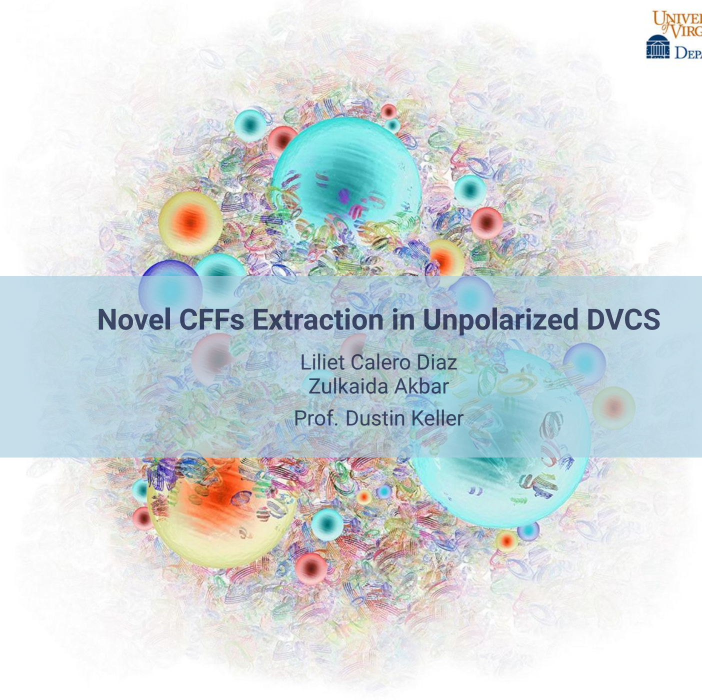


UNIVERSITY of VIRGINIA
DEPARTMENT of PHYSICS

Novel CFFs Extraction in Unpolarized DVCS

Liliet Calero Diaz
Zulkaida Akbar
Prof. Dustin Keller

SPIN2021

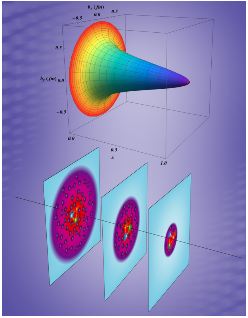
October 21^{th} 2021

GPDs provide correlated information of the **transverse position** and the **longitudinal momentum** distributions of partons.

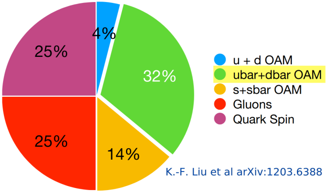
$$GPDs\,(x,\ \xi,\ t\ =\ \Lambda^2)$$

2 longitudinal momentum fractions (x, ξ) — squared momentum transfer to the proton (t)

$$t \to \Delta_T \xrightarrow{Fourier\ transform} \mathbf{b}\,(transverse\ position)$$



R. Dupre et al arXiv:1704.07330



K.-F. Liu et al arXiv:1203.6388

Proton spin contributions from Lattice QCD

Ji's angular momentum sum rule

$$\int_{-1}^{+1} dx x \left\{H^q(x,\xi,0) + E^q(x,\xi,0)\right\} = A(0) + B(0) = 2J^q$$

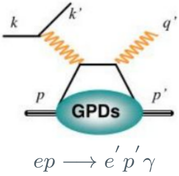
Access form factors of energy-momentum tensor:

$$\int_{-1}^{+1} dx x H^q(x,\xi,t) = A(t) + \xi^2 C(t)$$

$$\int_{-1}^{+1} dx x E^q(x,\xi,t) = B(t) - \xi^2 C(t)$$

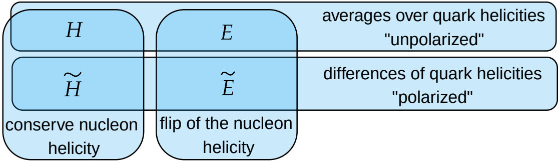
- **CFFs are directly linked to the tomography of the proton.**
- **CFFs give insights on: Spin structure, energy-momentum structure**

Deep Virtual Compton Scattering (DVCS) is the simplest process involving Generalized Parton Distribution functions (GPDs).



Twist-2

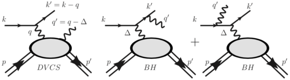
Chiral even GPDs: quark helicity is conserved



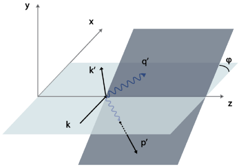
■ Accesing GPDs through DVCS

DVCS cross section is parametrized in terms of the Comptom Form Factors (CFFs). At twist-2 there are 8 CFFs $(\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}})$ considering their $\Re e$ and $\Im m$ parts, that are given by the convolution of GPDs:

$$\mathcal{H}\left(x_B,\ t,\ Q^2\right) = \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H\left(x,\ \xi,\ t,\ Q^2\right)$$



$$\underbrace{\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3 x_B y^2}{16\pi^2 Q^4\sqrt{1+\epsilon^2}}\frac{1}{e^6}\left[|\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 + \mathcal{I}\right]}_{f(k,Q^2,x_B,t,\phi)} .$$



[B. Kriesten, S. Liuti, et al arXiv:1903.05742]

- k Energy of the incoming electron.
- Q^2 Electron squared momentum transfer: $-(k-k')^2$
- t Squared momentum transfer to the proton: $(p'-p)^2$
- x_B Bjorken variable: $x_B = \frac{Q^2}{2(pq)}$
  Momentum fraction of the quark or gluon on which the photon scatters.

DVCS cross section formulations

- VA [B. Kriesten, S. Liuti, et al arXiv:1903.05742]
  - Written in terms of helicity amplitudes.
  - Covariant description
- BKM (2002) [A.V. Belitsky, D. Muller, A. Kirchner arXiv:0112108v2]
  - Written in terms of harmonics of the azimuthal angle, ϕ, and in kinematic powers of 1/Q.

Unpolarized Twist-2 → $\Re e\mathcal{H}$, $\Re e\mathcal{E}$, $\Re e\widetilde{\mathcal{H}}$

JLab Hall A @ 6 GeV

- Unpolarized beam
- Unpolarized H_2 target
- 20 kinematic sets in x_B, t, Q^2
- $Q^2[1.453, 2.375]GeV^2$
- $t[-0.121, -0.4]GeV^2$
- $x_B[0.336, 0.401]$

Extraction Methods ϕ space fit

$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3 x_B y^2}{16\pi^2 Q^4\sqrt{1+\epsilon^2}}\frac{1}{e^6}\Big[\underbrace{|\mathcal{T}^{BH}|^2}_{\substack{\text{Exact (QED)}\\ \text{FFs: } F_1,\, F_2}} + \underbrace{|\mathcal{T}^{DVCS}|^2}_{\phi\text{-indep}} + \underbrace{\mathcal{I}}_{\text{3 CFFs}}\Big].$$

V A

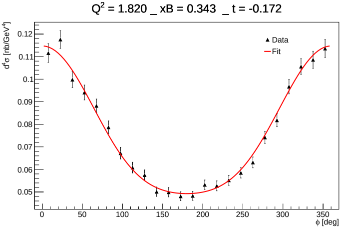
$$|\mathcal{T}_{DVCS}|^2 = \frac{1}{Q^2(1-\epsilon)}\underbrace{F_{UU,T}}_{\text{8 CFFs}}$$

$$\mathcal{I}^{VA} = \frac{1}{Q^2|t|}\Big[A_{UU}^{VA}\left(F_1\Re e\mathcal{H} - \frac{t}{4M^2}F_2\Re e\mathcal{E}\right) + B_{UU}^{VA}G_M\left(\Re e\mathcal{H} + \Re e\mathcal{E}\right) + C_{UU}^{VA}G_M\Re e\widetilde{\mathcal{H}}\Big]$$

B K M

$$|\mathcal{T}_{DVCS}|^2 = \frac{e^6}{y^2Q^2}\left\{2(2-2y-y^2)\right\}\underbrace{C_{unp}^{DVCS}(\mathcal{F},\mathcal{F}^*)}_{\text{8 CFFs}}$$

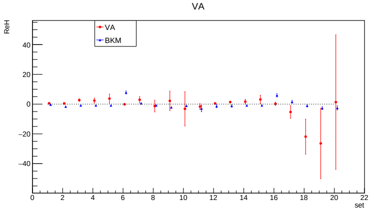
$$\mathcal{I}^{BMK} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\Big[A_{UU}^{BKM}\left(F_1\Re e\mathcal{H} - \frac{t}{4M^2}F_2\Re e\mathcal{E}\right) + B_{UU}^{BKM}G_M\left(\Re e\mathcal{H} + \Re e\mathcal{E}\right) + C_{UU}^{BKM}G_M\Re e\widetilde{\mathcal{H}}\Big]$$

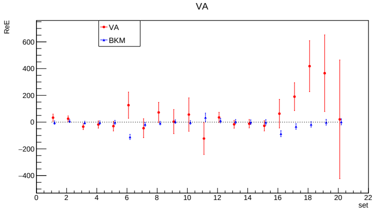


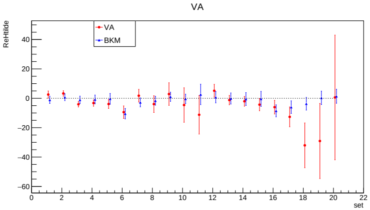
4 fit parameters:

$\Re e\mathcal{H}$, $\Re e\mathcal{E}$, $\Re e\widetilde{\mathcal{H}}$, pure DVCS

Extraction Methods ϕ space fit







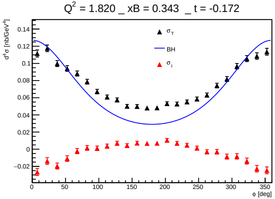
$k = 5.75 GeV$
$Q^2 [1.453, 2.375] GeV^2$
$t [-0.121, -0.4] GeV^2$
$x_B [0.336, 0.401]$

Improve results by imposing fit constraints.

VA Linear Method [B. Kriesten, S. Liuti, et al arXiv:1903.05742]

Change of variables

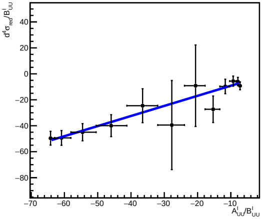
$$\phi \longrightarrow \frac{A^I_{UU}}{B^I_{UU}}$$



$$d^4\sigma^I_{UU} = d^4\sigma^T_{data} - d^4\sigma^{BH} - d^4\sigma^{DVCS}$$

$$\frac{Q^2(-t)}{B^I_{uu}\Gamma} d^4\sigma^I_{UU} = \frac{A^I_{uu}}{B^I_{uu}} \underbrace{(F_1\Re e\mathcal{H} + \tau F_2 \Re e\mathcal{E})}_{slope} + \underbrace{G_M(\Re e\mathcal{H} + \Re e\mathcal{E})}_{intercept}$$

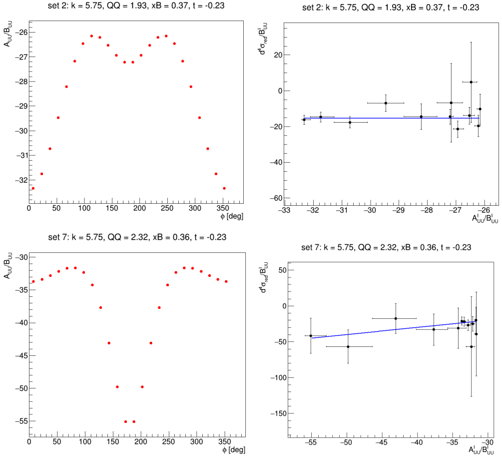
$$+ \underbrace{\frac{C^I_{uu}}{B^I_{uu}}}_{\sim small} G_M \Re e\widetilde{\mathcal{H}}$$



Extraction Methods A_{UU}/B_{UU} space fit

$\frac{A_{UU}}{B_{UU}}$ Systematics

$$\frac{Q^2(-t)}{B^I_{uu}\Gamma} d^4\sigma^I_{UU} = \frac{A^I_{uu}}{B^I_{uu}} \underbrace{(F_1 \Re e\mathcal{H} + \tau F_2 \Re e\mathcal{E})}_{slope} + \underbrace{G_M(\Re e\mathcal{H} + \Re e\mathcal{E})}_{intercept}$$



- Weighted average of symmetric points.
- $\frac{A_{UU}}{B_{UU}}(\phi)$ is not linear

$\Downarrow$

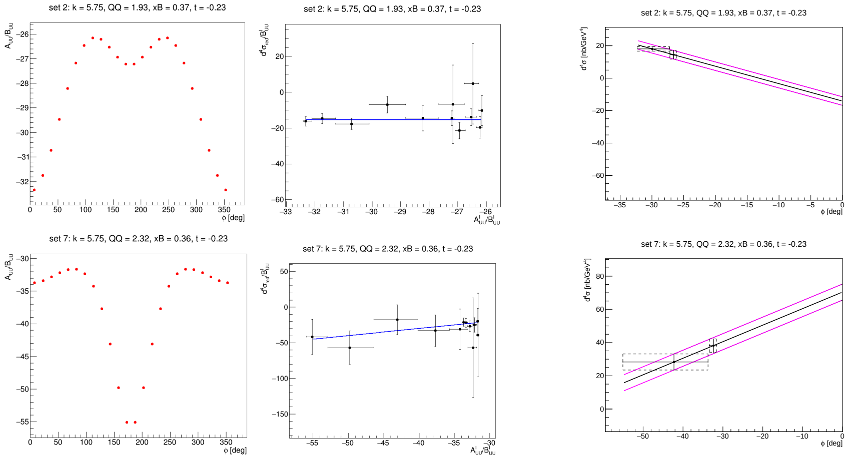
Asymmetric bins in $\frac{A_{UU}}{B_{UU}}$

Study systematic errors due to the $\frac{A_{UU}}{B_{UU}}$ mapping.

Extraction Methods A_{UU}/B_{UU} space fit

$\frac{A_{UU}}{B_{UU}}$ Systematics

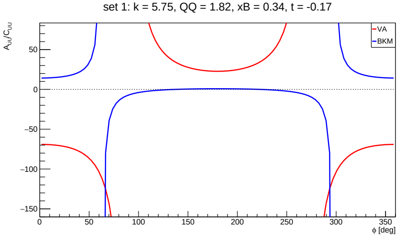
$$\frac{Q^2(-t)}{B^I_{uu}\Gamma} d^4\sigma^I_{UU} = \frac{A^I_{uu}}{B^I_{uu}} \underbrace{(F_1 \Re e\mathcal{H} + \tau F_2 \Re e\mathcal{E})}_{slope} + \underbrace{G_M(\Re e\mathcal{H} + \Re e\mathcal{E})}_{intercept}$$



Rebin all possible combinations to 2 points to find the widest error band that will correspond to the largest systematic error for the mapping to the $\frac{A_{UU}}{B_{UU}}$ space.

$\frac{A_{UU}}{B_{UU}}$ Systematics

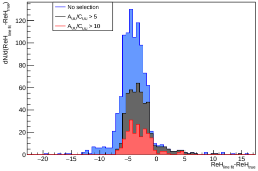
$$\frac{Q^2(-t)}{B^I_{uu}\Gamma} d^4\sigma^I_{UU} = \frac{A^I_{uu}}{B^I_{uu}} \underbrace{\left(F_1 \Re e\mathcal{H} + \tau F_2 \Re e\mathcal{E}\right)}_{slope} + \underbrace{G_M\left(\Re e\mathcal{H} + \Re e\mathcal{E}\right)}_{intercept} + \underbrace{\frac{C^I_{uu}}{B^I_{uu}}}_{\sim small} G_M \Re e\widetilde{\mathcal{H}}$$

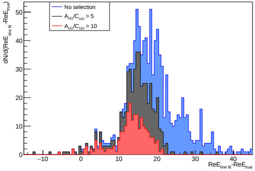


$\frac{A^I_{uu}}{C^I_{uu}} \implies$ Large

$\frac{C^I_{uu}}{B^I_{uu}}$ is generally small. BKM has a larger plateau around the largest values of the $\frac{C^I_{uu}}{B^I_{uu}}$. This behavior depends on the kinematic settings.

To account for the effect of this approximation, pseudo-data is generated at the HallA kinematics.





VA Pseudo-data

Toy Model

Higher ϕ resolution

Large kinematic range

1058 sets

ϕ-fit and VA line fit comparison

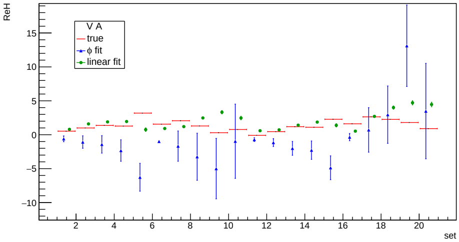
VA Pseudo-data

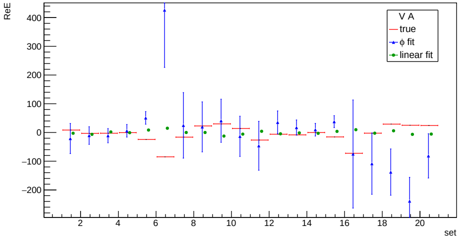
20 kinematics sets of the HallA data.

$k = 5.75 GeV$
$Q^2 [1.453, 2.375] GeV^2$
$t[-0.121, -0.4] GeV^2$
$x_B [0.336, 0.401]$

CFFs set at the values obtained from the data ϕ fit.

Cross sections with 5% variation.





VA linear method greatly improve the extraction of the $\Re e\mathcal{H}$ and $\Re e\mathcal{E}$ CFFs at the HallA kinematics.

Results will be reported using the **linear fit** method for the **VA formulation**.

ϕ-fit and VA line fit comparison

BKM Pseudo-data

20 kinematics sets of the HallA data.

$k = 5.75 GeV$

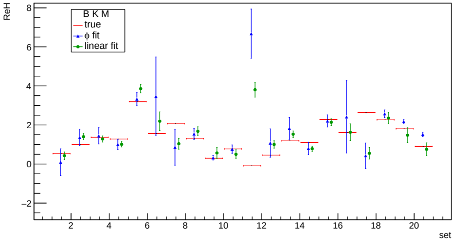
$Q^2 [1.453, 2.375] GeV^2$

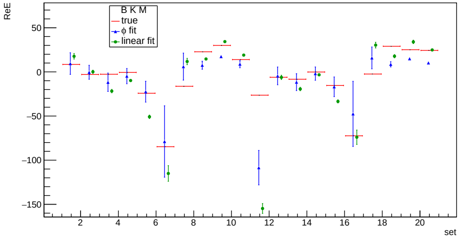
$t[-0.121, -0.4] GeV^2$

$x_B [0.336, 0.401]$

CFFs set at the values obtained from the data ϕ-fit.

Cross sections with 5% variation.



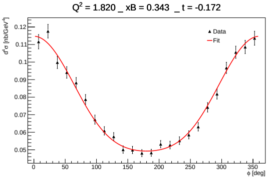


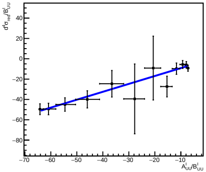
There are no marked improvements applying the VA linear method fit for the extraction of CFFs $\Re e\mathcal{H}$ and $\Re e\mathcal{E}$ at the HallA kinematics.

Results will be reported using the ϕ**-fit** for the **BKM formulation**.

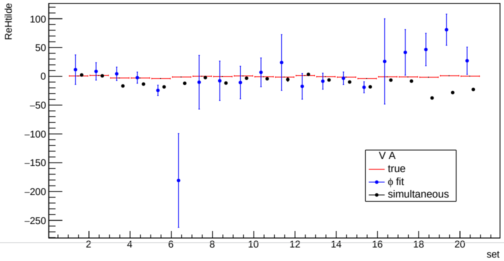
$\Re e\widetilde{\mathcal{H}}$ cannot be extracted from VA linear method.

Set constraints to extract $\Re e\widetilde{\mathcal{H}}$ by performing a simultaneous fit:





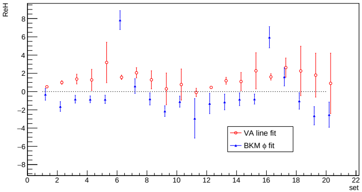
Simultaneous $\chi^2 = \chi^2_{\phi space} + \chi^2_{A_{UU}/B_{UU} space}$

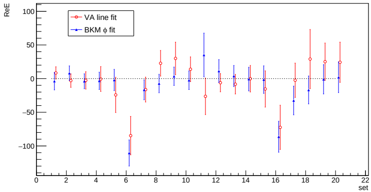


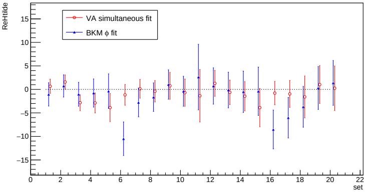
The results for the extraction of $\Re e\widetilde{\mathcal{H}}$ from the VA formalism are reported performing a **simultaneous** fit.

CFFs extraction with BKM formalism are shown with the ϕ results since the extraction does not improve with the VA line method.

Results







$k = 5.75 GeV$

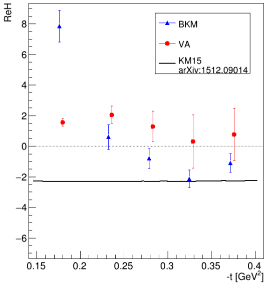
$Q^2[1.453, 2.375] GeV^2$

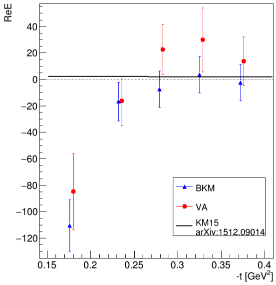
$t[-0.121, -0.4] GeV^2$

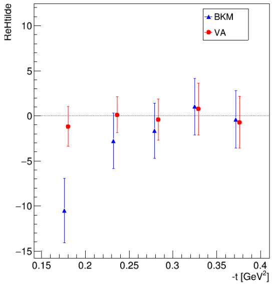
$x_B[0.336, 0.401]$

CFFs vs t

Kin 3: $x_B[0.345, 0.373]$, $Q^2[2.218, 2.375]GeV^2$







VA pseudo-data details

ϕ binning and kinematics sets of HallA data.

$k = 5.75 GeV$

$Q^2[1.453, 2.375]GeV^2$

$t[-0.121, -0.4]GeV^2$

$x_B[0.336, 0.401]$

Toy Model

$\Re e\mathcal{H} = -45t^4 + 10t + \frac{1.45}{x_B^2} - 7$

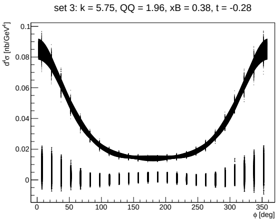
$\Re e\mathcal{E} = -\frac{1}{t^2} + 40x_B$

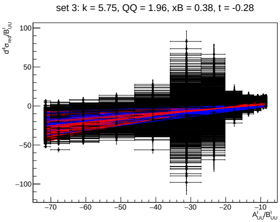
$\Re e\widetilde{\mathcal{H}} = 40t + \frac{5}{x_B}$

$\Re e\widetilde{\mathcal{E}} = -\frac{15}{t} + \frac{5}{x_B}$

$\Im m\mathcal{H} = \Im m\mathcal{E} = \Im m\widetilde{\mathcal{H}} = \Im m\widetilde{\mathcal{E}} = 0$

Sample the cross section within 5% error for each set to obtain the distribution of CFFs extracted with the VA linear method.



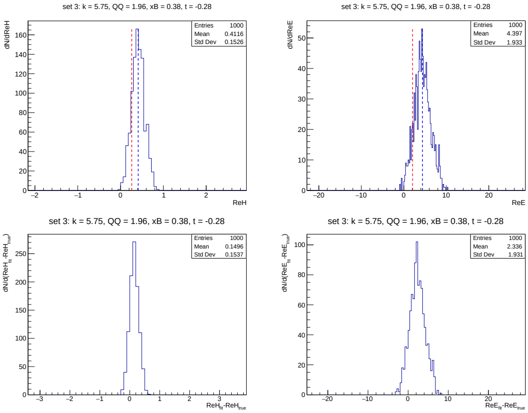


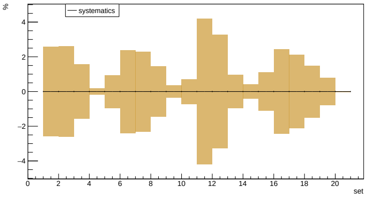
Fixing $\Re e\mathcal{E}$

Fixing $\Re e\mathcal{H}$

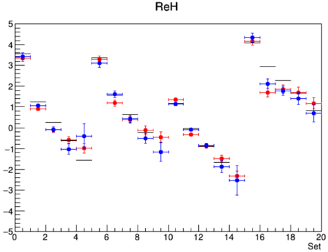
Results

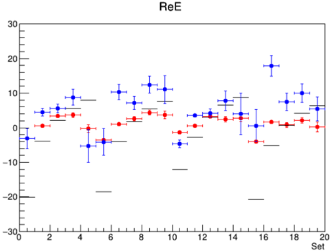
Systematics





Local fit using the VA linear method with ANN (pseudo-data)



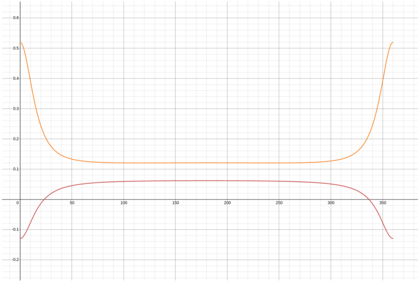


Minuit

ANN

Future Work — Falsification

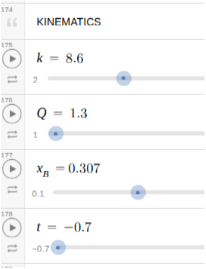
Propose experimental data taken at kinematic points were both formulations are expected to have different behaviors.



VA

BKM

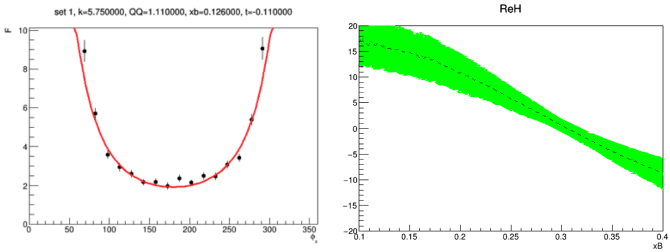
Assuming same CFFs



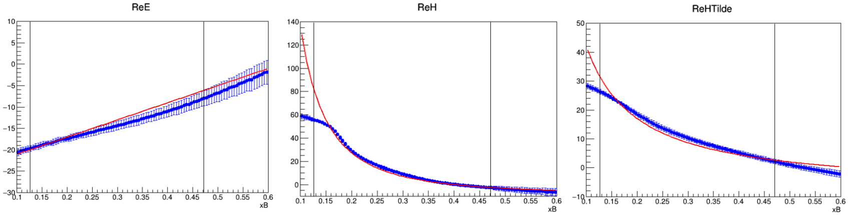
In this kinematic set the difference remains when the CFFs change significantly.

Using the local fits as input for the ANN global fit.

- HallB data - 110 sets



- pseudo-data



Summary

- The CFFs $\Re e\mathcal{H}$, $\Re e\mathcal{E}$ and $\Re e\widetilde{\mathcal{H}}$ were extracted from the JLab Hall A @ 6 GeV DVCS data using the VA and BKM(2002) model fit.
- The obtained CFFs are consistent in the 2 formulation within the errors for all kinematic settings, except for $\Re e\mathcal{H}$ that displays a different sign behavior.
- Use additional constraints with Artificial Neural Network to optimize the CFFs extraction.
- Study the systematic limits of the extraction in the A_{UU}/B_{UU}-space.

THANK YOU!