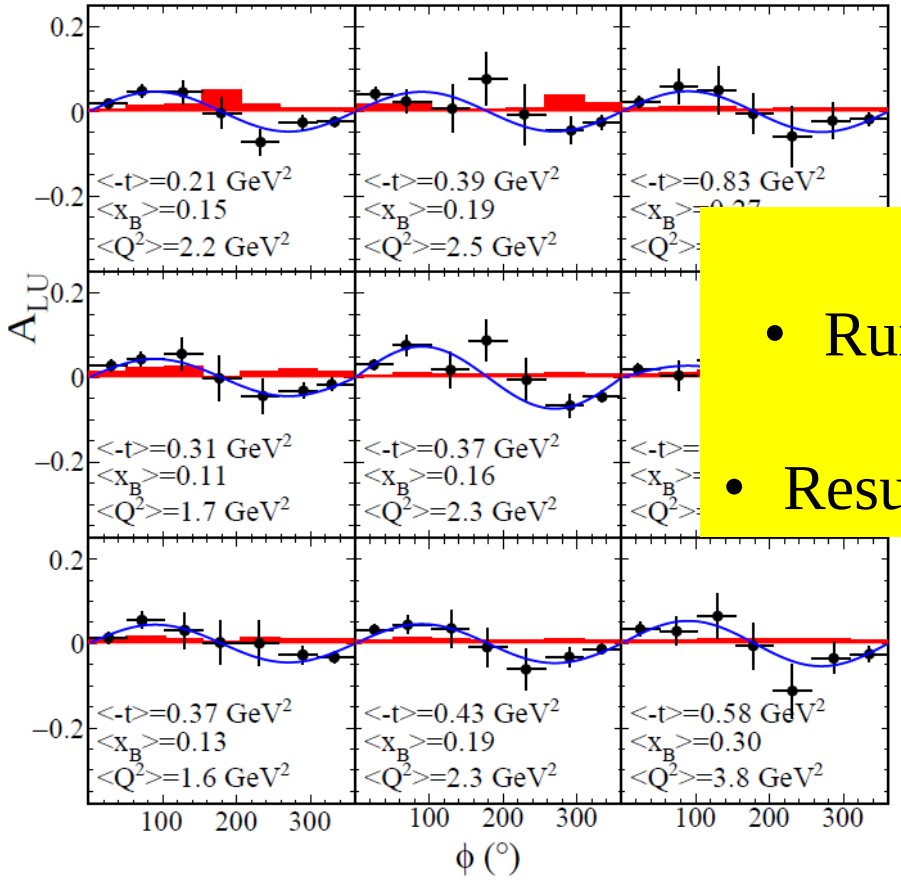
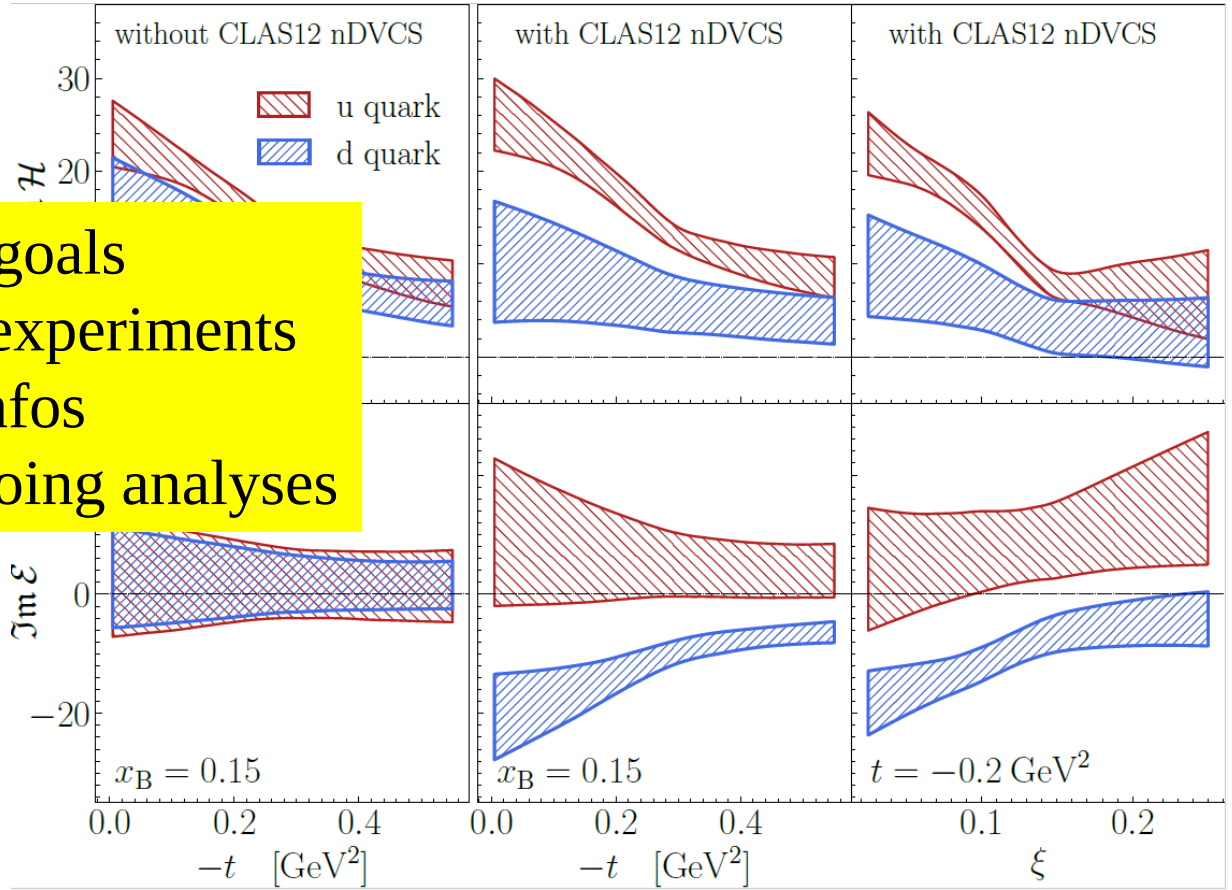
Run Group B

Electroproduction on deuterium with CLAS12



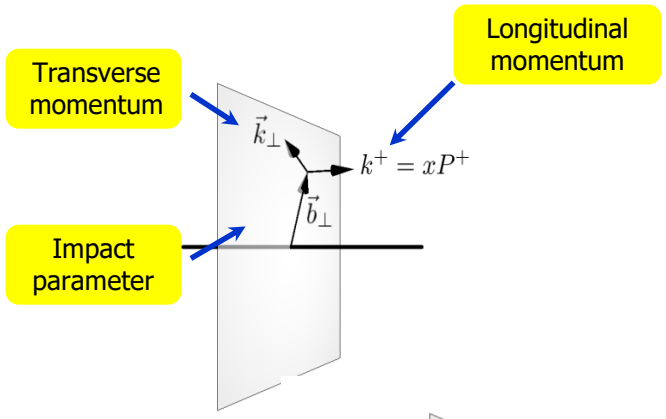
- Physics goals
- Run Group B experiments
- Run infos
- Results and ongoing analyses

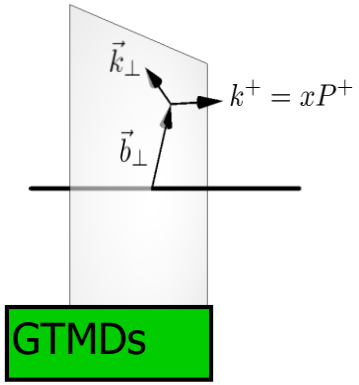


Silvia Niccolai, IJCLab Orsay (France)

CLAS Collaboration Meeting, 11/18/2025

Multi-dimensional mapping of the nucleon



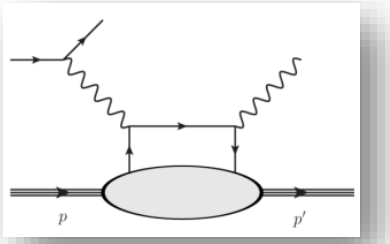


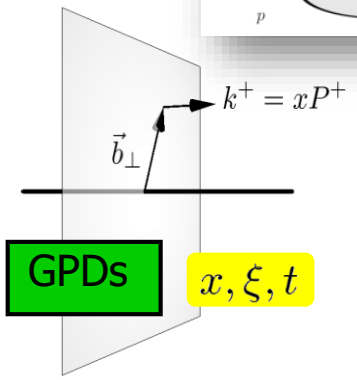
$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

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

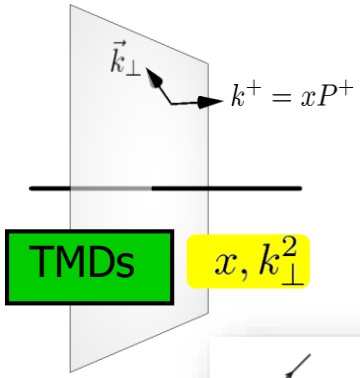
$\int \mathrm{d}^2\vec{b}_\perp$

DVCS and DVMP



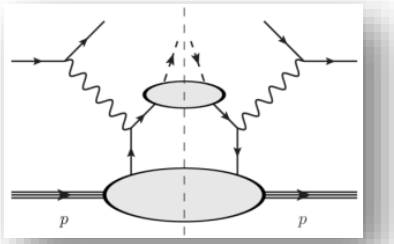


x, ξ, t



$x, k_\perp^2$

SIDIS

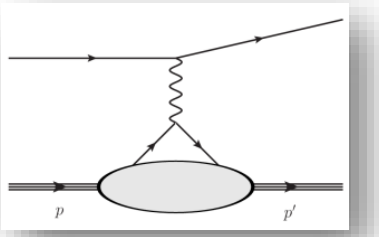


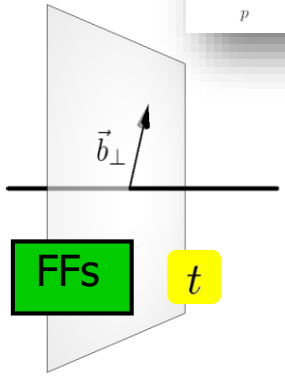
$\int \mathrm{d}x$

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

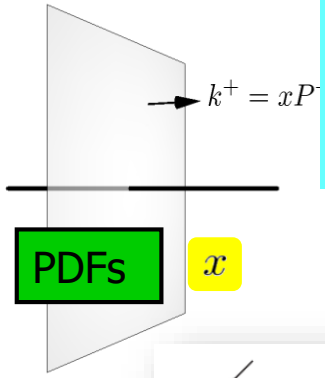
$\int \mathrm{d}^2\vec{k}_\perp$

Elastic Scattering



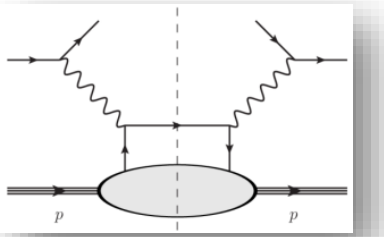


t



x

DIS

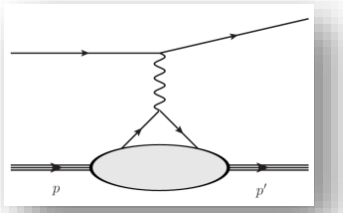


A complete picture of nucleon structure requires the **measurement of all these distributions**.

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

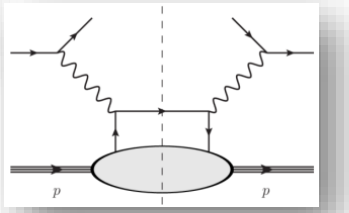
+ EMC effect, SRC
+ J/ψ photoproduction on deuteron

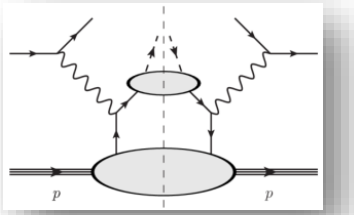
CLAS12 Run Group B: experiments



Elastic Scattering (G^n_M)

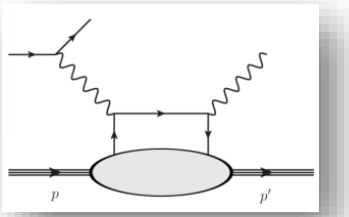
DIS (for SRC and EMC effect)

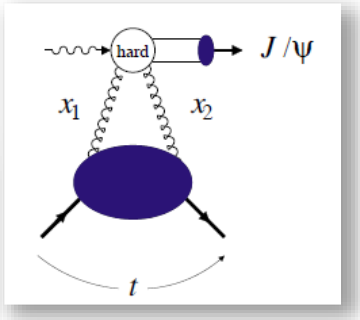




SIDIS (for PDFs and TMDs

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:

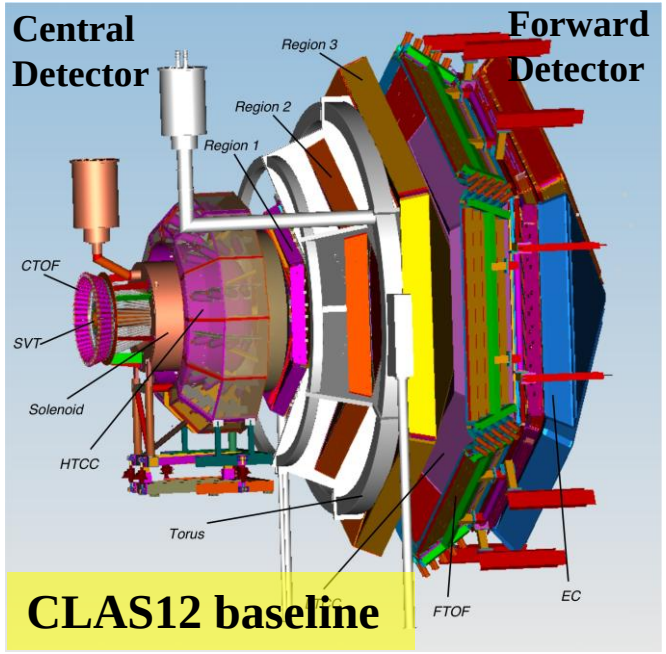
- 10.6 GeV (9.7 B inbending e^-) Spring19
- 10.2 GeV (11.7 B inbending e^-) Spring19
- 10.4 GeV (9 B outbending e^-) Fall19, **(**12.9 B inbending e^-) Spring20

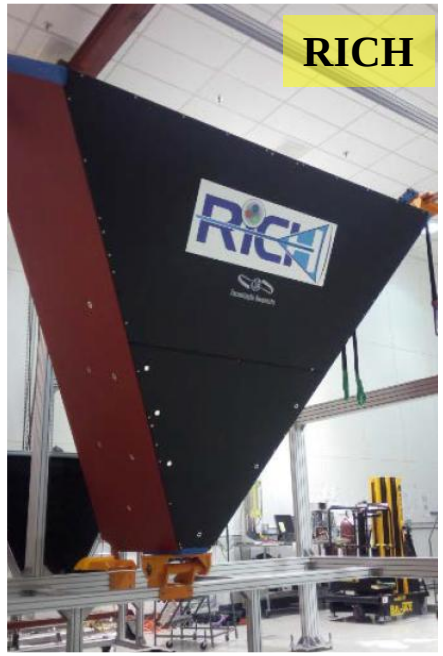
➢ Average beam polarization ~86%
➢ Liquid deuterium target, 5 cm long

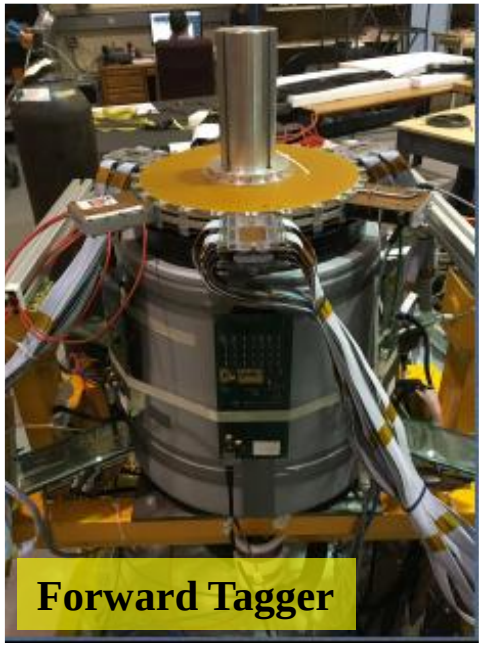
38.9 total PAC days according to ABUs
→ 51 PAC days left to run, approved by PAC52

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)







R. Tyson (JLab/Glasgow)

J/ψ Near-Threshold Photoproduction

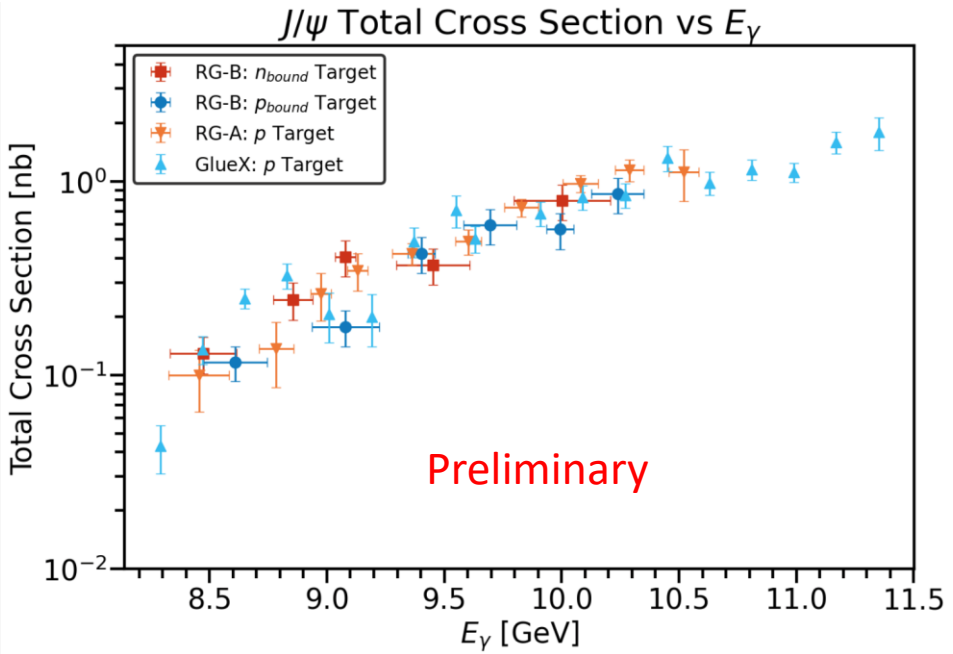
$\gamma N \rightarrow (e')J/\psi \rightarrow (e)e^+e^-N$

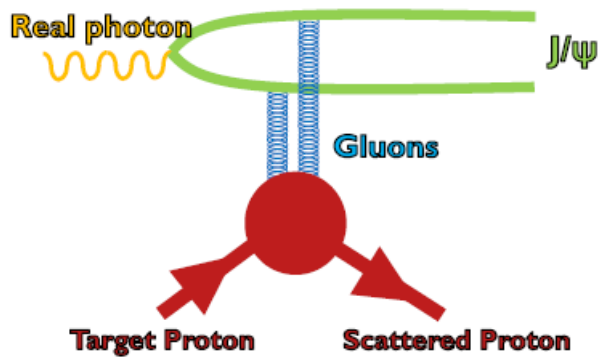
Close to the 8.2 GeV threshold, J/ψ photoproduction is predicted to be mediated by the **exchange of two gluons**.

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** via holographic QCD or GPD models.

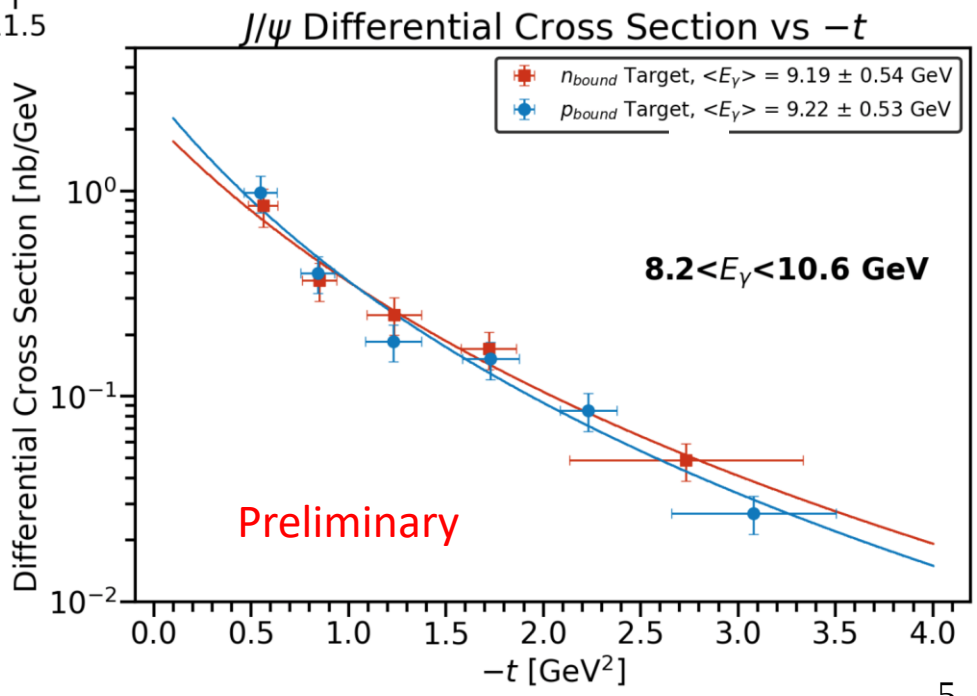
The analysis is under CLAS review (2nd round).





$$\frac{d\sigma}{dt} = \mathcal{N}^2 \frac{e^2}{64\pi(s-M_N^2)^2} \frac{[A^g(t)+\eta^2 D^g(t)]^2}{A^{g2}(0)} \cdot \tilde{F}(s) \cdot 8$$

$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2-M_N^2)^2} \frac{(16\pi\alpha_S)^2}{3M_V^3} |\phi_{NR}(0)|^2 |G(t,\xi)|^2$$



R. Tyson (JLab/Glasgow)

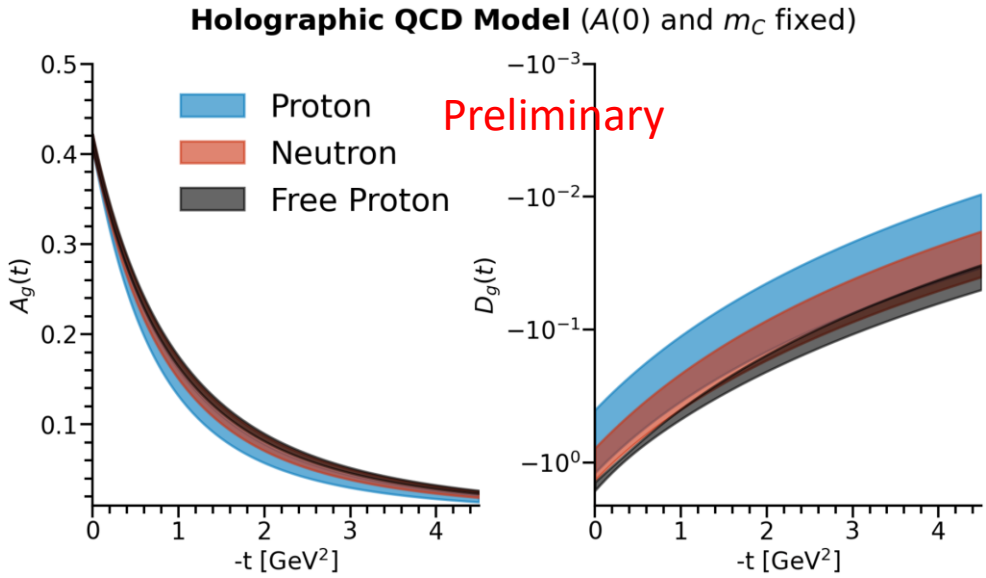
Mechanical Form Factors

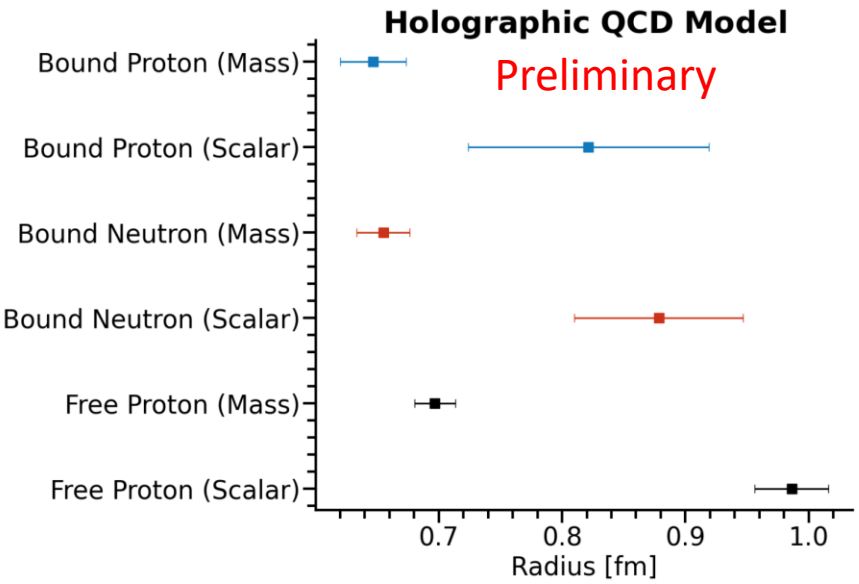
$\gamma N \rightarrow (e')J/\psi \rightarrow (e)e^+e^-N$

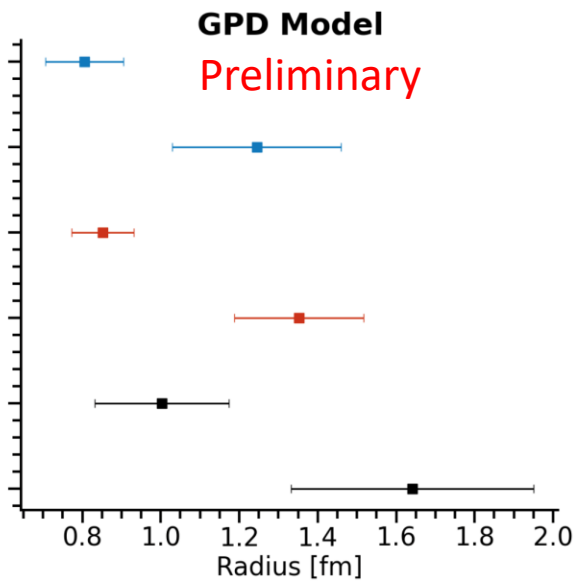
Fit the mechanical form factors to differential cross section

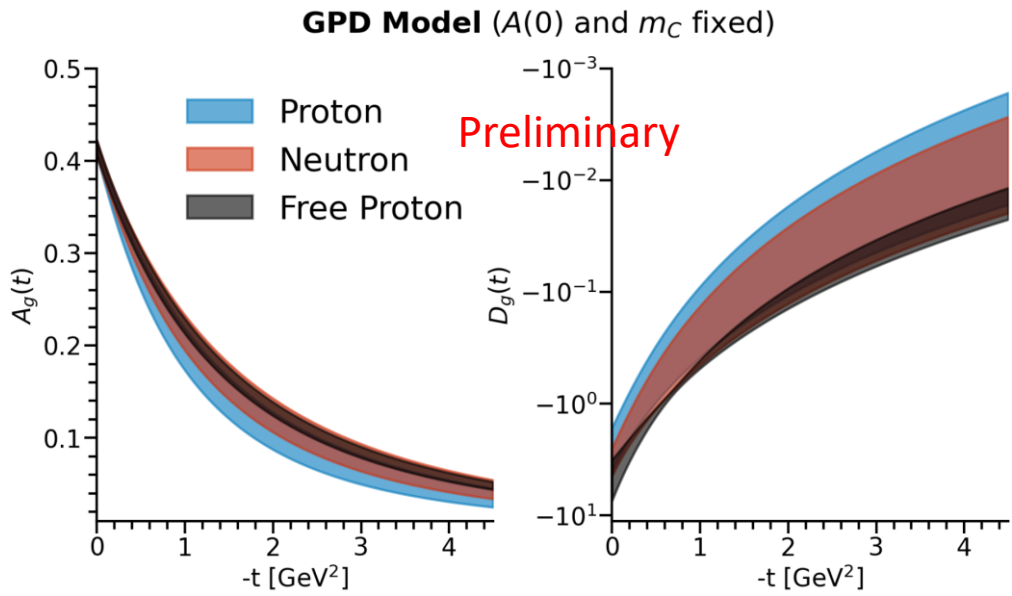
Some assumptions:

- Neglect $B(t)$ and $\bar{C}(t)$.
- Assume tripole shape for form factors (eg $C(t) = \frac{C_0}{\left(1 * \frac{t}{m_C^2}\right)^3}$).
- Fix A_0 to the average gluon PDF from CT18
- Fix m_C to free proton data
- Assume Final State Interactions contributions are negligible



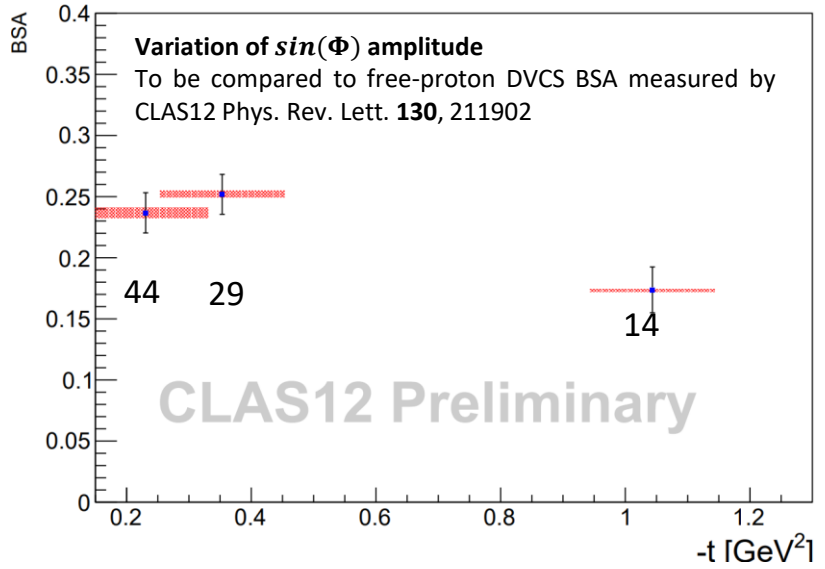


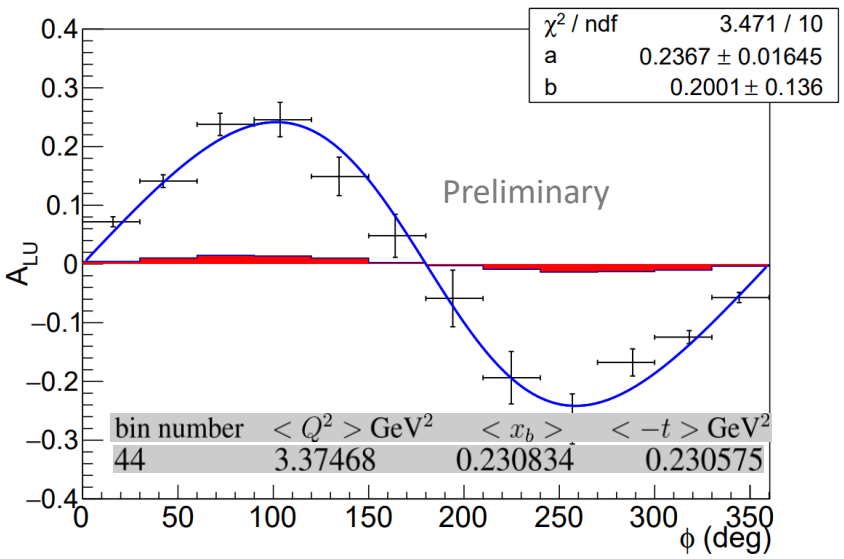


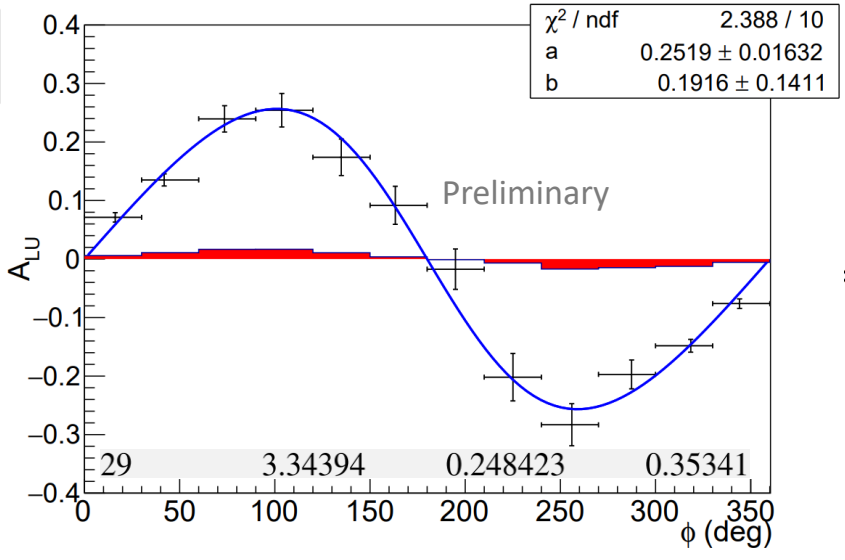


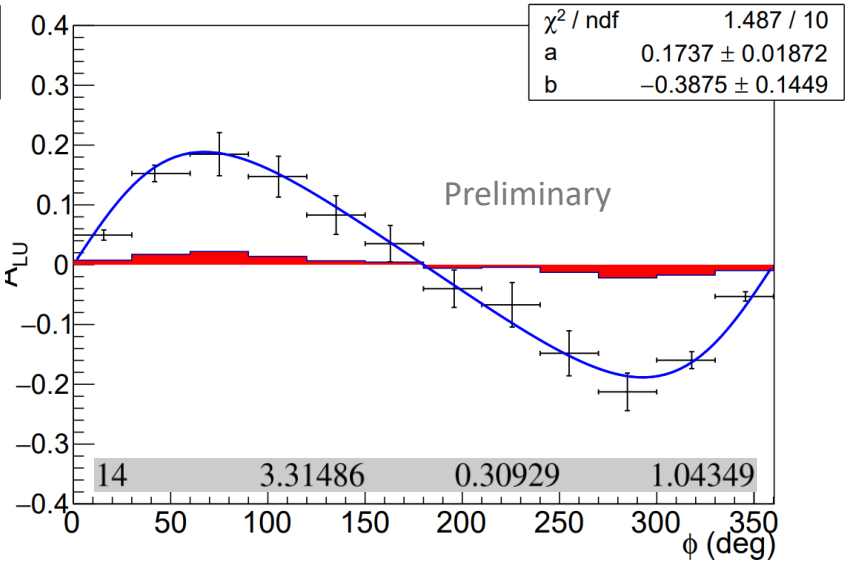
pDVCS on a deuterium target

- First-time measurement of incoherent pDVCS on deuteron
  - Quantify medium effects on GPDs by comparing to BSA from free proton target (RGA)
- Systematic errors include:
  - Error due to beam polarization
  - Error due to selection cuts
  - Error due to merging of data sets with different energies
- Statistics is expected to triple with remaining schedualed beam time and improvements in reconstruction software (currently using pass1 data)



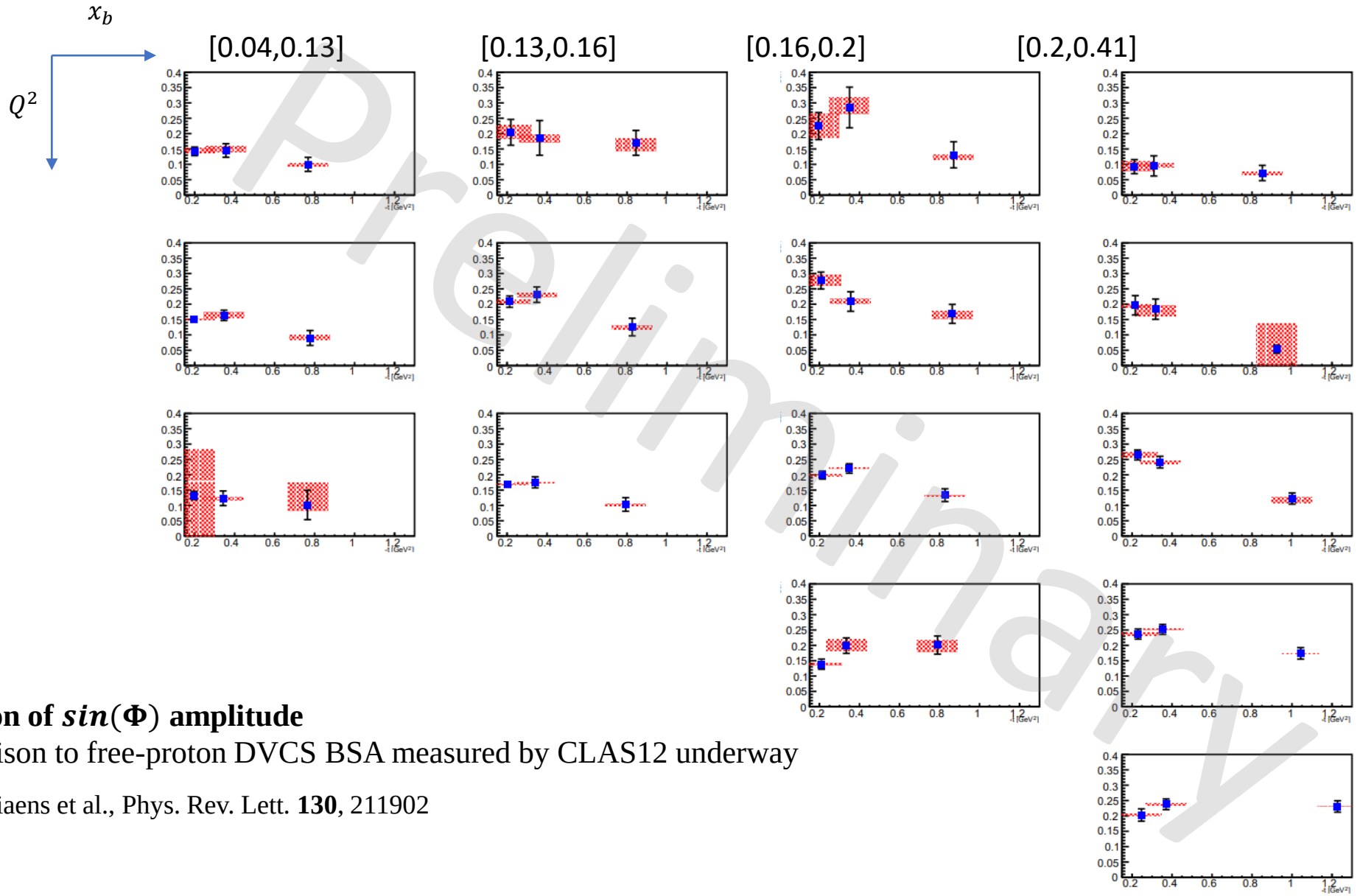






pDVCS on a deuterium target

$\vec{e}d \rightarrow en\gamma(p)$



Variation of $sin(\Phi)$ amplitude

Comparison to free-proton DVCS BSA measured by CLAS12 underway

G. Christiaens et al., Phys. Rev. Lett. **130**, 211902

Analysis note has been in review for a while, a new round of replies is in preparation

E. Segarra (MIT)
T. Kurtz (MIT)
J. Phelan (MIT)

BAND/CLAS12 tagged DIS analysis

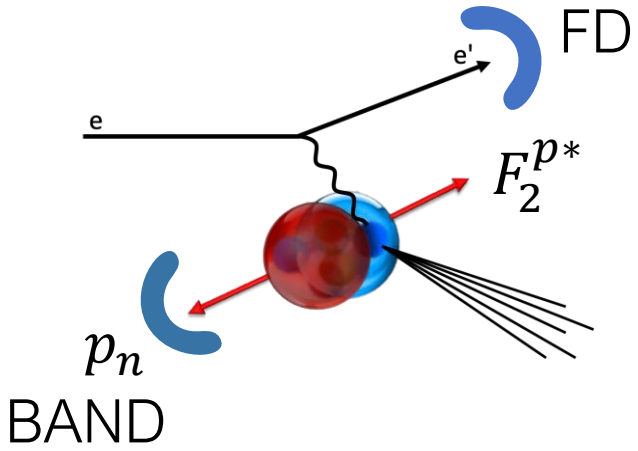
ed→enX

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

$x'_0=0.3$



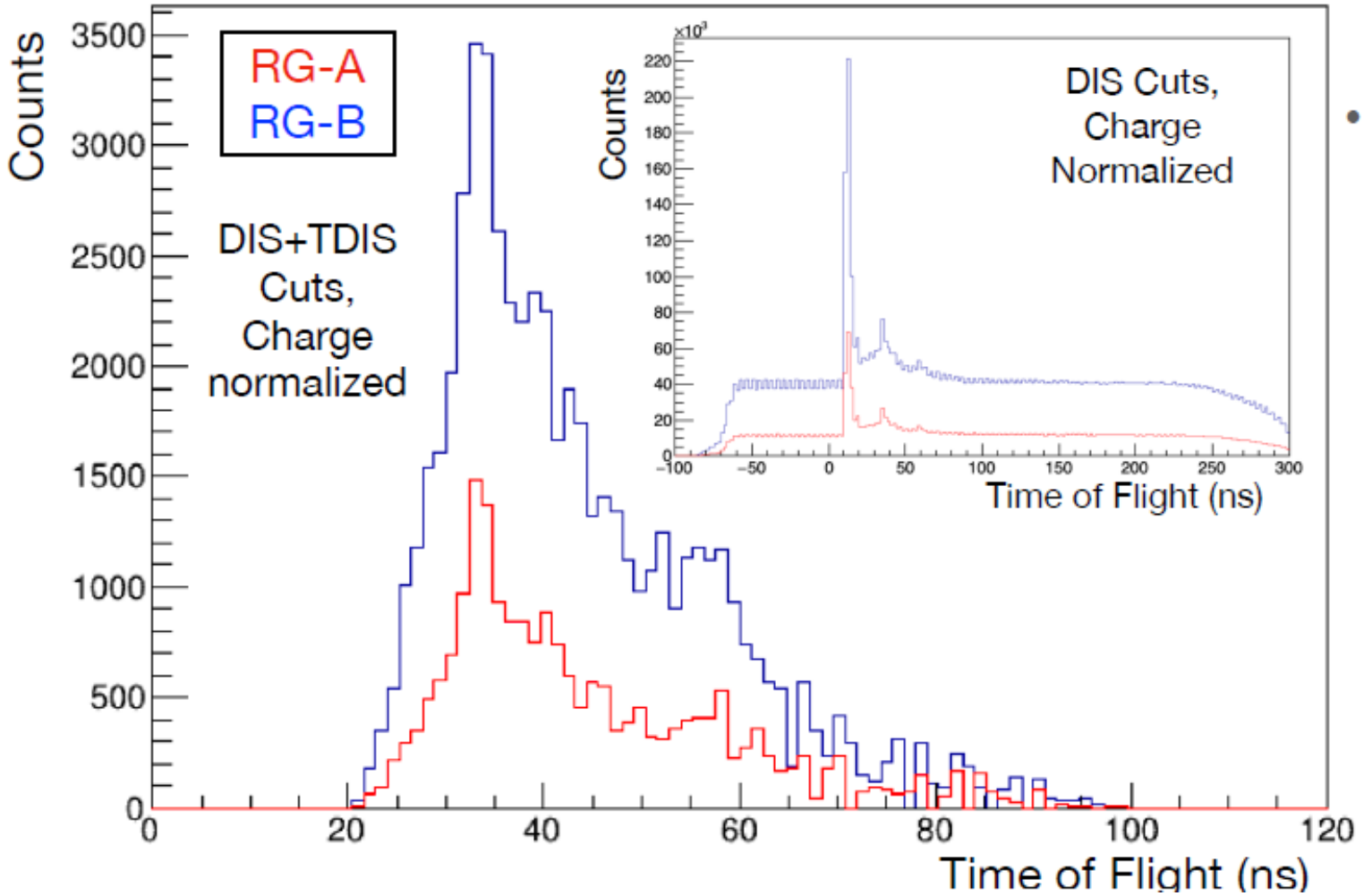
- Neutron-tagged DIS from deuterium, tagged by the detection of a **high-momentum spectator neutron**, allows the study of the **bound proton structure function F_2^{*p}** when the proton is in a high-momentum, highly-virtual state
- The experimental yield is proportional to the bound proton structure
- 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.
- An analysis note based upon RGB data is under review in the CLAS Collaboration

E. Segarra (MIT)
T. Kurtz (MIT)
J. Phelan (MIT)

BAND/CLAS12 tagged DIS analysis

ed→enX

Analysis note on measurement of $\mathscr{R} = \left(\frac{F_2^{p*}}{F_2^p}(x',\, \alpha_S)\right) \Big/ \left(\frac{F_2^{p*}}{F_2^p}(x' = .3,\, \alpha_S)\right)$ **in review**



Recent Analysis Updates

- Studying non-physics background contribution to $d(e, e'n_{spectator})$ signal in BAND using RG-A data
  - Analyzed $p(e, e'n)$ data, where it is kinematically impossible to produce a backward neutron from stationary proton target
  - Testing various methods to scale this background and subtract

More details in BAND Analysis Update

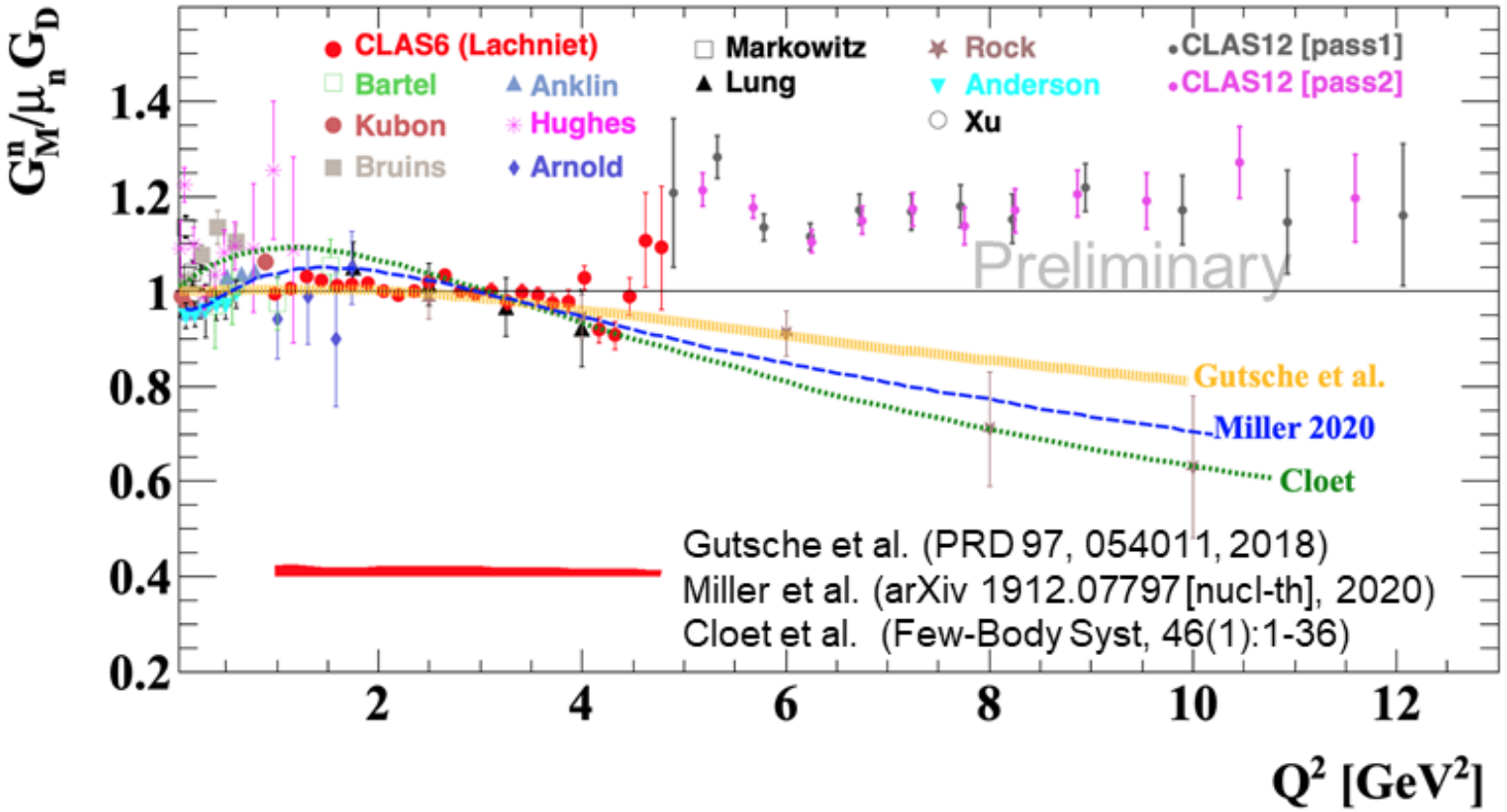
Measurement of the Neutron Magnetic Form Factor G_M^n at High Q^2 Using the Ratio Method on Deuterium

ed→en(p)

ed→ep(n)

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: $R = \frac{d(e,e'n)p}{d(e,e'p)n}$



Completed corrections to the e-n/e-p ratio R.

The e-n/e-p ratio has been corrected for nuclear effects, Fermi motion, radiative corrections, and the proton and neutron detection efficiencies.

1. The neutron magnetic form factor is a fundamental observable related to the distribution of magnetization in the neutron.

2. The form factor is extracted from the *e-n/e-p* ratio.

3. Figure to the left shows world's data for G_M^n including preliminary CLAS12 results that still require corrections.

4. Pass 1 extraction of ratio is complete – L. Baashen's FIU doctoral thesis.

5. Pass 2 data shows increased statistics and improved resolution.

$$R = \frac{d(e,e'n)p}{d(e,e'p)n}$$

Corrections to the e-n/e-p ratio

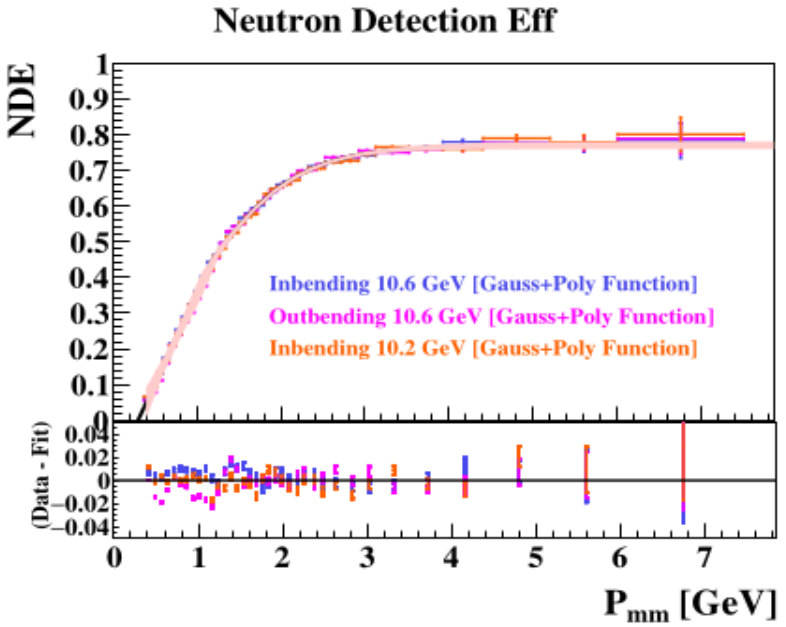
ed→en(p)

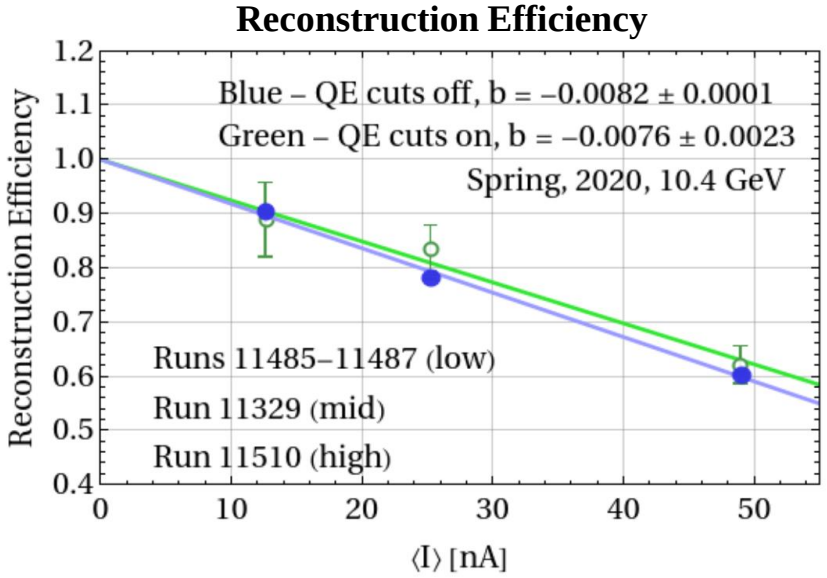
ed→ep(n)

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

Neutron Detection Efficiency (NDE) Method

1. NDE is the biggest ratio correction.
2. Detect a $p(e,e'\pi^+)X_n$ event and predict if the neutron strikes CLAS12 (expected neutrons). If it fails drop the event.
3. Search for neutron and, if found, include it as a detected neutron. The ratio of detected to expected forms the NDE.
4. Extract the missing mass distributions for 36 missing momentum bins in the range P_{mm} = 0.41-6.75 GeV.
5. The figure shows the NDE for three measurements from Run Group A. Bottom panel is the residuals between the measured NDE and a parameterization.
6. Draft of CLAS12-NOTE ongoing.





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 reconstruction efficiency. See figure below. Also see CLAS-NOTE-2020-005 for more details.
2. The plot shows the reconstruction efficiency for one data set for quasi-elastic (QE) events (green) and with the QE cuts turned off (blue) to increase the statistics. Slopes are consistent. Slopes for all data sets have been extracted and are consistent with each other.
3. Tests of analysis code on SIDIS data consistent with that analysis.
4. Low-luminosity data with added high-luminosity background data are now being studied to validate the analysis.

nDVCS cross section

- Unpolarized cross section

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

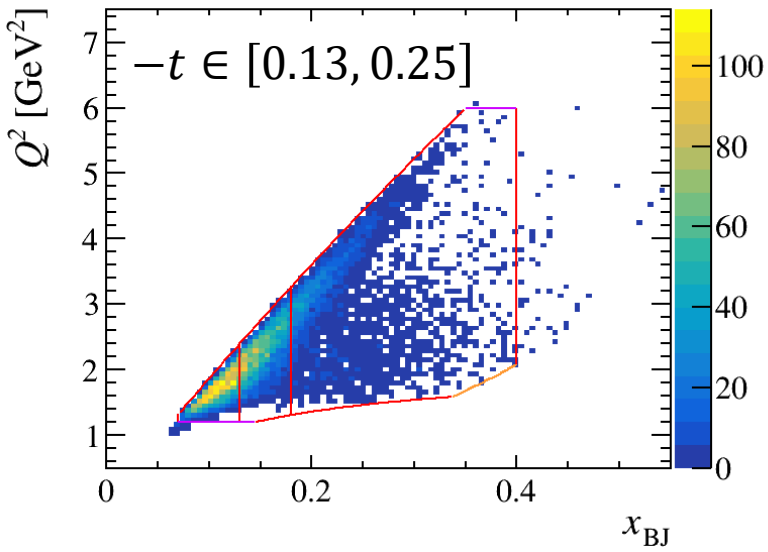
- $N_{en\to en\gamma}$ is the yield after π^0 background subtraction in each $(Q^2, x_{\mathrm{BJ}}, -t, \phi)$ bin
- Luminosity $L = 134.1 \times 10^3$ pb^{-1}
- Acceptance ε_{acc} determined from MC
  - Neutron detection efficiency is corrected using the RGB $ep \to en\pi^+$ data
  - BDT cut to remove fake neutrons; its efficiency is corrected with data ($\Delta\phi$ fit)
- V is the bin volume

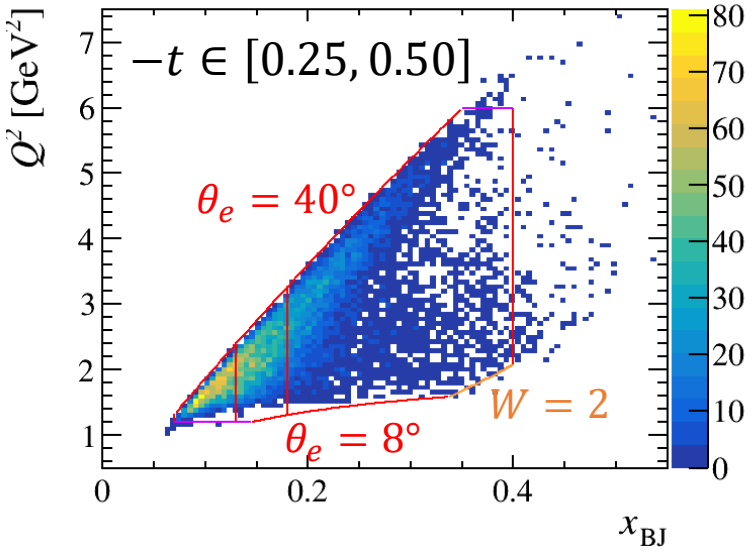
- Polarized cross-section difference

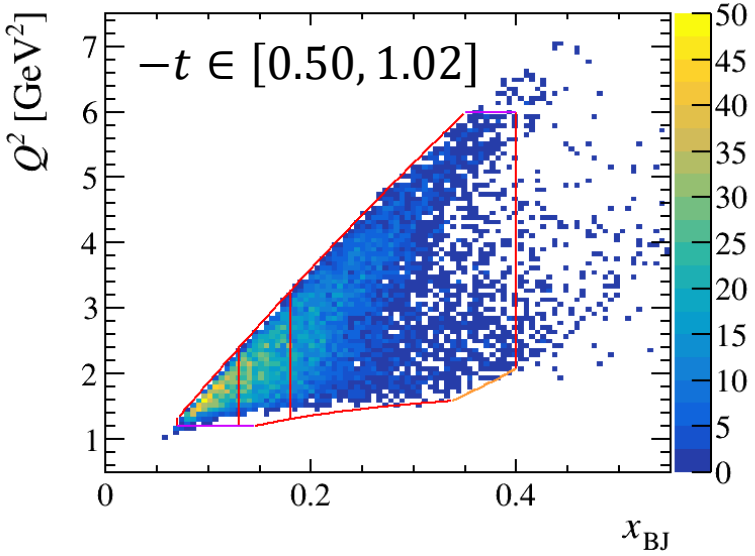
$$\frac{d^4\vec{\sigma}_{en\to en\gamma}}{dQ^2 dx_{\mathrm{BJ}} dt d\phi} - \frac{d^4\overleftarrow{\sigma}_{en\to en\gamma}}{dQ^2 dx_{\mathrm{BJ}} dt d\phi}$$

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

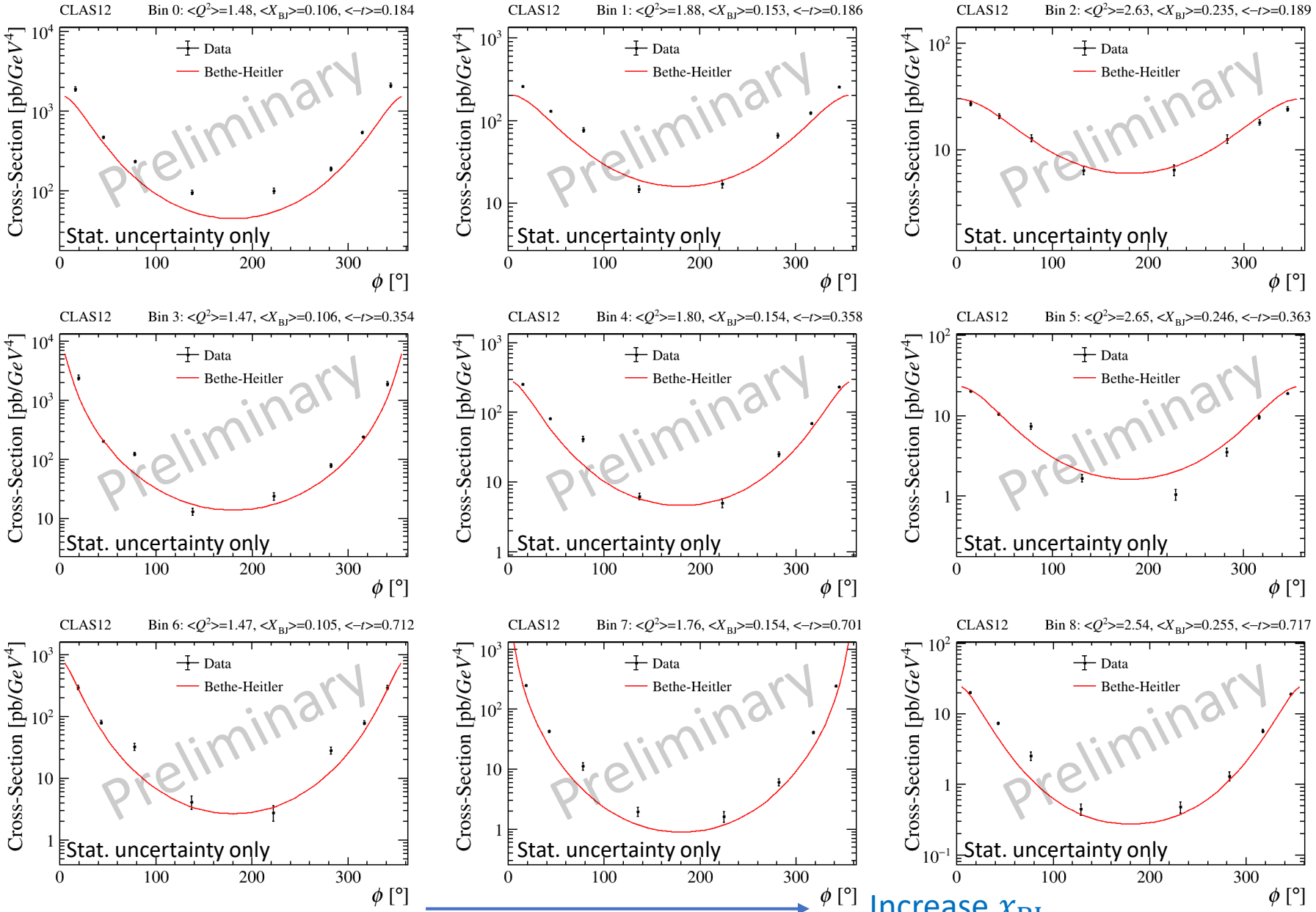
- N_+ is the yield for positive beam helicity
- N_- is the yield for negative beam helicity
- Luminosity $L_{+(-)} = 64.5 \times 10^3$ pb^{-1}
- Beam polarization $P = 86\%$







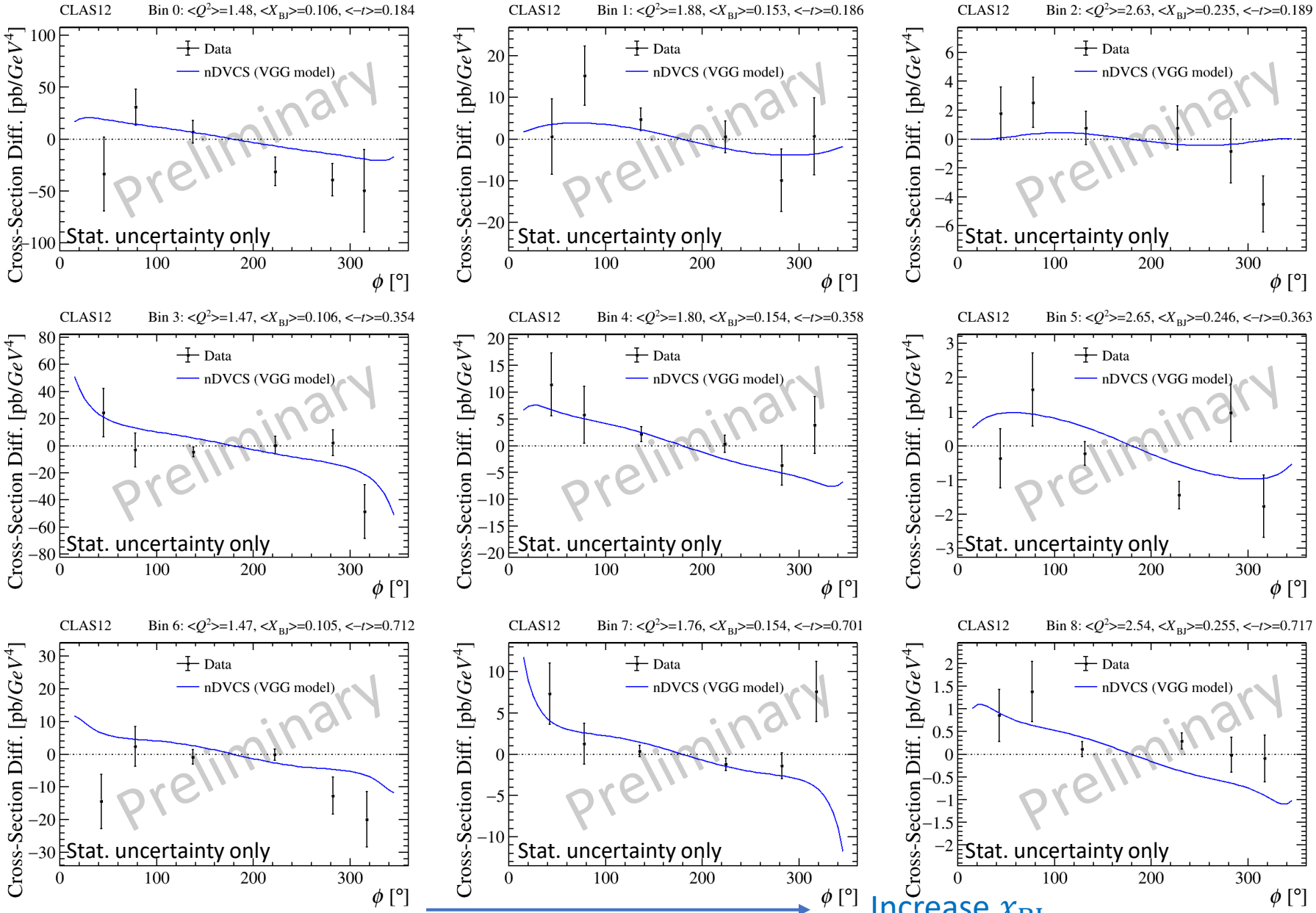
Unpolarized nDVCS cross section



$$\sigma = \frac{N_{en \rightarrow en\gamma}}{L \cdot \varepsilon_{\mathrm{acc}} \cdot V}$$

- **Linked mainly to the real CFF of *E***
- Only the statistical uncertainty is presented
- The measured results are at the same level with the BH calculations

Polarized cross-section difference

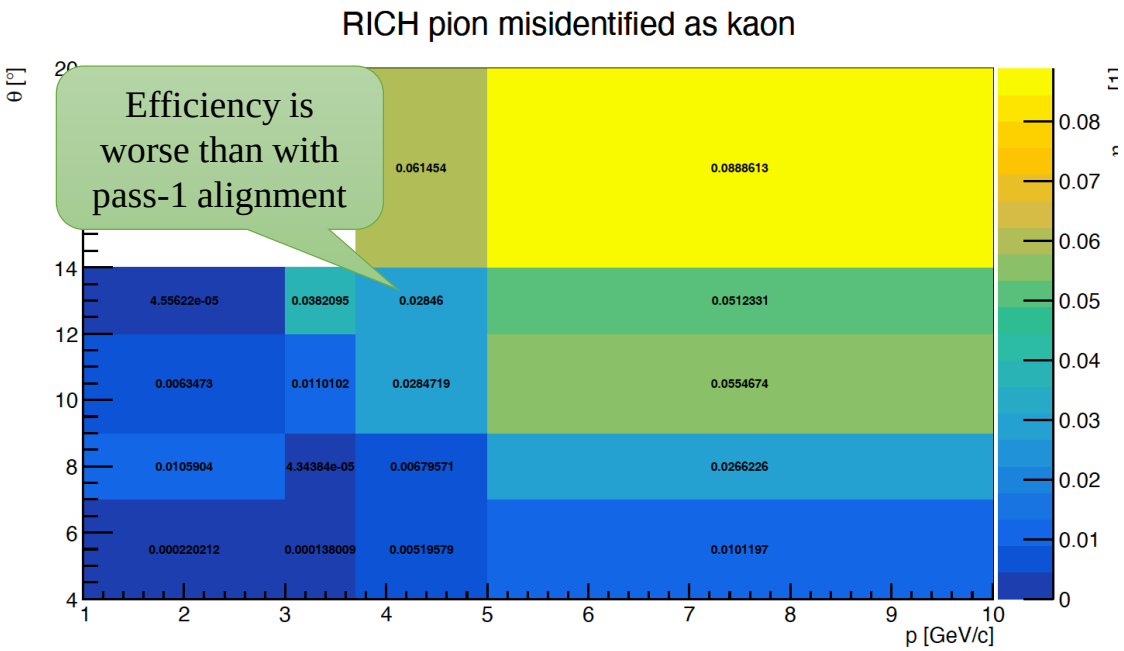


$$\Delta\sigma = \frac{N_+ - N_-}{L_{+(-)} \cdot P \cdot \varepsilon_{\mathrm{acc}} \cdot V}$$

- **Linked to the imaginary CFF of *E***
- Only the statistical uncertainty is presented
- nDVCS predictions: VGG model with parameters $J_u = 0.3$ and $J_d = 0.1$
- The measured results are consistent with the predictions given large statistical uncertainties
- **Systematic studies, radiative corrections, and finalization of analysis note are underway**

K^+ SIDIS: Beam Spin Asymmetry on deuterium target

Goal: to investigate the **flavor dependence** of the nucleon structure functions, by performing the first analysis including **high-momentum kaons** identified with the **RICH**.



Currently, the focus of the study is the evaluation of systematic uncertainty. The main updates are:

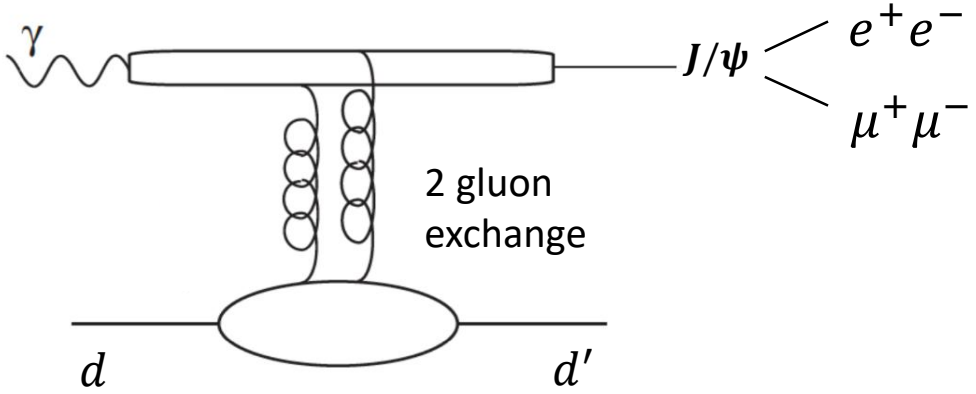
- The new pass-2 DC alignment worsened the RICH alignment, leading to an efficiency loss.
- A RICH alignment update is required to reduce pion contamination in the kaon sample. The goal is to define a new fiducial cut ensuring less than 1% contamination.
- The contamination will allow to evaluate the corresponding systematic uncertainty

$$F_{LU}^{meas} = F_{LU}^{K} + \delta F_{LU}^{cont} = F_{LU}^{K} + \left(\frac{N_\pi}{N_K} \Delta_{F_{LU}} \right)$$

- The study of radiative correction is ongoing, based on works by Akusevich, Ilyichev et al [1],[2]
- The RICH is almost available in simulation to evaluate bin migration uncertainty.

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

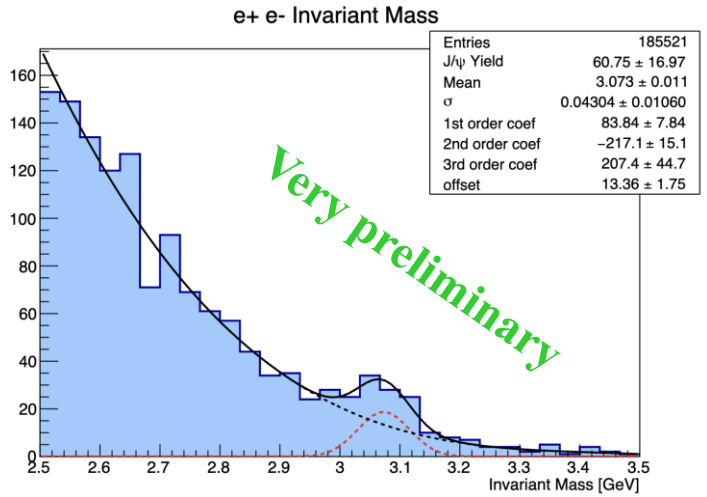
- **Reaction of Interest:** $\gamma d \rightarrow J/\psi d'$
- **Project Goal:** Estimate differential and/or total cross section
- **Technique:** $\gamma d \rightarrow J/\psi d'$ is measured in untagged quasi-real (virtual photon with very small virtuality) photoproduction
- **Means:** RGB data, proposal E12-11-003B
- **Purpose:** Learn about transverse gluon distribution in deuteron (following on the work done for the nucleon)
- **Data Analysis Plan:**
  - Yield extraction:
    1. Particle 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



- **J/ψ Identification :**
  - Via the e^+e^- decay: we detect both leptons and form IM distribution
  - The J/ψ peak has small statistics so reduction of background is critical

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

Results from exploratory studies:



Richard Tyson, Private Communication, 2024

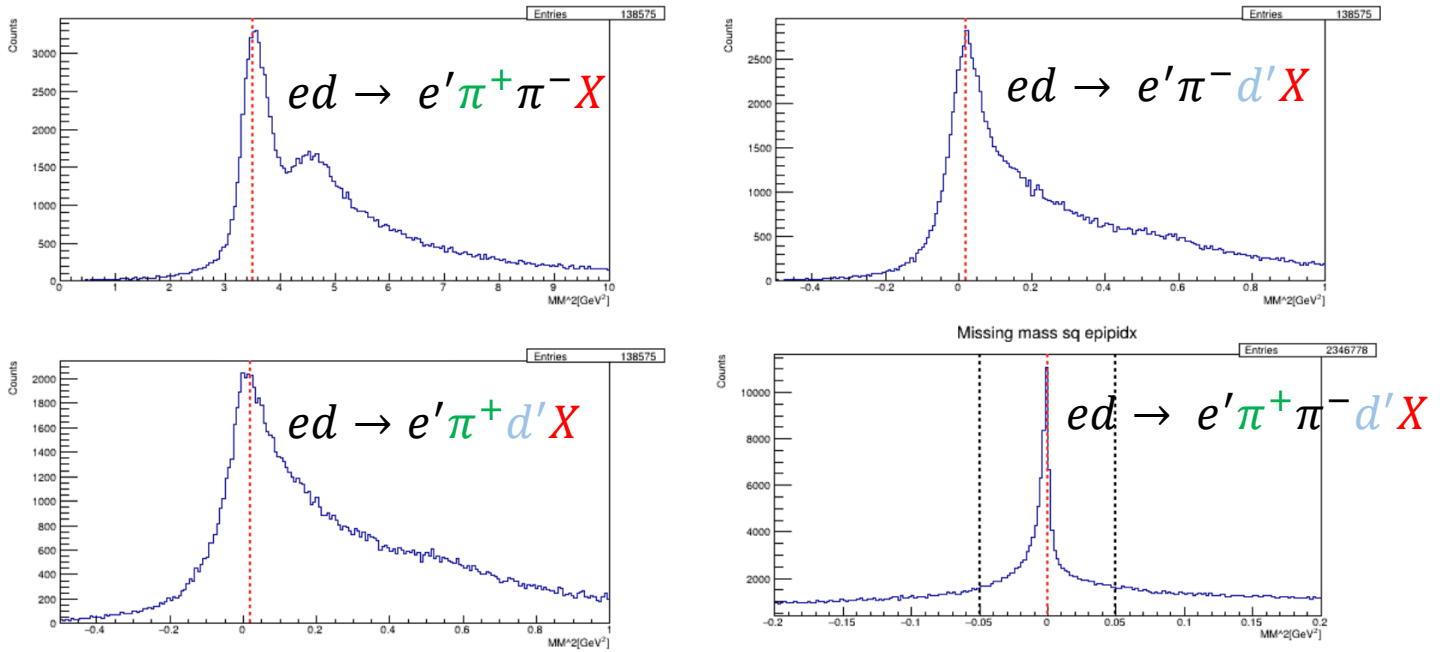
Event Selection (cuts):

- At least one e^-, at least one e^+, and at least one good d (ID=49)
- The leptons are detected in the Forward Detector
- Quasi-real photoproduction: $ed \rightarrow e'd'e^+e^-$ with a forward-going, undetected (missing) e', $Q^2<5$; $|MM^2| < 1$
- Reproduced at start of the analysis

Background reduction in deuteron PID:

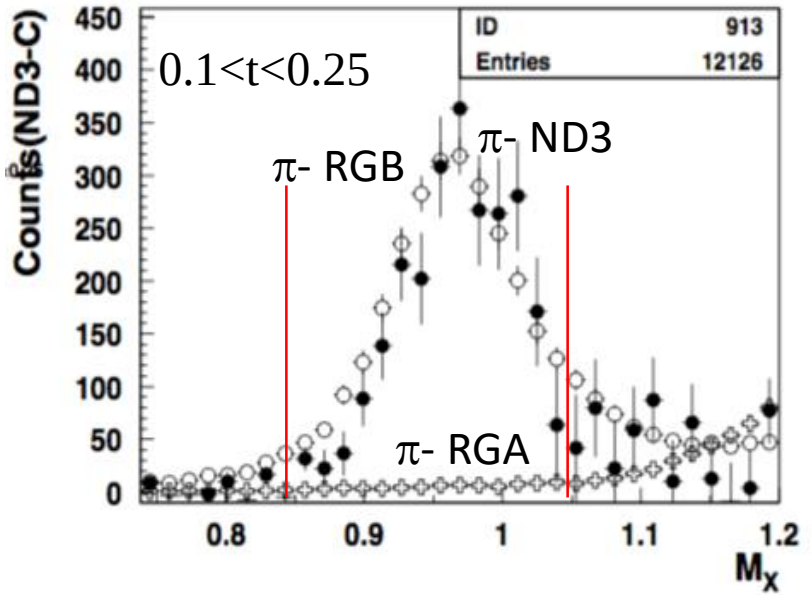
High accidental background in the l^+l^-d sample makes standard TOF PID insufficient; deuterons' large straggling prevents a simple energy-loss cut. A clean high-statistics deuteron sample is needed to establish/study more sophisticated deuteron PID method: we analyze $ed \rightarrow e'\pi^+\pi^-d'$ (RGB existing deuteron train)

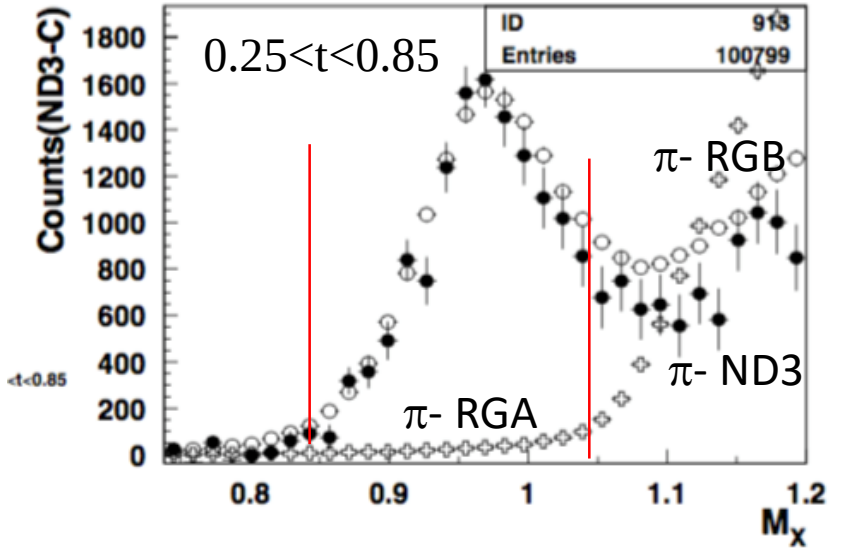
Reaction selection by means of 4-momentum conservation and kinematic cuts, a clear signal is observed. In the process of establishing a set of kinematic cuts.
The aim is to obtain a deuteron sample with <10% background.



Fully exclusive π^- A_{LU} from CLAS12 RGB

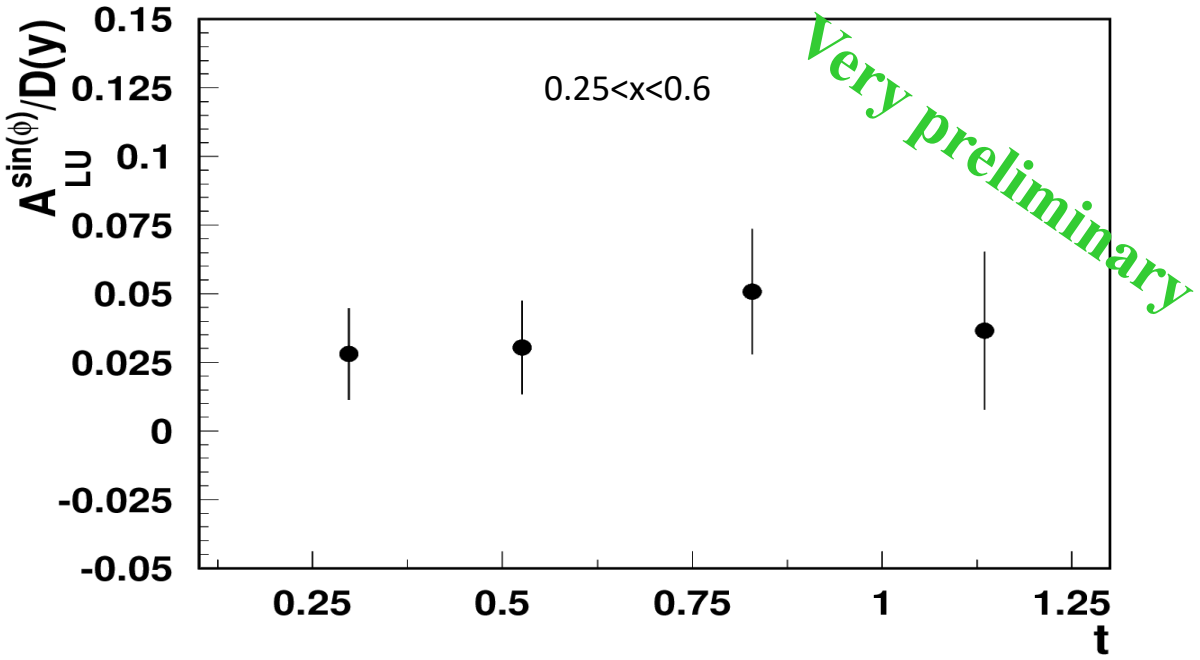
$\vec{e}d \rightarrow ep\pi^-(p)$





Using proton and cut $|E_{beam}+M-E_{e'}-E_p-E_\pi|<0.1$

$|Mx-0.92|<1$

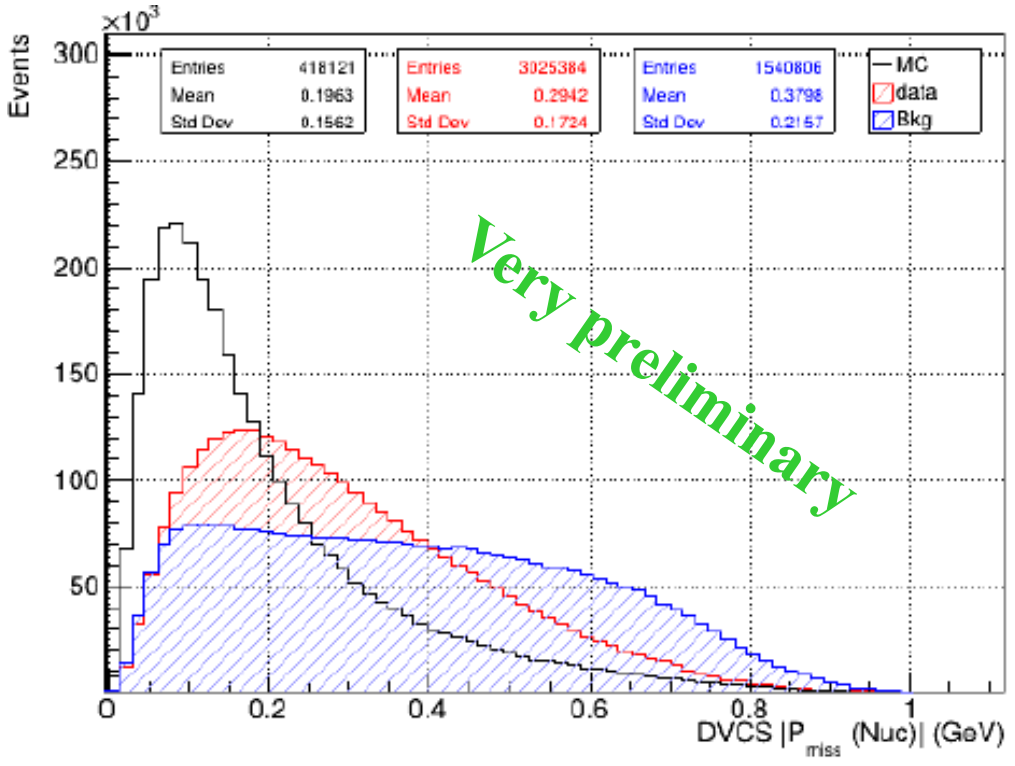


First measurement of beam SSA of exclusive π^-

Without detection of proton more events leak from $\pi^-\Delta^{++}$ channel on the proton at high t

Study of the Nucleon Structure Modifications Induced by Short-Range Correlated Nucleon-Nucleon Pairs via DVCS on Deuterium

- Understanding the partonic structure of the nucleon is essential for describing one of the fundamental building blocks of visible matter.
- DVCS provides direct access to GPDs, which encode correlations between the spatial and momentum structure of partons.
- Studying DVCS on bound protons in deuterium allows us to investigate modifications induced by short-range correlations (SRC).
- RGB provides the polarized ~10.5-GeV electron beam and deuterium target required for the extraction of the BSA.
- The results will contribute to a broader understanding of nucleon structure in nuclei.



Data
pDVCS MC simulations
Exclusive π0 MC simulations, analyzed as pDVCS

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
- Physics analyses in **advanced state**: G^n_M, nDVCS cross section, Di-hadron SIDIS (not shown)
- **New physics analyses ongoing/planned**: Coherent J/ψ, exclusive π^-, SRCs in pDVCS, d-DVCS, …
- RGB is interested to participate in the pass3 discussion (CVT tracking, RICH/BAND reconstruction, …)

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