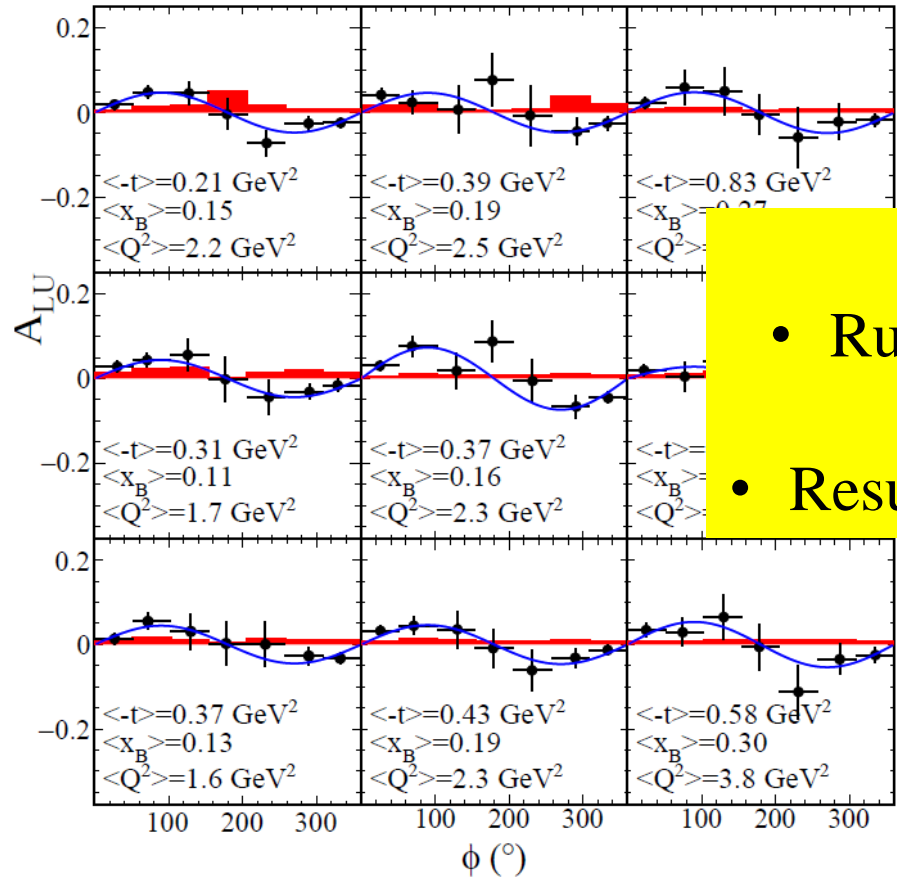
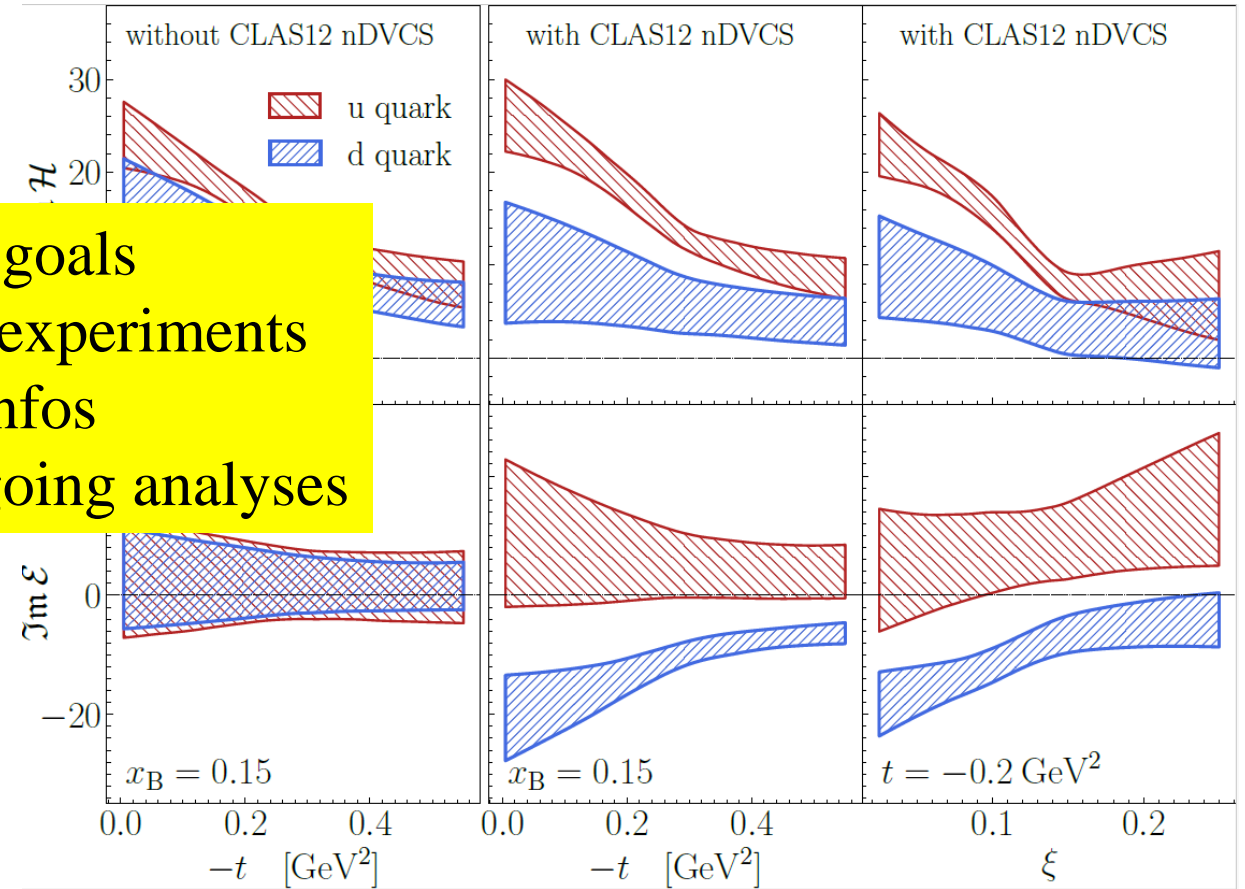


Run Group B

Electroproduction on deuterium with CLAS12



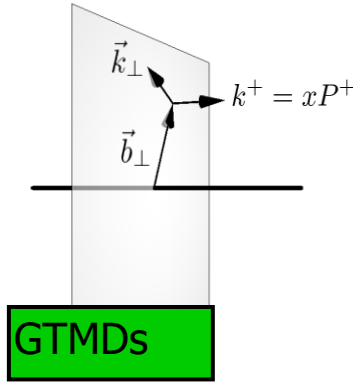
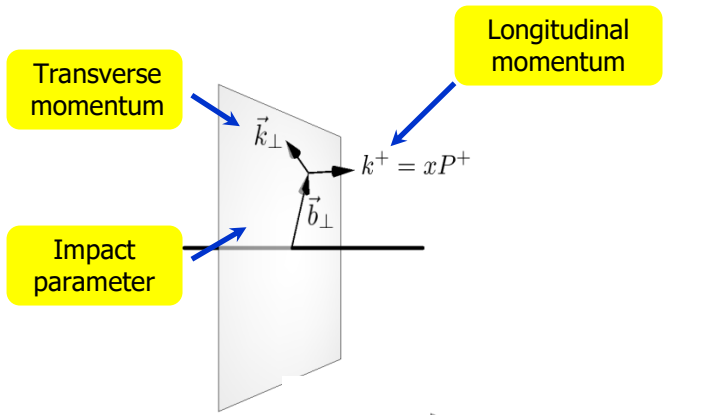
- Physics goals
- Run Group B experiments
- Run infos
- Results and ongoing analyses



Silvia Niccolai, IJCLab Orsay (France)
CLAS Collaboration Meeting, 7/1/2026



Multi-dimensional mapping of the nucleon

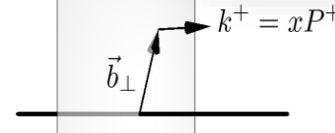
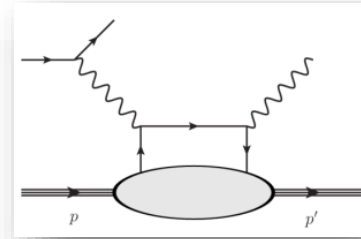


$x, \xi, k_{\perp}^2, \vec{k}_{\perp} \cdot \vec{\Delta}_{\perp}, t$

$\int d^2 \vec{k}_{\perp}$

$\int d^2 \vec{b}_{\perp}$

DVCS and DVMP

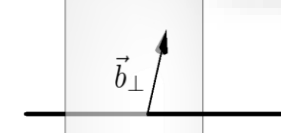
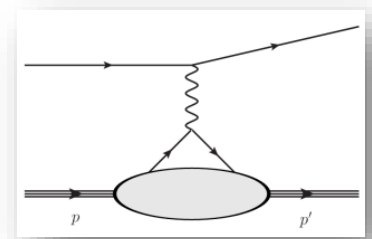


GPDs x, ξ, t

$\int dx$

$\int d^2 \vec{b}_{\perp}$

Elastic Scattering



FFs t



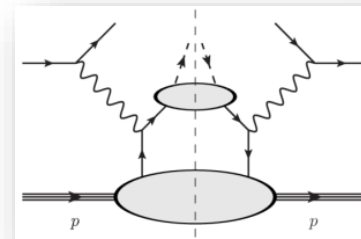
TMDs x, k_{\perp}^2

$\int d^2 \vec{k}_{\perp}$

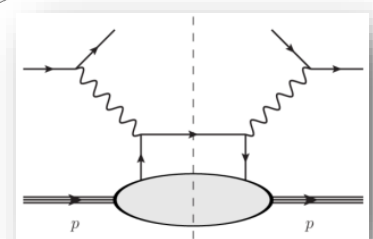


PDFs x

SIDIS



DIS

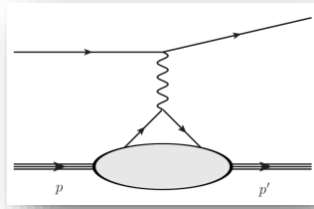


A complete picture of nucleon structure requires the measurement of all these distributions.

CLAS12 Run Group B aims to measure all these distributions, using **deuteron** as a **neutron target**
 → **Quark-flavor separation, combining with proton results**

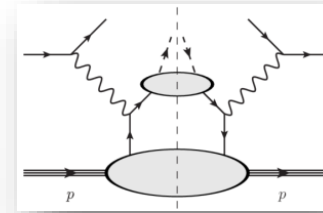
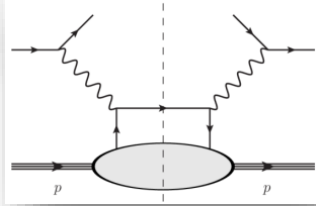
+ EMC effect, SRC
 + J/ψ photoproduction on deuteron

CLAS12 Run Group B: experiments

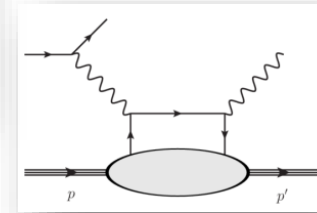


Elastic Scattering
(G_M^n)

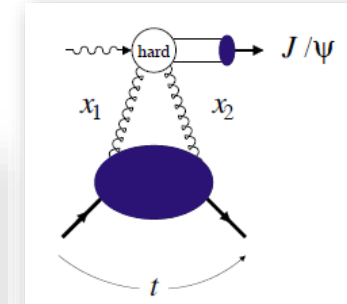
DIS (for SRC and EMC effect)



SIDIS (for PDFs and TMDs)



nDVCS



J/ ψ photoproduction

Experiment number	Title	Contact person	PAC days (rating)
E12-07-104	Neutron magnetic form factor	G. Gilfoyle	30 (A-)
E12-09-007a	Study of parton distributions in K SIDIS	W. Armstrong	56 (A-)
E12-09-008	Boer-Mulders asymmetry in K SIDIS	M. Contalbrigo	56 (A-)
E12-11-003	Deeply virtual Compton scattering on the neutron	S. Niccolai	90 (A High Impact)
E12-09-008b	Collinear nucleon structure at twist-3 in dihadron SIDIS	M. Mirazita	RG
E12-11-003a	In medium structure functions, SRC, and the EMC effect	O. Hen	RG
E12-11-003b	Study of J/ ψ photoproduction off the deuteron	Y. Ilieva	RG
E12-11-003c/E12-07-104a	Quasi-real photoproduction on deuterium	F. Hauenstein	RG

Common features to all experiments of Run Group B:

- **Liquid deuterium target**
- **Beam energy: « 11 » GeV**

Run Group B: setup and run summary

Scheduled beam time:

Spring19: February 6th - March 25th 2019

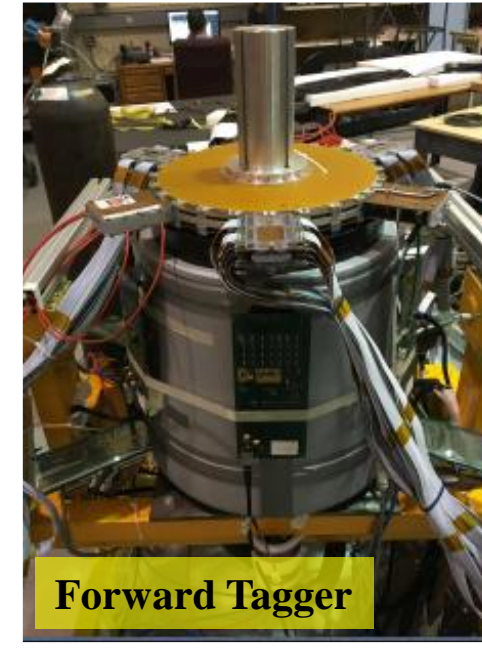
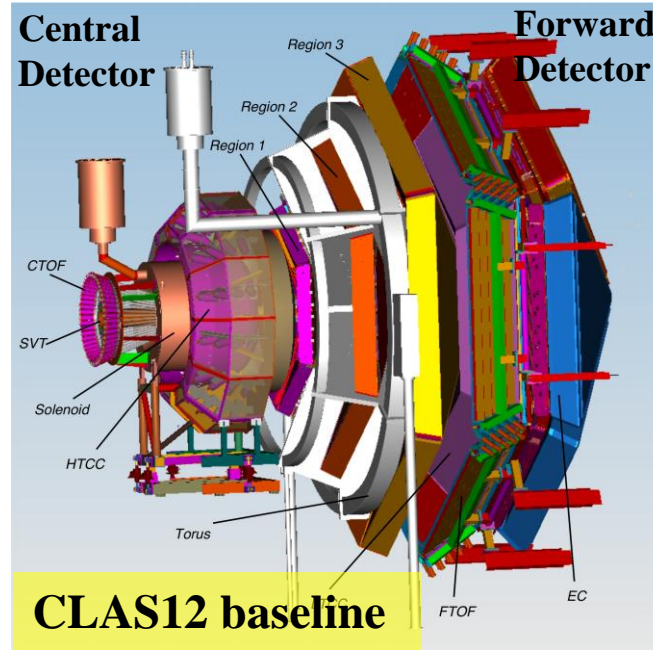
Fall19: December 3rd - 20th 2019

Spring20: January 6th - 30th 2020

43.3 B triggers collected at 3 different beam energies and two torus polarities:

- 10.6 GeV (9.7 B inbending e^-) Spring19
- 10.2 GeV (11.7 B inbending e^-) Spring19
- 10.4 GeV (9 B outbending e^-) Fall19, (12.9 B inbending e^-) Spring20

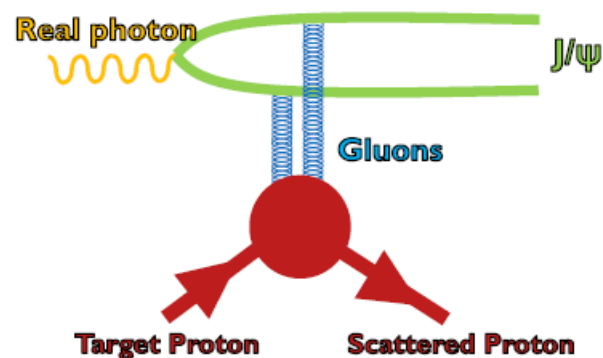
- Average beam polarization $\sim 86\%$
- Liquid deuterium target, 5 cm long



38.9 total PAC days according to ABUs
→ 51 PAC days left to run, approved by PAC52

Pass1 cooking completed in 2021
Pass2 cooking completed in 2024

One publication so far: nDVCS BSA (pass1)
A. Hobart et al. (CLAS), PRL 133 (2024)

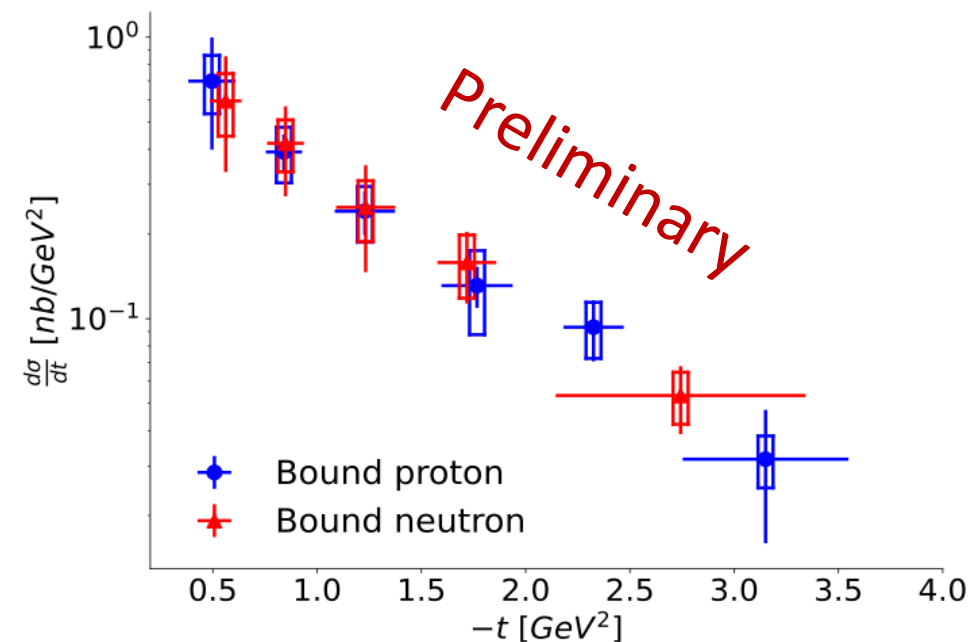
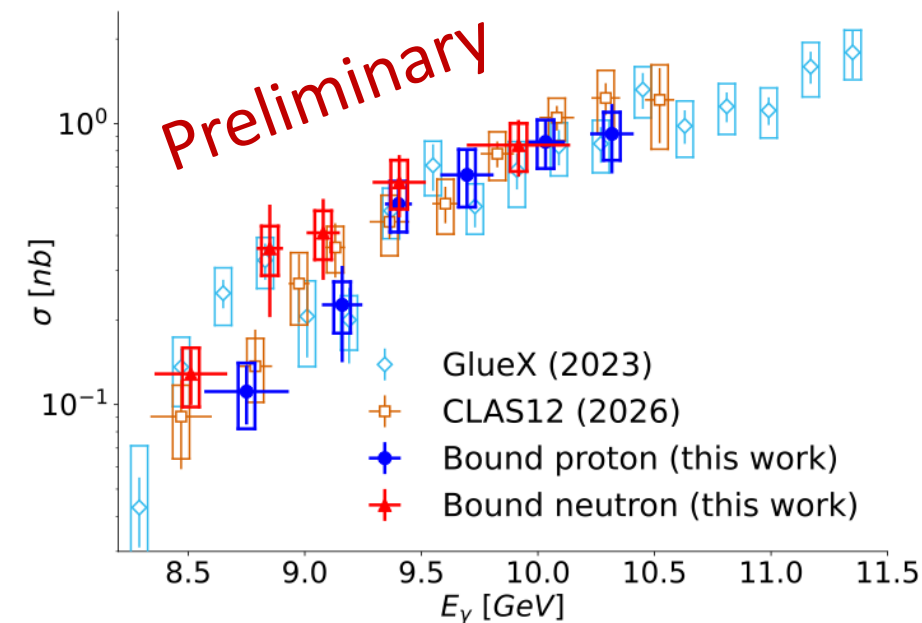


Close to the 8.2 GeV threshold, J/ ψ photoproduction is predicted to be mediated by the **exchange of two gluons**.

Use all RG-B data to make a first measurement of the near-threshold cross section on the bound neutron and proton in deuteron.

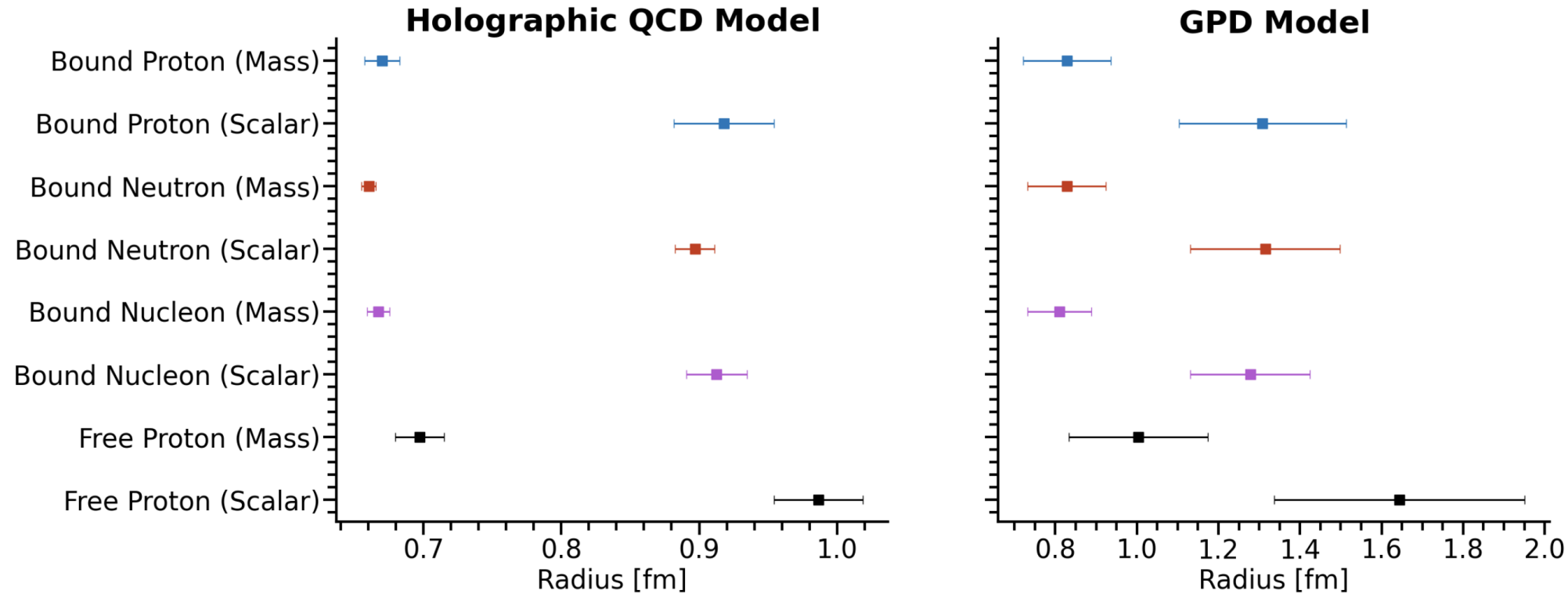
This can allow to probe the **gluon mechanical form factors of the nucleon**. May help place constraints on near-threshold J/ ψ production mechanism.

Analysis approved, **article in Ad-Hoc review**.



Mechanical Form Factors

Assuming dominant two-gluon exchange & negligible FSI contribution to cross section.



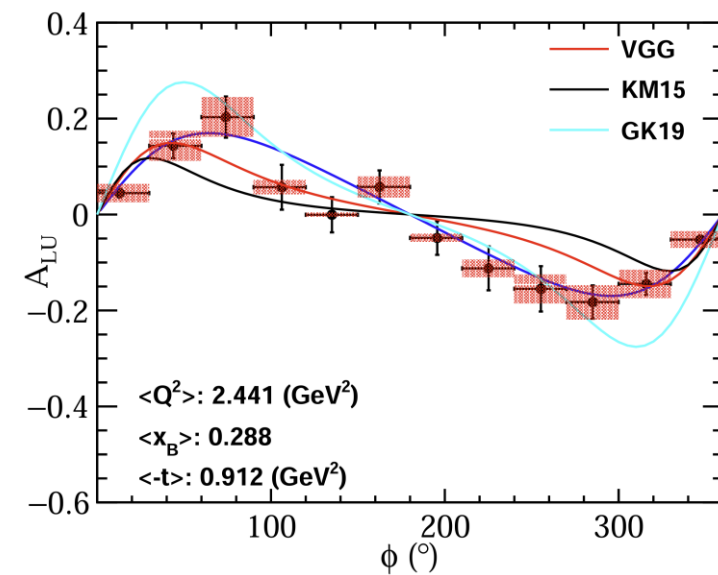
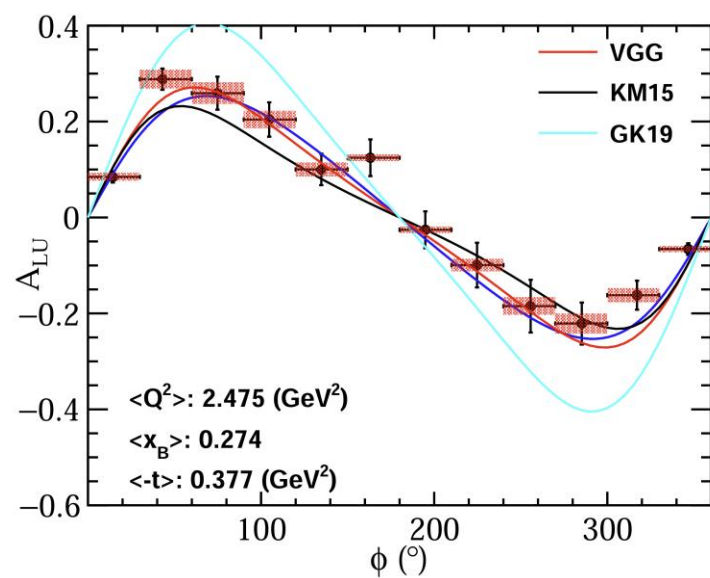
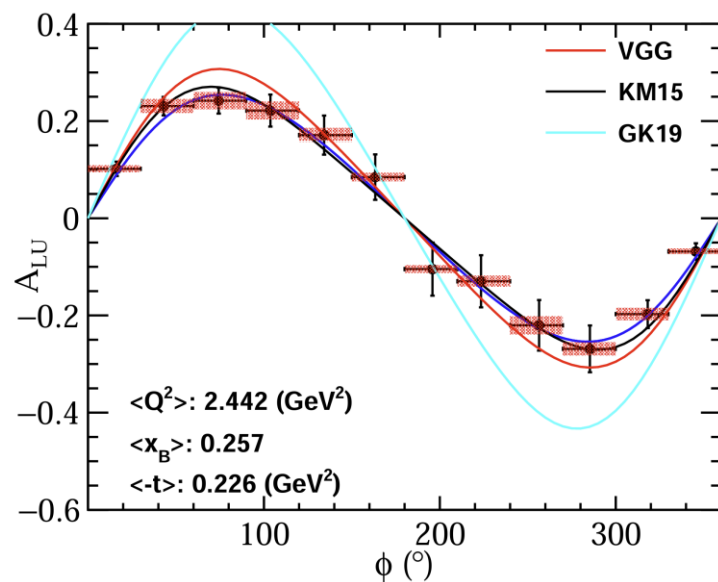
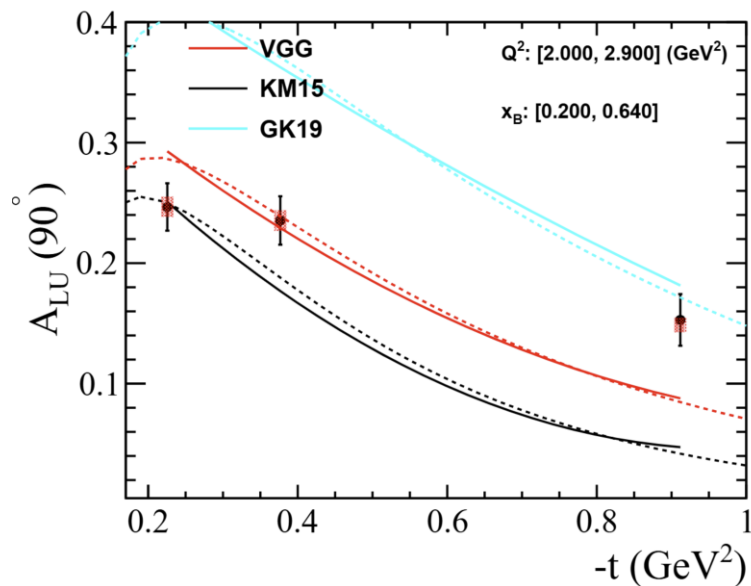
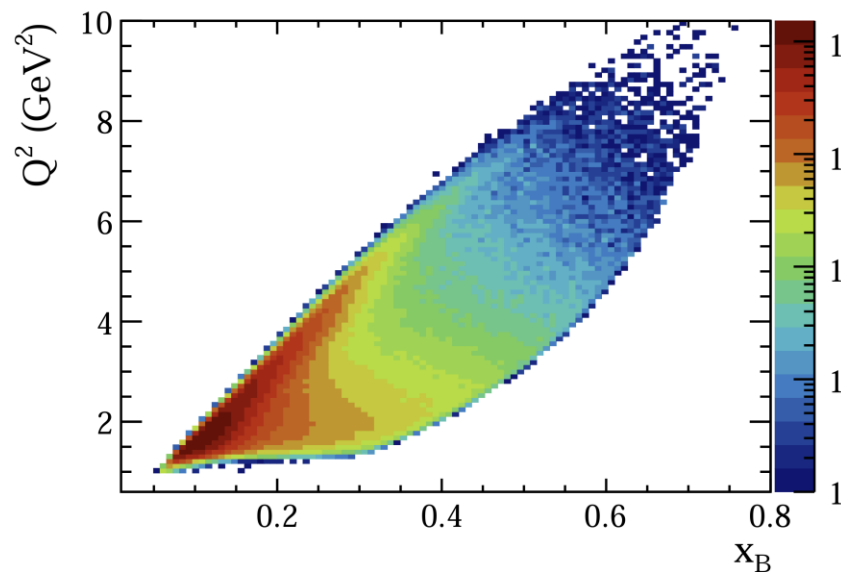
Fit holographic QCD and GPD based models to the differential cross section to extract the bound proton and neutron gluon mechanical form factors.

Combine the proton and neutron data to obtain the bound nucleon form factors.

Calculate mass and scalar radii from the form factors.

- First-time measurement of incoherent pDVCS in the deuteron
 - Quantify medium effects on GPDs

$$f = \frac{A_{LU} \sin(\phi)}{1 + b \cos(\phi)}$$



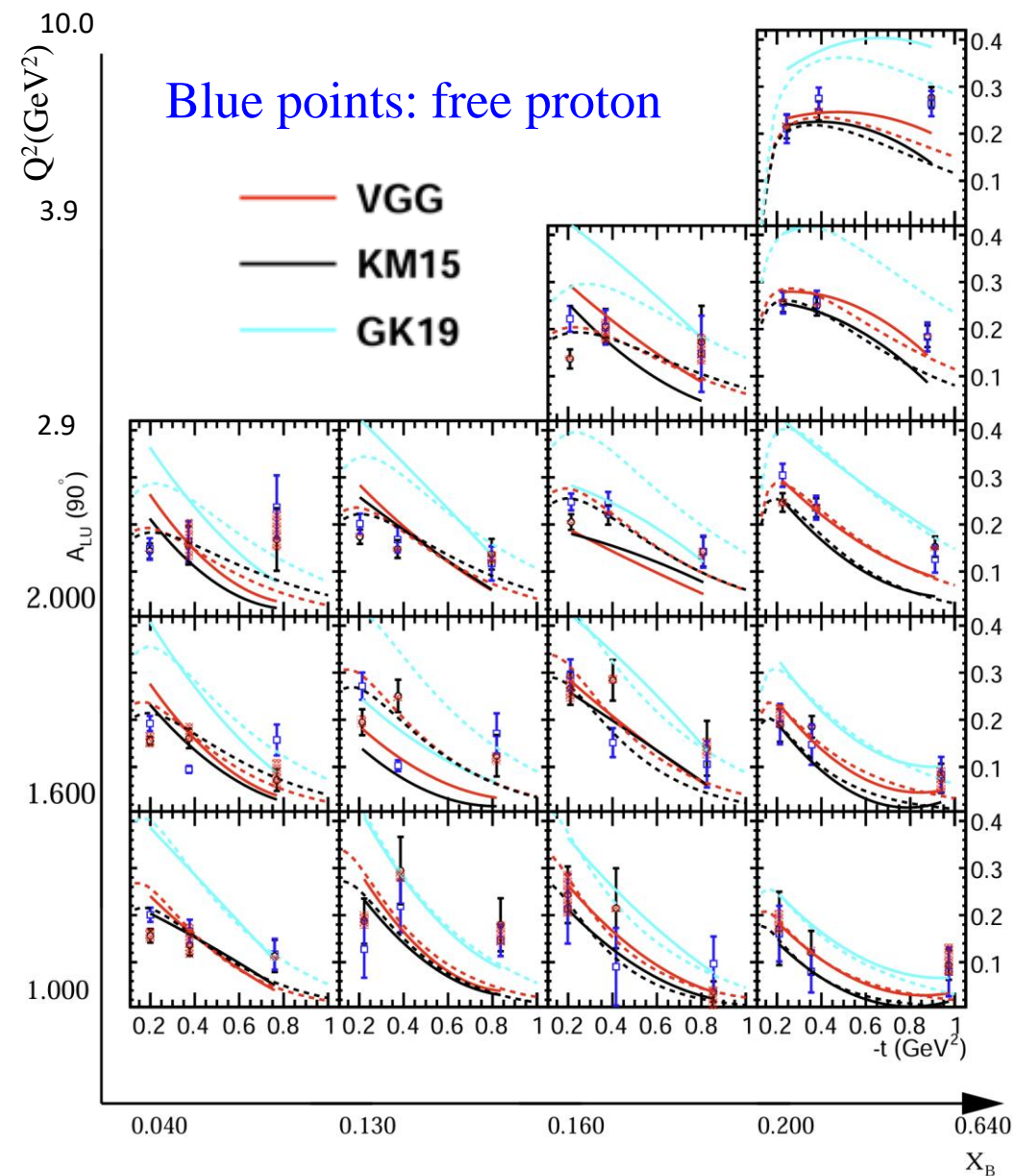
- Comparison with BSA from free proton shows very clear compatibility
 - Medium effects in deuterium are negligible
- More to understand with results from data taken on nuclear targets at CLAS12
 - Currenty being analyzed

K. Kumericki and D. Muller, 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)

Analysis approved
Paper draft in preparation



- Unpolarized cross section

$$\frac{d^4 \sigma_{en \rightarrow en \gamma}}{dQ^2 dx_{\text{BJ}} dt d\phi} = \frac{N_{en \rightarrow en \gamma}}{L \cdot \varepsilon_{\text{acc}} \cdot V}$$

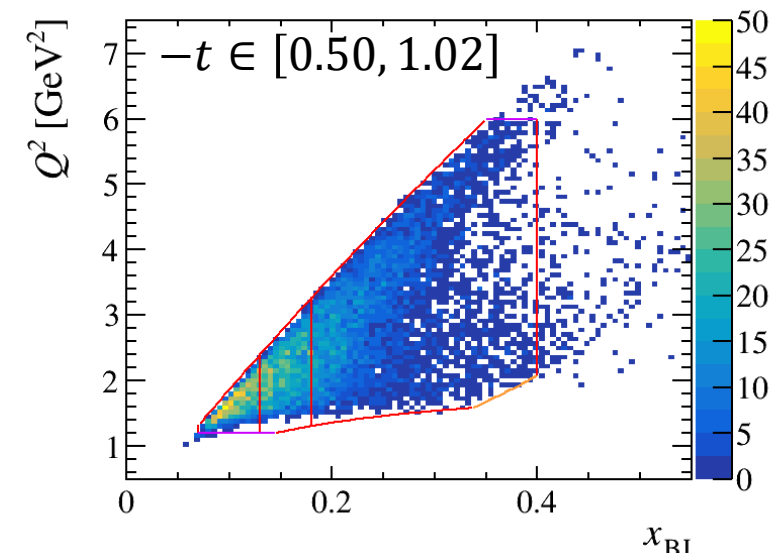
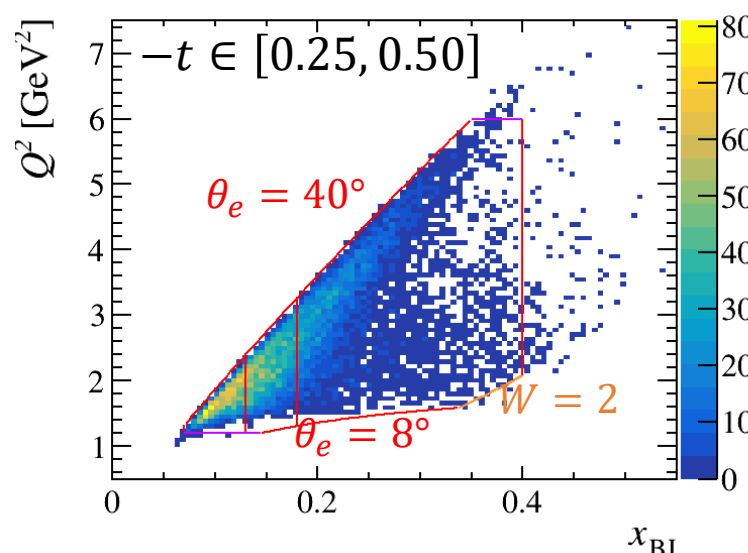
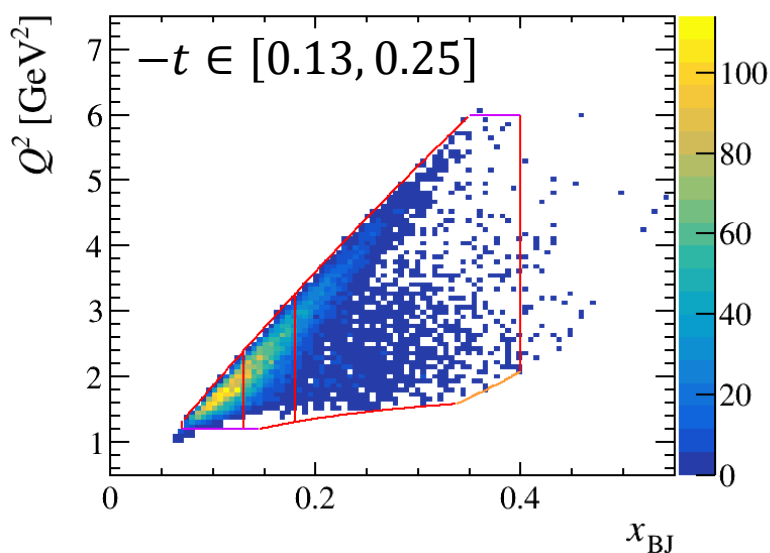
- $N_{en \rightarrow en \gamma}$ is the yield obtained after the background subtraction in each $(Q^2, x_{\text{BJ}}, -t, \phi)$ bin
- Luminosity $L = 134.1 \times 10^3 \text{ pb}^{-1}$
- Acceptance ε_{acc} determined from MC
 - Neutron detection efficiency is corrected using the RGB $ep \rightarrow en\pi^+$ data
 - BDT cut efficiency is corrected by data (performing the $\Delta\phi$ fit)
- V is the bin volume

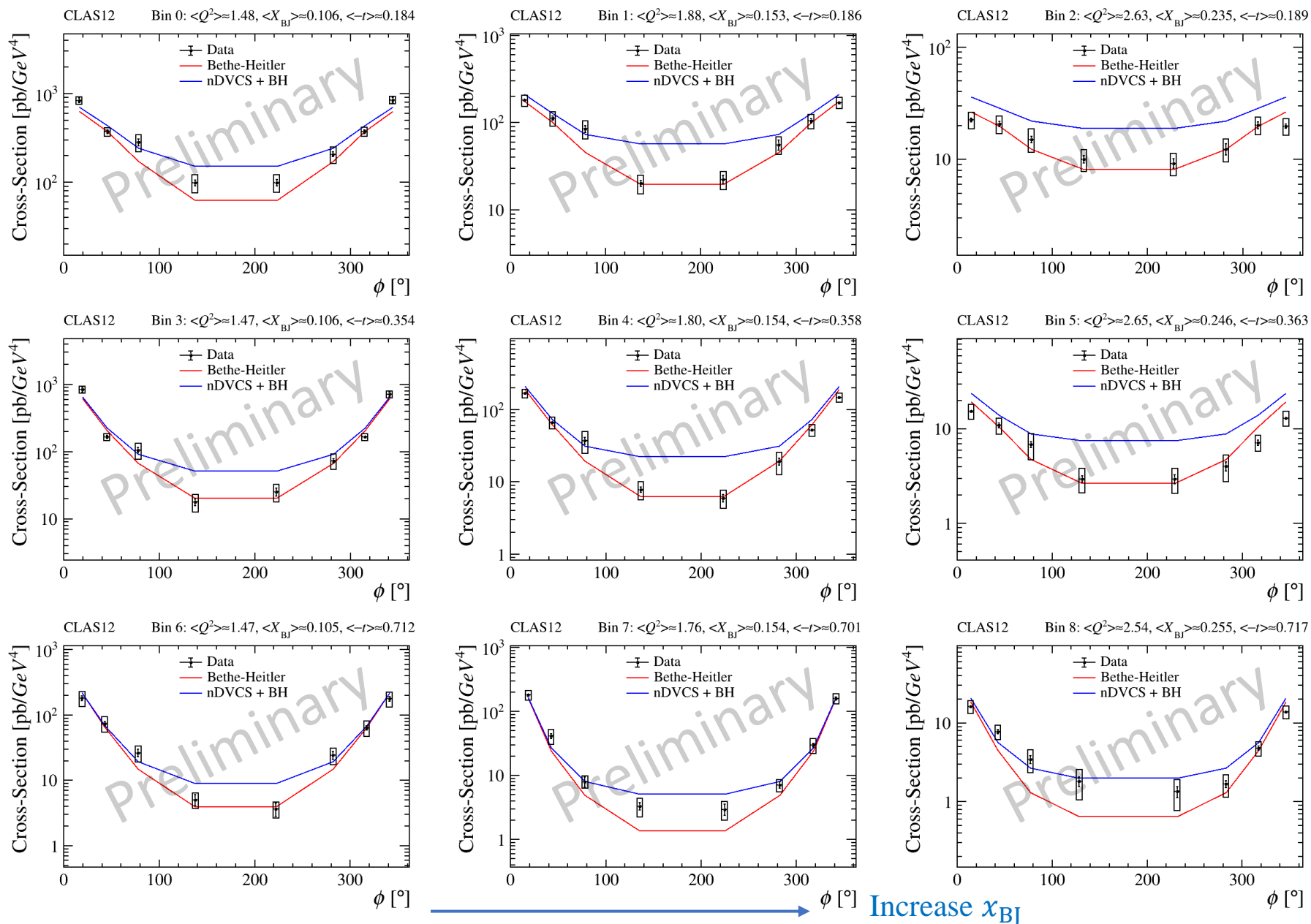
- Polarized cross-section difference

$$\frac{d^4 \vec{\sigma}_{en \rightarrow en \gamma}}{dQ^2 dx_{\text{BJ}} dt d\phi} - \frac{d^4 \overleftarrow{\sigma}_{en \rightarrow en \gamma}}{dQ^2 dx_{\text{BJ}} dt d\phi}$$

$$= \frac{N_+ - N_-}{L_{+(-)} \cdot P \cdot \varepsilon_{\text{acc}} \cdot V}$$

- N_+ is the yield for positive beam helicity
- N_- is the yield for negative beam helicity
- Luminosity $L_{+(-)} = 64.5 \times 10^3 \text{ pb}^{-1}$
- Beam polarization $P = 86\%$





- Linked mainly to the real CFF of GPD E

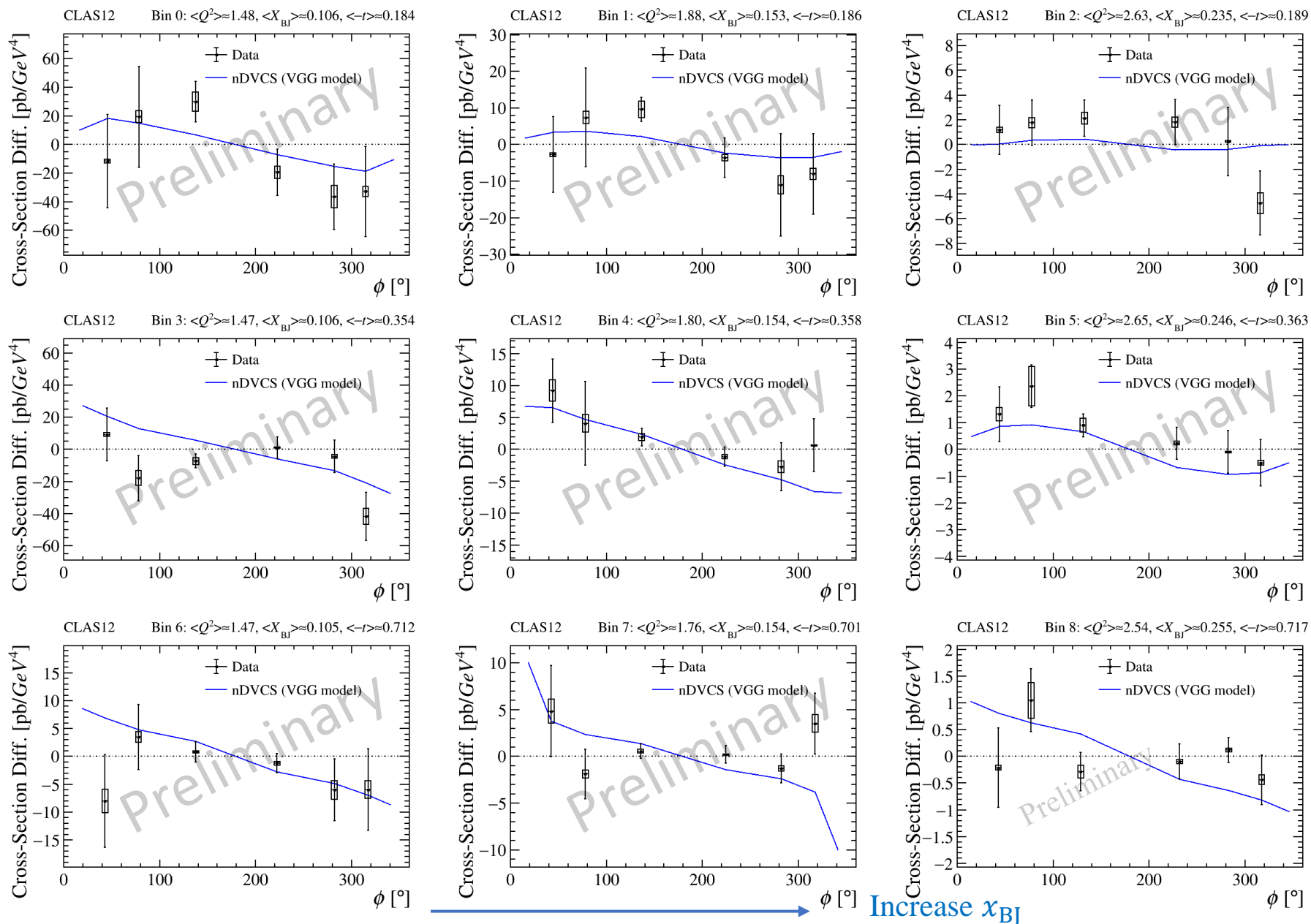
- Error bars: statistical
Boxed: systematic

- The data are compatible with the BH calculations at ϕ edges

- nDVCS+BH predictions: VGG model with $J_u = 0.3$ and $J_d = 0.1$

↓ Increase $-t$

- Predictions overshoot the data in the central- ϕ region, indicating the real CFF of E is not correctly parametrized in the VGG model



$$\Delta\sigma = \frac{N_+ - N_-}{L_{+(-)} \cdot P \cdot \varepsilon_{\text{acc}} \cdot V}$$

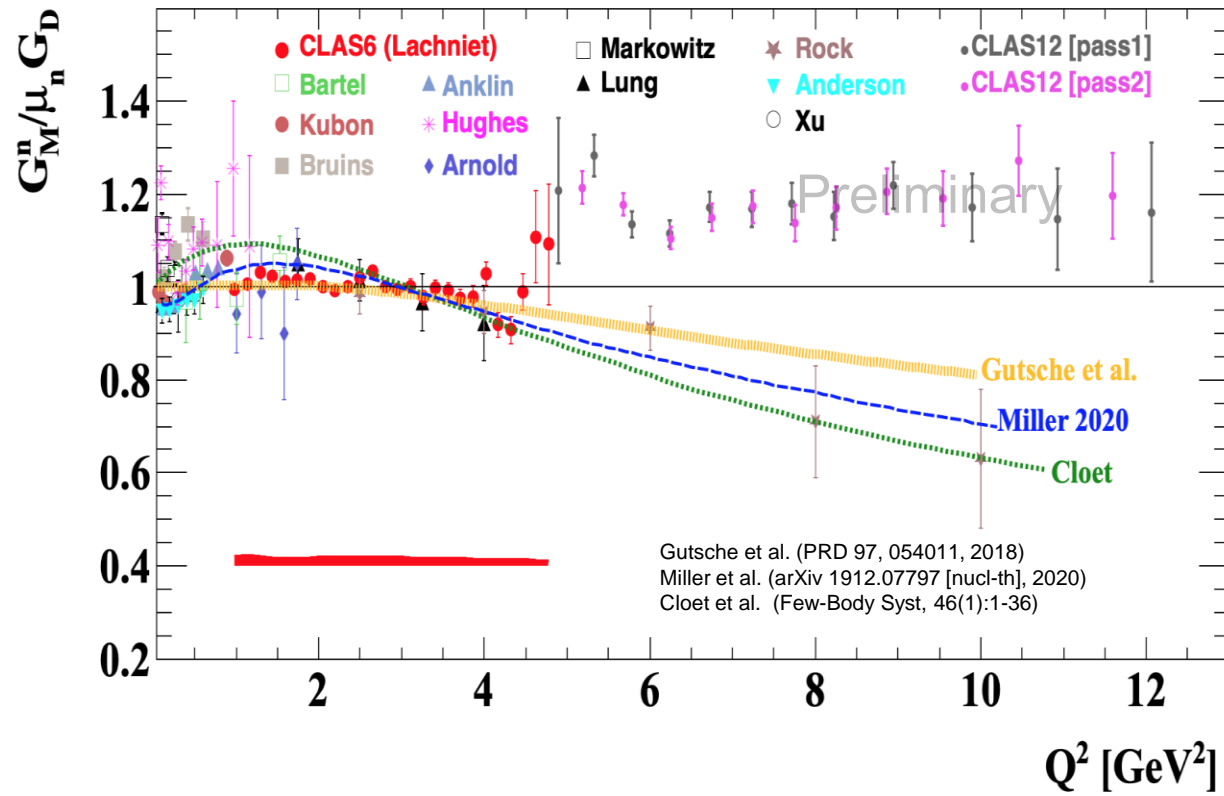
- Linked to the imaginary CFF of GPD E
- Error bars: statistical
Boxed: systematic
- nDVCS predictions: VGG model with $J_u = 0.3$ and $J_d = 0.1$
- The data are consistent with the predictions given the large statistical uncertainties

Analysis note under review (1st round)

Measurement of the Neutron Magnetic Form Factor G_M^n at High Q^2 Using the Ratio Method on Deuterium

L.Baashen (KSU), B.A.Raue (FIU), J.Carvajal (FIU), G.P.Gilfoyle (Richmond)

Goal: Extract G_M^n at high Q^2 using the ratio of quasi-elastic e-n and quasi-elastic e-p events on deuterium.



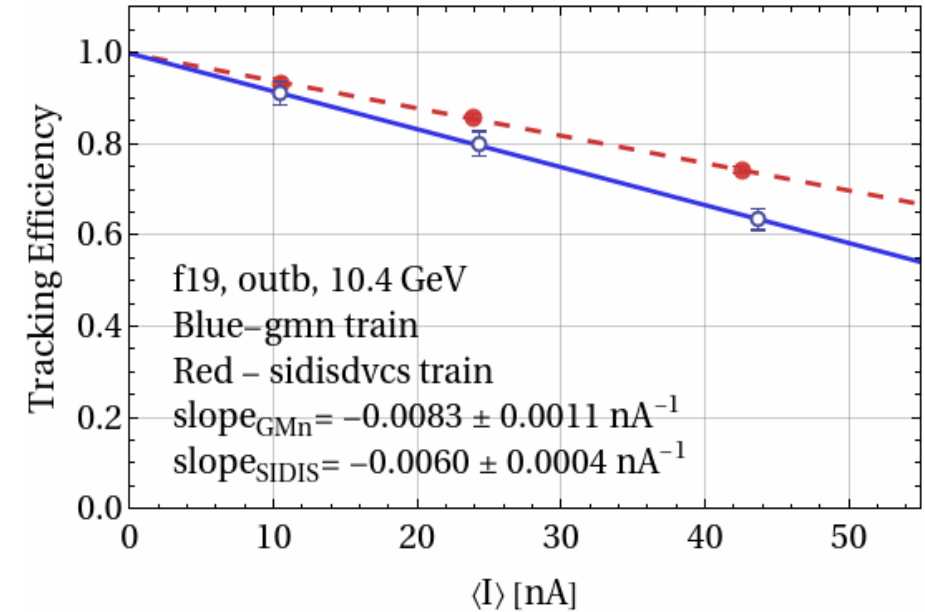
- The neutron magnetic form factor is a fundamental observable related to the distribution of magnetization in the neutron.
- The form factor is extracted from the $e-n/e-p$ ratio.
- Figure to the left shows world's data for G_M^n including preliminary CLAS12 results that still require corrections.
- Pass 1 extraction of ratio is done – Lamy Baashen's FIU thesis.
- Transition to Pass 2 has begun. We observed improvements in the statistics and resolution in preliminary studies.

Measurement of the Neutron Magnetic Form Factor G_M^n at High Q^2 Using the Ratio Method on Deuterium

L.Baashen (KSU), B.A.Raue (FIU), J.Carvajal (FIU), G.P.Gilfoyle (Richmond)

Luminosity Correction

1. The ratio of the number of ep to electron events, N_{ep}/N_e , is normalized to unity at zero current to form the tracking efficiency. See CLAS-NOTE-2020-005 for more details.
2. Average current is extracted from the event data.
3. This correction has a large effect (0.008 nA^{-1}). See plot.
4. Comparison using the same Pass 1 analysis code on SIDIS train data gave a slope consistent with that group's results.

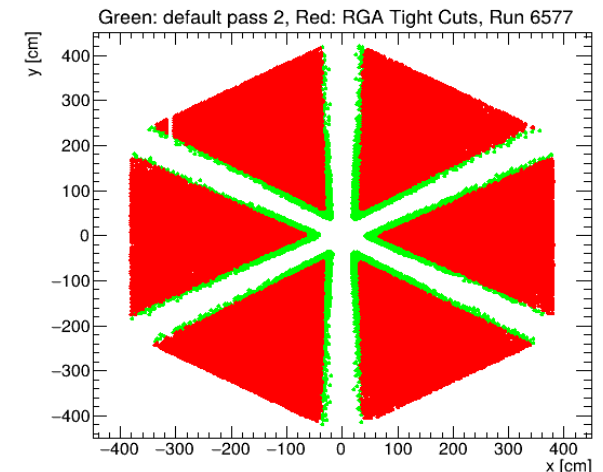


Another Luminosity Test and the Transition to Pass 2

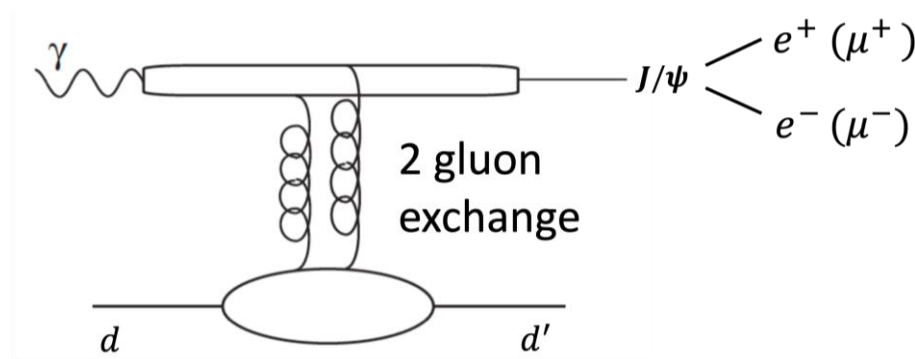
1. To further test the luminosity correction, low-current data (5 nA) are merged with background data generated at the appropriate current and then analyzed.
2. Updated analysis chain to Pass 2 - rebuilt data dictionaries, increased memory allocations, ... etc.
3. Next step - started update the G_M^n analysis code to Pass 2.
4. Effect of PCAL fiducial cuts are shown. RGB survival rates are higher than RGA.

Run Period Survival Rates

Period	Polarity	E_{beam}	Rate
S19	inb	10.6	0.75
S19	inb	10.2	0.84
F19	outb	10.4	0.70
S20	inb	10.4	0.88



Near-threshold cross-section determination for coherent J/ψ meson photoproduction off deuteron

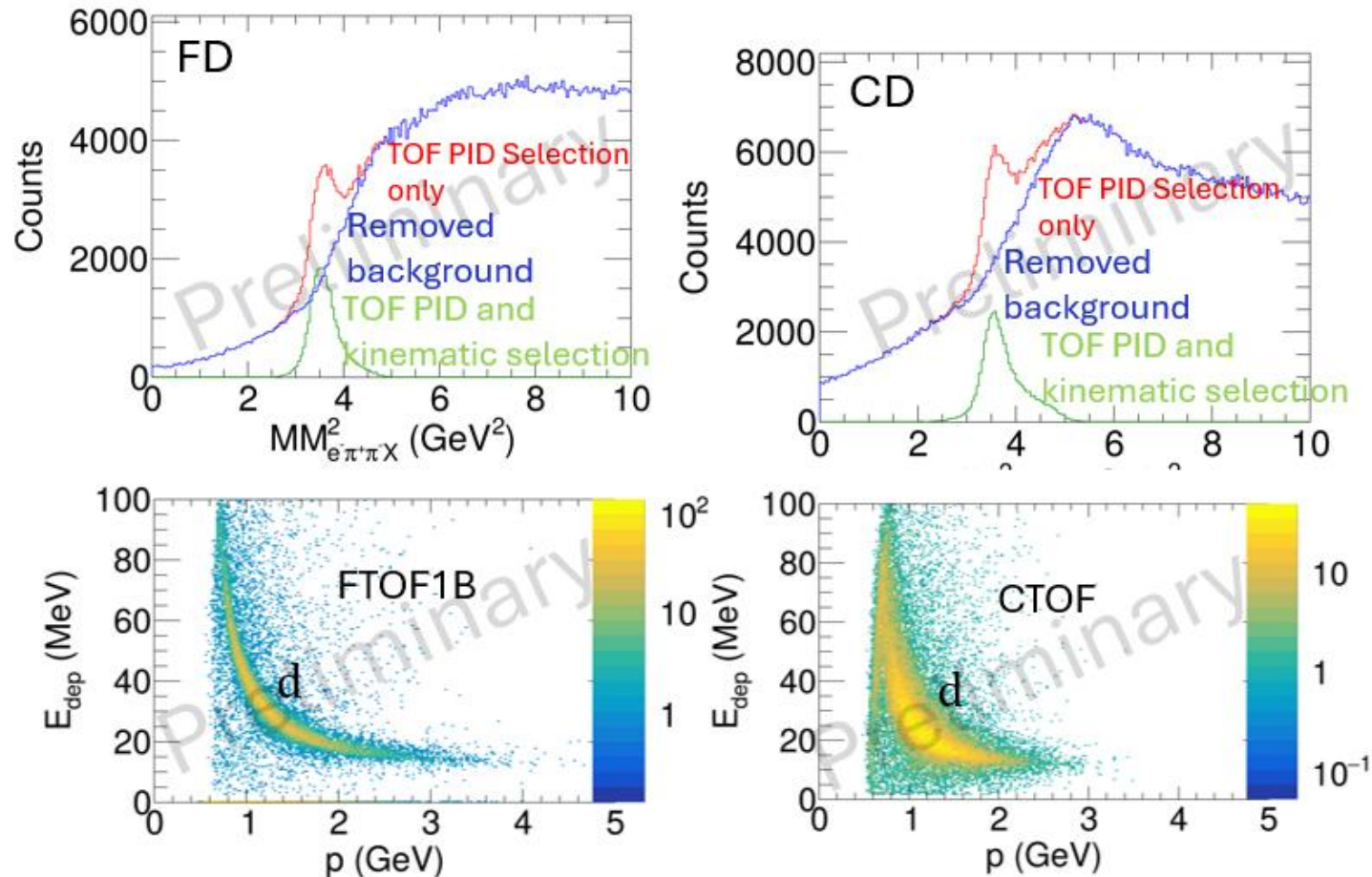


- **Technique:** $\gamma d \rightarrow J/\psi d'$ is measured in untagged quasi-real (virtual photon with very small virtuality) photoproduction. **All final-state particles are detected.**
- **Physics:** Access transverse gluon distribution in deuteron (following on the work done for the nucleon)
- **Data Analysis Plan:**
 - Yield extraction:
 1. **Particle identification** : recent work focuses on improving deuteron identification
 2. Reaction selection via four-momentum conservation
 3. Background subtraction
 - Luminosity determination
 - Determination of the CLAS12 acceptance for coherent process
 - Binning studies for cross section extraction

Obtaining Background-Free Deuterons: Analysis of $ed \rightarrow e' \pi^+ \pi^- d'$

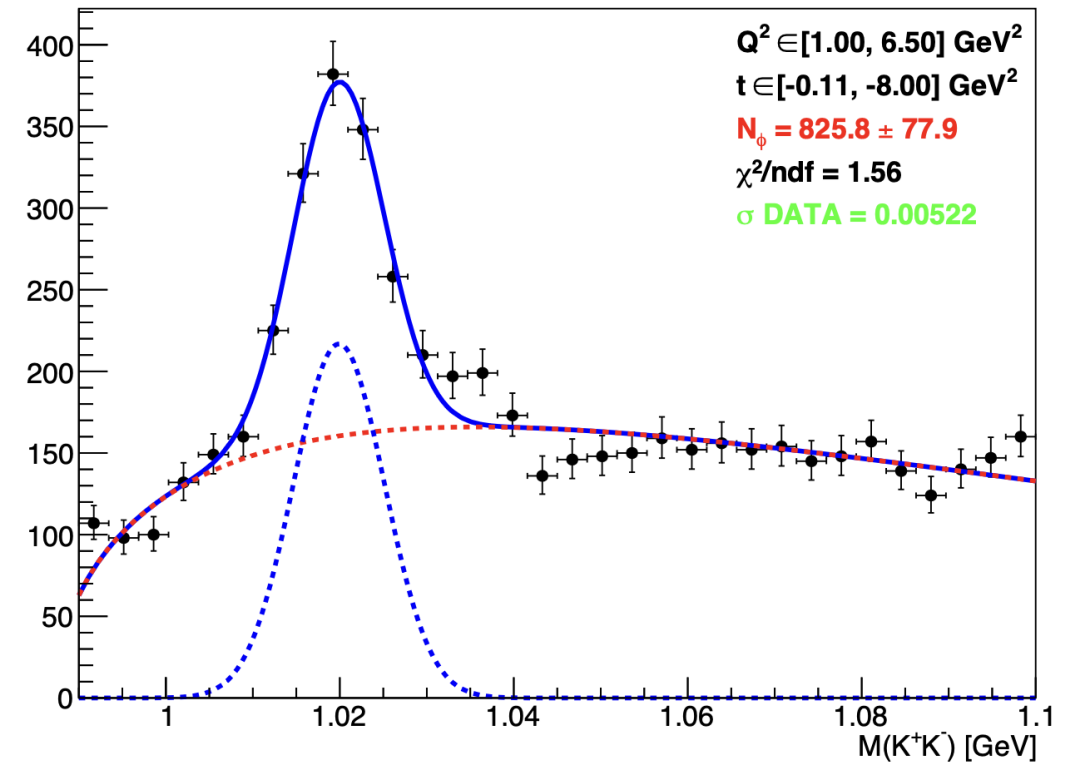
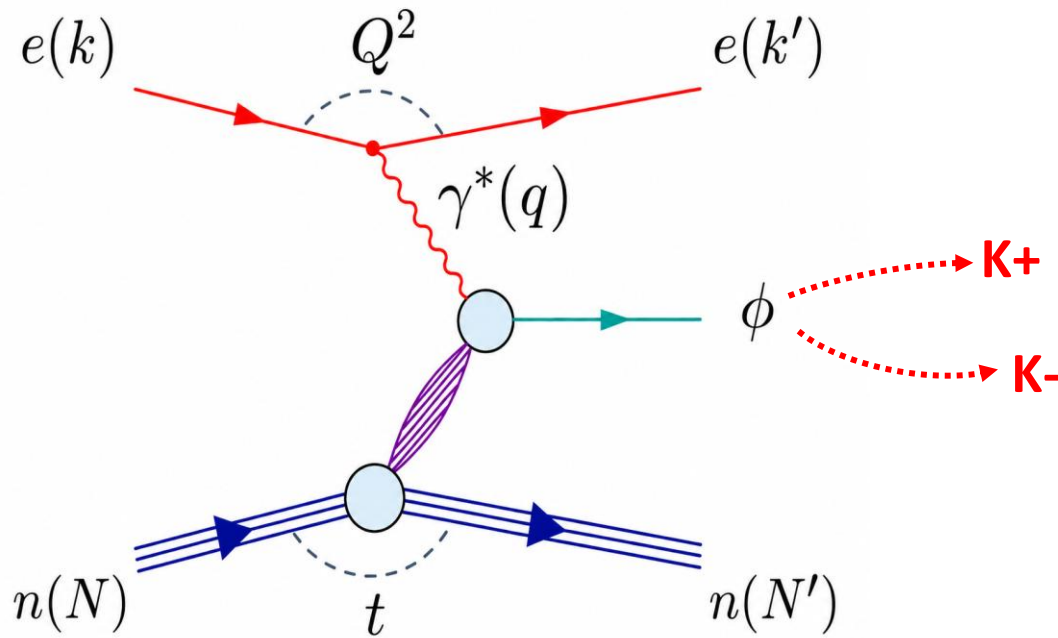
Improved deuteron ID: Aim to have a neural network trained on **clean deuteron and background samples**, making use of **all PID variables** (TOF, Edep) simultaneously to identify deuterons.

A clean high-statistics deuteron sample is obtained from the RGB data set, from the reaction $ed \rightarrow e' \pi^+ \pi^- d'$, where all final state particles are detected. A large set of kinematic cuts were defined to remove the background.



In both FD and CD the kinematic selection reduces the background to an acceptable level. We thus have a sufficiently clean deuteron sample for training.

Next: to obtain clean background samples from the data; to verify results by means of detector simulation.

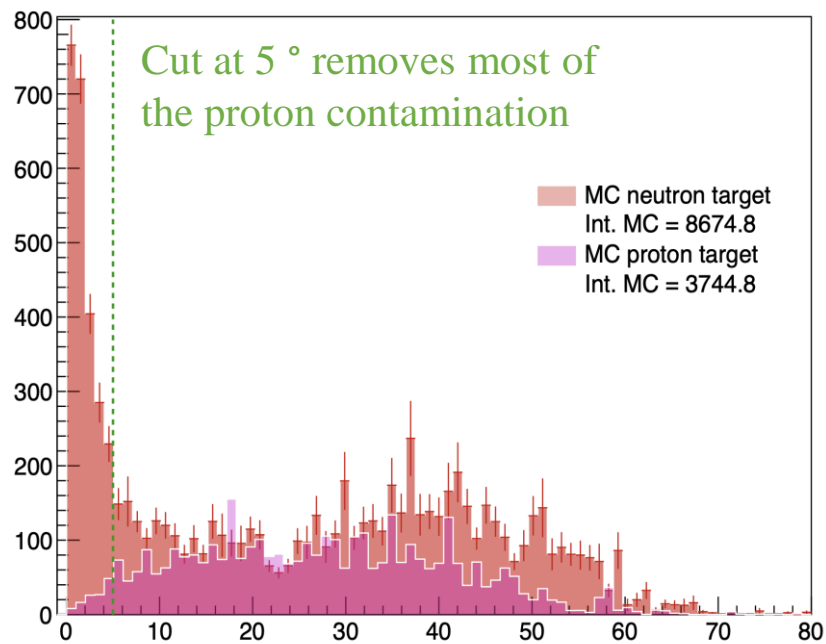
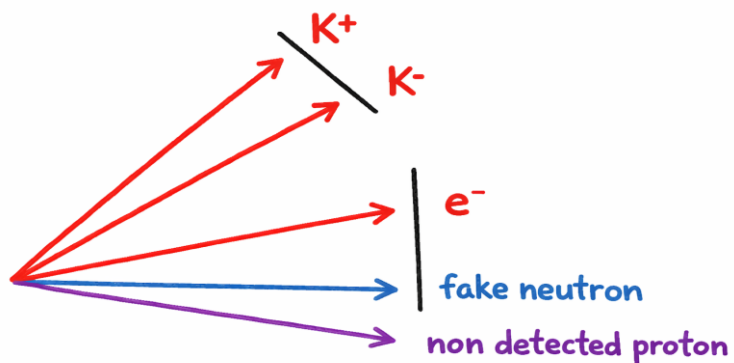


Fall2019 outbending

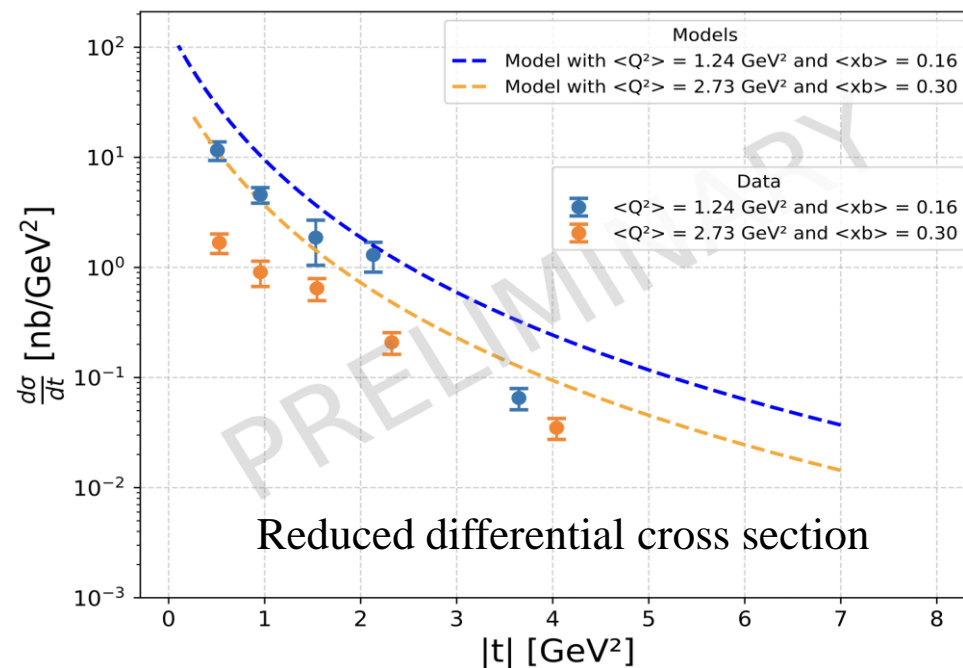
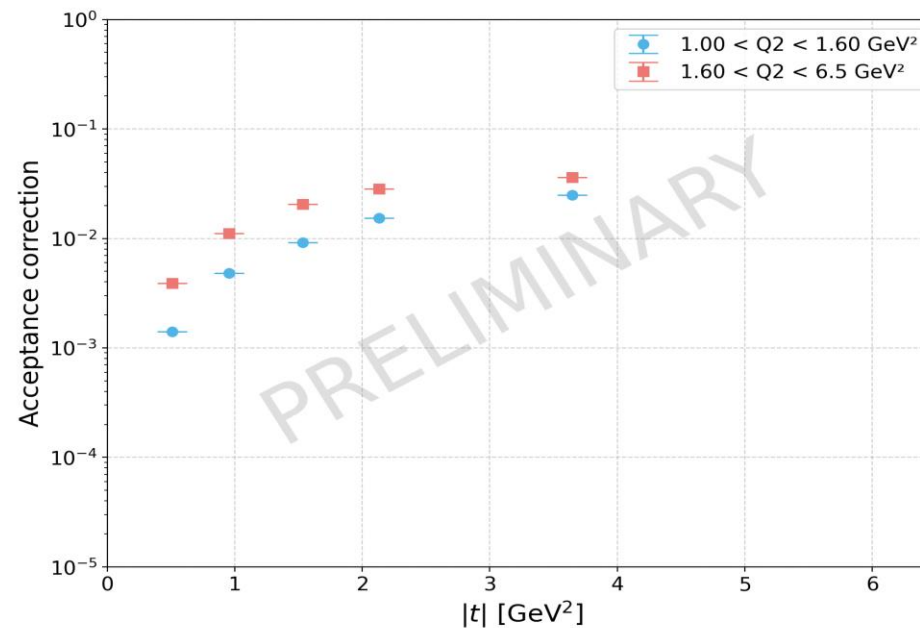
- Measurement sensitive to gluon GPDs of the neutron, unknown so far
- It will allow to compare to similar works on the proton

eK^+K^-n detected, n mainly in FD

Contamination from ϕ production on the proton when the **missing nucleon** is a **non detected proton** and there is a **fake neutron** signal



angle between the **missing nucleon** and the **detected neutron** (°)

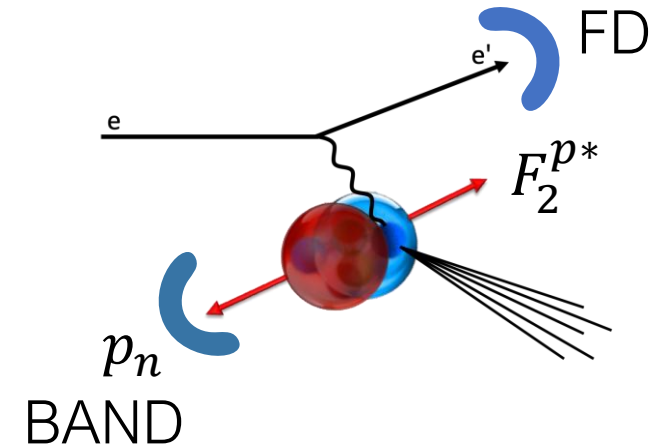


Observable (double ratio):
$$\mathcal{R}(\alpha_{S,i}, x') = \frac{Y_{exp}(\alpha_{S,i}, x') / Y_{exp}(\alpha_{S,i}, x'_0)}{Y_{sim}(\alpha_{S,i}, x') / Y_{sim}(\alpha_{S,i}, x'_0)}$$

α_s : spectator neutron light-cone momentum fraction

x' : Bjorken scaling variable for a moving nucleon

$x'_0 = 0.3$



- Neutron-tagged DIS from deuterium, tagged by the detection of a **high-momentum spectator neutron**, allows the study of the **bound proton structure function F_2^{p*}** when the proton is in a high-momentum, highly-virtual state
- The experimental yield is proportional to the bound proton structure
- The simulated yield is proportional to the free proton structure (free used in event generator)
- The double ratio is sensitive to bound/free proton cross section
- Comparing the ratio with theoretical predictions allows one to disentangle the various effects (nucleon motion, short-range correlations, binding) contributing to the modification of the structure function.
- **The analysis note based upon RGB data is under review in the CLAS Collaboration**

Current analysis task: Subtract non-physics background contribution

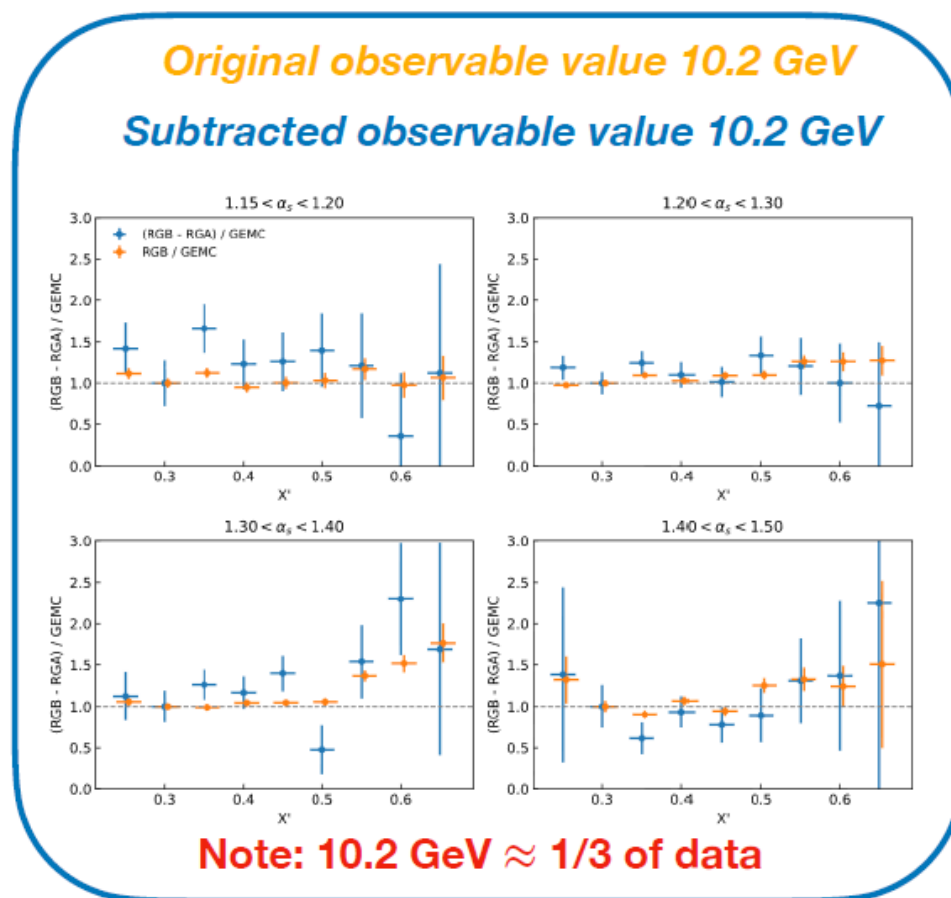
- BAND sees “neutrons” in RGA $H(e, e'n_{BAND})$
- Kinematically impossible for RGA signal from primary interaction (likely secondary γ 's)

Done:

- To account for σ_d^{DIS} vs. σ_p^{DIS} , scale RGA data by relative number inclusive electrons, subtract from RGB 10.2 GeV

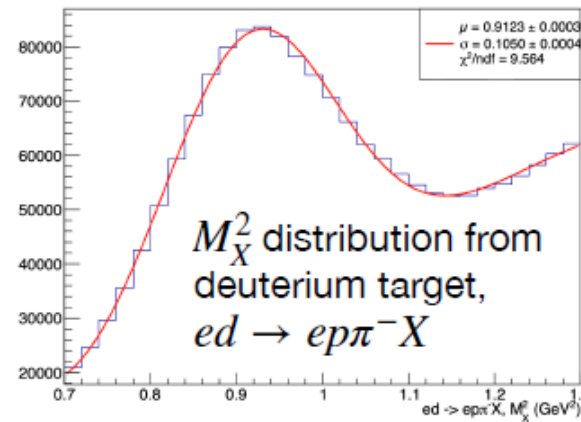
Next:

- Scale RGA 10.2 GeV data to subtract from RGB 10.4, 10.6 GeV and access all available statistics

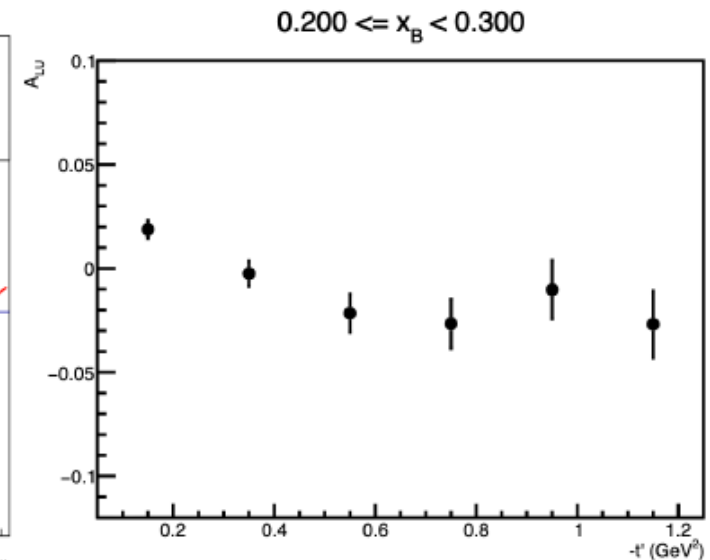
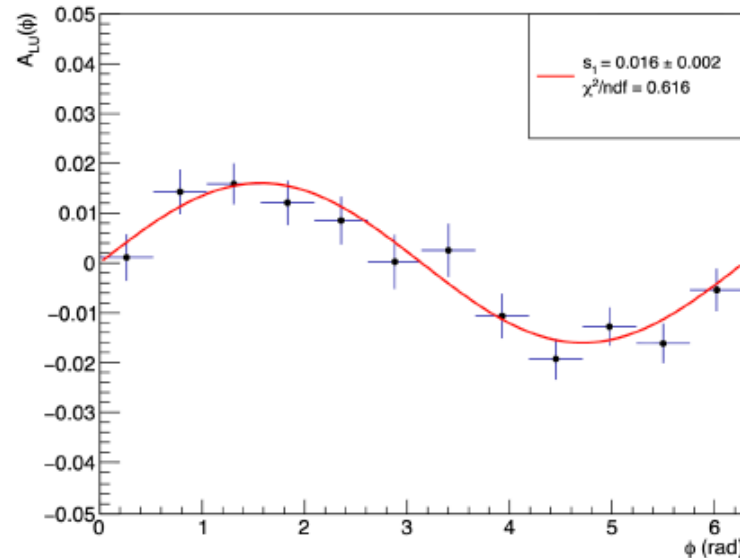


Exclusive π^- beam spin asymmetries

- Deeply virtual meson production \rightarrow access to chiral odd GPDs
 - $A_{LU}^{\sin \phi}$ sensitive to H_T, E_T
- Complementary study to RG-C analysis on set of DV π^- P asymmetries: no analysis yet of exclusive π^- BSA
 - Understanding behaviour on deuterium target helps interpret nuclear target
- Very preliminary results suggest considerable contributions of negative amplitude $A_{LU}^{\sin \phi}$ in $(x_B, -t')$ kinematics, leading to a small amplitude integrated asymmetry

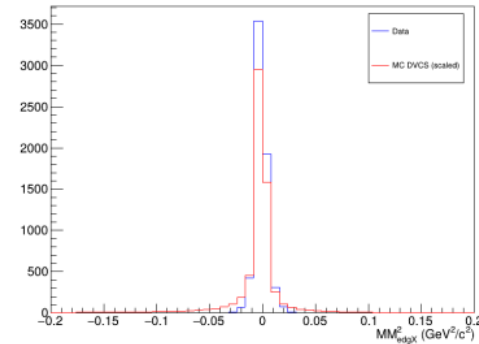
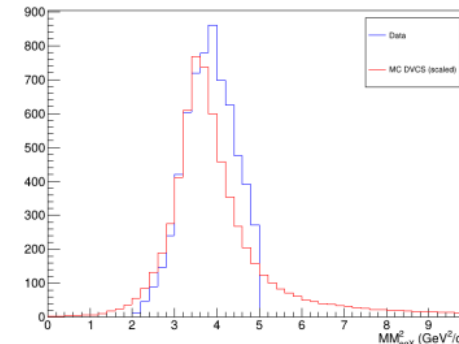
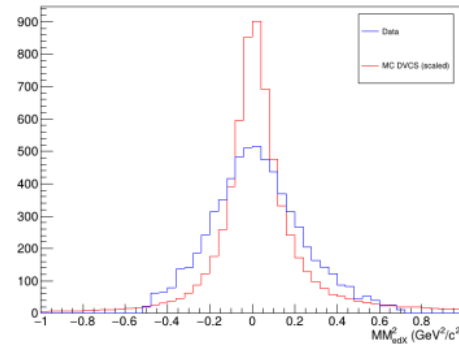


- (Left) M_X^2 distribution with deuterium target
- (Bottom left) Fully integrated beam spin asymmetry
- (Bottom right) Example of 2D $(x_B, -t')$ bins including negative asymmetry amplitudes

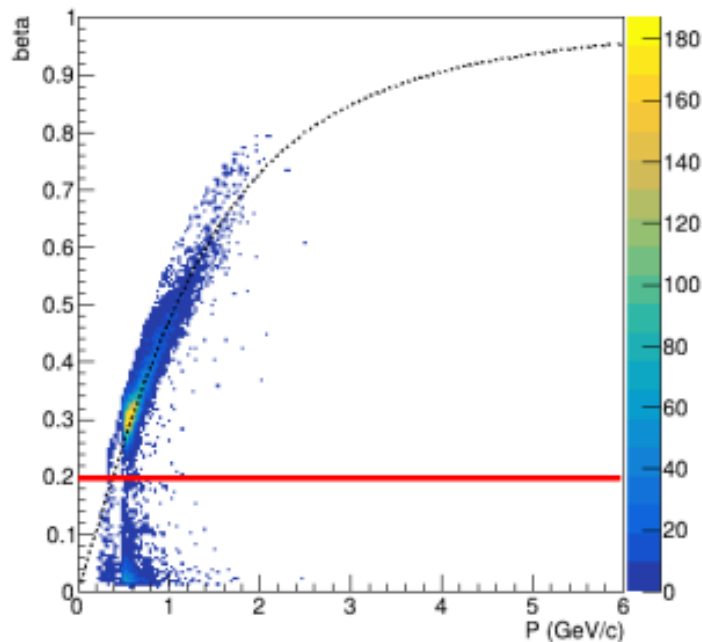


$$\mathcal{A}_{LU}^I(\phi) \simeq -\frac{x_D(2-y)\sqrt{\frac{-t}{Q^2}(1-y)}}{2-2y+y^2} \Im m \tilde{D}_U^{1,1} \sin \phi$$

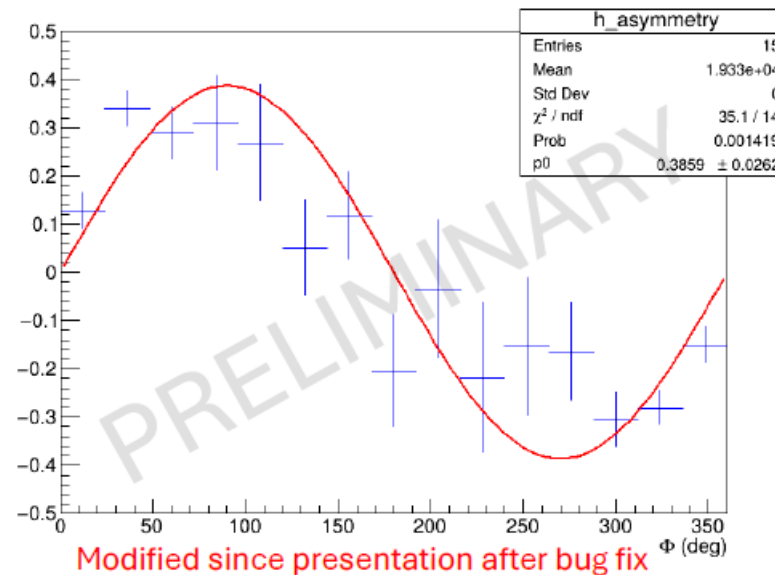
$$\tilde{D}_U^{1,1} \equiv \frac{3G_1(\mathcal{H}_1) - 2\tau[G_1(\mathcal{H}_3) + G_3(\mathcal{H}_1) - \frac{1}{3}(\mathcal{H}_5)] + 4\tau^2 G_3(\mathcal{H}_3)}{3G_1^2 - 4\tau G_1 G_3 + 4\tau^2 G_3^2}$$



CD: beta vs p after cuts



Raw BSA integrated over all kinematics



Fit function : $A \cdot \sin(\Phi)$

Next steps:

- Subtract π^0 background
- Refine cuts
- Estimate systematic errors
- Optimize binning
- Write analysis note

Conclusions

- Run Group B aims at mapping the **3D structure of the neutron** via electroproduction on deuterium
- **Quark-flavor separation** of the measured structure functions combining with proton data, and much more...
- The first « half » of RG-B running ended on January 30 2020
- **~38.9 PAC days collected out of the 90 PAC days approved for nDVCS**
- Three different beam energies for the 3 periods
- Physics analyses **published or under review** : **nDVCS BSA**, J/ψ , pDVCS BSA, Tagged-DIS, nDVCS cross section
- Physics analyses in **advanced state**: G_M^n , Di-hadron SIDIS (not shown), K^+ SIDIS (not shown)
- **New physics analyses ongoing/planned**: Coherent J/ψ , exclusive π^- , d-DVCS, SRCs in p/nDVCS (not shown)...

Thanks a lot to all the RGB analyzers for their contributions 😊