Studies of the Nucleon and Hadron Structure at CERN
theme 02-0-1085-2009/2019,
extention for 2020-2022

Participating Countries, Institutes and International organizations:

Country or Organization	City	Institute or Laboratory	Participants Name, Surname	Status
RUSSIA	Moscow	LPI	Zavertaev M.V.	Collaboration
RUSSIA	Moscow	NSC «Kurchatov institut», IHEP, Protvino	Donskov S.V.	Collaboration
RUSSIA	Tomsk	Polytechnic University	Lyubovitski V.Ye.	Collaboration
POLAND	Warsaw	NCBJ	Sandach A.	Collaboration
POLAND	Warsaw	TU	Zembitski M.	Collaboration
CZECH REPUBLIC	Prague, Brno , Liberec	CUNI, CTU, ISI Brno, TUL Liberec	Finger M.	Collaboration
GERMANY	Bohum	Rur University	Mayer V.	Collaboration
GERMANY	Bonn	University	Klein F.	Collaboration
GERMANY	Frieburg	University	Fisher H.	Collaboration
GERMANY	Mainz	University	Kabus E.	Collaboration
GERMANY	Munich	TUM	Paul C.	Collaboration
IZRAIL	Tel-Aviv	University	Lichtenstadt J.	Collaboration
ITALY	Trieat	INFN	Panzieri D.	Collaboration
ITALY	Turin	INFN	Martin A.	Collaboration
USA	Urbana	University	Peng J.	Collaboration
FRANCE	Saclay	CEA	Neyret D.	Collaboration
CERN	Geneva	ЦЕРН	Mallot G.	Collaboration
JAPAN	Jamagata	University	Iwata T.	Collaboration
INDIA	Calcuta	Matrivani Institute	Dasgupta S.	Collaboration
PORTUGAL	Aveiro	University	Azevedo C.	Collaboration
PORTUGAL	Lisbon	LIP	Quintans C.	Collaboration
TAIWAN	Taibei	Academia Sinica	Chang W.	Collaboration

LHEP participants (12):
Anosov V.A., Gavrishchuk O.P., Gushterski R.I, Ivanov A.V., IvanshinY.I., Kisselev Y.F. , Kouznetsov O.M., Meshcheryakov G.V. , Nagaytsev A.P., Peshekhonov D.V., Savin I.A., Zemlyanichkina E.V.
LNP participants (10):
Alexeev G.D., Anfimov N.V., Antoshkin A.I., Gridin A.O., Guskov A.V., Frolov V.N., Jouravlev N.I., Mitrofanov Ye.O., Olchevski A.G. ,,Selyunin A.S. ,
LTP participants (1): Efremov A.V.
INRNE, Sofia, Bulgaria(1): Gushterski R.I.

Leader A.P. Nagaytsev
Deputy A.V.Guskov

1. INTRODUCTION.

The COMPASS experiment has been proposed by the International Collaboration of 30 Institutions from 12 countries. The program of this experiment includes the nucleon spin structure studies in SIDIS of muons and studies of hadron structure in pion beams. It was approved at JINR and CERN in 1998.

The COMPASS-II proposal [1], suggested by the same Collaboration as continuation of COMPASS project, has been approved in May, 2010, and the corresponding theme at JINR was prolonged up to 2020. This stage of the Experiment is related to continuation the SIDIS measurements, particulary with studies of TMD PDFs, measurements of Generalized Parton Distributions (GPD) and Matveev-Muradyan-Tavkhelidze[1] or Drell-Yan (MMT-DY, further - DY) reactions. The COMPASS mesurements on SIDIS will be continued in 2021.

2. COMPASS-II RESULTS.

Up to now in the context of COMPASS Collaboration 53 papers were published (see the list in Appendix), 23 of them in 2017-2019. During this period COMPASS members have gave about 250 talks at the International Conferences and workshops. There are COMPASS results included in the meson tables of the latest version of the PDG (see Appendix).

In 2017 the COMPASS has continued a data taking on Generalized Parton Distribution (GPD) program with a muon 160 GeV beam and with use of the unpolarized hydrogen target.

JINR group has actively participated in setup preparation and in data taking. It is important to note the following important tasks which are carried out with the leading participation of JINR physicists: maintenance of new electromagnetic calorimeter (ECAL0); technical maintenance the experimental hall; the maintenance of hadron calorimeter (HCAL1) and systems of coordinate detectors (MW1).

In 2017 the analysis of the data taken in 2002-2016 was continued. In 2017 the collaboration published and prepared for the publication of 7 papers. Three articles were prepared with an essential contribution of JINR physicists. The main results for the reporting period are given below.

First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process

The first measurement of transverse-spin-dependent azimuthal asymmetries in the pion-induced Drell-Yan (DY) process was done by COMPASS with usage the CERN SPS 190 GeV/c $\pi-$ beam and a transversely polarized ammonia target [2]. Three azimuthal asymmetries giving access to different transverse-momentum-dependent (TMD) parton distribution functions (PDFs) are extracted using dimuon events with invariant mass between 4.3 $(GeV/c)^2$ and 8.5 $(GeV/c)^2$ (Fig.1). The observed sign of the Sivers asymmetry is found to be consistent with the fundamental prediction of QCD that the Sivers TMD PDFs extracted from DY have a sign opposite to the one extracted from semi-inclusive deep-inelastic scattering (SIDIS) data. Two other asymmetries originating from the pion Boer-Mulders TMD PDFs convoluted with either the nucleon transversity or pretzelosity TMD PDFs are also extracted from data. These DY results are obtained at a hard scale comparable to that of a recent COMPASS SIDIS measurement and hence allow unique tests of fundamental QCD universality predictions (Fig.2).

[1] V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze, Preprint OIYaI R2_4543 (Dubna, 1969); Preprint SLAC_TRANS_0098.

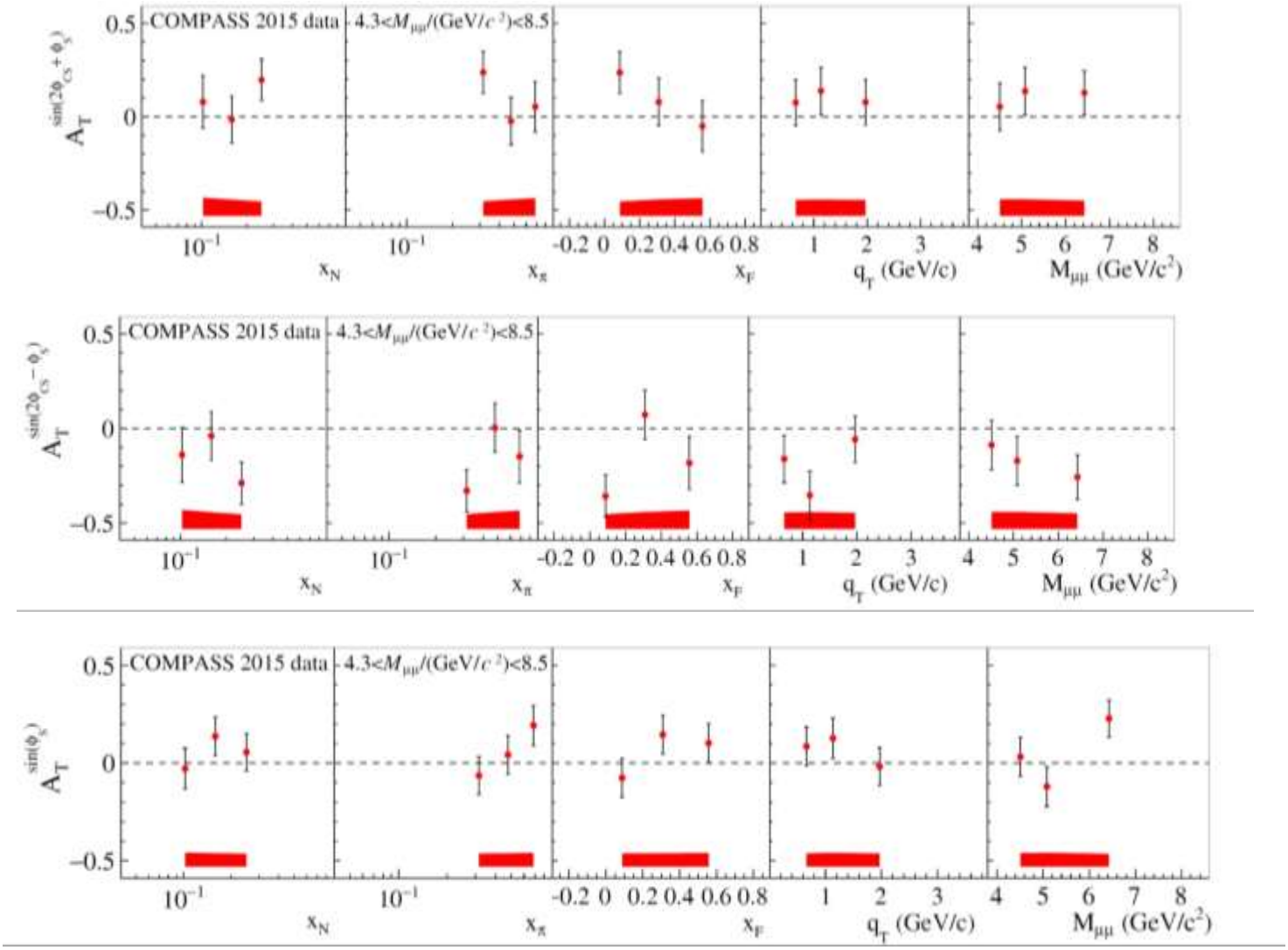

Figure 1:Extracted Drell-Yan TSAs related to pretzelosity, transversity and Sivers TMD PDFs (top to bottom).

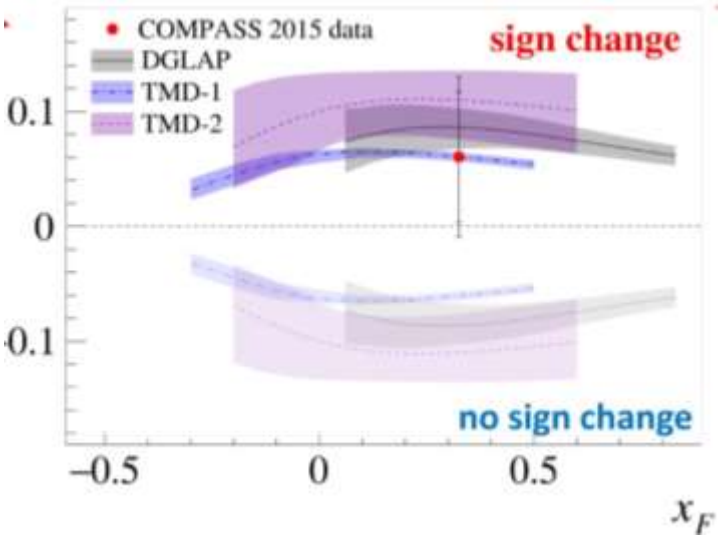

Figure 2: The measured mean Sivers asymmetry and the theoretical predictions for different Q^2 evolutions approaches.

First measurement of the Sivers asymmetry for gluons from SIDIS data

The Sivers function describes the correlation between the transverse spin of a nucleon and the transverse motion of its partons. It was extracted from measurements of the azimuthal asymmetry of hadrons produced in semi-inclusive deep inelastic scattering of leptons off transversely polarized nucleon targets, and it turned out to be non-zero for quarks. In this letter the evaluation of the Sivers asymmetry for gluons in the same process is presented. The analysis method is based on a Monte Carlo simulation that includes three hard processes: photon-gluon fusion, QCD Compton scattering and leading-order virtual-photon absorption process. The Sivers asymmetries of the three processes are simultaneously extracted using the LEPTO event generator and a neural network approach. The method is applied to samples of events containing at least two hadrons with large transverse momentum from the COMPASS data taken with a 160 GeV/c muon beam scattered off transversely polarized deuterons and protons. With a significance of more than two standard deviations a negative value is obtained for the gluon Sivers asymmetry. The result of a similar analysis for a Collins-like asymmetry for gluons is consistent with zero [3].

In 2018, the COMPASS has performed an additional data taking on the Drell-Yang measurements program using a polarized hydrogen target and a pion beam with energy equal to 160 GeV.
The JINR group made a significant contribution to the preparation of the facility and the data taking. It is important to note the following important tasks were performed with the essential participation of JINR team: engineering and technical support of the experimental hall; support of the hadron calorimeter (HCAL1), support and technical maintenance of the coordinate detector system (MW1), the polarized hydrogen target and the primary data collecting system (DAQ). In 2017, the collaboration published and prepared 8 articles for publication. Two papers were prepared with significant contributions from JINR physicists. Below the main results are given for the reporting period.

K − over K + multiplicity ratio for kaons produced in DIS with a large fraction of the virtual-photon energy

The K − over K + multiplicity ratio is measured in deep-inelastic scattering, for the first time for kaons carrying a large fraction z of the virtual-photon energy. The data were obtained by the COMPASS collaboration using a 160 GeV muon beam and an isoscalar ^{6}LiD target [4]. The regime of deep-inelastic scattering is ensured by requiring Q 2 > 1 (GeV/c) 2 for the photon virtuality and W > 5 GeV/c ^{2} for the invariant mass of the produced hadronic system. Kaons are identified in the momentum range from 12 GeV/c to 40 GeV/c, thereby restricting the range in Bjorken-x to $0.01 < x < 0.40$. The z-dependence of the multiplicity ratio is studied for $z > 0.75$ (Figs. 3,4). For very large values of z, i.e. $z > 0.8$, the results contradict expectations obtained using the formalism of (next-to-)leading order perturbative quantum chromodynamics. This may imply that cross-section factorisation or/and universality of (kaon) fragmentation functions do not hold. Our studies suggest that within this formalism an additional correction may be required, which takes into account the phase space available for hadronisation.

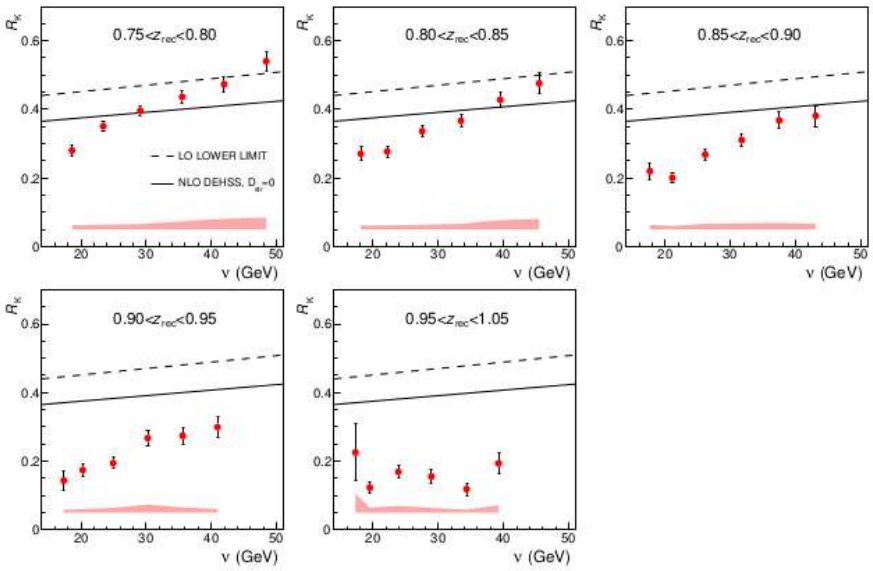

Figure 3:The K − over K + multiplicity ratio as a function of ν in bins of z, shown for the first bin in x. QCD predictions are given in solid and dashed lines.

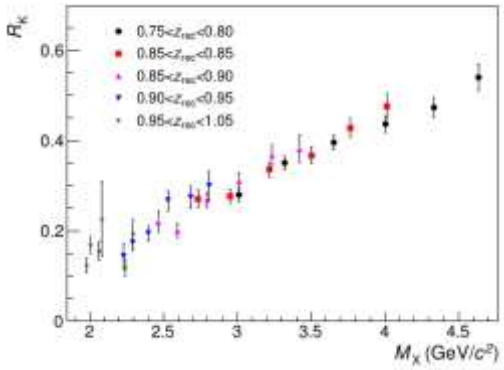

Figure 4: The K − over K + multiplicity ratio presented as a function of X.

Transverse Extension of Partons in the Proton probed by Deeply Virtual Compton Scattering

For first time COMPASS has performed the measurements of exclusive single-photon muoproduction on the proton using 160 GeV/c polarized μ + and μ − beams of the CERN SPS impinging on a liquid hydrogen target [5] . One has determined the dependence of the average of the measured μ + and μ − cross sections for deeply virtual Compton scattering on the squared four-momentum transfer t from the initial to the final final proton. The slope B of the t-dependence is fitted with a single exponential function for range $0.1 - 2\ (\mathrm{GeV/c})^2$ (Fig.6) which yields

$$B = (4.3 \pm 0.6_{\mathrm{stat}} \,{}^{+\,0.1}_{-\,0.3}\big|_{\mathrm{sys}})\,(\mathrm{GeV}/c)^{-2}$$

This result can be converted into an average transverse extension of partons in the proton,

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\mathrm{stat}} \,{}^{+\,0.01}_{-\,0.02}\big|_{\mathrm{sys}})\,\mathrm{fm}$$

for the average virtuality of the photon $<Q^2>=1.8\ (\mathrm{GeV/c})^2$ and the average value of the Bjorken variable equal to $x_{Bj} = 0.056$ (Fig.5).

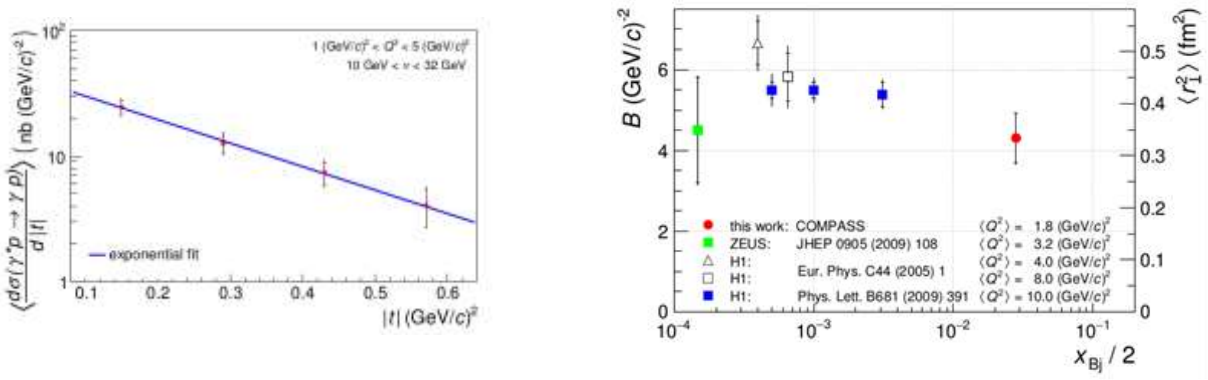

Figure 5: Differential DVCS cross section as a function of |t|(left). The results of measurements of the t-slope of parameter B, and, accordingly, the average squared transverse extension of partons in the proton, as a function of x_{Bj} /2.

Search for muoproduction of X(3872) at COMPASS and indication of a new state tilde-X(3872)

The searching for exclusive production of exotic charmonia in the reaction $\mu+N\rightarrow\mu+(J/\psi\pi^+\pi^-)\pi^{\pm}N$ was performed using COMPASS data collected with incoming muons of 160 GeV/c and 200 GeV/c momentum. In the $J/\psi\pi^+\pi^-$ mass distribution we observe a signal with a statistical significance of 4.1 σ (Fig.6). Its mass and width are consistent with those of the X(3872). The shape of the $\pi + \pi -$ mass distribution from the observed decay into $J/\psi\pi + \pi -$ shows disagreement with previous observations for X(3872). The observed signal may be interpreted as a possible evidence of a new charmonium state (Fig.7). It could be associated with a neutral partner of X(3872) with $C = -1$ predicted by a tetraquark model. The product of cross section and branching fraction of the decay of the observed state into $J/\psi\pi + \pi -$ is determined to be 71±28(stat)±39(syst) pb [6].

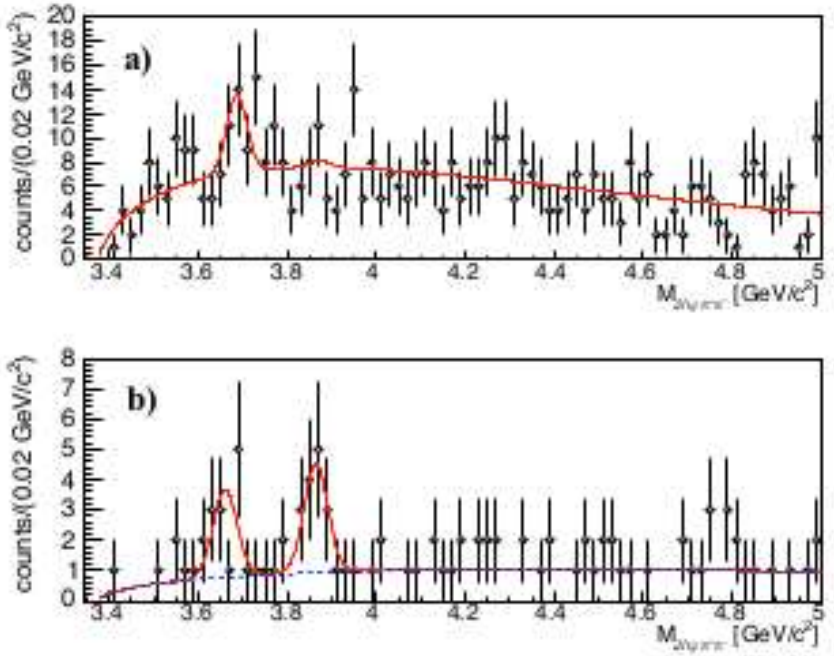

Figure 6: The $J/\psi\pi + \pi -$ invariant mass distributions for the $J/\psi\pi + \pi - \pi \pm$ final state (two entries per event) for non-exclusive events (-12 GeV $< \Delta E < -4$ GeV) and (b) for exclusive events (-4 GeV $< \Delta E <$ 4 GeV) with missing mass M miss above 3 GeV/c^2 .

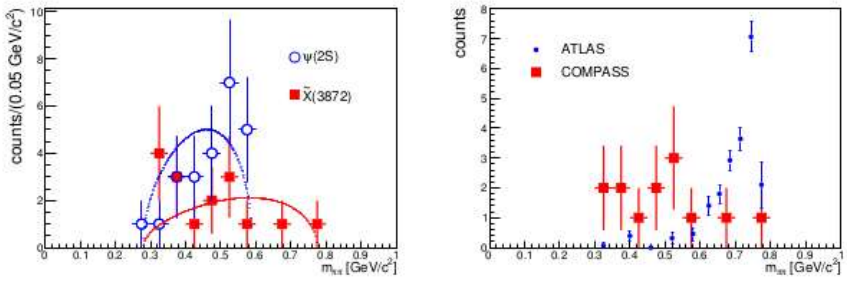

Figure 7: (a) Invariant mass spectra for the π + π − subsystem from the decay of X(3872) (red squares) and ψ(2S) (blue circles). (b) Invariant mass spectra for the π + π − subsystem from the decay of X(3872) measured by COMPASS with the applied cut M miss > 3 GeV/c 2 (red squares) and from the decay of X(3872) observed by ATLAS (blue points).

Azimuthal asymmetries of charged hadrons produced in high-energy muon scattering off longitudinally polarised deuterons

Single hadron azimuthal asymmetries in the cross sections of positive and negative hadron production in muon semi-inclusive deep inelastic scattering off longitudinally polarised deuterons are determined using the 2006 COMPASS data and also all deuteron COMPASS data [7]. For each hadron charge, the dependence of the azimuthal asymmetry on the hadron azimuthal angle φ is obtained by means of a five-parameter fitting function that besides a φ -independent term includes four modulations predicted by theory: sin φ , sin 2φ , sin 3φ and cos φ (Fig.8) . The amplitudes of the five terms have been first extracted for the data integrated over all kinematic variables. In further fits, the φ -dependence is determined as a function of one of three kinematic variables (Bjorken-x, fractional energy of virtual photon taken by the outgoing hadron and hadron transverse momentum), while disregarding the other two. Except the φ -independent term, all the modulation amplitudes are very small, and no clear kinematic dependence could be observed within experimental uncertainties (Fig.9).

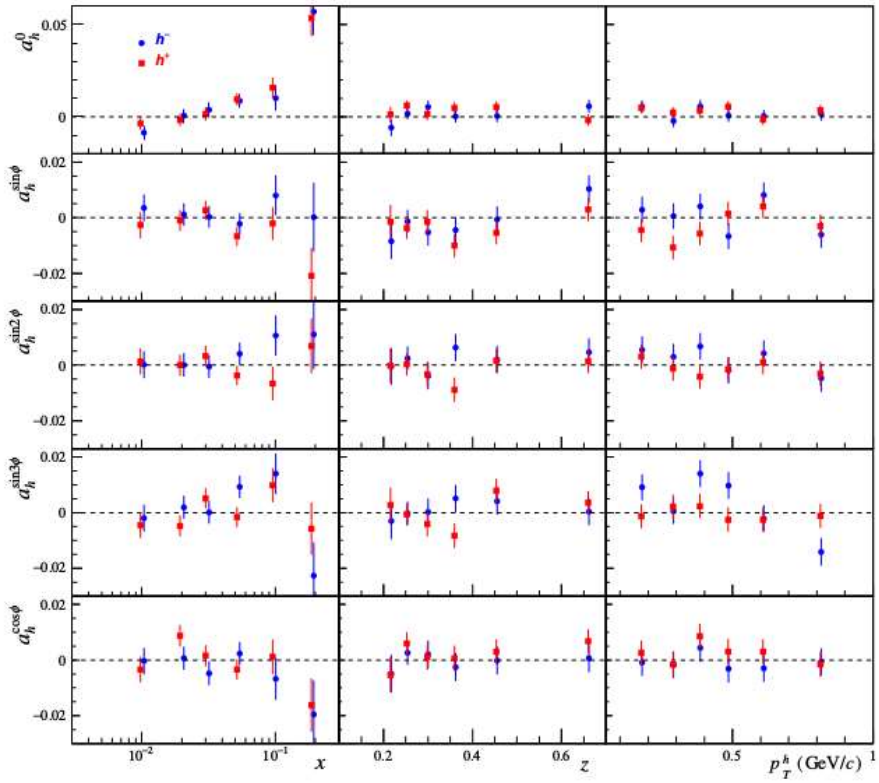

Figure 8: The modulation amplitudes of the h+ and h− azimuthal asymmetries as a function of x , z and p^h_T obtained from the combined 2002–2006 data on the muon SIDIS off longitudinally polarised deuterons. Only statistical uncertainties are shown.

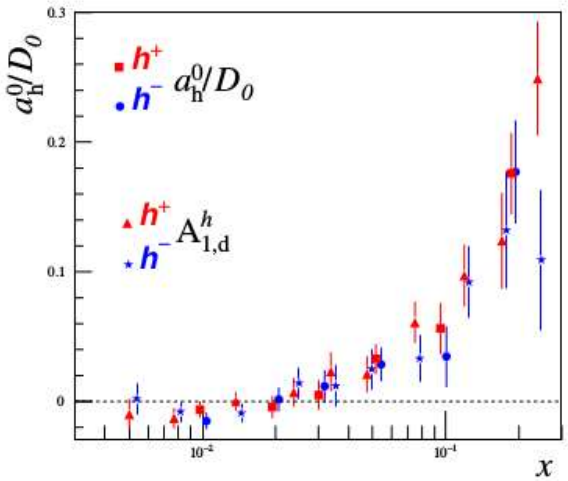

Figure 9: The x-dependences of the $a^0{}_{h\pm}/D_0(x, y)$ values for 2002–2006 data in comparison with the data of $A^h{}_{1,d}$ obtained by COMPASS.

3. COMPASS-II IN 2020-2022.

The COMPASS-II measurements started in 2012 with pion/kaon polarisability via Primakoff reactions and with GPD feasibility test using partially upgraded COMPASS-II spectrometer. The further measurements continued in 2014 after the accelerator shutdown. They are focused on studies of transverse momentum dependent (TMD) parton distributions in nucleons via Drell-Yan lepton pair production (2014-2015 and in 2018) and measurements of GPDs H via hard exclusive meson production and DVCS (2016-2017) (Fig.10). Also with the GPD program, data for TMD PDFs in SIDIS were collected.

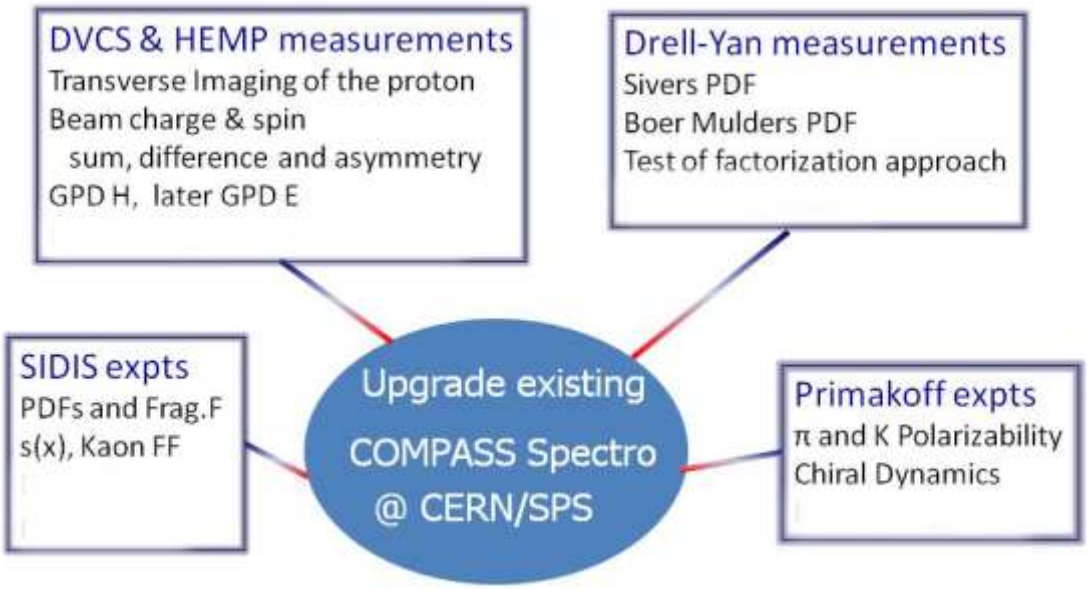

Figure 10: The schematic view of the COMPASS-II tasks.

The following table shows the COMPASS-II data taking in 2002-2018.

Muon beam	deuteron (^{6}LiD) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
Muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
Muon beam	LH_2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH_3) DT PT	2014 2015	Pilot DY run DY run
Muon beam	LH_2 target	2016 2017	DVCS & unpol. SIDIS
Hadron	Proton (NH_3) PT	2018	DY run

The periods of data taking (2002-2004, 2007 and 2010) on TMDS in SIDIS with transversely polarized targets are given in green. The data collected on this topic of COMPASS-II program was not allowed to get the statistically valid experimental results and the COMPASS-II has prepared the proposal [8] to prolong SIDIS measurements in 2021. This one was approved by CERN SPSC in 2018.

In the SIDIS cross-section they appear convoluted with fragmentation functions (FFs) [9, 10], and can be extracted from the data using independent information on the FFs. Particularly interesting is the measurement of the SIDIS cross-section when the target nucleon is transversely polarised. In this domain the HERMES and the COMPASS Collaborations have performed pioneering measurements at different beam energies (27 and 160 GeV respectively) and shown beyond any doubt the correctness of three most interesting recent conjectures:

- The Sivers function $f^{\perp}_{1T}$: in a nucleon that is polarised transversely to its momentum the quark distribution is not left-right symmetric with respect to the plane defined by the directions of the nucleon spin and momentum. This asymmetry of the distribution function is called the Sivers effect, and the asymmetric function is known as the Sivers PDF [11].

- The transversity distribution function h_1: the quarks in a transversely polarized nucleon are transversely polarised. Their polarisation is described by the h1 PDFs which a priori are different and have different properties from the helicity PDFs.

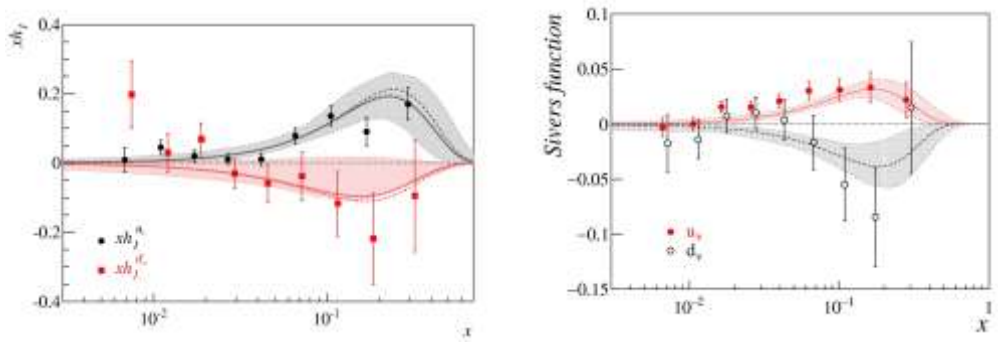

Figure 11: The transversity and Sivers PDFs extracted point-by-point using the existing COMPASS p and d data from Ref. [12] and [13]. The curves are the results of fits to the COMPASS and HERMES data and, for transversity, to the Belle data. Note that the uncertainty band for the d-quark transversity would be larger if the Soffer bound was not imposed.

- The Collins function $H_1^{\perp}$: the hadronization of a transversely polarised quark is not left-right symmetric with respect to the plane defined by the direction of the quark momentum and the quark spin [8]. This fact has been confirmed by the e+e− measurements at Belle, BaBar and BES and has been exploited to measure the quark transversity PDFs.

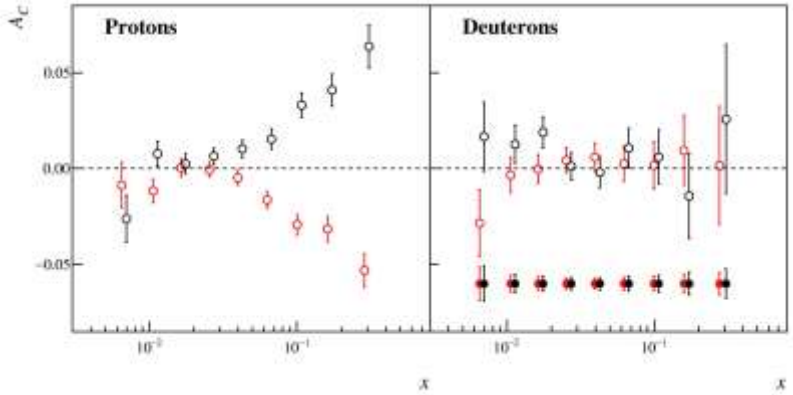

Figure 12: The Collins asymmetry A_C obtained from the 2010 data with the polarised proton NH_3 target as a function of x (left plot) compared to the results we obtained from the runs of 2002, 2003 and 2004 with polarised deuteron ^{6}LiD target (right plot). The red (black) points refer to positive (negative) hadrons. The full points at -0.06 in the right plot show the extrapolated statistical error from the proposed deuteron run.

COMPASS-II proposes to perform a standard one-year (150 days) measurement, scattering the M2 muon beam with 160 GeV/c momentum on a transversely polarised deuteron target, as soon as the LS2 will be over, using the COMPASS spectrometer. The polarised target system has been reassembled at the end of the DVCS/SIDIS run, last fall, it will be used for the Drell-Yan run of 2018, and will stay installed in Hall 888 for this new measurement.

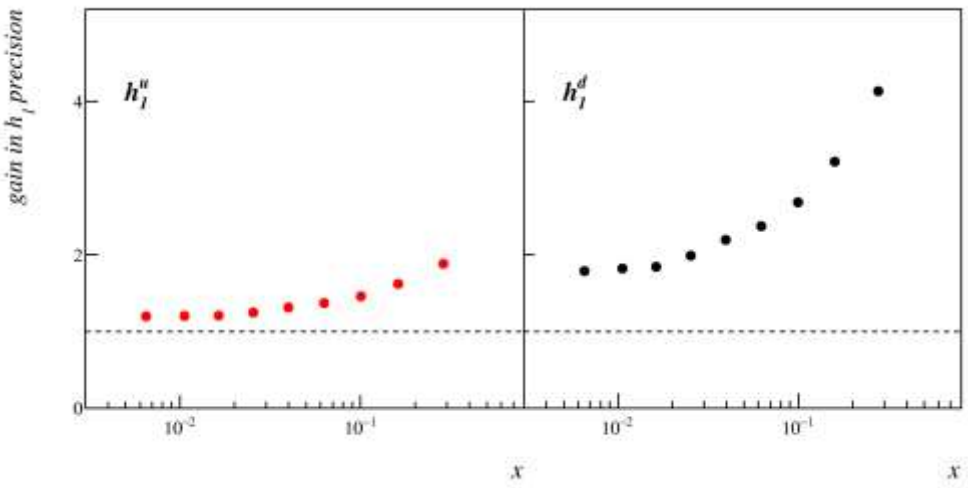

Figure 13: Ratio of the existing uncertainties on the extracted transversity and the projected uncertainties for u_v-quark (left) and d_v-quark (right).

The impact of the proposed measurement is quantified in Fig. 13, which gives the ratio, at each x value, of the present and projected errors on the extracted transversity PDFs. The gain in precision for the d-quark ranges from a factor of 2 at small x to more than a factor of 4 at large x, and is also important for the u-quark. Since in all our measurements the systematic uncertainties are a small fraction of the statistical ones here they are neglected.

To perform proposed measurements the COMPASS has to be prepared after long shutdown. The apparatus to be used for the deuteron run is basically the COMPASS Spectrometer as it was used in the 2010 muon run, shown schematically in Fig. 14. This implies removing the absorber which will be used for the 2018 Drell-Yan run, moving the polarised target 2 m downstream to the position it had for the SIDIS runs, and reinstalling all the trackers and all the counters which were used in 2010. The polarised target will be housed in the large acceptance COMPASS PT magnet, and the target material will be the same which was used in the years 2002, 2003, 2004 and 2006, namely ^{6}LiD. For a better usage of the muon beam, the target cells diameter will be increased from 3 to 4 cm. The average polarisation of the target is expected to be the same as in the past deuteron runs (about 50%). The beam request is the same as for the 2010 proton run, namely 2.5×10^{13} protons delivered to the T6 target of the M2 beam line every 40.8 s. With an accelerator chain efficiency of 90% and a running time of 150 days a total of 6.1×10^{18} protons at T6 is expected. This number of protons is the basis of all the projections presented in this document, which are obtained from the number of reconstructed hadrons in the 2010 run.

Two detectors supported by JINR group have to be used in 2021data taking: MW1 amd HCAL1 shown in Fig.14.

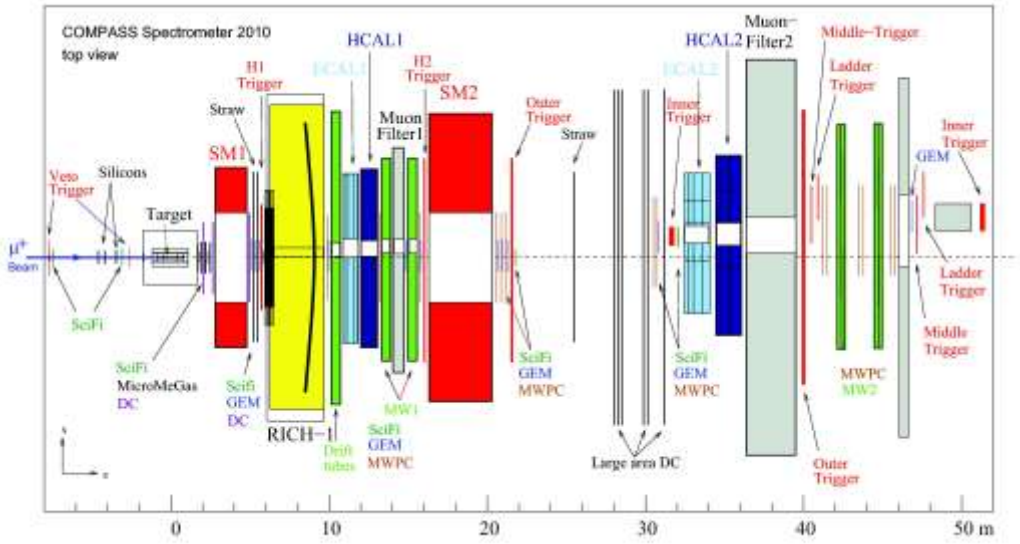

Figure 14: Schematic lay-out of the COMPASS spectrometer (top view) as it was used in 2010 and as it will be reassembled for the 2021 run.

We propose to improve our knowledge of the transverse spin structure of the nucleon by measuring 160 GeV muon semi inclusive DIS on a transversely polarised deuteron target. This measurement will complete the exploratory investigation of the transverse spin structure of the nucleon originally proposed by COMPASS 20 years ago. The measurement will be unique in the small x-Bjorken region, and complementary to corresponding measurements already approved at JLab. The proposed measurements will have a profound impact on the field, and their combination with the already taken proton data will allow to further clarify the properties of the up, down and sea quarks in the nucleon. Moreover, a combined analysis of the transversity measurement at CERN and at JLab will allow a determination of the isovector tensor charge with an accuracy of about 0. 06. Quoting from our last proposal for a polarised SIDIS measurement [6], "the high intensity and polarisation of the muon beam together with the COMPASS polarised target and spectrometer make CERN a unique place to perform such measurement. This will not change until the construction of a high energy and luminosity polarised electron-ion collider in the longer term future".

Analysis of COMPASS-II data taken in previous years will be continued with participation of JINR group. One of the main topic is the Drell-Yan 2015/2018 data analysis, where the following JINR members are: A.Guskov, A.Gridin, A.Denisenko and Ye.Mitrofanov (all LNP) and A/Ivanov (LHEP). Possible results can be obtained in 200-2022 with 205 Drell-Yan data are as follows:

•Double J/ψ production,
•Drell-Yan unpolarized asymmetries (targets- NH_3),
•Drell-Yan unpolarized asymmetries (target-NH_3, J/ψ production) ,
•Drell-Yan transverse spin dependent asymmetries in J/ψ mass range ,
•Drell-Yan cross-sections (with targets-NH_3, W),

The analysis of Drell-Yan 2018 data can give the following results:

•Drell-Yan transverse spin dependent asymmetries in high mass (>4 GeV) and J/ψ mass range
•Cross-sections, Unpolarized asymmetries

Analysis of DVCS data taken in 2012 and 2016/2017 will be done also with participation of JINR physisits (A.Guskov, A.Gridin, A.Olchevski (all-LNP) and O.Kouznetsov, R.Gusherski, E.Zemlysnichkina and I.Savin (all-LHEP), topics are:

•Preliminary DVCS results
•Multiplicities h, π, K (+ 2006 proton multiplicity ratios),
•Unpolarized asymmetries,
•Exclusive ρ meson production (2012 data),
•Exclusive φ meson production (2012 data) .

4. JINR OBLIGATIONS AT COMPASS

According to the COMPASS-II MoU, the obligations of JINR are the technical support of the HCAL1, MW1, and new electromagnetic calorimeter ECAL0 . The MoU for COMPASS-II sets:
- The COMPASS collaboration existing on the basis of the 1998 MoU, which consists of a group of collaborating institutions from CERN Member and non-Member States as well as CERN, have proposed to expand the original program and carry out a set of measurements to study the structure of hadrons in Deep Virtual Compton Scattering (DVCS), Hard Exclusive Meson Production (HEMP) and SIDIS, Polarized Drell-Yan and Primakoff reactions.
- At the end of each year a provisional budget for the next year is established, based on the foreseen running costs and contingencies. It should to be approved by the FRC (Financial Resources Committie). To cover the running costs, an M&O fund, with contributions from all the Collaborating Institutions, is setup. The contribution due by each Collaborating Institution for the following year is calculated "Per Capita" based on the number of members carrying a financial contribution to the M&O at July 1st of the running year.

The SIDIS and DVSC are tasks in COMPASS data analysis for this project.
The MoU enters into force on January 1, 2013, and will be valid until December 31, 2020. Extensions of this MoU for three year without changes will be approved by the FRC with recommendations from SPSC (SPS and PS experiments Committie) up to end of data taking.

5. TIME LINES and FINANCIAL PROFILE.

In period of 2020-2022 COMPASS-II collaboration is going to take the experimental data with muon (2021) and continue the analysis of the experimental data taken in previous years. The plan of work for three years is presented below.

2020:
- Development/support of MW1/HCAL1 software;
- Analysis of COMPASS experimental data;
- Preparation of dttectors for 2021 data taking.

2021:
- Participation in COMPASS data taking;
- Maintenance of MW1, HCAL1 during running ;
- Development/support of MW1/HCAL1software;
- Analysis of COMPASS experimental data;

2022:
- Analysis of COMPASS experimental data;

Common JINR expenses on the project (theme 1085) for period of 2017-2019 were equal to about $770 thousand. About $130 thousand were allocated by CERN (NA58, COMPASS-II) for support of experts from JINR in CERN. 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 an experiment for a data taking. In the last three years about $25 thousand were spent from a Czech Republic grants. Also funds from LHEP themes were spent for holding workshops in Suzdal (May 2015).

The sum of necessary financing for 2020 - 2022 equals to $485 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 and the program on-line complexes of monitoring of their work, and also for contributions to the common fund of collaboration according to obligations from MoU.

The finance profile includes the travel expenses for JINR physicists, contribution to the common COMPASS fund, money for maintenance of HCAL1 and MW1.

Total estimated cost of the theme

№ №	Activities	Total cost	Costs per years (thousand USD)		
			2020	2021	2022
1.	Preparation and maintenance of HCAL1 and MW1	65	35	20	10
2.	Contribution to common fund	120	40	40	40
3.	Scientific missions	300	80	120	100
Total		**485**	155	180	150

Cost estimates for the theme (in k$)

№№ of items	Budget items	Total 2020–2022	Including 2020
4	Scientific missions	300	80
5,6	Material, equipment, common fund	185	75
Total		**485**	155

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