**Template JRA**

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| **Work package number** | WP23 | **Start date** | 01/06/2019 |
| **Activity Type** | Joint Research Activity | | |
| **Work package acronym** | JRA5-GPD-ACT | | |
| **Work package title** | Generalized Parton Distributions | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

The concept of Generalized Parton Distributions (GPDs) allows to study the structure of nucleons in terms of quarks and gluons (partons) at a previously unexpected level. GPDs give information, for instance, on the correlation between the transverse spatial distributions and longitudinal momentum distributions of the partons, thus providing a three-dimensional mapping of the nucleon. They are related also to the orbital angular momentum contribution of partons to the nucleon's spin.

It is the objective of this WP to access GPDs experimentally through hard exclusive reactions such as the lepto-production of a photon (“Deep Virtual Compton Scattering”, DVCS) or of a meson (“Deep Virtual Meson Production”, DVMP) or in photo-production of a lepton pair (“Time-like Compton Scattering”, TCS). These exclusive reactions have been measured in certain kinematical regions and one particular objective of this WP is the analysis of the numerous data already collected these past years at COMPASS and TJNAF and not published.

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2: Progress made during the reporting period towards objectives***

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| --- |
| ***Task 1: GPD experiments at TJNAF@12 GeV*** |
| A prototype of ALERT was constructed and tested in magnetic field during 2023.  The full detector was constructed and delivered to JLab in the spring 2024, for data taking to start in the second half of 2024.  CLAS12 measured DVCS beam spin asymmetry on unpolarized LH2 target in a kinematic regions never covered before. In the previously measured kinematics, the new data are shown to be in good agreement with existing data and they improve the precision of GPD fits. (Phys. Rev. Lett. 130, 211902 (2023)).  CLAS12 measured DVCS beam spin asymmetry on deuteron target and determined this asymmetry for DVCS on neutron. The extracted beam-spin asymmetries, combined with DVCS observables measured on the proton, allowed a clean quark-flavor separation of the imaginary parts of the Compton form factors H and E. (arXiv:[2406.15539](https://arxiv.org/abs/2406.15539), submitted to Phys. Rev. Lett.) |
| ***Task 2: Analysis of COMPASS data*** |
| COMPASS collaboration performed analysis of exclusive pi0 production data collected in 2016 in polarized muon - proton scattering, demonstrating good agreement with GK model predictions.  Exclusive pi0 production results are presented on several conferences and a publication is due soon.  Spin Density Matrix Elements in exclusive rho meson production have been published ([EPJC (2023) 83 924](https://wwwcompass-private.cern.ch/compass/publications/papers/locked/journal/2023_epjc83_924.pdf); [hep-ex/2211.00093](https://arxiv.org/abs/2211.00093)). |
| ***Task 3: Building models, analysis of processes and extraction from data*** |
| There is an advancement in the combining lattice QCD and phenomenological inputs on GPDs at moderate skewness (arXiv:[2306.01647](https://arxiv.org/abs/2306.01647), *Eur.Phys.J.C* 84 (2024) 2, 201).  It was shown how to relate exclusive measurements to PDFs small Bjorken xB based on evolution equations (arXiv:[2302.07861](https://arxiv.org/abs/2302.07861), *Phys.Rev.D* 107 (2023) 11, 114019).  The operator definition of generalised transverse-momentum-dependent (GTMD) distribu-  tions is exploited to compute for the first time the full set of one-loop corrections to the  off-forward matching functions. (arXiv: [2207.09526](https://arxiv.org/abs/2207.09526), *Eur.Phys.J.C* 82 (2022) 10, 941),  and evolution equations for GPDs were recalculated (arXiv:[2206.01412](https://arxiv.org/abs/2206.01412), *Eur.Phys.J.C* 82 (2022) 10, 888) and implemented in the code. This was done in collaboration with VA2-3DPartons virtual access workpackage of H2020-STRONG.  Other exclusive processes were studied and found to be good candidates for GPD extraction.  (arXiv:[2212.00655](https://arxiv.org/abs/2212.00655), JHEP 03 (2003) 241.  NLO DVMP and multichannel ﬁts (in combination with DIS and DVCS) were performed  and the importance of inlusion of NLO corrections to DVMP amplitude was shown  (arXiv:[2310.13837](https://arxiv.org/abs/2310.13837), JHEP 12 (2023) 192, JHEP 02 (2024) 225 (erratum)).  Twist-3 contributions to the DVMP of pions are determined and favorable comparison to Jlab  and COMPASS measurements was demonstrated (arXiv: [2312.13164](https://arxiv.org/abs/2312.13164), PRD 109, 034008 (2024))  Public analysis code Gepard released in previous reporting period is completed by a public server serving numerical results in graphical and numerical form (in collaboration with VA2-3DPartons virtual access workpackage). See Sect. 4.3 for details on this. |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

On the experimental side, higlights are construction of a low energy recoil tracker (ALERT) increasing precision of measurements of GPD-related and other processes at JLab and publications of results on DVCS on proton (and soon neutron) in unprecedented kinematical span. (Phys. Rev. Lett. 130, 211902 (2023)).

On the theory side, it was demonstrated that exclusive photoproduction of photon-pion pair with large invariant mass can be used to access chiral-even quark GPDs (JHEP 03 (2003) 241.)

On the phenomenology side, Gepard code for GPD analysis has been completed with public server <https://gepard.phy.hr/> and used for first multichannel NLO fit of DIS, DVCS and DVMP data (JHEP 12 (2023) 192, JHEP 02 (2024) 225 (erratum))

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Delays or run-time reductions in the schedule of the TJNAF accelerator (medium)

Whether the risk has materialized? (Yes/No) Yes. There were indeed some unforeseen run-time reductions at JLab and only 50% of the proposed data were taken, for both proton and neutron targets.

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. Delays or cuts in the accelerator schedule would impact the TJNAF GPD program by reducing the statistics collected during the time frame of the WP, compared to the expected projections. However, reducing the number of kinematic bins can mitigate the issue, without affecting strongly the physics conclusions that can be drawn from the data. This is especially true for new measurements, such as TCS and nDVCS, for which basically no results exist as of today

Whether the risk-mitigation plan was applied? (Yes/No) Yes. Exactly as proposed, by limiting the bin size it was possible to still get meaningful and strong-impact results in spite of statistics being lower than hoped. The second half of the data will be taken in a couple of years.

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

The only deviation from the planned objectives and tasks is that one deliverable (D23.2) was only partially completed, as detailed in Section 4 of this report. There is some impact on the progress of the work package but one should note that (1) many measurements that should have been published as a part of this deliverable have already been presented at conferences so community can already assess the impact on the GPD physics, and (2) most of the other objectives of the workpackage were not directly dependent on this particular deliverable. Also, lack of these publications were compensated for by other unforeseen results achieved within this work package, ensuring that overall progress remained in line with the original expectations.

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

There has been no deviation between actual and planned person-months for the reporting period (both are zero)

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-2)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D23.2 | Publication of  COMPASS results | 24 - CEA | Report | PU | 54 | No | N/A | Comment in Sect. 4.3 below |
| D23.3 | Public software serving  GPD fit results | 26 - UNIZG | ORDP: Open  Research  Data Pilot | PU | 46 | Yes | 47 | Report in Sect. 4.3 below |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
| MS46 | Construction of ALERT, NPS,  and FT-hodoscope electronics | 1 - CNRS | 54 | Yes | 58 | Month 58 is for delivery of ALERT drift chamber. NPS and FT-hodoscope were delivered before that. |

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

**Deliverable D23.2 Publication of COMPASS results**

This deliverable was only partially realized. It was originally a very ambitious deliverable, promising "Publication of COMPASS results. Using the data taken in 2016-17 with a liquid hydrogen target, a recoil detector, and polarized mu+ and mu- beams: sum and difference of DVCS cross section, with study of the slope of dSigma\_DVCS/dt and of the D term; Pi, Rho, Omega, Phi, J/psi cross section and evolution in W, Q2 and t."

The main problem was that the DVCS analysis using the last data taken in 2016 was surprisingly not in agreement with a result obtained with test run data from 2012. The new result obtained using the data taken in 2016 is more precise and exhibits a difference of about 3 sigma with respect to the 2012 data. This then required a lot of extra work to recheck everything and with the help of several PhD students the analysis was further refined and the new result is now confirmed to be 2 sigma different from the 2012 results. For this latest results the cross check is still ongoing due to shortage of manpower. In the meantime a new group joined the analysis allowing COMPASS collaboration to proceed with the analysis of the complete set of data. A paper presenting the results is expected to be completed in the following months.

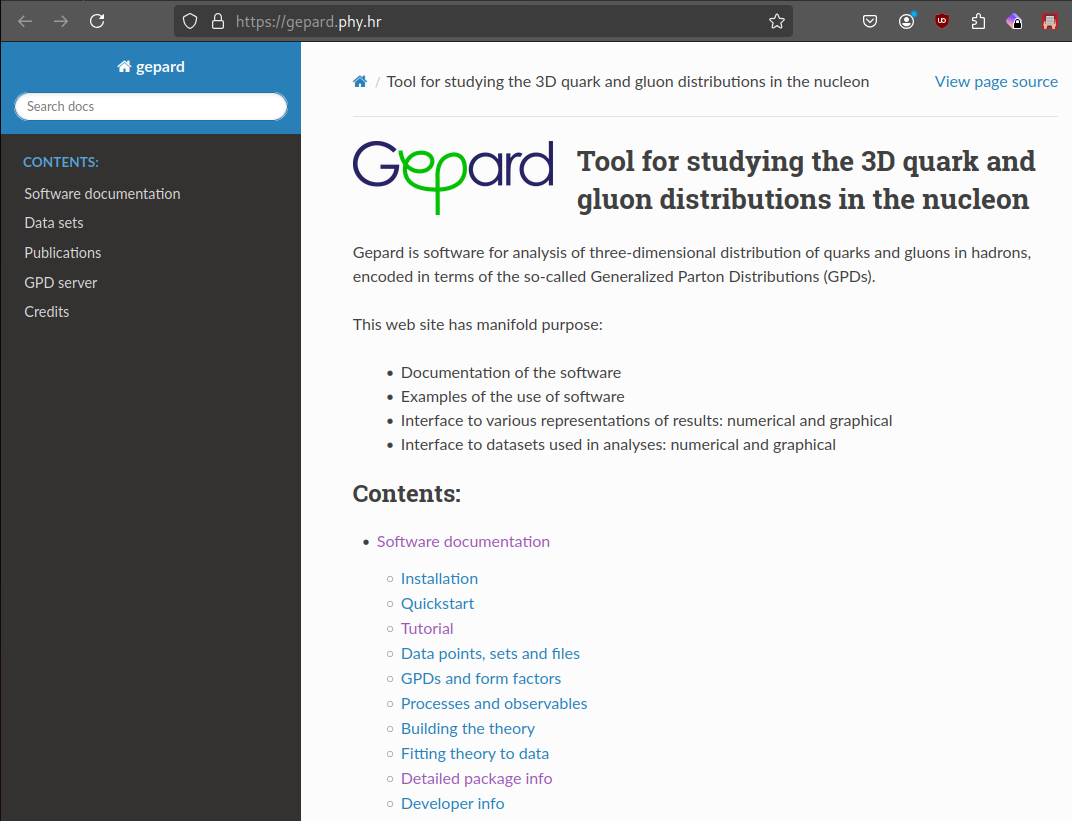
In the last two years collaboration found many improvements in the pi0 analysis, which are also applicable to the other channels. As a result parts of the analysis chains had to be redone. Presently the exclusive pi0 analysis data are released and publication is prepared, and the exclusive phi meson analysis is also in the final phase.

Spin Density Matrix Elements (SDME) for the exclusive rho0 production have been published ([EPJC (2023) 83 924](https://wwwcompass-private.cern.ch/compass/publications/papers/locked/journal/2023_epjc83_924.pdf); [hep-ex/2211.00093](https://arxiv.org/abs/2211.00093)) This result is by itself very important for the objectives of this workpackage, because SDME enable separation of transversal and longitudinal parts of the cross-section which are described by different GPDs.

Even if this deliverable is not yet formally delivered as promised, i.e. in terms of journal publications, results have been presented in many (10-15) international conferences and workshops, so community is well informed about these measurements and the resulting advancement in the understanding of GPD physics.

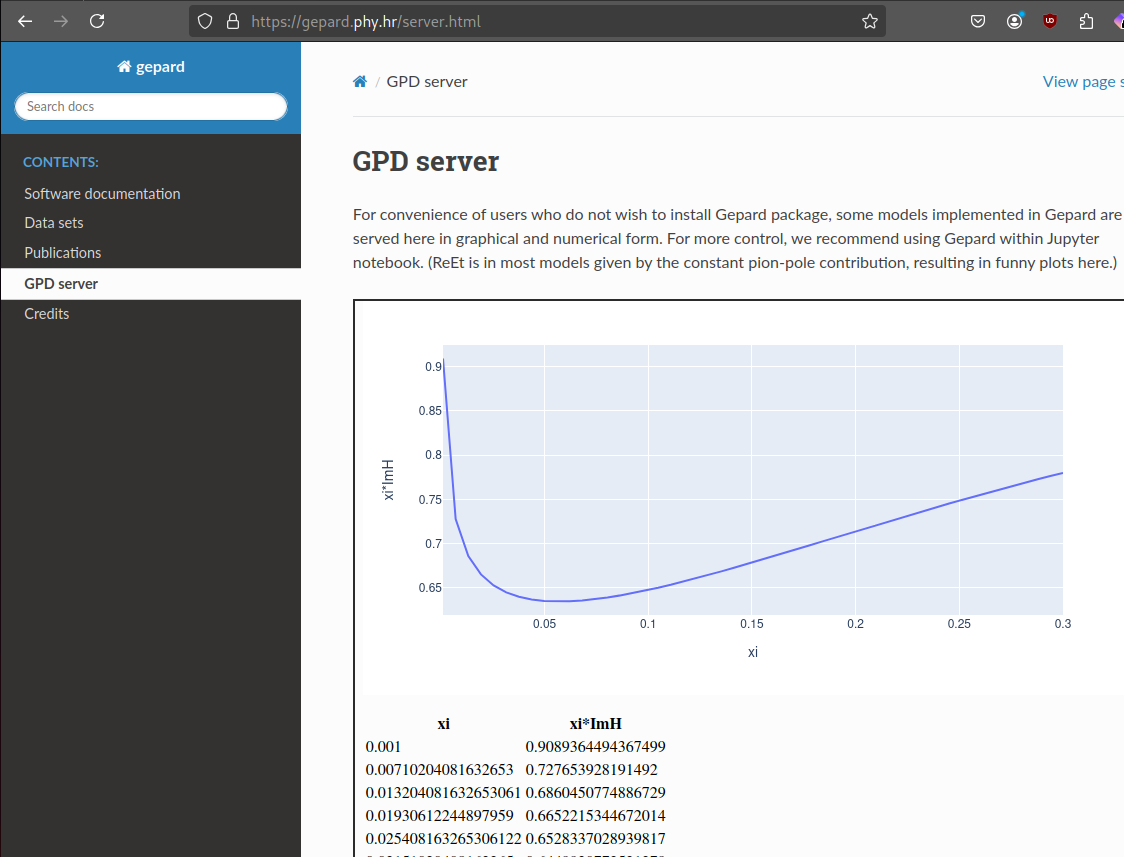
**Deliverable D23.3 Public software serving GPD fit results**

Gepard Python package, together with the related WWW site [gepard.phy.hr](https://gepard.phy.hr/), developed within the JRA5-GPD-ACT workpackage of STRONG-H2020 project, using also the framework provided by VA2-3DPartons virtual access workpackage, is providing the community the multi-purpose tool for studying the 3D quark-gluon structure of hadrons, as encoded in terms of Generalized Parton Distributions (GPDs).



Gepard [Python package](https://pypi.org/project/gepard/) is hosted on PyPI repository, and is directly installable on Linux, Windows, and MacOS platforms, while its source code is open and hosted on [github.com](https://github.com/kkumer/gepard). By installing the package user can easily build models of GPDs and DVCS and DVMP form factors, calculate related observables (light vector meson DVMP cross-sections, DVCS cross-sections and asymmetries) and compare to the available experimental measurements graphically and by using standard statistical tools (MINUIT fitting). Development version (available via github) provides also the possibility of extraction of structure functions usin PyTorch neural network library. Many experimental measurements by HERA and JLab collaborations are also provided, as well as models known to be in good agreement with this data (GK, KM), so Gepard can be used to make predictions and impact of future experiments.

WWW site gepard.phy.hr is hosting simple usage tutorials, detailed Gepard package information, and developer information. A [GPD server](https://gepard.phy.hr/server.html), serving the Compton Form Factors in graphical and numerical form is also provided for convenience of users who do not wish to install the Gepard Python package.



In separate [github.com repositories](https://github.com/openhep/dvcs-old), Jupyter notebooks are provided with example calculations corresponding to published GPD studies.

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-2)