High precision measurements of Deeply Virtual Compton Scattering at small nucleon momentum transfer

CLAS Collaboration meeting
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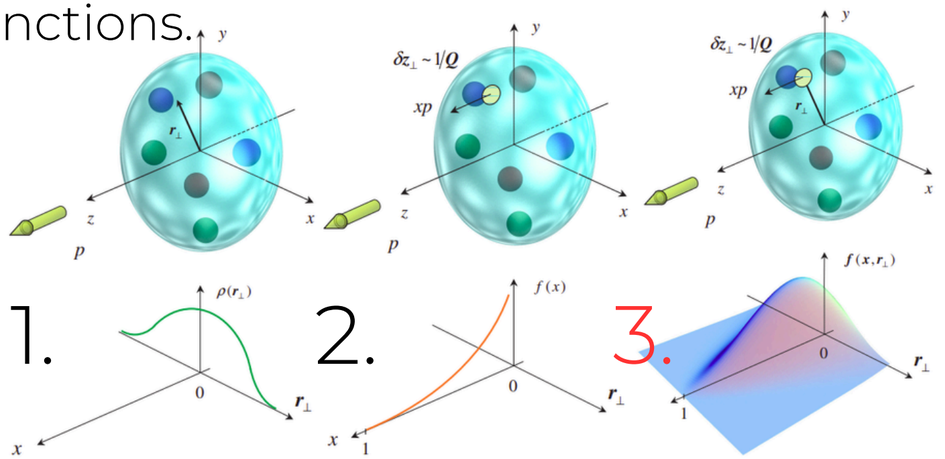
1. PROTON GPDS & DVCS

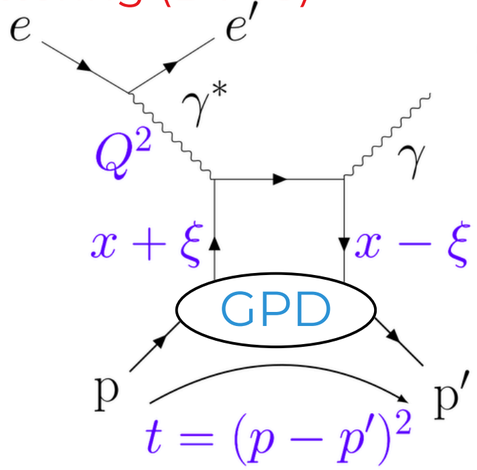
Nucleon internal dynamics is described in terms of structure functions.
They are introduced to describe the partons'

1. Transverse position distribution → FFs
2. Longitudinal momentum distribution → PDFs
3. Transverse position and longitudinal momentum → GPDs
4. Transverse position and transverse momentum → TMDs

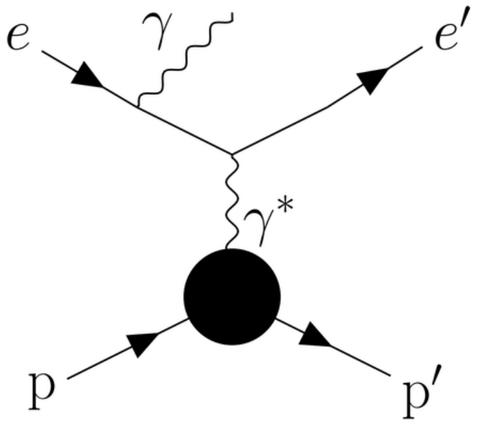


The proton features four chiral-even GPDs $F = H, E, \widetilde{H}, \widetilde{E}$
which can be **constrained via electro-production of a real photon ep→epγ**

Deeply Virtual Compton Scattering (DVCS)



Bethe-Heitler (BH)



They enter the amplitude through **Compton Form Factors (CFFs)**

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

In particular, the Beam Spin Asymmetry (BSA) access:

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

1. PROTON GPDS & DVCS

Detecting the proton ensures exclusivity of the reaction, but limits the |t| coverage

$$ep \to e'p'\gamma \qquad t(p' = 0.35\ \mathrm{GeV}/c) \simeq p'^2 = 0.1225\ \mathrm{GeV}^2/c^2$$

Access to Gravitational Form Factors.

H. Dutrieux *et al.*, Eur. Phys. J. C 81 (2021) 4, 300

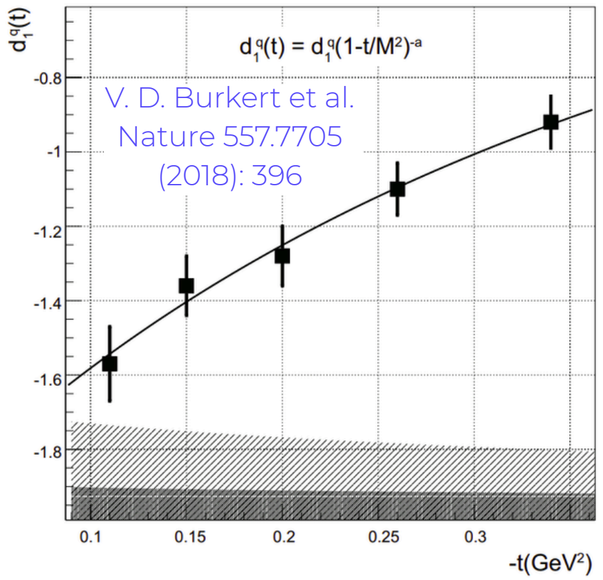
The **D-term** can be constrained through **cross-section (Re[CFFs]** and **BSA (Im[CFF]** measurements

$$D(t) = \mathfrak{Re}[\mathcal{H}(\xi,t)] - \frac{1}{\pi}\int_0^1 d\xi'\, \mathfrak{Im}[\mathcal{H}(\xi',t)]\left(\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right)$$

The **pressure distribution** within the nucleon can be accessed through **$d_1(t)$**

$$D(t) = \frac{1}{2}\int_{-1}^{1}\frac{dz}{1-z}(1-z^2)\left[d_1(t)C_1^{3/2}(z) + \cdots\right]$$

$$d_1(t) \equiv d_1(t=0) f_1(t)$$



Contributions to the nucleon total spin.

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

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

- Quark spin contribution
- Quark's orbital angular momentum

1. Missing the proton is beneficial

- Unlocks small |t| values inaccessible via proton-detection
  - Down to |t|=0.022 GeV²
  - Benefitial for a precise t=0 extrapolation
- Larger statistics can be achieved,

2. However,

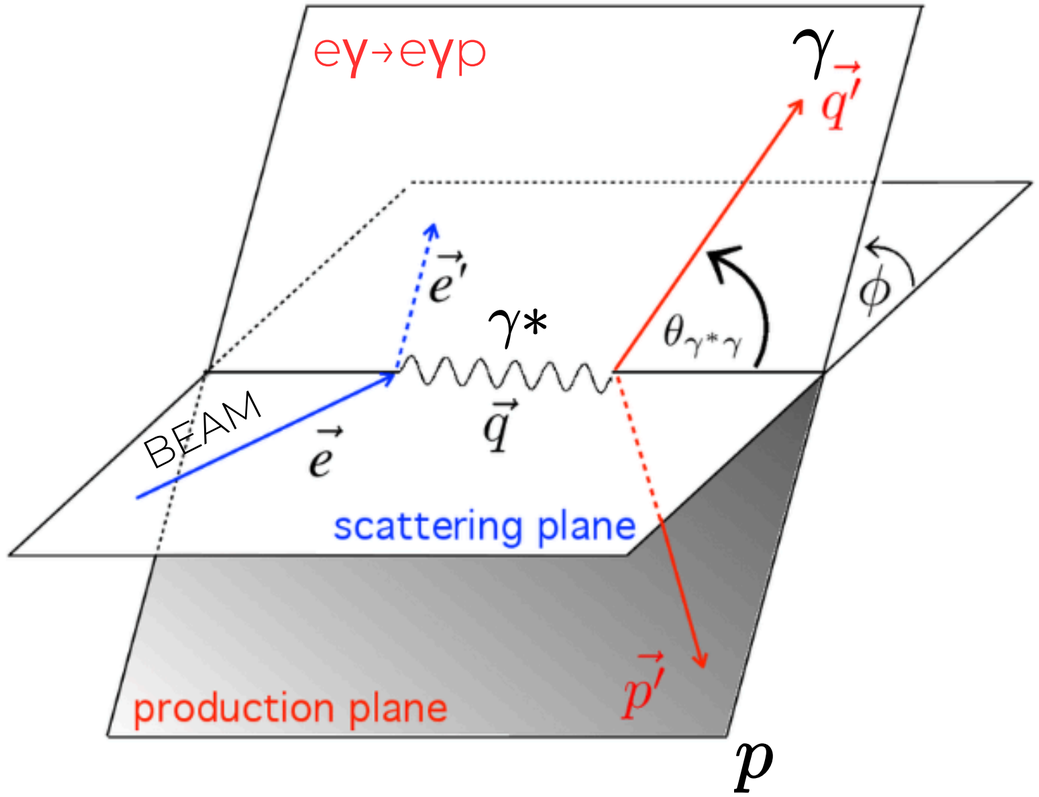
- There is an increased background
- There is less information to constrain the process

3. Therefore,

- We implement a ML approach for channel selection
- Physics results include measurements with and without requiring proton detection
- Validation relies on the consistency of both approaches

2. DATA SELECTION

- Fall-2018 RG-A data
  - Polarized electron beam, unpolarized LH_2 target
  - Inbending and outbending data
  - Pass2 reconstruction



KINEMATICS

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

EXCLUSIVITY CUTS
(only 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

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

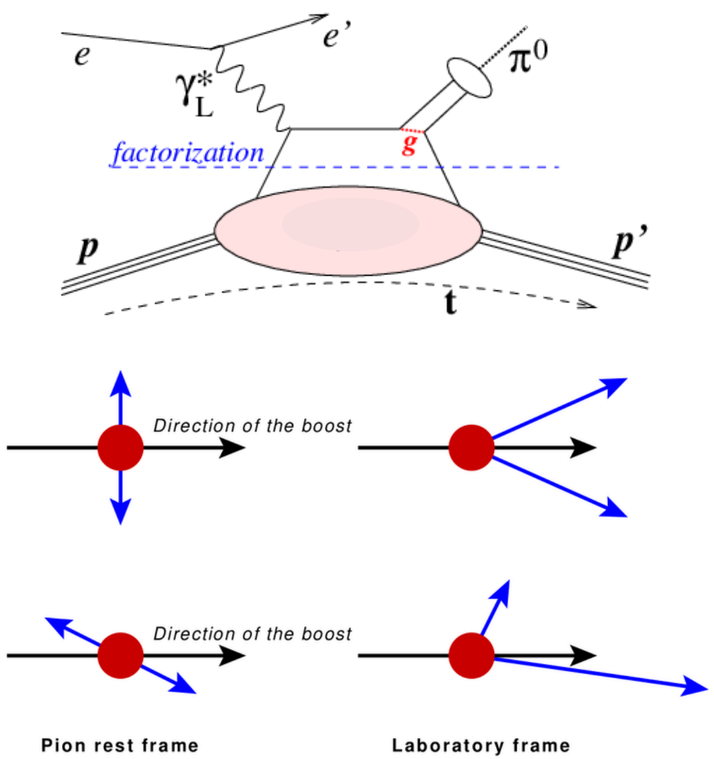
$t(p') = (p-p')^2$

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

2. DATA SELECTION

The main background contribution is exclusive π^0 production

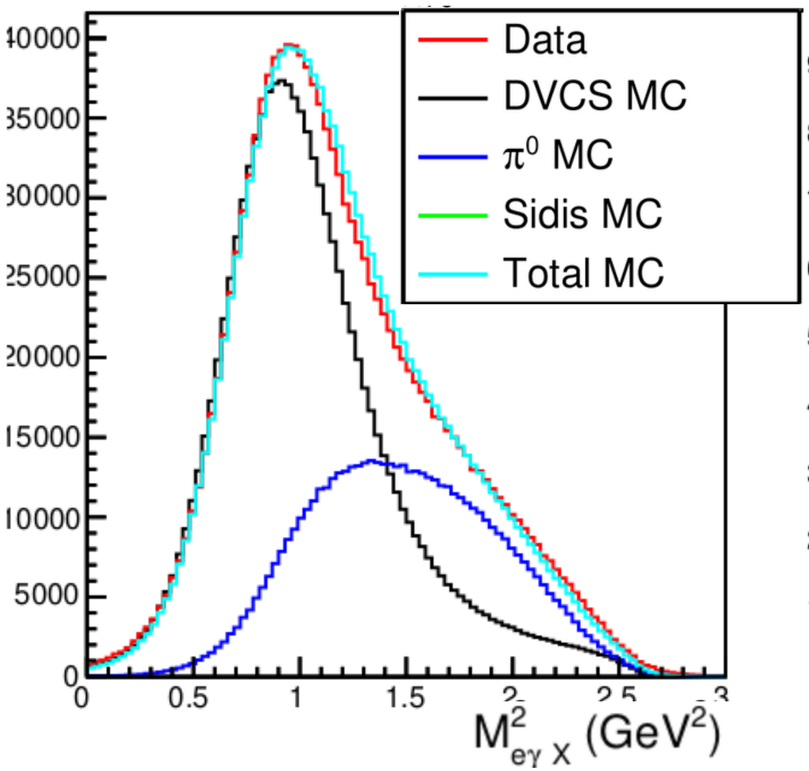
$ep \rightarrow ep\pi^0 \rightarrow ep\,\gamma(\gamma)$



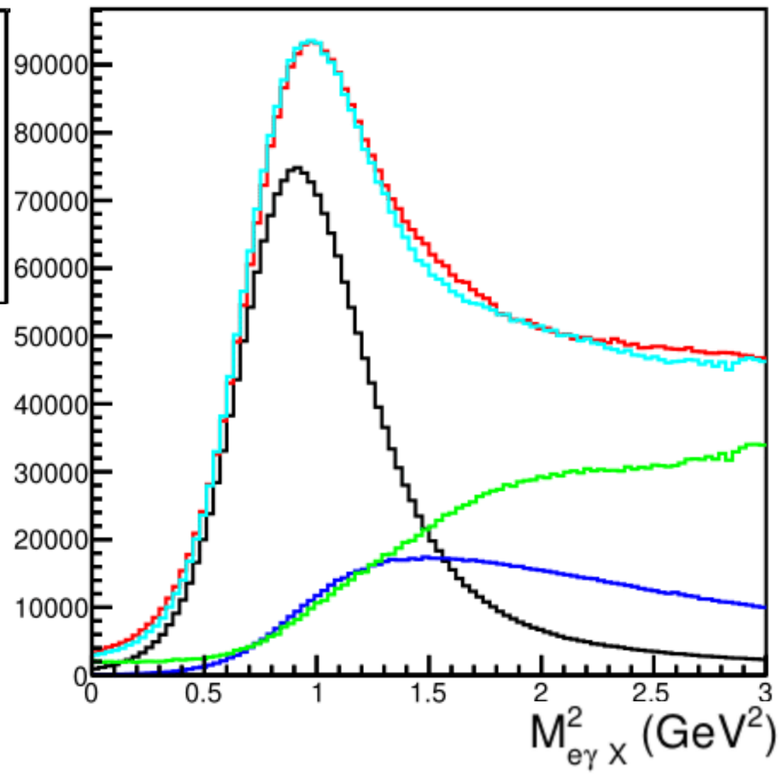
Missing proton mass distribution

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

With proton

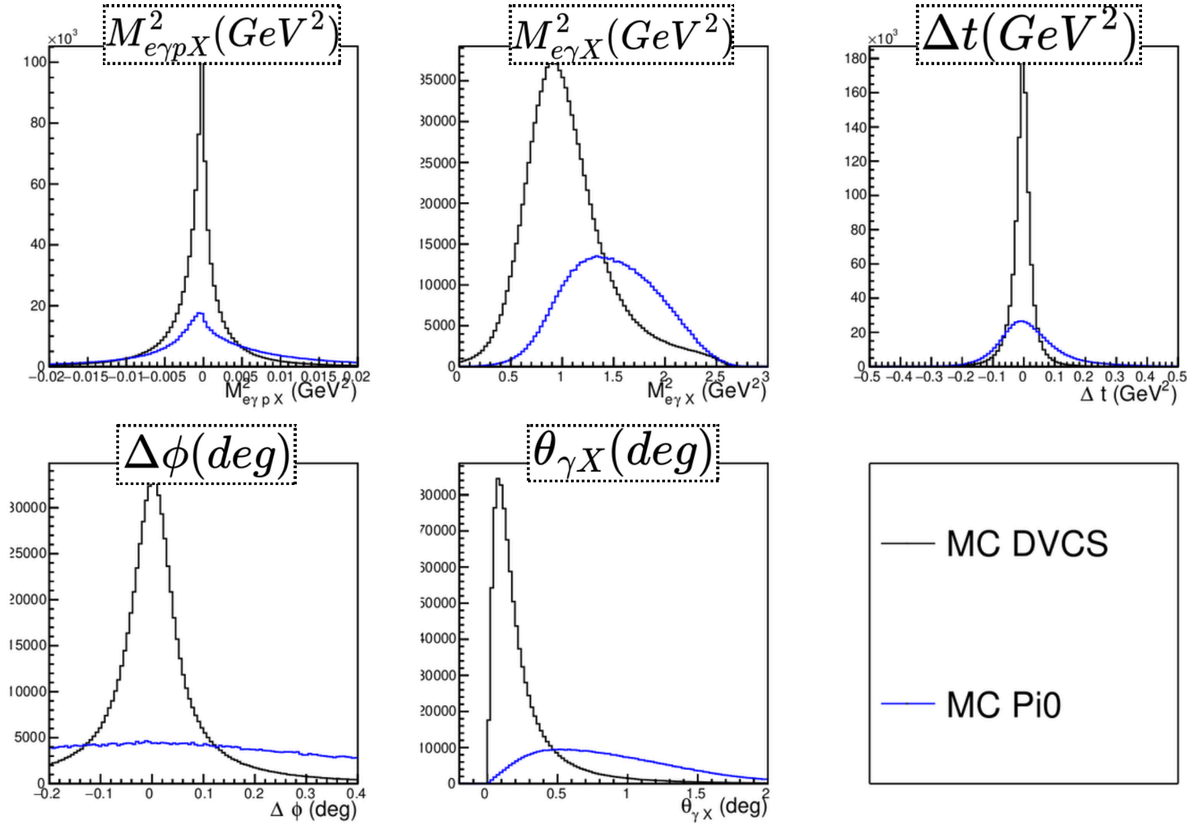


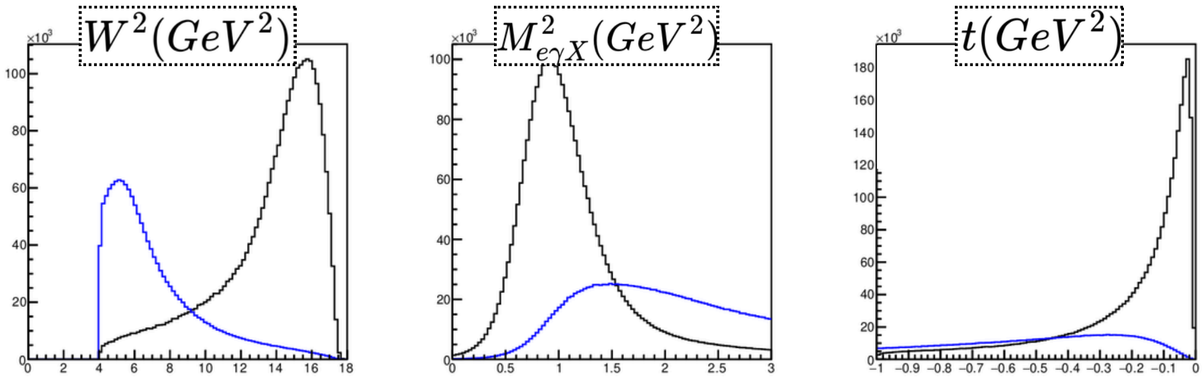
Without proton



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

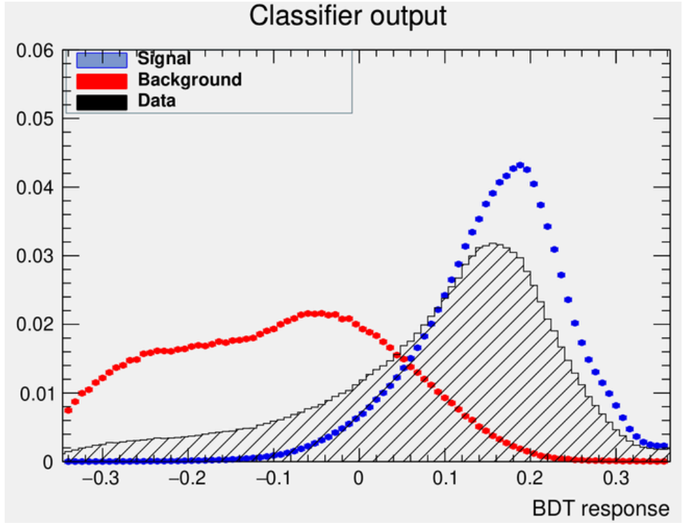
3. CHANNEL SELECTION





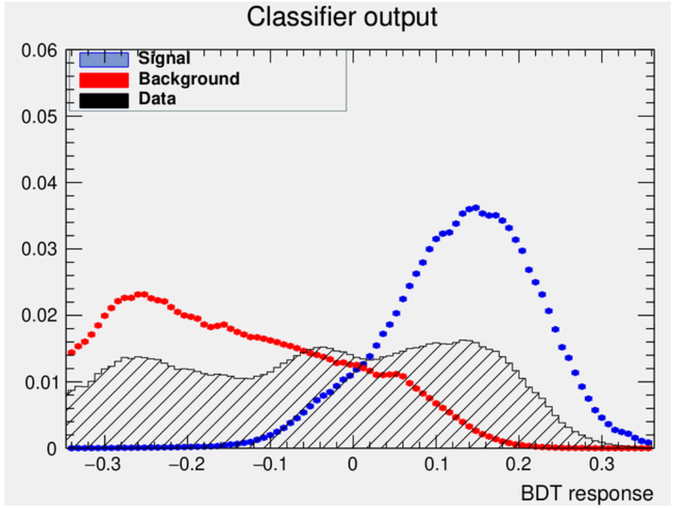
Rather than straight cuts, **we optimize data selection with Boosted Decision Trees.**

With proton

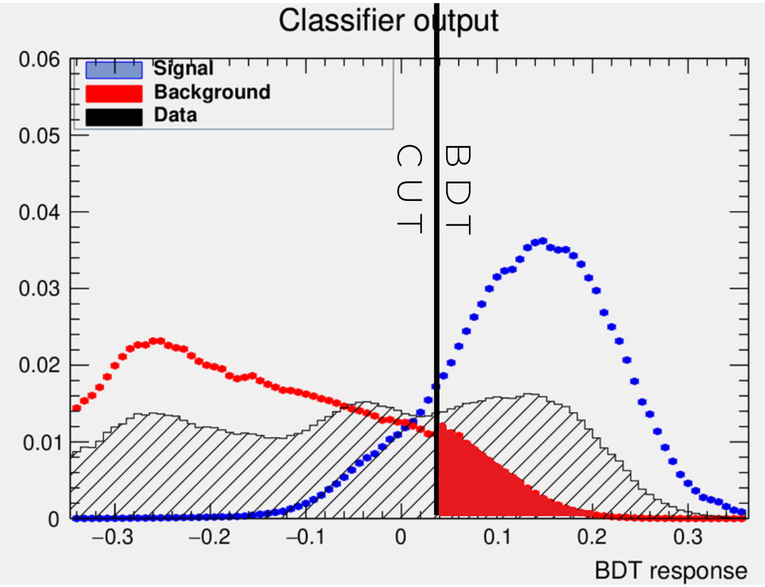


These variables are used to train the BDT model

W/out proton



3. CHANNEL SELECTION



The entirety of the background cannot be removed with a BDT

To estimate and remove the residual background, the **1γ/2γ - phase space ratio** is estimated with 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

Based on **ep→epπ⁰→epγγ simulations through GEMC,**

- $N^{MC}_{\pi^0\to\gamma}$: # of events passing DVCS selection (DVCS contamination)
- $N^{MC}_{\pi^0\to\gamma\gamma}$: # of reconstructed π^0 events

- $N_{\pi^0\to\gamma}$ / $N_{\pi^0\to\gamma\gamma}$ provides a bin-averaged estimation

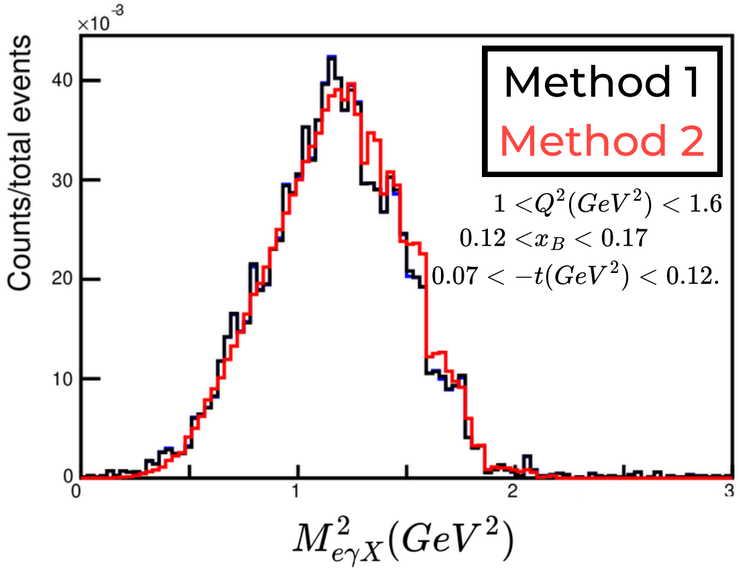
METHOD 2

We simulate 1500 decays for each experimentally reconstructed π⁰

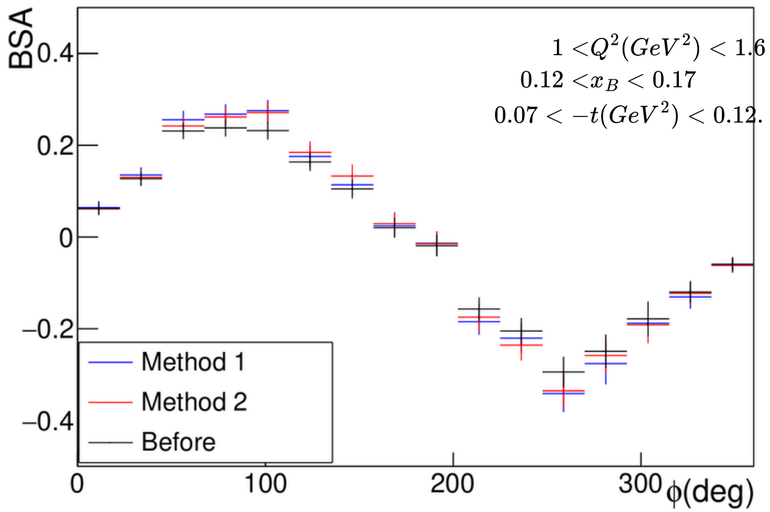
- $N^{MC}_{\pi^0\to\gamma}$: # of detected photons passing DVCS selection
- $N^{MC}_{\pi^0\to\gamma\gamma}$: # of two-photon detected decays
- Photon detection established through acceptance maps
- The total ratio is the sum of individual ratios

- $N_{\pi^0\to\gamma}$ / $N_{\pi^0\to\gamma\gamma}$ provides an event-by-event estimation

3. CHANNEL SELECTION

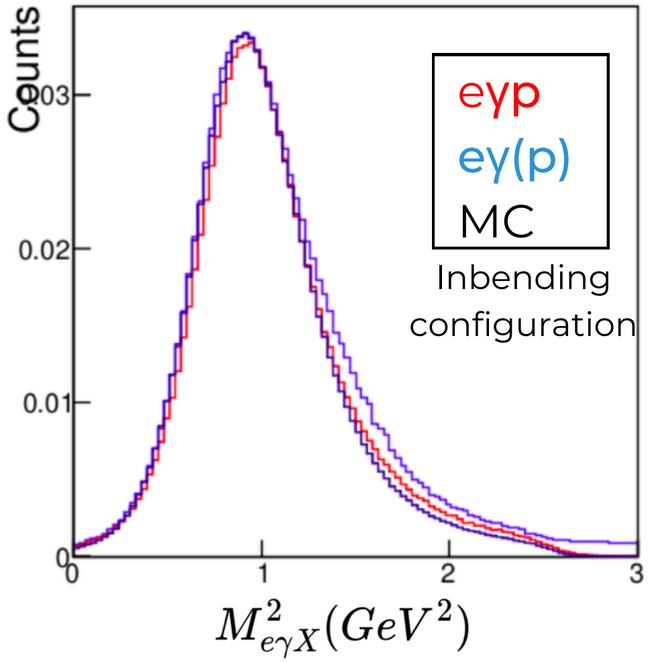


Consistent background estimation from both methods

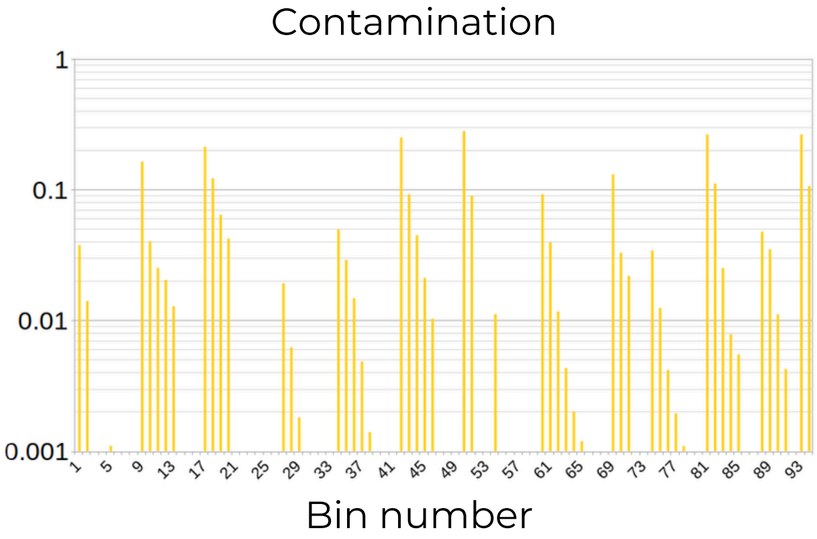


As the background is removed, the asymmetry increases

- Raw measurements are diluted by the π^0 asymmetry (~5%)



Consistent missing proton mass distributions whether or not the proton is detected

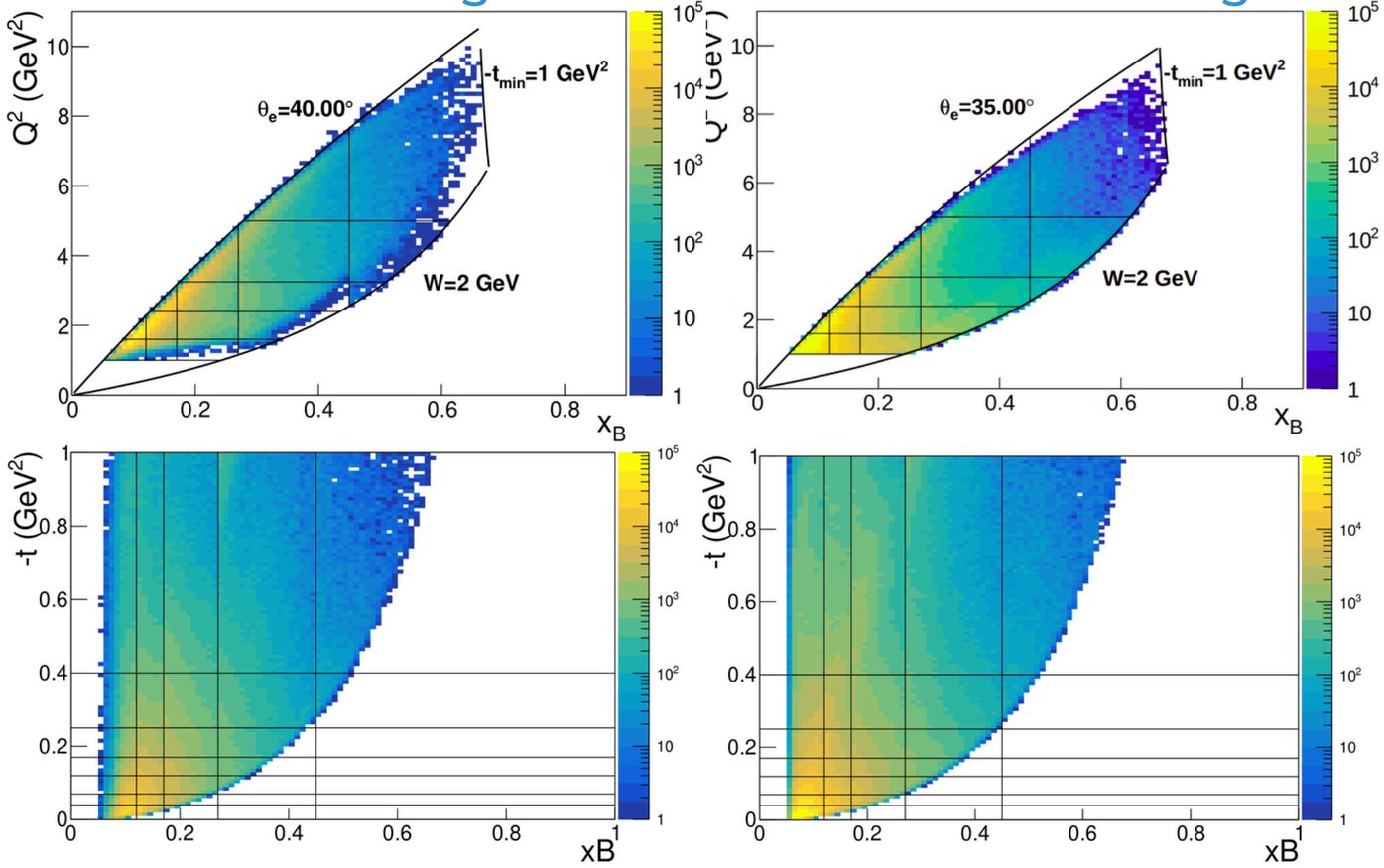


Overall contamination:

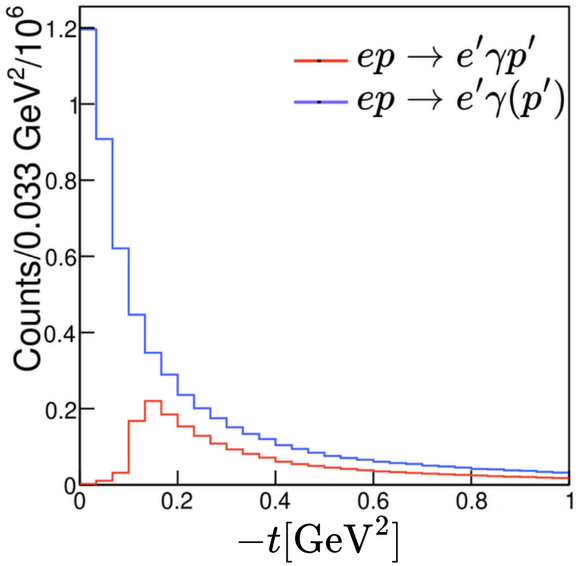
- **eγp:** (6± 3)%
- **eγ(p):** (4±1)%

3. CHANNEL SELECTION

Without proton
Inbending

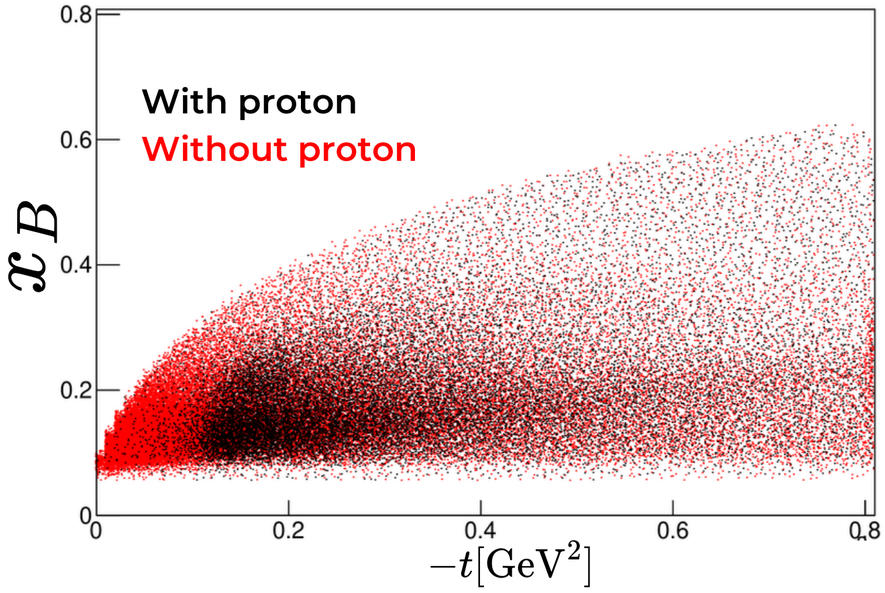


Without proton
Outbending



When not requiring a proton:

- Increased statistics
- Access to smaller -t values

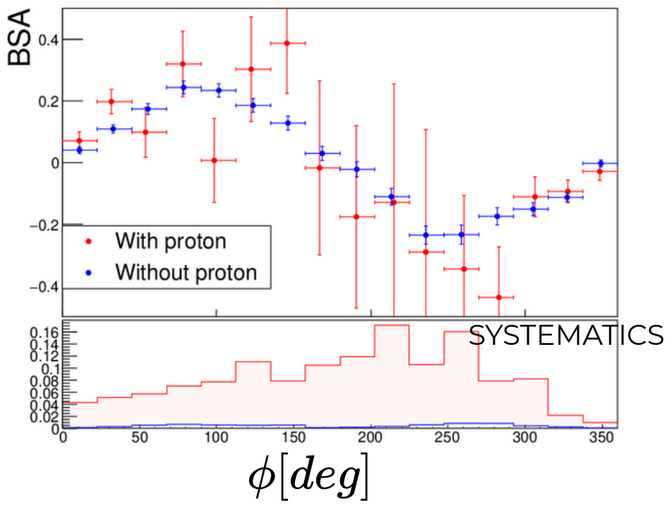


- 16 bins on (Q^2,x_B), 7 bins in t
- 94 effectively populated bins

4. BEAM SPIN ASYMMETRY

$2.4 < Q^2[\mathrm{GeV}^2] < 3.25, 0.17 < x_B < 0.27$

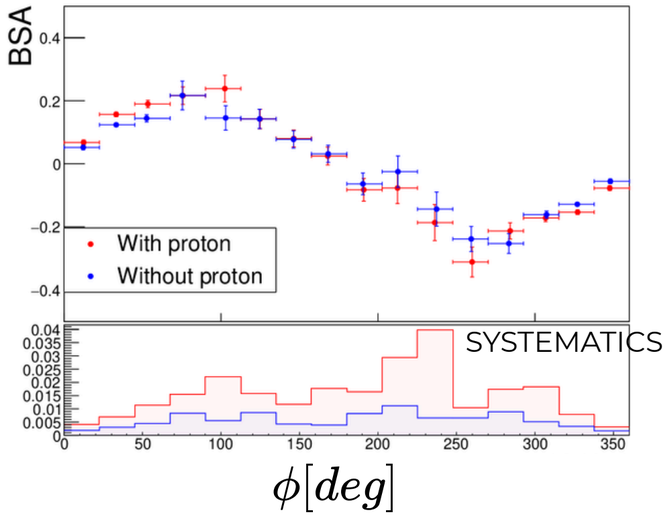
$0.07 < -t[\mathrm{GeV}^2] < 0.12$



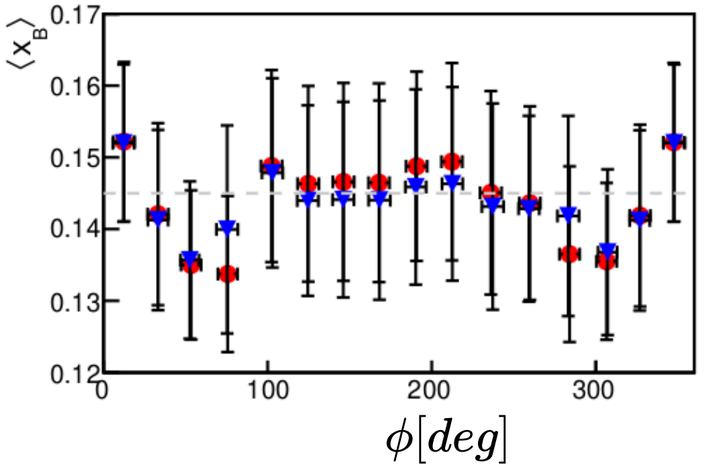
- Small -t access is granted by not detecting the proton
- Smaller systematic error when not requiring a detected proton

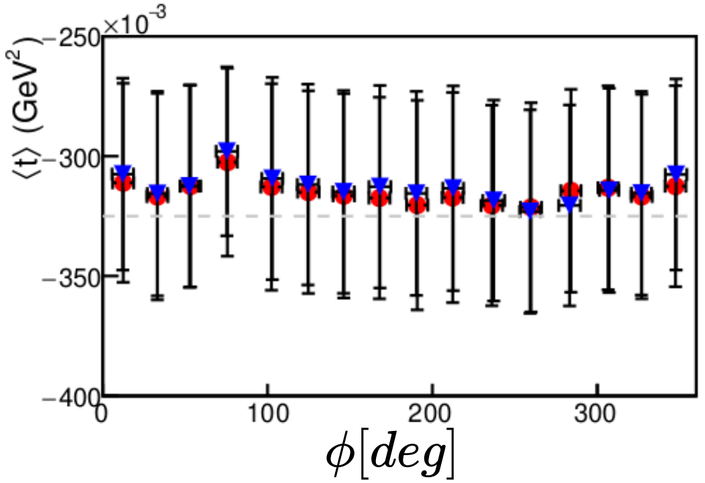
$1.6 < Q^2[\mathrm{GeV}^2] < 2.4, 0.12 < x_B < 0.17$

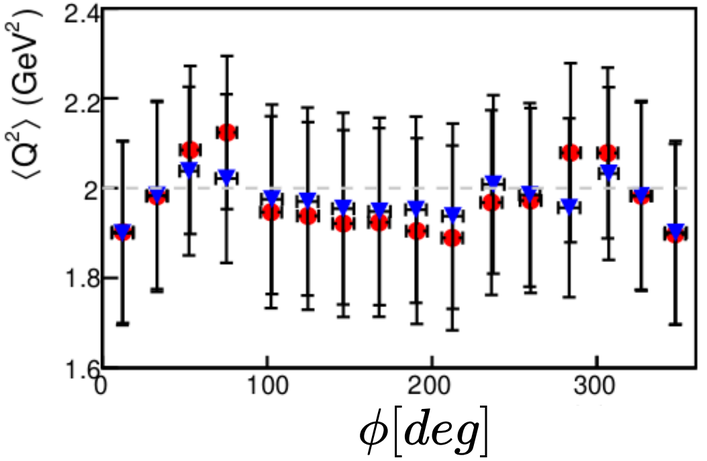
$0.25 < -t[\mathrm{GeV}^2] < 0.4$



In the overlapping region, identical measurements are retrieved







4. BEAM SPIN ASYMMETRY: SYSTEMATICS

Systematic uncertainties arise from three main sources:

Selection cuts / PID Selection / BDT cut

$$\delta A^{cuts} = \frac{\frac{A_{cut}}{\sigma(A_{cut})} - \frac{A}{\sigma(A)}}{\frac{1}{\sigma(A_{cut})} + \frac{1}{\sigma(A)}}$$

$|\Delta\phi| < 2^\circ \rightarrow |\Delta\phi| < 1.5^\circ$

$P_{miss} < 1$ GeV$\rightarrow P_{miss} < 0.8$ GeV.

$$\frac{E_{dep}^{ECIN}}{p_e} > 0.2 - \frac{E_{dep}^{PCAL}}{p_e}$$

$$-13 \text{ cm} < v_z^e < 12 \text{ cm}$$

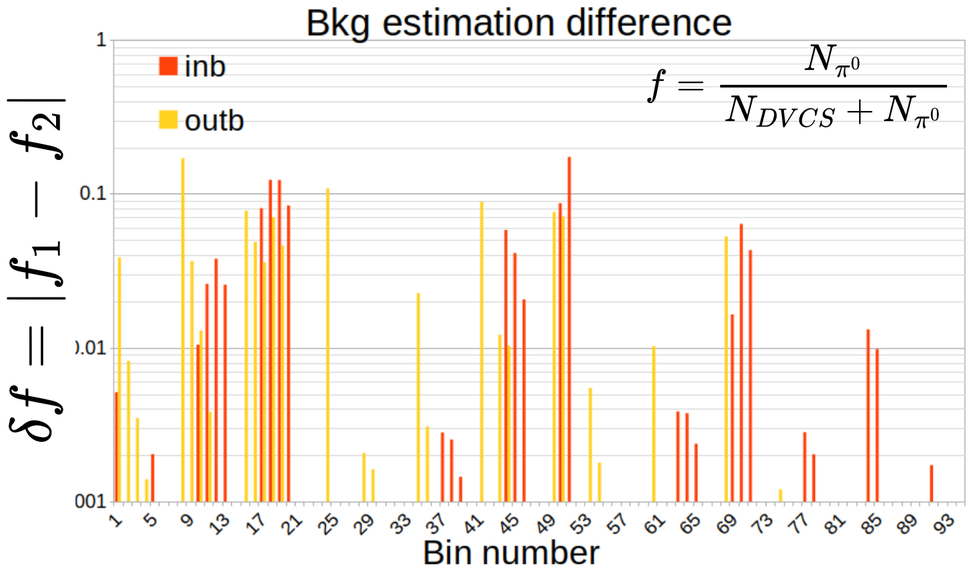
$$|v_z^e - v_z^p| < 20 \text{ cm}$$

$\text{BDT-Score} \rightarrow \text{BDT-Score} + 0.04$

BSA was extracted with a modified cut

Background subtraction.

$$\delta A^{Bkg} = \frac{A^{raw} - A^{\pi^0}}{(1-f)^2}\delta f$$



- The difference between the two estimation methods ($\delta f = |f_1 - f_2|$) yields the systematic error
- Differences are mainly smaller than 10%

Beam polarization

$$\delta A^{Pol} = A\frac{\delta P}{P}$$

About 2%

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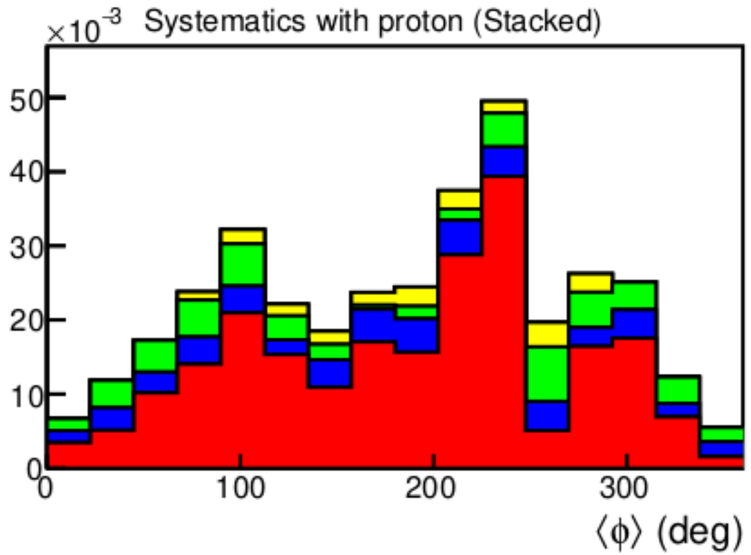
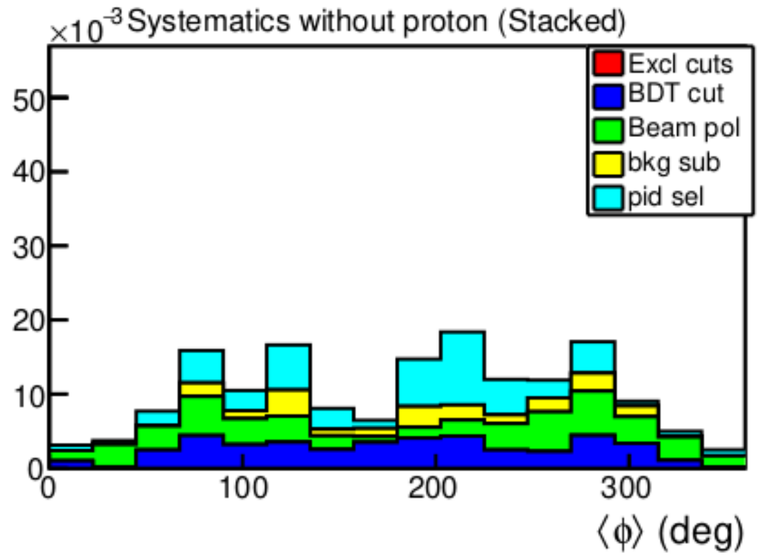




- Smaller systematics when not requiring a proton due to the absence of exclusivity cuts
- Total systematic error ranges from 3% to 30% on both torus configurations.
- Proton detection provides better control of the background subtraction systematics
- Exclusivity cuts is the main source of systematics

4. BEAM SPIN ASYMMETRY: MERGING DATASETS

BSA measurements were computed separately for each torus configuration, then **merged with a weighted sum**

$$A = \frac{\frac{A_{inb}}{\sigma(A_{inb})^2} + \frac{A_{outb}}{\sigma(A_{outb})^2}}{\frac{1}{\sigma(A_{inb})^2} + \frac{1}{\sigma(A_{outb})^2}}, \qquad \sigma(A) = \frac{1}{\sqrt{\frac{1}{\sigma(A_{inb})^2} + \frac{1}{\sigma(A_{outb})^2}}}$$

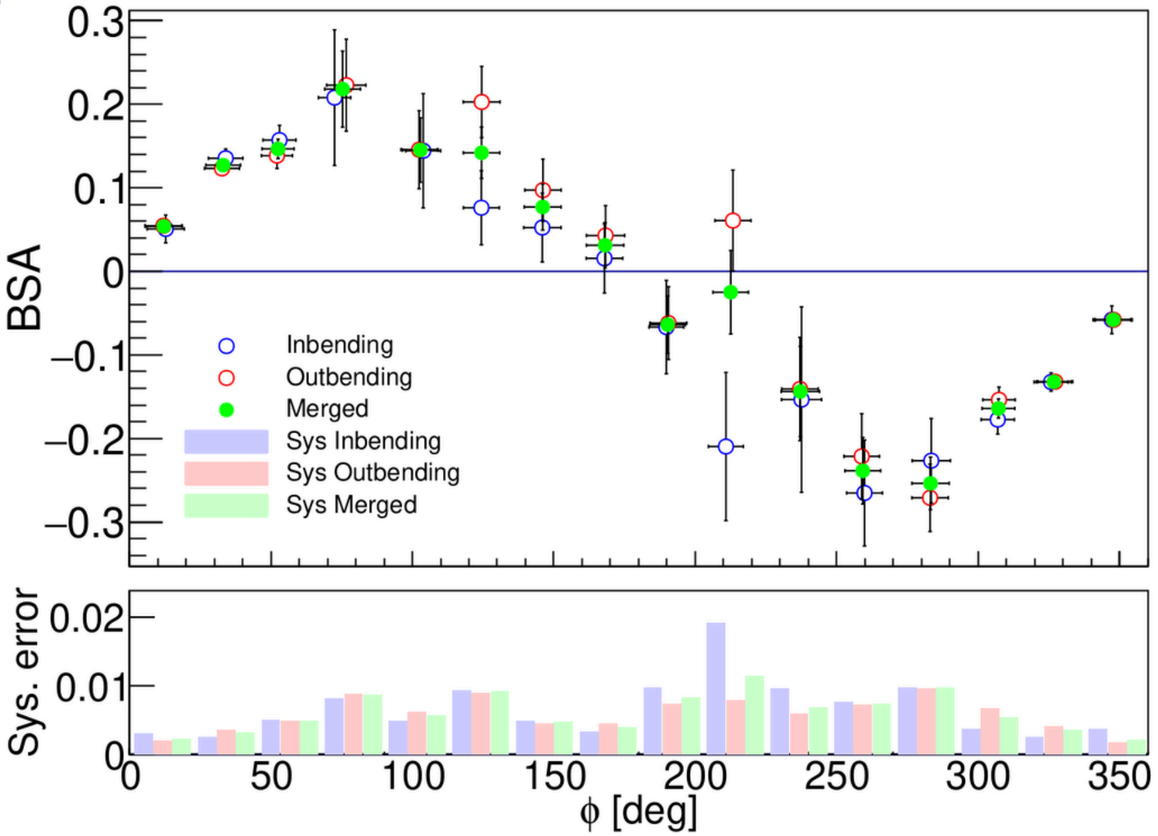
Merged systematics are determined by

1. Shifting each configuration BSA with their respective systematics. The computing the weighted average

$$A_{\pm} = \frac{\frac{A_{inb} \pm (\delta A)^{cut}_{inb}}{\sigma(A_{inb})^2} + \frac{A_{outb} \pm (\delta A)^{cut}_{outb}}{\sigma(A_{outb})^2}}{\frac{1}{\sigma(A_{inb})^2} + \frac{1}{\sigma(A_{outb})^2}}$$

2. Evaluating the quadratic average of the positive- and negative-shifted BSA

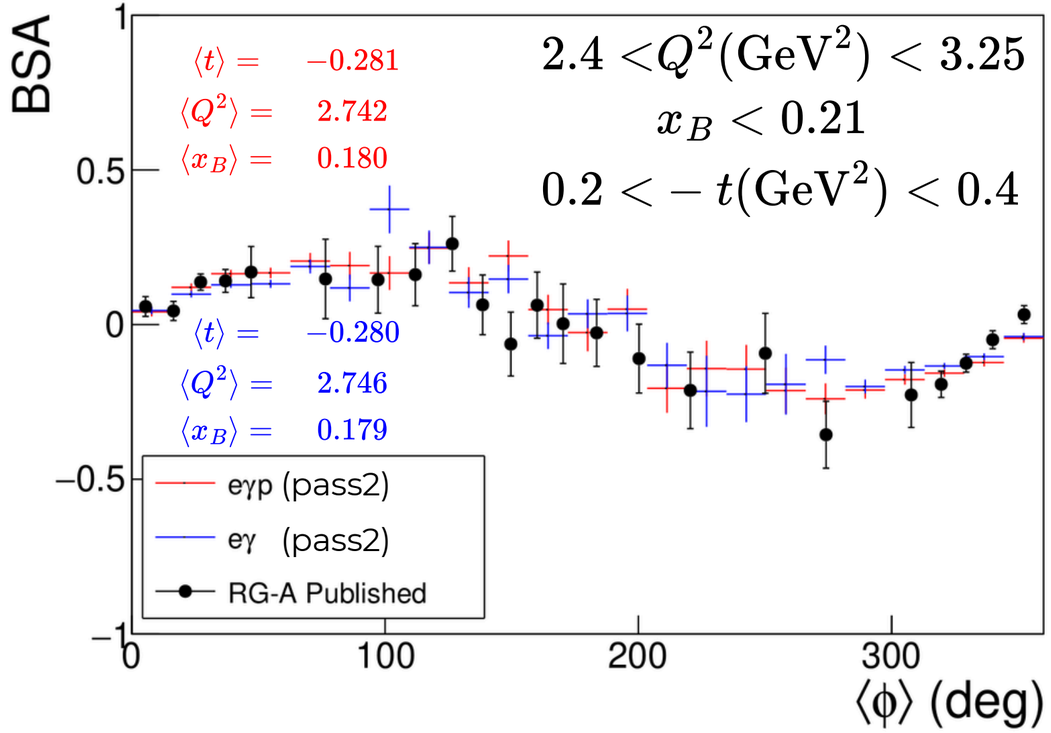
$$(\delta A)^{cut} = \sqrt{\frac{(A_+ - A_0)^2 + (A_- - A_0)^2}{2}}$$



$\delta A \rightarrow$ Systematic

$\sigma(A) \rightarrow$ Statistical

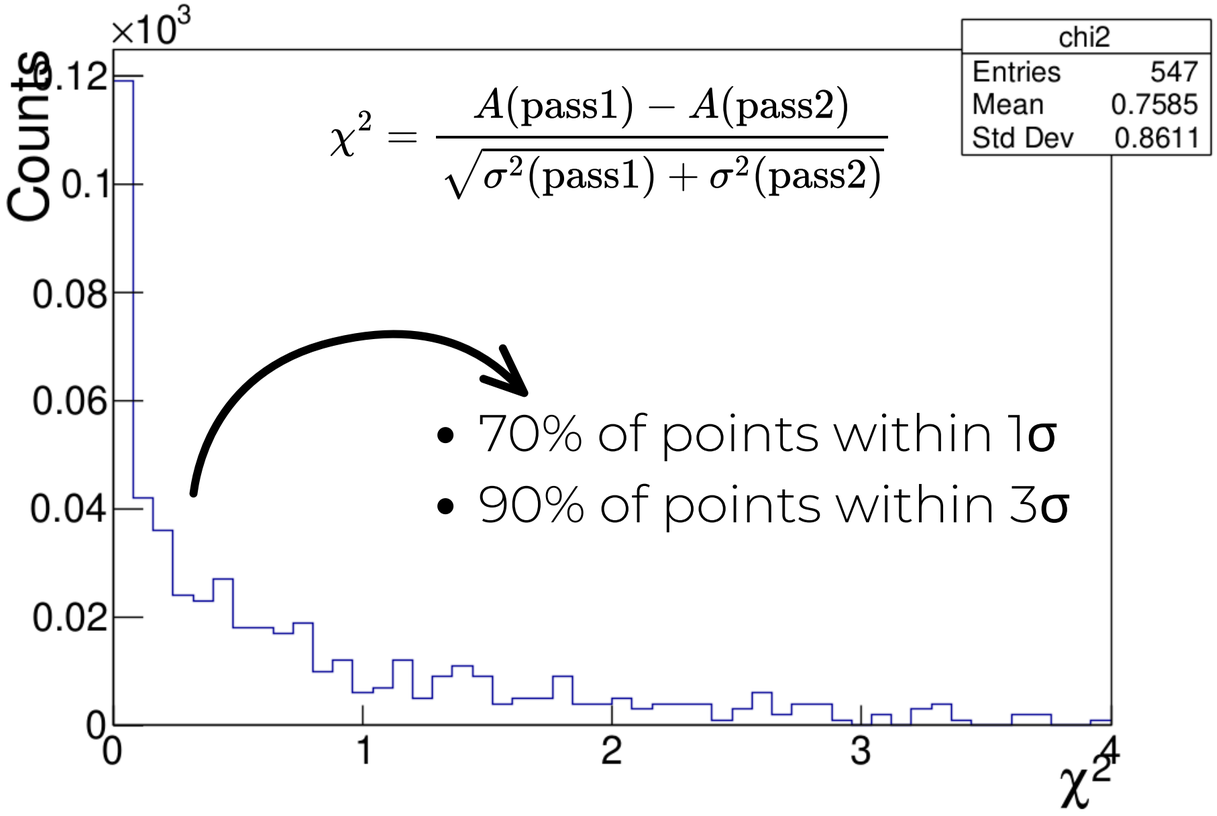
5. COMPARISON TO PASS1 MEASUREMENTS



- Mean kinematics are different point-to-point, and so the BSA
  - The χ^2 indicates that the two analyses are broadly consistent

Comparison of eγp (pass2) and published (pass1) results

- Using the pass1 binning scheme

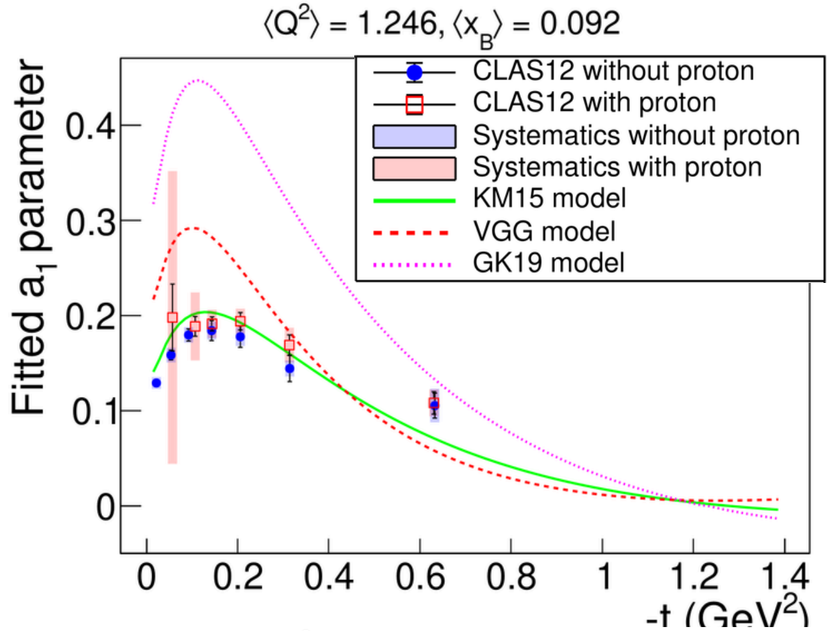


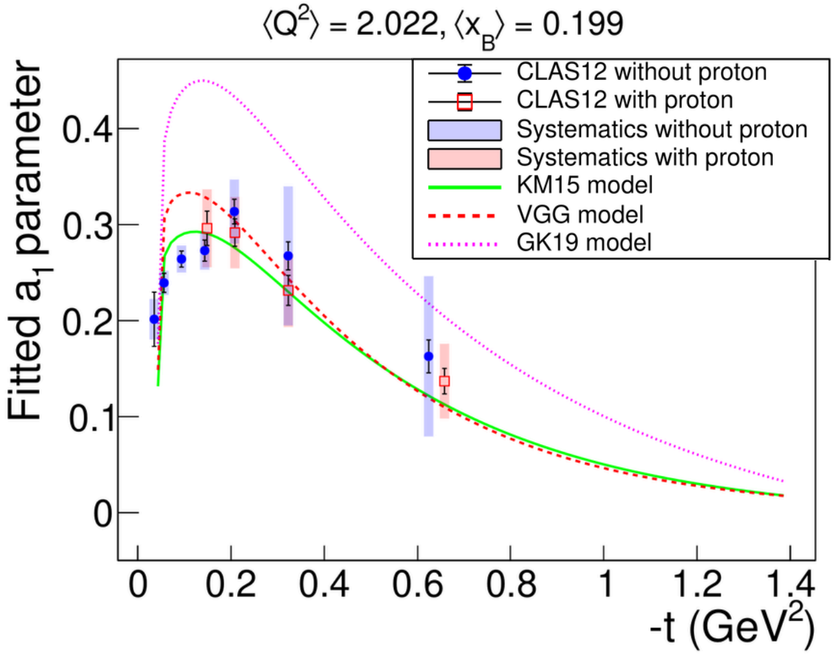
6. FITS TO THE BSA

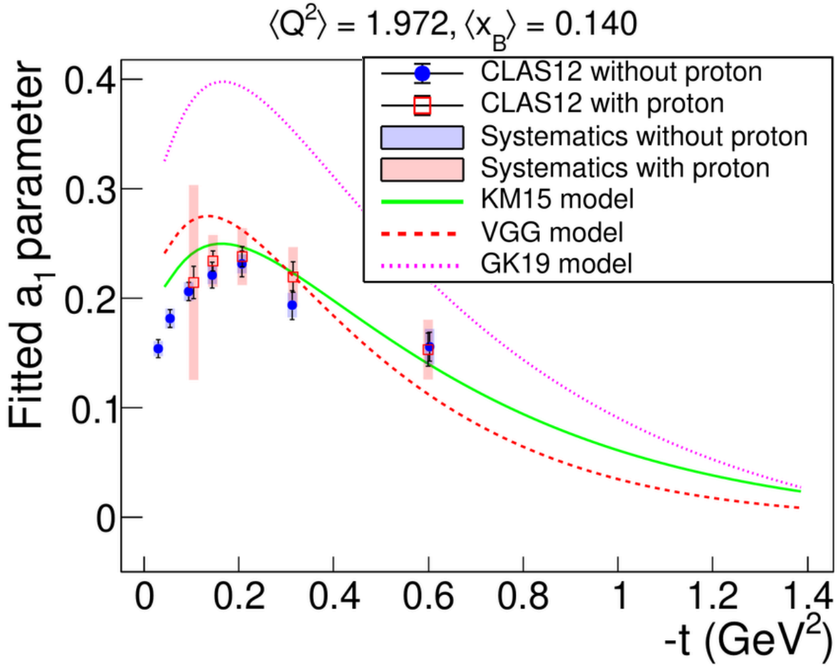
$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)} \qquad a_1 \propto \Im\mathrm{m}\left[\left(F_1\mathcal{H} - \frac{t}{4M^2}F_2\mathcal{E}\right) + \xi(F_1 + F_2)\widetilde{\mathcal{H}}\right]$$

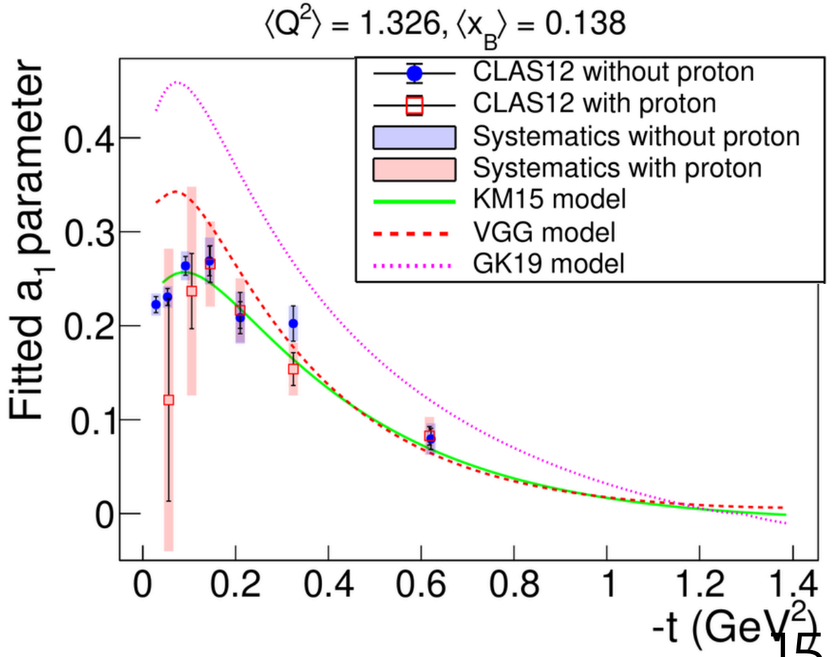
Fits to the BSA are displayed as a function of -t in bins of (Q^2,x_B)

- Agreement of measurements with and without proton
- GK model overestimates the asymmetry
- Large |t| behavior of VGG and KM15 are similar
  - VGG overestimates the asymmetry at small |t|.









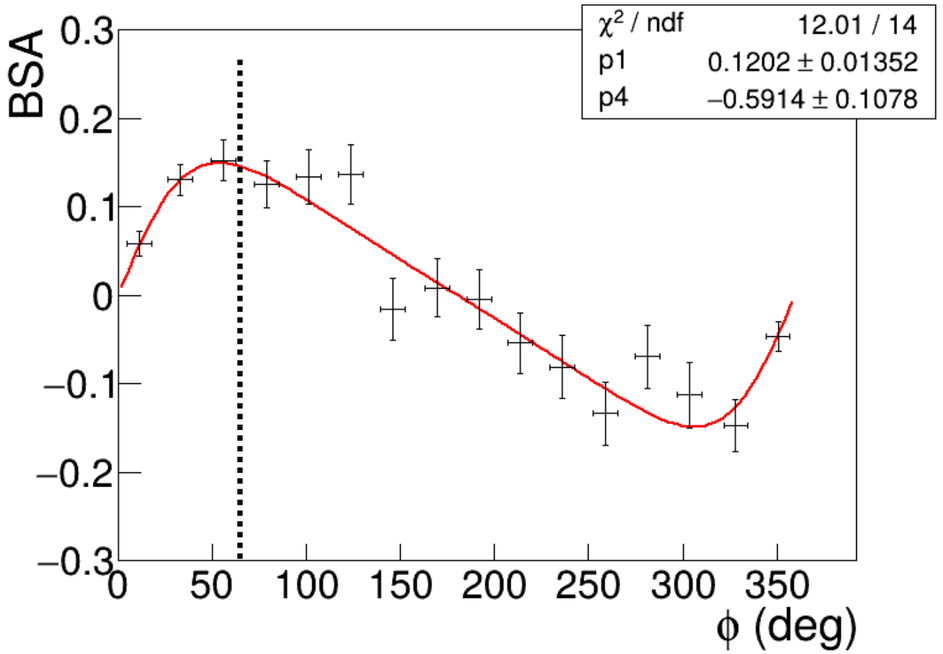
6. FITS TO THE BSA

$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)} \qquad a_2 \equiv a_2(\Re\mathfrak{e}[CFFs])$$

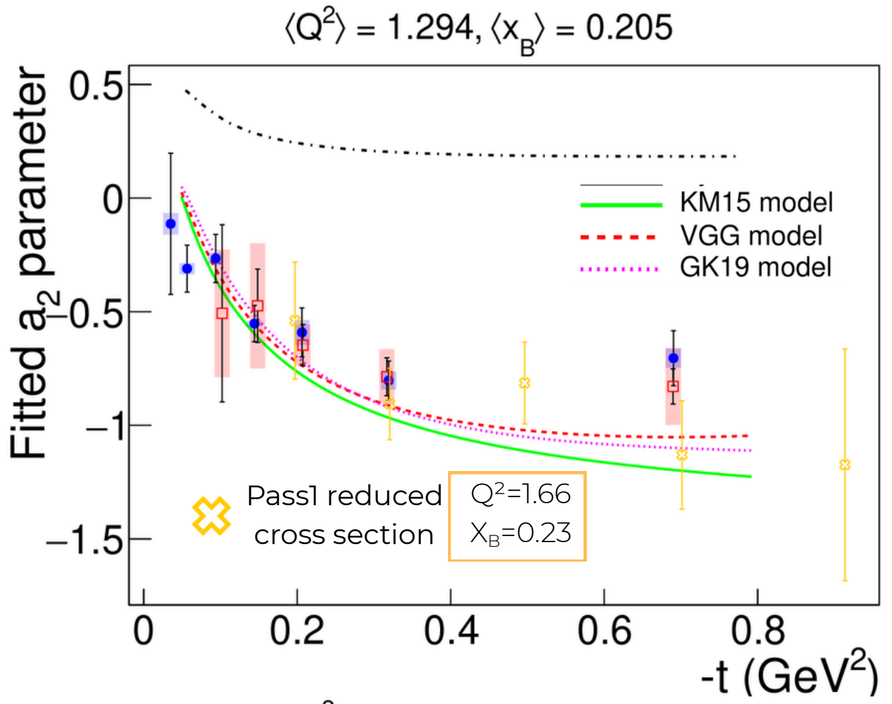
Given the achieved precision on the BSA, constraints on the real part of CFFs can be retrieved

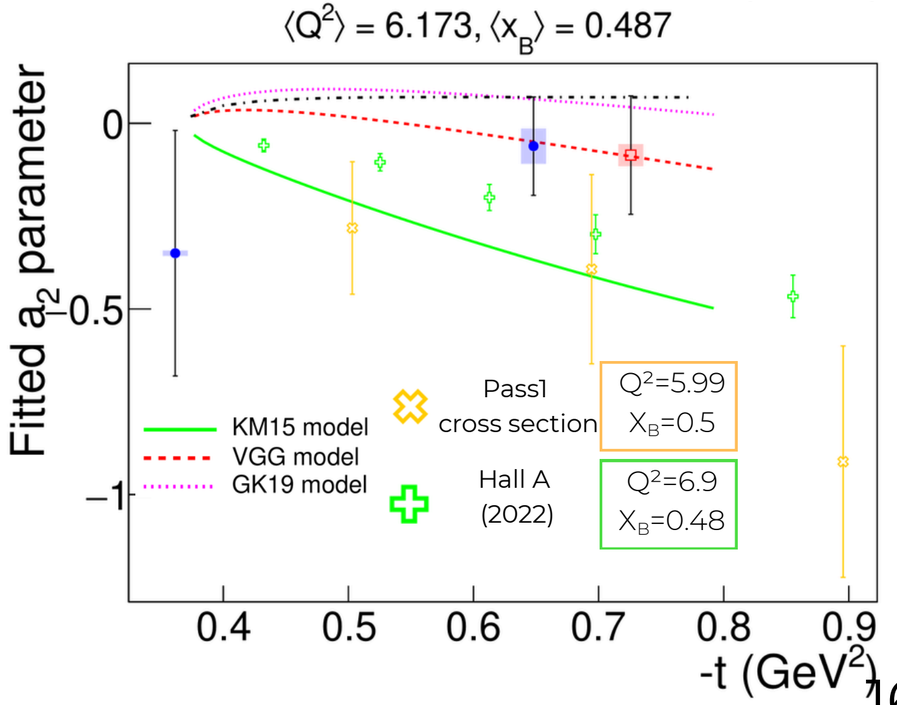
- It shows compatibility with the KM15 model
- It is not BH-dominated and given by:

$$a_2 = \frac{2\int_0^{2\pi} d\phi \; cos(\phi) \; \mathcal{P}_1\mathcal{P}_2(\phi) d^5\sigma_{unp}(\phi)}{\int_0^{2\pi} d\phi \; \mathcal{P}_1\mathcal{P}_2(\phi) d^5\sigma_{unp}(\phi)}$$



- The a_2 parameter shifts the BSA maximum
- a_2 is not small w.r.t. a_1
- For scarce statistics, a sinusoidal fit provide misleading results
- **It can be contrasted against cross-section measurements**



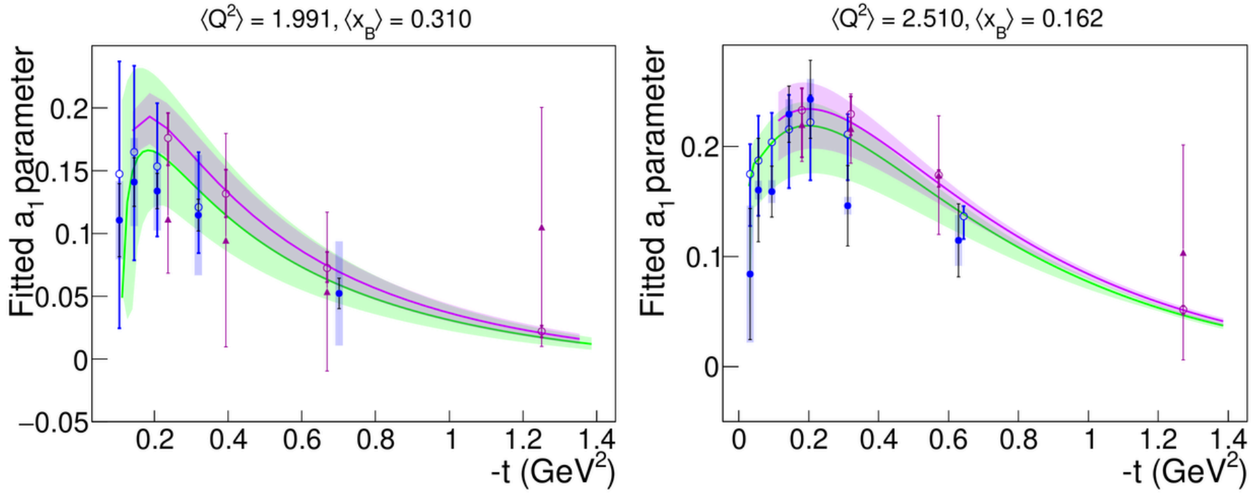


6. FITS TO THE PASS1 BSA

To provide a complete picture of the results, fits should be compared to pass1 results

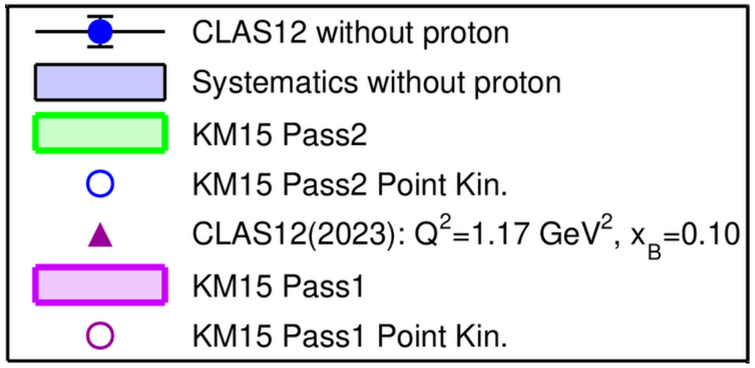
- I performed the fit to the published pass1 data it to the same function

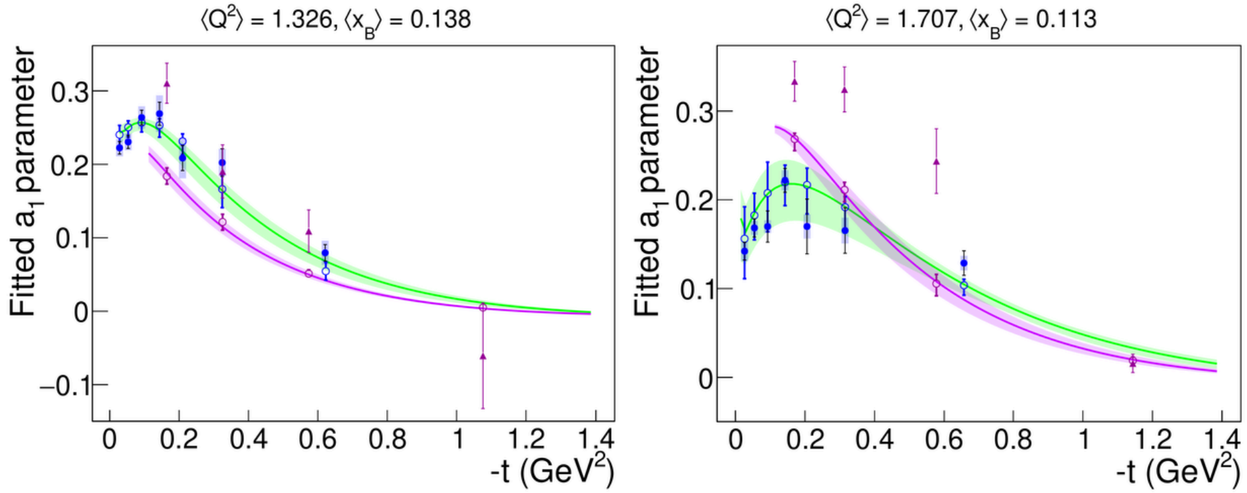
$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)}$$



<u>Most points are compatible within 1σ,</u>

- ...and consistent with the KM15 prediction





<u>Some points are compatible within 2σ-3σ</u>

- Data is not providing a suitable estimate of a2, thus biasing the a1 extraction
- Pass2 result compatible with KM15 prediction, pass1 not so much

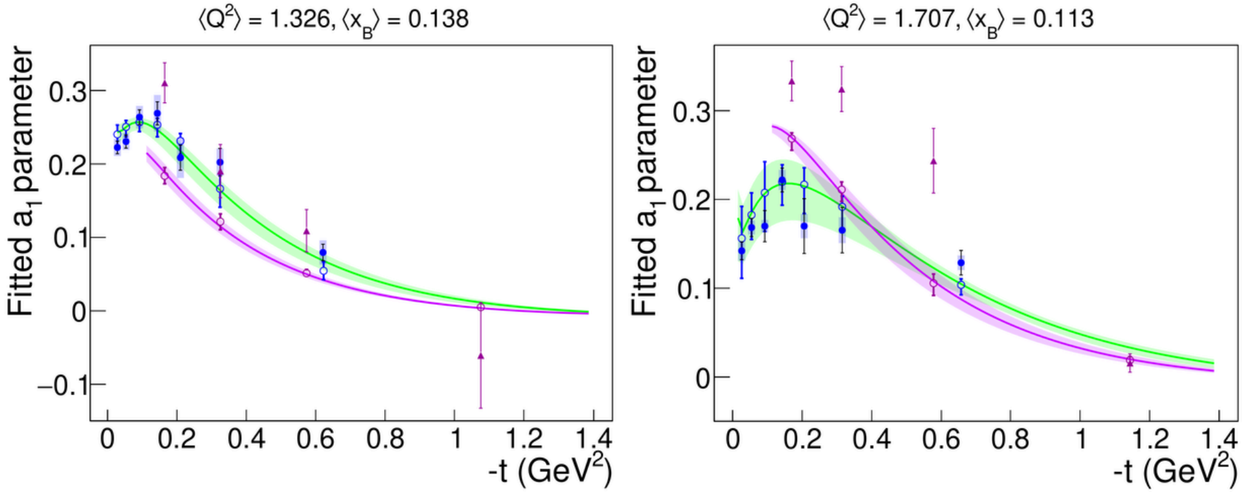
6. FITS TO THE PASS1 BSA

To provide a complete picture of the results, fits should be compared to pass1 results

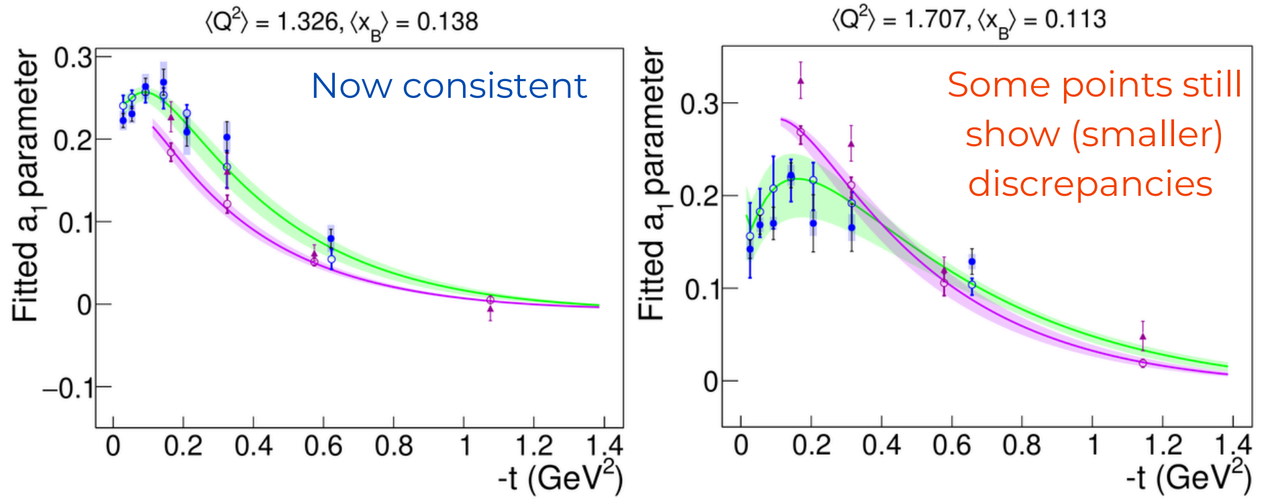
- I performed the fit to the published pass1 data it to the same function

$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)}$$

a_1 and a_2 as free parameters.

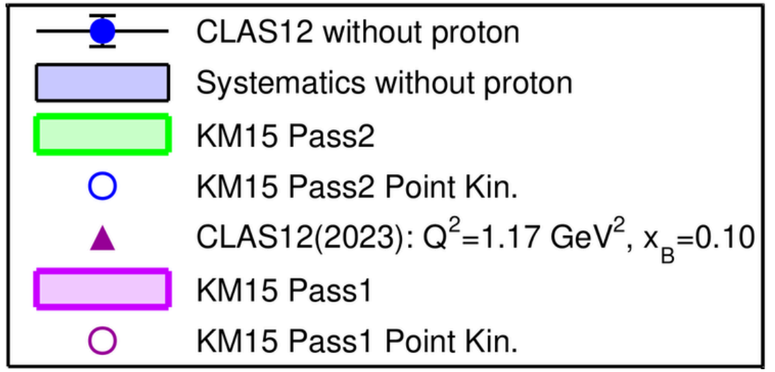


a_1 free, a_2 fixed to KM15 prediction



- Given the scarce statistics of the pass1 analysis, fits to the BSA do not provide strong constraints on a_2, thus biasing the a_1 estimation
- Fixing a_2 to the model prediction might improve certain a_1 estimations.

REMINDER: BSA was proven to be consistent.
The fit discrepancy is due to statistical constraints, not to inconsistencies in the data analysis

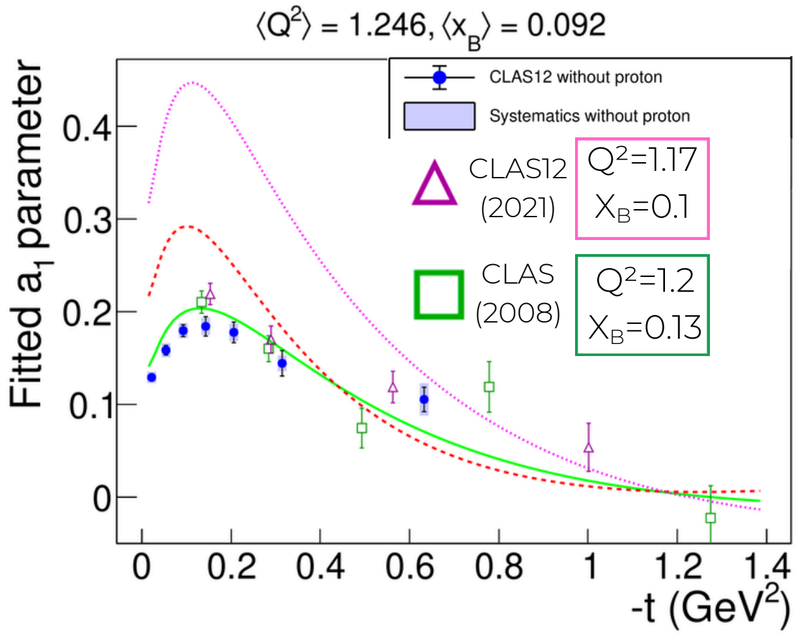


7. COMPARISON WITH PREVIOUS EXPERIMENTS

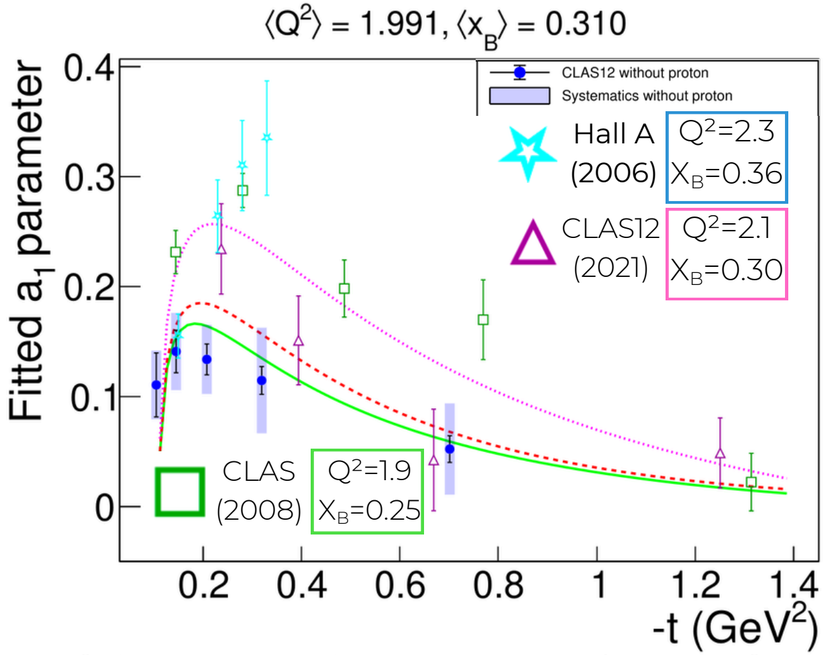
$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)} \qquad a_1 \propto \Im\mathrm{m}\left[\left(F_1\mathcal{H} - \frac{t}{4M^2}F_2\mathcal{E}\right) + \xi(F_1 + F_2)\widetilde{\mathcal{H}}\right]$$

We include measurements at close kinematics (yet not identical) from

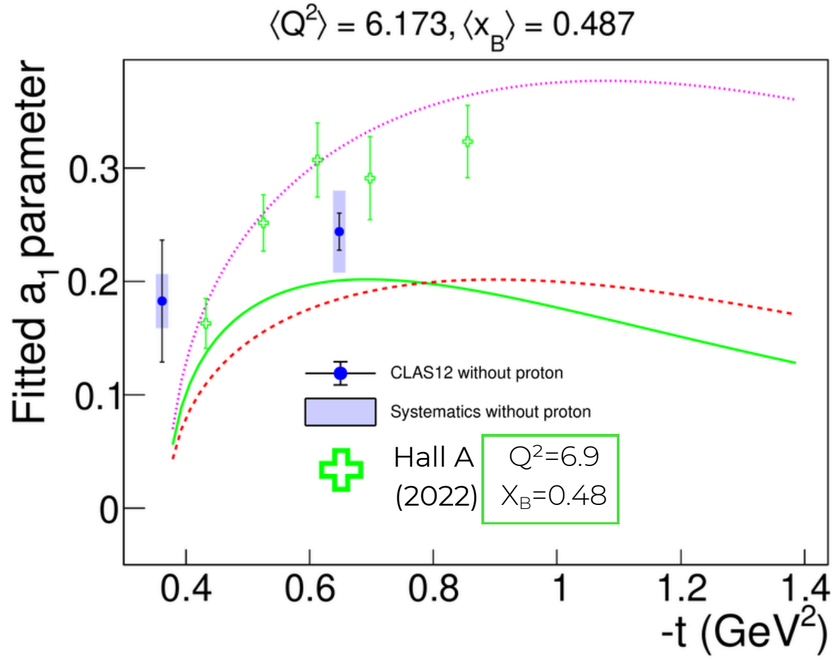
- **HallA(2006):** C. Camacho et al.. Phys. Rev. Lett. 97.26 (2006), p. 262002.
- **CLAS(2008):** F. X. Girod et al., Phys. Rev. Lett. 100.16 (2008), p. 162002.
- **HallA(2022):** F. Georges et al., Phys. Rev. Lett. 128.25 (2022): 252002.
- **CLAS12(2021)**: G. Christiaens, et al. Phys. Rev. Lett. 130 (2023) 211902.



At similar kinematics, results are consistent with CLAS measurements



A fair comparison cannot be performed due to **different kinematics**



At large x_B, Hall A precision is unmatched

8. SUMMARY

In brief, I have presented:

- **A DVCS event selection strategy based on Boosted Decision Trees.**
  - Provides good control of background sources. Leftover background subtraction needed
  - Optimizes the signal yield
- **A method for selecting DVCS events without requiring proton detection**
  - Boosts statistics
  - Access to a larger phase space (unique access to the small -t region)
- **BSA measurements, with and without proton detection**
  - e**γ**(p) measurements have smaller systematic errors
  - Results were shown to be consistent with the published pass1 results
- **Fits to the BSA**
  - Results show a fair agreement with the KM15 model predictions
  - Precise extractions of a_1 were presented
    - Data allows us to constrain the a_2 parameter as well.
  - Reduced pass 1 statistics demands a model-driven fit to reconcile with pass2 measurements
  - Consistent picture with the measurements of previous experiments
    - Not a fair comparison due to the different mean kinematics in several (Q^2,x_B) bins.
- **Article draft in ad-hoc review (PRL). First round of comments has been received.**

$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)}$$

THANKS