Application of novel computational techniques for the determination of the proton's gravitational form factors and mechanical properties: *A JLab LRDR project*

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19th of March 2024

Jefferson Lab

Outline

I **Motivations and scope of the project:**
Extraction of Gravitational Form Factors using Neural Networks,
from experimental data with constraints from LQCD

II **Current state of the project:**
Test of the Gepard framework and extraction of Form Factors using LQCD

III **Future directions**

Motivation and scope of the project:

Extraction of Gravitational Form Factors from experimental data using Neural Networks, with constraints from LQCD

Gravitational Form Factors (GFFs)...

Matrix element from the QCD Energy-Momentum Tensor

$$\langle p', s'|\hat{T}^a_{\mu\nu}(x)|p, s\rangle = \bar{u}'\left[A^a(t)\frac{P_\mu P_\nu}{m} + J^a(t)\frac{iP_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{2m} + D^a(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\bar{c}^a(t)g_{\mu\nu}\right]ue^{i(p'-p)x}$$

Properties of the proton

in unit of m_p

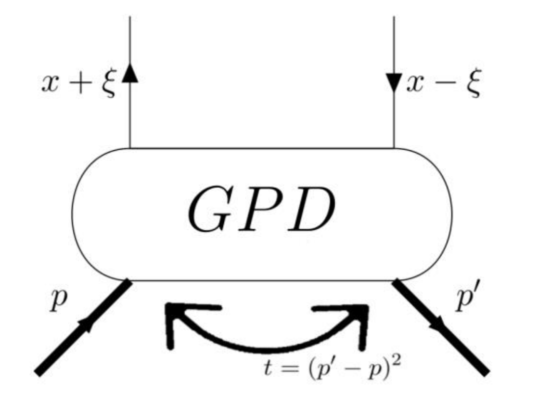
$$A(0) = \sum_a A^a(0) = 1 \qquad \bar{c}(t) = \sum_a \bar{c}^a(t) = 0 \qquad J(0) = \frac{1}{2}(A(0) + B(0)) = \frac{1}{2} \qquad D(0) = ? < 0$$

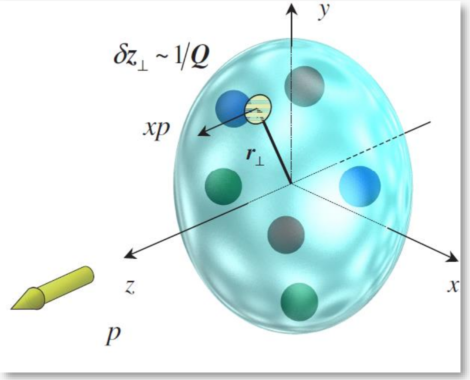
$$\langle r^2\rangle_{mech} = \frac{6D(0)}{\int_{-\infty}^0 dt D(t)} \qquad p(r) = \frac{1}{6M_N}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\tilde{D}(r) \qquad s(r) = \frac{1}{4M_N}r\frac{d}{dr}\frac{1}{r}\frac{d}{dr}\tilde{D}(r)$$

Full Review in Forces inside hadrons: pressure, surface tension, mechanical radius, and all that, Maxim V. Polyakov, Peter Schweitzer, Int.J.Mod.Phys. (2018)

… and their link to GPDs

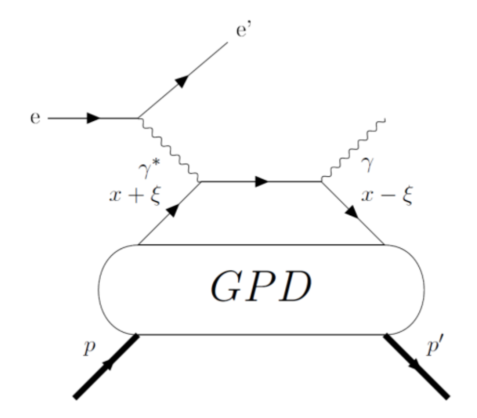
A "hand-wave" definition of GPDs:





Figures in A.V. Belitsky, A.V. Radyushkin, Unraveling hadron structure with generalized parton distributions, Physics Reports, Volume 418, Issues 1–6 2005

Deeply Virtual Compton Scattering



- DVCS amplitude depends on complex integral of GPDs, the Compton form factors:

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

- Accessing Gravitational Form Factors, which appear in the nucleon EMT matrix elements:

$$\int_{-1}^{1} dx\ xH^q(x,\xi,t) = A^q(t) + \xi^2 D^q(t) \qquad \int_{-1}^{1} dx\ xE^q(x,\xi,t) = B^q(t) - \xi^2 D^q(t)$$

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \mathrm{Im}\mathcal{H}(\xi,t) + \Delta(t) \qquad \Delta(t) \propto D(t) \propto \int d^3\mathbf{r}\ p(r) \frac{j_0(r\sqrt{-t})}{t}$$

DVCS beam charge asymmetry

- Understanding the spin composition of the nucleon (aka the "spin puzzle") using the Ji's sum rule:

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

Xiangdong Ji. Gauge-invariant decomposition of nucleon spin. Phys. Rev. Lett., 78:610613 (1997)

Existing tools

PARTONS

- C++ framework for the phenomenology of the 3D structure of the nucleon (TMDs & GPDs)
- Partons Website
- B. Berthou et al., PARTONS: PARtonic Tomography Of Nucleon Software: A computing platform for the phenomenology of Generalized Parton Distributions, Eur. Phys. J. C78 (2018), 478

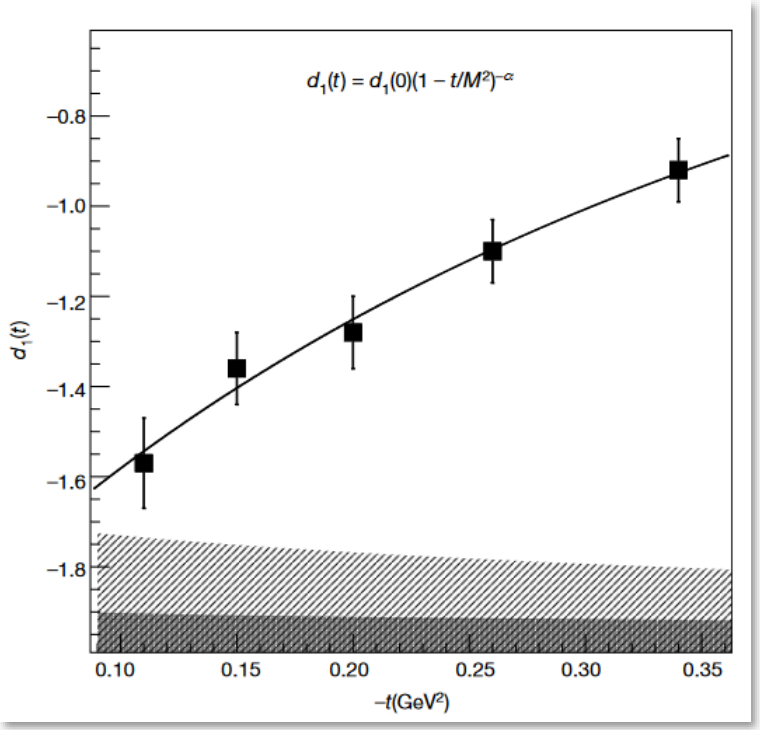
Gepard

- Python framework for the study of GPDs
- Gepard Website
- K. Kumerički, D. Müller, K. Passek-Kumerički, Towards a fitting procedure for deeply virtual Compton scattering at next-to-leading order and beyond, Nuclear Physics B, Volume 794, Issues 1–2, 2008

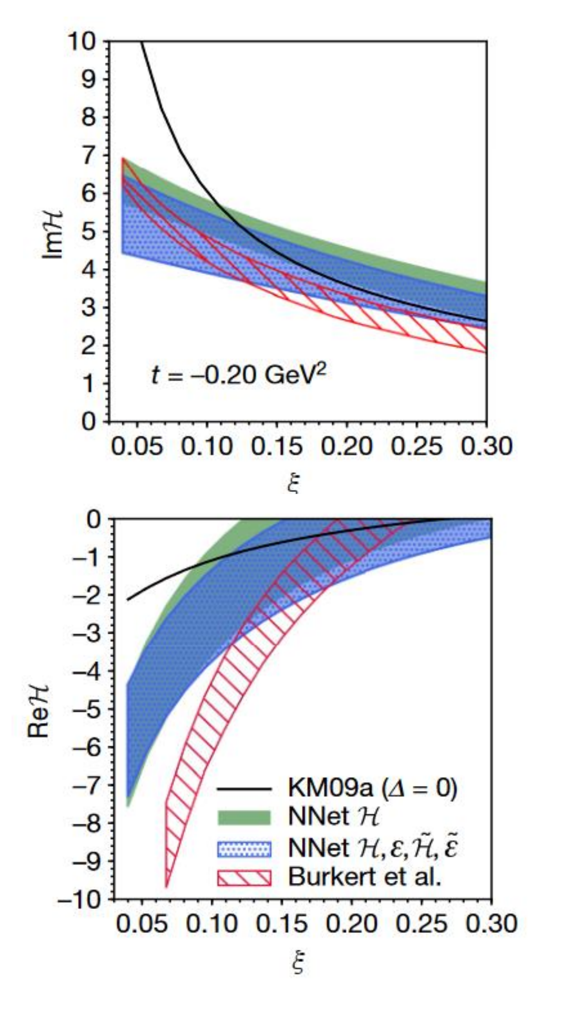
Limitations

- No dedicated methods to fit all GFFs
- Ad-hoc or outdated ML libraries

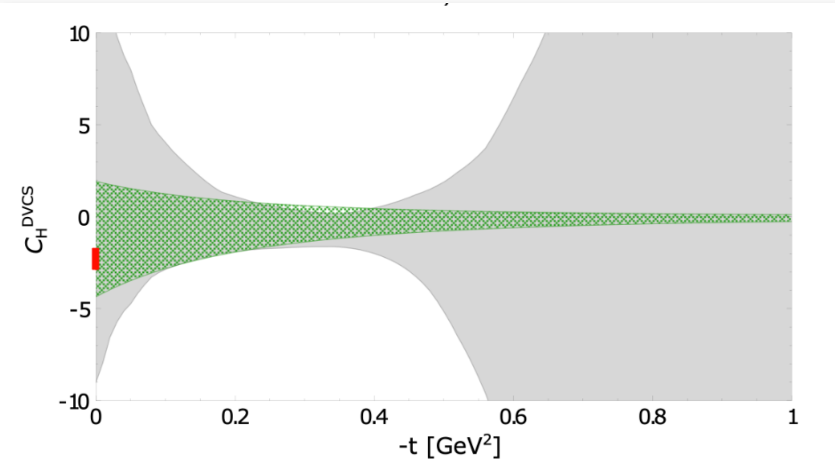
Previous works and results



Burkert, V.D., Elouadrhiri, L. & Girod, F.X. The pressure distribution inside the proton. *Nature* **557**, 396–399 (2018)



Kumerički, K. Measurability of pressure inside the proton. *Nature* **570**, E1–E2 (2019)



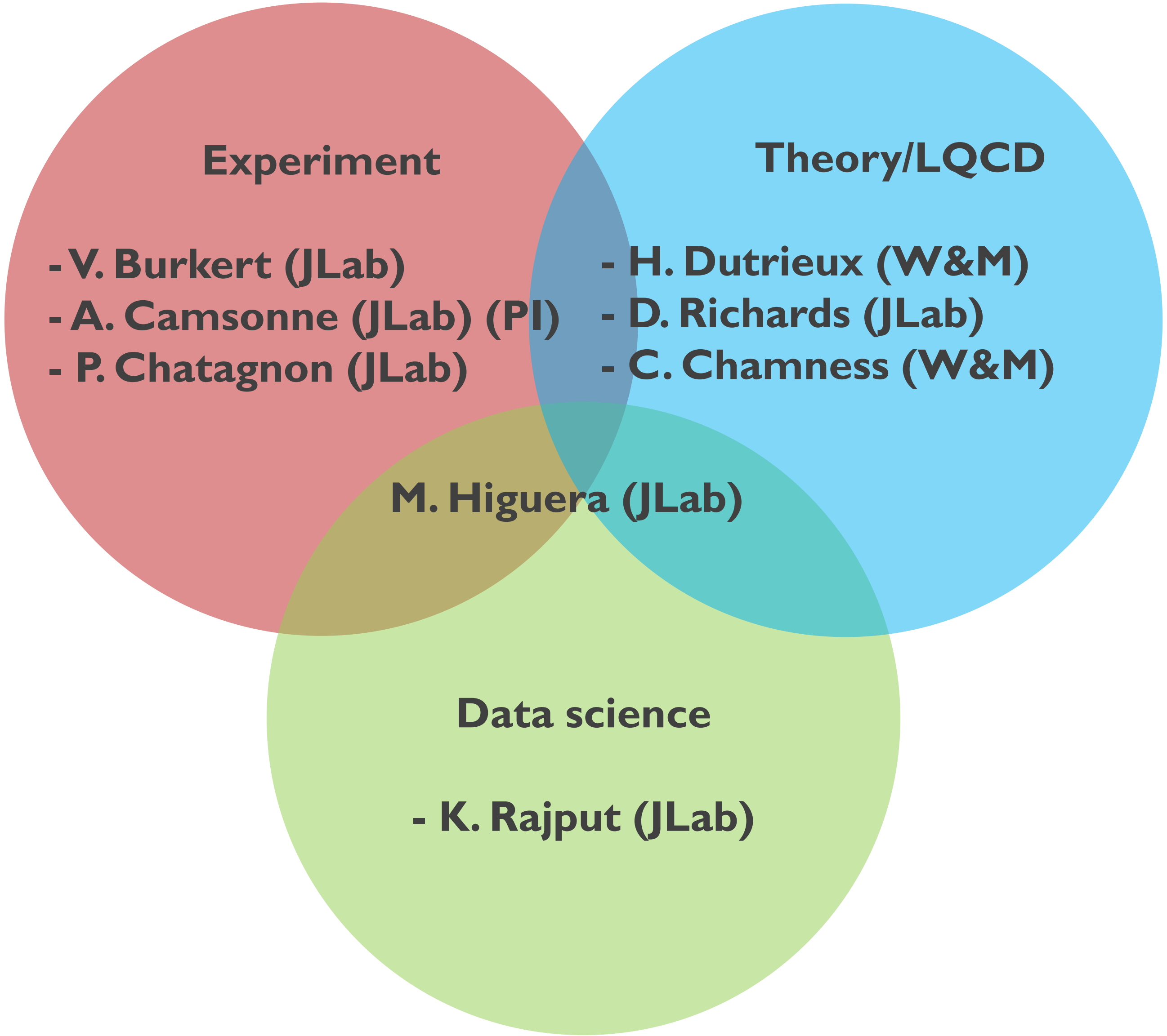
H. Dutrieux et al. Phenomenological assessment of proton mechanical properties from deeply virtual compton scattering. The European Physical Journal C, 81(4):300, Apr 2021

Deliverables

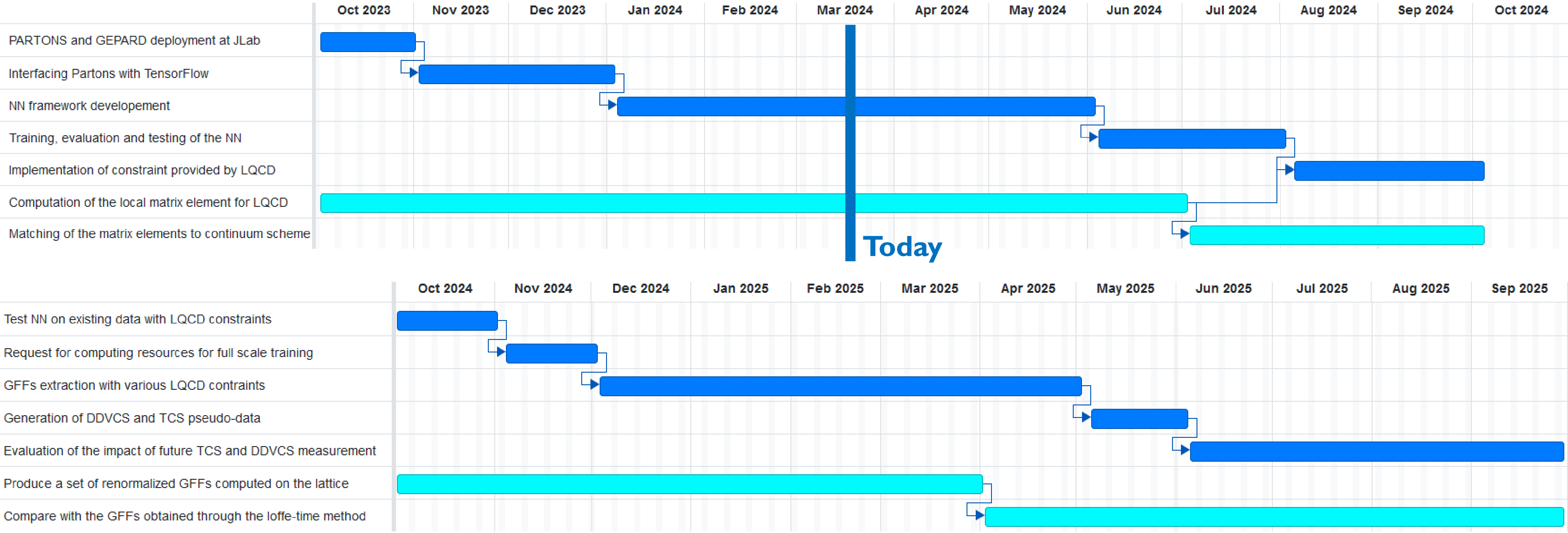
- A tools to fit all existing data using Neural Networks to extract GFFs
- Easy to use and interface with previous tools → python™
- Use State-of-the-art standard ML libraries → PyTorch
- Able to handle both experimental and LQCD data
- Able to test the impact of future experiments

Impact of the positron DVCS program

Personnel


Experiment
- V. Burkert (JLab)
- A. Camsonne (JLab) (PI)
- P. Chatagnon (JLab)
Theory/LQCD
- H. Dutrieux (W&M)
- D. Richards (JLab)
- C. Chamness (W&M)
M. Higuera (JLab)
Data science
- K. Rajput (JLab)

Timeline


Oct 2023
Nov 2023
Dec 2023
Jan 2024
Feb 2024
Mar 2024
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
Oct 2024
PARTONS and GEPARD deployment at JLab
Interfacing Partons with TensorFlow
NN framework developement
Training, evaluation and testing of the NN
Implementation of constraint provided by LQCD
Computation of the local matrix element for LQCD
Matching of the matrix elements to continuum scheme
Today
Oct 2024
Nov 2024
Dec 2024
Jan 2025
Feb 2025
Mar 2025
Apr 2025
May 2025
Jun 2025
Jul 2025
Aug 2025
Sep 2025
Test NN on existing data with LQCD constraints
Request for computing resources for full scale training
GFFs extraction with various LQCD contraints
Generation of DDVCS and TCS pseudo-data
Evaluation of the impact of future TCS and DDVCS measurement
Produce a set of renormalized GFFs computed on the lattice
Compare with the GFFs obtained through the Ioffe-time method

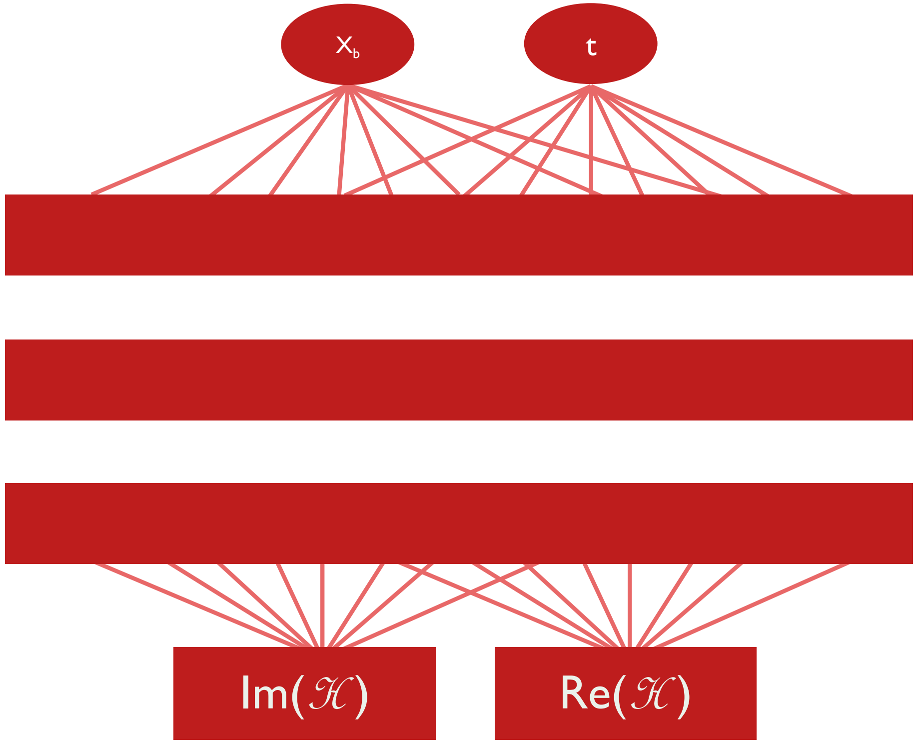
Current state of the project:

Test of the Gepard framework and extraction of Form Factors using LQCD

Fitting DVCS data using a Neural Network

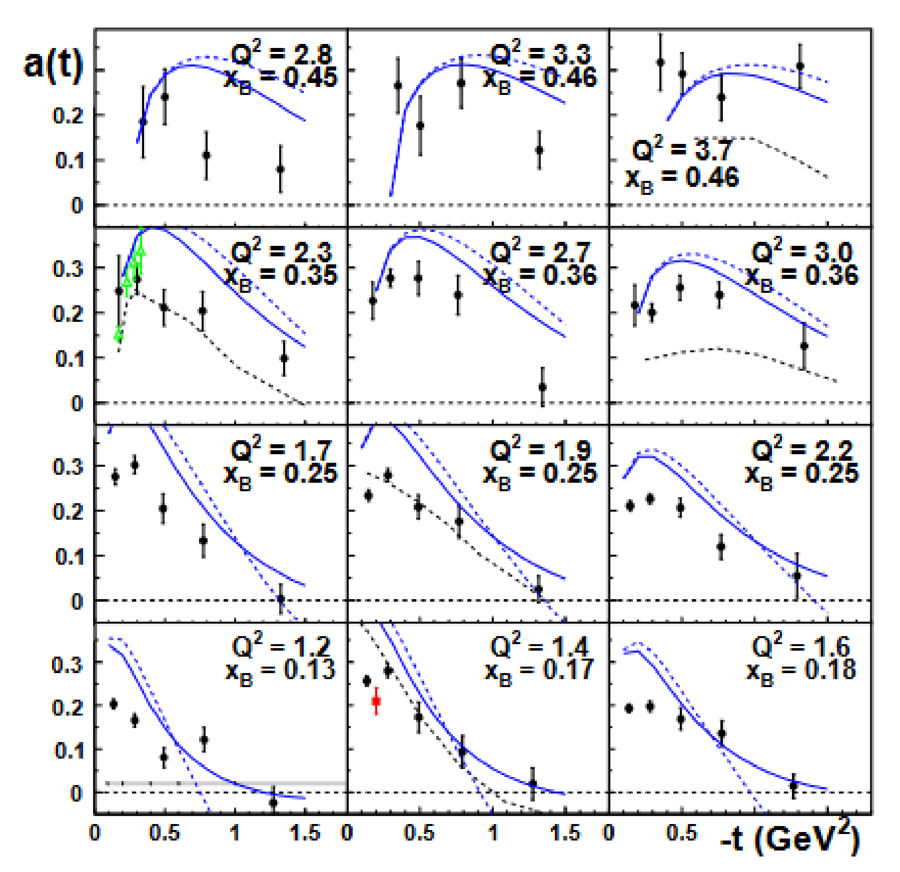
Test of the Gepard framework

- All results shown here are obtained based on the Gepard code available here
- Goal: test if one can reproduce *Kumerički, K. Measurability of pressure inside the proton. Nature **570**, E1–E2 (2019)* results to build upon it
- **Approach**:
  - Fit CLAS results with a neural network and extract Compton Form Factors
  - Pytorch is used to build and train the Neural Network
  - No constraints on the NN (in particular no dispersion relation)



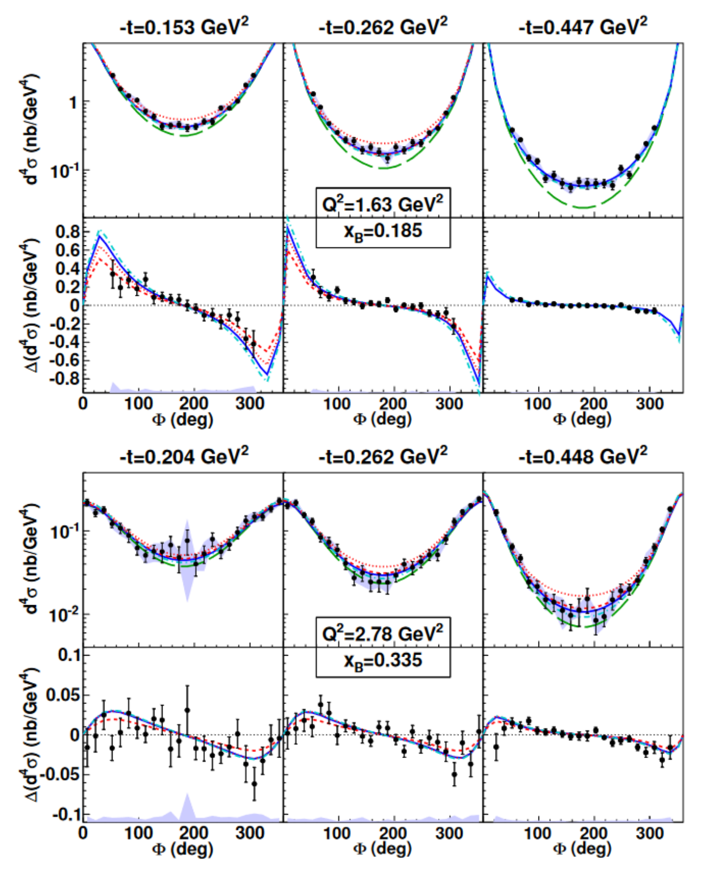
Data sets used for the fit

DVCS beam spin asymmetries measured by the CLAS experiment



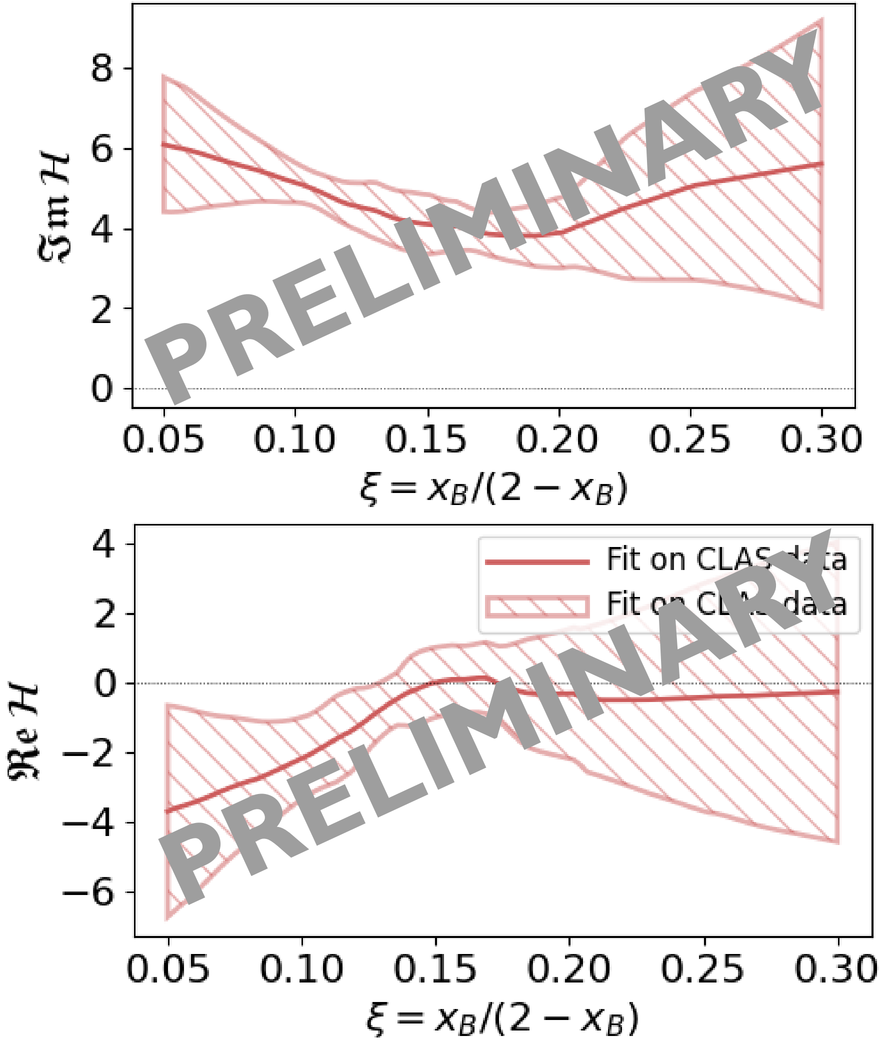
Measurement of Deeply Virtual Compton Scattering Beam-Spin Asymmetries
F. X. Girod *et al.* (CLAS Collaboration)
Phys. Rev. Lett. 100, 162002, 2008

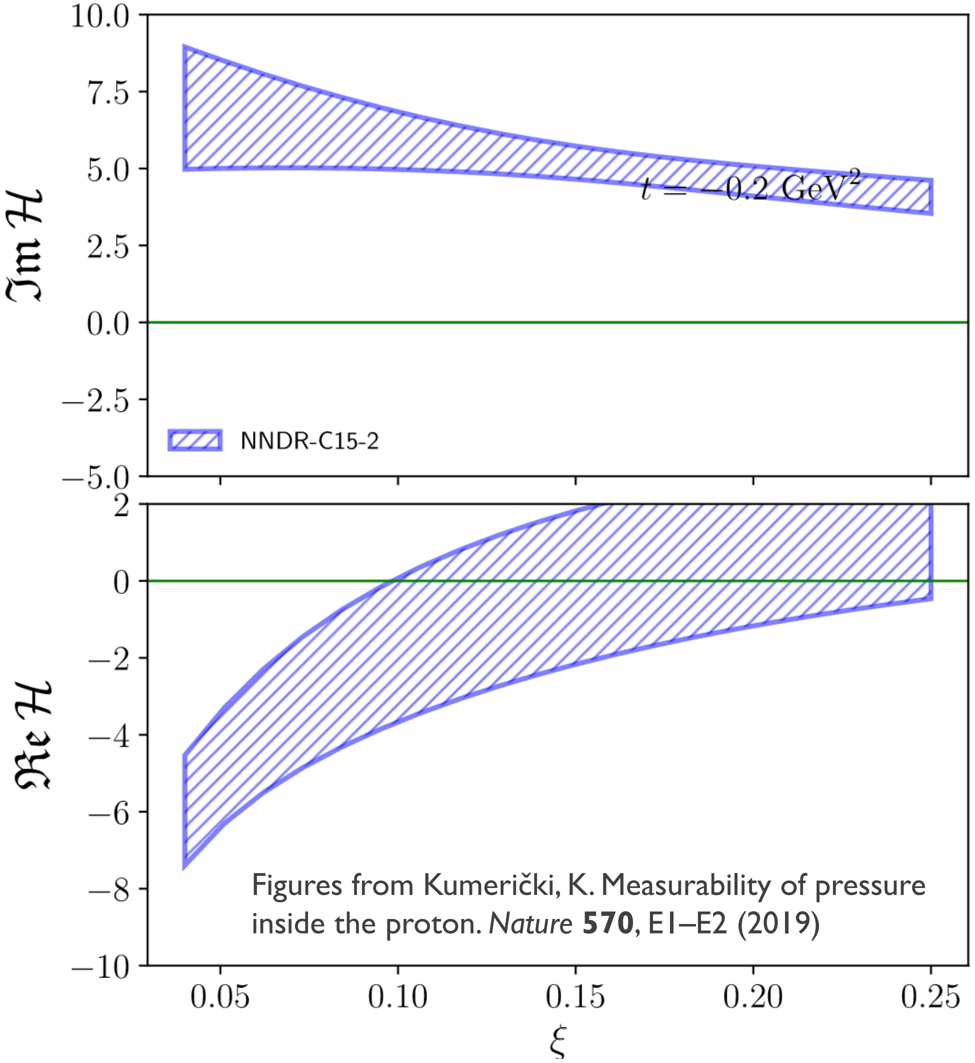
DVCS (un)polarized cross-section measured by the CLAS experiment



Cross Sections for the Exclusive Photon Electroproduction on the Proton and Generalized Parton Distributions, H. S. Jo *et al.* (CLAS Collaboration) Phys. Rev. Lett. 115, 212003, 2015

Results of the fit





Figures from Kumerički, K. Measurability of pressure inside the proton. *Nature* **570**, E1–E2 (2019)

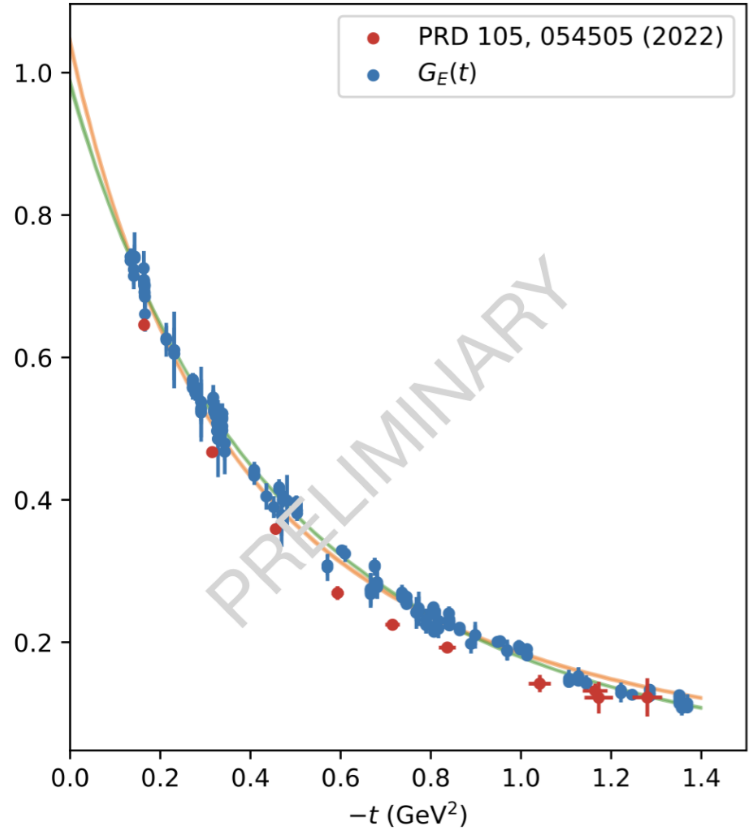
→ Qualitative good agreement, proof of concept to build upon

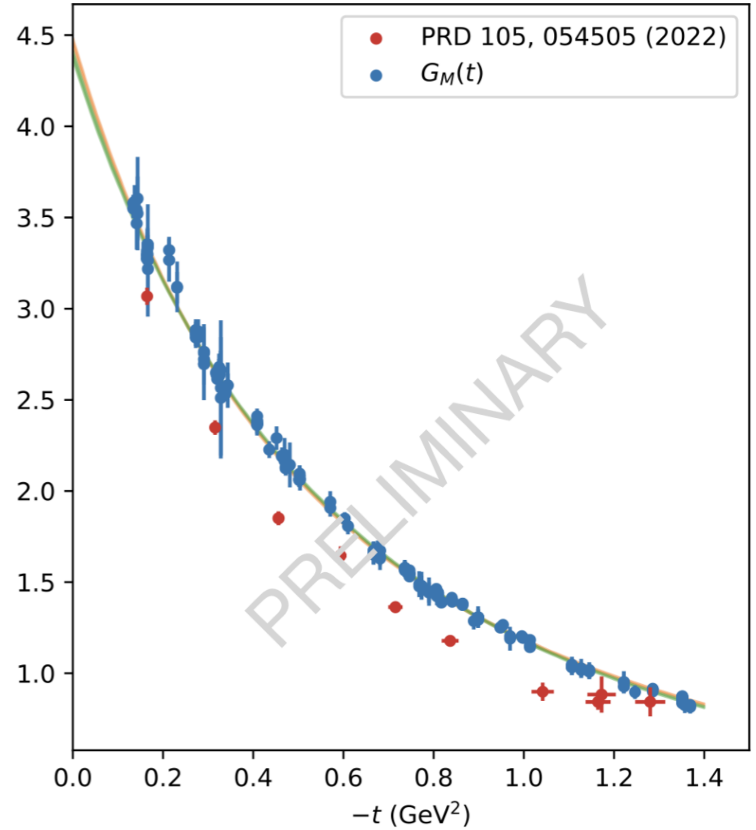
Input from LQCD

Material from H. Dutrieux – HadStruc Collaboration

- Extraction of EM FFs using the LQCD dataset which will be used for this work

$$\int_{-1}^{1} dx\, H^q(x,\xi,t,\mu^2) = F_1^q(t) \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t,\mu^2) = F_2^q(t)$$



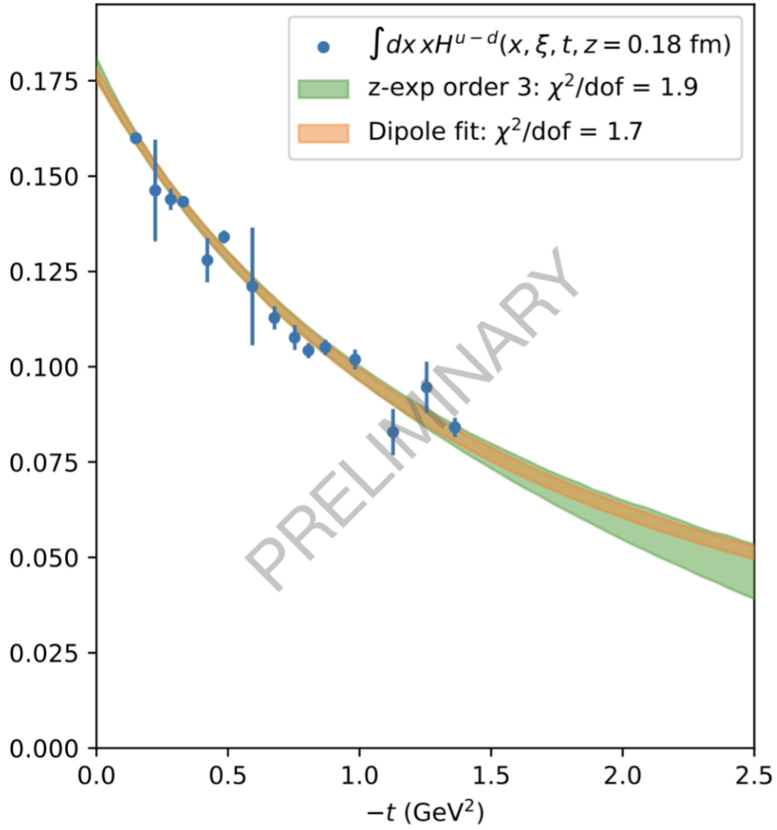


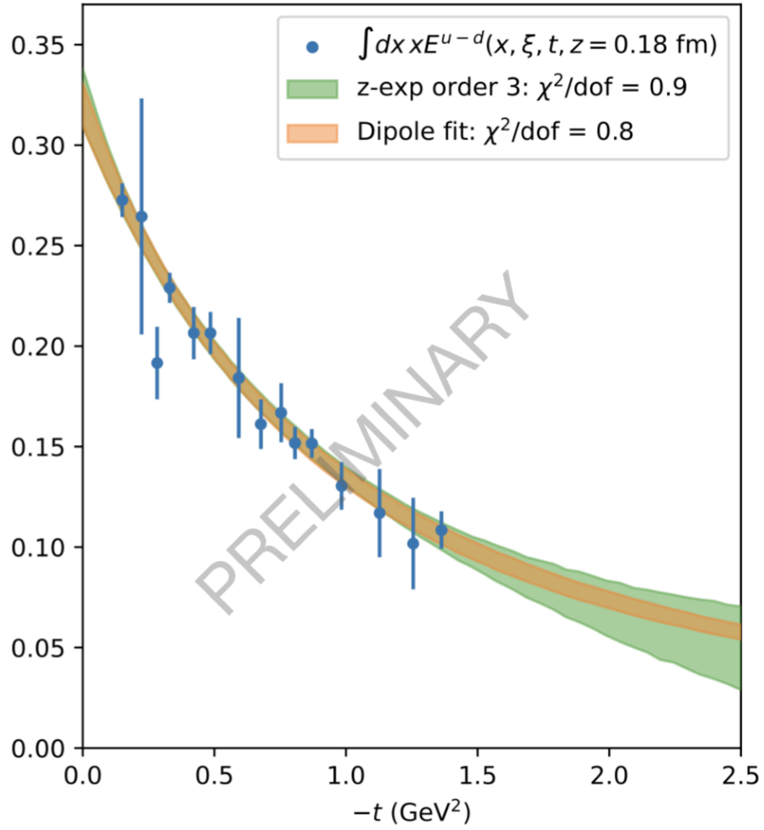
Input from LQCD

Material from H. Dutrieux – HadStruc Collaboration

- Using the same dataset, one can extract the integral of H
- So far only the "u-d" is extracted
- The obtained fit could be used as a constraint for the neural network

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





Future directions

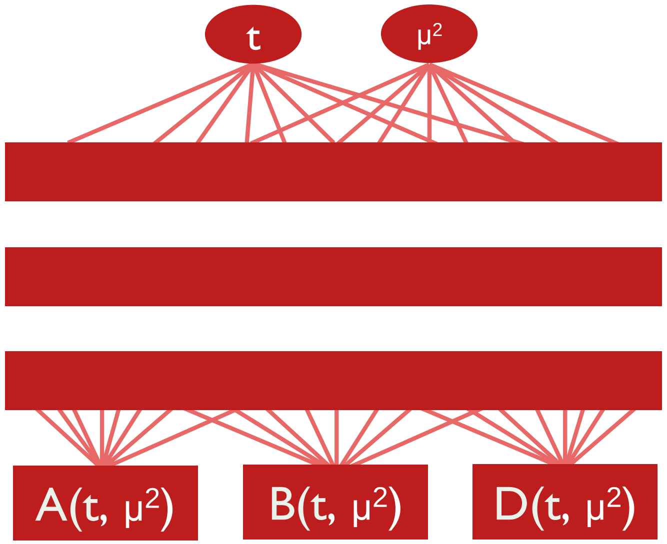
Next steps of the LDRD project

Lattice QCD computation of the GFFs

- Extract full GFFs A, B, D
- Provide parametrization for the NN approach (see below)

Fitting framework

- Implement NN architecture to extract GFFs
  - Adapt NN architecture
  - Test architecture dependence on extracted results
- Understand physical constraints (from LQCD, from EM FFs, from dispersion relation) and implement them (in the network architecture, in the loss function)



GPD database

- The goal is to fit all existing and future GPDs data.
- There is no unified common database storing these data (Partons and Gepard use ad-hoc DB).
- We have started implementing a DB format able to store both experimental data and LQCD data.
  - Involves many people across experiment and LQCD
- Based on JSON and planned to be hosted on Github.

Take-aways

I Gravitational Form Factors, which describe mass and force distributions in the nucleon, are now at the center of the attention.

II We are aiming at developing a versatile tool to extract these quantities. It will be based on Neural Networks and able to handle both experimental data points and input from LQCD.

III We are building upon existing tools, aiming to use state-of-the-art widely available libraries.

V **We aim at providing a tool to test the impact of new data on the extraction of GFFs.**

DVCS observable with positrons