Luminosity Measurement at COMPASS

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The measurement of absolutely normalized cross sections for high-energy scattering processes is an important reference for theoretical models. This paper discusses the first determination of the luminosity for data of the COMPASS experiment, which is the basis for such measurements. The resulting normalization is validated via the determination of the structure function F_2 from COMPASS data, which is compared to literature.

1 Introduction

COMPASS [1] is a fixed-target experiment at the CERN SPS which investigates the spin structure of nucleons and hadron spectroscopy with high-intensity muon and hadron beams. Nucleon spin-structure measurements are performed by scattering polarized muons off polarized solid-state targets (^{6}LiD or NH_3). COMPASS has published several important results in this field, for instance on gluon polarization from hadron-pair production with high transverse momenta (high-p_T) [2] and from open-charm production [3], on the spin-dependent structure function g_1 [4], on Collins and Sivers asymmetries [5], or on quark helicity distributions in nucleons [6]. These results have been obtained from direct measurements of double-spin asymmetries in which the absolute luminosity normalization cancels. Measurements of absolute interaction cross sections were not yet performed because the experiment does not have a dedicated luminosity monitor. However, such measurements provide important benchmarks for the ability of theoretical models to describe experimental data from high energy physics experiments. Examples are cross sections for high-p_T particle production, open-charm production, or exclusive photon production in the future Deeply Virtual Compton Scattering (DVCS) program of COMPASS-II [7]. The analysis presented here was performed in the framework of the measurement of the cross section for quasi-real photo-production of charged hadrons with high p_T in muon-deuteron scattering. The unpolarized and polarized cross sections for this process have been calculated in next-to-leading order perturbative quantum chromodynamics (NLO pQCD) [8]. A comparison of the calculated polarized cross section with the experimental spin asymmetries can be used to constrain the gluon-polarization distribution $\Delta g/g(x_g)$, which is an input for the calculation. Before this extraction can be carried out with confidence, the theory first has to be capable of correctly predicting the unpolarized cross section, which will soon be published by the COMPASS collaboration.

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This paper discusses the underlying estimation of the luminosity for the COMPASS data and presents a validation of the result via the measurement of the well known cross section for inclusive muon scattering. The paper is structured as follows: The terminology of cross section and luminosity measurements in the context of COMPASS is introduced in Sec. 2. The used data set is described in Sec. 3, followed by the data selection criteria in Sec. 4. Section 5 describes the measurement of the beam flux and is followed by Sec. 6 which explains the sources of dead times in the measurement and their corrections. Section 7 discusses the determination of the structure function F_2 using the resulting integrated luminosity. The comparison of the results to a parametrization obtained from measurements of F_2 by the NMC experiment [9] confirms that the COMPASS luminosity has been correctly determined within a systematic uncertainty of 10%. The normalized data set can hence be used to measure new and unknown unpolarized cross sections.

2 Luminosity

The interaction cross section for the observation of a particular final state is defined as:

$$\sigma = \frac{\dot{N}}{\mathcal{L}} = \frac{N}{L} \tag{1}$$

with the rate of occurrence of the final state $\dot{N}$ and the instantaneous luminosity $\mathcal{L}$ (and their respective time integrals N and L). For fixed target experiments, the instantaneous luminosity is defined as

$$\mathcal{L} = \Phi_{\text{beam}} \cdot N_{\text{target}} = \frac{R_{\text{beam}}}{A_{\text{target}}} \cdot N_{\text{target}} \tag{2}$$

where Φ_{beam} (R_{beam}) is the beam flux (rate) through the fiducial target volume, A_{target} is the area of the fiducial target, and N_{target} is the number of target nucleons in the fiducial target volume. The fiducial target volume is defined as the part of the target volume which is retained after the geometrical cuts on the primary vertices. Only event with beam tracks which cross the full length of the fiducial target volume are used for the analysis.

The observation of final states can be affected by misreconstruction of kinematical variables, detection inefficiencies, and dead times in which the experiment can not record events. The kinematical smearing and the detection inefficiencies, which are mostly due to incomplete geometrical coverage of the phase space by the detectors and trigger elements, are summarized in the acceptance correction factor ϵ. The cross section is then given as

$$\sigma = \frac{\tilde{N}/\epsilon}{\tilde{L}} \tag{3}$$

with the number of *observed* final states $\tilde{N}$ and the effective integrated luminosity $\tilde{L}$, which is corrected for the dead times of the experiment.

The COMPASS beam is delivered by the SPS accelerator in so-called spills[1]. In the 2004 beam time, when the discussed data set was taken, COMPASS was supplied with spills of muon beam of length 4.8 s, followed by breaks of 12 s. The dead times in the data taking caused by the

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[1] the term *spill* denotes an extraction from the accelerator.

data acquisition system (DAQ) and the veto system of the scattered-muon trigger [10] are rate dependent. Since the intensity of different spills can vary considerably, the dead times need to be corrected on a spill-by-spill basis. The acceptance correction factor ϵ, which is obtained from a Monte Carlo simulation of the experiment with a constant beam rate assumption, only includes effects which are not or only weakly rate dependent. All rate-dependent effects are absorbed into the definition of the effective integrated luminosity of a spill i

$$\tilde{L}_i = \int_{\text{time in spill } i} [\mathcal{L}_i(1 - d_{i,\text{DAQ}})(1 - d_{i,\text{veto}})]dt. \tag{4}$$

where $d_{i,\text{DAQ}}$ is the DAQ dead time, i.e. the fraction of data taking time in which the DAQ can not accept triggers because it is busy with readout of previously triggered events, and $d_{i,\text{veto}}$ is the dead time of the veto system of the muon trigger, i.e. the duty cycle of the veto signal (for details see Sec. 6). The total integrated luminosity $\tilde{L}$ is the sum over all spills which are used for the extraction of the number of final states $\tilde{N}$.

3 Data Set

The analyzed data set was recorded in 2004. This particular choice is motivated by the fact that the measurement of the hadron production cross section depends on semi-inclusive trigger systems which include the response of the two hadronic calorimeters of COMPASS. After the introduction of a new electromagnetic calorimeter (ECAL1) after the 2004 beam time, the efficiencies of these triggers have been compromised, which would make an absolutely normalized measurement more difficult, while spin asymmetry measurements are not affected. In the 2004 beam time, COMPASS was supplied with a tertiary polarized μ^+-beam at $160\,\text{GeV/c}$ with a nominal intensity of $40 \cdot 10^6\,\text{s}^{-1}$. The momenta of individual beam particles were measured with scintillator hodoscopes surrounding three beam-line dipole magnets (Beam Momentum Station). The target consisted of two oppositely polarized cells of ^{6}LiD granulate in a liquid helium bath. Each cell had a length of $60\,\text{cm}$ and a diameter of $3\,\text{cm}$. About 30% of the 2004 data set have been reprocessed with a newer version of the event reconstruction software CORAL, in which a small inefficiency in the reconstruction code of the beam momentum measurement system has been cured. Only this portion of the data set is considered for the luminosity analysis.

Due to an accelerator problem, COMPASS received only half of its nominal beam intensity for half of the data taking time under consideration here. Although this seems like an unpleasant problem to deal with at first glance, it provides a valuable tool to check the consistency of the obtained luminosity result. Although many rate-dependent factors enter in the luminosity determination, cross sections measured with the two different beam intensities have to be identical. It is shown in Sec. 7 that this is in fact the case.

4 Data Selection

After the beam intensity increases over the first second of each spill, it is stable within $\sim 10\%$. It is known that the COMPASS beam from the SPS can be poorly debunched in this period, which makes the estimations of dead times very difficult because beam and halo particles are not independent in their relative timing anymore. As the corrections shall be applied as scaling
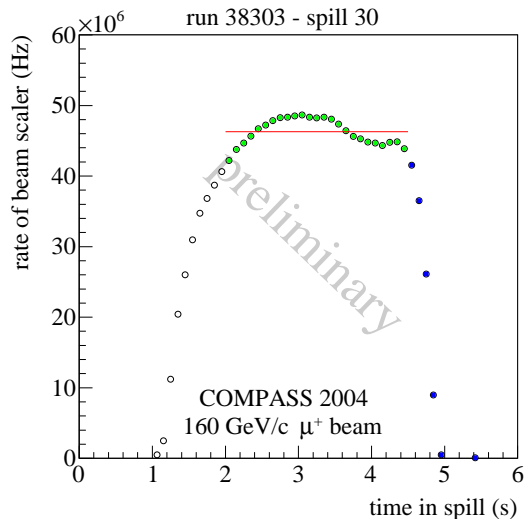
Figure 1: Spill structure for spill 30 of run 38303. The green markers indicate time bins which are used for the analysis starting at $t_1 = 2\,\mathrm{s}$. The blue markers indicate bins which are excluded by the t_2 cut ($t_{30,2} = 4.5\,\mathrm{s}$). The red line indicates the average rate.
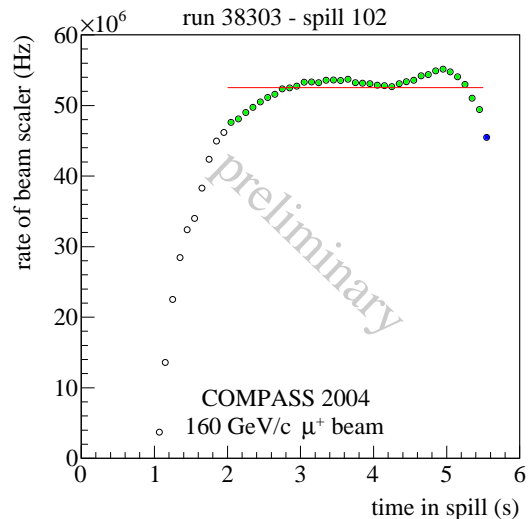

Figure 2: Spill structure for spill 102 of run 38303 ($t_{102,2} = 5.5\,\mathrm{s}$).

factors for each spill, only the flat top of the beam is selected for the normalized analysis. The flat top of spills is defined to start at time $t_1 = 2\,\mathrm{s}$ after the begin-of-spill signal from the SPS. The length of the flat top can vary between different spills. Thus, the time in spill i after which the data is discarded from the analysis, $t_{i,2}$, is determined for each spill individually. $t_{i,2}$ is defined as the time when the instantaneous beam rate in the spill has dropped below 90% of the average beam rate in the spill. The rate of incident beam particles is measured by a scaler which counts the number of signals from a scintillating fiber detector which is located just in front of the target (FI02Y). Figures 1 and 2 show two examples of spills with different average intensities and lengths.

The removal of spills which are affected by detector or data processing problems is essential for the determination of a correct luminosity for cross section measurements. Spills are removed from the data sample if they fall below their neighboring spills in one of the following four figures of merit:

- Number of primary vertices per reconstructed event.

- Number of outgoing tracks in the primary vertex per reconstructed event.

- Number of beam tracks per reconstructed event.

- Ratio of the number of reconstructed events in the spill over the number of triggered events during data taking. This criterion removes spills which are affected by very rarely occurring crashes of the reconstruction software or losses of data files due to tape problems.

The first three criteria are also applied in all COMPASS spin-asymmetry analyses, whereas the last criterion is just needed for absolutely normalized analyses. After these strict quality cuts, 54624 of 73591 spills are retained and are further used for the luminosity determination and cross section analyses.

5 Beam Flux Measurement

The rate of particles measured with the scaler on FI02Y, R_{Sc}, does not equal the rate of beam particles R_{beam} from equation (2) because not all beam particles which cross the beam counter also cross the complete length of the fiducial target volume. The geometrical acceptance of the target w.r.t. the COMPASS muon beam is 65%. Furthermore, the rate measurement with the scaler system and the beam counter can be affected by detection inefficiencies and dead times. A calibration of R_{Sc} with an unbiased measurement of R_{beam} is thus required. This calibration is performed on a sub-sample of twelve runs by counting the number of reconstructed beam tracks in random-trigger events[2]. The rate of beam particles measured in random-trigger events is

$$R_{\text{beam}} = \frac{N_{\text{beam tracks}}}{\Delta t \cdot N_{\text{random triggers}}} \tag{5}$$

with the time window $\Delta t = 3.8\,\text{ns}$ in which the detectors in the beam telescope are fully sensitive to traversing beam particles. $N_{\text{beam tracks}}$ counts the beam particles which are retained after the fiducial target cut and the requirement of a beam momentum measurement. The efficiency of the beam momentum reconstruction is 93% [1]. The small inefficiency is automatically included in the beam rate measurement from random-trigger events so that the resulting luminosity will correctly contain only the portion of the beam which is usable for the measurement of the yield of final states $\tilde{N}$ in equation (3). About every sixth random trigger contains a reconstructed beam track at nominal intensity. The resulting calibration is shown in Fig. 3. The rate dependence of the calibration constants is due to dead times in the scaler system. The difference of the calibration between the half and full intensity runs of more than 10% proves to be correct in the comparison of the inclusive muon scattering cross section in Sec. 7. The systematic error on this calibration factor is conservatively estimated to be 5%, which is given by the RMS of the twelve data points.

The rate of recorded random triggers, which was about $100/(t_{i,2} - t_1)$ per spill in the 2004 beam time, will be increased for future measurements for which a good luminosity normalization is required, e.g. the DVCS measurement. The beam flux will be estimated with negligible systematic uncertainty, if several thousand reconstructed beam tracks per spill are recorded in random-trigger events.

6 Corrections for Dead Times

The DAQ dead time $d_{i,\text{DAQ}}$ from equation (4) is defined as the fraction of data taking time in spill i in which no events can be recorded because the DAQ system is busy with the acquisition of data from previously triggered events. It is measured without any uncertainty in COMPASS

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[2]random triggers lead to a read-out of all detector electronics and are completely uncorrelated to the presence of beam tracks or scattering events.
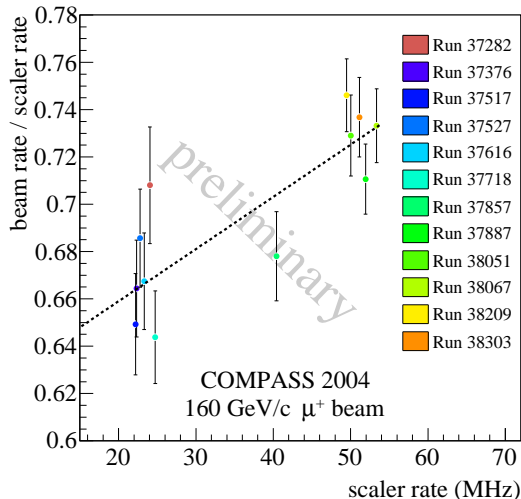
Figure 3: Calibration factor between R_{beam} and R_{Sc} as a function of R_{Sc}. The rate dependence is due to dead times in the scaler system. The dashed line indicates the function used for the spill-by-spill beam flux calibration.

by counting the number of trigger attempts which were accepted by the DAQ system and the total number of trigger attempts. The ratio of those two numbers gives the life time $1 - d_{i,\mathrm{DAQ}}$ of the system. It is measured in each spill in the flat top of the beam ($t \in [t_1, t_{i,2}]$, see Sec. 4). The trigger rate during the 2004 run at full intensity was about $11\,\mathrm{kHz}$ which resulted in a DAQ dead time of 9%.

The second source of dead times in the COMPASS experiment is the veto system of the muon triggers. These consist of coincidences between scintillator-hodoscope pairs with target pointing for different scattering kinematics. The hodoscopes are shielded by iron and concrete absorbers to ensure muon identification. The veto counters surround the beam region upstream of the target to ensure that the trigger coincidence was not due to one of the numerous halo tracks of the muon beam, for details please be referred to [10]. The veto dead time is defined as the fraction of data taking time during which no triggers can be accepted because veto signals are present, i.e. the duty cycle of the veto signal. The number of veto pulses in the flat top of each spill is counted with a scaler system. In combination with the gate width distribution of the individual signals contributing to the veto system, which is shown for one run in Fig. 4, it allows the calculation of the duty cycle. Figure 5 presents the resulting dead times for the same twelve runs that were used for the beam flux estimation. The linear function fitted to the data is used to estimate the veto dead time for all spills used in the analysis. The absolute systematic error of the veto dead time is estimated to be 0.03, which arises from the maximal difference with other measurements of the veto dead time during data taking [11].
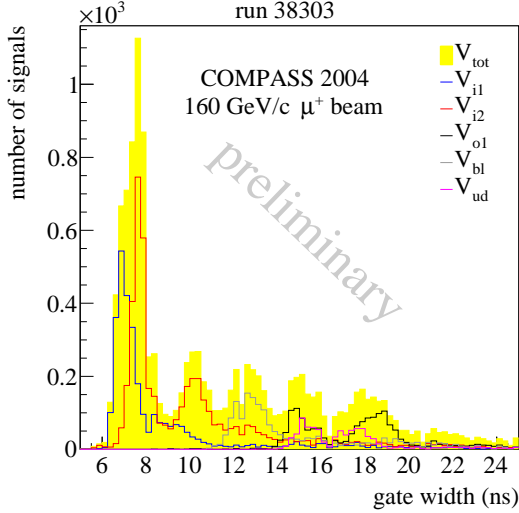
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Figure 4: Gate width distribution of the veto signals. The signal V_{tot} is made from a logical or of the individual veto signals V_{i1} to V_{ud}. The veto counters close to the beam have shorter gates, but fire with higher rates than the more remote counters.
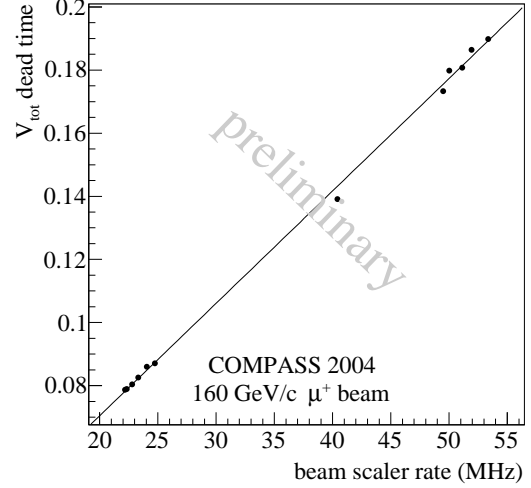
Figure 5: Veto dead time as a function of the beam scaler rate. At full intensity, the dead time reaches a maximum of 19%.

7 Luminosity Results and Determination of the Structure Function F_2

The COMPASS target in the 2004 data taking consisted (by number of nucleons) of 42.3% deuterium, 42.5% lithium, and 15.2% helium. The number of nucleons per unit area was $3.44 \cdot 10^{25}\,\text{cm}^{-2}$ [12] which was measured with a relative systematic uncertainty of 2%. The relative systematic uncertainty of the beam flux calibration is 5%. The reconstruction efficiency has a relative systematic error of 1.8%, and the veto dead time is measured with an absolute uncertainty of 0.03. From these individual contributions, the overall systematic uncertainty is conservatively estimated to be 10%.

The effective integrated luminosity for the discussed data sample, corrected for the DAQ dead time, is $\tilde{L} = 142.4\,\text{pb}^{-1}$. The correction for the veto dead time reduces this number to $122.6\,\text{pb}^{-1}$. Please note that not all triggers in COMPASS include the full veto system. The triggers for the quasi-real photo-production regime ($Q^2 < 0.5\,(\text{GeV/c})^2$, where Q^2 is the negative four momentum transfer of the muon), which are used for the soon to-be-released high-p_T hadron production cross section, are subject to a much lower veto dead time. The so-called inclusive middle trigger is used for the determination of the cross section for inclusive muon scattering and the subsequent extraction of the structure function F_2 in the deeply-inelastic scattering regime at $Q^2 > 1\,(\text{GeV/c})^2$. The scintillator hodoscopes contributing to this trigger are fully efficient. Events are accepted if the beam energy is $E_\mu \in [140, 180]\,\text{GeV}$ and the relative energy loss of the muon $y = (E_\mu - E_{\mu'})/E_\mu$ is greater than 0.1. Furthermore, the extrapolated beam track is required to cross the full length of the fiducial target volume

(same cut as in the beam flux determination of Sec. 5) and the muon scattering vertex position must lie in the fiducial target volume.

The acceptance factor $\epsilon = \epsilon(Q^2, y)$ from equation (3) is applied as a weighting factor on an event-by-event basis. It has been determined with a Monte Carlo simulation of inclusive muon scattering in the COMPASS experiment. The event generator LEPTO [13] has been used with the parton distribution functions from MSTW 2008 [14], including F_L. The generated events have been transported through the spectrometer with a GEANT3 [15] based program and analyzed with the same reconstruction software (CORAL) which is used for processing real experimental data. The acceptance as a function of Q^2 and y is shown in Fig. 6. It reaches a maximum of 66% which is mostly due to the partial phase space coverage of the selected muon trigger hodoscopes. A comparison of kinematical distributions of reconstructed Monte Carlo events and real data events, as shown in Fig. 7, indicates slight disagreements of up to 10% in some kinematical regions. This points towards an incomplete description of the acceptance of the same order of magnitude. Since it is the sole purpose of this analysis to check whether the normalization of the luminosity is correct within the systematic uncertainty of 10%, this disagreement has not been further investigated.

The structure function F_2 of the nucleon is given by the cross section for inclusive scattering with kinematical factors in the following way:

$$F_2(x_{\mathrm{Bj}}, Q^2) = \frac{d^2\sigma_{1\gamma}(x_{\mathrm{Bj}}, Q^2, E_\mu)}{dx_{\mathrm{Bj}}dQ^2} \frac{x_{\mathrm{Bj}} \cdot Q^4}{4\pi\alpha^2} \tag{6}$$

$$\cdot \{1 - y(x_{\mathrm{Bj}}, Q^2, E_\mu) - \frac{Q^2}{4E_\mu^2} + (1 - \frac{2m^2}{Q^2} \cdot \frac{y(x_{\mathrm{Bj}}, Q^2, E_\mu)^2 + Q^2/E_\mu^2}{2[1 + R(x_{\mathrm{Bj}}, Q^2)]})\}^{-1} \tag{7}$$

with the one-photon exchange (Born) cross section $\sigma_{1\gamma}$, the muon mass m, the Bjorken scaling variable x_{Bj}, the fine structure constant α, and the ratio of the longitudinal and transverse virtual photon absorption cross sections[3] $R(x_{\mathrm{Bj}}, Q^2)$. Since the experiments use different targets and do not measure the Born cross section directly, so-called radiative corrections have to be applied to the data. For a detailed discussion, please see [17]. The radiative event weight in a bin (x_{Bj}, Q^2) is defined as

$$\eta(x_{\mathrm{Bj}}, Q^2) = \frac{\sigma_{1\gamma}(x_{\mathrm{Bj}}, Q^2)}{\sigma_{\mathrm{measured}}(x_{\mathrm{Bj}}, Q^2)}.$$

The values are taken from analyses in the NMC experiment [16]. The corrections are $< 15\%$ in the selected kinematical range ($y < 0.5$). The fact that these corrections have not been iterated with the new COMPASS measurement is another reason why the extraction of F_2 presented here is not to be regarded as a new precision measurement. Nuclear effects on F_2 are negligible in the selected kinematical range. The measured structure function can thus be directly compared to values of the structure function of the deuteron F_2^{d} which are taken from a parametrization from the NMC experiment which covers the complete kinematical reach of the presented data. The ratio of the COMPASS result and the NMC parametrization is presented in Fig. 8 for eleven bins of x_{Bj}. The gray bands indicate the normalization uncertainty of 10% from the luminosity determination. The ratios lie within the bands thus proving consistency with the NMC result.

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[3] the same parametrization which had been used for the NMC F_2 extraction [16] was applied.
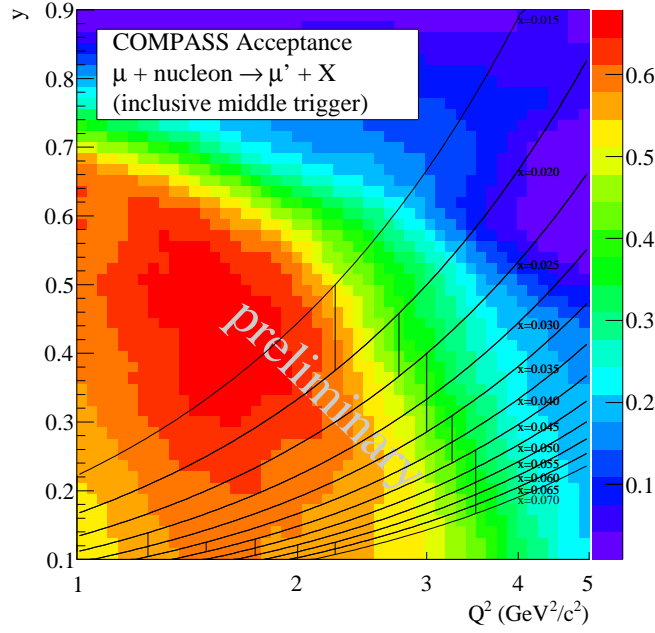
Figure 6: Acceptance for inclusive muon scattering in the inclusive middle trigger of COMPASS. It is determined with a Monte Carlo simulation consisting of LEPTO and GEANT3. The x_{Bj}-bins used in the analysis are indicated by the lines in the plot.
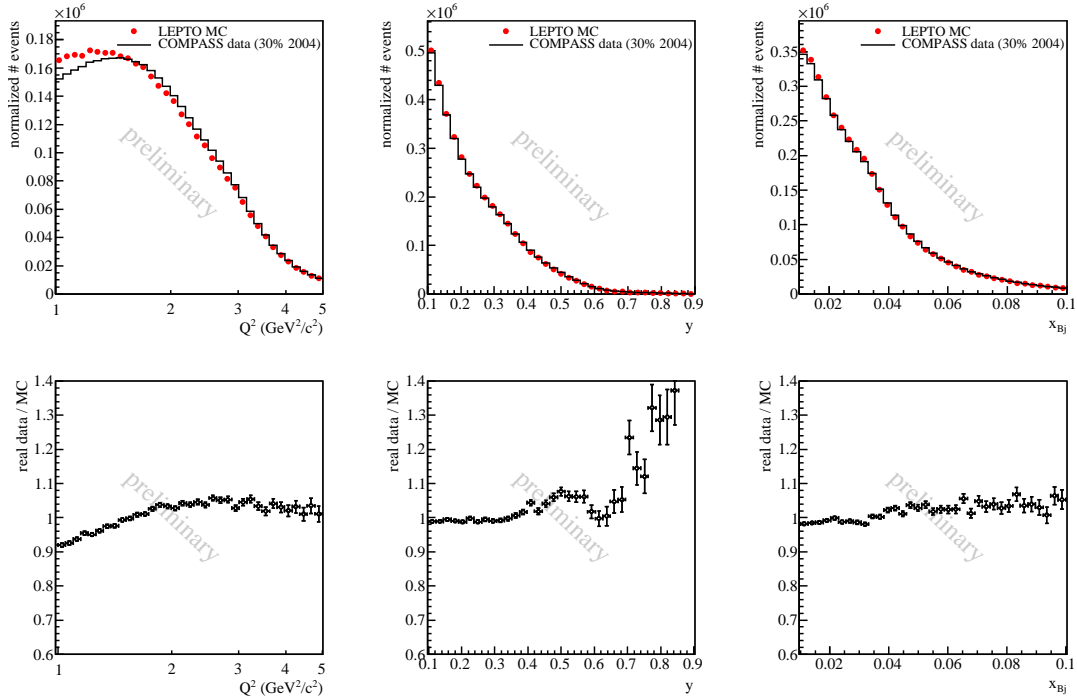

Figure 7: Comparison of real data (radiative correction applied) and Monte Carlo simulation in three kinematical variables. The slight deviation from unity might hint towards an incomplete description of the acceptance.

9

Half of the presented data set was taken with 50% of the nominal beam intensity due to an accelerator problem in the 2004 beam time. Many rate dependent factors enter in the luminosity determination. A comparison of F_2 determined from the two data sets with different beam intensities provides an important consistency check for the correctness of the result. Figure 9 shows this comparison in which no deviations from unity are visible.

8 Conclusions and Outlook

A method to determine the luminosity for data from the COMPASS experiment, taking into account corrections for all dead times and inefficiencies, has been developed. The luminosity for about 30% of the 2004 muon-deuteron scattering data set has been determined with a systematic error of 10%. The structure function F_2 has been determined via the cross section for inclusive scattering. A comparison of the result with a parametrization of F_2 from the NMC experiment proves that the normalization is correct within this uncertainty. The data set can hence be used for the determination of unknown cross sections with an effective integrated luminosity of $142.2\,\mathrm{pb}^{-1}$. The COMPASS experiment will soon publish the unpolarized cross section for the quasi-real photo-production of charged hadrons with high transverse momenta. This result will provide an important benchmark for the applicability of perturbative QCD calculations which are and will be used for accessing many aspects on the (spin-)structure of the nucleon in COMPASS. Future measurements of other cross sections, for instance in the DVCS program of COMPASS-II, will also be based on the techniques presented here. Improvements on the beam-flux measurement with a higher random-trigger rate and better measurements of the veto dead time will significantly reduce the systematic uncertainty of the luminosity measurement.

References

[1] P. Abbon et al. (COMPASS Collaboration), Nucl. Instr. Meth. A **577**, (2007) 455

[2] E.S. Ageev (COMPASS Collaboration), Phys. Lett. B **633**, (2006) 25

[3] M. Alekseev (COMPASS Collaboration), Phys. Lett. B **676**, (2009) 31

[4] M. Alekseev (COMPASS Collaboration), Phys. Lett. B **690**, (2010) 466

[5] M. Alekseev (COMPASS Collaboration), Phys. Lett. B **692**, (2010) 240

[6] M. Alekseev (COMPASS Collaboration), Phys. Lett. B **693**, (2010) 227

[7] COMPASS Collaboration, CERN-SPSC-2010-014, (2010)

[8] B. Jäger et al., Eur. Phys. J. C **44**, (2005) 533

[9] M. Arneodo et al. (NMC Collaboration), Phys. Lett. B **364**, (1995) 107

[10] C. Bernet et al., Nucl. Instr. Meth. A **550**, (2005) 217

[11] J. Pretz, private communication (COMPASS run logbook), (2004)

[12] J. Koivuniemi, private communication (COMPASS ELOG), (2009)

[13] G. Ingelmann et al., Comput. Phys. Commun. **101**, (1997) 108

[14] A. D. Martin et al., Eur. Phys. J. C **63**, (2009) 189

[15] GEANT - Detector Description and Simulation Tool, CERN Program Library W5013 (1993)

[16] B. Badelek, private communication, (2010)

[17] B. Badelek et al., Z. Phys. C Part. Fields **66**, (1995) 591
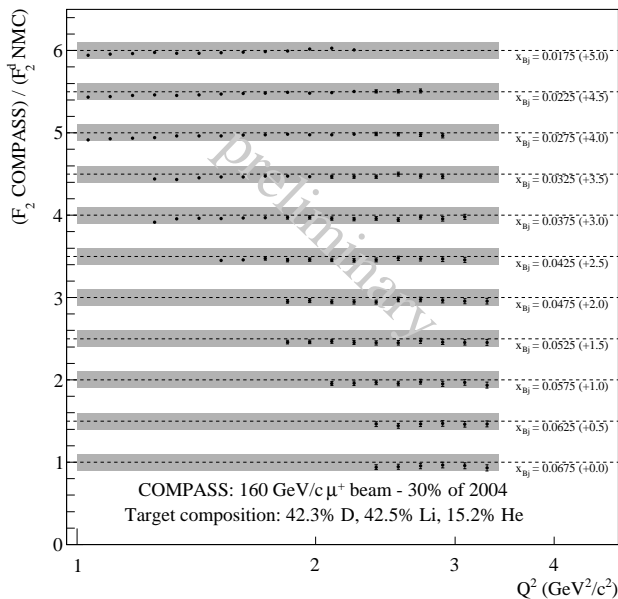
Figure 8: Comparison of the structure function F_2 extracted from COMPASS data with the parametrization from NMC [9]. The ratios for the individual x_{Bj} bins are offset by constant factors as indicated on the right hand side of the plot. The gray bands indicate the 10% normalization uncertainty arising from the systematic error on the luminosity. All value lie within the bands, thus proving consistency with the NMC result. The slight deviations from unity at the lower values of Q^2 can be due to wrong descriptions of the acceptance and to the fact that the radiative corrections have not been iterated.
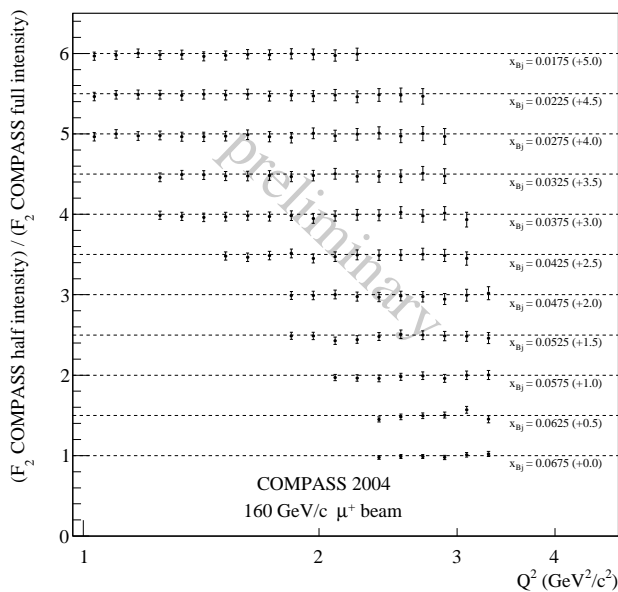

Figure 9: Comparison of F_2 determined from COMPASS with half and full beam intensities. The ratios for the individual x_{Bj} bins are offset by constant factors as indicated on the right hand side of the plot. Despite the many rate dependent factors that enter into the luminosity estimation, the results are fully consistent with each other.