COMPASS Status Report 2014

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 preparation for the short 2014 Drell-Yan 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 2012 data analysis is presented. Preparations for the short 2014 polarised Drell-Yan run are described.

A summary of the results presented, giving the level reached in the corresponding analyses, is displayed in Table 1.

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Table 1: Summary of the results presented in the report (sfp=sent for publication, pbw=paper being written).
2 Analysis and results with the hadron beams

2.1 Results on Peripheral Photon-Pion Interactions

Photon-pion reactions are studied at COMPASS using high-energy pion beams impinging on heavy target nuclei. Photons are provided by the Coulomb field of the nucleus, which in terms of the Weizsäcker-Williams approach constitute a quasi-real photon beam with a continuous energy spectrum in the \( \pi^0 \) rest frame. If we select the quasi-elastic channel \( \pi^- + \gamma^* \rightarrow \pi^- + \gamma \) we perform Compton scattering in inverse kinematics, while spectroscopic information can be extracted from the reaction \( \pi^- + \gamma^* \rightarrow \pi^- \pi^- \pi^+ \).

2.1.1 Measurement of the Pion Polarizability

The polarizability of the pion is a fundamental property of the lightest meson and describes the inertia of the internal structure with respect to external electromagnetic fields. Numerically it appears as a correction to the Compton scattering cross section with respect to Compton scattering on point-like spinless particles. Both electric \( \alpha_{\pi^-} \) and magnetic \( \beta_{\pi^-} \) polarisabilities exist separately, but the present analysis assumes a strong correlation implying the typical assumption of \( \alpha_{\pi^-} + \beta_{\pi^-} = 0 \), motivated by the approximate theoretical expectation from current algebra. COMPASS has recently measured this quantity using a technique pioneered by an experiment at Protvino which had been performed more than 30 years ago. The resulting photon spectrum from this Compton scattering process, normalized to that for point-like particles, is depicted in Fig. 1a. Owing to the much larger data sample and a parallel measurement using (point-like) muons (see Fig. 1b) we have performed many systematic tests. For pions, a value of \( \alpha_{\pi^-} = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{fm}^2 \) is extracted from the fit, while the value for muons is compatible with zero within the statistical and systematic uncertainties of the measurement. The systematic error includes contributions from the Monte-Carlo description of the COMPASS setup, the background subtraction, radiative corrections to the Born cross section (electron screening, vacuum polarization, multi-photon exchange), and pion electron scattering. The result agrees with the calculation done up to order \( \gamma^6 \) in chiral perturbation theory. This is depicted in Fig. 1c together with previous experimental results. A more refined measurement, which addresses a separate determination of \( \alpha_{\pi^-} \) and \( \beta_{\pi^-} \), is part of our COMPASS II program. Data have already been taken in 2012 and are presently being analyzed (see Sec. 4.1).

![Fig. 1: Results of the polarizability measurement in COMPASS using the 2009 data for the reaction \( \pi^+ + \text{Ni} \rightarrow \pi^- \gamma \text{Ni} \).](image)

(a) Normalized photon spectrum for the \( \pi^\gamma \) Compton scattering process. The yellow band represents systematic uncertainties, the curves depict the fit from which the value of the \( \pi^- \) polarizability is extracted.

![Fig. 1: Results of the polarizability measurement in COMPASS using the 2009 data for the reaction \( \mu^\gamma \) Compton scattering process. The yellow band represents systematic uncertainties, the curves depict the fit from which a value of the \( \mu^- \) polarizability compatible with zero is extracted.](image)

(b) Normalized photon spectrum for the \( \mu^\gamma \) Compton scattering process. The yellow band represents systematic uncertainties, the curves depict the fit from which a value of the \( \mu^- \) polarizability compatible with zero is extracted.

![Fig. 1: Ideogram for the measurements of the \( \pi^- \) polarization. The COMPASS value alone is in good agreement with \( \chi\text{PT} \) calculations, though at tension with previous experimental results.](image)

(c) Ideogram for the measurements of the \( \pi^- \) polarizability. The COMPASS value alone is in good agreement with \( \chi\text{PT} \) calculations, though at tension with previous experimental results.

Fig. 1: Results of the polarizability measurement in COMPASS using the 2009 data for the reaction \( \pi^+ + \text{Ni} \rightarrow \pi^- \gamma \text{Ni} \).

2.1.2 Determination of Radiative Width

The radiative width of excited hadrons is related to the (squared) electromagnetic transition amplitude to the hadronic ground state. Depending on the quantum numbers and the multipole transitions involved, these amplitudes are sensitive to current or charge distributions of the excited states and thus provide information not accessible otherwise. Using the reaction \( \pi^- + \gamma^* \rightarrow \pi^- \pi^- \pi^+ \) we study these transitions in production and
2.2 Results on Diffractive Pion Dissociation

Fig. 2: Left: Intensity of the $2^+ 1^+ \rho \pi D$ wave depicting the signal for the $a_2(1320)$ resonance. Right: Intensity of the $2^+ 1^+ f_2(1270) \pi S$ wave depicting the signal for the $a_2(1320)$ resonance. Data were obtained in the Primakoff region $t' < 10^{-3} (\text{GeV}/c)^2$. Selecting spin projection $M = 1$ strongly favors the photoproduction in the Coulomb field of a Pb-nucleus. The solid curves is a fit to the line shape of the resonance.

identify the states produced by means of partial-wave analysis. We can select the electromagnetic production process for partial waves with spin-projection quantum number $M = 1$ with respect to the beam direction at low four-momentum transfer $t'$. Normalizing the results to the luminosity of the experiment we can directly deduce the radiative width. Fig. 2 shows the signals observed for two mesons, namely $a_2(1320)$ and $\pi_2(1670)$, decaying into $\rho(770)\pi D$-wave and $f_2(1270)\pi S$-wave, respectively. Our analysis has allowed a very thorough study of the radiative width of $a_2(1320)$, which constitutes an electric dipole transition and the first determination of this quantity for the $\pi_2(1670)$, which is the first electric quadrupole transition observed in meson decays [2]. Few quark-model calculations exist for these transitions and they also should become a test bench for dynamical lattice calculations.

2.2 Results on Diffractive Pion Dissociation

During two beam times (2008 and 2009) COMPASS has studied pion and kaon diffractive dissociation on a hydrogen target. The goal of these measurements is the production of intermediate resonances $X$ from the incoming beam particle with the observation of their subsequent decay into various final-state particles. Each final state stems from a superposition of a large set of possible $X$ with quantum numbers $J^{PC}$. The composition depends on the mass $m_X$ and the four-momentum transfer $t'$ to the target nucleon. The production cross section exhibits a typical $t'$ dependence which can be roughly described by one or two exponential with slope parameters varying between 6 to 12 (GeV/c)$^2$. The minimum value of $t' = 0.1$ (GeV/c)$^2$ is given by the trigger acceptance. COMPASS can study final states involving charged and neutral particles (e.g., $K_S^0$, $\pi^0$, $\eta$, $\eta'$), the latter being identified by their decays.

In order to disentangle the coherent superposition of intermediate states $X$ characterized by $J^{PC}$ for a particular final state we perform a partial-wave analysis. For two-body final states this leads to a representation of the cross section as a squared sum of spherical harmonics with complex expansion coefficients, the production amplitudes. For $n$-body final states with $n \geq 3$ typically a more complex procedure has to be used which generally has larger model bias. The standard analysis assumes any transition from the initial state $X$ to the final $n$-body state to proceed through a series of two-body decays, in which additional intermediate states are produced which eventually result in the observation of (quasi-)stable final-state particles. In this so-called isobar model the quantum numbers $J^{PC}$ and masses of these intermediate systems correspond to known resonances or to any system that can be described analytically in terms of mass distribution and phase-space population. The cross section is described by a set of model amplitudes with various possible $J^{PC}$, each of which may have various decay paths (intermediate isobars) describing the transition from $X$ to the final state. The coherent sum of these so-called waves includes complex production amplitudes, the values of which are determined by a fit and result in the spin-density matrix. As this procedure is performed in narrow bins of $m_X$ no assumptions about possible $n$-body resonances are made at this point.

Based on the partial-wave decomposition of the observed intensity described above, the physics is extracted
in a second step by connecting the resulting spin-density matrices of different $m_X$ bins using a model which typically contains resonant and non-resonant contributions for $X$. The outcome can systematically depend on the choice of waves, parametrization of the isobars and on assumptions concerning the coherence of the amplitudes.

In the following we will specify waves by the $J^{PC}$ of $X$, its spin projection $M$ along the beam direction, the symmetry $\varepsilon$ of the amplitudes related to the naturally of the particle exchanged in the production process and the decay path of $X$. The complete wave definition typically reads $J^{PC} M^\varepsilon [\text{decay}].$

### 2.2.1 PWA of the $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ Final States and Observation of a New Iso-Vector Meson

Based on data taken in 2008 with 190 GeV/$c$ pions impinging on a $tH_2$ target we have selected about $4 \times 10^7$ exclusive scattering events with a $\pi^-\pi^-\pi^+$ final state, and about $3.6 \times 10^6$ events with $\pi^-\pi^0\pi^0$. The sample for the $\pi^-\pi^-\pi^+$ final state is about a factor 10–100 larger than in any previous experiment. The two different $3\pi$ final states are subject to similar but independent analyses. For both channels the PWA was performed not only in narrow bins of the three-pion mass $m_{3\pi}$ but also in bins of the reduced four-momentum transfer $t'$ in the range $0.1 < t' < 1.0 \text{(GeV/c)}^2$.

Figure 3 compares the total intensities, summed over all $t'$ bins, of several waves in the two channels (note the factor of 10 difference in the sample size). The histograms were normalized to the intensity integrals in each plot individually which allows for a direct shape comparison of each partial wave intensity. Although the systematics of the two final states is very different, in particular concerning the acceptance correction, the two analyses give very consistent results.

As in the $\pi^-\pi^-\pi^+$ channel also in the $\pi^-\pi^0\pi^0$ final state the peak in the $a_1(1260)$ region in the dominant $1^{++}$ $0^+ \rho \pi S$ wave exhibits a strong shift towards higher masses for increasing $t'$ as is shown in Fig. 4. Since the resonance parameters do not depend on $t'$ (as is illustrated by the $a_2(1320)$ peak in the $2^{++} 1^+ \rho \pi D$ wave in Fig. 4), this indicates that the $a_1(1260)$ peak is dominated by non-resonant contributions which change phase with $t'$. This observed effect was one of the main motivations to perform the PWA in bins of $t'$. As is shown below the additional information helps to better separate the resonant and non-resonant contributions in this and other partial waves.

A detailed study of the isospin symmetry that is expected to relate the intensities in the two channels is work in progress. It is complicated by the fact that the Bose symmetrization of the two final-state pions with equal charge, that has to be applied at the amplitude level, has a different effect in the two channels, because of the different isobar structure.

The $J^{PC} = 1^{-+}$ Spin-Exotic Wave The wave set used in the PWA of the $\pi^-\pi^-\pi^+$ and the $\pi^-\pi^0\pi^0$ final states is identical and contains the spin-exotic $1^{-+} 1^+ \rho \pi P$ wave, in which previous experiments claimed a resonant structure at 1.6 GeV/$c^2$, the $\pi_1(1600)$. Figure 5 left shows the observed intensity distribution (summed over all $t'$ bins) in this wave. The agreement of the two data sets is fair. Both analyses show a broad intensity distribution without a clear peak at 1.6 GeV/$c^2$. However, slow phase motions of about 50$^\circ$ are observed in the 1.6 GeV/$c^2$ region with respect to other waves (cf. Fig. 5 right). The region around 1.1 GeV/$c^2$, where no resonances are expected, exhibits fit instabilities. Improvements of the analysis model (extension of wave set, rank-1 PWA in $t'$ bins, and lowering of thresholds applied to some partial waves) led to a reduced scatter of points in this region. Still some artifacts remain.

Similar to the $a_1(1260)$ peak in the $1^{++} 0^+ \rho \pi S$ wave a striking $t'$ dependence of the spectral shape of the $1^{-+} 1^+ \rho \pi P$ wave is observed (see blue points in Fig. 6). At low $t'$ the wave exhibits a broad intensity distribution centered mainly at lower mass. With increasing $t'$ the intensity shifts towards higher masses leaving a narrower peak at about 1.6 GeV/$c^2$ in the two highest $t'$ bins. This hints that also the peak in the spin-exotic wave is significantly influenced by non-resonant contributions. Therefore an interpretation of the $1^{-+} 1^+ \rho \pi P$ wave in terms of resonances will strongly depend on how the non-resonant terms are modelled. In a first step towards a better understanding of the non-resonant contributions Monte Carlo data were generated, distributed according to a model of the Deck effect. Figure 6 shows in green the projection of these pseudo-data into the $1^{-+} 1^+ \rho \pi P$...
2.2 Results on Diffractive Pion Dissociation

Fig. 3: Comparison of some partial wave intensities, summed over all $t'$ bins, in the $\pi^-\pi^-\pi^+$ (red) and the $\pi^-\pi^0\pi^0$ (blue) final states. The $\pi^-\pi^-\pi^+$ points are scaled to the intensity integral in each plot individually so that shapes are directly comparable.
Fig. 4: Comparison of some partial wave intensities for similar $t'$ bins (low $t'$ in upper, intermediate $t'$ in lower row) in the $\pi^-\pi^-\pi^+$ (red) and the $\pi^-\pi^0\pi^0$ (blue) final states. The $\pi^-\pi^-\pi^+$ points are scaled to the intensity integral in each plot individually so that shapes are directly comparable. A significant shift of the $a_1(1260)$ peak towards higher masses is observed with increasing $t'$. In contrast the $a_2(1320)$ peak does not change with $t'$. 

(a) $1^{++} 0^+ \rho \pi S$ wave with the $a_1(1260)$ peak.
(b) $2^{++} 1^+ \rho \pi D$ wave with the $a_2(1320)$ peak.
2.2 Results on Diffractive Pion Dissociation

(a) $1^{++} 0^+ \rho \pi S$ wave with the $a_1(1260)$ peak.

(b) $2^{++} 1^+ \rho \pi D$ wave with the $a_2(1320)$ peak.

Fig. 5: (Left) Comparison of the intensity, summed over all $t'$ bins, of the spin-exotic $1^{++} 1^+ \rho \pi P$ wave in the $\pi^- \pi^- \pi^+$ (red) and the $\pi^- \pi^0 \pi^0$ (blue) final states. The $\pi^- \pi^- \pi^+$ points are scaled to the intensity integral so that shapes are directly comparable. (Right) Phase of the $1^{++} 1^+ \rho \pi P$ relative to the $1^{++} 0^+ \rho \pi S$ wave shown for four $t'$ bins together with the $t'$-summed intensity of the two waves.

wave for several $t'$ bins. The Deck Monte Carlo data are normalized to the intensity sum over all $t'$ bins in the spin-exotic wave. Although the simple comparison of Monte Carlo and real data neglects possible interference effects between the different contributions, the remarkable similarity of the intensity distributions at low and intermediate values of $t'$ supports the idea that the observed distributions are dominated by non-resonant terms. Whereas at larger $t'$ a resonance signal might be present.

By applying the PWA models of previous experiments we could also show that the previously published results from the BNL E852 and VES experiments, which had led to a dispute on the existence of this spin-exotic $\pi_1(1600)$ resonance, can all be reconciled using COMPASS data. Differences among those results could be attributed to a) different target nuclei chosen, b) different wave sets employed and c) different intervals for $t'$ being used in the analysis.

**Observation of a New Iso-Vector Meson** The most exciting result so far is the finding of a new iso-vector axial-vector meson with $J^{PC} = 1^{++}$, the $a_1(1420)$, at a mass of 1420 MeV/$c^2$ and a rather small width of 140 MeV/$c^2$. This state has exotic, i.e. non-$q\bar{q}$ features since it has only been observed decaying via $f_0(980)$, with the $f_0(980)$ in turn being a superposition of $q\bar{q}$ and $s\bar{s}$. The spectral function for the wave $1^{++} 0^+ f_0(980)\pi P$ is shown in Fig. 7a. The relative phase of this wave with respect to other major waves shows the expected $180^\circ$ modulation when moving across the resonance in $m_{3\pi}$ (see Fig. 7b and 7c).

Origin and interpretation of this resonance are still unclear. It is tempting to associate the new $a_1(1420)$ state with the $f_1(1420)$, an iso-scalar resonance with strong coupling to the $K \bar{K}$ final state and often interpreted as a molecular state. The affinity to strangeness of both states is intriguing, as are their almost equal masses and similar narrow widths. If confirmed, it would constitute the first time that isospin partners of exotic states were discovered. Another possibility is a dynamic generation through the strong coupling of the systems $a_1(1260)$, $f_0(980)$ and $K \bar{K}$. It should be noted that there is no signal observed in partial waves with the $[\pi\pi]S$-wave isobar, which is a $\pi\pi$ system having the same quantum numbers as $f_0(980)$, but with a different spectral mass function. The $a_1(1420)$ signal inside the $1^{++} 0^+ f_0(980)\pi P$ wave has a strength about 100 times less than the main wave, $1^{++} 0^+ \rho \pi S$. This could be the reason why it had escaped detection in all previous experiments performed within the last 40 years exploring the same mass region.

**Further Results** Exploring the $t'$ dependence of spectral distributions in all waves, we have been able to better separate resonant and non-resonant contributions to individual waves. Typically, non-resonant contributions
Fig. 6: Intensity of the spin-exotic $1^{-+} 1^{++} \rho \pi P$ wave in the $\pi^- \pi^- \pi^+$ final state for several $t'$ bins (blue). A significant change of the intensity distribution with $t'$ is observed. At high $t'$ the distribution looks similar to the one observed on a lead target [4]. The green points represent the projection of Monte Carlo pseudo-data that were generated according to a Deck model into this partial wave. The Deck Monte Carlo data are normalized to the intensity sum over all $t'$ bins in this wave.
2.2 Results on Diffractive Pion Dissociation

(a) Wave intensity: $\pi^- \pi^- \pi^+$ (red) and $\pi^- \pi^0 \pi^0$ (blue) as simple sum of intensities over all $t'$ bins.

Fig. 7: Characteristics of the $1^{++} 0^+ f_{0}(980) \pi P$ wave, showing the new $a_1(1420)$ resonance. The solid lines represent a fit to the spin-density matrix.

were found to have a much steeper dependence on $t'$. However, systematic issues still remain, which to a large extent are related to model uncertainties for these contributions. We do, however, expect the understanding of these processes to advance well owing to the wealth of new data COMPASS can supply. The current status of the extraction of resonances from the $\pi^- \pi^- \pi^+$ data is summarized in Table 2. COMPASS found strong evidence for two additional resonances, the $a'_1$ and the $a'_2$, being excited partners of the $a_1(1260)$ and $a_2(1320)$ ground states (see Fig. 8).

Table 2: Preliminary resonance parameters extracted from the mass-dependent fit of a $6 \times 6$ spin-density matrix in 11 $t'$ bins of the $\pi^- \pi^- \pi^+$ data. Here we only give ranges obtained from a large variety of fit models investigated in the course of systematic studies. Values from PDG [3] are listed for comparison.

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“Established” states

States not in PDG summary table

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Further states, in particular at higher masses, are tentatively observed but their confirmation and mass determination requires further development of analysis tools. For other states we believe having determined mass and width with better knowledge of systematic uncertainties, but also somewhat more reliably owing to a larger wave set and better estimation of the non-resonant contributions, which in some cases heavily interfere with the resonances themselves. Thus, we believe that COMPASS can cover good part of the light non-strange iso-vector spectrum in a consistent way.
Fig. 8: Intensities (diagonal plots; logarithmic scale) and relative phase (upper right plot) for the $1^{++} 0^+ \rho \pi S$ and $2^{++} 1^+ \rho \pi D$ waves for the lowest $t'$ bin together with the result of a fit to a larger spin-density matrix with 6 waves (red lines). The blue lines show the contributions from the resonances, the green lines the non-resonant terms. Within the fit range the lines are continuous, extrapolations are drawn as dashed lines. The need for the second resonances $a'_1$ and $a'_2$ is evident in order to describe the shoulder in the $1^{++} 0^+ \rho \pi S$ intensity and the destructive-interference dip in the $2^{++} 1^+ \rho \pi D$ wave, respectively.
### Outlook

The high statistical accuracy unraveled a series of systematic issues of the PWA method, which had not been addressed by any previous experiment. Thus, intense studies had been made and new tools had to be developed with the most important ones being listed below:

- The wave set was extended from the 42 waves originally used in [4] to 88 waves, after testing for relevant contributions from a total of more than 150 waves.
- At low values of $m_{3\pi}$ the five-dimensional phase space is too small to lead to stable results for the production amplitudes when using all 88 waves. For this reason mass thresholds motivated by physics and tuned for individual waves had been introduced in the past. We were able to lower these thresholds considerably, thereby reducing the artifacts, which affect the intensity distributions in several partial waves.
- In order to justify the concept of full coherence of all waves despite a variety of production processes with different $t'$ dependence, we introduced a PWA performed in bins of both $t'$ and $m_{3\pi}$.
- Model fits to a sub-matrix of the spin-density matrix are performed for all $t'$ bins simultaneously.
- Model fits to a sub-matrix of the spin-density matrix are performed using up to 20 waves simultaneously. This requires fits with more than 1000 parameters. New tools have been developed.
- Model fits including waves with identical $J^{PC}$ but different decay modes are now performed by linking the branching and the $t'$ dependence for the same resonances assumed in different waves.
- In order to estimate systematics in the fits to the spin-density matrix we have performed series of up to 10,000 fits and subsequently selected well-defined classes of the best fits.
- Tools have been developed to test the quality of the isobar model and to approach a more model-independent PWA where the $\pi\pi$ isobar amplitudes are extracted from data (instead of using model-dependent parametrization). Currently a bootstrapping method is under study that could eventually cover all isobars.

Although the development of new tools and methods is by far not completed, COMPASS has obtained a series of first results. The new methods employed may be considered as a breakthrough in light-meson spectroscopy.

As already mentioned above COMPASS has started to address the shape of isobars appearing in the decay chain of specific $J^{PC}$ and thus to test the validity of the isobar model. For this purpose the analytic description of isobars has been replaced by simple histograms at the expense of an increased number of fit parameters. The result is shown in Fig. 9 where we correlate the intensity observed in the underlying spectral distribution of the $\pi\pi$ system having $J^{PC} = 0^{++}$ with the spectral distribution of the $\pi^-\pi^-\pi^+$ mother wave with $J^{PC} = 0^{-+}$. We can directly identify the decay components of the $0^{-+} 0^{++}$ $[\pi\pi]_S$-wave $\pi S$ wave and study the underlying $\pi\pi$ system in this environment. Ultimately, this technique will allow to perform Dalitz-plot-like analyses and PWA of isobar states, which themselves had only been identified using PWA.

The present findings have been published in conference reports [5] and will be subject of a series of three publications, which are foreseen in 2014. The first paper will present the results from the partial-wave decomposition in mass and $t'$ bins and will include a detailed description of the analysis method. A short letter will announce the finding of the $a_1(1420)$ state, while a third long paper will present more detailed results on the parameters and $t'$ dependencies of various resonances. All three papers are currently in the drafting stage. These publications will be followed by letters specifically dealing in more detail with individual $J^{PC}$ sectors, including the spin-exotic $J^{PC} = 1^{-+}$, and combining the analyses of both the $\pi^-\pi^-\pi^+$ and the $\pi^-\pi^0\pi^0$ final states.

#### 2.2.2 PWA of $\eta\pi$ and $\eta'\pi$ Final States

Currently, a publication [7] of the results of a combined analysis of the 2008 COMPASS data for the reactions $\pi p \rightarrow \eta\pi p$ and $\pi p \rightarrow \eta'\pi p$ is in the final state of the collaboration review. For this analysis, samples of 115,000 and 40,000 events, respectively, were studied in the two final states. Previous experiments claimed
At high invariant masses, approximately 1.8 GeV, the resonance fits to the spin-exotic wave are subject to large model uncertainties and in particular that the $\pi\eta$ factor, odd partial waves do not show this systematics and are strongly suppressed in $\eta\pi$. Whereas for the $\eta\pi$ data set this distribution is almost symmetric between pion and $\eta$, the $\pi\eta'$ data shows a strong preference for a slow iso-scalar. In the range studied, partial waves up to and including spin 6 can accommodate these features of the data. In accordance with the stronger asymmetry in $\pi\eta'$, the (spin-exotic) odd partial waves are enhanced with respect to the $\pi\eta$ channel. Whereas even partial waves in both systems almost coincide after scaling with a simple mass- and angular-momentum-dependent factor, odd partial waves do not show this systematics and are strongly suppressed in $\pi\eta$. Figure [10] shows this for the two lowest partial waves. A connection to flavor symmetry and to $\eta-\eta'$ mixing in particular is expected [6].
2.3 Study of Zweig Rule in Vector-Meson Production

For the 2008/9 data a study of vector-meson production was performed in the reaction \( pp \to p V p \). Using the decay channels \( \omega \to \pi^+ \pi^- \pi^0 \) and \( \phi \to K^+ K^- \) the ratio of the production cross section was determined and compared to the prediction from the Zweig rule \([8]\). As shown in Fig. 11 (left) a considerable violation was found with some dependence on \( x_F \) which is reduced for large momenta of the vector meson, i.e. large proton-omega invariant masses \( M_{p\omega} \). This dependence gives a hint at a change of production mechanisms. This was further studied by investigating the spin alignment from angular distributions in different reference frames. Figure 11 (right) shows the dependence of the spin alignment \( \rho_{00} \) on \( M_{p\omega} \) in the helicity frame indicating a changeover from diffractive production to central production with increasing mass. The results of this analysis will be published soon \([9]\).

2.4 The search for the \( Z_c(3900) \) at COMPASS

The \( Z_c(3900)^\pm \) state was recently discovered by the BES-III and Belle Collaborations in \( e^+e^- \to \pi^+\pi^-J/\psi \) reactions at \( \sqrt{s} = 4.26 \text{ GeV} \) \([10, 11]\) via the decay

\[
Z_c^\pm(3900) \to J/\psi\pi^\pm.
\]  

(1)

The observed mass and width of the state is presented in Table 3. The \( Z_c^\pm(3900) \) signal has been interpreted as a tetraquark state \([12–15]\), although other explanations like a molecular state \([16–21]\), a cusp effect \([22]\) and an initial-single-pion-emission mechanism \([23]\) were also proposed. According to the vector meson dominance (VMD) model, a photon may behave like a \( J/\psi \) so that a \( Z_c(3900)^\pm \) can be produced by the interaction of an incoming photon with a virtual charged pion provided by the target nucleon (Fig. 12)

\[
\gamma N \to Z_c^\pm(3900) N.
\]  

(2)

Based on the VMD model, the authors of Ref. \([24]\) predict a sizable cross section of the reaction in Eq. \((2)\) for \( \sqrt{s}_{\gamma N} \sim 10 \text{ GeV} \). Under the assumption that the decay channel of Eq. \((1)\) is dominant and that the total width \( \Gamma_{\text{tot}} \) of the \( Z_c^\pm(3900) \) particle is \( 46 \text{ MeV/}c^2 \), as measured by BES-III, the cross section reaches a maximum value of 50 nb to 100 nb at \( \sqrt{s}_{\gamma N} = 7 \text{ GeV} \). Deep-inelastic photon-nucleon interactions at COMPASS cover the range \( \sqrt{s}_{\gamma N} = 10 – 18 \text{ GeV} \) and thus they can be used to study \( Z_c(3900)^\pm \) production and to estimate the partial width \( \Gamma_{J/\psi\pi^\pm} \) of the decay channel \( Z_c^\pm(3900) \to J/\psi\pi^\pm \).

All muon data are used in the analysis. The measurement of an absolute cross section involves the estimation of beam fluxes, acceptances and the efficiency of applied selection criteria. Since we use data collected during seven years with different beams, targets and setup configurations, such estimations are extremely time consuming. This can be avoided by using a reference process with known cross section and similar signature. We used the incoherent exclusive production of \( J/\psi \) in the reaction \( \mu^+N \to \mu^+J/\psi N \) (Fig. 13) since the cross section of
Table 3: The measured mass and width of $Z_c^\pm(3900)$.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>M, MeV/c^2</th>
<th>$\Gamma_{\text{tot}}$, MeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES-III [10]</td>
<td>3899 ± 3.6_{\text{stat}} ± 4.9_{\text{syst}}</td>
<td>46 ± 10_{\text{stat}} ± 20_{\text{syst}}</td>
</tr>
<tr>
<td>Belle [11]</td>
<td>3894.5 ± 6.6_{\text{stat}} ± 4.5_{\text{syst}}</td>
<td>63 ± 24_{\text{stat}} ± 26_{\text{syst}}</td>
</tr>
</tbody>
</table>

Fig. 12: Studied process $\mu^+ N \rightarrow \mu^+ Z_c^\pm N \rightarrow J/\psi \pi^\pm N$.

Fig. 13: Reference process $\mu^+ N \rightarrow \mu^+ J/\psi N$.

$\gamma N \rightarrow J/\psi N$ is known [25]-[27] as a reference to study the process $\mu^+ N \rightarrow \mu^+ Z_c^\pm(3900) N \rightarrow \mu^+ J/\psi \pi^\pm N$.

The following cuts were applied to select samples of exclusive $\mu^+ J/\psi \pi^\pm$ events:

- 2 positive and 1 negative muons in primary vertex;
- momentum of each muon is above 8 GeV/c;
- events containing any other track in addition to the beam and 2$\mu^+$, $\mu^-$ and $\pi^\pm$ tracks are rejected;
- dimuons are treated as $J/\psi$ candidate if one of the positive muons satisfy $|M_{\mu_1^+ \mu_-} - m_{J/\psi}| < 0.15$ GeV/c^2 while the second don’t, i.e. $|M_{\mu_2^+ \mu_-} - m_{J/\psi}| > 0.15$ GeV/c^2.
- for the pion tracks we reject events with $P_\pi < 2$ GeV/c both to reduce the background and to cut away a kinematic region where acceptance for pion is known poorly.
- The distribution of events as a function of the energy balance $\Delta E = E_{\mu'} + E_{J/\psi} + E_{\pi^\pm} - E_b$ is presented in Fig. [14]. We required $|\Delta E| < 10$ GeV.

The mass spectrum for $J/\psi \pi^\pm$ events is shown in Fig. [15]. The resolution for the $\psi(2S)$ peak in the $J/\psi \pi^+ \pi^-$ mass distribution is about 15 MeV/c^2, so the resolution for the $J/\psi \pi^\pm$ at the $Z_c$ mass should be about the same. The mass spectrum does not exhibit any statistically significant resonant structure around 3.9 GeV/c^2. The Armenteros-Podolanski plot (Fig. [16]) also does not contain any glimpse of $Z_c^\pm(3900)$. Due to this we may only estimate an upper limit for $Z_c^\pm(3900)$ production.

The observed number of events $N_{J/\psi \pi}$ in the signal interval 3.84 GeV/c^2 < $M_{J/\psi \pi}$ < 3.96 GeV/c^2, is treated as consisting of an a priori unknown $Z_c^\pm(3900)$ signal $N_{Z_c}$ and a background contribution $N_{bkg}$. The probability density function $g(N_{Z_c})$ is given by [28]:

$$g(N_{Z_c}) = \int_0^\infty h(N_{Z_c}, N_{bkg})dN_{Z_c}dN_{bkg} = n \int_0^\infty e^{-(N_{Z_c}+N_{bkg})} (N_{Z_c} + N_{bkg})^N N! f(N_{bkg})dN_{bkg},$$

(3)
where \( n \) is a normalization constant and the probability density function \( f(N_{\text{bkg}}) \), assumed to be Gaussian, describes the background contribution in the signal interval. The mean value and the Gaussian width of \( f(N_{\text{bkg}}) \) are estimated by fitting an exponential function to the \( J/\psi \pi^\pm \) mass spectrum in the range \( 3.5 \text{ GeV}/c^2 < M_{J/\psi\pi^+} < 5.0 \text{ GeV}/c^2 \) (while excluding the signal region of \( [3.84,3.96] \) GeV/c\(^2\)); this gives 52.5±2.7 events. The observed number of \( J/\psi \pi^\pm \) events \( N_{J/\psi\pi^\pm} \) in the signal interval is 51. The upper limit \( N_{Z_c}^{UL} \) for the number of produced \( Z_c^{\pm}(3900) \) events corresponding to a confidence level of \( CL = 90\% \) is then determined by fixing the upper limit of the integration in order to have: 

\[
\int_0^{N_{Z_c}^{UL}} g(N_{Z_c})dN_{Z_c} = 0.9 \text{ resulting in } N_{Z_c}^{UL} = 13 \text{ events.}
\]

The dimuon mass spectrum (Fig. 17) was fitted by the function

\[
f(M_{\mu\mu}) = [G_1(m_{J/\psi}, \sigma_1, N_1) + G_2(m_{J/\psi}, \sigma_2, N_2)] + G_3(m_{\psi(2S)}, \sigma_3, N_3) + A \times e^{-B x},
\]

(4)

to estimate the number of exclusively produced \( J/\psi \) mesons. Here the combination of the two Gaussian curves \( G_1 + G_2 \) represents the \( J/\psi \) peak, Gaussian curve \( G_3 \) corresponds to the \( \psi(2S) \) peak and exponential function described continuous background under the peaks. This gives \( 18.2 \times 10^3 \) exclusive \( J/\psi \) events in our sample. The distribution of the squared transverse momentum \( p_T^2 \) of the \( J/\psi \) (Fig. 18) for the exclusive sample is fitted by a sum of two exponential functions to separate the contributions from coherent production on the target nuclei by the production on (quasi-)free target nucleons. The contribution from coherent production is found to be 30.3\% for the \(^6\)LiD target and 38.9\% for NH\(_3\) target (36.1\% averaged over the sample). So, about \( 11.6 \times 10^3 \) exclusive \( J/\psi \) mesons were produced via incoherent process.

<table>
<thead>
<tr>
<th>( \sqrt{s_{\gamma N}} ) range (GeV)</th>
<th>( \langle \sqrt{s_{\gamma N}} \rangle ), GeV</th>
<th>( N_{J/\psi\pi} )</th>
<th>( N_{J/\psi\pi} )</th>
<th>( N_{bkg} \pm \sigma_{N_{bkg}} )</th>
<th>( N_{Z_c}^{UL} )</th>
<th>( \sigma_{Z_c}/\sigma_{J/\psi} \times BR(J/\psi\pi), 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>13.8</td>
<td>970</td>
<td>51</td>
<td>52.5±2.7</td>
<td>13.0</td>
<td>2.2</td>
</tr>
<tr>
<td>( &lt; 12.3 )</td>
<td>10.8</td>
<td>243</td>
<td>20</td>
<td>16.2±2.9</td>
<td>12.6</td>
<td>7.0</td>
</tr>
<tr>
<td>( [12.3, 14.1] )</td>
<td>13.2</td>
<td>240</td>
<td>8</td>
<td>13.5±1.4</td>
<td>4.6</td>
<td>2.2</td>
</tr>
<tr>
<td>( [14.1, 15.4] )</td>
<td>14.7</td>
<td>237</td>
<td>14</td>
<td>11.4±1.3</td>
<td>9.5</td>
<td>6.6</td>
</tr>
<tr>
<td>( \geq 15.4 )</td>
<td>16.4</td>
<td>250</td>
<td>9</td>
<td>12.1±1.3</td>
<td>5.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>
Fig. 16: Armenteros-Podolanski plot for $J/\psi\pi^\pm$ system. Arc corresponds to expected $Z_c^+(3900)$ decay.

Fig. 17: Mass spectrum for all (yellow) and exclusively produced dimuons (green).

Fig. 18: $p_T^2$ distribution for $J/\psi$ mesons exclusively produced on the $^6LiD$ (blue) and $NH_3$ (red) targets. Contributions of coherent and incoherent productions are visible.
2.4 The search for the $Z_c(3900)$ at COMPASS

Since exclusive $\mu^+ J/\psi$ and $\mu^+ J/\psi \pi^+$ events have similar distributions for $Q^2$, $\sqrt{s_{\gamma N}}$ and $E_{J/\psi}$, we assume

$$\frac{\sigma_{\mu^+ N \rightarrow \mu^+ Z_c^\pm(3900)N}}{\sigma_{\mu^+ N \rightarrow \mu^+ J/\psi N}} = \frac{\sigma_{\gamma N \rightarrow Z_c^\pm(3900)N}}{\sigma_{\gamma N \rightarrow J/\psi N}} = \frac{1}{a_\pi} \times \frac{N_{UL}^{Z_c^\pm}}{N_{J/\psi \text{ excl.}}},$$

(5)

where $BR(J/\psi \pi) = \Gamma_{J/\psi \pi}/\Gamma_{\text{full}}$ and $N_{J/\psi \text{ excl.}}$ is the measured number of exclusively produced $J/\psi$'s in incoherent process and $a_\pi$ is the acceptance for pion (estimated to be $a_\pi = 0.5 \pm 0.1$), resulting in:

$$\frac{BR(Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm)}{\sigma_{\gamma N \rightarrow Z_c^\pm(3900)N}} \bigg|_{\langle \sqrt{s_{\gamma N}} \rangle = 13.8 \text{ GeV}} < 2.2 \times 10^{-3}, \text{ CL} = 90\%.$$  

(6)

The values for each of the four subranges in $\sqrt{s_{\gamma N}}$ can be found in Table 5.

Finally, using the cross section ($\sigma_{\gamma N \rightarrow J/\psi N} = 14 \pm 1.6_{\text{stat}} \pm 2.5_{\text{syst}} \text{ nb}$) measured by the NA14 Collaboration at $\sqrt{s_{\gamma N}} = 13.7 \text{ GeV}$ [27], the result is

$$BR(Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm) \times \sigma_{\gamma N \rightarrow Z_c^\pm(3900)N} \bigg|_{\langle \sqrt{s_{\gamma N}} \rangle = 13.8 \text{ GeV}} < 31 \text{ pb}, \text{ CL} = 90\%.$$  

(7)

This result can be converted into an upper limit for the partial width $\Gamma_{J/\psi \pi}$ of the decay in Eq. (1) based on the VMD model. According to Ref. [24], the cross section for the reaction in Eq. (2), averaged over the measured distribution of $\sqrt{s_{\gamma N}}$ for the $J/\psi \pi^\pm$ events, is about $0.43 \text{ nb} \times \Gamma_{J/\psi \pi}/(\text{MeV}/c^2)$ for the cutoff $\Lambda_\pi = 0.6 \text{ GeV}$ being a free parameter of $\pi NN$ vertex. So

$$\Gamma_{J/\psi \pi} = \sqrt{(31 \text{ pb})/(0.43 \text{ nb} \times \Gamma_{\text{tot}}/(\text{MeV}/c^2))}$$

(8)

Assuming $\Gamma_{\text{tot}} = 46 \text{ MeV}/c^2$, we obtain an upper limit:

$$\Gamma_{J/\psi \pi} < 1.8 \text{ MeV}/c^2, \text{ CL} = 90\%.$$  

(9)

The main contributions to the systematic uncertainty are: limited knowledge of acceptance for soft pions (20%); background estimation (15%) and the cross section of incoherent exclusive production of $J/\psi$ meson (20%). This gives a total systematic error of about 25% on (6). The systematic uncertainty on (7) is $\sqrt{25^2 + 20^2} \approx 30\%$. Finally the systematic uncertainty on (9) is about 30%/$\sqrt{2} \approx 20\%$. The last value doesn’t include the uncertainty of $\Gamma_{\text{tot}}$ determination and choose of model parameter $\Lambda_\pi$.

<table>
<thead>
<tr>
<th>$\sqrt{s_{\gamma N}}$ range (GeV)</th>
<th>$\langle \sqrt{s_{\gamma N}} \rangle$, GeV</th>
<th>$\sigma_{Z_c}/\sigma_{J/\psi \pi} \times BR(J/\psi \pi), 10^{-3}$ (CL=90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>13.8</td>
<td>2.2</td>
</tr>
<tr>
<td>$&lt; 12.3$</td>
<td>10.8</td>
<td>7.0</td>
</tr>
<tr>
<td>[12.3, 14.1]</td>
<td>13.2</td>
<td>2.2</td>
</tr>
<tr>
<td>[14.1, 15.4]</td>
<td>14.7</td>
<td>6.6</td>
</tr>
<tr>
<td>$\geq 15.4$</td>
<td>16.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Table 5: Results for the different $\sqrt{s_{\gamma N}}$ ranges
3 Analysis and results with the muon beams

3.1 Global NLO QCD fit to world data on $g_1$

A new NLO QCD fit of all $g_1$ world data at $Q^2 > 1$ (GeV/c)$^2$ from proton, deuteron and $^3$He targets has been performed. The number of COMPASS data points used in the fit is 138, out of a total of 679. The fit is performed in the $\overline{\text{MS}}$ renormalisation and factorisation scheme and requires parametrisation of the quark singlet spin distribution $\Delta q_S(x)$, non-singlet distributions $\Delta q_3(x)$ and $\Delta q_8(x)$ and the gluon spin distribution $\Delta g(x)$. These distributions are given as an input at a reference scale $Q^2 = Q_0^2$ which is set to 1 (GeV/c)$^2$ and are evolved according to the DGLAP equations. The following parametrisation is taken:

$$\Delta f_k(x) = \eta_k \frac{x^{\alpha_k} (1 - x)^{\beta_k} (1 + \gamma_k x + \rho \sqrt{x})}{\int_0^1 x^{\alpha_k} (1 - x)^{\beta_k} (1 + \gamma_k x + \rho \sqrt{x}) \, dx},$$

where $\Delta f_k(x)$ represents each of the polarised parton distribution functions $\Delta q_S(x)$, $\Delta q_3(x)$, $\Delta q_8(x)$ and $\Delta g(x)$, and $\eta_k$ is the first moment of $\Delta f_k(x)$. The moments $\eta_k$ of the non-singlet distributions $\Delta q_3$ and $\Delta q_8$ are fixed by the baryon decay constants ($F + D$) and ($3F - D$) respectively, assuming $\text{SU}(2)_f$ and $\text{SU}(3)_f$ flavour symmetries. $\gamma$ and $\rho$ are non zero only for the singlet and the gluon distributions; $\beta_g$, not well determined from the data is fixed to 7.5.

Among the various functional shapes of parton distributions studied, three types are reported here; they represent three possible initial shapes for $\Delta g(x)$: one positive, one negative and one with a node.

As expected the parameters related to the quark distributions are determined with high precision in all cases, while the parameters of the gluon distributions are not well constrained. The different $\Delta g(x)$ hypotheses lead to slightly different polarized quark distributions (and first moments). Table 3 shows the resulting possible ranges for the first moments. The error bands shown in Fig. 19 were obtained by generating several sets of $g_1$ pseudo-data obtained by randomising the initial $g_1$ values within their statistical errors, according to normal distributions.

A detailed analysis of possible systematic effects was performed, including the following items:

- The choice of the functional shapes of the parton distributions: the shape chosen for $\Delta g(x)$, positive, negative or with a node, has an impact of the shapes of $\Delta q_S(x)$ and of $\Delta s(x) + \Delta \pi(x)$ (Fig. 19).
- The choice of the value of $\beta_g$ (varied between 6 and 16).
- The choice of the reference scale $Q_0^2$: different values, between 1 and 64 (GeV/c)$^2$ were tried. Only $\Delta g(x)$ changes, e.g. a positive distribution acquires a node for $Q_0^2$ larger than a few (GeV/c)$^2$. The position of a maximum in the distribution shifts to higher values of $x$ and a maximal value increases up to 2.5 times in the above $Q_0^2$ range. On can conclude that changing the reference scale $Q_0^2$ is almost equivalent to changing the functional shape.
- The choice of the set of unpolarised PDFs (MRST, MSTW...) used for the positivity condition.
- The uncertainties on $\alpha_s$ F+D and 3F-D values. $\alpha_s(M_Z) = 0.12018$ was taken from the MSTW08 fits, where it is fitted together with the PDFs. Therefore the uncertainties linked to $\alpha_s$ are studied together with the uncertainties linked to the choice of the PDF set.
- The F+D and 3F-D parameters were used to fix the values of the first moments $\eta_{3}$ and $\eta_{8}$ ($\text{SU}(2)_f$ and $\text{SU}(3)_f$ symmetries assumption). While left semi-free in the fit, within constraints of their errors, they deviated by about 0.08% from the world values. We included this contribution to the systematic error. In the contrary, varying the other parameter values ($\alpha_3$, $\alpha_8$, $\alpha_S$, ...) had a negligible effect.
- The experimental systematic errors on the input data (free normalisation factors are added).

The results of the global QCD fits to the world data on $g_1^p$, $g_1^d$ and $g_1^n$ are shown at $Q^2 = 3$ (GeV/c)$^2$ in Fig. 20, together with the data evolved to the same scale. On each plot the three curves correspond to three
### 3.2 Verification of the Bjorken sum rule

<table>
<thead>
<tr>
<th>Distribution</th>
<th>First moment at $Q^2 = 3$ (GeV/c)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Sigma$</td>
<td>$[0.25, 0.34]$</td>
</tr>
<tr>
<td>$\Delta u + \Delta \bar{u}$</td>
<td>$[0.82, 0.85]$</td>
</tr>
<tr>
<td>$\Delta d + \Delta \bar{d}$</td>
<td>$[-0.45, -0.42]$</td>
</tr>
<tr>
<td>$\Delta s + \Delta \bar{s}$</td>
<td>$[-0.11, -0.08]$</td>
</tr>
</tbody>
</table>

Table 6: Range of first moments of quark distributions from the QCD fits taking into account statistical and systematic uncertainties discussed in the text.

![Graphs](image)

**Fig. 19:** Results of the QCD fits to $g_1$ world data. Counterclockwise from top left: quark spin distributions $x \Delta q^S(x)$ and $x [\Delta q(x) + \Delta \bar{q}(x)]$ for $u$, $d$ and $s$ flavours, at $Q^2 = 3$ (GeV/c)². For each distribution, the three solutions corresponding to the three different hypotheses of $\Delta g(x)$ shapes are shown. Top right: three different functional forms of the gluon polarization distributions, $x \Delta g$. Shaded bands define the $\pm 1\sigma$ width of fitted pseudo-data distribution (see text for details).

![Graphs](image)

**Fig. 20:** Results of the QCD fits to $g_1$ world data at $Q^2 = 3$ (GeV/c)² as function of $x$. The curves correspond to three $\Delta q(x)$ distributions: positive, negative and with a node. $g_1^P$ is positive in the whole measured region, down to $x \approx 3 \cdot 10^{-3}$. It seems unlikely that it turns negative at least for $x$ values immediately below that value.

**3.2 Verification of the Bjorken sum rule**

The new data on $g_1^P$ also improves the precision on the non-singlet structure function $g_1^{NS}$:

$$g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^n(x, Q^2).$$

and hence on the evaluation of the Bjorken sum rule, which is done using the COMPASS data alone. The sum rule relates the integral of the non-singlet spin structure function $\Gamma^{NS}(Q^2)$ at a fixed $Q^2$ to the ratio $g_A/g_V$ of
Compared to the value obtained from the neutron $\beta$ decay ($|g_A/g_V| = 1.2701 \pm 0.002^{[3]}$), it provides a validation of the Bjorken sum rule within 4%. An estimation of the size and direction in which further perturbative orders will influence our result of $g_A/g_V$ is calculated using the coefficient function in NNLO. The obtained value $g_A/g_V = 1.256$ is slightly larger than our NLO result and closer to the neutron $\beta$ decay one.
3.3 Determination of $\Delta g/g$ using “all-$p_T$” events

We have studied a different approach of $\Delta g/g$ extraction from high-$p_T$ hadrons, $Q^2 > 1$ (GeV/c)$^2$ analysis, published in [31]. The main goal of the new method was to remove a few sources of systematic effects present in the previous analysis. However, also a considerable reduction of the statistical error of $\Delta g/g$ was achieved. The method is based on simultaneous extraction of signal and background asymmetries, which was used in the COMPASS open charm analysis of $\Delta g/g$, [32].

The helicity asymmetry for the production of hadrons in the large $Q^2$ regime, $Q^2 > 1$(GeV/c)$^2$, can be expressed as a function of $x$ as follows:

$$A_{LL}^{2i}(x) = R_{PGF} a_{LL}^{PGF} \frac{\Delta g}{g} (x_g) + R_{LP} D A_{LO}^{1i}(x) + R_{QCDC} a_{LL}^{QCDC} A_{LO}^{1i}(x_C),$$

(14)

where

$$A_{LO}^{1i} = \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i},$$

(15)

and $R_i$ are the fractions of the sub-processes (in the unpolarised sample) and $a_{LL}^i$ the so-called analysing powers (the asymmetries of the partonic cross sections). Labels LP, QCDC and PGF refer to the different processes: Leading Process, i.e. photon absorption by a quark; QCD Compton, i.e. gluon radiation by a quark; and Photon-Gluon Fusion. $D$ is the depolarisation factor which depends on $y$. The variables $x$, $x_g$ and $x_C$ are the interacting parton momentum fraction for the LP, PGF and QCDC process respectively. Observe that the analysis is performed on a event-by-event basis and not hadron by hadron.

Equation (14) is valid at LO in QCD assuming spin independent fragmentation. A possible spin dependence of the fragmentation process discussed in [33] can be neglected in COMPASS kinematic region. A linear dependence of $\Delta g/g$ in $x_g$ is assumed in order to justify the substitution of the convolution integrals with the averaged value of $\Delta g/g$. Although the shape of the gluon polarisation is not known, this assumption is always justified if $x_g$ intervals are small enough.

The evaluation of $\Delta g/g$ from Eq. (14) is possible only when the contribution from the background processes (LP, QCDC) can be computed and subtracted. Therefore the analysis requires a precise Monte Carlo (MC) description of the data. The fractions $R$ and the analysing powers $a_{LL}$ can be calculated using MC simulations based on the LEPTO generator. With the weighted method we extract simultaneously the background and signal asymmetries by minimizing the $\chi^2$ between the expected and observed weighted yields of events. The expected number of events for each of sub-processes: PGF, QCDC and LP is written using $A_{LO}^{LP}$, $A_{LO}^{QCDC}$ $\Delta g/g$, as parameters, the quantities $R$, $a_{LL}$, from the Monte Carlo, the measured muon flux, the acceptance and the unpolarised cross section. For each configuration of target spin and solenoid field directions (four in total) an independent set of such equations is required. The acceptance, the muon flux and the unpolarised cross section cancel. In the simplest case 12 equations are needed. However, $A_{LO}(x)$ is not constant in the measured $x$ range. Therefore, we want to extract $A_{LO}^{LP}$, $A_{LO}^{QCDC}$ and $\Delta g/g$ in several intervals of the corresponding $x$ variable. In the presented analysis we use 12 bins in $x$, 6 in $x_C$ and 1-3 $x_g$. In total we have 76-84 equations. The observed number of events of each type is calculated by summing weights of the given process over corresponding configuration. The weights are:

- $w_{LP} = f P_x D R_{LP}$
- $w_{QCDC} = f P_x a_{LL}^{QCDC} R_{QCDC}$
- $w_{PGF} = f P_x a_{LL}^{PGF} R_{PGF}$

The weights for the different processes depend on the kinematics ($w_{QCDC}$ and $w_{PGF}$ are close to zero at low $p_T$) but in general for a single event all three weights differ from 0. This means that the same event contributes
to each of the three process, at the value of $x$ given by the process. This is since we only know probabilities, $R$s, that a given event is LP, QCDC or PGF. For this reason in the minimization we have to use the correct covariance matrix, that includes non-zero off-diagonal elements in a form of $\sum w_i w_j$. The result of the minimization are the values of $\Delta g/g$ and $A_1^{LO}$, and $A_1^{QCDC}$ versus $x$.

Compared to the method used for the published results [34] the new method avoids the need to parametrize $A_1^g$, and the correlated uncertainty. It also doesn’t require some simplifications in the formulas that were used in the old method (and the associated systematic uncertainty; 2nd largest systematic effect). Other advantages of the new method are a simpler formula for $x_g$ and much simpler and intuitive weight for the PGF process.

\[
\text{new weight} = f P_b a^{PGF}_{LL} R_{PGF} \\
\text{old weight} = f P_b (a^{PGF}_{LL} R_{PGF} - a^{incl,PGF}_{LL} R_{LO} R^{incl,PGF}_{LO}) - a^{incl,PGF}_{LL} R_{QCDC} R^{incl,PGF}_{LO} a^{QCDC}_{LL} D
\]

The simpler weight allows an easier estimation of systematic errors related to MC, e.g. in the new method a change of $a^{PGF}_{LL}$ by a factor of 1.5 changes $\Delta g/g$ and its error by the same amount. In the previous method the impact of $a^{PGF}_{LL}$ on $\Delta g/g$ was much more complex. As already mentioned the new method allows to some extend to test MC tuning by comparing extracted asymmetries in bins of $x_C$ and $x$. Last but not least, an improvement in the statistical uncertainty is observed.

Only deuteron data were used in the analysis (2002-2006). Whenever possible the data selection follows the previous analysis, There are two important exceptions: all the $p_T$ cuts were removed and at least one hadron is required (instead of at least two). Standard DIS selections:

- $Q^2 > 1$ (GeV/c)$^2$
- $0.1 < y < 0.9$
- $x_{Bj} < 1.0$

are applied, while for the hadrons the maximum energy fraction accepted is $z_h < 0.85$. Couples of hadrons with $z_1 + z_2 > 0.95$ are also excluded to limit the contribution of vector meson produced in the diffraction process. Hadrons with $0.05 < p_T < 2.5$ GeV/c are kept.

Good agreement between data and Monte Carlo was observed for inclusive variables $x$, $Q^2$ and $y$. For the hadron variables, some instabilities are present. However, with the exception of very low and high $p_T$ the agreement is better than 20%. Concerning the discrepancy at low $p_T$, since the region is dominated by LP, the disagreement has a limited impact to the analysis i.e. the fraction of LP events is always high ($R_{LP} \approx 95\%$) in this region and does not depend on the quality of MC.

We have used several neural networks (NN) in the analysis, designed to provide a parametrisation of a given quantity $X$. We use four input parameters for the NN: $p_T$, $p_t$, $x$ and $Q^2$. Moreover to reduce systematic uncertainty related to the NNs we use 4 NNs for each of the parametrized variable, mixing learning and testing sets. The output of these 4 NNs is averaged, and used for the final $\Delta g/g$ extraction.

The NN results for the parametrisation of $a^{PGF}_{LL}/D$, $a^{QCDC}_{LL}/D$, $x_C$, and $x_G$ are given in Fig. 22. The correlation of $a_{LL}/D$ is good for PGF’s and poor for QCDC processes, as a consequence of the fact that QCDC $a_{LL}$ does not depend significantly upon any of the input variables. If the correlation between the NN output and the true value of $X$ is low, the figure of merit is reduced but no bias of $\Delta g/g$ is introduced. Moreover, since in the weight we use $a_{LL}$ and not $a_{LL}/D$, even for the QCDC process a correlation between true and parametrized $a_{LL}$ is larger than 80%.

An example of $R$ fraction parametrisation is presented on 2 dimensional plots as a function of $(p_T, p_t)$, and $(x_{Bj}, Q^2)$ (Fig. 23). Each time two out of four input parameters are fixed in the NN input: $x_{Bj} = 0.01$, $Q^2 = 2$ (GeV/c)$^2$, $p_T = 1.5$ GeV/c, $p_t = 30$ GeV/c. As expected when the value of transverse momentum of the leading $p_T$ hadron grows, the LP contribution to the sample is reduced while the contributions of QCDC

\[
\Delta g/g = 0.1, Q^2 = 2, p_T = 1.5, p_t = 30
\]
3.3 Determination of $\Delta g/g$ using “all-$p_T$” events

and PGF are enhanced. On the $(x, Q^2)$ plot one can observe that the fraction of PGF is very small for the high $x$ region; in addition it is clear that QCDC dominates at high value of $y$, while LP is concentrated on lower $y$ values.

The final result for $\Delta g/g$ measured at average value of $\langle x_g \rangle \approx 0.10$ and average $\mu^2 = \langle Q^2 \rangle = 3$ (GeV/c)$^2$ is:

$$\Delta g/g = 0.113 \pm 0.038 \pm 0.035.$$  \hspace{1cm} (16)

measured at average value of $\langle x_g \rangle \approx 0.10$ and average $\mu^2 = \langle Q^2 \rangle = 3$ (GeV/c)$^2$. The gluon polarisation results were also obtained in 3 bins of $x_g$ (Table 7). As in the already published result, $x_g$ is estimated using a NN, the correlation factor between true and extracted from NN $x_g$ is about 60%. Within error bars the results are consistent with each other. $\Delta g/g$ is almost $3\sigma_{stat}$ from zero, giving hints that $\Delta g/g$ might be positive in the region of the measurement. Similar conclusion is reached in the NLO DSSV++ fit, which includes 2009 RHIC data.

$$\begin{array}{|c|c|c|}
\hline
\langle x_g \rangle & x_g \text{ range} & \Delta g/g \\
\hline
x_g = 0.08 & 0.04 - 0.13 & 0.087 \pm 0.050 \\
x_g = 0.12 & 0.07 - 0.21 & 0.149 \pm 0.051 \\
x_g = 0.19 & 0.13 - 0.28 & 0.154 \pm 0.122 \\
\hline
\end{array}$$

Table 7: The values for $\Delta g/g$ in three $x_g$ bins.

The presented data agrees well with the published result [34] of $\Delta g/g = 0.125 \pm 0.060 \pm 0.065$. The difference is $0.012 \pm 0.046$, where the errors is assumed to be $\sqrt{0.060^2 - 0.038^2}$. There is a reduction of the statistical error by a factor 1.6. About half of the reduction factor is related to the usage of the new method. The remaining half is mostly related to the fact the events with $p_{T,1} > 1.5$ GeV/c and the second hadron having $p_T$ lower than
0.4 GeV/c are a relatively clean source of PGF, but were not used in the previous analysis. A comparison of old and new results obtained in 3 $x_g$ bins is presented in Fig. 24 (left). In addition to a clearly observed reduction of the statistical error a shift in average $x_g$ is also visible. There are two reasons why the $x_g$ is higher in the new analysis; first: in the enlarged phase space of the all-$p_T$ analysis higher $x_g$ is preferred; second: in the new method the given event is characterized by one $x_g$ value, while previously some subtraction of the so called $x'_g$ had to be done cf. Eq.(4) of [34].

In Fig. 24 (right) the new results are compared with the world $\Delta g/g$ extracted in LO analyses. [32, 35, 37]. Within uncertainties the agreement between data sets is very good. The new COMPASS data have the lowest combined statistical and systematic uncertainty. The new results were also compared with the newest COMPASS NLO fits, cf. Fig. 27. Our data do not agree with negative solutions of $\Delta g/g$. The presented analysis is performed in LO. Thus the curves and data points are not obtained by the same procedure. However, do note that NLO QCD is the lowest order of the QCD analysis where gluons do exist in the nucleon (in LO they are only a result of the $Q^2$ evolution).
3.4 Gluon contribution to the nucleon spin via single hadron photoproduction at high-$p_T$

In the analysis presented before, we used the Monte Carlo generator PYTHIA to unfold the partonic information at LO from the measurement of the double spin asymmetry $A_{LL}$. We now revisit this channel in the light of recent theoretical advances to apply a more genuinely pQCD-based approach to the gluon distribution, similar to that employed in the analysis of the $p\bar{p}$ asymmetries from RHIC [38, 39]. The theoretical framework was first introduced in [40], and has been updated in [41]. It relies on a standard factorization of the inclusive photoproduction of single hadrons into hard scattering partonic subprocesses and nonperturbative functions. The latter describe the initial (polarized) distribution of the partons in the nucleon, (p)PDFs, and their final state hadronization, FFs. One of the pPDFs is the coveted gluon polarized distribution, $\Delta g(x, \mu^2)$.

All the nonperturbative quantities considered are collinear. This implies that the measured $p_T$ is assumed to arise only from the hard subprocesses, which can then only be higher order ones. These include foremost PGF ($\gamma^* g \to q\bar{q}$), which then directly probes the gluons at LO, but also QCD Compton ($\gamma^* q \to qg$) as well as resolved photon processes whereby the photon fluctuates into a hadronic state before interacting with the nucleon. The expansion extends to the NLO in the coupling strength $\alpha_S$. On the contrary, soft processes such as the photoabsorption on a quark ($\gamma^* q \to q$), which make the bulk of the $p_T$-integrated cross section, are altogether disregarded. The applicability of the framework at a center of mass energy of $\sqrt{s} \approx 18$ GeV, was shown by our previous measurement of the cross section [34] and its comparison to theoretical calculations [41].

The $A_{LL}$ asymmetries for charged hadrons have been determined for the full statistics available, on both polarized deuteron and proton targets, cf. Fig. 26. They cover a range in $p_T$ from 0.7 to 4GeV/c, covering a domain where the hard scale is high enough to guarantee applicability of pQCD, and reaching also into the lower $p_T$’s that allow the systematics of the measurement to be better evaluated. Data will be compared to calculations
including the resummation of soft gluons, when they are available. The final goal is to include the data in a global fit of pPDFs to world spin-dependent data.

### 3.5 Quark fragmentation functions from pion multiplicities

Preliminary results on charged pion and kaon multiplicities were presented in last year’s report. Some additional studies were done in view of the publication of the results, like the estimation of the contribution from diffractive \( \rho^0 \) to the SIDIS pion sample and a better characterization of the RICH performance.

The multiplicities are defined as the differential cross section for hadron production normalized to the inclusive DIS cross section. They depend on unpolarised PDFs \( q(x, Q^2) \) and FFs \( D^h_{q}(z, Q^2) \):

\[
\frac{d^3\sigma^{h}(x, z, Q^2)/dx dz dQ^2}{d^2\sigma^{DIS}(x, Q^2)/dx dQ^2} = \frac{\sum q e_q^2 q(x, Q^2) D^b_{q}(z, Q^2)}{\sum q e_q^2 q(x, Q^2)}
\]

Here, \( z \) represents the energy fraction of the virtual photon carried by final-state hadron. We show in Fig. 28 the probabilities of positive hadrons to be identified as \( \pi^+ \) by the RICH detector. The efficiencies and misidentification probabilities were calculated by using samples of \( \pi, K \) or \( p \) coming from the decay of \( K_S, \phi \) or \( \Lambda \) and looking at the response of the RICH.

The \( \rho^0 \) contribution to the pion multiplicities vs \( z \) for eight bins of \( Q^2 \) is shown in Fig. 29. In most of the bins, this contribution is small, of a few %; it reaches high values, up to 40 % only at high \( z \) and small \( Q^2 \), where the multiplicities are very small.

The full data set of multiplicities comprises 476 data points for \( \pi^+ \) and \( \pi^- \), and about as many for kaons and represents an impressive improvement to the data base for NLO global fits of multiplicities in view of the extraction of pion FFs. In Fig. 30 our \( \pi^+ \) and \( \pi^- \) multiplicities are compared to a preliminary global fit by the DSS group [42] at NLO in pQCD to all world data in SIDIS (including our pion preliminary data, the latest HERMES pion data, \( e^+e^- \) and \( pp \) data. A very satisfactory agreement between our data and the fit is obtained, with a reduced \( \chi^2 \) of about 1.

We have also performed a fit at LO to the COMPASS pion data alone to extract the quark-to-pion FFs. The relation between multiplicities and FFs in LO is given by

\[
M^h = \frac{1}{N^{DIS}(x, Q^2)} \frac{dN^h}{dx dz dQ^2} = \frac{\sum q e_q^2 q(x, Q^2) D^b_{q}(z, Q^2)}{\sum q e_q^2 q(x, Q^2)}
\]

Imposing isospin and charge symmetry for FFs and assuming \( D^q_{\pi^\pm} = D^q_{\pi^0} \), only two independent FFs survive, the favored and the unfavored ones. The fit of pion multiplicities was done using MSTW08 for the PDFs and...
3.5 Quark fragmentation functions from pion multiplicities

Fig. 29: Correction factor to the multiplicities for the diffractive $\rho^0$ contamination, as a function of $z$ for various $Q^2$ bins.

Fig. 30: $\pi^+$ (left) and $\pi^-$ (right) multiplicities versus $z$ for 8 bins in $x$ and 5 bins in $y(Q^2)$. In each $x$ bin, the multiplicities at different $Q^2$ are staggered for clarity. Only statistical errors are shown. The curves correspond to the DSS NLO fit to $e^+e^-$, p-p and SIDIS world data (see text).
Fig. 31: The favored (left) and unfavored (right) pion fragmentation functions extracted at LO from our data alone plotted against DSS (dashed line) and HKNS (dotted line) global fits.

the functional form for the FFs:

\[ D_i(z,Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i} [1 + \gamma_i (1-z)^{\delta_i}] \]  

(19)

Figure 31 shows COMPASS results for the quark-to-pion favored and unfavored FFs obtained from the LO fit of COMPASS data alone, together with the FFs from DSS [42] and HKNS [44] (both NLO fits). Our FFs are in good agreement with the old fit from DSS, for which our data were not available, but rule out HKNS fit based only on $e^+e^-$ data, as expected. A publication with the final pion multiplicities and the resulting FFs is in preparation. A similar work is in progress using the kaon multiplicities.

3.6 The gluon Sivers asymmetry

Using the same approach of the published results on the $\Delta g/g$ measured from high-$p_T$ hadron pairs[31] we have extracted from the first time a value of Sivers asymmetry on gluons, from a transversely polarised deuteron target.

The Sivers asymmetry in the production of two high-$p_T$ hadrons at large $Q^2$ regime can be expressed as a combination of three QCD subprocesses:

\[ A_{UT}^{\sin(\phi_{2h}-\phi_s)} = R_{PGF} A_{PGF}^{\sin(\phi_{2h}-\phi_s)}(x_G) + R_{LP} A_{LP}^{\sin(\phi_{2h}-\phi_s)}(x) + R_{QDCC} A_{QDCC}^{\sin(\phi_{2h}-\phi_s)}(x_C). \]  

(20)

where $R_i$ are the fractions of the subprocesses. The fractions $R_i$ as a function of the event kinematics are parametrized by a neural network, trained on Monte Carlo samples. The minimization process for the extraction of the three asymmetries is very similar to what described in Sec. 3.3, even if in this case only events at high-$p_T$ are kept.

The data selection requires the standard selection of the DIS events, while for the hadron pairs:

- $p_{T1} > 0.7$ GeV/$c$; $p_{T2} > 0.4$ GeV/$c$ — high-$p_T$ cut that ensures that PGF fraction in the sample is higher and that the correlation between the azimuthal angle of the gluon and the azimuthal angle of the reconstructed hadron pair (constructed from the vector sum of two hadrons) is stronger.
- $z_1 > 0.1$; $z_2 > 0.1$ — current fragmentation region
- $z_1 + z_2 < 0.9$ — rejection of events from exclusive production

There are two major reasons for choosing the high-$p_T$ sample. First by this choice we enhance the fraction of PGF in the sample. Secondly we enhance the correlation between the azimuthal angle of the gluon momentum and the azimuthal angle of the reconstructed sum of two leading hadron momenta (leading in the sense of
3.7 Interplay between the dihadron asymmetry and the Collins asymmetry

There is a striking similarity among the Collins asymmetry for positive and for negative hadrons \([47]\) and the dihadron asymmetry as functions of \(x\), as clearly shown in Fig. \(34\) where the combined results from the 2007 and 2010 COMPASS runs are presented. First, there is a mirror symmetry between the Collins asymmetry for positive and for negative hadrons, the magnitude of the asymmetry being essentially identical and the sign being opposite. This symmetry has been phenomenologically described in terms of opposite signs of \(u\) and \(d\) quark.

Fig. 32: Correlation between the gluon momentum azimuthal angle \(\phi_G\) and the azimuthal angle \(\phi_{2h}\) with and without the \(p_T\) cuts.

Fig. 33: Sivers asymmetries for different QCD processes.

The results of the MC studies on a PGF sample are shown on Fig. \(32\) where the correlation between the two angles is plotted.

The Sivers asymmetry for the PGF process, i.e. the Sivers asymmetry on gluons is \(A^{\sin\phi_{2h} - \phi_S}_{PGF} = 0.14 \pm 0.15\) (stat.) at \(\langle x_G\rangle = 0.126\); For the leading process the asymmetry is \(A^{\sin\phi_{2h} - \phi_S}_{LP} = 0.033 \pm 0.024\) (stat.) at \(\langle x\rangle = 0.028\) while for the QCD-Compton the result is \(A^{\sin\phi_{2h} - \phi_S}_{QCDC} = 0.12 \pm 0.11\) (stat.) at \(\langle x_C\rangle = 0.137\) (Fig. \(33\)). The Sivers asymmetry for gluons is low, compatible with zero, as expected from the cancellation of the contribution of the \(u\) and \(d\) Sivers function.

It should be added that the \(A^{\sin\phi_{2h} - \phi_S}_{LP}\) should not be directly compared with integrated results of the Sivers asymmetry on deuteron since there is no selection of high-\(p_T\) events in that case.

3.7 Interplay between the dihadron asymmetry and the Collins asymmetry

There is a striking similarity among the Collins asymmetry for positive and for negative hadrons \([47]\) and the dihadron asymmetry as functions of \(x\), as clearly shown in Fig. \(34\) where the combined results from the 2007 and 2010 COMPASS runs are presented. First, there is a mirror symmetry between the Collins asymmetry for positive and for negative hadrons, the magnitude of the asymmetry being essentially identical and the sign being opposite. This symmetry has been phenomenologically described in terms of opposite signs of \(u\) and \(d\) quark.

The LP Sivers asymmetries on deuteron is compatible with zero, as expected from the cancellation of the contribution of the \(u\) and \(d\) Sivers function.
transversity distributions with almost equal magnitude and opposite sign for favoured and unfavoured Collins fragmentation functions [45].

The new results show that the values of the dihadron asymmetry are slightly larger in magnitude, but very close to the values of the Collins asymmetry for positive hadrons and to the mean of the values of the Collins asymmetry for positive and negative hadrons, after changing the sign of the asymmetry of the negative hadrons. The hadron samples on which these asymmetries are evaluated are different [46, 47] since at least one hadron with \( z > 0.2 \) is required to evaluate the Collins asymmetry, while all the combinations of positive and negative hadrons with \( z > 0.1 \) are used in the case of the dihadron asymmetry. It has been checked, however, that the similarity between the two different asymmetries stays the same when measuring the asymmetries for the common hadron sample, selected with the requirement of at least two oppositely charged hadrons produced in the primary vertex. This gives a strong indication that the analysing powers of the single and dihadron channels are almost the same.

More work has been done to understand these similarities. Since the Collins asymmetries are the amplitudes of the sine modulations of the Collins angles \( \phi_{C \pm} = \phi_{h \pm} + \phi_S - \pi \), where \( \phi_{h \pm} \) are the azimuthal angles of positive and negative hadrons in the \( \gamma^* \)-nucleon system, the mirror symmetry suggests that in the di-hadron fragmentation of the struck quark azimuthal angles of positive and negative hadrons created in the event differ by \( \approx \pi \), namely that when a transversely polarised quark fragments, oppositely charged hadrons have antiparallel transverse momenta. This anti-correlation between \( \phi_{h+} \) and \( \phi_{h-} \) could be due to a local transverse momentum conservation in the fragmentation, as it is present in the LEPTO generator for spin-independent DIS. The relevant point here is that such correlation shows up also in the Collins fragmentation function that describes the spin-dependent hadronization of a transversely polarised quark \( q \) into hadrons.

If this is the case, asymmetries correlated with the dihadrons can also be obtained in a way different from the one described above. For each pair of oppositely charged hadrons, using the unit vectors of their transverse momenta, we have evaluated the angle \( \phi_{2h} \) of the vector \( \mathbf{R}_N = \mathbf{p}_{T,h+} - \mathbf{p}_{T,h-} \) which is the arithmetic mean of the azimuthal angles of the two hadrons after correcting for the discussed \( \pi \) phase difference between both angles. This azimuthal angle of the dihadron is strongly correlated with \( \phi_R \), as can be seen in Fig. 35 where the difference of the two angles is shown. The same correlation is present also in the LEPTO generator for spin-independent DIS. Introducing the angle \( \phi_{2h,S} = \phi_{2h} - \phi_{S'} \), one simply obtains the mean of the Collins angle of the positive and negative hadrons (again after correcting for the discussed \( \pi \) phase difference between the two angles), i.e. a mean Collins type angle of the dihadron. The amplitudes of the modulations of \( \sin \phi_{2h,S} \), which could then be called the \textit{Collins asymmetry} for the dihadron, are shown as a function of \( x \) in Fig. 41 for all the \( h^+ h^- \) pairs with \( z > 0.1 \) in the 2010 data, and compared with the dihadron asymmetry evaluated with an additional cut of \( p_T > 0.1 \) GeV/c on the transverse momentum of the individual hadrons was applied for a precise determination of the azimuthal angles. The asymmetries are very close, hinting at a common physical origin for the Collins mechanism and the dihadron fragmentation function, as originally suggested in the \( ^3P_0 \) Lund model [48], in the recursive string fragmentation model [49] and in recent theoretical work [50].

3.8 The Sivers asymmetries in the Drell-Yan \( x - Q^2 \) region

We review here the analysis of the Sivers asymmetries in SIDIS in the same \( Q^2 \) range as the one accessed by the Drell-Yan experiment. The analysis described here is strongly connected to the DY measurement. The SIDIS Sivers PDF must be extracted in the same \( x \) and \( Q^2 \) interval than the Drell-Yan one, for a direct test of the change of sign of the Sivers function.

The different approach to access transverse nucleon structure in the future COMPASS program is via the Drell-Yan (DY) process (Fig. 36) using a 190 GeV negative pion beam impinging on a transversely polarized proton target (NH\(_3\)). The advantage of DY processes is that fragmentation functions are not involved. However, the price to pay is that observables stem from a convolution of two distribution func-
3.8 The Sivers asymmetries in the Drell-Yan $x - Q^2$ region

The Drell-Yan cross section is given by $\sigma^{DY} \propto \sum f f'_{\pi^-} \otimes f'_{\pi^+}$ where $f$ and $f'$ are generic place holders of PDFs. For $\pi^- p$ scattering the process is dominated by the up quark distributions. Polarized DY experiments can study TMD distributions like the Sivers and Boer-Mulders distributions. The theory predicts that these naive T-odd TMD distributions obey a restricted universality and change sign when observed in SIDIS and DY.

$$f^\perp_{1T} |_{DY} = -f^\perp_{1T} |_{SIDIS} \quad \text{and} \quad h^\perp_{1} |_{DY} = -h^\perp_{1} |_{SIDIS}$$

This sign change is due to switching from final-state interaction in SIDIS to initial-state interaction in DY. A violation of this prediction would imply drastic consequences on how cross sections are calculated. This has generated wide-spread interest in a direct comparison of TMD distributions obtained from SIDIS and DY, respectively. The DY experiment will primarily access the T-odd Sivers and Boer-Mulders TMD distributions, $f^\perp_{1T}$ and $h^\perp_{1}$ for up quarks in the proton. To avoid the $J/\psi$ mass region and the region of background from charm decays, the experiments will focus on dimuon masses $4 \text{ GeV}/c^2 < M_{\mu\mu} < 9 \text{ GeV}/c^2$, that corresponds to $Q^2 > 16 \text{ (GeV}/c)^2$ in SIDIS.

We show here The measurement of the whole set of transverse spin SIDIS-asymmetries in four ranges in $Q^2$, with the higher bin in $Q^2$ corresponding to the range that will be accessed by the DY measurements in 2014 and 2015: $1 \text{ (GeV}/c)^2 < Q^2 < 4.00 \text{ (GeV}/c)^2$, $4.00 \text{ (GeV}/c)^2 < Q^2 < 6.25 \text{ (GeV}/c)^2$, $6.25 \text{ (GeV}/c)^2 < Q^2 < 16 \text{ (GeV}/c)^2$, and $Q^2 > 16 \text{ (GeV}/c)^2$.

The SIDIS and DY accessible asymmetries are listed in the cross sections below. The schematic view of the corresponding frameworks and some notations and definitions adopted in this note are given in Fig.37

Using standard SIDIS notations, the transverse spin-dependent part of the cross section in a single photon exchange approximation, can be written in a following model-independent way[^51]:

$$\frac{d\sigma}{dx dy dz d\phi_{h} d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU;T} + \varepsilon F_{UU;L}) \times$$

[^51]: The twist-2 amplitudes are marked in red and those which have higher twist interpretation - in blue.
where,  
\( \varepsilon = (1 - y - \frac{1}{\gamma^2}y^2)/(1 - y + \frac{1}{\gamma^2}y^2), \gamma = 2Mx/Q \) and \( \psi \) is the laboratory azimuthal angle of the scattered lepton (in DIS kinematics \( d\psi \approx d\phi_S \)). The target transverse polarization dependent part of this general expression contains eight azimuthal modulations in \( \phi_h \) and \( \phi_S \) (azimuthal angles of the produced hadron and of the nucleon spin). Each modulation leads to a Double-Spin Asymmetry (DSA).

Using similar notations, the general form of the single-polarized (\( \pi N \)) DY cross section in terms of angular variables defined in Collins-Soper frame (Fig. 37) was defined in [53]. Quoting only the LO part we have:

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2 F_U^1} \left\{ 1 + \cos^2 \theta_{CS} + \sin^2 \theta_{CS} \cos (2\varphi_{CS}) A_{UU}^{\cos(2\varphi_h)} + \right. \\
\text{target longitudinal polarization dependent terms} + \\
\left. S_T \left[ (1 + \cos^2 \theta_{CS}) \sin \varphi_S A_T^{\sin \varphi_S} + \right. \\
\sin^2 \left( 2\varphi_{CS} + \varphi_S \right) A_T^{\sin(2\varphi_{CS} + \varphi_S)} + \sin (2\varphi_h - \varphi_S) A_T^{\sin(2\varphi_h - \varphi_S)} \right] \right\}
\]
As one can see, in the Drell-Yan cross section only one unpolarised and three target transverse spin dependent amplitudes arise at leading order.

Four of the eight SIDIS TSAs have LO interpretation (marked in red in Eq. (22)) and are described by the different convolutions of TMD twist-two PDFs and FFs. The first two are the well-known Sivers (access to $f^q_{1T}$ PDF) and Collins (access to $h^q_1$ PDF) asymmetries. The other two $A^\text{Boer-Mulders}_{1T}$ and $A^\text{Collins}_{1T}$ LO TSAs are related to the $g^q_{1T}$ (worm-gear) and $h^{q\perp}_{1T}$ (pretzelosity) PDFs. The remaining four SIDIS asymmetries are higher-twist effects (marked in blue in Eq. (22)), however they can be expressed in terms of twist-two PDFs being interpreted as Cahn kinematic corrections to twist-two spin effects on the transversely polarized nucleon [52,51]. Within the same model, DY TSAs are also interpreted in terms of TMD PDFs. In this case the asymmetries are related to the convolution of TMD PDFs of the beam and of the target hadron. For the DY the $A^\text{Sivers}_T$, $A^\text{Collins(2\pi CS-\varphi_S)}_{1T}$ and $A^\text{Collins(2\pi CS+\varphi_S)}_{1T}$ give access to the $f^q_{1T}$, $h^q_1$ and pretzelosity-$h^{q\perp}_{1T}$ PDFs of the nucleon (see the Table 8 for the complete list).

In view of the DY-SIDIS comparison, we present our SIDIS results in the same $x - Q^2$ kinematic regions which are selected for the DY measurement program.

Apart from the binning in $Q^2$ the standard cuts of previous analysis are used:

- $Q^2 > 1$ (GeV/c)$^2$;
- $0.1 < y < 0.9$;
- $W > 5$ GeV/c$^2$;
- $0.003 < x < 0.7$;
- relative energy of the hadron $0.2 < z < 1$;
- hadron transverse momentum $p_{hT} > 0.1$ GeV/c;

Fig. 38 shows the kinematic $x : Q^2$ phase-space covered by the analysis. The average TSAs at DY $Q^2$-ranges are shown in Fig. 39. The Sivers asymmetries as a function of the $x$, $z$, $p_T$ and $W$ for positive and negative unidentified hadrons are shown in Fig. 40.

### 3.9 Exclusive meson production with the transversely polarized proton target (2007 & 2010 data)

Exclusive meson leptonproduction provides a complementary tool for accessing the GPDs. Studies of the exclusive production of $\rho^0$ mesons from a transversely polarized target were initiated several years ago. In the absence of a dedicated recoil detector, the exclusivity of the $\mu p \rightarrow \mu p \rho^0$ reaction is imposed by applying kinematic cuts (mostly the missing energy as in Eq. (24)). The remaining background (about 20%) under the exclusive peak is evaluated using a dedicated Monte Carlo simulation.

For transversely polarized target protons the $\mu p \rightarrow \mu p \rho^0$ reaction gives access to the poorly known GPD $E$ and to the chiral odd (or transversity) GPDs $H_T$ and $E_T$, which cannot contribute to DVCS. Indeed, for the quark transversity GPDs the emitted and reabsorbed partons have opposite helicities. Since the interactions of light quarks with gluons or photons conserve helicity, the initial parton helicity flip can only be compensated
Fig. 38: $x - Q^2$ distributions for the ranges selected for the analysis.

Fig. 39: Mean TSAs at Drell-Yan $Q^2$-ranges
by higher-twist meson wave functions. The GPDs $H$, $E$, and $\bar{E}$ are related to the famous Sivers, transversity and Boer-Mulders TMDs.

A transverse polarization of the target allows us to determine the five single-spin asymmetries $A_{UT}$ and the three double-spin asymmetries $A_{LT}$. The involved angles are the azimuthal angle between the lepton scattering plane and the production plane, $\phi$, and the azimuthal angle of the transverse target spin vector relative to the lepton scattering plane, $\phi_S$. The values of all eight asymmetries depend on $x_{Bj}$, $Q^2$, and $p_T^2$. The values integrated over the kinematic variables, are shown in Fig. 42.

The asymmetry $A_{UT}^{\sin(\phi_S - \phi_S)}$ (published in [54]) is of special interest as it measures the interference term between the GPDs $H$ and $E$. It is proportional to a weighted sum of convolutions of the GPDs $E^u,d$ with the distribution amplitude of the produced meson and a hard scattering kernel. The weights depend on the wave function of the involved meson expressed in terms of contributing quarks of different flavours and gluons. In the GPD model of Goloskokov and Kroll [56] the small value of the asymmetry is explained as due to an approximate cancellation of two sizable contributions of opposite signs for the GPDs $E_u$ and $E_d$ for the valence $u$ and $d$ quarks. In contrast, the model predicts larger asymmetry for exclusive production of $\omega$, for which the analysis is ongoing.

The other asymmetries for exclusive $\rho^0$ production (published in [55]) are all found to be compatible with zero, except the asymmetry $A_{UT}^{\sin(\phi_S)}$ which deviates from zero by about two standard deviations. This asymmetry is proportional to a sum of two interference terms, each depending on a product of convolutions of chiral-odd and chiral-even GPDs. For simplicity, we denote these interference terms here as $H T \cdot H$ and $\bar{E} T \cdot E$. The asymmetry $A_{UT}^{\sin(2\phi_S - \phi_S)}$, which arises from the interference term $\bar{E} T \cdot E$ is consistent with zero. The observation of a non-zero asymmetry $A_{UT}^{\sin(\phi_S)}$ is the first experimental evidence of the non-negligible contribution of the chiral-odd GPD $H_T$.

The $x_{Bj}$, $Q^2$ and $p_T^2$ dependencies of the asymmetries $A_{UT}^{\sin(\phi_S - \phi_S)}$, $A_{UT}^{\sin(2\phi_S - \phi_S)}$ and $A_{UT}^{\sin(\phi_S)}$ are shown in Fig. 43 and found in excellent agreement with the prediction from Ref. [56].
Fig. 41: Comparison between the dihadron asymmetry (black points) and the Collins-like asymmetry for the dihadron sample (open blue points) as a function of $x$ for the 2010 data.

Fig. 42: Mean value $\langle A \rangle$ and the statistical error for every modulation. The error bars (left bands) represent the statistical (systematic) uncertainties.

Fig. 43: Single-spin azimuthal asymmetries for a transversely (T) polarized target and unpolarised (U) beam. The error bars (grey bands) represent the statistical (systematic) uncertainties. The curves show the predictions of the GPD model [56].
4 Status of the 2012 data analysis

4.1 Primakoff run

During the 2012 Primakoff run we have taken data in experimental conditions similar to the 2009 data taking (Sec. 2.1.1), with the goal to increase the number of Compton scattering events by at least a factor five. First investigations of the data quality is promising, as it is demonstrated for the achieved vertex position resolution, after careful run-by-run alignment shown in Fig. 44. The calibration of the electromagnetic calorimeters was delayed, however, due to the lack of man power and the necessity to complete the analysis and publication of the 2009 data. It has been resumed in the past two months, and the preparation of the first mass production is ongoing. The enhancements achieved for the feature extraction of the ECAL1 signals, as described along with the analysis of the 2012 DVCS data (next section), will be be useful when applied also for ECAL2; this is presently under study. After finishing the analysis and publication of the 2009 data the manpower is now available for the analysis of the 2012 data. All the tools are ready and due to the expertise built up on the 2009 analysis we expect the first results of the 2012 data to arrive within the year.

4.2 The 2012 DVCS pilot run

The experimental set-up (see Fig. 45) foreseen for the measurement of the exclusive single photon production ($\mu p \rightarrow \mu' \gamma p'$) cross section comprises a 2.5 m long liquid Hydrogen (LH$_2$) target, a new 4 m long recoil detector named CAMERA, and a new electromagnetic calorimeter ECAL0, which gives a compromise between an enlarged angular acceptance for photon detection and a reduced acceptance for charged particles detected in the first spectrometer. Note also that due to the new geometrical configuration, the very small area trackers consists of the scintillating fiber station SCiFi04 and new Micromegas detectors, equipped with pixels in their central part (only two new detectors were installed in the MM01 station in 2012). The very small area trackers provide an angular coverage for outgoing muon angles smaller than 10 mrad corresponding to the DVCS kinematic domain for $1 \leq Q^2 \leq 2.5$ (GeV/c)$^2$ (Fig. 47).

A commissioning has been performed at the end of 2012 using a setup almost identical to the final one, the main differences being the reduced size of ECAL0. After commissioning of the new detectors, four weeks of DVCS data were collected. A large effort was needed to understand the performance of CAMERA and to reduce the background level for the photon detection in ECAL1.

4.2.1 Recoil proton detector

The new large recoil proton detector, CAMERA, is based on a Time of Flight (ToF) measurement between two barrels of 24 scintillators read at both ends by fast photomultiplier tubes (PMTs). It allows detection of protons with momentum as low as 270 MeV/c. The expected timing resolution of 310 ps provides a proton momentum...
resolution ranging from 4% to 10% and a resolution on the momentum transfer $t$ from 8% to 18% for proton momentum varying from 300 to 700 MeV/c. Such a resolution is mandatory to build six bins in $t$ for an accurate determination of the $t$-dependence of the DVCS cross section.

To develop successful methods for a precise ToF determination and to cope for the weakness of the inner ring A appeared to be a more complex task than expected for reasons explained below.

**The readout electronics of the CAMERA detector:** The event readout is done with the GANDALF system, developed at Freiburg University. GANDALF collects the signals from the Photo Multiplier Tubes (PMTs) with a sampling at 1 GHz and provides their amplitudes corrected for time and amplitude dependence, using a constant fraction algorithm implemented in its FPGA. The difference and the sum of the time information collected at both ends of a scintillator represent, after final calibration, the position and the time, respectively, of the particle track crossing the scintillator. The proton momentum is determined from the evaluated velocity $\beta = \text{DoF}/(c \cdot \text{ToF})$ where DoF is the distance of the proton between the inner and outer rings.

GANDALF is used for the first time for a ToF measurement. In order to achieve the best possible time resolution, certain corrections have to be applied to the raw data. In particular, the effects of small deviations of the signal baseline as well as of the precise signal shape have been addressed very recently. Although this work is still in progress, the preliminary results are very encouraging. An example of the observed signal shape variations is shown in figure 46.

**Characterization of the scintillators with cosmic rays:** Time resolution and attenuation length of each element were measured prior to the data taking, using cosmic rays. In Table 9, the properties of A and B elements used in CAMERA are compared to the properties of the prototypes of same size, MUREX, built in 2006. The attenuation lengths $\lambda$ are close to 2.8 m for the B scintillators, while they are spread around 0.9 m for the A ones (see 2013 SPSC report). The values for scintillators A compare unfavorably with the attenuation lengths of about 2 m, measured on the MUREX prototypes. For the data taking in 2012, the best (with $\lambda > 0.9$ m) and worst (with $\lambda < 0.9$ m) scintillators A have been interleaved. The resulting negative impact (shown in the Table) is a timing resolution of 350 ps for the CAMERA inner ring significantly larger than the 270 ps measured for the 4 mm thick MUREX prototypes. This leads to a ToF resolution definitively larger than the expected 310 ps.

Further studies have shown that independently of the use of long light guides, the scintillating elements were not as performing as those of the prototype MUREX. However a replacement of the scintillators of the ring A before the 2012 data taking was not feasible.

**Time calibration procedure:** The tuning of the time calibration constants can be performed using reactions in which the detection of the forward outgoing particles in the spectrometer determines accurately the recoil...
4.2 The 2012 DVCS pilot run

Fig. 46: This plot shows two typical fits to different PMT signal shapes, each derived from the average of many tracks crossing one B ring element near the upstream (black curve) and downstream (red curve) end. A correction to the response of the constant fraction algorithm needs to be applied in order to compensate for this signal shape variation.

Table 9: Properties of the scintillators slabs of MUREX and CAMERA detectors.

<table>
<thead>
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<th>MUREX</th>
<th>CAMERA</th>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
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<td>material</td>
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</tr>
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<td>thickness (cm)</td>
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<td>fish tail</td>
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<td>160</td>
</tr>
<tr>
<td>ToF resolution (ps)</td>
<td>310</td>
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</table>
Fig. 47: \((Q^2, x_B)\) kinematic domain (in green) covered for \(y = (E_\mu - E_\mu')/E_\mu\) ranging from 0.9 to 0.05. The colored circles indicate various outgoing muon angles.

Fig. 48: B barrel proton energy loss versus velocity \(\beta\) for the \(\mu p \rightarrow \mu \rho^0 p\) reaction.

Proton kinematics. For this purpose, exclusive reactions with a large cross-sections like elastic \(\pi p \rightarrow \pi p\) scattering or \(\mu p \rightarrow \mu pp^0\) production are the most convenient. However, the experimental set-up for the DVCS measurement provides a poor resolution for the longitudinal vertex position in the case of two-body reactions at very small angles. For this reason, the elastic \(\pi p\) scattering reaction cannot be used for precise calibration.

Therefore, the three-body reaction \(\mu p \rightarrow \mu pp^0\) has been chosen for the CAMERA calibration. A kinematic fitting procedure has also been developed for this three-body reaction, which greatly improves the accuracy in the determination of the recoiling proton kinematics. Figure 48 shows the proton energy loss in B versus the proton velocity.

Proton momentum resolution: The kinematic fitting procedure applied to the observables measured in the spectrometer for the three-body reaction \(\mu p \rightarrow \mu pp^0\) allows us to determine the proton observables. They are considered as references and resolutions for proton momentum and for proton track position are determined as the difference between the observables measured by CAMERA and these references.

The momentum resolution \(\sigma(dP/P)\) (not yet deconvoluted from the reference resolution) was significantly improved after applying position and amplitude dependent pulse shape corrections. With the present understanding of the complex calibrations procedure \(\sigma(dP/P)\) varies from 6% at 300 MeV/c to about 13% at 700 MeV/c (Fig. 49 top), instead of the expected 4% at 300 MeV/c and 10% at 700 MeV/c. A small shift of the momentum of about 2% is still present after all corrections for energy losses in the target (Fig. 49 bottom). The mean values for the resolution in position and in polar angle are presented in Fig. 50. This is the result of a very recent work, which provides a major step in the understanding of the precise timing determination. Further improvements are still under development.

Impact of CAMERA and efficiencies: The impact of CAMERA on the reconstruction of the \(\mu p \rightarrow \mu \rho^0 p\) exclusive reaction is illustrated in Fig. 51. Without the use of CAMERA the exclusive reaction can be identified by detecting the incident and outgoing muons and the \(\rho^0\) meson using a cut on the missing energy:

\[
E_{\text{miss}} = (M_{\text{miss}}^2 - M_p^2)/2M_p
\]

where the missing particle defined by \(\vec{P}_{\text{miss}} = \vec{P}_\mu - \vec{P}_{\mu'} - \vec{P}_{\rho^0}\) should be a proton of mass \(M_p\). The contribution of non-exclusive events appears on the right of the missing energy peak and increases with the transfer \(t\) or the transverse momentum (with respect to the virtual photon direction) \(p_T\) of the vector meson \(\rho^0\). Detection of protons in CAMERA allows two additional cuts corresponding to differences between azimuthal angles and
4.2 The 2012 DVCS pilot run

Fig. 49: Momentum resolution $\sigma(\Delta P/P)$ (top) and shift of the evaluated momentum (bottom) as a function of the proton momentum. Note that the resolution effect of the reference is not subtracted.

Fig. 50: Resolution in position for rings A (top) and B (middle) and for polar angle (down). Note that the resolution effect of the reference is not subtracted.

The 2012 DVCS pilot run between transverse momenta of the proton given by the forward spectrometer or by CAMERA:

$$\Delta \phi = \phi_{\text{miss}} - \phi_{\text{CAMERA}} \quad \text{and} \quad \Delta p_T = |p_T^{\text{miss}}| - |p_T^{\text{CAMERA}}|,$$

where $p_T$ denotes the momentum in the transverse plane with respect to the incident muon direction and $\phi$ the azimuthal angle around this direction. As expected, these cuts significantly reduce the non-exclusive background. The resulting efficiency of CAMERA seems reasonably good ($\sim 76\pm2\%$) for $p_T \leq 0.8$ GeV/c. This value includes the contribution of the scintillator efficiencies, of the geometrical dead zones between each scintillator, and the contribution of nuclear reactions. On the other hand, for proton momenta above 270 MeV/c the angular acceptance of CAMERA covers the full kinematical range of the reactions under study.

The efficiency of each scintillator has been studied individually. A selection of protons from $\mu p \rightarrow \mu p^0 p$ exclusive events in the geometrical acceptance of a sector $A_iB_j$, identified by their position and typical energy loss in the scintillator $B_j$ provides a reference sample to study the efficiency of the scintillator $A_i$. Results for A and B efficiencies are shown in Fig. 52 for the various slabs. The mean efficiency is $0.82\pm0.01$ for the ring A and $0.94\pm0.01$ for the ring B, giving an overall efficiency of $0.77\pm0.01$ in agreement with the global measurement.
Fig. 51: Two distribution of $E_{\text{miss}}^{\mu p-\mu \rho^0 X} = \frac{M_{\text{miss}}^2 - m_p^2}{2m_p} = E_{\gamma \mu} - E_{\rho^0} + t/2m_p$ for two ranges in transverse momentum. The data in black (red) represent exclusive events reconstructed without (with) CAMERA, after subtraction of the non-exclusive background.

Fig. 52: Efficiencies of each scintillator of the ring A (left) and of the ring B (right).
4.2 The 2012 DVCS pilot run

Fig. 53: \( \pi^0 \) peak in the invariant mass \( \gamma \gamma \) spectrum (MeV) obtained after calibration with the pion beam for ECAL0 (left), ECAL1 (middle), and ECAL2 (right).

Conclusion for the ToF performances: The proton momentum resolution achieved at the present stage of the analysis has not yet reached the expectation. An additional ToF can be performed between a high-flux SciFi station on the beam axis and the B ring to help reaching the 300ps design resolution. It was partially implemented during the DVCS2012 data taking, and is being studied. Even with this proposed solution the Ring A is still mandatory to perform offline coincidence AiBj to suppress the strong background. The use of the information of one side only of the scintillators (up or down) is also being studied to improve the efficiency.

Following our studies, we do not necessarily foresee the exchange of the ring A slabs if the solution comprising the beam detector provides the expected accuracy. The analysis is ongoing and a decision will be taken by the end of this year.

4.2.2 Electromagnetic calorimeters

Calibration of ECAL0, ECAL1, ECAL2: A part of the new ECAL0, consisting of 56 modules (about 25% of total under construction at JINR), was placed 1.5 m downstream of the LH2 target. ECAL0 was designed to extend the available photon acceptance towards large angles and allows the detection of photon signals for energies as low as 100 MeV, an important feature for efficient background rejection for DVCS measurements, as outlined later. A calibration of ECAL0 was performed using the \( \pi^0 \) produced by the 190 GeV/c \( \pi^- \) beam impinging on the LH2 target. The calibration coefficients were determined by reconstructing the \( \pi^0 \) mass peak from its two-photon decay, and comparing it to its nominal value, as illustrated in Fig. 53 (width of about 10 MeV).

In order to match the angular acceptance of ECAL1 to that of ECAL2, the size of the central hole of ECAL1 was reduced, both horizontally and vertically by inserting 208 new radiation-hard Shashlik modules. After \( \pi^0 \) calibration, \( \pi^0 \) widths of 10 and 5 MeV are observed in ECAL1 and ECAL2, respectively (Fig. 53).

Better determination of time and amplitude for signals in ECAL1: Many ECAL1 modules in the central part (called GAMs) were found to be particularly noisy. Figure 54 (left) shows the ratio \( R \) between the number of events correlated with the trigger time and the number of random events in each module of ECAL1. \( R \) varies from 4 for good cells to 0.1 for bad cells in the central part of ECAL1 even for an energy threshold as high as 1 GeV (the threshold should be 300 MeV to collect at best all \( \pi^0 \) events which pollute DVCS events). For comparison, typical values of \( R \) of 7 for ECAL0 and 9 for ECAL2 are obtained in similar conditions.

An elaborated though fast algorithm based on a Fourier transform analysis of the pulse shape was developed in order to extract the precise amplitude and time of the signal. The comparison of time and amplitude obtained from the two methods (pulse shape analysis method and classic method) is presented in Fig. 55. The figure on left shows that noisy events, mainly with low amplitude, are characterized in the Fourier analysis by a smaller amplitude. Such an analysis will allow to decrease further the energy threshold. The impact of the Fourier analysis is illustrated in Fig. 54. The values of \( R \) increase to 45 and 13 for the good and bad cells, respectively. The method is currently under test and the efficiency and robustness of the filtering is being evaluated.
Fig. 54: Factor $R$ of number of correlated events over the number of random events in each module of the central part of ECAL1, before and after the Fourier analysis of the pulse shape.

Fig. 55: Comparison between Fourier analysis and classic method for amplitude (left) and time (right) for the central part of ECAL1.
4.2 The 2012 DVCS pilot run

Fig. 56: Stability of the DIS event (left) and the semi-inclusive $\pi^0$ production (right) yields per run (indicated with the numbers 108xxx) during the two first weeks of data taking W44 and W45 for $\mu^+$ and $\mu^-$ beams.

4.2.3 Muon flux determination and stability of the detectors

The DVCS experiment relies on the comparison between measurements made with positive and negative muon beams. The flux must be determined to better than 3%, a difficult task at high rates, since the positive muon flux is 2.6 times higher than the negative muon one. Beam tracks from random triggers are used for the determination. The measured fluxes, $4.1 \times 10^8 \mu^+$/spill and $1.6 \times 10^8 \mu^-$/spill, are in good agreement with the values used for the projected errors. However the accuracy of better than 3% is not yet reached. Systematic effects persist, e.g., the flux depends on the software analysis window. When the window varies from $[-2; 3]$ ns to $[-5; 5]$ ns, the $\mu^+$ and $\mu^-$ fluxes vary by 2% and 1% respectively.

The stability of the number of DIS events and semi-inclusive $\pi^0$ using $\mu^+$ and $\mu^-$ beams is presented in Fig. 56 for runs from the two first weeks of data taking. The DAQ dead time and the veto dead times (28% and 11% for $\mu^+$ and $\mu^-$ beam respectively) are taken into account. The DIS event yield is stable within an accuracy of 2% and is independent of the charge of the beam while the $\pi^0$ yield varies within 10% and indicates an evolution with the beam charge. Work is still in progress to understand these deviations.

Vertex reconstruction and Target position: The vertex is used to study the target position (Fig. 57). The beam ($\varnothing = 2$ cm) crosses the target ($\varnothing = 4$ cm) surrounded by a cryostat container ($\varnothing = 8$ cm). The target cell walls indicate that the extreme end of the target falls downward and should be supported by an extra spacer for the next data taking period in 2016. On the other hand, the data do not show any visible indication of an incomplete filling of the target.

4.2.4 Next plans for the DVCS2012 analysis

All the DVCS 2012 data are produced with preliminary calibrations. For CAMERA, the raw data have been kept for the next steps of the analysis, that are:

- Production of the calibration constants of CAMERA for all the runs. The method is being finalized, integrating all the last developments.
- Pulse shape analysis method: being implemented into the general ECAL software framework. Some potential for improvement is still investigated, also whether it may be used for ECAL2.
- Determination of the muon flux of each run: ongoing.
- Study of the stability of detectors: ongoing.
- Production of MC data with LEPTO and HEPGEN for DIS, SIDIS and exclusive events in order to evaluate acceptance corrections. A GEANT4 software is being prepared.
- Determination of DIS cross section using both $\mu^+$ and $\mu^-$ data with different fluxes.
Fig. 57: Vertex distribution $x$, $z$ (up left) and $y$, $z$ (up right); $z$ is along the beam, and $y$ vertical. The end of the target falls downward. Positions in $x$ (bottom left) and in $y$ (bottom right) of the calculated target centre versus $z$.

- Determination of the BH, DVCS and $\pi^0$ cross sections as a function of $x_{Bj}$.
- Study of the $t$-dependence of the sum of the DVCS cross sections induced with $\mu^+$ and $\mu^-$ beams.

5 Hardware preparation for the 2014 Drell-Yan run

The features of the COMPASS DY experiment are the following:

- a high-rate 190 GeV/$c\pi^-$ beam reaching up to $10^8\pi^-$/s, chosen to provide $\bar{u}$ in the valence region.
- a transversely polarized NH$_3$ proton target, thus allowing to study the reaction $\pi^-p^1 \rightarrow \mu^+\mu^-X$.
- an hadron absorber to stop the non interacting beam and hadrons produced in the target, allowing higher beam fluxes.
- a trigger system based on the detection of a multimuon final state.
- a beam telescope radiation hard and with excellent time resolution.

The rest of the setup coincides with the one used both for the SIDIS, DVCS and hadron spectroscopy measurements. For the DY experiment a massive hadron absorber downstream of the target reduces radiation and detector occupancy problems. Therefore, the polarised target has to be moved upstream by about 2.3 m including all services.

The set-up for the 2014 DY run is shown in Fig. 58. On the top figure is shown the side view of the spectrometer till SM2, the second spectrometer magnet. Well visible are the target magnet (in pink) and the absorber (green/purple) surrounded by the concrete shielding in gray. The bottom figures show the top view and top-left view of the target area.

In the following we review the main activities in preparation for the DY run that will start on the 15th of October, this year.

5.1 Magnet repair and installation of the PT target

The magnet system is repaired and upgraded. Since the last report, the repair was finished and many improvements to consolidate the magnet were applied:

- complete replacement of the electrical circuits inside the cryostat;
Fig. 58: (Top) side view of the COMPASS DY setup. Visible are the target magnet (in pink) and the absorber (green/purple) surrounded by the concrete shielding in gray. (Bottom) top and top-left views of the target area.
HARDWARE PREPARATION FOR THE 2014 DRELL-YAN RUN

– thermal insulation of the cold mass inside the cryostat was improved by removing thermal bridges to the outside vessel;
– extra cry-cooler head in contact with the thermal shielding added to decrease temperature gradients and to speed up the magnet cooling;
– new current leads and turret and new instrumentation turret;
– improvements on the cooling circuits both on the liquid He vessel and on the thermal shield;

Moreover to accommodate the new control system a modular platform was built, to be used both for the tests in 180 and for the final installation in 888.

The magnet was closed in December and pressure tested the same month. In the first months of 2014 the control system was commissioned and the magnet cooled down to superconducting temperature and tests were performed up to the middle of March. The main test results an results are:

– electrical insulation between coils and to ground ok;
– all coils show field including the shim coils;
– all shim coils energized up to 4A and show field and right polarity;
– dipole ramped to nominal and discharge tested;
– solenoid ramped to nominal and slow dump tested;
– solenoid fast dump tested at 200A and all is fully functional;
– all bridge and SQD quench detectors functional and balances adjusted;
– all instrumentation correct with the exception of one temperature sensor on the helium vessel;
– simulation of magnet behavior on fault conditions extensively simulated which gave us the confidence that it can taken back into normal operation.

It was therefore prooven that the system works as foreseen and is fully functional for generating the required magnetic field. The magnet was moved to 888 by the end of April and presently the work for reinstalling it is ongoing. Images of the consolidation work and on the tests in 180 are shown in Fig. 59.

We have renewed the heat-exchangers of the $^3$He pumping system that were aged. These heat exchangers are in direct contact with the $^3$He needed to cool the target material down to 50 mK reached for the frozen spin mode and therefore their leak tightness is vital for the run of the experiment. Fig. 60 shows the degree of aging of the old heat-exchangers and some of the new elements produced by Pfeiffer.

During the 2014-15 DY run we will use a two cell target setup, with a separation of 20 cm between the cells, in order to cope with the reduced vertex resolution given by the presence of the hadron absorber. The preparation of the new target is ongoing; in Fig. 61 the elements need to construct the target are shown; the two target cells, the coils for polarization measurements and the microwave stopper between the cells. For the DY measurement on polarized protons the NH$_3$ material will be used as previously because it has a higher dilution factor than alcohol materials and a higher resistance of the polarization against radiation damage, a point which is relevant for DY.

For the DY run, the main difference compared to previous measurements will be the use of a pion beam. This constitutes radiation issues for the NH$_3$ material itself but also for the target container materials (nylon, Kevlar, PCT-FE,...)

The energy dose expected from the ionizing radiations was calculated for the conditions of the DY run for the various areas around the target. Then, radiation tests have been made at the Jülich proton cyclotron (E = 45MeV)
Fig. 59: (top left) The cold mass inserted back inside the vessel after the repair and the improvements in the thermal separation. (top right) The new turrets for the current leads and for the signal wire together with the new cryo-cooler and the patch panel for all the signal wires. (middle left) The magnet fully cabled prepared for the working test. (middle right) The new control system prepared for the powering test. (bottom) The magnet on the PT platform in 888 with the services being reinstalled.
Fig. 60: Old (left) and new heat exchangers for the $^3$He pumping system.

Fig. 61: Elements for the construction of the new two cell target: the two target cells, the coils for polarization measurements and the microwave stopper between the cells.
at 100 Gy and up to 20 000 Gy. The results show that there is no effect (100 Gy) for NMR electronics, nor for

temperature sensors inside the target. It has still to be checked for temperature sensors outside the target. No

visible damage (20 000 Gy) was observed on the material for the target containers. However, radiation effects

may be more serious at low temperature (healing effects reduced, experience from NH3 material itself).

Concerning the polarization itself, the expectations are the following. The intensity of the pion beam will be

slightly higher than the muon one, but the heat import will be much higher for the hadron interactions in the
target (the target corresponds to about 1 interaction length). The reduction in polarisation will be therefore
higher due to heat import: 5 ÷ 10 mW bringing the target temperature to 80 ÷ 100 mK, compared to usual
50 ÷ 60 mK in frozen spin mode for the muon beam. To monitor the polarization, there will be 2 NMR coils
inside the target, and 3 outside. Protection sleeves are being developed for the inner coils using a 51 μm thick
PCT-FE foil, an hydrogen free material. It was checked that it does not induce an NMR signal.

The overall project is on good tracks.

5.2 New DAQ preparation

After more than 10 years of successful operation the DAQ system required a serious upgrade. A multi port PCI
technology, a back bone of the system, became obsolete. The DATE software requires a serious revision for
porting to SLC6, which was not planned by the developers. The COMPASS DAQ group has developed a new
system based on hardware event builder together with a set of software packages for control and monitoring.
The system architecture is shown in figure 62. The event builder is implemented in nine FPGA modules, one
of the modules is shown in figure 63. The first eight modules perform data concentration by merging sub
events from up to 15 front-end modules. The ninth module receives assembled sub-events from the first eight
modules, completes the event building, and distributes them to up to eight online computers. The sustained
system bandwidth is 1.5 GBytes/s. In photo 64 is shown a test-stand of the new DAQ. All hardware components
of the new DAQ, except 20 HOLA slink cards, are at place. The HOLA cards are expected to be delivered in
the beginning of July.

Currently the new DAQ system is being integrated into the experiment. It’s expected to commission the DAQ
together with all detectors’ front-end electronics in July during first 2014 data taking run.

Fig. 62: A new DAQ architecture.

5.3 DC5 construction and installation

The construction of the large size DC5 drift chamber has started at UIUC, Illinois, at ODU and at CERN. The
detector is built following plans and experience from the DC4 existing detector.

The time lines are the following. All necessary procurements are now realized. Using the new milling machine
purchased on purpose, the milling of the anode frames has started (G10 material) at full speed; then the cathode
frames and the other parts will follow. Phases of the construction of DC5 are shown in Fig. 65 top and middle.

It is foreseen to ship the cathode package from UIUC to CERN by end June so that the cathodes (stretching,
painting, etc..) can be done from June to August. The Saclay stretching machine is also being shipped from
Saclay to CERN The anode planes which are prepared at ODU should be sent to CERN by end of August. The final assembly of all pieces and the test of the detector are foreseen in the COMPASS clean area from mid August to October 6. Then DC5 will be moved into the 888 experimental hall, the installation and commissioning foreseen till October 20.

In parallel the finalization and production of the front end electronics is proceeding well. It will use CMAD and GANDALF modules. The noise level of the FEMs was tested on DC01 (smaller size chamber) and then DC04 at CERN. The 1-sigma noise level of DC01/DC04 +FEE was found to be around 1 fC, and the noise rate of most of channels at 4 fC, below 1kHz. These results satisfying the requirements, the mass production of DC5 FEE has been ordered. FEE will be delivered and installed before October. The front end electronics FEM and intermediate DCM module are shown in Fig. 65 (bottom).

Today, we think that DC5 can be finished in time to be installed in the 888 experimental area at the beginning of the 2014 run. However, since the schedule is extremely tight, we will take the decision on the installation by mid-July. Consequently, we will decide on removing or keeping the existing straw detectors for the 2-month run.

5.4 Absorber and vertex SciFi construction and installation

As said before, for the DY experiment a massive hadron absorber downstream of the target reduces radiation and detector occupancy problems. The absorber consists of a tungsten core surrounded by alumina (Al$_2$O$_3$), which minimises multiple scattering. This is essential to disentangle reactions in the oppositely polarised target cells by means of track reconstruction. The sketch of the absorber, some images of the construction and the absorber at CERN ready for installation are shown in Fig. 66. The installation will take place in the first week of July.

A new SciFi detector sitting between the nose of the rest of the absorber will improve the vertex resolution considerably. This vertex detector (Fig. 67 for some images of the construction) has been prepared by the HISKP group in Bonn and by the University of Erlangen and will be installed in August. The design and some images of the construction are shown in Fig. 67.
Fig. 65: (Top) Preparation of the G10 frames. (Middle) preparation of PCB the U plane on the stiffening frame. (Bottom) Modules of the front end electronics.
Fig. 66: (Top) Sketch of the hadron absorber. (Middle left and right) Phases of the construction of 1 of the 10 modules in Al and Al₂O₃ of the hadron absorber by the INFN in Torino. (Bottom left) The cradle that will house the absorber, together with the nose of the absorber entering the downstream conical flange of the superconducting magnet. (Bottom right) The fully assembled absorber at CERN.
Fig. 67: (Top) Sketch of the vertex detector. (Bottom left and center) Preparation and test of the fibers of one of the planes. (Bottom right) Housing of the SciFi vertex detector.
6 Publications and Presentation to Conferences

Publications


Presentation to Conferences:

- 138 presentations to Conferences and Workshops in 2013;
- 55 presentations to Conferences or Workshops in 2014, till June 20.
References


[7] COMPASS Collaboration, Odd and Even Partial Waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^-p \rightarrow \eta^{(\prime)}\pi^-p$ at 191 GeV/$c$, to be submitted to Phys. Lett. B.


