DVCS identification with $e\gamma$ detection @CLAS12

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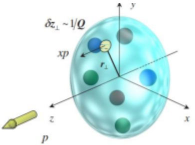
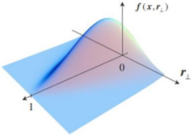
GPDs

- Due to the non-perturbative character of QCD at low energies, we need to introduce structure functions to describe the nucleon structure.
- Generalized Parton Distributions (GPDs) correlate the transverse position and longitudinal momentum of partons in the nucleon.
- They enter into the cross-section through Compton Form Factors (CFFs).

$$\mathcal{H}(\xi', \xi, t) = \mathcal{P}\int_{-1}^{1} dx\, H(x, \xi, t)\left[\frac{1}{x-\xi'} + \frac{1}{x+\xi'}\right] - i\pi\left[H(\xi', \xi, t) - H(-\xi', \xi, t)\right].$$

Direct GPD measurement through $\Im[\mathcal{H}]$

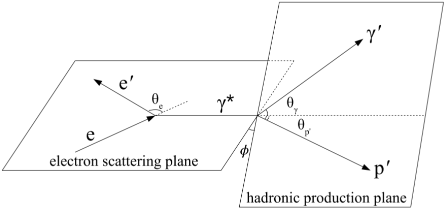


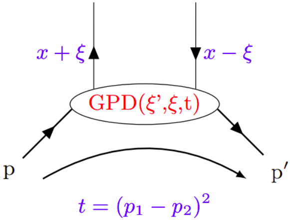


DVCS

The process depends on five kinematic variables:

- $Q^2 = -\gamma^{*2}$
- $t = (p' - p)^2$
- $x_B = \frac{Q^2}{2M\omega}$
- E_{beam}
- ϕ

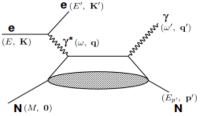




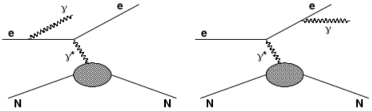
- x is the fraction of the average momentum $((p + p')/2)$carried by the quark.
- ξ is the fraction of the transferred momentum (t) carried by the quark.

Observables

DVCS is indistinguishable from the Bethe-Heitler process but thanks to their interference we can measure CFFs



DVCS



BH

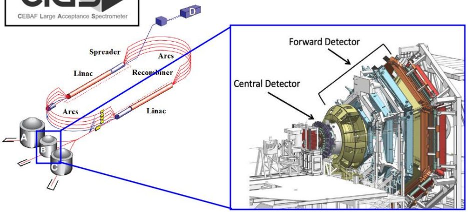
Considering a polarized electron beam we have access to the Beam Spin Asymmetry:

$$A_{LU} = \frac{d^5\sigma_{+U} - d^5\sigma_{-U}}{d^5\sigma_{UU}} \equiv \frac{\Delta\sigma_{LU}}{d^5\sigma_{UU}}$$
$$\propto \sin(\phi)\Im\left(\left(F_1\mathcal{H} - \frac{t}{4M^2}F_2\mathcal{E}\right) + \xi(F_1 + F_2)\widetilde{\mathcal{H}}\right),$$

where $d^5\sigma^{\text{Beam charge}}_{\text{Beam pol,Target pol}}$ denotes the differential cross section.

The observable access the interference part of the cross-section and it is linear in CFFs.

CLAS12 @ Jefferson Lab



- Located in the state of Virgina at Newport News (US).
- Home of the Continuous Electron Beam Accelerator Facility (CEBAF).
  - Electrons are accelerated and then sent to four different experimental Halls (A, B, C and D).
  - Hall B contains the CLAS12 spectrometer, cornerstone of the CLAS Collaboration.

Motivation

Advantages (with respect to $ep\gamma$ detection):

- Improves GPD studies at small $-t$.
- Higher statistics, hence more precise BSA measurements or smaller bins.
- Helpful for experiments that do not consider proton detection.

Difficulties:

- The $ep\gamma$ final state includes background contributions from the whole Deep Inelastic Scattering (DIS) spectra.
- Reduced options for cuts:
  - Only one exclusivity variable: Missing mass of $ep \to e\gamma$.

Solution:

- We need a method that ensures DVCS identification: Machine Learning
- The ML approach is tested on experimental data:
  1. Validation of the method when we include the proton information.
  2. Application to the case without proton information.

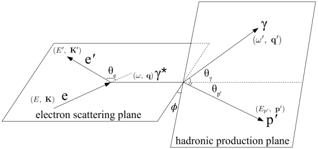
$ep \to e\gamma p$: Data selection

Analyzed data set

- Data already analyzed by the CLAS collaboration [1]
- Unpolarized liquid hydrogen target.

Kinematic window:

- $W > 2$ GeV,
- $Q^2 > 1$ GeV^2 ,
- $\mathbf{q}' > 2$ GeV (photon),
- $\mathbf{k}' > 1$ GeV (electron),
- $\mathbf{p}' > 0.3$ GeV (nucleon).



Exclusivity cuts:

We reconstruct ϕ and t in two ways:

1. Using $\gamma*$ and the outgoing photon γ: $\Rightarrow \phi(\gamma)$
2. Using $\gamma*$ and the recoil proton p: $\Rightarrow \phi(p')$

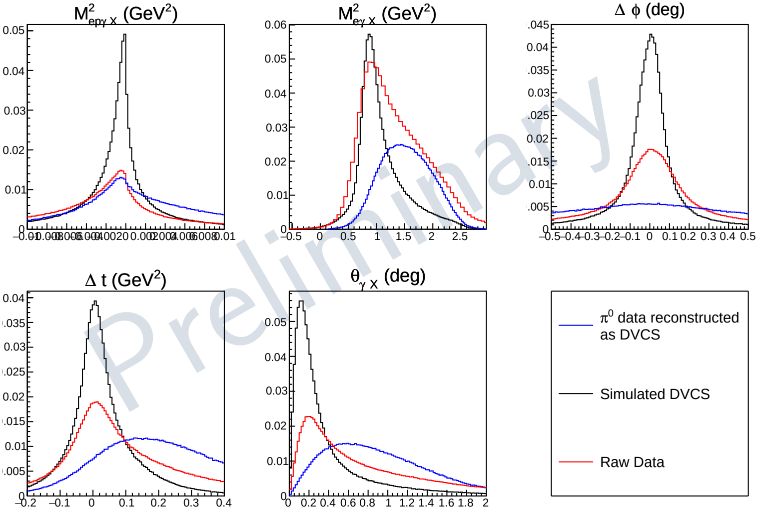
- $\Delta\phi = |\phi(p') - \phi(\gamma)| < 2°$,
- $\Delta t = |t(p') - t(\gamma)| < 2$ GeV^2,
- $\mathbf{P}_{miss} < 1$ GeV.

Event selection:

- If multiple e, γ or p detections, we select the set (e, γ, p) that minimizes the missing mass of the process $ep \to ep\gamma$

$ep \to e\gamma p$: Model training

The main contamination channel is $ep \to ep\pi^0 \to ep\gamma(\gamma)$.



Model training: event simulation

1. Events are generated using dvcsgen [2]
   - Including radiative corrections [3].
   - Events are weighted by the cross-section and selected by the keep-reject method.
   - For cross-section computation, the GPDs are taken from the VGG model [4]
2. Events are passed through Geant4 Monte-Carlo (GEMC)[5] to simulate the detector response
3. From the detector response, events are reconstructed with the same software used for experimental data.

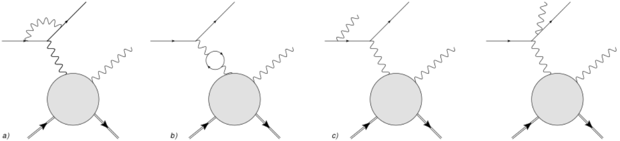
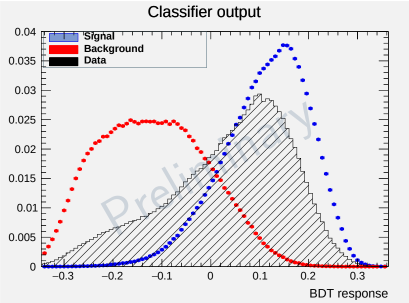


Figure: Radiative corrections included on the event generator.

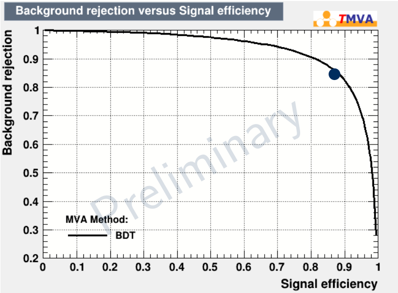
$ep \to e\gamma p$: BDT

To optimize the DVCS event selection, a Boosted Decision Tree (BDT) is trained to classify the events.

- Discriminating variables: $\{M^2_{ep\gamma}, M^2_{e\gamma}, \Delta\phi, \Delta t, \theta_{\gamma X}\}$.
- Simulated DVCS as signal.
- Simulated π^0 events, reconstructed as DVCS, as background.



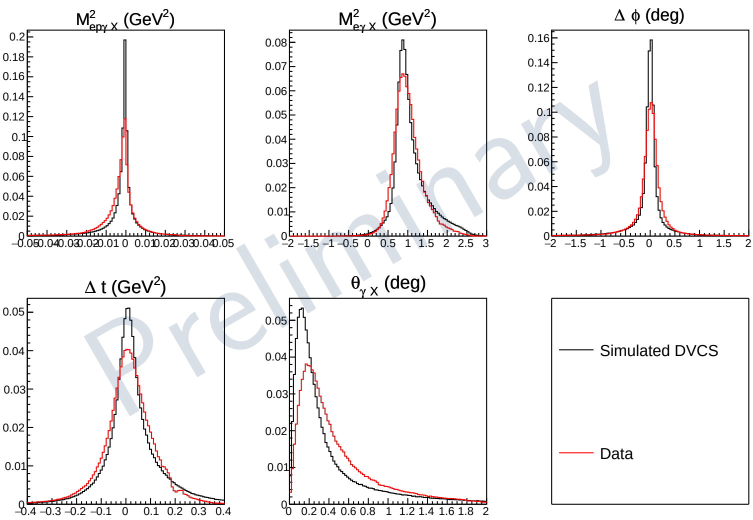
(a) BDT output distributions for different datasets.



(b) ROC curve of the model and applied cut.

$ep \to e\gamma p$: BDT

We extract a dataset with DVCS$\sim$ 94.5% and DVMP$\sim$ 5.5%.



Histograms are normalized to 1.

Data selection

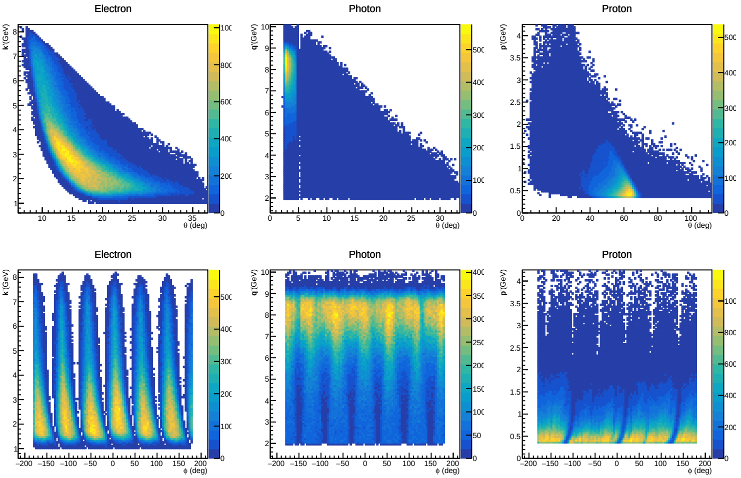
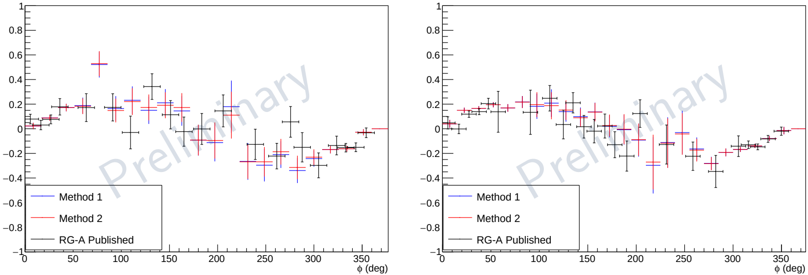


Figure: Momentum of the final particles as a function of the polar angle (first row) and detection polar vs azimuthal angle for each final state.

$ep \to e\gamma p$: BSA: benchmark measurements

The results of this approach is consistent with previous measurements.



(a) Bin 53 from [1]. **(b)** Bin 28 from [1].

- Bin 53: $3.25 < Q^2(\mathrm{GeV}^2) < 5.0$, $x_B < 0.33$, $0.4 < -t(\mathrm{GeV}^2) < 0.8$.
- Bin 28: $1.8 < Q^2(\mathrm{GeV}^2) < 2.4$, $x_B < 0.16$, $0.2 < -t(\mathrm{GeV}^2) < 0.4$

$ep \to e\gamma(p)$: Data selection

Kinematic window:
We apply the same kinematic restrictions:

- $W > 2$ GeV,
- $Q^2 > 1$ GeV^2 ,
- $\mathbf{q}' > 2$ GeV (photon),
- $\mathbf{k}' > 1$ GeV (electron).
- $-\frac{t}{Q^2} < 1$,

Exclusivity cuts:
However, our exclusivity cuts are no longer useful.

- ~~$\Delta\phi = |\phi(p) - \phi(\gamma)| mod(180) < 2°$~~,
- ~~$\Delta t = |t(p) - t(\gamma)| < 2$ GeV^2~~,
- ~~$\mathbf{P}_{miss} < 1$ GeV~~.

Event selection

- Only analyze events with 1 or 2 photons.
- The event is selected by taking the most energetic photon and electron.

BDT training:

- Training using **experimental data**:
  - (Background) signal are the events that (do not) pass the analysis with proton information.
- Discriminating variables: $\{M^2_{e\gamma X}, M^2_{eX}$, t $\}$.

$ep \to e\gamma(p)$: Model training

Taking the classified data with proton information, the following variables are used for training.

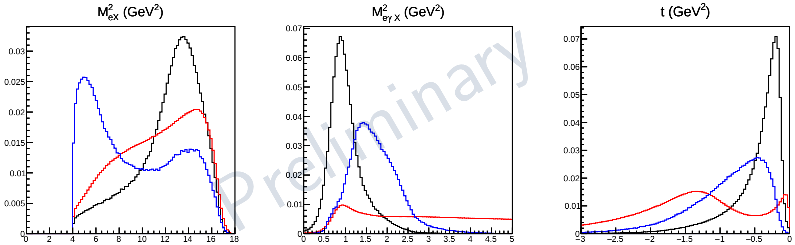


Figure: Missing masses $M^2_{e\gamma X}$, M^2_{eX} and t, normalized to 1, for raw data (red), training DVCS dataset (black) and training π^0 dataset (blue).

Histograms are normalized to 1.

$ep \to e\gamma(p)$: Comparison with $e\gamma p$ detection

There is an important increase on statistics

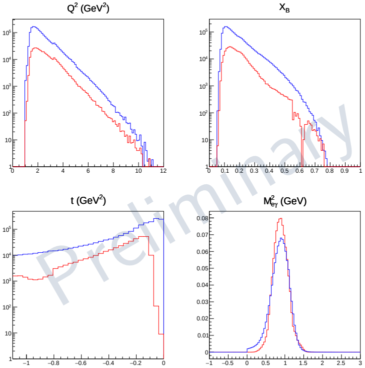


Figure: Kinematic variables for the analysis with proton (red) and without proton (blue) information.

We access a wider region in t.

Data selection

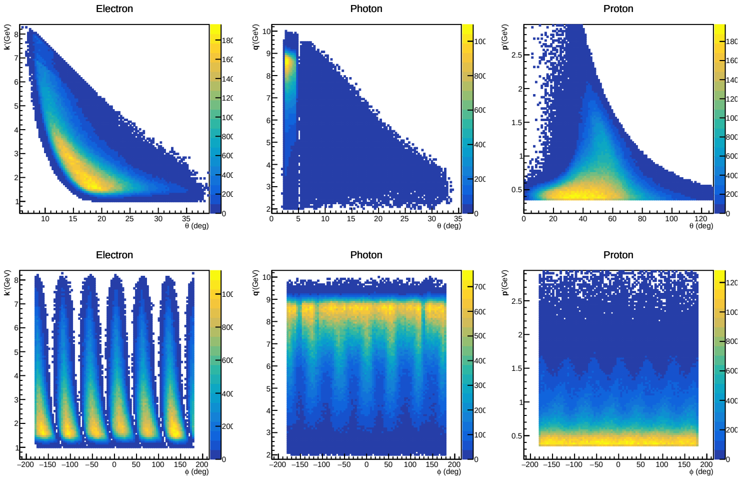
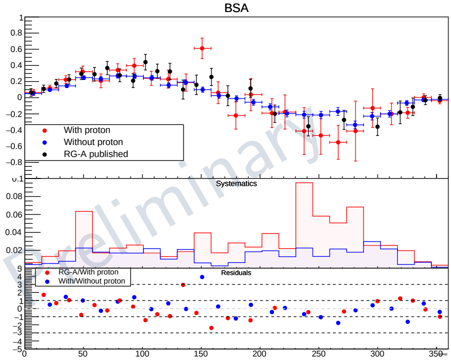


Figure: Momentum of the final particles as a function of the polar angle (first row) and detection polar vs azimuthal angle for each final state when the proton information is ignored.

$ep \to e\gamma(p)$: BSA - Benchmark measurements

Chosen bin*: $1.8 < Q^2(\text{GeV}^2) < 2.4,\ 0.16 < x_B < 0.26,\ -t(\text{GeV}^2) < 0.2$



- Measurements compatible within 2σ.
- Systematic error decreases when there is no nucleon detection.

*bin 26 from [1]

Conclusions

- Boosted decision trees allows to perform DVCS identification with $e\gamma$ detection
- On $e\gamma$ topology:
  - BSA measurements are compatible with the published results of the collaboration.
  - There is a boost of statistics.
  - There is a wider phase space exploration towards the small t region.
  - Provides BSA measurements with smaller systematic errors.

What's next?

- Cross-section measurements of proton-DVCS with $e\gamma$ detection.
- BSA measurements of neutron-DVCS.

References

[1] Christiaens G et al. In: *Physical Review Letters* 130.21 (2023), p. 211902.

[2] Korotkov VA and Nowak W-D. In: *The European Physical Journal C-Particles and Fields* 23 (2002), pp. 455–461.

[3] Igor Akushevich and Alexander Ilyichev. In: *Physical Review D* 98.1 (2018), p. 013005.

[4] Guidal M et al. In: *Physical Review D* 72.5 (2005), p. 054013.

[5] https://gemc.jlab.org/gemc/html/index.html.

Thanks

Backup

$ep \to e\gamma p$: Background subtraction

To estimate and remove the residual background on each (t, Q^2, x_B, ϕ) bin and helicity state we use two methods:

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 $1/n^{2\gamma}_{MC}$.

$ep \to e\gamma(p)$: Background subtraction

Without proton detection, the $e\gamma$ final state receives contributions from a large set of processes. However:

1. Photon emission comes mainly neutral meson decays, being π^0 the dominant one.
2. The contamination channel is now **inclusive** π^0 production.
3. Both background subtraction methods are valid for such case, and it only depends on a good π^0 reconstruction.

RGA bins

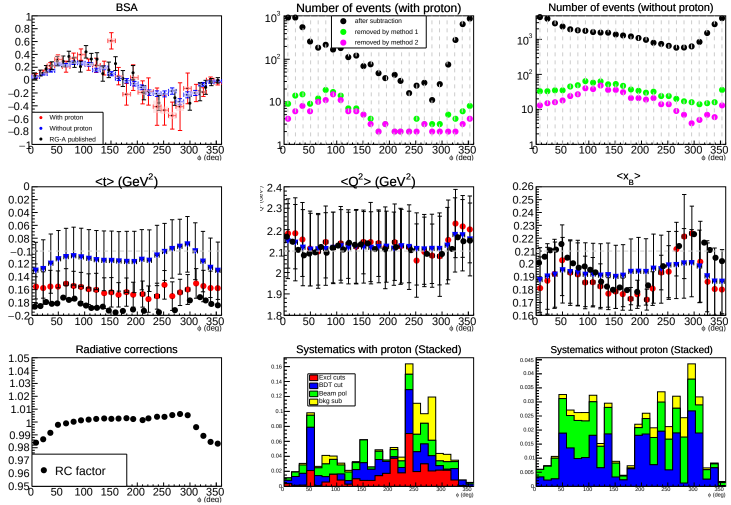
Bin no.	Q^2 (GeV^2)	x_B	$\lvert t'\rvert$ (GeV^2)
1		< 0.13	
2	< 1.4	0.13 – 0.21	< 0.2
3		> 0.21	
4		< 0.13	
5		0.13 – 0.21	0.2 – 0.4
6		> 0.21	
7		< 0.13	
8		0.13 – 0.21	0.4 – 0.8
9		> 0.21	
10		< 0.13	
11		0.13 – 0.21	> 0.8
12		> 0.21	
13		< 0.13	
14	1.4 – 1.8	0.13 – 0.21	< 0.2
15		> 0.21	
16		< 0.13	
17		0.13 – 0.21	0.2 – 0.4
18		> 0.21	
19		< 0.13	
20		0.13 – 0.21	0.4 – 0.8
21		> 0.21	
22		< 0.13	
23		0.13 – 0.21	> 0.8
24		> 0.21	

Bin no.	Q^2 (GeV^2)	x_B	$\lvert t'\rvert$ (GeV^2)
25		< 0.16	
26	1.8 – 2.4	0.16 – 0.26	< 0.2
27		> 0.26	
28		< 0.16	
29		0.16 – 0.26	0.2 – 0.4
30		> 0.26	
31		< 0.16	
32		0.16 – 0.26	0.4 – 0.8
33		> 0.26	
34		< 0.16	
35		0.16 – 0.26	> 0.8
36		> 0.26	
37		< 0.21	
38	2.4 – 3.25	0.21 – 0.33	< 0.2
39		> 0.33	
40		< 0.21	
41		0.21 – 0.33	0.2 – 0.4
42		> 0.33	
43		< 0.21	
44		0.21 – 0.33	0.4 – 0.8
45		> 0.33	
46		< 0.21	
47		0.21 – 0.33	> 0.8
48		> 0.33	

Bin no.	Q^2(GeV^2)	x_B	$\lvert t'\rvert$ (GeV^2)
49	3.25 – 5.0	< 0.33	< 0.2
50		> 0.33	
51		< 0.33	0.2 – 0.4
52		> 0.33	
53		< 0.33	0.4 – 0.8
54		> 0.33	
55		< 0.33	> 0.8
56		> 0.33	
57	> 5.0	< 0.55	< 0.2
58		> 0.55	
59		< 0.55	0.2 – 0.4
60		> 0.55	
61		< 0.55	0.4 – 0.8
62		> 0.55	
63		< 0.55	> 0.8
64		> 0.55	

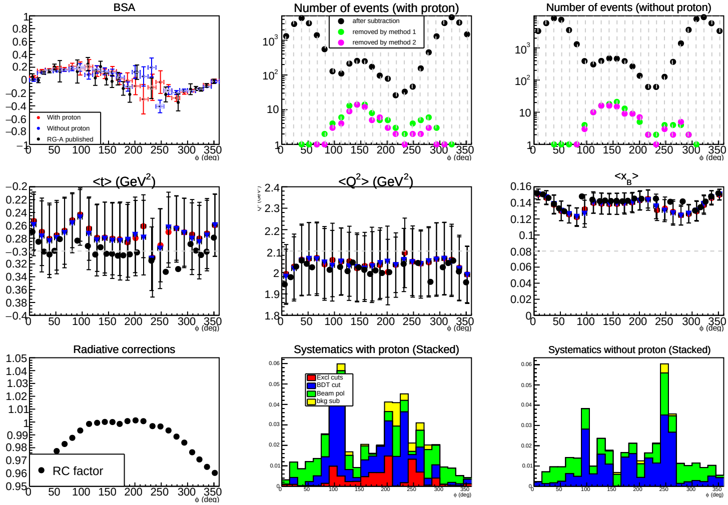
$ep \to e\gamma(p)$: BSA - Benchmark measurements

Bin 26: $1.8 < Q^2(\text{GeV}^2) < 2.4$, $0.16 < x_B < 0.26$, $-t(\text{GeV}^2) < 0.2$



$ep \to e\gamma(p)$: BSA - Benchmark measurements

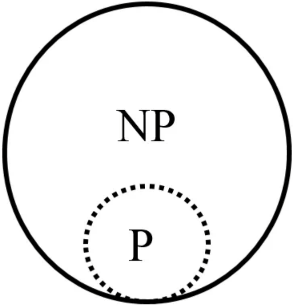
Bin 28: $1.8 < Q^2(\mathrm{GeV}^2) < 2.4,\ x_B < 0.16,\ 0.2 < -t(\mathrm{GeV}^2) < 0.4$



BDT score per bin

About the performance...

- BDT classification without proton information keeps 80% of the events classified with proton information
- That represents 30% (40%) of the in(out)bending datasets.



η contamination

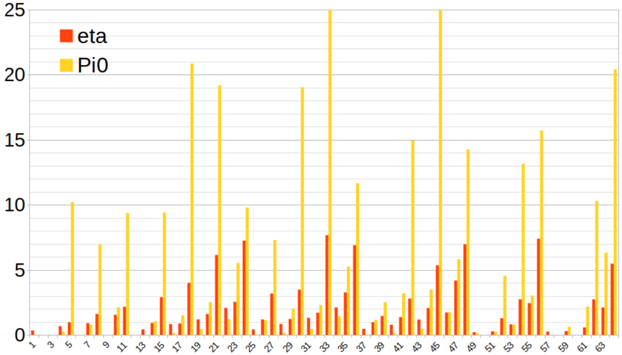
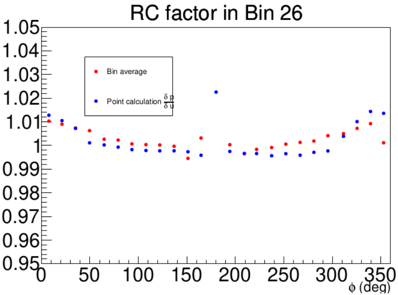


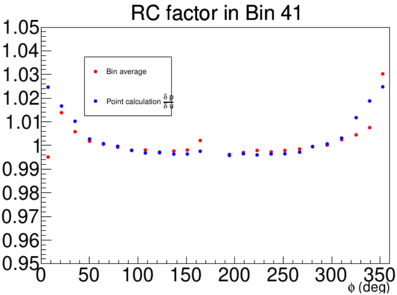
Figure: π^0 and η contamination (%) per bin after BDT without proton information.

- If proton information is included: contamination is less than 1% on all bins.
- If proton information is ignored: contamination is less than 2% on most bins. Maximum is 7%.

RC factor



(a) RC factor on bin 26.



(b) RC factor on bin 41.

Computing systematics

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

Merging kin $$Q^2 = \frac{Q^2_{inb} n_{inb} + Q^2_{outb} n_{outb}}{n_{inb} + n_{outb}}$$ $$\sigma(Q^2) = \frac{\sigma(Q^2_{inb}) n_{inb} + \sigma(Q^2_{outb}) n_{outb}}{n_{inb} + n_{outb}}$$

Merging sys $$A_{\pm} = \frac{\frac{A_{inb} \pm \sigma^{cut}_{inb}}{\sigma(A_{inb})} + \frac{A_{outb} \pm \sigma^{cut}_{outb}}{\sigma(A_{outb})}}{\sqrt{\frac{1}{\sigma(A_{inb})^2} + \frac{1}{\sigma(A_{outb})^2}}}$$ $$\sigma^{cut} = \sqrt{\frac{(A_+ - A_0)^2 + (A_- - A_0)^2}{2}}$$

Bkg sub sys err $$\sigma^{bkg} = \frac{A^{raw} - A^{\pi^0}}{(1-f)^2} \delta f$$