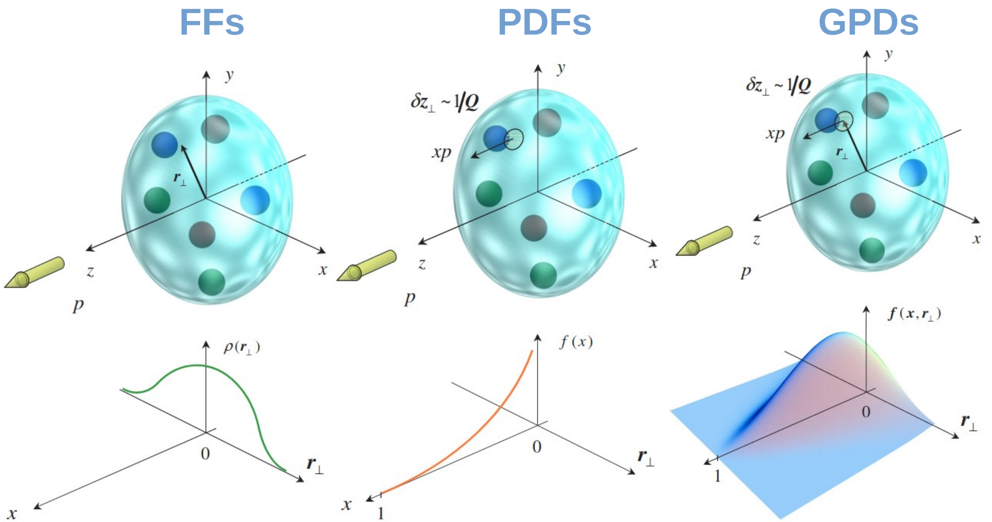
DVCS on a longitudinally polarised proton target

Introduction

- **Outstanding question : How does the nucleon's mass and spin arise from partons ?**
- First step is to map out the nucleon
- GPDs (Generalized Parton Distributions) describe correlations between the longitudinal momentum and transverse position of partons in the nucleon



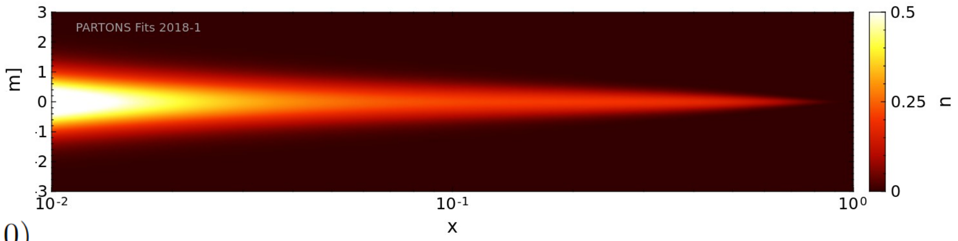
3D structure

→ Access to its mechanical properties

→ Access to the spin decomposition of the nucleon

$$\frac{1}{2} = \sum_q J^q + J^g$$

$$= \sum_q \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, x(H^q(x,\xi,0) + E^q(x,\xi,0)) + \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, H^g(x,\xi,0) + E^g(x,\xi,0)$$



[Phys.Rept.418:1-387] [Eur. Phys. J. C78 no. 11, 890]

Deeply Virtual Compton Scattering

- DVCS offers the most straightforward access to GPDs

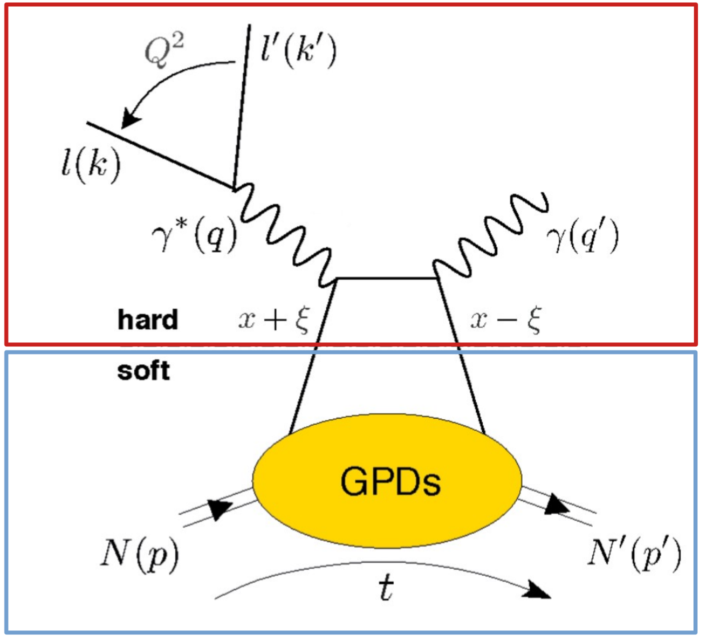
- DVCS can be factorised into :
  - **Hard part** γ*q scattering computed in perturbative QCD
  - **Soft part** described by 4 GPDs H, H̃, E, Ẽ at leading order & twist

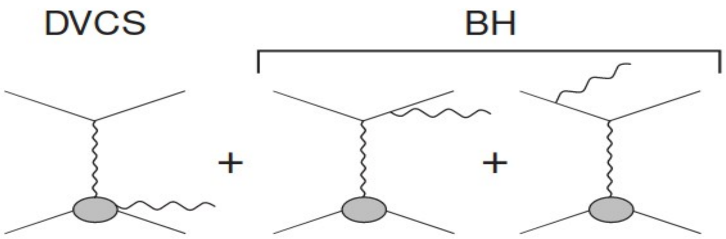
- Two indistinguishable processes, DVCS and Bethe-Heitler

$$|T|^2 = |T_{\mathrm{DVCS}}|^2 + |T_{\mathrm{BH}}|^2 + \underbrace{T_{\mathrm{DVCS}}T^*_{\mathrm{BH}} + T^*_{\mathrm{DVCS}}T_{\mathrm{BH}}}_{\mathrm{I}}$$

The amplitude is expressed as a function of FFs and CFFs which are functions of GPDs

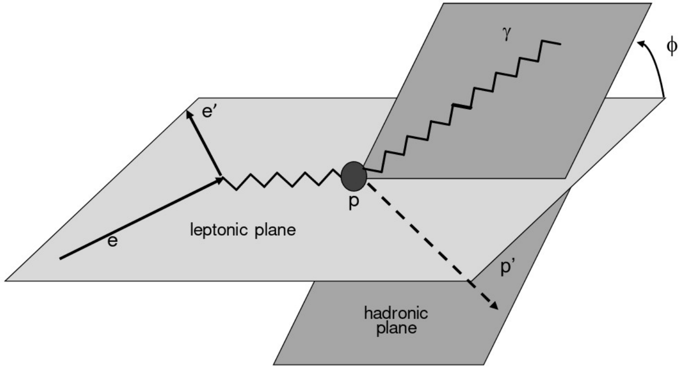
$$\mathcal{F} = \int_{-1}^{1} dx F(\mp x, \xi, t)\left[\frac{1}{x-\xi+i\epsilon} \pm \frac{1}{x+\xi-i\epsilon}\right]$$





[Eur. Phys. J. A 52, 151]

Observables



- Asymmetries in the DVCS cross section are sensitive to CFFs
- Beam spin asymmetry (BSA), polarised electron and unpolarised proton

$$A_{\mathrm{LU}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{unp}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + ...)\cos\phi ...} \qquad s^{\mathcal{I}}_{1,\mathrm{unp}} \propto \Im\mathrm{m}[F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}].$$

- Target spin asymmetry (TSA), unpolarised electron and longitudinally polarised proton

$$A_{\mathrm{UL}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{LP}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + ...)\cos\phi + ...} \qquad s^{\mathcal{I}}_{1,\mathrm{LP}} \propto \Im\mathrm{m}[F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + \frac{x_b}{2}\mathcal{E}) - \xi(\frac{x_b}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]$$

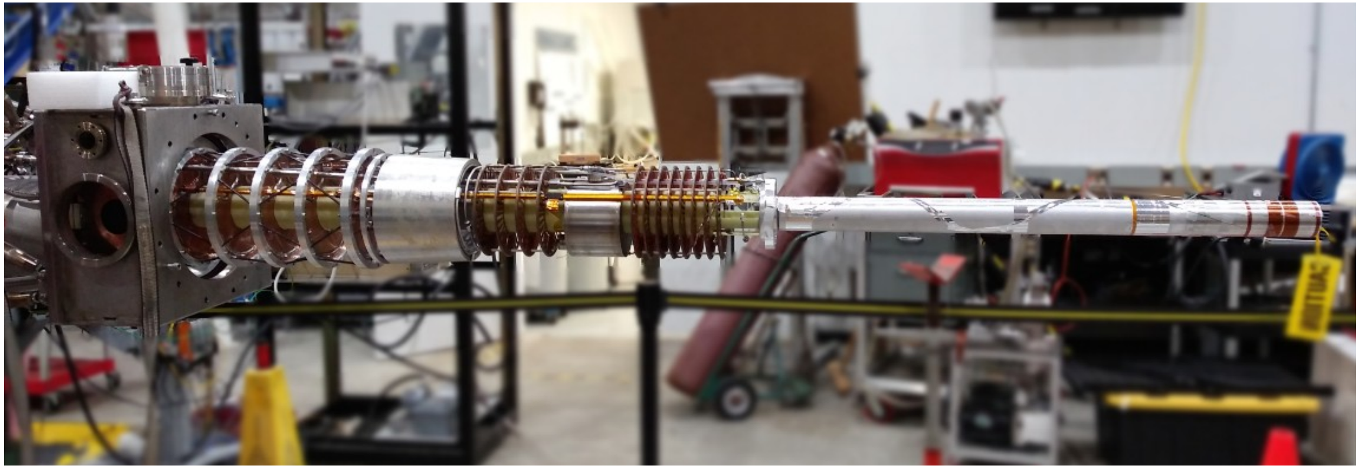
- Double spin asymmetry (DSA), aligned and anti-aligned electron and proton spin

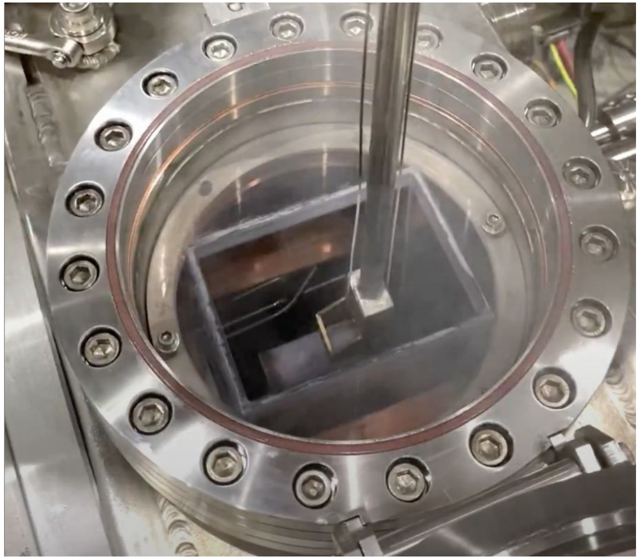
$$A_{\mathrm{LL}}(\phi) \sim \frac{c^{\mathrm{BH}}_{0,\mathrm{LP}} + c^{\mathcal{I}}_{0,\mathrm{LP}} + (c^{\mathrm{BH}}_{1,\mathrm{LP}} + c^{\mathcal{I}}_{1,\mathrm{LP}})\cos\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + ...)\cos\phi ...} \qquad c^{\mathcal{I}}_{0,\mathrm{LP}}, c^{\mathcal{I}}_{1,\mathrm{LP}} \propto \Re\mathrm{e}[F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + \frac{x_b}{2}\mathcal{E}) - \xi(\frac{x_b}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]$$

The RGC experiment

- New polarised target APOLLO, cryogenic solid target
- Dynamically polarised hydrogen or deuterium in NH3 or ND3 cells
- Data taking from June 2022 to March 2023 in three run periods, we will mainly focus on Summer 22 data
- **Goal of this analysis: Measure BSA, TSA and DSA on polarised proton**

	Summer 2022	Fall 2022	Spring 2023
FT	ON	OFF	ON
Magnets (solenoid, torus)	-1, -1	-1, -1 / +1, -1	-1, -1 / -1, +1
Run range	16089 - 16788	16843 - 17183 / 17185 - 17408	17477 - 17768 / 17769 - 17811
PAC days	28	30	22
Total charge on NH_3 [mC]	4.5	3.5 / 2.2	1.7 / 0.3

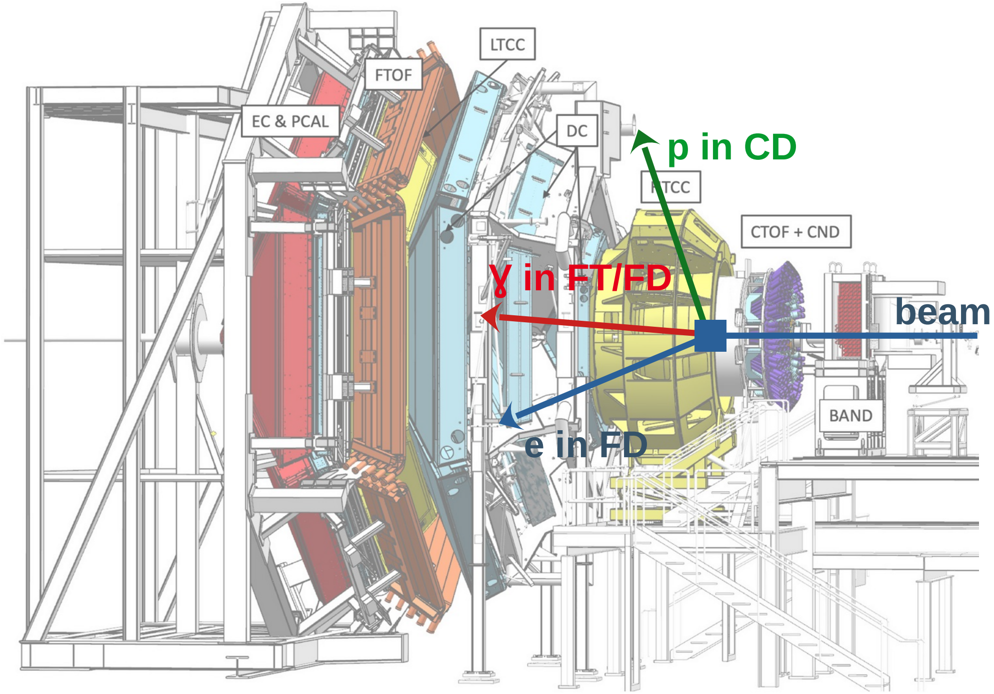




[DOI: 10.25777/36yz-ft35]

DVCS candidate selection

- Request at least one electron, one proton, and one photon in the event
- Kinematic cuts:
  - $Q^2 > 0.95$ GeV^2/c^4
  - W > 1.95 GeV/c^2
  - Electron P > 1 GeV/C
  - Photon E > 2 GeV
- Apply DC, ECAL, FTCAL fiducial cuts and PID cuts
- QADB selection of events fit for asymmetry measurements
- Application of GEMC based momentum corrections
- All three outgoing particles are detected so we can build exclusivity variables



DVCS event selection

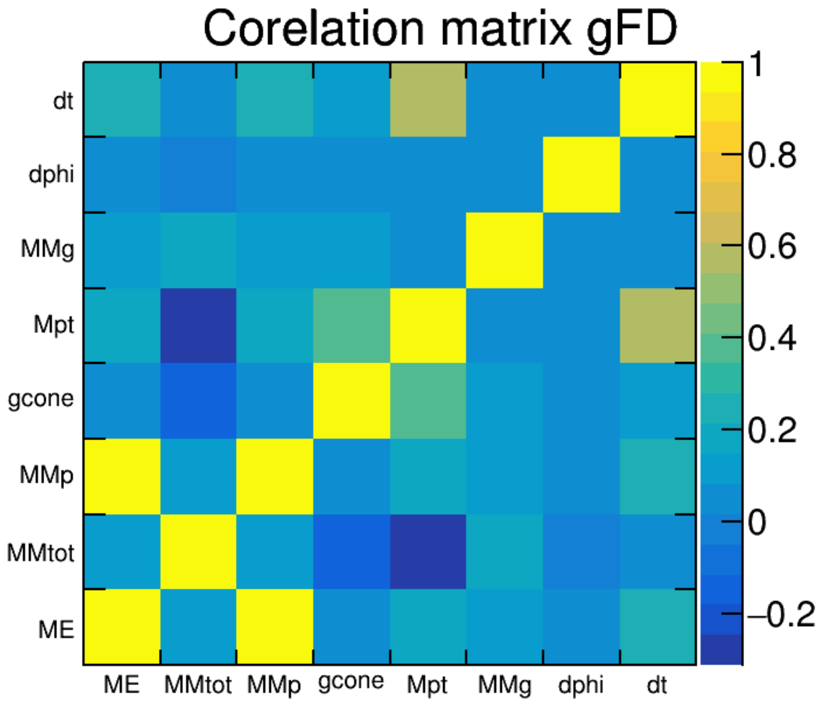
Variable	*level 2* cuts
MMtot [GeV^2/c^4]	$[-0.1, 0.1]$
MMp [GeV^2/c^4]	$[0, 3]$
ME [GeV]	$[-1.5, 1.5]$
Mpt [GeV/c]	$[0, 1]$
MMg [GeV^2/c^4]	$[-0.8, 0.8]$
g_cone [deg]	$[0, 2]$
$\Delta\phi$ [deg]	$[-3, 3]$
Δt [GeV^2/c^4]	$[0, 2]$

- Application of broad exclusivity cuts on 8 variables (level 2 cuts)
- Instead of applying fine cuts on all variable we compute a distance from each event to an ideal exclusive event (ME=0, Δϕ=0, …)
- The relative weights of each variable needs to be scaled to account for different with of the distributions, different units …
  - ➔ Mahalanobis distance: distance weighted by the covariance matrix between the different variables

$$d(\vec{x},\vec{y}) = \sqrt{(\vec{x}-\vec{y})^T\Sigma^{-1}(\vec{x}-\vec{y})}$$

- Covariance matrices computed from a GEMC simulation of DVCS events on a proton target (separated matrices for photons in the FD and FT)

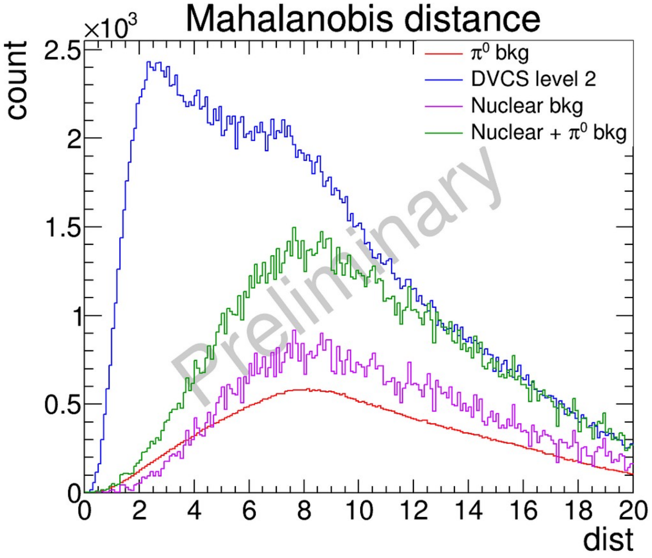
➔ Apply an exclusivity cut on one variable instead of 8 → simpler to adjust and improved efficiency

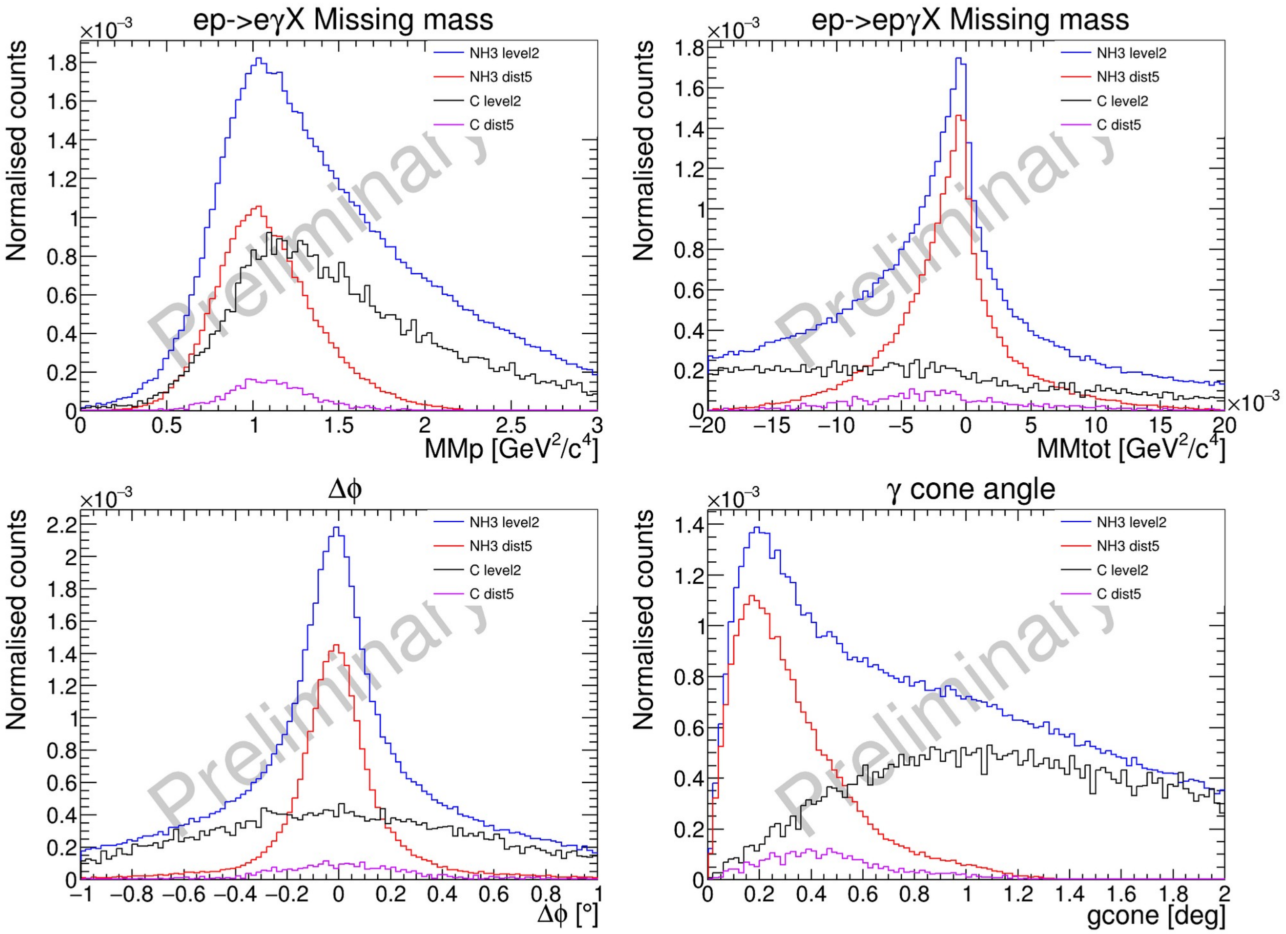


DVCS event selection

- Nuclear background
  - Data taken on a carbon target of similar area density to NH3 → background estimate

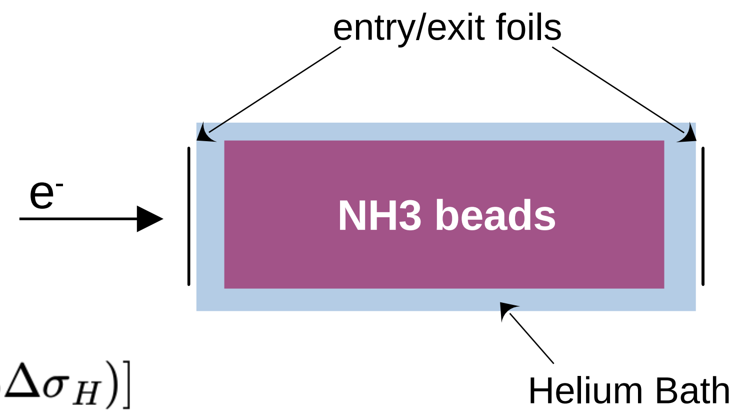
- Cut at distance < 5, able to cut almost all nuclear background





Nuclear background

$$A_{UL} = \frac{1}{D_f} \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$



- To take into account the remaining nuclear background, the TSA and DSA are scaled by the dilution factor

$$n_{NH3} = f_c[(L - l_{NH3})\rho_{He}\Delta\sigma_{He} + l_{NH3}\rho_{NH3}(\frac{7}{6}\Delta\sigma_C + 3\Delta\sigma_H)]$$

- The dilution factor is the fraction of the total number of events that comes from the polarised free protons

$$Df = \frac{3l\rho_{NH3}\Delta\sigma_H}{(L - l)\rho_{He}\Delta\sigma_{He} + l\rho_{NH3}(\frac{7}{6}\Delta\sigma_C + 3\Delta\sigma_H)}$$

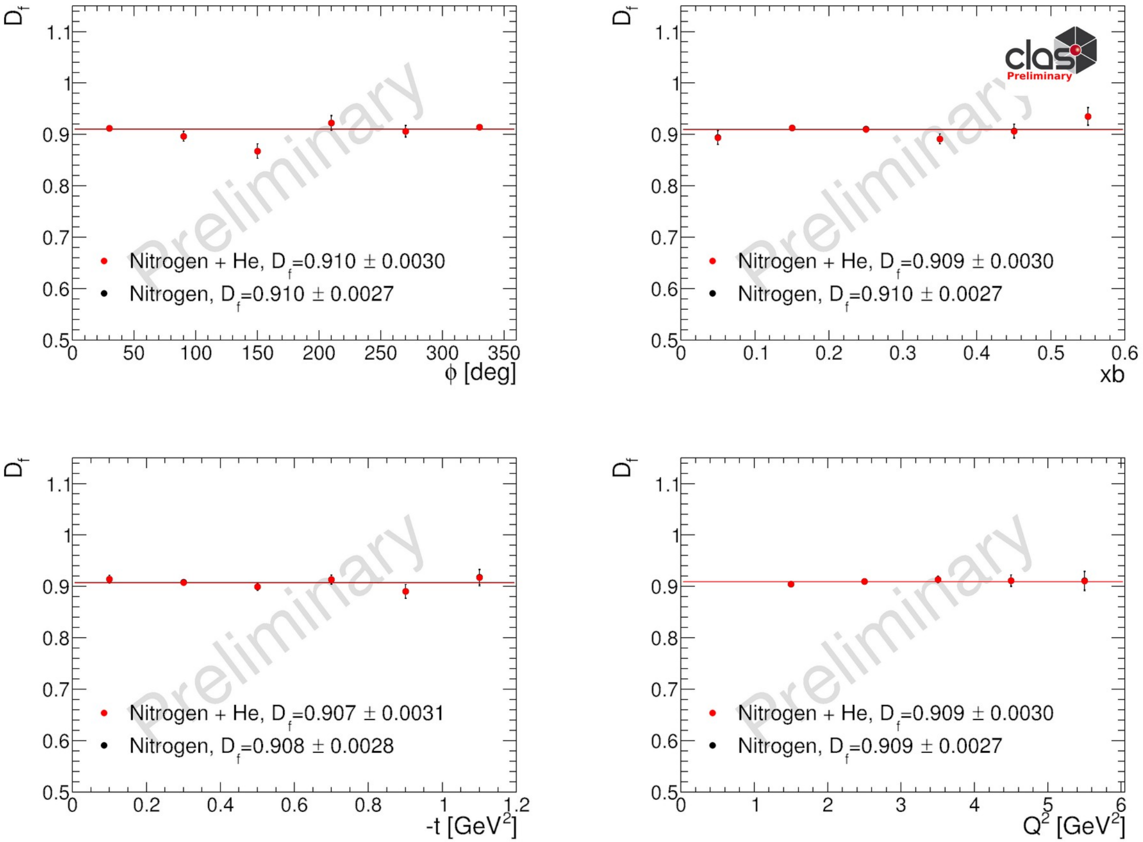
RGC took data with multiple targets:

- Empty target → Foil contribution
- He bath → He contribution
- Carbon → Nitrogen contribution
- CH2 → Hydrogen contribution

[S.E. Kuhn]

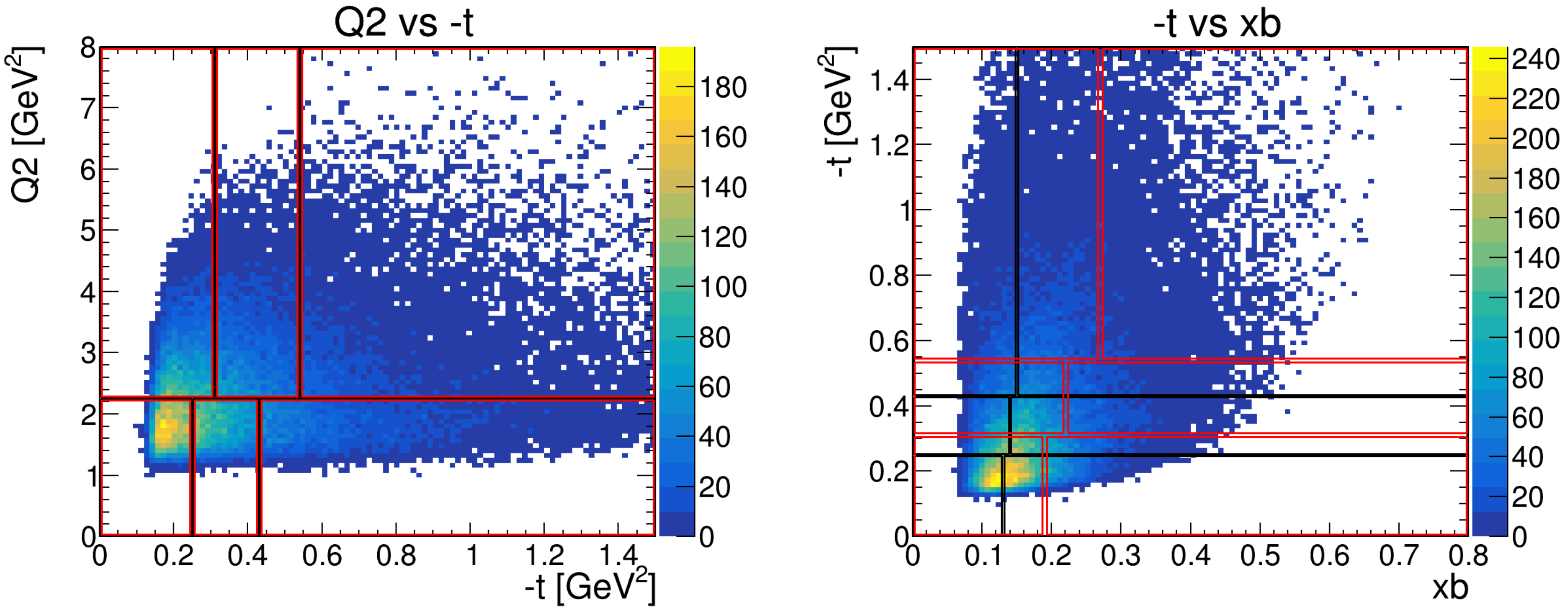
Dilution factor

- Foil contribution is neglected because less than 10 DVCS events collected in the empty target runs
- Helium contribution is very small
- Dilution factor is stable across all kinematic variables at 91 ± 1%
- Packing fraction, 58 ± 1 %



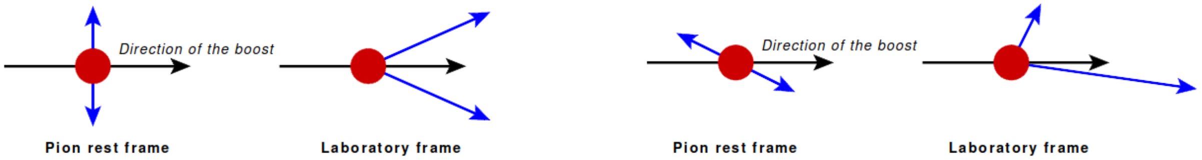
Binning

- Two bins in Q^2 and x_b and three bins in t, same number of DVCS events in each bin
- The binning in ϕ follows the distribution in each bin, with the following requirements
  - A minimum of 300 events per ϕ bin
  - At least 15° wide



π^0 subtraction method

- A $\pi^0 \rightarrow \gamma\gamma$ decay can pass the DVCS selection if one of the photons carries most of the momentum



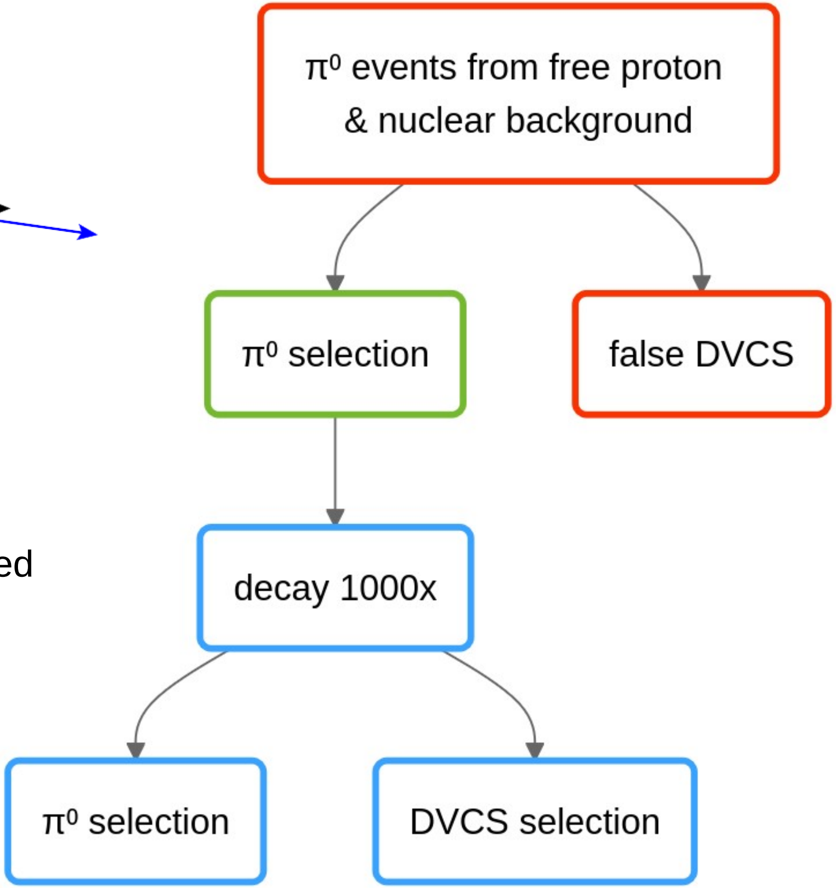
  - Significant background that needs to be subtracted

$$N^{bt} = \frac{Y^{bt}}{\text{Charge}^{bt}}(1 - R^{bt})$$

  - R is estimated from a data π^0 sample, each π^0 is decayed 1000x and passed through the CLAS12 simulation.

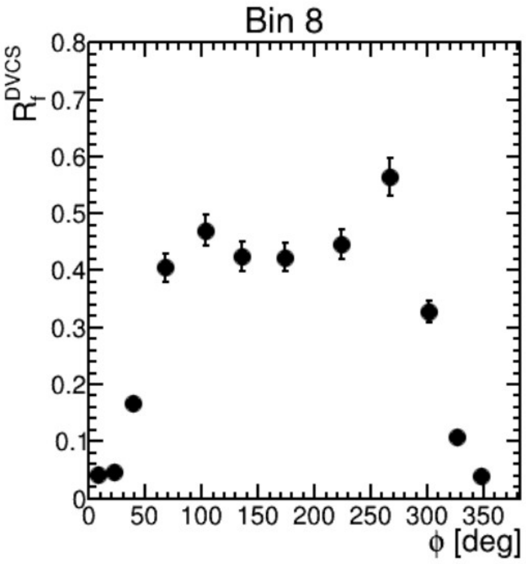
$$R = \frac{S^{\text{fDVCS}}}{S^{\pi^0}} \times \frac{Y^{\pi^0}}{Y^{\text{DVCS}}}$$

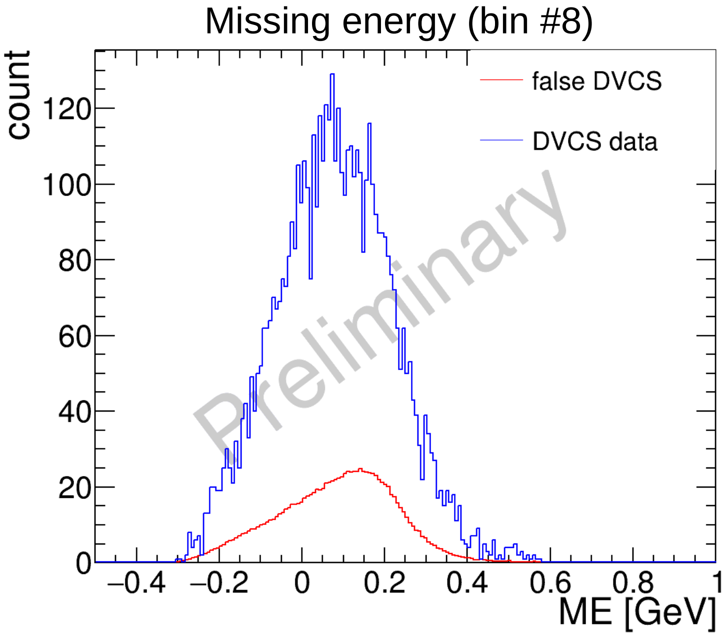
Y^i are the raw yields, S^i are the weighted number of decays that pass the DVCS or π^0 selection

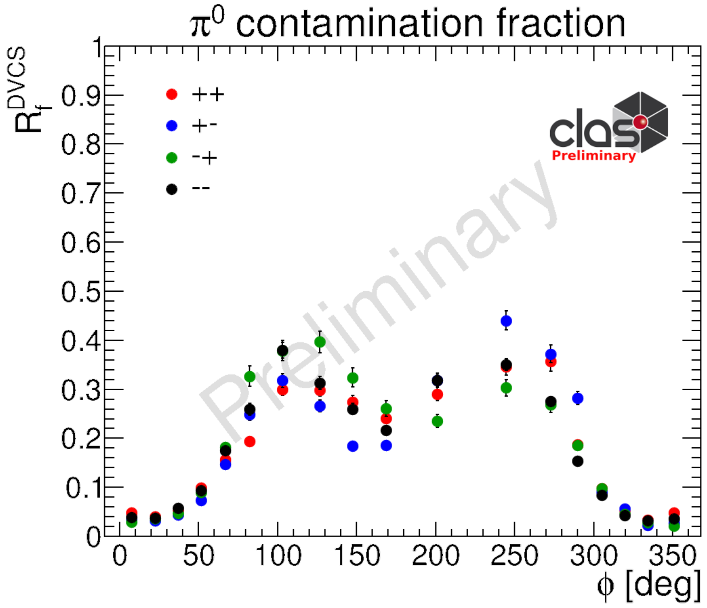


π^0 contamination in data

- Contamination of up to 60% in some kinematic bins (largest contamination in bin #8)
- The contamination is larger in central ϕ bins where the Bethe-Heitler cross-section is small







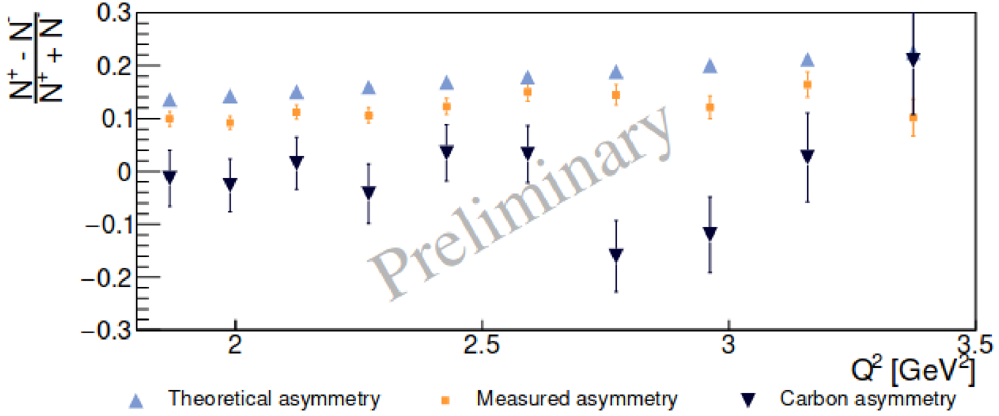
Target polarisation

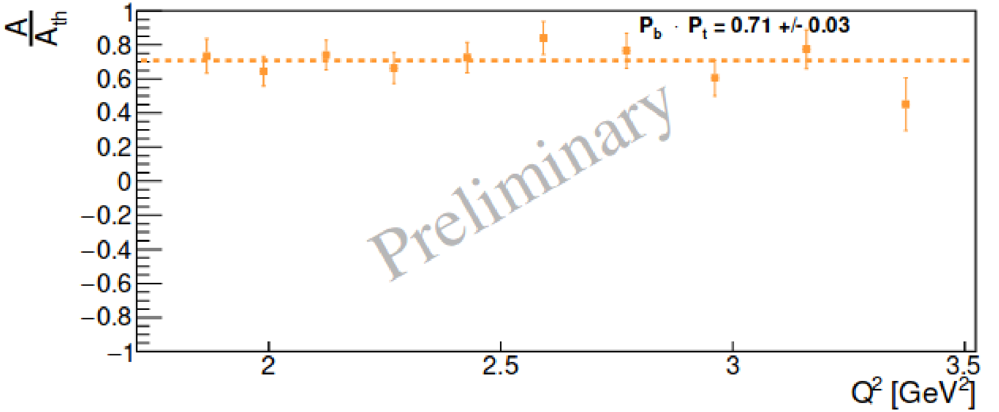
N. Pilleux

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

$$A_{th} = \frac{A_{exp}}{P_b P_t} \qquad A_{exp} = \frac{N^+ - N^-}{D_f(N^+ + N^-)}$$

- The target polarisation is extracted from the ratio of theoretical to measured elastic asymmetry
  - ➔ $P_t^+ = 86 \pm 3\ \%$
  - ➔ $P_t^- = 80 \pm 3\ \%$
- Efforts are ongoing to cross-check elastic results with target polarisation measured from DIS asymmetries, and from MNR readings

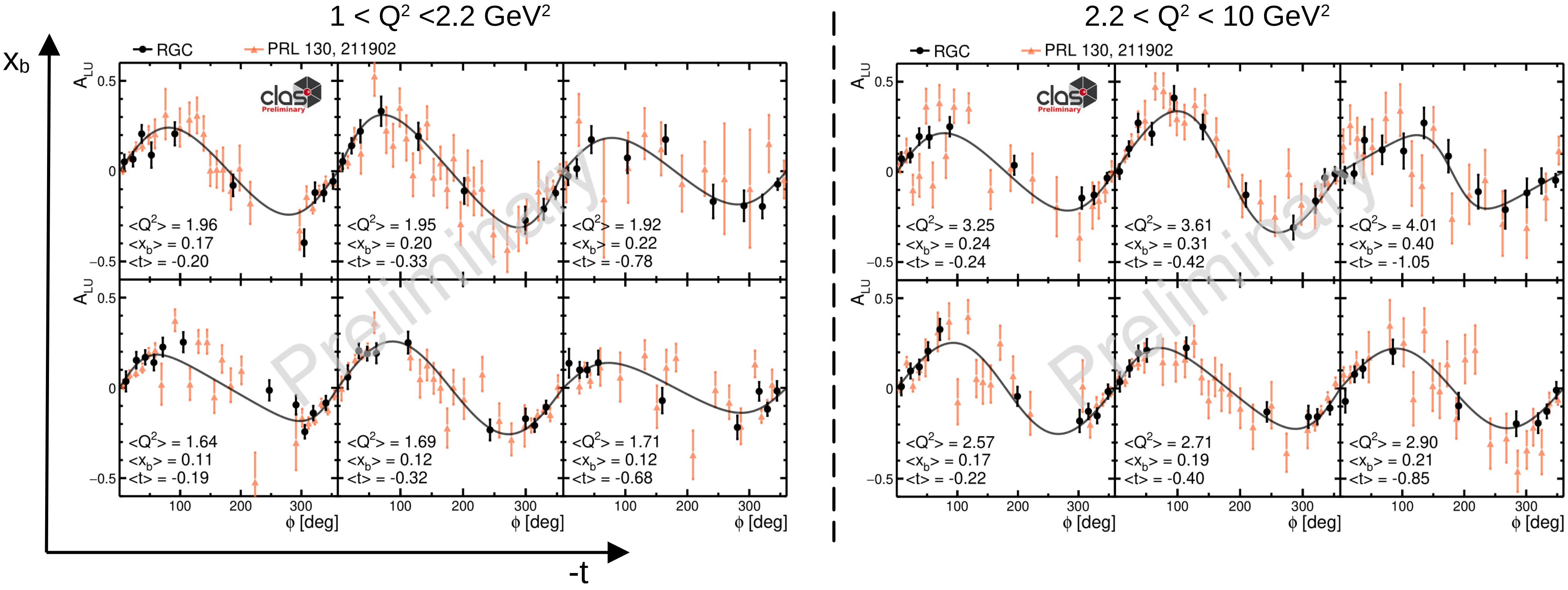




Comparison with RGA BSA on unpolarised proton

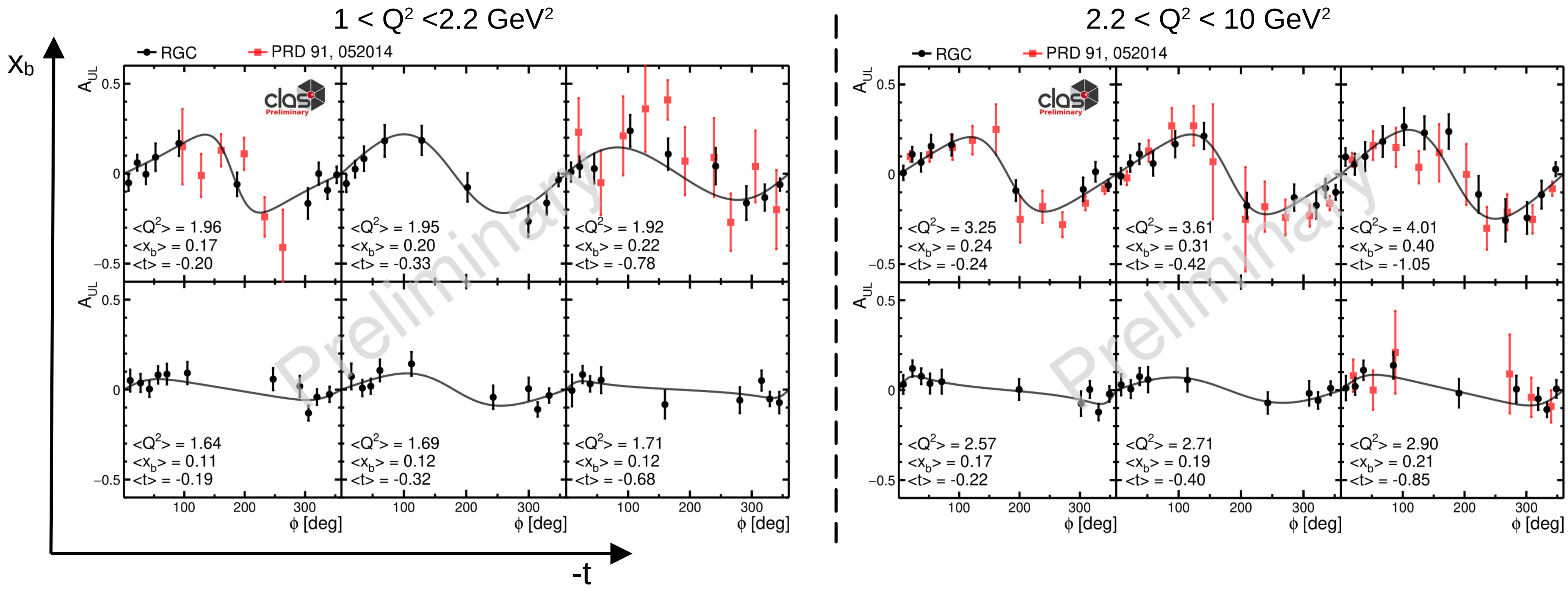
- RGA BSA measurement on a liquid hydrogen target, [Phys. Rev. Lett. 130, 211902]
  - Same kinematic reach and no nuclear background → Good cross check

⚠ This work only includes part of the systematics uncertainties



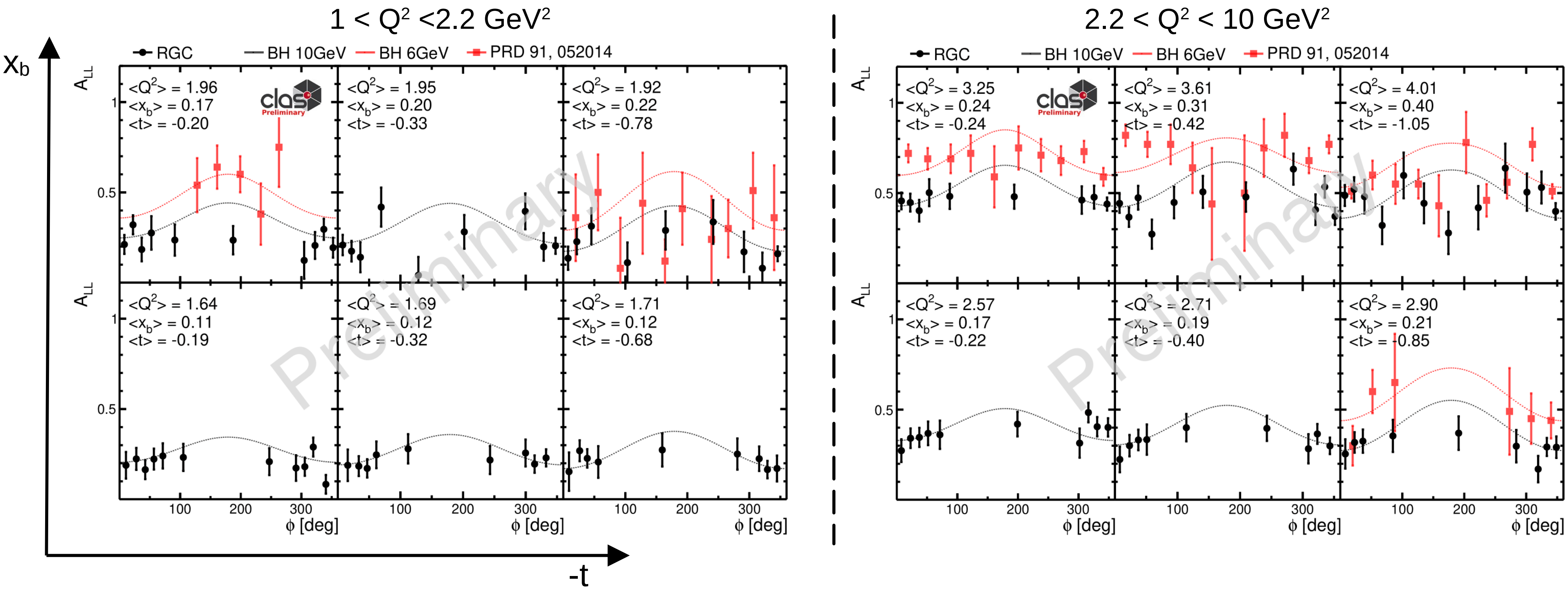
Comparison with CLAS6 TSA

- CLAS6 eg1-dvcs TSA measurement [Phys. Rev. D 91, 052014] → Different beam energy and kinematic reach
- ⚠ This work only includes part of the systematics uncertainties



Comparison with CLAS6 DSA

- The main contribution to the DSA is from the Bethe-Heitler asymmetry which is differs with the beam energy
- ⚠ This work only includes part of the systematics uncertainties



Comparison with models

- In the next slides the asymmetries are compared to models from the Partons and Gepard libraries

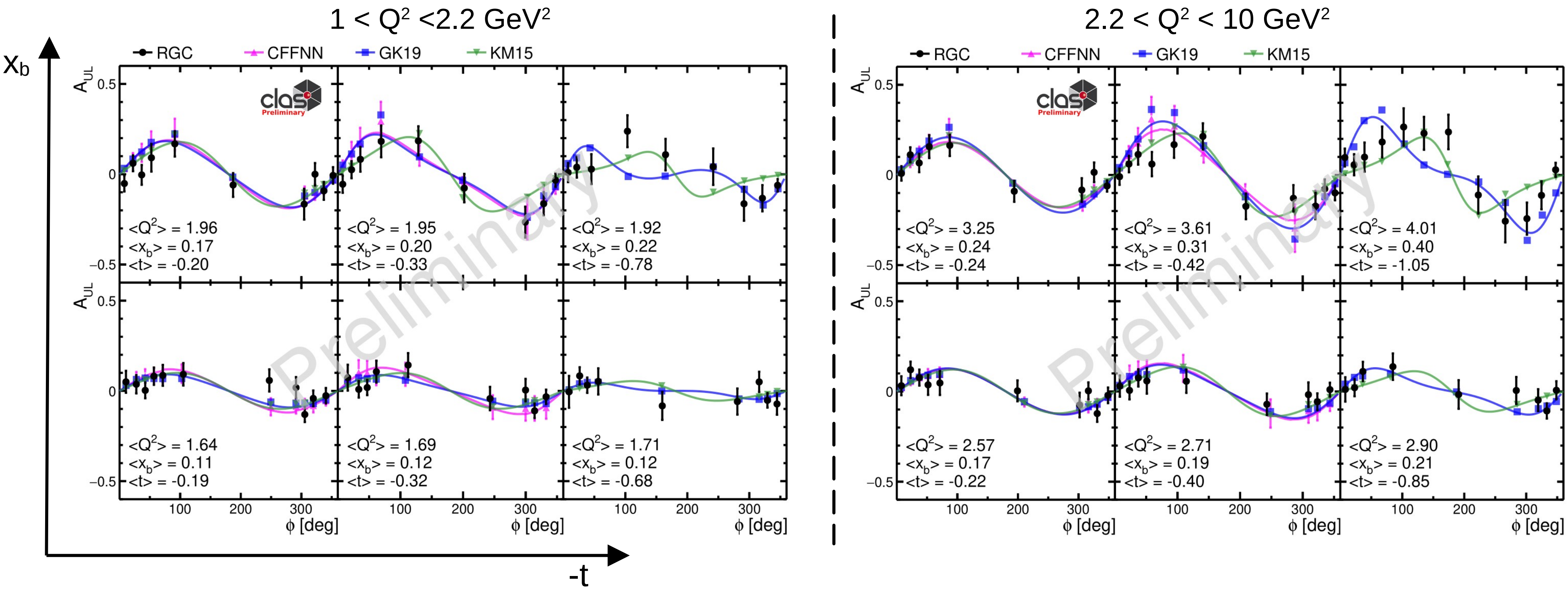
- Three models/fits are compared:
  - KM15 implemented in Gepard
  - GK19 implemented in Partons
  - CFFNN, 2019 CFF fit with a neural network parametrisation implemented in Partons. The comparison is restricted to bins with $-t/Q^2 < 0.2$, where the fit is constrained

- The model points are computed at the average kinematics of each ϕ bin, and over 100 ϕ points at the average kinematics of the Q^2, x_b, t bin to have a continuous line.

Thanks to K. Kumerički and P. Sznajder for their help !

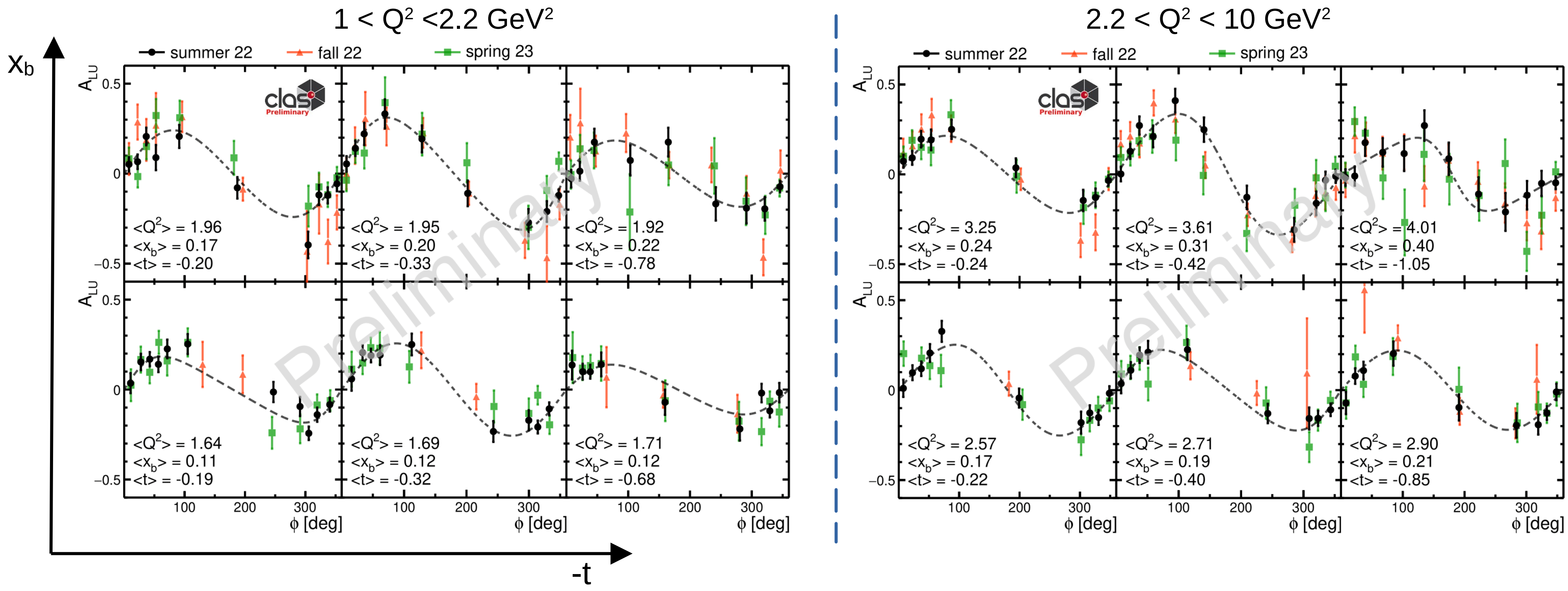
Comparison with models, TSA

- The model points are computed at the average kinematics of each specific phi bin, and the model line is computed at the kinematics of the Q^2, x_b, t bin

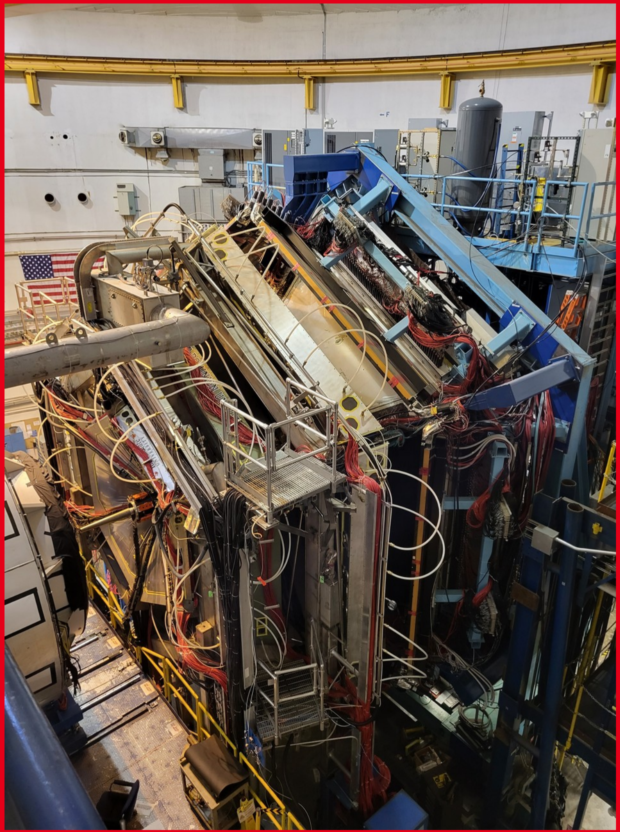


First look at the Fall 22 and Spring 23 BSA

- The QADB timelines are not available for Fall 22 and Spring 23 and no careful run selection has been done yet
- Fall 22 in the FTOFF configuration → different kinematic reach



Summary & outlook



- The analysis of DVCS spin asymmetries on the polarised proton with RGC data is well advanced
- Tools are in place to take into account nuclear and π^0 backgrounds
- Preliminary results are consistent with previous measurements by the CLAS collaboration
- The main remaining steps are:
  - Improvement of the momentum correction
  - Careful systematic uncertainty evaluation
  - Study how the different run period could be merged

Analysis overview

To measure the BSA, TSA, and DSA we need the following elements:

- **Corrected DVCS yields N^{bt}** in each **b**eam and **t**arget spin configurations
  - Selection of DVCS candidates
  - Subtract π^0 contamination
- **Dilution factor D_f**,
  - Accounts for the nuclear background in the NH3 target
- **Target polarisation P_t**
  - Measured from elastic scattering
- **Beam polarisation P_b**
  - Measured with a Moeller polarimeter in the experimental hall, $P_b = 82.5 \pm 0.2\%$

$$A_{LU} = \frac{1}{P_b} \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

$$A_{UL} = \frac{1}{D_f} \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

$$A_{LL} = \frac{1}{D_f P_b} \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

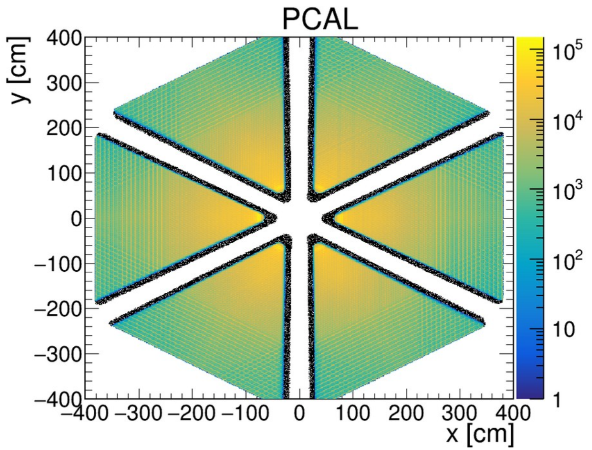
Fiducial cuts

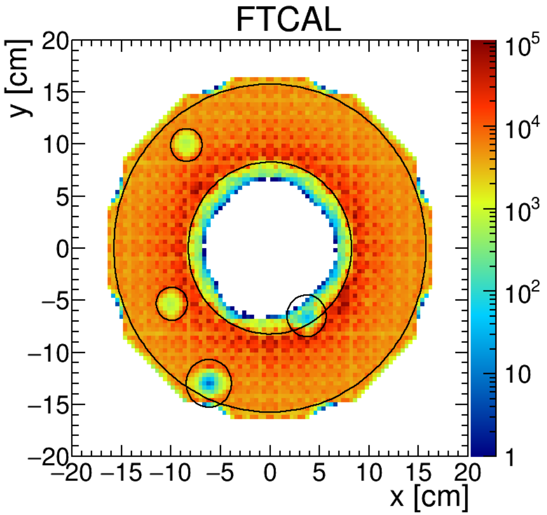
- DC fiducial cuts on the edge variable

Torus polarity	Region 1 [cm]	Region 2 [cm]	Region 3 [cm]
Inbending	4	3	7
Outbending	3	3	10

- PCAL, medium fiducial cuts, lu > 29 , lv,lv > 14cm
- FTCAL, cut using the the x,y coordinate of the track at the surface of FTCAL, $8.25 < \sqrt{x^2+y^2} < 15.75$ cm

Centre x [cm]	Centre y [cm]	Radius [cm]
-8.42	9.89	1.6
-9.89	-5.33	1.6
-6.15	-13	2.3
3.7	-6.5	2



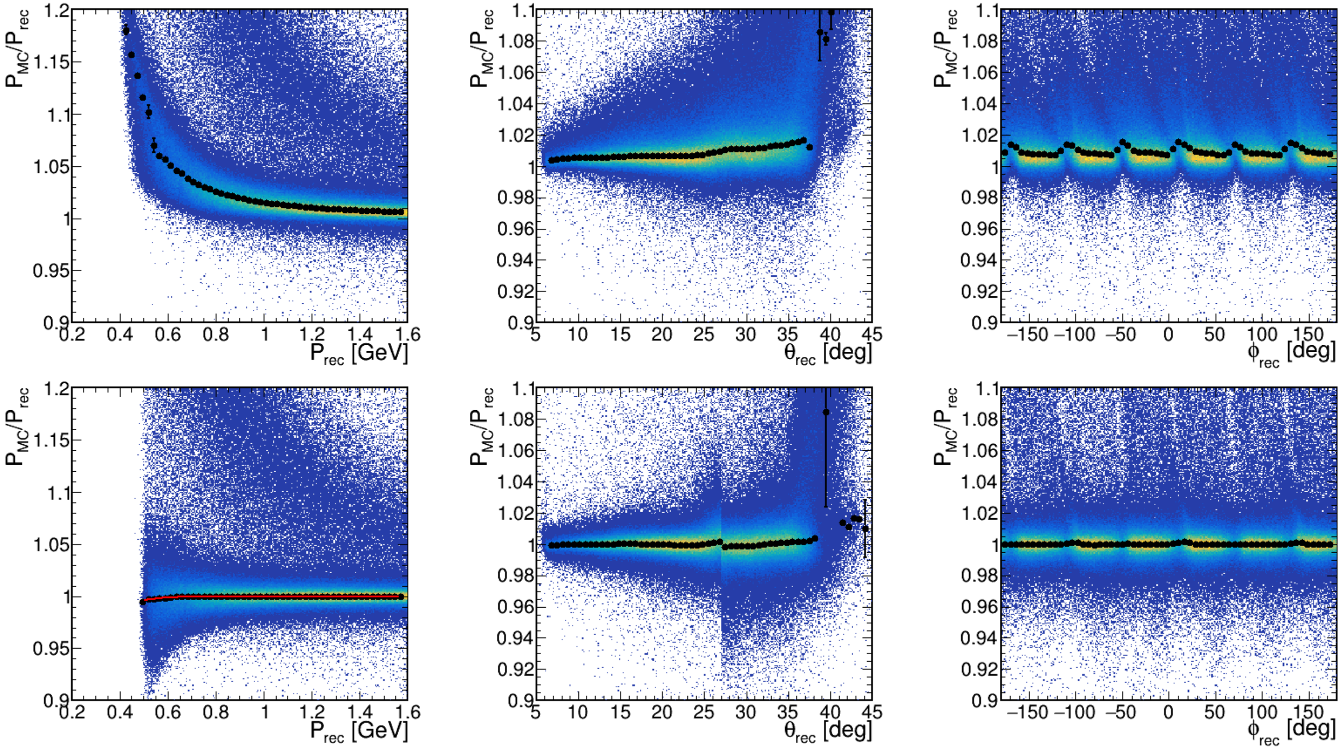


Energy loss corrections

- Monte-Carlo based momentum corrections on the electron and proton
- Small correction for the electron and proton in the CD (<1%)

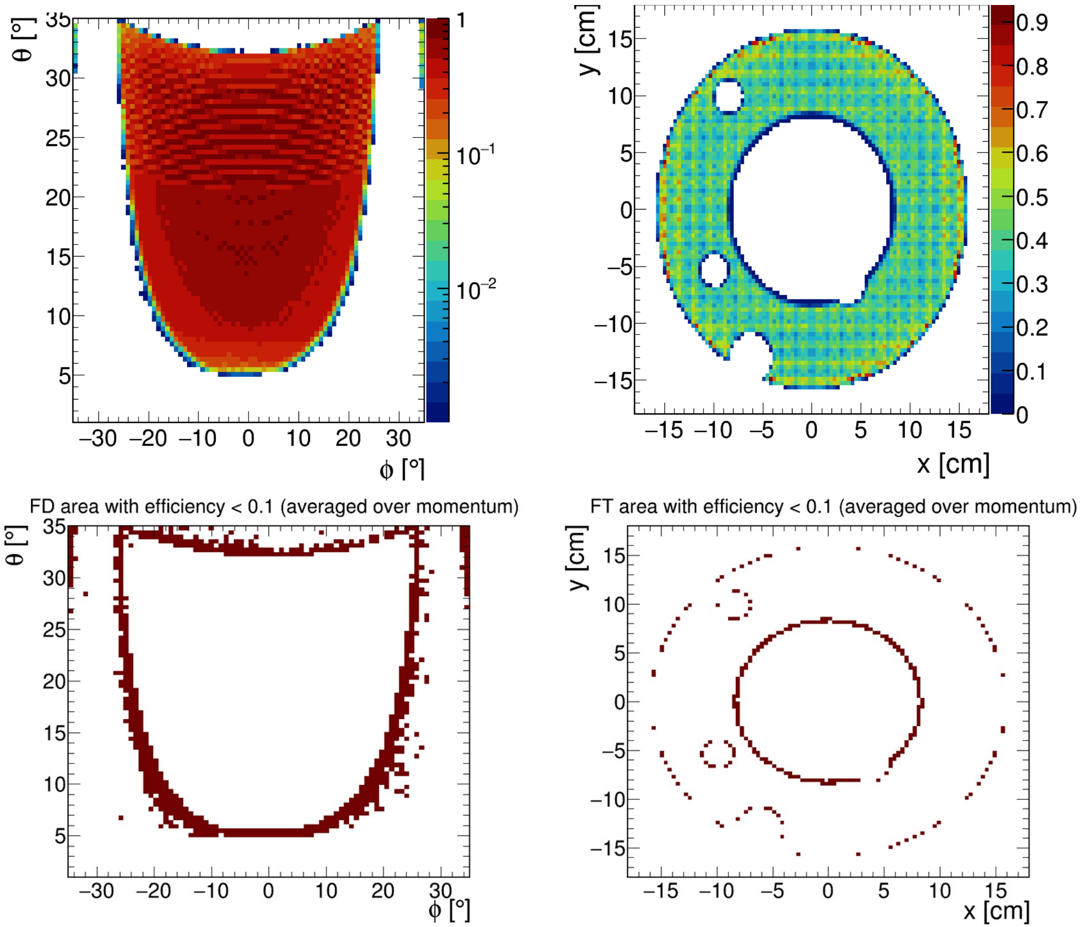
$$f(p) = a + b/p + c/p^2 + d/p^3$$

- Proton in FD, correction split in two θ region at 27° to account for the difference in material crossed



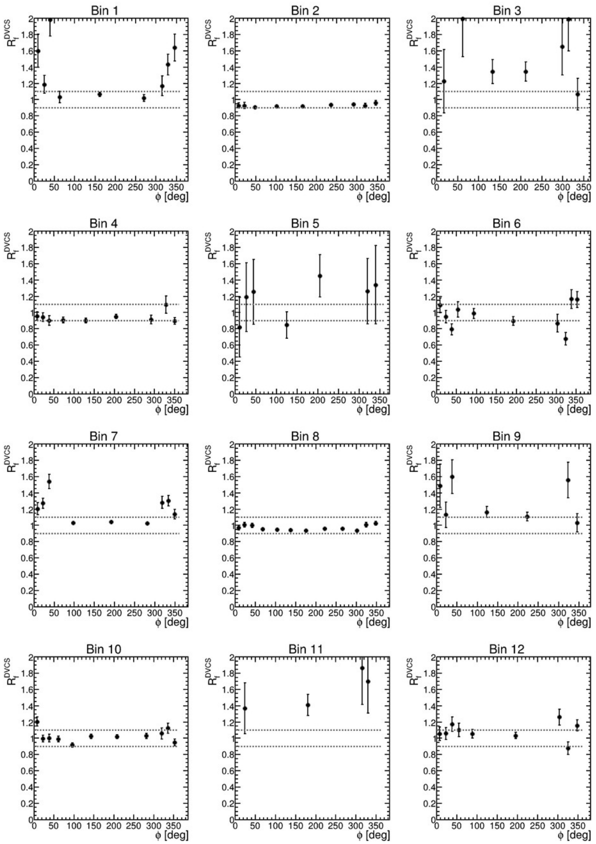
π^0 acceptance maps

- The DVCS analysis needs to be restricted to areas of the detector where π^0 can be measured so that the contamination can be estimated
- Flat generation of events of π^0 decays between 0 and 10 GeV over FD sector 1 and FT
- Count the number of well reconstructed π^0 and generated π^0 in bins of the leading photon position and momentum
- If a DVCS photon is in a bin where the leading photon of a π^0 decay has a less than 10% chance being detected, the event is cut
- Survival rate of DVCS events: 97%

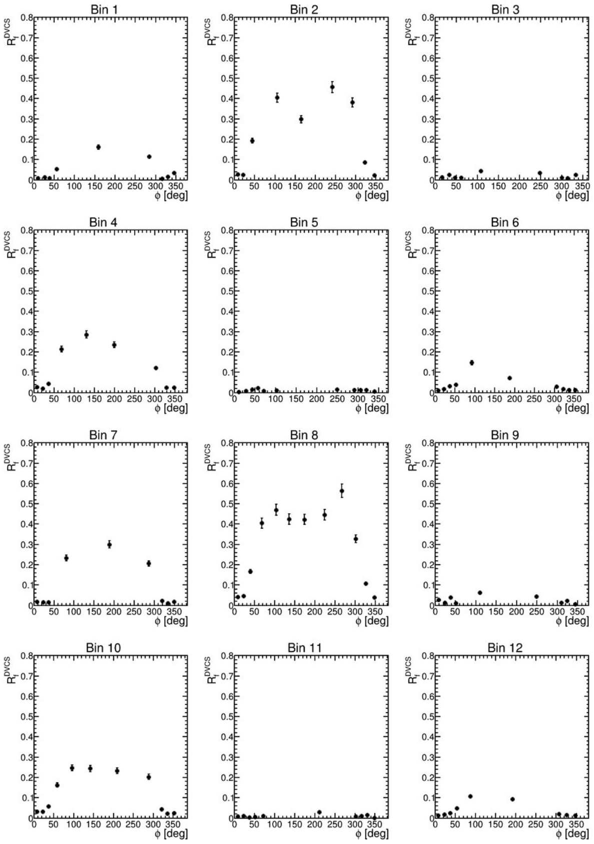


Contamination fraction in data

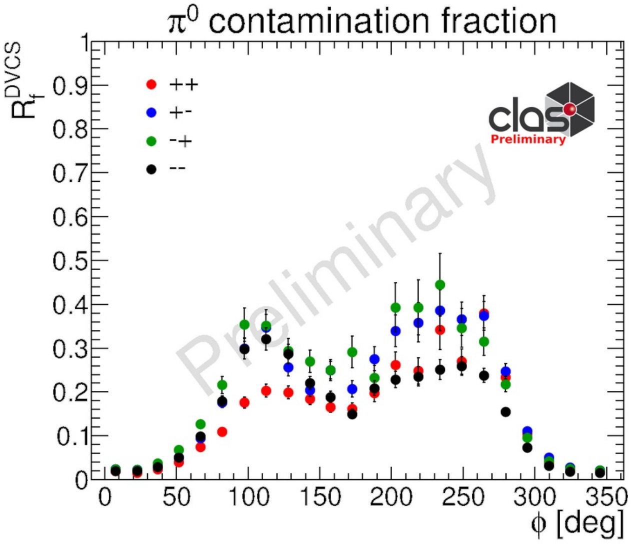
Validation



Data



Contamination fraction in data, integrated over Q^2, x_b, t



Asymmetries and uncertainties

- Two sources of uncertainty are included:
  - Statistical uncertainty on the DVCS yield
  - Statistical uncertainty in the π^0 yield used in the π^0 subtraction
- No systematic uncertainty on the dilution factor, on the target/beam polarisation or on the π^0 “acceptance ratio” is included

$$A_{LU} = \frac{1}{P_b} \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

$$A_{UL} = \frac{1}{D_f} \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

$$A_{LL} = \frac{1}{D_f P_b} \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--})}$$

$$N = \frac{1}{FC}\left(Y^{\mathrm{D}} - \frac{S^{\mathrm{fD}}}{S^{\pi^0}} Y^{\pi^0}\right)$$

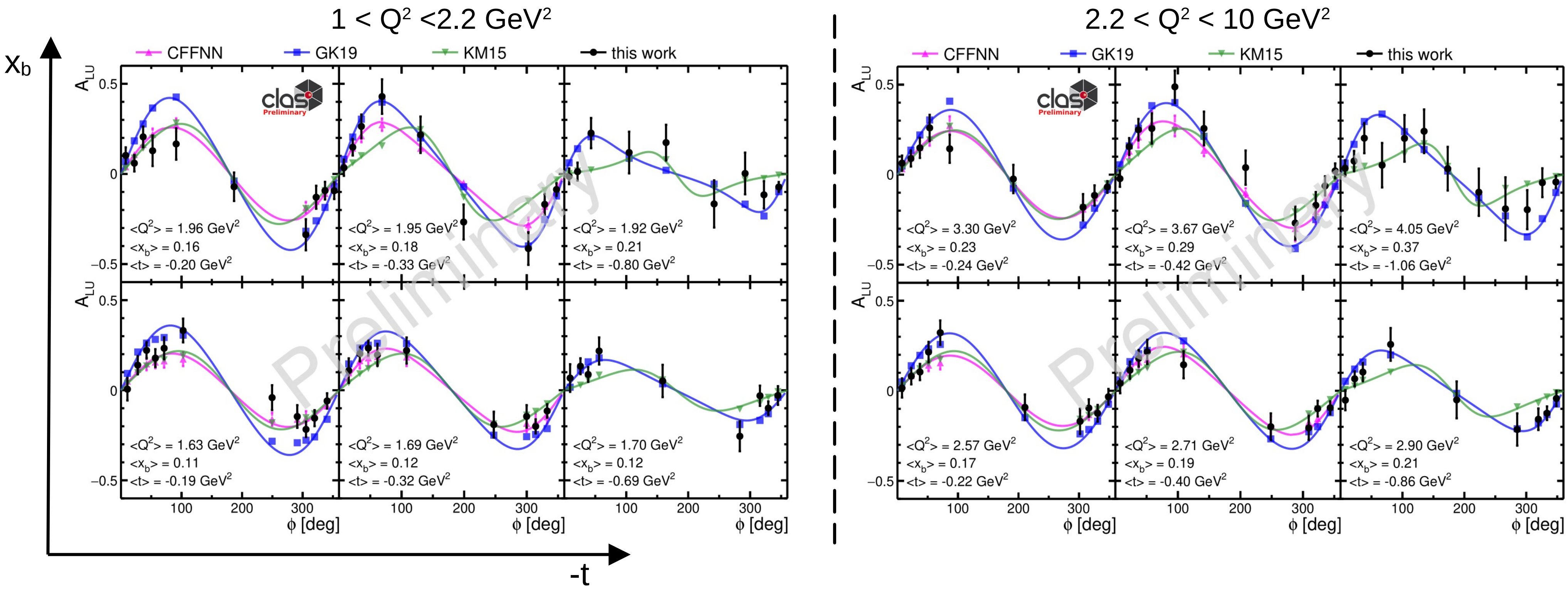
$$\sigma_N = \frac{1}{FC}\sqrt{\left(\frac{\partial N}{\partial Y^{\mathrm{D}}}\right)^2 \sigma^2_{Y^{\mathrm{D}}} + \left(\frac{\partial N}{\partial Y^{\pi^0}}\right)^2 \sigma^2_{Y^{\pi^0}}}$$

$$\sigma_N = \frac{1}{FC}\sqrt{\sigma^2_{Y^{\mathrm{D}}} + \left(\frac{S^{\mathrm{fD}}}{S^{\pi^0}}\right)^2 \sigma^2_{Y^{\pi^0}}}$$

$$\sigma A = \sqrt{\left(\frac{\partial A}{\partial N^{++}}\right)^2 \sigma^2_{N^{++}} + \left(\frac{\partial A}{\partial N^{+-}}\right)^2 \sigma^2_{N^{+-}} + \left(\frac{\partial A}{\partial N^{-+}}\right)^2 \sigma^2_{N^{-+}} + \left(\frac{\partial A}{\partial N^{--}}\right)^2 \sigma^2_{N^{--}}}$$

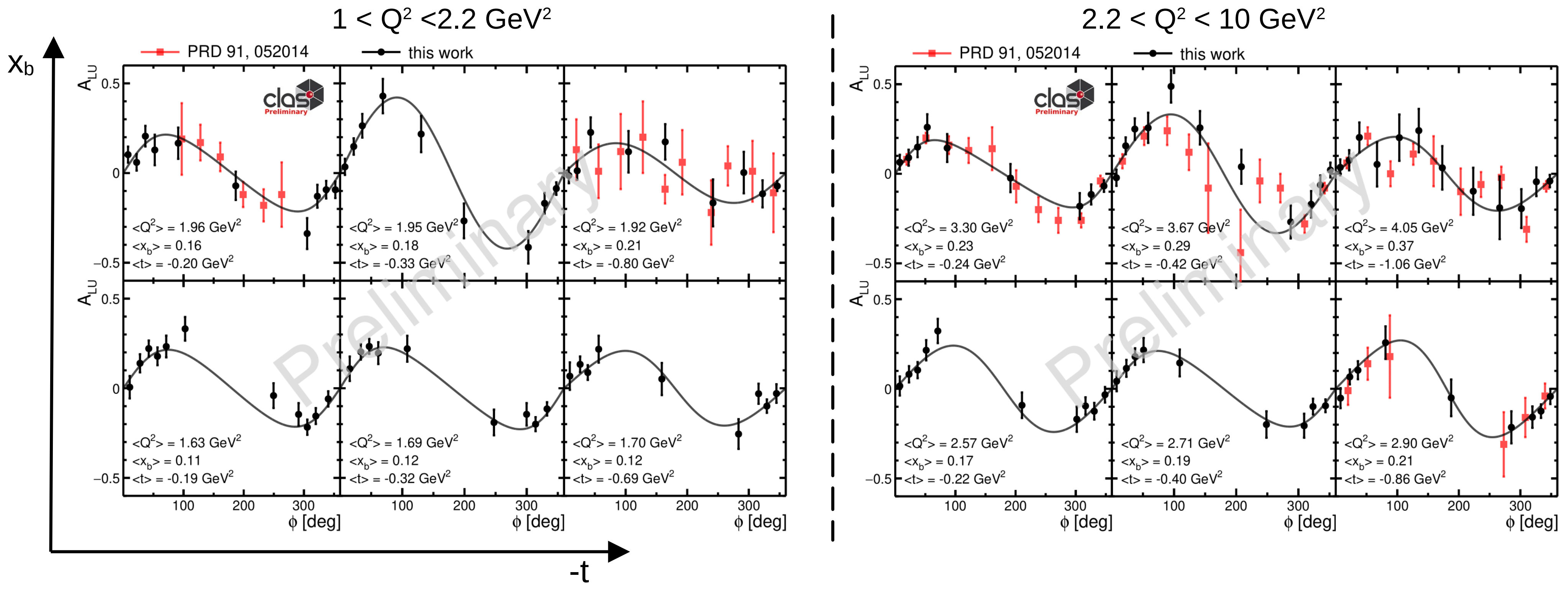
Comparison to models, BSA

- The model points are computed at the average kinematics of each specific phi bin, and the model line is computed at the kinematics of the Q^2, x_b, t bin



Comparison to CLAS6 BSA

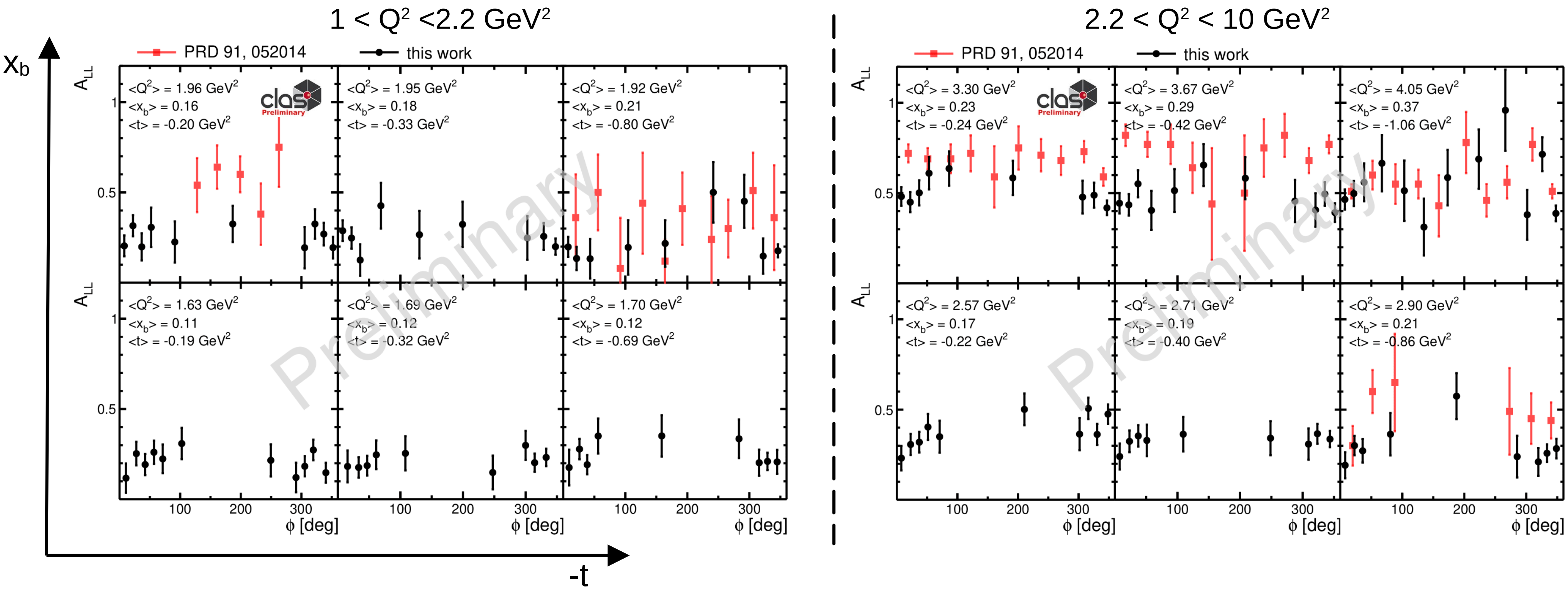
- CLAS6 BSA measurement [Phys. Rev. D 91, 052014] at JLab 6GeV → Different beam energy and kinematic reach
- ⚠ The published results include systematic uncertainties and this work only includes statistical uncertainties



Comparison to CLAS6 DSA

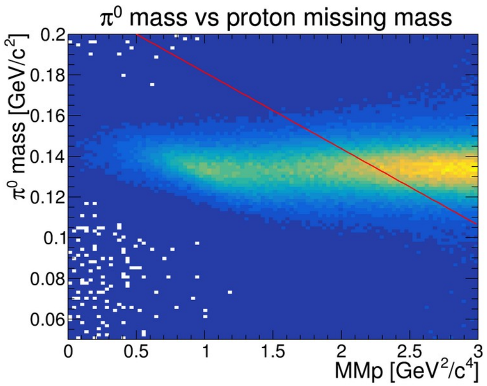
- CLAS6 DSA measurement [Phys. Rev. D 91, 052014] at JLab 6GeV → Different beam energy and kinematic reach

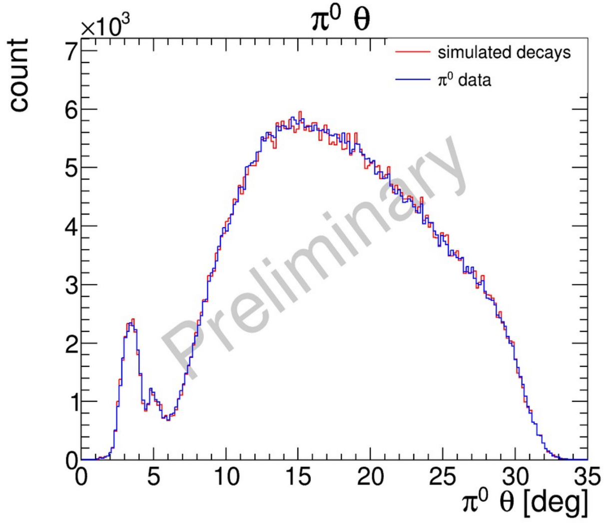
⚠ The published results include systematic uncertainties and this work only includes statistical uncertainties

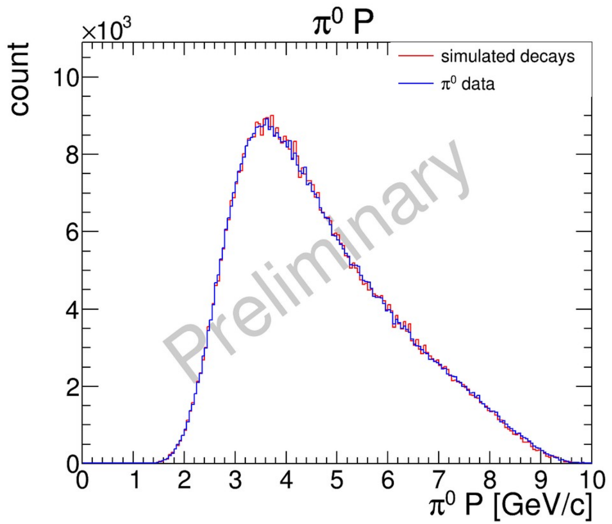


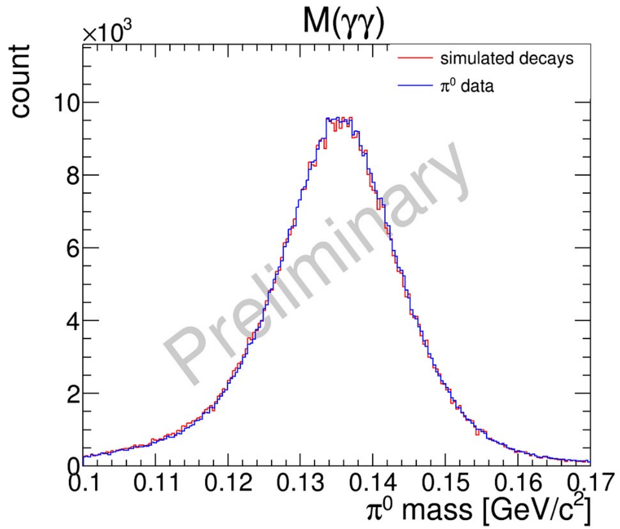
π^0 selection & decays

- Sample is selected with broad exclusivity cuts, to also include events from nuclear background and semi-inclusive channels
- Each π^0 is then decayed 1000x, decays are passed through the CLAS12 simulation software and weighted
- The π^0 selection is applied to the decays and weighted. The simulated decays and data distributions match.



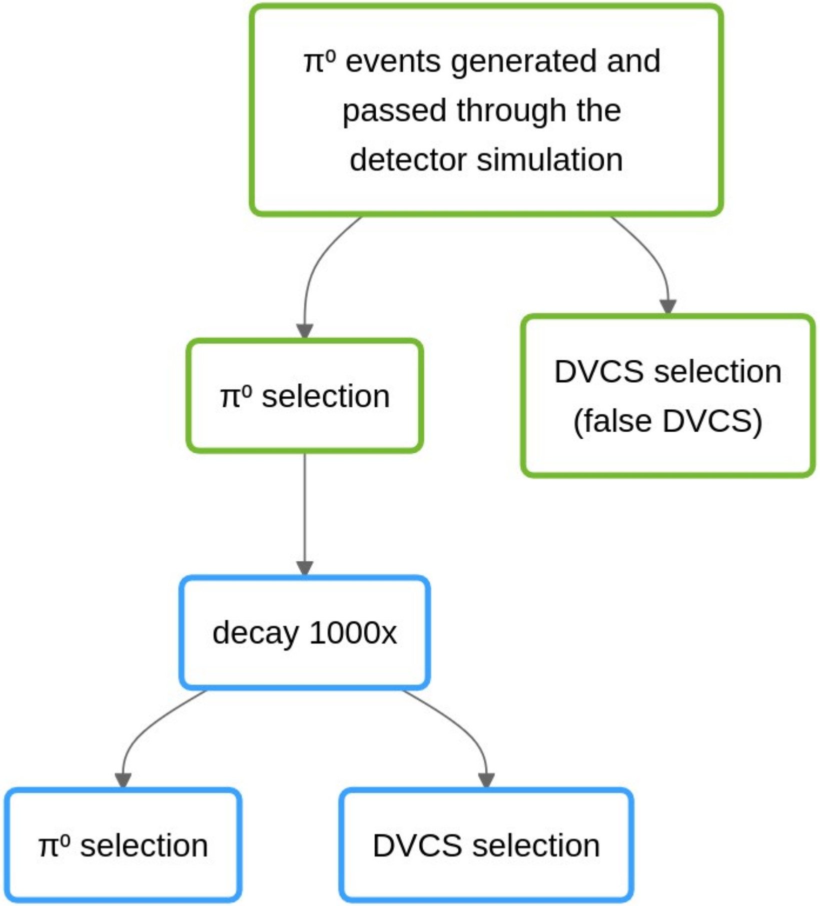






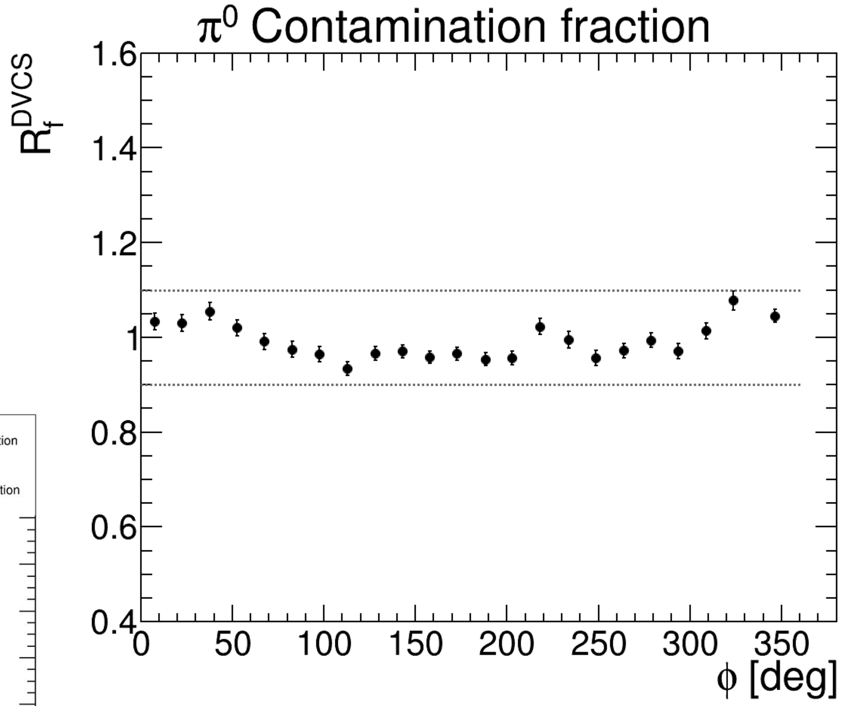
π^0 subtraction validation

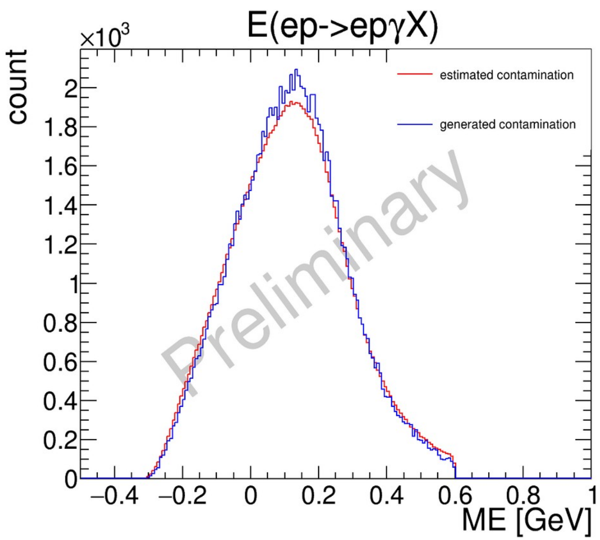
- Apply the method to a π^0 simulation
- All events selected as DVCS are π^0 contamination
  - ➔ Contamination fraction of a 100%
- Check if the subtraction method is able to reproduce the generated false DVCS background

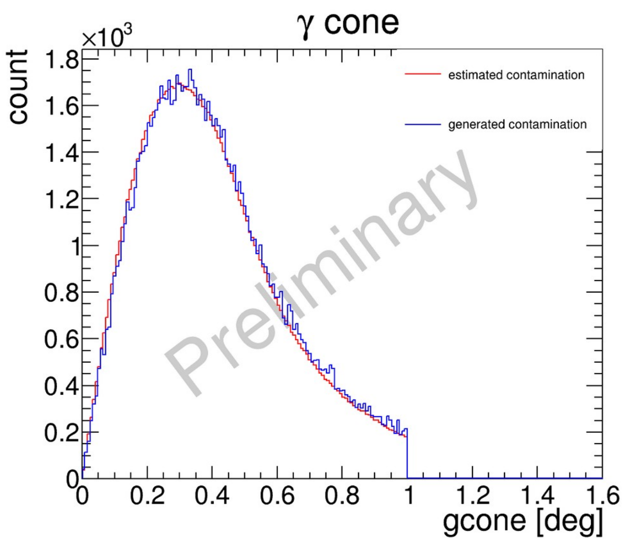


π^0 subtraction validation

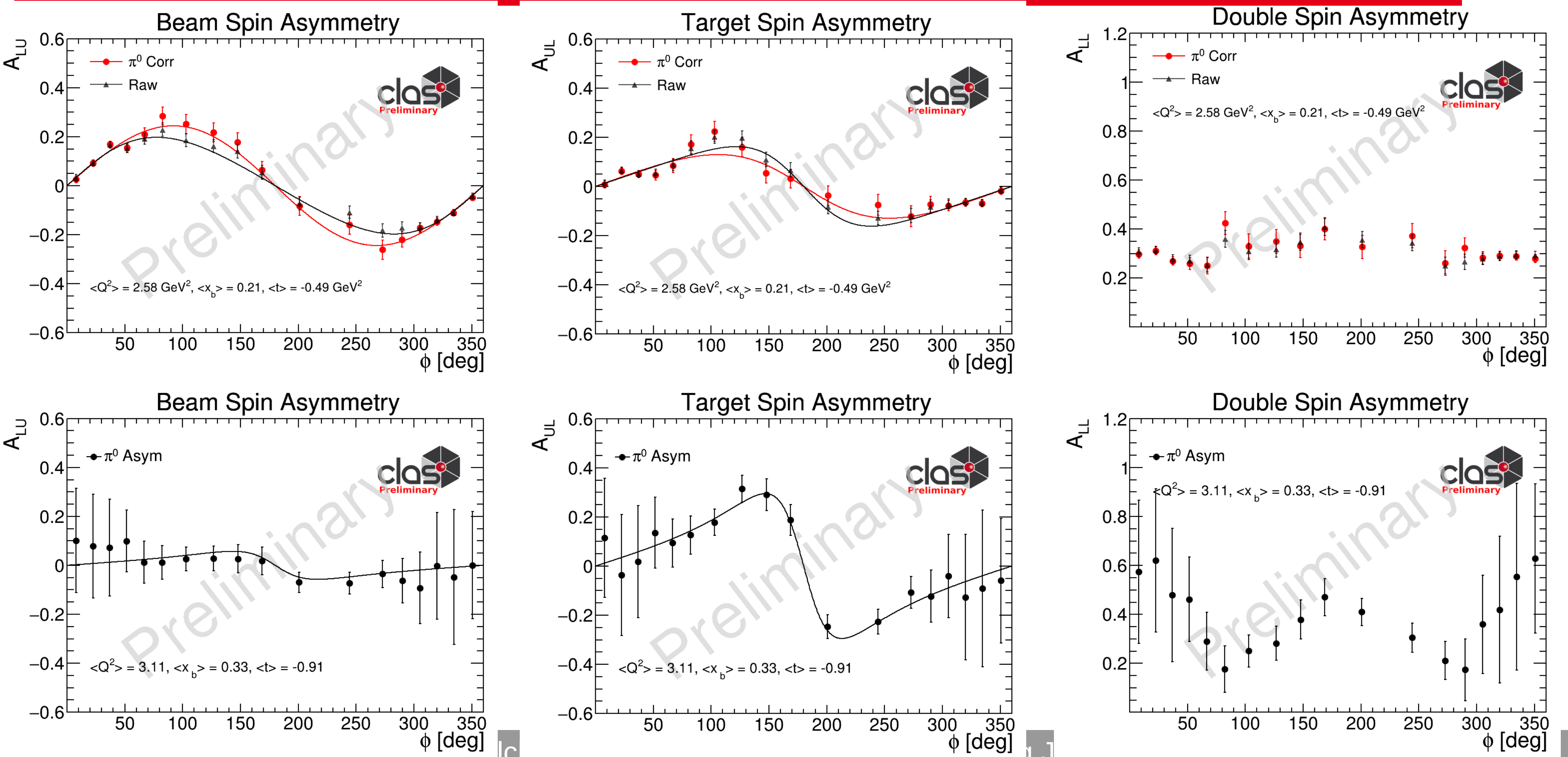
- The generated π^0 contamination is recovered
- The false DVCS distribution estimated with the method matches the generated contamination well







Integrated asymmetries



Comparison with models, DSA

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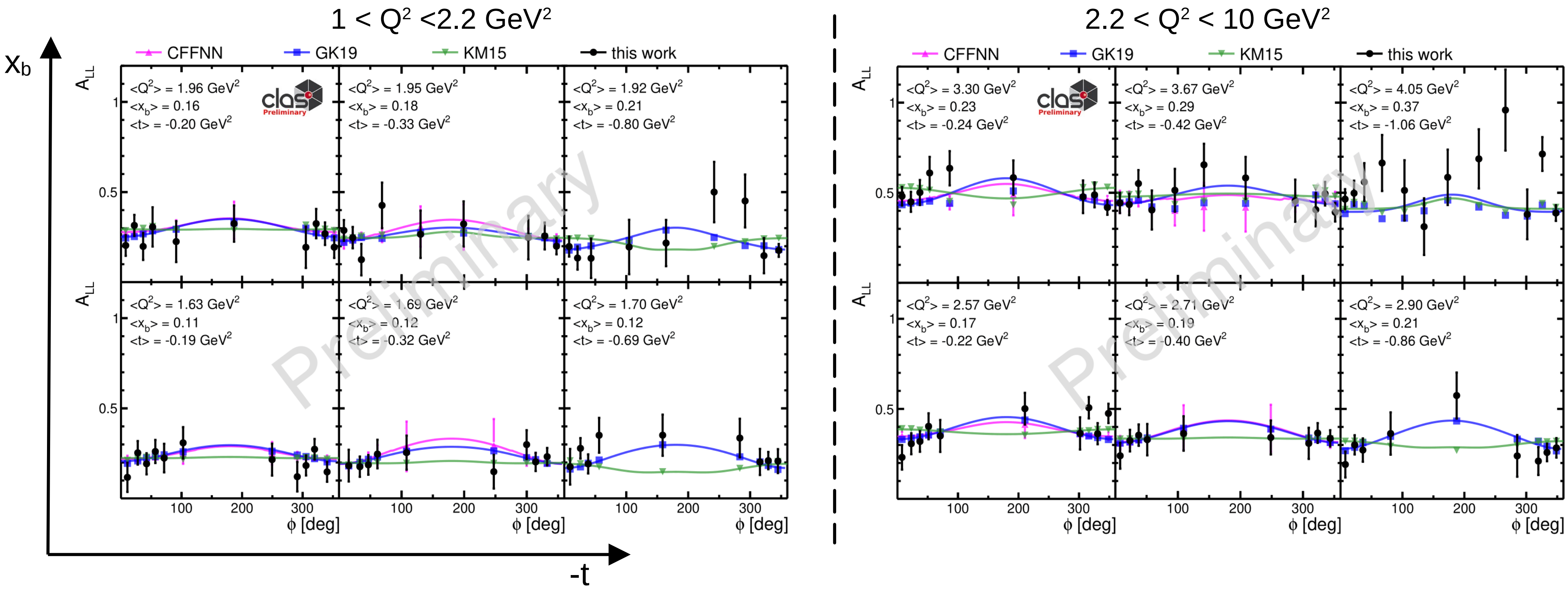
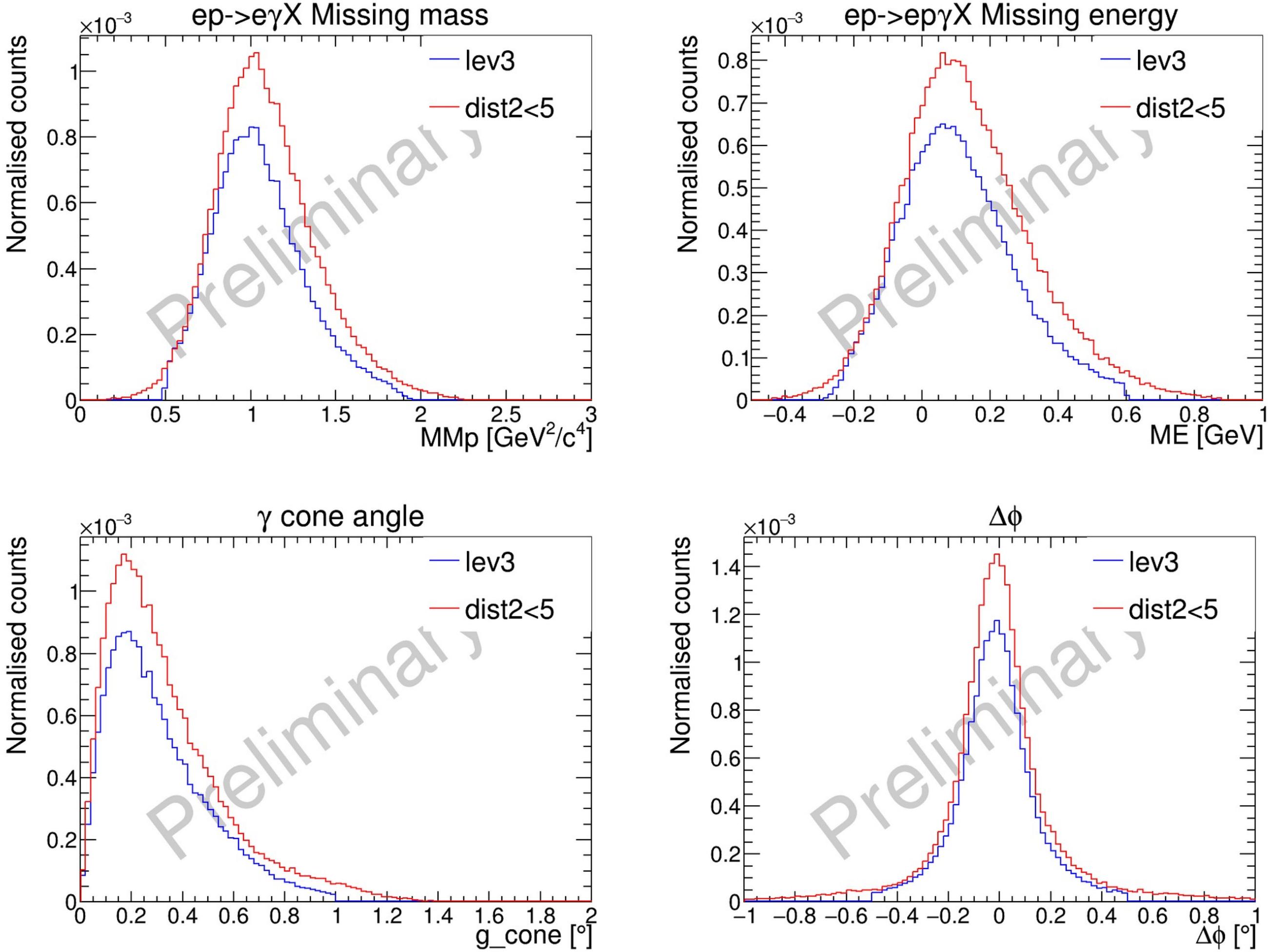
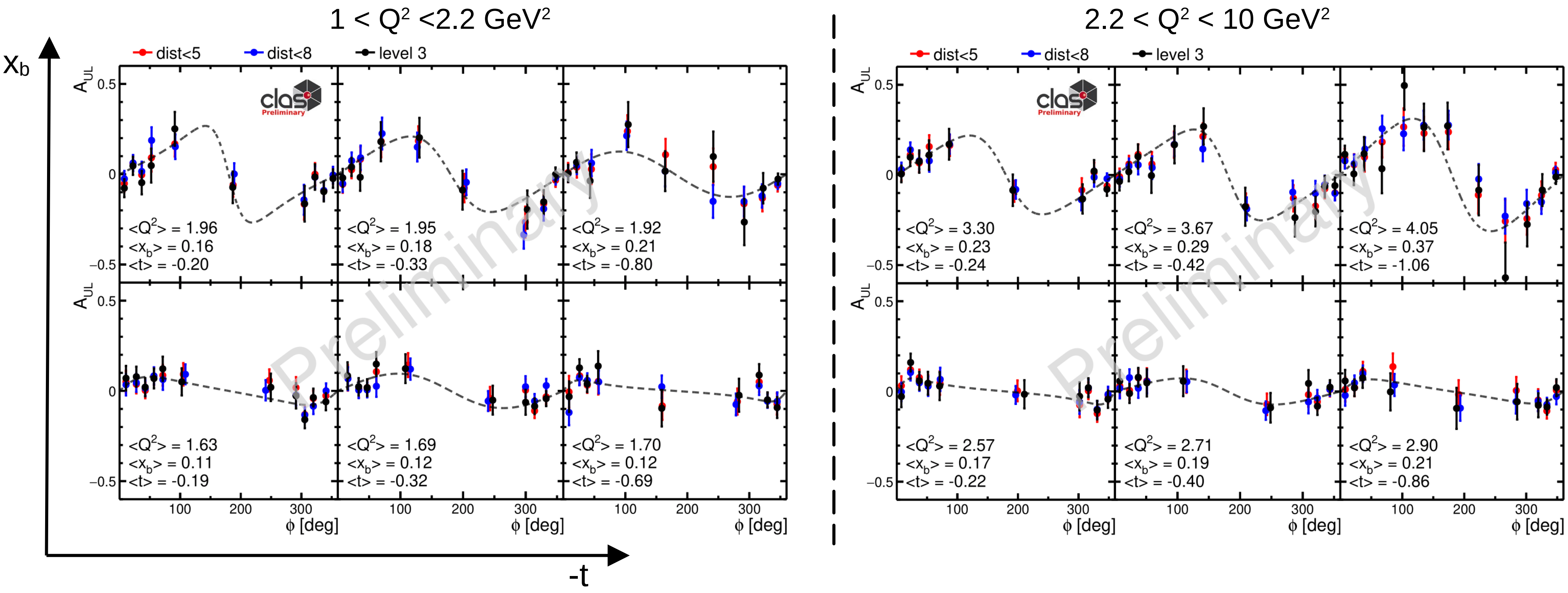


Cut comparison



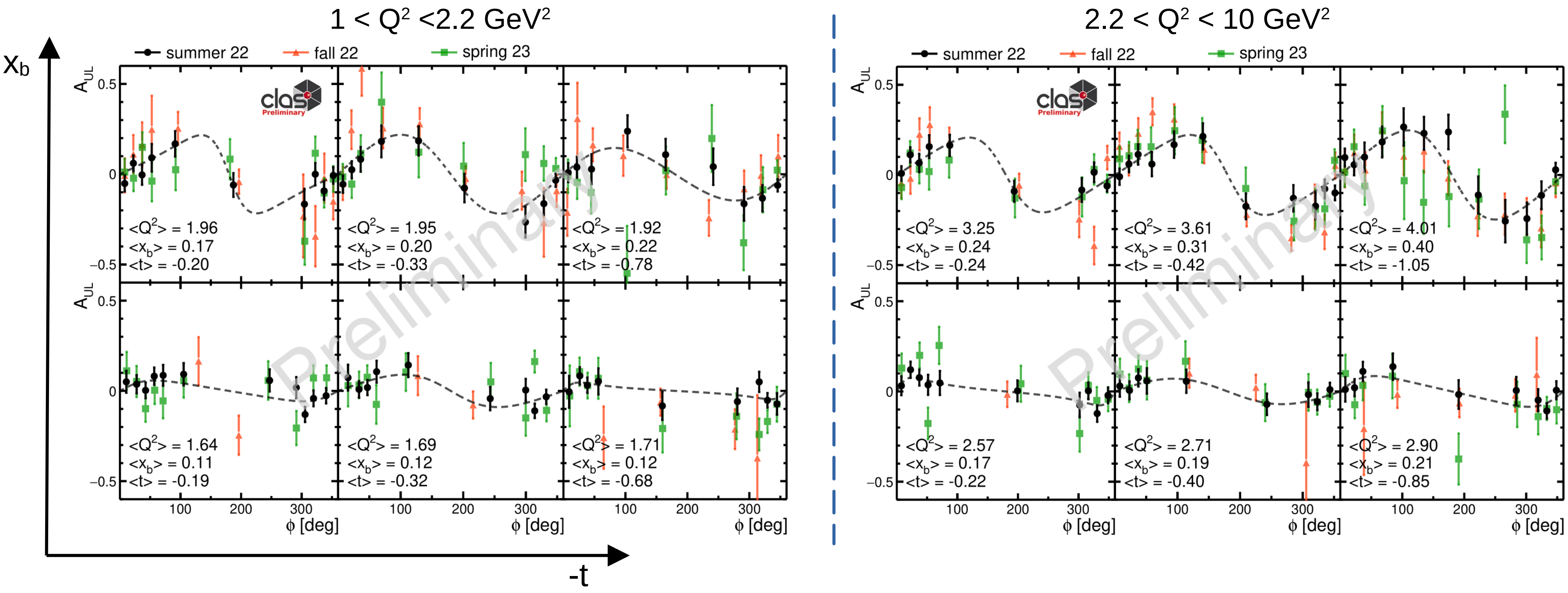
Variable	*level 2* cuts	*level 3* cuts
MMtot $[\mathrm{GeV}^2/\mathrm{c}^4]$	$[-0.1, 0.1]$	$[-0.008, 0.01]$
MMp $[\mathrm{GeV}^2/\mathrm{c}^4]$	$[0, 3]$	$[0.5, 2.2]$
ME $[\mathrm{GeV}]$	$[-1.5, 1.5]$	$[-0.5, 0.6]$
Mpt $[\mathrm{GeV/c}]$	$[0, 1]$	$[0, 0.1]$
MMg $[\mathrm{GeV}^2/\mathrm{c}^4]$	$[-0.8, 0.8]$	$[-0.25, 0.3]$
g_cone [deg]	$[0, 2]$	$[0, 1]$
$\Delta\phi$ [deg]	$[-3, 3]$	$[-0.5, 0.5]$
Δt $[\mathrm{GeV}^2/\mathrm{c}^4]$	$[0, 2]$	$[0, 0.2]$

Cut comparison, TSA



First look at the Fall 22 and Spring 23 TSA

- The QADB timelines are not available for Fall 22 and Spring 23 and no careful run selection has been done yet
- Fall 22 in the FTOFF configuration → different kinematic reach



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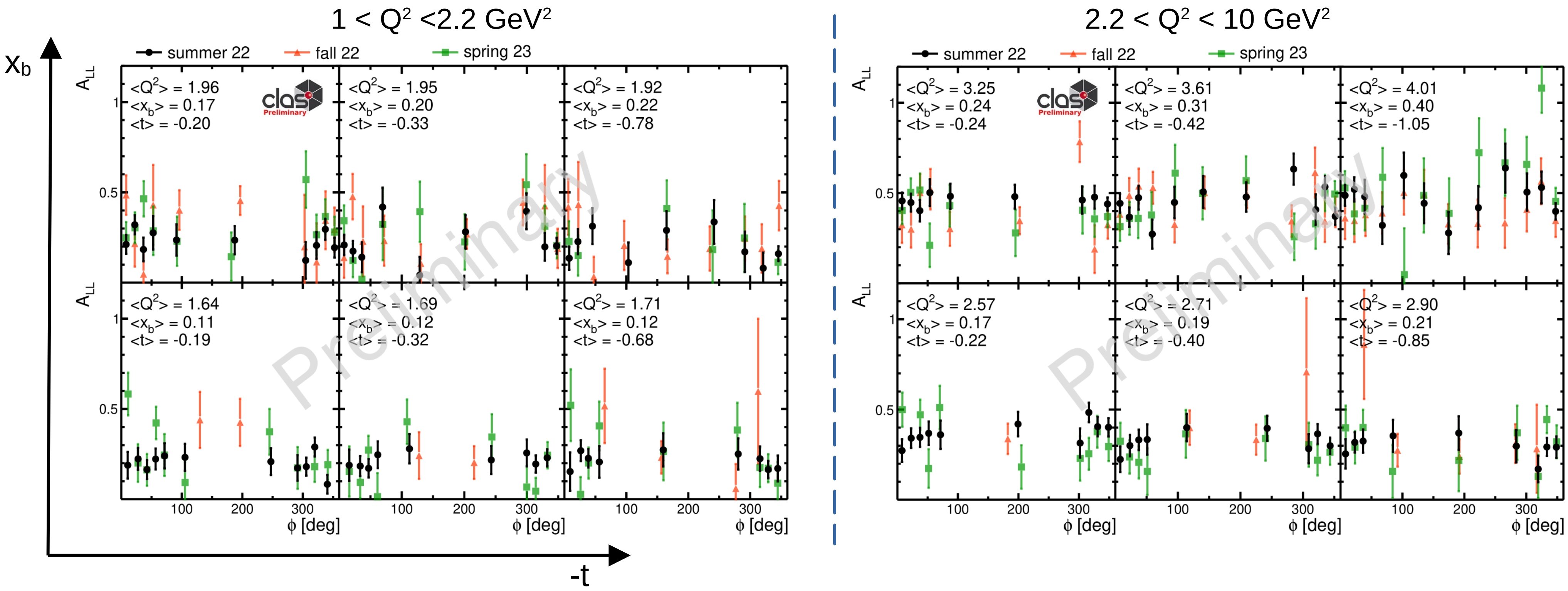

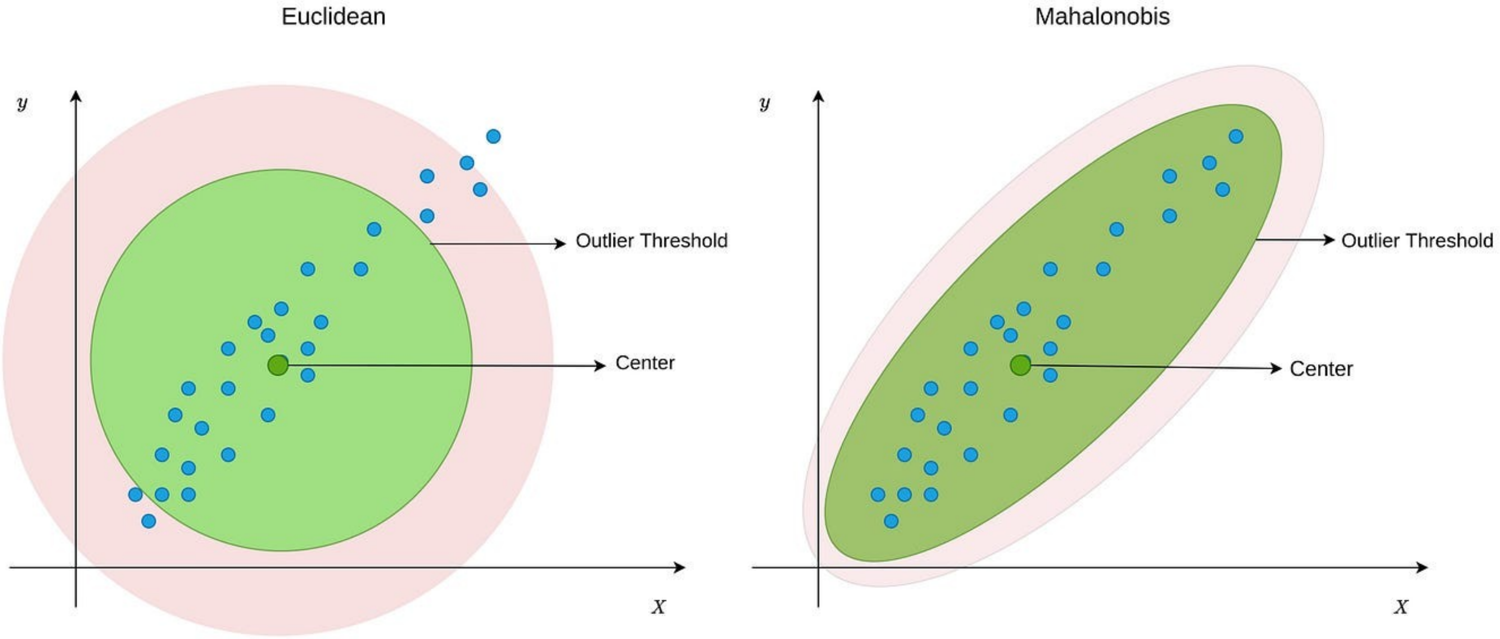
Euclidean
y
Outlier Threshold
Center
X
Mahalonobis
y
Outlier Threshold
Center
X