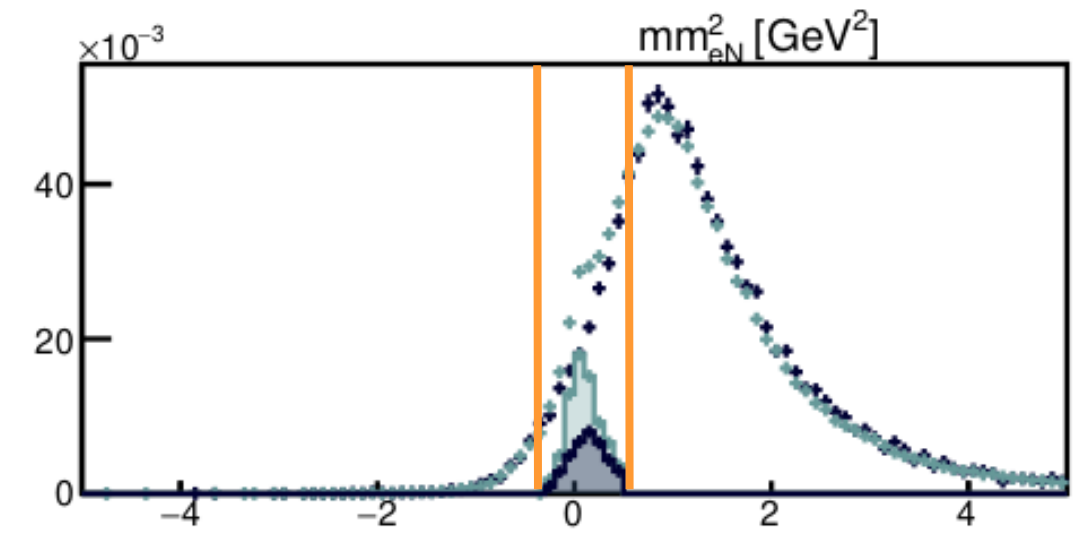
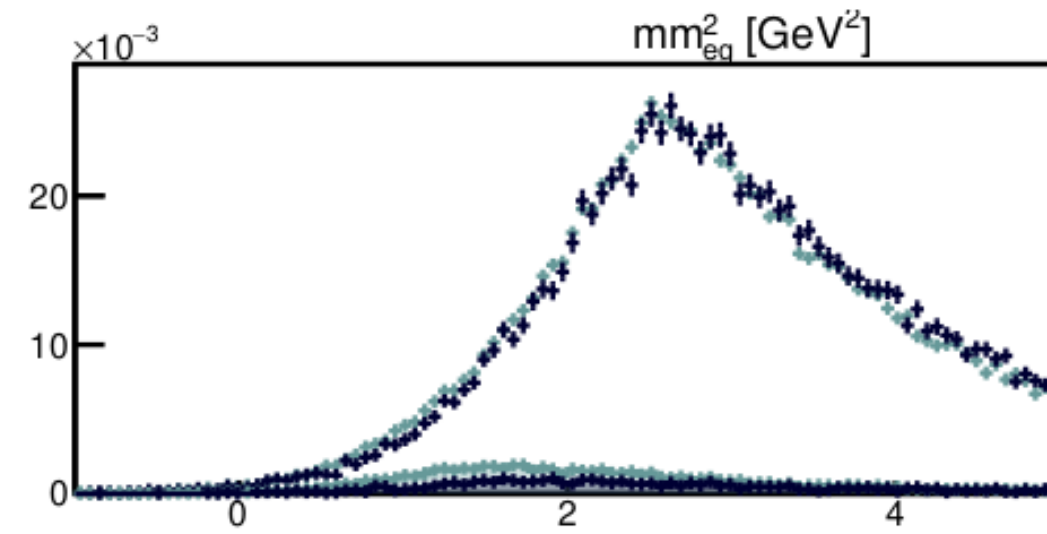
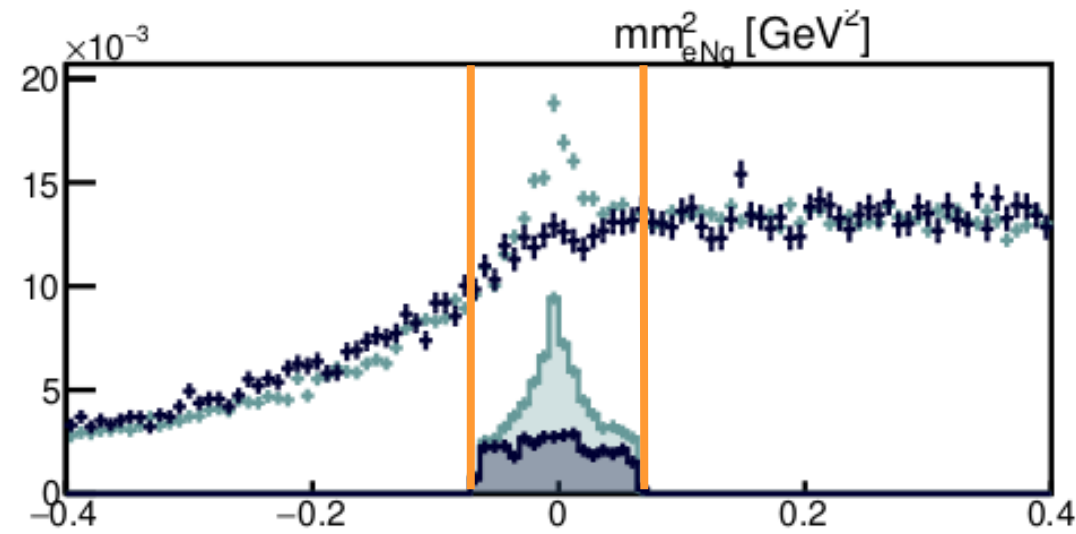


Preliminary

pDVCS event selection $ep \rightarrow e'p'\gamma$



γ FD
 p CD



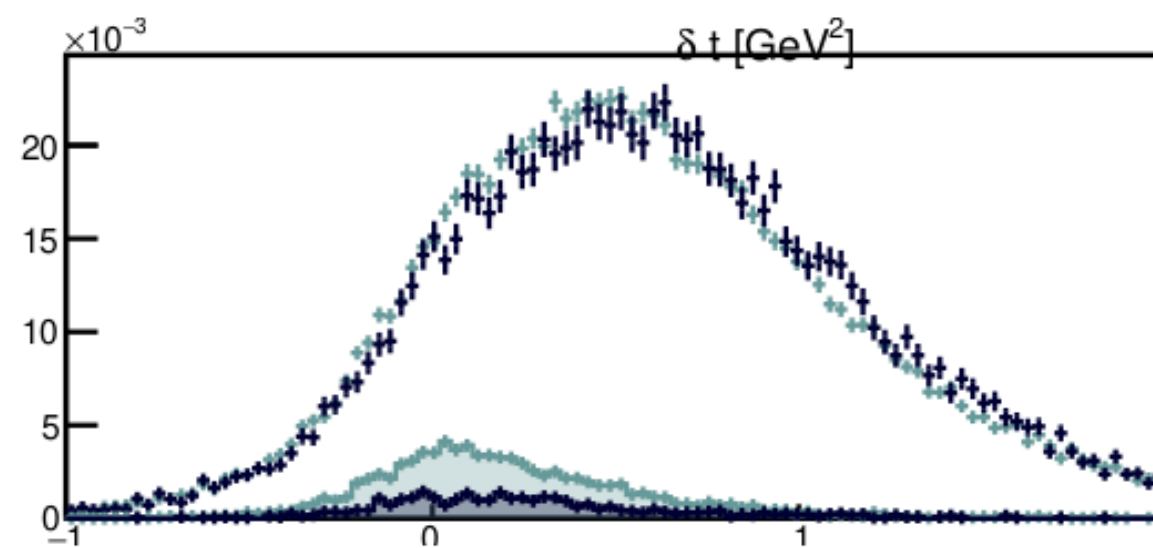
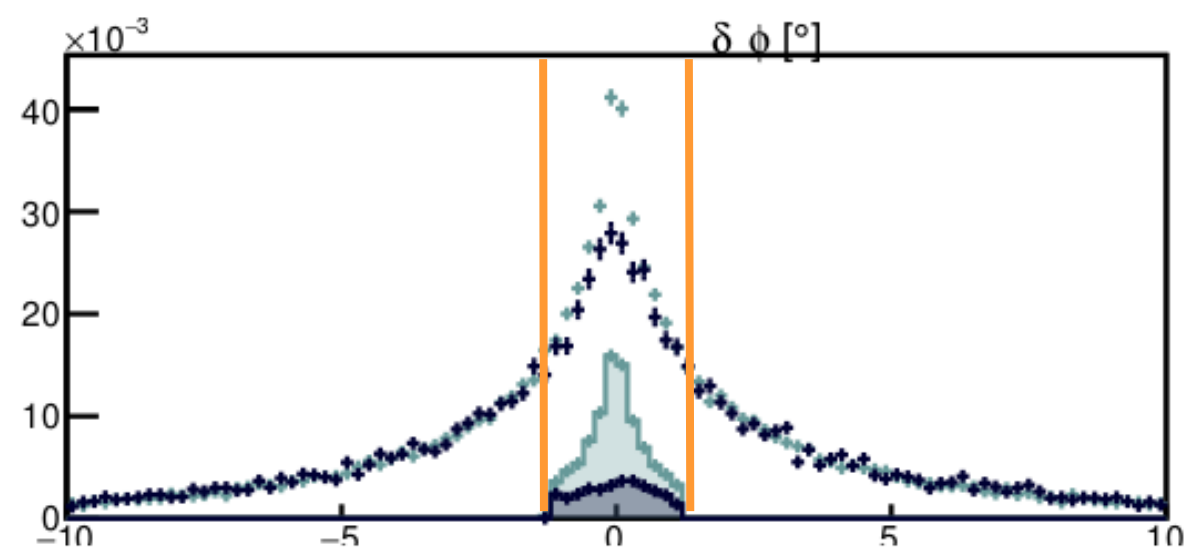
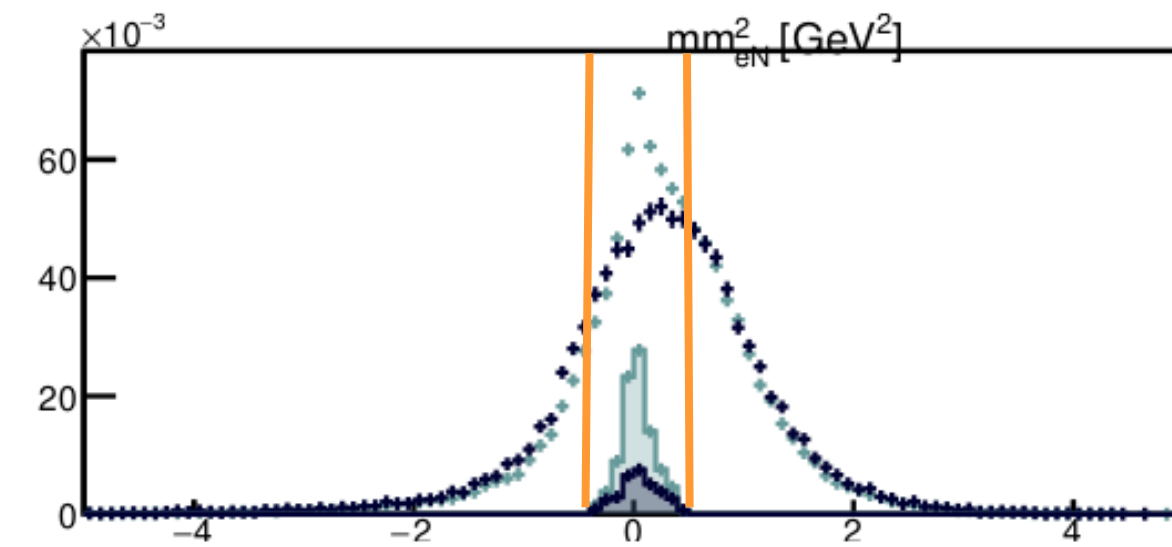
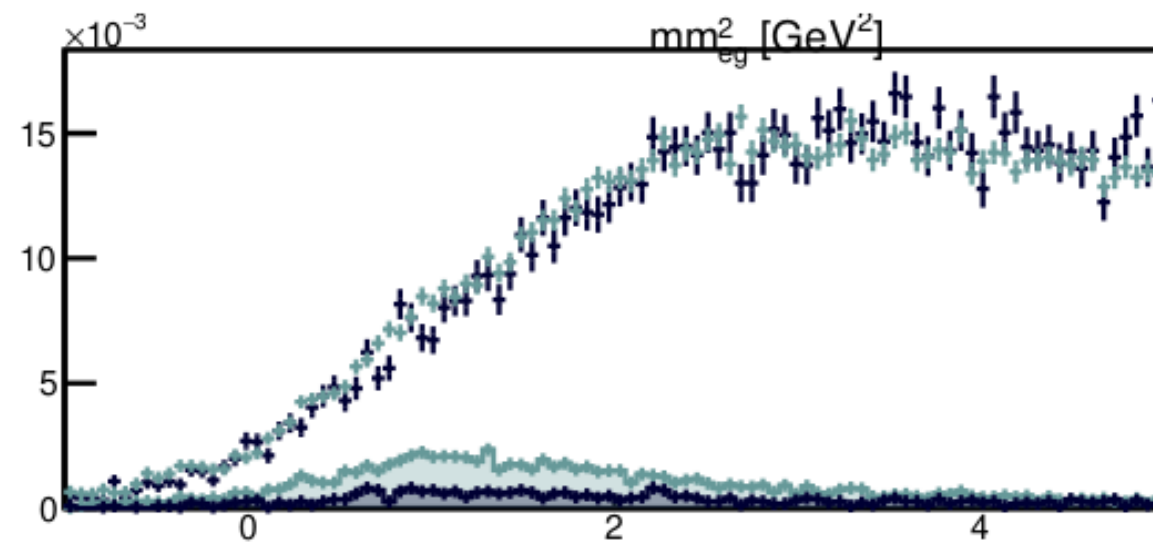
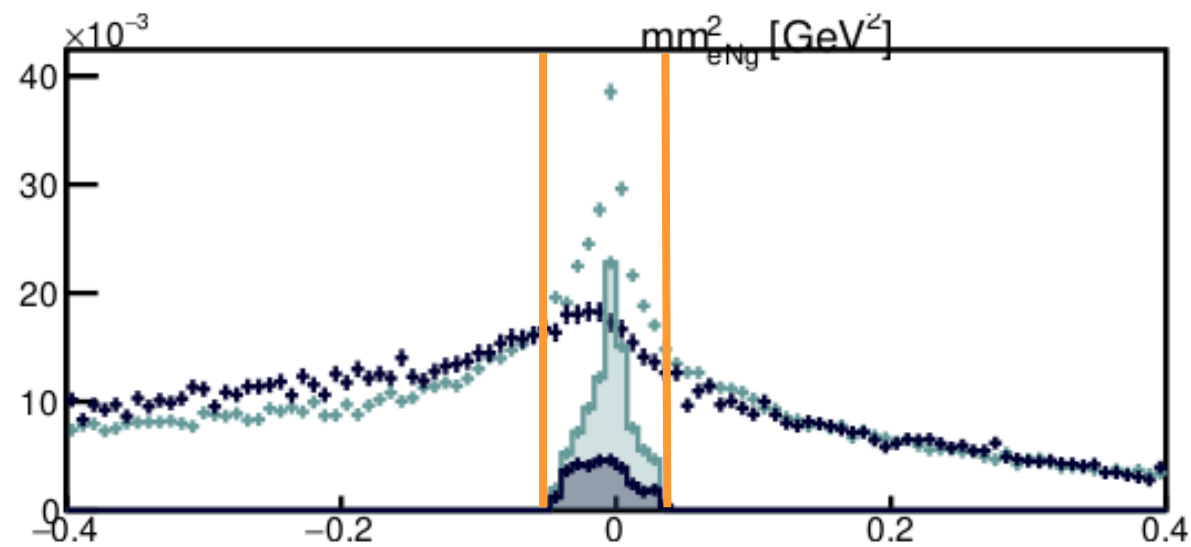
Preliminary

pDVCS event selection $ep \rightarrow e'p'\gamma$



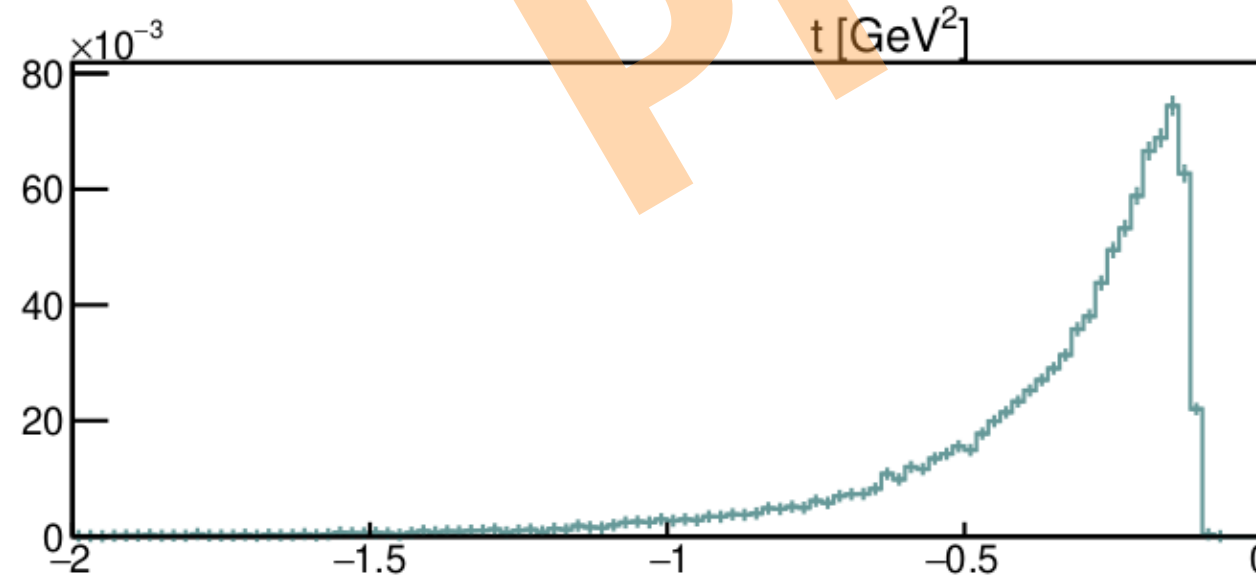
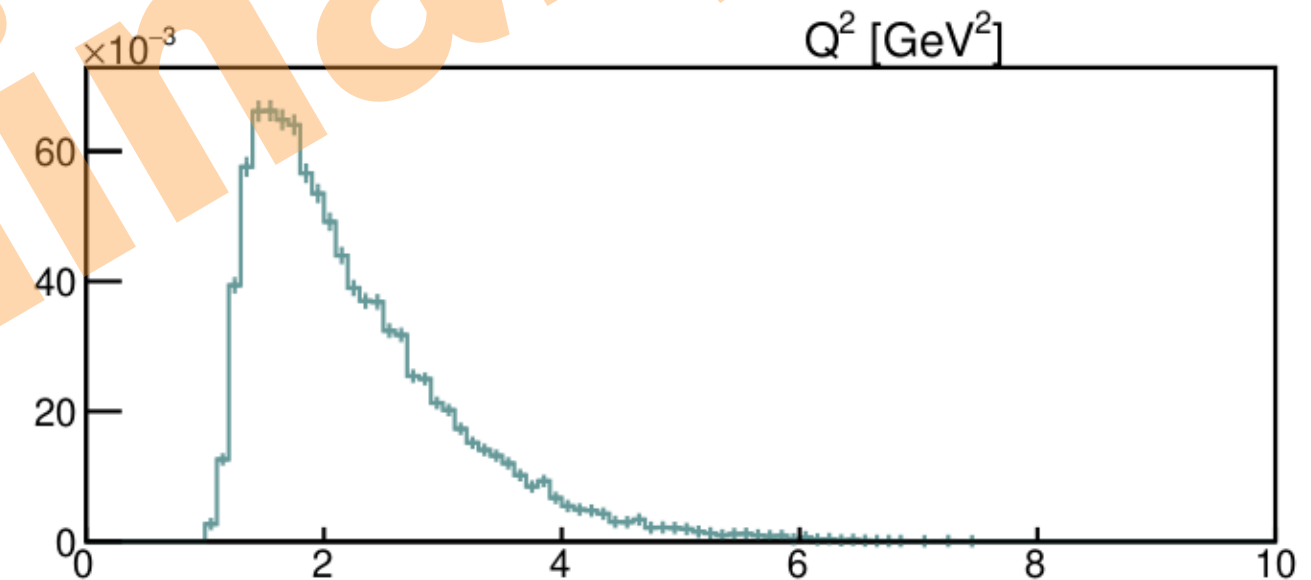
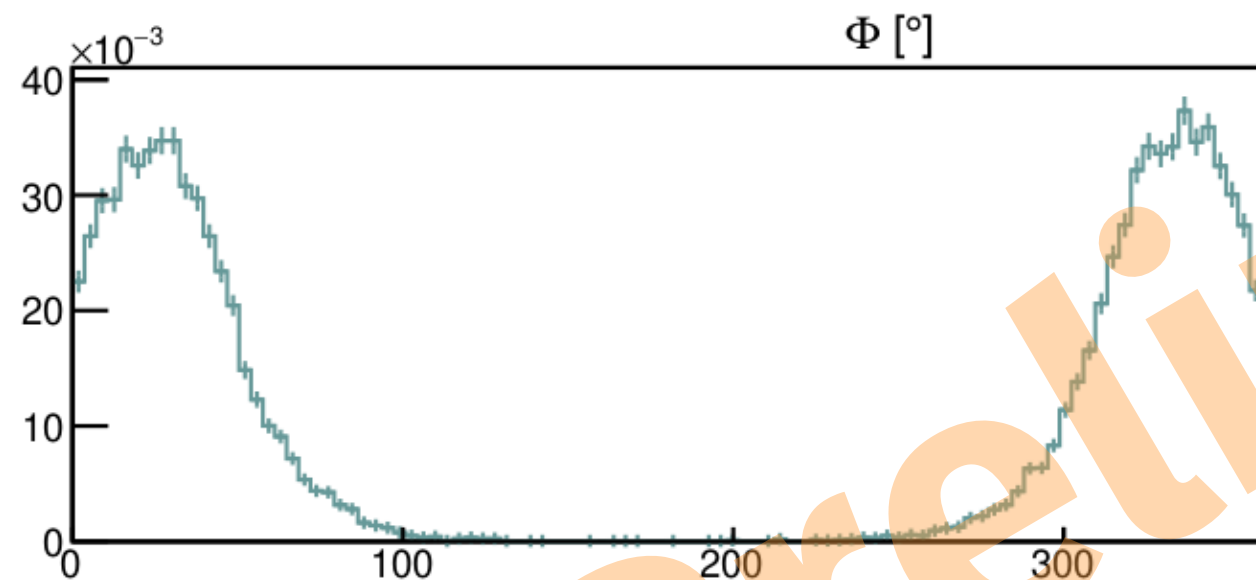
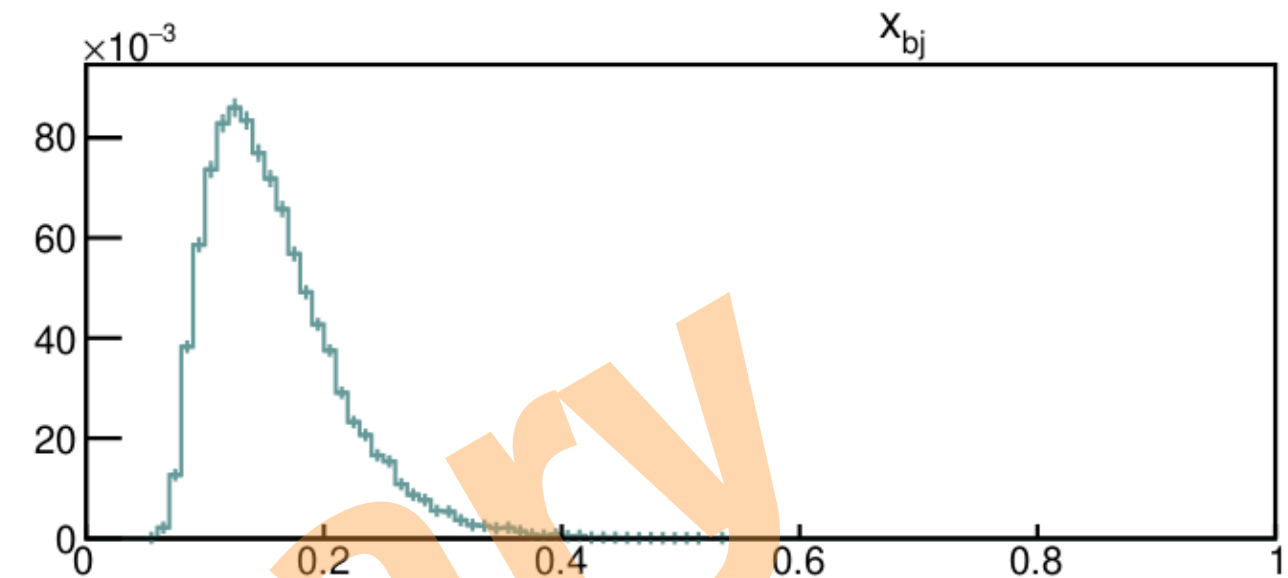
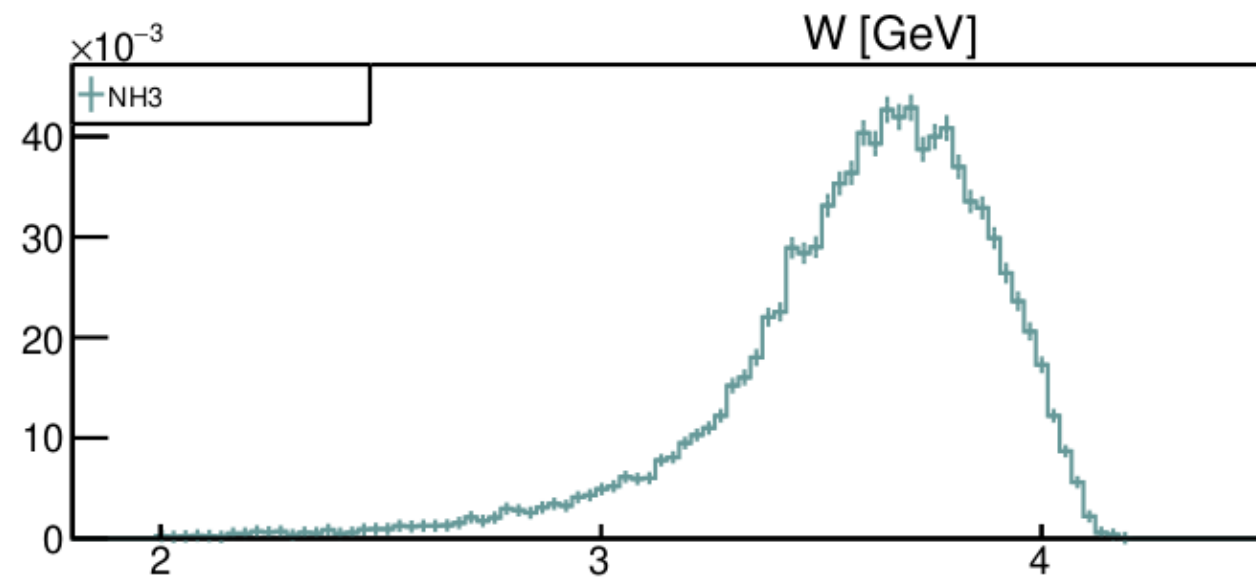
γ FD

p FD



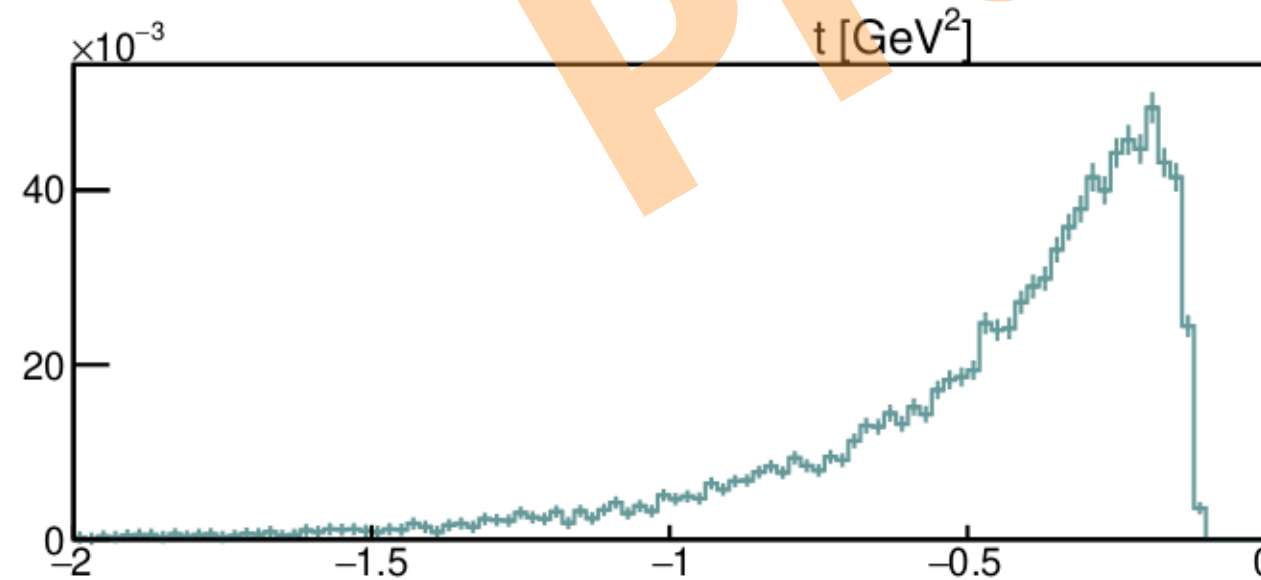
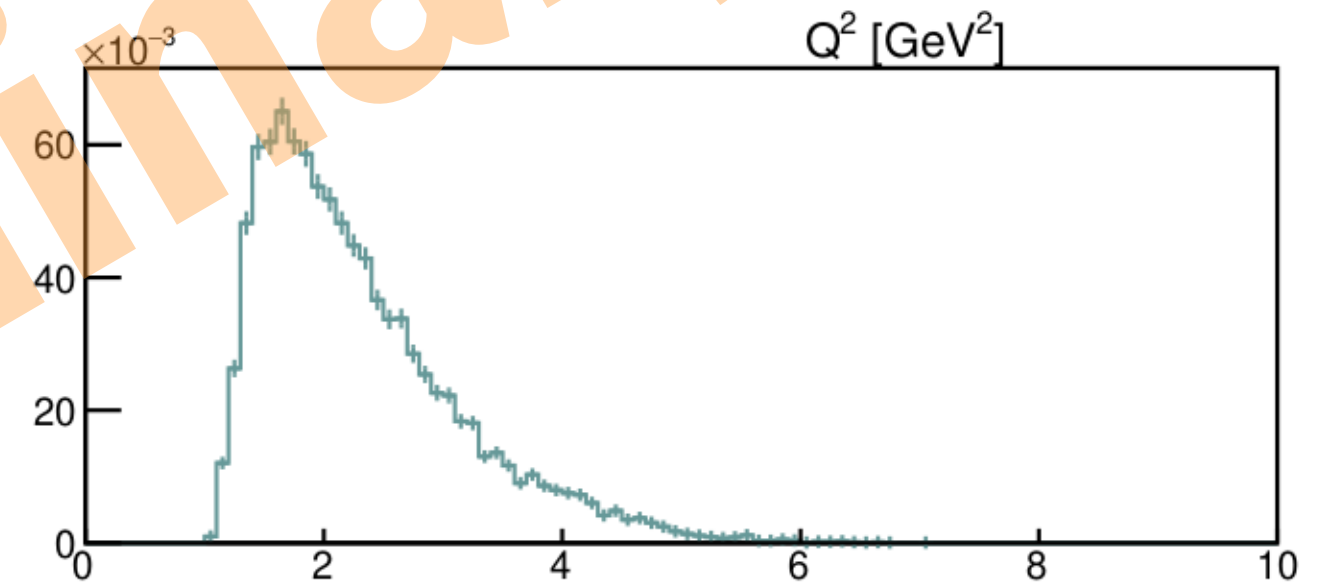
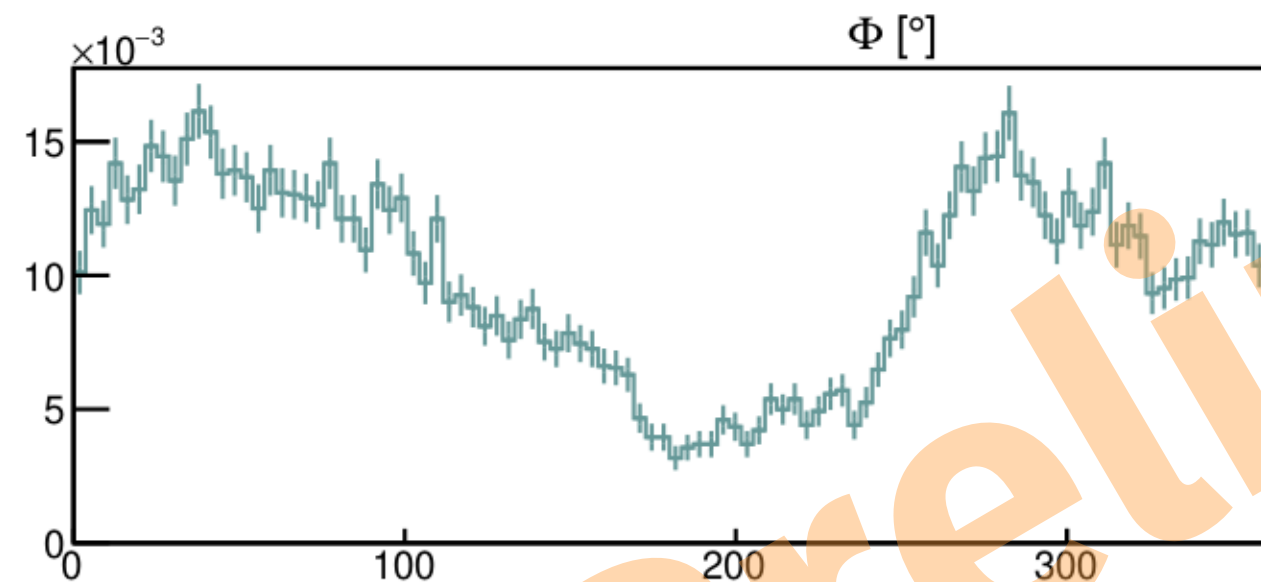
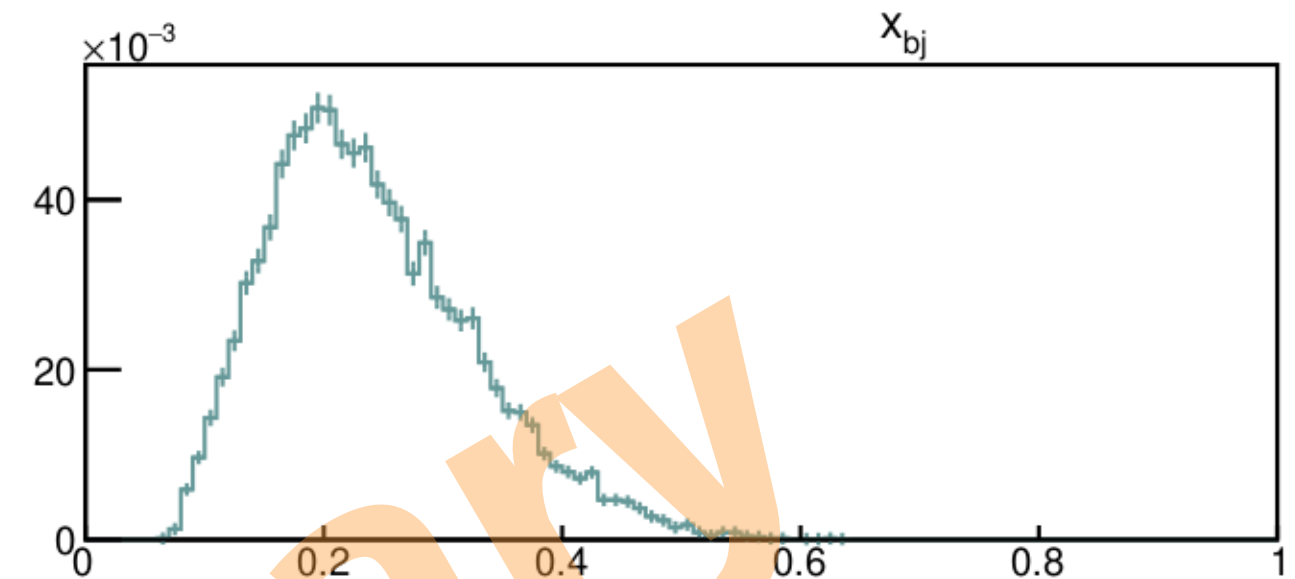
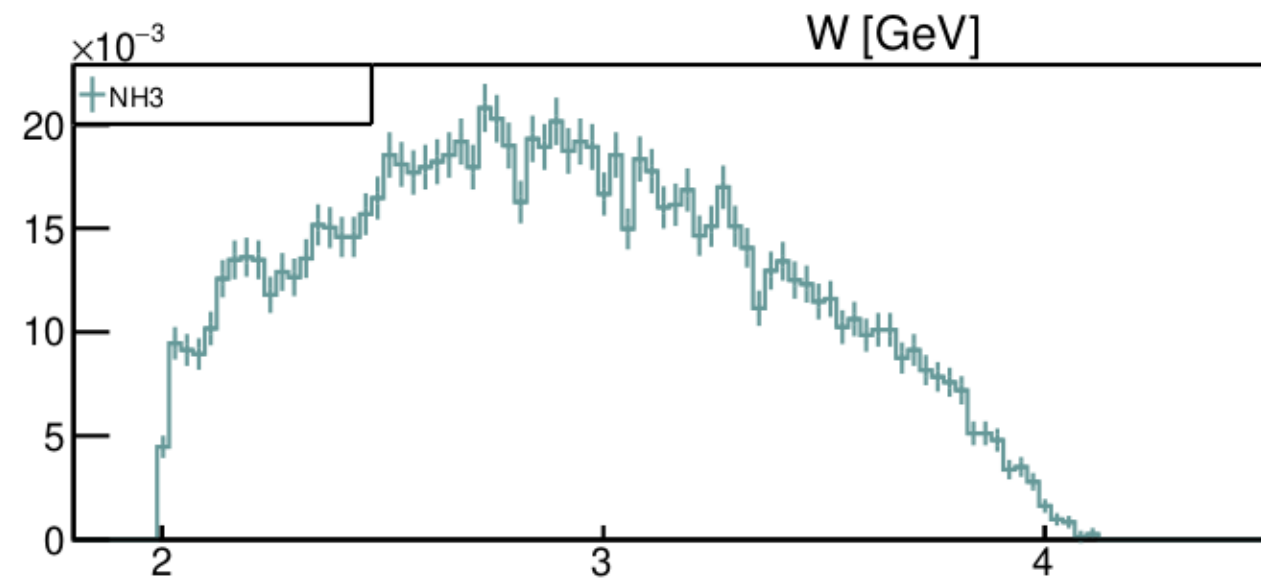
Preliminary

pDVCS Kinematics



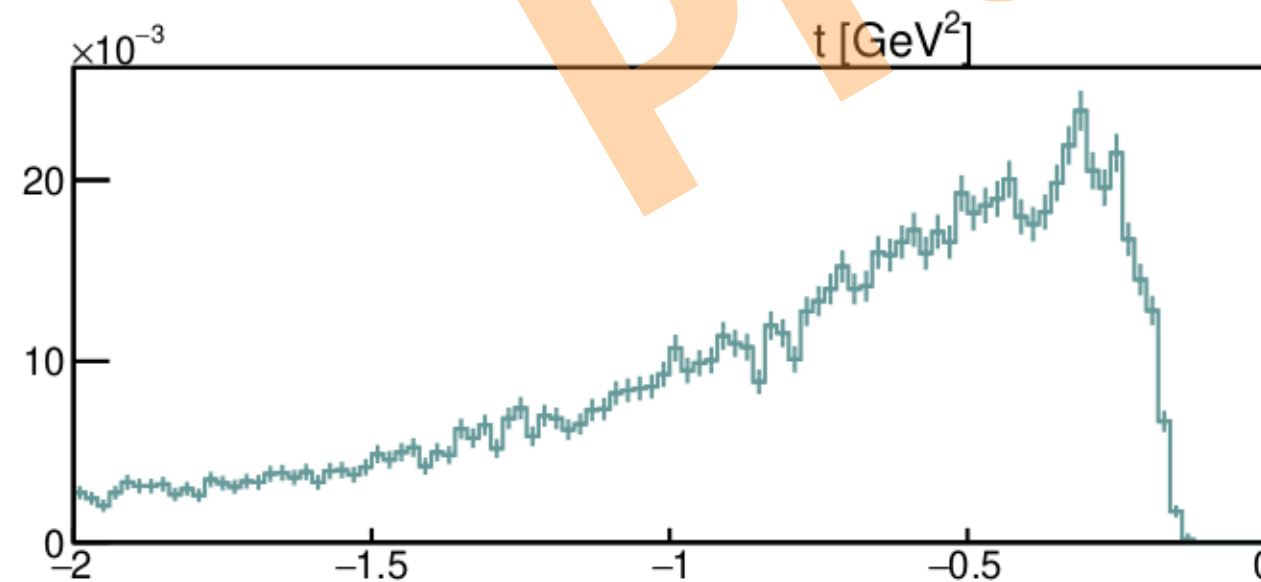
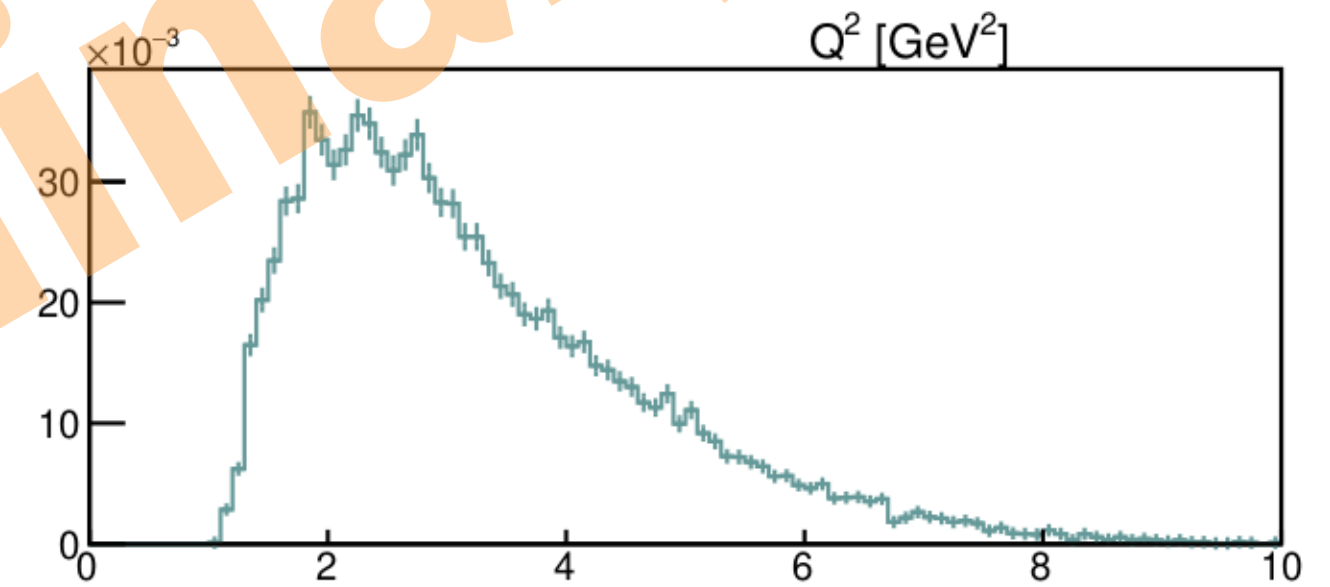
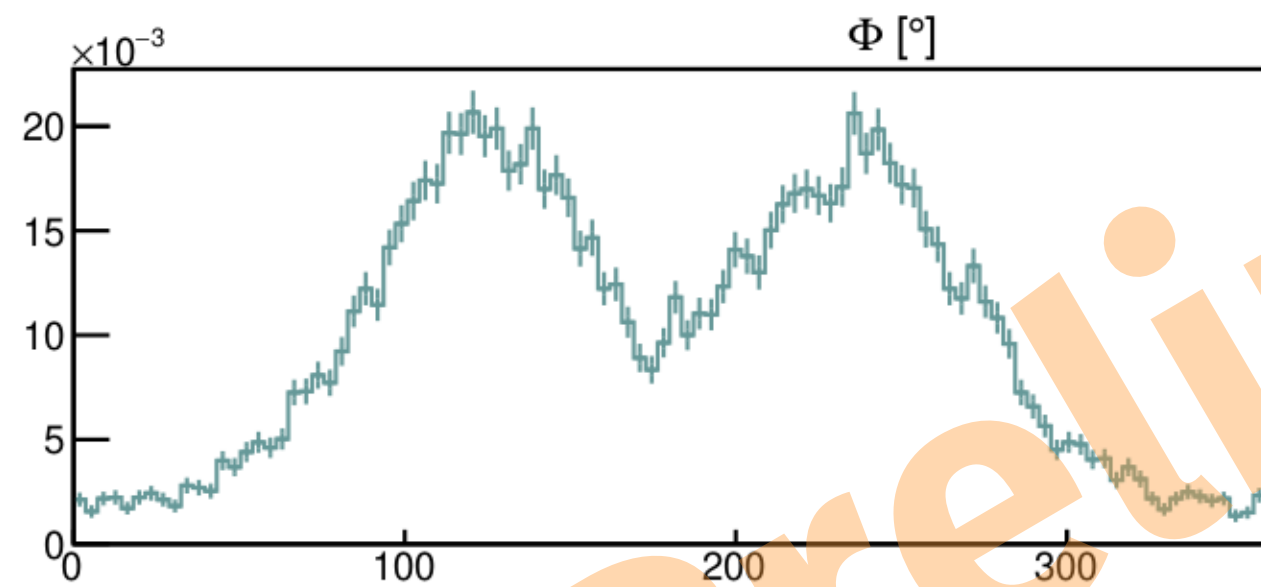
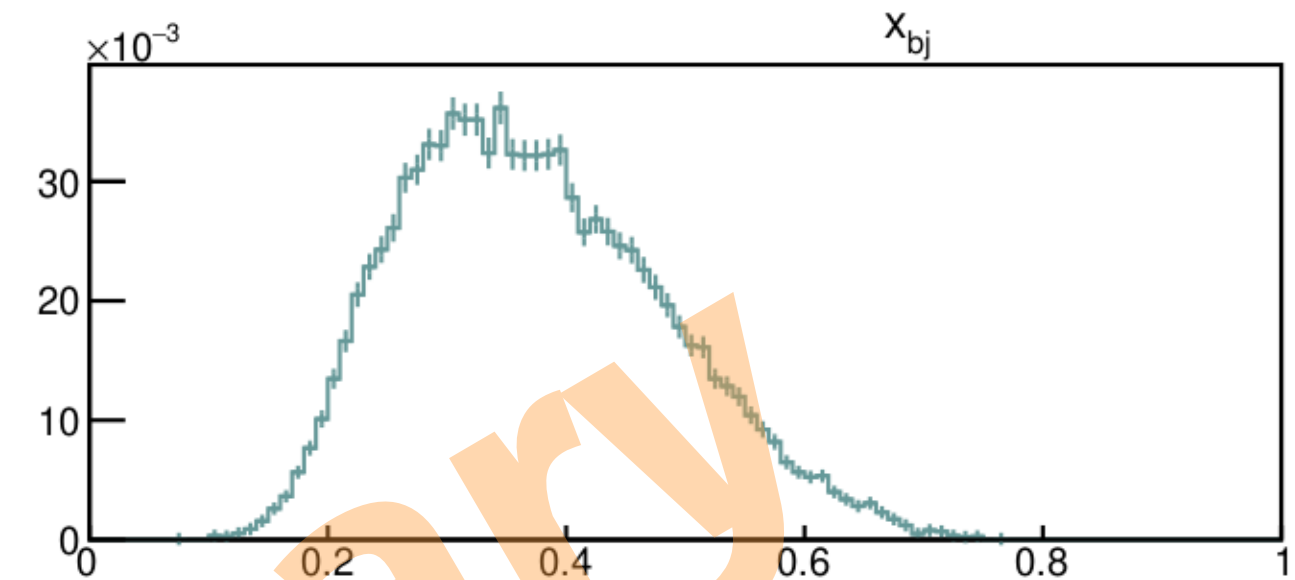
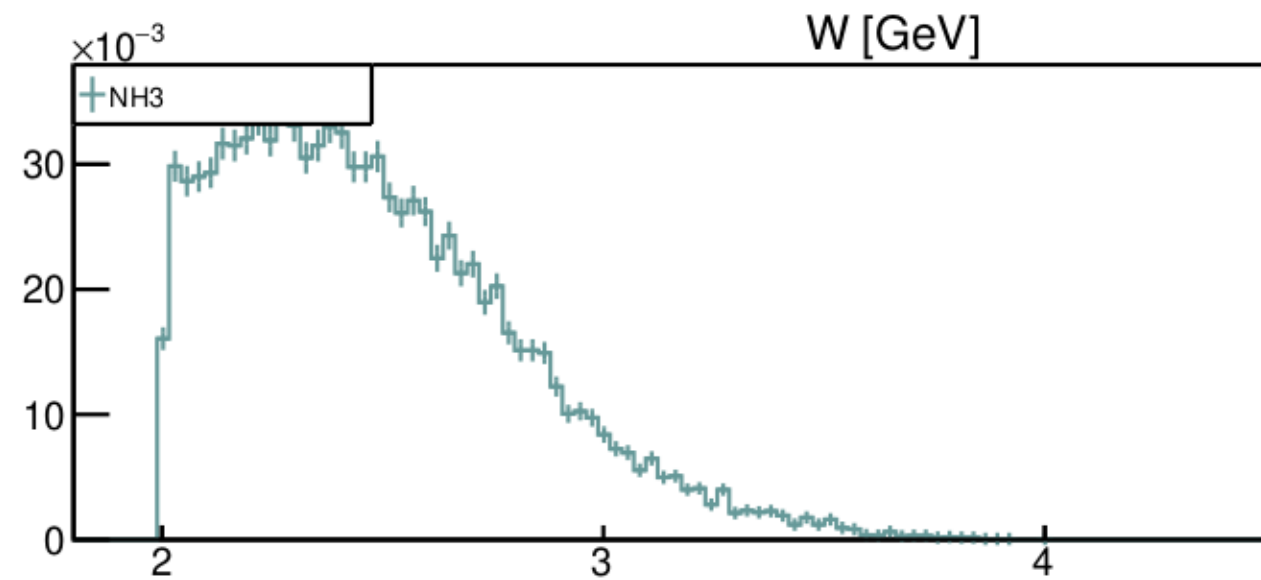
γ FT
p CD

pDVCS Kinematics



γ FD
p CD

pDVCS Kinematics



γ FD

p FD