COMPASS Status Report 2018

The COMPASS Collaboration

Abstract

The report reviews the activities and the achievements of the Collaboration during the last twelve months. Covered items are the results and ongoing analysis for the data collected in the previous years and the preparations of the 2018 run.
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1 Introduction

The report describes the new results obtained during the last twelve months both for what concerns the hadron spectroscopy and the structure of the nucleon. The status of the analysis of the 2016/17 DVCS and 2014/15 Drell-Yan data is presented. Preparations for the 2018 Drell-Yan run are described.
2 Hadron structure and hadron excitation spectrum

2.1 Measurement of the chiral anomaly from 2012 data

We study photon-pion induced reactions using high-energy pion beams that impinge on medium-heavy and heavy target nuclei. The photons are provided by the Coulomb field of the nucleus, which according to the Weizsäcker-Williams approach can be approximated by a beam of quasi-real photon. The photons have a continuous energy spectrum in the $\pi$ rest frame, reaching centre-of-momentum energies in the pion-photon system of about 2 GeV for COMPASS kinematics. The quasi-elastic channel $\pi^- + \gamma^* \rightarrow \pi^- + \gamma$ is used to investigate the structure-dependent parts of the cross section, which is to first order given by the pion polarizability. The channel $\pi^- \gamma \rightarrow \pi^- \pi^0$ contains information about the chiral anomaly $F_3^{\pi}$, which is an additional important low-energy parameter within chiral theory. We analyze this reaction using the approach of Hoferichter et al. They extend the amplitude from chiral perturbation theory from the low-mass region up to $m_{\pi\pi} = 1$ GeV/c$^2$ by including the $\rho(770)$ resonance via dispersion relations. This approach does not only yield a more precise measurement of $F_3^{\pi}$ but it allows us to also measure the radiative coupling $\rho(770)^- \rightarrow \pi^- \gamma$ at the same time. Figure 1 shows the $\pi^- \pi^0$ invariant mass spectrum together with a fit of the theory curve from Ref. [1]. Red indicates the fit range, green the extrapolation of the theory curve.

Fig. 1: Acceptance-corrected Invariant mass distribution of the $\pi^- \pi^0$ final state from the 2009 Primakoff data after subtraction of background from $\pi^- \pi^0 \pi^0$. The curve represents a fit of the theory curve from Ref. [1]. Red indicates the fit range, green the extrapolation of the theory curve.

2.2 Results on diffractive pion dissociation

COMPASS has recorded large data sets on diffractive dissociation reactions using a 190 GeV/c beam of pions and kaons on a hydrogen target. In these reactions, the beam particle gets excited into various intermediate resonances $X$ via $t$-channel Pomeron exchange with the target proton. The resonances are very short-lived and decay into various (quasi-)stable final-state hadrons measured by the spectrometer. The kinematic distribution of the final-state particles is a result of the quantum mechanical superposition of the amplitudes for the various contributing $X$. The intermediate states $X$ are characterized by the quantum numbers spin $J$, spin projection $M$, parity $P$, and $C$ or $G$ parity. The contributions of the various intermediate resonances depend on the mass $m_X$ and the reduced four-momentum transfer squared $t'$ to the target proton. For the analyzed data sets, the trigger acceptance limits the analysis to the kinematic region $t' > 0.1$ (GeV/c)$^2$. COMPASS studies final states involving charged as well as neutral hadrons.

We employ partial-wave analysis (PWA) techniques to decompose the coherent superposition of the amplitudes of the intermediate states $X$ according to their $J^P M$ quantum numbers. For two-body final states, this leads to a representation of the cross section in terms of the absolute value squared of the coherent sum of spherical harmonics with complex expansion coefficients, which are called transition amplitudes. For $n$-body final states with $n \geq 3$, a more complicated approach, the so-called isobar model, is used, which generally has a larger model bias. In such analyses, it is assumed that the decay of the intermediate state $X$ to the final $n$-body state proceeds via a series of sequential two-body decays. In these decays, additional unstable intermediate states,
the so-called isobars, appear. They correspond to known resonances or to any particle system, the amplitude of which can be described analytically in terms of mass and angular distributions. With the above assumptions, the amplitude for the decay of $X$ into the $n$-body final state is calculable for a given decay path. The observed kinematic distribution of the final-state particles is modelled by a set of decay amplitudes, each uniquely defined by the $J^{PC}$ quantum numbers of $X$, the absolute value $M$ of the spin projection of $X$ along the beam direction, the symmetry $\varepsilon$ of the amplitudes related to the naturality of the exchange particle in the production process, and the decay path of $X$. We use the short-hand notation $J^{PC} M^\varepsilon$ [decay path] to label partial waves.

We model the cross section as the absolute value squared of the coherent sum of the products of decay amplitudes, which describe the kinematic distribution of each wave, and complex-valued transition amplitudes, which determine strength and phase of each wave. The unknown values of the transition amplitudes are determined by a fit to the measured $(3n - 4)$-dimensional kinematic distribution of the $n$-body final state. This fit is performed independently in narrow bins of $m_X$ and for some channels also in bins of $t'$. Hence in this first analysis step, which is called mass-independent fit, we make no assumptions about the resonance content of the intermediate states $X$. However, the decay amplitudes and hence the isobar amplitudes have to be known precisely and without any free parameters.

The $n$-body resonances and their parameters are extracted in a second analysis step, the so-called mass-dependent fit, by modelling the $m_X$ dependence of a selected subset of transition amplitudes in terms of resonant and non-resonant wave components.

### 2.2.1 3π final states

The $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ data set consists of approximately $50 \cdot 10^6$ exclusive events, which is a factor 10 to 100 more than obtained by any previous experiment. The data are analyzed in 100 $m_{3\pi}$ bins ranging from 0.5 to 2.5 GeV/c$^2$. Each of the $m_{3\pi}$ bins is subdivided further into 11 non-equidistant $t'$ bins ranging from 0.1 to 1.0 (GeV/c)². This yields a total of 1100 $(m_{3\pi}, t')$ cells. The PWA model consists of a set of 88 partial waves, which includes waves up to spin $J = 6$. In combination with the large data set, this allows us to study the spectrum of isovector $a_{J'}$- and $\pi_{J}$-like mesons with spin $J$ in great detail.

Based on the result of the first analysis stage, which were published in Ref. [2], a subset of 14 waves, which together contribute about 60% to the total intensity, was selected for a resonance-model fit. The fit model describes the $m_{3\pi}$ dependence of the intensities and interference terms of 14 partial-wave amplitudes simultaneously. The model contains the well-known resonances $\pi(1800)$, $a_1(1260)$, $a_2(1290)$, $\pi_0(1670)$, $\pi_1(1800)$, and $a_4(2040)$. In addition, it includes the disputed $\pi_1(1600)$, the excited states $a_1(1640)$, $a_2(1700)$, and $\pi_2(2005)$, as well as the resonance-like $a_1(1420)$. In addition to these 11 resonant components, a non-resonant component is added coherently in each wave. Compared to previous analyses, which included only up to 6 waves [3], the current fit simultaneously describes a significantly larger number of partial waves. Another important improvement with respect to previous analyses is that the fit is performed simultaneously in 11 $t'$ bins. This leads to a better separation of resonant and non-resonant wave components, which in general have a different $t'$ dependence. In addition, this novel $t'$-resolved analysis approach allows us to extract the $t'$ dependence of the amplitudes of the resonant and non-resonant wave components for the first time. This provides information about the details of the production process.

The Breit-Wigner parameters of the resonances are shown in Fig. [2] Due to the high precision of the data, statistical uncertainties are negligible compared to systematic ones. Hence extensive studies have been performed to estimate the systematic uncertainties. The results of this analysis are described in a detailed paper that was accepted by Phys. Rev. D [4]. Here, we highlight only a few results from the analysis.

As shown in Fig. [3a] and b, the data require a spin-exotic resonance, the $\pi_1(1600)$ (blue curve), in the $1^{-+} 1^+$ $\rho(770) \pi P$ wave. The $t'$-resolved analysis allows us to establish for the first time that a significant $\pi_1(1600)$ signal appears only for $t' \gtrsim 0.5$ (GeV/c$^2$), whereas at low $t'$ the intensity of the spin-exotic wave is saturated by a Deck-like non-resonant component (green curve). The $\pi_1(1600)$ parameters of $m_{\pi_1(1600)} = 1600^{+110}_{-60}$ MeV/c$^2$ and $\Gamma_{\pi_1(1600)} = 580^{+100}_{-230}$ MeV/c$^2$ have large uncertainties. The measured width is significantly larger than that observed in previous experiments [5] including our own result from the data taken with a lead target [3], but it...
Fig. 2: Masses and widths of (a) $a_J$-like and (b) $\pi_J$-like resonances (points). The systematic uncertainties are represented by the boxes. The statistical uncertainties are at least an order of magnitude smaller than the systematic ones and are hence omitted. Different colors encode different resonances.

Fig. 3: (a) intensity of the $1^{-+} 1^+ \rho(770) \pi P$ wave in the highest $t'$ bin. (b) phase of the $1^{-+}$ wave relative to the $1^{++} 0^+ \rho(770) \pi S$ wave in the highest $t'$ bin. The data points are taken from Ref. [2] and represent the so-called mass-independent analysis. The result of the full model, which is the coherent sum of the wave components, is represented by the continuous red curves. The other curves represent the wave components: $\pi_1(1600)$ resonance (blue), non-resonant component (green). The extrapolations of the model and the wave components beyond the fit range are shown in lighter colors. The fit, in which the $\pi_1(1600)$ resonance was omitted from the fit model, is represented by the dashed red curves. These curves correspond to the non-resonant component. (c) intensity of the $1^{++} 0^+ f_0(980) \pi P$ wave in the lowest $t'$ bin. The blue curve represents the $a_1(1420)$ component.

has a large systematic uncertainty towards smaller values.

The resonance-like $a_1(1420)$ signal in the $1^{++} 0^+ f_0(980) \pi P$ wave that we first reported in Ref. [6] is confirmed with even smaller uncertainties of the resonance parameters (see Fig. [3]).

In order to describe the four $2^{--}$ partial-wave amplitudes that are included in the fit, three Breit-Wigner resonances are needed, the $\pi_2(1670)$, the $\pi_2(1880)$, and the $\pi_2(2005)$. The latter one is not an established state [5]. The measured $\pi_2(2005)$ parameter values of $m_{\pi_2(2005)} = 1962^{+17}_{-29}$ MeV/$c^2$ and $\Gamma_{\pi_2(2005)} = 371^{+16}_{-120}$ MeV/$c^2$ are consistent with the two measurements by previous experiments [7] [8]. The $\pi_2(1880) \rightarrow 3\pi$ decay mode is established for the first time.
2.2 Results on diffractive pion dissociation

The data also require excited $a_1(1640)$ and $a_2(1700)$ states. Because of the dominant $a_1(1260)$, the $a_1(1640)$ parameters are not well determined. The $a_2(1700)$ mass of $m_{a_2(1700)} = 1681^{+22}_{-35}$ MeV/c$^2$ is consistent with the PDG average while the width of $\Gamma_{a_2(1700)} = 436^{+20}_{-16}$ MeV/c$^2$ is 242 MeV/c$^2$ larger [5]. It is interesting to compare our results with an analysis of the $\eta\pi$ $D$-wave intensity distribution using an analytical model based on the principles of the relativistic $S$-matrix [9], which we presented in the 2017 SPSC report. The analysis is based on the partial-wave decomposition of COMPASS data from Ref. [7]. The extracted $a_2(1320)$ pole parameters from Ref. [9] are consistent with the values of our Breit-Wigner parameters. The same is true for the $a_2(1700)$ mass, but the $a_2(1700)$ width of $280^{+10}_{-70}$ MeV/c$^2$ that is found in Ref. [9] appears to be lower than our value. This is a hint that our simplifying model assumptions may cause an overestimation of the $a_2(1700)$ width.

Investigations on the structure of the $a_1(1420)$. The resonance-like signal observed by COMPASS in the $f_0(980)\pi P$ partial wave of the $3\pi$ final state at a mass of 1420 MeV/c$^2$ does not fit into the $q\bar{q}$ classification scheme of ordinary mesons. On the one hand, its mass is too close to that of the ground state $a_1(1260)$. On the other hand, its width of approximately 150 MeV/c$^2$ is too narrow to be associated with the first radial excitation. Hence it is either a tetraquark or a molecule-like state, or, equally interesting, a dynamically generated signal. Calculations show that a resonance-like signal at a mass of 1.4 GeV/c$^2$ is produced by a so-called triangle singularity in the decay of the broad ground state $a_1(1260)$ into $K^*(892)\bar{K} + c.c.$, and the subsequent rescattering of the $K$ from the decay of the $K^*$ into the observed $f_0(980)$ [10, 11]. Figure 4 shows the diagram corresponding to this process, Fig. 5 the real and imaginary part of the associated amplitude. It results in a resonance-like signal with a rapid phase motion at the observed mass, without introducing any new resonance. An estimate of the expected intensity yields about 1% with respect to the $a_1(1260)$ in the $\rho\pi$ final state, in very good agreement with the COMPASS result. In the meantime, these calculations have been confirmed by the group of E. Oset [12].

In order to investigate whether the COMPASS data can be adequately described by the triangle amplitude, we replaced the $a_1(1420)$ Breit-Wigner amplitude used in the fit of the spin-density matrix mentioned above by the triangle amplitude. In the model, the intensities and relative phases of three partial waves, $J^{PC}M^{\varepsilon}R_{3\pi}L = 1^{++}0^+ f_0(980)\pi P$ und $2^{++}1^+ \rho(770)\pi D$, as a function of $m_{3\pi}$ are fitted simultaneously in 11 bins of the squared 4-momentum transfer $t'$. Figure 6 shows the result for one specific $t'$ bin, $0.100 < t' < 0.113$ GeV$^2$/c$^2$.

The quality of the fit is practically identical to the model using a Breit-Wigner resonance for the $a_1(1420)$, as published by COMPASS [6]. This is a strong hint that a triangle singularity is indeed responsible for a large fraction of the $a_1(1420)$ signal. A small additional contribution of a genuine $K^*\bar{K}$ resonance, however, cannot be excluded at the moment. Triangle singularities are currently also discussed in the connection with the signals observed by LHCb in the $J/\psi p$ final state and interpreted as pentaquarks [13–15]. The COMPASS results are
2.2.2 Other ongoing analyses and published work

The first PWA stage, the mass-independent fit, depends on the fact that the decay amplitudes can be calculated and do not have any free parameters. This also means that the amplitudes of the isobar resonances that appear in the subsystems have to be known precisely. The parametrizations of the isobar amplitudes are one of the major sources of systematic uncertainty in a PWA. One way to circumvent this problem and to study the bias due to the employed isobar parametrizations is the so-called freed-isobar method. In this approach, the fixed parametrizations of the isobar amplitudes are replaced by piece-wise constant complex-valued functions that are determined from the data. A first application of this method to the $J_{PC} = 0^{++}$ two-pion isobars in the $\pi^{−}\pi^{−}\pi^{+}$ data showed promising results [2]. In a follow-up study, also the amplitudes of the $1^{−−}$ and $2^{++}$ isobars were replaced by piece-wise constant functions in addition to that of the $0^{++}$ isobars. With this extended set of freed-isobar waves, we found mathematical ambiguities for the solutions. They appear, if more than one isobar is freed for a particular $J_{PC}$ of the corresponding $3\pi$ system. Interestingly, the same ambiguity problem arises in the PWA of multi-body decays of heavy mesons, where the method of extracting the amplitudes of the subsystems is often referred to as model-independent PWA. We have developed methods to resolve these ambiguities and have verified them in extensive Monte Carlo studies. A paper describing the freed-isobar method and its verification based on Monte Carlo studies of $3\pi$ final states from decays of $D$ mesons and from diffractive production was accepted by Phys. Rev. D [16].

We are currently working on a partial-wave analysis of the diffractive dissociation reaction $K^{-}p \rightarrow K^{-}\pi^{-}\pi^{+}p$ in order to study excited kaon resonances. Improvements in the calibration procedure of the CEDAR detectors, which are used for beam-particle identification, and optimization of the cuts for the final-state particle identification increased the size of the data sample usable for the analysis. We expect about 800,000 exclusive $K^{-}\pi^{-}\pi^{+}$ events in the combined 2008 and 2009 data sample. This is four times larger than the largest data sample obtained so far, which was acquired by the WA03 experiment [17]. In addition to the CEDAR...
2.3 Search for muoproduction of the $X(3872)$ at COMPASS

In the 2017 report, the analysis of $\eta\pi$ resonances using an analytical model for the peripheral meson production in the scattering of high-energy pions, which satisfies the requirement of 2-body unitarity, was described. We extract two poles, which are identified as the $a_2(1320)$ and the $a'_2(1700)$, with the corresponding masses and widths

\[
m(a_2) = (1307 \pm 1 \pm 6) \text{ MeV}, \quad m(a'_2) = (1720 \pm 10 \pm 60) \text{ MeV},
\]
\[
\Gamma(a_2) = (112 \pm 1 \pm 8) \text{ MeV}, \quad \Gamma(a'_2) = (280 \pm 10 \pm 70) \text{ MeV}.
\]

The paper has recently been published in Phys. Lett. B [9].

Other ongoing projects are

- Development of a unitary model for $3\pi$ final states and application to the final states with $J_{PC} = 2^{-+}$.
- Event selection and partial-wave analysis of $\eta\pi$ and $\eta'/\pi$ final states with an improved calorimeter reconstruction and including an extended mass range. The goal is to perform a fit in bins of $t'$, as for the $3\pi$ final state, and finally to develop and apply a unitary model including the non-resonant background.

2.3 Search for muoproduction of the $X(3872)$ at COMPASS

COMPASS has searched for exclusive production of exotic charmonia by virtual photons in the charge-exchange reaction $\mu^+ N \rightarrow \mu'^+ X^0 \pi^\pm N'$ with $X^0 \rightarrow J/\psi \pi^+ \pi^-$ using data collected between 2003 and 2011 with incoming muons of 160 GeV/$c$ and 200 GeV/$c$ momentum. Here, $N$ denotes the target nucleon, $N'$ the unobserved recoil system, and $X^0$ an intermediate state. Figure 7 shows the $J/\psi \pi^+ \pi^-$ invariant mass distribution. In addition to an expected peak from the $\psi(2S)$, we observe a second peak with a statistical significance of 5.3 $\sigma$. The mass of the peak of 3860.4\pm10.0 MeV/$c^2$ and its width of 22.8\pm6.9 MeV/$c^2$ are consistent with the $X(3872)$ hypothesis. Since the peak width is consistent with the COMPASS mass resolution, we determine an upper limit for the resonance width of 51 MeV/$c^2$. The product of the production cross section and the branching fraction for the decay of the observed state into $J/\psi \pi^+ \pi^-$ is determined to be 71\pm28(stat)\pm39(syst) pb.
3 NUCLEON STRUCTURE FROM SIDIS

3.1 Longitudinal spin structure functions

The data analysis of all data taken with longitudinally polarised protons and deuterons to measure longitudinal double spin asymmetries is finished and the corresponding results are published. The last publication is the paper on $g_1^p$ at low $x$ and $Q^2$ [22].

3.2 Transverse spin and transverse momentum structure of the nucleon

The analyses of the SIDIS data collected with (polarized) protons and deuterons and the 160 GeV muon beam, finalised to the study of transverse spin and transverse momentum dependent (TMD) nucleon structure, continued during last year with relevant results which are summarised here and described in some detail in the following sections.

The analysis of the weighted Sivers asymmetry continued with the release of a new set of results, the $P_T/M$-weighted asymmetries (see section 3.2.1) [23]. From the previously released asymmetries (the $P_T/zM$-weighted Sivers asymmetries) we have extracted the Sivers functions for the $u$ and $d$ quark (section 3.2.1).
which has been used to calculate the $q_T$ weighted asymmetry in Drell-Yan to be compared with the corresponding newly measured asymmetry \cite{24, 25}.

The results for the $\Lambda/\bar{\Lambda}$ polarisation induced by the transversity PDF have been finalised (section 3.2.2) and presented at conferences \cite{23, 26}.

In the last year, the proposal for a new one full year of run to measure SIDIS off transversely polarised deuterons with the 160 GeV muon beam has been written (section 3.2.3) \cite{27}, submitted to the SPSC, and recommended for approval at the Research Board.

The data analysis for the measurement of TMD effects in SIDIS from the 2016/17 will start as soon as the final production of a relevant fraction of data will be over. In the mean time, preparatory work has been done in order to optimise the foreseen measurements and to understand the relevant physics processes involved.

Concerning the analyses which were discussed in the previous status reports, the following papers have been published:

### 3.2.1 Weighted Sivers asymmetries

#### Weight $P_T/zM$

The work we had started in 2016 on the Sivers asymmetries weighted with $P_T$, the transverse momentum of the final state hadrons with respect to the virtual photon direction, and which was already described in the status report of last year \cite{28}, has been continued in 2017 and more results have been obtained, released, and presented at international conferences.

In the standard Amsterdam notation the Sivers asymmetry can be written as

$$A_{Siv}(x, z) = \frac{\sum_q e_q^2 x f^{\perp 1}_T(x) \otimes D^q_1(z)}{\sum_q e_q^2 x f^q_1(x) \cdot D^q_1(z)}$$

(1)

where $x$ is the Bjorken variable, $z$ is the fraction of the available energy carried by the hadron, and $\otimes$ indicates a convolution over the transverse momenta of the Sivers function $f^{\perp 1}_T$ and of the fragmentation function $D_1$.

Assuming the transverse momentum dependence of all these functions to be Gaussian, the Sivers asymmetry becomes

$$A_{Siv,G}(x, z) = a_G \frac{\sum_q e_q^2 x f^{\perp 1(1)}_T(x) \cdot D^q_1(z)}{\sum_q e_q^2 x f^q_1(x) \cdot D^q_1(z)}$$

(2)

where

$$f^{\perp 1(1)}_T(x) = \int d^2 k_T \frac{k_T^2}{2M^2} f^{\perp 1}_T(x, k_T^2)$$

(3)

is the first moment of the Sivers function. The quantity $a_G$ is given by $a_G = \sqrt{\pi M/\sqrt{\langle k_T^2 \rangle_S + \langle p_{\perp}^2 \rangle/2}}$, where $\vec{k}_T$ is the quark intrinsic transverse momentum and $\vec{p}_{\perp}$ the transverse momentum of the hadron with respect to the quark direction. It is clear that the procedure allows to evaluate from the measured Sivers asymmetries the first moment of the Sivers function $f^{\perp 1(1)}_T$, and not the Sivers function itself.
As reported in Ref. [28] by weighting the spin-dependent part of the cross-section with $P_T/(zM)$ (where $M$ is the nucleon mass) and one gets the simple result that in the numerator of eq. (1) the convolution becomes the product of the first transverse moment of the Sivers function and the fragmentation function $D_1$. The weighted Sivers asymmetry is thus given by

$$A_{wSiv}^\pm(x, z) = \frac{2 \sum_q e_q^2 x f_{1T}^{\perp(1)}q(x) D_1^q(z)}{\sum_q e_q^2 x f_{1T}^T(x) D_1^q(z)}.$$  \hspace{1cm} (4)

From eq. (4) the first moment of the Sivers function can be directly accessed, and there is no need to make assumptions on the quark distributions and fragmentation functions. Several results for $A_{wSiv}$ were already shown in [28]. More work has been done on this item and in particular a new set of weighted asymmetries $A_{wSiv}'$ has been obtained using as weight $w' = P_T/M$.

**Extraction of $f_{1T}^{\perp(1)}$**

After measuring the $p_T/zM$ weighted asymmetries on proton for positive and negative hadrons, we have extracted for the first time without using the Gaussian ansatz the first moment of the Sivers function $f_{1T}^{\perp(1)}(x)$. Assuming that

- all the detected positive and negative hadrons are either pions or kaons;
- vanishing Sivers functions for the quark sea,$^1$

The weighted Sivers asymmetries of eq. (4) can explicitly be written as

$$A_{w,h}^{u,h\pm}(x) = 2 e_u^2 x f_{1T}^{\perp(1)}u(x) \tilde{D}_1^{u,h\pm} + e_d^2 x f_{1T}^{\perp(1)}d(x) \tilde{D}_1^{d,h\pm}$$

\hspace{1cm} \sum_q e_q^2 x f_{1T}^T(x) D_1^q(z),  \hspace{1cm} (5)

where

$$\tilde{D}_1^{q,h\pm} = \int_{\Omega_x} dz (D_1^{q,\pi\pm} + D_1^{q,K\pm}),  \hspace{1cm} (6)$$

and $\Omega_x = (0.2, 1.0)$ in our case. The asymmetries are then fitted using tables and parametrisations for the known PDFs $f_1^q(x)$ [30, 31] and FFs $D_1^{q,h\pm}$ [32], taken at the $Q^2$ corresponding, in the COMPASS kinematics, to the mean value of $x$ in each $x$ bin. The first $k_T^2$-moment of the Sivers function has been parametrised as

$$xf_{1T}^{\perp(1)}q(x) = a_q x^b_q (1 - x)^c$$  \hspace{1cm} (7)

where we have fixed $c = 5$, as suggested in ref. [33], since our data do not extend at large $x$. The estimates of the parameters are

$$a_u = -0.36 \pm 0.11; \quad b_u = 0.95 \pm 0.11; \quad a_d = 0.24 \pm 0.17; \quad b_d = 0.64 \pm 0.22$$

with strong correlations between all of them.

The fitting curves are compared with the measured asymmetries in the left panel of fig. [9] while the first moments of the Sivers functions as function of $x$ are shown in the right panel of the same figure. The bands indicate the statistical uncertainties only. Note that they are small, because of the fact that the sea contribution is put to

$^1$Note that this assumption is justified by the finding of previous extractions [29]. However, given the large statistical error of those results, this is a quite strong assumption. On the other hand, the weighted Sivers asymmetries are not and can not be measured from the existing COMPASS deuteron data, so that this assumption is needed to extract from the proton asymmetries alone the Sivers functions.
3.2 Transverse spin and transverse momentum structure of the nucleon

\begin{equation}
\langle \vec{P}^2_T \rangle \approx z^2 \langle k^2_T \rangle_S + \langle p^2_\perp \rangle.
\end{equation}

In particular one has \( R_G^{w'} = A_{Siv}^{w'}/A_{Siv,G} = 4\langle P_T^b \rangle / \pi M \approx 0.7 \).

Integrating over \( z \), the asymmetries become

\begin{equation}
A_{Siv}^{w'}(x) = 2 \frac{z f_{1T}^{1(1)}(x) \int_{\Omega_z} dz z D_1^q(z)}{x f_{1T}^u(x) \int_{\Omega_z} dz D_1^u(z)}
\end{equation}

and, assuming \( u \)-dominance

\begin{equation}
A_{Siv}^{w'}(x) = 2 \frac{f_{1T}^{1(1)}(x) \int_{\Omega_z} dz z D_1^u(z)}{x f_{1T}^u(x) \int_{\Omega_z} dz D_1^u(z)}
\end{equation}
Fig. 10: Comparison between $A_{Siv}^{w'}$, $w' = P_T^h/M$ as function of $x$ and the published results [34] (crosses) for positive (left) and negative (right) hadrons with $z > 0.2$.

Fig. 11: Ratio $A_{Siv}^{w'}/A_{Siv}$, $w' = P_T^h/M$ as function of $x$ for positive hadrons and $z > 0.2$. The black points are the values of $4\langle z \rangle / \pi M \langle z/P_T \rangle$. The results for $A_{Siv}^{w'}$ are shown in fig. 10 for positive (left) and negative (right) hadrons and compared with the published [34] Sivers asymmetry $A_{Siv}$ (crosses). As expected, being the weight $w' = P_T^h/M$, the $A_{Siv}^{w'}(x)$ values are smaller than those of the standard asymmetry.

Their ratio $R_{w'} = A_{Siv}^{w'}/A_{Siv}$ for positive hadrons is shown in fig 11. It is almost constant as function of $x$ with a mean value of 0.62, not far from the values expected in the Gaussian model, also shown in the figure.

In order to better investigate the $z$ dependence, as in the case of the $A_{Siv}^w$, $w = P_T/zM$ asymmetries, this analysis has been repeated adding the hadrons with $0.1 < z < 0.2$. The results for the $x$ integrated asymmetry $A_{Siv}^{w'}$ as function of $z$ are shown in fig. 12 for positive (left) and negative (right) hadrons. The values for positive hadrons are in qualitative agreement with the expectation, which, in case of $u$–dominance, can be written as:

$$A_{Siv}^{w'}(z) = 2z \frac{\int_{\Omega_z} dx C(x) x f_{1T}^{(1)u}(x)}{\int_{\Omega_z} dx C(x) x f_{1T}^{u}(x)}.$$  \hspace{1cm} (12)

For comparison the published [34] Sivers asymmetry $A_{Siv}$ (crosses) are also shown in the same figure.

This analysis is almost completed, a drafting committee to write the paper has been set up, and a first draft is almost ready for internal circulation.

### 3.2.2 Transversity induced $\Lambda/\bar{\Lambda}$ polarisation

The measurement of the transverse polarisation of $\Lambda$ hyperons produced in SIDIS off transversely polarised nucleons has always been indicated as a promising channel to access transversity [35]. The basic idea is that,
3.2 Transverse spin and transverse momentum structure of the nucleon

if transversity is different from zero, the polarisation of the fragmenting quark can be transferred to the $\Lambda$ according to the transversely polarised fragmentation function $H_{\Lambda/q}^{T}$, so that the $\Lambda$ is polarised.

$\Lambda$ hyperons are a natural choice to investigate such transversity transmitted polarisation: their weak decay channel $\Lambda \rightarrow p\pi^-$ is in fact self-analysing, that is, the polarisation is revealed through the angular asymmetry of the decay proton:

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_{\Lambda} \cos \theta$$

(13)

where $\alpha$ is the $\Lambda$ weak decay parameter and $\theta$ is the angle between the proton momentum and the polarisation vector, assumed to be coincident with that of the outgoing quark.

After the SIDIS measurements of transversely polarised proton targets of HERMES and COMPASS it is well known that both the $u$- and the $d$- quark transversity functions are different from zero, so it is possible to check whether there is any transfer of polarisation from them to the lambda, and obtain information on $H_{\Lambda/q}^{T}$. Summing over all quark species, one gets:

$$\vec{P}_{\Lambda} = \frac{\sum_{q} e_{q}^{2} f_{1}^{q}(x) H_{\Lambda/q}^{T}(z)}{\sum_{q} e_{q}^{2} f_{1}^{q}(x) D_{NN}^{L/q}(z)} D_{NN} R \vec{P}_{N}$$

(14)

where $R$ is the rotation about the normal to the scattering plane which brings the initial proton momentum along the $\Lambda$ momentum.

Studies of $\Lambda$ transversity transmitted polarisation were already carried out in COMPASS using 2002-2004 deuteron data and 2007 proton data, but the results have never been published. Now the analysis has been resumed and extended to the proton data collected in 2010. Since some aspects of the analysis are new, the 2007 data have also been re-analysed and results are presented here for the whole set of proton data. The $\bar{\Lambda}$ polarisation has also been extracted from the complete proton data set.

In Fig. 13 both the Armenteros-Podolanski plots and the mass distribution for $\Lambda$ candidates from 2010 data are shown after all cuts. The results for the polarisation from all the data collected with the transversely polarised proton target (runs of 2007 and 2010) are given in Fig. 14 as a function of $x$. All the values are compatible with zero. The interpretation of the results and the writing of the relative paper are ongoing.

3.2.3 Proposal for one year of SIDIS measurement on a transversely polarized deuteron target

A considerable amount of work was devoted to formulate the Proposal to measure, in 2021, soon after LS2, semi-inclusive DIS on transversely polarized deuterons ($^6$LiD target) [27], presently the “missing piece” in the COMPASS data set on transverse target spin orientations.
In 2010, a dedicated run was taken on a transversely polarised proton (NH$_3$) target which, together with the 2007 data and the previous HERMES results, provided pioneering and unique information on the transversity ($h_1$) and Sivers ($f_{1T}^\perp$) functions, underlining the importance of transverse spin in the QCD structure of the nucleon and the correctness of conjectures put forward 25 years ago. On the contrary we provided only a marginal (albeit unique) data set for the isoscalar deuteron target. The deuteron data have been taken at COMPASS only for short periods in the first years of running and with the small-aperture SMC target magnet so that the statistical uncertainties of the deuteron transverse spin asymmetries are considerably larger than those of the corresponding proton asymmetries. With one additional year of data taking the statistical error of the deuteron measurements will be almost two times smaller than those of the corresponding proton data in all Bjorken-$x$ bins, allowing accurate flavour separation for $h_1$ and $f_{1T}^\perp$ and measurements which will stay unique for many years to come.

The proposal for this new deuteron run is part of an Addendum[27] we submitted to SPSC, that recommended its approval to the CERN Research Board on April 20, 2018. The unbalance between the amount of transversely polarized SIDIS data collected on protons, where on top of the data from the 2007 and 2010 COMPASS runs there are the accurate HERMES data, and on deuterons, where only the poor statistics COMPASS data from 2002, 2003 and 2004 exist, makes not only the extraction of the $d$-quarks PDFs much less precise than that of the $u$-quarks, but introduces also a strong correlation between the $u$- and $d$- PDFs. This can be best understood looking at Fig. [15] which shows, as an example, the correlation between the values of the $u$-transversity $xh_1^{u\perp}$ and of the $d$-transversity $xh_1^{d\perp}$ extracted from all the existing proton and deuteron data (left plot) and when adding to all the existing proton data the projected data from the proposed run with the deuteron target (right plot). With the new deuteron run, proton and deuteron statistics will be well balanced, and the extracted $u$-
and $d$-transversity PDF will be essentially uncorrelated. The gain in the statistical accuracy of the $u$- and $d$-

and $d$-transversity PDF will be essentially uncorrelated. The gain in the statistical accuracy of the $u$- and $d$-

transversity PDFs is given by the comparison of the two plots shown in Fig. 16. The gain in the integrated
values of the transversity PDF, that is for the (truncated) tensor charges, is given in Table 1.

An alternative way to address the transversity function is via the dihadron asymmetries. Thanks to the large
COMPASS phase space the statistics of our di-hadron sample is very good, which makes our di-hadron mea-
surement almost unique. Consequently, the uncertainties in the extracted $xh_{1,u}$ and $xh_{1,d}$ values from the di-hadron asym-
metries are almost the same than for the Collins asymmetry case. The calculation of the projected errors for
$xh_{1,u}$ and $xh_{1,d}$ using the formulas of Ref. [36] is straightforward and the expected gain in the accuracy with
respect to the present situation is given in Fig. 17. The gain in accuracy is very similar to that expected from
the one hadron Collins asymmetry, namely up to a factor of 4 for the $d$-quark at large $x$, and up to a factor of
Table 1: Tensor charges in the range $0.008 < x < 0.21$ from the all existing proton and deuteron data (“present”) and with the projected uncertainties for the deuteron data (“projected”) from the three different methods (see [27]).

<table>
<thead>
<tr>
<th>Method</th>
<th>Present</th>
<th>Projected</th>
<th>Present</th>
<th>Projected</th>
<th>Present</th>
<th>Projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical integration</td>
<td>$0.201 \pm 0.032$</td>
<td>$0.201 \pm 0.019$</td>
<td>$-0.189 \pm 0.108$</td>
<td>$-0.189 \pm 0.040$</td>
<td>$0.390 \pm 0.087$</td>
<td>$0.390 \pm 0.044$</td>
</tr>
<tr>
<td>Method 1</td>
<td>$0.188 \pm 0.031$</td>
<td>$0.184 \pm 0.020$</td>
<td>$-0.182 \pm 0.102$</td>
<td>$-0.190 \pm 0.037$</td>
<td>$0.370 \pm 0.083$</td>
<td>$0.374 \pm 0.041$</td>
</tr>
<tr>
<td>Method 2</td>
<td>$0.187 \pm 0.029$</td>
<td>$0.184 \pm 0.018$</td>
<td>$-0.183 \pm 0.089$</td>
<td>$-0.194 \pm 0.031$</td>
<td>$0.370 \pm 0.071$</td>
<td>$0.378 \pm 0.035$</td>
</tr>
</tbody>
</table>

As underlined in Ref. [37] it is not clear whether the extracted di-hadron asymmetry and the Collins asymmetry can be regarded as independent (the data sample being the same), still this asymmetry is important because of the different evolution of the di-hadron fragmentation function and because of its interpretation in collinear QCD.

As outlined in the Addendum, transversity is not the only physics output of the new run. Most important advances will concern all the measured channels and in particular the Sivers function.

4 Hadron multiplicities and fragmentation functions

4.1 Measurement of charged kaon multiplicities

As discussed in the last annual report, a considerable tension was observed for NLO pQCD fits [38] with the results for charged kaon multiplicities [39] in the region of large $z$, where $z$ is the fractional energy the hadrons carry from the virtual photon energy $\nu$. Up to now only the region with $z < 0.85$ was studied in deep inelastic scattering.

To shed further light onto this finding COMPASS did a study of the kaon multiplicity ratio $K^- / K^+$, $R_K$, at very high $z$, namely $0.75 < z < 1$ [40], where multiplicities are small. As already described in the last annual report, in the ratio most uncertainties cancel (experimental systematics, uncertainties on radiative corrections). Using the full 2006 statistics and more triggers than in our published kaon data analysis, high precision is obtained. The analysis is performed for $0.01 < x < 0.40$. The result for the ratio vs. $z$ is shown in Fig. 18.
4.1 Measurement of charged kaon multiplicities

Fig. 18: Left: $z$ dependence of the ratio $R_K$ for the two $x$ bins. The insert shows the double ratio $D_K$. Right: Comparison of $R_K$ in the lower $x$ bin with expectations from LO and NLO pQCD.

The results for the lower $x$ bin are compared in Fig. 18 (right) to a LO lower boundary value for $(\bar{u} + \bar{d})/(u + d)$ of $0.469 \pm 0.015$ calculated at $x = 0.03$ using MSTW08 PDFs (LO LOWER LIMIT). Also shown are predictions using the Lund model or LO and NLO DSS fits. Note that using other PDFs, similar values within $\pm 10\%$ are obtained. Surprisingly, the data go far below the expectations. The same conclusion is also true for the higher $x$ bin.

The ratio $R_K$ was further investigated choosing seven bins in $\nu$. The resulting $\nu$ dependence is shown in Fig. 19 in bins of $z$. A strong dependence on $\nu$ is observed in most of the $z$ bins. While at large $\nu$ and lower $z$ the ratio is compatible with the QCD expectations, large deviations are observed at low $\nu$ (and high $z$). The results provide additional evidence that the above mentioned tension with NLO pQCD is of physical origin.

Fig. 19: The ratio $R_K$ as a function of $\nu$ in bins of $z$, shown for the lower $x$ bin.

If the produced kaon carries a large values of $z$, there is only a small amount of energy left to fulfill conservation laws as e.g. those for strangeness and baryon number, which are not taken into account in the pQCD expressions for the SIDIS cross section. The natural variable to study the “exclusivity” of a process is the missing mass $M_X$, which can be expressed as function of $z$, $\nu$ and $Q^2$, so that both the $z$ and $\nu$ dependence of $R_K$ may be described simultaneously by this variable. As is shown in Fig. 20, $R_K$ follows a rather smooth behaviour as function of $M_X$. Note, that our data can be reconciled with the standard pQCD predictions only above a rather high value of $M_X$ of about $4\text{ GeV}/c^2$. The investigation of multiplicity ratios at high $z$ from the 2006 data is
being continued studying proton/antiproton multiplicity ratios.

The investigation of multiplicities will now be continued using the 2016/17 data.

4.2 Radiative corrections for SIDIS measurements

One of the largest contribution to the systematic uncertainty of the published pion and kaon multiplicities is the contribution from radiative corrections. Up to now an analytic calculation was performed using the code TERAD [41] for the total correction for inclusive and semi-inclusive reactions in a grid of $x$ and $y$, where $y$ is the fractional energy transfer by the virtual photon. The dependence on the fractional hadron energy $z$ is not available in these calculations, so that the intergrated correction was used in the analysis and for the error estimate. Moreover, the change in the hadron kinematics due to the radiation of a hard photon was not accounted for in the MC simulation used for acceptance calculation.

To overcome both limitations it was tried to use the generator RADGEN [42], but we were unable to reach a good description of the COMPASS data, especially for the electron distributions. Thus, a new project was launched with the aim to find a better generator that generates events with internal Bremstrahlung which could be integrated into the COMPASS MC simulation. As generator the program DJANGOH [43] that was developed for DIS measurements at the HERA electron-proton collider was chosen. It was modified to be used with a muon beam and fixed target kinematics and is now integrated in the new COMPASS simulation code TGEANT based on GEANT4. Detailed studies were performed comparing the $z$ integrated new radiative corrections with the previously calculated ones yielding a very satisfactory agreement. The $z$ dependence of the new radiative corrections is shown in Fig. 21 in the bins of $x$ and $y$ used for the multiplicity analysis. These corrections have been obtained at generator level for a 160 GeV scattering off hydrogen. The new generator will be used in the future multiplicity analyses (For a comparison to the 2016/17 data see Sec. ??).

5 Status of the 2016-17 data analysis

5.1 Status of the data production and new tools for quality check

The entire DVCS data-taking time of 2016 and 2017 was divided into eleven and nine periods, respectively. During the data-taking special attention was given to keep the experimental conditions stable within a given period. Each of the periods consists of several consecutive sub-periods with positive and negative beam charges. The alignment (determination of detector positions and orientations) and subsequent event reconstruction (data production) campaigns are carried out for each period separately. The alignment is an iterative and time-consuming analysis, which requires several data productions to test the quality and to identify possible prob-
5.1 Status of the data production and new tools for quality check

Fig. 21: Radiative correction factor $\eta^h$ for hadron multiplicities vs. $z$ obtained using a 160 GeV muon beam scattering off hydrogen.

lems. By now reasonably good alignment has been achieved for the periods corresponding to the second half of 2016 and preliminary alignment is available for 2017 periods. The first half of 2016 data has been affected by event-scrambling for the DC05-detector. It took time to identify the problem and to apply the correction. Along with standard reconstruction and alignment software, a new software tool has been developed for detector performance studies providing information about alignment quality. Using raw hit and reconstructed track-hit information it calculates efficiency maps for each detector plane. Here the efficiency is either an unbiased efficiency or pseudo-performance (detector efficiency convoluted with the tracking efficiency). This new analysis tool in particular produces: resolution, time resolution and alignment quality histograms. These histograms are then used to study time-calibrations and RT relations for drift detectors, to determine effective resolutions and to evaluate alignment quality (basic alignment along measurement axis, alignment of the dead-zones). Another new package was developed to simultaneously monitor average detector pseudo-performances of all COMPASS tracking detector planes. An example of such an output (the so-called Hit-Map-Efficiency plot) is shown in Fig. 22. This monitoring tool allows to make quick evaluation of the alignment quality and possible tracking-related correlations.

In parallel a detailed analysis of the tracking detector profiles has been performed to check stability and performance of the apparatus during the data taking. By plane profile we mean number of counts per run as function of the channel number. If the detector plane is stable in time, the profile (once properly normalized) is expected to be the same for the different runs. The profile analysis, carried out grouping runs according to their period and beam charge, allows to identify, for each plane, missing channels or regions also via a graphical output (Fig. 23 on left). Instabilities (Fig. 23 on right) are identified with a statistical study of the profile evolution along each period. Mean and RMS values, extracted for each run, are compared to their average: a global analysis of resulting pull distributions of the mean value and of the RMS is successful in the identification of the unstable detector planes. The information on the unstable plane regions to be excluded during data processing (about 2% of the overall planes) and on the missing plane regions (about 3.5% of the overall planes) are then used in the MC geometry in order to improve the event simulation. The exclusion of detector planes from processing does not necessary imply a reduction of the final data sample of the same amount: the effect on the data is generally much smaller, achieved by the large number of detector planes.

In past year, we had in total over 12 data-production iterations for different periods of 2016 and 2017 and over 10 so-called DDD (DAQ Digit Decoding) service-productions to extract ECAL calibrations. It has to be mentioned that starting from January we are facing constant problems with file-fetching from CASTOR.
Fig. 22: Hit-Map-Efficiency plot (2016 P07 period, production slot t4, run 274510). The blue points correspond to pseudo-efficiencies of different tracking-detector planes. The horizontal lines indicate the corresponding planes (specific abscissa coordinates are assigned to different detectors as shown in lower right panel).

This is caused by quite high activity-rate in the tape system (a lot of data-reconstruction and data-recording by the LHC experiments) and internal repacking activities communicated by the CASTOR-management. As a result data-production takes significantly longer, which delays the analyses. Nevertheless, since September 2017 we are running the productions using newly developed production-system (PanDA-based system running on HTCondor batch system), which performs much more effectively compared to the old one (LSF-based...
5.2 Electromagnetic Calorimeter Calibration

system, now outdated because of LSF phase-out). In addition, we are currently working on integration of the new PanDA-based COMPASS production system at “Blue Waters” supercomputer (NCSA at the University of Illinois at Urbana-Champaign). This will allow us to run some relatively fast parallel productions also on the “Blue Waters” supercomputer and we already started to transfer the 2016 and 2017 data to the “Blue Waters” storage system. In parallel with the experimental data productions, we are running dedicated Monte-Carlo data simulations based on the same alignment files. Some of those simulation chains have already been migrated to the “Blue Waters”, which allow to generate large amount of MC in a reasonably short time.

5.2 Electromagnetic Calorimeter Calibration

Once per year of data taking, the Electromagnetic Calorimeters, ECAL1 and ECAL2, were calibrated online using a 40 GeV electron beam illuminating all the 5000 cells of the calorimeters, cell by cell. The time evolution of the performance of each cell during data taking is monitored by a laser light system for ECAL1 and by Light-Emitting Diode (LED) signals for ECAL2. This evolution is corrected in the offline analysis, by applying a rescaling factor on the run by run basis. The correction procedure is further fine-tuned by employing the reconstructed mass of \( \pi^0 \) in \( \pi^0 \rightarrow \gamma\gamma \). The LED system is a priori very stable, but an instability of the generator power, which caused jumps in the LED signal output, was identified. This issue has been corrected by applying an additional renormalization factor, which was evaluated based on comparing the global behavior of all the LEDs between runs. The effect of applying the renormalization factor correction is illustrated in Fig. 3.

A more refined correction, taking into account the Front-End Monitoring (FEM) signals that directly reflect the generator power evolution, will be applied to accurately resolve this instability.

Fig. 24: Invariant masse of two-photon clusters registered by ECAL2 in the 2016 P09 period, production slot t2. The two peak structure around the \( \pi^0 \) mass is gone after applying the renormalisation factor correction.

5.3 Monte-Carlo Simulation

A crucial ingredient for cross section determination is the precise knowledge of the acceptance, which includes the geometric and kinematic acceptances of the experimental set-up as well as detector efficiencies, resolutions and bin migration. The aim in the 2016/17 analysis is to improve the acceptance determination considerably compared to the MC simulations used in previous publications.

For the MC simulations we use the newly developed software package TGEANT (GEANT4-based COMPASS spectrometer simulation tool), which is based on the GEANT4 package, and includes a full simulation of the 2016/17 spectrometer set-up. Moreover, as reported in Sec. 4.2 a generator for radiative events can be included when generating DIS events.

In a first step, MC simulations for DIS are performed, which then are compared in detail to data distributions in detectors and for kinematic variables. For the data we are using the newly reconstructed data from 2016 P07
period, production slot t4, where most recent calibrations and detector alignments together with optimisation of the tracking were used in the reconstruction of the data set.

![Graphs showing Q^2, ν, z distributions for data of P07(2016) and MC.](image)

**Fig. 25:** $Q^2$ (top left), $\nu$ (top right) and $z$ (bottom left) distribution for data of P07(2016) and MC. Bottom right: Distribution of the azimuthal angle in the production plane for identified electrons in data and MC.

Figure 25 shows a first comparison of data and MC distributions for some kinematic variables, i.e. $Q^2$, $\nu$ and $z$. The overall agreement when summing over the physics triggers is quite reasonable, but observe that the statistics of the MC simulation is much lower than for the data. If one studies in detail other kinematic variables and distributions in the detectors, e.g. in the trigger hodoscopes, some differences are observed. Currently we are going through all the differences and check detector descriptions in the MC and the reconstruction software. The next step will be to incorporate detailed efficiencies, especially for the trigger detectors and regions with low redundancy.

The comparison for the azimuthal distribution of electrons in the production plane is shown in Figure 25 (bottom right). The peak at small angles is due to conversion electrons from Bremsstrahlung photons. The data distribution is quite well reproduced by the MC simulation with the DJANGOH generator. This is in contrast
5.4 Determination of $F_2$ and $\mu^+/\mu^-$ comparison

A good reconstruction and simulation of scattered muons is an important ingredient for the determination of DVCS cross sections. A detailed test of the quality can be performed using inclusive deep inelastic scattering measuring the well-known structure function $F_2(x, Q^2)$.

For this analysis the most recent production of 2016 P07 period, production slot t4 is used. To determine the acceptance two paths were followed. In one case we use a TGEANT MC simulation without radiative event generation. In the second case we use TGEANT with DJANGOH, where radiative events are included in the MC simulation. Both approaches yield quite compatible results for the acceptance. Below some results for the second simulation will be shown.

In addition to the acceptance, the flux of incoming muons is required for a cross section determination. In COMPASS the flux is measured using a true random trigger based on a radioactive source located far away from the experimental area. The flux is obtained counting reconstructed beam tracks that pass the liquid hydrogen target within the fiducial volume, which was determined using reconstructed events with an interaction vertex in the target region. The flux also includes the DAQ and veto deadtime of the experiment.

The determination of $F_2$ was done separately from the data of each trigger system. In Fig. 26 we show as an example the results for the acceptance and $F_2(Q^2)$ for the so-called middle trigger in two bins of $x$, a kinematic region with high acceptance for the middle trigger. As can been seen, the acceptance is quite flat at low $Q^2$ and drops fast at high $Q^2$ due to the geometry of middle trigger detectors. Albeit the MC statistics is still quite small, it is visible that the acceptance for positive and negative scattered muon is very similar (as expected from the set-up). The results for $F_2$ for data taken with $\mu^+$ and $\mu^-$ beam are quite close to the predictions obtained from the NMC $F_2$ measurements, with the $\mu^-$ results a few percent below the $\mu^+$ results. Even when the acceptance quickly drops below 20%, the results are close to the prediction indicating the good quality of the MC simulations.

At higher $Q^2$ the agreement with the prediction is getting worse, a similar observation is made for the other trigger systems. Thus, it is obvious that the data selection and acceptance calculation need further improvements. A thorough scrutinizing of the data quality on spill basis has been started, with the aim to remove spills with problems in the spectrometer or muon beam during data taking. As already mentioned above, also more detailed efficiency information has to be provided for the MC simulations.
5.5 Selection of exclusive $\rho^0$ events with CAMERA and $\mu^+ / \mu^-$ comparison

To determine very accurately the DVCS cross section for both $\mu^+$ and $\mu^-$ beams it is necessary to have a good reconstruction and simulation of the scattered muons, outgoing photon, recoiling proton as well as a good determination of the muon flux. Already a few points have been addressed in the previous section with a comparison to the well-known structure function $F_2(x, Q^2)$. Another important achievement will be a comparison to the well-known Bethe-Heitler cross section. We have to recall that during the pilot DVCS run in 2012, the DVCS data was collected at a $\mu^+$ beam intensity 2.7 times higher than that of the $\mu^-$ beam. The exclusive event yields for the two beam charges, normalized to the corresponding integrated beam fluxes, showed a residual discrepancy of about 25%. For the 2016-17 data taking it has been decided to use rather similar $\mu^+$ and $\mu^-$ beam intensities.

As far as the Electromagnetic Calorimeters are not yet fully calibrated (see section 5.2) we can look at exclusive $\rho^0$ production to investigate the agreement between the two beam charges. The exclusive production of $\rho^0$ corresponds to the reaction $\mu p \rightarrow \mu' \rho^0 p$ where $\rho^0$ decays in $\pi^+ \pi^-$. If we detect the 4 particles of the final state, i.e. the muons and pions in the COMPASS spectrometer and the proton in the recoil proton detector CAMERA, the exclusive reaction kinematics is overdetermined and the selection of exclusive events is done by cuts on the differences between the observables given by the spectrometer alone and those using CAMERA. If we denote $k, k', q, q', p, p'$ the four-momenta of the incident muon, outgoing muon, virtual photon, $\rho$ meson, target proton, outgoing proton respectively, $t = (q - q')^2 = (p - p')^2$ the transfer to the proton target, $\nu$ the energy of the virtual photon in the lab, the missing energy is defined by $E_{\text{miss}} = (M_X^2 - M_p^2)/2M_p$ where $M_X^2 = (k + p - k' - q)^2$ and $M_p$ is the proton mass.

![Fig. 27: Missing energy distributions for the selection of exclusive $\rho^0$ production for $\mu^+$ beam (in red) and $\mu^-$ beam (in blue) for two periods, P09, production slot t1 and P07, production slot t4. The following cuts are also applied: $0.05 < \nu/E < 0.9$, $0.2 < Q^2 < 10$ (GeV/c)$^2$, $80 < \nu < 144$ GeV, and $0.08 < t < 0.64$ GeV$^2$](image)

The missing energy distributions are represented in Fig. 27 for two periods, P09, production slot t1 and P07, production slot t4 for both $\mu^+$ and $\mu^-$ data sets. We can see that the ratio of exclusive $\rho^0$ events obtained for the two muon beam charges, $N_{\mu^+} / N_{\mu^-}$, is rather close to 1, but still varying between 0.99 and 1.03. The value of 1.03 for the P07 period, production slot t4 is also observed for $F_2$ determination (see Fig. 26). As mentioned before a thorough scrutinizing of the data quality on spill basis has been started as well a cross check of the beam flux normalisation determination. A slight shift of the center of the $E_{\text{miss}}$ distribution of less than 0.5 GeV is observed for both $\mu^+$ and $\mu^-$ beams on the P09 period, production slot t1 but only for the $\mu^+$ beam for the P07 period, production slot t4. $E_{\text{miss}}$ is rather sensitive to a very accurate determination of the 4-momenta of the particles in the spectrometer and in the beam momentum station. This reveals still small improvements to be done for track or incident beam reconstruction.
5.6 Estimate of the statistics collected in 2016 and 2017

Table 2 summarizes the statistics of collected muons for each muon charge during every year. These numbers are corrected for the DAQ live time and Veto live time. We can note the good balance between $\mu^+$ and $\mu^-$ data sets. We can remark that the statistics cumulated in 2017 in 1.8 times larger than in 2016 (mainly due to higher intensity).

In contrast to 2012 we have chosen to work in 2016 and 2017 with similar intensity for the two charges (changing the thickness of the T6 target from 500 mm to 100 mm). However the beam structure of 2 spills with $150 \cdot 10^{11}$ protons on T6 every 36 s is more favorable than 1 spill with $150 \cdot 10^{11}$ protons on T6 every 48 s. In total in 2016 and 2017 we have collected $5.6 \cdot 10^{12}$ muons. This raw number has to be corrected by a factor of about 0.80 for rejection of spills with problems. If so, the resulting number of muons is about 10 times more than the total number of used muons in the published COMPASS result \cite{44} with the 2012 data.

<table>
<thead>
<tr>
<th>Year</th>
<th>Spill Structure</th>
<th>$I_{\text{proton}}$ on T6 per spill</th>
<th>$I_{\mu}$ on IonCH per spill</th>
<th>Nb of spills</th>
<th>DAQ life time</th>
<th>Veto life time</th>
<th>Nb of collected muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>130 days - mainly 2 spills of 4.8 s every 36 s</td>
<td>$100 \cdot 10^{11}$</td>
<td>$7.6 \cdot 10^7$</td>
<td>135527</td>
<td>0.93</td>
<td>0.95</td>
<td>$10.0 \cdot 10^{12}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$70 \cdot 10^{11}$</td>
<td>$5.3 \cdot 10^7$</td>
<td>18592</td>
<td></td>
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<tr>
<td></td>
<td>$\mu^+$</td>
<td>$100 \cdot 10^{11}$</td>
<td>$6.3 \cdot 10^7$</td>
<td>143848</td>
<td>0.94</td>
<td>0.95</td>
<td>$9.2 \cdot 10^{12}$</td>
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<td>$70 \cdot 10^{11}$</td>
<td>$4.4 \cdot 10^7$</td>
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<tr>
<td></td>
<td>$\mu^-$</td>
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<td></td>
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</tr>
<tr>
<td>2017</td>
<td>130 days - mainly 2 spills of 4.8 s every 36 s</td>
<td>$150 \cdot 10^{11}$</td>
<td>$12.5 \cdot 10^7$</td>
<td>168000</td>
<td>0.91</td>
<td>0.93</td>
<td>$17.8 \cdot 10^{12}$</td>
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<td>$10.5 \cdot 10^7$</td>
<td></td>
<td>195000</td>
<td>0.91</td>
<td>0.93</td>
<td>$17.3 \cdot 10^{12}$</td>
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<tr>
<td></td>
<td>$\mu^+$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\mu^-$</td>
<td></td>
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<tr>
<td>2012</td>
<td>30 days - 1 spill of 9.6 s every 48 s</td>
<td>$250 \cdot 10^{11}$</td>
<td>$50. \cdot 10^7$</td>
<td>0.84</td>
<td>0.73</td>
<td>1.87 \cdot 10^{12}</td>
<td>2.33 \cdot 10^{12}</td>
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<td></td>
<td></td>
<td>$17.5 \cdot 10^7$</td>
<td>0.94</td>
<td>0.89</td>
<td>1.87 \cdot 10^{12}</td>
<td>2.33 \cdot 10^{12}</td>
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</tr>
</tbody>
</table>

Table 2: Summary of the cumulated statistics in 2016, 2017 and 2012

5.7 Upgrade of the RICH detector

RICH-1 is an essential ingredient of the COMPASS spectrometer and its performance is guaranteed by continuous maintenance and by a second upgrade of the photon detection system, following the major upgrade performed during 2005–06.

The upgrade of the photon detection system consists in the replacement of the the MWPCs with CsI photon converters that equip the peripheral regions of the read-out system. The central region equipped with MAPMTs coupled to individual telescopes by fused silica lenses has remained unchanged. This upgrade is requested because the effective gain at which the MWPCs operate is well below $10^4$, limiting the effective photoelectron detection efficiency and, due to the long signal integration time, the time resolution and the rate capability. Moreover, in case of an occasional discharge, the ion accumulated at the CsI surface require long times, of the order of a day, to be neutralized, a time interval during which the detectors cannot be operated. The four MWPCs with the most critical parameters have been replaced with novel photon detectors, based on MPGD (Micro-Pattern Gas Detector) technology. They are hybrid MPGD detectors of single photons, a concept that has been developed in an eight-year R&D program. The detector architecture (Fig. 28) consists in
three multiplication stages: two THick GEMs (THGEM) layers, the first one coated with a CsI film and acting as photocathode, followed by a MicroMegas (MM) multiplication stage. The MMs are equipped with resistive layers: the anode elements (pads) facing the micromesh are individually equipped with large-value resistors and the HV is provided, via these resistors, to the anode electrodes, while the micromesh is grounded. A second set of electrodes (pads parallel to the first ones) are embedded in the anode PCB: the signal is transferred by capacitive coupling to these electrodes, which are connected to the front-end read-out electronics. The two THGEMs are staggered: this configuration is beneficial both to reduce the Ion BackFlow (IBF) and to increase the maximum gain at which the detector can be operated. These photon detectors can operate at gains up to larger than 104 and exhibit an IBF rate lower than 5%. In particular, the gain is about five time higher than the effective gain of the previous photon detectors, while the detection dead-area is about 10-15% smaller. The resulting number of detected photons is expected to increase by 10-20%. The increased gain makes it possible to apply higher electronic thresholds, resulting in a much more effective rejection of the electronic noise and, as a consequence, a cleaner imaging and easier pattern recognition. More relevant, the detector stability is greatly increased: occasional sparks cause only local dead-times of the order of no more than 10 s.

The novel photon detectors will make use of the APV25-based read-out electronics already in operation for the previous gaseous photon detectors. These detectors are operated in Ar-CH4 mixtures, rich in methane in order to maximize the photoelectron extraction.

The construction of four novel gaseous photon detectors has been completed and the detectors have been installed onto RICH-1 by April 15, 2016, in time for commissioning during the 2016 COMPASS run. The first-year commissioning exercises have included: studies of the electronic noise response in the experiment environment; the commissioning of the HV distribution system; studying the long-term electrical stability in the experimental environment. The commissioning studies have suggested several improvements, that have been applied during the Winter 2016-2017 shut-down period in order to provide fully revised and optimized detectors for the 2017 run.

The main figures concerning the novel detector performance have been obtained by on-line monitoring and a preliminary characterization exercise. They include:

- 95% of the active surface electrically fully stable;
- perfectly stable micromegas stage;
- current sparks at low rate are observed in the THGEMs, rate lower than 1/h for all the four new detectors;
- the time recovery after a current spark is about 10s;
- the combination of the current spark rate and the recovery time results in a fully negligible dead-time due to spark episodes;
- high gain between 13k and 14k for the four detectors measured analyzing the amplitude spectra of pure single photon amplitude spectra (Fig. 29);
- electronic noise level is at 900 electron equivalent (standard deviation);
- from the gain and noise figure, the single photoelectron detection efficiency is extracted: it is larger than 80%;
- the resolution in the measurement of the Cherenkov angle for single photoelectrons is about 1.7-1.8 mrad (Fig. 30);
- the preliminary estimate of the number of detected photoelectrons at saturation is 11 for data collected with radiator gas mixture with 75% of C4F10 and 25% of N2.

The novel COMPASS RICH-1 photon detector represent the first use in a RICH of MPGD-based sensors; it is also the first use of THGEM in an experiment; no MPGD has ever been operated at gains larger than 10k in an experiment.
The RICH radiator gas in 2017 The RICH-I design radiator gas is C₄F₁₀, so far always purchased from 3M. Polluting contaminants not present in all the previous batches are present in the batch purchased for the needs of the 2017 run. The presence of these pollutants is confirmed by gaschromatography. They could not be removed with standard techniques; therefore, the gas is not transparent in the VUV domain and could not be added to the gas already present in the RICH. This resulted in a shortage of radiator gas and, therefore, in 2017, RICH-I has been operated with a mixture of C₄F₁₀ and N₂. The C₄F₁₀ percentage was about 90% at the start of run and about 65% at the end of run. The gas mixture has been varied in steps corresponding to the data taking periods, so to have stable detector conditions within these periods. The decrease in the resolution is up to 15%, in number of detected photoelectrons up to 20%. A different gas provider has been identified for future needs. Gas samples have been purchased and they will be analyzed in view of future needs.

6 GPDs and Exclusive \( \omega \) production using the 2012 data

In the SPSC reports of June 2016 and May 2017 we have presented, respectively, the exclusive single photon production and exclusive \( \pi^0 \) production using the data with \( \mu^+ \) and \( \mu^- \) beams of 160 GeV energy scattering off the liquid hydrogen target, which were collected in the pilot run in 2012. Now we present the results on
exclusive $\omega$ meson production using the same data. The subject of the analysis was the extraction of 23 Spin Density Matrix Elements (SDMEs) for hard exclusive $\omega$ muoproduction on unpolarized protons.

### 6.1 Exclusive $\omega$ production and GPDs

The considered process is

$$\mu + p \rightarrow \mu' + p' + \omega, \quad (15)$$

which can be described by the interaction of a virtual photon $\gamma^*$ with one of the partons from the target proton $p$,

$$\gamma^* + p \rightarrow p' + \omega. \quad (16)$$

Such process is an important tool to access Generalized Parton Distributions (GPDs) \[45-49\]. The SDMEs describe the spin structure of the reaction (15). They are related to the helicity amplitudes that describe transitions between specified spin states of the virtual photon, target proton, produced vector meson and recoil proton. For an unpolarised nucleon target, after summing up over initial and final spin states of the proton, the SDMEs depend just on helicities of the virtual photon and produced meson. The values of SDMEs allow us to test the $s$-channel helicity conservation (SCHC) hypothesis, as well as to investigate the role of transversity (parton helicity-flip) GPDs and of the unnatural parity exchange (UPE) mechanisms in exclusive $\omega$ production.

In addition to the results on cross sections and target spin azimuthal asymmetries for exclusive vector meson production, the SDMEs can provide further constrains on the GPD parameterisations. The phenomenological GPD model that presently provides predictions for all three types of mentioned experimental observables is the one of Goloskokov and Kroll \[50-54\] (GK model). It is a so-called handbag model that contains terms beyond the collinear factorisation, which was proven rigorously only for longitudinally polarised virtual photons. The model is applicable for a comparison with results of existing measurements, also without transverse vs. longitudinal separation.

The recent HERMES measurements of SDMEs for exclusive electroproduction of $\omega$ mesons \[55\] indicate sizable contributions of the helicity-flip $\gamma_T^* - \omega_L$ processes and of UPE processes in the energy range covered by this experiment.

In the framework of GK model the processes $\gamma_T^* - \omega_L$ are described \[53\] predominantly by the transversity GPDs $\tilde{H}_T$ and $\tilde{E}_T = 2\tilde{H}_T - \bar{E}_T$ combined with the higher-twist meson wave function. The UPE exchanges can be described by GPDs $\tilde{H}$ and $\bar{E}$, which are related to quark helicity distributions. In the framework of the GK model it turns out \[54\] that the pion pole exchange, which represents a dominant part of GPDs $\tilde{E}$, is an important contribution needed to reproduce the HERMES results. The effect of the pion pole exchange decreases with $W$, which is confirmed by COMPASS.

### 6.2 Definitions and experimental access to Spin Density Matrix Elements

The vector meson spin density matrix $\rho_{\lambda_V, \lambda_N'}$ are related to the helicity amplitudes $F_{\lambda_V, \lambda_N, \lambda_N'}$. These amplitudes describe the transition of a virtual photon with helicity $\lambda_\gamma$ to a vector meson with helicity $\lambda_V$, while $\lambda_N$ and $\lambda_N'$ are the helicities of the nucleon in the initial and final states, respectively. A helicity amplitude can be decomposed into a sum of a natural parity exchange (NPE) amplitude $T$ and an unnatural parity exchange (UPE) amplitude $U$,

$$F_{\lambda_V, \lambda_N, \lambda_N'} = T_{\lambda_V, \lambda_N, \lambda_N'} + U_{\lambda_V, \lambda_N, \lambda_N'}, \quad (17)$$

for details see Refs. \[56, 57\]. Helicity amplitudes depend on $W$, $Q^2$, and $t' = |t| - t_0$, where $t$ is the square of the four-momentum transfer to the target proton and $t_0$ represents the smallest kinematically allowed value.
of $|t|$ for a given virtual-photon energy $Q^2$ and meson mass. The quantity $t'$ is approximately equal to $p_T^2$, which is the square of the transverse momentum of the vector meson with respect to the direction of the virtual photon. In the $\gamma^*N$ centre-of-mass (CM) system the spin density matrix of the vector meson is given by the von Neumann equation [56],

$$\rho_{\lambda_V\lambda_N} = \frac{1}{2N} \sum_{\lambda_N'\lambda_N} F_{\lambda_V\lambda_N'\lambda_N'}^{U+L} \rho_{\lambda_N'\lambda_N}^{U+L} F_{\lambda_N'\lambda_N'}^{U+L}$$

(18)

where $N$ is a normalization factor [56, 57] and $\rho_{\lambda_N'\lambda_N}^{U+L}$ is the virtual photon spin density matrix [57]. The photon spin density matrix describes the subprocess $(\mu \to \mu' + \gamma^*)$ and can be calculated in quantum electrodynamics.

In case when contributions of transverse and longitudinal photons cannot be separated, as in the present measurement, the SDMEs are customarily defined as

$$r^{04}_{\lambda_V\lambda_N} = (\rho_{\lambda_V\lambda_N}^0 + \epsilon R \rho_{\lambda_V\lambda_N}^4)(1 + \epsilon R)^{-1},$$

$$r^\alpha_{\lambda_V\lambda_N} = \begin{cases} \rho_{\lambda_V\lambda_N}^\alpha (1 + \epsilon R)^{-1}, & \alpha = 1, 2, 3, \\ \sqrt{R} \rho_{\lambda_N'\lambda_N'}^\alpha (1 + \epsilon R)^{-1}, & \alpha = 5, 6, 7, 8. \end{cases}$$

(19)

(20)

The quantity $R = d\sigma_L/d\sigma_T$ is the longitudinal-to-transverse virtual-photon differential cross-section ratio and $\epsilon$ is the virtual photon polarisation parameter.

The SDMEs in exclusive electroproduction of $\omega$ mesons are determined using the process in Eq. (15). They are fitted as parameters of the three-dimensional angular distribution $W_{\lambda_N'\lambda_N}(\Phi, \phi, \cos \Theta)$ to the corresponding experimental distribution. Here, three angles are used, which are the azimuthal angle, $\Phi$, of produced $\omega$ meson as well as the polar and azimuthal angles, $\Theta$ and $\phi$, describing the $\omega$ three-pion decay. The angular distribution $W_{\lambda_N'\lambda_N}$ is decomposed into $W_{\lambda_N'}$ and $W_{\lambda_N}$, which are the respective distributions for unpolarized and longitudinally polarized beams. From the fit, 15 “unpolarised” SDMEs and 8 “polarised” SDMEs are extracted from data collected with a longitudinally polarized beam. Definitions of angles and reference frames are given e.g. in Ref. [56]. The directions of the axes of the hadronic CM system and of the $\omega$ meson rest frame follow the directions of the axes of the helicity frame.

6.3 Event selection

In this analysis two event samples were selected: the sample (A) when only the information from the forward spectrometer was considered, and the sample (B) when in addition the information from the recoil proton detector called CAMERA was used. An event to be accepted for further analysis was required to have the same topology as that of the following process

$$\mu N \to \mu' N' \omega \quad \pi^+ \pi^- \pi^0 \quad \gamma \gamma.$$ 

Therefore, the selected event should contain an incident muon track, a scattered muon track, two tracks of hadrons with opposite charges and two neutral clusters in an electromagnetic calorimeter. For the sample (B), in addition at least one track in CAMERA was required. Most of further selections, such as the vertex and spectrometer tracks selections, $\pi^0$ reconstruction and kinematic selections on $Q^2$, $y$ and $W$, were either the same or similar to those used for the published results on azimuthal asymmetries for exclusive $\omega$ production on transversely polarised protons from ammonia target [59]. An exception was the selection of different $p_T^2$ ranges, which was $0.01 < p_T^2 < 0.5$ (GeV/c)$^2$ for the sample (A) and $0.1 < p_T^2 < 0.5$ (GeV/c)$^2$ for the

$$\mu N \to \mu' N' \omega \quad \pi^+ \pi^- \pi^0 \quad \gamma \gamma.$$ 

Therefore, the selected event should contain an incident muon track, a scattered muon track, two tracks of hadrons with opposite charges and two neutral clusters in an electromagnetic calorimeter. For the sample (B), in addition at least one track in CAMERA was required. Most of further selections, such as the vertex and spectrometer tracks selections, $\pi^0$ reconstruction and kinematic selections on $Q^2$, $y$ and $W$, were either the same or similar to those used for the published results on azimuthal asymmetries for exclusive $\omega$ production on transversely polarised protons from ammonia target [59]. An exception was the selection of different $p_T^2$ ranges, which was $0.01 < p_T^2 < 0.5$ (GeV/c)$^2$ for the sample (A) and $0.1 < p_T^2 < 0.5$ (GeV/c)$^2$ for the
sample (B) compared to $0.05 < p_T^2 < 0.5(\text{GeV}/c)^2$ for the ammonia target. In order to suppress non-exclusive background, for the sample (A) a cut $|E_{\text{miss}}| < 3.0 \text{ GeV}$ was applied, with $E_{\text{miss}} = \frac{M^2 - p_T^2}{2M_P}$, where $M_P$ is the proton mass and $M^2 = (p + q - p_{x+} - p_{x-} - p_{\pi^0})^2$ is the missing mass squared, and $p, q, p_{x+}, p_{x-}$ and $p_{\pi^0}$ are the four-momenta of target nucleon, virtual photon and each of the three pions. For the sample (B), instead of the above cut a number of “exclusivity” selections were applied that are analogous to those for DVCS and exclusive $\pi^0$ analyses. These selections exploit the fact that for an exclusive event the kinematics is constrained by measurements from both the spectrometer and CAMERA. The sample (A) consists of 3060 events and was used for our final results, while the sample (B) contains 761 events. The later one was used for consistency checks, mostly to verify correctness of accounting for non-exclusive background in sample (A).

Selected kinematic distributions for the sample (A) are shown in Fig. 31. These are $E_{\text{miss}}$ distribution, the invariant mass of two photons and the invariant mass of $\pi^+\pi^-\pi^0$ system. Clear $\pi^0$ and $\omega$ signals are observed. In the $E_{\text{miss}}$ distribution the data are shown as open histogram, while the shaded one corresponds to the background evaluated using LEPTO Monte Carlo (MC). The amount of background in the signal window $|E_{\text{miss}}| < 3.0 \text{ GeV}$ depends on $Q^2, W$ and $p_T^2$, and when averaged over the whole sample it amounts to 28%.

$$E_{\text{miss}} = \frac{(p^2 - M_X^2)}{2M_P}$$

Fig. 31: Left: $E_{\text{miss}}$ distribution. Shaded histogram corresponds to non-exclusive background estimated using LEPTO MC. Middle: The $\gamma\gamma$ invariant mass distribution fitted by a sum of Gaussian function and a linear dependence for background. Right: The $\pi^+\pi^-\pi^0$ invariant mass fitted by a sum of Breit-Wigner function and a linear dependence for background. Dashed vertical lines denote the PDG values.

The SDMEs were determined by using the Unbinned Maximum Likelihood method to fit the function $W(R; \Phi, \cos \Theta, \phi)$ to the experimental three-dimensional angular distribution of $\omega$ production and decay. Here $R$ denotes the set of 23 SDMEs $r_{\lambda V, \lambda' V'}$. The fitted distribution was a weighted superposition of $W$ distributions for exclusive events and non-exclusive background. The fraction of background in the signal window was determined using $E_{\text{miss}}$ distribution as illustrated in Fig. 31. The parameters describing the background angular distributions were pre-determined by fitting either angular distributions in the signal window from LEPTO MC or distributions for real data in the $E_{\text{miss}}$ range outside of the signal window.

### 6.4 Results

SDMEs for exclusive $\omega$ production extracted for the entire kinematic region with $\langle Q^2 \rangle = 2.13 (\text{GeV}/c)^2$, $\langle W \rangle = 7.6 \text{ GeV}$ and $\langle p_T^2 \rangle = 0.16 (\text{GeV}/c)^2$ are presented in Fig. 32. These SDMEs are divided into five classes corresponding to different helicity transitions. The main terms in the expressions of SDMEs by helicity amplitudes of class A, correspond to the transitions from longitudinal virtual photons to longitudinal vector mesons, $\gamma_L^+ \to V_L$, and from transverse virtual photons to transverse vector mesons, $\gamma_T^+ \to V_T$. In class B the dominant terms correspond to the interference of the above two transition. The main terms of SDMEs in classes C, D and E are proportional to the products of small amplitudes describing $\gamma_T^+ \to V_L$, $\gamma_L^+ \to V_T$ and $\gamma_T^+ \to V_T$ transitions, respectively.

In Fig. 32 polarised SDMEs are shown in the shaded areas. Experimental uncertainties of these SDMEs are larger than those of the unpolarised SDMEs, because the lepton beam polarisation is smaller than unity ($|P_h| \approx 80\%$) and in the equation for the angular distribution they are multiplied by the small kinematic factor.
Fig. 32: The 23 SDMEs for exclusive $\omega$ leptoproduction extracted in the entire COMPASS kinematic region with $\langle Q^2 \rangle = 2.13$ GeV$^2$, $\langle W \rangle = 7.6$ GeV, $\langle p_T^2 \rangle = 0.16$ GeV$^2$. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in the unshaded (shaded) areas.

$|P_0|\sqrt{1 - \epsilon}$, where $\epsilon \approx 0.96$.

In case of SCHC only the seven SDMEs of classes A and B are not restricted to vanish. Six of them have to fulfill the following relations:

$$r_{1-1} = -\text{Im}\{r_{1-1}^2\},$$
$$\text{Re}\{r_{10}^5\} = -\text{Im}\{r_{10}^6\},$$
$$\text{Im}\{r_{10}^7\} = \text{Re}\{r_{10}^8\}.$$

The extracted SDMEs are consistent within uncertainties with these relations:

$$r_{1-1}^1 + \text{Im}\{r_{1-1}^2\} = -0.010 \pm 0.032 \pm 0.047,$$
$$\text{Re}\{r_{10}^5\} + \text{Im}\{r_{10}^6\} = 0.014 \pm 0.011 \pm 0.013,$$
$$\text{Im}\{r_{10}^7\} - \text{Re}\{r_{10}^8\} = -0.088 \pm 0.110 \pm 0.196.$$

Here, the first uncertainty is statistical and the second systematic.

However, for the transition $\gamma_T^* \to V_L$ (class C) one can observe a clear violation of SCHC. In the GK model [53] the SDMEs from class C are related to the contributions from transversity GPDs $\bar{E}_T$ and $H_T$ coupled with the higher-twist wave function of the meson. Kinematic dependences of these SDMEs may help to further constrain the model. As an example the results for SDME $r_{10}^5$, which is expected to be mostly affected by GPDs $\bar{E}_T$,
are shown in Fig.33. A point worth mentioning is that \( r_{00}^5 \propto \sqrt{p_T^2} \) for \( p_T^2 \to 0 \) as a consequence of angular momentum conservation.

![Graph](image1)

**Fig. 33:** Dependence of SDME \( r_{00}^5 \) on kinematic variables \( p_T^2, Q^2 \) and \( W \).

The existence of processes with unnatural parity exchange (UPE) in \( \omega \) production on the proton can be tested by examining linear combination of SDMEs such as

\[
u_1 = 1 - r_{00}^{04} + 2r_{11}^{04} - 2r_{11}^1 - 2r_{11}^1.
\]  

(21)

The quantity \( u_1 \) can be expressed in terms of helicity amplitudes as

\[
u_1 = \sum_{\lambda_N \lambda_N'} 4|U_{1\lambda_N'0\lambda_N}|^2 + 2|U_{1\lambda_N'1\lambda_N} + U_{-1\lambda_N'1\lambda_N}|^2.
\]  

(22)

As one can observe the numerator depends only on UPE amplitudes. Therefore, the different from zero value of \( u_1 \) would indicate a contribution of UPE processes. The kinematic dependence of \( u_1 \) on \( Q^2, W \) and \( p_T^2 \) is shown in Fig.34.

![Graph](image2)

**Fig. 34:** Dependence of quantity \( u_1 \) on kinematic variables \( Q^2, W \) and \( p_T^2 \). The open symbols represent the values over entire kinematic region.

In the GK model the dominant UPE process is the pion pole exchange [54], which implies decrease of \( u_1 \) with \( W \). The data support the expected decrease of UPE with \( W \).

### 7 Drell-Yan

In this section, various ongoing physics analyses using (un)polarized Drell-Yan (DY) data collected in 2015 are described. The modifications to the DY setup implemented for the 2018 data-taking period, and the present status of the 2018 Run are discussed.
The first ever polarized DY measurements were performed by the COMPASS experiment in 2015, during 106 effective days of physics data-taking. A relatively long period of target system and spectrometer commissioning was required at that time, before physics data could be collected. In 2018, thanks to the experience gained, this period is significantly shortened.

A negative pion beam of 190 GeV/c momentum (with 2.5% contamination from kaons and 0.5% from antiprotons), interacts in a set of targets: two transversely polarized ammonia cells, followed by a thin aluminum target (5 cm) and a 120 cm long tungsten plug (serving as beam dump and target). The presence of a massive hadron absorber immediately downstream of the polarized target keeps the detector occupancies relatively low, even at the nominal beam intensity of $\approx 1 \times 10^8$ particles/second, but degrades significantly the dimuon resolutions.

The target polarization is built up in the 2.5 T field of the superconducting solenoid magnet and rotated to the transverse direction with the 0.6 T dipole magnet, that holds the polarization for one week physics data taking. The average target proton polarization over the one week period is $\approx 75\%$. The relaxation time of the proton polarization at 0.6 T was measured in 2015 to be 500-1000 hours.

### 7.1 2015 polarised Drell-Yan data: $q_T$-weighted transverse spin asymmetries

The results on the target transverse spin dependent azimuthal asymmetries (TSAs) in DY were published in PRL journal in 2017 [67]. Soon after the TSA results were released we focused on the extraction of the $q_T$-weighted DY TSAs, an alternative way to access transverse momentum dependent (TMD) parton distribution functions (PDFs).

The nucleon structure can be described at leading twist by eight TMD PDFs which depend on the longitudinal momentum fraction $x$ and on the transverse component of the parton momentum $k_{T}^2$. They are probed in Semi-inclusive deep inelastic scattering (SIDIS), where the cross-section contains convolutions of the TMD PDFs and fragmentation functions. Comparison of SIDIS with the DY process, which gives access to convolutions of the TMD PDFs of the two colliding hadrons, can provide a test of the TMD PDFs universality and of the fundamental prediction of the Sivers (and Boer-Mulders) function(s) sign change, one of the main objectives of the pioneering COMPASS DY measurement.

The convolutions of TMDs that are present in the TSA observables are usually solved assuming a certain functional form of their dependence on $k_{T}^2$ (e.g. Gaussian). This assumption can be avoided in SIDIS measuring the TSAs weighted with powers of the outgoing hadron transverse momentum $P_T$ (see section 3.2.1) and in DY measuring the TSAs weighted with powers of dimuon transverse momentum $q_T$ [33, 60]. These transverse momentum weighted TSAs offer a complementary approach to the standard TSAs, their advantage being a more straightforward interpretation.

#### Measured asymmetries

The structure functions $F_{U,T}^{X_q}$ in the DY cross-section, which are the amplitudes of the $x$ modulation, can be written as convolutions of TMD PDFs over the intrinsic transverse momenta of the two colliding partons [61]. When the structure functions are integrated over $q_T$ with properly chosen weights, the convolutions can be disentangled:

$$\int d^2 q_T F_{U}^{1} = \frac{1}{3} \sum_q e_q^2 \left[ f_{1,\pi}^q(x_{\pi}) f_{1,N}^q(x_N) + f_{1,\pi}^q(x_{\pi}) f_{1,N}^q(x_N) \right]$$  \hspace{1cm} (23)

$$\int d^2 q_T \frac{q_T}{M_p} F_{T}^{\sin \phi_S} = -\frac{2}{3} \sum_q e_q^2 \left[ f_{1,\pi}^{(1)}(x_{\pi}) f_{1,T_p}^{(1)}(x_{\pi}) + (q \leftrightarrow \bar{q}) \right]$$  \hspace{1cm} (24)

$$\int d^2 q_T \frac{q_T^3}{2M_p M_p} F_{T}^{\sin(2\phi + \phi_S)} = -\frac{2}{3} \sum_q e_q^2 \left[ h_{1,\pi}^{(1)}(x_{\pi}) h_{1,T_p}^{(2)}(x_{\pi}) + (q \leftrightarrow \bar{q}) \right]$$  \hspace{1cm} (25)
Fig. 35: The $q_T$-weighted TSAs. The systematic uncertainty is denoted by blue bands. The normalisation uncertainties of about 8% (from target polarisation and dilution factor) are not shown.

\[
\int d^2q_T \frac{q_T}{M_\pi} \Gamma_T^{\sin(2\phi_S - \phi_S)} = -\frac{2}{3} \sum_q e_q^2 \left[ h_{1,T,\pi}^{(1)}(x_\pi) h_{1,u,p}^q(x_N) + (q \leftrightarrow \bar{q}) \right].
\] (26)

The sums run over quarks and antiquarks $q$, $e_q$ are quark fractional electric charges, and $M_{\pi,p}$ are the pion and proton masses. The functions $f^{(n)}$ or $h^{(n)}$ are the $n$-th $k_T^2$-moments of the TMD PDFs, e.g. $f^{(n)}(x) = \int d^2k_T \left[ k_T^2/(2M^2) \right]^n f(x,k_T^2)$.

We have measured the $q_T$-weighted TSAs, defined as

\[
A_T^{\sin \Phi W_\Phi} = \frac{\int d^2q_T W_\Phi F_T^{\sin \Phi}}{\int d^2q_T F_T^1}, \quad \Phi = \phi_S, 2\phi + \phi_S, 2\phi - \phi_S
\] (27)

where $W_\Phi$ denotes the weights from Eq. (23-26).

As in the standard DY TSA analysis [67], we have used a ratio method to cancel the acceptance $a(\Phi)$ and the dilution factor to correct the asymmetries for the target composition. Following the work done in the corresponding SIDIS analysis, the method has been modified in order to weight the spin dependent part only. The results for all the three asymmetries [24, 25] are shown on Fig. 35 as function of $x_N$, $x_\pi$, $x_F$ and $M$. The last column gives the values over the full kinematical range. The weighted Sivers asymmetry (first row) is closer to zero as expected, since the unweighted Sivers asymmetry is smaller at large $q_T$.

**Expected value of the $q_T$-weighted Sivers asymmetry**

Assuming $u$-quark dominance in the $\pi^- p \rightarrow \mu^+ \mu^- X$ DY reaction, using eq.s (24) and (27), the $q_T$ weighted Sivers asymmetry is given by:

\[
A_T^{\sin \phi_S \pi_T p} \approx -\frac{2 f^{(1)}_{1,u}}{f_{1,u}} A_T^{\sin \phi_S \pi_T p}.
\] (28)

It is then straightforward to estimate the $q_T$-weighted Sivers asymmetry in Drell-Yan using the first moment of the Sivers function obtained from SIDIS data (section 3.2.1).

The result [25], obtained assuming the change of sign and neglecting the evolution of the Sivers function to the higher (up to a factor of 3) $Q^2$ values in DY, are shown in Fig. 36. The 1σ error-band is statistical only, and
7.2 Unpolarized azimuthal asymmetries from 2015 data

Fig. 36: Weighted Sivers asymmetry in Drell-Yan from 2015 data and the expected values (curve) obtained using the Sivers function from the corresponding asymmetries in SIDIS. Only statistical errors are shown.

Fig. 37: Projection for combined analysis of 2015 and 2018 data. The statistics in 2018 is assumed 1.5 times larger than in 2015. Only statistical errors are shown.

much smaller than the uncertainties of predictions from global fits including some $Q^2$ evolution of the Sivers function. Different choices of the PDF and FF sets have been found to lead to negligible differences (of about 0.02). The full black points in Fig. 36 are the measurements in the three $x_N$ bins and the open red point the value of the asymmetry in the integrated $x_N$ range.

The projections for the measured asymmetries from the combined analysis of 2015 and 2018 data are shown in fig. 37 together with the estimated values. As can be seen, the 2018 data should allow for a definite answer about the change of sign of the Sivers function as measured in SIDIS and in DY.

7.2 Unpolarized azimuthal asymmetries from 2015 data

The same data sample which was already analysed for TSAs extraction is used to obtain the unpolarized azimuthal asymmetries present in the target polarization independent part of the DY cross-section:

$$\frac{d\sigma}{dq_Td\Omega} \propto (F^1_U + F^2_U) \left\{ 1 + A^U_w \cos^2 \theta_{CS} + \sin 2\theta_{CS} A^U_{CS} \cos \phi_{CS} + \sin^2 \theta_{CS} A^U_{2CS} \cos 2\phi_{CS} \right\}$$

(29)

where $q_T$ is the four-momentum of the virtual photon, $\phi_{CS}$ and $\theta_{CS}$ and $\Omega$ are the azimuthal, polar and the solid angle of one lepton defined in the Collins-Soper reference frame. The asymmetries $A^U_w$ are the amplitudes of the corresponding modulations $w$. They are given as the ratios of the corresponding structure functions to the sum of the polarization and azimuth-independent structure functions $F^1_U$ and $F^2_U$. The extraction of the physics unpolarized asymmetries (UAs), each being proportional to a convolution of two TMD PDFs (one referring to the pion beam, the other to the target nucleon), requires extensive knowledge of the azimuthal experimental acceptance. This is in fact the crucial and most difficult aspect of the whole UAs analysis.

The multidimensional acceptance and experimental smearing corrections are done using TGeant software package, Geant4-based COMPASS setup simulation tool. The variables chosen for the multi-D acceptance calculation are $M_{\mu\mu}$, $x_\pi$, $x_N$, $q_T$ and $Z_{\text{vertex}}$. The reason to include the latter relates to difficulties in describing equally well the two NH$_3$ target cells. The delicate procedure of cell filling lead in 2015 to inhomogeneities, and a potential contamination by ice affecting exclusively the downstream cell. To overcome this problem, the acceptance is calculated separately for each cell.

While the acceptance dependence on $M_{\mu\mu}$ and $q_T$ is given by a rather flat function, at the edges of the $x_\pi$ and $x_N$ distributions the acceptance is very steep. Careful evaluation of the multidimensional acceptance correction with precise description of such edge-effects requires generation of large data-samples and thus extensive MC
simulations only made possible by the allocation of huge CPU resources. To carry out those heavy simulations COMPASS profits from the resources provided by the Blue Waters petascale supercomputer [68].

A second step in the detailed description of the experimental COMPASS data-taking conditions involves the use of two-dimensional detector efficiency maps, evaluated plane by plane, and per sub-period of data-taking (each sub-period corresponds roughly to a one week time interval). The 2-D efficiencies are used in the reconstruction of the Monte-Carlo data samples, separately reproducing the conditions of each period/sub-period, and in the proportions corresponding to the statistics collected per period.

COMPASS results for unpolarized DY asymmetries will serve as the only experimental test of the Lam-Tung relation in the low $q_T$ regime in the past 20 years. Recent studies by Lambertsen and Vogelsang [69] have revived the topic, by claiming that pure $O(\alpha_S^2)$ corrections to the DY cross-section can explain the measured deviations from the Lam-Tung relation. The excellent data accuracy of the collider (mostly LHC) Drell-Yan-like measurements (near the $Z^0$ pole, with typical $q_T$ above 25 GeV/c) leaves not much doubts on the perturbative nature of these deviations. On the other hand, the large errors associated to existing pion-induced Drell-Yan measurements in the regime of much lower $q_T$ (where the TMD approach finds its applicability), and the apparent tension between the DY NNLO curves and these data, provide strong motivation for this new COMPASS measurement. A non-perturbative contribution, related to the intrinsic partons $k_T$ and its correlation to partons spin, might play an important role in this regime.

7.3 Drell-Yan and $J/\psi$ cross-sections

Pion-induced Drell-Yan differential cross-sections are an important input to the global analyses of TMD PDFs of the nucleon. In spite of their importance, the knowledge of the pion TMD PDF(s) is required, but this is a poorly constrained input at the moment. A COMPASS analysis is presently ongoing, aiming at the measurement of absolute Drell-Yan cross-sections. The cross-section measurement requires not only the detailed knowledge of the experimental acceptance $Acc$ and efficiencies involved $\epsilon_{tot}$, but also of the luminosity $L$:

$$\sigma_{DY}^{\mu\mu} = \frac{N_{\mu\mu}}{L} \times \frac{1}{Acc} \times \frac{1}{\epsilon_{tot}}$$

The experimental efficiency is $\epsilon_{tot} = \epsilon_{rec} \times \epsilon_{trig} \times \epsilon_{det}$, and it takes into account the reconstruction program, trigger and each detectors efficiencies, respectively. The luminosity on the other hand requires the knowledge of the integrated beam flux $F$ and of the area target density $\rho_T$: $L = F \times \rho_T$. Since COMPASS does not have a specific detector dedicated to precise beam flux measurement, a method is being followed to evaluate it, based in the (free of physics biases) random trigger events. The analysis requires additional data selection to guarantee correct flux calculation. This method is seen to be in agreement with the rough measurement given by an ionization chamber placed in the upstream COMPASS beam line, within 10% precision. The trigger efficiency is another important aspect being carefully studied. The dimuon trigger requires one or both muons of the dimuon pair to be seen in the large hodoscopes of the experiment, made of scintillating slabs 6 and 12 cm wide, depending on the hodoscope. Some of these slabs were not fully efficient during the 2015 run and this, together with inefficiencies of the trigger coincidences system itself has a non-negligible impact. Studies on the amount of ice contamination to the NH$_3$ material in the most downstream target cell are also ongoing, in order to accurately determine the area target density for the polarized target.

In what concerns the Drell-Yan cross-section from tungsten target, studies are being continued in order to evaluate the level of reinteractions (i.e. Drell-Yan events produced by secondary pions), and decide on the length of the tungsten target slice that minimizes the reinteractions effect. While the tungsten plug was 120 cm long, it is clear that the beam is absorbed within the first 20-40 cm, and that the amount of reinteractions after 20 cm of tungsten is already very large.

The pion induced Drell-Yan cross-section in both NH$_3$ and W targets is being studied, in terms of its $A$-dependence, and as well as a function of $q_T$ and $x_N$. The EMC effect will be studied from the cross-section ratio of the two target materials as function of $x_N$. The statistical error from this measurement is expected to be
much improved with respect to a previous study made by NA10 \[65\], thanks to much larger statistics obtained on the “light” target of NH3 as compared to the one from NA10 (using deuterium as light target).

In parallel to the Drell-Yan studies, also the J/ψ sample is the subject of analyses, aiming both at the measurements of differential cross-section and of the J/ψ polarization. The latter is an ideal indicator of the dominating production mechanisms, which are still nowadays subject of intense debate, specially in the low qT region accessed by COMPASS \[65\]. Finally, an analysis of double-J/ψ production is also ongoing, a process pointed out since long as giving access to the intrinsic charm content of the nucleon \[62\]. This process could also be a channel of discovery for a “all-charm” tetraquark state \[63\]. The preliminary analysis of a COMPASS selected sample of candidate events shows larger statistics, by at least a factor 2, than a previous measurement performed by the NA3 experiment at CERN \[64\].

### 7.4 Present status of 2018 DY data-taking

The preparation of the COMPASS spectrometer and polarized target system for the 2018 data-taking has started as soon as the 2017 data-taking period was over, given the significant modifications required: unmounting of the CAMERA recoil detector and unpolarized liquid hydrogen target, and re-installation of the polarized target system and the hadron absorber of the Drell-Yan setup, among others.

#### Polarized target

The PT magnet is an essential equipment for the polarized Drell-Yan program. Once the target is polarized with 2.5 T solenoid, the spin of the target is rotated to the perpendicular to the beam with the dipole magnet of 0.6 T (field rotation).

We observed a polarization loss of 0.5 This effect can be explained by collective spontaneous spin transition, the so-called super-radiance, at low magnetic field. The effect can be suppressed by non-homogeneity of magnetic field during the field rotation.

We modified the procedure of the field rotation with the support of EP-DT group, to make a non-homogeneous magnetic field with the 16 trim coils for the solenoid during the field rotation. We succeeded to suppress the polarization loss below 0.1% at 75% polarization with this new procedure.

#### Beam telescope

The data reconstruction in the Beam Telescope region was one important concern in 2015, given the low detectors redundancy there. The beam position reconstruction was achieved using three scintillating fiber stations of 2 planes (X,Y) in one of the stations, and 3 planes (X,Y,U) in the other 2 stations. This has shown to become problematic whenever one of the planes had a problem, with the average number of beams per event reconstructed in a wide time window of ±6 ns was seen to drop from 2.1 to 1.7 . The global efficiency of each scintillating fiber plane is above 95%, but in 2015 it was dropping by 5%-10% at nominal hadron beam intensity.

To overcome these problems, the redundancy was increased in 2018, by adding another scintillating fiber station of 3 projections (X,Y,U) in the Beam Telescope, thus relying now on 11 planes instead of the 8 used in 2015 data-taking. Additionally, several localized problems with plane sectors readout were fixed during the shutdown period, to guarantee optimal performance.

#### Dimuon trigger system

For the trigger setup in 2018 we rebuilt the coincidence logic for the dimuon triggers as it was used in 2015 COMPASS DY run. It is composed of different combinations of the single muon triggers in target pointing mode set in coincidence. Also, the geometry of the central parts of the hodoscopes was changed to achieve symmetrical acceptance for the muons of both charges in the spectrometer.

In addition, we performed the maintenance of the hodoscopes. Every discriminated signal from the photomultipliers is now splitted and read out in parallel by a scaler and a TDC, for monitoring purposes. This enables us to look for light leaks on the counters and also to perform a high voltage scan to determine the
optimal working point for each counter (trigger hodoscopes and veto hodoscopes). In addition a computation cluster was setup in the COMPASS network domain to have a convenient way to look into the decoded data and point out problems (timing, rate, latency, ...) as early as possible with a high statistics data sample on a daily basis.

For monitoring of the trigger efficiencies we collect dedicated runs with muon/pion beam during polarization of the target to test the single muon triggers without any prescaling factor applied. We also include a pre-scaled fraction of the calorimeter trigger in the normal data taking trigger mix. This enables us to check the detector and dimuon trigger efficiencies on a regular basis during normal data taking conditions.

**Commissioning and start of data-taking**

The change-over from the DVCS setup of 2017 Run to the DY setup of 2018 had to take place in the rather limited period of the winter shutdown. The operation of the polarized target system requires a high flux of cooling water. Despite the delay induced by the non-availability of the cooling tower at the early stages of the preparation, an alternative was found. Several compromise and work-around solutions allowed to keep the commissioning phase of the target and spectrometer within the planned five weeks of beam time. This comprises the validation of the operating system of the PT-magnets, the preparation of the CEDARs in parallel to the TE calibration of the loaded target, and the installation of the beam telescope. The latter could not be performed before the target material would be loaded.

We have been collecting polarised DY events since the 17th of May. The data-taking conditions are seen to be much more stable this year than they were in 2015, both from the detectors point of view and from the DAQ point of view. Several online analyses are ongoing to check the quality of the data, as well as to define possible improvements for the coming weeks. Figure 38 illustrates the performance of the COMPASS spectrometer and of the good data collection. The integrated beam delivered to COMPASS in the first week of physics data-taking (in red), is compared to the beam taken by the experiment (in blue) and to the integrated flux corresponding to the flagged-as-good data taken (in green). From this plot we can infer for this period a very good physics data-taking efficiency (about 95%).

![Fig. 38: Integrated beam intensity in the first week of physics data-taking. The red curve shows the intensity delivered by the SPS, the blue one represents the intensity recorded by COMPASS and the green one the expected intensity entering in the analysis.](image)

**8 Proton Radius Measurement with COMPASS**

According to the proposal of COMPASS, test measurements have been carried out with a setup downstream of the spectrometer (Fig. 39), employing a test TPC from GSI/Gatchina and COMPASS silicon detectors. Apart
from investigating the performance of the TPC in the muon beam, which was shown to be very promising, the main goal was to show coincidences of recoils in the TPC and muon scattering observed in the silicon telescopes. A very preliminary analysis shows evidence for observing such coincidences, cf. Fig. 40.

9 Publications, presentations to conferences and collaboration matters

Publications

1. First measurement of the Sivers asymmetry for gluons from SIDIS data, PLB 772 (2017) 854, [CERN-EP/2017-003](#)


4. Observation of X(3872) muoproduction at COMPASS, subm. PLB, [CERN-EP/2017-165](#)


6. Longitudinal double-spin asymmetry $A_1^L$ and spin dependent structure function $g_1^p$ of the proton at small values of $x$ and $Q^2$, PLB 781 (2018) 464, [CERN-EP/2017-263](#)


9. Light isovector resonances in $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ at 190 GeV/c, acc. PRD [CERN-EP/2018-021]

Presentation to Conferences:

- 97 presentations to Conferences and Workshops in 2017;
- 32 presentations to Conferences or Workshops in 2018, till June 5.
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