DVCS identification with $e\gamma$ detection @CLAS12

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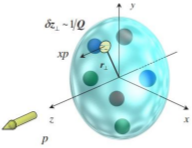
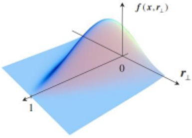
GPDs

- 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).

$$\mathcal{F}(\xi, t) \equiv \mathcal{P} \int_{-1}^{1} dx F(x, \xi, t) \left(\frac{1}{x - \xi + i\epsilon} \pm \frac{1}{x + \xi + i\epsilon} \right).$$

for $F = H, E, \tilde{H}, \tilde{E}$.





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

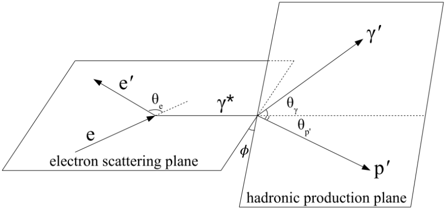
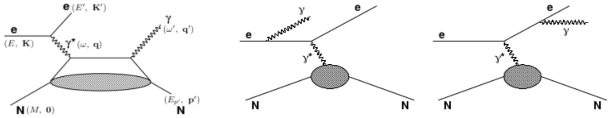


Figure: Kinematic planes on the DVCS reaction.

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



DVCS BH

Observables

Considering electron and positron beams we can construct observables sensitive to CFFs such as:

$$A_{LU}^{\pm} = \frac{d^5\sigma^{\pm}_{+U} - d^5\sigma^{\pm}_{-U}}{d^5\sigma^{\pm}_{UU}} \equiv \frac{\Delta\sigma^{\pm}_{LU}}{d^5\sigma^{\pm}_{UU}} \propto \Im(\mathcal{F}),$$

$$A_{LU}^{0} = \frac{\Delta\sigma^{+}_{LU} + \Delta\sigma^{-}_{LU}}{d^5\sigma^{+}_{UU} + d^5\sigma^{-}_{UU}} \propto \text{twist-3 effects},$$

$$A_{UU}^{C} = \frac{d^5\sigma^{+}_{UU} - d^5\sigma^{-}_{UU}}{d^5\sigma^{+}_{UU} + d^5\sigma^{-}_{UU}} \propto \Re(\mathcal{F}),$$

$$A_{LU}^{C} = \frac{\Delta\sigma^{+}_{LU} - \Delta\sigma^{-}_{LU}}{d^5\sigma^{+}_{UU} + d^5\sigma^{-}_{UU}} \propto \Im(\mathcal{F}).$$

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

CLAS12

- Forward Detector (FD): $5° < \theta < 35°$
  - Contains a torus magnetic field.
  - Full acceptance for the scattered electron
- Forward Tagger (FT): $2° < \theta < 5°$
  - Receives the bulk of the produced photons
- Central Detector (CD): $35° < \theta < 135°$
  - Contains a solenoid magnetic field.
  - Receives the bulk of the recoil protons

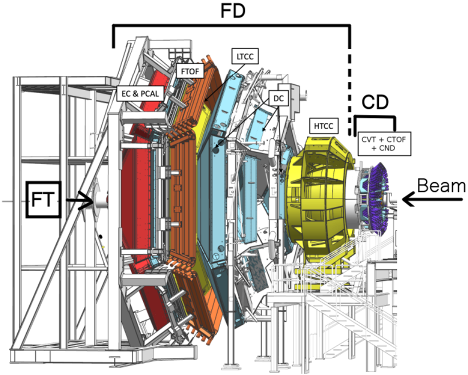
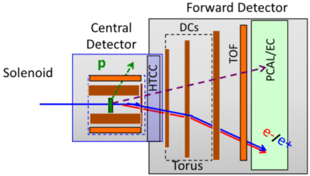


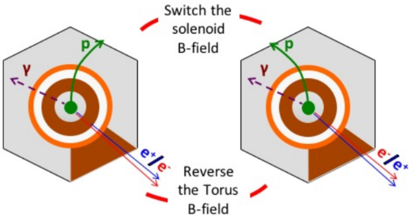
Figure: CLAS12 detector[1].

Motivation

When measuring Beam Charge Asymmetries there are some systematic effects we need to control:

- Same beam quality (energy, transverse profile, emittance etc.).
- Same statistics (accumulated charge, beam polarization).
- Same detector (efficiency, solid angle etc.):
  1. We want electrons and positrons to follow identical tracks
  2. Then we switch the torus and solenoid polarity.
  3. Protons are forced to follow opposite trajectories for the different beam charges, introducing then a **new systematic effect**.





We can overcome this effect if the proton is not detected.

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.

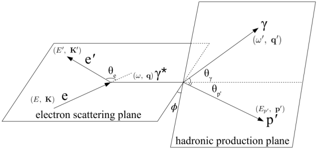
$ep \to e\gamma p$: Data selection

Analyzed data set

- Data already analyzed by the CLAS collaboration [2]
- 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: $\Rightarrow \phi(p')$

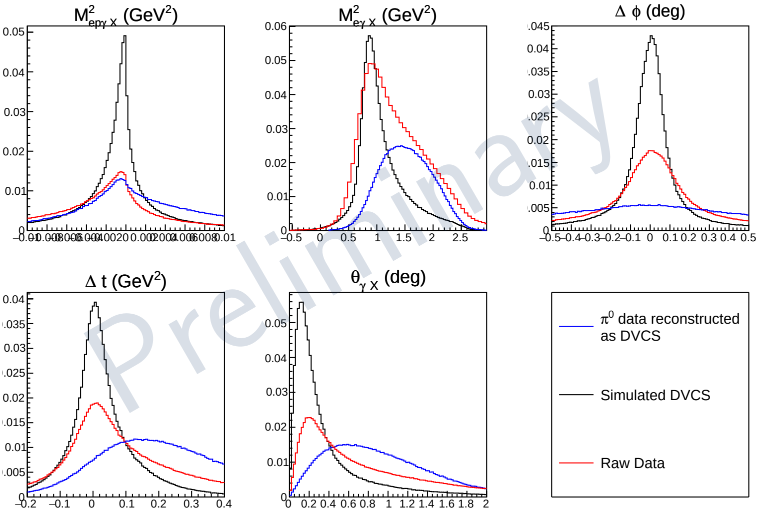
- $\Delta\phi = |\phi(p') - \phi(\gamma)| < 2°$,
- $\Delta t = |t(p') - t(\gamma)| < 2$ GeV^2,
- $\mathbf{P}_{miss} < 1$ GeV.

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 [3]
   - Including radiative corrections [4].
   - 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 [5]
2. Events are passed through Geant4 Monte-Carlo (GEMC)[6] to simulate the detector response
3. From the detector response, events are reconstructed with the same software used for experimental data.

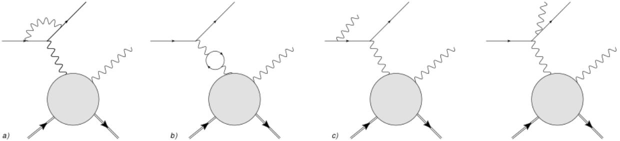
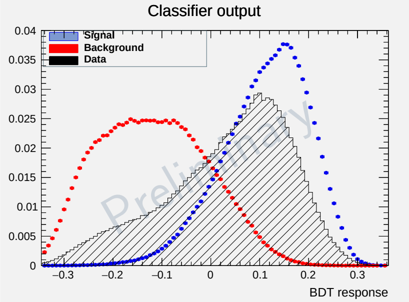


Figure: Radiative corrections included on the event generator.

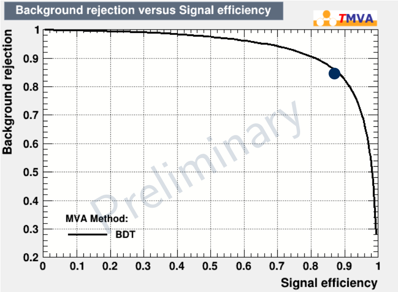
$ep \to e\gamma p$: BDT

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.



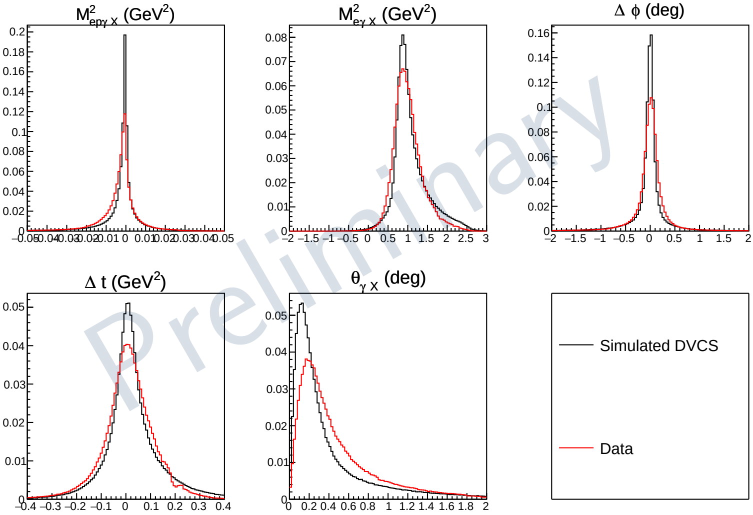
(a) BDT output distributions for different datasets.



(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

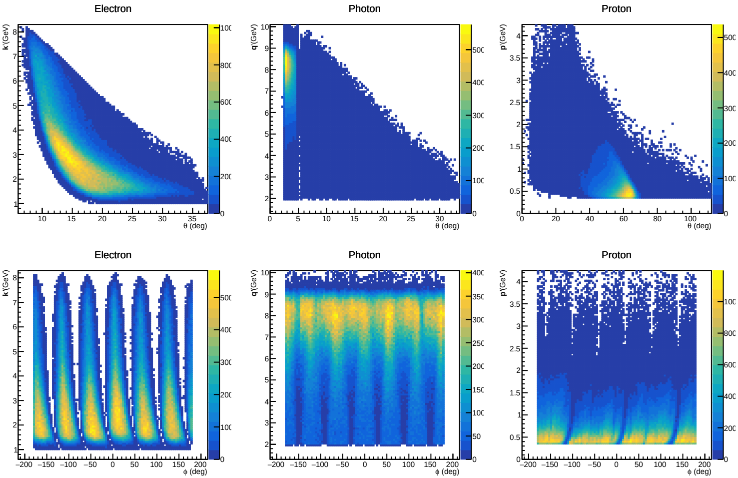
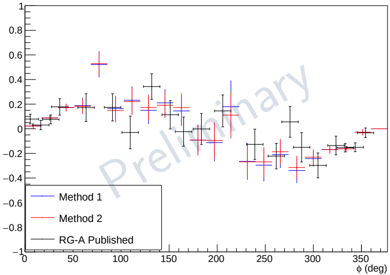


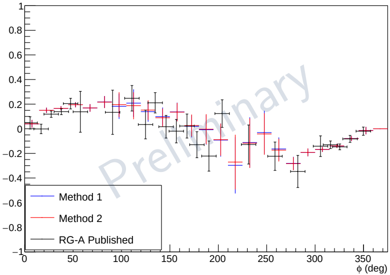
Figure: Momentum of the final particles as a function of the polar angle (first row) and detection polar vs azimuthal angle for each final state.

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

The results of this approach is consistent with previous measurements.



(a) Bin 53 from [2].



(b) Bin 28 from [2].

- 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: $\{M^2_{e\gamma X}, M^2_{eX}, \text{t}\}$.

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

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

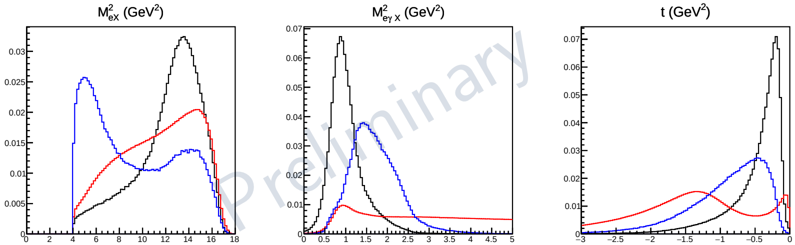


Figure: Missing masses $M^2_{e\gamma X}$, M^2_{eX} and t, normalized to 1, for raw data (red), training DVCS dataset (black) and training π^0 dataset (blue).

Histograms are normalized to 1.

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

There is an important increase on statistics

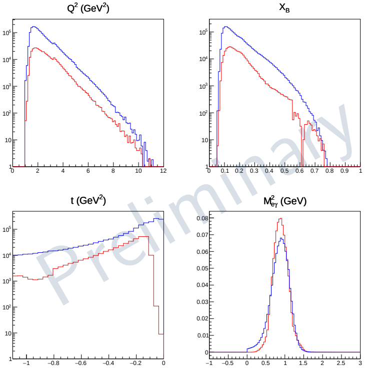


Figure: Kinematic variables for the analysis with proton (red) and without proton (blue) information.

We access a wider region in t.

Data selection

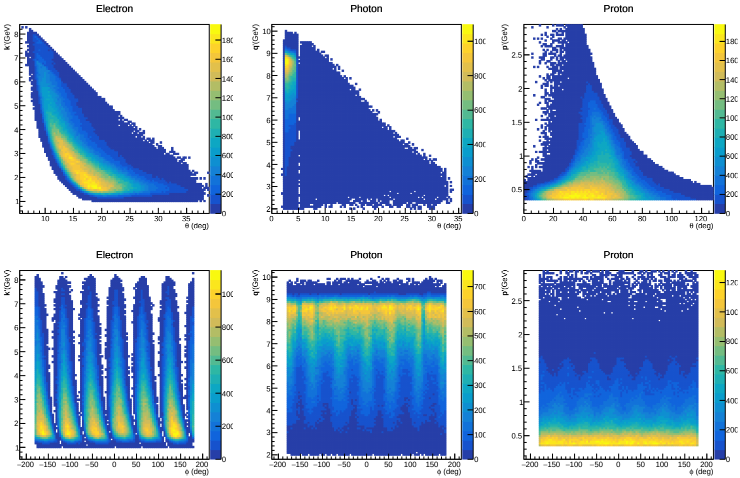
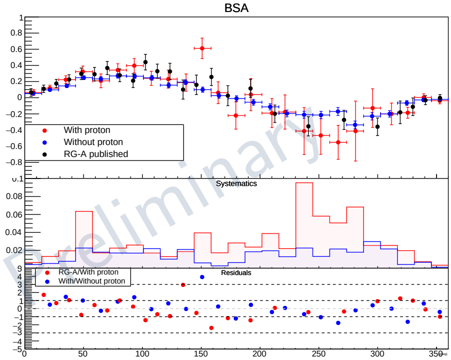


Figure: Momentum of the final particles as a function of the polar angle (first row) and detection polar vs azimuthal angle for each final state when the proton information is ignored.

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

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



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

*bin 26 from [2]

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.

References

[1] A. Accardi et al. In: *Eur. Phys. J. A* 57 (2021), p. 261.

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

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

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

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

[6] 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

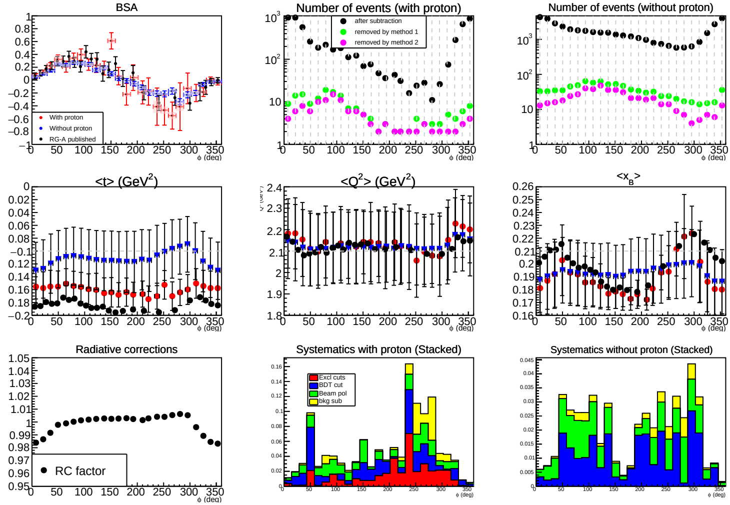
Bin no.	Q^2 (GeV^2)	x_B	$\lvert t'\rvert$ (GeV^2)
1		< 0.13	
2	< 1.4	0.13 – 0.21	< 0.2
3		> 0.21	
4		< 0.13	
5		0.13 – 0.21	0.2 – 0.4
6		> 0.21	
7		< 0.13	
8		0.13 – 0.21	0.4 – 0.8
9		> 0.21	
10		< 0.13	
11		0.13 – 0.21	> 0.8
12		> 0.21	
13		< 0.13	
14	1.4 – 1.8	0.13 – 0.21	< 0.2
15		> 0.21	
16		< 0.13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

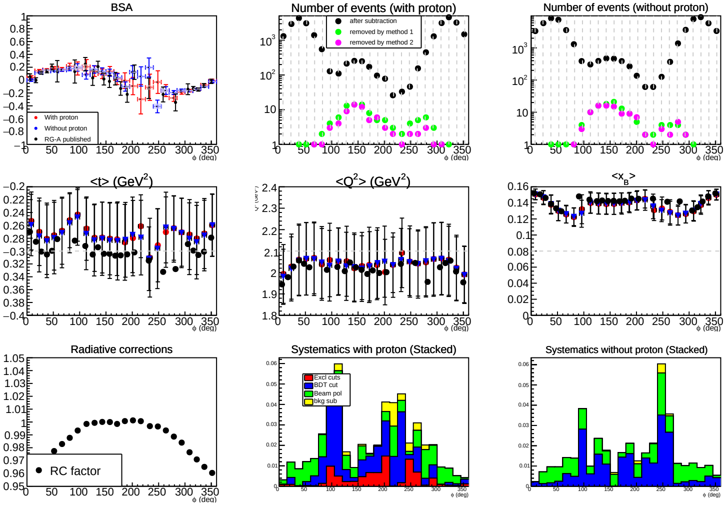
$ep \to e\gamma(p)$: BSA - Benchmark measurements

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



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

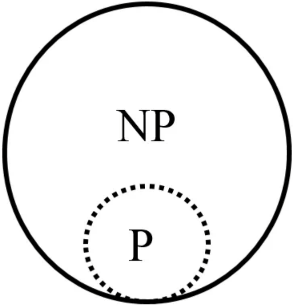
Bin 28: $1.8 < Q^2(\mathrm{GeV}^2) < 2.4,\ x_B < 0.16,\ 0.2 < -t(\mathrm{GeV}^2) < 0.4$



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

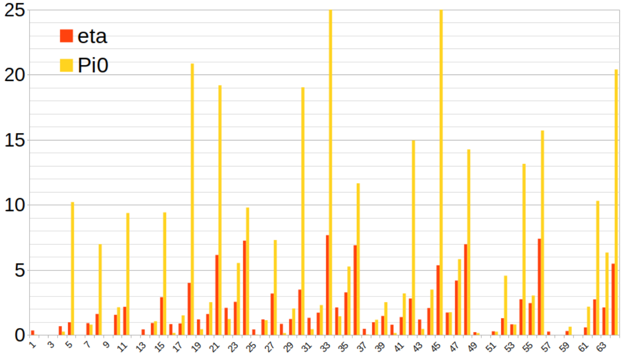
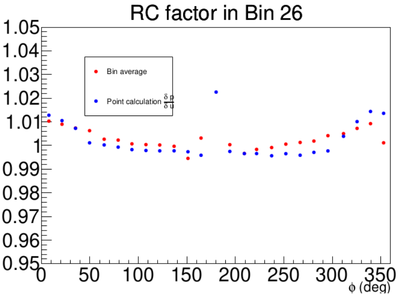


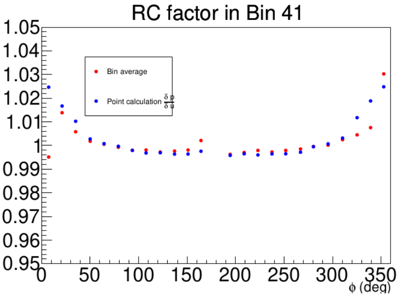
Figure: π^0 and η contamination (%) per bin after BDT without proton information.

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

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

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

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