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https://indico.in2p3.fr/event/30430

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

clas
CEBAF **L**arge **A**cceptance **S**pectrometer

ⓘ

BY:

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on behalf of the CLAS12 collaboration

EuNPC2025

23/09/2025

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PARIS-SACLAY**

École Doctorale
PHENIICS
Doctoral School

Jefferson Lab

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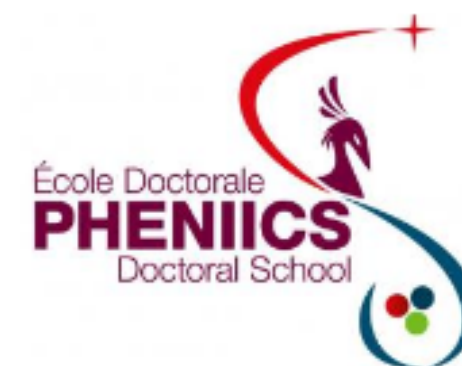
C O N T E N T S

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INTRODUCTION

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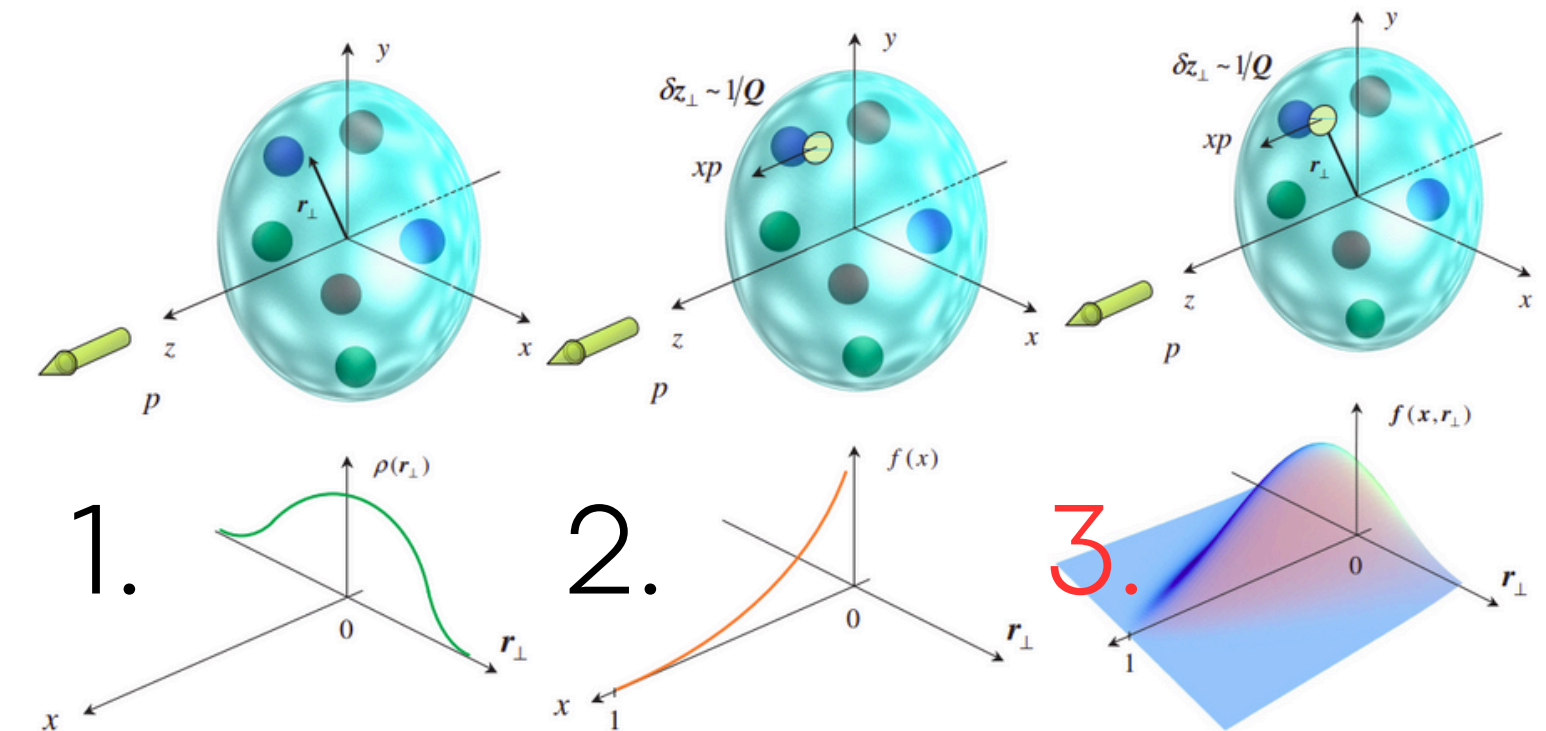
At low energy QCD, we describe the nucleon structure in terms of structure functions including:
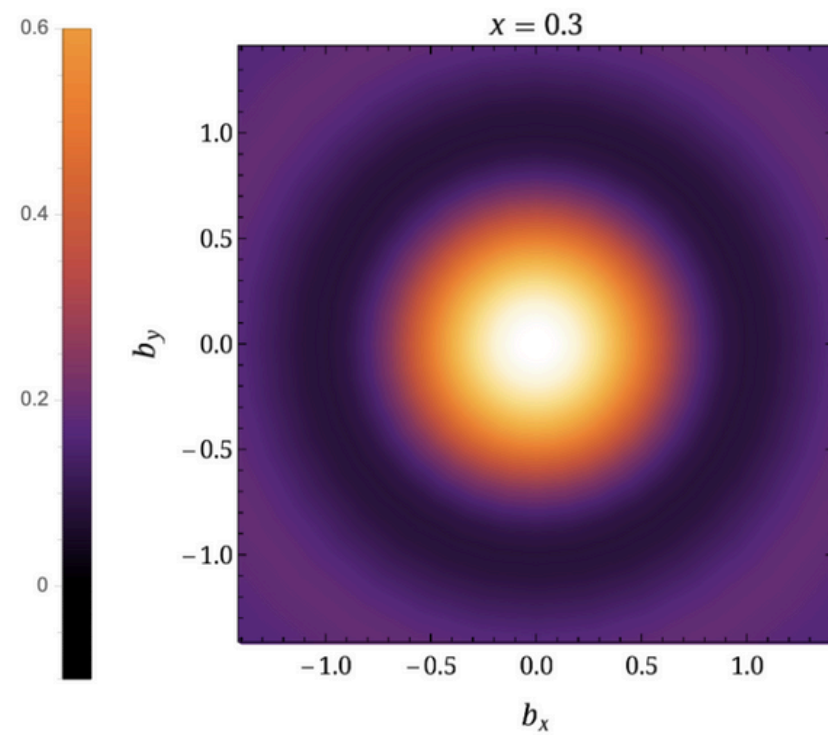
1. Form Factors describe transverse position of partons
2. Parton Distribution Functions describe longitudinal momentum distributions
3. Generalized Parton Distributions (GPDs) correlates transverse position and longitudinal momentum distributions

GPDs encode information of the nucleon structure such as:

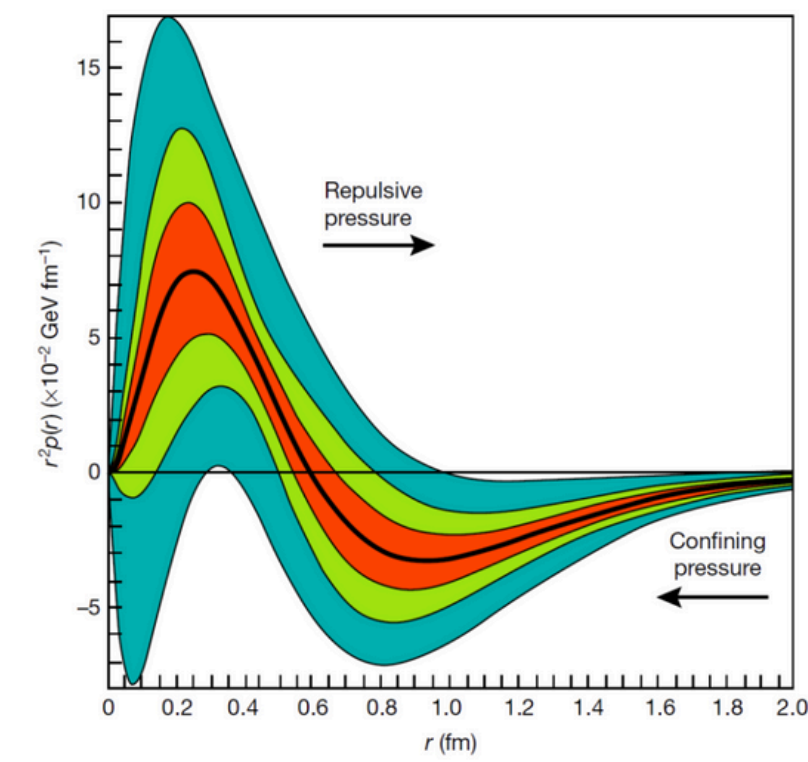| **Nucleon Tomography**	**Contributions to the nucleon total spin.**	**Access to Gravitational Form Factors.**
H.W. Lin, Phys. Rev. Lett. 127 (2021) 182001.	X. Ji, Phy.Rev.Lett.78,610(1997)	V. D. Burkert *et al*. Nature 557.7705 (2018): 396

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

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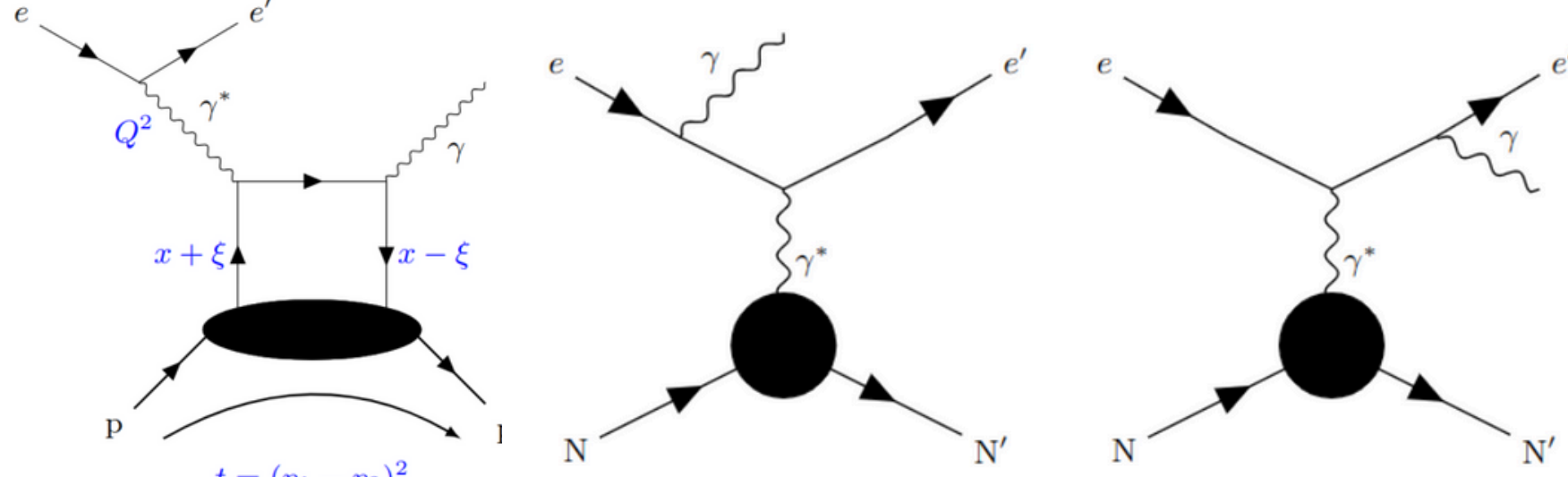- Quark's orbital angular momentum is accessed through GPDs
- Gluon contribution

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

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

Deeply Virtual Compton Scattering (DVCS)

Bethe-Heitler (BH)

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

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

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

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

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
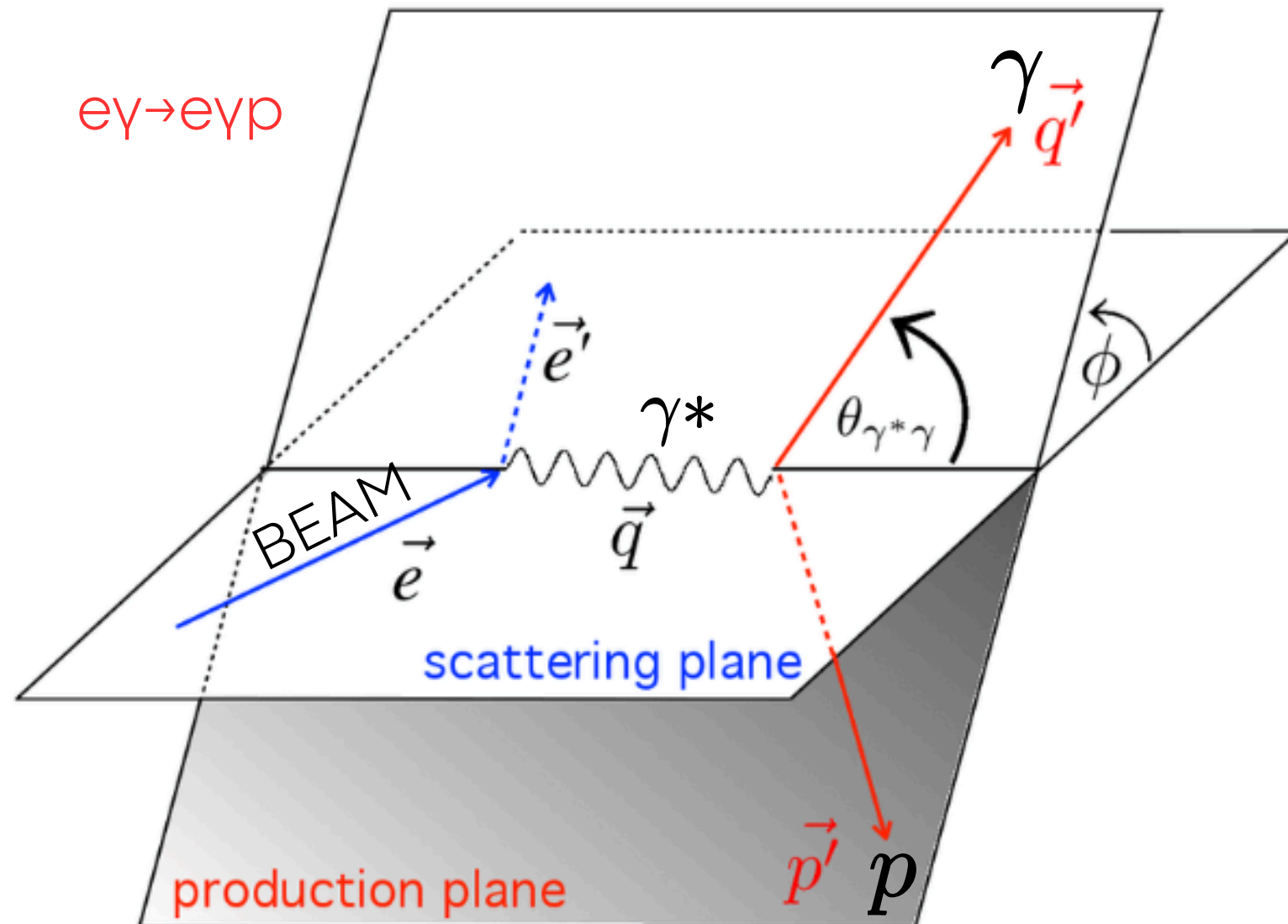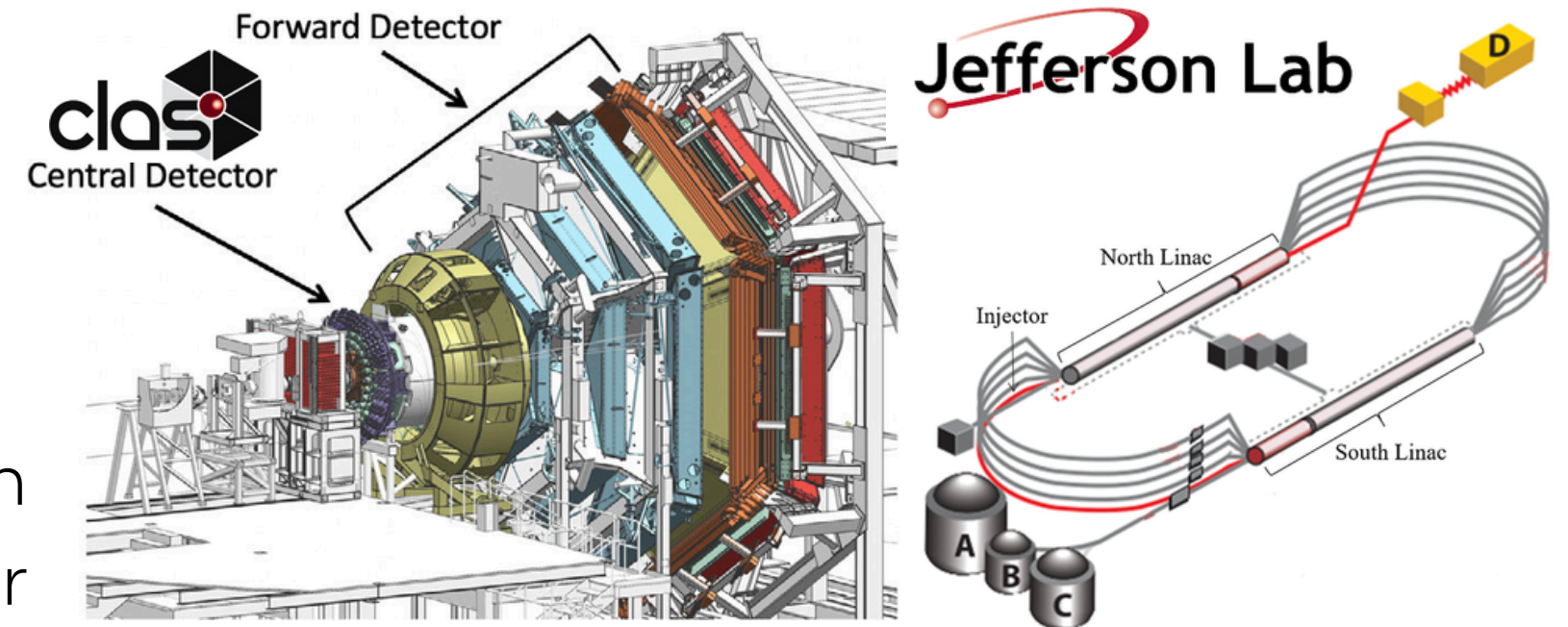
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DATA SELECTION

2. DATA SELECTION

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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)

eγ→eγp

KINEMATICS

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

EXCLUSIVITY CUTS (if proton detected)

- $\Delta\phi=|\phi(p')-\phi(\gamma)|<2°$
- $\Delta t=|t(p')-t(\gamma)|<2$ GeV^2
- P_{miss}<1 GeV/c

$\phi(p')$ uses γ* and p'
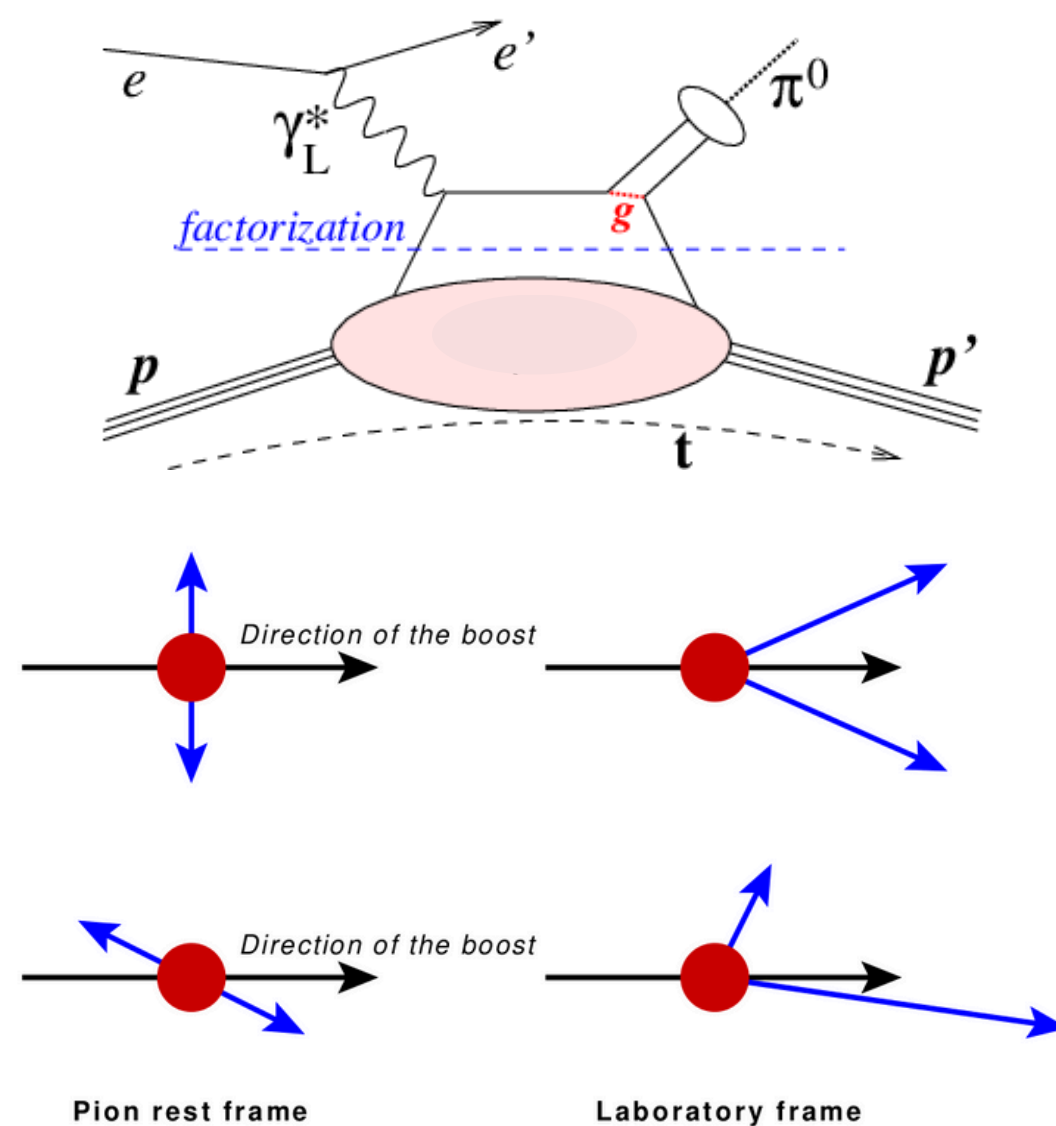$\phi(\gamma)$ uses γ* and γ
$t(p') = (p-p')^2$

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

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

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The main background contribution is exclusive π^0 production
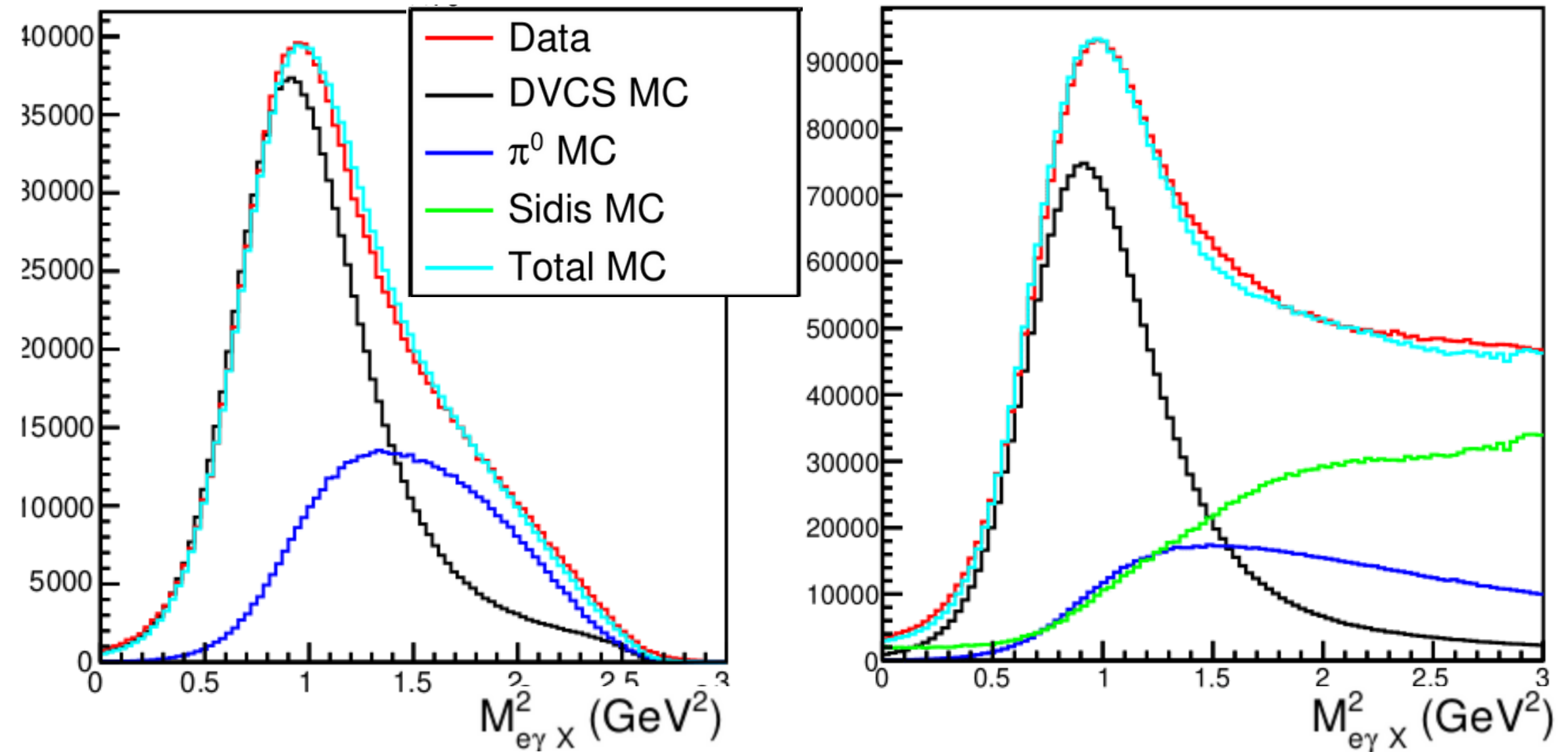
$ep \rightarrow ep\pi^0 \rightarrow ep$ $\gamma(\gamma)$

Missing proton mass distribution

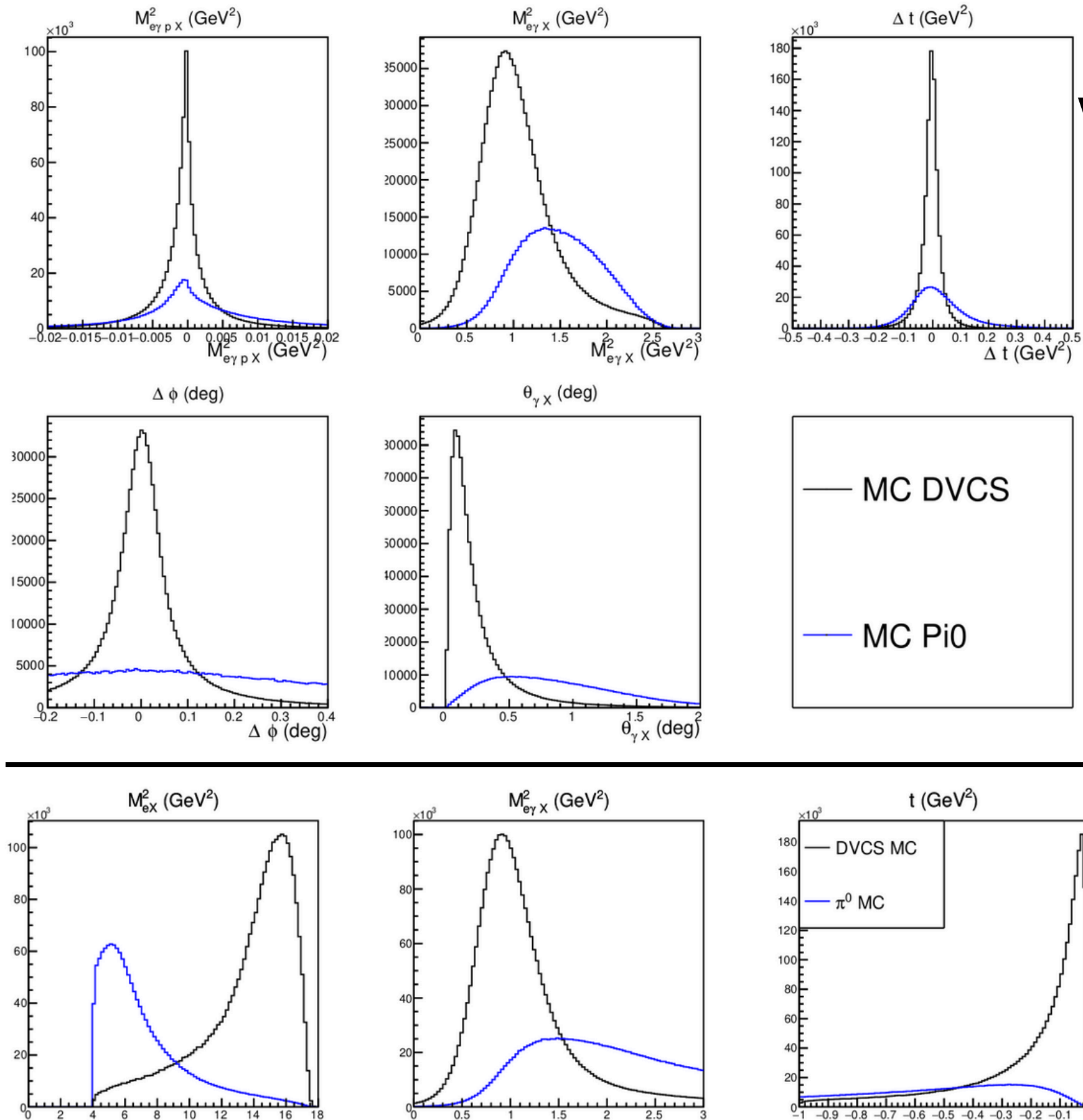$$M_{e\gamma X}^2 = (e + p - e' - \gamma)^2$$

With proton　　　　**Without proton**

—	Data
—	DVCS MC
—	π^0 MC
—	Sidis MC
—	Total MC

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

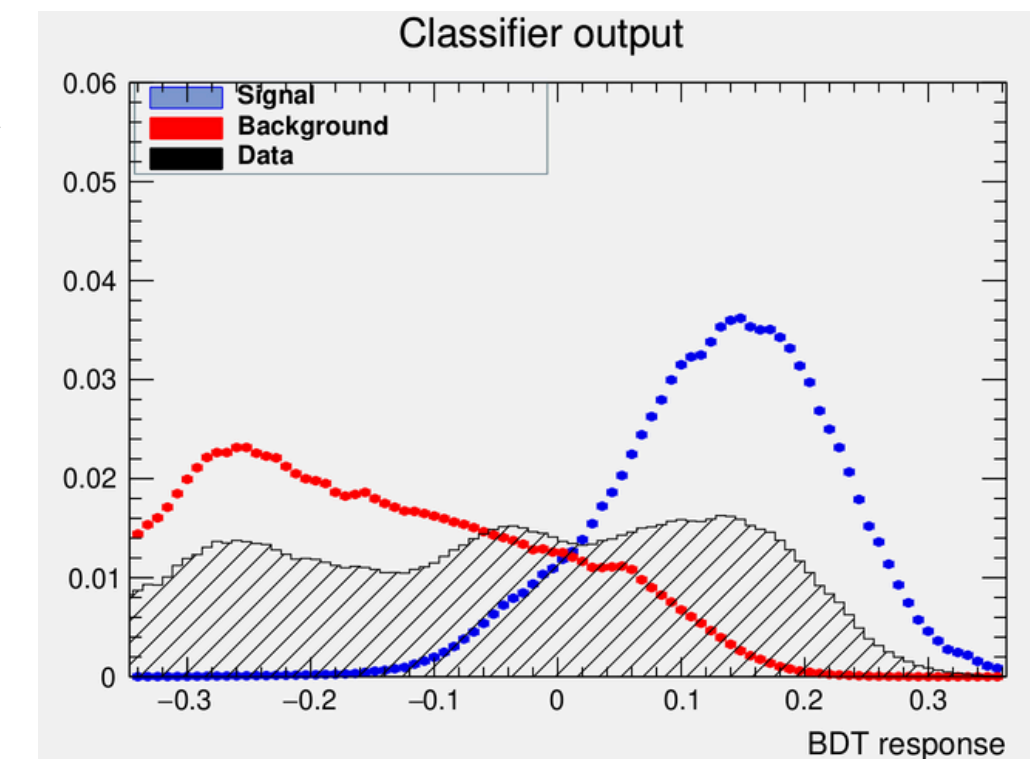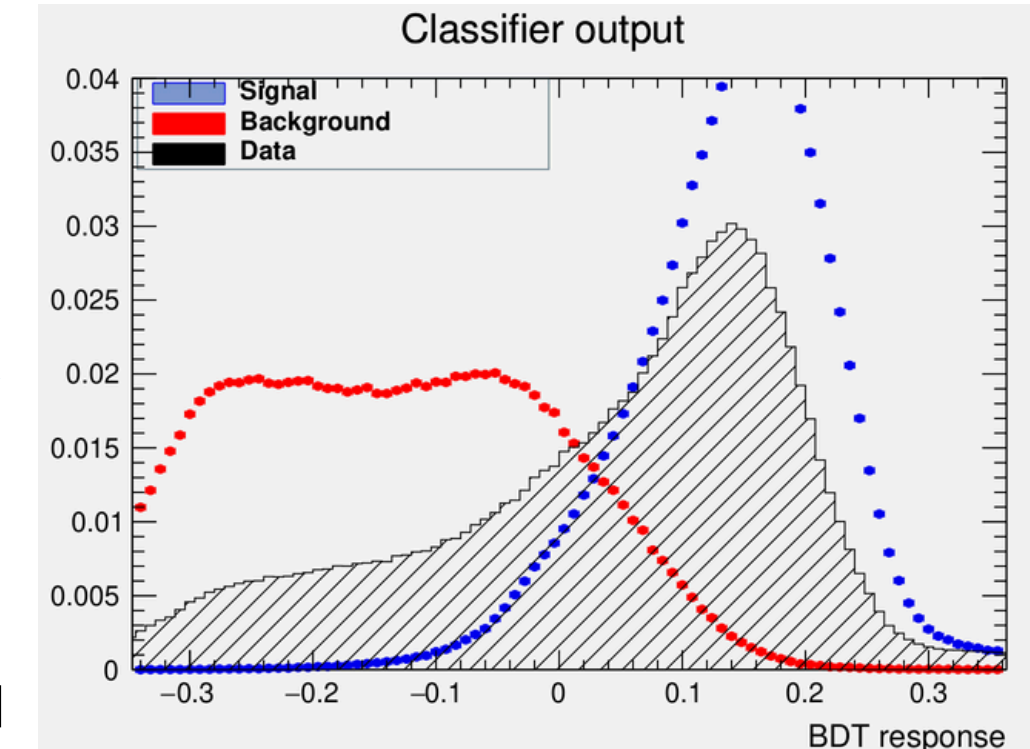Juan Sebastian Alvarado, Université Paris-Saclay - IJCLab

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

With proton

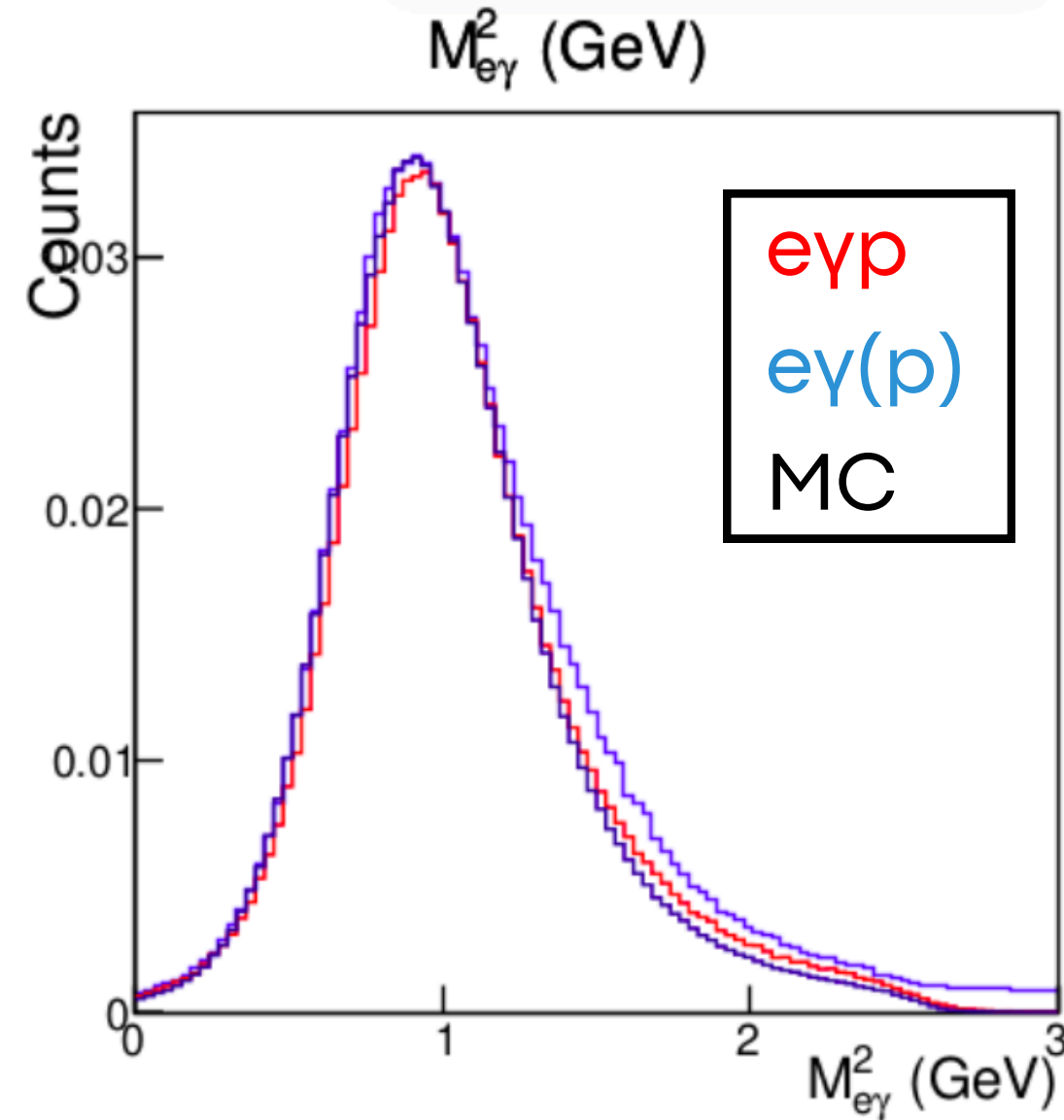The following variables are used to train a BDT due to its DVCS/DVMP separation power.

W/out proton

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

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Data/MC comparison

eγp/eγ(p) comparison

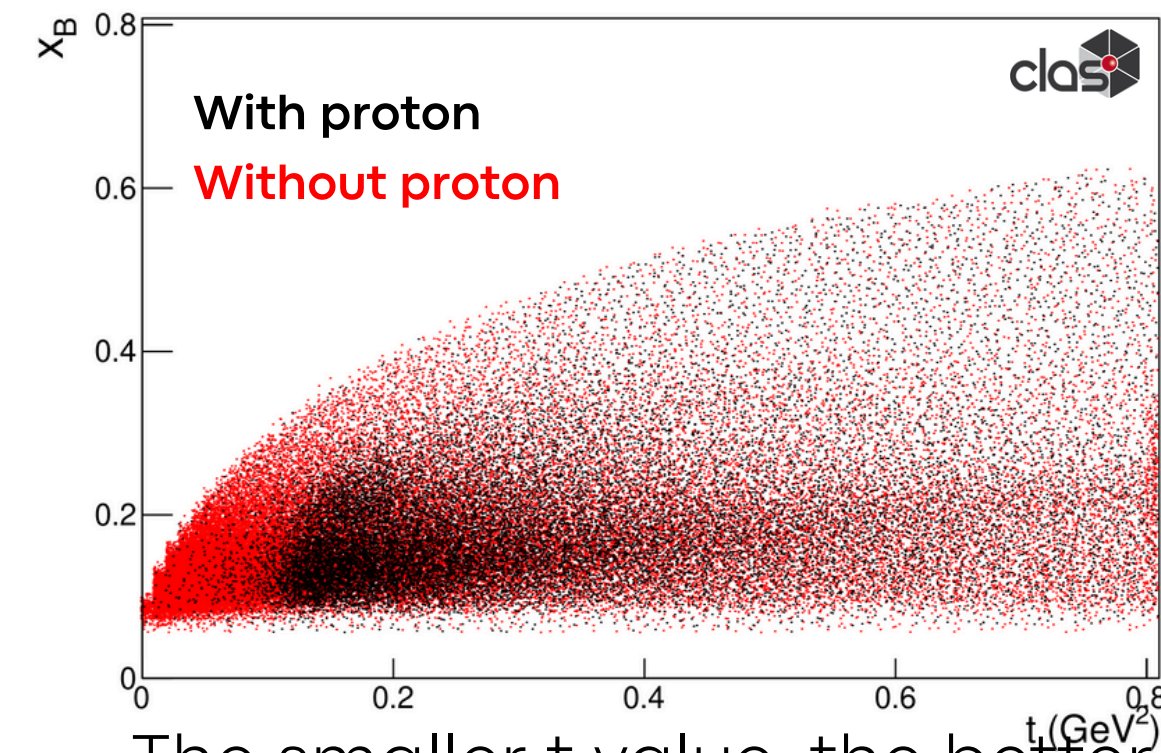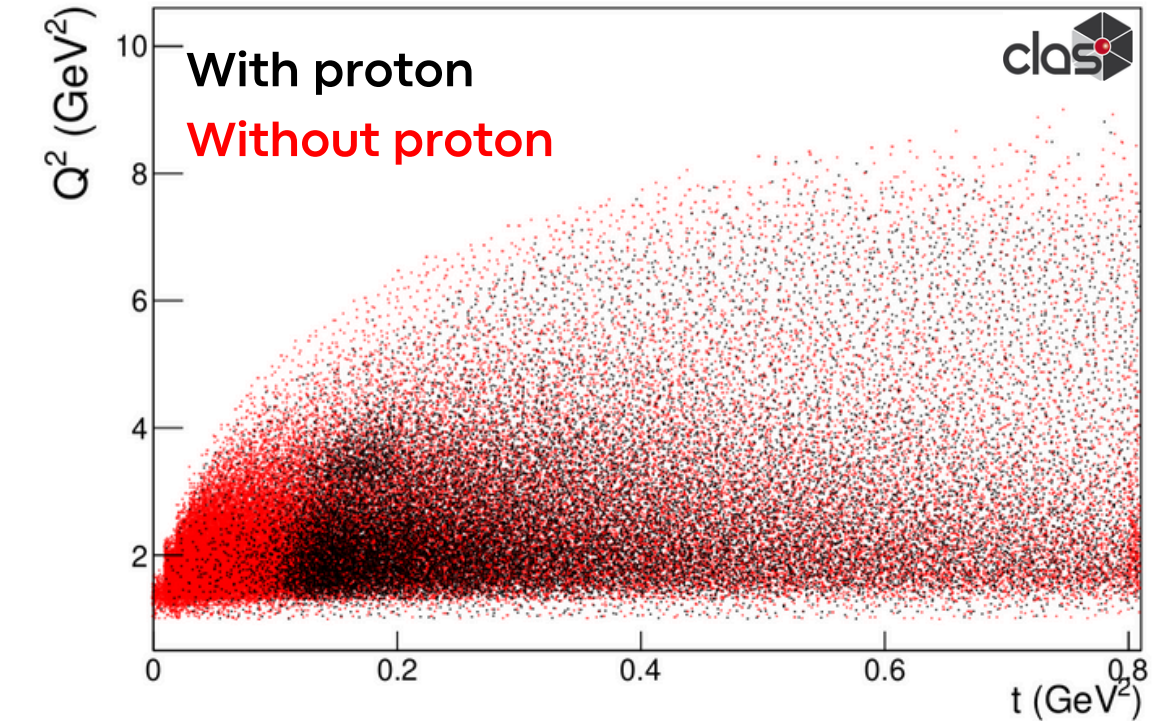
Most of the background was removed, leading to a good agreement between simulation and data.
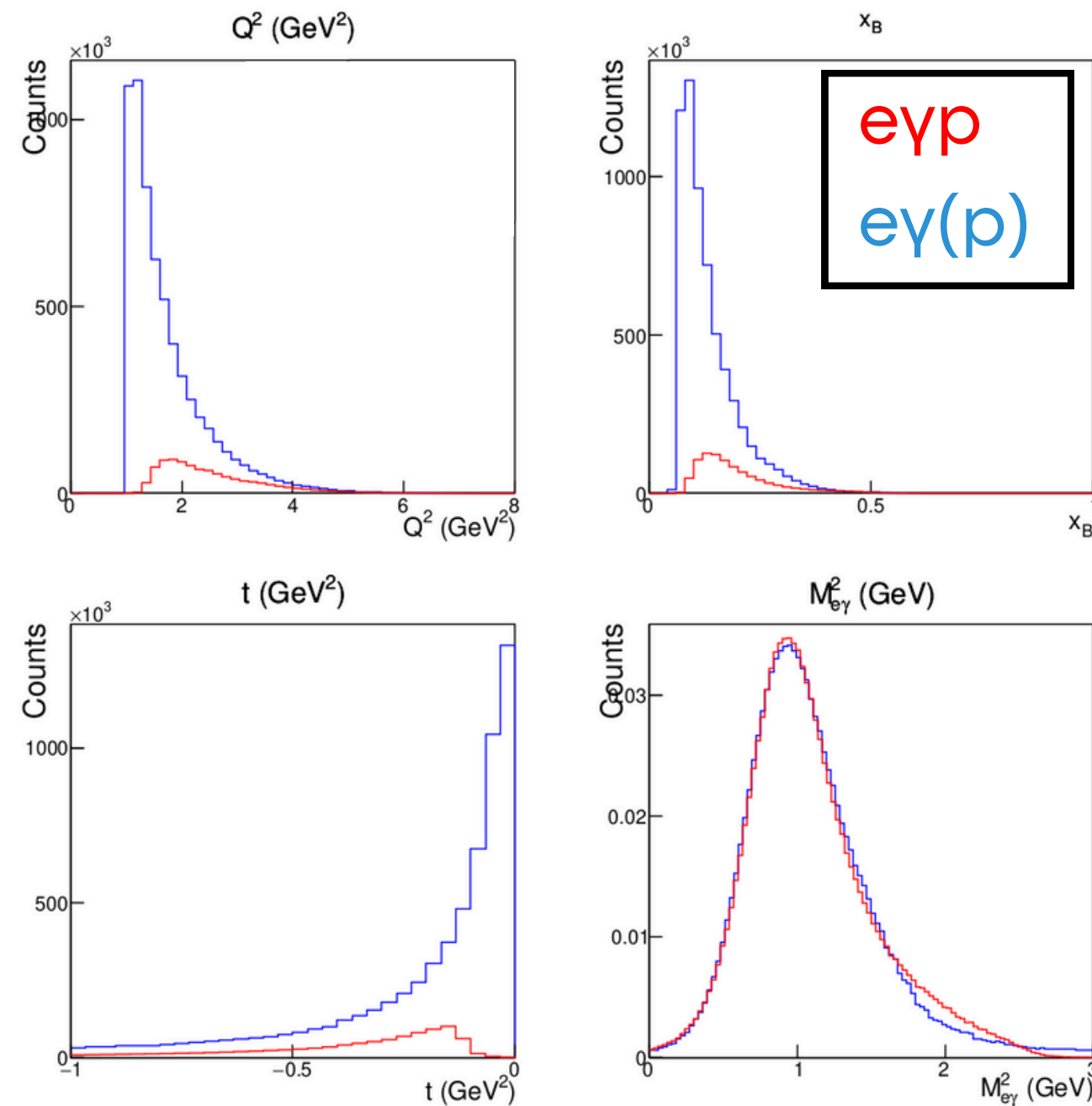
When not requiring a proton:
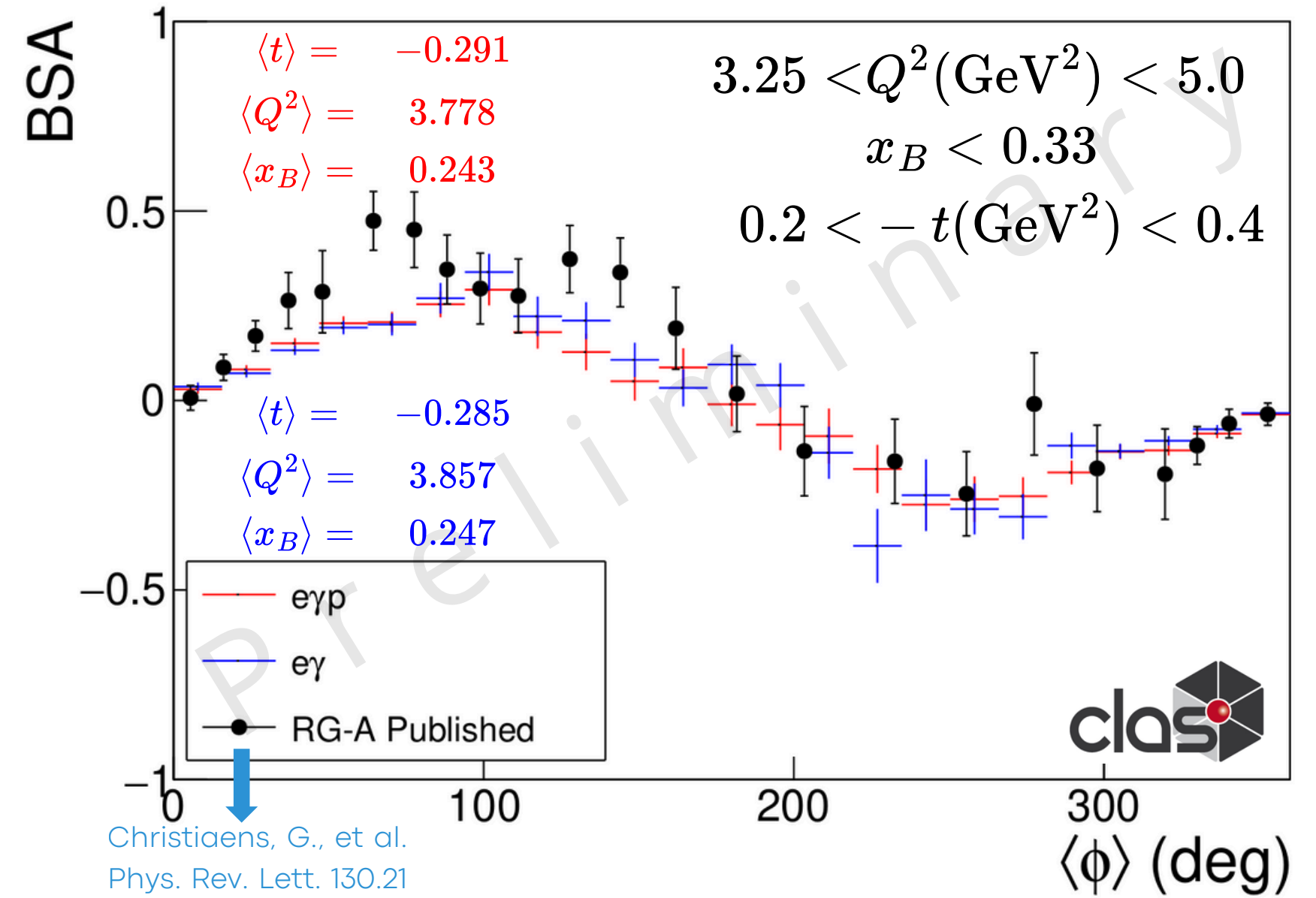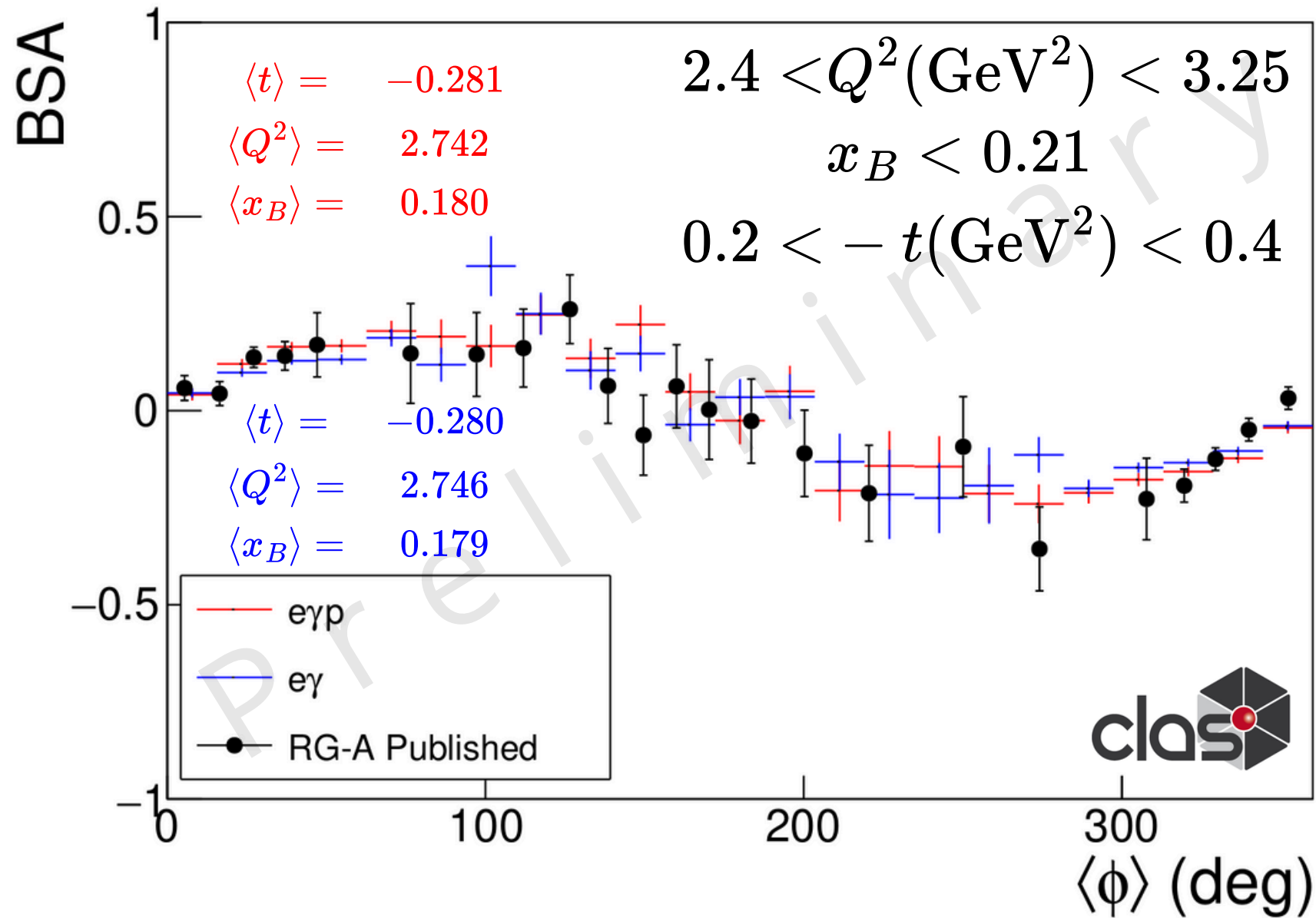
- Increased statistics
- Access to smaller -t values

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

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DVCS MEASUREMENTS

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Left plot:
$\langle t \rangle = -0.281$
$\langle Q^2 \rangle = 2.742$
$\langle x_B \rangle = 0.180$

$2.4 < Q^2(\text{GeV}^2) < 3.25$
$x_B < 0.21$
$0.2 < -t(\text{GeV}^2) < 0.4$

$\langle t \rangle = -0.280$
$\langle Q^2 \rangle = 2.746$
$\langle x_B \rangle = 0.179$

Legend: eγp, eγ, RG-A Published

$\langle \phi \rangle$ (deg)

Right plot:
$\langle t \rangle = -0.291$
$\langle Q^2 \rangle = 3.778$
$\langle x_B \rangle = 0.243$

$3.25 < Q^2(\text{GeV}^2) < 5.0$
$x_B < 0.33$
$0.2 < -t(\text{GeV}^2) < 0.4$

$\langle t \rangle = -0.285$
$\langle Q^2 \rangle = 3.857$
$\langle x_B \rangle = 0.247$

Legend: eγp, eγ, RG-A Published

$\langle \phi \rangle$ (deg)

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

$$\mathbf{BSA} = \frac{1}{P_{\text{beam}}} \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-}$$
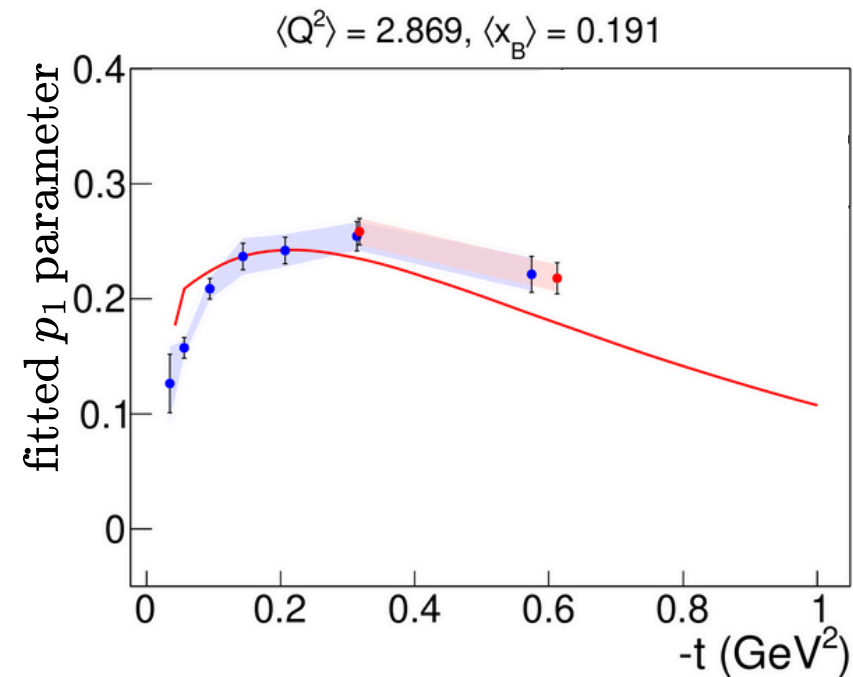
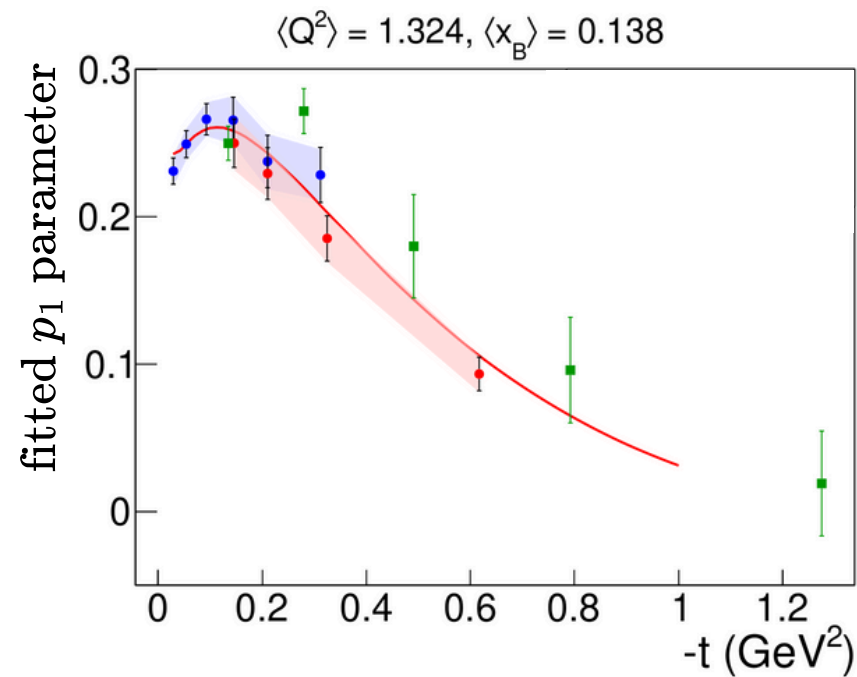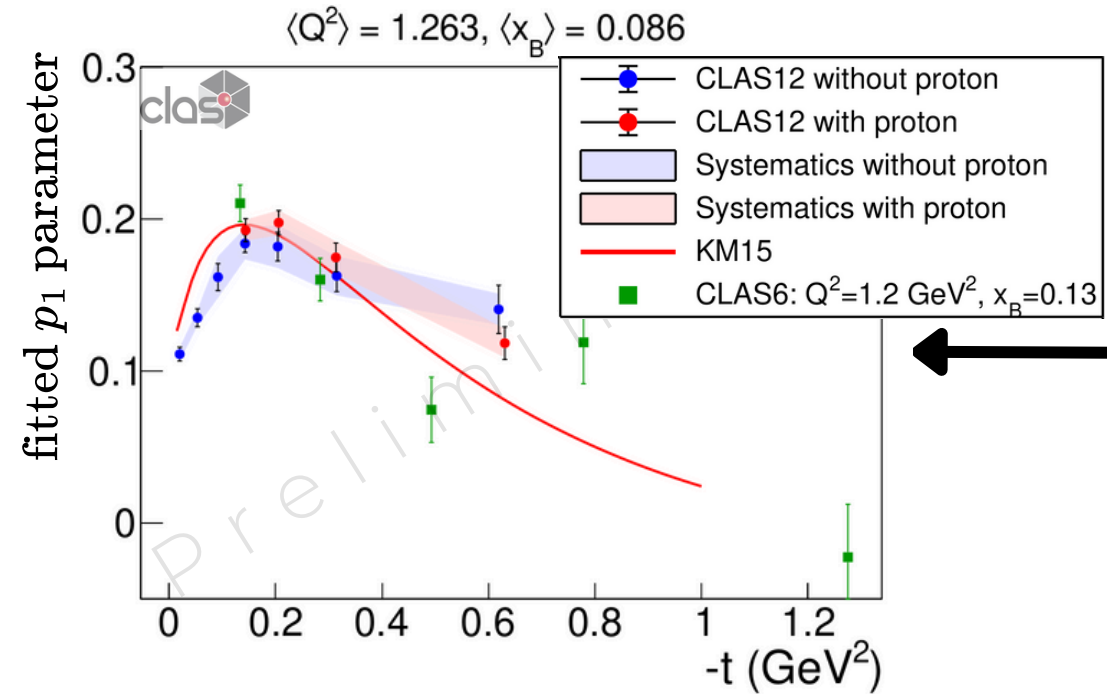$$\propto \Im \left\{ F_1 \mathcal{H} + \xi'(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right\},$$

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

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BSA amplitude as a function of -t
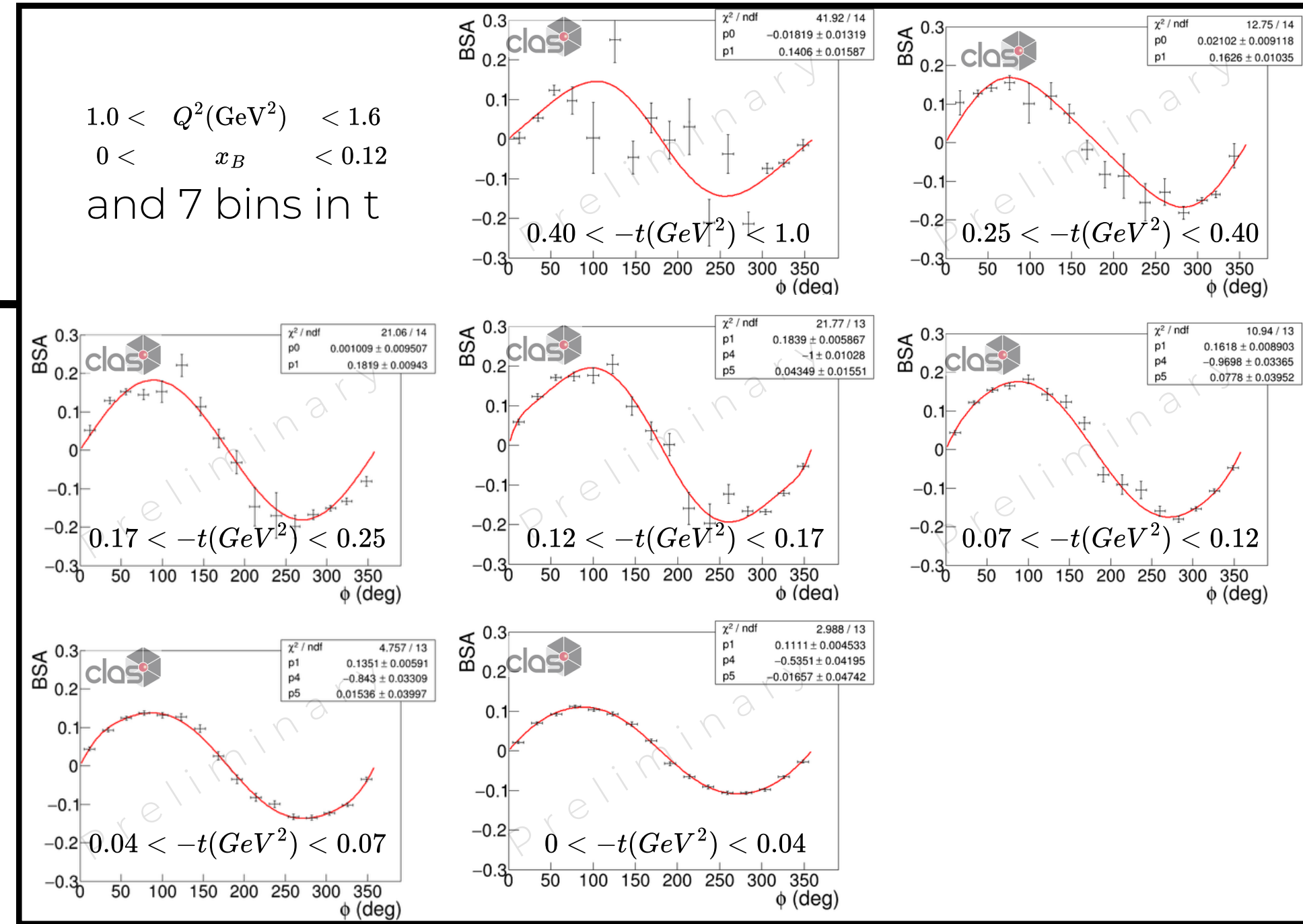

There is sensitivity to cosφ modulations at small -t

$$A_{LU}(\phi) \equiv \frac{p_1 \mathcal{P}_1(\phi) \mathcal{P}_2(\phi) \sin(\phi)}{1 + p_2 \cos(\phi) + p_3 \cos(2\phi)}$$
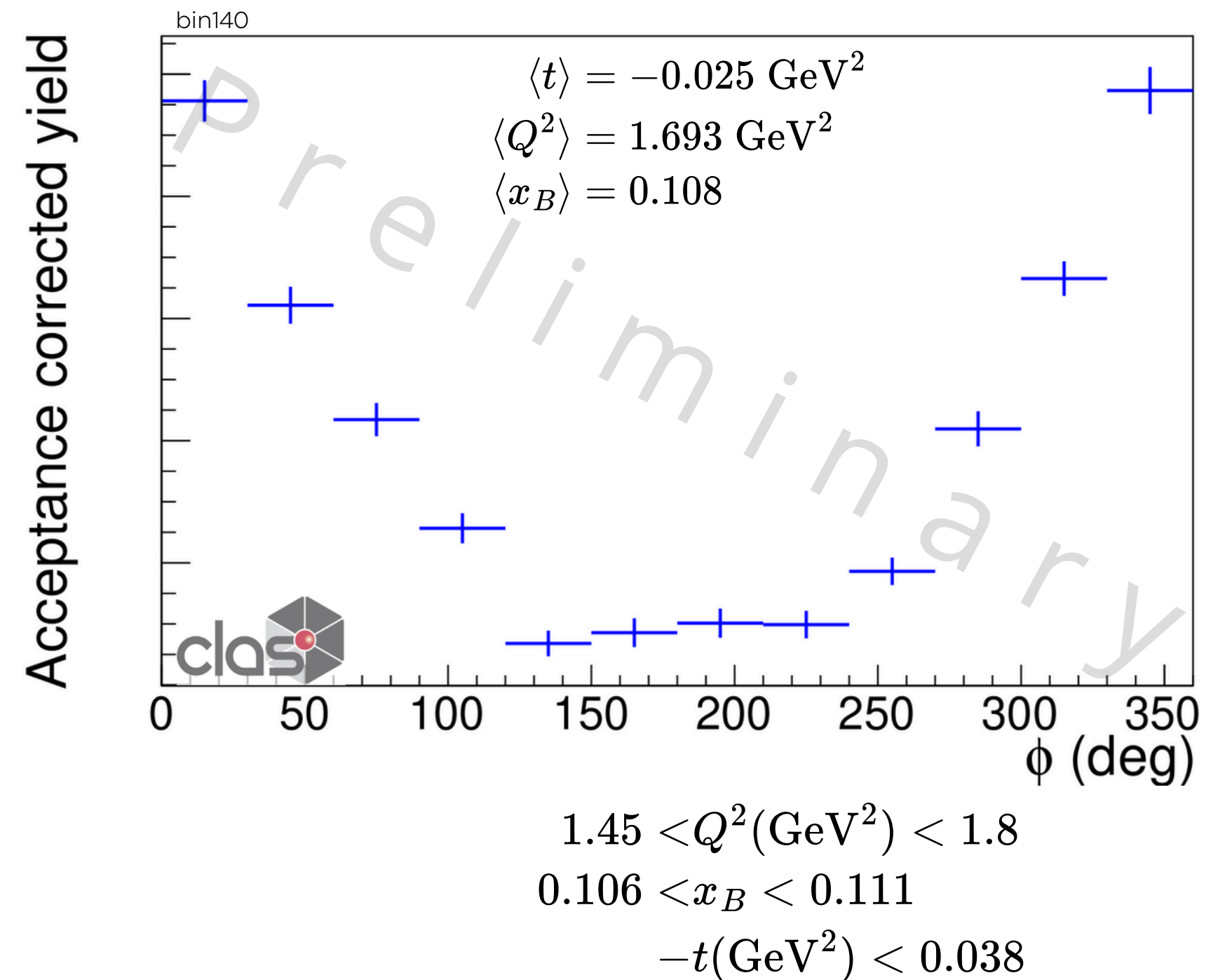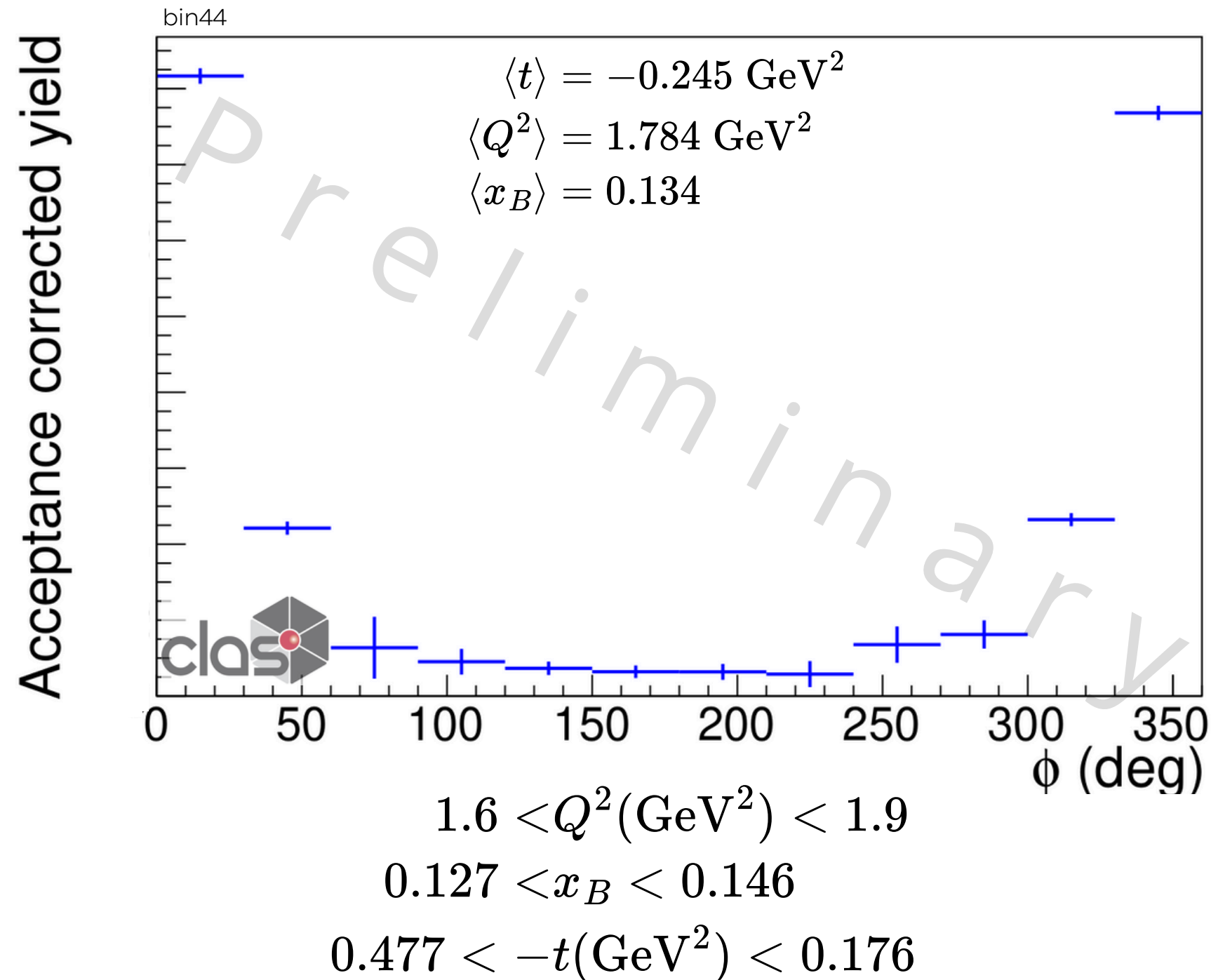
$$1.0 < \quad Q^2(\text{GeV}^2) \quad < 1.6$$
$$0 < \quad x_B \quad < 0.12$$

and 7 bins in t

- The **eγ(p)** selection gives access to the small -t region
- Results compatible previous measurements

Preliminary cross-section results

Case without proton information

bin44

$\langle t \rangle = -0.245 \text{ GeV}^2$

$\langle Q^2 \rangle = 1.784 \text{ GeV}^2$

$\langle x_B \rangle = 0.134$

Acceptance corrected yield — ϕ (deg)

$1.6 < Q^2(\text{GeV}^2) < 1.9$

$0.127 < x_B < 0.146$

$0.477 < -t(\text{GeV}^2) < 0.176$

bin140

$\langle t \rangle = -0.025 \text{ GeV}^2$

$\langle Q^2 \rangle = 1.693 \text{ GeV}^2$

$\langle x_B \rangle = 0.108$

Acceptance corrected yield — ϕ (deg)

$1.45 < Q^2(\text{GeV}^2) < 1.8$

$0.106 < x_B < 0.111$

$-t(\text{GeV}^2) < 0.038$

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

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- 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 large rates and 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.

THANKS

BDT cannot achieve a perfect separation between signal and background.

There is always a leftover contamination

Classifier output
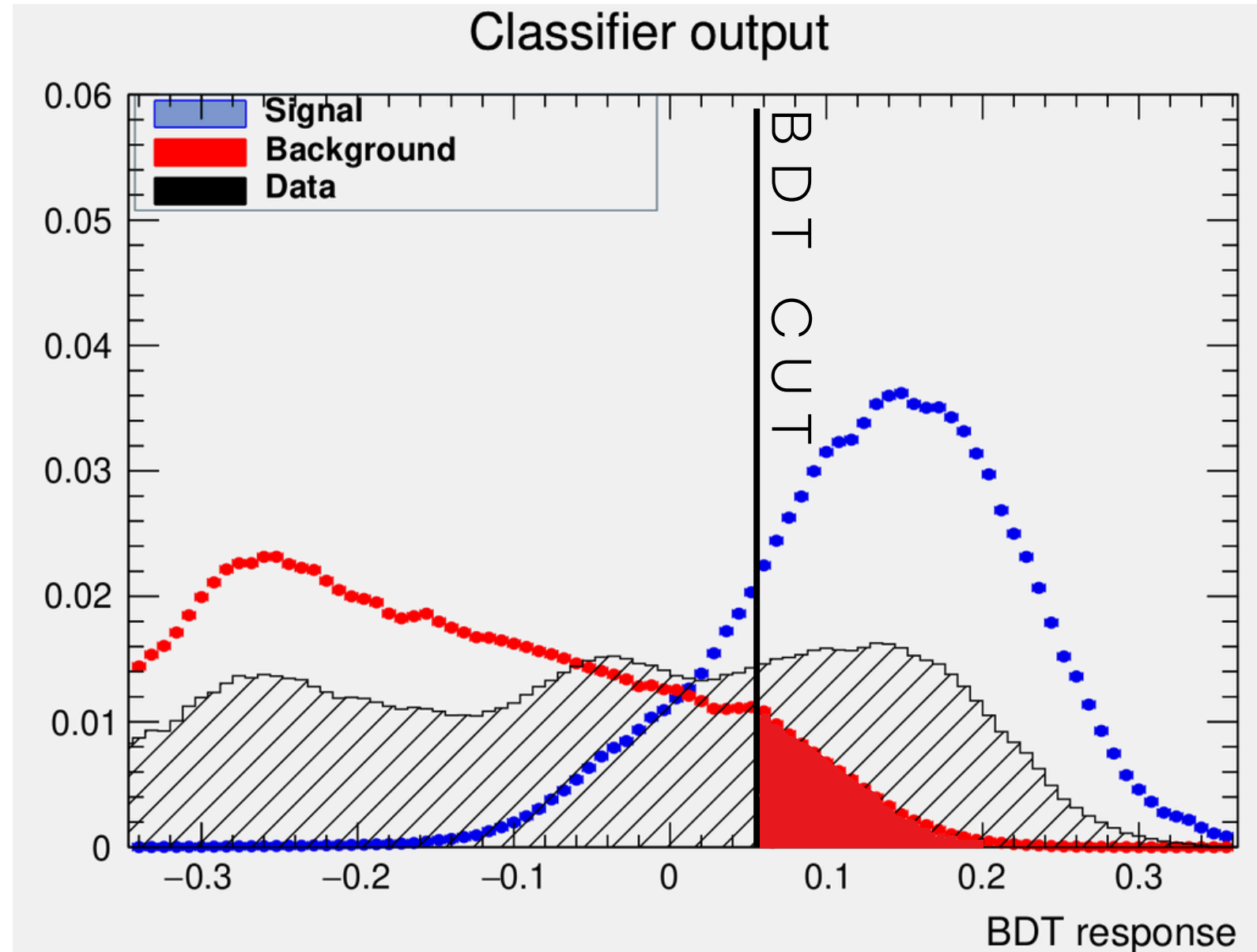
The entirety of the background cannot be removed with a BDT

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

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

Method 1:
Let us define:

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

- $n_{MC/Data}^{2\gamma}$ = Number of simulated π^0 events that are reconstructed.

The contamination is then:

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

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 $n_{MC}^{2\gamma}$ by the reconstruction efficiency.

5. At the end of the decays, DVCS events are normalized by $1/n_{MC}^{2\gamma}$.