Deeply Virtual Compton Scattering with CLAS12 and beyond

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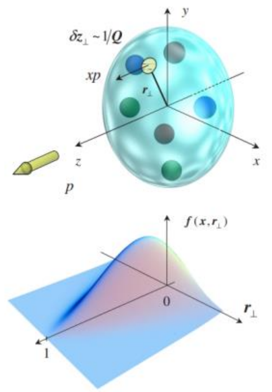
APCTP Focus Program in Nuclear Physics 2022, 18 – 23 July

- QCD at low energies: non perturbative regime
  - Need structure functions to describe nucleon structure

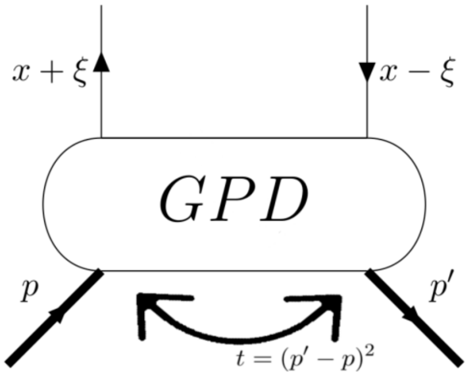
Belitsky, Radyushkin, Physics Reports, 2005

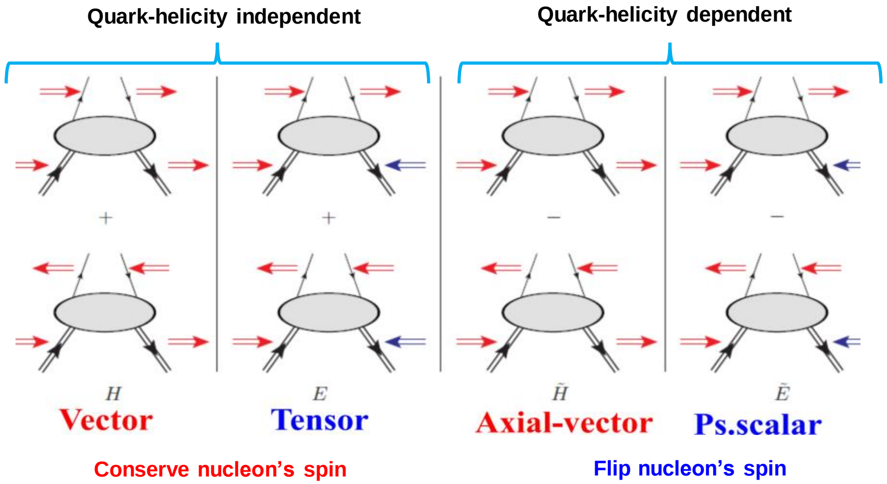


GPDs

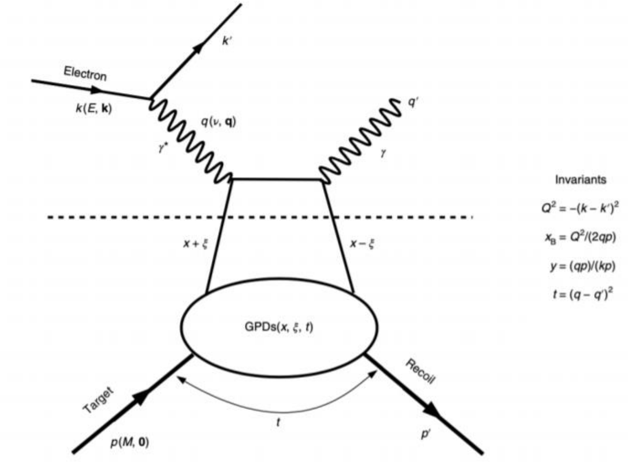
Correlation of transverse position and longitudinal momentum of partons in the nucleon & the spin structure - through Ji's sum rule X. Ji, Phy.Rev.Lett.78,610(1997)

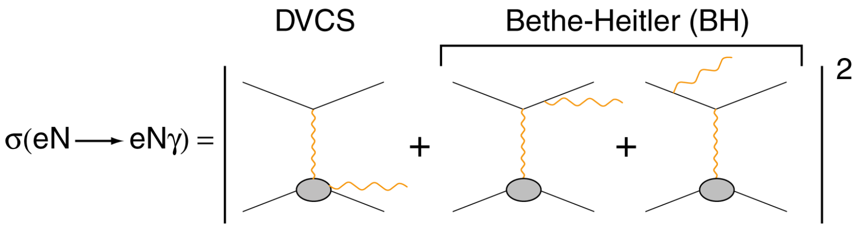
- GPDs can be accessed through exclusive leptoproduction reactions
- At leading order QCD, chiral-even (quark helicity is conserved), quark sector: 4 GPDs for each quark flavor $H, \widetilde{H}, E$ and $\tilde{E}$
- GPDs depend on x, ξ and t = (p' − p) 2





Deeply Virtual Compton Scattering of leptons off nucleons





BH is purely electromagnetic and parametrised by FFs

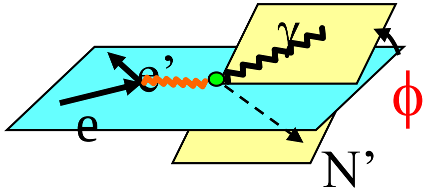
- DVCS allows access to 4 complex GPDs-related quantities:
  - Compton Form Factors (x, ξ,t) (CFFs)

$$\mathcal{H} = \sum_q e_q^2 \left\{ i\,\pi\,[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)] \;+\; \mathcal{P}\int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] \right\}$$

- x can not be accessed experimentally by DVCS: Models needed to map the x dependence

- Experimentally measured observables:
  - Contribution from both the DVCS and BH amplitudes
  - In order to be sensitive to the DVCS-BH interference part (linear in CFFs) we should have:
    - Beam polarized and/or target polarized
  - Each measured asymmetry gives access to combinations of CFFs
  - The separation of CFFs requires the measurement of several observables
  - Depending on the target (proton or neutron): different sensitivity to the CFFs (GPDs)
  - The flavor separation of GPDs requires measurements on both nucleons

$$(H,E)_u(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$
$$(H,E)_d(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$



Polarized beam, unpolarized taget

$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\{F_1\boldsymbol{H} + \xi(F_1 + F_2)\widetilde{\boldsymbol{H}} - k\,F_2\boldsymbol{E} + \ \dots\}$$

Unpolarized beam, polarized target

$$\Delta\sigma_{UL} \sim \sin(\phi)\,\Im\left\{F_1\,\widetilde{\boldsymbol{H}} + \xi(F_1 + F_2)\left(\boldsymbol{H} + \frac{x_b}{2}\boldsymbol{E}\right) - \xi k\,F_2\widetilde{\boldsymbol{E}}\right\}$$

polarized beam, longitudinal polarized target

$$\Delta\sigma_{LL} \sim (A + B\cos(\phi))\,\Re\{F_1\,\widetilde{\boldsymbol{H}} + \xi(F_1 + F_2)\left(\boldsymbol{H} + \frac{x_b}{2}\boldsymbol{E}\right) + \ \dots\}$$

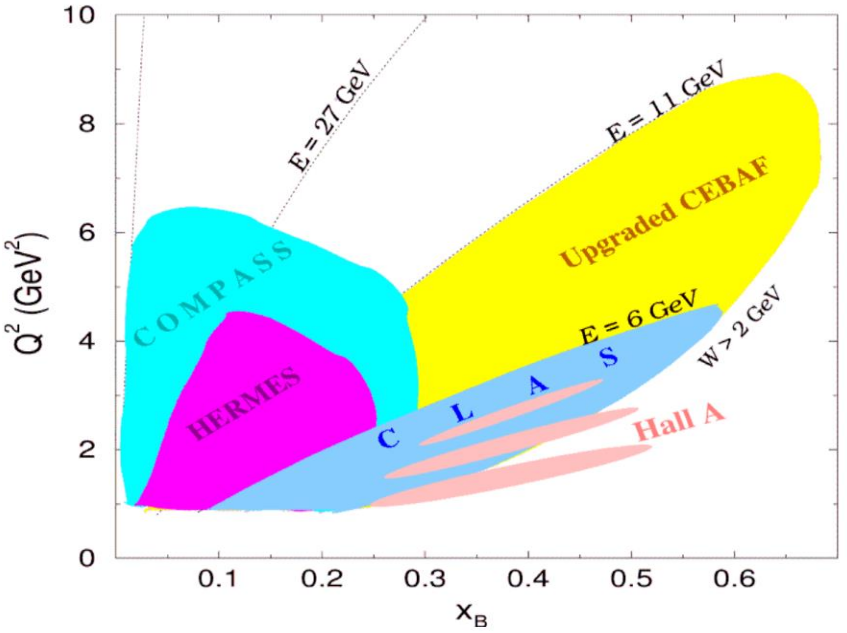
unpolarized beam, transverse polarized target

$$\Delta\sigma_{UT} \sim \cos(\phi)\,\sin(\phi_s - \phi)\,\Im\{k(F_2\,\boldsymbol{H} - F_1\boldsymbol{E}) + \ \dots\}$$

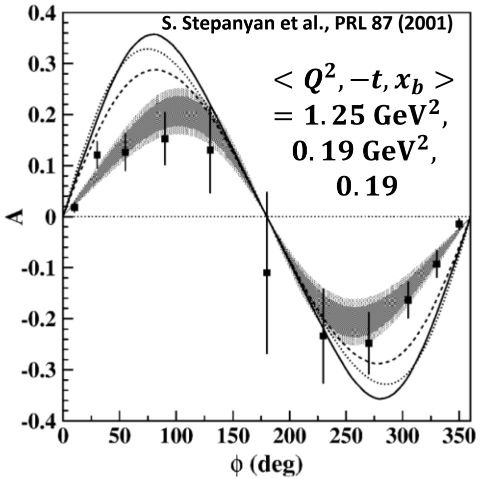
Observable	Proton	Neutron
$\Delta\sigma_{LU}$	$\Im\{\boldsymbol{H_p}, \widetilde{H}_p, E_p\}$	$\Im\{H_n, \widetilde{H}_n, \boldsymbol{E_n}\}$
$\Delta\sigma_{UL}$	$\Im\{\boldsymbol{H_p}, \widetilde{\boldsymbol{H}}_{\boldsymbol{p}}\}$	$\Im\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{LL}$	$\Re\{\boldsymbol{H_p}, \widetilde{\boldsymbol{H}}_{\boldsymbol{p}}\}$	$\Re\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{UT}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$	$\Im\{\boldsymbol{H_n}\}$

GPD-aimed experiments

- JLAB
  - Hall A:
    - Cross sections
    - Beam-polarised cross section differences
  - Hall B (CLAS/CLAS12):
    - Beam and target spin asymmetries
    - Cross section measurements over large phase-space acceptance



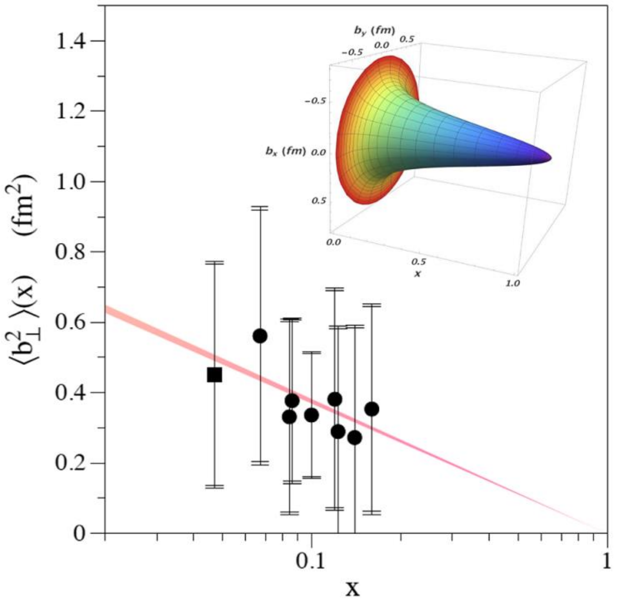
$ep \to epX$, from CLAS data: First observation of DVCS-BH interference

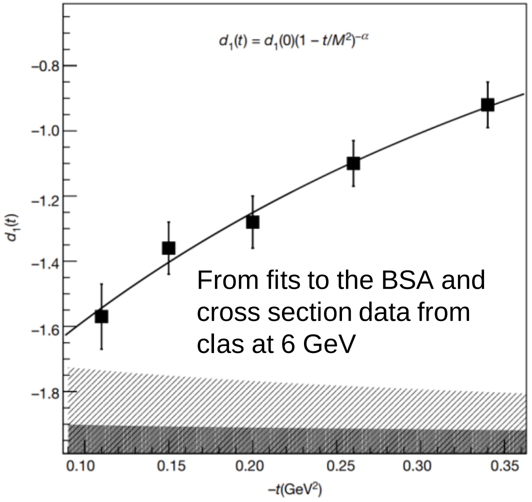


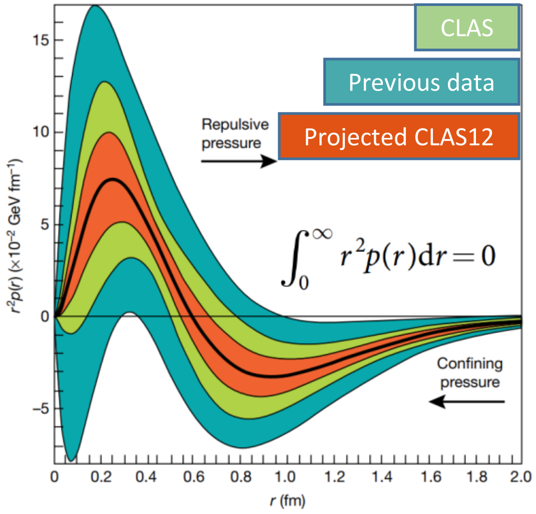
What did we learn from JLAB data at ~6 GeV?

- Tomography of the proton
  - Obtained from local fits to HERMES, CLAS, and Hall-A data ($\Im H$ + model dependent assumptions for x dependence)

- The pressure distribution inside the proton
  - Gravitational form factor
    - $\int xH(x,\xi,t)dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$
    - $d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t}\rho(r)d^3r$







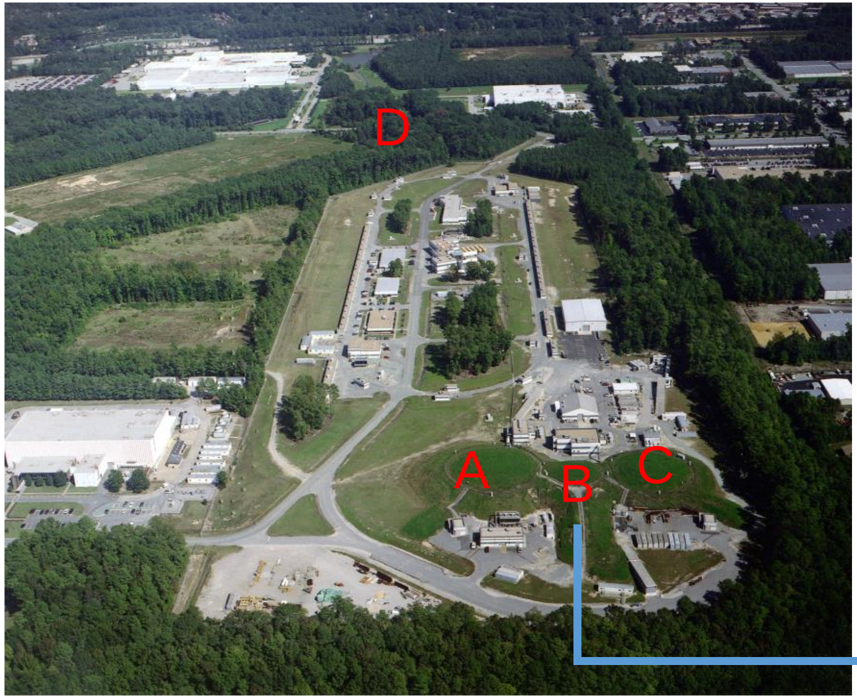
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)

V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

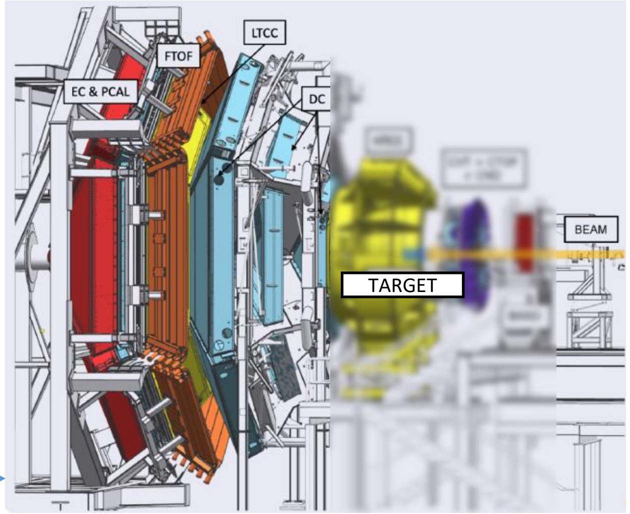
The CEBAF at Jefferson Laboratory

Continuos Electron Beam Accelerator Facility

- Up to 12 GeV electrons



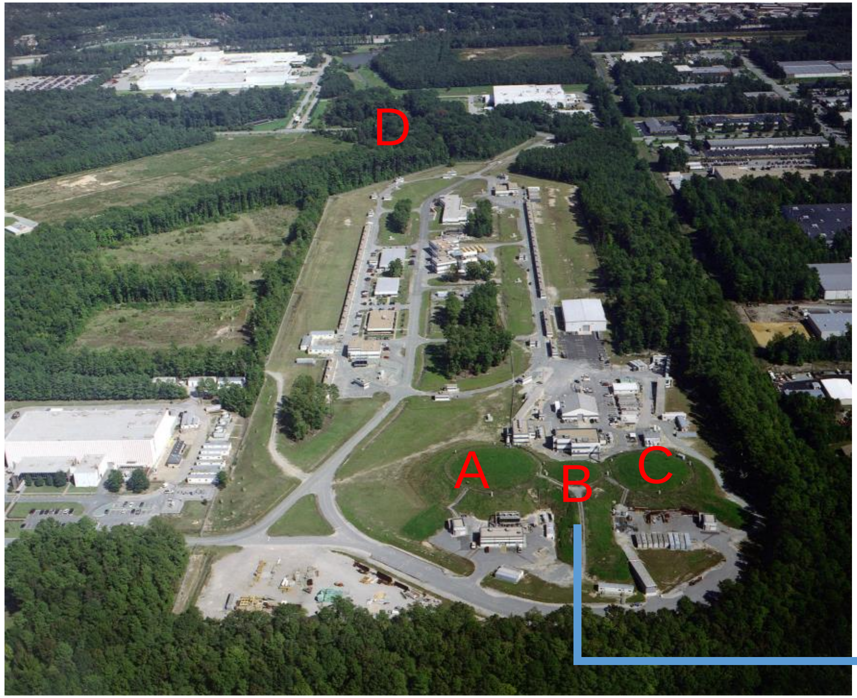
At ~6 GeV



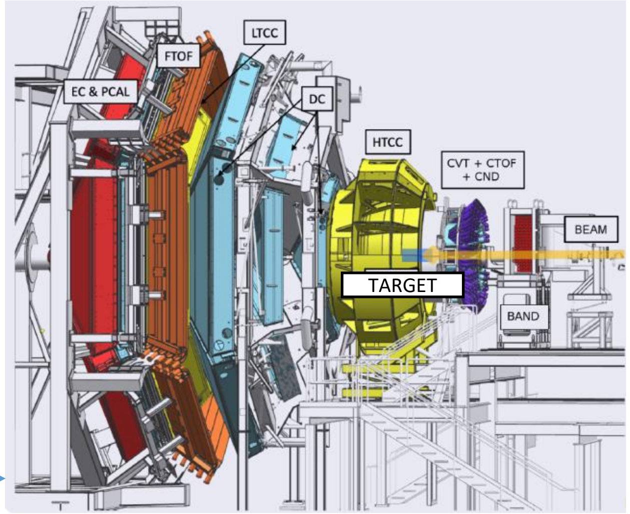
CLAS

Continuos Electron Beam Accelerator Facility
- Up to 12 GeV electrons

The 12 GeV energy upgrade was associated with detector upgrades



At ~11 GeV

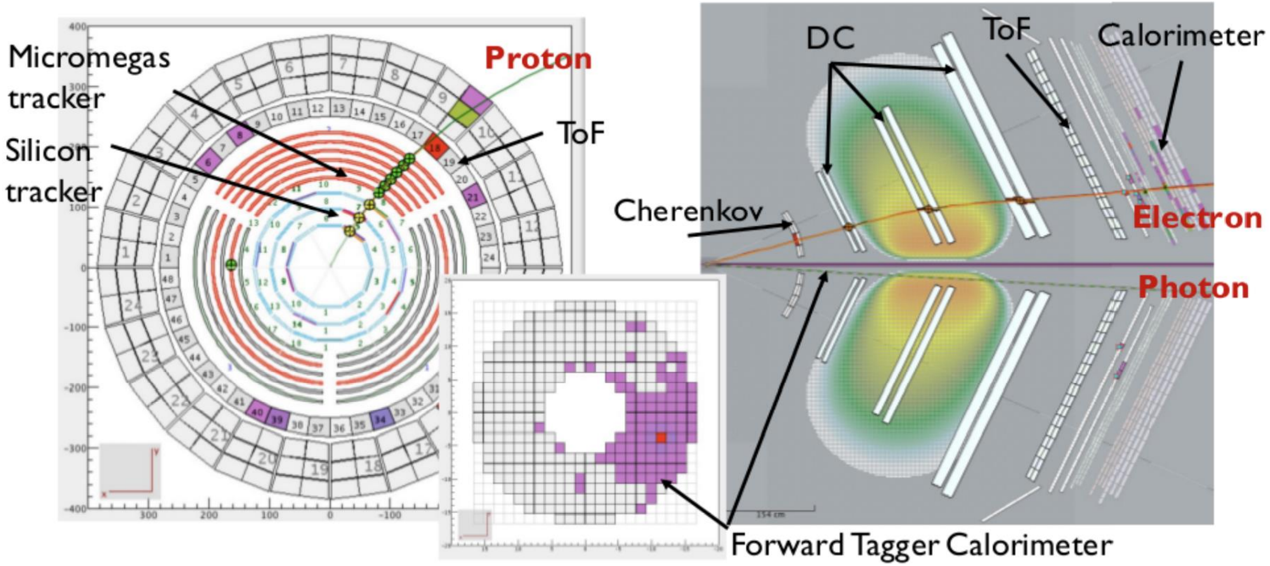


CLAS12

CLAS12: DVCS off proton

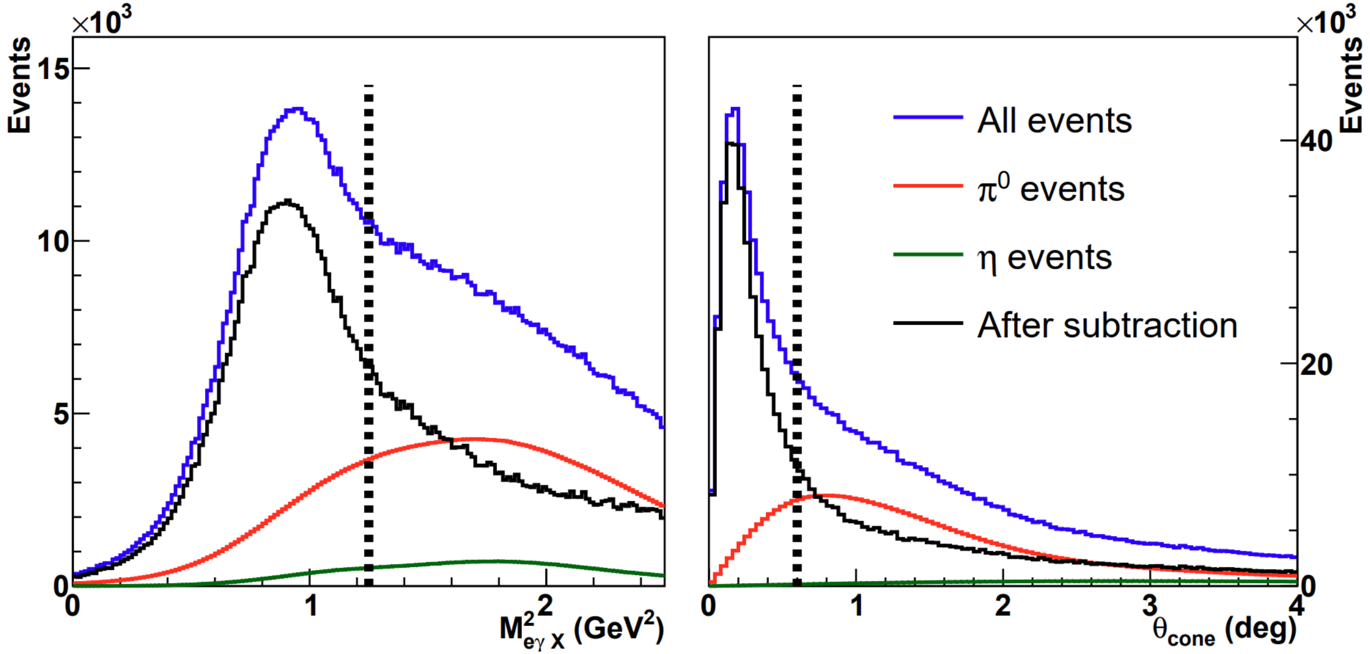
G. Christiaens, M. Defurne, D. Sokhan

- A 10.6 GeV electron beam
  - With an average polarization of 86%
  - Scattering off an unpolarized LH2 target of 5 cm length
- The full exclusivity of the event is insured by:
  - Electron detection: Cerenkov detector, drift chambers and electromagnetic calorimeter
  - Photon detection: sampling calorimeter or a small PbWO4-calorimeter close to the beamline
  - Proton detection: Silicon and Micromegas detector



To be published soon

- Exclusivity is enforced by cutting on 5 variables:
  - The missing mass ep→eγpX
  - The missing mass ep→eγX
  - The missing energy
  - The missing transverse momentum
  - The cone angle (angle between detected photon and expected photon assuming exclusivity)



CLAS12: DVCS off proton

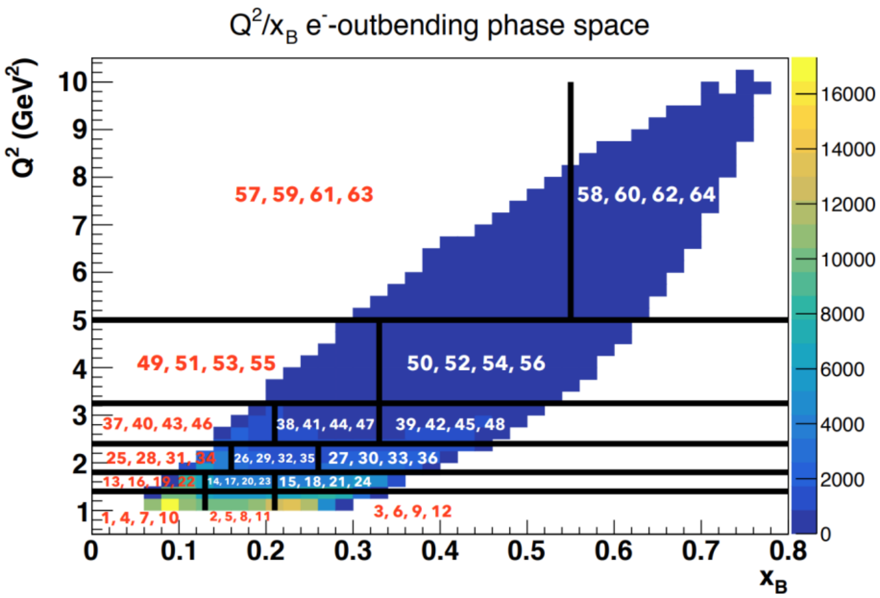
G. Christiaens, M. Defurne, D. Sokhan

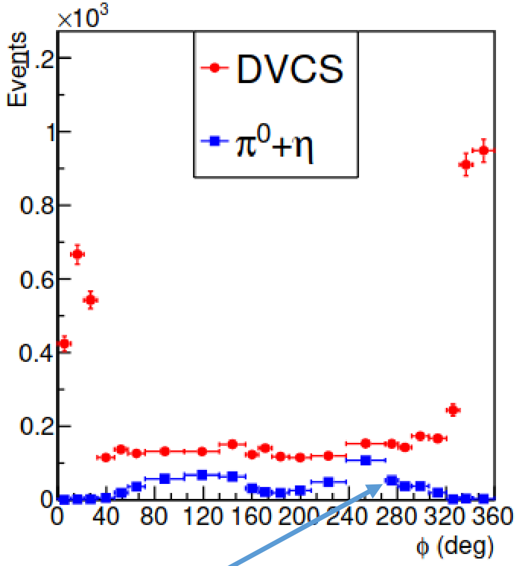
- For each Q^2/x_b, 4 bins in t are defined
  - 64 (Q^2, x_b, t) kinematical bins
- Φ: adaptative binning to accommodate for the steep dependence of the cross section.

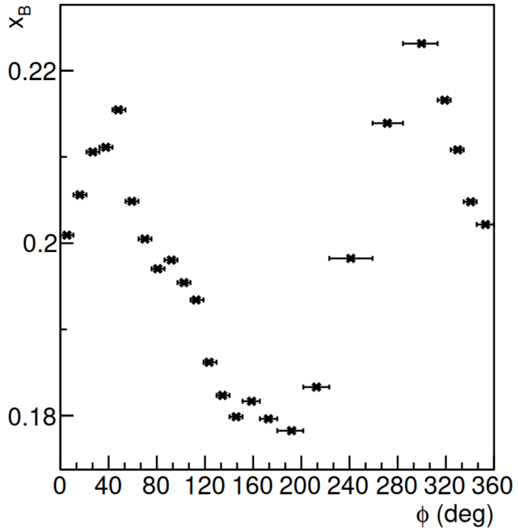
(Q^2, x_b, t) kinematics are Φ dependent

- Binning chosen to accommodate for this variation

Wide kinematical coverage







π^0/η background subtraction is insured using toy MC

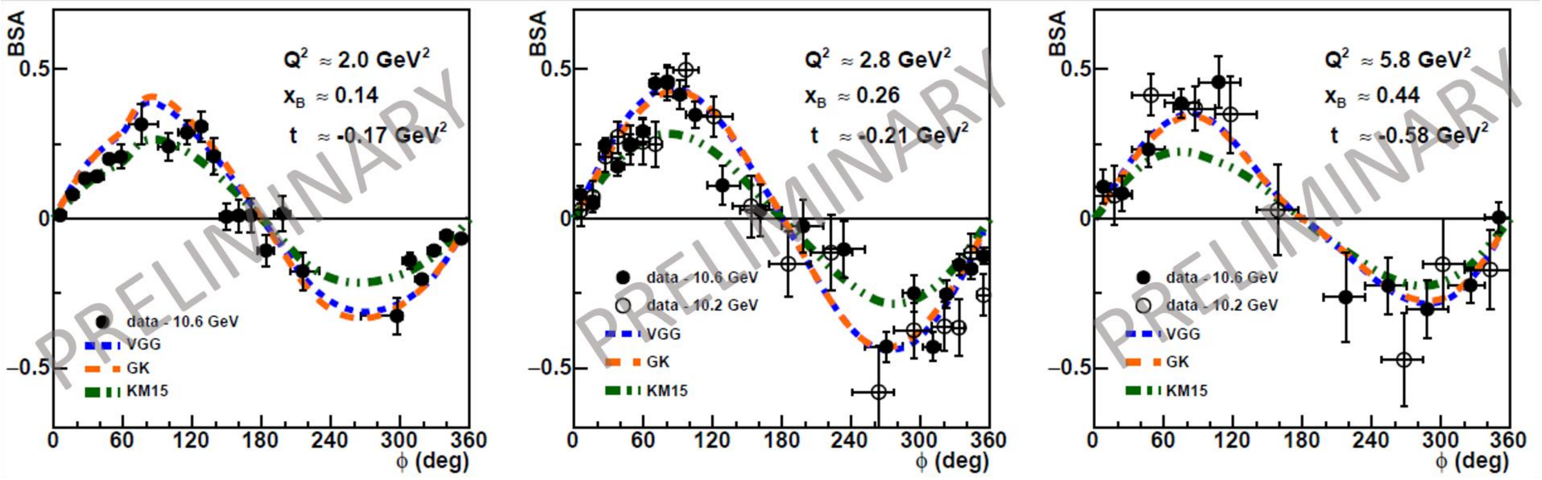
CLAS12: DVCS off proton G. Christiaens, M. Defurne, D. Sokhan

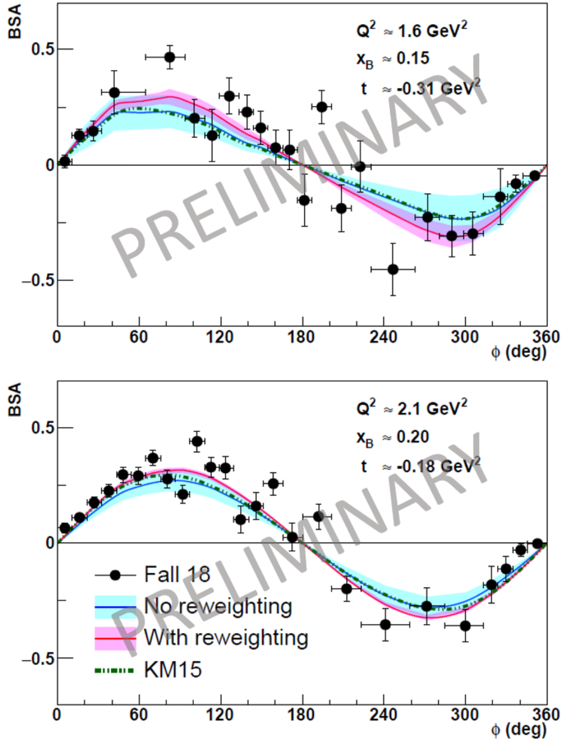
To be published soon

H. Moutarde, P. Sznajder, and J. Wagner, EPJC 79, 614 (2019)

- Deriving the mean and standard deviation of a 100 ANN-predictions produced by a global fit (PARTONS)
  - The new data are shown to be in good agreement
- Comparisons with KM15 and VGG/GK models
  - Data favors the KM15 model for most of the bins
  - At large x_b data favors the VGG/GK models

Kumericki, Kresimir and M uller, Dieter, EPJ Web of Conferences 112, 01012 (2016).
S. V. Goloskokov and P. Kroll, EPJC 65, 10.1140 (2009)
M. Vanderhaeghen, P. A. Guichon, and M. Guidal, Phys.Rev. D60, 094017 (1999)





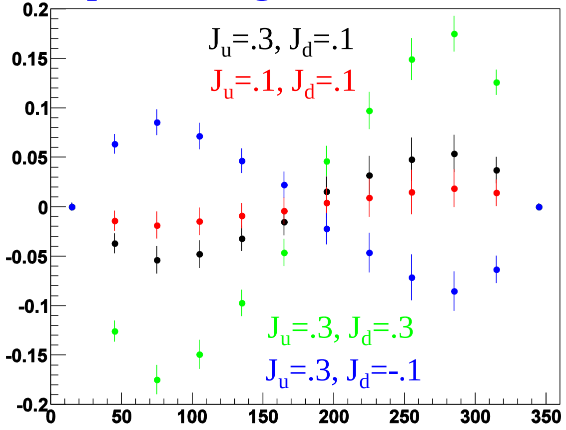
CLAS12: DVCS with an unpolarized deuterium target

- Physics observable: Beam Spin Asymmetry BSA
  - Scattering off neutron (nDVCS): GPD E
    - Determination of Ji sum rule
      - Contribution of orbital angular momentum of quarks to the nucleon spin

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

  - Scattering off proton (pDVCS): GPD H
    - Quantify medium effects
      - Essential for the extraction of BSA of a “free” neutron (de-convoluting medium effect via comparison with DVCS on hydrogen target)

Model predictions (VGG) for different values of quarks’ angular momentum



Polarized beam, unpolarized taget

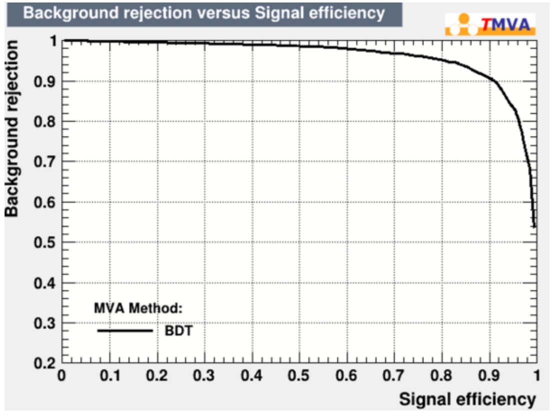
$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\{F_1 \boldsymbol{H} + \xi(F_1+F_2)\boldsymbol{\widetilde{H}} - k\, F_2 \boldsymbol{E} + \ \ldots\}$$

Observable	Proton	Neutron
$\Delta\sigma_{LU}$	$\Im\{\boldsymbol{H_p}, \widetilde{H}_p, E_p\}$	$\Im\{H_n, \widetilde{H}_n, \boldsymbol{E_n}\}$

CLAS12: DVCS with an unpolarized deuterium target

Under review

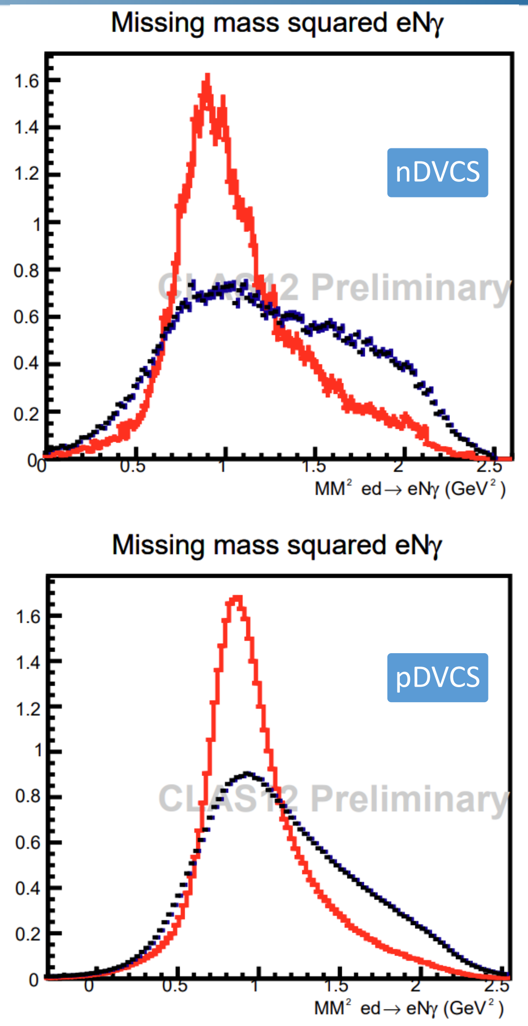
- A 10.6/10.4/10.2 GeV electron beam
  - With an average polarization of 86%
  - Scattering off an unpolarized Liquid Deuterium target of 5 cm length
- The exclusivity of the event is insured by:
  - Electron detection: Cerenkov detector, drift chambers and electromagnetic calorimeter
  - Photon detection: sampling calorimeter or a small PbWO4-calorimeter close to the beamline
  - Proton detection: Silicon and Micromegas detector OR Neutron detection: Central Neutron Detector
- For Neutron Detection:
  - Machine Learning techniques are applied to improve the Identification and reduce charged particle contamination

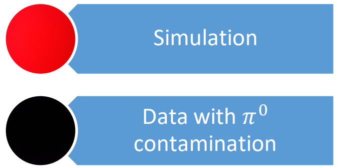


The ROC curve of a Boosted Decision Tree classifier indicating the high performance when identifying and removing charged particles contamination from neutron sample

CLAS12: DVCS with an unpolarized deuterium target

- The nDVCS (pDVCS) final state is selected with the following exclusivity criteria: (N:nucleon)
  - Missing mass
    - e d → e N γ X
    - e N → e N γ X
    - e N → e N X
  - Missing momentum
    - e d → e N γ X
  - ΔΦ, Δt, θ(γ,X)
    - Difference between two ways of calculating Φ and t
    - Cone angle between measured and reconstructed photon
- Exclusivity selection is optimized with a 4-D χ^2-like distribution including ΔΦ, Δt, θ(γ,X) and missing mass e N → e N X



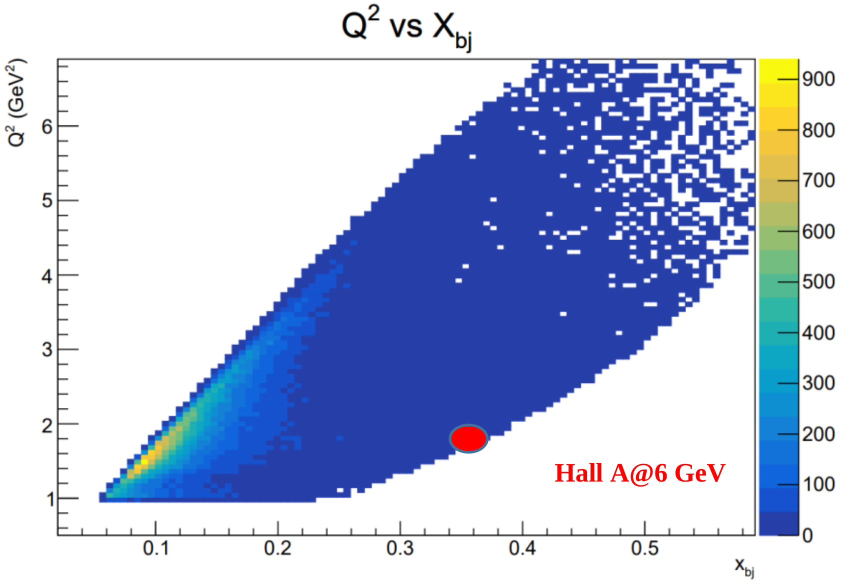


π^0 background contamination is estimated using simulations

CLAS12: nDVCS with an unpolarized deuterium target

Under review

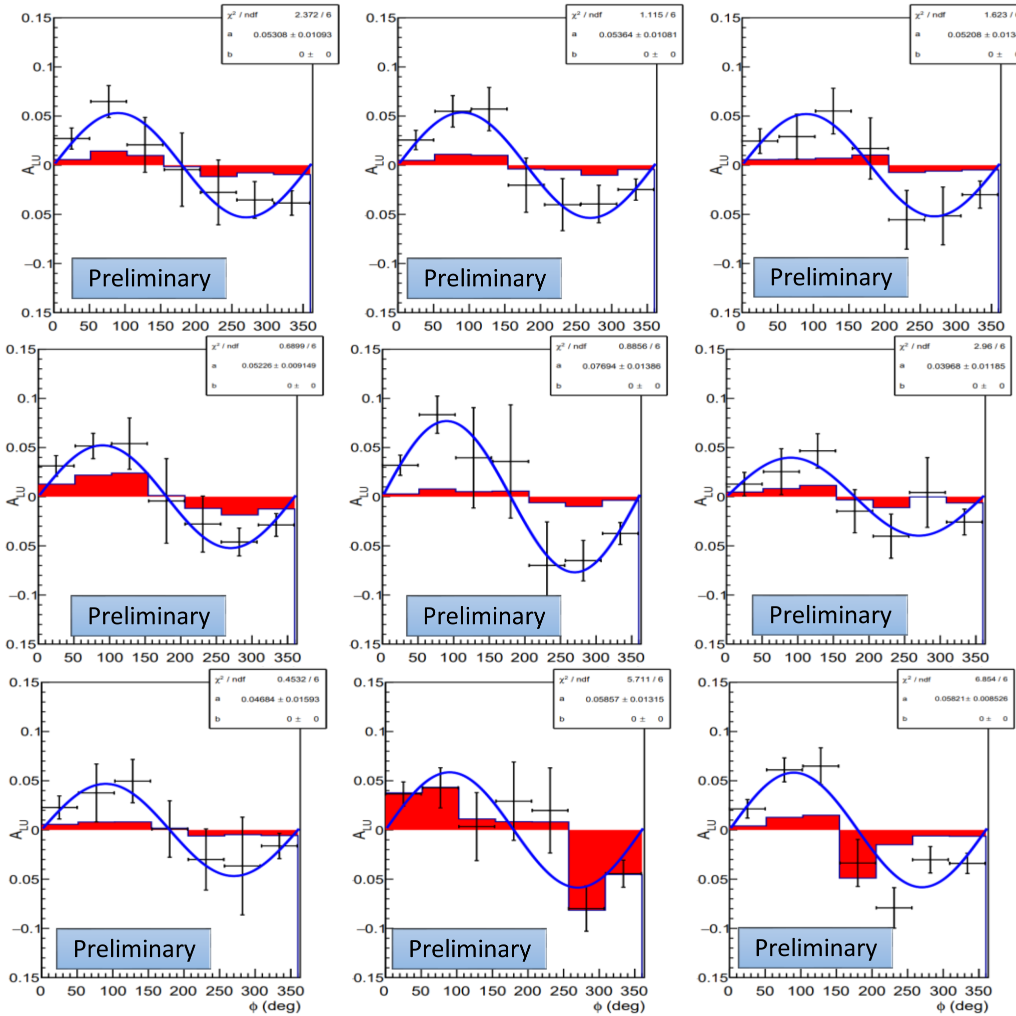
First-time measurement of nDVCS with detection of the active neutron



Q^2bins

$x_b$bins

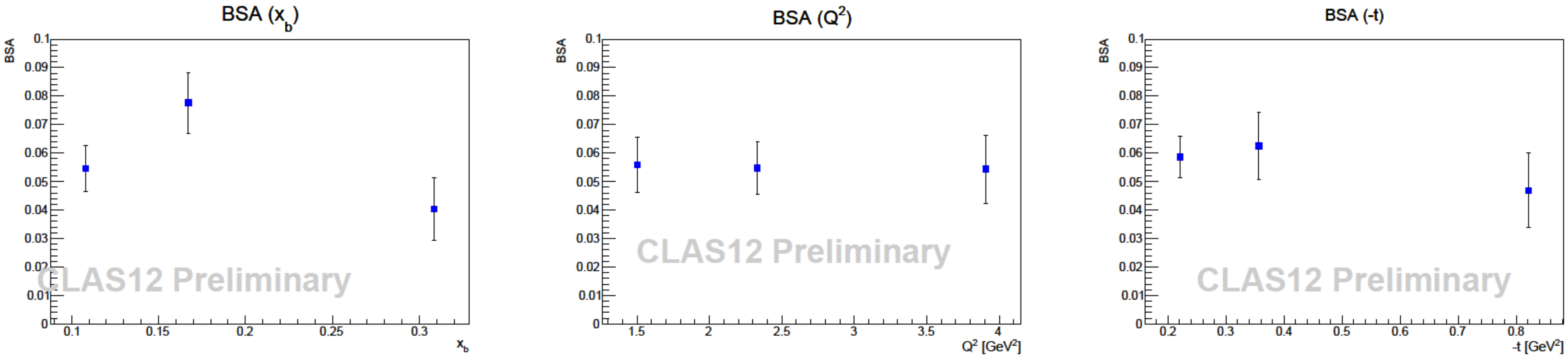
t bins



- Compared to the previous experiment, CLAS12 provides :
  - The possibility to scan the BSA of nDVCS on a wide phase space
  - The possibility to reach the high Q^2 high x_b region of the phase space
  - Exclusive measurement with the detection of the active neutron

CLAS12: nDVCS with an unpolarized deuterium target

$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\{F_1 \boldsymbol{H} + \xi(F_1 + F_2)\widetilde{\boldsymbol{H}} - k\, F_2 \boldsymbol{E} + \ \ldots\}$$

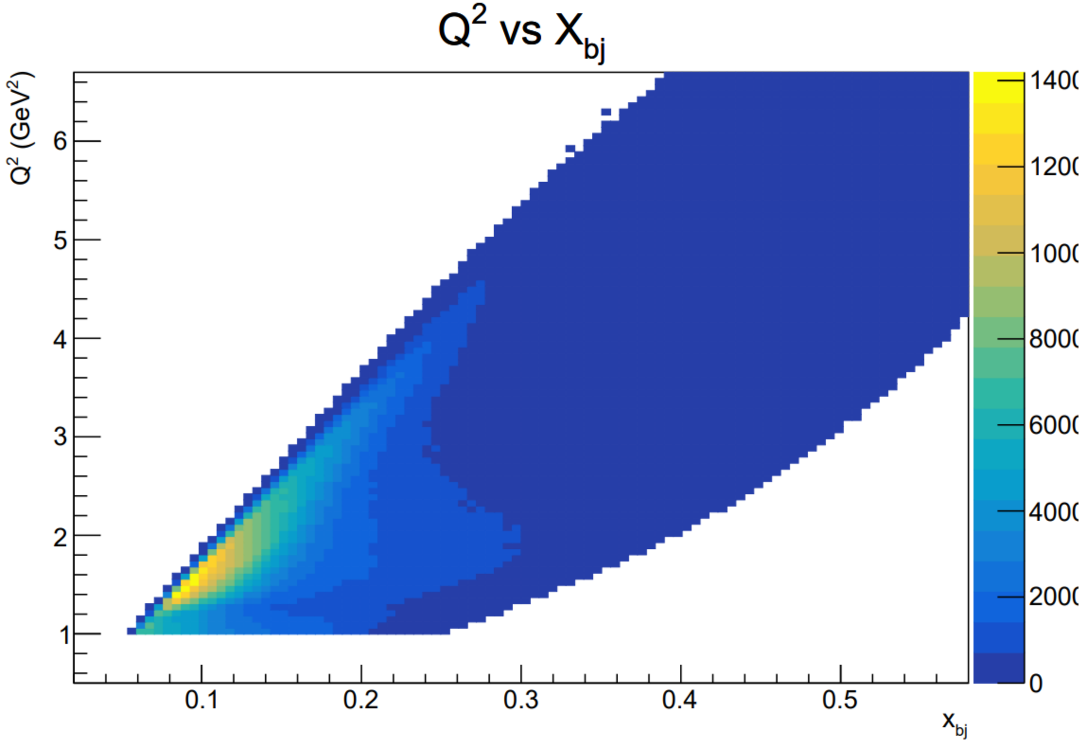


Variation of $sin(\Phi)$ amplitude

Errors are statistical only

Under review

First-time measurement of incoherent pDVCS on deuteron



Scattering off proton (pDVCS): GPD H

Quantify medium effects: Essential for the extraction of BSA of a "free" neutron (de-convoluting medium effect via comparison with DVCS on hydrogen target)

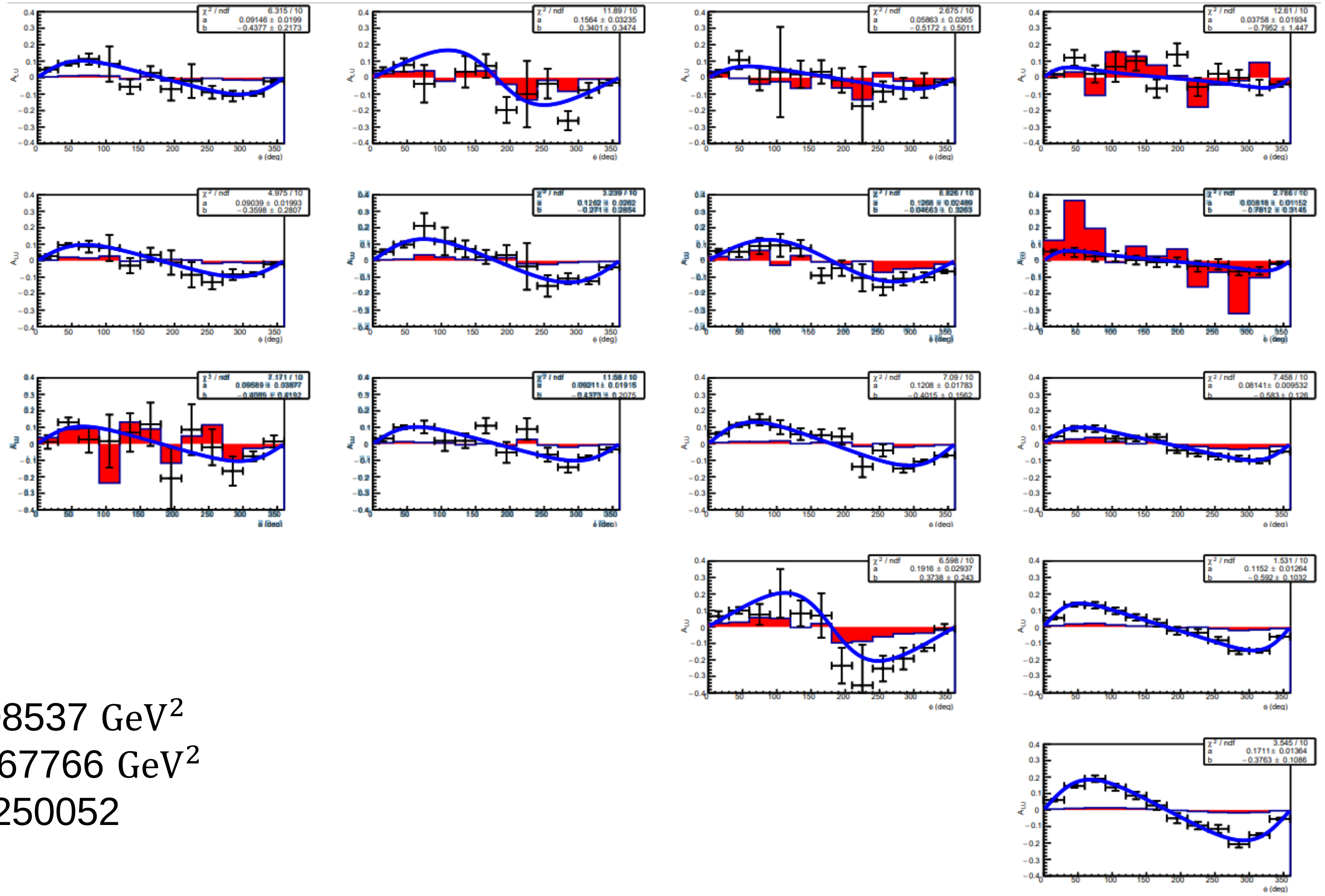
CLAS12: pDVCS with an unpolarized deuterium target

Under review

Preliminary

x_b: [0.04,0.13] | [0.13,0.16] | [0.16,0.2] | [0.2,0.41]

Q^2: [1,1.6] GeV^2 | [1.6,2] GeV^2 | [2,2.9] GeV^2 | [2.9,3.8] GeV^2 | [3.8,7.4] GeV^2



$< t >$ = -1.08537 GeV^2

$< Q^2 >$ = 2.67766 GeV^2

$< x_b >$ = 0.250052

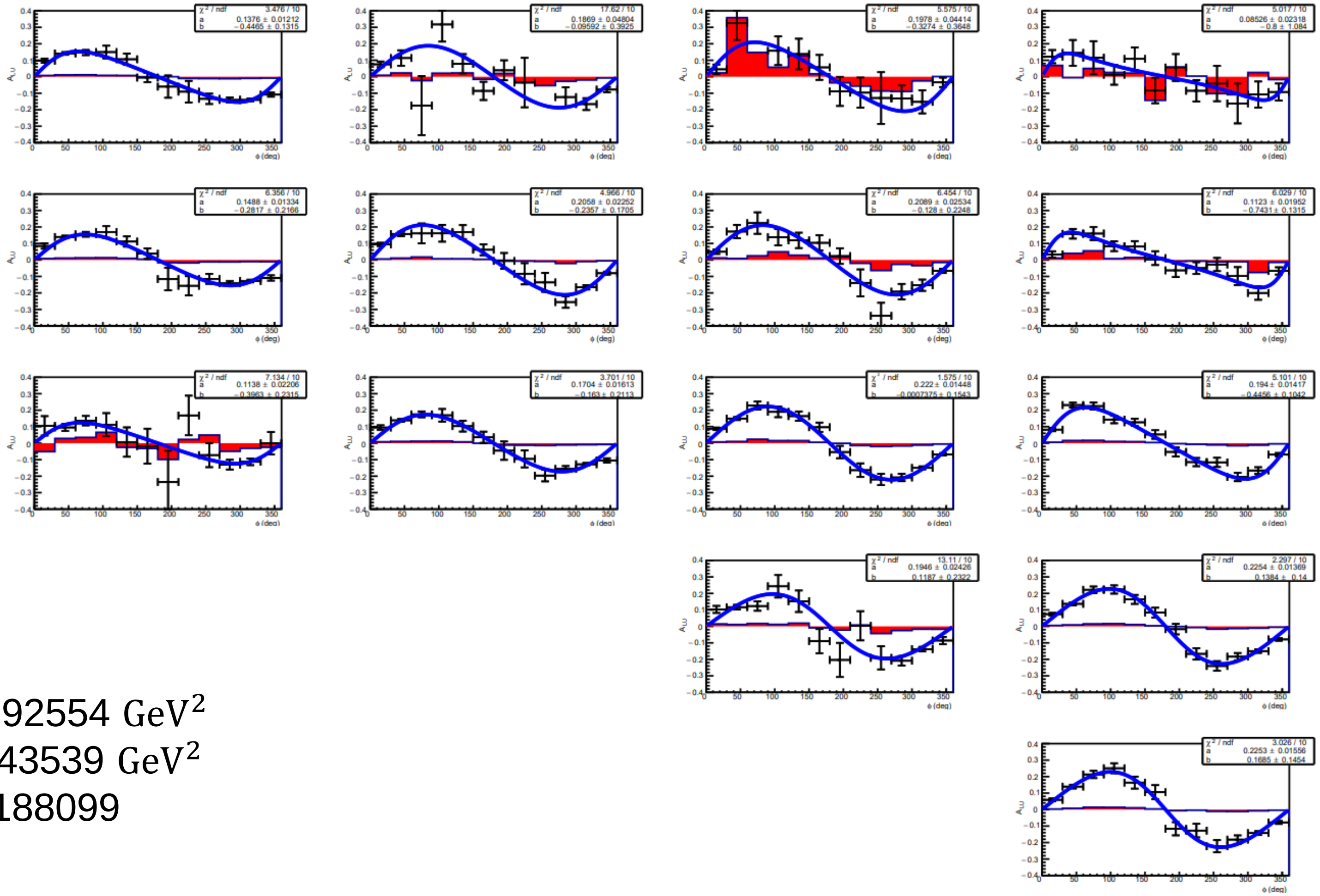
CLAS12: pDVCS with an unpolarized deuterium target

Under review

Preliminary

x_b → [0.04,0.13] [0.13,0.16] [0.16,0.2] [0.2,0.41]

Q^2 ↓ [1,1.6] GeV^2, [1.6,2] GeV^2, [2,2.9] GeV^2, [2.9,3.8] GeV^2, [3.8,7.4] GeV^2



$< t > =$ -0.392554 GeV^2

$< Q^2 > =$ 2.43539 GeV^2

$< x_b > =$ 0.188099

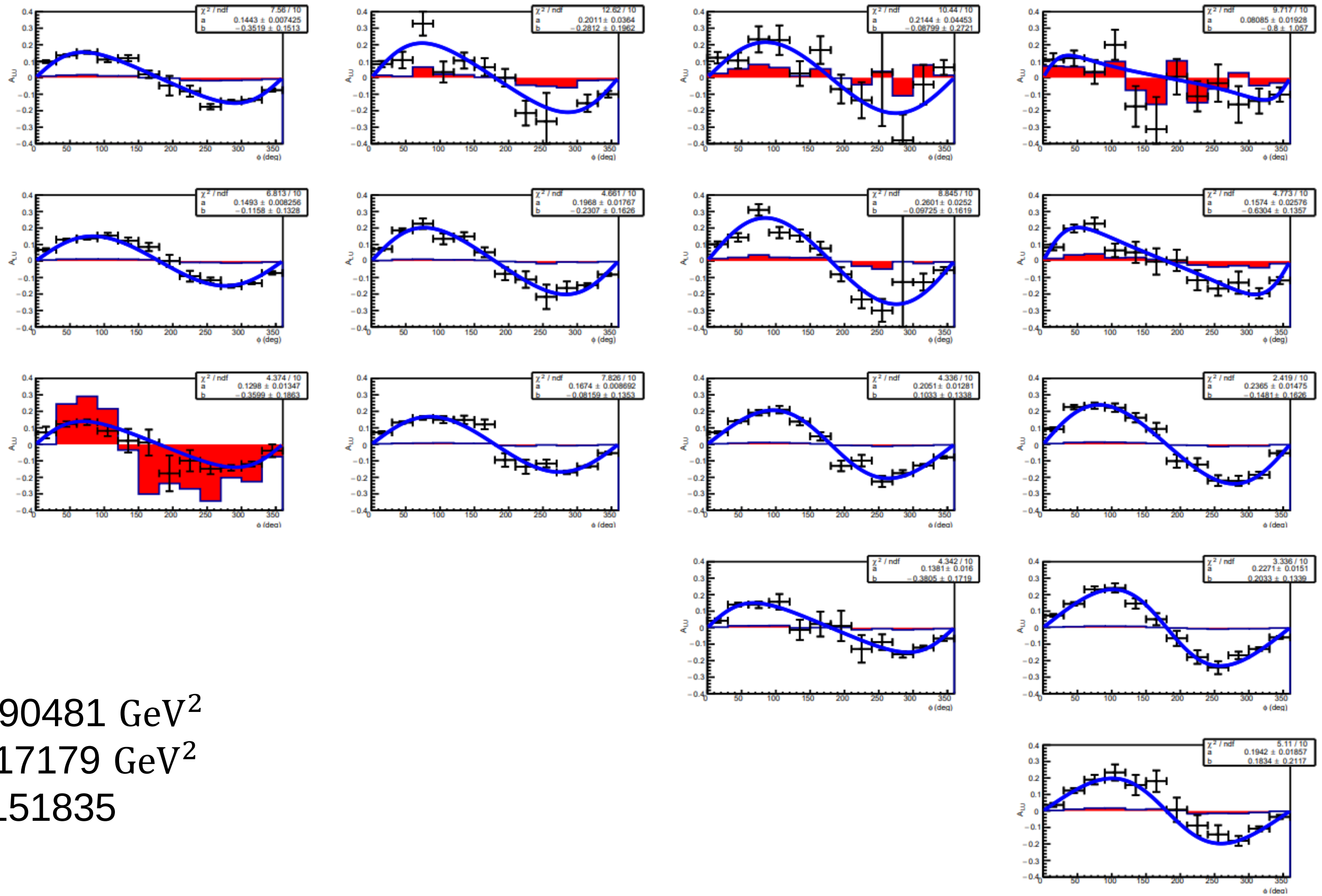
CLAS12: pDVCS with an unpolarized deuterium target

Preliminary

x_b →

[0.04,0.13] | [0.13,0.16] | [0.16,0.2] | [0.2,0.41]

Q^2 ↓



[1,1.6] GeV^2

[1.6,2] GeV^2

[2,2.9] GeV^2

[2.9,3.8] GeV^2

[3.8,7.4] GeV^2

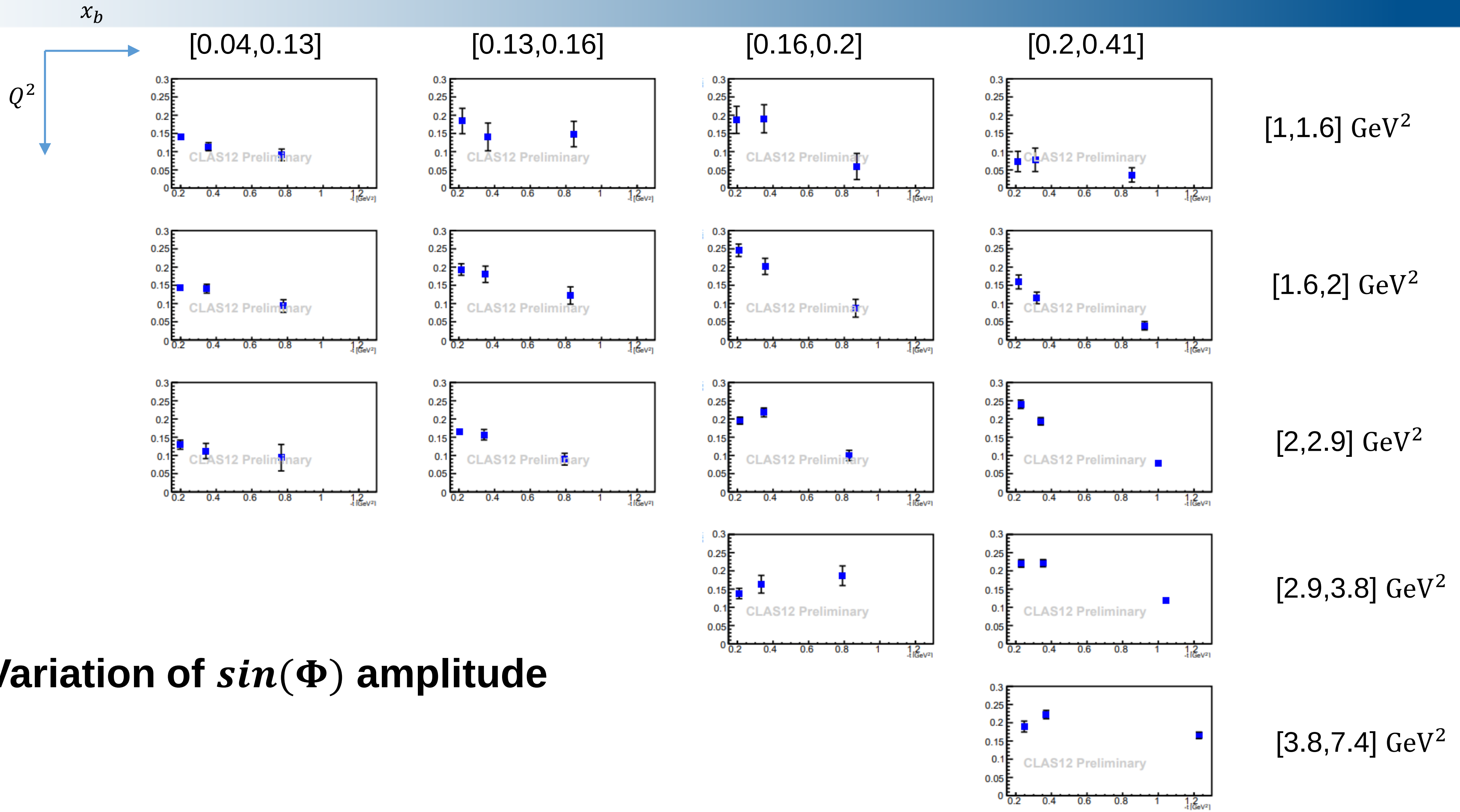
$< t >$ = -0.190481 GeV^2

$< Q^2 >$ = 2.17179 GeV^2

$< x_b >$ = 0.151835

CLAS12: pDVCS with an unpolarized deuterium target

Under review



Variation of $sin(\Phi)$ amplitude

CLAS12, what else?

Under review

Observable (target)	CFF sensitivity	Status
lTSA(p), lDSA(p)	$\Im\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}, \Re\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$	Data taking in progress
lTSA(n), lDSA(n)	$\Im\{\boldsymbol{H_n}\}, \Re\{\boldsymbol{H_n}\}$	Data taking in progress
tTSA(p)	$\Im\{\boldsymbol{H_p}\}, \Im\{\boldsymbol{E_p}\},$	Experiment foreseen for ~2025

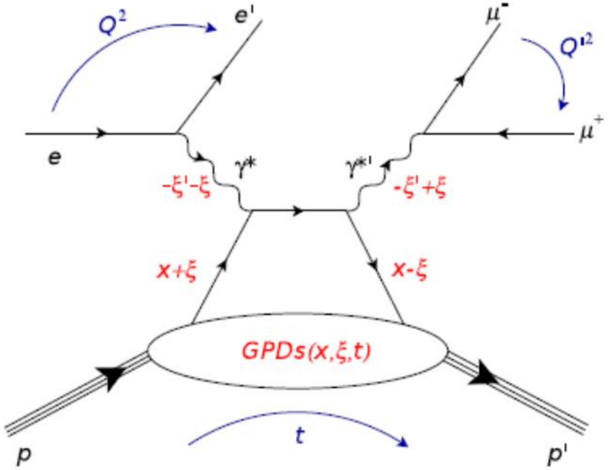
- Analysis ongoing: Deuteron DVCS
  - Phyisics observable to extract is Beam Spin Asymmetry (BSA)

$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\left\{\frac{2G_1\boldsymbol{H_1} + (G_1 - \tau G_3)(\boldsymbol{H_1} - 2\tau\boldsymbol{H_3}) + \frac{2}{3}\tau G_3\boldsymbol{H_5}}{2G_1^2 + (G_1 - 2\tau G_3)^2}\right\}$$

  - Spin 1: 9 GPDs for each quark flavor
    - BSA of DVCS off deuterium is sensitive to 3 of them

Upgrades?

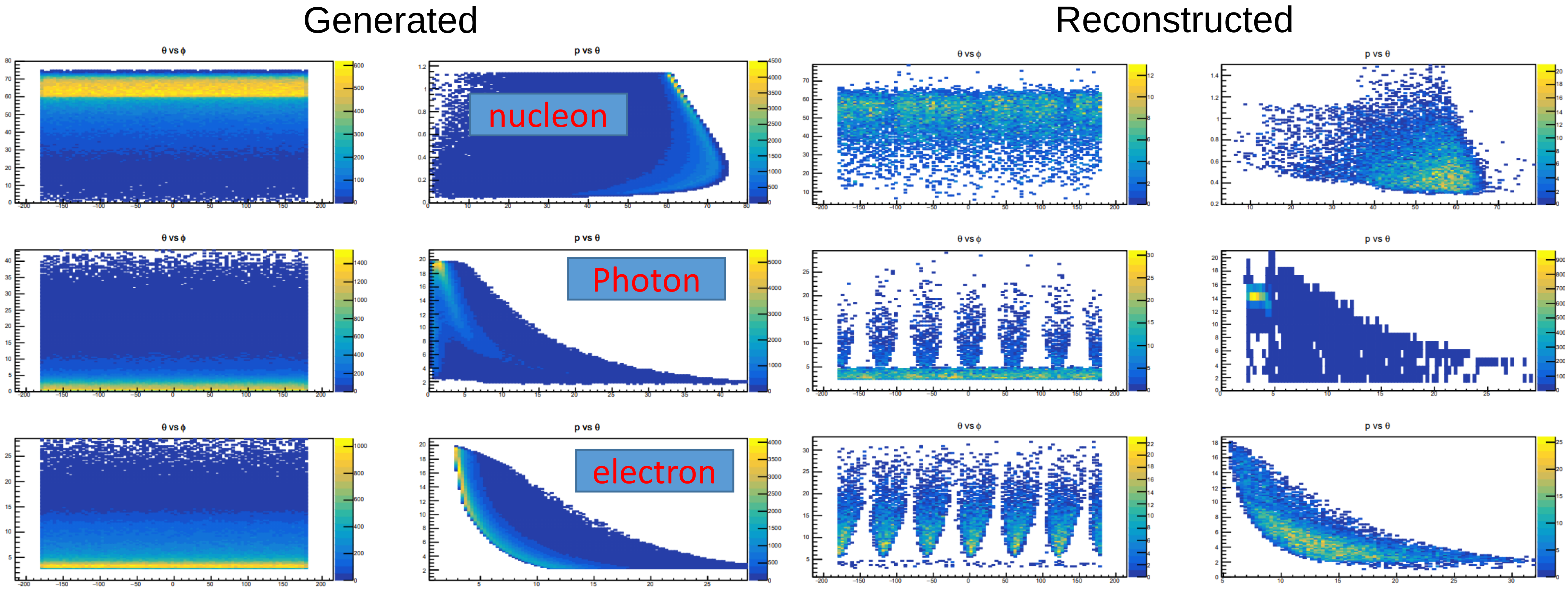
- pDVCS measurements will benefit from energy upgrade
  - Wider kinematical coverage for a complementary scan of GPDs
  - CLAS12 acceptance is OK(?) Associate energy upgrade with detector upgrades(?)
- nDVCS will surely benefit from both luminosity and energy upgrade
  - nDVCS BSA is of the order of ~2 to ~4 %: high luminosity beneficial for precise measurements
  - Wider kinematical coverage: comparable to pDVCS, beneficial for simultaneous fits of GPDs (flavor separation)
- But also: scan x dependence of GPDs; luminosity upgrade crucial for DDVCS!
  - Full kinematics mapping of GPDs: virtuality of final photon allows a unique direct access to GPDs at $x \neq \pm\xi$
  - Improved detection of muons



pDVCS with 22-GeV beam and current CLAS12 configuration

- Simulated pDVCS events at 22 GeV (H. Avakian)
- GEMC of current CLAS12
- Standard CLAS12 reconstruction

1% acceptance



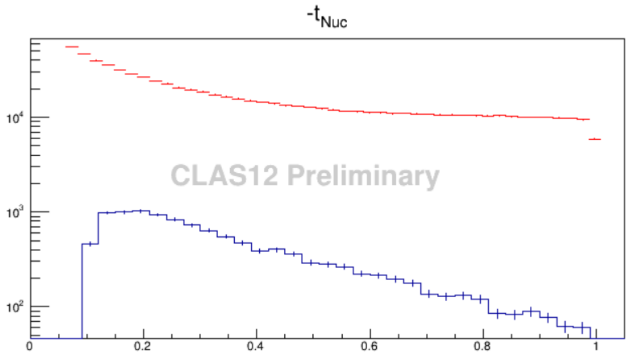
pDVCS with 22-GeV beam and current CLAS12 configuration

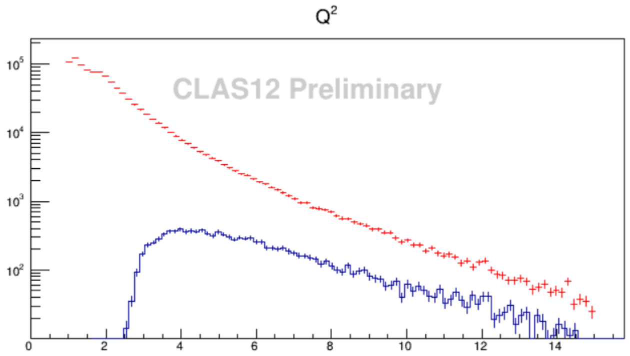
preliminary

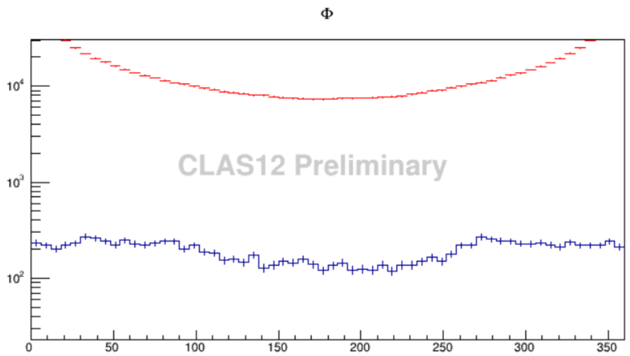
- Simulated pDVCS events at 22 GeV (H. Avakian)
- GEMC of current CLAS12
- Standard CLAS12 reconstruction

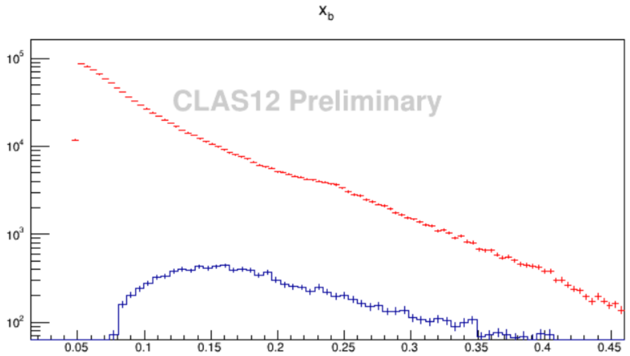
Generated

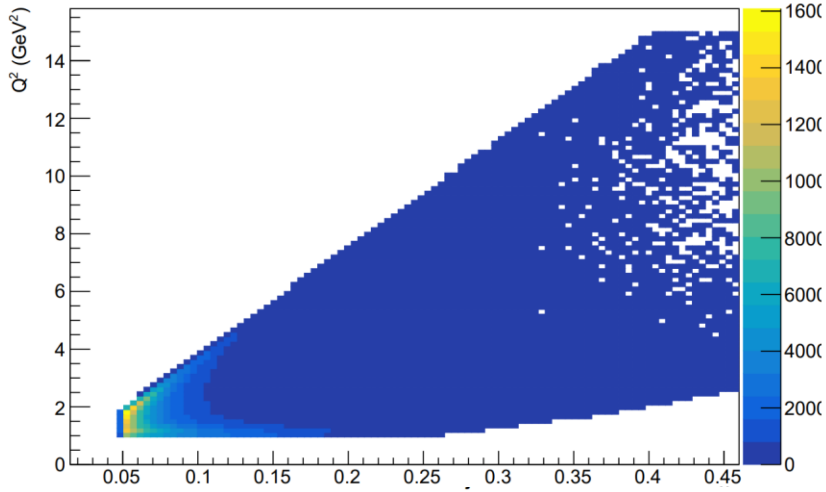
Reconstructed

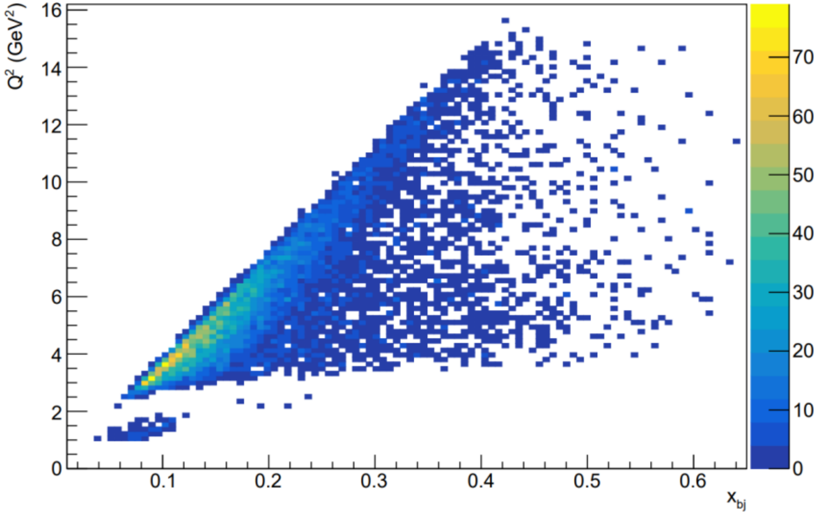












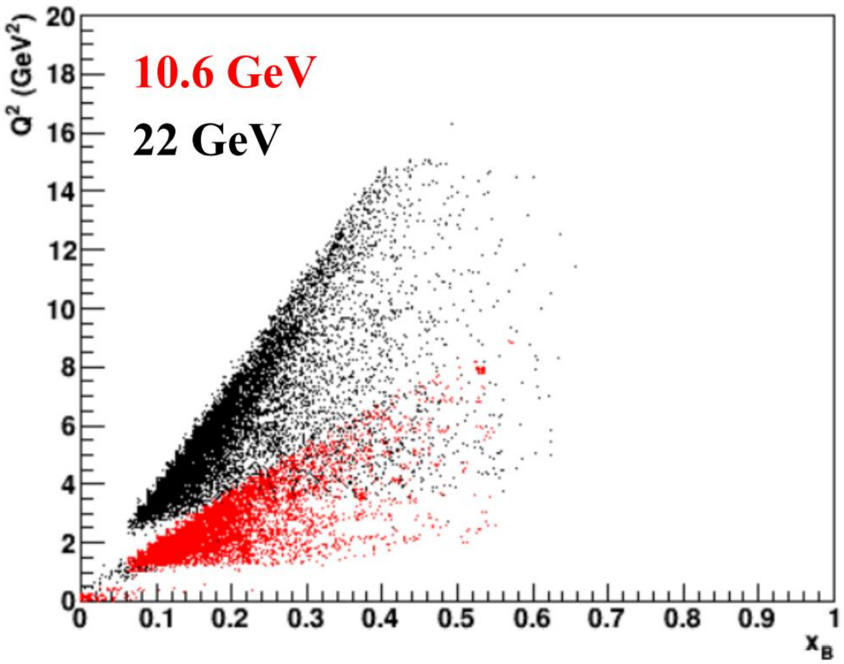
pDVCS with 22-GeV beam and current CLAS12 configuration

preliminary

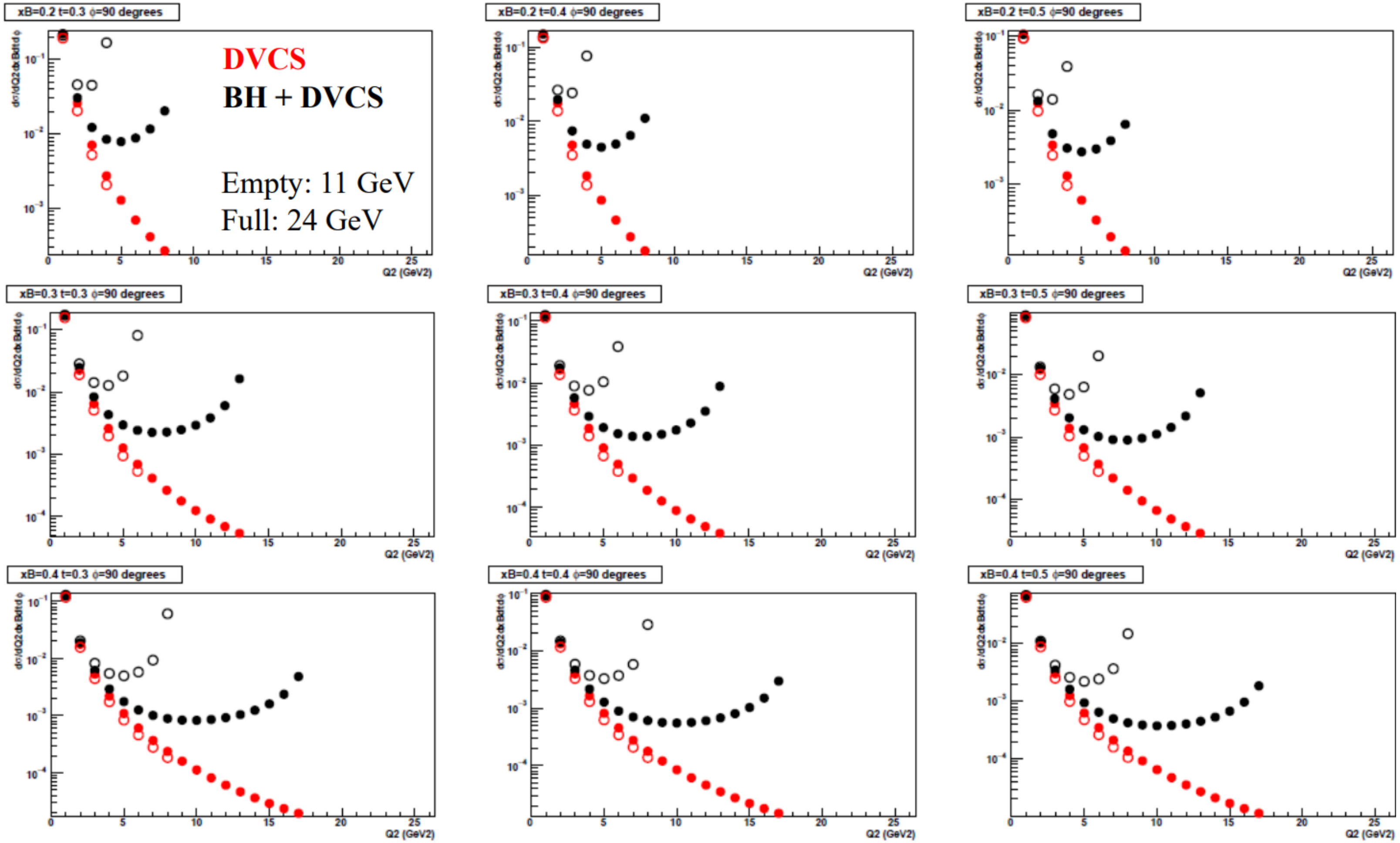
- Simulated pDVCS events at 22 GeV (H. Avakian)
- GEMC of current CLAS12
- Standard CLAS12 reconstruction

10.6 GeV

22 GeV



Process cross section: predictions from VGG

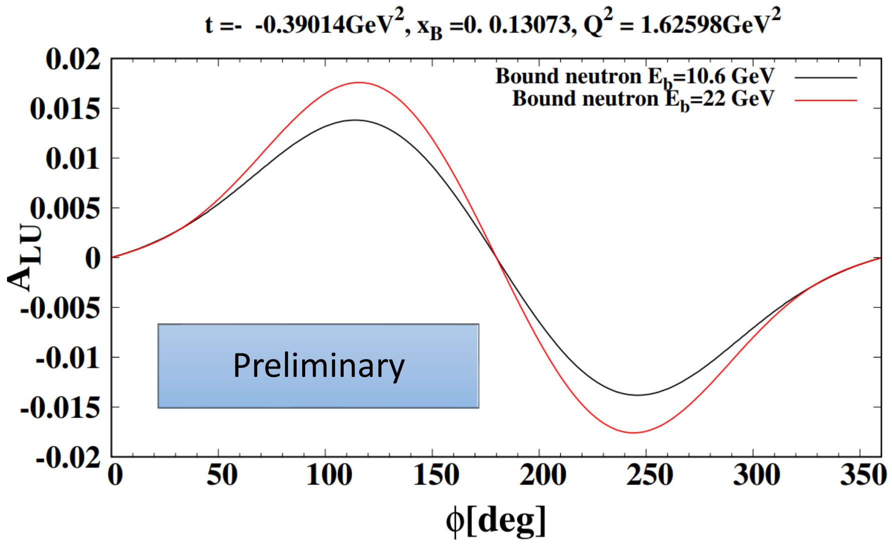


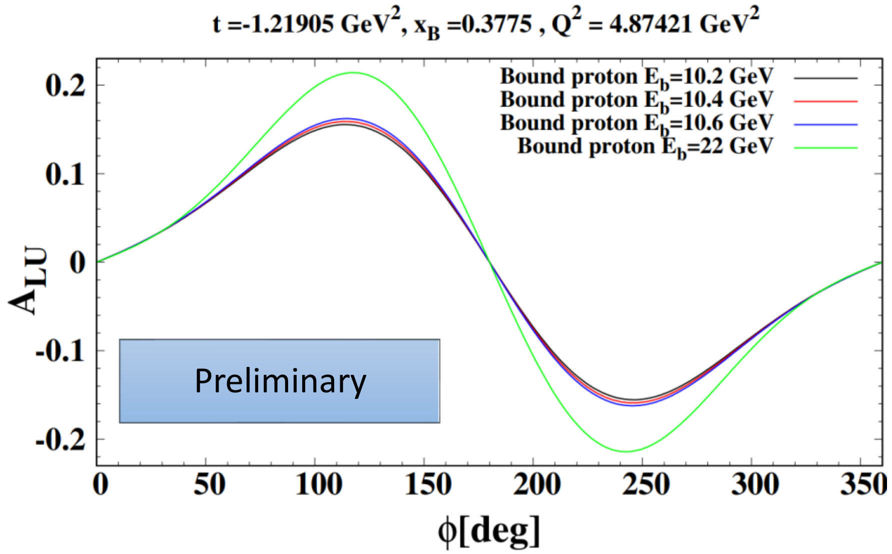
BSA at high energies

- BH dominance at higher energies
- However, BSA seems to be larger
  - pDVCS: Achieve good measurements with reasonable statistics
  - nDVCS: higher luminosity favorable given the low BSA

S. Fucini, R. Dupré, S. Scopetta to be published soon

Model predicting small nuclear effects as expected for deuteron





Larger effects are predicted for 3He (S. Fucini, S. Scopetta, M. Viviani PRC 102 (2021) and PRD 101 (2020))

Conclusions

- GPDs are powerful tool to explore the structure of the nucleons and nuclei
  - Nucleon tomography, quark angular momentum, distribution of forces in the nucleon
- Exclusive reactions can provide important information on nucleon structure via the extraction of GPDs
- CLAS12 offers a wide kinematical reach over which the GPDs dependence on different kinematical variables can be scanned
  - Data to add constraints on GPDs in unexplored regions of the phase space
  - Possibilities to measure new observables using different experimental configurations
    - Flavor separation of GPDs
- The 20+ GeV upgrade offers a unique opportunity for a wide phase-space scan of GPDs
  - Combined with luminosity upgrade would transform CLAS into a high precision experiment
    - Will allow for x-dependence GPD scan using DDVCS
- And maybe Positron beam?