Studies of the nucleon and hadron structure at CERN
(Project COMPASS-II, theme 02-0-1085-2017/2019)
extention of the theme for next 3 years

ABSTRACT

COMPASS is focused to study the nucleon structure and hadron spectroscopy by means of high intensity muon and hadron beams at the Super Proton Synchrotron (SPS) at CERN starting 2001. The data taking to study the nucleon structure was started in the summer of 2002 and continued till the autumn of 2004 using 160 GeV muon beam and polarised ^{6}LiD («deuterium») target. After one-year shutdown in 2005, COMPASS resumed data taking with the muon beam in 2006. The years 2008 and 2009 were dedicated to the COMPASS hadron spectroscopy program with pion and proton beam. In 2007 and 2011 nucleon structure function measurements with a NH_3 polarized («proton») target were performed.

In 2010 Research Board approved the extension of the COMPASS program. The COMPASS-II program included a set of measurements to study the Generalized Parton Distribution (GPD) in nucleons via Deep Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP), Transverse Momentum Dependent Parton Distribution Funstion (TMD PDFs) in SIDIS and TMD PDFs in polarized Drell-Yan processes. Further investigations in the field of hadron spectroscopy were envisaged as well. In January 2013, a new Memorandum of Understanding was signed, in order to fulfill this program. In 2012 the data to study the Primakoff reaction were taken. The first (pilot) run for the DVCS measurement was also conducted. The first polarised Drell-Yan measurement with the beam of negative pions and a polarised proton target was performed in 2015. The experimental set-up is modified for the GPD runs in 2016 and 2017 with a liquid hydrogen target and the muon beam. Throughout the entire period of carrying out an experiment, and also at a stage of preparation of its separate parts the JINR group participated and participates in its realization.

The COMPASS setup is a universal spectrometer based on two spectrometric magnets. It can be notionally divided into three parts along the beam axis: the beam part, responsible for the reconstruction and identification of beam particles, the Large Angle Spectrometer (LAS) and the Small Angle Spectrometer (SAS). Each of the spectrometers includes in addition to tracking detectors, electromagnetic and hadron calorimeters and a muon identification system. The LAS also includes a Ring Image Cherenkov detector (RICH) which provides identification of secondary hadrons. The third electromagnetic calorimeter ECAL0 was introduced in 2016 and is situated just downstream the target. Different targets have been used in the different physics programmes: polarized ^{6}LiD, NH_3 (DIS, DY), liquid hydrogen (DVCS, hadron spectroscopy) and nuclear targets, such as C, Ni, Pb, W (hadron spectroscopy, Primakoff reactions), surrounded by proton recoil detector. In addition, the tungsten absorber used in the Drell-Yan programme can be treated as an additional target for study of the EMC-effect. Positive (160 GeV/c and 200 GeV/c) and negative (190 GeV/c) muon beams and hadron beams of 190 GeV/c, positive (~75% of protons, ~24% of pions) and negative (~97% of pions and ~2% of kaons) have been used for the different physics programmes. The large set of the “beam-target” combinations provides unique possibility to solve a wide class of problems related to the properties of hadrons, hadronic interactions and hadron spectroscopy. Information about main data samples collected in 2002-2016 is presented in table below.

Year	Target	Beam particle	Beam momentum,GeV/c
2002	^{6}LiD	μ+	160
2003	^{6}LiD	μ+	160
2004	^{6}LiD	μ+	160
2006	^{6}LiD	μ+	160
2007	NH_3	μ+	160
2008	Liquid H_2	K- , π-	190
2009	Liquid H2, Ni,W,Pb	μ- , K- , π-	190
2010	NH_3	μ+	160
2011	NH_3	μ+	200
2012	Ni, C,W,Pb	μ- , K- , π-	190
2014	NH_3, W, Al	π-	190
2015	NH_3, W, Al	π-	190
2016	Liquid H_2	μ±	160
2017	Liquid H_2	μ±	160 (planned)
2018	NH_3, W, Al	π-	190 (planned)

In previous years JINR group made the essential contribution towards receiving new results in spin asymmetry of A_1^p and the longitudinal structure function g_1^p. These results were obtained by the COMPASS collaboration using polarised 200 GeV muons that were scattered off the longitudinally polarised target. The data were collected in 2011 and complement those collected in 2007 at 160 GeV, in particular at lower x values. They improved the statistical precision of g^1 (x) by about the factor of two in the region $x < 0.02$. A next-to-leading order QCD fit to the g^1 world data is performed. It lead to a new determination of the quark spin contribution to the nucleon spin, ΔΣ, ranging from 0.26 to 0.36, and to a re-evaluation of the first moment of g^1. The uncertainty of ΔΣ is mostly due to the large uncertainty of the present determinations of the gluon helicity distribution Δg/g = 0.113 ± 0.038 (stat.) ± 0.036 (syst.). A new evaluation of the Bjorken sum rule based on the COMPASS results for the non-singlet structure function g_1^{NS} (x,Q^2) yields ratio of the axial to vector coupling constants $|g_A/g_V|$ = 1.22 ± 0.05 (stat.) ± 0.10 (syst.), which validates the sum rule with accuracy of about 9%.

The COMPASS-II measurements have been started in 2012 with pion/kaon polarizability via Primakoff reactions and with GPD feasibility test using partially upgraded COMPASS-II spectrometer. The further measurements were continued in 2014 after the accelerator shutdown. One will be focused on studies of transverse momentum dependent (TMD) distributions of partons in nucleons via Drell-Yan lepton pair production (2014-2015 and in 2018) and measurements and generalized parton distributions (GPDs) via hard exclusive meson production and DVCS (2016-2017) . The program of measurements of an experiment COMPASS in 2012-2018 is given in Fig.1. In parallel with the GPD program, high statistic data for SIDIS will be taken.

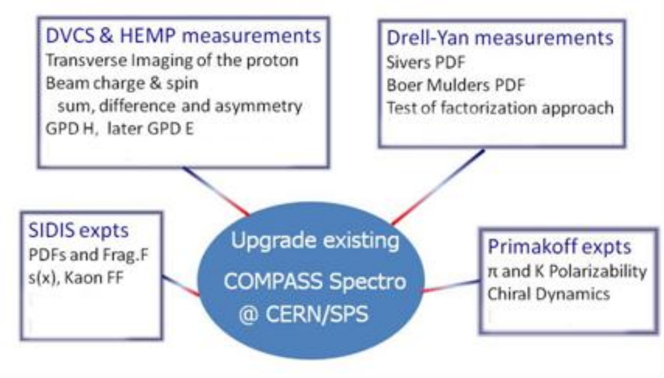

Figure 1: The schematic view of the COMPASS-II measurements for 2012-2018.

One of the results published by COMPASS is the measurement of pion polarisability confirming prediction of the chiral theory of strong interaction. Chiral Perturbation Theory (ChPT) predicts the following values for charged pion values α_π = $(2.9\pm0.5)\times10^{-4}$ fm^3 и β_π = $(-2.8\pm0.5)\times10\text{-}4$ fm^3 correspondingly. From the analyzed 63 000 events, the electric pion polarisability is determined to be α_π = (2.0 ± 0.6 stat ± 0.7 syst) × 10^{-4} fm^3 under the assumption $\alpha_\pi = -\beta_\pi$ that links the electric and magnetic dipole polarisabilities. The values of these polarizabilities can be directly extracted from the data on differential sections of Compton scattering.

In 2015 the COMPASS collaboration published the result for the measurement of the charged pion polarizabilities α π and β π extracted under the assumption $\alpha_\pi+\beta_\pi=0$ based on the analysis of 2009 data. At the moment the obtained result is the most precise dedicated measurement of this quantity. Analysis of the experimental data collected in 2012 will provide possibility to increase the accuracy of such kind of measurements and decrease both the statistical and the systematic uncertainties. In addition, larger statistics for the reaction $\pi Z\rightarrow\pi Z\gamma$ and an extended kinematic range will help us to perform independent measurements of α_π and β_π. Contamination of kaons in the hadron beam provides possibility to perform the first observation of the Compton scattering of a virtual photon off a charged kaon $KZ\rightarrow KZ\gamma$ and the first measurement of the kaon polarizabilities. The results for the pion and kaon polarizabilities are fundamentally important as a crucial test of the prediction power of the low energetic phenomenological QCD models such as the Chiral Perturbation Theory (ChPT).

The constant F 3π of the reaction $\pi Z\rightarrow Z\ \pi^0$, as well as the constant of the neutral pion decay is related to the hypothesis of the chiral anomaly. A precise measurement of this value can be the test of the chiral theory (ChPT) prediction. The accuracy of the measurements performed more than 30 years ago in the experiments FRAMM (CERN) and SIGMA (Protvino), at the moment is not good enough for such tests. The statistics for this reaction collected at COMPASS in 2009 and 2012 is more than one order of magnitude larger than the statistics of the previous experiments. Moreover, the new methods, proposed recently, give possibility to use for determination of the constant not only the data near the threshold but also the data in the mass range of the $\pi^-\ \pi^0$ system corresponding to the production and decay of the ρ-meson. Large statistics for the similar process $\pi Z\rightarrow\pi Z\eta$ gives opportunity to improve the result for the constant $F_{\pi\pi\eta}$, measured for the first time in the VES experiment in Protvino. Measurement of the cross section dynamics for the Primakoff reactions with a larger number of charged and neutral pions in the final state is also interesting for the chiral theory. The expected results are important for all phenomenological models of QCD in the low energy region.

As a part of the proposal in 2017-2019, COMPASS-II will study generalized parton distributions (GPDs) using scattering of the polarized muons off the liquid-hydrogen target surrounded by a recoil detector (RPD) and new electro-magnetic calorimeter ECAL0.

The ECAL0 calorimeter, suggested and developed at JINR, is a unique device of the "shashlyk"-type (scintillator, lead), in which the most advanced photodetectors – Micro-pixel Avalanche Photo Diodes (MAPD) with ultra-high pixel density (up to 15 thousand pixels / mm2) were used, instead of the traditional photomultiplier tubes.

In March-April 2016 the ECAL0 was fully assembled, tested, installed in the COMPASS setup, and currently it is successfully used for data taking. The main features of the new calorimeter may be formulated as follows: ECAL0 effectively registers direct photons of from the DVSC and DVMP reactions in the wide energy range (0.2-40 GeV). Together with ECAL1 (Fig. 2), ECAL0 effectively registers π^0, which can significantly reduce the photons background, which produced by π^0. These properties significantly expand the kinematic range measuring with minimal systematic uncertainties.

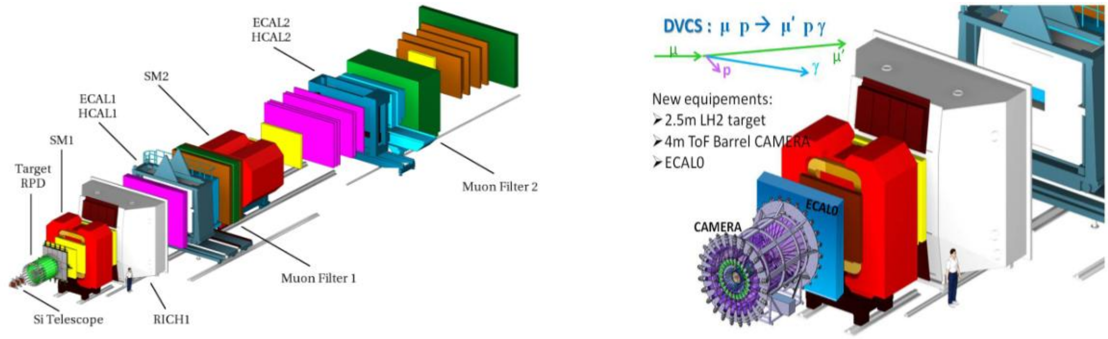

Figure 2: Experimental COMPASS setup (left) and the in front part of the spectrometer.

COMPASS collaboration highly appreciated stable work of the calorimeter. It is important to mention that groups from Russia, Germany (Munich), Poland (Warsaw) and Chech Republic (Prague) participated in the construction of ECAL0.

The GPD run has started in 2016 and will be continued in 2017. The first preliminary results are expected to be presented soon. The main tasks of GPDs investigations with Hard Exclusive Photon and Meson Production are as follows:

- measurements of the t-slope of the DVCS and HEMP cross section (transverse distribution of partons);
- studies of the beam-charge-and-spin sum and difference amplitudes (Re (TDVCS) and ImTDVCS for the GPD H determination);
- measurements of longitudinal contribution of Vector Mesons ρ0,ρ+,ω, Φ (GPD H);
- measurements of total contributions of ρ0 (GPDs E and E_T).

The projected precision of a t-slope measurements for two year of data taking is presented in Fig.2.

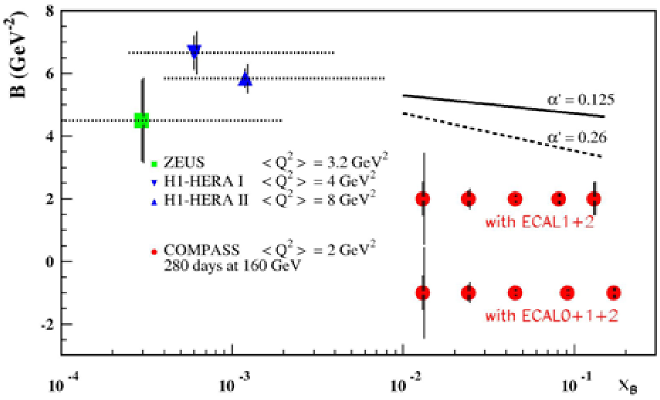

Figure 2: Projected measurements of the xB dependence of the t¬slope parameter $B(x_B)$ (red filled dots) using only ECAL1 and ECAL2 (upper row) and with an additional ECAL0 calorimeter (lower row).

With an unpolarized target, DVCS results will mainly provide information on the GPD H. The projected precision in one of bin is shown in Fig.3 for the beam charge and spin asymmetry.

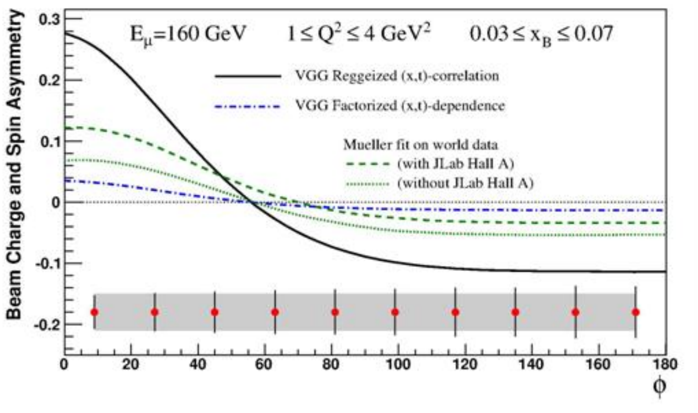

Figure 3: Projected precision of the beam charge¬ and ¬spin asymmetry measurements compared to various models.

The studies of SIDIS (Semi-Inclusive Deep Inelastic Scattering) reactions is the one of most advanced task of COMPASS-II physics program. The set analyses were performed yet with SIDIS data taken in 2002-2010 (see refs from Appendix 11, 23-26,31.32,45,49,51):

• Studies of transversity distributions:

-Collins asymmetry were measured with polarized deuteron and proton targets in reactions with h± , π± , and K± productions;

- The distributions and asymmetries were studied with polarized proton and deuteron targets in reaction with di-hadron productions (h± , π± , K±);

- The interplay between Collins and di-hadron asymmetries were investigated;

• Studies of TMD PDFs

- Sivers asymmetries were measured;

- The 6 (transverse single asymmetry) TSA were studied with polarized deuteron and proton targets in reactions with only charged hadrons and separately in h± , π±, K± productions;

- Gluon Sivers asymmetry from J/Psi and high p_T hadron pair production were measured on tranversely polarised deuteron and proton targets;

- The azimuthal asymmetries were studied on unpolarized deuteron target in reactions h± production.
• Studies of various hadron multiplicities
- Investigations of multiplicities in reactions with single hadron production versus p_T^2 on deuteron target;
– Studies of multiplicities in reactions with 2 hadrons production.

One expected that more results coming soon from already collected data:
- with transversely polarised proton target - on weighted asymmetries, p_T and Bessel distributions;
- with unpolarised deuteron target- on azimuthal asymmetries, two hadron multiplicities.
- with 2014-2015 data – for transversely polarized DY (sign test).
Also above mentioned analyses will be continued with the new data taken in 2016-2017 using unpolarised proton target (in parallel with DVCS).

As another part of the COMPASS-II proposal, the Collaboraton performed studies of the nucleon structure of DY lepton pairs production by pions off at the polarized protons target to access transverse-momentum-dependent parton distributions and compare them with the same measured in SIDIS. Among the distributions to be studied are the Sivers, Boer-Mulders and "pretzelosity". The data taking on Drell-Yan program will be continued in 2018.
The polarized DrellYan process (Fig.4) gives an alternative access to TMD PDFs, with the advantage over SIDIS that no fragmentation functions are involved, the measured spin asymmetries relating to convolutions of 2 TMD PDFs.

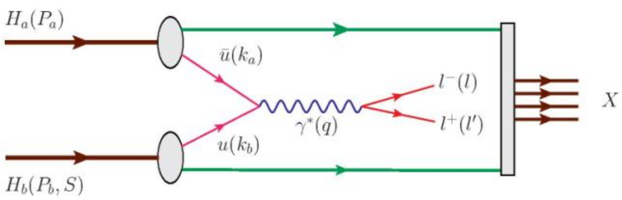

Figure 4: The diagram of the Drell-Yan process.

In leading order QCD, when having a transversely polarized target, the DrellYan cross section can be written in a form that highlights these azimuthal asymmetries, see Equation and Figure with explanation below.

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{ (1 + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi) + |\vec{S}_T| \Big(A_{UT}^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \Big) \Big) \Big\}$$

The 4 azimuthal asymmetries give access to the following convolutions:
- BoerMulder TMD from pion with BoerMulders from proton for $A_{UU}^{\cos2\varphi}$;
- unpolarized TMD from pion with Sivers TMD from proton for $A_{UT}^{\sin\varphi S}$;
- BoerMulders TMD from pion with pretzelosity TMD from proton for $A_{UT}^{\sin(2\varphi+\varphi S)}$;
- BoerMulders TMD from pion with transversity TMD from proton for $A_{UT}^{\sin(2\varphi-\varphi S)}$.

$$
\begin{aligned}
&\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = \\
&= 1 + \overline{h}_1^\perp \otimes h_1^\perp \cos(2\phi) \\
&+|S_T| \; \overline{f}_1 \otimes \overline{f}_{1T}^\perp \sin\phi_S \\
&+|S_T| \; \overline{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S) \\
&+|S_T| \; \overline{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S)
\end{aligned}
$$

beam pion — target proton

Figure 5: The cross section of the Drell-Yan process via PDFs.

One of the tasks JIRN team for 2017-2019 is to study the EMC-effect in the Drell-Yan process. The dependence of the parton distribution functions of the nucleon on the atomic number of the nucleus containing the nucleon, so-called the EMC-effect, is well-studied in the reaction of the deep inelastic scattering. Nevertheless, the origin of the effect is still not fully understood. The peculiarity of the EMC-effect in the negative pion-induced Drell-Yan process is that the dominating contribution is made by the parton distribution for u-quark while for the deep inelastic scattering the contributions of u- and d- quarks are comparable. The EMC-effect in the production of the J/ψ-meson is also interesting since in this case not only the process q qbar →J/ψbut also the process gg →J/ψcontributes. In this way indirect information about nuclear modification of the gluon distributions in the nucleon could be obtained.Since COMPASS has the world's largest statistics of DY-events among the fixed-target experiments, the measurements mentioned above are unique.
Additional analysis performed by JINR physicists is the search and study of exclusive lepto(photo)production of exotic charmonia. More than ten charmonium-like states with mass above 3.8 GeV were discovered during the last 15 years but their nature is still unknown. Several interpretations of such states do exist: tetraquarks, mesonic molecules etc. Till the moment all of them are observed either in decays of heavier particles, in e+e− annihilation or produced inclusively in hadronic interactions. Huge statistics for muon-nucleon scattering collected by COMPASS provides possibility to study the exclusive lepto(photo)production of such particles, that could be an important source of the information about their nature. The JINR group is the initiator of such kind of studies. In 2015 the COMPASS collaboration published the result for search for exclusive photoproduction of the charged hadron Z c (3900). At the moment the exclusive photoproduction of the charmonium-like state X(3872) is under investigation. The study of photoproduction of heavier charged and neutral XYZ states is planned for the future. It is worth to mention the potential possibility to search for the exclusive photoproduction of the pentaquarks P c+ , discovered by the LHCb collaboration in 2015, in the reaction μp→μP c+ →μpJ/ψ (s-channel).

According to the COMPASS-II MoU, JINR is obligated to support of the HCAL1, MW1, and new electromagnetic calorimeter ECAL0.
The main activities on data analysis in framework of COMPASS-II project will be focused on GPD and SIDIS analysis. The Drell-Yan and Primakoff studies mainly will be performed in the framework of new project proposed by LNP.
The MoU entered into force on January 1, 2013 and will be valid until December 31, 2017. Extensions of this MoU for three year without changes will be approved by the FRC basing on recommendations from SPSC (SPS and PS experiments Committee).

In 2017-2019 the COMPASS collaboration is going to plan to take the experimental data with muons (in 2017 and possibly in 2018) and with pions (possibly in 2018). The analysis of the experimental data will be continued and work on preparation of the proposal of the new physical program after 2020 is started. The detailed plan of works is presented below.

2017:
- Participation in COMPASS data taking ;
- Maintenance during running of MW1, HCAL1 and ECAL0 during running;
- Development/support of MW1/HCAL1/ECAL0 software;
- Analysis of COMPASS experimental data;

2018:
- Participation in COMPASS data taking;
- Maintenance of MW1, HCAL1 and ECAL0 during running;
- Development/support of MW1/HCAL1/ECAL0 software;
- Analysis of COMPASS experimental data;

2019:
- Analysis of COMPASS experimental data;

The common JINR expenses on the project during a stage of 2014-2016 on the project (theme 1085) was equal to$770 thousand. $130 thousand have been allocated by CERN for support of experts from JINR at CERN in 2014-2016. The collaboration of NA58 allocates also 40 thousand Swiss francs per year for payment of the common works performed by JINR engineers in CERN during preparation and support of the experiment for a data taking. In last three years $25 thousand were received from Czech Republic grants. Also funds from LHEP themes were spent for support Workshops in Suzdal (May 2015).

Expenses form JINR budget for 2017 - 2019 equal to $737 thousand from the JINR budget. The main part of these expenses are required for participation of JINR physicists in data taking, for maintenance of detectors at JINR responsibility and also for payment of contributions to the common fund according to obligations from MoU. The resources that are necessary for realization this stage of the project (2017-2019) are given below. The scheduled plan of work is given in Table 2.

TABLE 1: JINR FINANCE PROFILE FOR 2017-2019 (IN K$)

#	Item	Total	2017	2018	2019
1.	**design bureau (man-h)**				
2.	**workshops (man-h)**				
3.	**Materials**	**45**	**20**	**15**	**10**
4.	**Equipment**	**75**	**25**	**25**	**25**
5.	**Subcontracts (collab common fund)**	**222**	**72**	**75**	**75**
6.	**Travels, including outside RUSSIA inside RUSSIA**	 **380** **15**	 **150** **5**	 **130** **5**	 **100** **5**
	Total K$	**737**	**272**	**250**	**215**

TABLE 2: Scheduled plan of works on the project.

		Year											
№	Item	***2017***				***2018***				***2019***			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
1	Data taking												
2	ECAL0/HCAL1 preparation												
3	ECAL0 maintenance												
4	HCAL1 maintenance												
5	MW1 maintenance												
6	Low voltage system of MW1												
7	MW1/HCAL1/ECAL0 software												
8	Data analysis												