INPC 2025

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Measurement of beam-polarized Deeply Virtual Compton Scattering observables with eγ detection @ CLAS12

CEBAF Large Acceptance Spectrometer

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INTRODUCTION

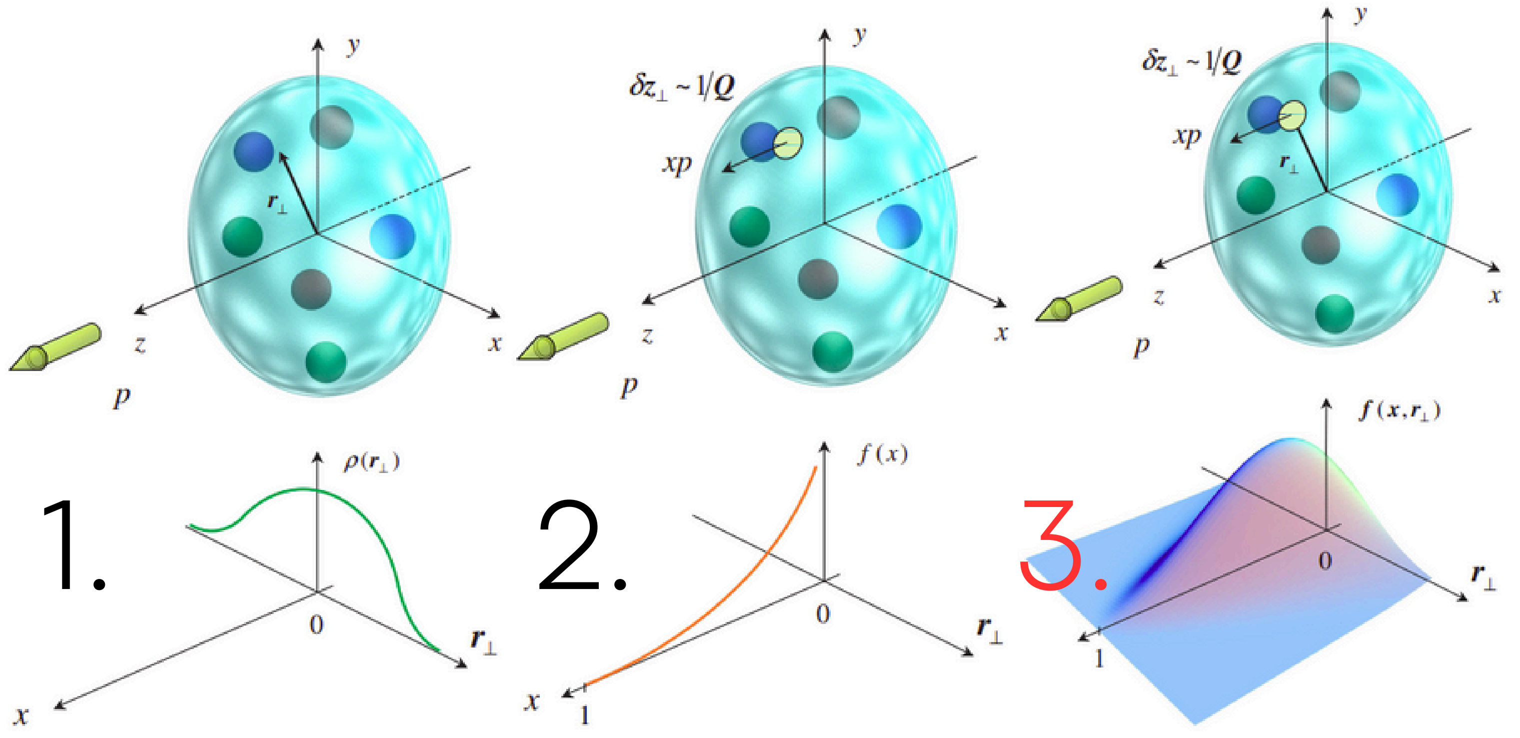
Generalized Parton Distributions

Motivation

1. INTRODUCTION

At low energy QCD, we describe the nucleon structure in terms of structure functions including:

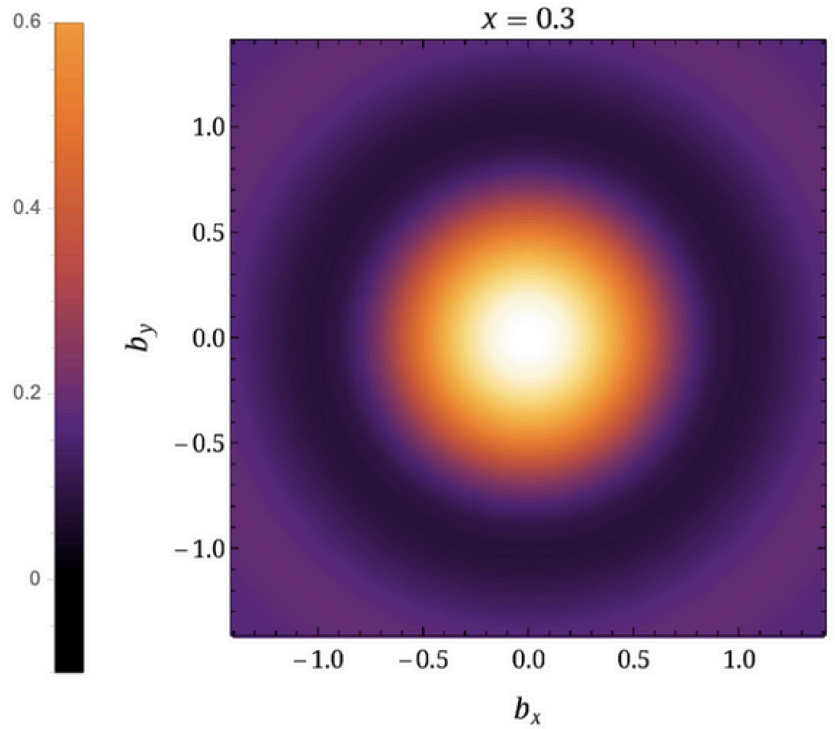
1. Form Factors describe transverse position of partons
2. Parton Distribution Functions describe longitudinal momentum distributions
3. Generalized Parton Distributions (GPDs) correlates transverse position and longitudinal momentum distributions



GPDs encode information of the nucleon structure such as:

Nucleon Tomography

H.W. Lin, Phys. Rev. Lett. 127 (2021) 182001.



Contributions to the nucleon total spin.

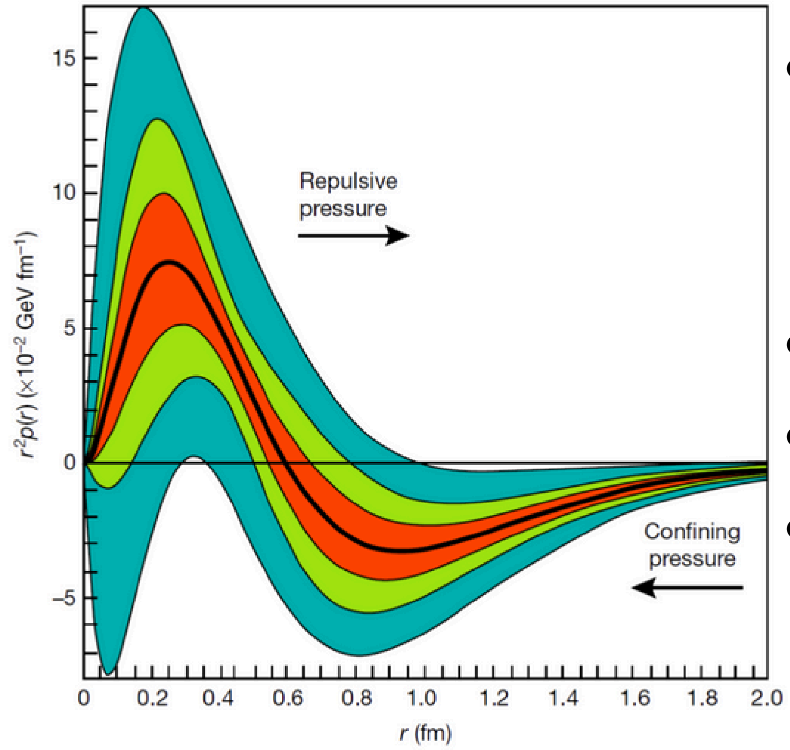
X. Ji, Phy.Rev.Lett.78,610(1997)

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

- Quark contribution is not the main contribution →Spin Crisis
- Quark's orbital angular momentum is accessed through GPDs
- Gluon contribution

Access to Gravitational Form Factors.

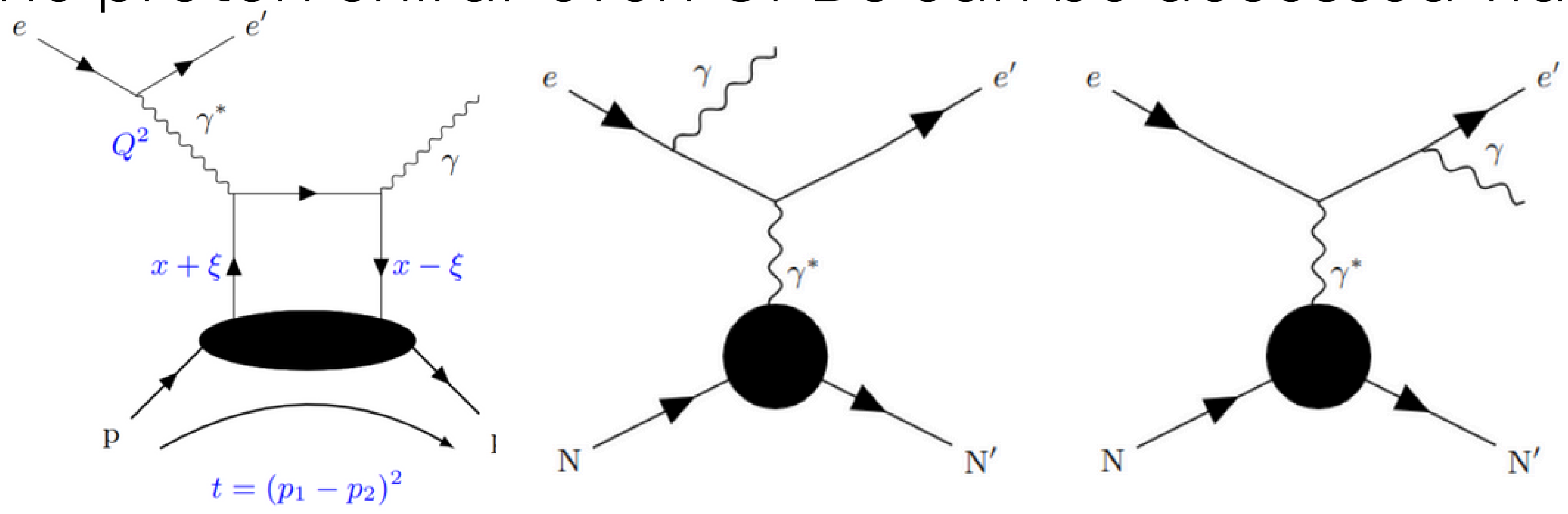
V. D. Burkert *et al*. Nature 557.7705 (2018): 396



- Mass/Energy distribution inside the nucleon
- Forces distribution.
- Nucleon radius
- Shear forces and pressure distribution

1. INTRODUCTION

The proton chiral-even GPDs can be accessed via electro-production of a real photon.



DVCS **BH**

For a spin $\frac{1}{2}$ particle, there are four chiral-even GPDs $F = H, E, \widetilde{H}, \widetilde{E}$

GPDs enters the DVCS-BH interference term through **Compton Form Factors**

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

which are measured in the Beam Spin Asymmetry

$$\mathbf{BSA} = \frac{1}{P_{\text{beam}}} \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-}$$

$$\propto \mathfrak{Im}\left\{ F_1\mathcal{H} + \xi'(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right\},$$

1. Detecting the proton is ideal, but by not detecting it:

- There is access to the small $-t=(p-p')^2$ region
- Larger statistics can be achieved, as the proton is not constrained by detector acceptance

2. However,

- There are background contributions from the whole SIDIS spectra.
- There are reduced options for cuts. Missing proton mass is the only exclusivity variable available

3. Therefore,

- We move to a ML approach for channel selection.
- It is first validated by including the proton information. Then applied to the no-proton case

2

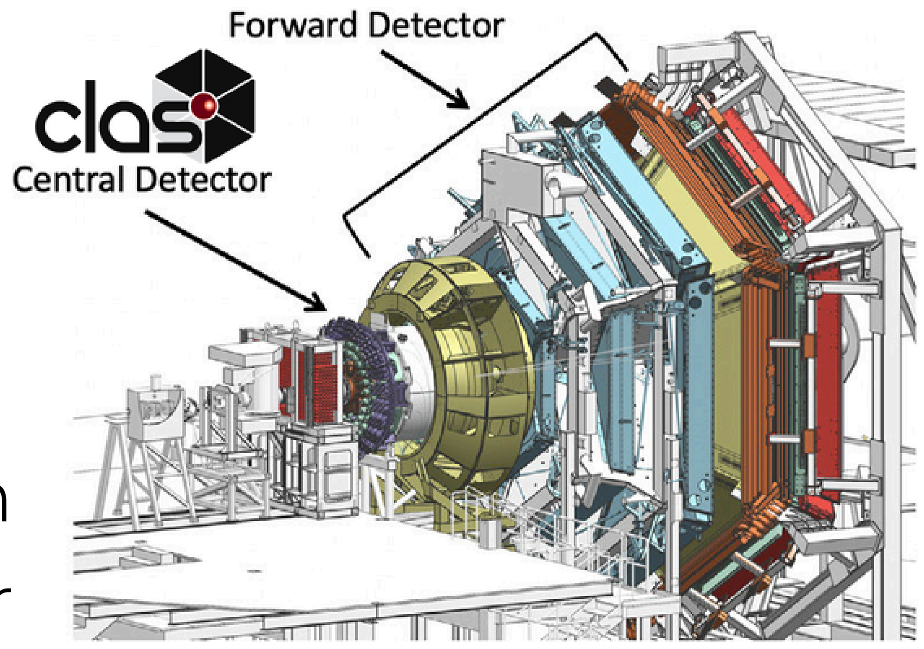
DATA SELECTION

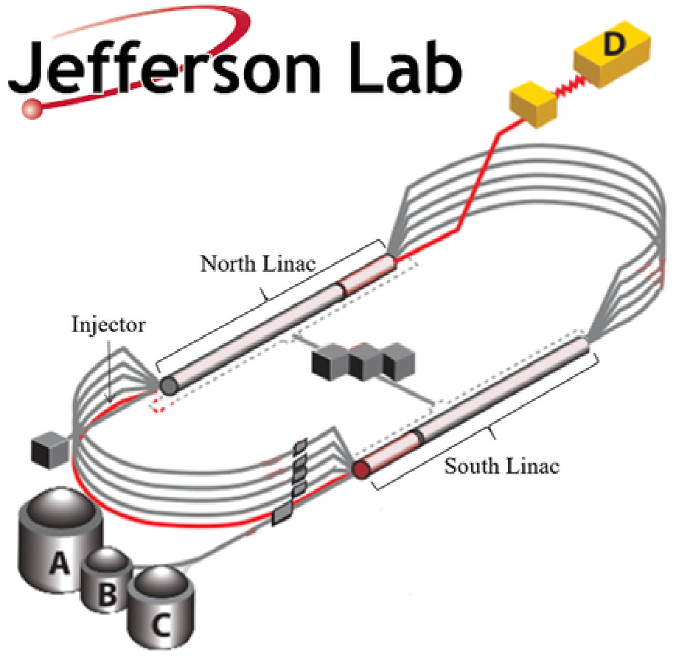
2. DATA SELECTION

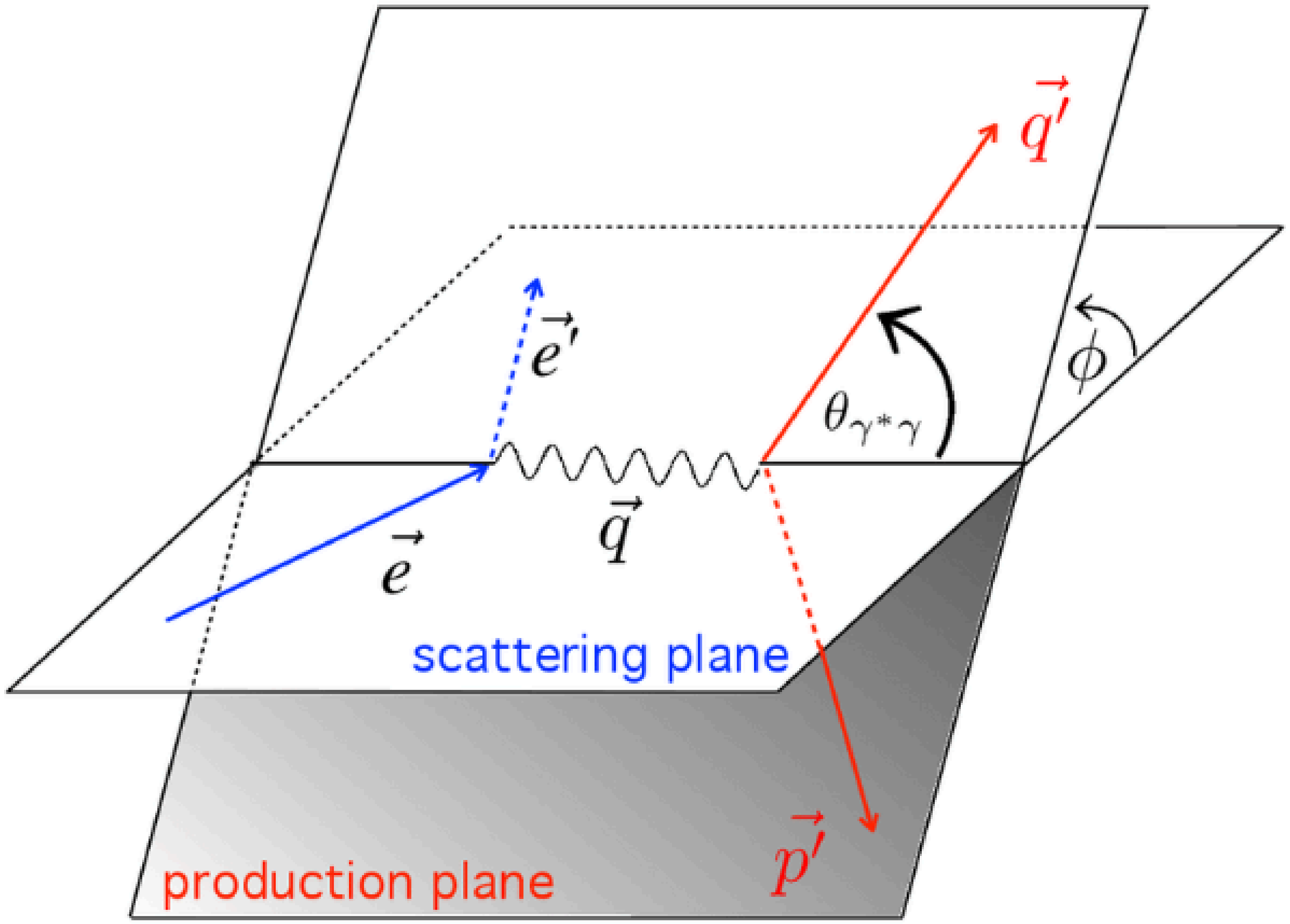
Data taken by the **CLAS12** detector in fall-2018

- Polarized electron beam towards an unpolarized fixed proton target

CLAS12 is the large acceptance spectrometer located in the Hall B of the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA)







KINEMATICS

- $W>2$ GeV
- $Q^2>1$ GeV^2
- $q' > 2$ GeV
- $e'>1$ GeV
- ($p' > 0.3$ GeV)

EXCLUSIVITY CUTS (if proton detected)

- $\Delta\phi=|\phi(p')-\phi(\gamma)|<2°$
- $\Delta t=|t(p')-t(\gamma)|<2$ GeV^2
- Pmiss<1 GeV

$\phi(p')$ uses γ^* and p'

$\phi(\gamma)$ uses γ^* and γ

$t(p') = (p-p')^2$

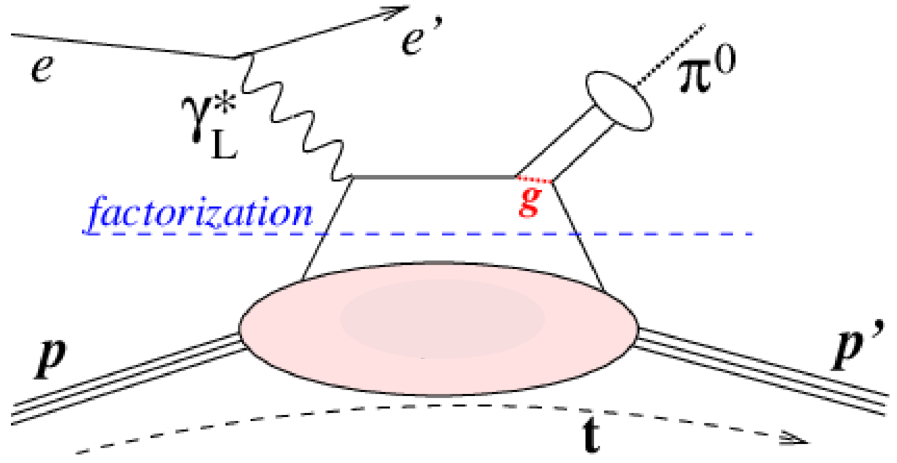
$$t(\gamma) = \frac{Q^2 M_p + 2\nu M_p \left(\nu - \sqrt{\nu^2+Q^2}\cos\theta_{\gamma^*\gamma}\right)}{\sqrt{\nu^2+Q^2}\cos\theta_{\gamma^*\gamma} - \nu - M_p}$$

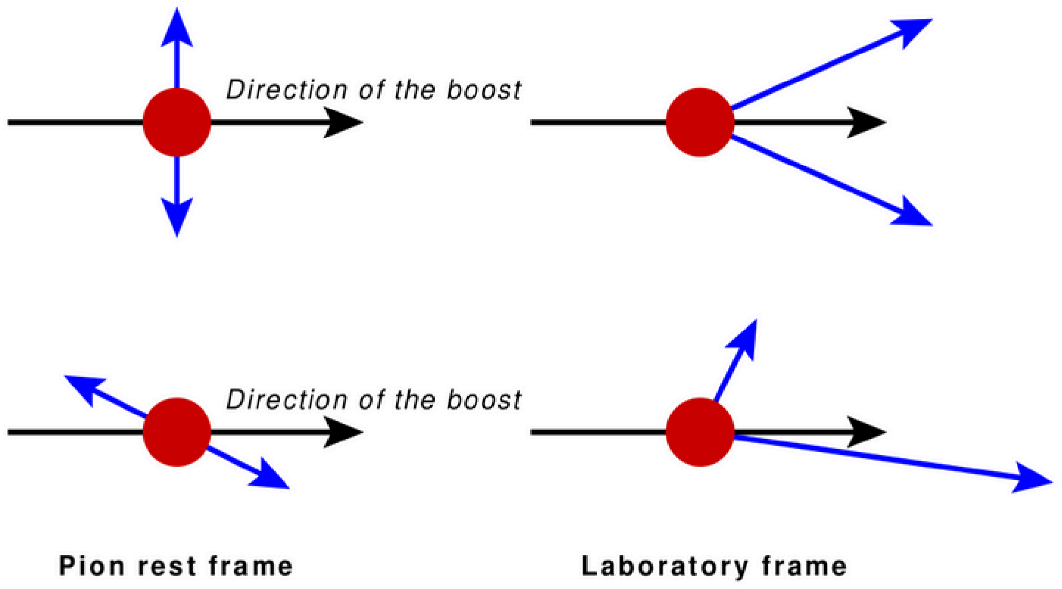
The event is built with the (e,γ,p) set with minimum missing ep → eγp missing mass

2. DATA SELECTION

The main contamination channel is exclusive π^0 production

$ep \rightarrow ep\pi^0 \rightarrow ep\ \gamma(\gamma)$

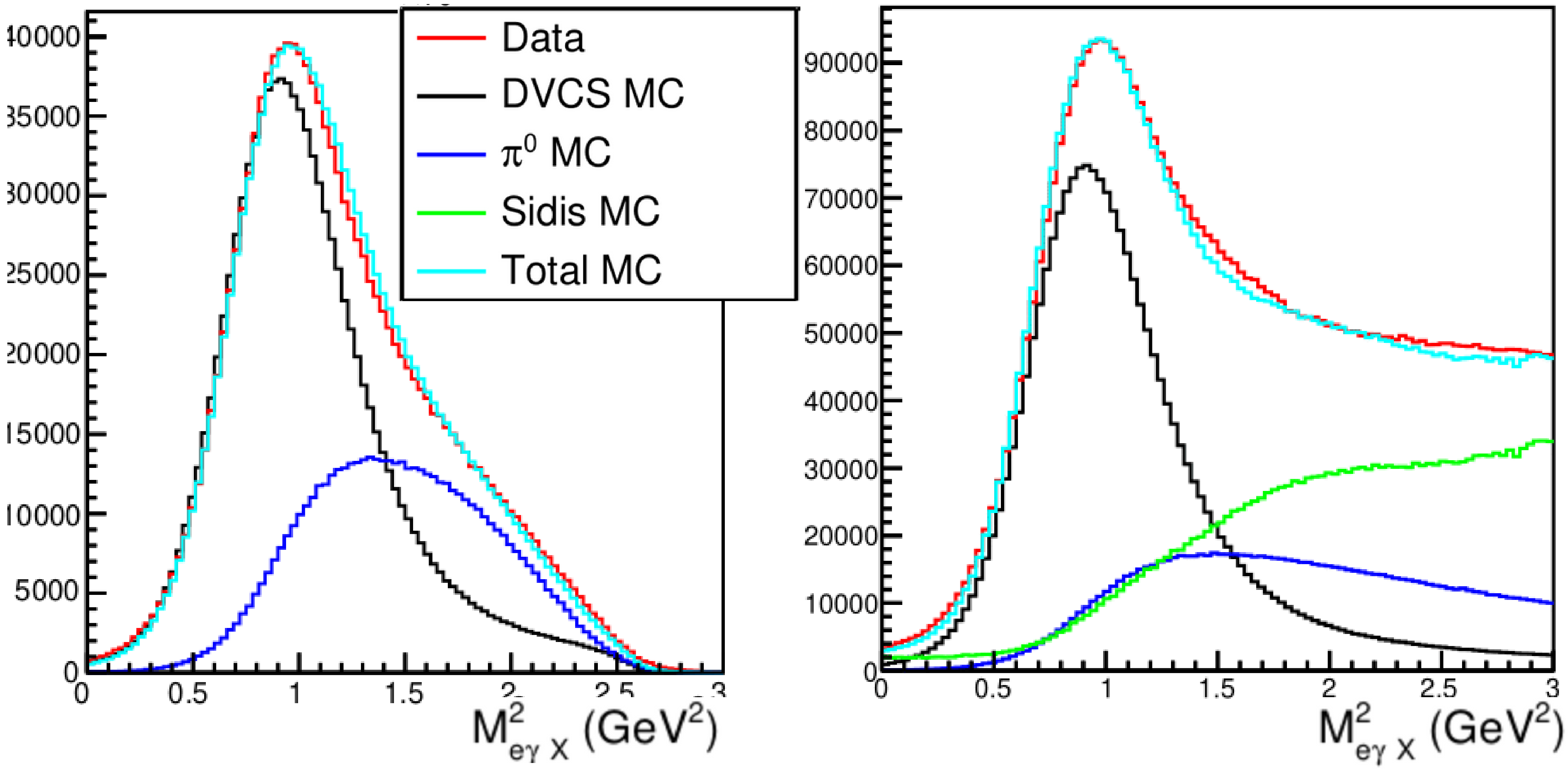




Missing proton mass distribution

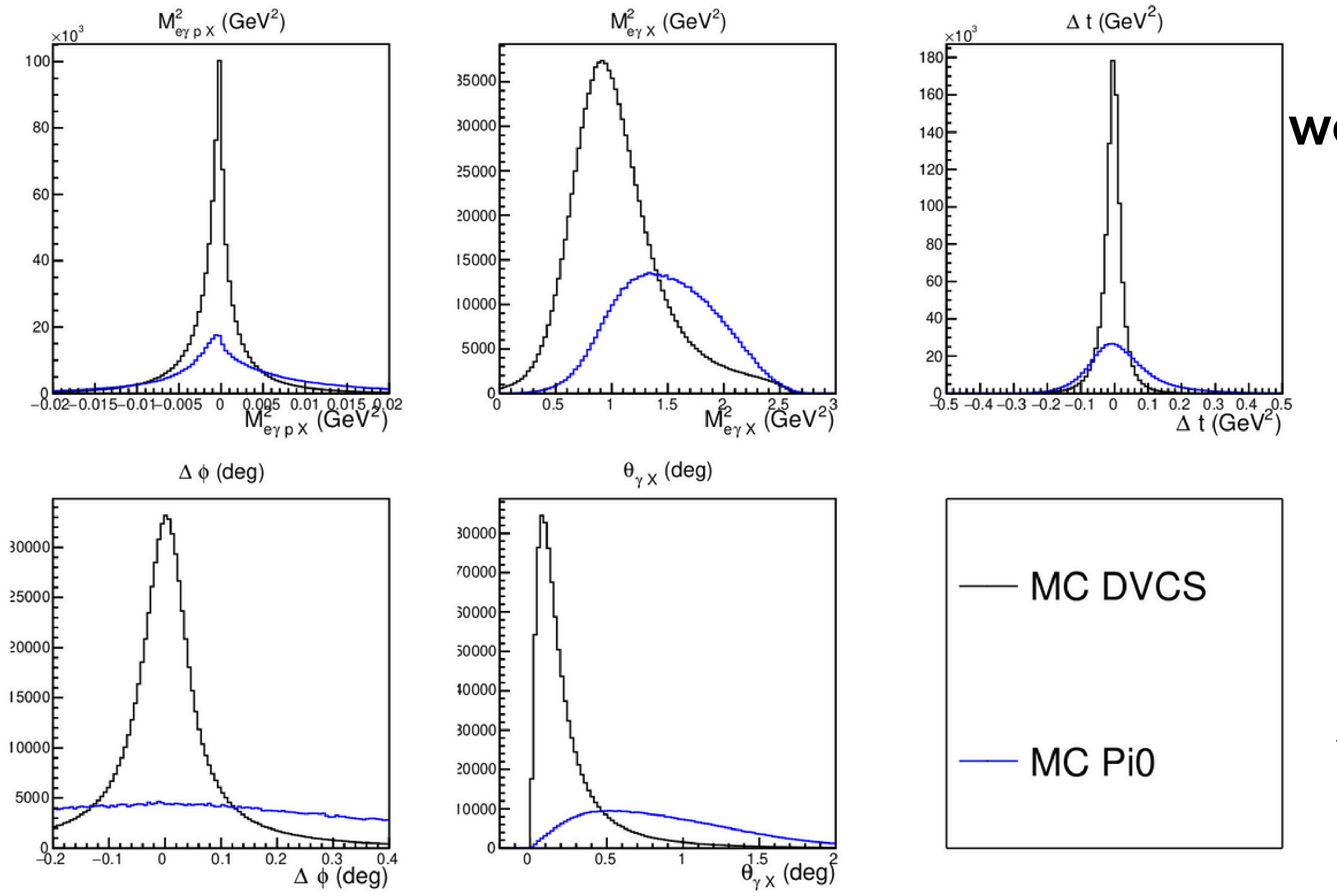
$$M_{e\gamma X}^2 = (e + p - e' - \gamma)^2$$

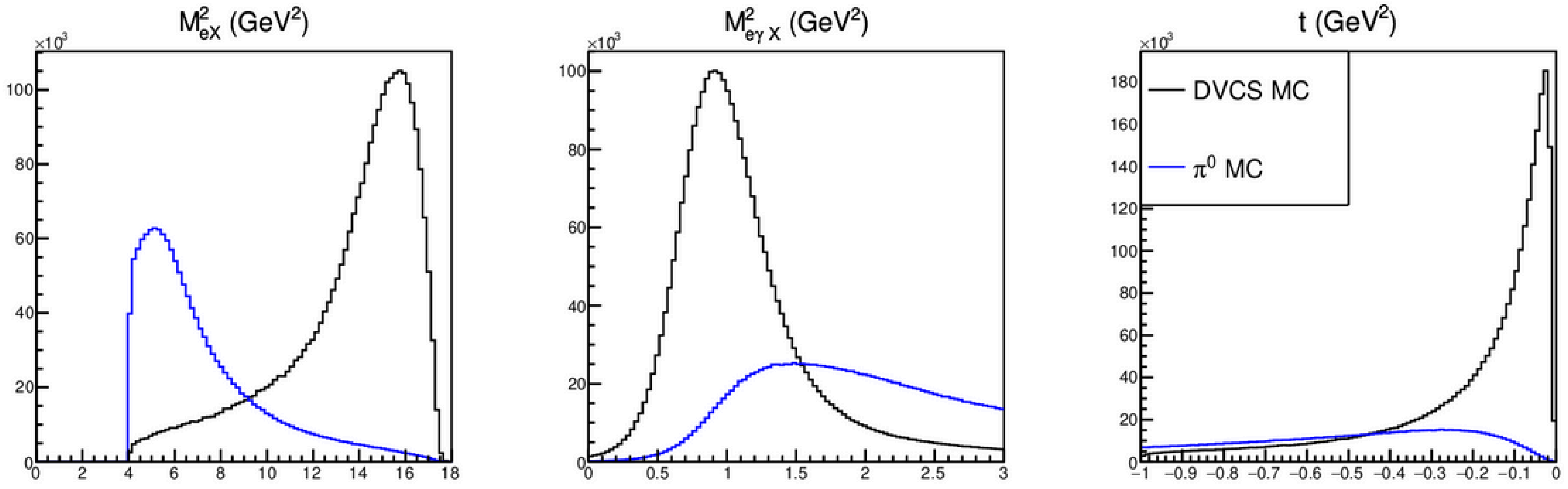
With proton **Without proton**



In the case of no proton detection, there is contamination from **inclusive** π^0 production in SIDIS

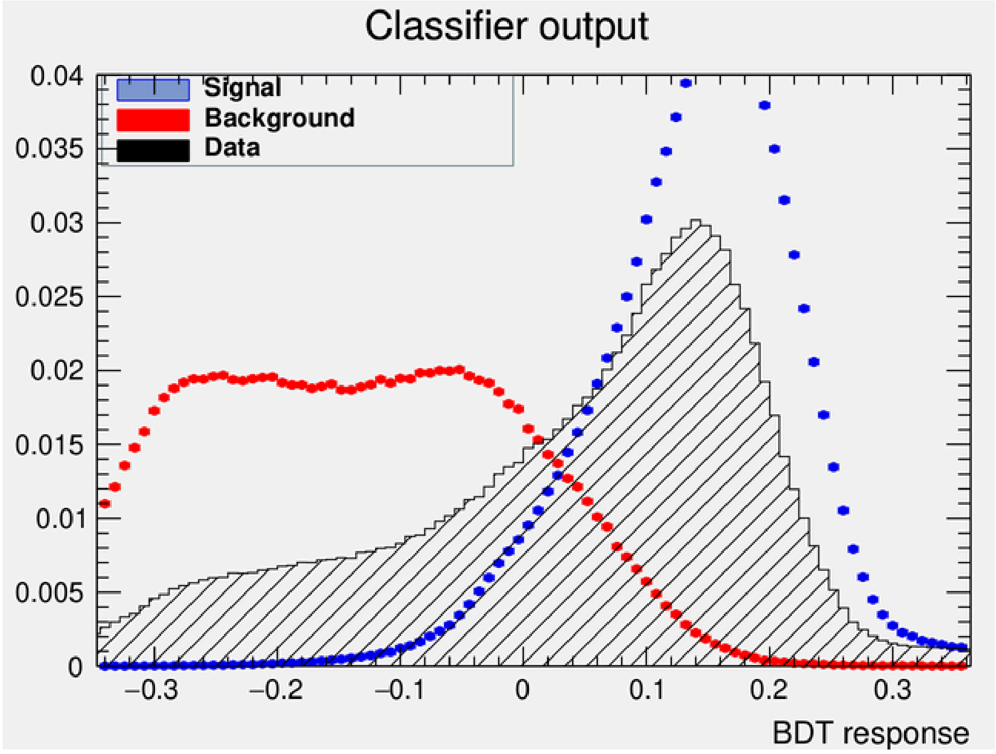
2. CHANNEL SELECTION





Instead of straight cuts on exclusivity variables,
we optimize data selection with Boosted Decision Trees.

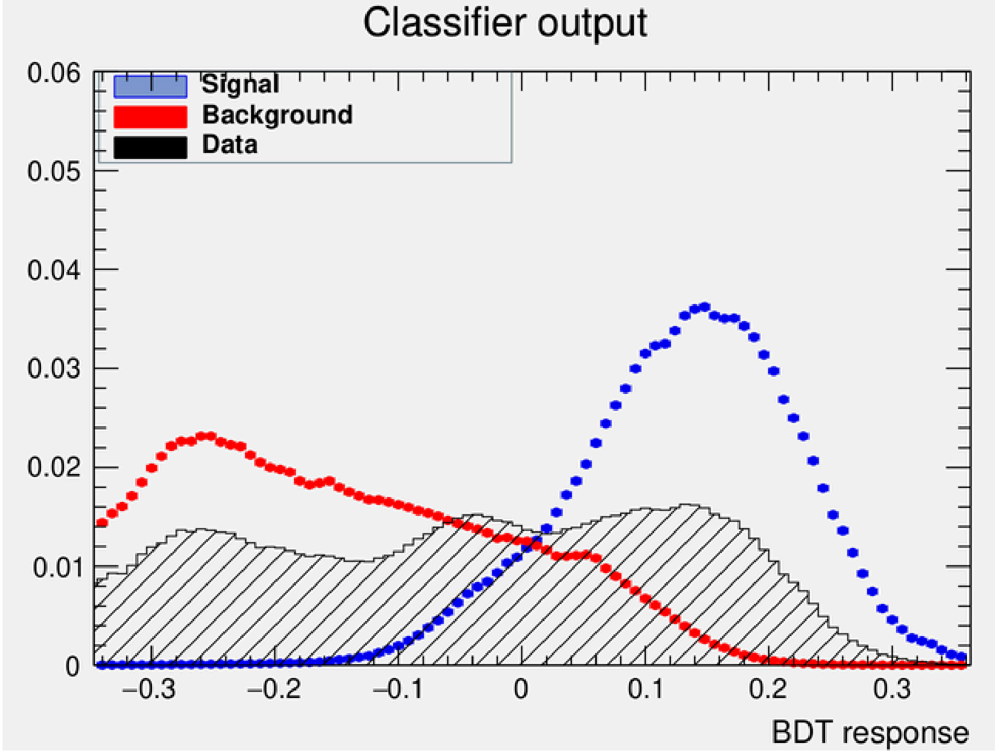
With proton



The following variables are used to train a BDT due to its DVCS/DVMP separation power.

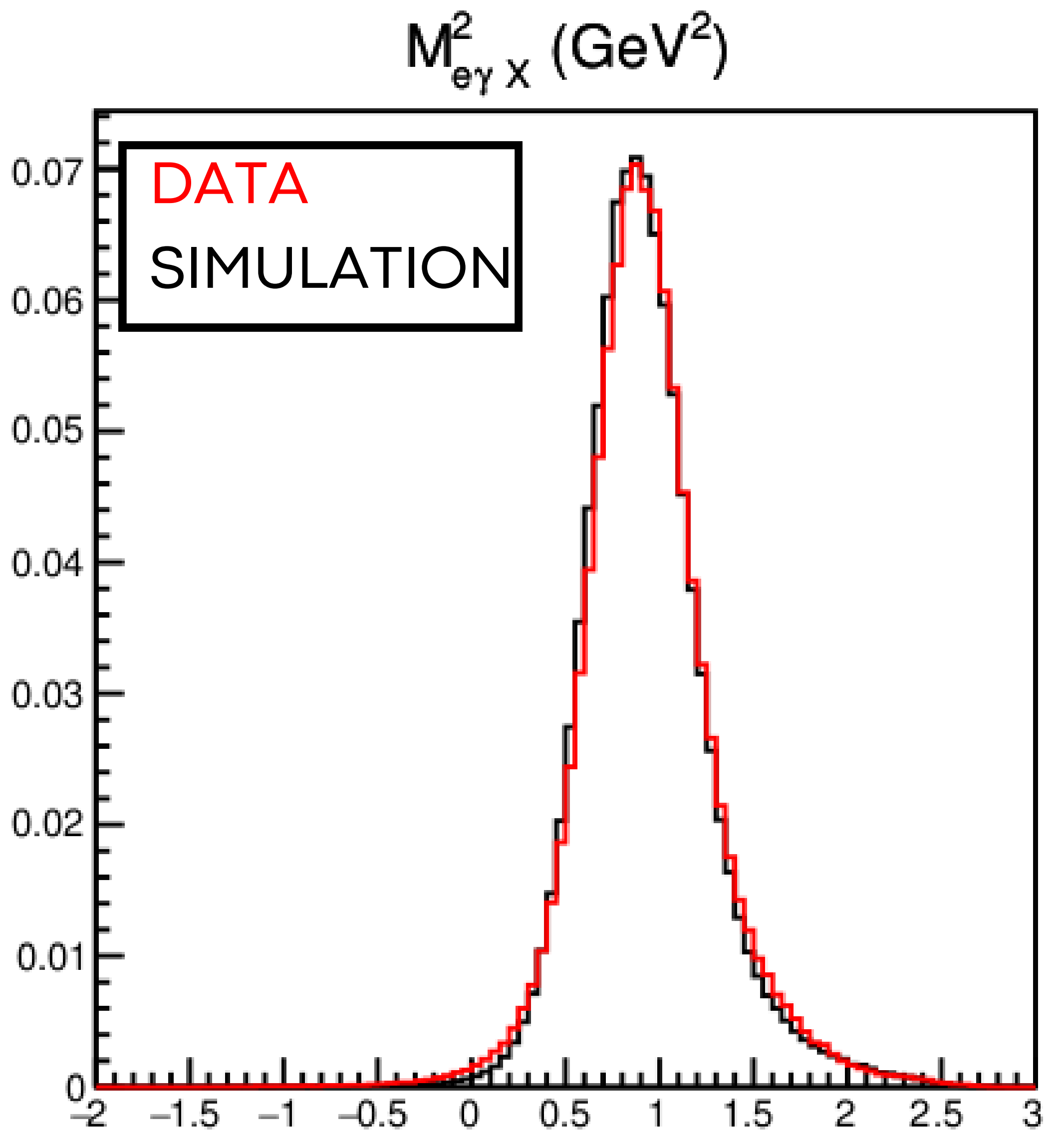
After BDT classification, residual background is removed with well known methods

W/out proton



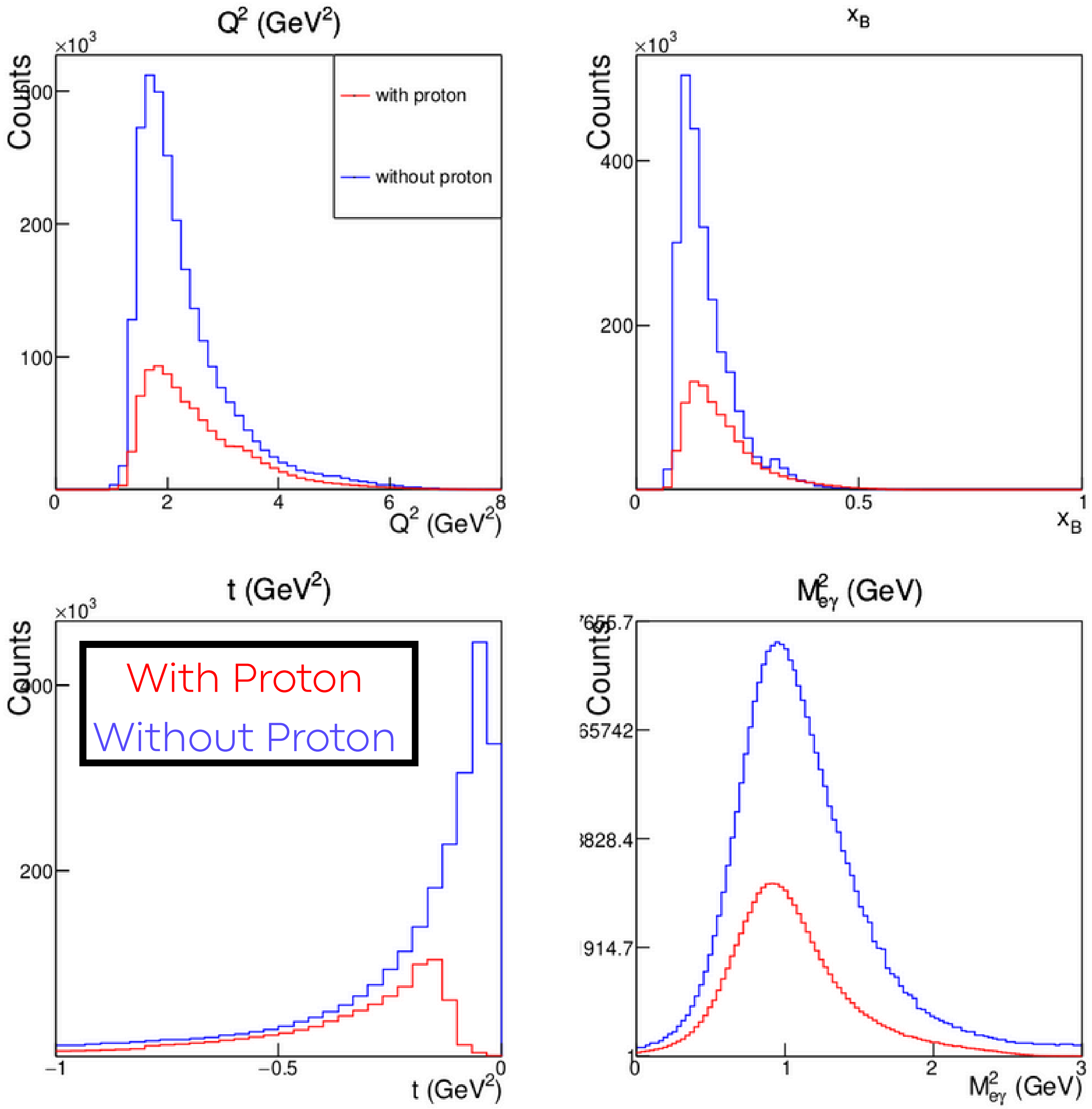
2. CHANNEL SELECTION

With proton



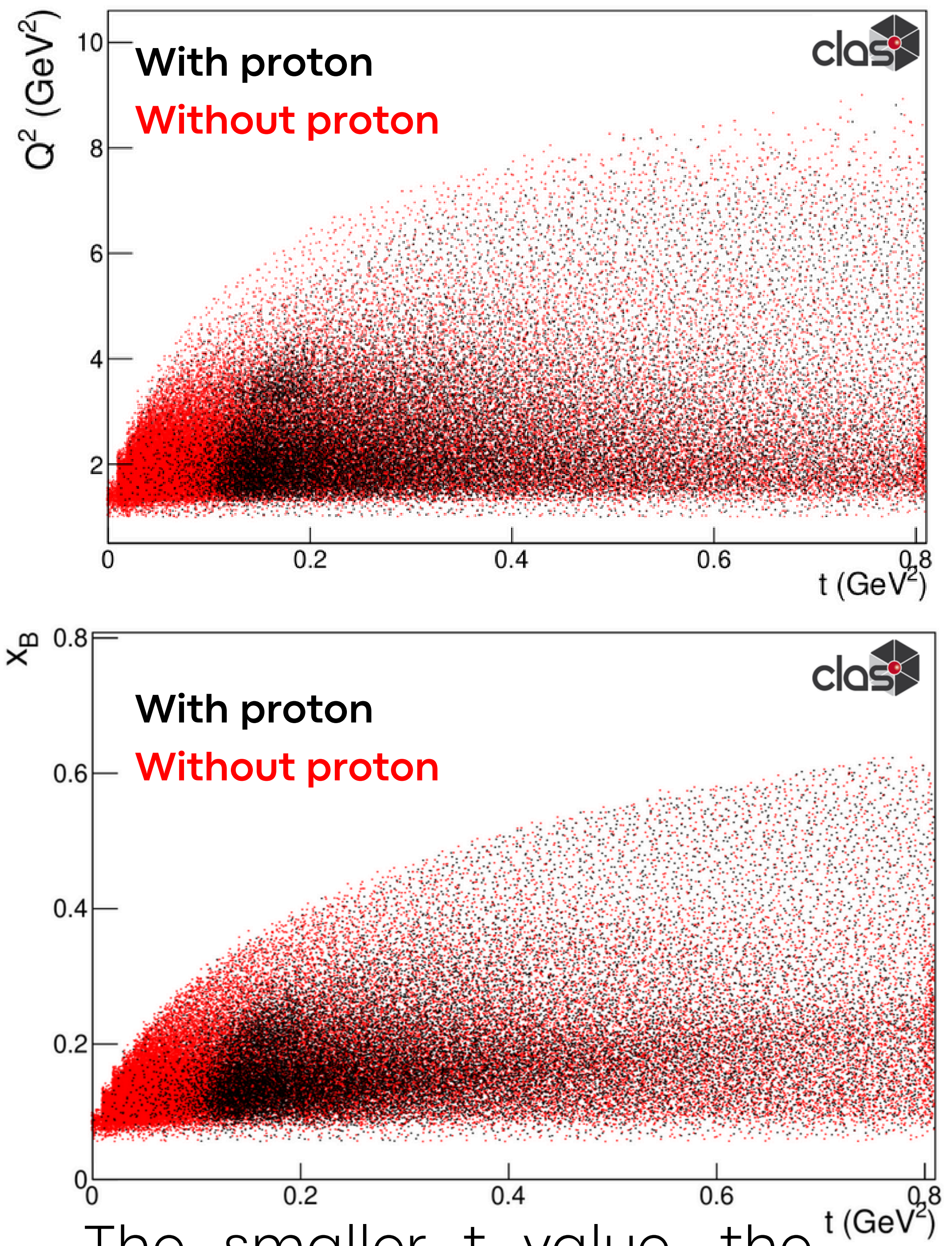
Most of the background was removed, leading to a good agreement between simulation and data.

Without proton



When not requiring a proton:

- Increased statistics
- Access to smaller -t values



The smaller t value, the better interpretation of DVCS in terms of GPDs!

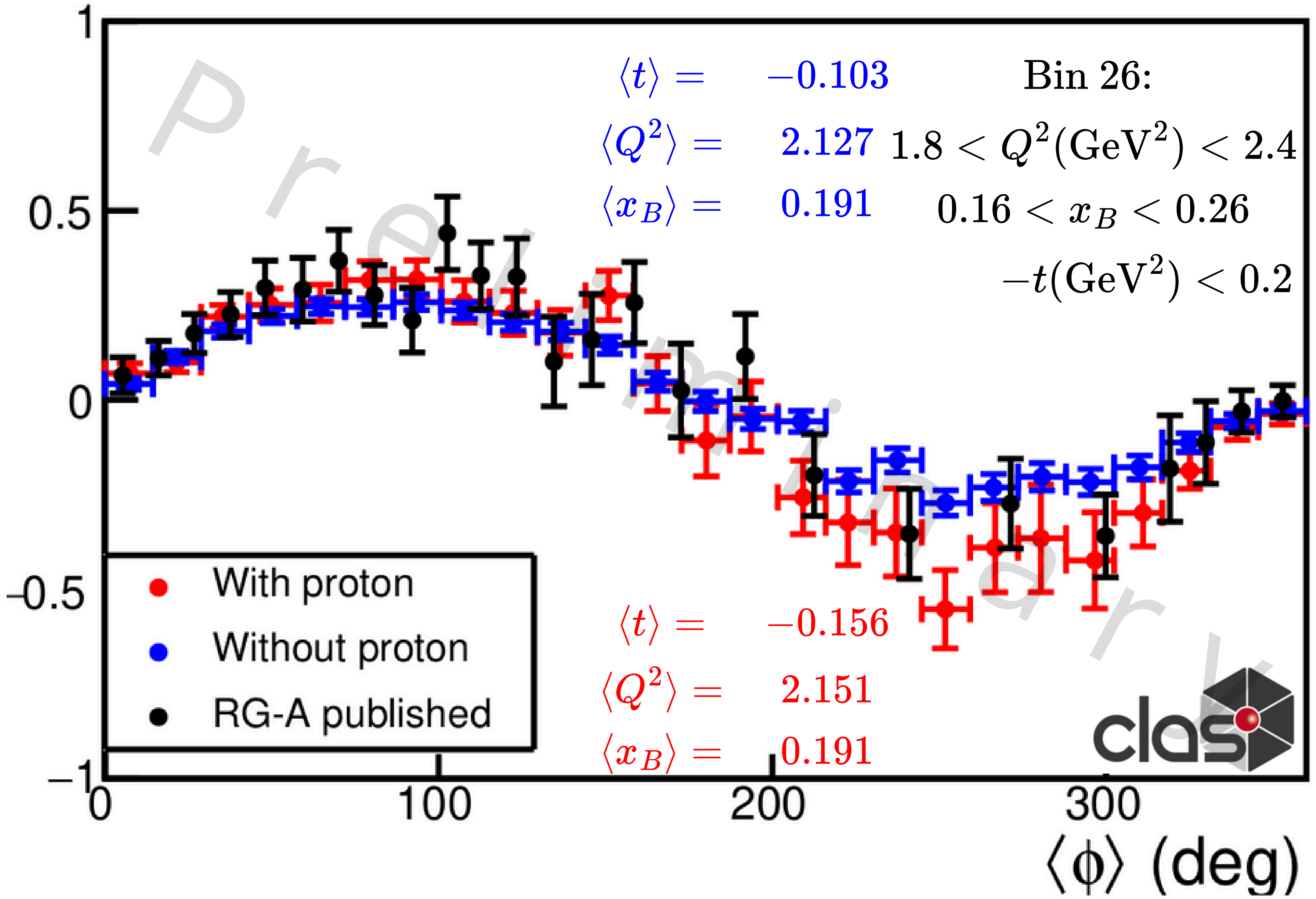
3

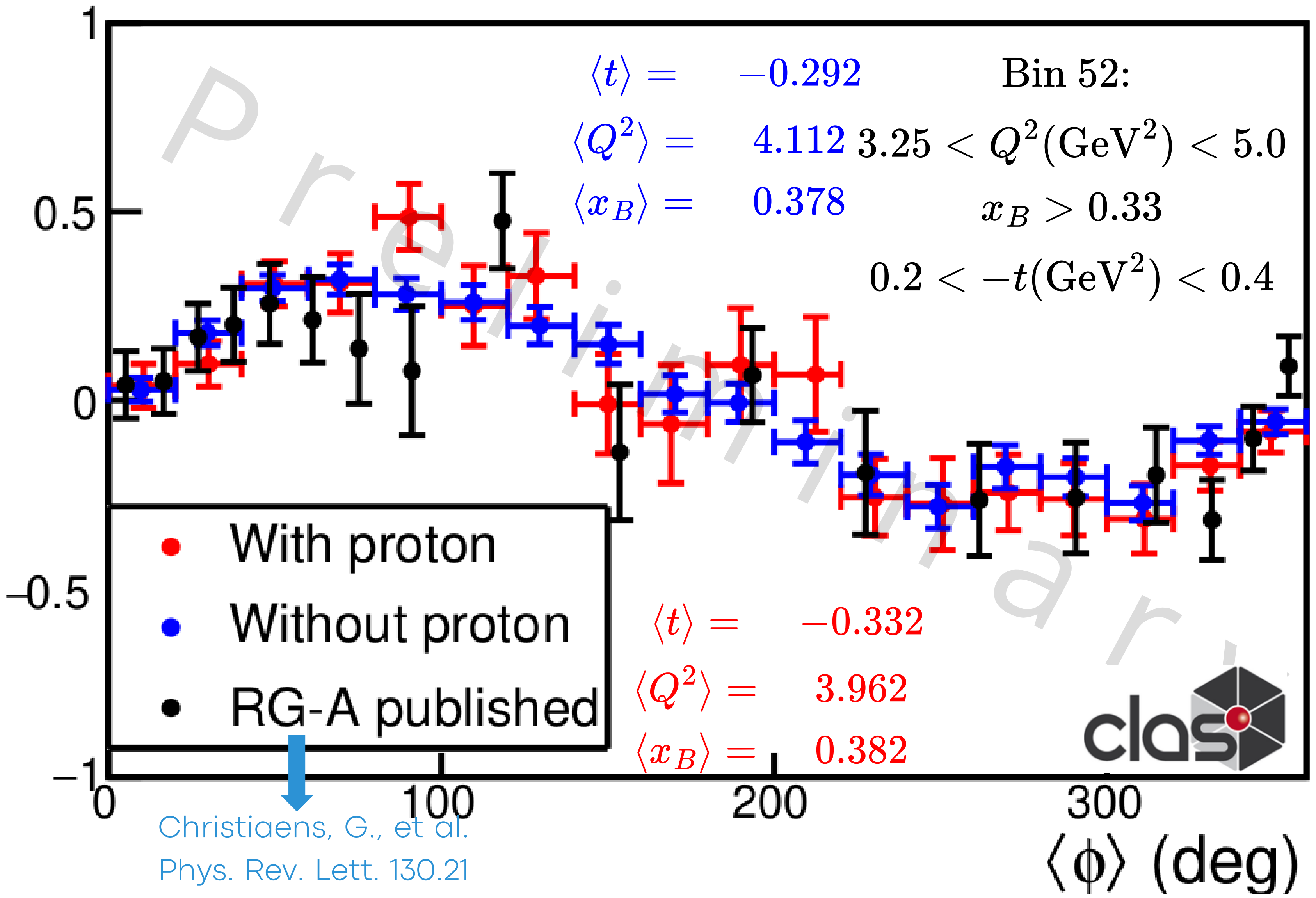
DVCS MEASUREMENTS

Beam Spin Asymmetry

Cross-section

3. DVCS BSA





Christiaens, G., et al. Phys. Rev. Lett. 130.21 (2023): 211902.

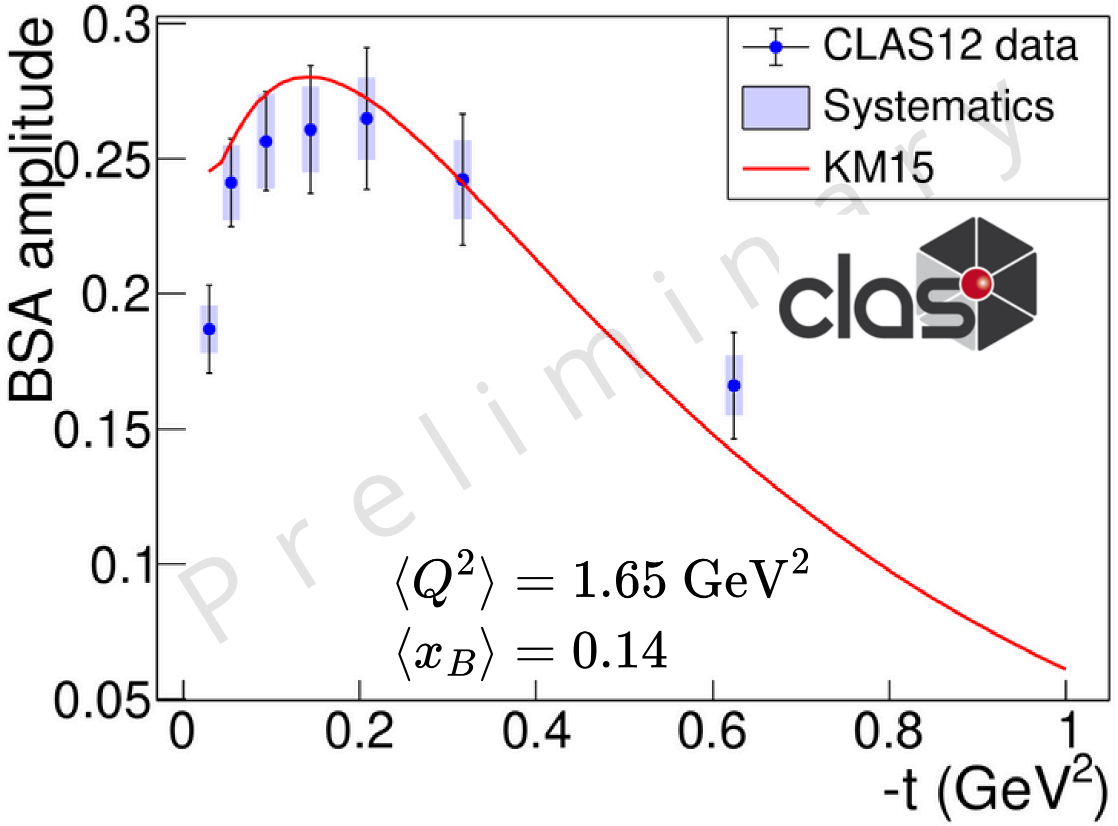
$$\mathbf{BSA} = \frac{1}{P_{\mathrm{beam}}} \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-}$$

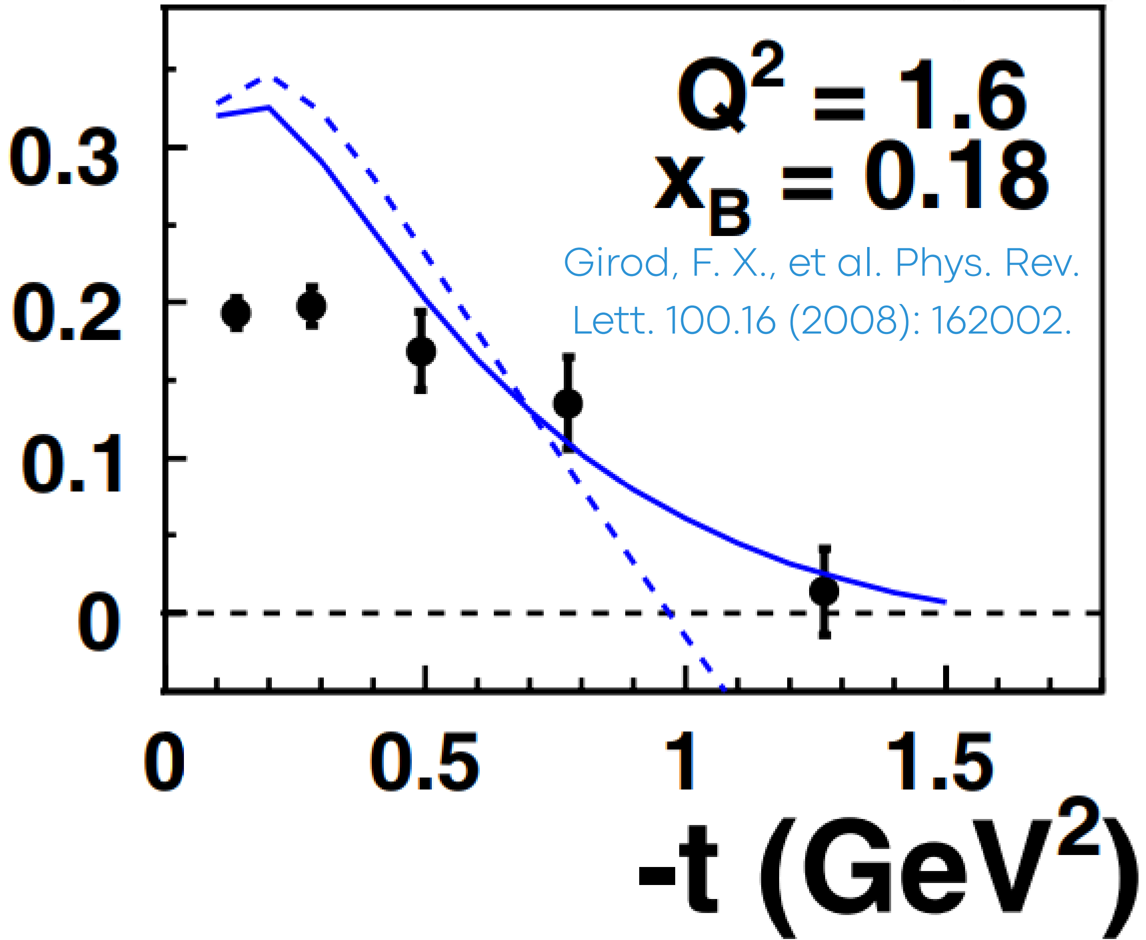
$$\propto \mathfrak{Im}\left\{ F_1 \mathcal{H} + \xi'(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right\},$$

- Results compatible with previously published results.
- By not detecting the proton there is a better coverage in ϕ

Juan Sebastian Alvarado, Université Paris-Saclay - IJCLab

BSA amplitude as a function of -t

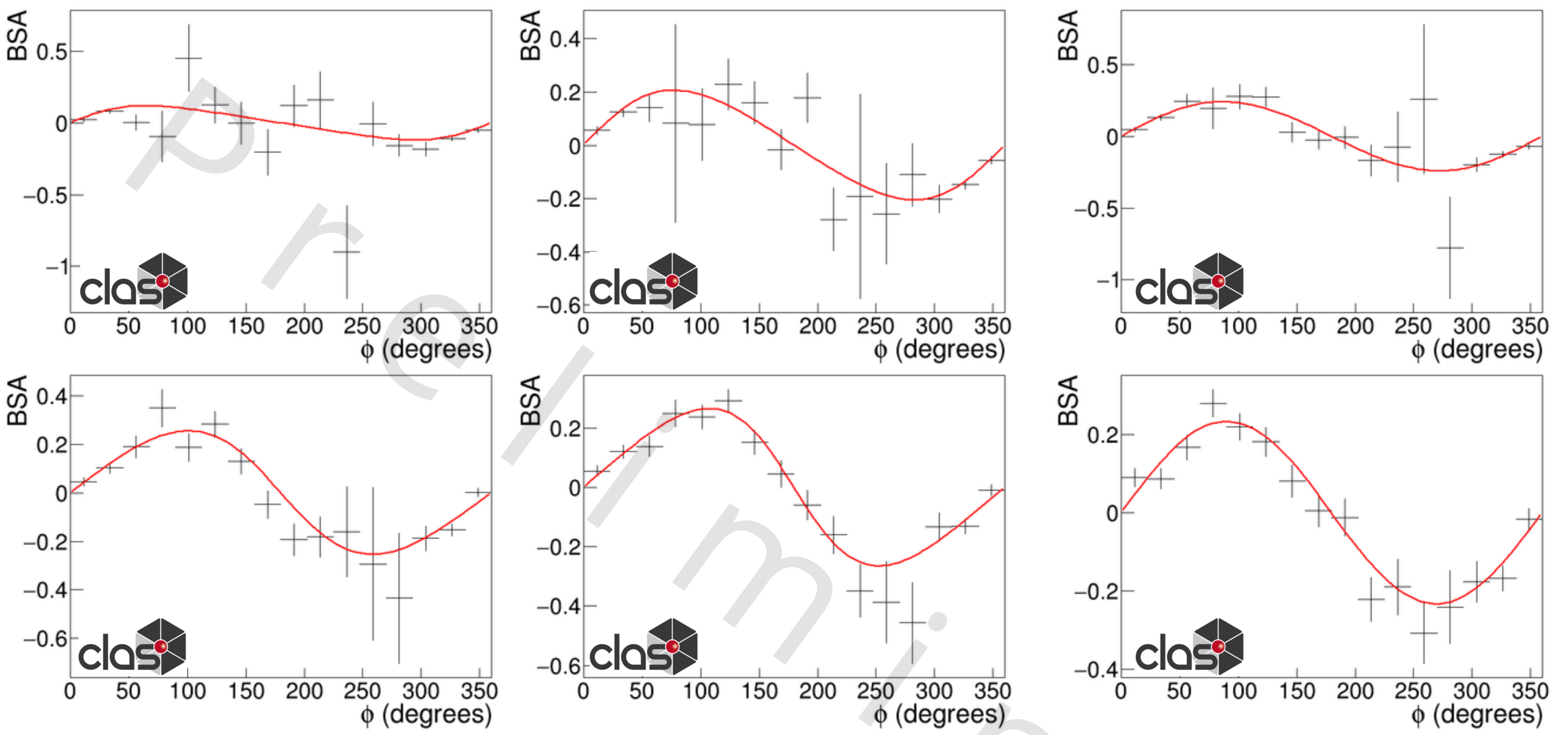




$1.0 < Q^2(\mathrm{GeV}^2) < 1.8$

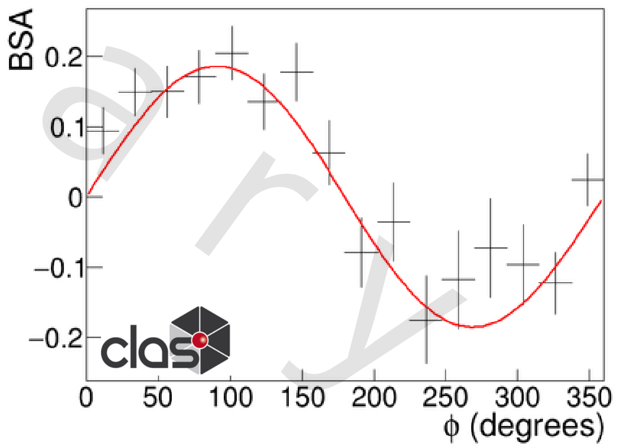
$0.12 < x_B < 0.2$

and 7 bins in t



Fit to a sinusoidal function

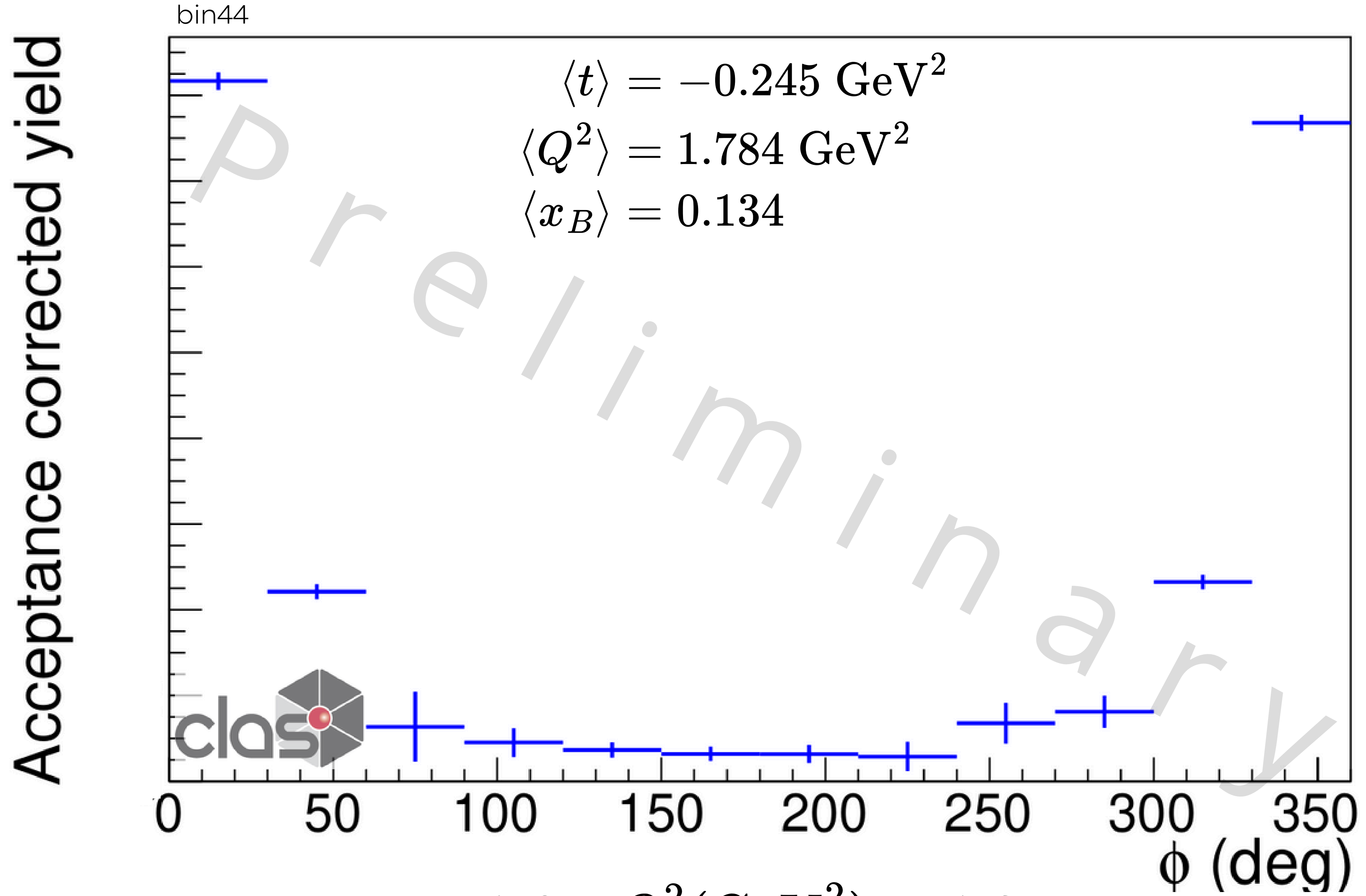
BSA = a * sin(ϕ)



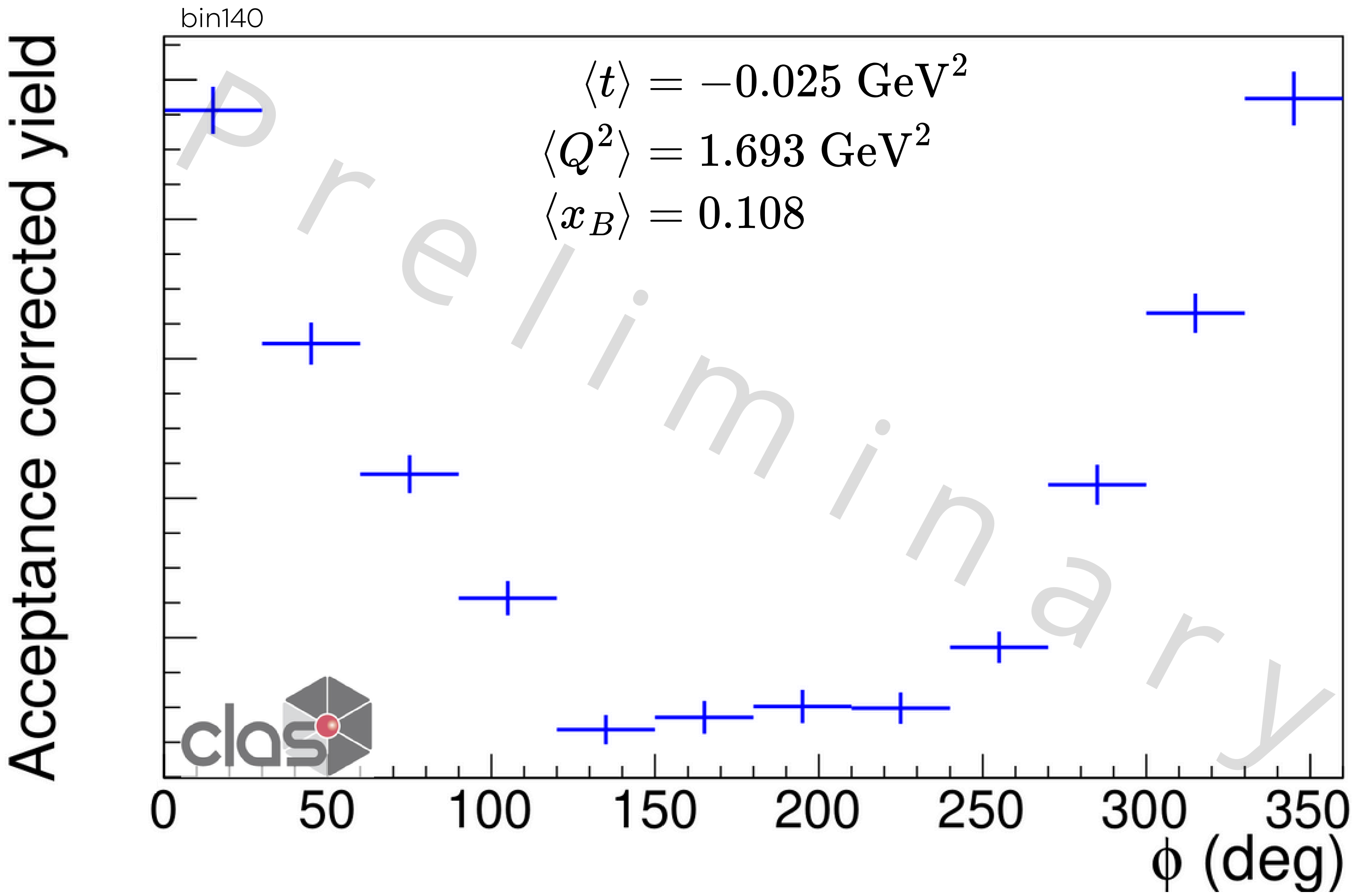
Results compatible with the KM15 model prediction

Preliminary cross-section results

Case without proton information



$1.6 < Q^2(\mathrm{GeV}^2) < 1.9$
$0.127 < x_B < 0.146$
$0.477 < -t(\mathrm{GeV}^2) < 0.176$



$1.45 < Q^2(\mathrm{GeV}^2) < 1.8$
$0.106 < x_B < 0.111$
$-t(\mathrm{GeV}^2) < 0.038$

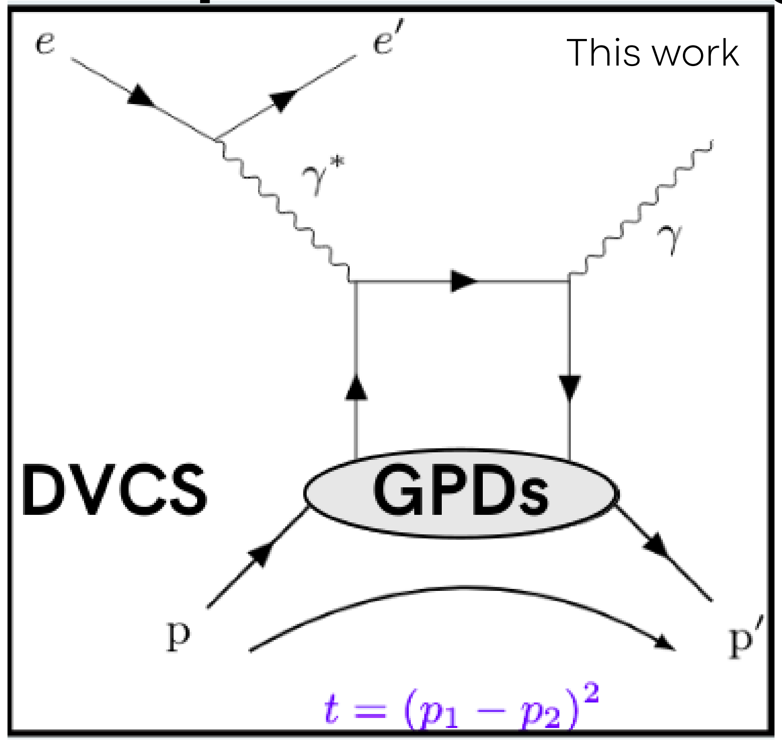
Results with proton information will be published soon by other members of the collaboration

4. SUMMARY

- GPDs are crucial for understanding the nucleon structure as they encode a variety of properties.
- DVCS is a golden channel for GPD studies due to its direct access to GPDs.
- The DVCS process was measured at Jefferson Lab, allowing the extraction of Beam Spin Asymmetry and cross-section measurements.
- While detecting the DVCS recoil proton is ideal, by not detecting it
    - There is a boost in statistics
    - There is access to a larger phase space
- Preliminary BSA and cross-section measurements were presented. Final results will be published soon.

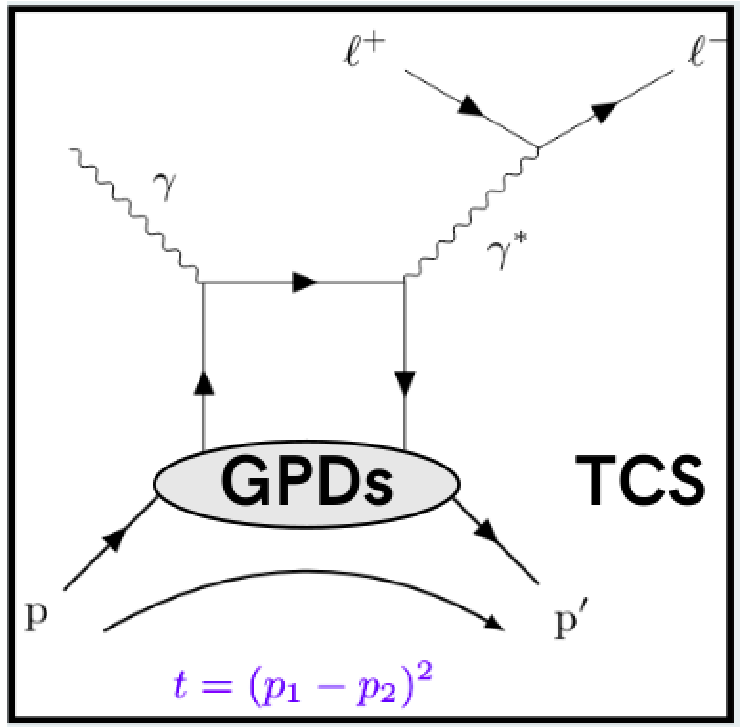
DVCS is not the only interesting channel to study GPDs

Deeply Virtual Compton Scattering



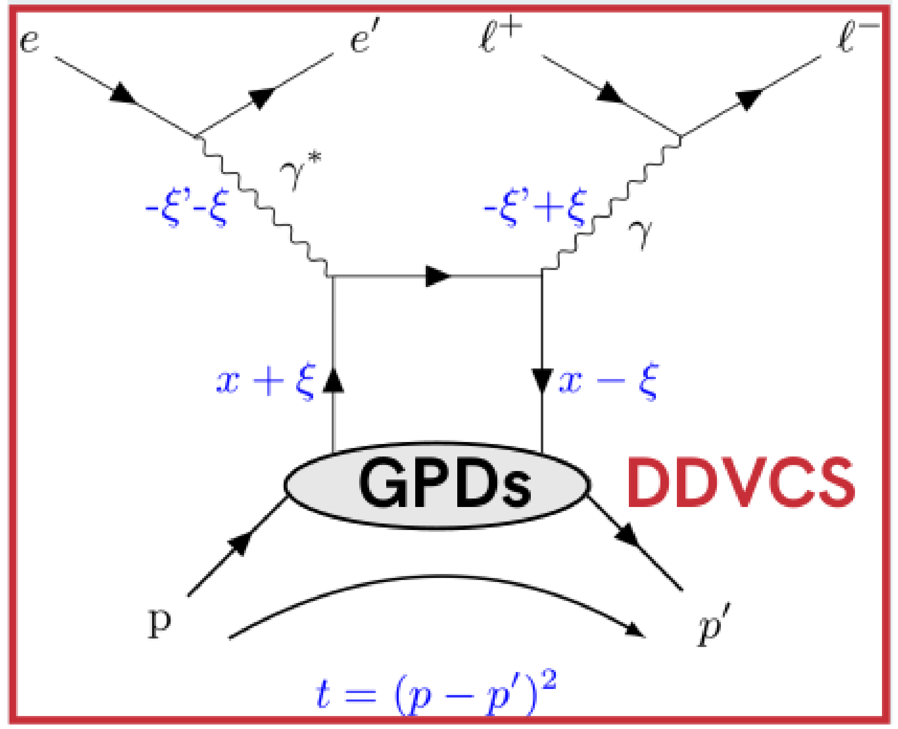
Christiaens, G., et al. Phys. Rev. Lett. 130.21 (2023): 211902.

Timelike Compton Scattering

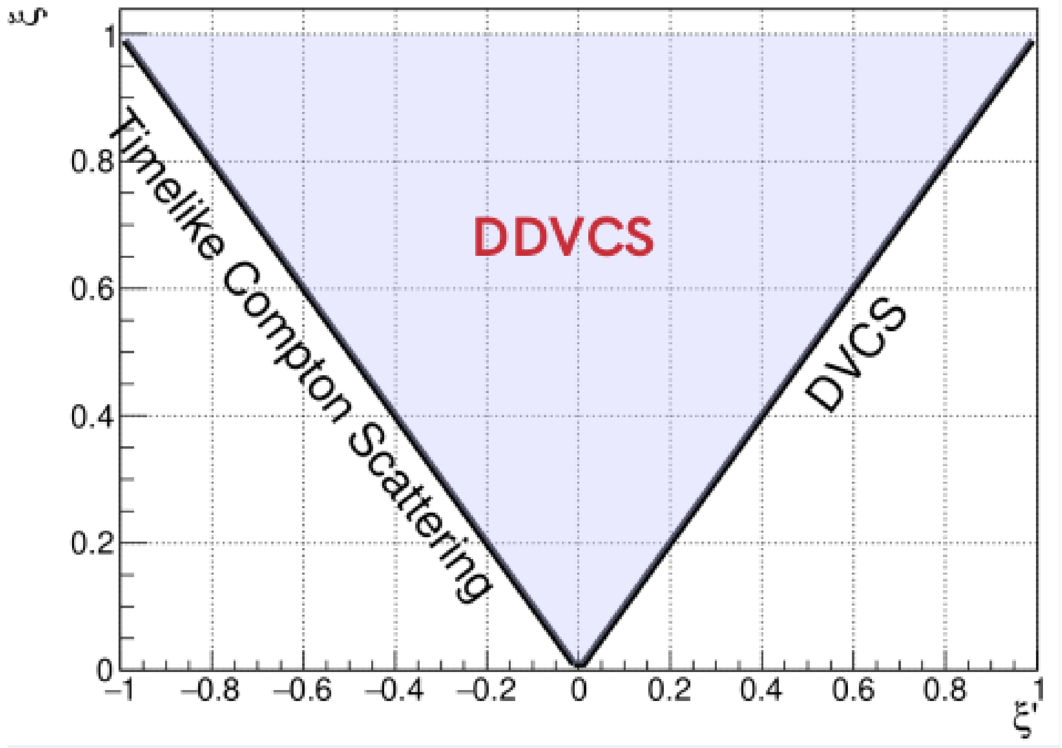


P. Chatagnon, et al. Phys. Rev. Lett. 127.26 (2021): 262501.

Double Deeply Virtual Compton Scattering



A.V. Belitsky and D. Mueller. Physi. Rev. D 68.11 (2003): 116005.



$$\mathcal{F}(\xi',\xi,t)=\sum_q e_q^2\left\{\mathcal{P}\int_{-1}^{1}dx\,F^q(x,\xi,t)\left[\frac{1}{x-\xi'}+\frac{1}{x+\xi'}\right]-i\pi\left[F^q(\xi',\xi,t)-F^q(-\xi',\xi,t)\right]\right\}$$

- Double DVCS have a more general access to GPDs.
- This process can be measured at Jefferon Lab.

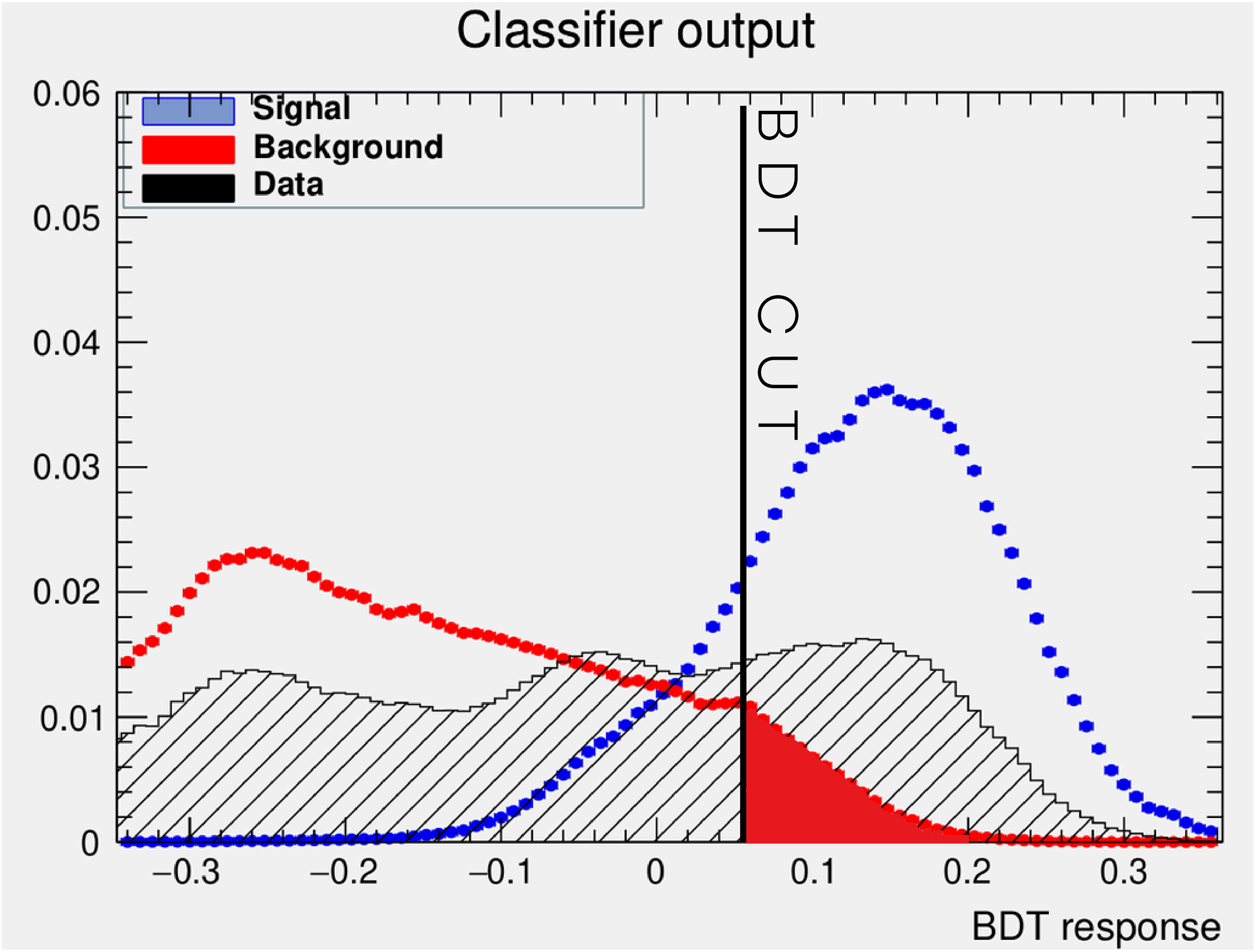
More info in the poster session

THANKS

2. CHANNEL SELECTION: BACKGROUND SUBTRACTION

BDT cannot achieve a perfect separation between signal and background.

There is always a leftover contamination



The entirety of the background cannot be removed with a BDT

To estimate and remove the residual background, we estimate the **1γ/2γ - phase space ratio** using two methods

$$\frac{(N^{MC}_{DVMP})_{ep\to ep\gamma}}{(N^{MC}_{DVMP})_{ep\to ep\gamma\gamma}} = \frac{(N^{Data}_{DVMP})_{ep\to ep\gamma}}{(N^{Data}_{DVMP})_{ep\to ep\gamma\gamma}}$$

Method 1:

Let us define:

- $n^{1\gamma}_{MC/Data}$ = Number of simulated π^0 events that pass the DVCS analysis.
- $n^{2\gamma}_{MC/Data}$ = Number of simulated π^0 events that are reconstructed.

The contamination is then:

$$n^{1\gamma}_{Data} = \left(\frac{n^{1\gamma}_{MC}}{n^{2\gamma}_{MC}}\right) n^{2\gamma}_{Data}.$$

Method 2:

1. Reconstruct π^0 events.
2. For each π^0, generate 1500 decays.
3. If the event pass the DVCS analysis with any photon, fill histograms.
4. If the event pass the DVMP analysis, increment $n^{2\gamma}_{MC}$ by the reconstruction efficiency.
5. At the end of the decays, DVCS events are normalized by $1/n^{2\gamma}_{MC}$.

4. DVCS MEASUREMENTS: CROSS-SECTION

MC - Data resolution matching was intended to eventually obtain cross-section measurements

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\phi} = \frac{1}{F_{Bin}} \times \frac{1}{F_{RC}} \times \frac{1}{\mathcal{L}\Delta\Omega} \times \left[\frac{N(e', p', \gamma)_{\text{bin mig}}}{F_{Acc}}\right]$$

Observed xsection

- Bin migration is done with RooUnfold
- To convert from reconstructed to generated yields

$$F_{Acc} = \frac{N_{rec}}{N_{gen}}$$

- Luminosity X phase space factor

$$\mathcal{L}\Delta\Omega$$

4. DVCS MEASUREMENTS: CROSS-SECTION

MC - Data resolution matching was intended to eventually obtain cross-section measurements

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\phi} = \frac{1}{F_{eff}} \times \left\{ \frac{1}{F_{Bin}} \times \frac{1}{F_{RC}} \times \frac{1}{\mathcal{L}\Delta\Omega} \times \left[\frac{N(e', p', \gamma)_{\text{bin mig}}}{F_{Acc}} \right] \right\}$$

Observed xsection

PRELIMINARY:

Cross-section relative to BH

Global normalization factor based on BH normalization at the endpoints

$$F_{eff} = \frac{1}{N} \sum_{\phi<30^\circ \text{ and } \phi>330^\circ} \frac{d^4\sigma_{measured}(\phi_i)}{d^4\sigma_{BH}(\phi_i)}$$

N is the number of points entering the sum

- Bin centering correction

$$F_{bin} = \frac{\overline{d\sigma}_{Born.}}{d\sigma_{Born.}(\langle x_B \rangle, \langle Q^2 \rangle, \langle -t \rangle, \langle \phi \rangle)}$$

- Observed cross-section includes radiative effects
- To convert it into the Born cross-section: $F_{RC} = \frac{\overline{d^5\sigma_{RC}}}{\overline{d^5\sigma_{born}}}$