Update on DVCS Compton Form Factor fitting with PARTONS package

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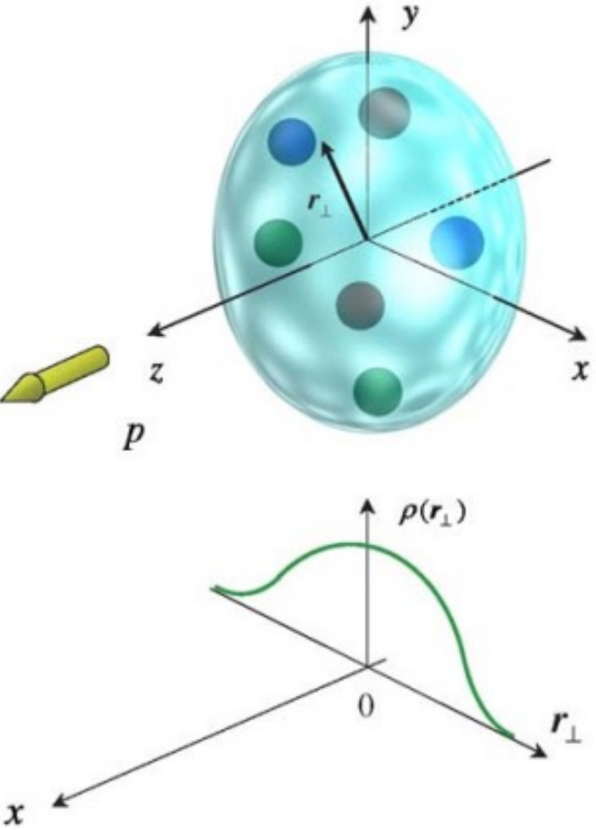
Outline

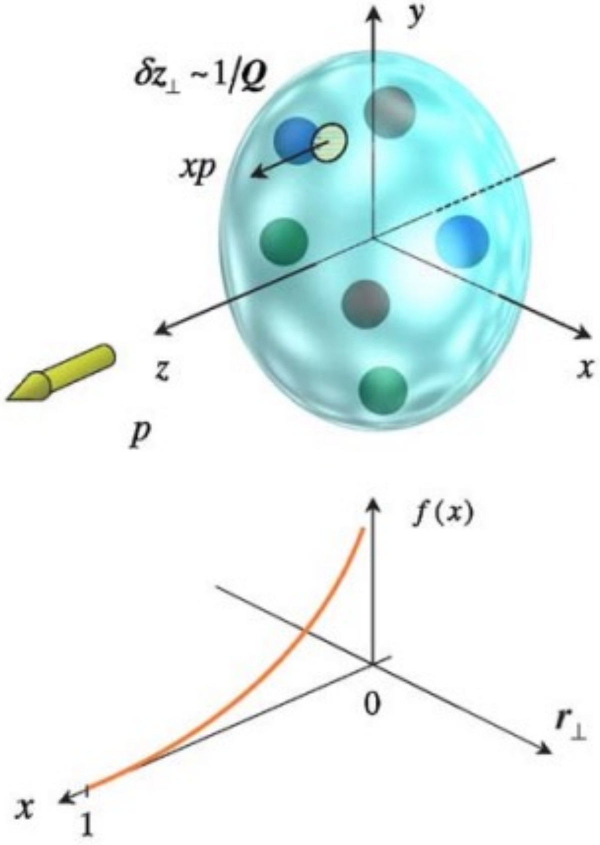
1. Motivation
2. DVCS CFF fitting strategy
3. PARTONS package
4. Observable calculation studies using PARTONS
5. Future work

Motivation: Spatial Imaging of hadrons: Generalized Parton Distributions (GPDs)

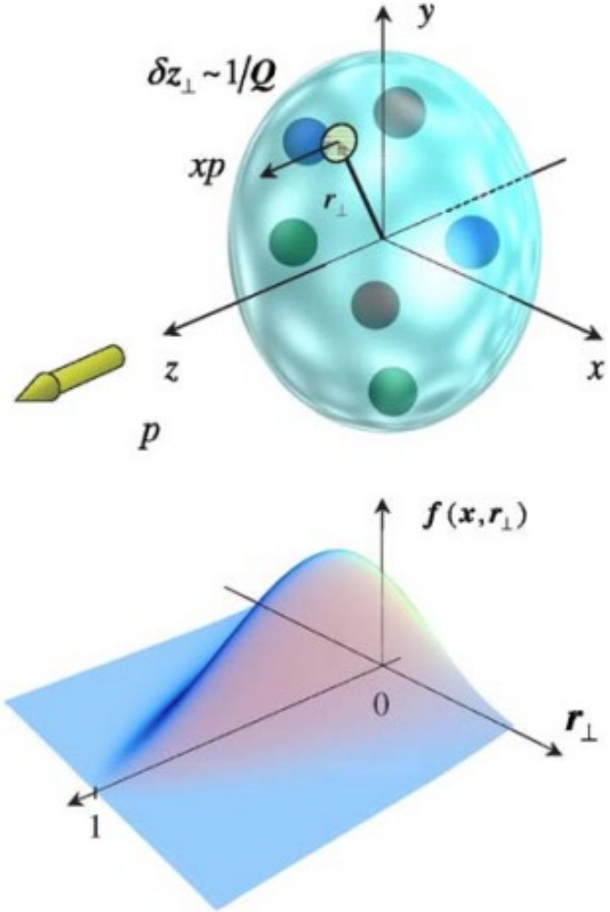
Elastic Scattering
Form Factors (FFs): Transverse charge and current density



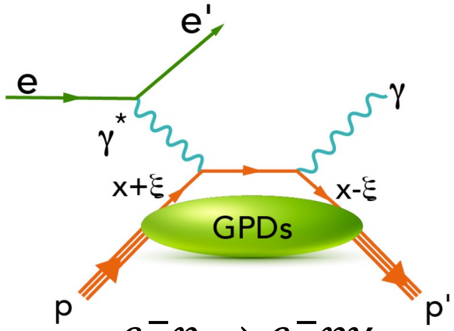
Deep Inelastic scattering
Parton Distribution Functions (PDFs): probability to find a parton i with xp longitudinal momentum



Hard Exclusive Processes
Generalized Parton Distributions: 3D image in transverse space and longitudinal momentum



Deeply Virtual Compton Scattering (DVCs)



$e^- p \rightarrow e^- p\gamma$

x-internal quark momentum fraction

p-hadron momentum

x_B- Bjorken variable

$\xi \approx \frac{x_B}{2-x_B}$- skewness (longitudinal momentum transfer)

A.V. Belitsky and A.V. Radyushkin, "Unraveling hadron structure with generalized parton distributions," *Phys. Rept.* **418** (2005) 1-151

Motivation: Deeply virtual Compton scattering (DVCS) observables

DVCs GPDs ($H(x,\xi,t)$, $E(x,\xi,t)$, $\widetilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$) are not observables.

The actual observables in DVCS are Compton form factors (CFFs) $\mathcal{H},\mathcal{E},\widetilde{\mathcal{H}},\tilde{\mathcal{E}}$ given by convolution integrals at LO:

$$\mathrm{Re}\mathcal{H}(\xi,t) + i\,\mathrm{Im}\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{+1} dx H_q(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

Similarly for other GPDs

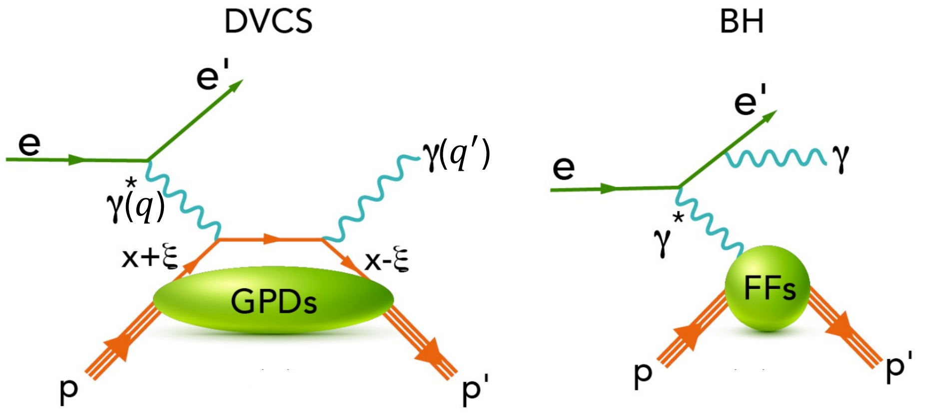
x - internal quark momentum fraction

e_q- electric charge of quark flavor q

$t=(p-p')^2$, $\Delta = p - p'$, $P = \frac{p+p'}{2}$, $q_M = \frac{q+q'}{2}$, $Q^2 = -q^2$

$\xi = \frac{\Delta\cdot q_M}{P\cdot q_M}$

DVCs interferes with Bethe-Heitler (BH)



CFFs $\mathcal{H}$ and $\mathcal{E}$ appear in the DVCS observables such as differential cross sections and beam and target polarization asymmetries.

DVCS-BH interference term contains $Im\mathcal{H}$ in the beam polarization asymmetry A_{LU}.

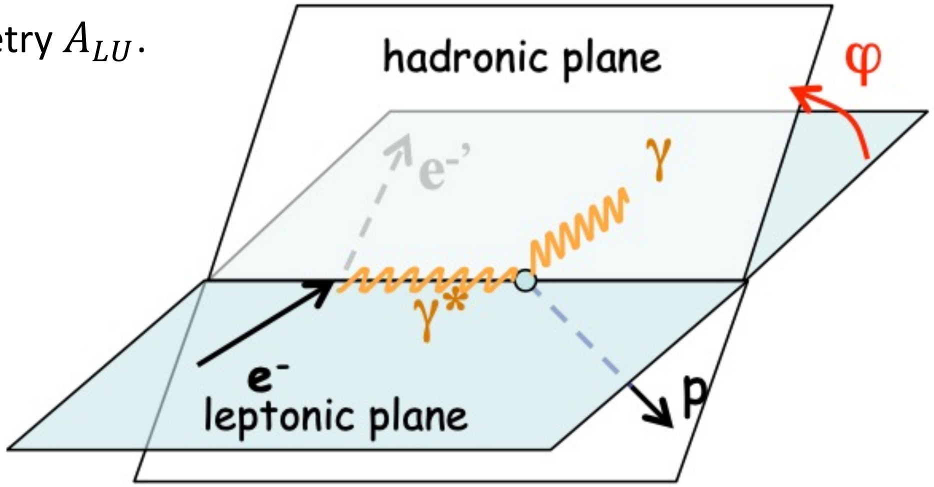
$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{A_{\mathrm{LU}}^{\sin\varphi}\sin\varphi}{1+\beta\cos\varphi}$$

$$A_{\mathrm{LU}}^{\sin\varphi} \propto Im\left(F_1\mathcal{H} + \xi G_M\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

$A_{\mathrm{LU}}^{\sin\varphi}$- first sine harmonic of the beam spin asymmetry (BSA)

F_1, G_M- Dirac and magnetic FFs

$d^4\sigma^{\rightarrow} = \frac{d^4\sigma^{\rightarrow}}{dx_B dQ^2 dt d\varphi}$ differential cross section for positive beam helicity



$Re\mathcal{H}$ appears in the differential cross section → Determine $\mathrm{Im}\mathcal{H}(\xi,t)$ and $\mathrm{Re}\mathcal{H}(\xi,t)$ from fits to BSA and the diff. cross section

Motivation: Fixed-t Dispersion Relation

The real and Imaginary $\mathcal{H}(\xi,t)$ are related via fixed-t dispersion relation (DR), where the subtraction constant $C_{\mathcal{H}}(t)$ is related to so called D-term.

$$\mathrm{Re}\mathcal{H}(\xi,t) = C_{\mathcal{H}}(t) + \frac{1}{\pi} P.V. \int_0^{+1} d\xi' \left[\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right] \mathrm{Im}\mathcal{H}(\xi',t)$$

$t=(p-p')^2$, $\Delta = p-p'$, $P = \frac{p+p'}{2}$, $q_M = \frac{q+q'}{2}$, $\xi = \frac{\Delta \cdot q_M}{P \cdot q_M}$, P.V. – Cauchy's principal value of the integral

The D-term related to the proton internal force. Neglecting gluon contribution at LO:

$$C_{\mathcal{H}}(t) = 2\sum_q e_q^2 \int_{-1}^{1} dz \frac{D_{\mathrm{term}}^q(z,t)}{1-z}$$

$$D_{\mathrm{term}}^q(z,t) = (1-z^2) \sum_{odd\ n} d_n^q(t) C_n^{\frac{3}{2}}(z)$$

q- quark flavor, $z = x/\xi$, $C_n^{\alpha}(z)$- Gegenbauer polynomials

In the limit of renormalization scale $\mu \to \infty$ only $d_1^q(t)$ contributes:

$$D_q(t) = \frac{4}{5} d_1^q(t) = \int_{-1}^{1} dz\, z\; D_{\mathrm{term}}^q(z,t)$$

Neglecting strange and heavy quark contribution

$$d_1^u \approx d_1^d \approx d_1^{u+d}/2$$

$$C_{\mathcal{H}}(t) \approx \frac{10}{9} d_1^{u+d}(t) = \frac{25}{18} D_{u+d}(t)$$

Gravitational Form Factor (GFF) describing mechanical properties of the proton

Analysis based on unconstrained ANN techniques (Eur. Phys. J. C 81 (2021), 300) report Subtraction term compatible with 0 within large uncertainties.

By utilizing this DR, along with other phenomenological assumptions, we can extract CFFs and GFFs from experimental data.

DVCS CFF fitting strategy: Artificial Neural Networks (ANNs)

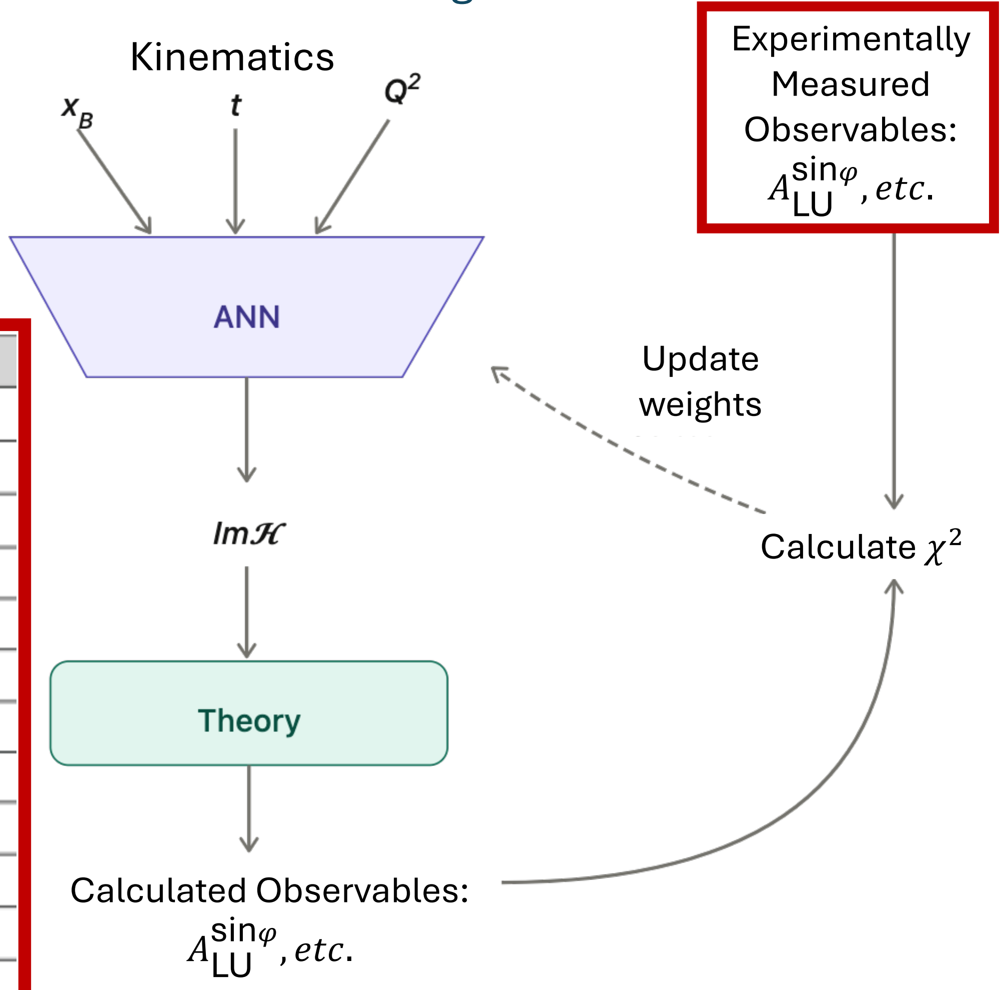
Use ANNs to describe CFF functional form model independent way.
Fit data for existing DVCS experimental observable measurements.
Use custom loss function in NN training:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i^{theory} - O_i^{exp})^2}{(\sigma_i^{exp})^2}$$

O_i-denoting observables calculated from theory and measured from experiment
σ_i^{exp}-uncertainty from experimental measurement
n-total number of kinematic points for observable measurements

Collab	Year	Observable	$E_{Beam}[GeV]$	x_B	$Q^2[GeV^2]$	$\|t\|[GeV^2]$
CLAS	2001	$A_{LU}^{sin(\phi)}$	4.25	0.19	1.25	0.19
CLAS	2006	$A_{UL}^{sin(\phi)}$	5.7	0.2-0.4	1.82	0.15-0.44
CLAS	2007	A_{LU}	5.77	0.13-0.35	1.1-3	0.1-0.3
CLAS	2009	A_{LU}	4.8	0.12-0.48	1.0-2.8	0.09-1.8
CLAS	2015	$A_{LU}(\phi), A_{UL}(\phi), A_{LL}(\phi)$	5.93	0.18-0.4	1.6-3.2	0.1-0.45
CLAS	2015	$\sigma(\phi), \Delta\sigma(\phi)$	5.75	0.1-0.58	1-4.6	0.09-0.52
CLAS	2018	$\sigma(\phi)$	5.88	0.12-0.5	1.1-4	0.1-1.6
CLAS	2023	A_{LU}	10.2	0.09-0.45	1.3-6	0.1-2.2
CLAS	2023	A_{LU}	10.6	0.09-0.62	1.1-7.2	0.1-2.8
HERMES	2001	$A_{LU}^{sin(\phi)}$	27.6	0.11	2.6	0.27
HERMES	2006	$A_{C}^{cos(\phi)}$	27.6	0.08-0.12	2.0-3.7	0.03-0.42
HERMES	2008	$A_C, A_{UT,I}, A_{UT,DVCS}$	27.6	0.03-0.35	1-10	<0.7
HERMES	2009	$A_C, A_{LU,I}, A_{LU,DVCS}$	27.6	0.05-0.24	1.2-5.75	<0.7
HERMES	2010	A_{UL}, A_{LL}	27.6	0.03-0.35	1-10	<0.7
HERMES	2011	$A_{LT,I}, A_{LT,BH+DVCS}$	27.6	0.03-0.35	1-10	<0.7
HERMES	2012	$A_{LU,I}, A_{LU,DVCS}, A_C$	27.6	0.03-0.35	1-10	<0.7
HALL A	2015	$\sigma(\phi), \Delta\sigma(\phi)$	5.75	0.33-0.40	1.5-2.6	0.17-0.37

Training schematics



DVCS CFF fitting strategy: Theory calculation with PARTONS

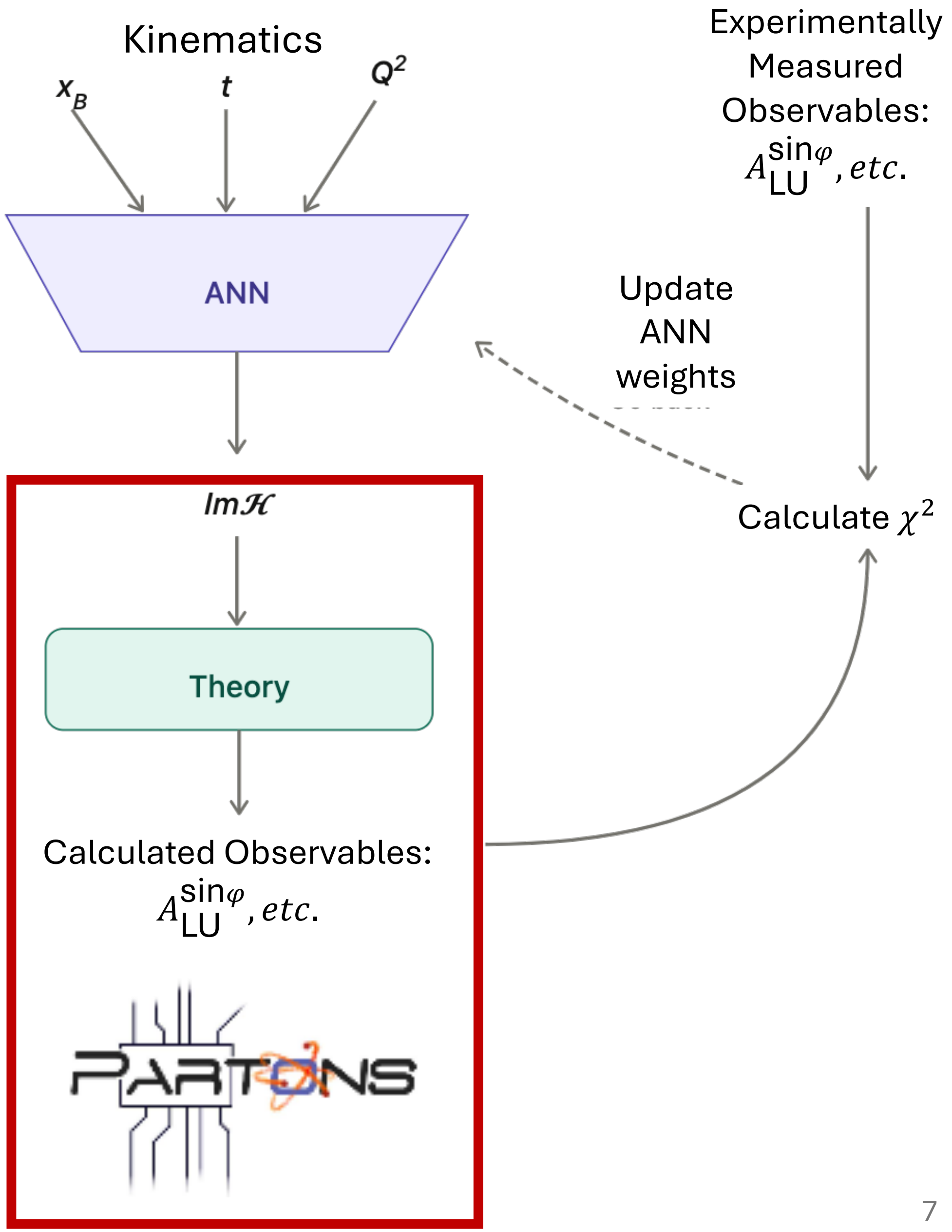
For ANN fitting of DVCS CFFs, we need to calculate observables from CFFs to estimate loss function at each step of training.
This is done using PARTONS: PARtonic Tomography Of Nucleon Software:

- official website https://3d-partons.github.io/partons/development.html
- C++ based package developed by a team of physicists primarily from CEA Saclay (France) and collaborating institutions.
- provides a necessary bridge between GPD models and experimental data
- many physics processes (DVCS, Double DVCS, timelike Compton scattering (TCS) and hard exclusive meson production (HEMP)).
- can be used via:
    - XML files
    - Writing standalone C++ program

Challenges:

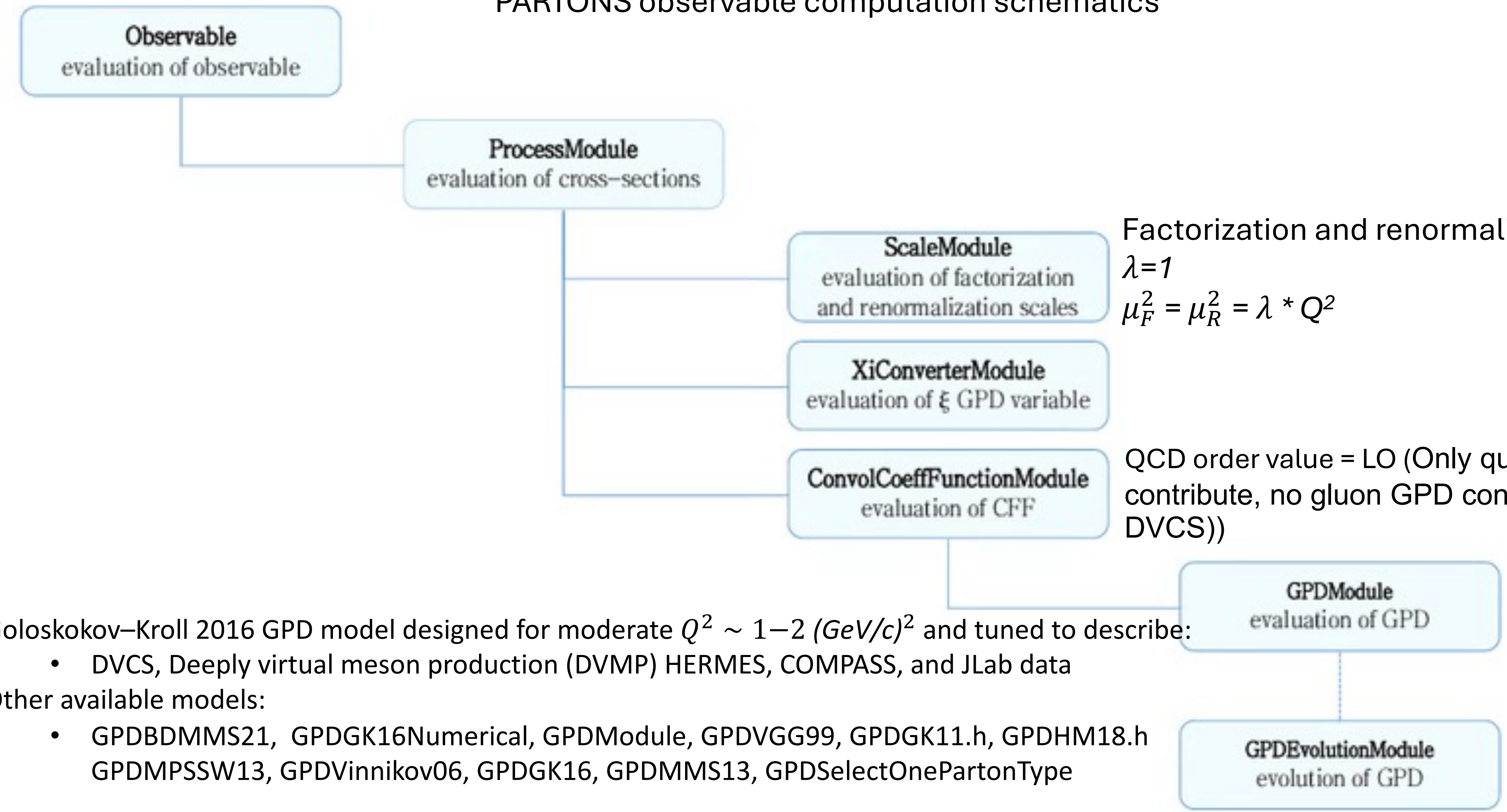
Need to implement ANN fitting in C++.

Training schematics



Observable calculation studies using PARTONS

PARTONS observable computation schematics



Factorization and renormalization scales
λ=1
$\mu_F^2 = \mu_R^2 = \lambda * Q^2$

QCD order value = LO (Only quark GPDs contribute, no gluon GPD contribution (in DVCS))

Goloskokov–Kroll 2016 GPD model designed for moderate $Q^2 \sim 1{-}2$ $(GeV/c)^2$ and tuned to describe:

- DVCS, Deeply virtual meson production (DVMP) HERMES, COMPASS, and JLab data

Other available models:

- GPDBDMMS21, GPDGK16Numerical, GPDModule, GPDVGG99, GPDGK11.h, GPDHM18.h GPDMPSSW13, GPDVinnikov06, GPDGK16, GPDMMS13, GPDSelectOnePartonType

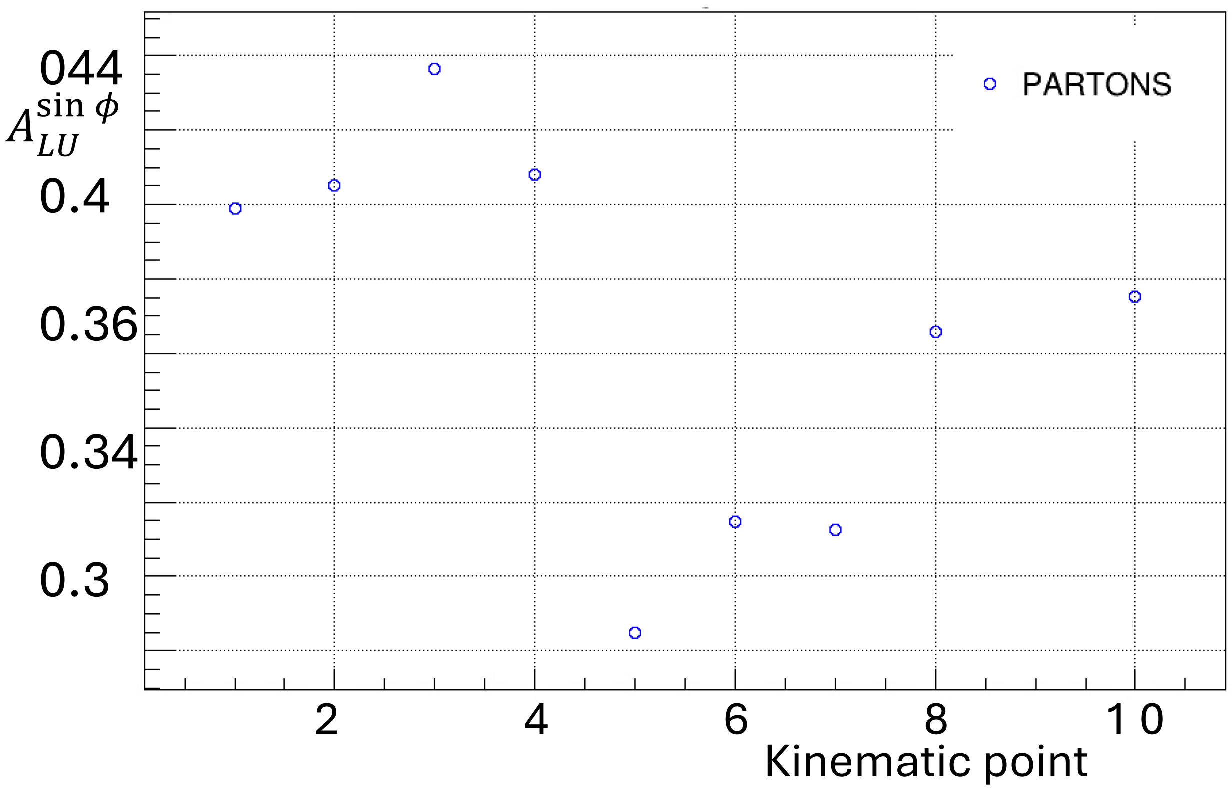
Calculation for $sin(\phi)$ first harmonic using Goloskokov–Kroll 2016 GPD model doesn't agree with data

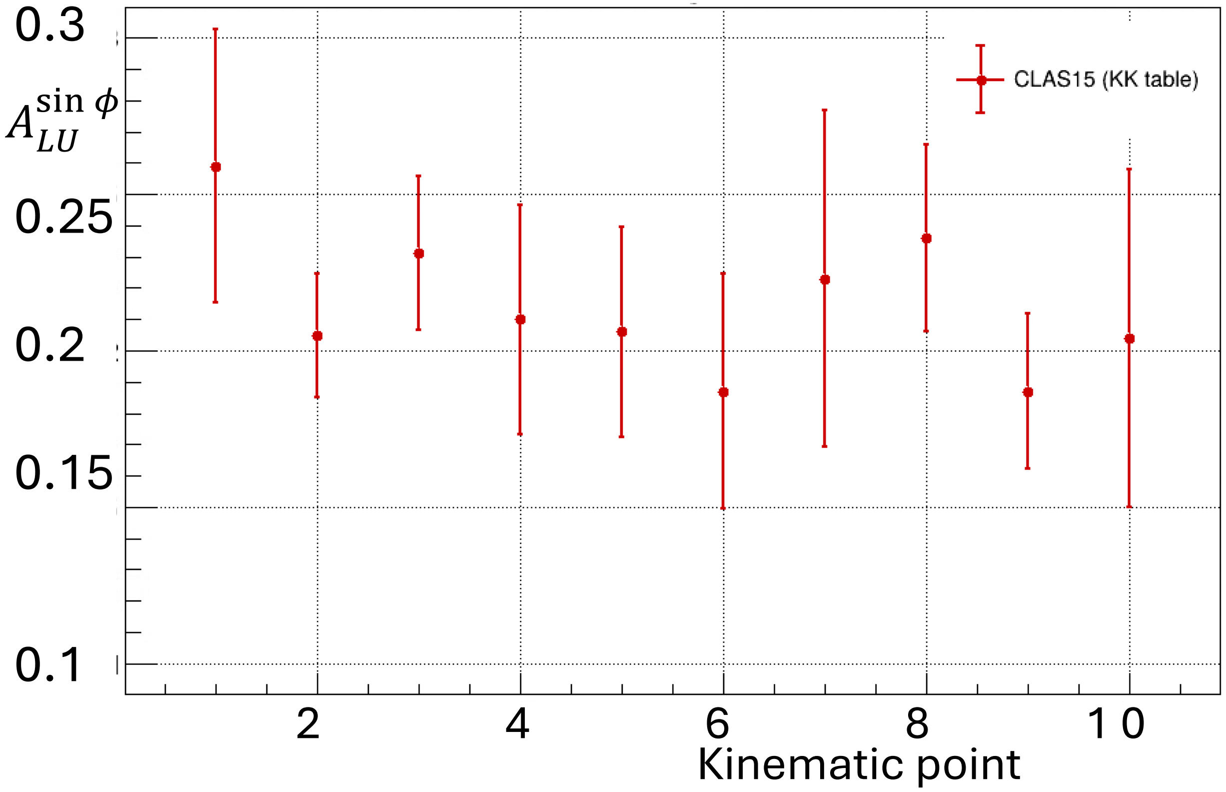
Important part of DVCS CFF ANN fitting is calculation of observables using PARTONS package.

As a first step calculate $A_{LU}^{\sin\phi}$ harmonic using PARTONS and compare to experimental values from DVCS measured with CLAS in 2015, at E_{beam}= 5.932 GeV (arXiv:1501.07052, harmonics fit by by Kresimir Kumerički) .

CLAS15 Data

#	Q^2	x_B	$-t$	$A_{LU}^{\sin\phi}$	stat	syst
1	1.554	0.181	0.129	0.259	0.042	0.012
2	1.979	0.247	0.136	0.205	0.017	0.010
3	2.048	0.259	0.228	0.231	0.022	0.011
4	1.943	0.258	0.457	0.210	0.030	0.021
5	2.362	0.255	0.138	0.206	0.027	0.020
6	2.448	0.265	0.229	0.187	0.031	0.021
7	2.458	0.265	0.443	0.223	0.038	0.038
8	2.670	0.337	0.240	0.236	0.026	0.015
9	2.665	0.350	0.456	0.187	0.021	0.013
10	3.314	0.442	0.507	0.204	0.041	0.035





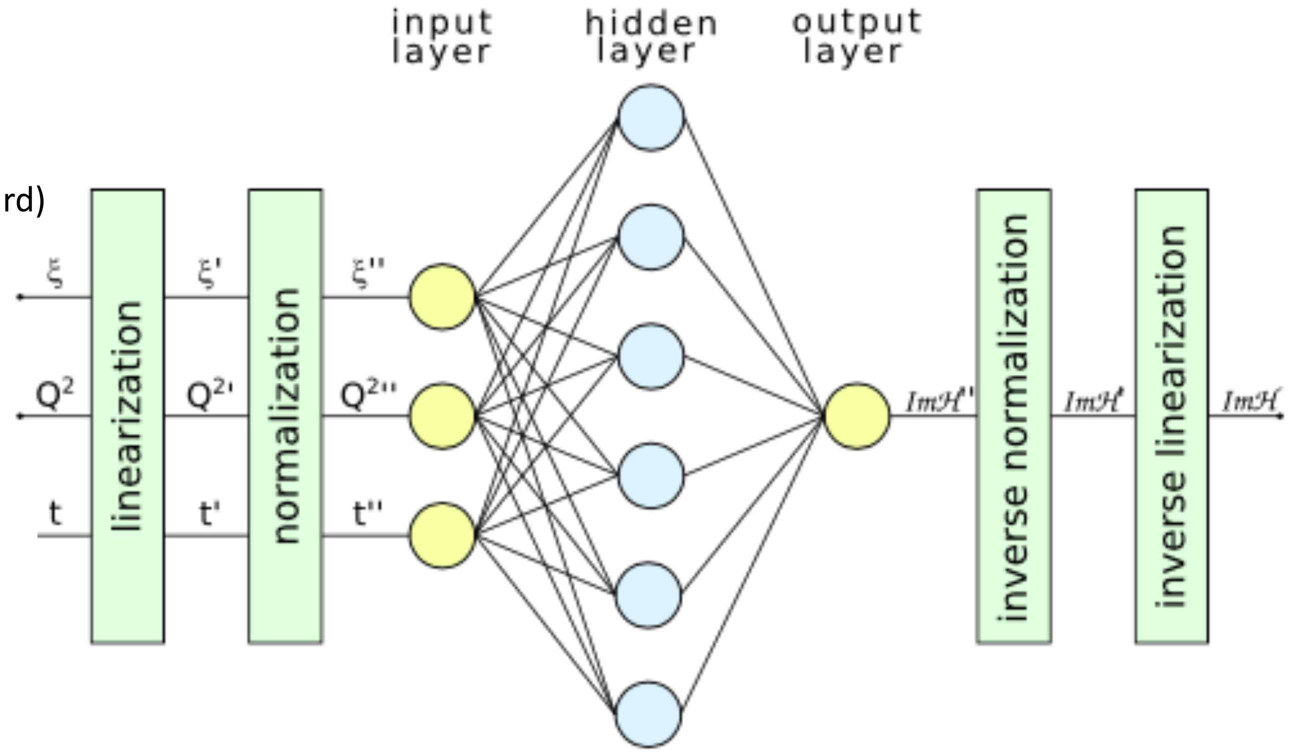
Observable calculations with Partons using ANN parametrization of DVCS CFFs by Moutarde, Sznajder & Wagner (EPJ C79 (2019) 614)

DVCS ANN fitting with PARTONS has been done previously and corresponding parametrizations were saved in PARTONS.

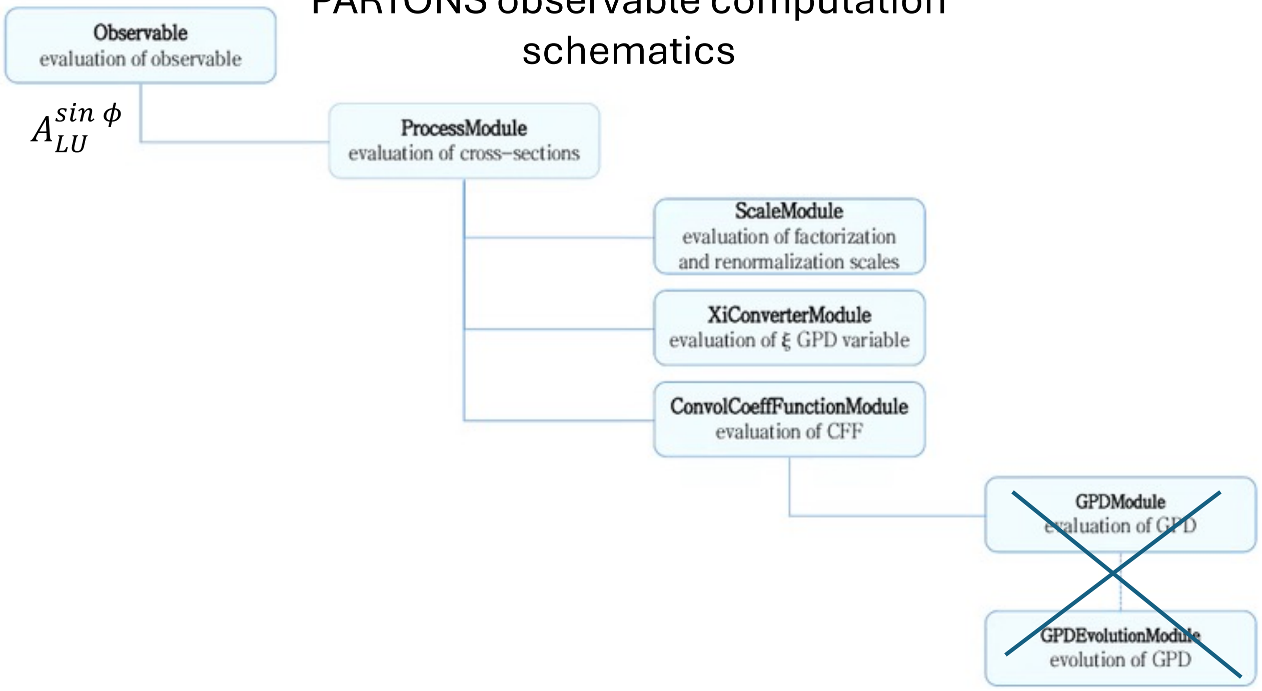
We have used this to calculate $A_{LU}^{\sin\phi}$ and compare with data.

Fitting details:

- Re$\mathcal{H}$, Im$\mathcal{H}$ treated independent (8 independent NNs))
- Training uses the genetic algorithm (backpropagation not straightforward)
- Regularization is done via early stopping
- Use replica Monte Carlo technique to propagate experimental uncertainties into the extracted CFFs:
  - ➢ One "central" fit + 100 replica fits = 101 total.



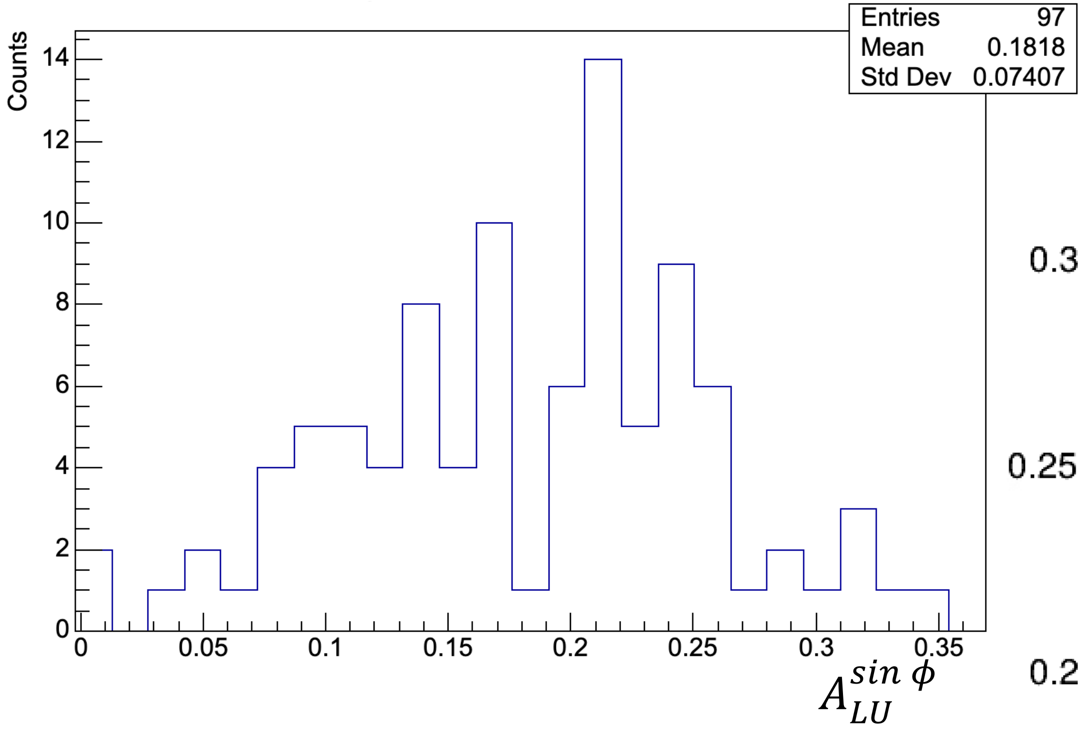
PARTONS observable computation schematics



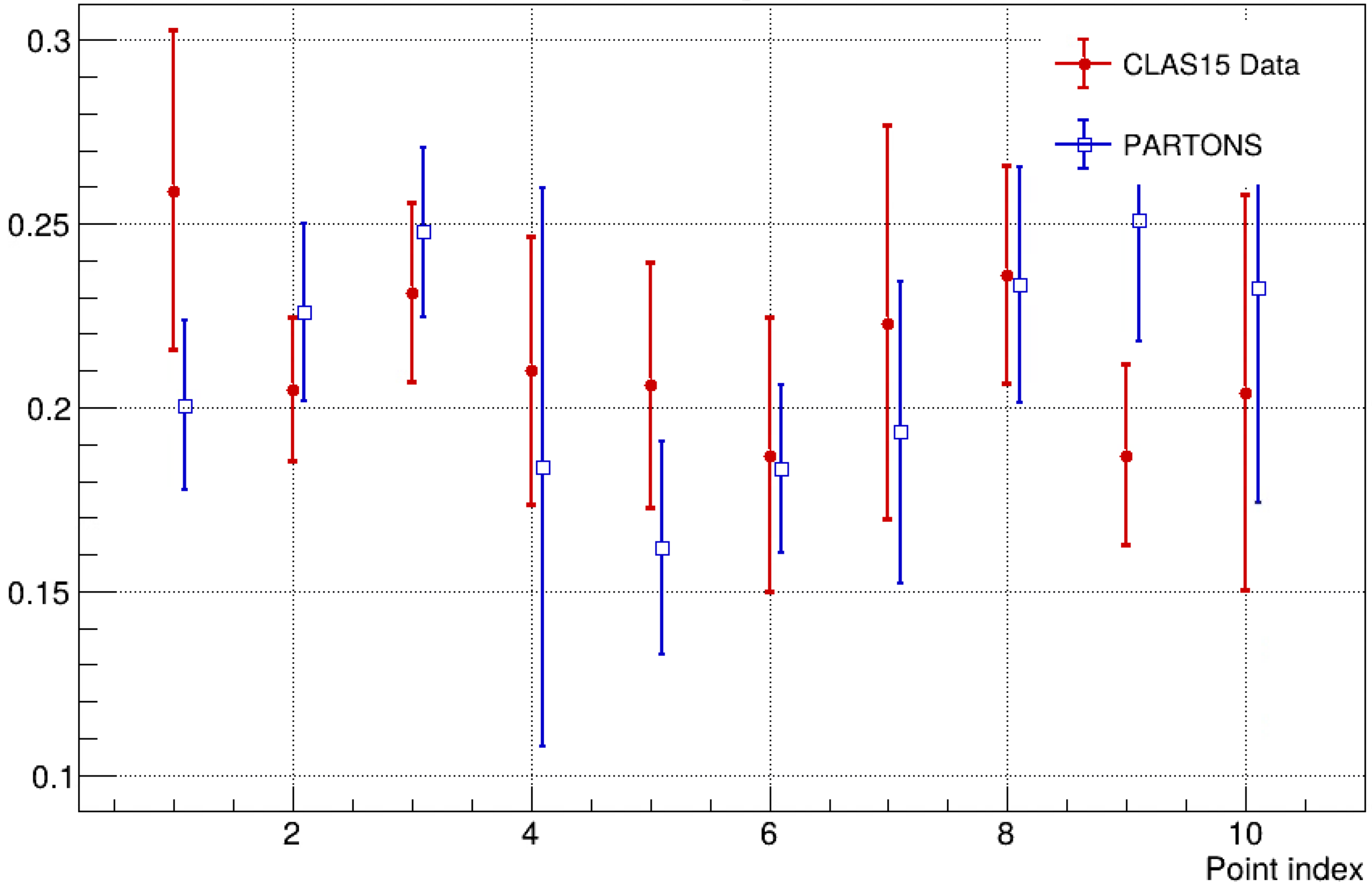
Instead of GPD → convolution → CFF
Neural Network → CFF

Calculation for $sin(\phi)$ first harmonic using ANNs from Partons

$A_{LU}^{sin\,\phi}$ for given kinematic point from 101 replicas



$A_{LU}^{sin\,\phi}$ for different kinematic points



Future work

- PARTONS package is powerful tool for DVCS and DDVCS studies.
- Implement DVCS CFF fitting using PARTONS
- Use CFF parametrization to estimate D-term and learn about mechanical properties of proton.

Acknowledgement

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